Phys. Lett. B 849 (2024) 138469

Contents lists available at ScienceDirect

Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

Letter

Probing the CP nature of the top–Higgs Yukawa coupling in $t\bar{t}H$ and tH events with $H \to b\bar{b}$ decays using the ATLAS detector at the LHC

The ATLAS Collaboration ⋆

ARTICLE INFO

Editor: M. Doser

ABSTRACT

The CP properties of the coupling between the Higgs boson and the top quark are investigated using 139 fb^{-1} of proton–proton collision data recorded by the ATLAS experiment at the LHC at a centre-of-mass energy of $\sqrt{s} = 13$ TeV. The CP structure of the top quark–Higgs boson Yukawa coupling is probed in events with a Higgs boson decaying into a pair of b-quarks and produced in association with either a pair of top quarks, $t\bar{t}H$, or a single top quark, tH. Events containing one or two electrons or muons are used for the measurement. Multivariate techniques are used to select regions enriched in $t\bar{t}H$ and tH events, where dedicated CP-sensitive observables are exploited. In an extension of the Standard Model (SM) with a CP-odd admixture in the top–Higgs Yukawa coupling, the mixing angle between CP-even and CP-odd couplings is measured to be $\alpha = 11^{\circ}{}^{+52^{\circ}}_{-73^{\circ}}$, compatible with the SM prediction corresponding to $\alpha = 0$.

1. Introduction

Since the observation of the Higgs boson at the LHC [1,2], its properties have been studied in great detail. In particular, the observation of the Higgs boson production in association with a top-quark pair, $t\bar{t}H$ [3,4], provides direct experimental access to the top-quark Yukawa coupling at the tree-level. The increasing datasets at the LHC have recently allowed the ATLAS and CMS Collaborations to probe the charge-conjugation and parity (CP) properties of this coupling using $t\bar{t}H$ events in different decay channels [5–7]. This letter reports on a study of the CP properties of the top-quark Yukawa coupling using $t\bar{t}H$ and tH production, in the $H \to b\bar{b}$ decay channel. The analysis targets final states where at least one top quark decays semi-leptonically to electrons or muons. It uses $\sqrt{s} = 13$ TeV pp collision data recorded by the ATLAS experiment during Run 2, corresponding to an integrated luminosity of 139 fb^{-1}.

The Standard Model (SM) predicts the Higgs boson to be a scalar particle with quantum numbers $J^{CP} = 0^{++}$. Considering the possibility of beyond the Standard Model (BSM) couplings, a CP-odd component of the vector-boson couplings to the Higgs boson is naturally suppressed by the scale at which new physics would become relevant [8,9]. This suppression does not happen for Yukawa couplings, where CP-odd Higgs–fermion couplings may be significant already at tree level [10]. One of the first ATLAS and CMS measurements have excluded the pure $J^P = 0^-$ hypothesis by more than 95% CL using $H \to \gamma\gamma$, $H \to ZZ^*$ and $H \to WW^*$ decays [11,12]. Dedicated searches for CP-mixed couplings between the Higgs boson and vector bosons set stringent limits on the CP-odd components [13–21]. Analyses of $t\bar{t}H$ events with $H \to \gamma\gamma$ decays [5,6] and in the multilepton final state [7] have also excluded pure CP-odd top–Higgs couplings at more than a 3 σ significance. But mixing of CP-odd and CP-even states has not been ruled out and is worth investigating. The observation of a non-zero CP-odd coupling component would in fact signal the existence of BSM physics, and open up the possibility of CP-violation in the Higgs sector [22–25]. Such a new source of CP violation could play a fundamental role in explaining the matter–antimatter asymmetry of the universe. This analysis targets $t\bar{t}H$ and tH events, which are sensitive to the top–Higgs coupling including any potential CP-mixing at the tree-level. This avoids the need for assumptions about the influence of BSM effects which may be present in other, more indirect measurements [26–28]. In particular, current limits on electron and neutron electrical dipole moments place indirect model-dependent constraints on a possible pseudoscalar component of the top-quark Yukawa coupling [29–31].

The top–Higgs interaction can be extended beyond the SM as [26]:

$$\mathcal{L}_{t\bar{t}H} = -\kappa_t' y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t\,, \quad (1)$$

where y_t is the SM Yukawa coupling strength, modified by a coupling modifier κ_t'; α is the CP-mixing angle; ϕ is the Higgs field; ψ_t and $\bar{\psi}_t$ are top-quark spinor fields and γ_5 is a Dirac matrix. The term containing γ_5 corresponds to a pseudoscalar component. The above expression reduces to the SM case for $\kappa_t' = 1$ and $\alpha = 0$. An anomalous value of α would produce an admixture with a pseudoscalar coupling ($J^{CP} = 0^{+-}$) and change the differential cross-section relative to the SM

⋆ *E-mail address:* atlas.publications@cern.ch.

https://doi.org/10.1016/j.physletb.2024.138469
Received 13 March 2023; Received in revised form 15 January 2024; Accepted 15 January 2024
Available online 18 January 2024
0370-2693/© 2024 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

expectation, while a variation of κ_t' would induce a change in the total cross-section [22,32–35].

This study measures simultaneously the values of κ_t' and α with a binned profile likelihood fit to data, exploiting dedicated CP-sensitive observables. It closely follows a recent analysis optimised for the measurement of the $t\bar{t}H(\to bb)$ production cross-section [36]. This analysis studies an identical phase space using the same physics object definitions and a similar methodology for event selection and evaluation of systematic uncertainties. A notable exception is that this analysis considers both the $t\bar{t}H$ and tH production modes as signals. No attempt was made to optimise the analysis strategy for the tH signal, as its small yield makes this channel relevant only in one analysis region. Other noteworthy differences with respect to the analysis documented in Ref. [36] are detailed in the text. These include the definition of signal regions, the signal-background discrimination strategy and a few details in the definition of systematic uncertainties in signal and background modelling. In the case of tH production, the destructive interference between the diagrams with t–H and W–H couplings leads to the negligible tH production cross-section in the SM. Any change in the relative t–H and W–H coupling strengths would result in a rapid increase in the cross-section. Considering the Lagrangian density in Eqn. 1, the tH production cross-section is expected to grow for values of the mixing angle α different from zero [23]. An opposite and less pronounced dependence exists for the $t\bar{t}H$ cross-section. The ratio of tH to $t\bar{t}H$ cross-sections varies from 0.06 in the SM scenario to more than 1.2 in the pure CP-odd scenario [23]. For the present measurement, the $H \to b\bar{b}$ branching ratio is assumed to be equal to its SM value of 58.2% ± 0.5% [37].

2. The ATLAS experiment

The ATLAS experiment [38–40] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near 4π coverage in solid angle.[1] It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadron calorimeters and a muon spectrometer. A two-level trigger system is used to reduce the total event rate to 1 kHz on average, depending on the data-taking conditions [41]. An extensive software suite [42] 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. The events used in this analysis are selected using single-lepton triggers [43,44], with either low thresholds for the lepton transverse momentum (p_{T}) and a lepton isolation requirement, or higher thresholds, looser identification criteria and without any isolation requirement. The lowest p_{T} threshold for muons is 20 (26) GeV, while for electrons the threshold is 24 (26) GeV for the data taken in 2015 (2016–2018).

3. Event preselection

Events are required to have at least one primary vertex, formed by two or more associated tracks with transverse momenta greater than 0.5 GeV. The vertex with the highest sum of p_{T}^2 of associated tracks is selected as the hard-scattering primary vertex. Events with exactly one lepton (electrons or muons, denoted as ℓ) or two oppositely charged leptons are considered in this analysis, referred to as the $\ell+$jets channel and dilepton channel, respectively. Electrons are identified using the 'Tight' likelihood criterion [45] and are required to have $p_{\mathrm{T}} > 10$ GeV and $|\eta| < 2.47$, excluding those in the calorimeter barrel–endcap transition region ($1.37 < |\eta| < 1.52$). Muons are selected with the 'Medium' identification criterion [46] and are required to have $p_{\mathrm{T}} > 10$ GeV and $|\eta| < 2.5$. Electrons (muons) are required to pass the 'Gradient' ('FixedCut-Tight-Track-Only') isolation requirements [45,46]. All leptons are required to originate from the primary vertex. At least one of the leptons must have $p_{\mathrm{T}} > 27$ GeV and match the corresponding lepton used in the trigger decision. In events with an ee or $\mu\mu$ pair, the dilepton invariant mass is required to be above 15 GeV and outside the Z boson mass window of 83–99 GeV.

This analysis targets events with high jet multiplicities, including b-quark jets expected in the final state of $t\bar{t}H$ and tH events with a subsequent $H \to b\bar{b}$ decay. Following the same procedure as Ref. [36], jets are reconstructed from topological clusters of energy depositions in the calorimeter [47,48] using the anti-k_t algorithm [49,50] with a radius parameter of $R = 0.4$. The MV2c10 algorithm [51] is used to identify (or 'b-tag') jets containing b-hadrons. By placing different selections on the MV2c10 discriminant, four working points are defined with average b-jet tagging efficiencies of 60%, 70%, 77% and 85% and different c- and light-jet rejection rates. The corresponding efficiencies and rejection rates are calibrated to data [51–53]. A pseudo-continuous b-tagging score is assigned to each jet. A score of two, three, four and five is assigned if a jet passes the 85%, 77%, 70% and 60% working point, but fails the adjacent tighter one. If a jet fails all working points, a score of one is assigned. In the $\ell+$jets (dilepton) channel, events are required to have at least five (three) jets with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$, and at least four (three) of the jets are required to be b-tagged at the 70% efficiency working point.

The missing transverse momentum is reconstructed as the negative vector sum of the p_{T} of all selected objects in the event, with an extra 'soft term' built from additional tracks associated with the primary vertex [54].

The analysis also exploits the collimated decay topology from high-p_{T} Higgs bosons. Jets with a radius parameter of $R = 0.4$ are reclustered [55] using the anti-k_t algorithm with a radius parameter of $R = 1.0$. The resulting jets are referred to as *large-R* jets. The large-R jets are required to have a mass larger than 50 GeV, $p_{\mathrm{T}} > 200$ GeV and at least two constituent jets with $R = 0.4$.

4. Signal and background modelling

After applying the above selection criteria, background events are dominated by $t\bar{t}$ production with additional jets ($t\bar{t}+$jets), that contain heavy-flavour hadrons (b- and c-hadrons). Other processes contribute less than 10% of the total expected background. All background processes are estimated using Monte Carlo (MC) simulations, closely following Ref. [36].

The simulated events were produced using the ATLAS detector simulation [56] based on Geant4 [57]. To simulate the effects of multiple interactions in the same and neighbouring bunch crossings (pile-up), additional interactions were generated using Pythia 8.186 [58] with a set of tuned parameters called the A3 tune [59] and overlaid on the simulated hard-scatter event. Simulated events are reweighted to match the pile-up conditions observed in the full Run 2 dataset. All simulated event samples are processed through the same reconstruction algorithms and analysis chain as the data [42].

Events in the simulated $t\bar{t}+$jets background sample are categorised according to the flavour of the additional jets which do not originate from the top-quark decay. The simulation of each set of backgrounds is treated independently as this allows for a more accurate modelling of $t\bar{t}+$jets events. The categorisation is based on 'MC-truth jets' that are clustered with stable generated particles (with mean lifetime $\tau > 3\times10^{-11}$ s) in the final state using the anti-k_t algorithm with $R = 0.4$. MC-truth jets with $p_{\mathrm{T}} > 15$ GeV and $|\eta| < 2.5$ in the simulated events are used for the categorisation. Their MC-truth flavour is

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

determined by counting the number of b/c-hadrons contained within $\Delta R = 0.4$ of the jet axis. Events with at least one MC-truth jet containing b-hadrons not originating from a top-quark decay are labelled as $t\bar{t} + \geq 1b$. This can be further separated into subcomponents corresponding to $t\bar{t} + 1b$ and $t\bar{t} + \geq 2b$. Events failing to satisfy that criterion but with at least one MC-truth jet containing c-hadrons not originating from top-quark decay are labelled $t\bar{t} + \geq 1c$. The rest of the events are labelled as $t\bar{t}$ + light. The dominant $t\bar{t} + \geq 1b$ background is modelled using a sample of $t\bar{t} + b\bar{b}$ events generated at next-to-leading order (NLO) in QCD in the four-flavour scheme, with two additional massive b-quarks produced at the matrix element (ME) level. The ME simulation was performed using the POWHEG BOX RES generator and OPENLOOPS [60–63], with the NNPDF3.0NLO nf4 [64] parton distribution function (PDF) set and PYTHIA 8.230 [58] with the A14 set of tuned parameters [65] for the simulation of the parton shower (PS) and hadronisation. Given that the production rate of $t\bar{t}$ with additional b-jets is observed to be underestimated by the current predictions [66,67], the normalisation of the $t\bar{t} + \geq 1b$ background is determined from the analysed data without prior constraints. The $t\bar{t} + \geq 1c$ and $t\bar{t}$ + light backgrounds are modelled from a subset of an inclusive $t\bar{t}$ + jets sample generated at NLO in QCD using POWHEG BOX v2 [68–71] as the ME generator interfaced with PYTHIA 8.230 for the PS and hadronisation. This inclusive $t\bar{t}$ + jets sample is generated with the five-flavour scheme, where c- and b-quarks not originating from a top-quark decay are assumed to be massless. Due to limited knowledge regarding $t\bar{t} + \geq 1c$ production, an additional 100% uncertainty is included in its normalisation. Additionally, a prior uncertainty of 6% is assigned to the inclusive $t\bar{t}$ + jets production cross-sections according to the predicted inclusive $t\bar{t}$ production cross-section at NNLO+NNLL [72–78]. Other background processes include the production of W+ jets, Z+ jets, $t\bar{t}W$, $t\bar{t}Z$, tZq, tWZ, $t\bar{t}t\bar{t}$ and $WW/WZ/ZZ$ events. These are all subdominant and modelled from simulation as detailed in Ref. [36]. A small fraction of events contains misidentified leptons or leptons originating from the decay of heavy-flavour hadrons. The contribution from these events is found to be negligible in the ℓ + jets channel. In the dilepton channel, this small contribution is modelled using a simulation.

The signal processes, $t\bar{t}H$ and tH, are simulated with different values of α and κ_t'. All other parameters were fixed to their SM values, including the $H \to b\bar{b}$ branching ratio. The alternative scenarios were simulated using the NLO Higgs Characterisation [37,79] model implemented in MADGRAPH5_AMC@NLO with FeynRules [80,81]. With a few exceptions, all signal samples were generated using the MADGRAPH5_AMC@NLO 2.6.2 [82] generator at NLO in QCD using the five-flavour scheme with the NNPDF3.0NNLO PDF set, interfaced with PYTHIA 8.230 with the A14 set of tune parameters for PS and hadronisation. The SM $t\bar{t}H$ events were simulated using MADGRAPH5_AMC@NLO 2.6.0. The renormalisation and factorisation scales were set to $\sqrt[3]{m_{\mathrm{T}}(t) \cdot m_{\mathrm{T}}(\bar{t}) \cdot m_{\mathrm{T}}(H)}$, where $m_{\mathrm{T}} = \sqrt{m^2 + p_{\mathrm{T}}^2}$ is the transverse mass of a particle. The cross-section is normalised to 507 fb from the fixed-order calculation including NLO QCD and electroweak corrections, with an uncertainty of 3.6% from variations in PDF and α_{s} and 9.2% due to variations of the renormalisation and factorisation scales [37,83–87]. A K-factor of 1.1 is derived by taking the ratio of the cross-section from the above fixed-order calculation to that from MADGRAPH5_AMC@NLO, and is applied to all $t\bar{t}H$ samples with different values of α and κ_t'. For the tH signal, two subprocesses, $tHjb$ and tWH, are considered. The $tHjb$ (tWH) events were generated in the four(five)-flavour scheme using the NNPDF3.0NNLO nf4 (NNPDF3.0NNLO) PDF set [64], with the renormalisation and factorisation scales set to the generator's default. The cross-sections for the $tHjb$ and tWH samples are obtained directly from MADGRAPH5_AMC@NLO. In the SM scenario, the cross-section for $tHjb$ and tWH are 60.1 fb and 16.7 fb, respectively. Variations of the renormalisation and factorisation scales, including the consideration of the flavour scheme choice for the $tHjb$ process, contribute 15% and 6.7% to the uncertainty of the cross-sections of $tHjb$ and tWH respectively. Similarly, variations of the PDFs and α_{s} result in a 3.7% and 6.3% uncertainty in the $tHjb$ and tWH cross-sections, respectively. A diagram removal scheme [88] is applied in the simulation of the tWH events in order to remove diagrams already included in the $t\bar{t}H$ simulation.

The yields of $t\bar{t}H$ and tH signals are parameterised as a function of the model parameters by smoothly interpolating between generated MC samples with varying α and κ_t'. The parameterisation is performed in each analysis bin. Two $t\bar{t}H$ samples with alternative values of α were generated, corresponding to a pure CP-odd interaction ($\alpha = 90°$) and maximal CP-odd/CP-even mixing ($\alpha = 45°$). The $t\bar{t}H$ yields, $N_{t\bar{t}H}(\kappa_t', \alpha)$, are parameterised using the SM sample and the pure CP-odd sample as $\kappa_t'^2 c_\alpha^2 N_{CP\text{-even}} + \kappa_t'^2 s_\alpha^2 N_{CP\text{-odd}}$, where $c_\alpha = \cos\alpha$, $s_\alpha = \sin\alpha$, and $N_{CP\text{-even}}$ and $N_{CP\text{-odd}}$ are the expected yields predicted by the SM and the CP-odd $t\bar{t}H$ simulations, respectively. This was verified to be a good approximation using the maximal mixing sample ($\alpha = 45°$), with the difference in any analysis bin smaller than the uncertainties due to the limited number of simulated events. In the case of tH, the interference between diagrams with CP-even and CP-odd $t-H$ and SM $W-H$ couplings are considered in the parameterisation, assuming contributions from lowest order diagrams of $tHjb$ and tWH processes. The signal yield in each analysis bin is parameterised as $N_{tH}(\kappa_t', \alpha) = A\kappa_t'^2 c_\alpha^2 + B\kappa_t'^2 s_\alpha^2 + C\kappa_t' c_\alpha + D\kappa_t' s_\alpha + E\kappa_t'^2 c_\alpha s_\alpha + F$. Coefficients A-F are derived separately for each analysis bin, by fitting to the yields predicted by multiple simulated samples with varying κ_t' and α. The terms with c_α^2 and s_α^2 correspond to the contribution from CP-even and CP-odd t-H coupling, respectively. The terms at the first order of c_α and s_α account for potential interference effects between CP-even and CP-odd t-H coupling and SM W-H coupling contributions. The term F represents the contribution from only the SM W-H coupling. Ten samples generated with different values of α and κ_t' in addition to the SM tH sample are used for the parameterisation. These samples include: samples where $\kappa_t' = 1$ and α is set between 15° to 90° in steps of 15°, samples with κ_t' = -1, 0.5, and 2 where $\alpha = 0°$ and an additional sample with $\alpha = 45°$ and $\kappa_t' = 2$. Uncertainties due to limited number of MC events in these simulated samples are considered when performing the parameterisation fit in each bin. Good closure was observed: the largest χ^2 per degree of freedom was 0.19 in any given bin. Uncertainties pertaining to the parameterisation of either signal were found to have a negligible impact on the measured values of α and κ_t'.

5. Analysis strategy

In order to optimise the analysis sensitivity, events satisfying the preselection criteria are categorised into orthogonal regions in two steps. In the first step, control regions (CR) and training regions (TR) are defined using requirements on jet multiplicity, b-tagging and large-R jets. The TRs are defined according to the expected numbers of objects from the decay of the signal events, whilst the CRs with lower object multiplicities are signal depleted. The TRs broadly contain the signals and are used to train various multivariate algorithms (MVA). Dedicated observables are constructed in the TRs to enhance sensitivity to the top-Higgs Yukawa CP coupling. In the second step, MVAs are used to divide the TRs into signal regions (SR) and additional CRs with relatively high and low signal purity, respectively. Given the small contribution expected from tH events, the categorisation, MVAs and CP-sensitive observables are optimised for the $t\bar{t}H$ signal. All regions labelled CR and SR are simultaneously fit to the data using either specific observables or simple yields as specified below. Both steps are described in detail below.

