Article:

Aad, G. orcid.org/0000-0002-6665-4934, Aakvaag, E. orcid.org/0000-0001-7616-1554, Abbott, B. orcid.org/0000-0002-5888-2734 et al. (2933 more authors) (2025) Combination of searches for singly produced vectorlike top quarks in pp collisions at √s=13 TeV with the ATLAS detector. Physical Review D, 111 (1). 012012. ISSN 2470-0010

https://doi.org/10.1103/physrevd.111.012012

Combination of searches for singly produced vectorlike top quarks in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

G. Aad *et al.*[*]
(ATLAS Collaboration)

(Received 21 August 2024; accepted 13 November 2024; published 29 January 2025)

A combination of searches for the single production of vectorlike top quarks (T) is presented. These analyses are based on proton-proton collisions at $\sqrt{s} = 13$ TeV recorded in 2015–2018 with the ATLAS detector at the Large Hadron Collider, corresponding to an integrated luminosity of 139 fb^{-1}. The T decay modes considered in this combination are into a top quark and either a Standard Model Higgs boson or a Z boson ($T \to Ht$ and $T \to Zt$). The individual searches used in the combination are differentiated by the number of leptons (e, μ) in the final state. The observed data are found to be in good agreement with the Standard Model background prediction. Interpretations are provided for a range of masses and couplings of the vectorlike top quark for benchmark models and generalized representations in terms of 95% confidence level limits. For a benchmark signal prediction of a vectorlike top quark SU(2) singlet with electroweak coupling, κ, of 0.5, masses below 2.1 TeV are excluded, resulting in the most restrictive limits to date.

DOI: 10.1103/PhysRevD.111.012012

I. INTRODUCTION

The formulation of electroweak interactions arising from a spontaneously broken gauge symmetry is a cornerstone of the Standard Model (SM). Experiments over the past four decades have confirmed this hypothesis, most notably through the precision measurements of the LEP and SLC collider programs [1,2]. A major milestone was achieved when the ATLAS and CMS Collaborations reported the discovery [3,4] of a new particle produced at CERN's Large Hadron Collider (LHC) possessing properties consistent with those predicted for the SM Higgs boson (H). The electroweak symmetry-breaking mechanism, where a weak-isospin doublet of fundamental scalar fields obtains a vacuum expectation value, remains the simplest hypothesis.

Following the discovery of the Higgs boson, the SM still cannot be considered a complete description of nature. For example, the theory does not explain the number of fermion generations and their mass hierarchy and mixing angles, nor the origin of the matter-antimatter asymmetry in the universe. It also does not have a viable dark matter particle. Therefore, the SM is generally regarded as a low-energy approximation of a more fundamental theory with new degrees of freedom and symmetries that would become manifest at higher energy. In fact, the SM violates a concept of naturalness [5] when extrapolated to energies above the electroweak scale. When extrapolated to the energy scale of new physics, a fine-tuning of the theory is required. The fine-tuning can be mitigated by the introduction of new interactions that cancel out the quadratic divergences in the Higgs boson mass. To this effect, several explanations are proposed in theories beyond the SM (BSM).

Proposed new models typically address the naturalness problem by postulating a new symmetry. For example, supersymmetry is a Bose-Fermi symmetry, and the new states related to the SM bosons and fermions by this symmetry introduce new interactions that cancel out the quadratically divergent ones [6–11]. Alternatively, the symmetry could be a spontaneously broken global symmetry of the extended theory, with the Higgs boson emerging as a pseudo-Nambu-Goldstone boson [12]. Examples of models that implement this idea are little Higgs [13,14] and composite Higgs [15,16] models. The new states realizing the enhanced symmetry are generically strongly coupled resonances of new confining dynamics. These include vectorlike quarks (VLQs), defined as color-triplet spin-$1/2$ fermions whose left- and right-handed chiral components have the same transformation properties under the weak-isospin gauge group. Such quarks could mix with like-charge SM quarks [17,18], and the mixing of the SM top quark with a charge $+2e/3$ vectorlike quark (where e is the electric charge of the electron) could play a role in regulating the sensitivity to the Higgs boson mass. Hence, VLQs emerge as a characteristic feature of several nonsupersymmetric models [19].

[*]Full author list given at the end of the article.

TABLE I. Possible VLQ multiplets allowed to mix with the SM quarks.

VLQ	(T)	(B)	$\begin{pmatrix} T \\ B \end{pmatrix}$	$\begin{pmatrix} X \\ T \end{pmatrix}$	$\begin{pmatrix} B \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ T \\ B \end{pmatrix}$	$\begin{pmatrix} T \\ B \\ Y \end{pmatrix}$
Isospin	0	0	1/2	1/2	1/2	1	1
Hypercharge	+2/3	−1/3	+1/6	+7/6	−5/6	+2/3	−1/3

In order for VLQs to mix with the SM quarks [17,18], some constraints are needed on their allowed quantum numbers to preserve gauge invariance. Therefore, in order to generate Yukawa terms in the Lagrangian without changing the scalar sector, only seven renormalizable possibilities [20] are allowed, which are summarized in Table I. The vectorlike T and B have electric charge $+2e/3$ and $-1e/3$, respectively. VLQs with other electric charges could also exist, such as the X and Y quarks with $+5e/3$ and $-4e/3$, respectively.

The renormalizable electroweak representations consist of (T) or (B) SU(2) singlets, (X,T), (T,B), or (B,Y) doublets and (X,T,B) or (T,B,Y) triplets. In all representations, they couple to the SM quarks via an exchange of charged $(W^{\pm})$ or neutral (Z,H) bosons. The simplified Lagrangian [21] below summarizes the interaction of the VLQ and SM quarks

$$\mathcal{L}=\sum_{Q,q,\zeta}\left[\frac{g_w}{\sqrt{2}}\kappa_{\zeta}^{Qq}\bar{Q}\not{W}P_{\zeta}q+\frac{g_w}{2c_W}\tilde{\kappa}_{\zeta}^{Qq}\bar{Q}\not{Z}P_{\zeta}q+\hat{\kappa}_{\zeta}^{Qq}H\bar{Q}P_{\zeta}q\right] +\mathrm{H.c.}, \quad (1)$$

where Q represents a VLQ, ζ represents the chirality with P_{ζ} being the corresponding projection operator, q represents a SM quark of up or down type, and the electroweak couplings $\kappa_{\zeta}^{Qq}, \tilde{\kappa}_{\zeta}^{Qq}$, and $\hat{\kappa}_{\zeta}^{Qq}$ determine the coupling strengths between Q and q when mediated by the W, Z, and H bosons, respectively. The mass hierarchy of the SM quarks suggests that VLQs interact predominantly with the third-generation SM quarks [22,23]. Hence, VLQ interactions with lighter generations are set to zero in the simplified representation of Eq. (1). Furthermore, this formulation assumes there are no additional mediators other than the W, Z, and H bosons [24].

In proton-proton (pp) collisions, VLQs can be produced singly via the electroweak interaction (as illustrated by the leading-order (LO) Feynman diagram in Fig. 1) or in pairs via the strong interaction. While the cross section for pair production is generally given by quantum chromodynamics, the single-production cross section explicitly depends on the coupling of the VLQs to SM electroweak bosons. Search strategies for VLQs were outlined previously [23,25–28]. Results of searches for chiral fourth-generation quarks apply, though interpreting the exclusions was difficult when the quarks were assumed to decay entirely via the charged-current process. When VLQs are added to the SM, flavor-changing tree-level neutral-current decays of such new heavy quarks appear [29], while they are not present for SM quarks at tree level and are also highly suppressed at loop level by the Glashow-Iliopoulos-Maiani (GIM) mechanism [30]. Following Ref. [31], the relative couplings of VLQs to W, Z and H bosons are given in terms of the parameters ξ_W, ξ_Z and ξ_H, respectively. In the asymptotic limit of large VLQ mass, the ξ parameters correspond to the branching ratios of the T quark decay to W, Z and H bosons. The asymptotic limit holds to good approximation for VLQ masses above 1 TeV. In the T SU(2) singlet representation, $\xi_W = 0.5$ and $\xi_Z = \xi_H = 0.25$. If the T quarks are part of an (X,T) or (T,B) SU(2) doublet then $\xi_W = 0.0$, and $\xi_Z = \xi_H = 0.5$.

Vectorlike T and B quarks were searched for both at ATLAS and CMS in Run 1, and more recently with the Run 2 data. The Run 2 searches focused on VLQ pair production [32–47], typically setting limits on narrow-width resonances, and recently also on VLQ single production [33,35,48–60]. Searches for VLQ are summarized by the ATLAS and CMS Collaborations in Refs. [61,62]. The most stringent limits on T- and B-quark masses come from the latest ATLAS and CMS searches. The excluded masses for VLQs depend on the branching ratio. In the case of SU(2) doublet representations (T,B) where both VLQs are considered and assumed to be mass degenerate, T quark masses below 1.6 TeV [47] are excluded at 95% confidence

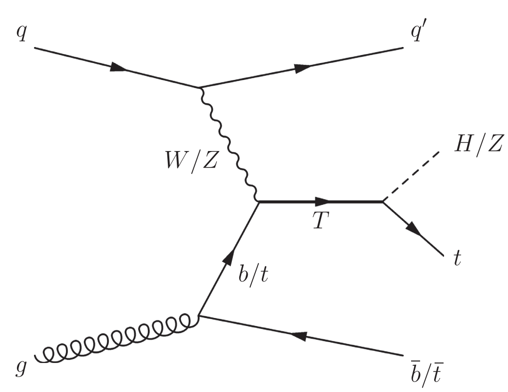

FIG. 1. Illustrative leading-order Feynman diagram of single vectorlike T production in association with a t or b quark and subsequent decay into either Ht or Zt.

level (CL). When no assumption is made on the branching ratio or mass degeneracy, then T quarks with masses below 1.5 TeV [45] are excluded. In the case of SU(2) singlet representations masses below 1.5 TeV [45] are excluded. The pair production limits assume a narrow-width resonance, an assumption not made for single production. In single production, for which the interpretation of results is more challenging due to the additional coupling factor, analyses have set limits in the coupling/mixing-angle-vs.-mass plane, reaching up to nearly 2 TeV [56] for large coupling and mixing angles.

This paper describes a combination of three analyses, differentiated by the number of light leptons (e, μ) in the final state. The search regions for each analysis, including the control regions, are designed to be orthogonal as they target different decay channels. This is achieved by requiring exactly zero leptons (electrons or muons) in the "Monotop" analysis [48], exactly one lepton in the "HtZt" analysis [63], and two or more leptons in the "Osml" (opposite-sign multilepton) analysis [56]. All searches use the full Run 2 ATLAS dataset collected with the ATLAS detector during 2015–2018, corresponding to 139 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV. The searches are combined taking into account correlations in the background modeling and systematic uncertainties. In the absence of a significant excess above the SM expectation, the results are used to set upper limits on the single production of T quarks for several scenarios of the mass, the universal coupling strength κ, and the relative couplings to W, Z and Higgs bosons. This is the first combination of searches for single T production by the ATLAS Collaboration and the results provide the most restrictive bounds to date.

II. ATLAS DETECTOR

The ATLAS experiment [64] at the LHC is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a near 4π coverage in solid angle.[1] It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity within the region $|\eta| < 3.2$. A steel/scintillator-tile hadronic calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The end cap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. The muon spectrometer includes a system of precision tracking chambers up to $|\eta| = 2.7$ and fast detectors for triggering up to $|\eta| = 2.4$. The luminosity is measured mainly by the LUCID–2 [65] detector, which is located close to the beampipe. A two-level trigger system is used to select events [66]. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate below 100 kHz. This is followed by a software-based trigger that reduces the accepted event rate to 1 kHz on average depending on the data-taking conditions. A software suite [67] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

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

III. DATA AND SIMULATED EVENT SAMPLES

This combination uses pp collision data collected with the ATLAS detector during the 2015–2018 data taking period, at a collision energy of $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 139 fb^{-1} [65,68]. Only events recorded with a single-electron trigger, a single-muon trigger or a $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger [69–71] under stable beam conditions, and for which all relevant detector subsystems were operational [72], are used in these analyses. The trigger requirements of the individual analyses can be found in the respective publications [48,56,63].

Monte Carlo (MC) simulated events are used to evaluate background contamination and modeling, signal acceptance, optimization of the event selection, and evaluation of systematic uncertainties. They are centrally produced with the well-established ATLAS event generation procedure [73]. For all samples, a full simulation of the ATLAS detector was performed using Geant4 [74]. A faster simulation, where the full Geant4 simulation of the calorimeter response is replaced by a detailed parametrization of the shower shapes [75], was adopted for some of the samples used to estimate systematic uncertainties.

The effect of multiple interactions in the same and neighboring bunch crossings (pile-up) was modeled by overlaying simulated hard-scattering events with inelastic pp events generated with PYTHIA8 (v8.186) [76] using the NNPDF2.3LO parton distribution function (PDF) set [77] and the A3 set of tuned parameters (tune) [78]. The MC events were weighted to reproduce the distribution of the average

TABLE II. Overview of the nominal simulated background samples, including information about the matrix element (ME) generator and parton distribution function (PDF) set, parton shower (PS), set of tuned parameters (Tune), and higher-order cross section used for normalization. For single top the t- and s-channel production cross sections are calculated at next-to-NLO (NNLO) in QCD, while the Wt production cross section is calculated at NLO and includes third-order corrections of soft-gluon emissions by resuming next-to-next-to-leading logarithm (NNLL) terms.

Process	ME event generator	ME PDF	PS and hadronization	Tune	Cross-section calculation
$W/Z+$ jets	Sherpa 2.2.1 [79]	NNPDF3.3NNLO [81]	Sherpa [79]	Default	NNLO [87]
$t\bar{t}W/Z$	MadGraph5_aMC@NLO 2.3.3 [88]	NNPDF3.3NLO [81]	PYTHIA 8.2 [80]	A14	NLO
tZ	MadGraph5_aMC@NLO 2.3.3 [88]	NNPDF2.3LO [77]	PYTHIA 8.2 [80]	A14	NLO
tWZ	MadGraph5_aMC@NLO 2.3.3 [88]	NNPDF2.3LO [77]	PYTHIA 8.2 [80]	A14	NLO
$t\bar{t}$	POWHEG-BOX [89]	NNPDF2.3LO [77]	PYTHIA 8.2 [80]	A14	NNLO+NNLL [90,91]
Single top	POWHEG-BOX [89]	NNPDF2.3LO [77]	PYTHIA 8.2 [80]	A14	NNLO/NLO+NNLL [92–96]
Multiboson	Sherpa 2.2.1–2.2.2 [79]	NNPDF3.0NNLO [81]	Sherpa	Default	NLO

number of interactions per bunch crossing ($\langle\mu\rangle$) observed in the data.

Table II summarizes the setups used in the simulated SM background samples. Except for the samples generated with Sherpa [79], all samples are interfaced with PYTHIA 8.2 [80] for the modeling of the parton shower (PS), hadronization and underlying event (UE) using the NNPDF2.3LO PDF set [81] and the A14 tune [82]. Alternative samples to study the impact of systematic uncertainties due to the PS and hadronization model are instead interfaced with Herwig 7 [83,84] using the MMHT2014LO PDF set [85] and the H7UE tune [83]. Additional details and other uncertainties in background modeling are given in the respective Refs. [48,56,63]. The EvtGen 1.6.0 [86] program was used to model b- and c-hadron decays for all samples showered using PYTHIA 8.2 or Herwig 7, with the exception of the $t\bar{t}V$ ($V = W$, Z) samples, where EvtGen 1.2.0 is used instead.

Samples modeling the single production of T quarks were generated using the MadGraph5_aMC@NLO program [88] at LO in quantum chromodynamics (QCD) for matrix elements (ME) with the "VLQ" universal FeynRules output (UFO) model [97] implementing the Buchkremer model introduced in Ref. [98] and Eq. (1). The generated events were interfaced with 8.2 using the NNPDF2.3LO PDF set and the A14 tune. This model uses the 4-flavor scheme and all tree-level processes are included. The VLQs are assumed to couple exclusively to SM quarks of the third generation and SM bosons. In these analyses the pair production of VLQs is not considered.

Separate samples were produced for the $T(\to Ht)qb$, $T(\to Zt)qb$, $T(\to Ht)qt$, and $T(\to Zt)qt$ processes. Samples were generated with a 200 GeV spacing for $T(\to Ht)qb$ and $T(\to Zt)qb$ processes, and ME-based weights were used to reweight the samples to intermediate mass points to create 100 GeV intervals in the mass grid. Since the relative variations in the resonance lineshape of $T(\to Ht)qt$ and $T(\to Zt)qt$ samples are larger as a function of the T quark mass, the reweighting requires additional mass points for the precision desired, and samples for these processes were generated with 100 GeV mass spacing.

For similar reasons, the universal coupling between the T quark and the gauge boson, κ, was set to a value of 1.0 for the $T(\to Ht)qb$ and $T(\to Zt)qb$ samples, and reweighted to other values of κ down to a value of 0.1, while this reweighting for the $T(\to Ht)qt$ and $T(\to Zt)qt$ samples is only valid within much narrower ranges of κ. Thus, for the latter two processes, samples were produced at κ values of 0.2, 0.4, 0.7 and 1.0, and used to reweight to neighboring coupling values.

Benchmark samples with specific values of the relative coupling parameters $\vec{\xi}$ (where $\vec{\xi} = (\xi_W, \xi_Z, \xi_H) = (0.50, 0.25, 0.25)$ for SU(2) singlets in the high-mass asymptotic limit)[2] were constructed by combining the samples for individual production and decay modes by their appropriate relative proportions. The samples were normalized by multiplying the LO cross section times branching ratio for given assumed couplings by a correction factor to account for finite width effects [31,99], and by next-to-leading-order (NLO) k-factors computed in the narrow-width approximation [100]. A change in the dynamic scale in MadGraph5 at the T width-over-mass threshold $\Gamma_\mathrm{T}/m_\mathrm{T} = 0.1$, leads to a discontinuity in the computed cross section [99]. As a result, two different parameterizations of the cross section are available: $\sigma_\mathrm{low}(\Gamma_\mathrm{T}/m_\mathrm{T})$ for the $\Gamma_\mathrm{T}/m_\mathrm{T} < 0.1$ regime, and $\sigma_\mathrm{high}(\Gamma_\mathrm{T}/m_\mathrm{T})$ for $\Gamma_\mathrm{T}/m_\mathrm{T} > 0.1$. An averaging procedure is used to obtain a smooth cross section $\sigma(\Gamma/M)$ across the

[2]The parameterization of VLQ Lagrangian in terms of the κ and $\vec{\xi}$ parameters was introduced in Ref. [31] and is used for the interpretation presented. The conversion to the coupling convention in Eq. (1) is obtained through a one-to-one mapping of the tree-level couplings in the Lagrangian. The ξ_W, ξ_Z, ξ_H parameters satisfy the constraint $\xi_W + \xi_Z + \xi_H = 1$ and represent the branching ratios of T decaying into Wb, Zt, and Ht in the narrow-width approximation.

TABLE III. Summary of the target signal and decay channels for the three analyses included in the combination and the discriminating variables used.

Analysis	Target signal	Decay channels	Discriminants
Monotop	$Wb/Zt \to T \to Zt$	$Zt \to \nu\nu bqq$ (0ℓ)	BDT score
HtZt	$Wb/Zt \to T \to Ht/Zt$	$Ht/Zt \to bbb\ell\nu/qqb\ell\nu$ (1ℓ)	m_{eff}
Osml	$Wb/Zt \to T \to Zt$	$Zt \to \ell\ell b\ell\nu$ (3ℓ), $Zt \to \ell\ell bqq$ (2ℓ)	Z boson p_{T}

mass and coupling grid:

$$\sigma(\Gamma_{\mathrm{T}}/m_{\mathrm{T}}) = \begin{cases} \sigma_{\mathrm{low}}(\Gamma_{\mathrm{T}}/m_{\mathrm{T}}) + \frac{1}{2}[\sigma_{\mathrm{high}}(0.1) - \sigma_{\mathrm{low}}(0.1)], & \text{if } \Gamma_{\mathrm{T}}/m_{\mathrm{T}} < 0.1 \\ \sigma_{\mathrm{high}}(\Gamma_{\mathrm{T}}/m_{\mathrm{T}}) - \frac{1}{2}[\sigma_{\mathrm{high}}(0.1) - \sigma_{\mathrm{low}}(0.1)], & \text{if } \Gamma_{\mathrm{T}}/m_{\mathrm{T}} \geq 0.1. \end{cases}$$

An additional uncertainty of $\frac{1}{2}[\sigma_{\mathrm{high}}(0.1) - \sigma_{\mathrm{low}}(0.1)]$ is assigned on the cross section at every point to account for this choice.

IV. DESCRIPTION OF INPUT ANALYSES

The analyses search for the production of charged $+2e/3$ vectorlike T quarks that decay into a H boson and a top quark ($T \to Ht$) or a Z boson and a top quark ($T \to Zt$). The targeted vectorlike T production topology is displayed in Fig. 1. Four production and decay modes are possible: $Wb \to T \to Ht$, $Wb \to T \to Zt$, $Zt \to T \to Ht$, and $Zt \to T \to Zt$. The final state is characterized by the presence of multiple (b-tagged) jets due to the SM quarks and bosons produced, along with the recoiling initial-state quark which typically manifests as a forward jet. Due to the difference between the masses of the top and bottom quarks, b-associated (or W-mediated) T production is kinematically favored over t-associated (or Z-mediated) production. However, in certain gauge representations, such as with a (T, B) or an (X, T) SU(2) doublet, the coupling to W bosons vanishes, and the t-associated mode is the only allowed production channel.

