

Search for flavour-changing neutral current top-quark decays $t \rightarrow qZ$ in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector



The ATLAS collaboration

E-mail: atlas.publications@cern.ch

ABSTRACT: A search for flavour-changing neutral-current processes in top-quark decays is presented. Data collected with the ATLAS detector from proton-proton collisions at the Large Hadron Collider at a centre-of-mass energy of $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 36.1 fb^{-1} , are analysed. The search is performed using top-quark pair events, with one top quark decaying through the $t \rightarrow qZ$ ($q = u, c$) flavour-changing neutral-current channel, and the other through the dominant Standard Model mode $t \rightarrow bW$. Only Z boson decays into charged leptons and leptonic W boson decays are considered as signal. Consequently, the final-state topology is characterized by the presence of three isolated charged leptons (electrons or muons), at least two jets, one of the jets originating from a b -quark, and missing transverse momentum from the undetected neutrino. The data are consistent with Standard Model background contributions, and at 95% confidence level the search sets observed (expected) upper limits of 1.7×10^{-4} (2.4×10^{-4}) on the $t \rightarrow uZ$ branching ratio and 2.4×10^{-4} (3.2×10^{-4}) on the $t \rightarrow cZ$ branching ratio, constituting the most stringent limits to date.

KEYWORDS: Hadron-Hadron scattering (experiments)

ARXIV EPRINT: [1803.09923](https://arxiv.org/abs/1803.09923)

Contents

1	Introduction	1
2	ATLAS detector and data samples	2
3	Signal and background simulation samples	3
4	Object reconstruction	6
5	Event selection and reconstruction	7
6	Background estimation and control regions	8
7	Systematic uncertainties	11
8	Results	12
9	Conclusions	14
	The ATLAS collaboration	25

1 Introduction

The top quark is the heaviest elementary particle known, with a mass $m_t = 173.3 \pm 0.8$ GeV [1]. In the Standard Model of particle physics (SM), it decays almost exclusively into bW while flavour-changing neutral current (FCNC) decays such as $t \rightarrow qZ$ are forbidden at tree level. FCNC decays occur at one-loop level but are strongly suppressed by the GIM mechanism [2] with a suppression factor of 14 orders of magnitude relative to the dominant decay mode [3]. However, several SM extensions predict higher branching ratios for top-quark FCNC decays. Examples of such extensions are the quark-singlet model (QS) [4], the two-Higgs-doublet model with (FC 2HDM) or without (2HDM) flavour conservation [5], the Minimal Supersymmetric Standard Model (MSSM) [6], the MSSM with R-parity violation (RPV SUSY) [7], models with warped extra dimensions (RS) [8], or extended mirror fermion models (EMF) [9]. Reference [10] gives a comprehensive review of the various extensions of the SM that have been proposed. Table 1 provides the maximum values for the branching ratios $\mathcal{B}(t \rightarrow qZ)$ predicted by these models and compares them to the value predicted by the SM.

Experimental limits on the FCNC branching ratio $\mathcal{B}(t \rightarrow qZ)$ were established by experiments at the Large Electron-Positron collider [11–15], HERA [16], the Tevatron [17, 18], and the Large Hadron Collider (LHC) [19–22]. Before the results reported here, the most stringent limits were $\mathcal{B}(t \rightarrow uZ) < 2.2 \times 10^{-4}$ and $\mathcal{B}(t \rightarrow cZ) < 4.9 \times 10^{-4}$ at

95% confidence level (CL), both set by the CMS Collaboration [22] using data collected at $\sqrt{s} = 8$ TeV. For the same centre-of-mass energy, the ATLAS Collaboration derived a limit of $\mathcal{B}(t \rightarrow qZ) < 7 \times 10^{-4}$ [20]. ATLAS results obtained at $\sqrt{s} = 7$ TeV are also available [19].

This analysis is a search for the FCNC decay $t \rightarrow qZ$ in top-quark-top-antiquark ($t\bar{t}$) events, in 36.1 fb^{-1} of data collected at $\sqrt{s} = 13$ TeV, where one top quark decays through the FCNC mode and the other through the dominant SM mode ($t \rightarrow bW$). Only Z boson decays into charged leptons and leptonic W boson decays are considered. The final-state topology is thus characterized by the presence of three isolated charged leptons,¹ at least two jets with exactly one being tagged as a jet containing b -hadrons, and missing transverse momentum from the undetected neutrino. The main sources of background events containing three prompt leptons are diboson, $t\bar{t}Z$, and tZ production. Events with two or fewer prompt leptons and additional non-prompt² leptons are also sources of background. Besides the signal region, control regions are defined to constrain the main backgrounds. Results are obtained using a binned likelihood fit to kinematic distributions in the signal and control regions.

The article is organized as follows. A brief description of the ATLAS detector is given in section 2. The collected data samples and the simulations of signal and SM background processes are described in section 3. Section 4 presents the object definitions, while the event analysis and kinematic reconstruction are explained in section 5. Background evaluation and sources of systematic uncertainty are described in sections 6 and 7. Results are presented in section 8, and conclusions are drawn in section 9.

2 ATLAS detector and data samples

The ATLAS experiment [23] is a multi-purpose particle physics detector consisting of several subdetector systems, which almost fully cover the solid angle³ around the interaction point. It is composed of an inner tracking system close to the interaction point and immersed in a 2 T axial magnetic field produced by a thin superconducting solenoid. A lead/liquid-argon (LAr) electromagnetic calorimeter, a steel/scintillator-tile hadronic calorimeter, copper/LAr hadronic endcap calorimeters, copper/LAr and tungsten/LAr forward calorimeters, and a muon spectrometer with three superconducting magnets, each one with eight toroid coils, complete the detector. A new innermost silicon pixel layer was added to the inner detector after Run 1 [24, 25]. The combination of all these systems provides charged-particle momentum measurements, together with efficient and precise lepton and

¹In this article, lepton is used to denote an electron or muon, including those coming from leptonic τ -lepton decays.

²Prompt leptons are leptons from the decay of W or Z bosons, either directly or through an intermediate $\tau \rightarrow \ell\nu\nu$ decay, or from the semileptonic decay of top quarks.

³ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the centre of the detector and the z -axis along the beam pipe. The x -axis points from the interaction point to the centre of the LHC ring, and the y -axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$. The ΔR distance is defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

Model:	SM	QS	2HDM	FC 2HDM	MSSM	RPV SUSY	RS	EMF
$\mathcal{B}(t \rightarrow qZ)$:	10^{-14}	10^{-4}	10^{-6}	10^{-10}	10^{-7}	10^{-6}	10^{-5}	10^{-6}

Table 1. Maximum allowed FCNC $t \rightarrow qZ$ ($q = u, c$) branching ratios predicted by several models [3–10].

photon identification in the pseudorapidity range $|\eta| < 2.5$. Energy deposits over the full coverage of the calorimeters, $|\eta| < 4.9$, are used to reconstruct jets and missing transverse momentum. A two-level trigger system is used to select interesting events [26]. The first level is implemented with custom hardware and uses a subset of detector information to reduce the event rate. It is followed by a software-based trigger level to reduce the event rate to approximately 1 kHz.

In this analysis, the combined 2015 and 2016 datasets from proton-proton (pp) collisions at $\sqrt{s} = 13$ TeV corresponding to an integrated luminosity of 36.1 fb^{-1} are used. Analysed events are selected by either a single-electron or a single-muon trigger. Triggers with different transverse-momentum thresholds are used to increase the overall efficiency. The triggers using a low electron transverse momentum (p_{T}^e) or muon transverse momentum (p_{T}^μ) threshold ($p_{\text{T}}^e > 24$ GeV or $p_{\text{T}}^\mu > 20$ GeV for 2015 data and $p_{\text{T}}^{e,\mu} > 26$ GeV for 2016 data) also have isolation requirements. At high p_{T} the isolation requirements incur small efficiency losses which are recovered by higher-threshold triggers ($p_{\text{T}}^e > 60$ GeV, $p_{\text{T}}^e > 120$ GeV, or $p_{\text{T}}^\mu > 50$ GeV for 2015 data and $p_{\text{T}}^e > 60$ GeV, $p_{\text{T}}^e > 140$ GeV, or $p_{\text{T}}^\mu > 50$ GeV for 2016 data) without isolation requirements.

3 Signal and background simulation samples

In pp collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV at the LHC, top quarks are produced according to the SM mainly in $t\bar{t}$ pairs with a predicted cross section of $\sigma_{t\bar{t}} = 0.83 \pm 0.05$ nb [27–32] for the top-quark mass value of 172.5 GeV used to simulate events as described in the following paragraphs; the uncertainty includes contributions from uncertainties in the factorization and renormalization scales, the parton distribution functions (PDF), the strong coupling α_s , and the top-quark mass. The cross section is calculated at next-to-next-to-leading order (NNLO) in QCD including resummation of next-to-next-to-leading logarithmic soft gluon terms with Top++ 2.0. The effects of PDF and α_s uncertainties are calculated using the PDF4LHC prescription [33] with the MSTW 2008 68% CL NNLO [34, 35], CT10 NNLO [36, 37] and NNPDF 2.3 5f FFN [38] PDF sets and are added in quadrature to those from the renormalization and factorization scale uncertainties.

The next-to-leading-order (NLO) simulation of signal events was performed with the event generator MG5_aMC@NLO [39] interfaced to Pythia8 [40] with the A14 [41] set of tuned parameters and the NNPDF2.3LO PDF set [38]. Dynamic factorization and renormalization scales were used. The factorization and renormalization scales were set equal to $\sqrt{m_t^2 + (p_{\text{T},t}^2 + p_{\text{T},\bar{t}}^2)/2}$ where $p_{\text{T},t}$ ($p_{\text{T},\bar{t}}$) is the transverse momentum of the top quark (top antiquark). For the matrix element, the PDF set NNPDF3.0NLO [42] was used. For the

top-quark FCNC decay, the effects of new physics at an energy scale Λ were included by adding dimension-six effective terms to the SM Lagrangian. No differences between the kinematical distributions from the $bWuZ$ and $bWcZ$ processes are observed. Due to the different b -tagging mistag rates for u - and c -quarks, the signal efficiencies differ after applying requirements on the b -tagged jet multiplicity. Hence limits on $\mathcal{B}(t \rightarrow qZ)$ are set separately for $q = u, c$. Only decays of the W and Z bosons with charged leptons were generated at the matrix-element level ($Z \rightarrow e^+e^-$, $\mu^+\mu^-$, or $\tau^+\tau^-$ and $W \rightarrow e\nu$, $\mu\nu$, or $\tau\nu$).

