Published for SISSA by Springer

Received: July 24, 2023
Accepted: September 14, 2023
Published: October 3, 2023

Search for a new heavy scalar particle decaying into a Higgs boson and a new scalar singlet in final states with one or two light leptons and a pair of τ-leptons with the ATLAS detector

The ATLAS collaboration

E-mail: atlas.publications@cern.ch

Abstract: A search for a new heavy scalar particle X decaying into a Standard Model (SM) Higgs boson and a new singlet scalar particle S is presented. The search uses a proton-proton (pp) collision data sample with an integrated luminosity of 140 fb^{-1} recorded at a centre-of-mass energy of $\sqrt{s} = 13$ TeV with the ATLAS detector at the Large Hadron Collider. The most sensitive mass parameter space is explored in X mass ranging from 500 to 1500 GeV, with the corresponding S mass in the range 200–500 GeV. The search selects events with two hadronically decaying τ-lepton candidates from $H \to \tau^+\tau^-$ decays and one or two light leptons ($\ell = e, \mu$) from $S \to VV$ ($V = W, Z$) decays while the remaining V boson decays hadronically or to neutrinos. A multivariate discriminant based on event kinematics is used to separate the signal from the background. No excess is observed beyond the expected SM background and 95% confidence level upper limits between 72 fb and 542 fb are derived on the cross-section $\sigma(pp \to X \to SH)$ assuming the same SM-Higgs boson-like decay branching ratios for the $S \to VV$ decay. Upper limits on the visible cross-sections $\sigma(pp \to X \to SH \to WW\tau\tau)$ and $\sigma(pp \to X \to SH \to ZZ\tau\tau)$ are also set in the ranges 3–26 fb and 6–33 fb, respectively.

Keywords: Hadron-Hadron Scattering

ArXiv ePrint: 2307.11120

Article funded by SCOAP^3.

https://doi.org/10.1007/JHEP10(2023)009

Contents

1 Introduction

The discovery of the Higgs boson (H) in 2012 [1, 2] by the ATLAS [3] and CMS [4] collaborations at the Large Hadron Collider (LHC) has led to a comprehensive programme of measurements and searches using proton-proton (pp) collision data. All measurements to date are consistent with the prediction of the Standard Model (SM) [5–8].

Many beyond-the-SM (BSM) theories predict the existence of a heavy scalar boson decaying into two Higgs bosons or additional scalars in an extended Higgs sector. Searches [9–12] for these scalars have been published by the ATLAS and CMS collaborations. The BSM scenarios tested include the two-Higgs-doublet model (2HDM) [13], the Minimal Supersymmetric Standard Model (MSSM) [14], and the extensions of the 2HDM model with a new singlet scalar (2HDM+S) [15, 16]. In the simplest extension of the MSSM, the Next-to-Minimal Supersymmetric Standard Model (NMSSM), an additional gauge singlet is introduced to generate the μ-term coupling to the superpotential dynamically and this leads to an enriched Higgs sector with two additional neutral Higgs bosons [17, 18]. The BSM models hypothesize the existence of a new scalar singlet, S, in the processes $X \to SH$, SS

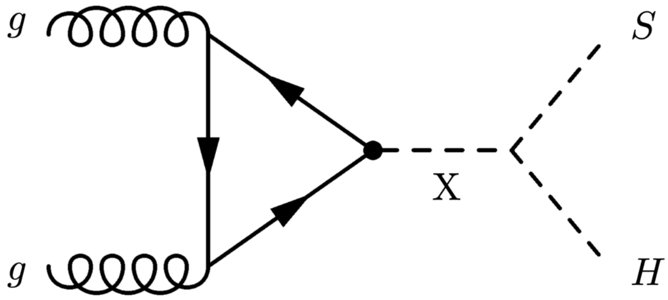


Figure 1. Representative diagram that contributes to $X \to SH$ production via the gluon fusion process.

where X is a heavy CP-even scalar boson produced predominantly through the gluon-gluon fusion process (ggF) [19]. The decay of the singlet scalar S is assumed to have the same relative couplings as a SM-Higgs boson of the specified mass. It can be produced via decay mode $X \to SH$ as shown in figure 1.

This study focuses on the decay $X \to SH$, assuming X masses range from 500 to 1500 GeV, while S is assumed to have a mass range from 200 to 500 GeV and decays predominantly into $W^{\pm}W^{\mp}$ and ZZ with the SM-Higgs boson-like decay branching ratios [20]. The search is performed by selecting events containing two hadronically decaying τ-lepton candidates (τ_{had}) from $H \to \tau^+\tau^-$ decays and one or two light leptons ($\ell = e$, μ) from $S \to WW$, ZZ decays. This signature-based search is the first of its kind and is competitive with other searches using the final states $VVbb$, $VV\gamma\gamma$, $bb\tau\tau$ [7], and $bbbb$ [8] in the high mass regions. A direct comparison between them is not possible due to the unknown branching fractions for S decays, but each provides independent constraints on the BSM models. To improve background rejection, a multivariate technique based on boosted decision trees (BDTs) is used to discriminate between signal and background based on their different kinematic distributions. Upper limits are set at the 95% confidence level (CL) on the model-dependent cross section $\sigma(pp \to X \to SH)$ and on the model-independent $\sigma(pp \to X \to SH \to WW\tau\tau)$ and $\sigma(pp \to X \to SH \to ZZ\tau\tau)$ cross sections.

2 ATLAS detector

The ATLAS detector [3] at the LHC covers almost the entire solid angle around the collision point.[1] It consists of an inner tracking detector surrounded by a thin superconducting solenoid that produces a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three large toroid magnet assemblies with eight coils each. The inner detector contains a high-granularity silicon pixel detector, including the

---

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

insertable B-layer [21–23] added as a new innermost layer in 2014, and a silicon microstrip tracker. Together they enable the precise reconstruction of tracks of charged particles in the pseudorapidity range $|\eta| < 2.5$. The inner detector also includes a transition radiation tracker that provides tracking and electron identification for $|\eta| < 2.0$. The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. Within the region $|\eta| < 3.2$, electromagnetic calorimetry is provided by barrel and endcap high-granularity lead/liquid-argon (LAr) sampling calorimeters, with an additional thin LAr presampler covering $|\eta| < 1.8$ to correct for energy loss in material upstream of the calorimeters. Hadronic calorimetry is provided by a steel/scintillator-tile calorimeter, segmented into three barrel structures in the region $|\eta| < 1.7$, and two copper/LAr hadronic endcap calorimeters. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules optimised for electromagnetic and hadronic measurements, respectively. The calorimeters are surrounded by a muon spectrometer in a magnetic field provided by air-core toroid magnets with a bending integral of about 2.5 T m in the barrel and up to 6.0 T m in the endcaps. The muon spectrometer measures the trajectories of muons in the region $|\eta| < 2.7$ using multiple layers of high-precision tracking chambers, and it is instrumented with separate trigger chambers that cover $|\eta| < 2.4$. A two-level trigger system [24], consisting of a hardware-based level-1 trigger followed by a software-based high-level trigger, is used to reduce the event rate to a maximum of around 1 kHz for offline storage. An extensive software suite [25] is used in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

3 Data and Monte Carlo simulation samples

The search is based on a data sample of pp collisions at $\sqrt{s} = 13$ TeV with 25 ns bunch spacing collected from 2015 to 2018, corresponding to an integrated luminosity of 140 fb^{-1}. Only events recorded with a single-electron trigger, a single-muon trigger, or a dilepton trigger [26–29] under stable beam conditions and for which all detector subsystems were operational are considered for analysis. The average number of pp interactions per bunch crossing in this dataset ranges from 8 to 45, with a mean of 24.

Events produced in the generic 2HDM+S model are considered as signals, where the kinematic parameters are model-independent, and the results can be interpreted in other BSM models. Events are generated to leading-order (LO) accuracy with Pythia8.2 [30] for matrix element calculation and use the NNPDF2.3 LO set of parton distribution functions (PDF) [31]. Parton showering (PS) and hadronisation are also simulated using the Pythia8.2 generator with the A14 tune [32] and using the same NNPDF2.3 LO PDF set. The detector response is simulated using AltFastII [33], which uses a fast, parameterised simulation of the calorimeter response. Two scalars, X and S, are assumed to have a narrow width relative to the experimental resolution. The heavier boson X is constrained to decay only to S and H, and S decays to a pair of W or Z bosons. The S decays to SM particles are assumed to be the same as those of a SM Higgs boson of the specified mass. To suppress QCD multijet backgrounds, only semileptonic and fully leptonic decays of WW pairs are considered in the analysis. For ZZ decays, the two-lepton final state is considered, with one Z decaying into two light leptons and the other into a pair of neutrinos or jets. The SM Higgs boson from the X decay is required to decay into a pair of τ-leptons. Thus three dedicated samples are generated independently by forcing $S \to WW$ or $S \to ZZ$ decays in the following final states: $\tau\tau + WW(\ell\nu q\bar{q}')$, $\tau\tau + WW(\ell\nu\ell\nu)$ and $\tau\tau + Z(\ell\ell)Z(q\bar{q}, \nu\nu)$. The choice of m_S considered is set to 200 GeV to enable S decay to on-shell W or Z boson pairs and up to 500 GeV to have a narrow width approximation. The background contribution limits the lower bound of m_X (500 GeV) while the upper bound of m_X (1500 GeV) is required to be in the resolvable $H \to \tau\tau$ decay region. Eighteen mass points corresponding to various combinations of m_X and m_S values for each of the three final states are generated to cover the most interesting phase space, and are enumerated in grids (in GeV) of m_X = [500, 750, 1000, 1250, 1500] for m_S = [200, 300] and m_X = [750, 1000, 1250, 1500] for m_S = [400, 500]. Simulated SM non-resonant HH from the ggF process is also generated, for the systematic studies of the $X \to SH$ signals, using the POWHEG-BOX v2 generator at the next-leading order (NLO) [34, 35] with the NNPDF2.3 LO PDF set and interfaced with PYTHIA8.2 for PS and hadronisation.

Monte Carlo (MC) simulation samples were produced for the different background processes. The dominant background is from falsely identified tau leptons originating from jets. The irreducible background with a real tau-lepton contribution is dominated by diboson processes that produce $\tau\tau$ pairs. The effects of additional pp collisions in the same or a nearby bunch crossing (pile-up) is modelled using events from minimum-bias interactions generated with PYTHIA8.1 [36] using the NNPDF2.3 LO set of PDFs and the A3 set of tuned parameters [37], and overlaid onto the simulated hard-scatter events according to the luminosity profile of the recorded data. The generated events were processed through a detailed simulation [38] of the ATLAS detector geometry and response using GEANT4 [39] and processed with the same reconstruction software as the data. Corrections were applied to the simulated events so that the selection efficiencies, energy scales, and energy resolutions of particle candidates match those determined from data control samples. The simulated samples are normalised to their SM cross sections, computed to the highest available order in perturbation theory.

The $t\bar{t}W$ and $t\bar{t}Z/\gamma^*$ samples are generated using the MADGRAPH5_AMC@NLO v2.6.2 [40] generator, which provides matrix elements at NLO in the strong coupling constant α_S with the NNPDF3.0 NLO PDF set [31]. The functional forms of the renormalisation and factorisation scales are set to $\mu_r = \mu_f = m_{\mathrm{T}}/4$ where m_{T} is defined as the scalar sum of the transverse masses $\sqrt{m^2 + p_{\mathrm{T}}^2}$ of the particles generated from the matrix element calculation. The events are interfaced with PYTHIA8.2 [30] for the parton shower (PS) and hadronisation, using the A14 set of tuned parameters and the NNPDF2.3 LO PDF set.

The $t\bar{t}H$ process is obtained from the POWHEG-BOX v2.0 generator at NLO and interfaced with PYTHIA8.2 for the parton showering and fragmentation with the A14 tune. This sample uses the NNPDF3.0 NLO PDF set.

Higgs boson production in association with a vector boson (WH or ZH, collectively referred to as VH) was simulated using POWHEG-BOX v2 with the NNPDF3.0 NLO PDF set and interfaced with PYTHIA8.2 for PS and non-perturbative effects. Separate

W^+H, W^-H, $qq \to ZH$ and $gg \to ZH$ samples are produced. The cross section is normalised at the next-to-next-to-leading order (NNLO) in QCD with NLO electroweak corrections for $q\bar{q} \to VH$ and at NLO and next-to-leading-logarithm accuracy in QCD for $gg \to ZH$ [41, 42].

The $t\bar{t}$ events are generated with POWHEG-BOX v2.0 and interfaced with PYTHIA8.2 for the parton showering and fragmentation with the A14 tune. The PDF set of NNPDF3.0 NLO is used. The single top-quark events are simulated with POWHEG-BOX v2.0 with the NNPDF3.0 NLO PDF set and interfaced with PYTHIA8.2, where the interference between Wt ad $t\bar{t}$ production is handled with the Diagram Removal (DR) procedure [43].

A dedicated $t\bar{t}$ sample including rare $t \to Wb\gamma^*(\to l^+l^-)$ radiative decays, $t\bar{t} \to W^+bW^-\bar{b}l^+l^-$, is generated using a MADGRAPH5_AMC@LO matrix element requiring $m(l^+l^-) > 1$ GeV and interfaced with PYTHIA8.2. In this sample, the photon can be radiated from the top quark, the W boson, or the b-quark. Both the $t\bar{t}Z/\gamma^*$ and $t\bar{t} \to W^+bW^-\bar{b}l^+l^-$ samples are combined and together form the "$t\bar{t}Z$ (high mass)" sample. The contribution from internal photon conversions ($\gamma^* \to l^+l^-$) with $m(l^+l^-) < 1$ GeV is modelled with SHERPA 2.2.11 [44] through QED multiphoton radiation via the PS in an inclusive $t\bar{t}$ sample and is referred to as "$t\bar{t}\gamma^*$ (low mass)" sample.

Diboson backgrounds are generated and normalised using the cross sections computed by SHERPA 2.2.2 [44] using the NNPDF3.0 NNLO PDF set and showered using Sherpa's default setting. The cross section is computed at NNLO accuracy in QCD and includes the electroweak (EW) corrections at NLO accuracy. The processes of W and Z production associated with jets (V+jets) are simulated with SHERPA 2.2.1 [44] using the NNPDF3.0 NNLO PDF and showered by the SHERPA built-in implementation using matrix elements for up to two additional jets at NLO and up to four additional jets at LO. The cross section used to normalise the simulation is calculated at NNLO accuracy in QCD and includes EW corrections at NLO accuracy. Low-mass Drell-Yan $m_{\ell\ell}$ production is also included.

The MC background samples are divided into five categories: data-driven fake τ_{had} , $t\bar{t}H$, $t\bar{t}V$, diboson, and 'others,' which includes $t\bar{t}$, V+jets, low-mass Drell-Yan, VH, Wt, and other small backgrounds.

4 Object reconstruction

Events are required to have at least one primary vertex with a minimum of two associated tracks, each with a transverse momentum (p_{T}) larger than 500 MeV. The primary vertex of an event is defined as the vertex with the highest scalar sum of squared transverse momenta of the associated tracks [45].

Electrons are reconstructed by matching tracks reconstructed in the inner detector (ID) to topological clusters of energy deposits in the electromagnetic calorimeter. They are required to have $p_{\text{T}} > 10$ GeV and $|\eta| < 2.47$, and to be outside the transition region between the barrel and endcap calorimeters, $1.37 < |\eta| < 1.52$. Electron candidates must satisfy a *Loose* likelihood-based identification requirement [46]. Additional requirements on the associated track p_{T} and the ratio of the electron's calorimeter energy and the track momentum are applied to electrons to suppress photon conversions. Electrons with incorrect charge assignments (arising from asymmetric photon conversions) are rejected using a BDT discriminant based on calorimeter and tracking quantities. An efficiency of 95% for electrons with correct charge assignment is obtained with a rejection factor of ~ 17 for electrons with incorrect charge assignment [46, 47].

Muon candidates are reconstructed from tracks in the muon spectrometer (MS) matched to tracks found in the ID. They are required to have $p_{\mathrm{T}} > 10$ GeV and $|\eta| < 2.5$ and to satisfy *Loose* identification requirements [48] based on the numbers of hits in the different ID and MS subsystems and on the significance of the charge-to-momentum ratio q/p.

Electrons (muons) are required to have associated tracks satisfying $|d_0|/\sigma_{d_0} < 5(3)$ and $|z_0 \sin\theta| < 0.5$ mm, where d_0 is the transverse impact parameter relative to the beam line, and z_0 is the longitudinal impact parameter relative to the primary vertex.

Jets are reconstructed using the anti-k_t jet clustering algorithm [49, 50] with a radius parameter of $R = 0.4$, applied to topological energy clusters [51, 52] and charged-particle tracks, processed using a particle-flow algorithm [53]. The reconstructed jets are corrected by the application of jet energy scale (JES) and resolution (JER) calibrations derived from simulation and in situ corrections based on $\sqrt{s} = 13$ TeV data [54, 55]. Only jet candidates with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$ are considered. Jets with $p_{\mathrm{T}} < 60$ GeV and $|\eta| < 2.4$ originating from pile-up are suppressed by the use of the jet vertex tagger (JVT) [56]. Quality criteria are imposed to reject events containing jets from non-collision backgrounds and calorimeter noise [57].

Jets containing b-hadrons (b-jets) are identified with the DL1r tagger algorithm [58, 59], a multivariate discriminant based on inputs such as the impact parameters of displaced tracks and the reconstructed secondary vertices in the jet. Working points are defined with different target efficiencies for tagging b-jets from an inclusive $t\bar{t}$ sample. This analysis uses the 77% b-tagging working point to veto b-jets.

The reconstruction of the hadronically decaying τ-lepton candidates (τ_{had}) is seeded by jets reconstructed with an anti-k_t algorithm using calibrated topological clusters with a radius parameter of $R = 0.4$ [51, 60]. They are required to have $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.5$, excluding the transition region between the barrel and endcap calorimeters ($1.37 < |\eta| < 1.52$). The τ_{had} candidates are required to have one or three associated tracks and a total charge of ± 1. An identification algorithm based on a recurrent neural network (RNN) [61] discriminates the visible decay products of the τ_{had} candidates from jets initiated by quarks or gluons. The τ_{had} candidates are required to satisfy the RNN *Medium* identification working point in the signal regions, corresponding to an efficiency of 75% (60%) for candidates with one (three) associated track(s). The efficiency is optimized to be flat as a function of the τ_{had} p_{T} and pile-up. A dedicated BDT discriminant is used to reject electrons misidentified as hadronic tau decays. To suppress fake τ_{had} candidates from muons, the candidates that overlap with low-p_{T} reconstructed muons are vetoed. Efficiency scale factors for the reconstruction, identification, and electron BDT rejection are applied to τ_{had} candidates in simulation [62].

Anti-τ_{had} candidates are defined to estimate the background from jets misidentified as τ_{had}, as described in section 7. They are required to satisfy the RNN *Very Loose* identification working point but fail the nominal RNN requirement applied to the τ_{had} candidates.

An overlap removal procedure is applied when two reconstructed objects are close in ΔR to avoid double-counting of objects.

Isolation criteria are applied to electrons and muons to suppress contributions from semileptonic decays of heavy-flavour hadrons or jets misidentified as leptons, collectively referred as non-prompt leptons, after the overlap removal procedure. A BDT discriminant is trained based on isolation and b-tagging variables and is referred to as the non-prompt lepton BDT [63]. The light leptons must satisfy the *Loose* BDT working point to reject non-prompt leptons.

The missing transverse momentum $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ (with magnitude E_T^{miss}) is defined as the negative vector sum of the $\vec{p}_{\mathrm{T}}$ of all selected and calibrated objects in the event, including a term to account for soft particles that are not associated with any of the selected objects. This soft term is calculated from ID tracks matched to the selected primary vertex to make it more resilient to contamination from pile-up interactions [64].

JHEP10(2023)009

5 Event selection

In this search three signal regions (SR) are considered, referred to as $WW1\ell 2\tau_{\mathrm{had}}$, $WW2\ell 2\tau_{\mathrm{had}}$, and $ZZ2\ell 2\tau_{\mathrm{had}}$ channels. Events in the $WW2\ell 2\tau_{\mathrm{had}}$ and $ZZ2\ell 2\tau_{\mathrm{had}}$ channels contain exactly two light leptons with opposite-sign electric charges, while events in the $WW1\ell 2\tau_{\mathrm{had}}$ channel contain exactly one light lepton.

Selected events must satisfy either the un-prescaled single lepton (SL) or dilepton (DL) triggers. The SL triggers are required in the $WW1\ell 2\tau_{\mathrm{had}}$ channel while a logical "or" between SL and DL triggers is required for the $WW2\ell 2\tau_{\mathrm{had}}$ and $ZZ2\ell 2\tau_{\mathrm{had}}$ channels. The offline reconstructed light leptons in the event must be matched to the trigger-level objects that caused the event to pass the trigger(s). The reconstructed light lepton p_{T} must exceed the threshold set for the online trigger object by at least 1 GeV to avoid threshold biases [63].

A Z candidate must be present in the $ZZ2\ell 2\tau_{\mathrm{had}}$ channel. It is defined by two leptons of the same flavour and opposite charge with an invariant mass that is consistent with the Z boson mass, $|m_{\ell\ell} - m_Z| < 10$ GeV. In the $WW2\ell 2\tau_{\mathrm{had}}$ channel the dilepton invariant mass must satisfy $m_{\ell\ell} > 12$ GeV and $Z \to \ell\ell$ candidates are vetoed.

For each channel, exactly two RNN medium τ_{had} candidates of opposite charge with $p_{\mathrm{T}} > 20$ GeV are required. The angular distance between the two τ_{had} candidates is required to satisfy $\Delta R_{(\tau_0,\tau_1)} \leq 2$ to suppress V+jets background events.

The event selection for each channel is summarised in table 1. A multivariate (MVA) technique is employed in all channels to enhance the sensitivity by discriminating signals from the SM background processes. The description of the MVA strategy is given in section 6.