The first step of categorisation adopts a strategy similar to that described in Ref. [36], devised to separate the SM signal from the various backgrounds. A 'boosted' region, labelled as $\mathrm{TR}_{\mathrm{boosted}}$, is firstly defined in the ℓ + jets channel by requiring the presence of a high-p_{T} Higgs boson candidate which is identified using a deep neural network (DNN). The DNN is trained to identify the boosted Higgs boson candidates from among large-R jets with $p_{\mathrm{T}} > 300$ GeV [36]. A mixture of constituent

Table 1
Definition of the CRs and TRs according to the number of jets and b-tagged jets using different b-tagging selection criteria, and the number of boosted Higgs boson candidates. For CRs, the bottom row indicates the observables used in the fit to data in the corresponding regions. For the $\mathrm{TR}_{\mathrm{boosted}}$region, the b-tagged jets flagged with † are not constituents of the boosted Higgs boson candidate. Events must pass $N_{b\text{-tag}}$ requirements for each b-tagging selection criteria.

Region		Dilepton				ℓ + jets			
		$\mathrm{TR}^{\geq 4j,\geq 4b}$	$\mathrm{CR}_{\mathrm{hi}}^{\geq 4j,3b}$	$\mathrm{CR}_{\mathrm{lo}}^{\geq 4j,3b}$	$\mathrm{CR}_{\mathrm{hi}}^{3j,3b}$	$\mathrm{TR}^{\geq 6j,\geq 4b}$	$\mathrm{CR}_{\mathrm{hi}}^{5j,\geq 4b}$	$\mathrm{CR}_{\mathrm{lo}}^{5j,\geq 4b}$	$\mathrm{TR}_{\mathrm{boosted}}$
N_{jets}		≥ 4			$= 3$	≥ 6	$= 5$		≥ 4
$N_{b\text{-tag}}$	@85%	–				≥ 4			
	@77%	–				–			$\geq 2^{\dagger}$
	@70%	≥ 4	$= 3$			≥ 4			–
	@60%	–	$= 3$	< 3	$= 3$	–	≥ 4	< 4	–
$N_{\text{boosted cand.}}$		–				0			≥ 1
Fit observable		–	Yield			–	$\Delta R_{bb}^{\mathrm{avg}}$		–

Table 2
Summary of the selections used to define SRs and CRs from the TRs, based on the classification BDT score. In the boosted region, the selection requirement is applied and rejected events are removed entirely from further analysis. In the dilepton channel, events with failed reconstruction due to absence of a real solution from the neutrino weighting are categorised into an additional region known as $\mathrm{CR}_{\text{no-reco}}^{\geq 4j,\geq 4b}$. The fitted discriminating variable in each region is indicated in the last column.

Channel (TR)	Final SRs and CRs	Classification BDT selection	Fitted observable
Dilepton ($\mathrm{TR}^{\geq 4j,\geq 4b}$)	$\mathrm{CR}_{\text{no-reco}}^{\geq 4j,\geq 4b}$	–	$\Delta\eta_{\ell\ell}$
	$\mathrm{CR}^{\geq 4j,\geq 4b}$	$\mathrm{BDT}^{\geq 4j,\geq 4b} \in [-1, -0.086)$	b_4
	$\mathrm{SR}_1^{\geq 4j,\geq 4b}$	$\mathrm{BDT}^{\geq 4j,\geq 4b} \in [-0.086, 0.186)$	b_4
	$\mathrm{SR}_2^{\geq 4j,\geq 4b}$	$\mathrm{BDT}^{\geq 4j,\geq 4b} \in [0.186, 1]$	b_4
ℓ + jets ($\mathrm{TR}^{\geq 6j,\geq 4b}$)	$\mathrm{CR}_1^{\geq 6j,\geq 4b}$	$\mathrm{BDT}^{\geq 6j,\geq 4b} \in [-1, -0.128)$	b_2
	$\mathrm{CR}_2^{\geq 6j,\geq 4b}$	$\mathrm{BDT}^{\geq 6j,\geq 4b} \in [-0.128, 0.249)$	b_2
	$\mathrm{SR}^{\geq 6j,\geq 4b}$	$\mathrm{BDT}^{\geq 6j,\geq 4b} \in [0.249, 1]$	b_2
ℓ + jets ($\mathrm{TR}_{\mathrm{boosted}}$)	$\mathrm{SR}_{\mathrm{boosted}}$	$\mathrm{BDT}^{\mathrm{boosted}} \in [-0.05, 1]$	$\mathrm{BDT}^{\mathrm{boosted}}$

jet masses, pseudo-continuous b-tagging scores and jet substructure observables [89] are used as input features for the training. Events failing this DNN selection defining the $\mathrm{TR}_{\mathrm{boosted}}$ region are categorised into CRs and TRs according to the number of jets (j) and various b-tagging (b) requirements. Events in the TRs are required to have at least the number of jets and b-tagged jets expected from the final state of the $t\bar{t}H$ signal. This results in four statistically independent regions in the dilepton channel, named $\mathrm{CR}_{\mathrm{hi}}^{3j,3b}$, $\mathrm{CR}_{\mathrm{lo}}^{\geq 4j,3b}$, $\mathrm{CR}_{\mathrm{hi}}^{\geq 4j,3b}$ and $\mathrm{TR}^{\geq 4j,\geq 4b}$, and three regions in the ℓ + jets channel, named $\mathrm{CR}_{\mathrm{lo}}^{5j,\geq 4b}$, $\mathrm{CR}_{\mathrm{hi}}^{5j,\geq 4b}$ and $\mathrm{TR}^{\geq 6j,\geq 4b}$. The yields of these regions enter the fit. The requirements used to define all CRs and TRs are summarised in Table 1. Regions labelled with 'hi' ('lo') have relatively higher (lower) fractions of events with true b-jets not from top-quark decays, and are selected with tight (loose) b-tagging requirements. The average ΔR separation between b-jets ($\Delta R_{bb}^{\mathrm{avg}}$) is used as the observable which enters the fit for $\mathrm{CR}_{\mathrm{lo}}^{5j,\geq 4b}$ and $\mathrm{CR}_{\mathrm{hi}}^{5j,\geq 4b}$ regions as it better constrains the shape of the backgrounds. All mentioned CRs have different fractions of $t\bar{t}$ + light, $t\bar{t} + \geq 1c$ and $t\bar{t} + \geq 1b$ events and this helps to constrain the systematic uncertainties in each of these components.

In the TRs, two sets of boosted decision trees (BDT) are trained: reconstruction BDTs and classification BDTs. The former is trained to assign jets as coming from the decay of the Higgs boson or top quarks in $t\bar{t}H$ events, while the latter is trained to discriminate the $t\bar{t}H$ signal against the backgrounds. Both the reconstruction and classification BDTs are trained using simulated SM $t\bar{t}H$ events. It was tested that their performance is equally good for a pure CP-odd signal. For both the reconstruction and classification BDTs, the training procedures are performed independently for each TR and are identical to those used in Ref. [36]. The reconstruction BDTs are trained to classify the correct combinations of jet assignments from random ones. The training explores the relative positional information between pairs of objects, and the invariant masses of object pairs and triplets that form W-boson and top-quark candidates. In order to reconstruct the top-quark and Higgs boson candidates, for each event, all possible permutations of jet assignments are evaluated and the permutation with the highest BDT score is selected. The reconstruction BDTs provide important information that improves the performance of the classification BDTs, whilst allowing for the calculation of observables sensitive to the CP nature of the Yukawa coupling. Classification BDT inputs include reconstruction BDT (DNN in the boosted channel) outputs, pseudo-continuous b-tagging discriminant scores of jets, and kinematic features, such as angular separations and invariant masses of pairs of b-tagged jets. The classification BDTs are used to further refine the TRs to define the final CRs and SRs, as detailed later. The classification BDTs used in $\mathrm{TR}^{\geq 4j,\geq 4b}$, $\mathrm{TR}^{\geq 6j,\geq 4b}$ and $\mathrm{TR}_{\mathrm{boosted}}$ are henceforth denoted by $\mathrm{BDT}^{\geq 4j,\geq 4b}$, $\mathrm{BDT}^{\geq 6j,\geq 4b}$ and $\mathrm{BDT}^{\mathrm{boosted}}$, respectively.

Dedicated CP-sensitive observables are computed in $\mathrm{TR}^{\geq 4j,\geq 4b}$ and $\mathrm{TR}^{\geq 6j,\geq 4b}$ and are used in the fit to determine the CP properties of the top-quark Yukawa coupling. Two CP observables, b_2 and b_4 [22, 35], were found to provide the best discrimination in $\mathrm{TR}^{\geq 6j,\geq 4b}$ of the ℓ + jets channel and $\mathrm{TR}^{\geq 4j,\geq 4b}$ of the dilepton channel, respectively. They are defined as:

$$b_2 = \frac{(\vec{p}_1 \times \hat{z}) \cdot (\vec{p}_2 \times \hat{z})}{|\vec{p}_1||\vec{p}_2|}, \text{ and } b_4 = \frac{(\vec{p}_1 \cdot \hat{z})(\vec{p}_2 \cdot \hat{z})}{|\vec{p}_1||\vec{p}_2|},$$

where $\vec{p}_i$ with $i = 1, 2$ are the momentum three-vectors of the two top quarks in the events and $\hat{z}$ is a unit vector in the direction of the beamline and defines the z-axis. The b_4 observable exploits the enhanced production of top quarks travelling in opposite longitudinal directions and closer to the beamline in CP-odd $t\bar{t}H$ production. The observ-

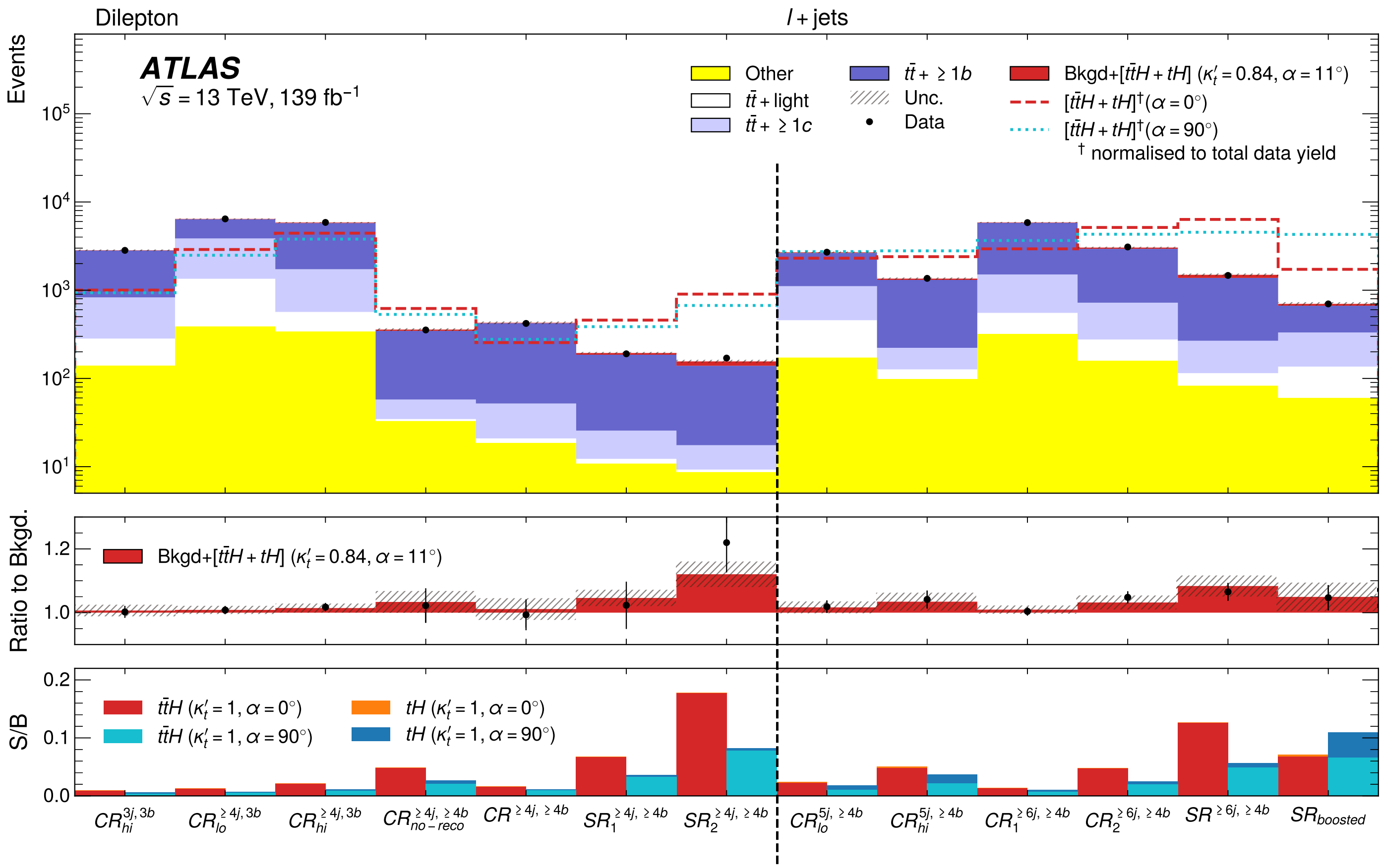

Fig. 1. Yields calculated following a fit with κ_t' and α as free parameters, compared to the observed data in all analysis regions. The different backgrounds and the signal are shown in coloured stack. The background component labelled "other" corresponds to the production of $W+$ jets, $Z+$ jets, $t\bar{t}W$, $t\bar{t}Z$, tZq, tWZ, $t\bar{t}t\bar{t}$ and $WW/WZ/ZZ$ events, as in Ref. [36]. The dashed and dotted lines show the sum of $t\bar{t}H + tH$ signals for pure CP-even and CP-odd hypotheses normalised to the total data yields including all regions. The hashed area around the prediction illustrates the total post-fit uncertainties. In the middle panel, the best-fit model is compared with the data by showing ratios of its value to the post-fit background prediction. The histogram represents the total post-fit model including the best-fit signals. The hashed band represents the total post-fit uncertainty as a ratio to the background. In the bottom panel, the S/B is shown for pure CP-even and CP-odd signals, separately. The histograms are shown as a stack of $t\bar{t}H$ and tH.

able b_2 relies simultaneously on the smaller azimuthal separation of top quarks and on their larger longitudinal fraction of momentum in CP-odd $t\bar{t}H$ production. The calculation of b_2 is performed in the $t\bar{t}H$ rest frame [35], which enhances the discrimination power.

Computation of b_2 and b_4 requires the full reconstruction of both top quarks and the Higgs boson. However, the reconstruction BDTs only resolve the hadronic part of the $t\bar{t}H$ system. In the $\ell+$jets channel, the missing transverse momentum is used as a proxy for the p_{T} of the undetected neutrino from the semileptonically decaying top quark. The z component of the neutrino four-momentum is obtained from a quadratic equation constructed from the lepton four-momentum and the missing transverse momentum, using as a constraint the leptonic W boson's mass, assumed to be its on-shell value. Both solutions of the quadratic equation are used to reconstruct the top-quark mass, and the one yielding a mass closer to 172.5 GeV is chosen. In the case of a negative determinant, a solution is obtained by setting the determinant to zero. In the dilepton channel, the neutrino weighting technique is used to determine the four momenta of the two neutrinos [90,91]. Neutrino weighting provides a solution for reconstructing the $t\bar{t}$ pair for 68% of the events in $\mathrm{TR}^{\geq 4j,\geq 4b}$.

In contrast to the $\mathrm{TR}^{\geq 4j,\geq 4b}$ and $\mathrm{TR}^{\geq 6j,\geq 4b}$ regions, the CP-odd signals are strongly enhanced in comparison with the CP-even signals in the $\mathrm{TR}_{\mathrm{boosted}}$ region. The yields of $t\bar{t}H$ with pure CP-even and CP-odd couplings are approximately equal in the $\mathrm{TR}_{\mathrm{boosted}}$ region. Additionally, the yield of the tH signal with a pure CP-odd coupling is comparable to the $t\bar{t}H$ signal yield. The total CP-odd signal is therefore expected to be 50% larger than a CP-even signal in this region. Given the substantial sensitivity provided by the yield in this region, the distribution of the classification BDT ($\mathrm{BDT}^{\mathrm{boosted}}$) is used instead of a dedicated CP-sensitive observable.

In the second step of the categorisation, TRs are further refined to CRs and SRs according to the output of the reconstruction and classification BDTs. A summary of the selections used to define the regions is detailed in Table 2. In $\mathrm{TR}_{\mathrm{boosted}}$, events below a classification BDT score of –0.05 are discarded to reduce contamination of $t\bar{t}+$light events. $\mathrm{TR}^{\geq 4j,\geq 4b}$ and $\mathrm{TR}^{\geq 6j,\geq 4b}$ are further categorised, each into three regions, according to the classification BDT score. The resulting regions have similar background compositions but different expected signal-to-background ratios (S/B). The BDT thresholds are determined by optimising the sensitivity to the SM $t\bar{t}H$ signal. The three regions (one in $\ell+$jets and two in dilepton) with an $S/B > 7\%$ are referred to as SRs. The remaining three regions (two in $\ell+$jets and one in dilepton) are used as additional CRs to constrain the modelling of the CP observables in the backgrounds events. The highest S/B in the resulting SRs is 22% (10%) for a pure CP-even (CP-odd) signal. For $\mathrm{SR}^{\geq 4j,\geq 4b}$ in the dilepton channel, b_4 cannot be calculated for events where the neutrino weighting fails to provide a solution. These events are categorised as an additional region, $\mathrm{CR}^{\geq 4j,\geq 4b}_{\text{no-reco}}$, where the difference in η between the two leptons, $\Delta\eta_{\ell\ell}$, is used as a CP-sensitive observable instead [26].

Table 3
The observed data yields and the expected signal and background yields in the $\ell+$ jets channel. The expected yields of pure CP-even and CP-odd $t\bar{t}H$ and tH signals, with $\kappa_t' = 1$, are shown at the top of the table. The uncertainties in the pure CP-even and CP-odd $t\bar{t}H$ and tH signals are the total uncertainties before fitting to data. Below that are shown the post-fit $t\bar{t}H$ and tH yields, corresponding to $\kappa_t' = 0.84$ and $\alpha = 11°$. The following seven rows show the yields and uncertainties of individual background sources, where "other" corresponds to $W+$ jets, $Z+$ jets, $t\bar{t}W$, $t\bar{t}Z$, tZq, tWZ, $t\bar{t}t\bar{t}$ and $WW/WZ/ZZ$ events, as in Ref. [36]. The row labelled 'Total' represents the total signal plus background post-fit yields. The uncertainties in the post-fit yields are evaluated from the post-fit nuisance parameters as well as the post-fit uncertainties in the fitted free parameters (α and κ_t' for the signals and $k_{t\bar{t}+b}$ for the $t\bar{t}+\geq 1b$ background) that affect the corresponding processes. The correlations amongst all fitted parameters are taken into account. Due to these correlations the uncertainties on the total yields do not correspond to the quadrature sum of uncertainties of individual signals and backgrounds.

	$\mathrm{CR}_{\mathrm{lo}}^{5j,\geq 4b}$	$\mathrm{CR}_{\mathrm{hi}}^{5j,\geq 4b}$	$\mathrm{CR}_{1}^{\geq 6j,\geq 4b}$	$\mathrm{CR}_{2}^{\geq 6j,\geq 4b}$	$\mathrm{SR}^{\geq 6j,\geq 4b}$	$\mathrm{SR}_{\mathrm{boosted}}$
$t\bar{t}H$ (1, 0°)	60±9	63±10	78±11	139±18	173±26	46±6
tH(1, 0°)	3.5±0.5	3.8±0.6	3.3±0.6	2.3±0.6	1.3±0.4	1.9±0.4
$t\bar{t}H$ (1, 90°)	28±6	28±6	45±11	61±12	68±16	45±6
tH(1, 90°)	19.0±2.8	19.4±3.1	17.4±3.1	13.1±3.5	10±4	29±6
$t\bar{t}H$ (0.84, 11°)	40±30	41±31	50±40	90±70	110±80	30±22
tH (0.84, 11°)	3±4	3.9±1.9	3.1±1.9	1.9±0.8	1.3±1.7	3±5
$t\bar{t}+\geq 1b$	1530±80	1090±60	4300±120	2220±120	1110±110	335±30
$t\bar{t}+\geq 1c$	650±50	96±11	950±80	450±40	153±15	196±22
$t\bar{t}+$ light	280±40	28±8	230±60	117±26	32±11	76±15
Other	173±30	99±20	320±50	159±21	83±11	60±11
Total	2690±50	1350±40	5870±80	3040±70	1500±50	701±31
Data	2696	1363	5837	3090	1470	699

Table 4
The observed data yields and the expected signal and background yields in the dilepton channel. The expected yields of pure CP-even and CP-odd $t\bar{t}H$ and tH signals, with $\kappa_t' = 1$, are shown at the top of the table. The uncertainties in the pure CP-even and CP-odd $t\bar{t}H$ and tH signals are the total uncertainties before fitting to data. Below that are shown the post-fit $t\bar{t}H$ and tH yields, corresponding to $\kappa_t' = 0.84$ and $\alpha = 11°$. The following seven rows show the yields and uncertainties of individual background sources, where "other" corresponds to $W+$ jets, $Z+$ jets, $t\bar{t}W$, $t\bar{t}Z$, tZq, tWZ, $t\bar{t}t\bar{t}$ and $WW/WZ/ZZ$ events, as in Ref. [36]. The row labelled 'Total' represents the total signal plus background post-fit yields. The uncertainties in the post-fit yields are evaluated from the post-fit nuisance parameters as well as the post-fit uncertainties in the fitted free parameters (α and κ_t' for the signals and $k_{t\bar{t}+b}$ for the $t\bar{t}+\geq 1b$ background) that affect the corresponding processes. The correlations amongst all fitted parameters are taken into account. Due to these correlations the uncertainties in the total yields do not correspond to the quadrature sum of uncertainties of individual signals and backgrounds.