Several SM processes have final-state topologies similar to the signal, with at least three prompt charged leptons, especially dibosons (WZ and ZZ), $t\bar{t}V$ (V is W or Z), $t\bar{t}WW$, $t\bar{t}H$, gluon-gluon fusion (ggF) H , vector-boson fusion (VBF) H , VH , tZ , WtZ , $ttt(t)$, and triboson (WWW , ZWW and ZZZ) production. The theoretical estimates for these backgrounds are further constrained by the simultaneous fit to the signal and control regions described below. Events with non-prompt leptons or events in which at least one jet is misidentified as an isolated charged lepton (labelled as non-prompt leptons throughout this article) can also fulfil the event selection requirements. These events, typically Z +jets (including γ emission), $t\bar{t}$, and single-top (Wt), are estimated with the semi-data-driven method explained in section 6, which also uses simulated samples which for the Z +jets events include Z production in association with heavy-flavour quarks.

Table 2 summarizes information about the generators, parton shower, and PDFs used to simulate the different event samples considered in the analysis. The associated production of a $t\bar{t}$ pair with one vector boson was generated at NLO with `MG5_aMC@NLO` interfaced to `Pythia8` with the `A14` set of tuned parameters and the `NNPDF2.3L0` PDF set. The $t\bar{t}Z$ and $t\bar{t}W$ samples were normalized to the NLO QCD+electroweak cross-section calculation using a fixed scale $(m_t + m_V/2)$ [43]. In the case of the $t\bar{t}Z$ sample with the $Z \rightarrow \ell^+\ell^-$ decay mode, the Z/γ^* interference was included with the criterion $m_{\ell\ell} > 5$ GeV applied. The t -channel production of a single top quark in association with a Z boson (tZ) was generated using `MG5_aMC@NLO` using the four-flavour PDF scheme. Production of a single top quark in the Wt -channel together with a Z boson (WtZ) was generated with `MG5_aMC@NLO` with the parton shower simulated using `Pythia8`, the PDF set `NNPDF2.3L0`, and the `A14` set of tuned parameters. The diagram removal technique [44] was employed to handle the overlap of WtZ with $t\bar{t}Z$ and $t\bar{t}$ production followed by a three-body top-quark decay ($t \rightarrow WZb$). The procedure also removes the interference between WtZ and these two processes. Diboson processes with four charged leptons (4ℓ), three charged leptons and one neutrino ($\ell\ell\ell\nu$), two charged leptons and two neutrinos ($\ell\ell\nu\nu$), and diboson processes having additional hadronic contributions ($\ell\ell\ell\nu jj$, $\ell\ell\ell jjj$, $gg\ell\ell\ell\ell$, $\ell\ell\nu\nu jj$) were simulated using the `Sherpa 2.1.1` [45] generator. The matrix elements contain all diagrams with four electroweak vertices. They were calculated for up to one (4ℓ , $2\ell + 2\nu$) or no additional partons ($3\ell + 1\nu$) at NLO and up to three partons at LO using the `Comix` [46] and `OpenLoops` [47] matrix element generators and were merged with the `Sherpa` parton shower using the `ME+PS@NLO` prescription [46–48]. The `CT10` PDF set was used in conjunction with a dedicated parton shower tuning developed by the `Sherpa` authors. The Higgs boson samples ($t\bar{t}H$, Higgs boson production via gluon-gluon fusion and vector boson fusion, and in association with a vector boson) were normalized to the theoretical calculations in ref. [43].

Sample	Generator	Parton shower	ME PDF	PS PDF	Tune parameters
$t\bar{t} \rightarrow bWqZ$	MG5_aMC@NLO [39]	Pythia8 [40]	NNPDF3.0NLO [42]	NNPDF2.3LO [38]	A14 [41]
$t\bar{t}V, t\bar{t}H$	MG5_aMC@NLO	Pythia8	NNPDF3.0NLO	NNPDF2.3LO	A14
$t\bar{t}Z$ (alternative)	Sherpa 2.2.0 [45]	Sherpa 2.2.0	NNPDF3.0NNLO	NNPDF3.0NNLO	Sherpa default
WZ, ZZ	Sherpa 2.1.1	Sherpa 2.1.1	CT10 [36]	CT10	Sherpa default
WZ (alternative)	Powheg-Box v2 [49]	Pythia8	CT10nlo	CTEQ6L1 [54]	AZNLO [55]
tZ	MG5_aMC@NLO	Pythia6 [56]	NNPDF3.0NLO	CTEQ6L1	Perugia2012 [57]
tZ (rad. syst.)	MG5_aMC@NLO	Pythia6	NNPDF3.0NLO	CTEQ6L1	P2012RadHi/Lo [57]
WtZ	MG5_aMC@NLO	Pythia8	NNPDF3.0NLO	NNPDF2.3LO	A14
WtZ (alternative)	MG5_aMC@NLO	Herwig++ [58]	CT10	CTEQ6L1	UE-EE-5 [59]
$ggF\ H, VBF\ H$	Powheg-Box v2	Pythia8	CT10	CTEQ6L1	AZNLO
WH, ZH	Pythia8	Pythia8	NNPDF2.3LO	NNPDF2.3LO	A14
$3t, 4t, t\bar{t}WW$	MG5_aMC@NLO	Pythia8	NNPDF3.0NLO	NNPDF2.3LO	A14
Tribosons	Sherpa 2.1.1	Sherpa 2.1.1	CT10	CT10	Sherpa default
Z +jets	Powheg-Box v2, Photos++ [50]	Pythia8	CT10	CTEQ6L1	AZNLO
$t\bar{t} \rightarrow bWbW$	Powheg-Box v2	Pythia8	CT10	NNPDF2.3LO	A14
$t\bar{t} \rightarrow bWbW$ (rad. syst.)	Powheg-Box v2	Pythia8	CT10	NNPDF2.3LO	A14v3cUp/Do [41]
$t\bar{t} \rightarrow bWbW$ (PS syst.)	Powheg-Box v2	Herwig7 [60]	NNPDF3.0NLO	MMHT20141o68c1 [61]	H7-UE-MMHT [60]
$t\bar{t} \rightarrow bWbW$ (ME syst.)	MG5_aMC@NLO	Pythia8	NNPDF3.0NLO	NNPDF2.3LO	A14
Wt	Powheg-Box v1	Pythia6	CT10f4	CTEQ6L1	Perugia2012

Table 2. Generators, parton shower simulation, parton distribution functions, and tune parameters used to produce simulated samples for this analysis. The acronyms ME and PS stand for matrix element and parton shower, respectively.

Events containing Z bosons + jets were simulated with **Powheg-Box v2** [49] interfaced to the **Pythia8** parton shower model, using **Photos++** version 3.52 [50] for QED emissions from electroweak vertices and charged leptons. The generation of $t\bar{t}$ and single top quarks in the Wt -channel was done with **Powheg-Box v2** and **Powheg-Box v1**, respectively. Due to the high lepton-multiplicity requirement of the event selection and to increase the sample size, the $t\bar{t}$ sample was produced by selecting only true dilepton events in the final state. The SM production of three or four top quarks and the associated production of a $t\bar{t}$ pair with two W bosons were generated at LO with **MG5_aMC@NLO+Pythia8**. The production of three massive vector bosons with subsequent leptonic decays of all three bosons was modelled at LO with the **Sherpa 2.1.1** generator. Up to two additional partons are included in the matrix element at LO.

A set of minimum-bias interactions generated with **Pythia 8.186** using the **A2** set of tuned parameters [51] and the **MSTW2008LO** [34] PDF set were overlaid on the hard-scattering event to account for additional pp collisions in the same or nearby bunch crossings (pile-up). Simulated samples were reweighted to match the pile-up conditions in data. For most samples, detailed simulation of the detector and trigger system was performed with standard ATLAS software using **GEANT4** [52, 53]. Fast simulation based on **ATLFASTII** [53] is alternatively used for a few samples dedicated to the evaluation of systematic uncertainties affecting background modelling. The same offline reconstruction methods used on data are also applied to the samples of simulated events. Simulated events are corrected so that the object identification, reconstruction, and trigger efficiencies; the energy scales; and the energy resolutions match those determined from data control samples.

4 Object reconstruction

The final states of interest for this search include electrons, muons, jets, b -tagged jets and missing transverse momentum.

Electron candidates are reconstructed [62] from energy deposits (clusters) in the electromagnetic calorimeter matched to reconstructed charged-particle tracks in the inner detector. The candidates are required to have a transverse energy $E_T > 15$ GeV and the pseudorapidity of the calorimeter energy cluster associated with the electron candidate must satisfy $|\eta_{\text{cluster}}| < 2.47$. Clusters in the transition region between the barrel and end-cap calorimeters, $1.37 \leq |\eta_{\text{cluster}}| \leq 1.52$, have poorer energy resolution and are excluded. To reduce the background from non-prompt sources, electron candidates are also required to satisfy $|d_0|/\sigma(d_0) < 5$ and $|z_0 \sin(\theta)| < 0.5$ mm criteria, where d_0 is the transverse impact parameter, with uncertainty $\sigma(d_0)$, and z_0 is the longitudinal impact parameter with respect to the primary vertex (defined in section 5). The sum of transverse energies of clusters in the calorimeter within a cone of $\Delta R = 0.2$ around the electron candidate, excluding the p_T of the electron candidate, is required to be less than 6% of the electron p_T . The scalar sum of particle transverse momenta around the electron candidate within a cone of $\min(10 \text{ GeV}/p_T, 0.2)$ must be less than 6% of the electron candidate's p_T .

Muon candidates are reconstructed from tracks in the inner detector and muon spectrometer, which are combined to improve the reconstruction precision and to increase the background rejection [63]. They are required to have $p_T > 15$ GeV and $|\eta| < 2.5$. Muons are also required to satisfy $|d_0|/\sigma(d_0) < 3$ and $|z_0 \sin(\theta)| < 0.5$ mm criteria. Additionally, the scalar sum of particle transverse momenta around the muon candidate within a cone of $\min(10 \text{ GeV}/p_T, 0.3)$ must be less than 6% of the muon candidate's p_T .

Jets are reconstructed from topological clusters of calorimeter cells that are noise-suppressed and calibrated to the electromagnetic scale [64] using the anti- k_t algorithm [65] with a radius parameter $R = 0.4$ as implemented in FastJet [66]. Corrections that change the angles and the energy are applied to the jets, starting with a subtraction procedure that uses the jet area to estimate and remove the average energy contributed by pile-up interactions [67]. This is followed by a jet-energy-scale calibration that restores the jet energy to the mean response of a particle-level simulation by correcting variations due to jet flavour and detector geometry and data driven corrections that match the data to the simulation energy scale [68]. Jets in the analysis have $p_T > 25$ GeV and $|\eta| < 2.5$.