Full descriptions of the event selection for the different analyses are available in Refs. [48,56,63]. A summary of the target signals, decay channels and discriminants of each analysis is given in Table III. Common features include the requirement of significant energy (or missing transverse momentum) observed in the detector as leptons (electrons or muons) and jets. Jets are reconstructed by applying the anti-k_t algorithm [101,102] to topological calorimeter-energy clusters and charged-particle tracks processed with a particle-flow algorithm [103] with fixed radius parameters of $R = 0.4$ (small-radius jets) and $R = 1.0$ (large-radius jets), and with a variable-radius parameter [104] optimized for top-quark tagging. Small-radius jets may be central ($|\eta| < 2.5$) or forward ($2.5 < |\eta| < 4.5$). Central jets may be b-tagged, while forward jets are a distinctive signature of singly produced T quarks, where the jet scatters off of a vector boson from one of the incoming partons. By design, these analyses have orthogonal selections. This is achieved by requiring exactly zero leptons in the Monotop analysis, exactly one lepton in the HtZt analysis, and two or more leptons in the Osml analysis. As a result, there are no overlapping events in the signal regions.

The Monotop analysis [48] focuses on events with a reconstructed boosted hadronically-decaying top quark produced in association with large missing transverse momentum and a forward jet. The output score of a boosted decision tree (BDT) algorithm is used in the definition of the signal, control and validation regions, and is the discriminating variable in the signal regions.

The HtZt search [63] analyzes data with final states containing a single lepton with multiple jets including b-jets and a forward jet. The presence of boosted heavy resonances in the event is exploited to discriminate the signal from the SM background. Due to the strong signal discrimination power, the "effective mass," m_{eff}, defined as the scalar sum of the transverse momentum (p_{T}) of all central small-radius jets and leptons in the event and the missing transverse energy, $E_{\mathrm{T}}^{\mathrm{miss}}$, is chosen as the observable. The analysis is split into five signal regions based on jet multiplicity to further enhance the sensitivity.

The final state of the Osml analysis [56] is characterized by the presence of a pair of electrons or muons with opposite-sign charges that forms a reconstructed Z boson candidate, and by the presence of b-tagged jets and a forward jet. Events with exactly two or at least three leptons are categorized into two independently optimized analysis channels. The transverse momentum of the Z boson is chosen as the observable due to its discriminating power.

V. STATISTICAL ANALYSIS AND SYSTEMATIC UNCERTAINTIES

For each benchmark scenario considered in this search, the distributions of the discriminating variables of each analysis across their respective search regions are jointly

TABLE IV. Summary of systematic uncertainties and normalization factors included in the combined likelihood fit. A ✓ indicates the uncertainty is included in a specific channel. The normalizations of the largest backgrounds in the HtZt analysis are constrained with nuisance parameters subject to Gaussian constraints.

Category	Monotop	HtZt	Osml	Correlating
Lepton and E_T^{miss} uncertainties				
Electron uncertainties		✓	✓	All
Muon uncertainties		✓	✓	All
E_T^{miss} uncertainties	✓	✓	✓	All
Jet uncertainties				
JES uncertainties	✓	✓	✓	All
JER uncertainties	✓	✓	✓	HtZt and Osml
JMS uncertainties		✓		None
JMR uncertainties	✓	✓		None
Tagging uncertainties				
Flavor-tagging uncertainties	✓	✓	✓	Monotop and Osml
Top-tagging uncertainties	✓			None
W/Z-tagging uncertainties	✓			None
Background modeling uncertainties (constrained)	✓	✓	✓	None
Background normalization factors (unconstrained)				
$t\bar{t}$ normalization	✓			None
$V+$jets normalization	✓			None
$Z+$light-jets normalization			✓	None
$Z+$heavy-flavor normalization			✓	None
$t\bar{t}V$ normalization			✓	None
VV normalization			✓	None

analyzed to test for the presence of signal. A combined likelihood function is constructed as a product of Poisson probability terms over all bins considered in each analysis. Systematic uncertainties are implemented as nuisance parameters with constraints described by Gaussian distributions.

The three analyses take different approaches to model their respective backgrounds with different associated systematic uncertainties. Although they explore significantly different phase spaces, $t\bar{t}$ (and $t\bar{t}V$), $Z+$jets and diboson production dominate the background in the signal regions. Each analysis applies a different background treatment, and as the specific background contributions vary, the normalization factors are also determined independently. As a result, uncertainties in the theoretical modeling and normalization of the background processes in each of the analyses are assumed to be uncorrelated as each analysis probes a significantly different region of phase space.

Detector-related uncertainties are applied, including those pertaining to the lepton measurement and identification, missing transverse momentum measurement, and jet-related quantities. These uncertainties are applied to both signal and background samples and are correlated where similar selection criteria are used (see Table IV). Furthermore, each of the analyses employs b-tagging to enhance the signal separation. In the Monotop and Osml analyses, the b-tagging implementation is identical and the associated systematic uncertainties are correlated. The HtZt analysis uses track-based jets instead of calorimeter-based jets and therefore the systematic uncertainties are left uncorrelated between this channel and the other two. In practice the choice of decorrelating this channel is observed to have no impact on the result.

Similar to the b-tagging uncertainties, jet-related systematic uncertainties are considered to be correlated only between analyses that use the same jet definition. There are three exceptions. First, the jet energy resolution (JER) uncertainty is decorrelated between the Monotop analysis and the others, as the former uses a more detailed scheme for this uncertainty, which was not necessary for the other analyses. Decorrelating results in a larger, more conservative uncertainty but has no impact on the combination result. Although this is a conservative choice, in practice it is observed to have no impact on the result due to the insensitivity of the analyses to these jet uncertainties. Second, the jet energy scale (JES) uncertainties for small-radius jets and large-radius jets are partially correlated. This is implemented via a set of nuisance parameters, a subset of which are common to both types of jets, while other nuisance parameters in the set apply only to one of the two types of jets. Third, the jet mass resolution (JMR) uncertainties are uncorrelated between the HtZt and Monotop analyses (and are not present in the Osml analysis). The Monotop analysis uses JMR uncertainties related to

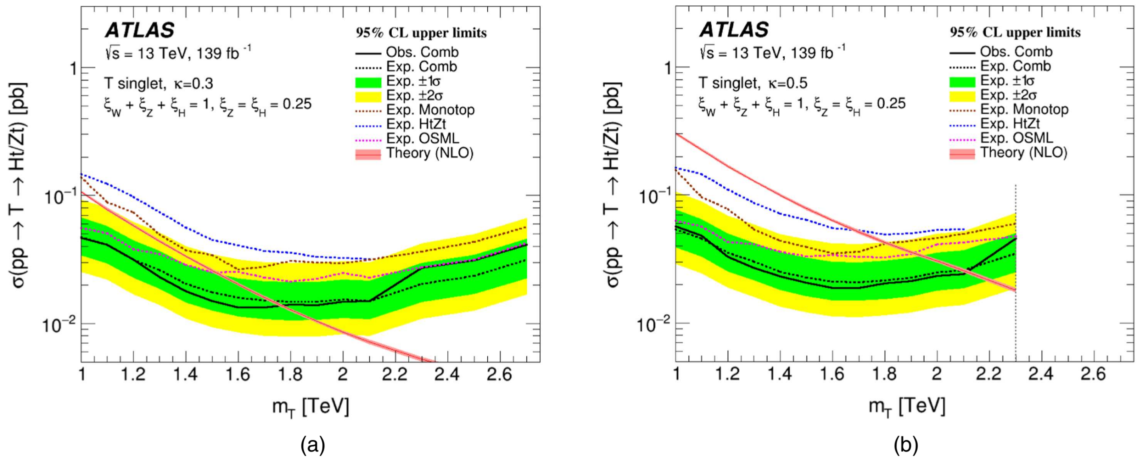

FIG. 2. Observed (solid line) and expected (dashed line) 95% CL upper limits on the total cross section $\sigma(pp \to T \to Ht/Zt)$ as a function of T mass in the SU(2) singlet representation assuming (a) $\kappa = 0.3$ and (b) $\kappa = 0.5$. The surrounding shaded bands correspond to 1 and 2 standard deviations around the expected limit. A vertical dashed line is drawn to indicate the lower edge of the region with $\Gamma_T/m_T > 50\%$ for which the theoretical calculations are no longer valid. The expected limits for the individual analyses are shown. The HtZt analysis is only included in the limit calculation for $m_T < 2.1$ TeV. The red line shows the NLO theoretical cross section prediction, with the surrounding shaded band representing the corresponding uncertainty.

large-radius jets, while the HtZt analysis uses JMR uncertainties related to small-radius jets.

Detector uncertainties affecting the signal acceptance are considered when setting exclusion limits, but uncertainties affecting the production cross section or signal shape are not. However, the uncertainty in the theoretical signal cross section prediction (Sec. III) is shown in Figs. 2 and 3.

Uncertainties due to the limited size of the simulated samples are taken into account with dedicated parameters in the fit that are independent across the bins. These parameters are included with Poisson constraints. Finally, a set of unconstrained parameters are included to control the normalization of certain background processes in each analysis. Table IV summarizes the systematic uncertainty model used in the fit.

The likelihood function depends on the signal-strength parameter μ, which multiplies the predicted production cross section for signal, and θ, the set of nuisance parameters that encode the effect of systematic

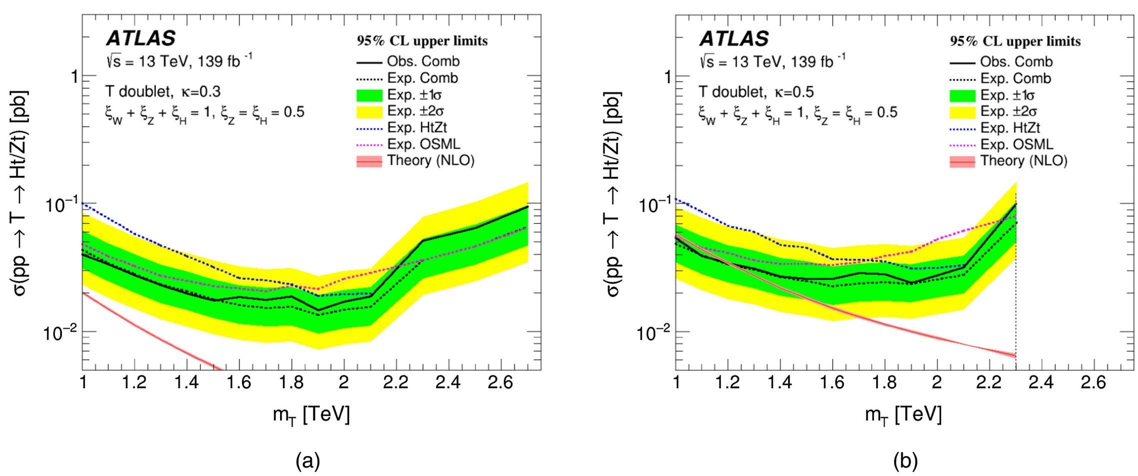

FIG. 3. Observed (solid line) and expected (dashed line) 95% CL upper limits on the total cross section $\sigma(pp \to T \to Ht/Zt)$ as a function of T mass in the SU(2) doublet representation assuming (a) $\kappa = 0.3$ and (b) $\kappa = 0.5$. The surrounding shaded bands correspond to 1 and 2 standard deviations around the expected limit. A vertical dashed line is drawn to indicate the lower edge of the region with $\Gamma_T/m_T > 50\%$ for which the theoretical calculations are no longer valid. The expected limits for HtZt and Osml analyses are shown; the Monotop analysis is not shown due to substantially less sensitivity in this scenario. However, the Monotop analysis is included in the combined limit calculation. The HtZt analysis is only included in the limit calculation for $m_T < 2.1$ TeV. The red line shows the NLO theoretical cross section prediction, with the surrounding shaded band representing the corresponding uncertainty.

uncertainties in the signal and background expectations. Therefore, the expected total number of events in a given bin depends on μ and θ.

The test statistic q_μ is defined as the profile likelihood ratio: $q_\mu = -2\ln(\mathcal{L}(\mu, \hat{\hat{\theta}}_\mu)/\mathcal{L}(\hat{\mu}, \hat{\theta}))$. Here, $\hat{\mu}$ and $\hat{\theta}$ are the values of the parameters μ and θ that simultaneously maximize the likelihood function $\mathcal{L}(\mu, \theta)$ (subject to the constraint $0 \leq \hat{\mu} \leq \mu$), whereas $\hat{\hat{\theta}}_\mu$ are the values of the nuisance parameters that maximize the likelihood function for a given value of μ. The statistic used for the discovery test, to compute the compatibility of the observed data with the background-only hypothesis, is obtained by setting $\mu = 0$ in the profile likelihood ratio and leaving $\hat{\mu}$ unconstrained: $q_0 = -2\ln(\mathcal{L}(0, \hat{\hat{\theta}}_0)/\mathcal{L}(\hat{\mu}, \hat{\theta}))$. The p-value of the discovery test is given by the integral of the probability distribution of q_0 above the observed q_0 value when assuming the background-only hypothesis, and it is computed using the asymptotic approximation detailed in Ref. [105]. For each signal scenario considered, the upper limit on the signal production cross section is computed using q_μ in the $\mathrm{CL_s}$ method [106,107], also in the asymptotic approximation. For a given signal scenario, values of the production cross section (parametrized by μ) yielding $\mathrm{CL_s} < 0.05$ are excluded at $\geq 95\%$ CL. The combination is performed with RooStats [108] with statistical models implemented using RooFit [109] and HistFactory [110].

VI. RESULTS

No significant excess above the SM expectations is observed in any of the analysis channels considered for the combination. A signal search is performed using the combined analyses and no significant excess is found. Scanning across the m_T and κ parameters, the most significant local p_0-value of 0.14 (0.10) for the SU(2) singlet (doublet) interpretation is found for the signal point $m_\mathrm{T} = 2.1$ TeV and $\kappa = 0.1$. Good agreement with SM predictions is also found in the combined background-only fit to data. Therefore, upper limits on the cross section are set at 95% CL as a function of m_T and κ. The limits are calculated for the sum of the production cross sections times branching ratio of the four production and decay modes considered and denoted as $\sigma(pp \to T \to Zt/Ht)$. In contrast, the Osml and Monotop analyses were not designed to be sensitive to the $T \to Ht$ decay mode, and thus the corresponding publications reported upper limits on a subset of the processes ($T \to Zt$).

By comparing the obtained cross-section limits with the theoretical cross section, limits are derived on m_T and κ. As the signal efficiencies for the considered signal modes are generally different, limits are independently determined for combinations of m_T, κ, and branching ratios. Motivated by the Goldstone equivalence theorem [111], which states that the branching ratios of T quark decaying into Zt and Ht become similar in the large-m_T limit under the narrow-width approximation, $\xi_Z = \xi_H$ is required.

The expected and observed limits on the $T \to Ht/Zt$ cross section from the combination are presented for several illustrative benchmark points for the SU(2) singlet (with a branching ratio $T \to Wb$ of 0.5) and doublet (with a branching ratio $T \to Wb$ of 0.0) representations. Figure 2 (Fig. 3) shows the limits on the total cross section of the sum of the production and decay processes for the SU(2) singlet (doublet) representation assuming $\kappa = 0.3$, 0.5.

Following Ref. [112], this interpretation is only used where $\Gamma_\mathrm{T}/m_\mathrm{T}$ is smaller than 50%, the region in which the correction factors for the finite-width approximation and the non-resonant contributions [31,99] are also valid. In Figs. 2(b) and 3(b) a vertical dashed line is drawn to indicate the lower edge of the region with $\Gamma_\mathrm{T}/m_\mathrm{T} > 50\%$. Such lower edge extends to lower mass values as the κ value increases. As a result, the highest mass for which the limit is shown decreases as the value of κ increases.

Results from the individual channels are overlaid on the combined results for comparison. The statistical combination improves the limits over the individual results for all masses and couplings. Existing limits from searches for VLQ pair production exclude T masses less than 1.5 TeV, with the assumption of narrow-width resonances. These analyses do not consider pair production signals. For the SU(2) doublet representation, the combination also includes the Monotop analysis, although its contribution is negligible. For this reason, Fig. 3 shows the limits from the Osml and HtZt analyses only. In both Figs. 2 and 3 the HtZt analysis is included in the combination for $m_\mathrm{T} < 2.1$ TeV, for consistency with the existing analysis.

The complementarity of the different analysis channels is also evident in Figs. 2 and 3. For example, the Osml analysis is most sensitive at low masses, while the sensitivity of the HtZt analysis can be seen to improve at higher masses. This is especially true in the SU(2) doublet representation, as the HtZt analysis includes signal regions that are specifically designed to target Z-mediated production processes. The experimental sensitivity of the individual channels and the combination depends on both the mass and width of the T quark. In the Osml analysis, the mass dependence is clear, with the limit degrading above 2.1 TeV. This is due to the choice of binning of the discriminant (the reconstructed Z boson p_T), which was optimized to search for T quarks with masses less than 2.0 TeV. On the other hand, all three analyses use discriminants that are relatively agnostic to the resonance width (e.g., the m_eff variable for the HtZt analysis, and the reconstructed Z boson p_T in the Osml analysis). Thus, the excluded cross section does not strongly depend on $\Gamma_\mathrm{T}/m_\mathrm{T}$ for the κ values shown in Figs. 2 and 3.

The combination increases the sensitivity to a wider range of model parameters (generalized as the coupling κ) beyond the existing analyses. The cross-section limits calculated for different choices of coupling are interpreted

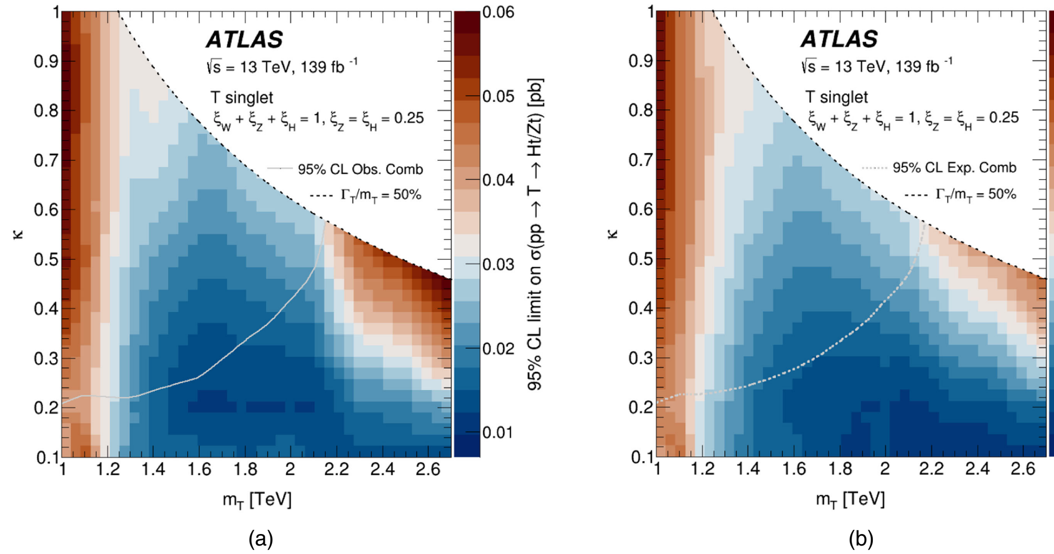

FIG. 4. (a) Observed and (b) expected 95% CL exclusion limits on the total cross section $\sigma(pp \to T \to Ht/Zt)$ as a function of the universal coupling constant κ and the T mass in the SU(2) singlet representation. All values of κ above the white contour line are excluded at each mass point. Limits are only presented in the regime $\Gamma_T/m_T < 50\%$, where the theory calculations are known to be valid.

as exclusion limits computed as a function of m_T and κ. Figure 4 (Fig. 5) shows the observed and expected limits on the total cross section for the SU(2) singlet (doublet) representation. The limits are obtained for points on the m_T–κ grid, spaced by 100 GeV in mass, and by 0.1 in κ. All three channels are combined for masses up to 2.1 TeV.

As a function of m_T and κ, Figs. 4 and 5 show the exclusion in a dashed line, where the region above and to the left (toward lower masses and larger couplings) is excluded. Figure 6 shows the excluded regions in the m_T–κ plane in more detail. The limits are computed for a finite number of points in the m_T–κ plane. As a result, the limits are interpolated using a piecewise function [113] between the measured points to obtain a continuous shape for the exclusion contours on the m_T–κ plane. The exclusion contours are shown both for the combination and for the individual channels. Also shown in Fig. 6 are the isolines corresponding to different values of Γ_T/m_T. Limits are only

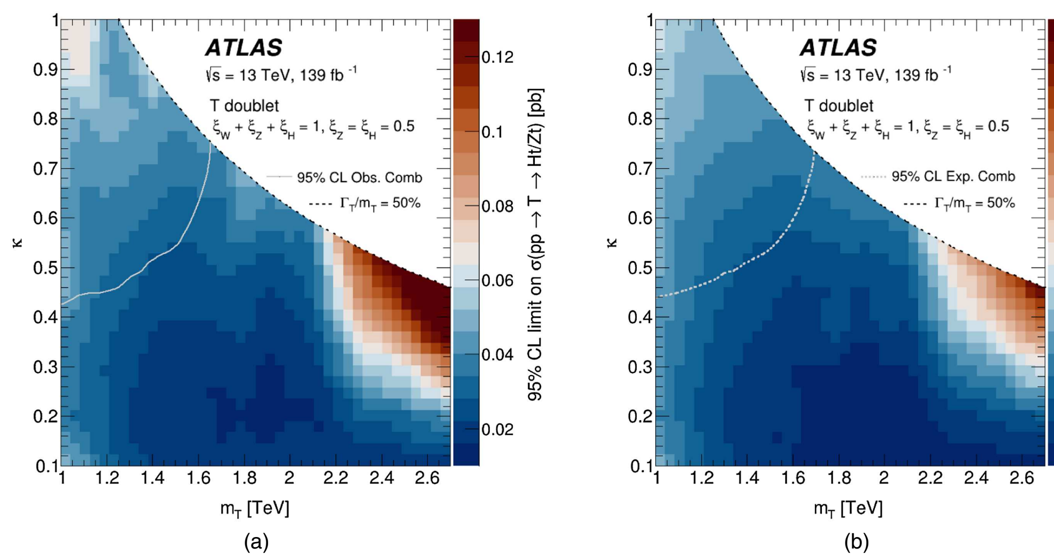

FIG. 5. (a) Observed and (b) expected 95% CL exclusion limits on the total cross section $\sigma(pp \to T \to Ht/Zt)$ as a function of the universal coupling constant κ and the T quark mass in the SU(2) doublet representation. All values of κ above the white contour line are excluded at each mass point. Limits are only presented in the regime $\Gamma_T/m_T < 50\%$, where the theory calculations are known to be valid.