Same-sign validation regions (VR) are also selected using the same event selection as in the signal regions, except that the two τ_{had} candidates must have the same charge (SS). In this VR, the signal contribution is negligible, and the background modelling can be checked using data.

Channels	Selections
$WW1\ell 2\tau_{\mathrm{had}}$	exactly one light lepton (electron or muon): $p_{\mathrm{T}} > 27$ GeV, $\lvert\eta\rvert < 2.5$ exactly two RNN medium τ_{had} with opposite-sign: $p_{\mathrm{T}} > 20$ GeV, $\lvert\eta\rvert < 2.5$ ΔR between two τ_{had} candidates: $\Delta R_{(\tau_0,\tau_1)} \leq 2$ number of jets and b-jets: $N_{\mathrm{jets}} \geq 2$ and $N_{b-\mathrm{jets}} == 0$
$WW2\ell 2\tau_{\mathrm{had}}$	exactly two light leptons with opposite-sign: $p_{\mathrm{T}} > 10$ GeV, $\lvert\eta\rvert < 2.5$ exactly two RNN medium τ_{had} with opposite-sign: $p_{\mathrm{T}} > 20$ GeV, $\lvert\eta\rvert < 2.5$ invariant dilepton mass: $m_{\ell\ell} > 12$ GeV Z-veto ($\lvert m_{\ell\ell} - m_Z\rvert > 10$ GeV) for same-flavour leptons $\Delta R_{(\tau_0,\tau_1)} \leq 2$ $N_{b-\mathrm{jets}} == 0$
$ZZ2\ell 2\tau_{\mathrm{had}}$	exactly two same-flavour light leptons with opposite-sign: $p_{\mathrm{T}} > 10$ GeV, $\lvert\eta\rvert < 2.5$ exactly two RNN medium τ_{had} with opposite-sign: $p_{\mathrm{T}} > 20$ GeV, $\lvert\eta\rvert < 2.5$ Z-peak selection ($\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV) $\Delta R_{(\tau_0,\tau_1)} \leq 2$ $N_{b-\mathrm{jets}} == 0$

Table 1. Selection criteria applied in the $WW1\ell 2\tau_{\mathrm{had}}$, $WW2\ell 2\tau_{\mathrm{had}}$ and $ZZ2\ell 2\tau_{\mathrm{had}}$ signal regions where m_Z=91.2 GeV is used.

6 Multivariate discriminant

Boosted decision trees implemented in the Toolkit for Multivariate Analysis (TMVA) [65] are used in each SR to improve the separation between signal and background. In the training process, all signal and background events are divided into independent training and test samples to avoid possible biases. To simplify the training procedure across the 18 mass hypotheses of X and S particles, a parameterised BDTG method [66] is used. This method trains a BDT using several m_X samples with the same m_S by including their generated m_X mass as an input parameter while the m_X values of background events are assigned randomly to match the signal population. The choice made for the parameterisation of the BDT is motivated by the fact that the signal kinematics are driven by the two-body decay $X \to SH$ for the given m_S. The training algorithm incorporates the m_X parameter so the BDT is parameterised in m_X for given m_S. This procedure is performed separately in three channels ($WW1\ell 2\tau_{\mathrm{had}}$, $WW2\ell 2\tau_{\mathrm{had}}$, and $ZZ2\ell 2\tau_{\mathrm{had}}$) with four m_S masses (200, 300, 400, 500 GeV), so 12 different BDTs are trained.

Many potential variables were investigated in each SR separately. These variables are chosen as they are expected to provide good separation between the background and signal topologies. Figure 2 shows the distributions of some highly discriminating variables described in table 2 in each SR. The discrimination of a given variable is quantified by the 'separation' (which measures the degree of overlap between background and signal distributions) and 'importance' (which ranks the power of the variable in the classification of the events) provided by the TMVA package. The BDT discriminant is trained for each SR starting from an extensive list of variables; then, the least important variables are

Variable	Definition	WW $1\ell2\tau_{\rm had}$	WW $2\ell2\tau_{\rm had}$	ZZ $2\ell2\tau_{\rm had}$
$m_{\rm X,\ truth}$	generated mass of generated X particle	×	×	×
$\Delta R(\tau\tau, \ell_0)$	angular distance between the leading lepton and the $\tau\tau$ system	×	×	×
$\min(\Delta R(\tau\tau, {\rm j}))$	minimum angular distance between a jet and the $\tau\tau$ system	×	—	—
$\Delta R(\ell, \ell)$	angular distance between two leptons	—	×	×
$\Delta\phi(\tau\tau, E_T^{\rm miss})$	azimuthal angle between the $\tau\tau$ system and $E_T^{\rm miss}$	×	×	×
$E_T^{\rm miss} + \Sigma p_{\rm T}({\rm jets})$	sum of $E_T^{\rm miss}$ momentum and $p_{\rm T}$ of jets	—	—	×
$p_{{\rm T}\tau0}$	leading tau-lepton $p_{\rm T}$	×	×	×
$m_{\tau\tau}$	visible invariant mass of the $\tau\tau$ system	×	×	×
$m_{\ell\ell}$	invariant mass of the dilepton system	—	×	—
$\min(\Delta R(\ell, {\rm j}))$	minimum angular distance between a jet and the lepton	×	—	—
$\min(\Delta R({\rm j}, {\rm j}))$	minimum angular distance between two jets	×	—	—
$p_{{\rm T}\tau1}$	subleading τ-lepton $p_{\rm T}$	×	×	×
$m_{\rm T}^{W}$	transverse mass calculated from the lepton(s) and $E_T^{\rm miss}$ in the event	×	×	×
dilep_type	dilepton type: one of $\mu\mu$, $e\mu$, μe, ee	—	×	—

Table 2. Input variables used in the BDT training for the $WW1\ell2\tau_{\rm had}$, $WW2\ell2\tau_{\rm had}$, and $ZZ2\ell2\tau_{\rm had}$ channels, where "×" stands for used and "-" stands for not used. The minimum angular distance is evaluated by using all jets in an event.

removed sequentially, and the BDT is retrained until the area under the receiver operating characteristic (ROC) curve drops by more than 1%. The final selected BDT input variables in each SR are summarised in table 2. In the $ZZ2\ell2\tau_{\rm had}$ channel, no explicit selection is applied for the second Z decay. But, it is required to have a sum of large $E_T^{\rm miss}$ from $Z \to \nu\nu$ and jets $p_{\rm T}$ from $Z \to qq$ decay in the BDT training to improve the background rejection without further dividing the data.

The BDT modelling in the signal regions is also checked using the data in the SS VR and in the low BDT regions with BDT < 0.1, where the signal contributions are negligible. The data is consistent with the background expectations in both validation regions. The final observable used to extract the signal contribution is the BDT distribution in each SR.

7 Background modelling

The reducible backgrounds arise from events where at least one of the $\tau_{\rm had}$ candidates originates from a source other than vector boson decay. A quark or gluon-initiated jet is usually misidentified as a $\tau_{\rm had}$ candidate in such backgrounds. These backgrounds with fake $\tau_{\rm had}$ candidates are estimated using the data-driven fake factor (FF) method [60]. The irreducible backgrounds with a real $\tau_{\rm had}$ candidate are modelled using simulation.

In all channels, the largest contribution to the total fake $\tau_{\rm had}$ background, including leading and subleading $\tau_{\rm had}$ candidates, arises from the V+jets process. The dominant source of the fake $\tau_{\rm had}$ are light-quark jets. Other types of fakes include gluon-initiated, b-, and c- jets, and an electron or muon misidentified as a fake $\tau_{\rm had}$ candidate. The background contribution from non-prompt light leptons ($\ell = e$, μ) is small in the signal regions and estimated from simulation.

The FF method is used to estimate the contribution of fake $\tau_{\rm had}$ background in the $WW1\ell2\tau_{\rm had}$, $WW2\ell2\tau_{\rm had}$, and $ZZ2\ell2\tau_{\rm had}$ signal regions. The method uses an extrapolation from a dedicated control region (CR) enriched in fake τ_{had} candidates to estimate the number of events with fake τ_{had} in the signal region by rescaling the templates of fake τ_{had} in the CR with the fake factors that discussed below. The CR event selection is the same as that used in the signal region, except that one or both τ_{had} candidates fail the RNN medium criteria but pass the RNN *Very Loose* (RNN > 0.05) criteria, referred to as anti-taus or fake τ_{had}. The templates are produced by subtracting the real τ_{had} contributions from the simulation.

The fake factor is a transfer factor defined as the ratio of the number of events with RNN medium τ_{had} candidate to the number of events with anti-τ_{had} candidates. FFs are measured from data in two dedicated control regions. These control regions are designed to be enriched in Z+jets ($Z(\ell\ell)$) and $t\bar{t}$ (b-tagged dilepton) backgrounds, by requiring zero b-tagged jets, in the former case, and one b-tagged jet and a Z boson veto in the latter case. The contribution of events with a real τ_{had} candidate from the simulation is at the 2% level and is subtracted in these control regions. The measured FFs in the Z+jets and $t\bar{t}$ control regions are consistent within the statistical uncertainties; however, differences between FFs are treated as systematic uncertainties arising from the different jet compositions. The fake τ_{had} background estimate is validated in a dedicated validation region for each channel. An overall 10% non-closure uncertainty is estimated by taking the ratio of data to the total predicted background in the $WW1\ell2\tau_{\text{had}}$ same-sign validation region.

The final irreducible and data-driven fake τ_{had} background contributions in the signal regions are summarised in table 3. The data are consistent with the background expectation. The leading sources of systematic uncertainty in the fake τ_{had} background before the fit to data come from the subtraction of real τ_{had} contribution $(^{+7.5}_{-12}\%)$, the non-closure uncertainty ($\pm 10\%$), and the uncertainty due to the fake τ_{had} background composition differences between the Z+jets and $t\bar{t}$ background control regions ($\pm 2\%$).

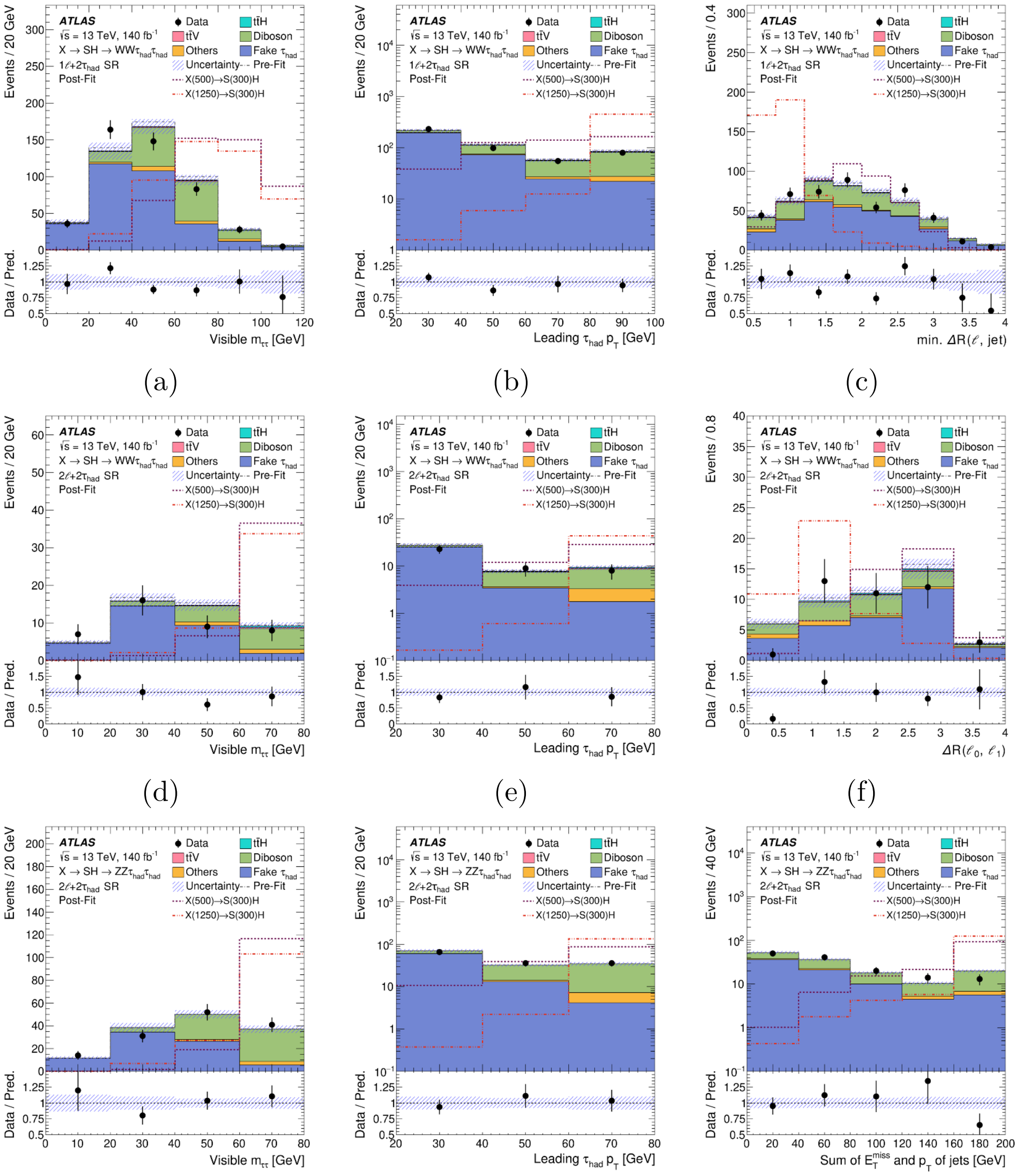
Event kinematic distributions are compared between the data and the predicted background for the visible invariant mass of the di-τ_{had} system ($m_{\tau\tau}$), the leading τ_{had} p_{T}, and other variables, after using a background-only fit to the data. Figure 2 shows the distributions for the $WW1\ell2\tau_{\text{had}}$, $WW2\ell2\tau_{\text{had}}$ and $ZZ2\ell2\tau_{\text{had}}$ channels. Good agreement is found between the data and the predicted background.

8 Systematic uncertainties

Systematic uncertainties can affect both the normalisation of signal and background and the shapes of their corresponding discriminant distributions. Each source of uncertainty is considered to be uncorrelated from other sources. For a given source, the uncertainties across all processes and channels are treated as correlated.

8.1 Luminosity

The uncertainty in the integrated luminosity is 0.83%, which affects the overall normalisation of all processes estimated from the simulation. It is derived following a methodology similar to that detailed in ref. [67] and uses the LUCID-2 detector for the baseline luminosity measurement [68] and a calibration of the luminosity scale from x–y beam-separation scans.



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Figure 2. Kinematic distributions obtained after a background-only fit to data (Post-fit) in the $WW1\ell2\tau_{\text{had}}$ signal region: $m_{\tau\tau}$ (a), leading τ_{had} p_{T} (b), $\Delta R(\ell,\text{j})$ (c); in the $WW2\ell2\tau_{\text{had}}$ signal region: $m_{\tau\tau}$ (d), leading τ_{had} p_{T} (e), $\Delta R(\ell,\ell)$ (f); in the $ZZ2\ell2\tau_{\text{had}}$ signal region: $m_{\tau\tau}$ (g), leading τ_{had} p_{T} (h), sum of E_T^{miss} and p_{T} of jets (i). The purple (red) dashed line represents the signal for $m_X = 500$ GeV and $m_S = 300$ GeV ($m_X = 1250$ GeV and $m_S = 300$ GeV) normalised to total background. The error band includes systematic and statistical uncertainties. The lower panel shows the ratio of data to post-fit background.

Process	$WW1\ell2\tau_{\text{had}}$	$WW2\ell2\tau_{\text{had}}$	$ZZ2\ell2\tau_{\text{had}}$
$t\bar{t}H$	2.6 ± 0.3	0.50 ± 0.06	0.035 ± 0.004
$t\bar{t}V$	3.4 ± 0.4	0.58 ± 0.07	0.10 ± 0.02
Others	15.6 ± 3.0	2.1 ± 0.4	4.7 ± 0.8
Diboson	135.1 ± 15.5	11.1 ± 1.3	55.0 ± 6.1
Fake τ_{had}	312.4 ± 21.5	30.1 ± 3.7	77.8 ± 9.0
Total background	468.6 ± 19.3	44.0 ± 3.9	138.0 ± 9.1
Data	464	40	138

Table 3. Event yields after a background-only fit and data in the three signal regions. All the backgrounds except the fake τ_{had} are estimated using the real τ_{had} contributions from MC. The fake τ_{had} background contribution is data-driven. The top-quark, V+jets, and small backgrounds are included in the "Others" category. The total uncertainties include systematic and statistical contributions. In the $WW1\ell2\tau_{\text{had}}$ channel, the smaller uncertainty in the total background than the fake τ_{had} is due to the anti-correlations between the nuisance parameters of the fake τ_{had} and diboson backgrounds obtained in the fit.

8.2 Reconstructed objects

Uncertainties associated with electrons, muons, and τ_{had} candidates arise from the trigger, reconstruction, momentum scale and resolution, particle identification, and, in the case of electrons and muons, isolation efficiencies. These are measured using $Z \to \ell^+\ell^-$ and $J/\psi \to \ell^+\ell^-$ events [47, 48] in the case of electrons and muons, and using $Z \to \tau^+\tau^-$ events in the case of τ_{had} candidates [60].

Uncertainties associated with jets arise from the jet energy scale (JES) and resolution (JER), and the efficiency to satisfy JVT requirements. The largest contribution comes from the jet energy scale, whose uncertainty dependence on jet p_{T} and η, jet flavour, and pile-up treatment is split into 43 uncorrelated components that are treated independently [54]. The total JES uncertainty is below 5% for most jets and below 1% for central jets with p_{T} between 300 GeV and 2 TeV. The difference between the JER values in data and simulated events is treated as a systematic uncertainty with one nuisance parameter. It is applied to the simulated events by smearing the jet p_{T} by the prescribed uncertainty.

Uncertainties associated with energy scales and resolutions of leptons and jets are propagated to E_T^{miss}. Additional uncertainties originating from the modelling of the underlying event, particularly its impact on the p_{T} scale and resolution of unclustered energy, are negligible.

Efficiencies to veto tagged b-jets and c-jets in the simulation are corrected by p_{T}-dependent factors to match the efficiencies in data, while the light-jet efficiency is scaled by p_{T}- and η-dependent factors. The b-jet efficiency is measured in a data sample enriched in $t\bar{t}$ events [58], while the c-jet efficiency is measured using $t\bar{t}$ events [69] or W+c-jet events [70]. The light-jet efficiency is measured in a multijet data sample enriched in light-flavour jets [71]. These systematic uncertainties are taken to be uncorrelated between b-jets, c-jets, and light jets.

Pile-up reweighting scale factors are applied to simulated events to reproduce the pile-up distribution corresponding to the data. The uncertainty in these scale factors is estimated by changing the profile in data within uncertainties.

8.3 Background modelling

Several sources of systematic uncertainty affecting the modelling of background are considered: the choice of renormalisation and factorisation scale in the matrix-element calculation, the choice of matching scale when matching the matrix elements to the parton shower generator, and the uncertainty in the value of α_s when modelling initial-state radiation (ISR). The uncertainty due to the choice of parton shower (PS) and hadronisation model is derived by comparing the predictions from POWHEG-BOX interfaced either to PYTHIA 8 or HERWIG 7. The latter uses the MMHT2014 LO [72] PDF set in combination with the H7UE tune [73]. The uncertainty in the modelling of additional radiation from the PS is assessed by varying the corresponding parameter of the A14 set [74] and by varying the radiation renormalisation and factorisation scales independently by factors of 2.0 and 0.5. The PDF uncertainty is estimated by taking the PDF variations as an envelope around the nominal PDF.

Uncertainties affecting the normalisation of the V+jets background are estimated to be approximately 30% by taking the maximum difference between the data and the total background prediction in three or more jets [75]. This is mainly driven by different simulations used in the V+jets regions where SHERPA 2.2.1 at NLO is used for up to two partons, and LO is used for three or more partons.

Uncertainties in the $t\bar{t}$+jets background normalisation include those estimated from variations of the renormalisation and factorisation scales, the choice of parton shower and hadronisation, the NNPDF3.0 NNLO PDF set uncertainties, and α_s variations. The contribution of $t\bar{t}$+jets is small after the b-tagging veto is applied.

Uncertainties affecting the modelling of the single-top-quark background include a $+5\%/-4\%$ uncertainty in the total cross section, which is estimated as a weighted average of the theoretical uncertainties in t-, tW- and s-channel production [76–78]. Additional uncertainties associated with the parton shower, hadronisation, and initial- and final-state radiation are also considered.

The diboson normalisation uncertainty is estimated to be ±15%, which includes those estimated from variations of the renormalisation and factorisation scales, NNPDF3.0 NNLO PDF set, and α_s variations. Uncertainties in the $t\bar{t}V$, $t\bar{t}H$, and VH cross sections are estimated to be ±10%, $[+5.8\%/-9.2\%]$, and ±1.4%, respectively, arising from the uncertainties in their respective NLO theoretical cross sections [79]. Most of the rare background contributions (tZ, $t\bar{t}t$, $t\bar{t}WW$, WtZ, VVV) are normalised using their NLO theoretical cross sections, and assigned a 50% normalisation uncertainty, except for tZ where a 5% normalisation uncertainty is used.

The statistical uncertainties of the fake τ_had background calibration are applied with uncorrelated uncertainties for different sources of fake τ-leptons. The uncertainties in the modelling of the processes used to evaluate the fake factors are taken into account in the fit.