To reduce the number of selected jets that originate from pile-up, an additional selection criterion based on a jet-vertex tagging technique is applied. Jet-vertex tagging is a likelihood discriminant combining information from several track-based variables [69] and is only applied to jets with $p_T < 60$ GeV and $|\eta| < 2.4$.

Jets containing b -hadrons are identified (b -tagged) [70, 71] using an algorithm based on multivariate techniques. It combines information from the impact parameters of displaced tracks and from topological properties of secondary and tertiary decay vertices reconstructed within the jet. Using simulated $t\bar{t}$ events, the b -tagging efficiency for jets originating from a b -quark is determined to be 77% for the chosen working point, while the rejection factors for light-flavour jets and charm jets are 134 and 6, respectively.

The missing transverse momentum \vec{p}_T^{miss} is the negative vector sum of the p_T of all selected and calibrated objects in the event, including a term to account for soft particles in the event that are not associated with any of the selected objects [72, 73]. To reduce contamination from pile-up interactions, the soft term is calculated from inner detector tracks matched to the selected primary vertex. The magnitude of the missing transverse momentum is E_T^{miss} .

To avoid double counting of single final-state objects, such as an isolated electron being reconstructed as both an electron and a jet, the following procedures are applied in the order given. Electron candidates which share a track with a muon candidate are removed. If the distance in ΔR between a jet and an electron candidate is $\Delta R < 0.2$, then the jet is dropped. If, for the same electron, multiple jets are found with this requirement, only the closest one is dropped. If the distance in ΔR between a jet and an electron is $0.2 < \Delta R < 0.4$, then the electron is dropped. If the distance in ΔR between a jet and a muon candidate is $\Delta R < 0.4$ and if the jet has more than two associated tracks, the muon is dropped; otherwise the jet is removed.

5 Event selection and reconstruction

Events considered in this analysis meet the following criteria. At least one of the selected leptons must be matched, with $\Delta R < 0.15$, to the appropriate trigger object and have transverse momentum greater than 25 GeV or 27 GeV for the data collected in 2015 or 2016, respectively. The events must have at least one primary vertex. The primary vertex must have at least two associated tracks, each with $p_T > 400$ MeV. The primary vertex with the highest sum of p_T^2 over all associated tracks is chosen. Exactly three isolated charged leptons with $|\eta| < 2.5$ and $p_T > 15$ GeV are required. The Z boson candidate is reconstructed from the two leptons that have the same flavour, opposite charge, and a reconstructed mass within 15 GeV of the Z boson mass (m_Z). If more than one compatible lepton pair is found, the one with the reconstructed mass closest to m_Z is chosen as the Z boson candidate. According to the signal topology, the events are then required to have $E_T^{\text{miss}} > 20$ GeV and at least two jets. All jets must have $p_T > 25$ GeV and $|\eta| < 2.5$, and exactly one of the jets must be b -tagged.

Applying energy-momentum conservation, the kinematic properties of the top quarks are reconstructed from the corresponding decay particles by minimizing

$$\chi^2 = \frac{\left(m_{j_a \ell_a \ell_b}^{\text{reco}} - m_{t_{\text{FCNC}}}\right)^2}{\sigma_{t_{\text{FCNC}}}^2} + \frac{\left(m_{j_b \ell_c \nu}^{\text{reco}} - m_{t_{\text{SM}}}\right)^2}{\sigma_{t_{\text{SM}}}^2} + \frac{\left(m_{\ell_c \nu}^{\text{reco}} - m_W\right)^2}{\sigma_W^2},$$

where $m_{j_a \ell_a \ell_b}^{\text{reco}}$, $m_{j_b \ell_c \nu}^{\text{reco}}$, and $m_{\ell_c \nu}^{\text{reco}}$ are the reconstructed masses of the qZ , bW , and $\ell\nu$ systems, respectively. For each jet combination, j_b corresponds to the b -tagged jet, while any jet can be assigned to j_a . Since the neutrino from the semileptonic decay of the top quark ($t \rightarrow bW \rightarrow b\ell\nu$) is undetected, its four-momentum must be estimated. This is done by assuming that the lepton not previously assigned to the Z boson and the b -tagged jet originate from the W boson and SM top-quark decay, respectively, and that \vec{p}_T^{miss} is

the transverse momentum vector of the neutrino in the W boson decay. The longitudinal component of the neutrino momentum (p_z^ν) is then determined by the minimization of the χ^2 . The central values of the masses and the widths of the top quarks and the W boson are taken from simulated signal events. This is done by matching the particles in the simulated events to the reconstructed ones, setting the longitudinal momentum of the neutrino to the p_z of the simulated neutrino, and then performing Bukin fits⁴ [74] to the masses of the matched reconstructed top quarks and W boson. The obtained values are $m_{t_{\text{FCNC}}} = 169.6$ GeV, $\sigma_{t_{\text{FCNC}}} = 12.0$ GeV, $m_{t_{\text{SM}}} = 167.2$ GeV, $\sigma_{t_{\text{SM}}} = 24.0$ GeV, $m_W = 81.2$ GeV and $\sigma_W = 15.1$ GeV. The χ^2 minimization gives the most probable value for p_z^ν for a given combination. The combination with the minimum χ^2 is chosen, which fixes the assignment of reconstructed particles and the corresponding p_z^ν value. The jet from the top-quark FCNC decay is referred to as the light-quark (q) jet. The fractions of correct assignments between the reconstructed top quarks and the true simulated particles (evaluated as a match within a cone of size $\Delta R = 0.4$) are $\epsilon_{t_{\text{FCNC}}} = 80\%$ and $\epsilon_{t_{\text{SM}}} = 58\%$, where the difference comes from the fact that for the SM top-quark decay the match of the E_T^{miss} with the simulated neutrino is less efficient.

The final requirements defining the signal region (SR) are $|m_{j_a \ell_a \ell_b}^{\text{reco}} - 172.5 \text{ GeV}| < 40 \text{ GeV}$, $|m_{j_b \ell_c \nu}^{\text{reco}} - 172.5 \text{ GeV}| < 40 \text{ GeV}$, and $|m_{\ell_c \nu}^{\text{reco}} - 80.4 \text{ GeV}| < 30 \text{ GeV}$. Figure 1 shows the mass of the Z boson candidate as well as the E_T^{miss} and the masses of both top-quark candidates for the events fulfilling these requirements. The stacked histograms show backgrounds with three prompt leptons, normalized to the theory predictions, and the scaled background from non-prompt leptons, normalized as discussed in the next section.

6 Background estimation and control regions

The main sources of background events containing three prompt leptons are: diboson production, $t\bar{t}Z$, and tZ processes. In addition, events where one or more of the reconstructed leptons are non-prompt, either mis-reconstructed or from heavy-flavour decays, are background sources. To assess how well the data agree with the simulated samples of the expected background, five control regions (CRs) are defined and included in the final fit. This allows rescaling of the background expectations to the best fit with observed data and reduces the background uncertainties. Systematic uncertainties in the signal yield are also reduced by the final fit (section 8).

Backgrounds from events containing at least one non-prompt lepton are estimated by means of a semi-data-driven technique using dedicated selections. This technique uses the data to determine the normalization for simulated Z +jets and $t\bar{t}$ events with a non-prompt electron and non-prompt muon separately. In order to determine the non-prompt lepton scale factors (λ^e , λ^μ) for simulated Z +jets and $t\bar{t}$ events, four regions are defined each enriched with non-prompt electrons or muons from Z +jets events (“light” region) or $t\bar{t}$

⁴These fits use a piecewise function with a Gaussian function in the centre and two asymmetric tails. Six parameters determine the overall normalization, the peak position, the width of the core, the asymmetry, the size of the lower tail, and the size of the higher tail. Of these, only the peak position and the width enter the χ^2 .