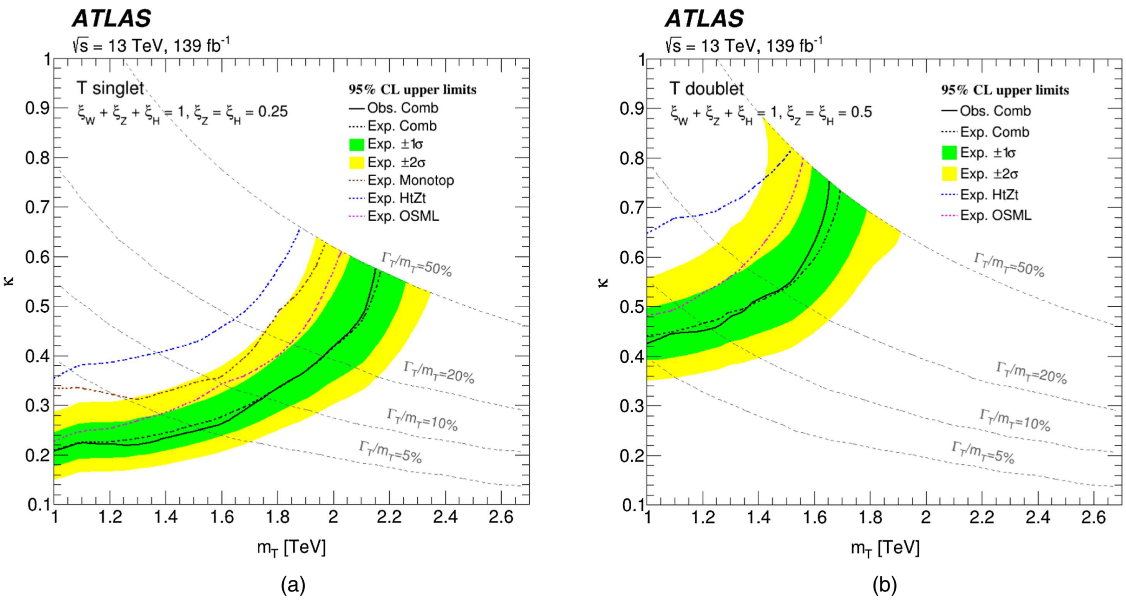

FIG. 6. Observed (solid line) and expected (dashed line) 95% CL exclusion limits on the universal coupling constant κ as a function of the T quark mass in the (a) SU(2) singlet and (b) SU(2) doublet representations for the combination. All values of κ above the black contour lines are excluded at each mass point. The shaded bands correspond to 1 and 2 standard deviations around the expected limit. Also shown are the expected limits for the individual analyses. The gray dashed lines represent configurations of (m_T, κ) resulting in equal values of the relative resonance width $\Gamma_\mathrm{T}/m_\mathrm{T}$. Limits are only presented in the regime $\Gamma_\mathrm{T}/m_\mathrm{T} < 50\%$, where the theory calculations are known to be valid.

shown for the parameter range where $\Gamma_\mathrm{T}/m_\mathrm{T} < 50\%$, where the theory calculations are known to be valid.

The combination of the three searches significantly improves the exclusion limits from the individual channels. In the SU(2) singlet representation, the coupling parameter κ is constrained to be below 0.2 for the lower masses, and the mass is excluded up to 2.1 TeV for κ values near 0.6. The cross section of a singly-produced T quark is constrained to be below 18 fb for masses in the range of 1.4–2.2 TeV and $\kappa = 0.3$ for the SU(2) singlet representation. Similarly, for the SU(2) doublet representation the coupling parameter κ is constrained to be below 0.4 for the lower masses, and the mass is excluded up to 1.7 TeV for κ values near 0.7. The cross section of a singly produced T quark is constrained to be below 20 fb for masses in the range of 1.4–2.1 TeV and $\kappa = 0.3$ in the SU(2) doublet

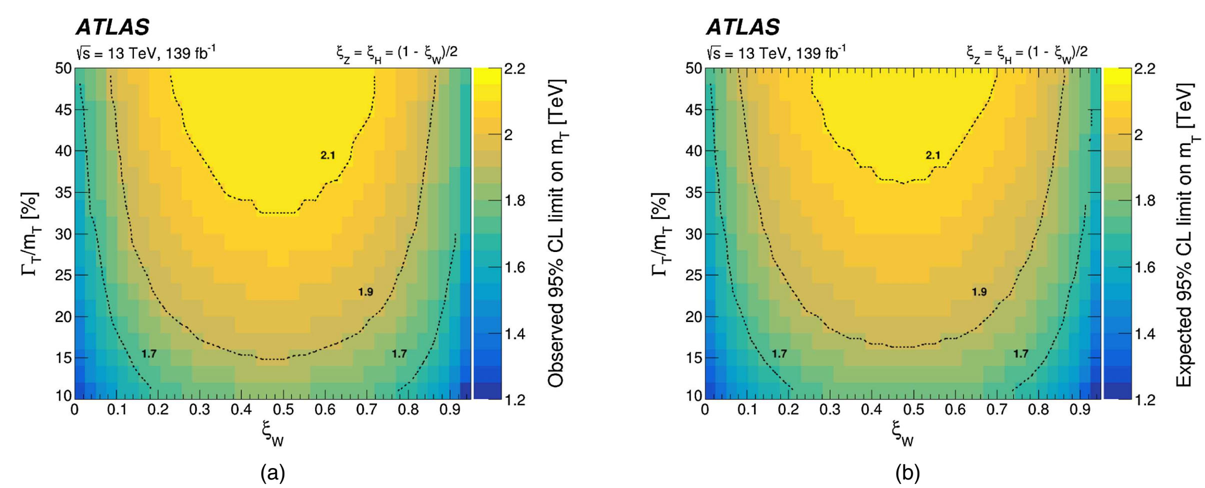

FIG. 7. (a) Observed and (b) expected upper limits at 95% CL on the T-quark mass as a function of the relative resonance width $(\Gamma_\mathrm{T}/m_\mathrm{T})$ and the relative coupling parameter ξ_W, for the assumption $\xi_Z = \xi_W$. The values $\xi_W = 0.5$ and $\xi_W = 0.0$ correspond to the SU(2) singlet and SU(2) doublet representations, respectively. The dashed contour lines denote exclusion limits of equal mass in units of TeV.

TABLE V. Summary of mass limits for SU(2) singlet and doublet representations with varying Γ_T/m_T ratios. Both observed (Obs.) and expected (Exp.) limits are presented.

Representation	Γ_T/m_T [%]	Obs./Exp. mass limit [TeV]
SU(2) singlet ($\xi_W = 0.5$)	20	2.0/2.0
SU(2) singlet ($\xi_W = 0.5$)	50	2.1/2.1
SU(2) doublet ($\xi_W = 0.0$)	20	1.4/1.4
SU(2) doublet ($\xi_W = 0.0$)	50	1.6/1.7

representation. In both the SU(2) singlet and doublet representations, the observed cross section limits are slightly higher than the expected cross-section limits for $\kappa = 0.3$ and $\kappa = 0.5$ for $m_T > 2.2$ TeV.

The exclusion limits shown can be generalized for arbitrary values of the ξ_W parameter. Figure 7 shows the observed and expected exclusions on the T quark mass across the plane spanned by ξ_W and Γ_T/m_T. The relative width Γ_T/m_T of the T quark is completely determined by the m_T and κ parameters. The results are shown under the theoretically motivated assumption $\xi_Z = \xi_H$.

As expected from the previous results, the combination improves the exclusion limits from the individual channels. The largest excluded mass is 2.1 TeV for large Γ_T/m_T and $\xi_W = 0.5$. This is equivalent to the SU(2) singlet representation, with a branching ratio to Wb of 50%. The lowest excluded masses are observed for small Γ_T/m_T (lower cross section) near $\xi_W = 0.0$ and $\xi_W = 1.0$. As ξ_W approaches 0.0, the T quark only decays into Zt and Ht, while as ξ_W approaches 1.0 there is no decay to either Zt or Ht. The overview of benchmark mass limits is shown in Table V.

VII. CONCLUSIONS

The first combination of results from the ATLAS Collaboration of searches for the single production of vectorlike top quarks (T) decaying into Ht or Zt in hadronic and semileptonic final states has been presented. Data from pp collisions at $\sqrt{s} = 13$ TeV collected with the ATLAS detector at the LHC during 2015–2018 were used. The dataset corresponds to an integrated luminosity of $139 \mathrm{fb}^{-1}$. The observed data are consistent with the background prediction of the SM. Without a significant excess above the SM expectation, upper limits at 95% CL are provided for a range of masses and couplings of the vectorlike top quark, based on benchmark models and generalized representations. Additionally, the exclusion limits as a function of mass (m_T), coupling (κ), relative width (Γ_T/m_T) and branching ratio are provided.

The 95% CL limits on the cross section for T production in the SU(2) singlet representation are less than 47 fb (57 fb) for all m_T between 1.0 and 2.7 (2.3) TeV for coupling $\kappa = 0.3$ (0.5), with a limit of 13 fb for $\kappa = 0.3$ and $m_T = 1.6$ TeV. In the SU(2) doublet representation, the 95% CL limits on the cross section are less than 95 fb (100 pb) over the same mass region and coupling values, with a limit of 15 fb for $\kappa = 0.3$ and $m_T = 1.9$ TeV. The combined results improves the cross-section limits over the individual analysis limits by a factor of two in some cases. In the SU(2) singlet (doublet) representation, T production is entirely excluded for $\kappa > 0.57$ (0.72), with the requirement that $\Gamma_T/m_T < 50\%$. For $\Gamma_T/m_T < 5\%$, SU(2) singlet T production is excluded for $m_T < 1.5$ TeV and $\kappa < 0.25$.

In the benchmark scenario of SU(2) singlet T production with $\Gamma_T/m_T = 20\%$, masses less than 2.0 TeV are excluded at the 95% CL, while in the SU(2) doublet representation with $\Gamma_T/m_T = 20\%$ masses less than 1.4 TeV are excluded. The highest excluded mass is found for the SU(2) singlet representation assuming $\Gamma_T/m_T = 50\%$, where masses up to 2.1 TeV are excluded. This significantly surpasses the reach of the individual searches. These results provide the most restrictive limits on the single production of T quarks to date.

ACKNOWLEDGMENTS

We thank CERN for the very successful operation of the LHC and its injectors, as well as the support staff at CERN and at our institutions worldwide without whom ATLAS could not be operated efficiently. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF/SFU (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [114]. We gratefully 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; MNiSW, Poland; FCT, Portugal; MNE/IFA, Romania; MSTDI, Serbia; MSSR, Slovakia; ARIS and MVZI, Slovenia; DSI/NRF, South Africa; MICIU/AEI, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; NSTC, Taipei; TENMAK, Türkiye; STFC/UKRI, United Kingdom; DOE and NSF, U.S. Individual groups and members have received support from BCKDF, CANARIE, CRC and DRAC, Canada; CERN-CZ, FORTE and PRIMUS, Czech Republic;

COST, ERC, ERDF, Horizon 2020, ICSC-NextGenerationEU and Marie Skłodowska-Curie Actions, European Union; Investissements d'Avenir Labex, Investissements d'Avenir Idex and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and MINERVA, Israel; NCN and NAWA, Poland; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom. In addition, individual members wish to acknowledge support from Armenia: Yerevan Physics Institute (FAPERJ); CERN: European Organization for Nuclear Research (CERN PJAS); Chile: Agencia Nacional de Investigación y Desarrollo (FONDECYT 1230812, FONDECYT 1230987, FONDECYT 1240864); China: Chinese Ministry of Science and Technology (MOST-2023YFA1605700), National Natural Science Foundation of China (NSFC—12175119, NSFC 12275265, NSFC-12075060); Czech Republic: Czech Science Foundation (GACR—24-11373S), Ministry of Education Youth and Sports (FORTE CZ.02.01.01/00/22_008/0004632), PRIMUS Research Programme (PRIMUS/21/SCI/017); EU: H2020 European Research Council (ERC—101002463); European Union: European Research Council (ERC—948254, ERC 101089007), Horizon 2020 Framework Programme (MUCCA—CHIST-ERA-19-XAI-00), European Union, Future Artificial Intelligence Research (FAIR-NextGenerationEU PE00000013), Italian Center for High Performance Computing, Big Data and Quantum Computing (ICSC, NextGenerationEU); France: Agence Nationale de la Recherche (ANR-20-CE31-0013, ANR-21-CE31-0013, ANR-21-CE31-0022, ANR-22-EDIR-0002), Investissements d'Avenir Labex (ANR-11-LABX-0012); Germany: Baden-Württemberg Stiftung (BW Stiftung-Postdoc Eliteprogramme), Deutsche Forschungsgemeinschaft (DFG—469666862, DFG—CR 312/5-2); Italy: Istituto Nazionale di Fisica Nucleare (ICSC, NextGenerationEU), Ministero dell'Università e della Ricerca (PRIN—20223N7F8K—PNRR M4.C2.1.1); Japan: Japan Society for the Promotion of Science (JSPS KAKENHI JP22H01227, JSPS KAKENHI JP22H04944, JSPS KAKENHI JP22KK0227, JSPS KAKENHI JP23KK0245); Netherlands: Netherlands Organisation for Scientific Research (NWO Veni 2020—VI.Veni.202.179); Norway: Research Council of Norway (RCN-314472); Poland: Ministry of Science and Higher Education (IDUB AGH, POB8, D4 no 9722), Polish National Agency for Academic Exchange (PPN/PPO/2020/1/00002/U/00001), Polish National Science Centre (NCN 2021/42/E/ST2/00350, NCN OPUS nr 2022/47/B/ST2/03059, NCN UMO-2019/34/E/ST2/00393, NCN & H2020 MSCA 945339, UMO-2020/37/B/ST2/01043, UMO-2021/40/C/ST2/00187, UMO-2022/47/O/ST2/00148, UMO-2023/49/B/ST2/04085, UMO-2023/51/B/ST2/00920); Slovenia: Slovenian Research Agency (ARIS grant J1-3010); Spain: Generalitat Valenciana (Artemisa, FEDER, IDIFEDER/2018/048), Ministry of Science and Innovation (MCIN & NextGenEU PCI2022-135018-2, MICIN & FEDER PID2021-125273NB, RYC2019-028510-I, RYC2020-030254-I, RYC2021-031273-I, RYC2022-038164-I), PROMETEO and GenT Programmes Generalitat Valenciana (CIDEGENT/2019/027); Sweden: Carl Trygger Foundation (Carl Trygger Foundation CTS 22:2312), Swedish Research Council (Swedish Research Council 2023-04654, VR 2018-00482, VR 2022-03845, VR 2022-04683, VR 2023-03403, VR grant 2021-03651), Knut and Alice Wallenberg Foundation (KAW 2018.0157, KAW 2018.0458, KAW 2019.0447, KAW 2022.0358); Switzerland: Swiss National Science Foundation (SNSF—PCEFP2_194658); United Kingdom: Leverhulme Trust (Leverhulme Trust RPG-2020-004), Royal Society (NIF-R1-231091); U.S.: U.S. Department of Energy (ECA DE-AC02-76SF00515), Neubauer Family Foundation.

[1] The ALEPH, DELPHI, L3, OPAL, SLD, the LEP Electroweak Working Group, the SLD Electroweak and Heavy Flavor Groups, Precision electroweak measurements on the Z resonance, Phys. Rep. **427**, 257 (2006).

[2] The ALEPH, DELPHI, L3, OPAL Collaborations and the LEP Electroweak Working Group, Electroweak measurements in electron-positron collisions at W-boson-pair energies at LEP, Phys. Rep. **532**, 119 (2013).

[3] 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**, 1 (2012).

[4] CMS Collaboration, Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, Phys. Lett. B **716**, 30 (2012).

[5] L. Susskind, Dynamics of spontaneous symmetry breaking in the Weinberg-Salam theory, Phys. Rev. D **20**, 2619 (1979).

[6] Y. A. Golfand and E. P. Likhtman, Extension of the algebra of Poincare group generators and violation of P invariance, JETP Lett. **13**, 323 (1971).

[7] D. Volkov and V. Akulov, Is the neutrino a Goldstone particle?, Phys. Lett. **46B**, 109 (1973).

[8] J. Wess and B. Zumino, Supergauge transformations in four dimensions, Nucl. Phys. **B70**, 39 (1974).
[9] J. Wess and B. Zumino, Supergauge invariant extension of quantum electrodynamics, Nucl. Phys. **B78**, 1 (1974).
[10] S. Ferrara and B. Zumino, Supergauge invariant Yang-Mills theories, Nucl. Phys. **B79**, 413 (1974).
[11] A. Salam and J. Strathdee, Super-symmetry and non-Abelian gauges, Phys. Lett. **51B**, 353 (1974).
[12] C. T. Hill and E. H. Simmons, Strong dynamics and electroweak symmetry breaking, Phys. Rep. **381**, 235 (2003).
[13] N. Arkani-Hamed, A. Cohen, E. Katz, and A. Nelson, The littlest Higgs, J. High Energy Phys. 07 (2002) 034.
[14] M. Schmaltz and D. Tucker-Smith, Little Higgs theories, Annu. Rev. Nucl. Part. Sci. **55**, 229 (2005).
[15] D. B. Kaplan, H. Georgi, and S. Dimopoulos, Composite Higgs scalars, Phys. Lett. **136B**, 187 (1984).
[16] K. Agashe, R. Contino, and A. Pomarol, The minimal composite Higgs model, Nucl. Phys. **B719**, 165 (2005).
[17] F. del Aguila and M. J. Bowick, The possibility of new fermions with Δ I = 0 mass, Nucl. Phys. **B224**, 107 (1983).
[18] F. del Aguila, M. Pérez-Victoria, and J. Santiago, Effective description of quark mixing, Phys. Lett. B **492**, 98 (2000).
[19] J. Berger, J. Hubisz, and M. Perelstein, A fermionic top partner: Naturalness and the LHC, J. High Energy Phys. 07 (2012) 016.
[20] F. del Aguila, J. Santiago, and M. Pérez-Victoria, Observable contributions of new exotic quarks to quark mixing, J. High Energy Phys. 09 (2000) 011.
[21] B. Fuks and H.-S. Shao, QCD next-to-leading-order predictions matched to parton showers for vectorlike quark models, Eur. Phys. J. C **77**, 135 (2017).
[22] Y. Okada and L. Panizzi, LHC signatures of vector-like quarks, Adv. High Energy Phys. **2013**, 364936 (2013).
[23] J. Aguilar-Saavedra, R. Benbrik, S. Heinemeyer, and M. Pérez-Victoria, Handbook of vectorlike quarks: Mixing and single production, Phys. Rev. D **88**, 094010 (2013).
[24] A. Banerjee, V. Ellajosyula, and L. Panizzi, Heavy vector-like quarks decaying to exotic scalars: A case study with triplets, J. High Energy Phys. 01 (2024) 187.
[25] R. Contino and G. Servant, Discovering the top partners at the LHC using same-sign dilepton final states, J. High Energy Phys. 06 (2008) 026.
[26] J. Aguilar-Saavedra, Identifying top partners at LHC, J. High Energy Phys. 11 (2009) 030.
[27] A. De Simone, O. Matsedonskyi, R. Rattazzi, and A. Wulzer, A first top partner hunter's guide, J. High Energy Phys. 04 (2013) 004.
[28] O. Matsedonskyi, G. Panico, and A. Wulzer, On the interpretation of top partners searches, J. High Energy Phys. 12 (2014) 097.
[29] F. del Aguila, L. Ametller, G. L. Kane, and J. Vidal, Vector-like fermion and standard Higgs production at hadron colliders, Nucl. Phys. **B334**, 1 (1990).
[30] S. Glashow, J. Iliopoulos, and L. Maiani, Weak interactions with lepton-hadron symmetry, Phys. Rev. D **2**, 1285 (1970).
[31] A. Roy, N. Nikiforou, N. Castro, and T. Andeen, Novel interpretation strategy for searches of singly produced vectorlike quarks at the LHC, Phys. Rev. D **101**, 115027 (2020).
[32] ATLAS Collaboration, Combination of the searches for pair-produced vectorlike partners of the third-generation quarks at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Rev. Lett. **121**, 211801 (2018).
[33] ATLAS Collaboration, Search for pair and single production of vectorlike quarks in final states with at least one Z boson decaying into a pair of electrons or muons in pp collision data collected with the ATLAS detector, Phys. Rev. D **98**, 112010 (2018).
[34] ATLAS Collaboration, Search for pair production of heavy vectorlike quarks decaying into hadronic final states in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Rev. D **98**, 092005 (2018).
[35] ATLAS Collaboration, Search for new phenomena in events with same-charge leptons and b-jets in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, J. High Energy Phys. 12 (2018) 039.
[36] ATLAS Collaboration, Search for pair production of heavy vector-like quarks decaying into high-p_T W bosons and top quarks in the lepton-plus-jets final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, J. High Energy Phys. 08 (2018) 048.
[37] ATLAS Collaboration, Search for pair production of up-type vector-like quarks and for four-top-quark events in final states with multiple b-jets with the ATLAS detector, J. High Energy Phys. 07 (2018) 089.
[38] ATLAS Collaboration, Search for pair production of heavy vector-like quarks decaying to high-p_T W bosons and b quarks in the lepton-plus-jets final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, J. High Energy Phys. 10 (2017) 141.
[39] ATLAS Collaboration, Search for pair production of vector-like top quarks in events with one lepton, jets, and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector, J. High Energy Phys. 08 (2017) 052.
[40] CMS Collaboration, Search for pair production of vector-like quarks in the fully hadronic final state, Phys. Rev. D **100**, 072001 (2019).
[41] CMS Collaboration, Search for vector-like quarks in events with two oppositely charged leptons and jets in proton-proton collisions at $\sqrt{s} = 13$ TeV, Eur. Phys. J. C **79**, 364 (2019).
[42] CMS Collaboration, Search for vector-like T and B quark pairs in final states with leptons at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 08 (2018) 177.
[43] CMS Collaboration, Search for pair production of vector-like quarks in the $\mathrm{bW\bar{b}W}$ channel from proton-proton collisions at $\sqrt{s} = 13$ TeV, Phys. Lett. B **779**, 82 (2018).
[44] ATLAS Collaboration, Search for pair-production of vector-like quarks in pp collision events at $\sqrt{s} = 13$ TeV with at least one leptonically decaying Z boson and a third-generation quark with the ATLAS detector, Phys. Lett. B **843**, 138019 (2023).
[45] CMS Collaboration, Search for pair production of vector-like quarks in leptonic final states in proton–proton collisions at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 07 (2023) 020.