8.4 Signal modelling

Several normalisation and shape uncertainties are considered and they are treated as fully correlated for the $X \to SH$ signals. Uncertainties in the S and H decay branching ratios are considered by following the recommendation in ref. [20]. The BDT variations due to ISR, FSR, scale, and PDF uncertainties are estimated from a non-resonant HH sample and are applied to the SH signal as fully correlated in all SRs. The PS uncertainty is also estimated by comparing the BDT shape from a HH sample with an alternative sample interfaced with HERWIG 7 and is applied to the SH signal. This choice is motivated by the fact that the modelling of the non-resonant HH signal is calculated to higher order than the SH simulation, and their kinematics are quite similar to those in the low m_X mass points. These uncertainties are cross-checked and found to be consistent with those calculated in the resonant $X \to HH \to bb\tau\tau$ analysis [80].

9 Statistical analysis

The final discriminant distributions are the BDT outputs from all considered analysis regions. They are jointly analysed for the presence of a signal. The BDT distributions are binned to maximise the sensitivity to the signal and the binning is optimised to reduce the statistical fluctuations.

The statistical analysis uses a binned likelihood function $\mathcal{L}(\mu, \theta)$ constructed as a product of Poisson probability terms over all bins considered in the search [81]. This function depends on the signal-strength parameter μ, defined as a factor multiplying the expected yield of signal events normalised to an arbitrary reference cross section $\sigma(pp \to X \to SH) = 1$ pb, and on θ, a set of nuisance parameters (NPs) that encode the effect of systematic uncertainties in the signal and background expectations. The expected total number of events in a given bin depends on μ and θ. All nuisance parameters are subject to Gaussian constraints in the likelihood function. For a given value of μ, the NPs θ allow variations of the expectations for signal and background consistent with the corresponding systematic uncertainties, hence their fitted values result in deviations from the nominal expectations that globally provide the best fit to the data. This procedure reduces the impact of systematic uncertainties on the sensitivity of the search by taking advantage of the highly populated background-dominated bins included in the likelihood fit. Statistical uncertainties in each bin of the predicted final discriminant distributions are considered through dedicated parameters (gammas) in the fit. The best-fit μ is obtained by performing a binned likelihood fit to the data under the signal-plus-background hypothesis and maximising the likelihood function $\mathcal{L}(\mu, \theta)$ over μ and θ.

The fitting procedure was initially validated through extensive studies using pseudo-data (which is defined as the sum of all predicted backgrounds plus an injected signal of variable strength) and by performing fits to the data considering only those bins of the final discriminating variable that lie in the low BDT signal-depleted regions defined by BDT < 0.1. In both cases, the robustness of the model for systematic uncertainties was established by verifying the stability of the fitted background when varying the leading sources of uncertainty. After this, the whole BDT distribution in the data is fitted under the signal-plus-background hypothesis. Further checks involve the comparison of the fitted nuisance parameters before and after removal of the blinding requirements. In addition, it is verified that the fit is able to determine the strength of a simulated signal injected into the real data.

The test statistic q_μ is defined as the profile likelihood ratio, $q_\mu = -2\ln(\mathcal{L}(\mu,\hat{\hat{\theta}}_\mu)/\mathcal{L}(\hat{\mu},\hat{\theta}))$, where $\hat{\mu}$ and $\hat{\theta}$ are the values of the parameters that maximise the likelihood function (subject to the constraint $\hat{\mu} \geq 0$), and $\hat{\hat{\theta}}_\mu$ are the values of NPs that maximise the likelihood function for a given value of μ. The test statistic q_μ is evaluated with the RooFit package [82].

Exclusion limits are set on μ, derived by using q_μ in the $\mathrm{CL_s}$ method [83, 84]. For a given signal scenario, values of μ yielding $\mathrm{CL_s} < 0.05$, where $\mathrm{CL_s}$ is computed using the asymptotic approximation [81], are excluded with at least 95% confidence. Exclusion limits are also verified using pseudo-experiments, which give consistent results to within 25%.

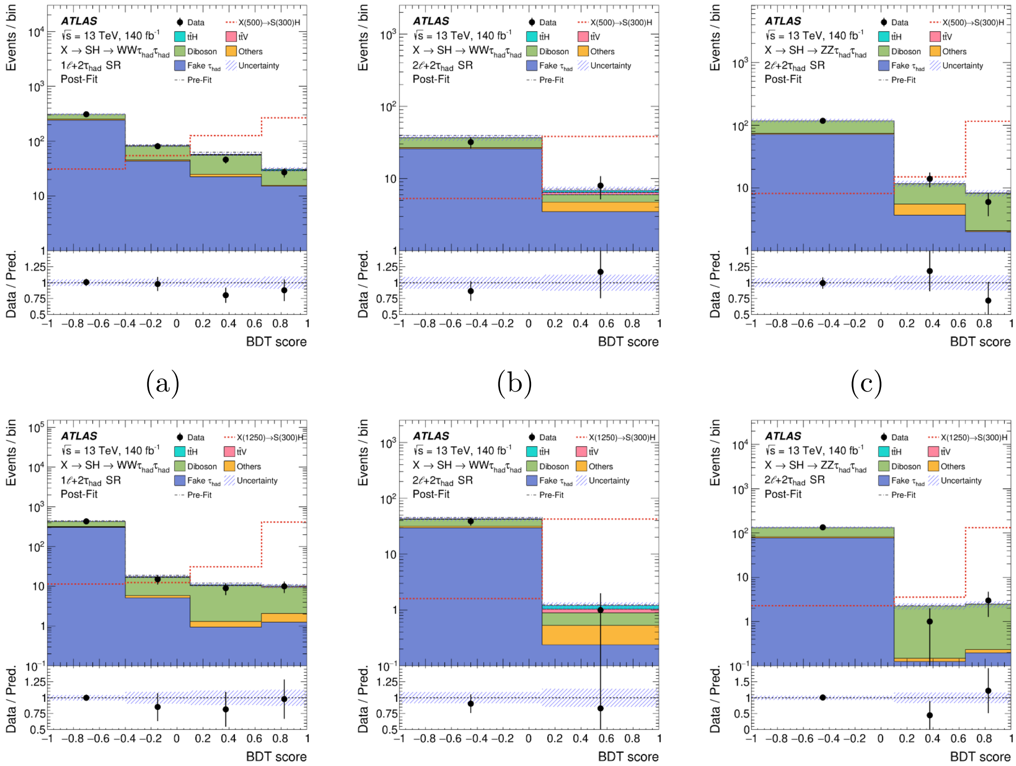
10 Results

A binned likelihood fit under the signal-plus-background hypothesis is performed on each BDT discriminant distribution for each mass point (m_X, m_S), in the three signal regions, in the two WW regions combined, and in all three regions combined. This gives a total of $5 \times 18 = 90$ fits. The unconstrained parameter of the fit is the signal strength (μ).

Figure 3 shows the BDT output distributions after the background-only fit to the data for the $X \to SH$ searches for the most sensitive high mass point ($m_X = 1250$ GeV, $m_S = 300$ GeV) and the least sensitive low mass point ($m_X = 500$ GeV, $m_S = 300$ GeV), respectively. No significant pulls or constraints are obtained for the fitted nuisance parameters, resulting in a post-fit background prediction in each signal region that is very close to the pre-fit prediction, except with reduced uncertainties resulting from the fit.

No excess of events is observed beyond the expected SM background, hence 95% CL upper limits are set on the production cross section $\sigma(pp \to X \to SH)$ as shown in table 4 for the combined WW regions, the ZZ region, and all regions combined after correcting the $S \to WW$, ZZ branching fractions assuming the S decays like a SM Higgs boson [85]. The combined limit is dominated by the $WW1\ell2\tau_{\text{had}}$ channel and is improved by 26%–53% after adding the $WW2\ell2\tau_{\text{had}}$ and $ZZ2\ell2\tau_{\text{had}}$ channels. The results are dominated by the statistical uncertainty. The main contributions to the total systematic uncertainty arise from the tau-lepton fakes, the diboson modelling, the τ_{had} identification efficiency, lepton identification, and trigger efficiencies. Their impact on the cross section $\sigma(pp \to X \to SH)$ is summarized in table 5 for the least- and most-sensitive mass points. The impact on the combined limits is between 2% and 14% across all mass points.

The best expected combined limit is 85 fb for $\sigma(pp \to X \to SH)$ for $m_X = 1250$ GeV and $m_S = 300$ GeV. The observed and expected 95% CL upper limits are summarized in figure 4 for $\sigma(pp \to X \to SH)$, $\sigma(pp \to X \to SH \to WW\tau^+\tau^-)$, and $\sigma(pp \to X \to SH \to ZZ\tau^+\tau^-)$ as a function of combined m_S and m_X masses (m_S+m_X/25) in GeV. The maximum values allowed for $\sigma(pp \to X \to SH \to WW\tau^+\tau^-)$ and $\sigma(pp \to X \to SH \to ZZ\tau^+\tau^-)$ as a function of m_X and m_S in the NMSSM parameter space are also shown for comparison. These values are obtained via a parameter space scan using NMSSMTOOLS



(a) (b) (c)

(d) (e) (f)

Figure 3. BDT output distributions obtained from a background-only fit to the data for the $X \to SH$ search with $m_X = 500$ GeV and $m_S = 300$ GeV in the channel of (a) $WW1\ell2\tau_{\text{had}}$, (b) $WW2\ell2\tau_{\text{had}}$, (c) $ZZ2\ell2\tau_{\text{had}}$; and with $m_X = 1250$ GeV and $m_S = 300$ GeV in the channel of (d) $WW1\ell2\tau_{\text{had}}$, (e) $WW2\ell2\tau_{\text{had}}$, (f) $ZZ2\ell2\tau_{\text{had}}$. The red dashed line represents the signal normalised to total background. The error band includes systematic and statistical uncertainties.

6.0.0 [86–88] and NMSSMCALC [89], following recommendations from ref. [20]. The scan uses measurements of Higgs boson properties, searches for supersymmetry, B-meson physics, and searches for dark matter to exclude cross section values above the indicated line. The observed limits approach the allowed cross sections in the low-m_X and low-m_S part of the NMSSM parameter space. This NMSSM scan for $VV\tau\tau$ is also compatible with other NMSSN scans using $X \to SH \to bbbb$, $bb\tau\tau$, and $bb\gamma\gamma$ final states.

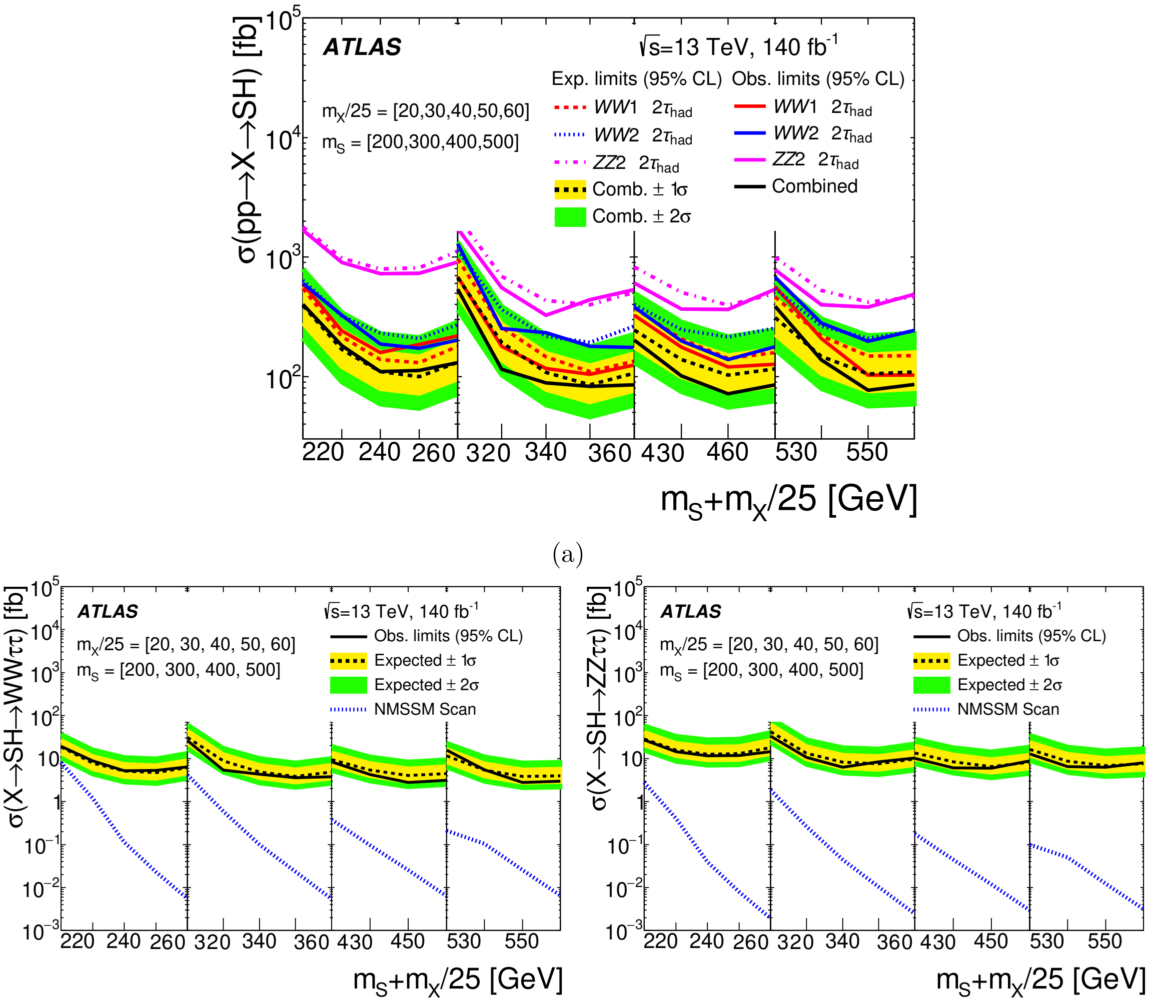
The corresponding 2D limits are also shown in figure 5 as a function of m_X and m_S masses in GeV. The limit at each mass point is compared to the limits obtained using the BDTs trained for the (lower or upper) neighbouring mass values in the fit and found to be consistent within 15%, indicating that interpolating the limits between mass points is unnecessary. The fit results are also used to set limits on the cross sections for $X \to SH \to VV\tau\tau$ decays in events with a pair of τ-leptons and multiple light-leptons.

m_X	m_S	Combined $\sigma(pp \to X \to SH)$ [fb]		$\sigma(pp \to X \to WW\tau\tau)$ [fb]		$\sigma(pp \to X \to ZZ\tau\tau)$ [fb]	
(GeV)	(GeV)	Observed	Expected	Observed	Expected	Observed	Expected
500	200	400	391^{+170}_{-110}	19	18^{+8}_{-5}	27	28^{+13}_{-8}
750	200	182	168^{+74}_{-47}	8.8	$8^{+3.5}_{-2}$	14	16^{+7}_{-4}
1000	200	110	110^{+49}_{-31}	5.3	5^{+2}_{-1}	12	13^{+6}_{-4}
1250	200	112	100^{+46}_{-28}	5.4	5^{+2}_{-1}	12	13^{+6}_{-4}
1500	200	131	132^{+62}_{-37}	6.4	6^{+3}_{-2}	14	18^{+9}_{-5}
500	300	538	672^{+290}_{-190}	26	31^{+13}_{-9}	33	42^{+19}_{-12}
750	300	115	192^{+83}_{-54}	5.3	9^{+4}_{-2}	11	13^{+6}_{-4}
1000	300	88.6	108^{+48}_{-30}	4.3	5^{+2}_{-1}	6.3	8^{+4}_{-2}
1250	300	82.6	85^{+38}_{-24}	3.6	4^{+2}_{-1}	8.4	8^{+4}_{-2}
1500	300	85.4	107^{+49}_{-30}	3.7	5^{+2}_{-1}	10	10^{+5}_{-3}
750	400	202	245^{+107}_{-68}	8.4	10^{+4}_{-3}	10	14^{+6}_{-4}
1000	400	101	139^{+62}_{-39}	4.2	$5^{+2}_{-1.5}$	6	8^{+4}_{-2}
1250	400	71.7	103^{+46}_{-29}	2.8	4^{+2}_{-1}	6	6.5^{+3}_{-2}
1500	400	85.1	116^{+53}_{-32}	3.1	4.5^{+2}_{-1}	8.9	8^{+4}_{-2}
750	500	387	312^{+135}_{-87}	16	11^{+5}_{-3}	13	$16^{+8}_{-4.5}$
1000	500	138	147^{+65}_{-41}	5.5	$5^{+2}_{-1.5}$	6.5	9^{+4}_{-2}
1250	500	77	105^{+47}_{-29}	2.8	4^{+2}_{-1}	6.2	7^{+3}_{-2}
1500	500	85.9	109^{+50}_{-31}	3	4^{+2}_{-1}	8	8^{+4}_{-2}

Table 4. Summary of observed and expected 95% CL upper limits on the production cross section of $\sigma(pp \to X \to SH)$ in fb in the combination of $WW + ZZ$, and in the WW and ZZ individual channels. The best expected limit is 85 fb for $m_X = 1250$ GeV and $m_S = 300$ GeV. The combination limits gain about 26%–53% over the best individual limit from the $WW1\ell2\tau_{\text{had}}$ channel.

Source of uncertainty	$\Delta\sigma/\sigma(pp \to X \to SH)$ [%]	
	$m_X = 500$, $m_S = 300$ [GeV]	$m_X = 1250$, $m_S = 300$ [GeV]
Lepton ID	5	1
JES and JER	6	4
MC modelling	11	9
Fake τ modelling	10	5
τ ID	11	6
Luminosity and triggers	3	2
MC (CR) statistics	8	5
Total systematic uncertainty	27	15
Data statistical uncertainty	46	40
Total uncertainties	53	43

Table 5. Relative uncertainties in the observed 95% CL upper limits of $\sigma(pp \to X \to SH)$ obtained from the combined fit to the data for the least- and most-sensitive mass points. The uncertainties are symmetrized and grouped into the categories described in the systematic section.



(a)

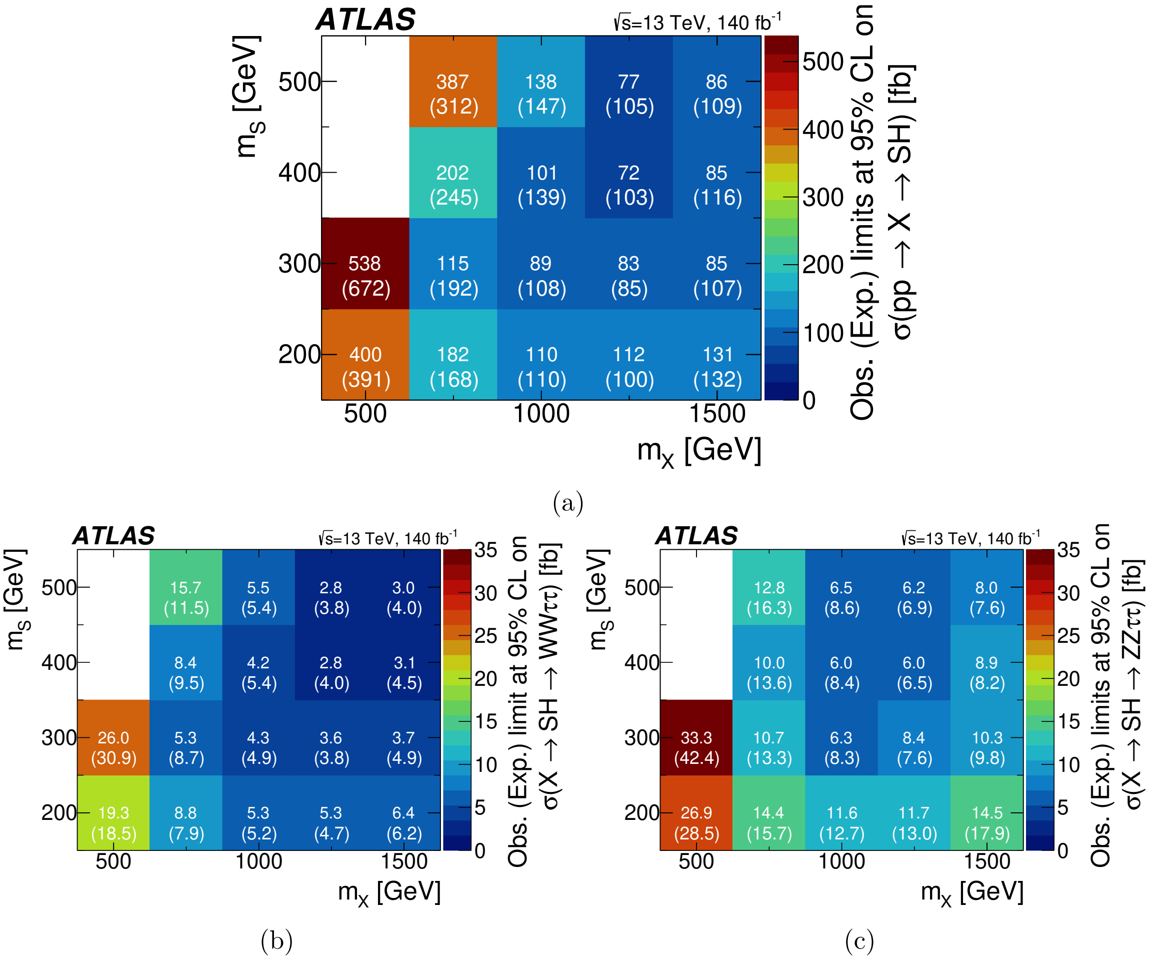
(b)

(c)

Figure 4. Observed and expected 95% CL upper limits are shown for (a) $\sigma(pp \to X \to SH)$ obtained from three channels and their combination; (b) $\sigma(pp \to X \to SH \to WW\tau^+\tau^-)$ obtained from the combination of $WW1\ell2\tau_{\text{had}}$ and $WW2\ell2\tau_{\text{had}}$ channels; (c) $\sigma(pp \to X \to SH \to ZZ\tau^+\tau^-)$ obtained from $ZZ2\ell2\tau_{\text{had}}$ channel, as a function of combined m_S and m_X masses (m_S+m_X/25) in GeV. The NMSSM scans of the allowed cross sections for $\sigma(pp \to X \to SH \to WW\tau^+\tau^-)$ and $\sigma(pp \to X \to SH \to ZZ\tau^+\tau^-)$ are also shown.