	$\mathrm{CR}_{\mathrm{hi}}^{3j,3b}$	$\mathrm{CR}_{\mathrm{lo}}^{\geq 4j,3b}$	$\mathrm{CR}_{\mathrm{hi}}^{\geq 4j,3b}$	$\mathrm{CR}_{\mathrm{no\text{-}reco}}^{\geq 4j,\geq 4b}$	$\mathrm{CR}^{\geq 4j,\geq 4b}$	$\mathrm{SR}_{1}^{\geq 4j,\geq 4b}$	$\mathrm{SR}_{2}^{\geq 4j,\geq 4b}$
$t\bar{t}H$ (1, 0°)	26±4	79±8	120±12	16.9±2.1	6.9±1.1	12.5±1.5	24.8±2.9
tH(1, 0°)	1.12±0.13	0.90±0.13	1.74±0.20	0.19±0.08	0.087±0.035	0.100±0.033	0.09±0.06
$t\bar{t}H$ (1, 90°)	10.6±1.6	35.6±3.5	54±5	7.2±0.9	4.3±0.6	6.1±0.7	10.9±1.3
tH(1, 90°)	5.4±0.6	7.0±1.0	10.7±1.2	1.8±0.8	0.48±0.19	0.48±0.16	0.5±0.4
$t\bar{t}H$ (0.84, 11°)	18±14	50±40	80±60	11±9	4.7±3.4	8±6	17±12
tH (0.84, 11°)	0.9±0.5	1.0±1.9	1.5±1.3	0.17±0.16	0.068±0.016	0.08±0.14	0.07±0.09
$t\bar{t}+\geq 1b$	1990±80	2520±110	4040±130	288±15	371±16	160±8	122±11
$t\bar{t}+\geq 1c$	550±50	2510±150	1160±90	23±4	31.1±2.5	13.4±1.6	8.2±1.0
$t\bar{t}+$ light	143±27	960±130	230±40	1.7±0.4	2.3±0.8	1.4±0.8	0.57±0.25
Other	140±11	390±19	340±40	33±8	18.6±2.5	10.9±1.3	8.7±1.0
Total	2840±50	6430±80	5850±80	358±12	428±15	194±5	156±6
Data	2827	6429	5865	354	420	190	170

6. Systematic uncertainties

Systematic uncertainties are assessed for three main sources: theoretical modelling of the signal processes, background modelling which is dominated by the uncertainties in the $t\bar{t}+\geq 1b$ background and experimental sources involving the (mis)identification rates and energy calibration of leptons, jets, b-jets and missing transverse momentum. Uncertainties accounting for the limited number of events in all simulated samples are also considered. Systematic variations can affect the overall yields, relative yields between analysis regions and shapes of observables.

Uncertainties associated with the modelling of the $t\bar{t}H$ signals include variations due to initial and final state radiation (ISR and FSR), choice of the NLO matching procedure as well as the PS and hadronisation model. These uncertainties are evaluated using events generated with Powheg Box + Pythia 8, which are produced with the same PDF set and renormalisation and factorisation scales as the nominal MadGraph5_aMC@NLO + Pythia 8 sample, unless otherwise specified.

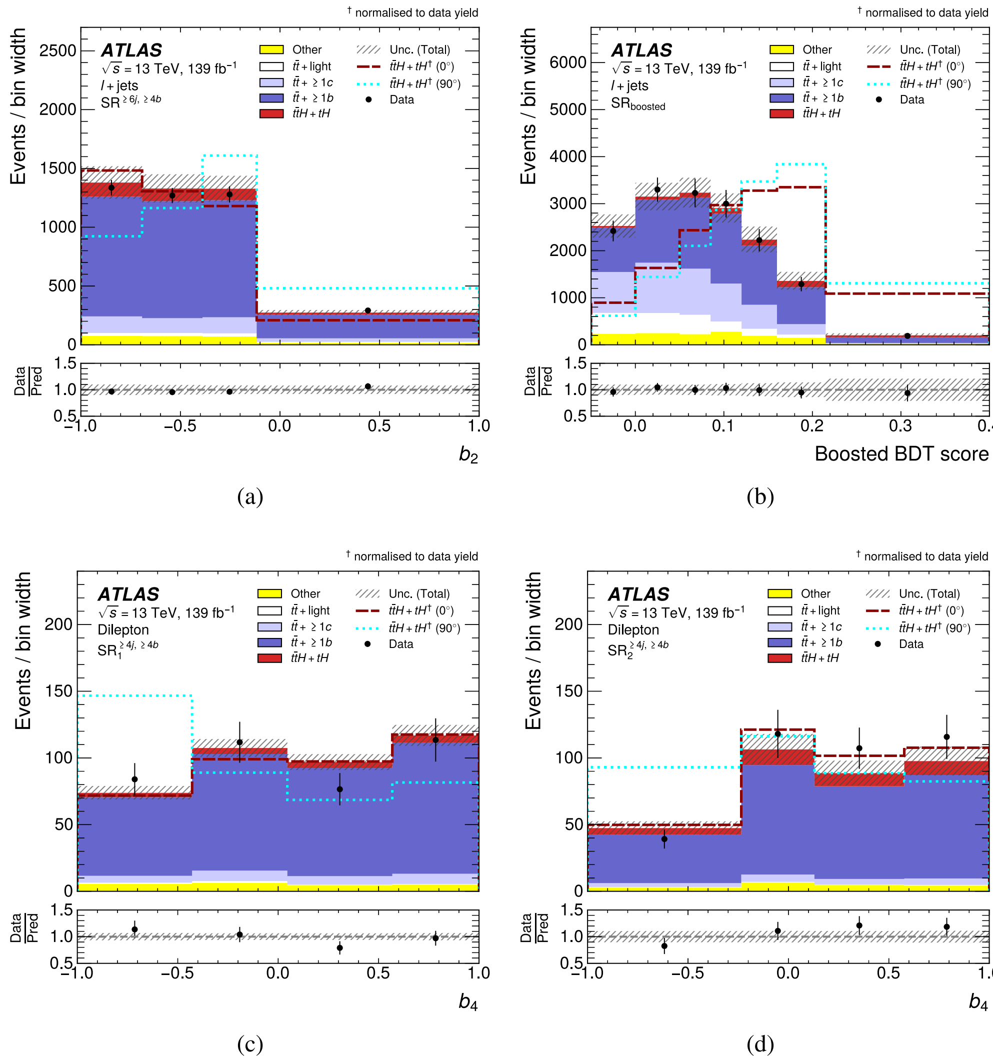

Fig. 2. The distributions of the fitted variables in all signal regions. The stacked histograms represent the predictions from a fit of signal and background to data with both κ_t' and α as free parameters. This is compared with data shown with black dots. The solid red histogram shows the best-fit signal with $\alpha = 11°$ and $\kappa_t' = 0.84$. The dashed and dotted lines show $t\bar{t}H + tH$ signal predictions for pure CP-even and CP-odd hypotheses, respectively, normalised to the total data yield per region in order to illustrate the shapes of the signal distribution. The hashed area around the prediction illustrates the total post-fit uncertainties. The lower panel shows the ratio of data to the predicted yields from a fit of signal and background in which κ_t' and α are free parameters.

Variations relative to the SM hypothesis are propagated to scenarios with alternative values of α and κ_t'. To estimate the uncertainty related to the amount of partonic ISR, the renormalisation and factorisation scales in the ME and α_S^{ISR} in the PS are varied simultaneously [92]. The impact of the FSR is evaluated by varying α_S^{FSR} in the PS. The impact of varying the PS and hadronisation models is estimated by comparing $t\bar{t}H$ samples generated using POWHEG BOX + PYTHIA 8.230 with those generated from POWHEG BOX + HERWIG 7.04 [93]. The uncertainty due to the choice of NLO matching procedure is derived by directly comparing the POWHEG BOX + PYTHIA 8 sample with the nominal MADGRAPH5_AMC@NLO + PYTHIA 8 sample. The uncertainties in the modelling of tH are estimated using the nominal sample generated using MADGRAPH5_AMC@NLO + PYTHIA 8. For each tH subprocess ($tHjb$ and tWH), two sources of modelling uncertainty are considered: that associated with the description of PDFs, and the uncertainty due to missing higher-order QCD contributions. The former is estimated from the standard deviation of the expected yields using 100 NNPDF3.0NLO eigenvector PDF sets, in each analysis bin used to build the likelihood function. The latter is estimated by coherently varying μ_r and μ_f by factors of 0.5 and 2.

The most important uncertainties in the background estimation come from the modelling of the $t\bar{t} + \geq 1b$ background. These uncertainties are designed to account for the choice of NLO matching procedure, PS and hadronisation model as well as the flavour scheme utilised in the $t\bar{t} + \geq 1b$ event generation. An uncertainty in the ME-to-PS matching procedure is assessed by comparing the POWHEG BOX + PYTHIA 8 sample with a sample generated using MADGRAPH5_AMC@NLO + PYTHIA 8, both in the five-flavour scheme. The variation by comparing these two samples is propagated to the nominal $t\bar{t} + \geq 1b$ sample generated with POWHEG BOX RES + PYTHIA 8 in the four-flavour scheme. This uncertainty is separated into three components that are treated independently: one for the dilepton channel, another for the non-boosted regions in the ℓ + jets channel, and a third for the ℓ + jets boosted region. This treatment is found to be important because it provides the fit with enough flexibility to cover the potential background mismodelling. Uncertainties in the choice of the PS model are evaluated by comparing the nominal sample with the one produced with POWHEG BOX + HERWIG 7. These uncertainties are treated in the same way as the uncertainty in the NLO matching procedure. An additional source of systematic uncertainty is introduced to address the choice of flavour scheme used for the generation of the $t\bar{t} + \geq 1b$ events. It is evaluated by comparing the nominal sample, generated in the four-flavour scheme using POWHEG + PYTHIA 8, with that produced in the five-flavour scheme reweighted to remove differences in scale settings. Uncertainties in ISR and FSR are estimated using the same procedure as used for the $t\bar{t}H$ signals. An uncertainty due to differences in relative fraction of $t\bar{t}+1b$ and $t\bar{t}+\geq 2b$ subcomponents from different MC predictions is also considered. Other uncertainties in $t\bar{t}+\geq 1b$ and uncertainties in other background components are treated identically to the procedure described in Ref. [36].

Aside from the modelling uncertainties described above, experimental uncertainties are also considered. These arise from the modelling of trigger, reconstruction, identification and isolation efficiencies, as well as the calibration of energy and momentum scales for all physics objects, including electrons, muons, jets, b-tagged jets and $E_{\mathrm{T}}^{\mathrm{miss}}$. Uncertainties in the measured integrated luminosity and in the modelling of additional pp collisions are included.

7. Results

A binned profile likelihood fit is performed including all analysis regions simultaneously in order to determine the α and κ_t' parameters. The likelihood function, $\mathcal{L}(\alpha, \kappa_t', \boldsymbol{\theta})$, is constructed as the product of Poisson terms, with each term corresponding to an analysis bin. The value of the likelihood varies according to the expected signal yields, as a function of α and κ_t', and background yields of the analysis bins, as well as $\boldsymbol{\theta}$, representing the nuisance parameters encoding the effects of the systematic uncertainties and a single parameter controlling the normalisation of the $t\bar{t}+\geq 1b$ background. The nuisance parameters are constrained with Gaussian or log-normal functions. The normalisation of the $t\bar{t}+\geq 1b$ background is controlled by an unconstrained parameter $k_{t\bar{t}+b}$. A profile likelihood ratio is used as the test statistic, following Ref. [94]. By scanning the value of the test statistic in grid points in κ_t' and α, two-dimensional exclusion contours in the (κ_t', α) plane are obtained.

Fig. 1 compares the observed yield of data in each analysis region with that expected after the fit to data (post-fit). The expected yields for pure CP-even and CP-odd signals, normalised to the total data yields, are overlaid and shown with dashed lines in the top panels. These illustrate the signal-to-background separation provided by the classification BDTs. In the middle panel, the best-fit model is compared with the data by showing ratios of its value to the post-fit background prediction. The post-fit model agrees well with the observed data. In addition, the expected S/B for pure CP-even and CP-odd signals are shown for both $t\bar{t}H$ and tH. The post-fit yields for all backgrounds and the signals are summarised in Tables 3 and 4 for the $\ell+$jets and dilepton channels, respectively. The expected yields of pure CP-even and CP-odd signals are compared with the post-fit yields. In all fitted regions, the best-fit signal yields are lower than their SM predictions. The fitted value of $k_{t\bar{t}+b}$ is $1.30^{+0.09}_{-0.08}$, consistent with the value measured in Ref. [36]. Fig. 2 shows the distributions of the fitted observables in the four SRs. The post-fit predictions are in agreement with data. Goodness-of-fit was evaluated using a likelihood ratio test, comparing the likelihood value from the nominal fit with the one obtained from a saturated model built with one free-floating normalisation factor for each fitted bin [95]. The probability that the post-fit prediction is compatible with the observed data is 80%. The pure CP-even and CP-odd signals are shown overlaid and normalised to the data yield to indicate the kinematic discrimination of the b_2 and b_4 observables.

The best-fit values and the exclusion contours in α and κ_t' are displayed in Fig. 3 in the $(\kappa_t' \cos\alpha, \kappa_t' \sin\alpha)$ plane. The best-fit value for the CP mixing angle α is $11^{\circ}{}^{+52^{\circ}}_{-73^{\circ}}$ and overall coupling strength κ_t' is $0.84^{+0.30}_{-0.46}$, which are in agreement with the SM expectations of $\alpha = 0^{\circ}$ and $\kappa_t' = 1$. The data disfavour the pure CP-odd hypothesis with a 1.2 σ significance. The significance of the observed $t\bar{t}H$ and tH signals over the background prediction is 1.3 σ. The compatibility of this analysis with the $t\bar{t}H$ cross-section measurement [36] was tested with the same

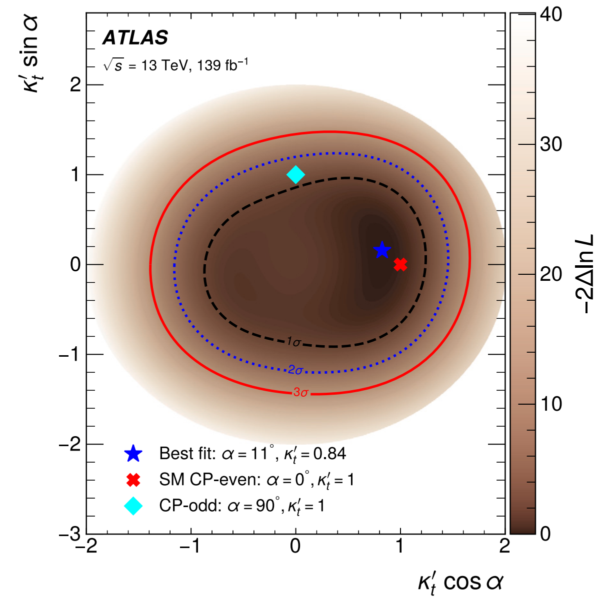

Fig. 3. The observed exclusion contours in the $(\kappa_t' \cos\alpha, \kappa_t' \sin\alpha)$ plane. Regions contained in the dashed, dotted and solid lines are compatible with the best-fit results at 1, 2 and 3 σ standard deviations. The cross (diamond) represents the CP-even (CP-odd) with $\kappa_t' = 1$ and the best-fit result is represented with a pentagram.

parameter of interest: a single free-floating signal strength, $\mu_{t\bar{t}H}$, controlling the normalisation of $t\bar{t}H$ production in the SM scenario. The tH process was fixed to its SM prediction with an identical systematic model. The compatibility is tested using the bootstrap technique [96]. The difference in the measured $\mu_{t\bar{t}H}$ is sampled by fitting to toy datasets generated by varying the event weights entering the Asimov dataset according to the Poisson fluctuations expected in data. The measured values of $\mu_{t\bar{t}H}$ were found to be compatible within one standard deviation, when accounting for the statistical correlations between the two measurements.

The impact of a group of systematic uncertainties on α (κ_t') is assessed by fixing the nuisance parameters to their best fit values and subtracting the subsequent α (κ_t') uncertainty in quadrature from the total α (κ_t') uncertainty. The uncertainty in the measured value of α is dominated by $t\bar{t}+\geq 1b$ modelling uncertainties which contribute $^{+37^{\circ}}_{-51^{\circ}}$ to the overall uncertainty. This is driven by: the NLO matching procedure between the ME and PS; PS and hadronisation; and the choice of flavour scheme. These uncertainties contribute $^{+22^{\circ}}_{-33^{\circ}}$, $^{+16^{\circ}}_{-24^{\circ}}$ and $^{+23^{\circ}}_{-37^{\circ}}$, respectively. Smaller effects from the $t\bar{t}+\geq 1b$ modelling originate from the ISR uncertainty and the relative fractions of $t\bar{t}+\geq 2b$ and $t\bar{t}+1b$, contributing $^{+14^{\circ}}_{-24^{\circ}}$ and $^{+14^{\circ}}_{-21^{\circ}}$. The $t\bar{t}+\geq 1c$ modelling uncertainties contribute only $^{+6.6^{\circ}}_{-11^{\circ}}$ to the uncertainty in α. The 100% $t\bar{t}+\geq 1c$ normalisation uncertainty is constrained to 50% with a pull of 0.6 σ, and has negligible impact on the fitted α and κ_t'. Through a correlation with α, the measured κ_t' contributes $^{+17^{\circ}}_{-33^{\circ}}$ to the α uncertainty. Experimental uncertainties are smaller than the $t\bar{t}+\geq 1b$ modelling uncertainties. The statistical uncertainty is $^{+32^{\circ}}_{-49^{\circ}}$.

8. Summary

In conclusion, the CP properties of the top-quark's Yukawa coupling to the Higgs boson are probed in $t\bar{t}H$ and tH production with $H \to b\bar{b}$ decays, which had not been studied before. Dedicated CP-sensitive variables relying on angular separations between reconstructed top quarks or lepton candidates were used directly. Assuming the SM branching ratio for the Higgs boson decay, the best-fit values of the CP-mixing angle and the overall coupling strength are $\alpha = 11^{\circ}{}^{+52^{\circ}}_{-73^{\circ}}$

and $\kappa_t' = 0.84^{+0.30}_{-0.46}$. These values can be compared with the expected allowed 1 σ ranges of α and κ_t', obtained using Asimov datasets constructed with either a pure CP-even or -odd signal. For a CP-even scenario $\alpha \in [-180°, -173°] \cup [-50°, 52°] \cup [171°, 180°]$ and $\kappa_t' = 1.00^{+0.29}_{-0.27}$, whilst for a pure CP-odd scenario $\alpha \in [-157°, -41°] \cup [43°, 157°]$ and $\kappa_t' = 1.00^{+0.22}_{-0.33}$. The sensitivity of this measurement is driven by the systematic uncertainties.

These results complement previous ATLAS measurements in the $H \to \gamma\gamma$ decay channel and will allow for a future combined measurement of the CP properties of the top-quark Yukawa coupling. Due to the tree-level sensitivity and the high $H \to b\bar{b}$ branching ratio, it can be expected that future measurements in the $t\bar{t}H$ and tH channels will become quite sensitive to the CP properties of the top-quark Yukawa coupling. Additional LHC data and a better theoretical understanding of the $t\bar{t} + \geq 1b$ process will be essential ingredients in order to achieve this sensitivity.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgements

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

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; 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, ICSC-NextGenerationEU and Marie Skłodowska-Curie Actions, European Union; Investissements d'Avenir Labex, Investissements d'Avenir Idex and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and MINERVA, Israel; 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 CRN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [97].

References

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

[2] CMS Collaboration, Observation of a new boson with mass near 125 GeV in pp collisions at $\sqrt{s} = 7$ and 8 TeV, J. High Energy Phys. 06 (2013) 081, arXiv:1303.4571 [hep-ex].