[46] ATLAS Collaboration, Search for pair-production of vector-like quarks in lepton + jets final states containing at least one b-tagged jet using the Run 2 data from the ATLAS experiment, Phys. Lett. B **854**, 138743 (2024).
[47] ATLAS Collaboration, Search for pair-produced vector-like top and bottom partners in events with large missing transverse momentum in pp collisions with the ATLAS detector, Eur. Phys. J. C **83**, 719 (2023).
[48] ATLAS Collaboration, Search for new particles in final states with a boosted top quark and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, J. High Energy Phys. 05 (2024) 263.
[49] ATLAS Collaboration, Search for single production of vector-like quarks decaying into Wb in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, J. High Energy Phys. 05 (2019) 164.
[50] CMS Collaboration, Search for electroweak production of a vector-like T quark using fully hadronic final states, J. High Energy Phys. 01 (2020) 036.
[51] CMS Collaboration, Search for single production of vector-like quarks decaying to a top quark and a W boson in proton-proton collisions at $\sqrt{s} = 13$ TeV, Eur. Phys. J. C **79**, 90 (2019).
[52] CMS Collaboration, Search for single production of vector-like quarks decaying to a b quark and a Higgs boson, J. High Energy Phys. 06 (2018) 031.
[53] ATLAS Collaboration, Search for pair and single production of vectorlike quarks in final states with at least one Z boson decaying into a pair of electrons or muons in pp collision data collected with the ATLAS detector, Phys. Rev. D **98**, 112010 (2018).
[54] CMS Collaboration, Search for single production of a vector-like T quark decaying to a Z boson and a top quark in proton-proton collisions at $\sqrt{s} = 13$ TeV, Phys. Lett. B **781**, 574 (2018).
[55] ATLAS Collaboration, Search for single production of a vectorlike T quark decaying into a Higgs boson and top quark with fully hadronic final states using the ATLAS detector, Phys. Rev. D **105**, 092012 (2022).
[56] ATLAS Collaboration, Search for singly produced vector-like top partners in multilepton final states with 139 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Rev. D **109**, 112012 (2024).
[57] ATLAS Collaboration, Search for single production of vector-like T quarks decaying into Ht or Zt in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, J. High Energy Phys. 08 (2023) 153.
[58] CMS Collaboration, Search for single production of a vector-like T quark decaying to a top quark and a Z boson in the final state with jets and missing transverse momentum at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 05 (2022) 093.
[59] CMS Collaboration, Search for a vector-like quark $T' \to tH$ via the diphoton decay mode of the Higgs boson in proton–proton collisions at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 09 (2023) 057.
[60] CMS Collaboration, Search for production of a single vector-like quark decaying to tH or tZ in the all-hadronic final state in pp collisions at $\sqrt{s} = 13$ TeV, Phys. Rev. D **110**, 072012 (2024).
[61] ATLAS Collaboration, Exploration at the high-energy frontier: ATLAS Run 2 searches investigating the exotic jungle beyond the standard model, arXiv:2403.09292.
[62] CMS Collaboration, Review of searches for vector-like quarks, vector-like leptons, and heavy neutral leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV at the CMS experiment, arXiv:2405.17605.
[63] ATLAS Collaboration, Search for single production of vector-like T quarks decaying into Ht or Zt in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, J. High Energy Phys. 08 (2023) 153.
[64] ATLAS Collaboration, The ATLAS experiment at the CERN Large Hadron Collider, J. Instrum. **3**, S08003 (2008).
[65] G. Avoni *et al.*, The new LUCID-2 detector for luminosity measurement and monitoring in ATLAS, J. Instrum. **13**, P07017 (2018).
[66] ATLAS Collaboration, Performance of the ATLAS trigger system in 2015, Eur. Phys. J. C **77**, 317 (2017).
[67] ATLAS Collaboration, Software and computing for Run 3 of the ATLAS experiment at the LHC, arXiv:2404.06335.
[68] ATLAS Collaboration, Luminosity determination in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC, Eur. Phys. J. C **83**, 982 (2023).
[69] ATLAS Collaboration, Performance of electron and photon triggers in ATLAS during LHC Run 2, Eur. Phys. J. C **80**, 47 (2020).
[70] ATLAS Collaboration, Performance of the ATLAS muon triggers in Run 2, J. Instrum. **15**, P09015 (2020).
[71] ATLAS Collaboration, Performance of the ATLAS Level-1 topological trigger in Run 2, Eur. Phys. J. C **82**, 7 (2022).
[72] ATLAS Collaboration, ATLAS data quality operations and performance for 2015–2018 data-taking, J. Instrum. **15**, P04003 (2020).
[73] ATLAS Collaboration, The ATLAS simulation infrastructure, Eur. Phys. J. C **70**, 823 (2010).
[74] S. Agostinelli *et al.*, Geant4—A simulation toolkit, Nucl. Instrum. Methods Phys. Res., Sect. A **506**, 250 (2003).
[75] ATLAS Collaboration, The simulation principle and performance of the ATLAS fast calorimeter simulation FastCaloSim, Report No. ATL-PHYS-PUB-2010-013, 2010, https://cds.cern.ch/record/1300517.
[76] T. Sjöstrand, S. Mrenna, and P. Skands, A brief introduction to PYTHIA 8.1, Comput. Phys. Commun. **178**, 852 (2008).
[77] R. D. Ball *et al.* (NNPDF Collaboration), Parton distributions with LHC data, Nucl. Phys. **B867**, 244 (2013).
[78] ATLAS Collaboration, The PYTHIA 8 A3 tune description of ATLAS minimum bias and inelastic measurements incorporating the Donnachie–Landshoff diffractive model, Report No. ATL-PHYS-PUB-2016-017, 2016, https://cds.cern.ch/record/2206965.
[79] T. Gleisberg, S. Hoche, F. Krauss, M. Schonherr, S. Schumann, F. Siegert, and J. Winter, Event generation with Sherpa 1.1, J. High Energy Phys. 02 (2009) 007.
[80] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, An introduction to PYTHIA 8.2, Comput. Phys. Commun. **191**, 159 (2015).

[81] R. D. Ball et al. (NNPDF Collaboration), Parton distributions for the LHC Run II, J. High Energy Phys. 04 (2015) 040.
[82] ATLAS Collaboration, ATLAS PYTHIA 8 tunes to 7 TeV data, Report No. ATL-PHYS-PUB-2014-021, 2014, https://cds.cern.ch/record/1966419.
[83] J. Bellm et al., Herwig 7.0/Herwig++ 3.0 release note, Eur. Phys. J. C **76**, 196 (2016).
[84] M. Bähr et al., Herwig++ physics and manual, Eur. Phys. J. C **58**, 639 (2008).
[85] L. A. Harland-Lang, A. D. Martin, P. Motylinski, and R. S. Thorne, Parton distributions in the LHC era: MMHT 2014 PDFs, Eur. Phys. J. C **75**, 204 (2015).
[86] D. J. Lange, The EvtGen particle decay simulation package, Nucl. Instrum. Methods Phys. Res., Sect. A **462**, 152 (2001).
[87] S. Catani, L. Cieri, G. Ferrera, D. de Florian, and M. Grazzini, Vector boson production at hadron colliders: A fully exclusive QCD calculation at next-to-next-to-leading order, Phys. Rev. Lett. **103**, 082001 (2009).
[88] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, 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.
[89] S. Alioli, P. Nason, C. Oleari, and E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: The POWHEG BOX, J. High Energy Phys. 06 (2010) 043.
[90] M. Cacciari, M. Czakon, M. Mangano, A. Mitov, and P. Nason, Top-pair production at hadron colliders with next-to-next-to-leading logarithmic soft-gluon resummation, Phys. Lett. B **710**, 612 (2012).
[91] M. Czakon and A. Mitov, Top++: A program for the calculation of the top-pair cross section at hadron colliders, Comput. Phys. Commun. **185**, 2930 (2014).
[92] J. Campbell, T. Neumann, and Z. Sullivan, Single-top-quark production in the t-channel at NNLO, J. High Energy Phys. 02 (2021) 040.
[93] N. Kidonakis, Next-to-next-to-leading-order collinear and soft gluon corrections for t-channel single top quark production, Phys. Rev. D **83**, 091503 (2011).
[94] N. Kidonakis, Two-loop soft anomalous dimensions for single top quark associated production with a W^- or H^-, Phys. Rev. D **82**, 054018 (2010).
[95] N. Kidonakis, Next-to-next-to-leading logarithm resummation for s-channel single top quark production, Phys. Rev. D **81**, 054028 (2010).
[96] N. Kidonakis and N. Yamanaka, Higher-order corrections for tW production at high-energy hadron colliders, J. High Energy Phys. 05 (2021) 278.
[97] http://feynrules.irmp.ucl.ac.be/wiki/VLQ.
[98] M. Buchkremer, G. Cacciapaglia, A. Deandrea, and L. Panizzi, Model-independent framework for searches of top partners, Nucl. Phys. **B876**, 376 (2013).
[99] A. Roy and T. Andeen, Non-resonant diagrams for single production of top and bottom partners, Phys. Lett. B **833**, 137330 (2022).
[100] G. Cacciapaglia, A. Carvalho, A. Deandrea, T. Flacke, B. Fuks, D. Majumder, L. Panizzi, and H.-S. Shao, Next-to-leading-order predictions for single vector-like quark production at the LHC, Phys. Lett. B **793**, 206 (2019).
[101] M. Cacciari, G. P. Salam, and G. Soyez, The anti-k_t jet clustering algorithm, J. High Energy Phys. 04 (2008) 063.
[102] M. Cacciari, G. P. Salam, and G. Soyez, FastJet user manual, Eur. Phys. J. C **72**, 1896 (2012).
[103] ATLAS Collaboration, Jet reconstruction and performance using particle flow with the ATLAS detector, Eur. Phys. J. C **77**, 466 (2017).
[104] D. Krohn, J. Thaler, and L.-T. Wang, Jets with variable R, J. High Energy Phys. 06 (2009) 059.
[105] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, Asymptotic formulae for likelihood-based tests of new physics, Eur. Phys. J. C **71**, 1554 (2011).**73**, 2501(E) (2013).
[106] T. Junk, Confidence level computation for combining searches with small statistics, Nucl. Instrum. Methods Phys. Res., Sect. A **434**, 435 (1999).
[107] A. L. Read, Presentation of search results: The CL_S technique, J. Phys. G **28**, 2693 (2002).
[108] L. Moneta et al., The RooStats project, Proc. Sci. ACAT2010 (**2010**) 057 [arXiv:1009.1003].
[109] W. Verkerke and D. Kirkby, The RooFit toolkit for data modeling, arXiv:physics/0306116.
[110] K. Cranmer, G. Lewis, L. Moneta, A. Shibata, and W. Verkerke, HistFactory: A tool for creating statistical models for use with RooFit and RooStats, Technical Report No. CERN-OPEN-2012-016, CERN, 2012, https://cds.cern.ch/record/1456844.
[111] M. S. Chanowitz and M. K. Gaillard, The TeV physics of strongly interacting W's and Z's, Nucl. Phys. **B261**, 379 (1985).
[112] A. Deandrea, T. Flacke, B. Fuks, L. Panizzi, and H.-S. Shao, Single production of vector-like quarks: The effects of large width, interference and NLO corrections, J. High Energy Phys. 08 (2021) 107.
[113] P. Virtanen et al., SciPy 1.0: Fundamental algorithms for scientific computing in Python, Nat. Methods **17**, 261 (2020).
[114] ATLAS Collaboration, ATLAS computing acknowledgements, Report No. ATL-SOFT-PUB-2023-001, 2023, https://cds.cern.ch/record/2869272.

G. Aad,[104] E. Aakvaag,[17] B. Abbott,[123] S. Abdelhameed,[119a] K. Abeling,[56] N. J. Abicht,[50] S. H. Abidi,[30] M. Aboelela,[45] A. Aboulhorma,[36e] H. Abramowicz,[155] H. Abreu,[154] Y. Abulaiti,[120] B. S. Acharya,[70a,70b,b] A. Ackermann,[64a] C. Adam Bourdarios,[4] L. Adamczyk,[87a] S. V. Addepalli,[27] M. J. Addison,[103] J. Adelman,[118]

A. Adiguzel,[22c] T. Adye,[137] A. A. Affolder,[139] Y. Afik,[40] M. N. Agaras,[13] J. Agarwala,[74a,74b] A. Aggarwal,[102] C. Agheorghiesei,[28c] F. Ahmadov,[39,c] W. S. Ahmed,[106] S. Ahuja,[97] X. Ai,[63e] G. Aielli,[77a,77b] A. Aikot,[166] M. Ait Tamlihat,[36e] B. Aitbenchikh,[36a] M. Akbiyik,[102] T. P. A. Åkesson,[100] A. V. Akimov,[38] D. Akiyama,[171] N. N. Akolkar,[25] S. Aktas,[22a] K. Al Khoury,[42] G. L. Alberghi,[24b] J. Albert,[168] P. Albicocco,[54] G. L. Albouy,[61] S. Alderweireldt,[53] Z. L. Alegria,[124] M. Aleksa,[37] I. N. Aleksandrov,[39] C. Alexa,[28b] T. Alexopoulos,[10] F. Alfonsi,[24b] M. Algren,[57] M. Alhroob,[170] B. Ali,[135] H. M. J. Ali,[93,d] S. Ali,[32] S. W. Alibocus,[94] M. Aliev,[34c] G. Alimonti,[72a] W. Alkakhi,[56] C. Allaire,[67] B. M. M. Allbrooke,[150] J. S. Allen,[103] J. F. Allen,[53] C. A. Allendes Flores,[140f] P. P. Allport,[21] A. Aloisio,[73a,73b] F. Alonso,[92] C. Alpigiani,[142] Z. M. K. Alsolami,[93] M. Alvarez Estevez,[101] A. Alvarez Fernandez,[102] M. Alves Cardoso,[57] M. G. Alviggi,[73a,73b] M. Aly,[103] Y. Amaral Coutinho,[84b] A. Ambler,[106] C. Amelung,[37] M. Amerl,[103] C. G. Ames,[111] D. Amidei,[108] B. Amini,[55] K. J. Amirie,[158] S. P. Amor Dos Santos,[133a] K. R. Amos,[166] D. Amperiadou,[156] S. An,[85] V. Ananiev,[128] C. Anastopoulos,[143] T. Andeen,[11] J. K. Anders,[37] A. C. Anderson,[60] S. Y. Andrean,[48a,48b] A. Andreazza,[72a,72b] S. Angelidakis,[9] A. Angerami,[42] A. V. Anisenkov,[38] A. Annovi,[75a] C. Antel,[57] E. Antipov,[149] M. Antonelli,[54] F. Anulli,[76a] M. Aoki,[85] T. Aoki,[157] M. A. Aparo,[150] L. Aperio Bella,[49] C. Appelt,[19] A. Apyan,[27] S. J. Arbiol Val,[88] C. Arcangeletti,[54] A. T. H. Arce,[52] J-F. Arguin,[110] S. Argyropoulos,[156] J.-H. Arling,[49] O. Arnaez,[4] H. Arnold,[149] G. Artoni,[76a,76b] H. Asada,[113] K. Asai,[121] S. Asai,[157] N. A. Asbah,[37] R. A. Ashby Pickering,[170] K. Assamagan,[30] R. Astalos,[29a] K. S. V. Astrand,[100] S. Atashi,[162] R. J. Atkin,[34a] M. Atkinson,[165] H. Atmani,[36f] P. A. Atmasiddha,[131] K. Augsten,[135] S. Auricchio,[73a,73b] A. D. Auriol,[21] V. A. Austrup,[103] G. Avolio,[37] K. Axiotis,[57] G. Azuelos,[110,e] D. Babal,[29b] H. Bachacou,[138] K. Bachas,[156,f] A. Bachiu,[35] E. Bachmann,[51] F. Backman,[48a,48b] A. Badea,[40] T. M. Baer,[108] P. Bagnaia,[76a,76b] M. Bahmani,[19] D. Bahner,[55] K. Bai,[126] J. T. Baines,[137] L. Baines,[96] O. K. Baker,[175] E. Bakos,[16] D. Bakshi Gupta,[8] L. E. Balabram Filho,[84b] V. Balakrishnan,[123] R. Balasubramanian,[4] E. M. Baldin,[38] P. Balek,[87a] E. Ballabene,[24b,24a] F. Balli,[138] L. M. Baltes,[64a] W. K. Balunas,[33] J. Balz,[102] I. Bamwidhi,[119b] E. Banas,[88] M. Bandieramonte,[132] A. Bandyopadhyay,[25] S. Bansal,[25] L. Barak,[155] M. Barakat,[49] E. L. Barberio,[107] D. Barberis,[58b,58a] M. Barbero,[104] M. Z. Barel,[117] T. Barillari,[112] M-S. Barisits,[37] T. Barklow,[147] P. Baron,[125] D. A. Baron Moreno,[103] A. Baroncelli,[63a] A. J. Barr,[129] J. D. Barr,[98] F. Barreiro,[101] J. Barreiro Guimarães da Costa,[14] U. Barron,[155] M. G. Barros Teixeira,[133a] S. Barsov,[38] F. Bartels,[64a] R. Bartoldus,[147] A. E. Barton,[93] P. Bartos,[29a] A. Basan,[102] M. Baselga,[50] A. Bassalat,[67,g] M. J. Basso,[159a] S. Bataju,[45] R. Bate,[167] R. L. Bates,[60] S. Batlamous,[101] B. Batool,[145] M. Battaglia,[139] D. Battulga,[19] M. Bauce,[76a,76b] M. Bauer,[80] P. Bauer,[25] L. T. Bazzano Hurrell,[31] J. B. Beacham,[52] T. Beau,[130] J. Y. Beaucamp,[92] P. H. Beauchemin,[161] P. Bechtle,[25] H. P. Beck,[20,h] K. Becker,[170] A. J. Beddall,[83] V. A. Bednyakov,[39] C. P. Bee,[149] L. J. Beemster,[16] T. A. Beermann,[37] M. Begalli,[84d] M. Begel,[30] A. Behera,[149] J. K. Behr,[49] J. F. Beirer,[37] F. Beisiegel,[25] M. Belfkir,[119b] G. Bella,[155] L. Bellagamba,[24b] A. Bellerive,[35] P. Bellos,[21] K. Beloborodov,[38] D. Benchekroun,[36a] F. Bendebba,[36a] Y. Benhammou,[155] K. C. Benkendorfer,[62] L. Beresford,[49] M. Beretta,[54] E. Bergeaas Kuutmann,[164] N. Berger,[4] B. Bergmann,[135] J. Beringer,[18a] G. Bernardi,[5] C. Bernius,[147] F. U. Bernlochner,[25] F. Bernon,[37] A. Berrocal Guardia,[13] T. Berry,[97] P. Berta,[136] A. Berthold,[51] S. Bethke,[112] A. Betti,[76a,76b] A. J. Bevan,[96] N. K. Bhalla,[55] S. Bhatta,[149] D. S. Bhattacharya,[169] P. Bhattarai,[147] K. D. Bhide,[55] V. S. Bhopatkar,[124] R. M. Bianchi,[132] G. Bianco,[24b,24a] O. Biebel,[111] R. Bielski,[126] M. Biglietti,[78a] C. S. Billingsley,[45] Y. Bimgdi,[36f] M. Bindi,[56] A. Bingul,[22b] C. Bini,[76a,76b] G. A. Bird,[33] M. Birman,[172] M. Biros,[136] S. Biryukov,[150] T. Bisanz,[50] E. Bisceglie,[44b,44a] J. P. Biswal,[137] D. Biswas,[145] I. Bloch,[49] A. Blue,[60] U. Blumenschein,[96] J. Blumenthal,[102] V. S. Bobrovnikov,[38] M. Boehler,[55] B. Boehm,[169] D. Bogavac,[37] A. G. Bogdanchikov,[38] L. S. Boggia,[130] C. Bohm,[48a] V. Boisvert,[97] P. Bokan,[37] T. Bold,[87a] M. Bomben,[5] M. Bona,[96] M. Boonekamp,[138] C. D. Booth,[97] A. G. Borbély,[60] I. S. Bordulev,[38] G. Borissov,[93] D. Bortoletto,[129] D. Boscherini,[24b] M. Bosman,[13] J. D. Bossio Sola,[37] K. Bouaouda,[36a] N. Bouchhar,[166] L. Boudet,[4] J. Boudreau,[132] E. V. Bouhova-Thacker,[93] D. Boumediene,[41] R. Bouquet,[58b,58a] A. Boveia,[122] J. Boyd,[37] D. Boye,[30] I. R. Boyko,[39] L. Bozianu,[57] J. Bracinik,[21] N. Brahimi,[4] G. Brandt,[174] O. Brandt,[33] F. Braren,[49] B. Brau,[105] J. E. Brau,[126] R. Brener,[172] L. Brenner,[117] R. Brenner,[164] S. Bressler,[172] G. Brianti,[79a,79b] D. Britton,[60] D. Britzger,[112] I. Brock,[25] R. Brock,[109] G. Brooijmans,[42] E. M. Brooks,[159b] E. Brost,[30] L. M. Brown,[168] L. E. Bruce,[62] T. L. Bruckler,[129] P. A. Bruckman de Renstrom,[88] B. Brüers,[49]