11 Conclusion

A search for a new heavy scalar particle X decaying into a Standard Model (SM) Higgs boson (with $H \to \tau^+\tau^-$) and a new singlet scalar particle S ($S \to VV$ with $V = W, Z$) is presented. The search is based on a data sample of pp collisions at $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of 140 fb^{-1} recorded with the ATLAS detector at the Large Hadron Collider. The explored X masses range from 500 to 1500 GeV, with the corresponding S mass in the range 200–500 GeV. The search selects events with two hadronically decaying τ-lepton candidates from $H \to \tau^+\tau^-$ decays and one or two light



(a)

(b)

(c)

Figure 5. Observed (expected) 2D limits are shown for (a) $\sigma(pp \to X \to SH)$, (b) $\sigma(pp \to X \to SH \to WW\tau^+\tau^-)$, and (c) $\sigma(pp \to X \to SH \to ZZ\tau^+\tau^-)$ as a function of m_X and m_S masses in GeV.

leptons ($\ell = e, \mu$) from $S \to VV$ decays. A multivariate discriminant based on event kinematics is used to separate the signal from the background. No excess of events is observed beyond the expected SM background and 95% CL upper limits on the cross-section for $\sigma(pp \to X \to SH)$, assuming the same SM-Higgs boson-like decay branching ratios for $S \to VV$ decay, are derived between 72 fb and 542 fb. Upper limits on the visible cross-sections $\sigma(pp \to X \to SH \to WW\tau\tau)$ and $\sigma(pp \to X \to SH \to ZZ\tau\tau)$ are set in the ranges 3–26 fb and 5–33 fb, respectively.

Acknowledgments

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

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; ANID, Chile; CAS, MOST and NSFC, China; Minciencias, Colombia; MEYS CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF and MPG, Germany; GSRI, Greece; RGC and Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MEiN, Poland; FCT, Portugal; MNE/IFA, Romania; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DSI/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TENMAK, Türkiye; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, CANARIE, Compute Canada and CRC, Canada; PRIMUS 21/SCI/017 and UNCE SCI/013, Czech Republic; COST, ERC, ERDF, Horizon 2020 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; Norwegian Financial Mechanism 2014-2021, Norway; 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.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (U.K.) and BNL (U.S.A.), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in ref. [90].

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] [INSPIRE].

[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] [INSPIRE].

[3] ATLAS collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, 2008 *JINST* **3** S08003 [INSPIRE].

[4] CMS collaboration, *The CMS Experiment at the CERN LHC*, 2008 *JINST* **3** S08004 [INSPIRE].

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

[6] ATLAS collaboration, *A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery*, *Nature* **607** (2022) 52 [*Erratum ibid.* **612** (2022) E24] [arXiv:2207.00092] [INSPIRE].

[7] CMS collaboration, *A portrait of the Higgs boson by the CMS experiment ten years after the discovery*, *Nature* **607** (2022) 60 [arXiv:2207.00043] [INSPIRE].

[8] CMS collaboration, *Search for a massive scalar resonance decaying to a light scalar and a Higgs boson in the four b quarks final state with boosted topology*, *Phys. Lett. B* **842** (2023) 137392 [arXiv:2204.12413] [INSPIRE].

[9] ATLAS collaboration, *Searches for Higgs boson pair production in the* $hh \to bb\tau\tau, \gamma\gamma WW^*, \gamma\gamma bb, bbbb$ *channels with the ATLAS detector*, *Phys. Rev. D* **92** (2015) 092004 [arXiv:1509.04670] [INSPIRE].

[10] ATLAS collaboration, *Combination of searches for Higgs boson pairs in pp collisions at* $\sqrt{s} = 13$ *TeV with the ATLAS detector*, *Phys. Lett. B* **800** (2020) 135103 [arXiv:1906.02025] [INSPIRE].

[11] CMS collaboration, *Combination of searches for Higgs boson pair production in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*, *Phys. Rev. Lett.* **122** (2019) 121803 [arXiv:1811.09689] [INSPIRE].

[12] CMS collaboration, *Search for a heavy Higgs boson decaying into two lighter Higgs bosons in the* $\tau\tau bb$ *final state at 13 TeV*, *JHEP* **11** (2021) 057 [arXiv:2106.10361] [INSPIRE].

[13] G.C. Branco et al., *Theory and phenomenology of two-Higgs-doublet models*, *Phys. Rept.* **516** (2012) 1 [arXiv:1106.0034] [INSPIRE].

[14] P. Fayet, *Supersymmetry and Weak, Electromagnetic and Strong Interactions*, *Phys. Lett. B* **64** (1976) 159 [INSPIRE].

[15] S. von Buddenbrock et al., *Phenomenological signatures of additional scalar bosons at the LHC*, *Eur. Phys. J. C* **76** (2016) 580 [arXiv:1606.01674] [INSPIRE].

[16] S. von Buddenbrock et al., *Constraints on a 2HDM with a singlet scalar and implications in the search for heavy bosons at the LHC*, *J. Phys. G* **46** (2019) 115001 [arXiv:1809.06344] [INSPIRE].

[17] U. Ellwanger, C. Hugonie and A.M. Teixeira, *The Next-to-Minimal Supersymmetric Standard Model*, *Phys. Rept.* **496** (2010) 1 [arXiv:0910.1785] [INSPIRE].

[18] T. Robens, T. Stefaniak and J. Wittbrodt, *Two-real-scalar-singlet extension of the SM: LHC phenomenology and benchmark scenarios*, *Eur. Phys. J. C* **80** (2020) 151 [arXiv:1908.08554] [INSPIRE].

[19] M. Mühlleitner, M.O.P. Sampaio, R. Santos and J. Wittbrodt, *Phenomenological Comparison of Models with Extended Higgs Sectors*, *JHEP* **08** (2017) 132 [arXiv:1703.07750] [INSPIRE].

[20] LHC Higgs Cross Section Working Group collaboration, *Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector*, arXiv:1610.07922 [DOI:10.23731/CYRM-2017-002] [INSPIRE].

[21] ATLAS collaboration, *ATLAS Insertable B-Layer Technical Design Report*, CERN-LHCC-2010-013 (2010).

[22] ATLAS collaboration, *ATLAS Insertable B-Layer Technical Design Report Addendum*, CERN-LHCC-2012-009 (2012).

[23] ATLAS IBL collaboration, *Production and Integration of the ATLAS Insertable B-Layer*, 2018 *JINST* **13** T05008 [arXiv:1803.00844] [INSPIRE].

[24] ATLAS collaboration, *Performance of the ATLAS Trigger System in 2015*, *Eur. Phys. J. C* **77** (2017) 317 [arXiv:1611.09661] [INSPIRE].

[25] ATLAS collaboration, *The ATLAS Collaboration Software and Firmware*, ATL-SOFT-PUB-2021-001, CERN, Geneva (2021).

[26] ATLAS collaboration, *Performance of electron and photon triggers in ATLAS during LHC Run 2*, *Eur. Phys. J. C* **80** (2020) 47 [arXiv:1909.00761] [INSPIRE].

[27] ATLAS collaboration, *Performance of the ATLAS muon triggers in Run 2*, 2020 *JINST* **15** P09015 [arXiv:2004.13447] [INSPIRE].

[28] ATLAS collaboration, *The ATLAS inner detector trigger performance in pp collisions at 13 TeV during LHC Run 2*, *Eur. Phys. J. C* **82** (2022) 206 [arXiv:2107.02485] [INSPIRE].

[29] ATLAS collaboration, *Performance of the ATLAS Level-1 topological trigger in Run 2*, *Eur. Phys. J. C* **82** (2022) 7 [arXiv:2105.01416] [INSPIRE].

[30] T. Sjöstrand et al., *An introduction to PYTHIA 8.2*, *Comput. Phys. Commun.* **191** (2015) 159 [arXiv:1410.3012] [INSPIRE].

[31] NNPDF collaboration, *Parton distributions for the LHC Run II*, *JHEP* **04** (2015) 040 [arXiv:1410.8849] [INSPIRE].

[32] ATLAS collaboration, *ATLAS Pythia 8 tunes to 7 TeV data*, ATL-PHYS-PUB-2014-021, CERN, Geneva (2014).

[33] ATLAS collaboration, *The simulation principle and performance of the ATLAS fast calorimeter simulation FastCaloSim*, ATL-PHYS-PUB-2010-013, CERN, Geneva (2010).

[34] E. Re, *Single-top Wt-channel production matched with parton showers using the POWHEG method*, *Eur. Phys. J. C* **71** (2011) 1547 [arXiv:1009.2450] [INSPIRE].

[35] S. Alioli, P. Nason, C. Oleari and E. Re, *NLO single-top production matched with shower in POWHEG: s- and t-channel contributions*, *JHEP* **09** (2009) 111 [*Erratum ibid.* **02** (2010) 011] [arXiv:0907.4076] [INSPIRE].

[36] T. Sjöstrand, S. Mrenna and P.Z. Skands, *A Brief Introduction to PYTHIA 8.1*, *Comput. Phys. Commun.* **178** (2008) 852 [arXiv:0710.3820] [INSPIRE].

[37] 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, CERN, Geneva (2016).

[38] ATLAS collaboration, *The ATLAS Simulation Infrastructure*, *Eur. Phys. J. C* **70** (2010) 823 [arXiv:1005.4568] [INSPIRE].

[39] GEANT4 collaboration, *GEANT4 — a simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250 [INSPIRE].

[40] J. Alwall et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, *JHEP* **07** (2014) 079 [arXiv:1405.0301] [INSPIRE].

[41] L. Altenkamp et al., *Gluon-induced Higgs-strahlung at next-to-leading order QCD*, *JHEP* **02** (2013) 078 [arXiv:1211.5015] [INSPIRE].

[42] O. Brein, R.V. Harlander and T.J.E. Zirke, *vh@nnlo — Higgs Strahlung at hadron colliders*, *Comput. Phys. Commun.* **184** (2013) 998 [`arXiv:1210.5347`] [INSPIRE].

[43] S. Frixione et al., *Single-top hadroproduction in association with a W boson*, *JHEP* **07** (2008) 029 [`arXiv:0805.3067`] [INSPIRE].

[44] SHERPA collaboration, *Event Generation with Sherpa 2.2*, *SciPost Phys.* **7** (2019) 034 [`arXiv:1905.09127`] [INSPIRE].

[45] ATLAS collaboration, *Vertex Reconstruction Performance of the ATLAS Detector at* $\sqrt{s} = 13$ *TeV*, ATL-PHYS-PUB-2015-026, CERN, Geneva (2015).

[46] ATLAS collaboration, *Electron and photon performance measurements with the ATLAS detector using the 2015-2017 LHC proton-proton collision data*, 2019 *JINST* **14** P12006 [`arXiv:1908.00005`] [INSPIRE].

[47] ATLAS collaboration, *Electron reconstruction and identification in the ATLAS experiment using the 2015 and 2016 LHC proton-proton collision data at* $\sqrt{s} = 13$ TeV, *Eur. Phys. J. C* **79** (2019) 639 [`arXiv:1902.04655`] [INSPIRE].

[48] ATLAS collaboration, *Muon reconstruction performance of the ATLAS detector in proton-proton collision data at* $\sqrt{s} = 13$ *TeV*, *Eur. Phys. J. C* **76** (2016) 292 [`arXiv:1603.05598`] [INSPIRE].

[49] M. Cacciari, G.P. Salam and G. Soyez, *The anti-*k_t *jet clustering algorithm*, *JHEP* **04** (2008) 063 [`arXiv:0802.1189`] [INSPIRE].

[50] M. Cacciari, G.P. Salam and G. Soyez, *FastJet User Manual*, *Eur. Phys. J. C* **72** (2012) 1896 [`arXiv:1111.6097`] [INSPIRE].

[51] 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`] [INSPIRE].

[52] ATLAS collaboration, *Properties of Jets and Inputs to Jet Reconstruction and Calibration with the ATLAS Detector Using Proton-Proton Collisions at* $\sqrt{s} = 13$ *TeV*, ATL-PHYS-PUB-2015-036, CERN, Geneva (2015).

[53] ATLAS collaboration, *Jet reconstruction and performance using particle flow with the ATLAS Detector*, *Eur. Phys. J. C* **77** (2017) 466 [`arXiv:1703.10485`] [INSPIRE].

[54] ATLAS collaboration, *Jet energy scale measurements and their systematic uncertainties in proton-proton collisions at* $\sqrt{s} = 13$ *TeV with the ATLAS detector*, *Phys. Rev. D* **96** (2017) 072002 [`arXiv:1703.09665`] [INSPIRE].

[55] ATLAS collaboration, *Jet energy scale and resolution measured in proton-proton collisions at* $\sqrt{s} = 13$ *TeV with the ATLAS detector*, *Eur. Phys. J. C* **81** (2021) 689 [`arXiv:2007.02645`] [INSPIRE].

[56] ATLAS collaboration, *Performance of pile-up mitigation techniques for jets in pp collisions at* $\sqrt{s} = 8$ *TeV using the ATLAS detector*, *Eur. Phys. J. C* **76** (2016) 581 [`arXiv:1510.03823`] [INSPIRE].

[57] ATLAS collaboration, *Selection of jets produced in 13TeV proton-proton collisions with the ATLAS detector*, ATLAS-CONF-2015-029, CERN, Geneva (2015).

[58] ATLAS collaboration, *ATLAS b-jet identification performance and efficiency measurement with* $t\bar{t}$ *events in pp collisions at* $\sqrt{s} = 13$ *TeV*, *Eur. Phys. J. C* **79** (2019) 970 [`arXiv:1907.05120`] [INSPIRE].

[59] ATLAS collaboration, *Optimisation and performance studies of the ATLAS b-tagging algorithms for the 2017-18 LHC run*, ATL-PHYS-PUB-2017-013, CERN, Geneva (2017).

[60] 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, CERN, Geneva (2017).

[61] ATLAS collaboration, *Identification of hadronic tau lepton decays using neural networks in the ATLAS experiment*, ATL-PHYS-PUB-2019-033, CERN, Geneva (2019).

[62] ATLAS collaboration, *Measurements of Higgs boson production cross-sections in the $H \to \tau^+\tau^-$ decay channel in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *JHEP* **08** (2022) 175 [`arXiv:2201.08269`] [INSPIRE].

[63] ATLAS collaboration, *Evidence for the associated production of the Higgs boson and a top quark pair with the ATLAS detector*, *Phys. Rev. D* **97** (2018) 072003 [`arXiv:1712.08891`] [INSPIRE].

[64] ATLAS collaboration, *Performance of missing transverse momentum reconstruction with the ATLAS detector using proton-proton collisions at $\sqrt{s} = 13$ TeV*, *Eur. Phys. J. C* **78** (2018) 903 [`arXiv:1802.08168`] [INSPIRE].

[65] A. Hoecker et al., *TMVA — Toolkit for Multivariate Data Analysis*, `physics/0703039`.

[66] P. Baldi et al., *Parameterized neural networks for high-energy physics*, *Eur. Phys. J. C* **76** (2016) 235 [`arXiv:1601.07913`] [INSPIRE].

[67] ATLAS collaboration, *Luminosity determination in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC*, `arXiv:2212.09379` [INSPIRE].

[68] G. Avoni et al., *The new LUCID-2 detector for luminosity measurement and monitoring in ATLAS*, 2018 *JINST* **13** P07017 [INSPIRE].

[69] ATLAS collaboration, *Measurement of b-tagging Efficiency of c-jets in $t\bar{t}$ Events Using a Likelihood Approach with the ATLAS Detector*, ATLAS-CONF-2018-001, CERN, Geneva (2018).

[70] ATLAS collaboration, *Performance of b-Jet Identification in the ATLAS Experiment*, 2016 *JINST* **11** P04008 [`arXiv:1512.01094`] [INSPIRE].

[71] ATLAS collaboration, *Calibration of light-flavour b-jet mistagging rates using ATLAS proton-proton collision data at $\sqrt{s} = 13$ TeV*, ATLAS-CONF-2018-006, CERN, Geneva (2018).

[72] L.A. Harland-Lang, A.D. Martin, P. Motylinski and R.S. Thorne, *Parton distributions in the LHC era: MMHT 2014 PDFs*, *Eur. Phys. J. C* **75** (2015) 204 [`arXiv:1412.3989`] [INSPIRE].

[73] J. Bellm et al., *Herwig 7.0/Herwig++ 3.0 release note*, *Eur. Phys. J. C* **76** (2016) 196 [`arXiv:1512.01178`] [INSPIRE].

[74] ATLAS collaboration, *Simulation of top quark production for the ATLAS experiment at $\sqrt{s} = 13$ TeV*, ATL-PHYS-PUB-2016-004, CERN, Geneva (2016).

[75] ATLAS collaboration, *Cross-section measurements for the production of a Z boson in association with high-transverse-momentum jets in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *JHEP* **06** (2023) 080 [`arXiv:2205.02597`] [INSPIRE].

[76] N. Kidonakis, *Next-to-next-to-leading-order collinear and soft gluon corrections for t-channel single top quark production*, *Phys. Rev. D* **83** (2011) 091503 [`arXiv:1103.2792`] [INSPIRE].

[77] N. Kidonakis, *Two-loop soft anomalous dimensions for single top quark associated production with a W^- or H^-*, Phys. Rev. D **82** (2010) 054018 [`arXiv:1005.4451`] [INSPIRE].

[78] N. Kidonakis, *NNLL resummation for s-channel single top quark production*, Phys. Rev. D **81** (2010) 054028 [`arXiv:1001.5034`] [INSPIRE].

[79] ATLAS collaboration, *Measurements of the inclusive and differential production cross sections of a top-quark-antiquark pair in association with a Z boson at $\sqrt{s} = 13$ TeV with the ATLAS detector*, Eur. Phys. J. C **81** (2021) 737 [`arXiv:2103.12603`] [INSPIRE].

[80] ATLAS collaboration, *Search for resonant and non-resonant Higgs boson pair production in the $b\bar{b}\tau^+\tau^-$ decay channel using 13 TeV pp collision data from the ATLAS detector*, JHEP **07** (2023) 040 [`arXiv:2209.10910`] [INSPIRE].

[81] G. Cowan, K. Cranmer, E. Gross and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics*, Eur. Phys. J. C **71** (2011) 1554 [*Erratum ibid.* **73** (2013) 2501] [`arXiv:1007.1727`] [INSPIRE].

[82] W. Verkerke and D. Kirkby, *The RooFit toolkit for data modeling*, `physics/0306116`.

[83] T. Junk, *Confidence level computation for combining searches with small statistics*, Nucl. Instrum. Meth. A **434** (1999) 435 [`hep-ex/9902006`] [INSPIRE].

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

[85] LHC Higgs Cross Section Working Group collaboration, *Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector*, `arXiv:1610.07922` [`DOI:10.23731/CYRM-2017-002`] [INSPIRE].

[86] U. Ellwanger, J.F. Gunion and C. Hugonie, *NMHDECAY: A Fortran code for the Higgs masses, couplings and decay widths in the NMSSM*, JHEP **02** (2005) 066 [`hep-ph/0406215`] [INSPIRE].

[87] U. Ellwanger and C. Hugonie, *NMHDECAY 2.0: An Updated program for sparticle masses, Higgs masses, couplings and decay widths in the NMSSM*, Comput. Phys. Commun. **175** (2006) 290 [`hep-ph/0508022`] [INSPIRE].

[88] B.C. Allanach et al., *SUSY Les Houches Accord 2*, Comput. Phys. Commun. **180** (2009) 8 [`arXiv:0801.0045`] [INSPIRE].

[89] J. Baglio et al., *NMSSMCALC: A Program Package for the Calculation of Loop-Corrected Higgs Boson Masses and Decay Widths in the (Complex) NMSSM*, Comput. Phys. Commun. **185** (2014) 3372 [`arXiv:1312.4788`] [INSPIRE].

[90] ATLAS collaboration, *ATLAS Computing Acknowledgements*, ATL-SOFT-PUB-2021-003, CERN, Geneva (2021).