[3] ATLAS Collaboration, Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector, Phys. Lett. B 784 (2018) 173, arXiv:1806.00425 [hep-ex].

[4] CMS Collaboration, Observation of $t\bar{t}H$ production, Phys. Rev. Lett. 120 (2018) 231801, arXiv:1804.02610 [hep-ex].

[5] ATLAS Collaboration, CP properties of Higgs boson interactions with top quarks in the $t\bar{t}H$ and tH processes using $H \to \gamma\gamma$ with the ATLAS detector, Phys. Rev. Lett. 125 (2020) 061802, arXiv:2004.04545 [hep-ex].

[6] CMS Collaboration, Measurements of $t\bar{t}H$ production and the CP structure of the Yukawa interaction between the Higgs boson and top quark in the diphoton decay channel, Phys. Rev. Lett. 125 (2020) 061801, arXiv:2003.10866 [hep-ex].

[7] CMS Collaboration, Search for CP violation in ttH and tH production in multilepton channels in proton–proton collisions at $\sqrt{s} = 13\,TeV$, J. High Energy Phys. 07 (2022) 092, arXiv:2208.02686 [hep-ex].

[8] W. Buchmüller, D. Wyler, Effective Lagrangian analysis of new interactions and flavour conservation, Nucl. Phys. B (ISSN 0550-3213) 268 (1986) 621.

[9] V. Hankele, G. Klämke, D. Zeppenfeld, T. Figy, Anomalous Higgs boson couplings in vector boson fusion at the CERN LHC, Phys. Rev. D 74 (2006).

[10] D. Fontes, J.C. Romão, R. Santos, J.P. Silva, Large pseudoscalar Yukawa couplings in the complex 2HDM, J. High Energy Phys. 2015 (2015) 60, arXiv:1502.01720v2 [hep-ph].

[11] ATLAS Collaboration, Evidence for the spin-0 nature of the Higgs boson using ATLAS data, Phys. Lett. B 726 (2013) 120, arXiv:1307.1432 [hep-ex].

[12] CMS Collaboration, Study of the mass and spin-parity of the Higgs boson candidate via its decays to Z boson pairs, Phys. Rev. Lett. 110 (2013) 081803, arXiv:1212.6639 [hep-ex].

[13] ATLAS Collaboration, Search for a CP-odd Higgs boson decaying to Zh in pp collisions at $\sqrt{s} = 8\,TeV$ with the ATLAS detector, Phys. Lett. B 744 (2015) 163, arXiv:1502.04478 [hep-ex].

[14] ATLAS Collaboration, Test of CP invariance in vector-boson fusion production of the Higgs boson in the $H \to \tau\tau$ channel in proton–proton collisions at $\sqrt{s} = 13\,TeV$ with the ATLAS detector, Phys. Lett. B 805 (2020) 135426, arXiv:2002.05315 [hep-ex].

[15] ATLAS Collaboration, Measurements of Higgs boson properties in the diphoton decay channel with 36 fb^{-1} of pp collision data at $\sqrt{s} = 13\,TeV$ with the ATLAS detector, Phys. Rev. D 98 (2018) 052005, arXiv:1802.04146 [hep-ex].

[16] ATLAS Collaboration, Measurement of the Higgs boson coupling properties in the $H \to ZZ^* \to 4\ell$ decay channel at $\sqrt{s} = 13\,TeV$ with the ATLAS detector, J. High Energy Phys. 03 (2018) 095, arXiv:1712.02304 [hep-ex].

[17] CMS Collaboration, Combined search for anomalous pseudoscalar HVV couplings in $VH(H \to b\bar{b})$ production and $H \to VV$ decay, Phys. Lett. B 759 (2016) 672, arXiv:1602.04305 [hep-ex].

[18] CMS Collaboration, Constraints on anomalous Higgs boson couplings using production and decay information in the four-lepton final state, Phys. Lett. B 775 (2017) 1, arXiv:1707.00541 [hep-ex].

[19] CMS Collaboration, Measurements of the Higgs boson width and anomalous HVV couplings from on-shell and off-shell production in the four-lepton final state, Phys. Rev. D 99 (2019) 112003, arXiv:1901.00174 [hep-ex].

[20] CMS Collaboration, Constraints on anomalous Higgs boson couplings to vector bosons and fermions from the production of Higgs bosons using the $\tau\tau$ final state, arXiv:2205.05120 [hep-ex], 2022.

[21] ATLAS Collaboration, Test of CP-invariance of the Higgs boson in vector-boson fusion production and its decay into four leptons, arXiv:2304.09612 [hep-ex], 2023.

[22] J.F. Gunion, X.-G. He, Determining the CP nature of a neutral Higgs boson at the CERN large hadron collider, Phys. Rev. Lett. 76 (1996) 4468, arXiv:hep-ph/9602226.

[23] J. Ellis, D.S. Hwang, K. Sakurai, M. Takeuchi, Disentangling Higgs-top couplings in associated production, J. High Energy Phys. 04 (2014) 004, arXiv:1312.5736 [hep-ph].

[24] X.-G. He, G.-N. Li, Y.-J. Zheng, Probing Higgs boson CP properties with $t\bar{t}H$ at the LHC and the 100 TeV pp collider, Int. J. Mod. Phys. A 30 (2014) 1550156, arXiv:1501.00012 [hep-ph].

[25] F. Boudjema, D. Guadagnoli, R.M. Godbole, K.A. Mohan, Laboratory-frame observables for probing the top-Higgs boson interaction, Phys. Rev. D 92 (2015) 015019, arXiv:1501.03157 [hep-ph].

[26] F. Demartin, F. Maltoni, K. Mawatari, B. Page, M. Zaro, Higgs characterisation at NLO in QCD: CP properties of the top-quark Yukawa interaction, Eur. Phys. J. C 74 (2014) 3065, arXiv:1407.5089 [hep-ph].

[27] H. Bahl, et al., Indirect CP probes of the Higgs-top-quark interaction: current LHC constraints and future opportunities, J. High Energy Phys. 2020 (2020) 127, arXiv:2007.08542 [hep-ph].

[28] D. Gonçalves, J.H. Kim, K. Kong, Y. Wu, Direct Higgs-top CP-phase measurement with $t\bar{t}h$ at the 14 TeV LHC and 100 TeV FCC, J. High Energy Phys. 2022 (2022) 158, arXiv:2108.01083 [hep-ph].

[29] J. Brod, U. Haisch, J. Zupan, Constraints on CP-violating Higgs couplings to the third generation, J. High Energy Phys. 11 (2013) 180, arXiv:1310.1385 [hep-ph].

[30] V. Andreev, et al., Improved limit on the electric dipole moment of the electron, Nature 562 (2018) 355.

[31] C. Abel, et al., Measurement of the permanent electric dipole moment of the neutron, Phys. Rev. Lett. 124 (2020) 081803, arXiv:2001.11966 [hep-ex].

[32] M.R. Buckley, D. Goncalves, Boosting the direct CP measurement of the Higgs-top coupling, Phys. Rev. Lett. 116 (2016) 091801, arXiv:1507.07926 [hep-ph].

[33] D. Gonçalves, J.H. Kim, K. Kong, Probing the top-Higgs Yukawa CP structure in dileptonic $t\bar{t}h$ with M $_2$-assisted reconstruction, J. High Energy Phys. 06 (2018) 079, arXiv:1804.05874 [hep-ph].

[34] D. Azevedo, A. Onofre, F. Filthaut, R. Gonçalo, CP tests of Higgs couplings in $t\bar{t}h$ semileptonic events at the LHC, Phys. Rev. D 98 (2018) 033004, arXiv:1711.05292 [hep-ph].

[35] A. Ferroglia, M.C.N. Fiolhais, E. Gouveia, A. Onofre, Role of the $t\bar{t}h$ rest frame in direct top-quark Yukawa coupling measurements, Phys. Rev. D 100 (2019) 075034, arXiv:1909.00490 [hep-ph].

[36] ATLAS Collaboration, Measurement of Higgs boson decay into b-quarks in associated production with a top-quark pair in pp collisions at $\sqrt{s} = 13\,TeV$ with the ATLAS detector, J. High Energy Phys. 06 (2022) 097, arXiv:2111.06712 [hep-ex].

[37] D. de Florian, et al., Handbook of LHC Higgs cross sections: 4. deciphering the nature of the Higgs sector, arXiv:1610.07922 [hep-ph], 2016.

[38] ATLAS Collaboration, The ATLAS experiment at the CERN large hadron collider, J. Instrum. 3 (2008) S08003.

[39] ATLAS Collaboration, ATLAS insertable B-layer: technical design report, ATLAS-TDR-19; CERN-LHCC-2010-013, https://cds.cern.ch/record/1291633, 2010; Addendum: ATLAS-TDR-19-ADD-1; CERN-LHCC-2012-009, https://cds.cern.ch/record/1451888, 2012.

[40] B. Abbott, et al., Production and integration of the ATLAS insertable B-layer, J. Instrum. 13 (2018) T05008, arXiv:1803.00844 [physics.ins-det].

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

[42] ATLAS Collaboration, The ATLAS Collaboration software and firmware, ATL-SOFT-PUB-2021-001, https://cds.cern.ch/record/2767187, 2021.

[43] ATLAS Collaboration, Performance of the ATLAS muon triggers in Run 2, J. Instrum. 15 (2020) P09015, arXiv:2004.13447 [physics.ins-det].

[44] ATLAS Collaboration, Performance of electron and photon triggers in ATLAS during LHC Run 2, Eur. Phys. J. C 80 (2020) 47, arXiv:1909.00761 [hep-ex].

[45] ATLAS Collaboration, Electron and photon performance measurements with the ATLAS detector using the 2015–2017 LHC proton–proton collision data, J. Instrum. 14 (2019) P12006, arXiv:1908.00005 [hep-ex].

[46] ATLAS Collaboration, Muon reconstruction and identification efficiency in ATLAS using the full Run 2 pp collision data set at $\sqrt{s} = 13\,TeV$, Eur. Phys. J. C 81 (2021) 578, arXiv:2012.00578 [hep-ex].

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

[48] 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 (2020) 689, arXiv:2007.02645 [hep-ex].

[49] M. Cacciari, G.P. Salam, G. Soyez, The anti-k_t jet clustering algorithm, J. High Energy Phys. 04 (2008) 063, arXiv:0802.1189 [hep-ph].

[50] M. Cacciari, G.P. Salam, G. Soyez, FastJet user manual, Eur. Phys. J. C 72 (2012) 1896, arXiv:1111.6097 [hep-ph].

[51] 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 [hep-ex].

[52] 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, https://cds.cern.ch/record/2306649, 2018.

[53] 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, https://cds.cern.ch/record/2314418, 2018.

[54] 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 [hep-ex].

[55] B. Nachman, P. Nef, A. Schwartzman, M. Swiatlowski, C. Wanotayaroj, Jets from jets: re-clustering as a tool for large radius jet reconstruction and grooming at the LHC, J. High Energy Phys. 02 (2015) 075, arXiv:1407.2922 [hep-ph].

[56] ATLAS Collaboration, The ATLAS simulation infrastructure, Eur. Phys. J. C 70 (2010) 823, arXiv:1005.4568 [physics.ins-det].

[57] S. Agostinelli, et al., Geant4 – a simulation toolkit, Nucl. Instrum. Methods A 506 (2003) 250.

[58] T. Sjöstrand, et al., An introduction to PYTHIA 8.2, Comput. Phys. Commun. 191 (2015) 159, arXiv:1410.3012 [hep-ph].

[59] 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, https://cds.cern.ch/record/2206965, 2016.

[60] T. Ježo, J.M. Lindert, N. Moretti, S. Pozzorini, New NLOPS predictions for $t\bar{t} + b$-jet production at the LHC, Eur. Phys. J. C 78 (2018) 502, arXiv:1802.00426 [hep-ph].

[61] F. Cascioli, P. Maierhöfer, S. Pozzorini, Scattering amplitudes with open loops, Phys. Rev. Lett. 108 (2012) 111601, arXiv:1111.5206 [hep-ph].

[62] A. Denner, S. Dittmaier, L. Hofer, Collier: a fortran-based complex one-loop library in extended regularizations, Comput. Phys. Commun. 212 (2017) 220, arXiv:1604.06792 [hep-ph].

[63] T. Ježo, Powheg-Box-Res ttbb source code, https://gitlab.cern.ch/tjezo/powheg-box-res_ttbb/, 2019.

[64] The NNPDF Collaboration, R.D. Ball, et al., Parton distributions for the LHC run II, J. High Energy Phys. 04 (2015) 040, arXiv:1410.8849 [hep-ph].

[65] ATLAS Collaboration, ATLAS Pythia 8 tunes to 7 *TeV* data, ATL-PHYS-PUB-2014-021, https://cds.cern.ch/record/1966419, 2014.

[66] ATLAS Collaboration, Measurements of inclusive and differential fiducial cross-sections of $t\bar{t}$ production with additional heavy-flavour jets in proton–proton collisions at $\sqrt{s} = 13\,TeV$ with the ATLAS detector, J. High Energy Phys. 04 (2019) 046, arXiv:1811.12113 [hep-ex].

[67] CMS Collaboration, Measurement of the $t\bar{t}b\bar{b}$ production cross section in the all-jet final state in pp collisions at $\sqrt{s} = 13\,TeV$, Phys. Lett. B 803 (2020) 135285, arXiv:1909.05306 [hep-ex].

[68] P. Nason, A new method for combining NLO QCD with shower Monte Carlo algorithms, J. High Energy Phys. 11 (2004) 040, arXiv:hep-ph/0409146.

[69] S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method, J. High Energy Phys. 11 (2007) 070, arXiv:0709.2092 [hep-ph].

[70] S. Alioli, P. Nason, C. Oleari, E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX, J. High Energy Phys. 06 (2010) 043, arXiv:1002.2581 [hep-ph].

[71] H.B. Hartanto, B. Jäger, L. Reina, D. Wackeroth, Higgs boson production in association with top quarks in the POWHEG BOX, Phys. Rev. D 91 (2015) 094003, arXiv:1501.04498 [hep-ph].

[72] M. Beneke, P. Falgari, S. Klein, C. Schwinn, Hadronic top-quark pair production with NNLL threshold resummation, Nucl. Phys. B 855 (2012) 695, arXiv:1109.1536 [hep-ph].

[73] M. Cacciari, M. Czakon, M. Mangano, A. Mitov, P. Nason, Top-pair production at hadron colliders with next-to-next-to-leading logarithmic soft-gluon resummation, Phys. Lett. B 710 (2012) 612, arXiv:1111.5869 [hep-ph].

[74] P. Bärnreuther, M. Czakon, A. Mitov, Percent-level-precision physics at the tevatron: next-to-next-to-leading order QCD corrections to $q\bar{q} \to t\bar{t} + X$, Phys. Rev. Lett. 109 (2012) 132001, arXiv:1204.5201 [hep-ph].

[75] M. Czakon, A. Mitov, NNLO corrections to top-pair production at hadron colliders: the all-fermionic scattering channels, J. High Energy Phys. 12 (2012) 054, arXiv:1207.0236 [hep-ph].

[76] M. Czakon, A. Mitov, NNLO corrections to top pair production at hadron colliders: the quark-gluon reaction, J. High Energy Phys. 01 (2013) 080, arXiv:1210.6832 [hep-ph].

[77] M. Czakon, P. Fiedler, A. Mitov, Total top-quark pair-production cross section at hadron colliders through $O(\alpha_S^4)$, Phys. Rev. Lett. 110 (2013) 252004, arXiv:1303.6254 [hep-ph].

[78] M. Czakon, A. Mitov, Top++: a program for the calculation of the top-pair cross-section at hadron colliders, Comput. Phys. Commun. 185 (2014) 2930, arXiv:1112.5675 [hep-ph].

[79] P. Artoisenet, et al., A framework for Higgs characterisation, J. High Energy Phys. 11 (2013) 043, arXiv:1306.6464 [hep-ph].

[80] A. Alloul, N.D. Christensen, C. Degrande, C. Duhr, B. Fuks, FeynRules 2.0 - a complete toolbox for tree-level phenomenology, Comput. Phys. Commun. 185 (2014) 2250, arXiv:1310.1921 [hep-ph].

[81] C. Degrande, et al., UFO - the universal FeynRules output, Comput. Phys. Commun. 183 (2012) 1201, arXiv:1108.2040 [hep-ph].

[82] 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, J. High Energy Phys. 07 (2014) 079, arXiv:1405.0301 [hep-ph].

[83] R. Raitio, W.W. Wada, Higgs-boson production at large transverse momentum in quantum chromodynamics, Phys. Rev. D 19 (1979) 941.

[84] W. Beenakker, et al., NLO QCD corrections to $t\bar{t}H$ production in hadron collisions, Nucl. Phys. B 653 (2003) 151, arXiv:hep-ph/0211352 [hep-ph].

[85] S. Dawson, C. Jackson, L.H. Orr, L. Reina, D. Wackeroth, Associated Higgs boson production with top quarks at the CERN Large Hadron Collider: NLO QCD corrections, Phys. Rev. D 68 (2003) 034022, arXiv:hep-ph/0305087v2 [hep-ph].

[86] Y. Zhang, W.-G. Ma, R.-Y. Zhang, C. Chen, L. Guo, QCD NLO and EW NLO corrections to $t\bar{t}H$ production with top quark decays at hadron collider, Phys. Lett. B 738 (2014) 1, arXiv:1407.1110 [hep-ph].

[87] S. Frixione, V. Hirschi, D. Pagani, H.-S. Shao, M. Zaro, Electroweak and QCD corrections to top-pair hadroproduction in association with heavy bosons, J. High Energy Phys. 06 (2015) 184, arXiv:1504.03446 [hep-ph].

[88] S. Frixione, E. Laenen, P. Motylinski, B.R. Webber, Angular correlations of lepton pairs from vector boson and top quark decays in Monte Carlo simulations, J. High Energy Phys. 04 (2007) 081, arXiv:hep-ph/0702198.

[89] ATLAS Collaboration, Performance of jet substructure techniques for large-R jets in proton–proton collisions at $\sqrt{s} = 7\,TeV$ using the ATLAS detector, J. High Energy Phys. 09 (2013) 076, arXiv:1306.4945 [hep-ex].

[90] DØ Collaboration, Measurement of the top quark mass using dilepton events, Phys. Rev. Lett. 80 (1998) 2063, arXiv:hep-ex/9706014.
[91] ATLAS Collaboration, Measurements of top-quark pair differential cross-sections in the $e\mu$ channel in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector, Eur. Phys. J. C 77 (2017) 292, arXiv:1612.05220 [hep-ex].
[92] ATLAS Collaboration, Study of top-quark pair modelling and uncertainties using ATLAS measurements at $\sqrt{s} = 13$ TeV, ATL-PHYS-PUB-2020-023, https://cds.cern.ch/record/2730443, 2020.
[93] J. Bellm, et al., Herwig 7.0/Herwig++ 3.0 release note, Eur. Phys. J. C 76 (2016) 196, arXiv:1512.01178 [hep-ph].
[94] G. Cowan, K. Cranmer, E. Gross, O. Vitells, Asymptotic formulae for likelihood-based tests of new physics, Eur. Phys. J. C 71 (2011) 1554, arXiv:1007.1727 [physics.data-an]; Erratum: Eur. Phys. J. C 73 (2013) 2501.
[95] R. Cousins, Generalization of chisquare goodness-of-fit test for binned data using saturated models, with application to histograms, http://www.physics.ucla.edu/~cousins/stats/cousins_saturated.pdf, 2013.
[96] ATLAS Collaboration, Evaluating statistical uncertainties and correlations using the bootstrap method, ATL-PHYS-PUB-2021-011, https://cds.cern.ch/record/2759945, 2021.
[97] ATLAS Collaboration, ATLAS computing acknowledgements, ATL-SOFT-PUB-2023-001, https://cds.cern.ch/record/2869272, 2023.