A. Bruni,[24b] G. Bruni,[24b] M. Bruschi,[24b] N. Bruscino,[76a,76b] T. Buanes,[17] Q. Buat,[142] D. Buchin,[112] A. G. Buckley,[60] O. Bulekov,[38] B. A. Bullard,[147] S. Burdin,[94] C. D. Burgard,[50] A. M. Burger,[37] B. Burghgrave,[8] O. Burlayenko,[55] J. Burleson,[165] J. T. P. Burr,[33] J. C. Burzynski,[146] E. L. Busch,[42] V. Büscher,[102] P. J. Bussey,[60] J. M. Butler,[26] C. M. Buttar,[60] J. M. Butterworth,[98] W. Buttinger,[137] C. J. Buxo Vazquez,[109] A. R. Buzykaev,[38] S. Cabrera Urbán,[166] L. Cadamuro,[67] D. Caforio,[59] H. Cai,[132] Y. Cai,[14,114c] Y. Cai,[114a] V. M. M. Cairo,[37] O. Cakir,[3a] N. Calace,[37] P. Calafiura,[18a] G. Calderini,[130] P. Calfayan,[69] G. Callea,[60] L. P. Caloba,[84b] D. Calvet,[41] S. Calvet,[41] M. Calvetti,[75a,75b] R. Camacho Toro,[130] S. Camarda,[37] D. Camarero Munoz,[27] P. Camarri,[77a,77b] M. T. Camerlingo,[73a,73b] D. Cameron,[37] C. Camincher,[168] M. Campanelli,[98] A. Camplani,[43] V. Canale,[73a,73b] A. C. Canbay,[3a] E. Canonero,[97] J. Cantero,[166] Y. Cao,[165] F. Capocasa,[27] M. Capua,[44b,44a] A. Carbone,[72a,72b] R. Cardarelli,[77a] J. C. J. Cardenas,[8] G. Carducci,[44b,44a] T. Carli,[37] G. Carlino,[73a] J. I. Carlotto,[13] B. T. Carlson,[132,i] E. M. Carlson,[168,159a] J. Carmignani,[94] L. Carminati,[72a,72b] A. Carnelli,[138] M. Carnesale,[37] S. Caron,[116] E. Carquin,[140f] I. B. Carr,[107] S. Carrá,[72a] G. Carratta,[24b,24a] A. M. Carroll,[126] M. P. Casado,[13,j] M. Caspar,[49] F. L. Castillo,[4] L. Castillo Garcia,[13] V. Castillo Gimenez,[166] N. F. Castro,[133a,133e] A. Catinaccio,[37] J. R. Catmore,[128] T. Cavaliere,[4] V. Cavaliere,[30] N. Cavalli,[24b,24a] L. J. Caviedes Betancourt,[23b] Y. C. Cekmecelioglu,[49] E. Celebi,[83] S. Cella,[37] M. S. Centonze,[71a,71b] V. Cepaitis,[57] K. Cerny,[125] A. S. Cerqueira,[84a] A. Cerri,[150] L. Cerrito,[77a,77b] F. Cerutti,[18a] B. Cervato,[145] A. Cervelli,[24b] G. Cesarini,[54] S. A. Cetin,[83] D. Chakraborty,[118] J. Chan,[18a] W. Y. Chan,[157] J. D. Chapman,[33] E. Chapon,[138] B. Chargeishvili,[153b] D. G. Charlton,[21] M. Chatterjee,[20] C. Chauhan,[136] Y. Che,[114a] S. Chekanov,[6] S. V. Chekulaev,[159a] G. A. Chelkov,[39,k] A. Chen,[108] B. Chen,[155] B. Chen,[168] H. Chen,[114a] H. Chen,[30] J. Chen,[63c] J. Chen,[146] M. Chen,[129] S. Chen,[89] S. J. Chen,[114a] X. Chen,[63c] X. Chen,[15,l] Y. Chen,[63a] C. L. Cheng,[173] H. C. Cheng,[65a] S. Cheong,[147] A. Cheplakov,[39] E. Cheremushkina,[49] E. Cherepanova,[117] R. Cherkaoui El Moursli,[36e] E. Cheu,[7] K. Cheung,[66] L. Chevalier,[138] V. Chiarella,[54] G. Chiarelli,[75a] N. Chiedde,[104] G. Chiodini,[71a] A. S. Chisholm,[21] A. Chitan,[28b] M. Chitishvili,[166] M. V. Chizhov,[39,m] K. Choi,[11] Y. Chou,[142] E. Y. S. Chow,[116] K. L. Chu,[172] M. C. Chu,[65a] X. Chu,[14,114c] Z. Chubinidze,[54] J. Chudoba,[134] J. J. Chwastowski,[88] D. Cieri,[112] K. M. Ciesla,[87a] V. Cindro,[95] A. Ciocio,[18a] F. Cirotto,[73a,73b] Z. H. Citron,[172] M. Citterio,[72a] D. A. Ciubotaru,[28b] A. Clark,[57] P. J. Clark,[53] N. Clarke Hall,[98] C. Clarry,[158] J. M. Clavijo Columbie,[49] S. E. Clawson,[49] C. Clement,[48a,48b] Y. Coadou,[104] M. Cobal,[70a,70c] A. Coccaro,[58b] R. F. Coelho Barrue,[133a] R. Coelho Lopes De Sa,[105] S. Coelli,[72a] L. S. Colangeli,[158] B. Cole,[42] J. Collot,[61] P. Conde Muiño,[133a,133g] M. P. Connell,[34c] S. H. Connell,[34c] E. I. Conroy,[129] F. Conventi,[73a,n] H. G. Cooke,[21] A. M. Cooper-Sarkar,[129] F. A. Corchia,[24b,24a] A. Cordeiro Oudot Choi,[130] L. D. Corpe,[41] M. Corradi,[76a,76b] F. Corriveau,[106,o] A. Cortes-Gonzalez,[19] M. J. Costa,[166] F. Costanza,[4] D. Costanzo,[143] B. M. Cote,[122] J. Couthures,[4] G. Cowan,[97] K. Cranmer,[173] L. Cremer,[50] D. Cremonini,[24b,24a] S. Crépé-Renaudin,[61] F. Crescioli,[130] M. Cristinziani,[145] M. Cristoforetti,[79a,79b] V. Croft,[117] J. E. Crosby,[124] G. Crosetti,[44b,44a] A. Cueto,[101] H. Cui,[98] Z. Cui,[7] W. R. Cunningham,[60] F. Curcio,[166] J. R. Curran,[53] P. Czodrowski,[37] M. J. Da Cunha Sargedas De Sousa,[58b,58a] J. V. Da Fonseca Pinto,[84b] C. Da Via,[103] W. Dabrowski,[87a] T. Dado,[37] S. Dahbi,[152] T. Dai,[108] D. Dal Santo,[20] C. Dallapiccola,[105] M. Dam,[43] G. D'amen,[30] V. D'Amico,[111] J. Damp,[102] J. R. Dandoy,[35] D. Dannheim,[37] M. Danninger,[146] V. Dao,[149] G. Darbo,[58b] S. J. Das,[30] F. Dattola,[49] S. D'Auria,[72a,72b] A. D'Avanzo,[73a,73b] C. David,[34a] T. Davidek,[136] I. Dawson,[96] H. A. Day-hall,[135] K. De,[8] R. De Asmundis,[73a] N. De Biase,[49] S. De Castro,[24b,24a] N. De Groot,[116] P. de Jong,[117] H. De la Torre,[118] A. De Maria,[114a] A. De Salvo,[76a] U. De Sanctis,[77a,77b] F. De Santis,[71a,71b] A. De Santo,[150] J. B. De Vivie De Regie,[61] J. Debevc,[95] D. V. Dedovich,[39] J. Degens,[94] A. M. Deiana,[45] F. Del Corso,[24b,24a] J. Del Peso,[101] L. Delagrange,[130] F. Deliot,[138] C. M. Delitzsch,[50] M. Della Pietra,[73a,73b] D. Della Volpe,[57] A. Dell'Acqua,[37] L. Dell'Asta,[72a,72b] M. Delmastro,[4] P. A. Delsart,[61] S. Demers,[175] M. Demichev,[39] S. P. Denisov,[38] L. D'Eramo,[41] D. Derendarz,[88] F. Derue,[130] P. Dervan,[94] K. Desch,[25] C. Deutsch,[25] F. A. Di Bello,[58b,58a] A. Di Ciaccio,[77a,77b] L. Di Ciaccio,[4] A. Di Domenico,[76a,76b] C. Di Donato,[73a,73b] A. Di Girolamo,[37] G. Di Gregorio,[37] A. Di Luca,[79a,79b] B. Di Micco,[78a,78b] R. Di Nardo,[78a,78b] K. F. Di Petrillo,[40] M. Diamantopoulou,[35] F. A. Dias,[117] T. Dias Do Vale,[146] M. A. Diaz,[140a,140b] F. G. Diaz Capriles,[25] A. R. Didenko,[39] M. Didenko,[166] E. B. Diehl,[108] S. Díez Cornell,[49] C. Diez Pardos,[145] C. Dimitriadi,[164] A. Dimitrievska,[21] J. Dingfelder,[25] T. Dingley,[129] I-M. Dinu,[28b] S. J. Dittmeier,[64b] F. Dittus,[37] M. Divisek,[136]

B. Dixit,[94] F. Djama,[104] T. Djobava,[153b] C. Doglioni,[103,100] A. Dohnalova,[29a] J. Dolejsi,[136] Z. Dolezal,[136] K. Domijan,[87a] K. M. Dona,[40] M. Donadelli,[84d] B. Dong,[109] J. Donini,[41] A. D'Onofrio,[73a,73b] M. D'Onofrio,[94] J. Dopke,[137] A. Doria,[73a] N. Dos Santos Fernandes,[133a] P. Dougan,[103] M. T. Dova,[92] A. T. Doyle,[60] M. A. Draguet,[129] M. P. Drescher,[56] E. Dreyer,[172] I. Drivas-koulouris,[10] M. Drnevich,[120] M. Drozdova,[57] D. Du,[63a] T. A. du Pree,[117] F. Dubinin,[38] M. Dubovsky,[29a] E. Duchovni,[172] G. Duckeck,[111] O. A. Ducu,[28b] D. Duda,[53] A. Dudarev,[37] E. R. Duden,[27] M. D'uffizi,[103] L. Duflot,[67] M. Dührssen,[37] I. Duminica,[28g] A. E. Dumitriu,[28b] M. Dunford,[64a] S. Dungs,[50] K. Dunne,[48a,48b] A. Duperrin,[104] H. Duran Yildiz,[3a] M. Düren,[59] A. Durglishvili,[153b] B. L. Dwyer,[118] G. I. Dyckes,[18a] M. Dyndal,[87a] B. S. Dziedzic,[37] Z. O. Earnshaw,[150] G. H. Eberwein,[129] B. Eckerova,[29a] S. Eggebrecht,[56] E. Egidio Purcino De Souza,[84e] L. F. Ehrke,[57] G. Eigen,[17] K. Einsweiler,[18a] T. Ekelof,[164] P. A. Ekman,[100] S. El Farkh,[36b] Y. El Ghazali,[63a] H. El Jarrari,[37] A. El Moussaouy,[36a] V. Ellajosyula,[164] M. Ellert,[164] F. Ellinghaus,[174] N. Ellis,[37] J. Elmsheuser,[30] M. Elsawy,[119a] M. Elsing,[37] D. Emeliyanov,[137] Y. Enari,[85] I. Ene,[18a] S. Epari,[13] P. A. Erland,[88] D. Ernani Martins Neto,[88] M. Errenst,[174] M. Escalier,[67] C. Escobar,[166] E. Etzion,[155] G. Evans,[133a] H. Evans,[69] L. S. Evans,[97] A. Ezhilov,[38] S. Ezzarqtouni,[36a] F. Fabbri,[24b,24a] L. Fabbri,[24b,24a] G. Facini,[98] V. Fadeyev,[139] R. M. Fakhrutdinov,[38] D. Fakoudis,[102] S. Falciano,[76a] L. F. Falda Ulhoa Coelho,[37] F. Fallavollita,[112] G. Falsetti,[44b,44a] J. Faltova,[136] C. Fan,[165] K. Y. Fan,[65b] Y. Fan,[14] Y. Fang,[14,114c] M. Fanti,[72a,72b] M. Faraj,[70a,70b] Z. Farazpay,[99] A. Farbin,[8] A. Farilla,[78a] T. Farooque,[109] S. M. Farrington,[53] F. Fassi,[36e] D. Fassouliotis,[9] M. Faucci Giannelli,[77a,77b] W. J. Fawcett,[33] L. Fayard,[67] P. Federic,[136] P. Federicova,[134] O. L. Fedin,[38,k] M. Feickert,[173] L. Feligioni,[104] D. E. Fellers,[126] C. Feng,[63b] Z. Feng,[117] M. J. Fenton,[162] L. Ferencz,[49] R. A. M. Ferguson,[93] S. I. Fernandez Luengo,[140f] P. Fernandez Martinez,[68] M. J. V. Fernoux,[104] J. Ferrando,[93] A. Ferrari,[164] P. Ferrari,[117,116] R. Ferrari,[74a] D. Ferrere,[57] C. Ferretti,[108] D. Fiacco,[76a,76b] F. Fiedler,[102] P. Fiedler,[135] S. Filimonov,[38] A. Filipčič,[95] E. K. Filmer,[159a] F. Filthaut,[116] M. C. N. Fiolhais,[133a,133c,p] L. Fiorini,[166] W. C. Fisher,[109] T. Fitschen,[103] P. M. Fitzhugh,[138] I. Fleck,[145] P. Fleischmann,[108] T. Flick,[174] M. Flores,[34d,q] L. R. Flores Castillo,[65a] L. Flores Sanz De Acedo,[37] F. M. Follega,[79a,79b] N. Fomin,[33] J. H. Foo,[158] A. Formica,[138] A. C. Forti,[103] E. Fortin,[37] A. W. Fortman,[18a] M. G. Foti,[18a] L. Fountas,[9,r] D. Fournier,[67] H. Fox,[93] P. Francavilla,[75a,75b] S. Francescato,[62] S. Franchellucci,[57] M. Franchini,[24b,24a] S. Franchino,[64a] D. Francis,[37] L. Franco,[116] V. Franco Lima,[37] L. Franconi,[49] M. Franklin,[62] G. Frattari,[27] Y. Y. Frid,[155] J. Friend,[60] N. Fritzsche,[37] A. Froch,[55] D. Froidevaux,[37] J. A. Frost,[129] Y. Fu,[63a] S. Fuenzalida Garrido,[140f] M. Fujimoto,[104] K. Y. Fung,[65a] E. Furtado De Simas Filho,[84e] M. Furukawa,[157] J. Fuster,[166] A. Gaa,[56] A. Gabrielli,[24b,24a] A. Gabrielli,[158] P. Gadow,[37] G. Gagliardi,[58b,58a] L. G. Gagnon,[18a] S. Gaid,[163] S. Galantzan,[155] J. Gallagher,[1] E. J. Gallas,[129] B. J. Gallop,[137] K. K. Gan,[122] S. Ganguly,[157] Y. Gao,[53] F. M. Garay Walls,[140a,140b] B. Garcia,[30] C. García,[166] A. Garcia Alonso,[117] A. G. Garcia Caffaro,[175] J. E. García Navarro,[166] M. Garcia-Sciveres,[18a] G. L. Gardner,[131] R. W. Gardner,[40] N. Garelli,[161] D. Garg,[81] R. B. Garg,[147] J. M. Gargan,[53] C. A. Garner,[158] C. M. Garvey,[34a] V. K. Gassmann,[161] G. Gaudio,[74a] V. Gautam,[13] P. Gauzzi,[76a,76b] J. Gavranovic,[95] I. L. Gavrilenko,[38] A. Gavrilyuk,[38] C. Gay,[167] G. Gaycken,[126] E. N. Gazis,[10] A. A. Geanta,[28b] C. M. Gee,[139] A. Gekow,[122] C. Gemme,[58b] M. H. Genest,[61] A. D. Gentry,[115] S. George,[97] W. F. George,[21] T. Geralis,[47] P. Gessinger-Befurt,[37] M. E. Geyik,[174] M. Ghani,[170] K. Ghorbanian,[96] A. Ghosal,[145] A. Ghosh,[162] A. Ghosh,[7] B. Giacobbe,[24b] S. Giagu,[76a,76b] T. Giani,[117] A. Giannini,[63a] S. M. Gibson,[97] M. Gignac,[139] D. T. Gil,[87b] A. K. Gilbert,[87a] B. J. Gilbert,[42] D. Gillberg,[35] G. Gilles,[117] L. Ginabat,[130] D. M. Gingrich,[2,e] M. P. Giordani,[70a,70c] P. F. Giraud,[138] G. Giugliarelli,[70a,70c] D. Giugni,[72a] F. Giuli,[77a,77b] I. Gkialas,[9,r] L. K. Gladilin,[38] C. Glasman,[101] G. R. Gledhill,[126] G. Glemža,[49] M. Glisic,[126] I. Gnesi,[44b] Y. Go,[30] M. Goblirsch-Kolb,[37] B. Gocke,[50] D. Godin,[110] B. Gokturk,[22a] S. Goldfarb,[107] T. Golling,[57] M. G. D. Gololo,[34g] D. Golubkov,[38] J. P. Gombas,[109] A. Gomes,[133a,133b] G. Gomes Da Silva,[145] A. J. Gomez Delegido,[166] R. Gonçalo,[133a] L. Gonella,[21] A. Gongadze,[153c] F. Gonnella,[21] J. L. Gonski,[147] R. Y. González Andana,[53] S. González de la Hoz,[166] R. Gonzalez Lopez,[94] C. Gonzalez Renteria,[18a] M. V. Gonzalez Rodrigues,[49] R. Gonzalez Suarez,[164] S. Gonzalez-Sevilla,[57] L. Goossens,[37] B. Gorini,[37] E. Gorini,[71a,71b] A. Gorišek,[95] T. C. Gosart,[131] A. T. Goshaw,[52] M. I. Gostkin,[39] S. Goswami,[124] C. A. Gottardo,[37] S. A. Gotz,[111] M. Gouighri,[36b] V. Goumarre,[49] A. G. Goussiou,[142] N. Govender,[34c] R. P. Grabarczyk,[129] I. Grabowska-Bold,[87a] K. Graham,[35] E. Gramstad,[128] S. Grancagnolo,[71a,71b] C. M. Grant,[1,138] P. M. Gravila,[28f] F. G. Gravili,[71a,71b]