The ATLAS collaboration

G. Aad[102], B. Abbott[120], K. Abeling[55], N.J. Abicht[49], S.H. Abidi[29], A. Aboulhorma[35e], H. Abramowicz[151], H. Abreu[150], Y. Abulaiti[117], B.S. Acharya[69a,69b,q], C. Adam Bourdarios[4], L. Adamczyk[86a], L. Adamek[155], S.V. Addepalli[26], M.J. Addison[101], J. Adelman[115], A. Adiguzel[21c], T. Adye[134], A.A. Affolder[136], Y. Afik[36], M.N. Agaras[13], J. Agarwala[73a,73b], A. Aggarwal[100], C. Agheorghiesei[27c], A. Ahmad[36], F. Ahmadov[38,aj], W.S. Ahmed[104], S. Ahuja[95], X. Ai[62a], G. Aielli[76a,76b], A. Aikot[163], M. Ait Tamlihat[35e], B. Aitbenchikh[35a], I. Aizenberg[169], M. Akbiyik[100], T.P.A. Åkesson[98], A.V. Akimov[37], D. Akiyama[168], N.N. Akolkar[24], K. Al Khoury[41], G.L. Alberghi[23b], J. Albert[165], P. Albicocco[53], G.L. Albouy[60], S. Alderweireldt[52], M. Aleksa[36], I.N. Aleksandrov[38], C. Alexa[27b], T. Alexopoulos[10], F. Alfonsi[23b], M. Algren[56], M. Alhroob[120], B. Ali[132], H.M.J. Ali[91], S. Ali[148], S.W. Alibocus[92], M. Aliev[145], G. Alimonti[71a], W. Alkakhi[55], C. Allaire[66], B.M.M. Allbrooke[146], J.F. Allen[52], C.A. Allendes Flores[137f], P.P. Allport[20], A. Aloisio[72a,72b], F. Alonso[90], C. Alpigiani[138], M. Alvarez Estevez[99], A. Alvarez Fernandez[100], M. Alves Cardoso[56], M.G. Alviggi[72a,72b], M. Aly[101], Y. Amaral Coutinho[83b], A. Ambler[104], C. Amelung[36], M. Amerl[101], C.G. Ames[109], D. Amidei[106], S.P. Amor Dos Santos[130a], K.R. Amos[163], V. Ananiev[125], C. Anastopoulos[139], T. Andeen[11], J.K. Anders[36], S.Y. Andrean[47a,47b], A. Andreazza[71a,71b], S. Angelidakis[9], A. Angerami[41,an], A.V. Anisenkov[37], A. Annovi[74a], C. Antel[56], M.T. Anthony[139], E. Antipov[145], M. Antonelli[53], F. Anulli[75a], M. Aoki[84], T. Aoki[153], J.A. Aparisi Pozo[163], M.A. Aparo[146], L. Aperio Bella[48], C. Appelt[18], A. Apyan[26], N. Aranzabal[36], C. Arcangeletti[53], A.T.H. Arce[51], E. Arena[92], J-F. Arguin[108], S. Argyropoulos[54], J.-H. Arling[48], O. Arnaez[4], H. Arnold[114], G. Artoni[75a,75b], H. Asada[111], K. Asai[118], S. Asai[153], N.A. Asbah[61], J. Assahsah[35d], K. Assamagan[29], R. Astalos[28a], S. Atashi[160], R.J. Atkin[33a], M. Atkinson[162], H. Atmani[35f], P.A. Atmasiddha[106], K. Augsten[132], S. Auricchio[72a,72b], A.D. Auriol[20], V.A. Austrup[101], G. Avolio[36], K. Axiotis[56], G. Azuelos[108,av], D. Babal[28b], H. Bachacou[135], K. Bachas[152,w], A. Bachiu[34], F. Backman[47a,47b], A. Badea[61], P. Bagnaia[75a,75b], M. Bahmani[18], A.J. Bailey[163], V.R. Bailey[162], J.T. Baines[134], L. Baines[94], C. Bakalis[10], O.K. Baker[172], E. Bakos[15], D. Bakshi Gupta[8], V. Balakrishnan[120], R. Balasubramanian[114], E.M. Baldin[37], P. Balek[86a], E. Ballabene[23b,23a], F. Balli[135], L.M. Baltes[63a], W.K. Balunas[32], J. Balz[100], E. Banas[87], M. Bandieramonte[129], A. Bandyopadhyay[24], S. Bansal[24], L. Barak[151], M. Barakat[48], E.L. Barberio[105], D. Barberis[57b,57a], M. Barbero[102], M.Z. Barel[114], K.N. Barends[33a], T. Barillari[110], M-S. Barisits[36], T. Barklow[143], P. Baron[122], D.A. Baron Moreno[101], A. Baroncelli[62a], G. Barone[29], A.J. Barr[126], J.D. Barr[96], L. Barranco Navarro[47a,47b], F. Barreiro[99], J. Barreiro Guimarães da Costa[14a], U. Barron[151], M.G. Barros Teixeira[130a], S. Barsov[37], F. Bartels[63a], R. Bartoldus[143], A.E. Barton[91], P. Bartos[28a], A. Basan[100,ae], M. Baselga[49], A. Bassalat[66,b], M.J. Basso[156a], C.R. Basson[101], R.L. Bates[59], S. Batlamous[35e], J.R. Batley[32], B. Batool[141], M. Battaglia[136], D. Battulga[18], M. Bauce[75a,75b], M. Bauer[36], P. Bauer[24], L.T. Bazzano Hurrell[30], J.B. Beacham[51], T. Beau[127], P.H. Beauchemin[158], F. Becherer[54], P. Bechtle[24], H.P. Beck[19,u],

K. Becker[167], A.J. Beddall[82], V.A. Bednyakov[38], C.P. Bee[145], L.J. Beemster[15],
T.A. Beermann[36], M. Begalli[83d], M. Begel[29], A. Behera[145], J.K. Behr[48], J.F. Beirer[55],
F. Beisiegel[24], M. Belfkir[159], G. Bella[151], L. Bellagamba[23b], A. Bellerive[34], P. Bellos[20],
K. Beloborodov[37], D. Benchekroun[35a], F. Bendebba[35a], Y. Benhammou[151], M. Benoit[29],
J.R. Bensinger[26], S. Bentvelsen[114], L. Beresford[48], M. Beretta[53],
E. Bergeaas Kuutmann[161], N. Berger[4], B. Bergmann[132], J. Beringer[17a], G. Bernardi[5],
C. Bernius[143], F.U. Bernlochner[24], F. Bernon[36,102], T. Berry[95], P. Berta[133],
A. Berthold[50], I.A. Bertram[91], S. Bethke[110], A. Betti[75a,75b], A.J. Bevan[94],
M. Bhamjee[33c], S. Bhatta[145], D.S. Bhattacharya[166], P. Bhattarai[143], V.S. Bhopatkar[121],
R. Bi[29,ay], R.M. Bianchi[129], G. Bianco[23b,23a], O. Biebel[109], R. Bielski[123], M. Biglietti[77a],
M. Bindi[55], A. Bingul[21b], C. Bini[75a,75b], A. Biondini[92], C.J. Birch-sykes[101],
G.A. Bird[20,134], M. Birman[169], M. Biros[133], S. Biryukov[146], T. Bisanz[49],
E. Bisceglie[43b,43a], J.P. Biswal[134], D. Biswas[141], A. Bitadze[101], K. Bjørke[125],
I. Bloch[48], C. Blocker[26], A. Blue[59], U. Blumenschein[94], J. Blumenthal[100],
G.J. Bobbink[114], V.S. Bobrovnikov[37], M. Boehler[54], B. Boehm[166], D. Bogavac[36],
A.G. Bogdanchikov[37], C. Bohm[47a], V. Boisvert[95], P. Bokan[48], T. Bold[86a],
M. Bomben[5], M. Bona[94], M. Boonekamp[135], C.D. Booth[95], A.G. Borbély[59,as],
I.S. Bordulev[37], H.M. Borecka-Bielska[108], G. Borissov[91], D. Bortoletto[126],
D. Boscherini[23b], M. Bosman[13], J.D. Bossio Sola[36], K. Bouaouda[35a], N. Bouchhar[163],
J. Boudreau[129], E.V. Bouhova-Thacker[91], D. Boumediene[40], R. Bouquet[5], A. Boveia[119],
J. Boyd[36], D. Boye[29], I.R. Boyko[38], J. Bracinik[20], N. Brahimi[62d], G. Brandt[171],
O. Brandt[32], F. Braren[48], B. Brau[103], J.E. Brau[123], R. Brener[169], L. Brenner[114],
R. Brenner[161], S. Bressler[169], D. Britton[59], D. Britzger[110], I. Brock[24],
G. Brooijmans[41], W.K. Brooks[137f], E. Brost[29], L.M. Brown[165,n], L.E. Bruce[61],
T.L. Bruckler[126], P.A. Bruckman de Renstrom[87], B. Brüers[48], A. Bruni[23b], G. Bruni[23b],
M. Bruschi[23b], N. Bruscino[75a,75b], T. Buanes[16], Q. Buat[138], D. Buchin[110],
A.G. Buckley[59], O. Bulekov[37], B.A. Bullard[143], S. Burdin[92], C.D. Burgard[49],
A.M. Burger[40], B. Burghgrave[8], O. Burlayenko[54], J.T.P. Burr[32], C.D. Burton[11],
J.C. Burzynski[142], E.L. Busch[41], V. Büscher[100], P.J. Bussey[59], J.M. Butler[25],
C.M. Buttar[59], J.M. Butterworth[96], W. Buttinger[134], C.J. Buxo Vazquez[107],
A.R. Buzykaev[37], S. Cabrera Urbán[163], L. Cadamuro[66], D. Caforio[58], H. Cai[129],
Y. Cai[14a,14e], V.M.M. Cairo[36], O. Cakir[3a], N. Calace[36], P. Calafiura[17a],
G. Calderini[127], P. Calfayan[68], G. Callea[59], L.P. Caloba[83b], D. Calvet[40], S. Calvet[40],
T.P. Calvet[102], M. Calvetti[74a,74b], R. Camacho Toro[127], S. Camarda[36],
D. Camarero Munoz[26], P. Camarri[76a,76b], M.T. Camerlingo[72a,72b], D. Cameron[36,h],
C. Camincher[165], M. Campanelli[96], A. Camplani[42], V. Canale[72a,72b], A. Canesse[104],
J. Cantero[163], Y. Cao[162], F. Capocasa[26], M. Capua[43b,43a], A. Carbone[71a,71b],
R. Cardarelli[76a], J.C.J. Cardenas[8], F. Cardillo[163], T. Carli[36], G. Carlino[72a],
J.I. Carlotto[13], B.T. Carlson[129,x], E.M. Carlson[165,156a], L. Carminati[71a,71b],
A. Carnelli[135], M. Carnesale[75a,75b], S. Caron[113], E. Carquin[137f], S. Carrá[71a,71b],
G. Carratta[23b,23a], F. Carrio Argos[33g], J.W.S. Carter[155], T.M. Carter[52],
M.P. Casado[13,k], M. Caspar[48], E.G. Castiglia[172], F.L. Castillo[4], L. Castillo Garcia[13],
V. Castillo Gimenez[163], N.F. Castro[130a,130e], A. Catinaccio[36], J.R. Catmore[125],

V. Cavaliere[29], N. Cavalli[23b,23a], V. Cavasinni[74a,74b], Y.C. Cekmecelioglu[48], E. Celebi[21a], F. Celli[126], M.S. Centonze[70a,70b], V. Cepaitis[56], K. Cerny[122], A.S. Cerqueira[83a], A. Cerri[146], L. Cerrito[76a,76b], F. Cerutti[17a], B. Cervato[141], A. Cervelli[23b], G. Cesarini[53], S.A. Cetin[82], Z. Chadi[35a], D. Chakraborty[115], J. Chan[170], W.Y. Chan[153], J.D. Chapman[32], E. Chapon[135], B. Chargeishvili[149b], D.G. Charlton[20], T.P. Charman[94], M. Chatterjee[19], C. Chauhan[133], S. Chekanov[6], S.V. Chekulaev[156a], G.A. Chelkov[38,a], A. Chen[106], B. Chen[151], B. Chen[165], H. Chen[14c], H. Chen[29], J. Chen[62c], J. Chen[142], M. Chen[126], S. Chen[153], S.J. Chen[14c], X. Chen[62c,135], X. Chen[14b,au], Y. Chen[62a], C.L. Cheng[170], H.C. Cheng[64a], S. Cheong[143], A. Cheplakov[38], E. Cheremushkina[48], E. Cherepanova[114], R. Cherkaoui El Moursli[35e], E. Cheu[7], K. Cheung[65], L. Chevalier[135], V. Chiarella[53], G. Chiarelli[74a], N. Chiedde[102], G. Chiodini[70a], A.S. Chisholm[20], A. Chitan[27b], M. Chitishvili[163], M.V. Chizhov[38], K. Choi[11], A.R. Chomont[75a,75b], Y. Chou[103], E.Y.S. Chow[114], T. Chowdhury[33g], K.L. Chu[169], M.C. Chu[64a], X. Chu[14a,14e], J. Chudoba[131], J.J. Chwastowski[87], D. Cieri[110], K.M. Ciesla[86a], V. Cindro[93], A. Ciocio[17a], F. Cirotto[72a,72b], Z.H. Citron[169,o], M. Citterio[71a], D.A. Ciubotaru[27b], B.M. Ciungu[155], A. Clark[56], P.J. Clark[52], J.M. Clavijo Columbie[48], S.E. Clawson[48], C. Clement[47a,47b], J. Clercx[48], L. Clissa[23b,23a], Y. Coadou[102], M. Cobal[69a,69c], A. Coccaro[57b], R.F. Coelho Barrue[130a], R. Coelho Lopes De Sa[103], S. Coelli[71a], H. Cohen[151], A.E.C. Coimbra[71a,71b], B. Cole[41], J. Collot[60], P. Conde Muiño[130a,130g], M.P. Connell[33c], S.H. Connell[33c], I.A. Connelly[59], E.I. Conroy[126], F. Conventi[72a,aw], H.G. Cooke[20], A.M. Cooper-Sarkar[126], A. Cordeiro Oudot Choi[127], F. Cormier[164], L.D. Corpe[40], M. Corradi[75a,75b], F. Corriveau[104,ah], A. Cortes-Gonzalez[18], M.J. Costa[163], F. Costanza[4], D. Costanzo[139], B.M. Cote[119], G. Cowan[95], K. Cranmer[170], D. Cremonini[23b,23a], S. Crépé-Renaudin[60], F. Crescioli[127], M. Cristinziani[141], M. Cristoforetti[78a,78b], V. Croft[114], J.E. Crosby[121], G. Crosetti[43b,43a], A. Cueto[99], T. Cuhadar Donszelmann[160], H. Cui[14a,14e], Z. Cui[7], W.R. Cunningham[59], F. Curcio[43b,43a], P. Czodrowski[36], M.M. Czurylo[63b], M.J. Da Cunha Sargedas De Sousa[57b,57a], J.V. Da Fonseca Pinto[83b], C. Da Via[101], W. Dabrowski[86a], T. Dado[49], S. Dahbi[33g], T. Dai[106], D. Dal Santo[19], C. Dallapiccola[103], M. Dam[42], G. D'amen[29], V. D'Amico[109], J. Damp[100], J.R. Dandoy[128], M.F. Daneri[30], M. Danninger[142], V. Dao[36], G. Darbo[57b], S. Darmora[6], S.J. Das[29,ay], S. D'Auria[71a,71b], C. David[156b], T. Davidek[133], B. Davis-Purcell[34], I. Dawson[94], H.A. Day-hall[132], K. De[8], R. De Asmundis[72a], N. De Biase[48], S. De Castro[23b,23a], N. De Groot[113], P. de Jong[114], H. De la Torre[115], A. De Maria[14c], A. De Salvo[75a], U. De Sanctis[76a,76b], A. De Santo[146], J.B. De Vivie De Regie[60], D.V. Dedovich[38], J. Degens[114], A.M. Deiana[44], F. Del Corso[23b,23a], J. Del Peso[99], F. Del Rio[63a], F. Deliot[135], C.M. Delitzsch[49], M. Della Pietra[72a,72b], D. Della Volpe[56], A. Dell'Acqua[36], L. Dell'Asta[71a,71b], M. Delmastro[4], P.A. Delsart[60], S. Demers[172], M. Demichev[38], S.P. Denisov[37], L. D'Eramo[40], D. Derendarz[87], F. Derue[127], P. Dervan[92], K. Desch[24], C. Deutsch[24], F.A. Di Bello[57b,57a], A. Di Ciaccio[76a,76b], L. Di Ciaccio[4], A. Di Domenico[75a,75b], C. Di Donato[72a,72b], A. Di Girolamo[36], G. Di Gregorio[36], A. Di Luca[78a,78b], B. Di Micco[77a,77b], R. Di Nardo[77a,77b], C. Diaconu[102], M. Diamantopoulou[34], F.A. Dias[114], T. Dias Do Vale[142],

M.A. Diaz[137a,137b], F.G. Diaz Capriles[24], M. Didenko[163], E.B. Diehl[106], L. Diehl[54],
S. Díez Cornell[48], C. Diez Pardos[141], C. Dimitriadi[161,24,161], A. Dimitrievska[17a],
J. Dingfelder[24], I-M. Dinu[27b], S.J. Dittmeier[63b], F. Dittus[36], F. Djama[102],
T. Djobava[149b], J.I. Djuvsland[16], C. Doglioni[101,98], A. Dohnalova[28a], J. Dolejsi[133],
Z. Dolezal[133], K.M. Dona[39], M. Donadelli[83c], B. Dong[107], J. Donini[40],
A. D'Onofrio[77a,77b], M. D'Onofrio[92], J. Dopke[134], A. Doria[72a],
N. Dos Santos Fernandes[130a], P. Dougan[101], M.T. Dova[90], A.T. Doyle[59],
M.A. Draguet[126], E. Dreyer[169], I. Drivas-koulouris[10], A.S. Drobac[158], M. Drozdova[56],
D. Du[62a], T.A. du Pree[114], F. Dubinin[37], M. Dubovsky[28a], E. Duchovni[169],
G. Duckeck[109], O.A. Ducu[27b], D. Duda[52], A. Dudarev[36], E.R. Duden[26], M. D'uffizi[101],
L. Duflot[66], M. Dührssen[36], C. Dülsen[171], A.E. Dumitriu[27b], M. Dunford[63a],
S. Dungs[49], K. Dunne[47a,47b], A. Duperrin[102], H. Duran Yildiz[3a], M. Düren[58],
A. Durglishvili[149b], B.L. Dwyer[115], G.I. Dyckes[17a], M. Dyndal[86a], S. Dysch[101],
B.S. Dziedzic[87], Z.O. Earnshaw[146], G.H. Eberwein[126], B. Eckerova[28a], S. Eggebrecht[55],
E. Egidio Purcino De Souza[127], L.F. Ehrke[56], G. Eigen[16], K. Einsweiler[17a], T. Ekelof[161],
P.A. Ekman[98], S. El Farkh[35b], Y. El Ghazali[35b], H. El Jarrari[35e,148],
A. El Moussaouy[108,aa], V. Ellajosyula[161], M. Ellert[161], F. Ellinghaus[171], A.A. Elliot[94],
N. Ellis[36], J. Elmsheuser[29], M. Elsing[36], D. Emeliyanov[134], Y. Enari[153], I. Ene[17a],
S. Epari[13], J. Erdmann[49], P.A. Erland[87], M. Errenst[171], M. Escalier[66], C. Escobar[163],
E. Etzion[151], G. Evans[130a], H. Evans[68], L.S. Evans[95], M.O. Evans[146], A. Ezhilov[37],
S. Ezzarqtouni[35a], F. Fabbri[59], L. Fabbri[23b,23a], G. Facini[96], V. Fadeyev[136],
R.M. Fakhrutdinov[37], S. Falciano[75a], L.F. Falda Ulhoa Coelho[36], P.J. Falke[24],
J. Faltova[133], C. Fan[162], Y. Fan[14a], Y. Fang[14a,14e], M. Fanti[71a,71b], M. Faraj[69a,69b],
Z. Farazpay[97], A. Farbin[8], A. Farilla[77a], T. Farooque[107], S.M. Farrington[52], F. Fassi[35e],
D. Fassouliotis[9], M. Faucci Giannelli[76a,76b], W.J. Fawcett[32], L. Fayard[66], P. Federic[133],
P. Federicova[131], O.L. Fedin[37,a], G. Fedotov[37], M. Feickert[170], L. Feligioni[102],
D.E. Fellers[123], C. Feng[62b], M. Feng[14b], Z. Feng[114], M.J. Fenton[160], A.B. Fenyuk[37],
L. Ferencz[48], R.A.M. Ferguson[91], S.I. Fernandez Luengo[137f], M.J.V. Fernoux[102],
J. Ferrando[48], A. Ferrari[161], P. Ferrari[114,113], R. Ferrari[73a], D. Ferrere[56],
C. Ferretti[106], F. Fiedler[100], P. Fiedler[132], A. Filipčič[93], E.K. Filmer[1], F. Filthaut[113],
M.C.N. Fiolhais[130a,130c,d], L. Fiorini[163], W.C. Fisher[107], T. Fitschen[101], P.M. Fitzhugh[135],
I. Fleck[141], P. Fleischmann[106], T. Flick[171], M. Flores[33d,ao], L.R. Flores Castillo[64a],
L. Flores Sanz De Acedo[36], F.M. Follega[78a,78b], N. Fomin[16], J.H. Foo[155], B.C. Forland[68],
A. Formica[135], A.C. Forti[101], E. Fortin[36], A.W. Fortman[61], M.G. Foti[17a],
L. Fountas[9,l], D. Fournier[66], H. Fox[91], P. Francavilla[74a,74b], S. Francescato[61],
S. Franchellucci[56], M. Franchini[23b,23a], S. Franchino[63a], D. Francis[36], L. Franco[113],
V. Franco Lima[36], L. Franconi[48], M. Franklin[61], G. Frattari[26], A.C. Freegard[94],
W.S. Freund[83b], Y.Y. Frid[151], J. Friend[59], N. Fritzsche[50], A. Froch[54], D. Froidevaux[36],
J.A. Frost[126], Y. Fu[62a], M. Fujimoto[118,ap], E. Fullana Torregrosa[163,*], K.Y. Fung[64a],
E. Furtado De Simas Filho[83b], M. Furukawa[153], J. Fuster[163], A. Gabrielli[23b,23a],
A. Gabrielli[155], P. Gadow[36], G. Gagliardi[57b,57a], L.G. Gagnon[17a], E.J. Gallas[126],
B.J. Gallop[134], K.K. Gan[119], S. Ganguly[153], J. Gao[62a], Y. Gao[52],
F.M. Garay Walls[137a,137b], B. Garcia[29,ay], C. García[163], A. Garcia Alonso[114],