The ATLAS Collaboration

G. Aad[101], B. Abbott[119], D.C. Abbott[102], K. Abeling[55], S.H. Abidi[29], A. Aboulhorma[35e], H. Abramowicz[150], H. Abreu[149], Y. Abulaiti[116], A.C. Abusleme Hoffman[136a], B.S. Acharya[68a,68b,p], B. Achkar[55], L. Adam[99], C. Adam Bourdarios[4], L. Adamczyk[84a], L. Adamek[154], S.V. Addepalli[26], J. Adelman[114], A. Adiguzel[21c], S. Adorni[56], T. Adye[133], A.A. Affolder[135], Y. Afik[36], M.N. Agaras[13], J. Agarwala[72a,72b], A. Aggarwal[99], C. Agheorghiesei[27c], J.A. Aguilar-Saavedra[129f], A. Ahmad[36], F. Ahmadov[38,z], W.S. Ahmed[103], S. Ahuja[94], X. Ai[48], G. Aielli[75a,75b], I. Aizenberg[168], M. Akbiyik[99], T.P.A. Åkesson[97], A.V. Akimov[37], K. Al Khoury[41], G.L. Alberghi[23b], J. Albert[164], P. Albicocco[53], M.J. Alconada Verzini[89], S. Alderweireldt[52], M. Aleksa[36], I.N. Aleksandrov[38], C. Alexa[27b], T. Alexopoulos[10], A. Alfonsi[113], F. Alfonsi[23b], M. Alhroob[119], B. Ali[131], S. Ali[147], M. Aliev[37], G. Alimonti[70a], C. Allaire[36], B.M.M. Allbrooke[145], P.P. Allport[20], A. Aloisio[71a,71b], F. Alonso[89], C. Alpigiani[137], E. Alunno Camelia[75a,75b], M. Alvarez Estevez[98], M.G. Alviggi[71a,71b], Y. Amaral Coutinho[81b], A. Ambler[103], C. Amelung[36], C.G. Ames[108], D. Amidei[105], S.P. Amor Dos Santos[129a], S. Amoroso[48], K.R. Amos[162], C.S. Amrouche[56], V. Ananiev[124], C. Anastopoulos[138], N. Andari[134], T. Andeen[11], J.K. Anders[19], S.Y. Andrean[47a,47b], A. Andreazza[70a,70b], S. Angelidakis[9], A. Angerami[41,ac], A.V. Anisenkov[37], A. Annovi[73a], C. Antel[56], M.T. Anthony[138], E. Antipov[120], M. Antonelli[53], D.J.A. Antrim[17a], F. Anulli[74a], M. Aoki[82], J.A. Aparisi Pozo[162], M.A. Aparo[145], L. Aperio Bella[48], C. Appelt[18], N. Aranzabal[36], V. Araujo Ferraz[81a], C. Arcangeletti[53], A.T.H. Arce[51], E. Arena[91], J-F. Arguin[107], S. Argyropoulos[54], J.-H. Arling[48], A.J. Armbruster[36], O. Arnaez[154], H. Arnold[113], Z.P. Arrubarrena Tame[108], G. Artoni[74a,74b], H. Asada[110], K. Asai[117], S. Asai[152], N.A. Asbah[61], E.M. Asimakopoulou[160], K. Assamagan[29], R. Astalos[28a], R.J. Atkin[33a], M. Atkinson[161], N.B. Atlay[18], H. Atmani[62b], P.A. Atmasiddha[105], K. Augsten[131], S. Auricchio[71a,71b], A.D. Auriol[20], V.A. Austrup[170], G. Avner[149], G. Avolio[36], K. Axiotis[56], M.K. Ayoub[14c], G. Azuelos[107,ag], D. Babal[28a], H. Bachacou[134], K. Bachas[151,s], A. Bachiu[34], F. Backman[47a,47b], A. Badea[61], P. Bagnaia[74a,74b], M. Bahmani[18], A.J. Bailey[162], V.R. Bailey[161], J.T. Baines[133], C. Bakalis[10], O.K. Baker[171], P.J. Bakker[113], E. Bakos[15], D. Bakshi Gupta[8], S. Balaji[146], R. Balasubramanian[113], E.M. Baldin[37], P. Balek[132], E. Ballabene[70a,70b], F. Balli[134], L.M. Baltes[63a], W.K. Balunas[32], J. Balz[99], E. Banas[85], M. Bandieramonte[128], A. Bandyopadhyay[24], S. Bansal[24], L. Barak[150], E.L. Barberio[104], D. Barberis[57b,57a], M. Barbero[101], G. Barbour[95], K.N. Barends[33a], T. Barillari[109], M-S. Barisits[36], J. Barkeloo[122], T. Barklow[142], R.M. Barnett[17a], P. Baron[121], D.A. Baron Moreno[100], A. Baroncelli[62a], G. Barone[29], A.J. Barr[125], L. Barranco Navarro[47a,47b], F. Barreiro[98], J. Barreiro Guimarães da Costa[14a], U. Barron[150], M.G. Barros Teixeira[129a], S. Barsov[37], F. Bartels[63a], R. Bartoldus[142], A.E. Barton[90], P. Bartos[28a], A. Basalaev[48],

A. Basan [99], M. Baselga [49], I. Bashta [76a,76b], A. Bassalat [66,b], M.J. Basso [154], C.R. Basson [100], R.L. Bates [59], S. Batlamous [35e], J.R. Batley [32], B. Batool [140], M. Battaglia [135], M. Bauce [74a,74b], P. Bauer [24], A. Bayirli [21a], J.B. Beacham [51], T. Beau [126], P.H. Beauchemin [157], F. Becherer [54], P. Bechtle [24], H.P. Beck [19,r], K. Becker [166], C. Becot [48], A.J. Beddall [21d], V.A. Bednyakov [38], C.P. Bee [144], L.J. Beemster [15], T.A. Beermann [36], M. Begalli [81b,81d], M. Begel [29], A. Behera [144], J.K. Behr [48], C. Beirao Da Cruz E Silva [36], J.F. Beirer [55,36], F. Beisiegel [24], M. Belfkir [158], G. Bella [150], L. Bellagamba [23b], A. Bellerive [34], P. Bellos [20], K. Beloborodov [37], K. Belotskiy [37], N.L. Belyaev [37], D. Benchekroun [35a], F. Bendebba [35a], Y. Benhammou [150], D.P. Benjamin [29], M. Benoit [29], J.R. Bensinger [26], S. Bentvelsen [113], L. Beresford [36], M. Beretta [53], D. Berge [18], E. Bergeaas Kuutmann [160], N. Berger [4], B. Bergmann [131], J. Beringer [17a], S. Berlendis [7], G. Bernardi [5], C. Bernius [142], F.U. Bernlochner [24], T. Berry [94], P. Berta [132], A. Berthold [50], I.A. Bertram [90], O. Bessidskaia Bylund [170], S. Bethke [109], A. Betti [74a,74b], A.J. Bevan [93], M. Bhamjee [33c], S. Bhatta [144], D.S. Bhattacharya [165], P. Bhattarai [26], V.S. Bhopatkar [6], R. Bi [128], R. Bi [29,aj], R.M. Bianchi [128], O. Biebel [108], R. Bielski [122], N.V. Biesuz [73a,73b], M. Biglietti [76a], T.R.V. Billoud [131], M. Bindi [55], A. Bingul [21b], C. Bini [74a,74b], S. Biondi [23b,23a], A. Biondini [91], C.J. Birch-sykes [100], G.A. Bird [20,133], M. Birman [168], T. Bisanz [36], D. Biswas [169,l], A. Bitadze [100], K. Bjørke [124], I. Bloch [48], C. Blocker [26], A. Blue [59], U. Blumenschein [93], J. Blumenthal [99], G.J. Bobbink [113], V.S. Bobrovnikov [37], M. Boehler [54], D. Bogavac [36], A.G. Bogdanchikov [37], C. Bohm [47a], V. Boisvert [94], P. Bokan [48], T. Bold [84a], M. Bomben [5], M. Bona [93], M. Boonekamp [134], C.D. Booth [94], A.G. Borbély [59], H.M. Borecka-Bielska [107], L.S. Borgna [95], G. Borissov [90], D. Bortoletto [125], D. Boscherini [23b], M. Bosman [13], J.D. Bossio Sola [36], K. Bouaouda [35a], J. Boudreau [128], E.V. Bouhova-Thacker [90], D. Boumediene [40], R. Bouquet [5], A. Boveia [118], J. Boyd [36], D. Boye [29], I.R. Boyko [38], J. Bracinik [20], N. Brahimi [62d,62c], G. Brandt [170], O. Brandt [32], F. Braren [48], B. Brau [102], J.E. Brau [122], W.D. Breaden Madden [59], K. Brendlinger [48], R. Brener [168], L. Brenner [36], R. Brenner [160], S. Bressler [168], B. Brickwedde [99], D. Britton [59], D. Britzger [109], I. Brock [24], G. Brooijmans [41], W.K. Brooks [136f], E. Brost [29], P.A. Bruckman de Renstrom [85], B. Brüers [48], D. Bruncko [28b,*], A. Bruni [23b], G. Bruni [23b], M. Bruschi [23b], N. Bruscino [74a,74b], L. Bryngemark [142], T. Buanes [16], Q. Buat [137], P. Buchholz [140], A.G. Buckley [59], I.A. Budagov [38,*], M.K. Bugge [124], O. Bulekov [37], B.A. Bullard [61], S. Burdin [91], C.D. Burgard [48], A.M. Burger [40], B. Burghgrave [8], J.T.P. Burr [32], C.D. Burton [11], J.C. Burzynski [141], E.L. Busch [41], V. Büscher [99], P.J. Bussey [59], J.M. Butler [25], C.M. Buttar [59], J.M. Butterworth [95], W. Buttinger [133], C.J. Buxo Vazquez [106], A.R. Buzykaev [37], G. Cabras [23b], S. Cabrera Urbán [162], D. Caforio [58], H. Cai [128], Y. Cai [14a,14d], V.M.M. Cairo [36], O. Cakir [3a], N. Calace [36], P. Calafiura [17a], G. Calderini [126], P. Calfayan [67], G. Callea [59], L.P. Caloba [81b], D. Calvet [40], S. Calvet [40], T.P. Calvet [101], M. Calvetti [73a,73b], R. Camacho Toro [126], S. Camarda [36], D. Camarero Munoz [98], P. Camarri [75a,75b], M.T. Camerlingo [76a,76b], D. Cameron [124], C. Camincher [164], M. Campanelli [95], A. Camplani [42], V. Canale [71a,71b], A. Canesse [103], M. Cano Bret [79], J. Cantero [162], Y. Cao [161], F. Capocasa [26], M. Capua [43b,43a], A. Carbone [70a,70b], R. Cardarelli [75a], J.C.J. Cardenas [8], F. Cardillo [162], T. Carli [36], G. Carlino [71a], B.T. Carlson [128,t], E.M. Carlson [164,155a], L. Carminati [70a,70b], M. Carnesale [74a,74b], S. Caron [112], E. Carquin [136f], S. Carrá [70a], G. Carratta [23b,23a], F. Carrio Argos [33g], J.W.S. Carter [154], T.M. Carter [52], M.P. Casado [13,i], A.F. Casha [154], E.G. Castiglia [171], F.L. Castillo [63a], L. Castillo Garcia [13], V. Castillo Gimenez [162], N.F. Castro [129a,129e], A. Catinaccio [36], J.R. Catmore [124],

V. Cavaliere [29], N. Cavalli [23b,23a], V. Cavasinni [73a,73b], E. Celebi [21a], F. Celli [125], M.S. Centonze [69a,69b], K. Cerny [121], A.S. Cerqueira [81a], A. Cerri [145], L. Cerrito [75a,75b], F. Cerutti [17a], A. Cervelli [23b], S.A. Cetin [21d], Z. Chadi [35a], D. Chakraborty [114], M. Chala [129f], J. Chan [169], W.S. Chan [113], W.Y. Chan [152], J.D. Chapman [32], B. Chargeishvili [148b], D.G. Charlton [20], T.P. Charman [93], M. Chatterjee [19], S. Chekanov [6], S.V. Chekulaev [155a], G.A. Chelkov [38,a], A. Chen [105], B. Chen [150], B. Chen [164], C. Chen [62a], H. Chen [14c], H. Chen [29], J. Chen [62c], J. Chen [26], S. Chen [152], S.J. Chen [14c], X. Chen [62c], X. Chen [14b,af], Y. Chen [62a], C.L. Cheng [169], H.C. Cheng [64a], A. Cheplakov [38], E. Cheremushkina [48], E. Cherepanova [113], R. Cherkaoui El Moursli [35e], E. Cheu [7], K. Cheung [65], L. Chevalier [134], V. Chiarella [53], G. Chiarelli [73a], G. Chiodini [69a], A.S. Chisholm [20], A. Chitan [27b], Y.H. Chiu [164], M.V. Chizhov [38], K. Choi [11], A.R. Chomont [74a,74b], Y. Chou [102], E.Y.S. Chow [113], T. Chowdhury [33g], L.D. Christopher [33g], K.L. Chu [64a], M.C. Chu [64a], X. Chu [14a,14d], J. Chudoba [130], J.J. Chwastowski [85], D. Cieri [109], K.M. Ciesla [84a], V. Cindro [92], A. Ciocio [17a], F. Cirotto [71a,71b], Z.H. Citron [168,m], M. Citterio [70a], D.A. Ciubotaru [27b], B.M. Ciungu [154], A. Clark [56], P.J. Clark [52], J.M. Clavijo Columbie [48], S.E. Clawson [100], C. Clement [47a,47b], J. Clercx [48], L. Clissa [23b,23a], Y. Coadou [101], M. Cobal [68a,68c], A. Coccaro [57b], R.F. Coelho Barrue [129a], R. Coelho Lopes De Sa [102], S. Coelli [70a], H. Cohen [150], A.E.C. Coimbra [70a,70b], B. Cole [41], J. Collot [60], P. Conde Muiño [129a,129g], S.H. Connell [33c], I.A. Connelly [59], E.I. Conroy [125], F. Conventi [71a,ah], H.G. Cooke [20], A.M. Cooper-Sarkar [125], F. Cormier [163], L.D. Corpe [36], M. Corradi [74a,74b], E.E. Corrigan [97], F. Corriveau [103,y], A. Cortes-Gonzalez [18], M.J. Costa [162], F. Costanza [4], D. Costanzo [138], B.M. Cote [118], G. Cowan [94], J.W. Cowley [32], K. Cranmer [116], S. Crépé-Renaudin [60], F. Crescioli [126], M. Cristinziani [140], M. Cristoforetti [77a,77b,d], V. Croft [157], G. Crosetti [43b,43a], A. Cueto [36], T. Cuhadar Donszelmann [159], H. Cui [14a,14d], Z. Cui [7], A.R. Cukierman [142], W.R. Cunningham [59], F. Curcio [43b,43a], P. Czodrowski [36], M.M. Czurylo [63b], M.J. Da Cunha Sargedas De Sousa [62a], J.V. Da Fonseca Pinto [81b], C. Da Via [100], W. Dabrowski [84a], T. Dado [49], S. Dahbi [33g], T. Dai [105], C. Dallapiccola [102], M. Dam [42], G. D'amen [29], V. D'Amico [76a,76b], J. Damp [99], J.R. Dandoy [127], M.F. Daneri [30], M. Danninger [141], V. Dao [36], G. Darbo [57b], S. Darmora [6], S.J. Das [29,aj], A. Dattagupta [122], S. D'Auria [70a,70b], C. David [155b], T. Davidek [132], D.R. Davis [51], B. Davis-Purcell [34], I. Dawson [93], K. De [8], R. De Asmundis [71a], M. De Beurs [113], S. De Castro [23b,23a], N. De Groot [112], P. de Jong [113], H. De la Torre [106], A. De Maria [14c], A. De Salvo [74a], U. De Sanctis [75a,75b], M. De Santis [75a,75b], A. De Santo [145], J.B. De Vivie De Regie [60], D.V. Dedovich [38], J. Degens [113], A.M. Deiana [44], F. Del Corso [23b,23a], J. Del Peso [98], F. Del Rio [63a], F. Deliot [134], C.M. Delitzsch [49], M. Della Pietra [71a,71b], D. Della Volpe [56], A. Dell'Acqua [36], L. Dell'Asta [70a,70b], M. Delmastro [4], P.A. Delsart [60], S. Demers [171], M. Demichev [38], S.P. Denisov [37], L. D'Eramo [114], D. Derendarz [85], F. Derue [126], P. Dervan [91], K. Desch [24], K. Dette [154], C. Deutsch [24], P.O. Deviveiros [36], F.A. Di Bello [74a,74b], A. Di Ciaccio [75a,75b], L. Di Ciaccio [4], A. Di Domenico [74a,74b], C. Di Donato [71a,71b], A. Di Girolamo [36], G. Di Gregorio [73a,73b], A. Di Luca [77a,77b], B. Di Micco [76a,76b], R. Di Nardo [76a,76b], C. Diaconu [101], F.A. Dias [113], T. Dias Do Vale [141], M.A. Diaz [136a,136b], F.G. Diaz Capriles [24], M. Didenko [162], E.B. Diehl [105], L. Diehl [54], S. Díez Cornell [48], C. Diez Pardos [140], C. Dimitriadi [24,160], A. Dimitrievska [17a], W. Ding [14b], J. Dingfelder [24], I-M. Dinu [27b], S.J. Dittmeier [63b], F. Dittus [36], F. Djama [101], T. Djobava [148b], J.I. Djuvsland [16], D. Dodsworth [26], C. Doglioni [100,97], J. Dolejsi [132], Z. Dolezal [132], M. Donadelli [81c], B. Dong [62c], J. Donini [40], A. D'Onofrio [14c], M. D'Onofrio [91], J. Dopke [133], A. Doria [71a], M.T. Dova [89], A.T. Doyle [59], M.A. Draguet [125], E. Drechsler [141], E. Dreyer [168], I. Drivas-koulouris [10], A.S. Drobac [157], D. Du [62a], T.A. du Pree [113], F. Dubinin [37],