H. M. Gray,[18a] M. Greco,[71a,71b] M. J. Green,[1] C. Grefe,[25] A. S. Grefsrud,[17] I. M. Gregor,[49] K. T. Greif,[162] P. Grenier,[147] S. G. Grewe,[112] A. A. Grillo,[139] K. Grimm,[32] S. Grinstein,[13,s] J.-F. Grivaz,[67] E. Gross,[172] J. Grosse-Knetter,[56] L. Guan,[108] J. G. R. Guerrero Rojas,[166] G. Guerrieri,[37] R. Gugel,[102] J. A. M. Guhit,[108] A. Guida,[19] E. Guilloton,[170] S. Guindon,[37] F. Guo,[14,114c] J. Guo,[63c] L. Guo,[49] L. Guo,[14] Y. Guo,[108] A. Gupta,[50] R. Gupta,[132] S. Gurbuz,[25] S. S. Gurdasani,[55] G. Gustavino,[76a,76b] P. Gutierrez,[123] L. F. Gutierrez Zagazeta,[131] M. Gutsche,[51] C. Gutschow,[98] C. Gwenlan,[129] C. B. Gwilliam,[94] E. S. Haaland,[128] A. Haas,[120] M. Habedank,[60] C. Haber,[18a] H. K. Hadavand,[8] A. Hadef,[51] S. Hadzic,[112] A. I. Hagan,[93] J. J. Hahn,[145] E. H. Haines,[98] M. Haleem,[169] J. Haley,[124] G. D. Hallewell,[104] L. Halser,[20] K. Hamano,[168] M. Hamer,[25] E. J. Hampshire,[97] J. Han,[63b] L. Han,[114a] L. Han,[63a] S. Han,[18a] Y. F. Han,[158] K. Hanagaki,[85] M. Hance,[139] D. A. Hangal,[42] H. Hanif,[146] M. D. Hank,[131] J. B. Hansen,[43] P. H. Hansen,[43] D. Harada,[57] T. Harenberg,[174] S. Harkusha,[176] M. L. Harris,[105] Y. T. Harris,[25] J. Harrison,[13] N. M. Harrison,[122] P. F. Harrison,[170] N. M. Hartman,[112] N. M. Hartmann,[111] R. Z. Hasan,[97,137] Y. Hasegawa,[144] F. Haslbeck,[129] S. Hassan,[17] R. Hauser,[109] C. M. Hawkes,[21] R. J. Hawkings,[37] Y. Hayashi,[157] D. Hayden,[109] C. Hayes,[108] R. L. Hayes,[117] C. P. Hays,[129] J. M. Hays,[96] H. S. Hayward,[94] F. He,[63a] M. He,[14,114c] Y. He,[49] Y. He,[98] N. B. Heatley,[96] V. Hedberg,[100] A. L. Heggelund,[128] N. D. Hehir,[96,a] C. Heidegger,[55] K. K. Heidegger,[55] J. Heilman,[35] S. Heim,[49] T. Heim,[18a] J. G. Heinlein,[131] J. J. Heinrich,[126] L. Heinrich,[112,t] J. Hejbal,[134] A. Held,[173] S. Hellesund,[17] C. M. Helling,[167] S. Hellman,[48a,48b] R. C. W. Henderson,[93] L. Henkelmann,[33] A. M. Henriques Correia,[37] H. Herde,[100] Y. Hernández Jiménez,[149] L. M. Herrmann,[25] T. Herrmann,[51] G. Herten,[55] R. Hertenberger,[111] L. Hervas,[37] M. E. Hesping,[102] N. P. Hessey,[159a] J. Hessler,[112] M. Hidaoui,[36b] N. Hidic,[136] E. Hill,[158] S. J. Hillier,[21] J. R. Hinds,[109] F. Hinterkeuser,[25] M. Hirose,[127] S. Hirose,[160] D. Hirschbuehl,[174] T. G. Hitchings,[103] B. Hiti,[95] J. Hobbs,[149] R. Hobincu,[28e] N. Hod,[172] M. C. Hodgkinson,[143] B. H. Hodkinson,[129] A. Hoecker,[37] D. D. Hofer,[108] J. Hofer,[166] T. Holm,[25] M. Holzbock,[37] L. B. A. H. Hommels,[33] B. P. Honan,[103] J. J. Hong,[69] J. Hong,[63c] T. M. Hong,[132] B. H. Hooberman,[165] W. H. Hopkins,[6] M. C. Hoppesch,[165] Y. Horii,[113] M. E. Horstmann,[112] S. Hou,[152] A. S. Howard,[95] J. Howarth,[60] J. Hoya,[6] M. Hrabovsky,[125] A. Hrynevich,[49] T. Hryn'ova,[4] P. J. Hsu,[66] S.-C. Hsu,[142] T. Hsu,[67] M. Hu,[18a] Q. Hu,[63a] S. Huang,[33] X. Huang,[14,114c] Y. Huang,[143] Y. Huang,[102] Y. Huang,[14] Z. Huang,[103] Z. Hubacek,[135] M. Huebner,[25] F. Huegging,[25] T. B. Huffman,[129] M. Hufnagel Maranha De Faria,[84a] C. A. Hugli,[49] M. Huhtinen,[37] S. K. Huiberts,[17] R. Hulsken,[106] N. Huseynov,[12,u] J. Huston,[109] J. Huth,[62] R. Hyneman,[147] G. Iacobucci,[57] G. Iakovidis,[30] L. Iconomidou-Fayard,[67] J. P. Iddon,[37] P. Iengo,[73a,73b] R. Iguchi,[157] Y. Iiyama,[157] T. Iizawa,[129] Y. Ikegami,[85] N. Ilic,[158] H. Imam,[84c] G. Inacio Goncalves,[84d] T. Ingebretsen Carlson,[48a,48b] J. M. Inglis,[96] G. Introzzi,[74a,74b] M. Iodice,[78a] V. Ippolito,[76a,76b] R. K. Irwin,[94] M. Ishino,[157] W. Islam,[173] C. Issever,[19] S. Istin,[22a,v] H. Ito,[171] R. Iuppa,[79a,79b] A. Ivina,[172] J. M. Izen,[46] V. Izzo,[73a] P. Jacka,[134] P. Jackson,[1] C. S. Jagfeld,[111] G. Jain,[159a] P. Jain,[49] K. Jakobs,[55] T. Jakoubek,[172] J. Jamieson,[60] W. Jang,[157] M. Javurkova,[105] P. Jawahar,[103] L. Jeanty,[126] J. Jejelava,[153a,w] P. Jenni,[55,x] C. E. Jessiman,[35] C. Jia,[63b] H. Jia,[167] J. Jia,[149] X. Jia,[14,114c] Z. Jia,[114a] C. Jiang,[53] S. Jiggins,[49] J. Jimenez Pena,[13] S. Jin,[114a] A. Jinaru,[28b] O. Jinnouchi,[141] P. Johansson,[143] K. A. Johns,[7] J. W. Johnson,[139] F. A. Jolly,[49] D. M. Jones,[150] E. Jones,[49] K. S. Jones,[8] P. Jones,[33] R. W. L. Jones,[93] T. J. Jones,[94] H. L. Joos,[56,37] R. Joshi,[122] J. Jovicevic,[16] X. Ju,[18a] J. J. Junggeburth,[105] T. Junkermann,[64a] A. Juste Rozas,[13,s] M. K. Juzek,[88] S. Kabana,[140e] A. Kaczmarska,[88] M. Kado,[112] H. Kagan,[122] M. Kagan,[147] A. Kahn,[131] C. Kahra,[102] T. Kaji,[157] E. Kajomovitz,[154] N. Kakati,[172] I. Kalaitzidou,[55] C. W. Kalderon,[30] N. J. Kang,[139] D. Kar,[34g] K. Karava,[129] M. J. Kareem,[159b] E. Karentzos,[55] O. Karkout,[117] S. N. Karpov,[39] Z. M. Karpova,[39] V. Kartvelishvili,[93] A. N. Karyukhin,[38] E. Kasimi,[156] J. Katzy,[49] S. Kaur,[35] K. Kawade,[144] M. P. Kawale,[123] C. Kawamoto,[89] T. Kawamoto,[63a] E. F. Kay,[37] F. I. Kaya,[161] S. Kazakos,[109] V. F. Kazanin,[38] Y. Ke,[149] J. M. Keaveney,[34a] R. Keeler,[168] G. V. Kehris,[62] J. S. Keller,[35] J. J. Kempster,[150] O. Kepka,[134] B. P. Kerridge,[137] S. Kersten,[174] B. P. Kerševan,[95] L. Keszeghova,[29a] S. Ketabchi Haghighat,[158] R. A. Khan,[132] A. Khanov,[124] A. G. Kharlamov,[38] T. Kharlamova,[38] E. E. Khoda,[142] M. Kholodenko,[133a] T. J. Khoo,[19] G. Khoriauli,[169] J. Khubua,[153b,a] Y. A. R. Khwaira,[130] B. Kibirige,[34g] D. Kim,[6] D. W. Kim,[48a,48b] Y. K. Kim,[40] N. Kimura,[98] M. K. Kingston,[56] A. Kirchhoff,[56] C. Kirfel,[25] F. Kirfel,[25] J. Kirk,[137] A. E. Kiryunin,[112] S. Kita,[160] C. Kitsaki,[10] O. Kivernyk,[25] M. Klassen,[161] C. Klein,[35] L. Klein,[169] M. H. Klein,[45] S. B. Klein,[57] U. Klein,[94] A. Klimentov,[30] T. Klioutchnikova,[37] P. Kluit,[117] S. Kluth,[112] E. Kneringer,[80] T. M. Knight,[158]

A. Knue,[50] D. Kobylianskii,[172] S. F. Koch,[129] M. Kocian,[147] P. Kodyš,[136] D. M. Koeck,[126] P. T. Koenig,[25] T. Koffas,[35] O. Kolay,[51] I. Koletsou,[4] T. Komarek,[88] K. Köneke,[55] A. X. Y. Kong,[1] T. Kono,[121] N. Konstantinidis,[98] P. Kontaxakis,[57] B. Konya,[100] R. Kopeliansky,[42] S. Koperny,[87a] K. Korcyl,[88] K. Kordas,[156,y] A. Korn,[98] S. Korn,[56] I. Korolkov,[13] N. Korotkova,[38] B. Kortman,[117] O. Kortner,[112] S. Kortner,[112] W. H. Kostecka,[118] V. V. Kostyukhin,[145] A. Kotsokechagia,[37] A. Kotwal,[52] A. Koulouris,[37] A. Kourkoumeli-Charalampidi,[74a,74b] C. Kourkoumelis,[9] E. Kourlitis,[112,t] O. Kovanda,[126] R. Kowalewski,[168] W. Kozanecki,[126] A. S. Kozhin,[38] V. A. Kramarenko,[38] G. Kramberger,[95] P. Kramer,[102] M. W. Krasny,[130] A. Krasznahorkay,[37] A. C. Kraus,[118] J. W. Kraus,[174] J. A. Kremer,[49] T. Kresse,[51] L. Kretschmann,[174] J. Kretzschmar,[94] K. Kreul,[19] P. Krieger,[158] M. Krivos,[136] K. Krizka,[21] K. Kroeninger,[50] H. Kroha,[112] J. Kroll,[134] J. Kroll,[131] K. S. Krowpman,[109] U. Kruchonak,[39] H. Krüger,[25] N. Krumnack,[82] M. C. Kruse,[52] O. Kuchinskaia,[38] S. Kuday,[3a] S. Kuehn,[37] R. Kuesters,[55] T. Kuhl,[49] V. Kukhtin,[39] Y. Kulchitsky,[38,k] S. Kuleshov,[140d,140b] M. Kumar,[34g] N. Kumari,[49] P. Kumari,[159b] A. Kupco,[134] T. Kupfer,[50] A. Kupich,[38] O. Kuprash,[55] H. Kurashige,[86] L. L. Kurchaninov,[159a] O. Kurdysh,[67] Y. A. Kurochkin,[38] A. Kurova,[38] M. Kuze,[141] A. K. Kvam,[105] J. Kvita,[125] T. Kwan,[106] N. G. Kyriacou,[108] L. A. O. Laatu,[104] C. Lacasta,[166] F. Lacava,[76a,76b] H. Lacker,[19] D. Lacour,[130] N. N. Lad,[98] E. Ladygin,[39] A. Lafarge,[41] B. Laforge,[130] T. Lagouri,[175] F. Z. Lahbabi,[36a] S. Lai,[56] J. E. Lambert,[168] S. Lammers,[69] W. Lampl,[7] C. Lampoudis,[156,y] G. Lamprinoudis,[102] A. N. Lancaster,[118] E. Lançon,[30] U. Landgraf,[55] M. P. J. Landon,[96] V. S. Lang,[55] O. K. B. Langrekken,[128] A. J. Lankford,[162] F. Lanni,[37] K. Lantzsch,[25] A. Lanza,[74a] M. Lanzac Berrocal,[166] J. F. Laporte,[138] T. Lari,[72a] F. Lasagni Manghi,[24b] M. Lassnig,[37] V. Latonova,[134] A. Laurier,[154] S. D. Lawlor,[143] Z. Lawrence,[103] R. Lazaridou,[170] M. Lazzaroni,[72a,72b] B. Le,[103] H. D. M. Le,[109] E. M. Le Boulicaut,[175] L. T. Le Pottier,[18a] B. Leban,[24b,24a] A. Lebedev,[82] M. LeBlanc,[103] F. Ledroit-Guillon,[61] S. C. Lee,[152] S. Lee,[48a,48b] T. F. Lee,[94] L. L. Leeuw,[34c] H. P. Lefebvre,[97] M. Lefebvre,[168] C. Leggett,[18a] G. Lehmann Miotto,[37] M. Leigh,[57] W. A. Leight,[105] W. Leinonen,[116] A. Leisos,[156,z] M. A. L. Leite,[84c] C. E. Leitgeb,[19] R. Leitner,[136] K. J. C. Leney,[45] T. Lenz,[25] S. Leone,[75a] C. Leonidopoulos,[53] A. Leopold,[148] R. Les,[109] C. G. Lester,[33] M. Levchenko,[38] J. Levêque,[4] L. J. Levinson,[172] G. Levrini,[24b,24a] M. P. Lewicki,[88] C. Lewis,[142] D. J. Lewis,[4] L. Lewitt,[143] A. Li,[30] B. Li,[63b] C. Li,[63a] C-Q. Li,[112] H. Li,[63a] H. Li,[63b] H. Li,[114a] H. Li,[15] H. Li,[63b] J. Li,[63c] K. Li,[14] L. Li,[63c] M. Li,[14,114c] S. Li,[14,114c] S. Li,[63d,63c] T. Li,[5] X. Li,[106] Z. Li,[157] Z. Li,[14,114c] Z. Li,[63a] S. Liang,[14,114c] Z. Liang,[14] M. Liberatore,[138] B. Liberti,[77a] K. Lie,[65c] J. Lieber Marin,[84e] H. Lien,[69] H. Lin,[108] K. Lin,[109] R. E. Lindley,[7] J. H. Lindon,[2] J. Ling,[62] E. Lipeles,[131] A. Lipniacka,[17] A. Lister,[167] J. D. Little,[69] B. Liu,[14] B. X. Liu,[114b] D. Liu,[63d,63c] E. H. L. Liu,[21] J. B. Liu,[63a] J. K. K. Liu,[33] K. Liu,[63d] K. Liu,[63d,63c] M. Liu,[63a] M. Y. Liu,[63a] P. Liu,[14] Q. Liu,[63d,142,63c] X. Liu,[63a] X. Liu,[63b] Y. Liu,[114b,114c] Y. L. Liu,[63b] Y. W. Liu,[63a] S. L. Lloyd,[96] E. M. Lobodzinska,[49] P. Loch,[7] E. Lodhi,[158] T. Lohse,[19] K. Lohwasser,[143] E. Loiacono,[49] J. D. Lomas,[21] J. D. Long,[42] I. Longarini,[162] R. Longo,[165] I. Lopez Paz,[68] A. Lopez Solis,[49] N. A. Lopez-canelas,[7] N. Lorenzo Martinez,[4] A. M. Lory,[111] M. Losada,[119a] G. Löschcke Centeno,[150] O. Loseva,[38] X. Lou,[48a,48b] X. Lou,[14,114c] A. Lounis,[67] P. A. Love,[93] G. Lu,[14,114c] M. Lu,[67] S. Lu,[131] Y. J. Lu,[66] H. J. Lubatti,[142] C. Luci,[76a,76b] F. L. Lucio Alves,[114a] F. Luehring,[69] O. Lukianchuk,[67] B. S. Lunday,[131] O. Lundberg,[148] B. Lund-Jensen,[148,a] N. A. Luongo,[6] M. S. Lutz,[37] A. B. Lux,[26] D. Lynn,[30] R. Lysak,[134] E. Lytken,[100] V. Lyubushkin,[39] T. Lyubushkina,[39] M. M. Lyukova,[149] M. Firdaus M. Soberi,[53] H. Ma,[30] K. Ma,[63a] L. L. Ma,[63b] W. Ma,[63a] Y. Ma,[124] J. C. MacDonald,[102] P. C. Machado De Abreu Farias,[84e] R. Madar,[41] T. Madula,[98] J. Maeda,[86] T. Maeno,[30] H. Maguire,[143] V. Maiboroda,[138] A. Maio,[133a,133b,133d] K. Maj,[87a] O. Majersky,[49] S. Majewski,[126] N. Makovec,[67] V. Maksimovic,[16] B. Malaescu,[130] Pa. Malecki,[88] V. P. Maleev,[38] F. Malek,[61,aa] M. Mali,[95] D. Malito,[97] U. Mallik,[81,a] S. Maltezos,[10] S. Malyukov,[39] J. Mamuzic,[13] G. Mancini,[54] M. N. Mancini,[27] G. Manco,[74a,74b] J. P. Mandalia,[96] S. S. Mandarry,[150] I. Mandić,[95] L. Manhaes de Andrade Filho,[84a] I. M. Maniatis,[172] J. Manjarres Ramos,[91] D. C. Mankad,[172] A. Mann,[111] S. Manzoni,[37] L. Mao,[63c] X. Mapekula,[34c] A. Marantis,[156,z] G. Marchiori,[5] M. Marcisovsky,[134] C. Marcon,[72a] M. Marinescu,[21] S. Marium,[49] M. Marjanovic,[123] A. Markhoos,[55] M. Markovitch,[67] E. J. Marshall,[93] Z. Marshall,[18a] S. Marti-Garcia,[166] J. Martin,[98] T. A. Martin,[137] V. J. Martin,[53] B. Martin dit Latour,[17] L. Martinelli,[76a,76b] M. Martinez,[13,s] P. Martinez Agullo,[166] V. I. Martinez Outschoorn,[105] P. Martinez Suarez,[13] S. Martin-Haugh,[137] G. Martinovicova,[136] V. S. Martoiu,[28b] A. C. Martyniuk,[98] A. Marzin,[37] D. Mascione,[79a,79b]

L. Masetti,[102] J. Masik,[103] A. L. Maslennikov,[38] S. L. Mason,[42] P. Massarotti,[73a,73b] P. Mastrandrea,[75a,75b] A. Mastroberardino,[44b,44a] T. Masubuchi,[127] T. T. Mathew,[126] T. Mathisen,[164] J. Matousek,[136] D. M. Mattern,[50] J. Maurer,[28b] T. Maurin,[60] A. J. Maury,[67] B. Maček,[95] D. A. Maximov,[38] A. E. May,[103] R. Mazini,[152] I. Maznas,[118] M. Mazza,[109] S. M. Mazza,[139] E. Mazzeo,[72a,72b] C. Mc Ginn,[30] J. P. Mc Gowan,[168] S. P. Mc Kee,[108] C. A. Mc Lean,[6] C. C. McCracken,[167] E. F. McDonald,[107] A. E. McDougall,[117] J. A. Mcfayden,[150] R. P. McGovern,[131] R. P. Mckenzie,[34g] T. C. Mclachlan,[49] D. J. Mclaughlin,[98] S. J. McMahon,[137] C. M. Mcpartland,[94] R. A. McPherson,[168,o] S. Mehlhase,[111] A. Mehta,[94] D. Melini,[166] B. R. Mellado Garcia,[34g] A. H. Melo,[56] F. Meloni,[49] A. M. Mendes Jacques Da Costa,[103] H. Y. Meng,[158] L. Meng,[93] S. Menke,[112] M. Mentink,[37] E. Meoni,[44b,44a] G. Mercado,[118] S. Merianos,[156] C. Merlassino,[70a,70c] L. Merola,[73a,73b] C. Meroni,[72a,72b] J. Metcalfe,[6] A. S. Mete,[6] E. Meuser,[102] C. Meyer,[69] J-P. Meyer,[138] R. P. Middleton,[137] L. Mijović,[53] G. Mikenberg,[172] M. Mikestikova,[134] M. Mikuž,[95] H. Mildner,[102] A. Milic,[37] D. W. Miller,[40] E. H. Miller,[147] L. S. Miller,[35] A. Milov,[172] D. A. Milstead,[48a,48b] T. Min,[114a] A. A. Minaenko,[38] I. A. Minashvili,[153b] L. Mince,[60] A. I. Mincer,[120] B. Mindur,[87a] M. Mineev,[39] Y. Mino,[89] L. M. Mir,[13] M. Miralles Lopez,[60] M. Mironova,[18a] M. C. Missio,[116] A. Mitra,[170] V. A. Mitsou,[166] Y. Mitsumori,[113] O. Miu,[158] P. S. Miyagawa,[96] T. Mkrtchyan,[64a] M. Mlinarevic,[98] T. Mlinarevic,[98] M. Mlynarikova,[37] S. Mobius,[20] P. Mogg,[111] M. H. Mohamed Farook,[115] A. F. Mohammed,[14,114c] S. Mohapatra,[42] G. Mokgatitswane,[34g] L. Moleri,[172] B. Mondal,[145] S. Mondal,[135] K. Mönig,[49] E. Monnier,[104] L. Monsonis Romero,[166] J. Montejo Berlingen,[13] A. Montella,[48a,48b] M. Montella,[122] F. Montereali,[78a,78b] F. Monticelli,[92] S. Monzani,[70a,70c] A. Morancho Tarda,[43] N. Morange,[67] A. L. Moreira De Carvalho,[49] M. Moreno Llácer,[166] C. Moreno Martinez,[57] J. M. Moreno Perez,[23b] P. Morettini,[58b] S. Morgenstern,[37] M. Morii,[62] M. Morinaga,[157] M. Moritsu,[90] F. Morodei,[76a,76b] P. Moschovakos,[37] B. Moser,[129] M. Mosidze,[153b] T. Moskalets,[45] P. Moskvitina,[116] J. Moss,[32,bb] P. Moszkowicz,[87a] A. Moussa,[36d] E. J. W. Moyse,[105] O. Mtintsilana,[34g] S. Muanza,[104] J. Mueller,[132] D. Muenstermann,[93] R. Müller,[37] G. A. Mullier,[164] A. J. Mullin,[33] J. J. Mullin,[131] A. E. Mulski,[62] D. P. Mungo,[158] D. Munoz Perez,[166] F. J. Munoz Sanchez,[103] M. Murin,[103] W. J. Murray,[170,137] M. Muškinja,[95] C. Mwewa,[30] A. G. Myagkov,[38,k] A. J. Myers,[8] G. Myers,[108] M. Myska,[135] B. P. Nachman,[18a] O. Nackenhorst,[50] K. Nagai,[129] K. Nagano,[85] R. Nagasaka,[157] J. L. Nagle,[30,cc] E. Nagy,[104] A. M. Nairz,[37] Y. Nakahama,[85] K. Nakamura,[85] K. Nakkalil,[5] H. Nanjo,[127] E. A. Narayanan,[45] I. Naryshkin,[38] L. Nasella,[72a,72b] M. Naseri,[35] S. Nasri,[119b] C. Nass,[25] G. Navarro,[23a] J. Navarro-Gonzalez,[166] R. Nayak,[155] A. Nayaz,[19] P. Y. Nechaeva,[38] S. Nechaeva,[24b,24a] F. Nechansky,[134] L. Nedic,[129] T. J. Neep,[21] A. Negri,[74a,74b] M. Negrini,[24b] C. Nellist,[117] C. Nelson,[106] K. Nelson,[108] S. Nemecek,[134] M. Nessi,[37,dd] M. S. Neubauer,[165] F. Neuhaus,[102] J. Neundorf,[49] J. Newell,[94] P. R. Newman,[21] C. W. Ng,[132] Y. W. Y. Ng,[49] B. Ngair,[119a] H. D. N. Nguyen,[110] R. B. Nickerson,[129] R. Nicolaidou,[138] J. Nielsen,[139] M. Niemeyer,[56] J. Niermann,[56] N. Nikiforou,[37] V. Nikolaenko,[38,k] I. Nikolic-Audit,[130] K. Nikolopoulos,[21] P. Nilsson,[30] I. Ninca,[49] G. Ninio,[155] A. Nisati,[76a] N. Nishu,[2] R. Nisius,[112] N. Nitika,[70a,70c] J-E. Nitschke,[51] E. K. Nkadimeng,[34g] T. Nobe,[157] T. Nommensen,[151] M. B. Norfolk,[143] B. J. Norman,[35] M. Noury,[36a] J. Novak,[95] T. Novak,[95] L. Novotny,[135] R. Novotny,[115] L. Nozka,[125] K. Ntekas,[162] N. M. J. Nunes De Moura Junior,[84b] J. Ocariz,[130] A. Ochi,[86] I. Ochoa,[133a] S. Oerdek,[49,ee] J. T. Offermann,[40] A. Ogrodnik,[136] A. Oh,[103] C. C. Ohm,[148] H. Oide,[85] R. Oishi,[157] M. L. Ojeda,[37] Y. Okumura,[157] L. F. Oleiro Seabra,[133a] I. Oleksiyuk,[57] S. A. Olivares Pino,[140d] G. Oliveira Correa,[13] D. Oliveira Damazio,[30] J. L. Oliver,[162] Ö. O. Öncel,[55] A. P. O'Neill,[20] A. Onofre,[133a,133e] P. U. E. Onyisi,[11] M. J. Oreglia,[40] G. E. Orellana,[92] D. Orestano,[78a,78b] N. Orlando,[13] R. S. Orr,[158] L. M. Osojnak,[131] R. Ospanov,[63a] Y. Osumi,[113] G. Otero y Garzon,[31] H. Otono,[90] P. S. Ott,[64a] G. J. Ottino,[18a] M. Ouchrif,[36d] F. Ould-Saada,[128] T. Ovsiannikova,[142] M. Owen,[60] R. E. Owen,[137] V. E. Ozcan,[22a] F. Ozturk,[88] N. Ozturk,[8] S. Ozturk,[83] H. A. Pacey,[129] A. Pacheco Pages,[13] C. Padilla Aranda,[13] G. Padovano,[76a,76b] S. Pagan Griso,[18a] G. Palacino,[69] A. Palazzo,[71a,71b] J. Pampel,[25] J. Pan,[175] T. Pan,[65a] D. K. Panchal,[11] C. E. Pandini,[117] J. G. Panduro Vazquez,[137] H. D. Pandya,[1] H. Pang,[15] P. Pani,[49] G. Panizzo,[70a,70c] L. Panwar,[130] L. Paolozzi,[57] S. Parajuli,[165] A. Paramonov,[6] C. Paraskevopoulos,[54] D. Paredes Hernandez,[65b] A. Pareti,[74a,74b] K. R. Park,[42] T. H. Park,[158] M. A. Parker,[33] F. Parodi,[58b,58a] E. W. Parrish,[118] V. A. Parrish,[53] J. A. Parsons,[42] U. Parzefall,[55] B. Pascual Dias,[110] L. Pascual Dominguez,[101] E. Pasqualucci,[76a] S. Passaggio,[58b] F. Pastore,[97] P. Patel,[88] U. M. Patel,[52] J. R. Pater,[103] T. Pauly,[37] F. Pauwels,[136] C. I. Pazos,[161] M. Pedersen,[128] R. Pedro,[133a]