A.G. Garcia Caffaro[172], J.E. García Navarro[163], M. Garcia-Sciveres[17a], G.L. Gardner[128], R.W. Gardner[39], N. Garelli[158], D. Garg[80], R.B. Garg[143,t], J.M. Gargan[52], C.A. Garner[155], C.M. Garvey[33a], S.J. Gasiorowski[138], P. Gaspar[83b], G. Gaudio[73a], V. Gautam[13], P. Gauzzi[75a,75b], I.L. Gavrilenko[37], A. Gavrilyuk[37], C. Gay[164], G. Gaycken[48], E.N. Gazis[10], A.A. Geanta[27b], C.M. Gee[136], C. Gemme[57b], M.H. Genest[60], S. Gentile[75a,75b], A.D. Gentry[112], S. George[95], W.F. George[20], T. Geralis[46], P. Gessinger-Befurt[36], M.E. Geyik[171], M. Ghani[167], M. Ghneimat[141], K. Ghorbanian[94], A. Ghosal[141], A. Ghosh[160], A. Ghosh[7], B. Giacobbe[23b], S. Giagu[75a,75b], T. Giani[114], P. Giannetti[74a], A. Giannini[62a], S.M. Gibson[95], M. Gignac[136], D.T. Gil[86b], A.K. Gilbert[86a], B.J. Gilbert[41], D. Gillberg[34], G. Gilles[114], N.E.K. Gillwald[48], L. Ginabat[127], D.M. Gingrich[2,av], M.P. Giordani[69a,69c], P.F. Giraud[135], G. Giugliarelli[69a,69c], D. Giugni[71a], F. Giuli[36], I. Gkialas[9,l], L.K. Gladilin[37], C. Glasman[99], G.R. Gledhill[123], G. Glemža[48], M. Glisic[123], I. Gnesi[43b,g], Y. Go[29,ay], M. Goblirsch-Kolb[36], B. Gocke[49], D. Godin[108], B. Gokturk[21a], S. Goldfarb[105], T. Golling[56], M.G.D. Gololo[33g], D. Golubkov[37], J.P. Gombas[107], A. Gomes[130a,130b], G. Gomes Da Silva[141], A.J. Gomez Delegido[163], R. Gonçalo[130a,130c], G. Gonella[123], L. Gonella[20], A. Gongadze[149c], F. Gonnella[20], J.L. Gonski[41], R.Y. González Andana[52], S. González de la Hoz[163], S. Gonzalez Fernandez[13], R. Gonzalez Lopez[92], C. Gonzalez Renteria[17a], M.V. Gonzalez Rodrigues[48], R. Gonzalez Suarez[161], S. Gonzalez-Sevilla[56], G.R. Gonzalvo Rodriguez[163], L. Goossens[36], B. Gorini[36], E. Gorini[70a,70b], A. Gorišek[93], T.C. Gosart[128], A.T. Goshaw[51], M.I. Gostkin[38], S. Goswami[121], C.A. Gottardo[36], S.A. Gotz[109], M. Gouighri[35b], V. Goumarre[48], A.G. Goussiou[138], N. Govender[33c], I. Grabowska-Bold[86a], K. Graham[34], E. Gramstad[125], S. Grancagnolo[70a,70b], M. Grandi[146], C.M. Grant[1,135], P.M. Gravila[27f], F.G. Gravili[70a,70b], H.M. Gray[17a], M. Greco[70a,70b], C. Grefe[24], I.M. Gregor[48], P. Grenier[143], S.G. Grewe[110], C. Grieco[13], A.A. Grillo[136], K. Grimm[31], S. Grinstein[13,ac], J.-F. Grivaz[66], E. Gross[169], J. Grosse-Knetter[55], C. Grud[106], J.C. Grundy[126], L. Guan[106], W. Guan[29], C. Gubbels[164], J.G.R. Guerrero Rojas[163], G. Guerrieri[69a,69c], F. Guescini[110], R. Gugel[100], J.A.M. Guhit[106], A. Guida[18], T. Guillemin[4], E. Guilloton[167,134], S. Guindon[36], F. Guo[14a,14e], J. Guo[62c], L. Guo[48], Y. Guo[106], R. Gupta[48], S. Gurbuz[24], S.S. Gurdasani[54], G. Gustavino[36], M. Guth[56], P. Gutierrez[120], L.F. Gutierrez Zagazeta[128], C. Gutschow[96], C. Gwenlan[126], C.B. Gwilliam[92], E.S. Haaland[125], A. Haas[117], M. Habedank[48], C. Haber[17a], H.K. Hadavand[8], A. Hadef[100], S. Hadzic[110], J.J. Hahn[141], E.H. Haines[96], M. Haleem[166], J. Haley[121], J.J. Hall[139], G.D. Hallewell[102], L. Halser[19], K. Hamano[165], M. Hamer[24], G.N. Hamity[52], E.J. Hampshire[95], J. Han[62b], K. Han[62a], L. Han[14c], L. Han[62a], S. Han[17a], Y.F. Han[155], K. Hanagaki[84], M. Hance[136], D.A. Hangal[41,an], H. Hanif[142], M.D. Hank[128], R. Hankache[101], J.B. Hansen[42], J.D. Hansen[42], P.H. Hansen[42], K. Hara[157], D. Harada[56], T. Harenberg[171], S. Harkusha[37], M.L. Harris[103], Y.T. Harris[126], J. Harrison[13], N.M. Harrison[119], P.F. Harrison[167], N.M. Hartman[110], N.M. Hartmann[109], Y. Hasegawa[140], R. Hauser[107], C.M. Hawkes[20], R.J. Hawkings[36], Y. Hayashi[153], S. Hayashida[111], D. Hayden[107], C. Hayes[106], R.L. Hayes[114], C.P. Hays[126], J.M. Hays[94], H.S. Hayward[92], F. He[62a], M. He[14a,14e],

Y. He[154], Y. He[48], N.B. Heatley[94], V. Hedberg[98], A.L. Heggelund[125], N.D. Hehir[94], C. Heidegger[54], K.K. Heidegger[54], W.D. Heidorn[81], J. Heilman[34], S. Heim[48], T. Heim[17a], J.G. Heinlein[128], J.J. Heinrich[123], L. Heinrich[110,at], J. Hejbal[131], L. Helary[48], A. Held[170], S. Hellesund[16], C.M. Helling[164], S. Hellman[47a,47b], R.C.W. Henderson[91], L. Henkelmann[32], A.M. Henriques Correia[36], H. Herde[98], Y. Hernández Jiménez[145], L.M. Herrmann[24], T. Herrmann[50], G. Herten[54], R. Hertenberger[109], L. Hervas[36], M.E. Hesping[100], N.P. Hessey[156a], H. Hibi[85], E. Hill[155], S.J. Hillier[20], J.R. Hinds[107], F. Hinterkeuser[24], M. Hirose[124], S. Hirose[157], D. Hirschbuehl[171], T.G. Hitchings[101], B. Hiti[93], J. Hobbs[145], R. Hobincu[27e], N. Hod[169], M.C. Hodgkinson[139], B.H. Hodkinson[32], A. Hoecker[36], J. Hofer[48], T. Holm[24], M. Holzbock[110], L.B.A.H. Hommels[32], B.P. Honan[101], J. Hong[62c], T.M. Hong[129], B.H. Hooberman[162], W.H. Hopkins[6], Y. Horii[111], S. Hou[148], A.S. Howard[93], J. Howarth[59], J. Hoya[6], M. Hrabovsky[122], A. Hrynevich[48], T. Hryn'ova[4], P.J. Hsu[65], S.-C. Hsu[138], Q. Hu[62a], Y.F. Hu[14a,14e], S. Huang[64b], X. Huang[14c], Y. Huang[139,m], Y. Huang[14a], Z. Huang[101], Z. Hubacek[132], M. Huebner[24], F. Huegging[24], T.B. Huffman[126], C.A. Hugli[48], M. Huhtinen[36], S.K. Huiberts[16], R. Hulsken[104], N. Huseynov[12,a], J. Huston[107], J. Huth[61], R. Hyneman[143], G. Iacobucci[56], G. Iakovidis[29], I. Ibragimov[141], L. Iconomidou-Fayard[66], P. Iengo[72a,72b], R. Iguchi[153], T. Iizawa[126,r], Y. Ikegami[84], N. Ilic[155], H. Imam[35a], M. Ince Lezki[56], T. Ingebretsen Carlson[47a,47b], G. Introzzi[73a,73b], M. Iodice[77a], V. Ippolito[75a,75b], R.K. Irwin[92], M. Ishino[153], W. Islam[170], C. Issever[18,48], S. Istin[21a,ba], H. Ito[168], J.M. Iturbe Ponce[64a], R. Iuppa[78a,78b], A. Ivina[169], J.M. Izen[45], V. Izzo[72a], P. Jacka[131,132], P. Jackson[1], R.M. Jacobs[48], B.P. Jaeger[142], C.S. Jagfeld[109], G. Jain[156a], P. Jain[54], G. Jäkel[171], K. Jakobs[54], T. Jakoubek[169], J. Jamieson[59], K.W. Janas[86a], M. Javurkova[103], F. Jeanneau[135], L. Jeanty[123], J. Jejelava[149a,ak], P. Jenni[54,i], C.E. Jessiman[34], S. Jézéquel[4], C. Jia[62b], J. Jia[145], X. Jia[61], X. Jia[14a,14e], Z. Jia[14c], Y. Jiang[62a], S. Jiggins[48], J. Jimenez Pena[13], S. Jin[14c], A. Jinaru[27b], O. Jinnouchi[154], P. Johansson[139], K.A. Johns[7], J.W. Johnson[136], D.M. Jones[32], E. Jones[48], P. Jones[32], R.W.L. Jones[91], T.J. Jones[92], H.L. Joos[55,36], R. Joshi[119], J. Jovicevic[15], X. Ju[17a], J.J. Junggeburth[103,v], T. Junkermann[63a], A. Juste Rozas[13,ac], M.K. Juzek[87], S. Kabana[137e], A. Kaczmarska[87], M. Kado[110], H. Kagan[119], M. Kagan[143], A. Kahn[41], A. Kahn[128], C. Kahra[100], T. Kaji[153], E. Kajomovitz[150], N. Kakati[169], I. Kalaitzidou[54], C.W. Kalderon[29], A. Kamenshchikov[155], N.J. Kang[136], D. Kar[33g], K. Karava[126], M.J. Kareem[156b], E. Karentzos[54], I. Karkanias[152], O. Karkout[114], S.N. Karpov[38], Z.M. Karpova[38], V. Kartvelishvili[91], A.N. Karyukhin[37], E. Kasimi[152], J. Katzy[48], S. Kaur[34], K. Kawade[140], M.P. Kawale[120], C. Kawamoto[88], T. Kawamoto[135], E.F. Kay[36], F.I. Kaya[158], S. Kazakos[107], V.F. Kazanin[37], Y. Ke[145], J.M. Keaveney[33a], R. Keeler[165], G.V. Kehris[61], J.S. Keller[34], A.S. Kelly[96], J.J. Kempster[146], K.E. Kennedy[41], P.D. Kennedy[100], O. Kepka[131], B.P. Kerridge[167], S. Kersten[171], B.P. Kerševan[93], S. Keshri[66], L. Keszeghova[28a], S. Ketabchi Haghighat[155], M. Khandoga[127], A. Khanov[121], A.G. Kharlamov[37], T. Kharlamova[37], E.E. Khoda[138], M. Kholodenko[37], T.J. Khoo[18], G. Khoriauli[166], J. Khubua[149b], Y.A.R. Khwaira[66], A. Kilgallon[123], D.W. Kim[47a,47b], Y.K. Kim[39], N. Kimura[96], M.K. Kingston[55],

A. Kirchhoff[55], C. Kirfel[24], F. Kirfel[24], J. Kirk[134], A.E. Kiryunin[110], C. Kitsaki[10], O. Kivernyk[24], M. Klassen[63a], C. Klein[34], L. Klein[166], M.H. Klein[106], M. Klein[92], S.B. Klein[56], U. Klein[92], P. Klimek[36], A. Klimentov[29], T. Klioutchnikova[36], P. Kluit[114], S. Kluth[110], E. Kneringer[79], T.M. Knight[155], A. Knue[49], R. Kobayashi[88], D. Kobylianskii[169], S.F. Koch[126], M. Kocian[143], P. Kodyš[133], D.M. Koeck[123], P.T. Koenig[24], T. Koffas[34], M. Kolb[135], I. Koletsou[4], T. Komarek[122], K. Köneke[54], A.X.Y. Kong[1], T. Kono[118], N. Konstantinidis[96], B. Konya[98], R. Kopeliansky[68], S. Koperny[86a], K. Korcyl[87], K. Kordas[152,f], G. Koren[151], A. Korn[96], S. Korn[55], I. Korolkov[13], N. Korotkova[37], B. Kortman[114], O. Kortner[110], S. Kortner[110], W.H. Kostecka[115], V.V. Kostyukhin[141], A. Kotsokechagia[135], A. Kotwal[51], A. Koulouris[36], A. Kourkoumeli-Charalampidi[73a,73b], C. Kourkoumelis[9], E. Kourlitis[110,at], O. Kovanda[146], R. Kowalewski[165], W. Kozanecki[135], A.S. Kozhin[37], V.A. Kramarenko[37], G. Kramberger[93], P. Kramer[100], M.W. Krasny[127], A. Krasznahorkay[36], J.W. Kraus[171], J.A. Kremer[48], T. Kresse[50], J. Kretzschmar[92], K. Kreul[18], P. Krieger[155], S. Krishnamurthy[103], M. Krivos[133], K. Krizka[20], K. Kroeninger[49], H. Kroha[110], J. Kroll[131], J. Kroll[128], K.S. Krowpman[107], U. Kruchonak[38], H. Krüger[24], N. Krumnack[81], M.C. Kruse[51], J.A. Krzysiak[87], O. Kuchinskaia[37], S. Kuday[3a], S. Kuehn[36], R. Kuesters[54], T. Kuhl[48], V. Kukhtin[38], Y. Kulchitsky[37,a], S. Kuleshov[137d,137b], M. Kumar[33g], N. Kumari[48], A. Kupco[131], T. Kupfer[49], A. Kupich[37], O. Kuprash[54], H. Kurashige[85], L.L. Kurchaninov[156a], O. Kurdysh[66], Y.A. Kurochkin[37], A. Kurova[37], M. Kuze[154], A.K. Kvam[103], J. Kvita[122], T. Kwan[104], N.G. Kyriacou[106], L.A.O. Laatu[102], C. Lacasta[163], F. Lacava[75a,75b], H. Lacker[18], D. Lacour[127], N.N. Lad[96], E. Ladygin[38], B. Laforge[127], T. Lagouri[137e], F.Z. Lahbabi[35a], S. Lai[55], I.K. Lakomiec[86a], N. Lalloue[60], J.E. Lambert[165,n], S. Lammers[68], W. Lampl[7], C. Lampoudis[152,f], A.N. Lancaster[115], E. Lançon[29], U. Landgraf[54], M.P.J. Landon[94], V.S. Lang[54], R.J. Langenberg[103], O.K.B. Langrekken[125], A.J. Lankford[160], F. Lanni[36], K. Lantzsch[24], A. Lanza[73a], A. Lapertosa[57b,57a], J.F. Laporte[135], T. Lari[71a], F. Lasagni Manghi[23b], M. Lassnig[36], V. Latonova[131], A. Laudrain[100], A. Laurier[150], S.D. Lawlor[139], Z. Lawrence[101], M. Lazzaroni[71a,71b], B. Le[101], E.M. Le Boulicaut[51], B. Leban[93], A. Lebedev[81], M. LeBlanc[101,ar], F. Ledroit-Guillon[60], A.C.A. Lee[96], S.C. Lee[148], S. Lee[47a,47b], T.F. Lee[92], L.L. Leeuw[33c], H.P. Lefebvre[95], M. Lefebvre[165], C. Leggett[17a], G. Lehmann Miotto[36], M. Leigh[56], W.A. Leight[103], W. Leinonen[113], A. Leisos[152,ab], M.A.L. Leite[83c], C.E. Leitgeb[48], R. Leitner[133], K.J.C. Leney[44], T. Lenz[24], S. Leone[74a], C. Leonidopoulos[52], A. Leopold[144], C. Leroy[108], R. Les[107], C.G. Lester[32], M. Levchenko[37], J. Levêque[4], D. Levin[106], L.J. Levinson[169], M.P. Lewicki[87], D.J. Lewis[4], A. Li[5], B. Li[62b], C. Li[62a], C-Q. Li[62c], H. Li[62a], H. Li[62b], H. Li[14c], H. Li[14b], H. Li[62b], K. Li[138], L. Li[62c], M. Li[14a,14e], Q.Y. Li[62a], S. Li[14a,14e], S. Li[62d,62c,e], T. Li[5,c], X. Li[104], Z. Li[126], Z. Li[104], Z. Li[92], Z. Li[14a,14e], S. Liang[14a,14e], Z. Liang[14a], M. Liberatore[135,al], B. Liberti[76a], K. Lie[64c], J. Lieber Marin[83b], H. Lien[68], K. Lin[107], R.E. Lindley[7], J.H. Lindon[2], E. Lipeles[128], A. Lipniacka[16], A. Lister[164], J.D. Little[4], B. Liu[14a], B.X. Liu[142], D. Liu[62d,62c], J.B. Liu[62a], J.K.K. Liu[32], K. Liu[62d,62c], M. Liu[62a], M.Y. Liu[62a], P. Liu[14a], Q. Liu[62d,138,62c], X. Liu[62a], Y. Liu[14d,14e], Y.L. Liu[62b], Y.W. Liu[62a],

J. Llorente Merino[142], S.L. Lloyd[94], E.M. Lobodzinska[48], P. Loch[7], S. Loffredo[76a,76b], T. Lohse[18], K. Lohwasser[139], E. Loiacono[48], M. Lokajicek[131,*], J.D. Lomas[20], J.D. Long[162], I. Longarini[160], L. Longo[70a,70b], R. Longo[162], I. Lopez Paz[67], A. Lopez Solis[48], J. Lorenz[109], N. Lorenzo Martinez[4], A.M. Lory[109], O. Loseva[37], X. Lou[47a,47b], X. Lou[14a,14e], A. Lounis[66], J. Love[6], P.A. Love[91], G. Lu[14a,14e], M. Lu[80], S. Lu[128], Y.J. Lu[65], H.J. Lubatti[138], C. Luci[75a,75b], F.L. Lucio Alves[14c], A. Lucotte[60], F. Luehring[68], I. Luise[145], O. Lukianchuk[66], O. Lundberg[144], B. Lund-Jensen[144], N.A. Luongo[123], M.S. Lutz[151], A.B. Lux[25], D. Lynn[29], H. Lyons[92], R. Lysak[131], E. Lytken[98], V. Lyubushkin[38], T. Lyubushkina[38], M.M. Lyukova[145], H. Ma[29], K. Ma[62a], L.L. Ma[62b], Y. Ma[121], D.M. Mac Donell[165], G. Maccarrone[53], J.C. MacDonald[100], P.C. Machado De Abreu Farias[83b], R. Madar[40], W.F. Mader[50], T. Madula[96], J. Maeda[85], T. Maeno[29], H. Maguire[139], V. Maiboroda[135], A. Maio[130a,130b,130d], K. Maj[86a], O. Majersky[48], S. Majewski[123], N. Makovec[66], V. Maksimovic[15], B. Malaescu[127], Pa. Malecki[87], V.P. Maleev[37], F. Malek[60], M. Mali[93], D. Malito[95,s], U. Mallik[80], S. Maltezos[10], S. Malyukov[38], J. Mamuzic[13], G. Mancini[53], G. Manco[73a,73b], J.P. Mandalia[94], I. Mandić[93], L. Manhaes de Andrade Filho[83a], I.M. Maniatis[169], J. Manjarres Ramos[102,am], D.C. Mankad[169], A. Mann[109], B. Mansoulie[135], S. Manzoni[36], A. Marantis[152,ab], G. Marchiori[5], M. Marcisovsky[131], C. Marcon[71a,71b], M. Marinescu[20], M. Marjanovic[120], E.J. Marshall[91], Z. Marshall[17a], S. Marti-Garcia[163], T.A. Martin[167], V.J. Martin[52], B. Martin dit Latour[16], L. Martinelli[75a,75b], M. Martinez[13,ac], P. Martinez Agullo[163], V.I. Martinez Outschoorn[103], P. Martinez Suarez[13], S. Martin-Haugh[134], V.S. Martoiu[27b], A.C. Martyniuk[96], A. Marzin[36], D. Mascione[78a,78b], L. Masetti[100], T. Mashimo[153], J. Masik[101], A.L. Maslennikov[37], L. Massa[23b], P. Massarotti[72a,72b], P. Mastrandrea[74a,74b], A. Mastroberardino[43b,43a], T. Masubuchi[153], T. Mathisen[161], J. Matousek[133], N. Matsuzawa[153], J. Maurer[27b], B. Maček[93], D.A. Maximov[37], R. Mazini[148], I. Maznas[152], M. Mazza[107], S.M. Mazza[136], E. Mazzeo[71a,71b], C. Mc Ginn[29], J.P. Mc Gowan[104], S.P. Mc Kee[106], E.F. McDonald[105], A.E. McDougall[114], J.A. Mcfayden[146], R.P. McGovern[128], G. Mchedlidze[149b], R.P. Mckenzie[33g], T.C. Mclachlan[48], D.J. Mclaughlin[96], S.J. McMahon[134], C.M. Mcpartland[92], R.A. McPherson[165,ah], S. Mehlhase[109], A. Mehta[92], D. Melini[150], B.R. Mellado Garcia[33g], A.H. Melo[55], F. Meloni[48], A.M. Mendes Jacques Da Costa[101], H.Y. Meng[155], L. Meng[91], S. Menke[110], M. Mentink[36], E. Meoni[43b,43a], C. Merlassino[126], L. Merola[72a,72b], C. Meroni[71a,71b], G. Merz[106], O. Meshkov[37], J. Metcalfe[6], A.S. Mete[6], C. Meyer[68], J-P. Meyer[135], R.P. Middleton[134], L. Mijović[52], G. Mikenberg[169], M. Mikestikova[131], M. Mikuž[93], H. Mildner[100], A. Milic[36], C.D. Milke[44], D.W. Miller[39], L.S. Miller[34], A. Milov[169], D.A. Milstead[47a,47b], T. Min[14c], A.A. Minaenko[37], I.A. Minashvili[149b], L. Mince[59], A.I. Mincer[117], B. Mindur[86a], M. Mineev[38], Y. Mino[88], L.M. Mir[13], M. Miralles Lopez[163], M. Mironova[17a], A. Mishima[153], M.C. Missio[113], A. Mitra[167], V.A. Mitsou[163], Y. Mitsumori[111], O. Miu[155], P.S. Miyagawa[94], T. Mkrtchyan[63a], M. Mlinarevic[96], T. Mlinarevic[96], M. Mlynarikova[36], S. Mobius[19], P. Moder[48], P. Mogg[109], A.F. Mohammed[14a,14e], S. Mohapatra[41], G. Mokgatitswane[33g], L. Moleri[169], B. Mondal[141], S. Mondal[132],