M. Dubovsky [28a], E. Duchovni [168], G. Duckeck [108], O.A. Ducu [36], D. Duda [109], A. Dudarev [36], M. D'uffizi [100], L. Duflot [66], M. Dührssen [36], C. Dülsen [170], A.E. Dumitriu [27b], M. Dunford [63a], S. Dungs [49], K. Dunne [47a,47b], A. Duperrin [101], H. Duran Yildiz [3a], M. Düren [58], A. Durglishvili [148b], B.L. Dwyer [114], G.I. Dyckes [17a], M. Dyndal [84a], S. Dysch [100], B.S. Dziedzic [85], Z.O. Earnshaw [145], B. Eckerova [28a], M.G. Eggleston [51], E. Egidio Purcino De Souza [81b], L.F. Ehrke [56], G. Eigen [16], K. Einsweiler [17a], T. Ekelof [160], P.A. Ekman [97], Y. El Ghazali [35b], H. El Jarrari [35e,147], A. El Moussaouy [35a], V. Ellajosyula [160], M. Ellert [160], F. Ellinghaus [170], A.A. Elliot [93], N. Ellis [36], J. Elmsheuser [29], M. Elsing [36], D. Emeliyanov [133], A. Emerman [41], Y. Enari [152], I. Ene [17a], S. Epari [13], J. Erdmann [49], A. Ereditato [19], P.A. Erland [85], M. Errenst [170], M. Escalier [66], C. Escobar [162], E. Etzion [150], G. Evans [129a], H. Evans [67], M.O. Evans [145], A. Ezhilov [37], S. Ezzarqtouni [35a], F. Fabbri [59], L. Fabbri [23b,23a], G. Facini [95], V. Fadeyev [135], R.M. Fakhrutdinov [37], S. Falciano [74a], L.F. Falda Ulhoa Coelho [36], P.J. Falke [24], S. Falke [36], J. Faltova [132], Y. Fan [14a], Y. Fang [14a,14d], G. Fanourakis [46], M. Fanti [70a,70b], M. Faraj [68a,68b], A. Farbin [8], A. Farilla [76a], T. Farooque [106], S.M. Farrington [52], F. Fassi [35e], D. Fassouliotis [9], M. Faucci Giannelli [75a,75b], W.J. Fawcett [32], L. Fayard [66], O.L. Fedin [37,a], G. Fedotov [37], M. Feickert [161], L. Feligioni [101], A. Fell [138], D.E. Fellers [122], C. Feng [62b], M. Feng [14b], M.J. Fenton [159], A.B. Fenyuk [37], L. Ferencz [48], S.W. Ferguson [45], J. Ferrando [48], A. Ferrari [160], P. Ferrari [113], R. Ferrari [72a], D. Ferrere [56], C. Ferretti [105], F. Fiedler [99], A. Filipčič [92], E.K. Filmer [1], F. Filthaut [112], M.C.N. Fiolhais [129a,129c,c], L. Fiorini [162], F. Fischer [140], W.C. Fisher [106], T. Fitschen [20,66], I. Fleck [140], P. Fleischmann [105], T. Flick [170], L. Flores [127], M. Flores [33d,ad], L.R. Flores Castillo [64a], F.M. Follega [77a,77b], N. Fomin [16], J.H. Foo [154], B.C. Forland [67], A. Formica [134], A.C. Forti [100], E. Fortin [101], A.W. Fortman [61], M.G. Foti [17a], L. Fountas [9,j], D. Fournier [66], H. Fox [90], P. Francavilla [73a,73b], S. Francescato [61], M. Franchini [23b,23a], S. Franchino [63a], D. Francis [36], L. Franco [112], L. Franconi [19], M. Franklin [61], G. Frattari [26], A.C. Freegard [93], P.M. Freeman [20], W.S. Freund [81b], N. Fritzsche [50], A. Froch [54], D. Froidevaux [36], J.A. Frost [125], Y. Fu [62a], M. Fujimoto [117], E. Fullana Torregrosa [162,*], J. Fuster [162], A. Gabrielli [23b,23a], A. Gabrielli [36], P. Gadow [48], G. Gagliardi [57b,57a], L.G. Gagnon [17a], G.E. Gallardo [125], E.J. Gallas [125], B.J. Gallop [133], R. Gamboa Goni [93], K.K. Gan [118], S. Ganguly [152], J. Gao [62a], Y. Gao [52], F.M. Garay Walls [136a,136b], B. Garcia [29], C. García [162], J.E. García Navarro [162], J.A. García Pascual [14a], M. Garcia-Sciveres [17a], R.W. Gardner [39], D. Garg [79], R.B. Garg [142,q], S. Gargiulo [54], C.A. Garner [154], V. Garonne [29], S.J. Gasiorowski [137], P. Gaspar [81b], G. Gaudio [72a], V. Gautam [13], P. Gauzzi [74a,74b], I.L. Gavrilenko [37], A. Gavrilyuk [37], C. Gay [163], G. Gaycken [48], E.N. Gazis [10], A.A. Geanta [27b], C.M. Gee [135], J. Geisen [97], M. Geisen [99], C. Gemme [57b], M.H. Genest [60], S. Gentile [74a,74b], S. George [94], W.F. George [20], T. Geralis [46], L.O. Gerlach [55], P. Gessinger-Befurt [36], M. Ghasemi Bostanabad [164], M. Ghneimat [140], A. Ghosal [140], A. Ghosh [159], A. Ghosh [7], B. Giacobbe [23b], S. Giagu [74a,74b], N. Giangiacomi [154], P. Giannetti [73a], A. Giannini [62a], S.M. Gibson [94], M. Gignac [135], D.T. Gil [84b], A.K. Gilbert [84a], B.J. Gilbert [41], D. Gillberg [34], G. Gilles [113], N.E.K. Gillwald [48], L. Ginabat [126], D.M. Gingrich [2,ag], M.P. Giordani [68a,68c], P.F. Giraud [134], G. Giugliarelli [68a,68c], D. Giugni [70a], F. Giuli [36], I. Gkialas [9,j], L.K. Gladilin [37], C. Glasman [98], G.R. Gledhill [122], M. Glisic [122], I. Gnesi [43b,f], Y. Go [29,aj], M. Goblirsch-Kolb [26], D. Godin [107], S. Goldfarb [104], T. Golling [56], M.G.D. Gololo [33g], D. Golubkov [37], J.P. Gombas [106], A. Gomes [129a,129b], G. Gomes Da Silva [140], A.J. Gomez Delegido [162], R. Goncalves Gama [55], R. Gonçalo [129a,129c], G. Gonella [122], L. Gonella [20], A. Gongadze [38], F. Gonnella [20], J.L. Gonski [41], R.Y. González Andana [52], S. González de la Hoz [162], S. Gonzalez Fernandez [13], R. Gonzalez Lopez [91], C. Gonzalez Renteria [17a], R. Gonzalez Suarez [160], S. Gonzalez-Sevilla [56], G.R. Gonzalvo Rodriguez [162], L. Goossens [36], N.A. Gorasia [20], P.A. Gorbounov [37], B. Gorini [36], E. Gorini [69a,69b], A. Gorišek [92], A.T. Goshaw [51], M.I. Gostkin [38], C.A. Gottardo [112], M. Gouighri [35b], V. Goumarre [48], A.G. Goussiou [137], N. Govender [33c], C. Goy [4], I. Grabowska-Bold [84a], K. Graham [34], E. Gramstad [124], S. Grancagnolo [18], M. Grandi [145], V. Gratchev [37,*], P.M. Gravila [27f], F.G. Gravili [69a,69b], H.M. Gray [17a], M. Greco [69a,69b], C. Grefe [24], I.M. Gregor [48], P. Grenier [142], C. Grieco [13], A.A. Grillo [135], K. Grimm [31,n], S. Grinstein [13,v], J.-F. Grivaz [66], E. Gross [168], J. Grosse-Knetter [55], C. Grud [105], A. Grummer [111], J.C. Grundy [125], L. Guan [105], W. Guan [169], C. Gubbels [163], J.G.R. Guerrero Rojas [162], G. Guerrieri [68a,68c], F. Guescini [109], R. Gugel [99], J.A.M. Guhit [105], A. Guida [48], T. Guillemin [4], E. Guilloton [166,133], S. Guindon [36], F. Guo [14a,14d], J. Guo [62c], L. Guo [66], Y. Guo [105], R. Gupta [48], S. Gurbuz [24], S.S. Gurdasani [54], G. Gustavino [36], M. Guth [56], P. Gutierrez [119], L.F. Gutierrez Zagazeta [127], C. Gutschow [95], C. Guyot [134], C. Gwenlan [125], C.B. Gwilliam [91], E.S. Haaland [124], A. Haas [116], M. Habedank [48], C. Haber [17a], H.K. Hadavand [8], A. Hadef [99], S. Hadzic [109], M. Haleem [165], J. Haley [120], J.J. Hall [138], G.D. Hallewell [101], L. Halser [19], K. Hamano [164], H. Hamdaoui [35e], M. Hamer [24], G.N. Hamity [52], J. Han [62b], K. Han [62a], L. Han [14c], L. Han [62a], S. Han [17a], Y.F. Han [154], K. Hanagaki [82], M. Hance [135], D.A. Hangal [41,ac], M.D. Hank [39], R. Hankache [100], J.B. Hansen [42], J.D. Hansen [42], P.H. Hansen [42], K. Hara [156], D. Harada [56], T. Harenberg [170], S. Harkusha [37], Y.T. Harris [125], N.M. Harrison [118], P.F. Harrison [166], N.M. Hartman [142], N.M. Hartmann [108], Y. Hasegawa [139], A. Hasib [52], S. Haug [19], R. Hauser [106], M. Havranek [131], C.M. Hawkes [20], R.J. Hawkings [36], S. Hayashida [110], D. Hayden [106], C. Hayes [105], R.L. Hayes [163], C.P. Hays [125], J.M. Hays [93], H.S. Hayward [91], F. He [62a], Y. He [153], Y. He [126], M.P. Heath [52], V. Hedberg [97], A.L. Heggelund [124], N.D. Hehir [93,*], C. Heidegger [54], K.K. Heidegger [54], W.D. Heidorn [80], J. Heilman [34], S. Heim [48], T. Heim [17a], J.G. Heinlein [127], J.J. Heinrich [122], L. Heinrich [36], J. Hejbal [130], L. Helary [48], A. Held [116], S. Hellesund [124], C.M. Helling [163], S. Hellman [47a,47b], C. Helsens [36], R.C.W. Henderson [90], L. Henkelmann [32], A.M. Henriques Correia [36], H. Herde [142], Y. Hernández Jiménez [144], H. Herr [99], M.G. Herrmann [108], T. Herrmann [50], G. Herten [54], R. Hertenberger [108], L. Hervas [36], N.P. Hessey [155a], H. Hibi [83], E. Higón-Rodriguez [162], S.J. Hillier [20], I. Hinchliffe [17a], F. Hinterkeuser [24], M. Hirose [123], S. Hirose [156], D. Hirschbuehl [170], T.G. Hitchings [100], B. Hiti [92], J. Hobbs [144], R. Hobincu [27e], N. Hod [168], M.C. Hodgkinson [138], B.H. Hodkinson [32], A. Hoecker [36], J. Hofer [48], D. Hohn [54], T. Holm [24], M. Holzbock [109], L.B.A.H. Hommels [32], B.P. Honan [100], J. Hong [62c], T.M. Hong [128], Y. Hong [55], J.C. Honig [54], A. Hönle [109], B.H. Hooberman [161], W.H. Hopkins [6], Y. Horii [110], S. Hou [147], A.S. Howard [92], J. Howarth [59], J. Hoya [89], M. Hrabovsky [121], A. Hrynevich [37], T. Hryn'ova [4], P.J. Hsu [65], S.-C. Hsu [137], Q. Hu [41,ac], Y.F. Hu [14a,14d,ai], D.P. Huang [95], S. Huang [64b], X. Huang [14c], Y. Huang [62a], Y. Huang [14a], Z. Huang [100], Z. Hubacek [131], M. Huebner [24], F. Huegging [24], T.B. Huffman [125], M. Huhtinen [36], S.K. Huiberts [16], R. Hulsken [103], N. Huseynov [12,a], J. Huston [106], J. Huth [61], R. Hyneman [142], S. Hyrych [28a], G. Iacobucci [56], G. Iakovidis [29], I. Ibragimov [140], L. Iconomidou-Fayard [66], P. Iengo [71a,71b], R. Iguchi [152], T. Iizawa [56], Y. Ikegami [82], A. Ilg [19], N. Ilic [154], H. Imam [35a], T. Ingebretsen Carlson [47a,47b], G. Introzzi [72a,72b], M. Iodice [76a], V. Ippolito [74a,74b], M. Ishino [152], W. Islam [169], C. Issever [18,48], S. Istin [21a,ak], H. Ito [167], J.M. Iturbe Ponce [64a], R. Iuppa [77a,77b], A. Ivina [168], J.M. Izen [45],

V. Izzo [71a], P. Jacka [130,131], P. Jackson [1], R.M. Jacobs [48], B.P. Jaeger [141], C.S. Jagfeld [108], G. Jäkel [170], K. Jakobs [54], T. Jakoubek [168], J. Jamieson [59], K.W. Janas [84a], G. Jarlskog [97], A.E. Jaspan [91], T. Javůrek [36], M. Javurkova [102], F. Jeanneau [134], L. Jeanty [122], J. Jejelava [148a,aa], P. Jenni [54,g], C.E. Jessiman [34], S. Jézéquel [4], J. Jia [144], X. Jia [61], X. Jia [14a,14d], Z. Jia [14c], Y. Jiang [62a], S. Jiggins [52], J. Jimenez Pena [109], S. Jin [14c], A. Jinaru [27b], O. Jinnouchi [153], H. Jivan [33g], P. Johansson [138], K.A. Johns [7], C.A. Johnson [67], D.M. Jones [32], E. Jones [166], P. Jones [32], R.W.L. Jones [90], T.J. Jones [91], J. Jovicevic [15], X. Ju [17a], J.J. Junggeburth [36], A. Juste Rozas [13,v], S. Kabana [136e], A. Kaczmarska [85], M. Kado [74a,74b], H. Kagan [118], M. Kagan [142], A. Kahn [41], A. Kahn [127], C. Kahra [99], T. Kaji [167], E. Kajomovitz [149], N. Kakati [168], C.W. Kalderon [29], A. Kamenshchikov [154], N.J. Kang [135], Y. Kano [110], D. Kar [33g], K. Karava [125], M.J. Kareem [155b], E. Karentzos [54], I. Karkanias [151], S.N. Karpov [38], Z.M. Karpova [38], V. Kartvelishvili [90], A.N. Karyukhin [37], E. Kasimi [151], C. Kato [62d], J. Katzy [48], S. Kaur [34], K. Kawade [139], K. Kawagoe [88], T. Kawaguchi [110], T. Kawamoto [134], G. Kawamura [55], E.F. Kay [164], F.I. Kaya [157], S. Kazakos [13], V.F. Kazanin [37], Y. Ke [144], J.M. Keaveney [33a], R. Keeler [164], G.V. Kehris [61], J.S. Keller [34], A.S. Kelly [95], D. Kelsey [145], J.J. Kempster [20], J. Kendrick [20], K.E. Kennedy [41], O. Kepka [130], B.P. Kerridge [166], S. Kersten [170], B.P. Kerševan [92], L. Keszeghova [28a], S. Ketabchi Haghighat [154], M. Khandoga [126], A. Khanov [120], A.G. Kharlamov [37], T. Kharlamova [37], E.E. Khoda [137], T.J. Khoo [18], G. Khoriauli [165], J. Khubua [148b], Y.A.R. Khwaira [66], M. Kiehn [36], A. Kilgallon [122], D.W. Kim [47a,47b], E. Kim [153], Y.K. Kim [39], N. Kimura [95], A. Kirchhoff [55], D. Kirchmeier [50], C. Kirfel [24], J. Kirk [133], A.E. Kiryunin [109], T. Kishimoto [152], D.P. Kisliuk [154], C. Kitsaki [10], O. Kivernyk [24], M. Klassen [63a], C. Klein [34], L. Klein [165], M.H. Klein [105], M. Klein [91], U. Klein [91], P. Klimek [36], A. Klimentov [29], F. Klimpel [109], T. Klingl [24], T. Klioutchnikova [36], F.F. Klitzner [108], P. Kluit [113], S. Kluth [109], E. Kneringer [78], T.M. Knight [154], A. Knue [54], D. Kobayashi [88], R. Kobayashi [86], M. Kocian [142], T. Kodama [152], P. Kodyš [132], D.M. Koeck [145], P.T. Koenig [24], T. Koffas [34], N.M. Köhler [36], M. Kolb [134], I. Koletsou [4], T. Komarek [121], K. Köneke [54], A.X.Y. Kong [1], T. Kono [117], N. Konstantinidis [95], B. Konya [97], R. Kopeliansky [67], S. Koperny [84a], K. Korcyl [85], K. Kordas [151], G. Koren [150], A. Korn [95], S. Korn [55], I. Korolkov [13], N. Korotkova [37], B. Kortman [113], O. Kortner [109], S. Kortner [109], W.H. Kostecka [114], V.V. Kostyukhin [140], A. Kotsokechagia [66], A. Kotwal [51], A. Koulouris [36], A. Kourkoumeli-Charalampidi [72a,72b], C. Kourkoumelis [9], E. Kourlitis [6], O. Kovanda [145], R. Kowalewski [164], W. Kozanecki [134], A.S. Kozhin [37], V.A. Kramarenko [37], G. Kramberger [92], P. Kramer [99], M.W. Krasny [126], A. Krasznahorkay [36], J.A. Kremer [99], T. Kresse [50], J. Kretzschmar [91], K. Kreul [18], P. Krieger [154], F. Krieter [108], S. Krishnamurthy [102], A. Krishnan [63b], M. Krivos [132], K. Krizka [17a], K. Kroeninger [49], H. Kroha [109], J. Kroll [130], J. Kroll [127], K.S. Krowpman [106], U. Kruchonak [38], H. Krüger [24], N. Krumnack [80], M.C. Kruse [51], J.A. Krzysiak [85], A. Kubota [153], O. Kuchinskaia [37], S. Kuday [3a], D. Kuechler [48], J.T. Kuechler [48], S. Kuehn [36], T. Kuhl [48], V. Kukhtin [38], Y. Kulchitsky [37,a], S. Kuleshov [136d,136b], M. Kumar [33g], N. Kumari [101], M. Kuna [60], A. Kupco [130], T. Kupfer [49], A. Kupich [37], O. Kuprash [54], H. Kurashige [83], L.L. Kurchaninov [155a], Y.A. Kurochkin [37], A. Kurova [37], E.S. Kuwertz [36], M. Kuze [153], A.K. Kvam [102], J. Kvita [121], T. Kwan [103], K.W. Kwok [64a], C. Lacasta [162], F. Lacava [74a,74b], H. Lacker [18], D. Lacour [126], N.N. Lad [95], E. Ladygin [38], B. Laforge [126], T. Lagouri [136e], S. Lai [55], I.K. Lakomiec [84a], N. Lalloue [60], J.E. Lambert [119], S. Lammers [67], W. Lampl [7], C. Lampoudis [151], A.N. Lancaster [114],

E. Lançon [29], U. Landgraf [54], M.P.J. Landon [93], V.S. Lang [54], R.J. Langenberg [102], A.J. Lankford [159], F. Lanni [29], K. Lantzsch [24], A. Lanza [72a], A. Lapertosa [57b,57a], J.F. Laporte [134], T. Lari [70a], F. Lasagni Manghi [23b], M. Lassnig [36], V. Latonova [130], T.S. Lau [64a], A. Laudrain [99], A. Laurier [34], S.D. Lawlor [94], Z. Lawrence [100], M. Lazzaroni [70a,70b], B. Le [100], B. Leban [92], A. Lebedev [80], M. LeBlanc [36], T. LeCompte [6], F. Ledroit-Guillon [60], A.C.A. Lee [95], G.R. Lee [16], L. Lee [61], S.C. Lee [147], S. Lee [47a,47b], L.L. Leeuw [33c], H.P. Lefebvre [94], M. Lefebvre [164], C. Leggett [17a], K. Lehmann [141], G. Lehmann Miotto [36], W.A. Leight [102], A. Leisos [151,u], M.A.L. Leite [81c], C.E. Leitgeb [48], R. Leitner [132], K.J.C. Leney [44], T. Lenz [24], S. Leone [73a], C. Leonidopoulos [52], A. Leopold [143], C. Leroy [107], R. Les [106], C.G. Lester [32], M. Levchenko [37], J. Levêque [4], D. Levin [105], L.J. Levinson [168], D.J. Lewis [20], B. Li [14b], B. Li [62b], C. Li [62a], C-Q. Li [62c,62d], H. Li [62a], H. Li [62b], H. Li [14c], H. Li [62b], J. Li [62c], K. Li [137], L. Li [62c], M. Li [14a,14d], Q.Y. Li [62a], S. Li [62d,62c,e], T. Li [62b], X. Li [103], Z. Li [62b], Z. Li [125], Z. Li [103], Z. Li [91], Z. Liang [14a], M. Liberatore [48], B. Liberti [75a], K. Lie [64c], J. Lieber Marin [81b], K. Lin [106], R.A. Linck [67], R.E. Lindley [7], J.H. Lindon [2], A. Linss [48], E. Lipeles [127], A. Lipniacka [16], T.M. Liss [161,ae], A. Lister [163], J.D. Little [4], B. Liu [14a], B.X. Liu [141], 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,137,62c], X. Liu [62a], Y. Liu [48], Y. Liu [14c,14d], Y.L. Liu [105], Y.W. Liu [62a], M. Livan [72a,72b], J. Llorente Merino [141], S.L. Lloyd [93], E.M. Lobodzinska [48], P. Loch [7], S. Loffredo [75a,75b], T. Lohse [18], K. Lohwasser [138], M. Lokajicek [130,*], J.D. Long [161], I. Longarini [74a,74b], L. Longo [69a,69b], R. Longo [161], I. Lopez Paz [36], A. Lopez Solis [48], J. Lorenz [108], N. Lorenzo Martinez [4], A.M. Lory [108], A. Lösle [54], X. Lou [47a,47b], X. Lou [14a,14d], A. Lounis [66], J. Love [6], P.A. Love [90], J.J. Lozano Bahilo [162], G. Lu [14a,14d], M. Lu [79], S. Lu [127], Y.J. Lu [65], H.J. Lubatti [137], C. Luci [74a,74b], F.L. Lucio Alves [14c], A. Lucotte [60], F. Luehring [67], I. Luise [144], O. Lukianchuk [66], O. Lundberg [143], B. Lund-Jensen [143], N.A. Luongo [122], M.S. Lutz [150], D. Lynn [29], H. Lyons [91], R. Lysak [130], E. Lytken [97], F. Lyu [14a], V. Lyubushkin [38], T. Lyubushkina [38], H. Ma [29], L.L. Ma [62b], Y. Ma [95], D.M. Mac Donell [164], G. Maccarrone [53], J.C. MacDonald [138], R. Madar [40], W.F. Mader [50], J. Maeda [83], T. Maeno [29], M. Maerker [50], V. Magerl [54], J. Magro [68a,68c], H. Maguire [138], D.J. Mahon [41], C. Maidantchik [81b], A. Maio [129a,129b,129d], K. Maj [84a], O. Majersky [28a], S. Majewski [122], N. Makovec [66], V. Maksimovic [15], B. Malaescu [126], Pa. Malecki [85], V.P. Maleev [37], F. Malek [60], D. Malito [43b,43a], U. Mallik [79], C. Malone [32], S. Maltezos [10], S. Malyukov [38], J. Mamuzic [13], G. Mancini [53], G. Manco [72a,72b], J.P. Mandalia [93], I. Mandić [92], L. Manhaes de Andrade Filho [81a], I.M. Maniatis [151], M. Manisha [134], J. Manjarres Ramos [50], D.C. Mankad [168], K.H. Mankinen [97], A. Mann [108], A. Manousos [78], B. Mansoulie [134], S. Manzoni [36], A. Marantis [151,u], G. Marchiori [5], M. Marcisovsky [130], L. Marcoccia [75a,75b], C. Marcon [97], M. Marinescu [20], M. Marjanovic [119], Z. Marshall [17a], S. Marti-Garcia [162], T.A. Martin [166], V.J. Martin [52], B. Martin dit Latour [16], L. Martinelli [74a,74b], M. Martinez [13,v], P. Martinez Agullo [162], V.I. Martinez Outschoorn [102], P. Martinez Suarez [13], S. Martin-Haugh [133], V.S. Martoiu [27b], A.C. Martyniuk [95], A. Marzin [36], S.R. Maschek [109], L. Masetti [99], T. Mashimo [152], J. Masik [100], A.L. Maslennikov [37], L. Massa [23b], P. Massarotti [71a,71b], P. Mastrandrea [73a,73b], A. Mastroberardino [43b,43a], T. Masubuchi [152], T. Mathisen [160], A. Matic [108], N. Matsuzawa [152], J. Maurer [27b], B. Maček [92], D.A. Maximov [37], R. Mazini [147], I. Maznas [151], M. Mazza [106], S.M. Mazza [135], C. Mc Ginn [29], J.P. Mc Gowan [103], S.P. Mc Kee [105], T.G. McCarthy [109], W.P. McCormack [17a], E.F. McDonald [104], A.E. McDougall [113], J.A. Mcfayden [145], G. Mchedlidze [148b], R.P. Mckenzie [33g], T.C. Mclachlan [48], D.J. Mclaughlin [95], K.D. McLean [164], S.J. McMahon [133], P.C. McNamara [104], R.A. McPherson [164,y], J.E. Mdhluli [33g], S. Meehan [36],