S. V. Peleganchuk,[38] O. Penc,[37] E. A. Pender,[53] S. Peng,[15] G. D. Penn,[175] K. E. Penski,[111] M. Penzin,[38] B. S. Peralva,[84d] A. P. Pereira Peixoto,[142] L. Pereira Sanchez,[147] D. V. Perepelitsa,[30,cc] G. Perera,[105] E. Perez Codina,[159a] M. Perganti,[10] H. Pernegger,[37] S. Perrella,[76a,76b] O. Perrin,[41] K. Peters,[49] R. F. Y. Peters,[103] B. A. Petersen,[37] T. C. Petersen,[43] E. Petit,[104] V. Petousis,[135] C. Petridou,[156,y] T. Petru,[136] A. Petrukhin,[145] M. Pettee,[18a] A. Petukhov,[38] K. Petukhova,[37] R. Pezoa,[140f] L. Pezzotti,[37] G. Pezzullo,[175] A. J. Pfleger,[37] T. M. Pham,[173] T. Pham,[107] P. W. Phillips,[137] G. Piacquadio,[149] E. Pianori,[18a] F. Piazza,[126] R. Piegaia,[31] D. Pietreanu,[28b] A. D. Pilkington,[103] M. Pinamonti,[70a,70c] J. L. Pinfold,[2] B. C. Pinheiro Pereira,[133a] J. Pinol Bel,[13] A. E. Pinto Pinoargote,[138] L. Pintucci,[70a,70c] K. M. Piper,[150] A. Pirttikoski,[57] D. A. Pizzi,[35] L. Pizzimento,[65b] A. Pizzini,[117] M.-A. Pleier,[30] V. Pleskot,[136] E. Plotnikova,[39] G. Poddar,[96] R. Poettgen,[100] L. Poggioli,[130] I. Pokharel,[56] S. Polacek,[136] G. Polesello,[74a] A. Poley,[146,159a] A. Polini,[24b] C. S. Pollard,[170] Z. B. Pollock,[122] E. Pompa Pacchi,[76a,76b] N. I. Pond,[98] D. Ponomarenko,[69] L. Pontecorvo,[37] S. Popa,[28a] G. A. Popeneciu,[28d] A. Poreba,[37] D. M. Portillo Quintero,[159a] S. Pospisil,[135] M. A. Postill,[143] P. Postolache,[28c] K. Potamianos,[170] P. A. Potepa,[87a] I. N. Potrap,[39] C. J. Potter,[33] H. Potti,[151] J. Poveda,[166] M. E. Pozo Astigarraga,[37] A. Prades Ibanez,[77a,77b] J. Pretel,[168] D. Price,[103] M. Primavera,[71a] L. Primomo,[70a,70c] M. A. Principe Martin,[101] R. Privara,[125] T. Procter,[60] M. L. Proffitt,[142] N. Proklova,[131] K. Prokofiev,[65c] G. Proto,[112] J. Proudfoot,[6] M. Przybycien,[87a] W. W. Przygoda,[87b] A. Psallidas,[47] J. E. Puddefoot,[143] D. Pudzha,[55] D. Pyatiizbyantseva,[38] J. Qian,[108] R. Qian,[109] D. Qichen,[103] Y. Qin,[13] T. Qiu,[53] A. Quadt,[56] M. Queitsch-Maitland,[103] G. Quetant,[57] R. P. Quinn,[167] G. Rabanal Bolanos,[62] D. Rafanoharana,[55] F. Raffaeli,[77a,77b] F. Ragusa,[72a,72b] J. L. Rainbolt,[40] J. A. Raine,[57] S. Rajagopalan,[30] E. Ramakoti,[38] L. Rambelli,[58b,58a] I. A. Ramirez-Berend,[35] K. Ran,[49,114c] D. S. Rankin,[131] N. P. Rapheeha,[34g] H. Rasheed,[28b] V. Raskina,[130] D. F. Rassloff,[64a] A. Rastogi,[18a] S. Rave,[102] S. Ravera,[58b,58a] B. Ravina,[56] I. Ravinovich,[172] M. Raymond,[37] A. L. Read,[128] N. P. Readioff,[143] D. M. Rebuzzi,[74a,74b] G. Redlinger,[30] A. S. Reed,[112] K. Reeves,[27] J. A. Reidelsturz,[174] D. Reikher,[126] A. Rej,[50] C. Rembser,[37] M. Renda,[28b] F. Renner,[49] A. G. Rennie,[162] A. L. Rescia,[49] S. Resconi,[72a] M. Ressegotti,[58b,58a] S. Rettie,[37] J. G. Reyes Rivera,[109] E. Reynolds,[18a] O. L. Rezanova,[38] P. Reznicek,[136] H. Riani,[36d] N. Ribaric,[52] E. Ricci,[79a,79b] R. Richter,[112] S. Richter,[48a,48b] E. Richter-Was,[87b] M. Ridel,[130] S. Ridouani,[36d] P. Rieck,[120] P. Riedler,[37] E. M. Riefel,[48a,48b] J. O. Rieger,[117] M. Rijssenbeek,[149] M. Rimoldi,[37] L. Rinaldi,[24b,24a] P. Rincke,[56,164] T. T. Rinn,[30] M. P. Rinnagel,[111] G. Ripellino,[164] I. Riu,[13] J. C. Rivera Vergara,[168] F. Rizatdinova,[124] E. Rizvi,[96] B. R. Roberts,[18a] S. S. Roberts,[139] S. H. Robertson,[106,o] D. Robinson,[33] M. Robles Manzano,[102] A. Robson,[60] A. Rocchi,[77a,77b] C. Roda,[75a,75b] S. Rodriguez Bosca,[37] Y. Rodriguez Garcia,[23a] A. Rodriguez Rodriguez,[55] A. M. Rodríguez Vera,[118] S. Roe,[37] J. T. Roemer,[37] A. R. Roepe-Gier,[139] O. Røhne,[128] R. A. Rojas,[105] C. P. A. Roland,[130] J. Roloff,[30] A. Romaniouk,[80] E. Romano,[74a,74b] M. Romano,[24b] A. C. Romero Hernandez,[165] N. Rompotis,[94] L. Roos,[130] S. Rosati,[76a] B. J. Rosser,[40] E. Rossi,[129] E. Rossi,[73a,73b] L. P. Rossi,[62] L. Rossini,[55] R. Rosten,[122] M. Rotaru,[28b] B. Rottler,[55] C. Rougier,[91] D. Rousseau,[67] D. Rousso,[49] A. Roy,[165] S. Roy-Garand,[158] A. Rozanov,[104] Z. M. A. Rozario,[60] Y. Rozen,[154] A. Rubio Jimenez,[166] A. J. Ruby,[94] V. H. Ruelas Rivera,[19] T. A. Ruggeri,[1] A. Ruggiero,[129] A. Ruiz-Martinez,[166] A. Rummler,[37] Z. Rurikova,[55] N. A. Rusakovich,[39] H. L. Russell,[168] G. Russo,[76a,76b] J. P. Rutherfoord,[7] S. Rutherford Colmenares,[33] M. Rybar,[136] E. B. Rye,[128] A. Ryzhov,[45] J. A. Sabater Iglesias,[57] H. F-W. Sadrozinski,[139] F. Safai Tehrani,[76a] B. Safarzadeh Samani,[137] S. Saha,[1] M. Sahinsoy,[83] A. Saibel,[166] M. Saimpert,[138] M. Saito,[157] T. Saito,[157] A. Sala,[72a,72b] D. Salamani,[37] A. Salnikov,[147] J. Salt,[166] A. Salvador Salas,[155] D. Salvatore,[44b,44a] F. Salvatore,[150] A. Salzburger,[37] D. Sammel,[55] E. Sampson,[93] D. Sampsonidis,[156,y] D. Sampsonidou,[126] J. Sánchez,[166] V. Sanchez Sebastian,[166] H. Sandaker,[128] C. O. Sander,[49] J. A. Sandesara,[105] M. Sandhoff,[174] C. Sandoval,[23b] L. Sanfilippo,[64a] D. P. C. Sankey,[137] T. Sano,[89] A. Sansoni,[54] L. Santi,[37,76b] C. Santoni,[41] H. Santos,[133a,133b] A. Santra,[172] E. Sanzani,[24b,24a] K. A. Saoucha,[163] J. G. Saraiva,[133a,133d] J. Sardain,[7] O. Sasaki,[85] K. Sato,[160] C. Sauer,[64b] E. Sauvan,[4] P. Savard,[158,e] R. Sawada,[157] C. Sawyer,[137] L. Sawyer,[99] C. Sbarra,[24b] A. Sbrizzi,[24b,24a] T. Scanlon,[98] J. Schaarschmidt,[142] U. Schäfer,[102] A. C. Schaffer,[67,45] D. Schaile,[111] R. D. Schamberger,[149] C. Scharf,[19] M. M. Schefer,[20] V. A. Schegelsky,[38] D. Scheirich,[136] M. Schernau,[162] C. Scheulen,[56] C. Schiavi,[58b,58a] M. Schioppa,[44b,44a] B. Schlag,[147] S. Schlenker,[37] J. Schmeing,[174] M. A. Schmidt,[174] K. Schmieden,[102] C. Schmitt,[102] N. Schmitt,[102] S. Schmitt,[49] L. Schoeffel,[138] A. Schoening,[64b] P. G. Scholer,[35] E. Schopf,[129] M. Schott,[25] J. Schovancova,[37] S. Schramm,[57]

T. Schroer,[57] H-C. Schultz-Coulon,[64a] M. Schumacher,[55] B. A. Schumm,[139] Ph. Schune,[138] A. J. Schuy,[142] H. R. Schwartz,[139] A. Schwartzman,[147] T. A. Schwarz,[108] Ph. Schwemling,[138] R. Schwienhorst,[109] F. G. Sciacca,[20] A. Sciandra,[30] G. Sciolla,[27] F. Scuri,[75a] C. D. Sebastiani,[94] K. Sedlaczek,[118] S. C. Seidel,[115] A. Seiden,[139] B. D. Seidlitz,[42] C. Seitz,[49] J. M. Seixas,[84b] G. Sekhniaidze,[73a] L. Selem,[61] N. Semprini-Cesari,[24b,24a] D. Sengupta,[57] V. Senthilkumar,[166] L. Serin,[67] M. Sessa,[77a,77b] H. Severini,[123] F. Sforza,[58b,58a] A. Sfyrla,[57] Q. Sha,[14] E. Shabalina,[56] A. H. Shah,[33] R. Shaheen,[148] J. D. Shahinian,[131] D. Shaked Renous,[172] L. Y. Shan,[14] M. Shapiro,[18a] A. Sharma,[37] A. S. Sharma,[167] P. Sharma,[81] P. B. Shatalov,[38] K. Shaw,[150] S. M. Shaw,[103] Q. Shen,[63c] D. J. Sheppard,[146] P. Sherwood,[98] L. Shi,[98] X. Shi,[14] S. Shimizu,[85] C. O. Shimmin,[175] J. D. Shinner,[97] I. P. J. Shipsey,[129,a] S. Shirabe,[90] M. Shiyakova,[39,ff] M. J. Shochet,[40] D. R. Shope,[128] B. Shrestha,[123] S. Shrestha,[122,gg] I. Shreyber,[38] M. J. Shroff,[168] P. Sicho,[134] A. M. Sickles,[165] E. Sideras Haddad,[34g] A. C. Sidley,[117] A. Sidoti,[24b] F. Siegert,[51] Dj. Sijacki,[16] F. Sili,[92] J. M. Silva,[53] I. Silva Ferreira,[84b] M. V. Silva Oliveira,[30] S. B. Silverstein,[48a] S. Simion,[67] R. Simoniello,[37] E. L. Simpson,[103] H. Simpson,[150] L. R. Simpson,[108] S. Simsek,[83] S. Sindhu,[56] P. Sinervo,[158] S. Singh,[30] S. Sinha,[49] S. Sinha,[103] M. Sioli,[24b,24a] I. Siral,[37] E. Sitnikova,[49] J. Sjölin,[48a,48b] A. Skaf,[56] E. Skorda,[21] P. Skubic,[123] M. Slawinska,[88] V. Smakhtin,[172] B. H. Smart,[137] S. Yu. Smirnov,[38] Y. Smirnov,[38] L. N. Smirnova,[38,k] O. Smirnova,[100] A. C. Smith,[42] D. R. Smith,[162] E. A. Smith,[40] J. L. Smith,[103] R. Smith,[147] M. Smizanska,[93] K. Smolek,[135] A. A. Snesarev,[38] H. L. Snoek,[117] S. Snyder,[30] R. Sobie,[168,o] A. Soffer,[155] C. A. Solans Sanchez,[37] E. Yu. Soldatov,[38] U. Soldevila,[166] A. A. Solodkov,[38] S. Solomon,[27] A. Soloshenko,[39] K. Solovieva,[55] O. V. Solovyanov,[41] P. Sommer,[51] A. Sonay,[13] W. Y. Song,[159b] A. Sopczak,[135] A. L. Sopio,[53] F. Sopkova,[29b] J. D. Sorenson,[115] I. R. Sotarriva Alvarez,[141] V. Sothilingam,[64a] O. J. Soto Sandoval,[140c,140b] S. Sottocornola,[69] R. Soualah,[163] Z. Soumaimi,[36e] D. South,[49] N. Soybelman,[172] S. Spagnolo,[71a,71b] M. Spalla,[112] D. Sperlich,[55] G. Spigo,[37] B. Spisso,[73a,73b] D. P. Spiteri,[60] M. Spousta,[136] E. J. Staats,[35] R. Stamen,[64a] A. Stampekis,[21] E. Stanecka,[88] W. Stanek-Maslouska,[49] M. V. Stange,[51] B. Stanislaus,[18a] M. M. Stanitzki,[49] B. Stapf,[49] E. A. Starchenko,[38] G. H. Stark,[139] J. Stark,[91] P. Staroba,[134] P. Starovoitov,[64a] S. Stärz,[106] R. Staszewski,[88] G. Stavropoulos,[47] A. Stefl,[37] P. Steinberg,[30] B. Stelzer,[146,159a] H. J. Stelzer,[132] O. Stelzer-Chilton,[159a] H. Stenzel,[59] T. J. Stevenson,[150] G. A. Stewart,[37] J. R. Stewart,[124] M. C. Stockton,[37] G. Stoicea,[28b] M. Stolarski,[133a] S. Stonjek,[112] A. Straessner,[51] J. Strandberg,[148] S. Strandberg,[48a,48b] M. Stratmann,[174] M. Strauss,[123] T. Strebler,[104] P. Strizenec,[29b] R. Ströhmer,[169] D. M. Strom,[126] R. Stroynowski,[45] A. Strubig,[48a,48b] S. A. Stucci,[30] B. Stugu,[17] J. Stupak,[123] N. A. Styles,[49] D. Su,[147] S. Su,[63a] W. Su,[63d] X. Su,[63a] D. Suchy,[29a] K. Sugizaki,[157] V. V. Sulin,[38] M. J. Sullivan,[94] D. M. S. Sultan,[129] L. Sultanaliyeva,[38] S. Sultansoy,[3b] T. Sumida,[89] S. Sun,[173] O. Sunneborn Gudnadottir,[164] N. Sur,[104] M. R. Sutton,[150] H. Suzuki,[160] M. Svatos,[134] M. Swiatlowski,[159a] T. Swirski,[169] I. Sykora,[29a] M. Sykora,[136] T. Sykora,[136] D. Ta,[102] K. Tackmann,[49,ee] A. Taffard,[162] R. Tafirout,[159a] J. S. Tafoya Vargas,[67] Y. Takubo,[85] M. Talby,[104] A. A. Talyshev,[38] K. C. Tam,[65b] N. M. Tamir,[155] A. Tanaka,[157] J. Tanaka,[157] R. Tanaka,[67] M. Tanasini,[149] Z. Tao,[167] S. Tapia Araya,[140f] S. Tapprogge,[102] A. Tarek Abouelfadl Mohamed,[109] S. Tarem,[154] K. Tariq,[14] G. Tarna,[28b] G. F. Tartarelli,[72a] M. J. Tartarin,[91] P. Tas,[136] M. Tasevsky,[134] E. Tassi,[44b,44a] A. C. Tate,[165] G. Tateno,[157] Y. Tayalati,[36e,hh] G. N. Taylor,[107] W. Taylor,[159b] R. Teixeira De Lima,[147] P. Teixeira-Dias,[97] J. J. Teoh,[158] K. Terashi,[157] J. Terron,[101] S. Terzo,[13] M. Testa,[54] R. J. Teuscher,[158,o] A. Thaler,[80] O. Theiner,[57] T. Theveneaux-Pelzer,[104] O. Thielmann,[174] D. W. Thomas,[97] J. P. Thomas,[21] E. A. Thompson,[18a] P. D. Thompson,[21] E. Thomson,[131] R. E. Thornberry,[45] C. Tian,[63a] Y. Tian,[57] V. Tikhomirov,[38,k] Yu. A. Tikhonov,[38] S. Timoshenko,[38] D. Timoshyn,[136] E. X. L. Ting,[1] P. Tipton,[175] A. Tishelman-Charny,[30] S. H. Tlou,[34g] K. Todome,[141] S. Todorova-Nova,[136] S. Todt,[51] L. Toffolin,[70a,70c] M. Togawa,[85] J. Tojo,[90] S. Tokár,[29a] K. Tokushuku,[85] O. Toldaiev,[69] M. Tomoto,[85,113] L. Tompkins,[147,ii] K. W. Topolnicki,[87b] E. Torrence,[126] H. Torres,[91] E. Torró Pastor,[166] M. Toscani,[31] C. Tosciri,[40] M. Tost,[11] D. R. Tovey,[143] I. S. Trandafir,[28b] T. Trefzger,[169] A. Tricoli,[30] I. M. Trigger,[159a] S. Trincaz-Duvoid,[130] D. A. Trischuk,[27] B. Trocmé,[61] A. Tropina,[39] L. Truong,[34c] M. Trzebinski,[88] A. Trzupek,[88] F. Tsai,[149] M. Tsai,[108] A. Tsiamis,[156] P. V. Tsiareshka,[38] S. Tsigaridas,[159a] A. Tsirigotis,[156,z] V. Tsiskaridze,[158] E. G. Tskhadadze,[153a] M. Tsopoulou,[156] Y. Tsujikawa,[89] I. I. Tsukerman,[38] V. Tsulaia,[18a] S. Tsuno,[85] K. Tsuri,[121] D. Tsybychev,[149] Y. Tu,[65b] A. Tudorache,[28b] V. Tudorache,[28b] A. N. Tuna,[62] S. Turchikhin,[58b,58a] I. Turk Cakir,[3a] R. Turra,[72a]