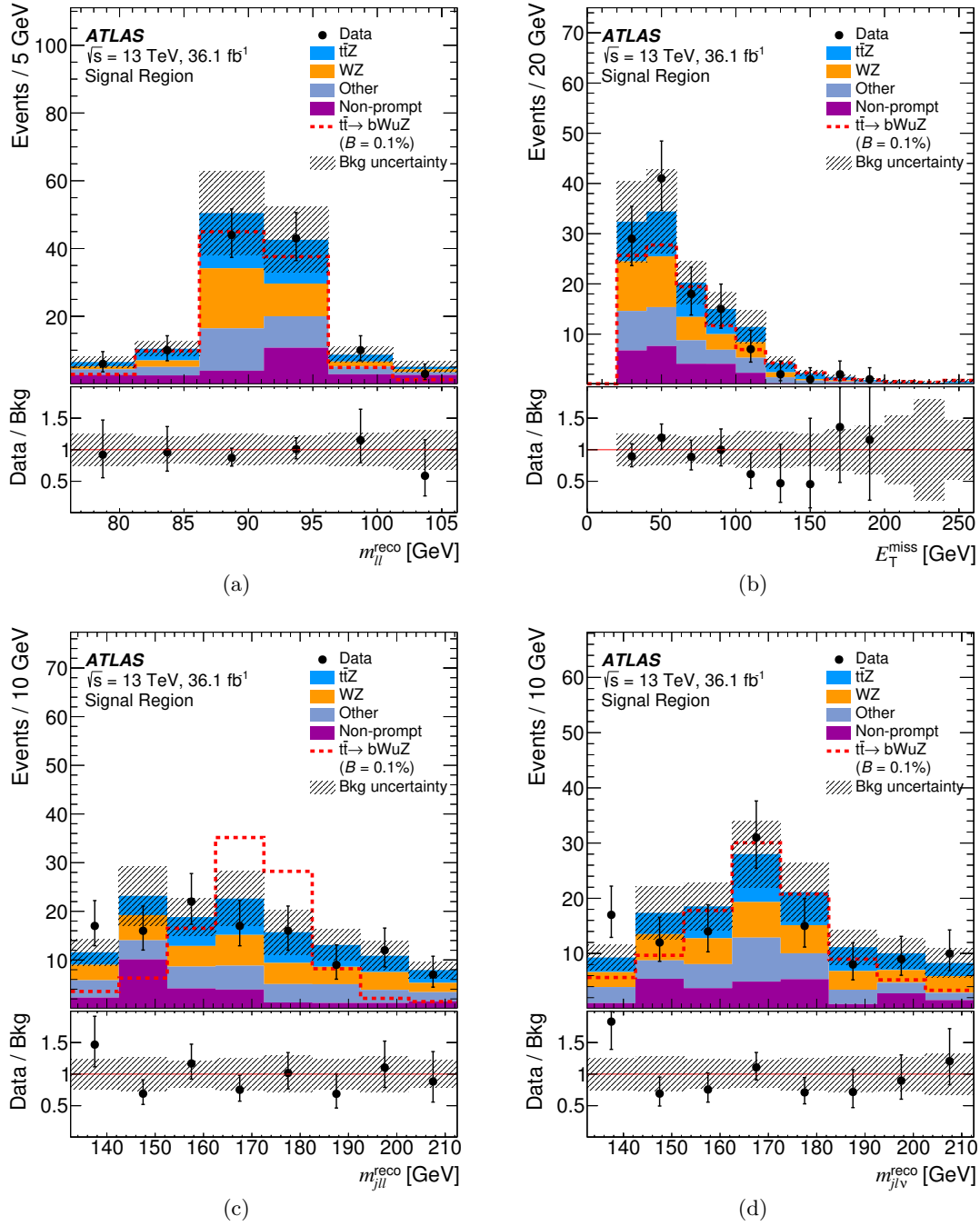


Figure 1. Expected (filled histogram) and observed (points with error bars) distributions in the SR before the combined fit under the background-only hypothesis of (a) the mass of the Z boson candidate, (b) E_T^{miss} , (c) the mass of the top-quark candidate with FCNC decay, and (d) the mass of the top-quark candidate with SM decay. For comparison, distributions for the FCNC $t\bar{t} \rightarrow bWuZ$ signal (dashed line), normalized to $\mathcal{B}(t \rightarrow uZ) = 0.1\%$, are also shown. The dashed area represents the total uncertainty in the background prediction. The first (last) bin in all distributions includes the underflow (overflow). The “Other” category includes all remaining backgrounds described in section 3.

“Light” region — e	“Light” region — μ	“Heavy” region — e	“Heavy” region — μ
eee or $e\mu\mu$, OSSF	$\mu\mu\mu$ or μee , OSSF	$e\mu\mu$, OS no OSSF	μee , OS no OSSF
$ m_{\ell\ell} - 91.2 \text{ GeV} < 15 \text{ GeV}$	$ m_{\ell\ell} - 91.2 \text{ GeV} < 15 \text{ GeV}$		
$\geq 1 \text{ jet}$	$\geq 1 \text{ jet}$	$\geq 2 \text{ jet}$	$\geq 2 \text{ jet}$
$E_{\text{T}}^{\text{miss}} < 40 \text{ GeV}$	$E_{\text{T}}^{\text{miss}} < 40 \text{ GeV}$		
$m_{\text{T}} \leq 50 \text{ GeV}$	$m_{\text{T}} \leq 50 \text{ GeV}$		

Table 3. Selection criteria applied to derive the four scale factors of the non-prompt leptons background. OS indicates a pair of opposite-sign leptons, OSSF indicates a pair of opposite-sign, same-flavour leptons. Additionally, events with at least two jets, one of them b -tagged, and $20 \text{ GeV} < E_{\text{T}}^{\text{miss}} < 40 \text{ GeV}$ in the SR are rejected from the “light” regions.

events (“heavy” region). The selections used, which are given in table 3, make the four regions orthogonal to the CRs and SR used in the final fit (section 8). The non-prompt lepton scale factors for Z +jets and $t\bar{t}$ events are expected to be different due to differences in background sources and are determined by a simultaneous likelihood fit to the inclusive yields in the four regions, taking into account statistical and systematic uncertainties, leading to $\lambda_{Z+\text{jets}}^e = 2.2 \pm 0.8$, $\lambda_{Z+\text{jets}}^\mu = 1.9 \pm 0.9$, $\lambda_{t\bar{t}}^e = 1.1 \pm 0.3$, and $\lambda_{t\bar{t}}^\mu = 1.1 \pm 0.7$. These non-prompt lepton scale factors are applied to the Z +jets and $t\bar{t}$ samples in the CRs and SR used in the final fit (section 8). Agreement between data and expectations in the CRs is significantly improved after applying the non-prompt lepton scale factors to the simulated samples.

The $t\bar{t}Z$ CR requires exactly three leptons, two of them with the same flavour, opposite charge, and a reconstructed $m_{\ell\ell}$ within 15 GeV of the Z boson mass. Furthermore, the events are required to have at least four jets with $p_{\text{T}} > 25 \text{ GeV}$ and $|\eta| < 2.5$, two of which must be b -tagged.

The WZ CR requires three leptons, two of them with the same flavour, opposite charge, and a reconstructed $m_{\ell\ell}$ within 15 GeV of the Z boson mass. Additional requirements are the presence of at least two jets with $p_{\text{T}} > 25 \text{ GeV}$ and $|\eta| < 2.5$, the leading jet having $p_{\text{T}} > 35 \text{ GeV}$, no b -tagged jets with $p_{\text{T}} > 25 \text{ GeV}$, $E_{\text{T}}^{\text{miss}} > 40 \text{ GeV}$, and a transverse mass $m_{\text{T}}^{\ell\nu} > 50 \text{ GeV}$, where $m_{\text{T}}^{\ell\nu}$ is calculated from the momentum of the non- Z lepton and the missing transverse momentum vector.

The ZZ CR requires two pairs of leptons, each with the same flavour, opposite charge, and a reconstructed $m_{\ell\ell}$ within 15 GeV of the Z boson mass. At least one jet with $p_{\text{T}} > 25 \text{ GeV}$ and $|\eta| < 2.5$, no b -tagged jets with $p_{\text{T}} > 25 \text{ GeV}$, and $E_{\text{T}}^{\text{miss}} > 20 \text{ GeV}$ are also required.

The CR for the non-prompt lepton backgrounds requires three leptons with two of them having the same flavour, opposite charge, and a reconstructed $m_{\ell\ell}$ outside 15 GeV of the Z boson mass, at least one jet with $p_{\text{T}} > 25 \text{ GeV}$, and $E_{\text{T}}^{\text{miss}} > 20 \text{ GeV}$. This CR is split into two regions, with either zero (CR0) or exactly one (CR1) b -tagged jet.

Table 4 summarizes the selection requirements described above. The expected and observed yields in these regions, before the background fit described in section 8, are shown in table 5.

Selection	$t\bar{t}Z$ CR	WZ CR	ZZ CR	Non-prompt lepton CR0 (CR1)	SR
No. leptons	3	3	4	3	3
OSSF	Yes	Yes	Yes	Yes	Yes
$ m_{\ell\ell}^{\text{reco}} - 91.2 \text{ GeV} $	$< 15 \text{ GeV}$	$< 15 \text{ GeV}$	$< 15 \text{ GeV}$	$> 15 \text{ GeV}$	$< 15 \text{ GeV}$
No. jets	≥ 4	≥ 2	≥ 1	≥ 2	≥ 2
No. b -tagged jets	2	0	0	0 (1)	1
$E_{\text{T}}^{\text{miss}}$	$> 20 \text{ GeV}$	$> 40 \text{ GeV}$	$> 20 \text{ GeV}$	$> 20 \text{ GeV}$	$> 20 \text{ GeV}$
$m_{\text{T}}^{\ell\nu}$	—	$> 50 \text{ GeV}$	—	—	—
$ m_{\ell\nu}^{\text{reco}} - 80.4 \text{ GeV} $	—	—	—	—	$< 30 \text{ GeV}$
$ m_{j\ell\nu}^{\text{reco}} - 172.5 \text{ GeV} $	—	—	—	—	$< 40 \text{ GeV}$
$ m_{j\ell\ell}^{\text{reco}} - 172.5 \text{ GeV} $	—	—	—	—	$< 40 \text{ GeV}$

Table 4. The selection requirements applied for the background control and signal regions. OSSF refers to the presence of a pair of opposite-sign, same-flavour leptons.

Sample	$t\bar{t}Z$ CR	WZ CR	ZZ CR	Non-prompt lepton CR0	Non-prompt lepton CR1
$t\bar{t}Z$	61 ± 9	16.3 ± 3.1	0 ± 0	6.1 ± 1.2	22.1 ± 3.2
WZ	9 ± 9	560 ± 240	0 ± 0	150 ± 70	20 ± 9
ZZ	0.07 ± 0.03	48 ± 11	92 ± 20	58 ± 16	9.0 ± 2.3
Non-prompt leptons	3 ± 6	28 ± 16	0 ± 0	150 ± 50	140 ± 70
Other backgrounds	13.4 ± 2.7	22 ± 5	1.0 ± 0.6	17 ± 6	32 ± 6
Total background	87 ± 15	670 ± 240	93 ± 20	380 ± 90	230 ± 70
Data	81	734	87	433	260
Data / Bkg	0.94 ± 0.19	1.1 ± 0.4	0.94 ± 0.23	1.13 ± 0.28	1.1 ± 0.4

Table 5. Event yields in the background CRs for all significant sources of events before the combined fit under the background-only hypothesis described in section 8. The uncertainties shown include all of the systematic uncertainties described in section 7. The entry labelled “other backgrounds” includes all remaining backgrounds described in section 3 and in table 2.

7 Systematic uncertainties

The background fit to the CRs, described in section 8, reduces the systematic uncertainty from some sources, due to the constraints introduced by the data. The effect on shape and normalization of each source of systematic uncertainty before the fit is studied by independently varying each parameter within its estimated uncertainty and propagating this through the full analysis chain.

The main uncertainties, in both the background and signal estimations, are from theoretical normalization uncertainties and uncertainties in the modelling of background processes in the simulation.

The theoretical normalization uncertainties are estimated to be 12% for $t\bar{t}Z$, 13% for $t\bar{t}W$ [39], and 30% for tZ production [75]. For dibosons, the uncertainties in the normalization of the cross section [76] and from the choice of values for the electroweak parameters [77] are added in quadrature, yielding a 12.5% uncertainty. An uncertainty of +10% and −28% is assigned to the WtZ background cross section following the methodology of

ref. [78]. For the remaining small backgrounds, a 50% uncertainty is assumed. The $t\bar{t}$ production cross-section uncertainties from the independent variation of the factorization and renormalization scales, the PDF choice, and α_S variations (see refs. [32, 33] and references therein and refs. [35, 37, 38]) give a 5% uncertainty in the signal normalization.