G. Monig[146], K. Mönig[48], E. Monnier[102], L. Monsonis Romero[163], J. Montejo Berlingen[13], M. Montella[119], F. Montereali[77a,77b], F. Monticelli[90], S. Monzani[69a,69c], N. Morange[66], A.L. Moreira De Carvalho[130a], M. Moreno Llácer[163], C. Moreno Martinez[56], P. Morettini[57b], S. Morgenstern[36], M. Morii[61], M. Morinaga[153], A.K. Morley[36], F. Morodei[75a,75b], L. Morvaj[36], P. Moschovakos[36], B. Moser[36], M. Mosidze[149b], T. Moskalets[54], P. Moskvitina[113], J. Moss[31,p], E.J.W. Moyse[103], O. Mtintsilana[33g], S. Muanza[102], J. Mueller[129], D. Muenstermann[91], R. Müller[19], G.A. Mullier[161], A.J. Mullin[32], J.J. Mullin[128], D.P. Mungo[155], D. Munoz Perez[163], F.J. Munoz Sanchez[101], M. Murin[101], W.J. Murray[167,134], A. Murrone[71a,71b], J.M. Muse[120], M. Muškinja[17a], C. Mwewa[29], A.G. Myagkov[37,a], A.J. Myers[8], A.A. Myers[129], G. Myers[68], M. Myska[132], B.P. Nachman[17a], O. Nackenhorst[49], A. Nag[50], K. Nagai[126], K. Nagano[84], J.L. Nagle[29,ay], E. Nagy[102], A.M. Nairz[36], Y. Nakahama[84], K. Nakamura[84], K. Nakkalil[5], H. Nanjo[124], R. Narayan[44], E.A. Narayanan[112], I. Naryshkin[37], M. Naseri[34], S. Nasri[159], C. Nass[24], G. Navarro[22a], J. Navarro-Gonzalez[163], R. Nayak[151], A. Nayaz[18], P.Y. Nechaeva[37], F. Nechansky[48], L. Nedic[126], T.J. Neep[20], A. Negri[73a,73b], M. Negrini[23b], C. Nellist[114], C. Nelson[104], K. Nelson[106], S. Nemecek[131], M. Nessi[36,j], M.S. Neubauer[162], F. Neuhaus[100], J. Neundorf[48], R. Newhouse[164], P.R. Newman[20], C.W. Ng[129], Y.W.Y. Ng[48], B. Ngair[35e], H.D.N. Nguyen[108], R.B. Nickerson[126], R. Nicolaidou[135], J. Nielsen[136], M. Niemeyer[55], J. Niermann[55,36], N. Nikiforou[36], V. Nikolaenko[37,a], I. Nikolic-Audit[127], K. Nikolopoulos[20], P. Nilsson[29], I. Ninca[48], H.R. Nindhito[56], G. Ninio[151], A. Nisati[75a], N. Nishu[2], R. Nisius[110], J-E. Nitschke[50], E.K. Nkadimeng[33g], T. Nobe[153], D.L. Noel[32], T. Nommensen[147], M.B. Norfolk[139], R.R.B. Norisam[96], B.J. Norman[34], J. Novak[93], T. Novak[48], L. Novotny[132], R. Novotny[112], L. Nozka[122], K. Ntekas[160], N.M.J. Nunes De Moura Junior[83b], E. Nurse[96], J. Ocariz[127], A. Ochi[85], I. Ochoa[130a], S. Oerdek[48,y], J.T. Offermann[39], A. Ogrodnik[133], A. Oh[101], C.C. Ohm[144], H. Oide[84], R. Oishi[153], M.L. Ojeda[48], M.W. O'Keefe[92], Y. Okumura[153], L.F. Oleiro Seabra[130a], S.A. Olivares Pino[137d], D. Oliveira Damazio[29], D. Oliveira Goncalves[83a], J.L. Oliver[160], A. Olszewski[87], Ö.O. Öncel[54], A.P. O'Neill[19], A. Onofre[130a,130e], P.U.E. Onyisi[11], M.J. Oreglia[39], G.E. Orellana[90], D. Orestano[77a,77b], N. Orlando[13], R.S. Orr[155], V. O'Shea[59], L.M. Osojnak[128], R. Ospanov[62a], G. Otero y Garzon[30], H. Otono[89], P.S. Ott[63a], G.J. Ottino[17a], M. Ouchrif[35d], J. Ouellette[29], F. Ould-Saada[125], M. Owen[59], R.E. Owen[134], K.Y. Oyulmaz[21a], V.E. Ozcan[21a], N. Ozturk[8], S. Ozturk[82], H.A. Pacey[126], A. Pacheco Pages[13], C. Padilla Aranda[13], G. Padovano[75a,75b], S. Pagan Griso[17a], G. Palacino[68], A. Palazzo[70a,70b], S. Palestini[36], J. Pan[172], T. Pan[64a], D.K. Panchal[11], C.E. Pandini[114], J.G. Panduro Vazquez[95], H.D. Pandya[1], H. Pang[14b], P. Pani[48], G. Panizzo[69a,69c], L. Paolozzi[56], C. Papadatos[108], S. Parajuli[44], A. Paramonov[6], C. Paraskevopoulos[10], D. Paredes Hernandez[64b], T.H. Park[155], M.A. Parker[32], F. Parodi[57b,57a], E.W. Parrish[115], V.A. Parrish[52], J.A. Parsons[41], U. Parzefall[54], B. Pascual Dias[108], L. Pascual Dominguez[151], E. Pasqualucci[75a], S. Passaggio[57b], F. Pastore[95], P. Pasuwan[47a,47b], P. Patel[87], U.M. Patel[51], J.R. Pater[101], T. Pauly[36], J. Pearkes[143], M. Pedersen[125], R. Pedro[130a], S.V. Peleganchuk[37], O. Penc[36], E.A. Pender[52], H. Peng[62a], K.E. Penski[109],

M. Penzin[37], B.S. Peralva[83d], A.P. Pereira Peixoto[60], L. Pereira Sanchez[47a,47b], D.V. Perepelitsa[29,ay], E. Perez Codina[156a], M. Perganti[10], L. Perini[71a,71b,*], H. Pernegger[36], O. Perrin[40], K. Peters[48], R.F.Y. Peters[101], B.A. Petersen[36], T.C. Petersen[42], E. Petit[102], V. Petousis[132], C. Petridou[152,f], A. Petrukhin[141], M. Pettee[17a], N.E. Pettersson[36], A. Petukhov[37], K. Petukhova[133], R. Pezoa[137f], L. Pezzotti[36], G. Pezzullo[172], T.M. Pham[170], T. Pham[105], P.W. Phillips[134], G. Piacquadio[145], E. Pianori[17a], F. Piazza[71a,71b], R. Piegaia[30], D. Pietreanu[27b], A.D. Pilkington[101], M. Pinamonti[69a,69c], J.L. Pinfold[2], B.C. Pinheiro Pereira[130a], A.E. Pinto Pinoargote[100,135], L. Pintucci[69a,69c], K.M. Piper[146], A. Pirttikoski[56], D.A. Pizzi[34], L. Pizzimento[64b], A. Pizzini[114], M.-A. Pleier[29], V. Plesanovs[54], V. Pleskot[133], E. Plotnikova[38], G. Poddar[4], R. Poettgen[98], L. Poggioli[127], I. Pokharel[55], S. Polacek[133], G. Polesello[73a], A. Poley[142,156a], R. Polifka[132], A. Polini[23b], C.S. Pollard[167], Z.B. Pollock[119], V. Polychronakos[29], E. Pompa Pacchi[75a,75b], D. Ponomarenko[113], L. Pontecorvo[36], S. Popa[27a], G.A. Popeneciu[27d], A. Poreba[36], D.M. Portillo Quintero[156a], S. Pospisil[132], M.A. Postill[139], P. Postolache[27c], K. Potamianos[167], P.A. Potepa[86a], I.N. Potrap[38], C.J. Potter[32], H. Potti[1], T. Poulsen[48], J. Poveda[163], M.E. Pozo Astigarraga[36], A. Prades Ibanez[163], J. Pretel[54], D. Price[101], M. Primavera[70a], M.A. Principe Martin[99], R. Privara[122], T. Procter[59], M.L. Proffitt[138], N. Proklova[128], K. Prokofiev[64c], G. Proto[110], S. Protopopescu[29], J. Proudfoot[6], M. Przybycien[86a], W.W. Przygoda[86b], J.E. Puddefoot[139], D. Pudzha[37], D. Pyatiizbyantseva[37], J. Qian[106], D. Qichen[101], Y. Qin[101], T. Qiu[52], A. Quadt[55], M. Queitsch-Maitland[101], G. Quetant[56], R.P. Quinn[164], G. Rabanal Bolanos[61], D. Rafanoharana[54], F. Ragusa[71a,71b], J.L. Rainbolt[39], J.A. Raine[56], S. Rajagopalan[29], E. Ramakoti[37], K. Ran[48,14e], N.P. Rapheeha[33g], H. Rasheed[27b], V. Raskina[127], D.F. Rassloff[63a], S. Rave[100], B. Ravina[55], I. Ravinovich[169], M. Raymond[36], A.L. Read[125], N.P. Readioff[139], D.M. Rebuzzi[73a,73b], G. Redlinger[29], A.S. Reed[110], K. Reeves[26], J.A. Reidelsturz[171,z], D. Reikher[151], A. Rej[141], C. Rembser[36], A. Renardi[48], M. Renda[27b], M.B. Rendel[110], F. Renner[48], A.G. Rennie[160], A.L. Rescia[48], S. Resconi[71a], M. Ressegotti[57b,57a], S. Rettie[36], J.G. Reyes Rivera[107], E. Reynolds[17a], O.L. Rezanova[37], P. Reznicek[133], N. Ribaric[91], E. Ricci[78a,78b], R. Richter[110], S. Richter[47a,47b], E. Richter-Was[86b], M. Ridel[127], S. Ridouani[35d], P. Rieck[117], P. Riedler[36], E.M. Riefel[47a,47b], M. Rijssenbeek[145], A. Rimoldi[73a,73b], M. Rimoldi[48], L. Rinaldi[23b,23a], T.T. Rinn[29], M.P. Rinnagel[109], G. Ripellino[161], I. Riu[13], P. Rivadeneira[48], J.C. Rivera Vergara[165], F. Rizatdinova[121], E. Rizvi[94], B.A. Roberts[167], B.R. Roberts[17a], S.H. Robertson[104,ah], D. Robinson[32], C.M. Robles Gajardo[137f], M. Robles Manzano[100], A. Robson[59], A. Rocchi[76a,76b], C. Roda[74a,74b], S. Rodriguez Bosca[63a], Y. Rodriguez Garcia[22a], A. Rodriguez Rodriguez[54], A.M. Rodríguez Vera[156b], S. Roe[36], J.T. Roemer[160], A.R. Roepe-Gier[136], J. Roggel[171], O. Røhne[125], R.A. Rojas[103], C.P.A. Roland[68], J. Roloff[29], A. Romaniouk[37], E. Romano[73a,73b], M. Romano[23b], A.C. Romero Hernandez[162], N. Rompotis[92], L. Roos[127], S. Rosati[75a], B.J. Rosser[39], E. Rossi[126], E. Rossi[72a,72b], L.P. Rossi[57b], L. Rossini[54], R. Rosten[119], M. Rotaru[27b], B. Rottler[54], C. Rougier[102,am], D. Rousseau[66], D. Rousso[32], A. Roy[162], S. Roy-Garand[155], A. Rozanov[102],

Y. Rozen[150], X. Ruan[33g], A. Rubio Jimenez[163], A.J. Ruby[92], V.H. Ruelas Rivera[18], T.A. Ruggeri[1], A. Ruggiero[126], A. Ruiz-Martinez[163], A. Rummler[36], Z. Rurikova[54], N.A. Rusakovich[38], H.L. Russell[165], G. Russo[75a,75b], J.P. Rutherfoord[7], S. Rutherford Colmenares[32], K. Rybacki[91], M. Rybar[133], E.B. Rye[125], A. Ryzhov[44], J.A. Sabater Iglesias[56], P. Sabatini[163], L. Sabetta[75a,75b], H.F-W. Sadrozinski[136], F. Safai Tehrani[75a], B. Safarzadeh Samani[134], M. Safdari[143], S. Saha[165], M. Sahinsoy[110], M. Saimpert[135], M. Saito[153], T. Saito[153], D. Salamani[36], A. Salnikov[143], J. Salt[163], A. Salvador Salas[13], D. Salvatore[43b,43a], F. Salvatore[146], A. Salzburger[36], D. Sammel[54], D. Sampsonidis[152,f], D. Sampsonidou[123], J. Sánchez[163], A. Sanchez Pineda[4], V. Sanchez Sebastian[163], H. Sandaker[125], C.O. Sander[48], J.A. Sandesara[103], M. Sandhoff[171], C. Sandoval[22b], D.P.C. Sankey[134], T. Sano[88], A. Sansoni[53], L. Santi[75a,75b], C. Santoni[40], H. Santos[130a,130b], S.N. Santpur[17a], A. Santra[169], K.A. Saoucha[116b], J.G. Saraiva[130a,130d], J. Sardain[7], O. Sasaki[84], K. Sato[157], C. Sauer[63b], F. Sauerburger[54], E. Sauvan[4], P. Savard[155,av], R. Sawada[153], C. Sawyer[134], L. Sawyer[97], I. Sayago Galvan[163], C. Sbarra[23b], A. Sbrizzi[23b,23a], T. Scanlon[96], J. Schaarschmidt[138], P. Schacht[110], U. Schäfer[100], A.C. Schaffer[66,44], D. Schaile[109], R.D. Schamberger[145], C. Scharf[18], M.M. Schefer[19], V.A. Schegelsky[37], D. Scheirich[133], F. Schenck[18], M. Schernau[160], C. Scheulen[55], C. Schiavi[57b,57a], E.J. Schioppa[70a,70b], M. Schioppa[43b,43a], B. Schlag[143,t], K.E. Schleicher[54], S. Schlenker[36], J. Schmeing[171], M.A. Schmidt[171], K. Schmieden[100], C. Schmitt[100], S. Schmitt[48], L. Schoeffel[135], A. Schoening[63b], P.G. Scholer[54], E. Schopf[126], M. Schott[100], J. Schovancova[36], S. Schramm[56], F. Schroeder[171], T. Schroer[56], H-C. Schultz-Coulon[63a], M. Schumacher[54], B.A. Schumm[136], Ph. Schune[135], A.J. Schuy[138], H.R. Schwartz[136], A. Schwartzman[143], T.A. Schwarz[106], Ph. Schwemling[135], R. Schwienhorst[107], A. Sciandra[136], G. Sciolla[26], F. Scuri[74a], C.D. Sebastiani[92], K. Sedlaczek[115], P. Seema[18], S.C. Seidel[112], A. Seiden[136], B.D. Seidlitz[41], C. Seitz[48], J.M. Seixas[83b], G. Sekhniaidze[72a], S.J. Sekula[44], L. Selem[60], N. Semprini-Cesari[23b,23a], D. Sengupta[56], V. Senthilkumar[163], L. Serin[66], L. Serkin[69a,69b], M. Sessa[76a,76b], H. Severini[120], F. Sforza[57b,57a], A. Sfyrla[56], E. Shabalina[55], R. Shaheen[144], J.D. Shahinian[128], D. Shaked Renous[169], L.Y. Shan[14a], M. Shapiro[17a], A. Sharma[36], A.S. Sharma[164], P. Sharma[80], S. Sharma[48], P.B. Shatalov[37], K. Shaw[146], S.M. Shaw[101], A. Shcherbakova[37], Q. Shen[62c,5], P. Sherwood[96], L. Shi[96], X. Shi[14a], C.O. Shimmin[172], J.D. Shinner[95], I.P.J. Shipsey[126], S. Shirabe[56,j], M. Shiyakova[38,af], J. Shlomi[169], M.J. Shochet[39], J. Shojaii[105], D.R. Shope[125], B. Shrestha[120], S. Shrestha[119,az], E.M. Shrif[33g], M.J. Shroff[165], P. Sicho[131], A.M. Sickles[162], E. Sideras Haddad[33g], A. Sidoti[23b], F. Siegert[50], Dj. Sijacki[15], R. Sikora[86a], F. Sili[90], J.M. Silva[20], M.V. Silva Oliveira[29], S.B. Silverstein[47a], S. Simion[66], R. Simoniello[36], E.L. Simpson[59], H. Simpson[146], L.R. Simpson[106], N.D. Simpson[98], S. Simsek[82], S. Sindhu[55], P. Sinervo[155], S. Singh[155], S. Sinha[48], S. Sinha[101], M. Sioli[23b,23a], I. Siral[36], E. Sitnikova[48], S.Yu. Sivoklokov[37,*], J. Sjölin[47a,47b], A. Skaf[55], E. Skorda[20,aq], P. Skubic[120], M. Slawinska[87], V. Smakhtin[169], B.H. Smart[134], J. Smiesko[36], S.Yu. Smirnov[37], Y. Smirnov[37], L.N. Smirnova[37,a], O. Smirnova[98], A.C. Smith[41], E.A. Smith[39], H.A. Smith[126], J.L. Smith[92], R. Smith[143], M. Smizanska[91], K. Smolek[132], A.A. Snesarev[37], S.R. Snider[155], H.L. Snoek[114],

S. Snyder[29], R. Sobie[165,ah], A. Soffer[151], C.A. Solans Sanchez[36], E.Yu. Soldatov[37],
U. Soldevila[163], A.A. Solodkov[37], S. Solomon[26], A. Soloshenko[38], K. Solovieva[54],
O.V. Solovyanov[40], V. Solovyev[37], P. Sommer[36], A. Sonay[13], W.Y. Song[156b],
J.M. Sonneveld[114], A. Sopczak[132], A.L. Sopio[96], F. Sopkova[28b], V. Sothilingam[63a],
S. Sottocornola[68], R. Soualah[116b], Z. Soumaimi[35e], D. South[48], N. Soybelman[169],
S. Spagnolo[70a,70b], M. Spalla[110], D. Sperlich[54], G. Spigo[36], S. Spinali[91], D.P. Spiteri[59],
M. Spousta[133], E.J. Staats[34], A. Stabile[71a,71b], R. Stamen[63a], A. Stampekis[20],
M. Standke[24], E. Stanecka[87], M.V. Stange[50], B. Stanislaus[17a], M.M. Stanitzki[48],
B. Stapf[48], E.A. Starchenko[37], G.H. Stark[136], J. Stark[102,am], D.M. Starko[156b],
P. Staroba[131], P. Starovoitov[63a], S. Stärz[104], R. Staszewski[87], G. Stavropoulos[46],
J. Steentoft[161], P. Steinberg[29], B. Stelzer[142,156a], H.J. Stelzer[129], O. Stelzer-Chilton[156a],
H. Stenzel[58], T.J. Stevenson[146], G.A. Stewart[36], J.R. Stewart[121], M.C. Stockton[36],
G. Stoicea[27b], M. Stolarski[130a], S. Stonjek[110], A. Straessner[50], J. Strandberg[144],
S. Strandberg[47a,47b], M. Stratmann[171], M. Strauss[120], T. Strebler[102], P. Strizenec[28b],
R. Ströhmer[166], D.M. Strom[123], L.R. Strom[48], R. Stroynowski[44], A. Strubig[47a,47b],
S.A. Stucci[29], B. Stugu[16], J. Stupak[120], N.A. Styles[48], D. Su[143], S. Su[62a], W. Su[62d],
X. Su[62a,66], K. Sugizaki[153], V.V. Sulin[37], M.J. Sullivan[92], D.M.S. Sultan[78a,78b],
L. Sultanaliyeva[37], S. Sultansoy[3b], T. Sumida[88], S. Sun[106], S. Sun[170],
O. Sunneborn Gudnadottir[161], N. Sur[102], M.R. Sutton[146], H. Suzuki[157], M. Svatos[131],
M. Swiatlowski[156a], T. Swirski[166], I. Sykora[28a], M. Sykora[133], T. Sykora[133], D. Ta[100],
K. Tackmann[48,ad], A. Taffard[160], R. Tafirout[156a], J.S. Tafoya Vargas[66], E.P. Takeva[52],
Y. Takubo[84], M. Talby[102], A.A. Talyshev[37], K.C. Tam[64b], N.M. Tamir[151], A. Tanaka[153],
J. Tanaka[153], R. Tanaka[66], M. Tanasini[57b,57a], Z. Tao[164], S. Tapia Araya[137f],
S. Tapprogge[100], A. Tarek Abouelfadl Mohamed[107], S. Tarem[150], K. Tariq[14a],
G. Tarna[102,27b], G.F. Tartarelli[71a], P. Tas[133], M. Tasevsky[131], E. Tassi[43b,43a],
A.C. Tate[162], G. Tateno[153], Y. Tayalati[35e,ag], G.N. Taylor[105], W. Taylor[156b], H. Teagle[92],
A.S. Tee[170], R. Teixeira De Lima[143], P. Teixeira-Dias[95], J.J. Teoh[155], K. Terashi[153],
J. Terron[99], S. Terzo[13], M. Testa[53], R.J. Teuscher[155,ah], A. Thaler[79], O. Theiner[56],
N. Themistokleous[52], T. Theveneaux-Pelzer[102], O. Thielmann[171], D.W. Thomas[95],
J.P. Thomas[20], E.A. Thompson[17a], P.D. Thompson[20], E. Thomson[128], Y. Tian[55],
V. Tikhomirov[37,a], Yu.A. Tikhonov[37], S. Timoshenko[37], D. Timoshyn[133], E.X.L. Ting[1],
P. Tipton[172], S.H. Tlou[33g], A. Tnourji[40], K. Todome[154], S. Todorova-Nova[133], S. Todt[50],
M. Togawa[84], J. Tojo[89], S. Tokár[28a], K. Tokushuku[84], O. Toldaiev[68], R. Tombs[32],
M. Tomoto[84,111], L. Tompkins[143,t], K.W. Topolnicki[86b], E. Torrence[123], H. Torres[102,am],
E. Torró Pastor[163], M. Toscani[30], C. Tosciri[39], M. Tost[11], D.R. Tovey[139], A. Traeet[16],
I.S. Trandafir[27b], T. Trefzger[166], A. Tricoli[29], I.M. Trigger[156a], S. Trincaz-Duvoid[127],
D.A. Trischuk[26], B. Trocmé[60], C. Troncon[71a], L. Truong[33c], M. Trzebinski[87],
A. Trzupek[87], F. Tsai[145], M. Tsai[106], A. Tsiamis[152,f], P.V. Tsiareshka[37],
S. Tsigaridas[156a], A. Tsirigotis[152,ab], V. Tsiskaridze[155], E.G. Tskhadadze[149a],
M. Tsopoulou[152,f], Y. Tsujikawa[88], I.I. Tsukerman[37], V. Tsulaia[17a], S. Tsuno[84],
O. Tsur[150], K. Tsuri[118], D. Tsybychev[145], Y. Tu[64b], A. Tudorache[27b], V. Tudorache[27b],
A.N. Tuna[36], S. Turchikhin[57b,57a], I. Turk Cakir[3a], R. Turra[71a], T. Turtuvshin[38,ai],
P.M. Tuts[41], S. Tzamarias[152,f], P. Tzanis[10], E. Tzovara[100], F. Ukegawa[157],