T. Turtuvshin,[39] P. M. Tuts,[42] S. Tzamarias,[156,y] E. Tzovara,[102] F. Ukegawa,[160] P. A. Ulloa Poblete,[140c,140b] E. N. Umaka,[30] G. Unal,[37] A. Undrus,[30] G. Unel,[162] J. Urban,[29b] P. Urrejola,[140a] G. Usai,[8] R. Ushioda,[141] M. Usman,[110] F. Ustuner,[53] Z. Uysal,[83] V. Vacek,[135] B. Vachon,[106] T. Vafeiadis,[37] A. Vaitkus,[98] C. Valderanis,[111] E. Valdes Santurio,[48a,48b] M. Valente,[159a] S. Valentinetti,[24b,24a] A. Valero,[166] E. Valiente Moreno,[166] A. Vallier,[91] J. A. Valls Ferrer,[166] D. R. Van Arneman,[117] T. R. Van Daalen,[142] A. Van Der Graaf,[50] P. Van Gemmeren,[6] M. Van Rijnbach,[37] S. Van Stroud,[98] I. Van Vulpen,[117] P. Vana,[136] M. Vanadia,[77a,77b] U. M. Vande Voorde,[148] W. Vandelli,[37] E. R. Vandewall,[124] D. Vannicola,[155] L. Vannoli,[54] R. Vari,[76a] E. W. Varnes,[7] C. Varni,[18b] T. Varol,[152] D. Varouchas,[67] L. Varriale,[166] K. E. Varvell,[151] M. E. Vasile,[28b] L. Vaslin,[85] G. A. Vasquez,[168] A. Vasyukov,[39] L. M. Vaughan,[124] R. Vavricka,[102] T. Vazquez Schroeder,[37] J. Veatch,[32] V. Vecchio,[103] M. J. Veen,[105] I. Veliscek,[30] L. M. Veloce,[158] F. Veloso,[133a,133c] S. Veneziano,[76a] A. Ventura,[71a,71b] S. Ventura Gonzalez,[138] A. Verbytskyi,[112] M. Verducci,[75a,75b] C. Vergis,[96] M. Verissimo De Araujo,[84b] W. Verkerke,[117] J. C. Vermeulen,[117] C. Vernieri,[147] M. Vessella,[105] M. C. Vetterli,[146,e] A. Vgenopoulos,[102] N. Viaux Maira,[140f] T. Vickey,[143] O. E. Vickey Boeriu,[143] G. H. A. Viehhauser,[129] L. Vigani,[64b] M. Vigl,[112] M. Villa,[24b,24a] M. Villaplana Perez,[166] E. M. Villhauer,[53] E. Vilucchi,[54] M. G. Vincter,[35] A. Visibile,[117] C. Vittori,[37] I. Vivarelli,[24b,24a] E. Voevodina,[112] F. Vogel,[111] J. C. Voigt,[51] P. Vokac,[135] Yu. Volkotrub,[87b] E. Von Toerne,[25] B. Vormwald,[37] V. Vorobel,[136] K. Vorobev,[38] M. Vos,[166] K. Voss,[145] M. Vozak,[117] L. Vozdecky,[123] N. Vranjes,[16] M. Vranjes Milosavljevic,[16] M. Vreeswijk,[117] N. K. Vu,[63d,63c] R. Vuillermet,[37] O. Vujinovic,[102] I. Vukotic,[40] I. K. Vyas,[35] S. Wada,[160] C. Wagner,[147] J. M. Wagner,[18a] W. Wagner,[174] S. Wahdan,[174] H. Wahlberg,[92] C. H. Waits,[123] J. Walder,[137] R. Walker,[111] W. Walkowiak,[145] A. Wall,[131] E. J. Wallin,[100] T. Wamorkar,[6] A. Z. Wang,[139] C. Wang,[102] C. Wang,[11] H. Wang,[18a] J. Wang,[65c] P. Wang,[98] R. Wang,[62] R. Wang,[6] S. M. Wang,[152] S. Wang,[63b] S. Wang,[14] T. Wang,[63a] W. T. Wang,[81] W. Wang,[14] X. Wang,[114a] X. Wang,[165] X. Wang,[63c] Y. Wang,[63d] Y. Wang,[114a] Y. Wang,[63a] Z. Wang,[108] Z. Wang,[63d,52,63c] Z. Wang,[108] A. Warburton,[106] R. J. Ward,[21] N. Warrack,[60] S. Waterhouse,[97] A. T. Watson,[21] H. Watson,[53] M. F. Watson,[21] E. Watton,[60,137] G. Watts,[142] B. M. Waugh,[98] J. M. Webb,[55] C. Weber,[30] H. A. Weber,[19] M. S. Weber,[20] S. M. Weber,[64a] C. Wei,[63a] Y. Wei,[55] A. R. Weidberg,[129] E. J. Weik,[120] J. Weingarten,[50] C. Weiser,[55] C. J. Wells,[49] T. Wenaus,[30] B. Wendland,[50] T. Wengler,[37] N. S. Wenke,[112] N. Wermes,[25] M. Wessels,[64a] A. M. Wharton,[93] A. S. White,[62] A. White,[8] M. J. White,[1] D. Whiteson,[162] L. Wickremasinghe,[127] W. Wiedenmann,[173] M. Wielers,[137] C. Wiglesworth,[43] D. J. Wilbern,[123] H. G. Wilkens,[37] J. J. H. Wilkinson,[33] D. M. Williams,[42] H. H. Williams,[131] S. Williams,[33] S. Willocq,[105] B. J. Wilson,[103] P. J. Windischhofer,[40] F. I. Winkel,[31] F. Winklmeier,[126] B. T. Winter,[55] J. K. Winter,[103] M. Wittgen,[147] M. Wobisch,[99] T. Wojtkowski,[61] Z. Wolffs,[117] J. Wollrath,[162] M. W. Wolter,[88] H. Wolters,[133a,133c] M. C. Wong,[139] E. L. Woodward,[42] S. D. Worm,[49] B. K. Wosiek,[88] K. W. Woźniak,[88] S. Wozniewski,[56] K. Wraight,[60] C. Wu,[21] M. Wu,[114b] M. Wu,[116] S. L. Wu,[173] X. Wu,[57] Y. Wu,[63a] Z. Wu,[4] J. Wuerzinger,[112,t] T. R. Wyatt,[103] B. M. Wynne,[53] S. Xella,[43] L. Xia,[114a] M. Xia,[15] M. Xie,[63a] S. Xin,[14,114c] A. Xiong,[126] J. Xiong,[18a] D. Xu,[14] H. Xu,[63a] L. Xu,[63a] R. Xu,[131] T. Xu,[108] Y. Xu,[15] Z. Xu,[53] Z. Xu,[114a] B. Yabsley,[151] S. Yacoob,[34a] Y. Yamaguchi,[85] E. Yamashita,[157] H. Yamauchi,[160] T. Yamazaki,[18a] Y. Yamazaki,[86] S. Yan,[60] Z. Yan,[105] H. J. Yang,[63c,63d] H. T. Yang,[63a] S. Yang,[63a] T. Yang,[65c] X. Yang,[37] X. Yang,[14] Y. Yang,[45] Y. Yang,[63a] Z. Yang,[63a] W-M. Yao,[18a] H. Ye,[114a] H. Ye,[56] J. Ye,[14] S. Ye,[30] X. Ye,[63a] Y. Yeh,[98] I. Yeletskikh,[39] B. Yeo,[18b] M. R. Yexley,[98] T. P. Yildirim,[129] P. Yin,[42] K. Yorita,[171] S. Younas,[28b] C. J. S. Young,[37] C. Young,[147] C. Yu,[14,114c] Y. Yu,[63a] J. Yuan,[14,114c] M. Yuan,[108] R. Yuan,[63d,63c] L. Yue,[98] M. Zaazoua,[63a] B. Zabinski,[88] E. Zaid,[53] Z. K. Zak,[88] T. Zakareishvili,[166] S. Zambito,[57] J. A. Zamora Saa,[140d,140b] J. Zang,[157] D. Zanzi,[55] O. Zaplatilek,[135] C. Zeitnitz,[174] H. Zeng,[14] J. C. Zeng,[165] D. T. Zenger Jr.,[27] O. Zenin,[38] T. Ženiš,[29a] S. Zenz,[96] S. Zerradi,[36a] D. Zerwas,[67] M. Zhai,[14,114c] D. F. Zhang,[143] J. Zhang,[63b] J. Zhang,[6] K. Zhang,[14,114c] L. Zhang,[63a] L. Zhang,[114a] P. Zhang,[14,114c] R. Zhang,[173] S. Zhang,[108] S. Zhang,[91] T. Zhang,[157] X. Zhang,[63c] X. Zhang,[63b] Y. Zhang,[142] Y. Zhang,[98] Y. Zhang,[114a] Z. Zhang,[18a] Z. Zhang,[63b] Z. Zhang,[67] H. Zhao,[142] T. Zhao,[63b] Y. Zhao,[139] Z. Zhao,[63a] Z. Zhao,[63a] A. Zhemchugov,[39] J. Zheng,[114a] K. Zheng,[165] X. Zheng,[63a] Z. Zheng,[147] D. Zhong,[165] B. Zhou,[108] H. Zhou,[7] N. Zhou,[63c]

Y. Zhou,[15] Y. Zhou,[114a] Y. Zhou,[7] C. G. Zhu,[63b] J. Zhu,[108] X. Zhu,[63d] Y. Zhu,[63c] Y. Zhu,[63a] X. Zhuang,[14] K. Zhukov,[69] N. I. Zimine,[39] J. Zinsser,[64b] M. Ziolkowski,[145] L. Živković,[16] A. Zoccoli,[24b,24a] K. Zoch,[62] T. G. Zorbas,[143] O. Zormpa,[47] W. Zou,[42] and L. Zwalinski[37]

(ATLAS Collaboration)

[1]*Department of Physics, University of Adelaide, Adelaide, Australia*
[2]*Department of Physics, University of Alberta, Edmonton, Alberta, Canada*
[3a]*Department of Physics, Ankara University, Ankara, Türkiye*
[3b]*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, Illinois, USA*
[7]*Department of Physics, University of Arizona, Tucson, Arizona, USA*
[8]*Department of Physics, University of Texas at Arlington, Arlington, Texas, USA*
[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, Texas, USA*
[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]*Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China*
[15]*Physics Department, Tsinghua University, Beijing, China*
[16]*Institute of Physics, University of Belgrade, Belgrade, Serbia*
[17]*Department for Physics and Technology, University of Bergen, Bergen, Norway*
[18a]*Physics Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA*
[18b]*University of California, Berkeley, California, USA*
[19]*Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany*
[20]*Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*
[21]*School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
[22a]*Department of Physics, Bogazici University, Istanbul, Türkiye*
[22b]*Department of Physics Engineering, Gaziantep University, Gaziantep, Türkiye*
[22c]*Department of Physics, Istanbul University, Istanbul, Türkiye*
[23a]*Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogotá, Colombia*
[23b]*Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia*
[24a]*Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna, Italy*
[24b]*INFN Sezione di Bologna, Bologna, Italy*
[25]*Physikalisches Institut, Universität Bonn, Bonn, Germany*
[26]*Department of Physics, Boston University, Boston, Massachusetts, USA*
[27]*Department of Physics, Brandeis University, Waltham, Massachusetts, USA*
[28a]*Transilvania University of Brasov, Brasov, Romania*
[28b]*Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
[28c]*Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania*
[28d]*National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania*
[28e]*National University of Science and Technology Politechnica, Bucharest, Romania*
[28f]*West University in Timisoara, Timisoara, Romania*
[28g]*Faculty of Physics, University of Bucharest, Bucharest, Romania*
[29a]*Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic*
[29b]*Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
[30]*Physics Department, Brookhaven National Laboratory, Upton, New York, USA*
[31]*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*
[32]*California State University, California, USA*
[33]*Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
[34a]*Department of Physics, University of Cape Town, Cape Town, South Africa*
[34b]*iThemba Labs, Western Cape, South Africa*

[34c]Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa
[34d]National Institute of Physics, University of the Philippines Diliman, Quezon City, Philippines
[34e]University of South Africa, Department of Physics, Pretoria, South Africa
[34f]University of Zululand, KwaDlangezwa, South Africa
[34g]School of Physics, University of the Witwatersrand, Johannesburg, South Africa
[35]Department of Physics, Carleton University, Ottawa, Ontario, Canada
[36a]Faculté des Sciences Ain Chock, Université Hassan II de Casablanca, Morocco
[36b]Faculté des Sciences, Université Ibn-Tofail, Kénitra, Morocco
[36c]Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
[36d]LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda, Morocco
[36e]Faculté des sciences, Université Mohammed V, Rabat, Morocco
[36f]Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco
[37]CERN, Geneva, Switzerland
[38]Affiliated with an institute covered by a cooperation agreement with CERN
[39]Affiliated with an international laboratory covered by a cooperation agreement with CERN
[40]Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
[41]LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France
[42]Nevis Laboratory, Columbia University, Irvington, New York, USA
[43]Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
[44a]Dipartimento di Fisica, Università della Calabria, Rende, Italy
[44b]INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
[45]Physics Department, Southern Methodist University, Dallas, Texas, USA
[46]Physics Department, University of Texas at Dallas, Richardson, Texas, USA
[47]National Centre for Scientific Research "Demokritos", Agia Paraskevi, Greece
[48a]Department of Physics, Stockholm University, Stockholm, Sweden
[48b]Oskar Klein Centre, Stockholm, Sweden
[49]Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany
[50]Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany
[51]Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
[52]Department of Physics, Duke University, Durham, North Carolina, USA
[53]SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
[54]INFN e Laboratori Nazionali di Frascati, Frascati, Italy
[55]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
[56]II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
[57]Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland
[58a]Dipartimento di Fisica, Università di Genova, Genova, Italy
[58b]INFN Sezione di Genova, Genova, Italy
[59]II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
[60]SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
[61]LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
[62]Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
[63a]Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China
[63b]Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China
[63c]School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai, China
[63d]Tsung-Dao Lee Institute, Shanghai, China
[63e]School of Physics, Zhengzhou University, Zhengzhou, China
[64a]Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[64b]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[65a]Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
[65b]Department of Physics, University of Hong Kong, Hong Kong, China
[65c]Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
[66]Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
[67]IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay, France
[68]Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona, Spain
[69]Department of Physics, Indiana University, Bloomington, Indiana, USA

[70a]*INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy*
[70b]*ICTP, Trieste, Italy*
[70c]*Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy*
[71a]*INFN Sezione di Lecce, Lecce, Italy*
[71b]*Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy*
[72a]*INFN Sezione di Milano, Milano, Italy*
[72b]*Dipartimento di Fisica, Università di Milano, Milano, Italy*
[73a]*INFN Sezione di Napoli, Napoli, Italy*
[73b]*Dipartimento di Fisica, Università di Napoli, Napoli, Italy*
[74a]*INFN Sezione di Pavia, Pavia, Italy*
[74b]*Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
[75a]*INFN Sezione di Pisa, Pisa, Italy*
[75b]*Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
[76a]*INFN Sezione di Roma, Roma, Italy*
[76b]*Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy*
[77a]*INFN Sezione di Roma Tor Vergata, Roma, Italy*
[77b]*Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
[78a]*INFN Sezione di Roma Tre, Roma, Italy*
[78b]*Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy*
[79a]*INFN-TIFPA, Trento, Italy*
[79b]*Università degli Studi di Trento, Trento, Italy*
[80]*Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck, Austria*
[81]*University of Iowa, Iowa City, Iowa, USA*
[82]*Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA*
[83]*Istinye University, Sariyer, Istanbul, Türkiye*
[84a]*Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil*
[84b]*Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil*
[84c]*Instituto de Física, Universidade de São Paulo, São Paulo, Brazil*
[84d]*Rio de Janeiro State University, Rio de Janeiro, Brazil*
[84e]*Federal University of Bahia, Bahia, Brazil*
[85]*KEK, High Energy Accelerator Research Organization, Tsukuba, Japan*
[86]*Graduate School of Science, Kobe University, Kobe, Japan*
[87a]*AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow, Poland*
[87b]*Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland*
[88]*Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland*
[89]*Faculty of Science, Kyoto University, Kyoto, Japan*
[90]*Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan*
[91]*L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse, France*
[92]*Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*
[93]*Physics Department, Lancaster University, Lancaster, United Kingdom*
[94]*Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
[95]*Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia*
[96]*School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom*
[97]*Department of Physics, Royal Holloway University of London, Egham, United Kingdom*
[98]*Department of Physics and Astronomy, University College London, London, United Kingdom*
[99]*Louisiana Tech University, Ruston, Louisiana, USA*
[100]*Fysiska institutionen, Lunds universitet, Lund, Sweden*
[101]*Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain*
[102]*Institut für Physik, Universität Mainz, Mainz, Germany*
[103]*School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
[104]*CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France*
[105]*Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA*
[106]*Department of Physics, McGill University, Montreal, Quebec, Canada*
[107]*School of Physics, University of Melbourne, Victoria, Australia*
[108]*Department of Physics, University of Michigan, Ann Arbor, Michigan, USA*
[109]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA*
[110]*Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada*

[111]Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
[112]Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
[113]Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
[114a]Department of Physics, Nanjing University, Nanjing, China
[114b]School of Science, Shenzhen Campus of Sun Yat-sen University, China
[114c]University of Chinese Academy of Science (UCAS), Beijing, China
[115]Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA
[116]Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen, Netherlands
[117]Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
[118]Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
[119a]New York University Abu Dhabi, Abu Dhabi, United Arab Emirates
[119b]United Arab Emirates University, Al Ain, United Arab Emirates
[120]Department of Physics, New York University, New York, New York, USA
[121]Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan
[122]The Ohio State University, Columbus, Ohio, USA
[123]Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
[124]Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
[125]Palacký University, Joint Laboratory of Optics, Olomouc, Czech Republic
[126]Institute for Fundamental Science, University of Oregon, Eugene, Oregon, USA
[127]Graduate School of Science, Osaka University, Osaka, Japan
[128]Department of Physics, University of Oslo, Oslo, Norway
[129]Department of Physics, Oxford University, Oxford, United Kingdom
[130]LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris, France
[131]Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
[132]Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
[133a]Laboratório de Instrumentação e Física Experimental de Partículas—LIP, Lisboa, Portugal
[133b]Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
[133c]Departamento de Física, Universidade de Coimbra, Coimbra, Portugal
[133d]Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal
[133e]Departamento de Física, Universidade do Minho, Braga, Portugal
[133f]Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain), Spain
[133g]Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal
[134]Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
[135]Czech Technical University in Prague, Prague, Czech Republic
[136]Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
[137]Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
[138]IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
[139]Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA
[140a]Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
[140b]Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago, Chile
[140c]Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena, Chile
[140d]Universidad Andres Bello, Department of Physics, Santiago, Chile
[140e]Instituto de Alta Investigación, Universidad de Tarapacá, Arica, Chile
[140f]Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
[141]Department of Physics, Institute of Science, Tokyo, Japan
[142]Department of Physics, University of Washington, Seattle, Washington, USA
[143]Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
[144]Department of Physics, Shinshu University, Nagano, Japan
[145]Department Physik, Universität Siegen, Siegen, Germany
[146]Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada
[147]SLAC National Accelerator Laboratory, Stanford, California, USA
[148]Department of Physics, Royal Institute of Technology, Stockholm, Sweden
[149]Departments of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA
[150]Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom

[151]*School of Physics, University of Sydney, Sydney, Australia*
[152]*Institute of Physics, Academia Sinica, Taipei, Taiwan*
[153a]*E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia*
[153b]*High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia*
[153c]*University of Georgia, Tbilisi, Georgia*
[154]*Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel*
[155]*Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*
[156]*Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*
[157]*International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan*
[158]*Department of Physics, University of Toronto, Toronto, Ontario, Canada*
[159a]*TRIUMF, Vancouver, British Columbia, Canada*
[159b]*Department of Physics and Astronomy, York University, Toronto, Ontario, Canada*
[160]*Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan*
[161]*Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA*
[162]*Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA*
[163]*University of Sharjah, Sharjah, United Arab Emirates*
[164]*Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*
[165]*Department of Physics, University of Illinois, Urbana, Illinois, USA*
[166]*Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain*
[167]*Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada*
[168]*Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada*
[169]*Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany*
[170]*Department of Physics, University of Warwick, Coventry, United Kingdom*
[171]*Waseda University, Tokyo, Japan*
[172]*Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot, Israel*
[173]*Department of Physics, University of Wisconsin, Madison, Wisconsin, USA*
[174]*Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
[175]*Department of Physics, Yale University, New Haven, Connecticut, USA*
[176]*Yerevan Physics Institute, Yerevan, Armenia*

[a]Deceased.
[b]Also at Department of Physics, King's College London, London, United Kingdom.
[c]Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
[d]Also at Imam Mohammad Ibn Saud Islamic University, Saudi Arabia.
[e]Also at TRIUMF, Vancouver, British Columbia, Canada.
[f]Also at Department of Physics, University of Thessaly, Greece.
[g]Also at An-Najah National University, Nablus, Palestine.
[h]Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
[i]Also at Department of Physics, Westmont College, Santa Barbara, California, USA.
[j]Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain.
[k]Also at Affiliated with an institute covered by a cooperation agreement with CERN.
[l]Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.
[m]Also at Faculty of Physics, Sofia University, 'St. Kliment Ohridski', Sofia, Bulgaria.
[n]Also at Università di Napoli Parthenope, Napoli, Italy.
[o]Also at Institute of Particle Physics (IPP), Canada.
[p]Also at Borough of Manhattan Community College, City University of New York, New York, New York, USA.
[q]Also at National Institute of Physics, University of the Philippines Diliman (Philippines), Quezon City, Philippines.
[r]Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
[s]Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
[t]Also at Technical University of Munich, Munich, Germany.
[u]Also at CMD-AC UNEC Research Center, Azerbaijan State University of Economics (UNEC), Baku, Azerbaijan.
[v]Also at Yeditepe University, Physics Department, Istanbul, Türkiye.
[w]Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
[x]Also at CERN, Geneva, Switzerland.
[y]Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki, Greece.

[z]Also at Hellenic Open University, Patras, Greece.
[aa]Also at Department of Physics, Stellenbosch University, Stellenbosch, South Africa.
[bb]Also at Department of Physics, California State University, Sacramento, California, USA.
[cc]Also at University of Colorado Boulder, Department of Physics, Colorado, Boulder, USA.
[dd]Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.
[ee]Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
[ff]Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.
[gg]Also at Washington College, Chestertown, Maryland, USA.
[hh]Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco.
[ii]Also at Department of Physics, Stanford University, Stanford, California, USA.