The uncertainties in the modelling of $t\bar{t}Z$ and WZ processes in the simulation are taken from alternative generators (**Sherpa 2.2.0** and **Powheg-Box v2** interfaced to the **Pythia8**, respectively) which yield 4% and 50% uncertainties in the SR, respectively. The WtZ parton-shower uncertainty is estimated as 6% in the SR by using a sample interfaced to **Herwig++** [58]. The effect of QCD radiation on the tZ production process is estimated to be below 2% in the SR by using alternative **MG5_aMC@NLO_Pythia6** [56] tZ samples with additional radiation. The uncertainty due to the choice of NLO generator for the $t\bar{t}$ event production is evaluated using the alternative sample generated with **MG5_aMC@NLO** interfaced to **Pythia8**. The uncertainty in the total non-prompt leptons background in the SR is 25%. To evaluate the uncertainty due to the choice of parton shower algorithm, $t\bar{t}$ samples generated using **Powheg** interfaced to **Herwig7** [60] are used, yielding 2% uncertainty in the total non-prompt leptons background in the SR. To estimate the effect of QCD radiation on the $t\bar{t}$ samples, alternative samples generated with **Powheg+Pythia8** are considered where the factorization and renormalization scales are varied up and down by a factor of two and the A14 set of tuned parameters is changed to a version that varied the **VAR3c** [41] parameter, changing the amount of QCD radiation. This leads to a 10% uncertainty in the total non-prompt leptons background in the SR. Non-prompt lepton scale factor uncertainties are considered in the estimation of the backgrounds from events containing at least one non-prompt lepton.

For both the estimated signal and background event yields, experimental uncertainties resulting from detector effects are considered, including the lepton reconstruction, identification and trigger efficiencies, as well as lepton momentum scales and resolutions [62, 79, 80]. Uncertainties of the E_T^{miss} scale [72], pile-up effects, and jet-energy scale and resolution [81, 82] are also considered. The b -tagging uncertainty component, which includes the uncertainty of the b -, c -, mistagged- and τ -jet scale factors (the τ and charm uncertainties are highly correlated and evaluated as such) is evaluated by varying the η -, p_T - and flavour-dependent scale factors applied to each jet in the simulated samples. The relative impact of each type of systematic uncertainty on the total background and signal yields is summarized before and after the fit in table 6 and table 7, respectively.

The uncertainty related to the integrated luminosity for the dataset used in this analysis is 2.1%. It is derived following the methodology described in ref. [83] and only affects background estimates from simulated samples.

8 Results

A simultaneous fit to the SR and all CRs defined in table 4 is used to search for a signal from FCNC decays of the top quark. A maximum-likelihood fit is performed to kinematic distributions in the signal and control regions to test for the presence of signal events. Contamination of the CRs by the signal is negligible. The inclusion of the CRs in a

Pre-fit Source	$t\bar{t}Z$ CR	WZ CR	ZZ CR	Non-prompt lepton CR0	Non-prompt lepton CR1	SR	
	B [%]	B [%]	B [%]	B [%]	B [%]	B [%]	S [%]
Event modelling	29	40	13	24	40	30	5
Leptons	2.1	2.4	3.0	2.6	2.9	2.6	1.9
Jets	6	8	15	10	4	9	4
b -tagging	7	1.5	0.6	2.3	3.0	5	3.4
E_T^{miss}	0.4	4	2.6	3.0	0.8	5	1.4
Non-prompt leptons	1.1	1.3	—	12	15	6	—
Pile-up	5	1.3	5	3.5	1.8	4	2.3
Luminosity	2.0	2.0	2.1	1.3	0.8	1.7	2.1

Table 6. Summary of the relative impact of each type of uncertainty on the total background (B) yield in the background control regions and on the background and signal (S) yields in the signal region before the combined fit under the background-only hypothesis.

Post-fit Source	$t\bar{t}Z$ CR	WZ CR	ZZ CR	Non-prompt lepton CR0	Non-prompt lepton CR1	SR	
	B [%]	B [%]	B [%]	B [%]	B [%]	B [%]	S [%]
Event modelling	22	10	11	9	23	18	5
Leptons	2.0	2.4	2.9	2.6	2.9	2.6	1.8
Jets	5	6	11	8	4	8	4
b -tagging	7	1.4	0.6	2.1	2.8	4	3.1
E_T^{miss}	0.3	3.3	2.5	2.8	0.7	4	1.4
Non-prompt leptons	1.1	1.1	—	8	12	5	—
Pile-up	5	1.2	5	3.3	1.7	3.5	2.2
Luminosity	2.0	2.0	2.1	1.3	0.8	1.6	2.1

Table 7. Summary of the relative impact of each type of uncertainty on the total background (B) yield in the background control regions and on the background and signal (S) yields in the signal region after the combined fit under the background-only hypothesis.

combined fit with the SR constrains backgrounds and reduces systematic uncertainties. The kinematic distributions used in the fit are the χ^2 of the kinematical reconstruction for the SR, the leading lepton's p_T for the non-prompt leptons and $t\bar{t}Z$ CRs, the transverse mass for the WZ CR, and the reconstructed mass of the four leptons for the ZZ CR.

The statistical analysis to extract the signal is based on a binned likelihood function $L(\mu, \theta)$ constructed as a product of Poisson probability terms over all bins in each considered distribution, and Gaussian constraint terms for θ , a set of nuisance parameters that parameterize effects of statistical and systematic uncertainties on the signal and background expectations. The parameter μ is a multiplicative factor for the number of signal events normalized to a branching ratio $\mathcal{B}_{\text{ref}}(t \rightarrow qZ) = 0.1\%$. The nuisance parameters are floated in the combined fit to adjust the expectations for signal and background according to the corresponding systematic uncertainties, and their fitted values are the adjustment that best fits the data.

The test statistic is the profile likelihood ratio $q_\mu = -2\ln(L(\mu, \hat{\hat{\theta}}_\mu)/L(\hat{\mu}, \hat{\theta}))$, where $\hat{\mu}$ and $\hat{\theta}$ are the values of the parameters that maximize the likelihood function (with the constraints $0 \leq \hat{\mu} \leq \mu$), and $\hat{\hat{\theta}}_\mu$ are the values of the nuisance parameters that maximize the likelihood function for a given value of μ . This test statistic is used to measure the probability that the observed data is compatible with the background-only hypothesis (i.e. for $\mu = 0$) and to make statistical inferences about μ .

The distributions used in the combined fit under the background-only hypothesis are presented in figure 2. The same distributions after the fit are presented in figure 3. Table 8 shows the expected number of background events, number of selected data events, and signal yields in the SR before and after the fit. The post-fit signal yield changes relative to the pre-fit one due to the fitted nuisance parameters. The yields in the CRs after the fit are shown in table 9. Good agreement between data and the expectation from the background-only hypothesis is observed, and no evidence of a FCNC signal is found. The upper limits on $\mathcal{B}(t \rightarrow qZ)$ are computed with the CL_s method [84, 85] using the asymptotic properties of q_μ [86–88] and assuming that only one FCNC mode contributes. Figure 4 shows the observed CL_s for $\mathcal{B}(t \rightarrow uZ)$ and $\mathcal{B}(t \rightarrow cZ)$ together with the $\pm 1\sigma$ and $\pm 2\sigma$ bands for the expected values. The 95% confidence level (CL) limit on $\mathcal{B}(t \rightarrow uZ)$ is 1.7×10^{-4} , and on $\mathcal{B}(t \rightarrow cZ)$ it is 2.4×10^{-4} . The observed and expected limits are shown in table 10. It can be seen that the observed limit is about 1σ more stringent than expected due to a smaller number of observed events in the first bin of the χ^2 distribution in the SR, which is the one with the largest sensitivity to the signal.

Using the effective field theory framework developed in the TopFCNC model [89, 90] and assuming a cut-off scale $\Lambda = 1$ TeV and that only one operator has a non-zero value, the upper limits on $\mathcal{B}(t \rightarrow uZ)$ and $\mathcal{B}(t \rightarrow cZ)$ are converted to 95% CL upper limits on the moduli of the operators contributing to the FCNC decay $t \rightarrow qZ$, which are presented in table 11.

9 Conclusions

An analysis is performed to search for $t\bar{t}$ events with one top quark decaying through the FCNC $t \rightarrow qZ$ ($q = u, c$) channel and the other through the dominant Standard Model mode $t \rightarrow bW$, where only Z boson decays into charged leptons and leptonic W boson decays are considered as signal. The data were collected by the ATLAS experiment in pp collisions corresponding to an integrated luminosity of 36.1 fb^{-1} at the LHC at a centre-of-mass energy of $\sqrt{s} = 13$ TeV. There is good agreement between the data and Standard Model expectations, and no evidence of a signal is found. The 95% CL limits on the $t \rightarrow qZ$ branching ratio are $\mathcal{B}(t \rightarrow uZ) < 1.7 \times 10^{-4}$ and $\mathcal{B}(t \rightarrow cZ) < 2.4 \times 10^{-4}$, improving previous ATLAS results by more than 60%. These limits constrain the values of effective field theory operators contributing to the $t \rightarrow uZ$ and $t \rightarrow cZ$ FCNC decays of the top quark.

Sample	Yields	
	Pre-fit	Post-fit
$t\bar{t}Z$	37 ± 5	37 ± 4
WZ	32 ± 19	32 ± 8
ZZ	6.2 ± 3.2	6.4 ± 3.0
Non-prompt leptons	26 ± 11	20 ± 7
Other backgrounds	23 ± 4	23 ± 4
Total background	124 ± 26	119 ± 10
Data	116	116
Data / Bkg	0.94 ± 0.21	0.97 ± 0.12
Signal $t \rightarrow uZ$ ($\mathcal{B} = 0.1\%$)	101 ± 8	103 ± 8
Signal $t \rightarrow cZ$ ($\mathcal{B} = 0.1\%$)	85 ± 7	87 ± 7

Table 8. Expected number of background events, number of selected data events, and number of signal events (arbitrarily normalized to a branching ratio of $\mathcal{B}(t \rightarrow qZ) = 0.1\%$) in the signal region before and after the combined fit under the background-only hypothesis. The uncertainties shown include all of the systematic uncertainties described in section 7. The entry labelled “other backgrounds” includes all remaining backgrounds described in section 3 and in table 2. The uncertainties in the post-fit yields are calculated using the full correlation matrix from the fit.