T. Megy[40], S. Mehlhase[108], A. Mehta[91], B. Meirose[45], D. Melini[149], B.R. Mellado Garcia[33g], A.H. Melo[55], F. Meloni[48], E.D. Mendes Gouveia[129a], A.M. Mendes Jacques Da Costa[20], H.Y. Meng[154], L. Meng[90], S. Menke[109], M. Mentink[36], E. Meoni[43b,43a], C. Merlassino[125], L. Merola[71a,71b], C. Meroni[70a,70b], G. Merz[105], O. Meshkov[37], J.K.R. Meshreki[140], J. Metcalfe[6], A.S. Mete[6], C. Meyer[67], J-P. Meyer[134], M. Michetti[18], R.P. Middleton[133], L. Mijović[52], G. Mikenberg[168], M. Mikestikova[130], M. Mikuž[92], H. Mildner[138], A. Milic[154], C.D. Milke[44], D.W. Miller[39], L.S. Miller[34], A. Milov[168], D.A. Milstead[47a,47b], T. Min[14c], A.A. Minaenko[37], I.A. Minashvili[148b], L. Mince[59], A.I. Mincer[116], B. Mindur[84a], M. Mineev[38], Y. Minegishi[152], Y. Mino[86], L.M. Mir[13], M. Miralles Lopez[162], M. Mironova[125], T. Mitani[167], A. Mitra[166], V.A. Mitsou[162], O. Miu[154], P.S. Miyagawa[93], Y. Miyazaki[88], A. Mizukami[82], J.U. Mjörnmark[97], T. Mkrtchyan[63a], M. Mlynarikova[114], T. Moa[47a,47b], S. Mobius[55], K. Mochizuki[107], P. Moder[48], P. Mogg[108], A.F. Mohammed[14a,14d], S. Mohapatra[41], G. Mokgatitswane[33g], B. Mondal[140], S. Mondal[131], K. Mönig[48], E. Monnier[101], L. Monsonis Romero[162], J. Montejo Berlingen[36], M. Montella[118], F. Monticelli[89], N. Morange[66], A.L. Moreira De Carvalho[129a], M. Moreno Llácer[162], C. Moreno Martinez[13], P. Morettini[57b], S. Morgenstern[166], M. Morii[61], M. Morinaga[152], V. Morisbak[124], A.K. Morley[36], F. Morodei[74a,74b], L. Morvaj[36], P. Moschovakos[36], B. Moser[36], M. Mosidze[148b], T. Moskalets[54], P. Moskvitina[112], J. Moss[31,o], E.J.W. Moyse[102], S. Muanza[101], J. Mueller[128], D. Muenstermann[90], R. Müller[19], G.A. Mullier[97], J.J. Mullin[127], D.P. Mungo[70a,70b], J.L. Munoz Martinez[13], D. Munoz Perez[162], F.J. Munoz Sanchez[100], M. Murin[100], W.J. Murray[166,133], A. Murrone[70a,70b], J.M. Muse[119], M. Muškinja[17a], C. Mwewa[29], A.G. Myagkov[37,a], A.J. Myers[8], A.A. Myers[128], G. Myers[67], M. Myska[131], B.P. Nachman[17a], O. Nackenhorst[49], A. Nag[50], K. Nagai[125], K. Nagano[82], J.L. Nagle[29,aj], E. Nagy[101], A.M. Nairz[36], Y. Nakahama[82], K. Nakamura[82], H. Nanjo[123], R. Narayan[44], E.A. Narayanan[111], I. Naryshkin[37], M. Naseri[34], C. Nass[24], G. Navarro[22a], J. Navarro-Gonzalez[162], R. Nayak[150], P.Y. Nechaeva[37], F. Nechansky[48], T.J. Neep[20], A. Negri[72a,72b], M. Negrini[23b], C. Nellist[112], C. Nelson[103], K. Nelson[105], S. Nemecek[130], M. Nessi[36,h], M.S. Neubauer[161], F. Neuhaus[99], J. Neundorf[48], R. Newhouse[163], P.R. Newman[20], C.W. Ng[128], Y.S. Ng[18], Y.W.Y. Ng[159], B. Ngair[35e], H.D.N. Nguyen[107], R.B. Nickerson[125], R. Nicolaidou[134], J. Nielsen[135], M. Niemeyer[55], N. Nikiforou[36], V. Nikolaenko[37,a], I. Nikolic-Audit[126], K. Nikolopoulos[20], P. Nilsson[29], H.R. Nindhito[56], A. Nisati[74a], N. Nishu[2], R. Nisius[109], J-E. Nitschke[50], E.K. Nkadimeng[33g], S.J. Noacco Rosende[89], T. Nobe[152], D.L. Noel[32], Y. Noguchi[86], T. Nommensen[146], M.A. Nomura[29], M.B. Norfolk[138], R.R.B. Norisam[95], B.J. Norman[34], J. Novak[92], T. Novak[48], O. Novgorodova[50], L. Novotny[131], R. Novotny[111], L. Nozka[121], K. Ntekas[159], E. Nurse[95], F.G. Oakham[34,ag], J. Ocariz[126], A. Ochi[83], I. Ochoa[129a], S. Oda[88], S. Oerdek[160], A. Ogrodnik[84a], A. Oh[100], C.C. Ohm[143], H. Oide[153], R. Oishi[152], M.L. Ojeda[48], Y. Okazaki[86], M.W. O'Keefe[91], Y. Okumura[152], A. Olariu[27b], L.F. Oleiro Seabra[129a], S.A. Olivares Pino[136e], D. Oliveira Damazio[29], D. Oliveira Goncalves[81a], J.L. Oliver[159], M.J.R. Olsson[159], A. Olszewski[85], J. Olszowska[85,*], Ö.O. Öncel[54], D.C. O'Neil[141], A.P. O'Neill[19], A. Onofre[129a,129e], P.U.E. Onyisi[11], M.J. Oreglia[39], G.E. Orellana[89], D. Orestano[76a,76b], N. Orlando[13], R.S. Orr[154], V. O'Shea[59], R. Ospanov[62a], G. Otero y Garzon[30], H. Otono[88], P.S. Ott[63a], G.J. Ottino[17a], M. Ouchrif[35d], J. Ouellette[29,aj], F. Ould-Saada[124], M. Owen[59], R.E. Owen[133], K.Y. Oyulmaz[21a], V.E. Ozcan[21a], N. Ozturk[8], S. Ozturk[21d], J. Pacalt[121], H.A. Pacey[32], A. Pacheco Pages[13], C. Padilla Aranda[13],

G. Padovano [74a,74b], S. Pagan Griso [17a], G. Palacino [67], A. Palazzo [69a,69b], S. Palazzo [52], S. Palestini [36], M. Palka [84b], J. Pan [171], T. Pan [64a], D.K. Panchal [11], C.E. Pandini [113], J.G. Panduro Vazquez [94], H. Pang [14b], P. Pani [48], G. Panizzo [68a,68c], L. Paolozzi [56], C. Papadatos [107], S. Parajuli [44], A. Paramonov [6], C. Paraskevopoulos [10], D. Paredes Hernandez [64b], T.H. Park [154], M.A. Parker [32], F. Parodi [57b,57a], E.W. Parrish [114], V.A. Parrish [52], J.A. Parsons [41], U. Parzefall [54], B. Pascual Dias [107], L. Pascual Dominguez [150], V.R. Pascuzzi [17a], F. Pasquali [113], E. Pasqualucci [74a], S. Passaggio [57b], F. Pastore [94], P. Pasuwan [47a,47b], J.R. Pater [100], J. Patton [91], T. Pauly [36], J. Pearkes [142], M. Pedersen [124], R. Pedro [129a], S.V. Peleganchuk [37], O. Penc [130], C. Peng [64b], H. Peng [62a], M. Penzin [37], B.S. Peralva [81a,81d], A.P. Pereira Peixoto [60], L. Pereira Sanchez [47a,47b], D.V. Perepelitsa [29,aj], E. Perez Codina [155a], M. Perganti [10], L. Perini [70a,70b,*], H. Pernegger [36], A. Perrevoort [112], O. Perrin [40], K. Peters [48], R.F.Y. Peters [100], B.A. Petersen [36], T.C. Petersen [42], E. Petit [101], V. Petousis [131], C. Petridou [151], A. Petrukhin [140], M. Pettee [17a], N.E. Pettersson [36], A. Petukhov [37], K. Petukhova [132], A. Peyaud [134], R. Pezoa [136f], L. Pezzotti [36], G. Pezzullo [171], T. Pham [104], P.W. Phillips [133], M.W. Phipps [161], G. Piacquadio [144], E. Pianori [17a], F. Piazza [70a,70b], R. Piegaia [30], D. Pietreanu [27b], A.D. Pilkington [100], M. Pinamonti [68a,68c], J.L. Pinfold [2], B.C. Pinheiro Pereira [129a], C. Pitman Donaldson [95], D.A. Pizzi [34], L. Pizzimento [75a,75b], A. Pizzini [113], M.-A. Pleier [29], V. Plesanovs [54], V. Pleskot [132], E. Plotnikova [38], G. Poddar [4], R. Poettgen [97], R. Poggi [56], L. Poggioli [126], I. Pogrebnyak [106], D. Pohl [24], I. Pokharel [55], S. Polacek [132], G. Polesello [72a], A. Poley [141,155a], R. Polifka [131], A. Polini [23b], C.S. Pollard [125], Z.B. Pollock [118], V. Polychronakos [29], D. Ponomarenko [37], L. Pontecorvo [36], S. Popa [27a], G.A. Popeneciu [27d], D.M. Portillo Quintero [155a], S. Pospisil [131], P. Postolache [27c], K. Potamianos [125], I.N. Potrap [38], C.J. Potter [32], H. Potti [1], T. Poulsen [48], J. Poveda [162], G. Pownall [48], M.E. Pozo Astigarraga [36], A. Prades Ibanez [162], M.M. Prapa [46], J. Pretel [54], D. Price [100], M. Primavera [69a], M.A. Principe Martin [98], M.L. Proffitt [137], N. Proklova [37], K. Prokofiev [64c], G. Proto [75a,75b], S. Protopopescu [29], J. Proudfoot [6], M. Przybycien [84a], J.E. Puddefoot [138], D. Pudzha [37], P. Puzo [66], D. Pyatiizbyantseva [37], J. Qian [105], Y. Qin [100], T. Qiu [93], A. Quadt [55], M. Queitsch-Maitland [24], G. Rabanal Bolanos [61], D. Rafanoharana [54], F. Ragusa [70a,70b], J.L. Rainbolt [39], J.A. Raine [56], S. Rajagopalan [29], E. Ramakoti [37], K. Ran [14a,14d], V. Raskina [126], D.F. Rassloff [63a], S. Rave [99], B. Ravina [59], I. Ravinovich [168], M. Raymond [36], A.L. Read [124], N.P. Readioff [138], D.M. Rebuzzi [72a,72b], G. Redlinger [29], K. Reeves [45], J.A. Reidelsturz [170], D. Reikher [150], A. Reiss [99], A. Rej [140], C. Rembser [36], A. Renardi [48], M. Renda [27b], M.B. Rendel [109], A.G. Rennie [59], S. Resconi [70a], M. Ressegotti [57b,57a], E.D. Resseguie [17a], S. Rettie [95], B. Reynolds [118], E. Reynolds [17a], M. Rezaei Estabragh [170], O.L. Rezanova [37], P. Reznicek [132], E. Ricci [77a,77b], R. Richter [109], S. Richter [47a,47b], E. Richter-Was [84b], M. Ridel [126], P. Rieck [116], P. Riedler [36], M. Rijssenbeek [144], A. Rimoldi [72a,72b], M. Rimoldi [48], L. Rinaldi [23b,23a], T.T. Rinn [29], M.P. Rinnagel [108], G. Ripellino [143], I. Riu [13], P. Rivadeneira [48], J.C. Rivera Vergara [164], F. Rizatdinova [120], E. Rizvi [93], C. Rizzi [56], B.A. Roberts [166], B.R. Roberts [17a], S.H. Robertson [103,y], M. Robin [48], D. Robinson [32], C.M. Robles Gajardo [136f], M. Robles Manzano [99], A. Robson [59], A. Rocchi [75a,75b], C. Roda [73a,73b], S. Rodriguez Bosca [63a], Y. Rodriguez Garcia [22a], A. Rodriguez Rodriguez [54], A.M. Rodríguez Vera [155b], S. Roe [36], J.T. Roemer [159], A.R. Roepe-Gier [119], J. Roggel [170], O. Røhne [124], R.A. Rojas [164], B. Roland [54], C.P.A. Roland [67], J. Roloff [29], A. Romaniouk [37], E. Romano [72a,72b], M. Romano [23b], A.C. Romero Hernandez [161], N. Rompotis [91], L. Roos [126], S. Rosati [74a], B.J. Rosser [39], E. Rossi [4],

E. Rossi [71a,71b], L.P. Rossi [57b], L. Rossini [48], R. Rosten [118], M. Rotaru [27b], B. Rottler [54], D. Rousseau [66], D. Rousso [32], G. Rovelli [72a,72b], A. Roy [161], A. Rozanov [101], Y. Rozen [149], X. Ruan [33g], A. Rubio Jimenez [162], A.J. Ruby [91], T.A. Ruggeri [1], F. Rühr [54], A. Ruiz-Martinez [162], A. Rummler [36], Z. Rurikova [54], N.A. Rusakovich [38], H.L. Russell [164], J.P. Rutherfoord [7], E.M. Rüttinger [138], K. Rybacki [90], M. Rybar [132], E.B. Rye [124], A. Ryzhov [37], J.A. Sabater Iglesias [56], P. Sabatini [162], L. Sabetta [74a,74b], H.F-W. Sadrozinski [135], F. Safai Tehrani [74a], B. Safarzadeh Samani [145], M. Safdari [142], S. Saha [103], M. Sahinsoy [109], M. Saimpert [134], M. Saito [152], T. Saito [152], D. Salamani [36], G. Salamanna [76a,76b], A. Salnikov [142], J. Salt [162], A. Salvador Salas [13], D. Salvatore [43b,43a], F. Salvatore [145], A. Salzburger [36], D. Sammel [54], D. Sampsonidis [151], D. Sampsonidou [62d,62c], J. Sánchez [162], A. Sanchez Pineda [4], V. Sanchez Sebastian [162], H. Sandaker [124], C.O. Sander [48], J.A. Sandesara [102], M. Sandhoff [170], C. Sandoval [22b], D.P.C. Sankey [133], A. Sansoni [53], L. Santi [74a,74b], C. Santoni [40], H. Santos [129a,129b], S.N. Santpur [17a], A. Santra [168], K.A. Saoucha [138], J.G. Saraiva [129a,129d], J. Sardain [101], O. Sasaki [82], K. Sato [156], C. Sauer [63b], F. Sauerburger [54], E. Sauvan [4], P. Savard [154,ag], R. Sawada [152], C. Sawyer [133], L. Sawyer [96], I. Sayago Galvan [162], C. Sbarra [23b], A. Sbrizzi [23b,23a], T. Scanlon [95], J. Schaarschmidt [137], P. Schacht [109], D. Schaefer [39], U. Schäfer [99], A.C. Schaffer [66], D. Schaile [108], R.D. Schamberger [144], E. Schanet [108], C. Scharf [18], V.A. Schegelsky [37], D. Scheirich [132], F. Schenck [18], M. Schernau [159], C. Scheulen [55], C. Schiavi [57b,57a], Z.M. Schillaci [26], E.J. Schioppa [69a,69b], M. Schioppa [43b,43a], B. Schlag [99], K.E. Schleicher [54], S. Schlenker [36], K. Schmieden [99], C. Schmitt [99], S. Schmitt [48], L. Schoeffel [134], A. Schoening [63b], P.G. Scholer [54], E. Schopf [125], M. Schott [99], J. Schovancova [36], S. Schramm [56], F. Schroeder [170], H-C. Schultz-Coulon [63a], M. Schumacher [54], B.A. Schumm [135], Ph. Schune [134], A. Schwartzman [142], T.A. Schwarz [105], Ph. Schwemling [134], R. Schwienhorst [106], A. Sciandra [135], G. Sciolla [26], F. Scuri [73a], F. Scutti [104], C.D. Sebastiani [91], K. Sedlaczek [49], P. Seema [18], S.C. Seidel [111], A. Seiden [135], B.D. Seidlitz [41], T. Seiss [39], C. Seitz [48], J.M. Seixas [81b], G. Sekhniaidze [71a], S.J. Sekula [44], L. Selem [4], N. Semprini-Cesari [23b,23a], S. Sen [51], D. Sengupta [56], V. Senthilkumar [162], L. Serin [66], L. Serkin [68a,68b], M. Sessa [76a,76b], H. Severini [119], S. Sevova [142], F. Sforza [57b,57a], A. Sfyrla [56], E. Shabalina [55], R. Shaheen [143], J.D. Shahinian [127], N.W. Shaikh [47a,47b], D. Shaked Renous [168], L.Y. Shan [14a], M. Shapiro [17a], A. Sharma [36], A.S. Sharma [163], P. Sharma [79], S. Sharma [48], P.B. Shatalov [37], K. Shaw [145], S.M. Shaw [100], Q. Shen [62c], P. Sherwood [95], L. Shi [95], C.O. Shimmin [171], Y. Shimogama [167], J.D. Shinner [94], I.P.J. Shipsey [125], S. Shirabe [60], M. Shiyakova [38,x], J. Shlomi [168], M.J. Shochet [39], J. Shojaii [104], D.R. Shope [143], S. Shrestha [118], E.M. Shrif [33g], M.J. Shroff [164], P. Sicho [130], A.M. Sickles [161], E. Sideras Haddad [33g], O. Sidiropoulou [36], A. Sidoti [23b], F. Siegert [50], Dj. Sijacki [15], R. Sikora [84a], F. Sili [89], J.M. Silva [20], M.V. Silva Oliveira [36], S.B. Silverstein [47a], S. Simion [66], R. Simoniello [36], E.L. Simpson [59], N.D. Simpson [97], S. Simsek [21d], S. Sindhu [55], P. Sinervo [154], V. Sinetckii [37], S. Singh [141], S. Singh [154], S. Sinha [48], S. Sinha [33g], M. Sioli [23b,23a], I. Siral [122], S.Yu. Sivoklokov [37,*], J. Sjölin [47a,47b], A. Skaf [55], E. Skorda [97], P. Skubic [119], M. Slawinska [85], V. Smakhtin [168], B.H. Smart [133], J. Smiesko [132], S.Yu. Smirnov [37], Y. Smirnov [37], L.N. Smirnova [37,a], O. Smirnova [97], E.A. Smith [39], H.A. Smith [125], J.L. Smith [91], R. Smith [142], M. Smizanska [90], K. Smolek [131], A. Smykiewicz [85], A.A. Snesarev [37], H.L. Snoek [113], S. Snyder [29], R. Sobie [164,y], A. Soffer [150], C.A. Solans Sanchez [36], E.Yu. Soldatov [37], U. Soldevila [162], A.A. Solodkov [37], S. Solomon [54], A. Soloshenko [38], K. Solovieva [54], O.V. Solovyanov [37], V. Solovyev [37], P. Sommer [36], A. Sonay [13], W.Y. Song [155b], A. Sopczak [131], A.L. Sopio [95], F. Sopkova [28b], V. Sothilingam [63a], S. Sottocornola [72a,72b],