P.A. Ulloa Poblete[137c,137b], E.N. Umaka[29], G. Unal[36], M. Unal[11], A. Undrus[29], G. Unel[160], J. Urban[28b], P. Urquijo[105], G. Usai[8], R. Ushioda[154], M. Usman[108], Z. Uysal[21b], L. Vacavant[102], V. Vacek[132], B. Vachon[104], K.O.H. Vadla[125], T. Vafeiadis[36], A. Vaitkus[96], C. Valderanis[109], E. Valdes Santurio[47a,47b], M. Valente[156a], S. Valentinetti[23b,23a], A. Valero[163], E. Valiente Moreno[163], A. Vallier[102,am], J.A. Valls Ferrer[163], D.R. Van Arneman[114], T.R. Van Daalen[138], A. Van Der Graaf[49], P. Van Gemmeren[6], M. Van Rijnbach[125,36], S. Van Stroud[96], I. Van Vulpen[114], M. Vanadia[76a,76b], W. Vandelli[36], M. Vandenbroucke[135], E.R. Vandewall[121], D. Vannicola[151], L. Vannoli[57b,57a], R. Vari[75a], E.W. Varnes[7], C. Varni[17b], T. Varol[148], D. Varouchas[66], L. Varriale[163], K.E. Varvell[147], M.E. Vasile[27b], L. Vaslin[40], G.A. Vasquez[165], A. Vasyukov[38], F. Vazeille[40], T. Vazquez Schroeder[36], J. Veatch[31], V. Vecchio[101], M.J. Veen[103], I. Veliscek[126], L.M. Veloce[155], F. Veloso[130a,130c], S. Veneziano[75a], A. Ventura[70a,70b], S. Ventura Gonzalez[135], A. Verbytskyi[110], M. Verducci[74a,74b], C. Vergis[24], M. Verissimo De Araujo[83b], W. Verkerke[114], J.C. Vermeulen[114], C. Vernieri[143], M. Vessella[103], M.C. Vetterli[142,av], A. Vgenopoulos[152,f], N. Viaux Maira[137f], T. Vickey[139], O.E. Vickey Boeriu[139], G.H.A. Viehhauser[126], L. Vigani[63b], M. Villa[23b,23a], M. Villaplana Perez[163], E.M. Villhauer[52], E. Vilucchi[53], M.G. Vincter[34], G.S. Virdee[20], A. Vishwakarma[52], A. Visibile[114], C. Vittori[36], I. Vivarelli[146], E. Voevodina[110], F. Vogel[109], P. Vokac[132], Yu. Volkotrub[86a], J. Von Ahnen[48], E. Von Toerne[24], B. Vormwald[36], V. Vorobel[133], K. Vorobev[37], M. Vos[163], K. Voss[141], J.H. Vossebeld[92], M. Vozak[114], L. Vozdecky[94], N. Vranjes[15], M. Vranjes Milosavljevic[15], M. Vreeswijk[114], R. Vuillermet[36], O. Vujinovic[100], I. Vukotic[39], S. Wada[157], C. Wagner[103], J.M. Wagner[17a], W. Wagner[171], S. Wahdan[171], H. Wahlberg[90], M. Wakida[111], J. Walder[134], R. Walker[109], W. Walkowiak[141], A. Wall[128], T. Wamorkar[6], A.Z. Wang[170], C. Wang[100], C. Wang[62c], H. Wang[17a], J. Wang[64a], R.-J. Wang[100], R. Wang[61], R. Wang[6], S.M. Wang[148], S. Wang[62b], T. Wang[62a], W.T. Wang[80], W. Wang[14a], X. Wang[14c], X. Wang[162], X. Wang[62c], Y. Wang[62d], Y. Wang[14c], Z. Wang[106], Z. Wang[62d,51,62c], Z. Wang[106], A. Warburton[104], R.J. Ward[20], N. Warrack[59], A.T. Watson[20], H. Watson[59], M.F. Watson[20], E. Watton[59,134], G. Watts[138], B.M. Waugh[96], C. Weber[29], H.A. Weber[18], M.S. Weber[19], S.M. Weber[63a], C. Wei[62a], Y. Wei[126], A.R. Weidberg[126], E.J. Weik[117], J. Weingarten[49], M. Weirich[100], C. Weiser[54], C.J. Wells[48], T. Wenaus[29], B. Wendland[49], T. Wengler[36], N.S. Wenke[110], N. Wermes[24], M. Wessels[63a], A.M. Wharton[91], A.S. White[61], A. White[8], M.J. White[1], D. Whiteson[160], L. Wickremasinghe[124], W. Wiedenmann[170], C. Wiel[50], M. Wielers[134], C. Wiglesworth[42], D.J. Wilbern[120], H.G. Wilkens[36], D.M. Williams[41], H.H. Williams[128], S. Williams[32], S. Willocq[103], B.J. Wilson[101], P.J. Windischhofer[39], F.I. Winkel[30], F. Winklmeier[123], B.T. Winter[54], J.K. Winter[101], M. Wittgen[143], M. Wobisch[97], Z. Wolffs[114], J. Wollrath[160], M.W. Wolter[87], H. Wolters[130a,130c], A.F. Wongel[48], S.D. Worm[48], B.K. Wosiek[87], K.W. Woźniak[87], S. Wozniewski[55], K. Wraight[59], C. Wu[20], J. Wu[14a,14e], M. Wu[64a], M. Wu[113], S.L. Wu[170], X. Wu[56], Y. Wu[62a], Z. Wu[135], J. Wuerzinger[110,at], T.R. Wyatt[101], B.M. Wynne[52], S. Xella[42], L. Xia[14c], M. Xia[14b], J. Xiang[64c], M. Xie[62a], X. Xie[62a], S. Xin[14a,14e], A. Xiong[123], J. Xiong[17a], D. Xu[14a], H. Xu[62a],

L. Xu[62a], R. Xu[128], T. Xu[106], Y. Xu[14b], Z. Xu[52], Z. Xu[14a], B. Yabsley[147], S. Yacoob[33a], Y. Yamaguchi[154], E. Yamashita[153], H. Yamauchi[157], T. Yamazaki[17a], Y. Yamazaki[85], J. Yan[62c], S. Yan[126], Z. Yan[25], H.J. Yang[62c,62d], H.T. Yang[62a], S. Yang[62a], T. Yang[64c], X. Yang[62a], X. Yang[14a], Y. Yang[44], Y. Yang[62a], Z. Yang[62a], W-M. Yao[17a], Y.C. Yap[48], H. Ye[14c], H. Ye[55], J. Ye[14a], S. Ye[29], X. Ye[62a], Y. Yeh[96], I. Yeletskikh[38], B.K. Yeo[17b], M.R. Yexley[96], P. Yin[41], K. Yorita[168], S. Younas[27b], C.J.S. Young[36], C. Young[143], C. Yu[14a,14e,ax], Y. Yu[62a], M. Yuan[106], R. Yuan[62b], L. Yue[96], M. Zaazoua[62a], B. Zabinski[87], E. Zaid[52], T. Zakareishvili[149b], N. Zakharchuk[34], S. Zambito[56], J.A. Zamora Saa[137d,137b], J. Zang[153], D. Zanzi[54], O. Zaplatilek[132], C. Zeitnitz[171], H. Zeng[14a], J.C. Zeng[162], D.T. Zenger Jr[26], O. Zenin[37], T. Ženiš[28a], S. Zenz[94], S. Zerradi[35a], D. Zerwas[66], M. Zhai[14a,14e], B. Zhang[14c], D.F. Zhang[139], J. Zhang[62b], J. Zhang[6], K. Zhang[14a,14e], L. Zhang[14c], P. Zhang[14a,14e], R. Zhang[170], S. Zhang[106], T. Zhang[153], X. Zhang[62c], X. Zhang[62b], Y. Zhang[62c,5], Y. Zhang[96], Z. Zhang[17a], Z. Zhang[66], H. Zhao[138], P. Zhao[51], T. Zhao[62b], Y. Zhao[136], Z. Zhao[62a], A. Zhemchugov[38], J. Zheng[14c], K. Zheng[162], X. Zheng[62a], Z. Zheng[143], D. Zhong[162], B. Zhou[106], H. Zhou[7], N. Zhou[62c], Y. Zhou[7], C.G. Zhu[62b], J. Zhu[106], Y. Zhu[62c], Y. Zhu[62a], X. Zhuang[14a], K. Zhukov[37], V. Zhulanov[37], N.I. Zimine[38], J. Zinsser[63b], M. Ziolkowski[141], L. Živković[15], A. Zoccoli[23b,23a], K. Zoch[61], T.G. Zorbas[139], O. Zormpa[46], W. Zou[41], L. Zwalinski[36]

[1] *Department of Physics, University of Adelaide, Adelaide; Australia*

[2] *Department 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*

[4] *LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; France*

[5] *APC, Université Paris Cité, CNRS/IN2P3, Paris; France*

[6] *High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America*

[7] *Department of Physics, University of Arizona, Tucson AZ; United States of America*

[8] *Department of Physics, University of Texas at Arlington, Arlington TX; United States of America*

[9] *Physics Department, National and Kapodistrian University of Athens, Athens; Greece*

[10] *Physics Department, National Technical University of Athens, Zografou; Greece*

[11] *Department of Physics, University of Texas at Austin, Austin TX; United States of America*

[12] *Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan*

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

[14] [(a)] *Institute of High Energy Physics, Chinese Academy of Sciences, Beijing;*[(b)] *Physics Department, Tsinghua University, Beijing;*[(c)] *Department of Physics, Nanjing University, Nanjing;*[(d)] *School of Science, Shenzhen Campus of Sun Yat-sen University;*[(e)] *University of Chinese Academy of Science (UCAS), Beijing; China*

[15] *Institute of Physics, University of Belgrade, Belgrade; Serbia*

[16] *Department for Physics and Technology, University of Bergen, Bergen; Norway*

[17] [(a)] *Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA;*[(b)] *University of California, Berkeley CA; United States of America*

[18] *Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany*

[19] *Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland*

[20] *School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom*

[21] [(a)] *Department of Physics, Bogazici University, Istanbul;*[(b)] *Department of Physics Engineering, Gaziantep University, Gaziantep;*[(c)] *Department of Physics, Istanbul University, Istanbul; Türkiye*

[22] (a) *Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogotá;* (b) *Departamento de Física, Universidad Nacional de Colombia, Bogotá;* (c) *Pontificia Universidad Javeriana, Bogota; Colombia*

[23] (a) *Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna;* (b) *INFN Sezione di Bologna; Italy*

[24] *Physikalisches Institut, Universität Bonn, Bonn; Germany*

[25] *Department of Physics, Boston University, Boston MA; United States of America*

[26] *Department of Physics, Brandeis University, Waltham MA; United States of America*

[27] (a) *Transilvania University of Brasov, Brasov;* (b) *Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest;* (c) *Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi;* (d) *National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca;* (e) *University Politehnica Bucharest, Bucharest;* (f) *West University in Timisoara, Timisoara;* (g) *Faculty of Physics, University of Bucharest, Bucharest; Romania*

[28] (a) *Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava;* (b) *Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic*

[29] *Physics Department, Brookhaven National Laboratory, Upton NY; United States of America*

[30] *Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires; Argentina*

[31] *California State University, CA; United States of America*

[32] *Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom*

[33] (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*

[34] *Department of Physics, Carleton University, Ottawa ON; Canada*

[35] (a) *Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies — Université Hassan II, 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*

[36] *CERN, Geneva; Switzerland*

[37] *Affiliated with an institute covered by a cooperation agreement with CERN*

[38] *Affiliated with an international laboratory covered by a cooperation agreement with CERN*

[39] *Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America*

[40] *LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France*

[41] *Nevis Laboratory, Columbia University, Irvington NY; United States of America*

[42] *Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark*

[43] (a) *Dipartimento di Fisica, Università della Calabria, Rende;* (b) *INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy*

[44] *Physics Department, Southern Methodist University, Dallas TX; United States of America*

[45] *Physics Department, University of Texas at Dallas, Richardson TX; United States of America*

[46] *National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece*

[47] (a) *Department of Physics, Stockholm University;* (b) *Oskar Klein Centre, Stockholm; Sweden*

[48] *Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany*

[49] *Fakultät Physik, Technische Universität Dortmund, Dortmund; Germany*

[50] *Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany*

[51] *Department of Physics, Duke University, Durham NC; United States of America*

[52] *SUPA — School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom*

[53] *INFN e Laboratori Nazionali di Frascati, Frascati; Italy*

[54] *Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany*

[55] *II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany*
[56] *Département 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*
[58] *II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany*
[59] *SUPA — School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom*
[60] *LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France*
[61] *Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America*
[62] *(a) Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei;(b) Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao;(c) School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai;(d) Tsung-Dao Lee Institute, Shanghai; 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*
[65] *Department of Physics, National Tsing Hua University, Hsinchu; Taiwan*
[66] *IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France*
[67] *Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona; Spain*
[68] *Department 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*
[79] *Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria*
[80] *University of Iowa, Iowa City IA; United States of America*
[81] *Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America*
[82] *Istinye 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; Brazil*
[84] *KEK, High Energy Accelerator Research Organization, Tsukuba; Japan*
[85] *Graduate 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*
[87] *Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland*
[88] *Faculty of Science, Kyoto University, Kyoto; Japan*
[89] *Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka; Japan*
[90] *Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina*

[91] *Physics Department, Lancaster University, Lancaster; United Kingdom*
[92] *Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom*
[93] *Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia*
[94] *School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom*
[95] *Department of Physics, Royal Holloway University of London, Egham; United Kingdom*
[96] *Department of Physics and Astronomy, University College London, London; United Kingdom*
[97] *Louisiana Tech University, Ruston LA; United States of America*
[98] *Fysiska institutionen, Lunds universitet, Lund; Sweden*
[99] *Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain*
[100] *Institut für Physik, Universität Mainz, Mainz; Germany*
[101] *School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom*
[102] *CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France*
[103] *Department of Physics, University of Massachusetts, Amherst MA; United States of America*
[104] *Department of Physics, McGill University, Montreal QC; Canada*
[105] *School of Physics, University of Melbourne, Victoria; Australia*
[106] *Department of Physics, University of Michigan, Ann Arbor MI; United States of America*
[107] *Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America*
[108] *Group of Particle Physics, University of Montreal, Montreal QC; Canada*
[109] *Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany*
[110] *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany*
[111] *Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan*
[112] *Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America*
[113] *Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands*
[114] *Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands*
[115] *Department of Physics, Northern Illinois University, DeKalb IL; United States of America*
[116] (a) *New York University Abu Dhabi, Abu Dhabi;*(b) *University of Sharjah, Sharjah; United Arab Emirates*
[117] *Department of Physics, New York University, New York NY; United States of America*
[118] *Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan*
[119] *Ohio State University, Columbus OH; United States of America*
[120] *Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America*
[121] *Department of Physics, Oklahoma State University, Stillwater OK; United States of America*
[122] *Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic*
[123] *Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America*
[124] *Graduate School of Science, Osaka University, Osaka; Japan*
[125] *Department of Physics, University of Oslo, Oslo; Norway*
[126] *Department of Physics, Oxford University, Oxford; United Kingdom*
[127] *LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris; France*
[128] *Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America*
[129] *Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America*
[130] (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, 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*
[131] *Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic*

[132] *Czech Technical University in Prague, Prague; Czech Republic*
[133] *Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic*
[134] *Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom*
[135] *IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France*
[136] *Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America*
[137] *(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*
[138] *Department of Physics, University of Washington, Seattle WA; United States of America*
[139] *Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom*
[140] *Department of Physics, Shinshu University, Nagano; Japan*
[141] *Department Physik, Universität Siegen, Siegen; Germany*
[142] *Department of Physics, Simon Fraser University, Burnaby BC; Canada*
[143] *SLAC National Accelerator Laboratory, Stanford CA; United States of America*
[144] *Department of Physics, Royal Institute of Technology, Stockholm; Sweden*
[145] *Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America*
[146] *Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom*
[147] *School of Physics, University of Sydney, Sydney; Australia*
[148] *Institute of Physics, Academia Sinica, Taipei; Taiwan*
[149] *(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*
[150] *Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel*
[151] *Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel*
[152] *Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece*
[153] *International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan*
[154] *Department of Physics, Tokyo Institute of Technology, Tokyo; Japan*
[155] *Department of Physics, University of Toronto, Toronto ON; Canada*
[156] *(a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON; Canada*
[157] *Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan*
[158] *Department of Physics and Astronomy, Tufts University, Medford MA; United States of America*
[159] *United Arab Emirates University, Al Ain; United Arab Emirates*
[160] *Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America*
[161] *Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden*
[162] *Department of Physics, University of Illinois, Urbana IL; United States of America*
[163] *Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia — CSIC, Valencia; Spain*
[164] *Department of Physics, University of British Columbia, Vancouver BC; Canada*
[165] *Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada*
[166] *Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany*
[167] *Department of Physics, University of Warwick, Coventry; United Kingdom*
[168] *Waseda University, Tokyo; Japan*
[169] *Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel*
[170] *Department of Physics, University of Wisconsin, Madison WI; United States of America*

[171] Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany
[172] Department of Physics, Yale University, New Haven CT; United States of America

[a] Also Affiliated with an institute covered by a cooperation agreement with CERN
[b] Also at An-Najah National University, Nablus; Palestine
[c] Also at APC, Université Paris Cité, CNRS/IN2P3, Paris; France
[d] Also at Borough of Manhattan Community College, City University of New York, New York NY; United States of America
[e] Also at Center for High Energy Physics, Peking University; China
[f] Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki; Greece
[g] Also at Centro Studi e Ricerche Enrico Fermi; Italy
[h] Also at CERN Tier-0; Switzerland
[i] Also at CERN, Geneva; Switzerland
[j] Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland
[k] Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona; Spain
[l] Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece
[m] Also at Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom
[n] Also at Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada
[o] Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva; Israel
[p] Also at Department of Physics, California State University, Sacramento; United States of America
[q] Also at Department of Physics, King's College London, London; United Kingdom
[r] Also at Department of Physics, Oxford University, Oxford; United Kingdom
[s] Also at Department of Physics, Royal Holloway University of London, Egham; United Kingdom
[t] Also at Department of Physics, Stanford University, Stanford CA; United States of America
[u] Also at Department of Physics, University of Fribourg, Fribourg; Switzerland
[v] Also at Department of Physics, University of Massachusetts, Amherst MA; United States of America
[w] Also at Department of Physics, University of Thessaly; Greece
[x] Also at Department of Physics, Westmont College, Santa Barbara; United States of America
[y] Also at Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany
[z] Also at Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany
[aa] Also at Group of Particle Physics, University of Montreal, Montreal QC; Canada
[ab] Also at Hellenic Open University, Patras; Greece
[ac] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain
[ad] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany
[ae] Also at Institut für Physik, Universität Mainz, Mainz; Germany
[af] Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria
[ag] Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco
[ah] Also at Institute of Particle Physics (IPP); Canada
[ai] Also at Institute of Physics and Technology, Ulaanbaatar; Mongolia
[aj] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan
[ak] Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia
[al] Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France
[am] Also at L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse; France
[an] Also at Lawrence Livermore National Laboratory, Livermore; United States of America
[ao] Also at National Institute of Physics, University of the Philippines Diliman (Philippines); Philippines
[ap] Also at Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan
[aq] Also at School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom
[ar] Also at School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom
[as] Also at SUPA — School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom
[at] Also at Technical University of Munich, Munich; Germany

[au] Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China
[av] Also at TRIUMF, Vancouver BC; Canada
[aw] Also at Università di Napoli Parthenope, Napoli; Italy
[ax] Also at University of Chinese Academy of Sciences (UCAS), Beijing; China
[ay] Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America
[az] Also at Washington College, Chestertown, MD; United States of America
[ba] Also at Yeditepe University, Physics Department, Istanbul; Türkiye
[*] Deceased