Sample	$t\bar{t}Z$ CR	WZ CR	ZZ CR	Non-prompt lepton CR0	Non-prompt lepton CR1
$t\bar{t}Z$	61 ± 6	16.5 ± 3.1	0 ± 0	6.1 ± 1.2	21.9 ± 2.9
WZ	6 ± 4	610 ± 40	0 ± 0	166 ± 13	20 ± 5
ZZ	0.07 ± 0.02	49 ± 9	89 ± 12	59 ± 10	9.0 ± 2.2
Non-prompt leptons	2.0 ± 2.3	41 ± 15	0 ± 0	177 ± 32	174 ± 21
Other backgrounds	13.4 ± 2.6	23 ± 5	1.1 ± 0.6	19 ± 6	33 ± 7
Total background	82 ± 7	737 ± 35	90 ± 12	426 ± 30	258 ± 20
Data	81	734	87	433	260
Data / Bkg	0.99 ± 0.14	1.00 ± 0.06	0.97 ± 0.16	1.02 ± 0.09	1.01 ± 0.10

Table 9. Event yields in the background control regions for all significant sources of events after the combined fit under the background-only hypothesis. The uncertainties shown include all of the systematic uncertainties described in section 7. The entry labelled “other backgrounds” includes all remaining backgrounds described in section 3 and in table 2. The uncertainties in the post-fit yields are calculated using the full correlation matrix from the fit.

	$\mathcal{B}(t \rightarrow uZ)$	$\mathcal{B}(t \rightarrow cZ)$
Observed	1.7×10^{-4}	2.4×10^{-4}
Expected -1σ	1.7×10^{-4}	2.2×10^{-4}
Expected	2.4×10^{-4}	3.2×10^{-4}
Expected $+1\sigma$	3.4×10^{-4}	4.6×10^{-4}

Table 10. Observed and expected 95% CL upper limits on the FCNC top-quark decay branching ratios. The expected central value is shown together with the $\pm 1\sigma$ bands, which includes the contribution from the statistical and systematic uncertainties.

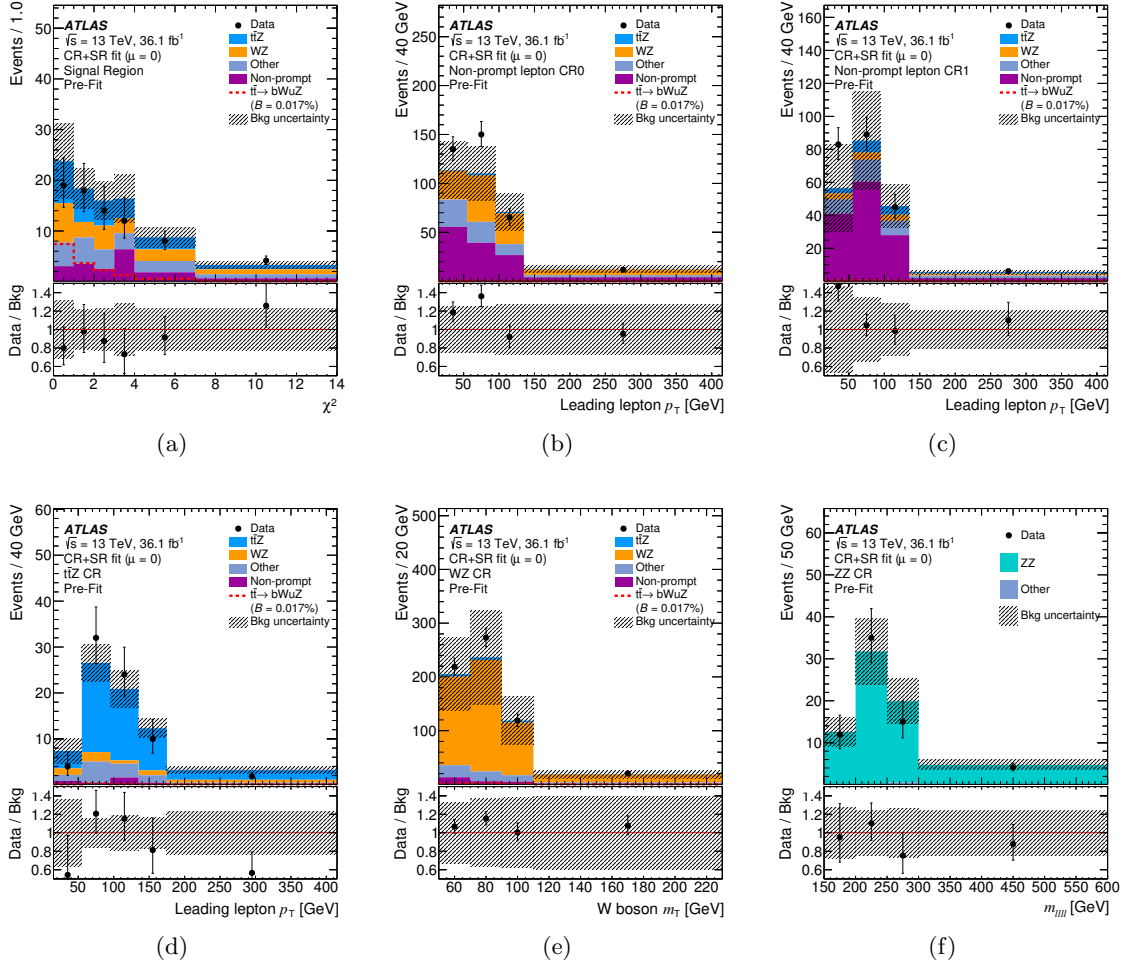


Figure 2. Expected (filled histogram) and observed (points with error bars) distributions before the combined fit under the background-only hypothesis of (a) the χ^2 of the kinematical reconstruction in the SR; (b) p_T of the leading lepton in the non-prompt lepton CR with b -tag veto; (c) p_T of the leading lepton in the non-prompt lepton CR with b -tag; (d) p_T of the leading lepton in the $t\bar{t}Z$ CR; (e) the transverse mass in the WZ CR and (f) the reconstructed mass of the four leptons in the ZZ CR. For comparison, distributions for the FCNC $t\bar{t} \rightarrow bWuZ$ signal (dashed line), normalized to the observed limit, are also shown. The “Other” category includes all remaining backgrounds described in section 3. The dashed area represents the total uncertainty in the background prediction.

Operator	Observed	Expected
$ C_{uB}^{(31)} $	0.25	0.30
$ C_{uW}^{(31)} $	0.25	0.30
$ C_{uB}^{(32)} $	0.30	0.34
$ C_{uW}^{(32)} $	0.30	0.34

Table 11. Observed and expected 95% CL upper limits on the moduli of the operators contributing to the FCNC decays $t \rightarrow uZ$ and $t \rightarrow cZ$ within the TopFCNC model for a new-physics energy scale $\Lambda = 1$ TeV.

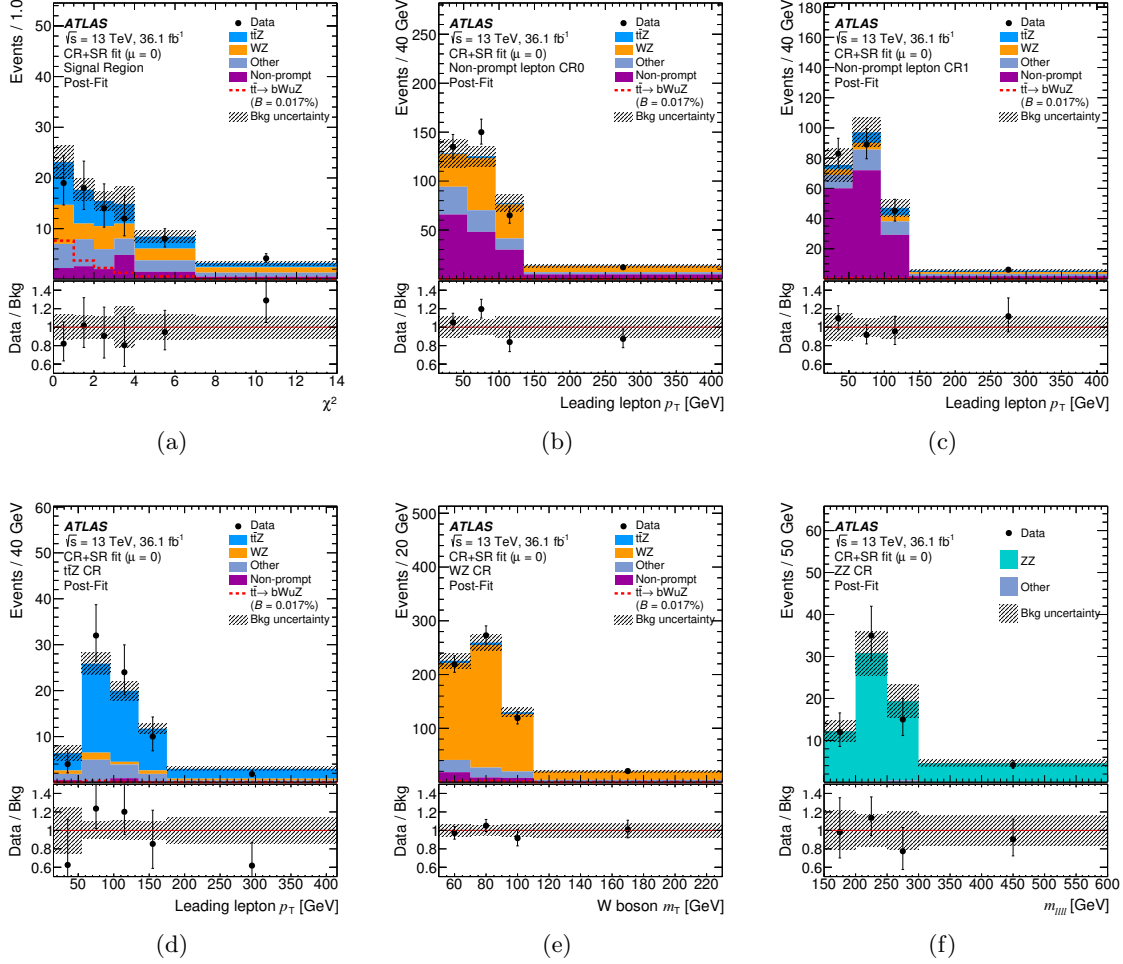


Figure 3. Expected (filled histogram) and observed (points with error bars) distributions after the combined fit under the background-only hypothesis of (a) the χ^2 of the kinematical reconstruction in the SR; (b) p_T of the leading lepton in the non-prompt lepton CR with b -tag veto; (c) p_T of the leading lepton in the non-prompt lepton CR with b -tag; (d) p_T of the leading lepton in the $t\bar{t}Z$ CR; (e) the transverse mass in the WZ CR and (f) the reconstructed mass of the four leptons in the ZZ CR. For comparison, distributions for the FCNC $t\bar{t} \rightarrow bWuZ$ signal (dashed line), normalized to the observed limit, are also shown. The “Other” category includes all remaining backgrounds described in section 3. The dashed area represents the total uncertainty in the background prediction.