R. Soualah [115b], Z. Soumaimi [35e], D. South [48], S. Spagnolo [69a,69b], M. Spalla [109], F. Spanò [94], D. Sperlich [54], G. Spigo [36], M. Spina [145], S. Spinali [90], D.P. Spiteri [59], M. Spousta [132], E.J. Staats [34], A. Stabile [70a,70b], R. Stamen [63a], M. Stamenkovic [113], A. Stampekis [20], M. Standke [24], E. Stanecka [85], B. Stanislaus [17a], M.M. Stanitzki [48], M. Stankaityte [125], B. Stapf [48], E.A. Starchenko [37], G.H. Stark [135], J. Stark [101,ab], D.M. Starko [155b], P. Staroba [130], P. Starovoitov [63a], S. Stärz [103], R. Staszewski [85], G. Stavropoulos [46], J. Steentoft [160], P. Steinberg [29], A.L. Steinhebel [122], B. Stelzer [141,155a], H.J. Stelzer [128], O. Stelzer-Chilton [155a], H. Stenzel [58], T.J. Stevenson [145], G.A. Stewart [36], M.C. Stockton [36], G. Stoicea [27b], M. Stolarski [129a], S. Stonjek [109], A. Straessner [50], J. Strandberg [143], S. Strandberg [47a,47b], M. Strauss [119], T. Strebler [101], P. Strizenec [28b], R. Ströhmer [165], D.M. Strom [122], L.R. Strom [48], R. Stroynowski [44], A. Strubig [47a,47b], S.A. Stucci [29], B. Stugu [16], J. Stupak [119], N.A. Styles [48], D. Su [142], S. Su [62a], W. Su [62d,137,62c], X. Su [62a,66], K. Sugizaki [152], V.V. Sulin [37], M.J. Sullivan [91], D.M.S. Sultan [77a,77b], L. Sultanaliyeva [37], S. Sultansoy [3b], T. Sumida [86], S. Sun [105], S. Sun [169], O. Sunneborn Gudnadottir [160], M.R. Sutton [145], M. Svatos [130], M. Swiatlowski [155a], T. Swirski [165], I. Sykora [28a], M. Sykora [132], T. Sykora [132], D. Ta [99], K. Tackmann [48,w], A. Taffard [159], R. Tafirout [155a], J.S. Tafoya Vargas [66], R.H.M. Taibah [126], R. Takashima [87], K. Takeda [83], E.P. Takeva [52], Y. Takubo [82], M. Talby [101], A.A. Talyshev [37], K.C. Tam [64b], N.M. Tamir [150], A. Tanaka [152], J. Tanaka [152], R. Tanaka [66], M. Tanasini [57b,57a], J. Tang [62c], Z. Tao [163], S. Tapia Araya [80], S. Tapprogge [99], A. Tarek Abouelfadl Mohamed [106], S. Tarem [149], K. Tariq [62b], G. Tarna [27b], G.F. Tartarelli [70a], P. Tas [132], M. Tasevsky [130], E. Tassi [43b,43a], A.C. Tate [161], G. Tateno [152], Y. Tayalati [35e], G.N. Taylor [104], W. Taylor [155b], H. Teagle [91], A.S. Tee [169], R. Teixeira De Lima [142], P. Teixeira-Dias [94], J.J. Teoh [154], K. Terashi [152], J. Terron [98], S. Terzo [13], M. Testa [53], R.J. Teuscher [154,y], A. Thaler [78], N. Themistokleous [52], T. Theveneaux-Pelzer [18], O. Thielmann [170], D.W. Thomas [94], J.P. Thomas [20], E.A. Thompson [48], P.D. Thompson [20], E. Thomson [127], E.J. Thorpe [93], Y. Tian [55], V. Tikhomirov [37,a], Yu.A. Tikhonov [37], S. Timoshenko [37], E.X.L. Ting [1], P. Tipton [171], S. Tisserant [101], S.H. Tlou [33g], A. Tnourji [40], K. Todome [23b,23a], S. Todorova-Nova [132], S. Todt [50], M. Togawa [82], J. Tojo [88], S. Tokár [28a], K. Tokushuku [82], R. Tombs [32], M. Tomoto [82,110], L. Tompkins [142,q], P. Tornambe [102], E. Torrence [122], H. Torres [50], E. Torró Pastor [162], M. Toscani [30], C. Tosciri [39], D.R. Tovey [138], A. Traeet [16], I.S. Trandafir [27b], T. Trefzger [165], A. Tricoli [29], I.M. Trigger [155a], S. Trincaz-Duvoid [126], D.A. Trischuk [163], B. Trocmé [60], A. Trofymov [66], C. Troncon [70a], L. Truong [33c], M. Trzebinski [85], A. Trzupek [85], F. Tsai [144], M. Tsai [105], A. Tsiamis [151], P.V. Tsiareshka [37], S. Tsigaridas [155a], A. Tsirigotis [151,u], V. Tsiskaridze [144], E.G. Tskhadadze [148a], M. Tsopoulou [151], Y. Tsujikawa [86], I.I. Tsukerman [37], V. Tsulaia [17a], S. Tsuno [82], O. Tsur [149], D. Tsybychev [144], Y. Tu [64b], A. Tudorache [27b], V. Tudorache [27b], A.N. Tuna [36], S. Turchikhin [38], I. Turk Cakir [3a], R. Turra [70a], T. Turtuvshin [38], P.M. Tuts [41], S. Tzamarias [151], P. Tzanis [10], E. Tzovara [99], K. Uchida [152], F. Ukegawa [156], P.A. Ulloa Poblete [136c], G. Unal [36], M. Unal [11], A. Undrus [29], G. Unel [159], K. Uno [152], J. Urban [28b], P. Urquijo [104], G. Usai [8], R. Ushioda [153], M. Usman [107], Z. Uysal [21b], V. Vacek [131], B. Vachon [103], K.O.H. Vadla [124], T. Vafeiadis [36], C. Valderanis [108], E. Valdes Santurio [47a,47b], M. Valente [155a], S. Valentinetti [23b,23a], A. Valero [162], A. Vallier [101,ab], J.A. Valls Ferrer [162], T.R. Van Daalen [137], P. Van Gemmeren [6], S. Van Stroud [95], I. Van Vulpen [113], M. Vanadia [75a,75b], W. Vandelli [36], M. Vandenbroucke [134], E.R. Vandewall [120], D. Vannicola [150], L. Vannoli [57b,57a], R. Vari [74a], E.W. Varnes [7], C. Varni [17a], T. Varol [147], D. Varouchas [66],

L. Varriale [162], K.E. Varvell [146], M.E. Vasile [27b], L. Vaslin [40], G.A. Vasquez [164], F. Vazeille [40], T. Vazquez Schroeder [36], J. Veatch [31], V. Vecchio [100], M.J. Veen [113], I. Veliscek [125], L.M. Veloce [154], F. Veloso [129a,129c], S. Veneziano [74a], A. Ventura [69a,69b], A. Verbytskyi [109], M. Verducci [73a,73b], C. Vergis [24], M. Verissimo De Araujo [81b], W. Verkerke [113], J.C. Vermeulen [113], C. Vernieri [142], P.J. Verschuuren [94], M. Vessella [102], M.L. Vesterbacka [116], M.C. Vetterli [141,ag], A. Vgenopoulos [151], N. Viaux Maira [136f], T. Vickey [138], O.E. Vickey Boeriu [138], G.H.A. Viehhauser [125], L. Vigani [63b], M. Villa [23b,23a], M. Villaplana Perez [162], E.M. Villhauer [52], E. Vilucchi [53], M.G. Vincter [34], G.S. Virdee [20], A. Vishwakarma [52], C. Vittori [23b,23a], I. Vivarelli [145], V. Vladimirov [166], E. Voevodina [109], F. Vogel [108], P. Vokac [131], J. Von Ahnen [48], E. Von Toerne [24], B. Vormwald [36], V. Vorobel [132], K. Vorobev [37], M. Vos [162], J.H. Vossebeld [91], M. Vozak [113], L. Vozdecky [93], N. Vranjes [15], M. Vranjes Milosavljevic [15], M. Vreeswijk [113], R. Vuillermet [36], O. Vujinovic [99], I. Vukotic [39], S. Wada [156], C. Wagner [102], W. Wagner [170], S. Wahdan [170], H. Wahlberg [89], R. Wakasa [156], M. Wakida [110], V.M. Walbrecht [109], J. Walder [133], R. Walker [108], W. Walkowiak [140], A.M. Wang [61], A.Z. Wang [169], C. Wang [62a], C. Wang [62c], H. Wang [17a], J. Wang [64a], P. Wang [44], R.-J. Wang [99], R. Wang [61], R. Wang [6], S.M. Wang [147], S. Wang [62b], T. Wang [62a], W.T. Wang [79], W.X. Wang [62a], X. Wang [14c], X. Wang [161], X. Wang [62c], Y. Wang [62d], Y. Wang [14c], Z. Wang [105], Z. Wang [62d,51,62c], Z. Wang [105], A. Warburton [103], R.J. Ward [20], N. Warrack [59], A.T. Watson [20], M.F. Watson [20], G. Watts [137], B.M. Waugh [95], A.F. Webb [11], C. Weber [29], M.S. Weber [19], S.A. Weber [34], S.M. Weber [63a], C. Wei [62a], Y. Wei [125], A.R. Weidberg [125], J. Weingarten [49], M. Weirich [99], C. Weiser [54], C.J. Wells [48], T. Wenaus [29], B. Wendland [49], T. Wengler [36], N.S. Wenke [109], N. Wermes [24], M. Wessels [63a], K. Whalen [122], A.M. Wharton [90], A.S. White [61], A. White [8], M.J. White [1], D. Whiteson [159], L. Wickremasinghe [123], W. Wiedenmann [169], C. Wiel [50], M. Wielers [133], N. Wieseotte [99], C. Wiglesworth [42], L.A.M. Wiik-Fuchs [54], D.J. Wilbern [119], H.G. Wilkens [36], D.M. Williams [41], H.H. Williams [127], S. Williams [32], S. Willocq [102], P.J. Windischhofer [125], F. Winklmeier [122], B.T. Winter [54], M. Wittgen [142], M. Wobisch [96], A. Wolf [99], R. Wölker [125], J. Wollrath [159], M.W. Wolter [85], H. Wolters [129a,129c], V.W.S. Wong [163], A.F. Wongel [48], S.D. Worm [48], B.K. Wosiek [85], K.W. Woźniak [85], K. Wraight [59], J. Wu [14a,14d], M. Wu [64a], S.L. Wu [169], X. Wu [56], Y. Wu [62a], Z. Wu [134,62a], J. Wuerzinger [125], T.R. Wyatt [100], B.M. Wynne [52], S. Xella [42], L. Xia [14c], M. Xia [14b], J. Xiang [64c], X. Xiao [105], M. Xie [62a], X. Xie [62a], J. Xiong [17a], I. Xiotidis [145], D. Xu [14a], H. Xu [62a], H. Xu [62a], L. Xu [62a], R. Xu [127], T. Xu [105], W. Xu [105], Y. Xu [14b], Z. Xu [62b], Z. Xu [142], B. Yabsley [146], S. Yacoob [33a], N. Yamaguchi [88], Y. Yamaguchi [153], H. Yamauchi [156], T. Yamazaki [17a], Y. Yamazaki [83], J. Yan [62c], S. Yan [125], Z. Yan [25], H.J. Yang [62c,62d], H.T. Yang [17a], S. Yang [62a], T. Yang [64c], X. Yang [62a], X. Yang [14a], Y. Yang [44], Z. Yang [62a,105], W-M. Yao [17a], Y.C. Yap [48], H. Ye [14c], J. Ye [44], S. Ye [29], X. Ye [62a], Y. Yeh [95], I. Yeletskikh [38], M.R. Yexley [90], P. Yin [41], K. Yorita [167], C.J.S. Young [54], C. Young [142], M. Yuan [105], R. Yuan [62b,k], L. Yue [95], X. Yue [63a], M. Zaazoua [35e], B. Zabinski [85], E. Zaid [52], T. Zakareishvili [148b], N. Zakharchuk [34], S. Zambito [56], J. Zang [152], D. Zanzi [54], O. Zaplatilek [131], S.V. Zeißner [49], C. Zeitnitz [170], J.C. Zeng [161], D.T. Zenger Jr [26], O. Zenin [37], T. Ženiš [28a], S. Zenz [93], S. Zerradi [35a], D. Zerwas [66], B. Zhang [14c], D.F. Zhang [138], G. Zhang [14b], J. Zhang [6], K. Zhang [14a,14d], L. Zhang [14c], R. Zhang [169], S. Zhang [105], T. Zhang [152], X. Zhang [62c], X. Zhang [62b], Z. Zhang [17a], Z. Zhang [66], H. Zhao [137], P. Zhao [51], T. Zhao [62b], Y. Zhao [135], Z. Zhao [62a], A. Zhemchugov [38], Z. Zheng [142], D. Zhong [161], B. Zhou [105], C. Zhou [169], H. Zhou [7], N. Zhou [62c], Y. Zhou [7], C.G. Zhu [62b],

C. Zhu [14a,14d], H.L. Zhu [62a], H. Zhu [14a], J. Zhu [105], Y. Zhu [62a], X. Zhuang [14a], K. Zhukov [37], V. Zhulanov [37], N.I. Zimine [38], J. Zinsser [63b], M. Ziolkowski [140], L. Živković [15], A. Zoccoli [23b,23a], K. Zoch [56], T.G. Zorbas [138], 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)] *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;* [(d)] *Istinye University, Sariyer, Istanbul; Türkiye*
[22] [(a)] *Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogotá;* [(b)] *Departamento de Física, Universidad Nacional de Colombia, Bogotá; 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] Department of Physics, Indiana University, Bloomington IN; United States of America
[68] [(a)] INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; [(b)] ICTP, Trieste; [(c)] Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine; Italy
[69] [(a)] INFN Sezione di Lecce; [(b)] Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy
[70] [(a)] INFN Sezione di Milano; [(b)] Dipartimento di Fisica, Università di Milano, Milano; Italy
[71] [(a)] INFN Sezione di Napoli; [(b)] Dipartimento di Fisica, Università di Napoli, Napoli; Italy
[72] [(a)] INFN Sezione di Pavia; [(b)] Dipartimento di Fisica, Università di Pavia, Pavia; Italy
[73] [(a)] INFN Sezione di Pisa; [(b)] Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy
[74] [(a)] INFN Sezione di Roma; [(b)] Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy
[75] [(a)] INFN Sezione di Roma Tor Vergata; [(b)] Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy
[76] [(a)] INFN Sezione di Roma Tre; [(b)] Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy
[77] [(a)] INFN-TIFPA; [(b)] Università degli Studi di Trento, Trento; Italy
[78] Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria
[79] University of Iowa, Iowa City IA; United States of America
[80] Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America
[81] [(a)] Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora; [(b)] Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; [(c)] Instituto de Física, Universidade de São Paulo, São Paulo; [(d)] Rio de Janeiro State University, Rio de Janeiro; Brazil
[82] KEK, High Energy Accelerator Research Organization, Tsukuba; Japan
[83] Graduate School of Science, Kobe University, Kobe; Japan
[84] [(a)] AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow; [(b)] Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland
[85] Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland
[86] Faculty of Science, Kyoto University, Kyoto; Japan
[87] Kyoto University of Education, Kyoto; Japan
[88] Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka; Japan
[89] Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina
[90] Physics Department, Lancaster University, Lancaster; United Kingdom
[91] Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom
[92] Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia
[93] School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom
[94] Department of Physics, Royal Holloway University of London, Egham; United Kingdom
[95] Department of Physics and Astronomy, University College London, London; United Kingdom
[96] Louisiana Tech University, Ruston LA; United States of America
[97] Fysiska institutionen, Lunds universitet, Lund; Sweden
[98] Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain
[99] Institut für Physik, Universität Mainz, Mainz; Germany
[100] School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom
[101] CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France
[102] Department of Physics, University of Massachusetts, Amherst MA; United States of America
[103] Department of Physics, McGill University, Montreal QC; Canada
[104] School of Physics, University of Melbourne, Victoria; Australia
[105] Department of Physics, University of Michigan, Ann Arbor MI; United States of America
[106] Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America
[107] Group of Particle Physics, University of Montreal, Montreal QC; Canada
[108] Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany
[109] Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany
[110] Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan
[111] Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America
[112] Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands
[113] Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands
[114] Department of Physics, Northern Illinois University, DeKalb IL; United States of America
[115] [(a)] New York University Abu Dhabi, Abu Dhabi; [(b)] University of Sharjah, Sharjah; United Arab Emirates
[116] Department of Physics, New York University, New York NY; United States of America
[117] Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan
[118] Ohio State University, Columbus OH; United States of America
[119] Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America
[120] Department of Physics, Oklahoma State University, Stillwater OK; United States of America
[121] Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic
[122] Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America
[123] Graduate School of Science, Osaka University, Osaka; Japan
[124] Department of Physics, University of Oslo, Oslo; Norway
[125] Department of Physics, Oxford University, Oxford; United Kingdom
[126] LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris; France
[127] Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America
[128] Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America
[129] [(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
[130] Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic
[131] Czech Technical University in Prague, Prague; Czech Republic
[132] Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic
[133] Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom
[134] IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France
[135] Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America
[136] [(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
[137] Department of Physics, University of Washington, Seattle WA; United States of America

[138] Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom
[139] Department of Physics, Shinshu University, Nagano; Japan
[140] Department Physik, Universität Siegen, Siegen; Germany
[141] Department of Physics, Simon Fraser University, Burnaby BC; Canada
[142] SLAC National Accelerator Laboratory, Stanford CA; United States of America
[143] Department of Physics, Royal Institute of Technology, Stockholm; Sweden
[144] Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America
[145] Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom
[146] School of Physics, University of Sydney, Sydney; Australia
[147] Institute of Physics, Academia Sinica, Taipei; Taiwan
[148] [(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
[149] Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel
[150] Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel
[151] Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece
[152] International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan
[153] Department of Physics, Tokyo Institute of Technology, Tokyo; Japan
[154] Department of Physics, University of Toronto, Toronto ON; Canada
[155] [(a)] TRIUMF, Vancouver BC; [(b)] Department of Physics and Astronomy, York University, Toronto ON; Canada
[156] Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan
[157] Department of Physics and Astronomy, Tufts University, Medford MA; United States of America
[158] United Arab Emirates University, Al Ain; United Arab Emirates
[159] Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America
[160] Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden
[161] Department of Physics, University of Illinois, Urbana IL; United States of America
[162] Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia – CSIC, Valencia; Spain
[163] Department of Physics, University of British Columbia, Vancouver BC; Canada
[164] Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada
[165] Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany
[166] Department of Physics, University of Warwick, Coventry; United Kingdom
[167] Waseda University, Tokyo; Japan
[168] Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel
[169] Department of Physics, University of Wisconsin, Madison WI; United States of America
[170] Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany
[171] 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 Borough of Manhattan Community College, City University of New York, New York NY; United States of America.
[d] Also at Bruno Kessler Foundation, Trento; Italy.
[e] Also at Center for High Energy Physics, Peking University; China.
[f] Also at Centro Studi e Ricerche Enrico Fermi; Italy.
[g] Also at CERN, Geneva; Switzerland.
[h] Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
[i] Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona; Spain.
[j] Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
[k] Also at Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.
[l] Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY; United States of America.
[m] Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva; Israel.
[n] Also at Department of Physics, California State University, East Bay; United States of America.
[o] Also at Department of Physics, California State University, Sacramento; United States of America.
[p] Also at Department of Physics, King's College London, London; United Kingdom.
[q] Also at Department of Physics, Stanford University, Stanford CA; United States of America.
[r] Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
[s] Also at Department of Physics, University of Thessaly; Greece.
[t] Also at Department of Physics, Westmont College, Santa Barbara; United States of America.
[u] Also at Hellenic Open University, Patras; Greece.
[v] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
[w] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
[x] Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria.
[y] Also at Institute of Particle Physics (IPP); Canada.
[z] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
[aa] Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.
[ab] Also at L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse; France.
[ac] Also at Lawrence Livermore National Laboratory, Livermore; United States of America.
[ad] Also at National Institute of Physics, University of the Philippines Diliman (Philippines); Philippines.
[ae] Also at The City College of New York, New York NY; United States of America.
[af] Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
[ag] Also at TRIUMF, Vancouver BC; Canada.
[ah] Also at Università di Napoli Parthenope, Napoli; Italy.
[ai] Also at University of Chinese Academy of Sciences (UCAS), Beijing; China.
[aj] Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America.
[ak] Also at Yeditepe University, Physics Department, Istanbul; Türkiye.
[*] Deceased.