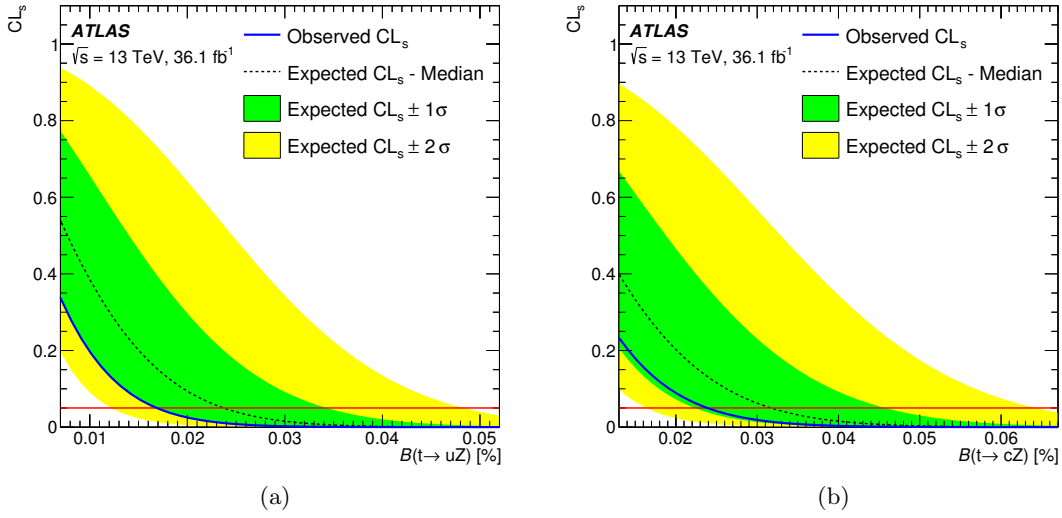


Figure 4. (a) CL_s vs $B(t \rightarrow uZ)$ and (b) CL_s vs $B(t \rightarrow cZ)$ taking into account systematic and statistical uncertainties. The observed CL_s values (solid line) are compared to the expected (median) CL_s values under the background-only hypothesis (dashed line). The surrounding shaded bands correspond to the 68% and 95% CL intervals around the expected CL_s values, denoted by $\pm 1\sigma$ and $\pm 2\sigma$, respectively. The solid line at $CL_s = 0.05$ denotes the threshold below which the hypothesis is excluded at 95% CL.

Acknowledgments

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

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRf and DNSRC, Denmark; IN2P3-CNRS, CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, the Canada Council, CANARIE, CRC, Compute Canada, FQRNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, ERDF, FP7, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex and Idex, ANR, Région Auvergne and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia

programmes co-financed by EU-ESF and the Greek NSRF; BSF, GIF and Minerva, Israel; BRF, Norway; CERCA Programme Generalitat de Catalunya, Generalitat Valenciana, Spain; the Royal Society and Leverhulme Trust, United Kingdom.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (U.K.) and BNL (U.S.A.), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in ref. [91].

Open Access. This article is distributed under the terms of the Creative Commons Attribution License ([CC-BY 4.0](https://creativecommons.org/licenses/by/4.0/)), which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.

References

- [1] ATLAS, CDF, CMS and D0 collaborations, *First combination of Tevatron and LHC measurements of the top-quark mass*, [ATLAS-CONF-2014-008](#) (2014).
- [2] S.L. Glashow, J. Iliopoulos and L. Maiani, *Weak interactions with lepton-hadron symmetry*, *Phys. Rev. D* **2** (1970) 1285 [[INSPIRE](#)].
- [3] J.A. Aguilar-Saavedra, *Top flavor-changing neutral interactions: Theoretical expectations and experimental detection*, *Acta Phys. Polon. B* **35** (2004) 2695 [[hep-ph/0409342](#)] [[INSPIRE](#)].
- [4] J.A. Aguilar-Saavedra, *Effects of mixing with quark singlets*, *Phys. Rev. D* **67** (2003) 035003 [*Erratum ibid.* **D 69** (2004) 099901] [[hep-ph/0210112](#)] [[INSPIRE](#)].
- [5] D. Atwood, L. Reina and A. Soni, *Phenomenology of two Higgs doublet models with flavor changing neutral currents*, *Phys. Rev. D* **55** (1997) 3156 [[hep-ph/9609279](#)] [[INSPIRE](#)].
- [6] J.J. Cao et al., *SUSY-induced FCNC top-quark processes at the Large Hadron Collider*, *Phys. Rev. D* **75** (2007) 075021 [[hep-ph/0702264](#)] [[INSPIRE](#)].
- [7] J.M. Yang, B.-L. Young and X. Zhang, *Flavor changing top quark decays in r parity violating SUSY*, *Phys. Rev. D* **58** (1998) 055001 [[hep-ph/9705341](#)] [[INSPIRE](#)].
- [8] K. Agashe, G. Perez and A. Soni, *Collider signals of top quark flavor violation from a warped extra dimension*, *Phys. Rev. D* **75** (2007) 015002 [[hep-ph/0606293](#)] [[INSPIRE](#)].
- [9] P.Q. Hung, Y.-X. Lin, C.S. Nugroho and T.-C. Yuan, *Top quark rare decays via loop-induced FCNC interactions in extended mirror fermion model*, *Nucl. Phys. B* **927** (2018) 166 [[arXiv:1709.01690](#)] [[INSPIRE](#)].
- [10] SNOWMASS TOP QUARK WORKING GROUP, K. Agashe et al., *Snowmass 2013 top quark working group report*, [arXiv:1311.2028](#).
- [11] ALEPH collaboration, A. Heister et al., *Search for single top production in e^+e^- collisions at \sqrt{s} up to 209-GeV*, *Phys. Lett. B* **543** (2002) 173 [[hep-ex/0206070](#)] [[INSPIRE](#)].
- [12] DELPHI collaboration, J. Abdallah et al., *Search for single top production via FCNC at LEP at $\sqrt{s} = 189$ GeV to 208 GeV*, *Phys. Lett. B* **590** (2004) 21 [[hep-ex/0404014](#)] [[INSPIRE](#)].
- [13] OPAL collaboration, G. Abbiendi et al., *Search for single top quark production at LEP-2*, *Phys. Lett. B* **521** (2001) 181 [[hep-ex/0110009](#)] [[INSPIRE](#)].

- [14] L3 collaboration, P. Achard et al., *Search for single top production at LEP*, *Phys. Lett. B* **549** (2002) 290 [[hep-ex/0210041](#)] [[INSPIRE](#)].
- [15] LEP EXOTICA working group, *Search for single top production via flavour changing neutral currents : preliminary combined results of the LEP experiments*, *Exotica-WG-2001-01* (2001).
- [16] ZEUS collaboration, H. Abramowicz et al., *Search for single-top production in ep collisions at HERA*, *Phys. Lett. B* **708** (2012) 27 [[arXiv:1111.3901](#)] [[INSPIRE](#)].
- [17] CDF collaboration, T. Aaltonen et al., *Search for the flavor changing neutral current decay $t \rightarrow Zq$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV*, *Phys. Rev. Lett.* **101** (2008) 192002 [[arXiv:0805.2109](#)] [[INSPIRE](#)].
- [18] D0 collaboration, V.M. Abazov et al., *Search for flavor changing neutral currents in decays of top quarks*, *Phys. Lett. B* **701** (2011) 313 [[arXiv:1103.4574](#)] [[INSPIRE](#)].
- [19] ATLAS collaboration, *A search for flavour changing neutral currents in top-quark decays in pp collision data collected with the ATLAS detector at $\sqrt{s} = 7$ TeV*, *JHEP* **09** (2012) 139 [[arXiv:1206.0257](#)] [[INSPIRE](#)].
- [20] ATLAS collaboration, *Search for flavour-changing neutral current top-quark decays to qZ in pp collision data collected with the ATLAS detector at $\sqrt{s} = 8$ TeV*, *Eur. Phys. J. C* **76** (2016) 12 [[arXiv:1508.05796](#)] [[INSPIRE](#)].
- [21] CMS collaboration, *Search for flavor-changing neutral currents in top-quark decays $t \rightarrow Zq$ in pp collisions at $\sqrt{s} = 8$ TeV*, *Phys. Rev. Lett.* **112** (2014) 171802 [[arXiv:1312.4194](#)] [[INSPIRE](#)].
- [22] CMS collaboration, *Search for associated production of a Z boson with a single top quark and for tZ flavour-changing interactions in pp collisions at $\sqrt{s} = 8$ TeV*, *JHEP* **07** (2017) 003 [[arXiv:1702.01404](#)] [[INSPIRE](#)].
- [23] ATLAS collaboration, *The ATLAS experiment at the CERN Large Hadron Collider*, *2008 JINST* **3** S08003 [[INSPIRE](#)].
- [24] ATLAS collaboration, *ATLAS insertable B-layer technical design report*, *ATLAS-TDR-19* (2010).
- [25] ATLAS collaboration, *ATLAS insertable B-layer technical design report addendum*, *ATLAS-TDR-19-ADD-1* (2012).
- [26] ATLAS collaboration, *Performance of the ATLAS trigger system in 2015*, *Eur. Phys. J. C* **77** (2017) 317 [[arXiv:1611.09661](#)] [[INSPIRE](#)].
- [27] M. Cacciari et al., *Top-pair production at hadron colliders with next-to-next-to-leading logarithmic soft-gluon resummation*, *Phys. Lett. B* **710** (2012) 612 [[arXiv:1111.5869](#)] [[INSPIRE](#)].
- [28] P. Bärnreuther, M. Czakon and A. Mitov, *Percent level precision physics at the Tevatron: first genuine NNLO QCD corrections to $q\bar{q} \rightarrow t\bar{t} + X$* , *Phys. Rev. Lett.* **109** (2012) 132001 [[arXiv:1204.5201](#)] [[INSPIRE](#)].
- [29] M. Czakon and A. Mitov, *NNLO corrections to top-pair production at hadron colliders: the all-fermionic scattering channels*, *JHEP* **12** (2012) 054 [[arXiv:1207.0236](#)] [[INSPIRE](#)].
- [30] M. Czakon and A. Mitov, *NNLO corrections to top pair production at hadron colliders: the quark-gluon reaction*, *JHEP* **01** (2013) 080 [[arXiv:1210.6832](#)] [[INSPIRE](#)].

- [31] M. Czakon, P. Fiedler and A. Mitov, *Total top-quark pair-production cross section at hadron colliders through $O(\alpha_s^4)$* , *Phys. Rev. Lett.* **110** (2013) 252004 [[arXiv:1303.6254](#)] [[INSPIRE](#)].
- [32] M. Czakon and A. Mitov, *Top++: a program for the calculation of the top-pair cross-section at hadron colliders*, *Comput. Phys. Commun.* **185** (2014) 2930 [[arXiv:1112.5675](#)] [[INSPIRE](#)].
- [33] M. Botje et al., *The PDF4LHC working group interim recommendations*, [arXiv:1101.0538](#).
- [34] A.D. Martin, W.J. Stirling, R.S. Thorne and G. Watt, *Parton distributions for the LHC*, *Eur. Phys. J. C* **63** (2009) 189 [[arXiv:0901.0002](#)] [[INSPIRE](#)].
- [35] A.D. Martin, W.J. Stirling, R.S. Thorne and G. Watt, *Uncertainties on α_s in global PDF analyses and implications for predicted hadronic cross sections*, *Eur. Phys. J. C* **64** (2009) 653 [[arXiv:0905.3531](#)] [[INSPIRE](#)].
- [36] H.-L. Lai et al., *New parton distributions for collider physics*, *Phys. Rev. D* **82** (2010) 074024 [[arXiv:1007.2241](#)] [[INSPIRE](#)].
- [37] J. Gao et al., *CT10 next-to-next-to-leading order global analysis of QCD*, *Phys. Rev. D* **89** (2014) 033009 [[arXiv:1302.6246](#)] [[INSPIRE](#)].
- [38] R.D. Ball et al., *Parton distributions with LHC data*, *Nucl. Phys. B* **867** (2013) 244 [[arXiv:1207.1303](#)] [[INSPIRE](#)].
- [39] J. Alwall et al., *The automated computation of tree-level and next-to-leading order differential cross sections and their matching to parton shower simulations*, *JHEP* **07** (2014) 079 [[arXiv:1405.0301](#)] [[INSPIRE](#)].
- [40] T. Sjöstrand et al., *An introduction to PYTHIA 8.2*, *Comput. Phys. Commun.* **191** (2015) 159 [[arXiv:1410.3012](#)] [[INSPIRE](#)].
- [41] ATLAS collaboration, *ATLAS run 1 PYTHIA8 tunes*, [ATL-PHYS-PUB-2014-021](#) (2014).
- [42] NNPDF collaboration, R.D. Ball et al., *Parton distributions for the LHC Run II*, *JHEP* **04** (2015) 040 [[arXiv:1410.8849](#)] [[INSPIRE](#)].
- [43] LHC HIGGS CROSS SECTION WORKING GROUP collaboration, D. de Florian et al., *Handbook of LHC Higgs Cross Sections: 4. Deciphering the nature of the Higgs sector*, [arXiv:1610.07922](#) [[INSPIRE](#)].
- [44] S. Frixione et al., *Single-top hadroproduction in association with a W boson*, *JHEP* **07** (2008) 029 [[arXiv:0805.3067](#)] [[INSPIRE](#)].
- [45] T. Gleisberg et al., *Event generation with SHERPA 1.1*, *JHEP* **02** (2009) 007 [[arXiv:0811.4622](#)] [[INSPIRE](#)].
- [46] T. Gleisberg and S. Hoeche, *Comix, a new matrix element generator*, *JHEP* **12** (2008) 039 [[arXiv:0808.3674](#)] [[INSPIRE](#)].
- [47] F. Cascioli, P. Maierhofer and S. Pozzorini, *Scattering amplitudes with open loops*, *Phys. Rev. Lett.* **108** (2012) 111601 [[arXiv:1111.5206](#)] [[INSPIRE](#)].
- [48] S. Hoeche et al., *QCD matrix elements + parton showers: The NLO case*, *JHEP* **04** (2013) 027 [[arXiv:1207.5030](#)] [[INSPIRE](#)].
- [49] S. Alioli, P. Nason, C. Oleari and E. Re, *A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX*, *JHEP* **06** (2010) 043 [[arXiv:1002.2581](#)] [[INSPIRE](#)].

- [50] N. Davidson, T. Przedzinski and Z. Was, *PHOTOS interface in C++: technical and physics documentation*, *Comput. Phys. Commun.* **199** (2016) 86 [[arXiv:1011.0937](#)] [[INSPIRE](#)].
- [51] ATLAS collaboration, *Summary of ATLAS PYTHIA 8 tunes*, *ATL-PHYS-PUB-2012-003* (2012).
- [52] GEANT4 collaboration, S. Agostinelli et al., *GEANT4: a simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250 [[INSPIRE](#)].
- [53] ATLAS collaboration, *The ATLAS simulation infrastructure*, *Eur. Phys. J. C* **70** (2010) 823 [[arXiv:1005.4568](#)] [[INSPIRE](#)].
- [54] J. Pumplin et al., *New generation of parton distributions with uncertainties from global QCD analysis*, *JHEP* **07** (2002) 012 [[hep-ph/0201195](#)] [[INSPIRE](#)].
- [55] ATLAS collaboration, *Measurement of the Z/γ^* boson transverse momentum distribution in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, *JHEP* **09** (2014) 145 [[arXiv:1406.3660](#)] [[INSPIRE](#)].
- [56] T. Sjöstrand, S. Mrenna and P.Z. Skands, *PYTHIA 6.4 physics and manual*, *JHEP* **05** (2006) 026 [[hep-ph/0603175](#)] [[INSPIRE](#)].
- [57] P.Z. Skands, *Tuning Monte Carlo generators: the Perugia tunes*, *Phys. Rev. D* **82** (2010) 074018 [[arXiv:1005.3457](#)] [[INSPIRE](#)].
- [58] M. Bahr et al., *HERWIG++ physics and manual*, *Eur. Phys. J. C* **58** (2008) 639 [[arXiv:0803.0883](#)] [[INSPIRE](#)].
- [59] S. Gieseke, C. Rohr and A. Siódmok, *Colour reconnections in HERWIG++*, *Eur. Phys. J. C* **72** (2012) 2225 [[arXiv:1206.0041](#)] [[INSPIRE](#)].
- [60] J. Bellm et al., *HERWIG 7.0/HERWIG++ 3.0 release note*, *Eur. Phys. J. C* **76** (2016) 196 [[arXiv:1512.01178](#)] [[INSPIRE](#)].
- [61] L.A. Harland-Lang, A.D. Martin, P. Motylinski and R.S. Thorne, *Parton distributions in the LHC era: MMHT 2014 PDFs*, *Eur. Phys. J. C* **75** (2015) 204 [[arXiv:1412.3989](#)] [[INSPIRE](#)].
- [62] ATLAS collaboration, *Electron reconstruction and identification efficiency measurements with the ATLAS detector using the 2011 LHC proton-proton collision data*, *Eur. Phys. J. C* **74** (2014) 2941 [[arXiv:1404.2240](#)] [[INSPIRE](#)].
- [63] ATLAS collaboration, *Muon reconstruction performance of the ATLAS detector in proton-proton collision data at $\sqrt{s} = 13$ TeV*, *Eur. Phys. J. C* **76** (2016) 292 [[arXiv:1603.05598](#)] [[INSPIRE](#)].
- [64] ATLAS collaboration, *Topological cell clustering in the ATLAS calorimeters and its performance in LHC Run 1*, *Eur. Phys. J. C* **77** (2017) 490 [[arXiv:1603.02934](#)] [[INSPIRE](#)].
- [65] M. Cacciari, G.P. Salam and G. Soyez, *The anti- k_t jet clustering algorithm*, *JHEP* **04** (2008) 063 [[arXiv:0802.1189](#)] [[INSPIRE](#)].
- [66] M. Cacciari, G.P. Salam and G. Soyez, *FastJet user manual*, *Eur. Phys. J. C* **72** (2012) 1896 [[arXiv:1111.6097](#)] [[INSPIRE](#)].
- [67] M. Cacciari and G.P. Salam, *Pileup subtraction using jet areas*, *Phys. Lett. B* **659** (2008) 119 [[arXiv:0707.1378](#)] [[INSPIRE](#)].
- [68] ATLAS collaboration, *Jet energy scale measurements and their systematic uncertainties in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *Phys. Rev. D* **96** (2017) 072002 [[arXiv:1703.09665](#)] [[INSPIRE](#)].

- [69] ATLAS collaboration, *Performance of pile-up mitigation techniques for jets in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector*, *Eur. Phys. J. C* **76** (2016) 581 [[arXiv:1510.03823](#)] [[INSPIRE](#)].
- [70] ATLAS collaboration, *Performance of b-jet identification in the ATLAS experiment*, 2016 *JINST* **11** P04008 [[arXiv:1512.01094](#)] [[INSPIRE](#)].
- [71] ATLAS collaboration, *Optimisation of the ATLAS b-tagging performance for the 2016 LHC Run*, *ATL-PHYS-PUB-2016-012* (2016).
- [72] ATLAS collaboration, *Performance of missing transverse momentum reconstruction in proton-proton collisions at 7 TeV with ATLAS*, *Eur. Phys. J. C* **72** (2012) 1844 [[arXiv:1108.5602](#)] [[INSPIRE](#)].
- [73] ATLAS collaboration, *Performance of algorithms that reconstruct missing transverse momentum in $\sqrt{s} = 8$ TeV proton-proton collisions in the ATLAS detector*, *Eur. Phys. J. C* **77** (2017) 241 [[arXiv:1609.09324](#)] [[INSPIRE](#)].
- [74] A.D. Bukin, *Fitting function for asymmetric peaks*, [arXiv:0711.4449](#).
- [75] ATLAS collaboration, *Measurement of the production cross-section of a single top quark in association with a Z boson in proton-proton collisions at 13 TeV with the ATLAS detector*, *CERN-EP-2017-188* (2017).
- [76] ATLAS collaboration, *Measurement of the $W^\pm Z$ boson pair-production cross section in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector*, *Phys. Lett. B* **762** (2016) 1 [[arXiv:1606.04017](#)] [[INSPIRE](#)].
- [77] S. Hoche, F. Krauss, M. Schonherr and F. Siegert, *NLO matrix elements and truncated showers*, *JHEP* **08** (2011) 123 [[arXiv:1009.1127](#)] [[INSPIRE](#)].
- [78] ATLAS collaboration, *Measurement of the $t\bar{t}Z$ and $t\bar{t}W$ production cross sections in multilepton final states using 3.2 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *Eur. Phys. J. C* **77** (2017) 40 [[arXiv:1609.01599](#)] [[INSPIRE](#)].
- [79] ATLAS collaboration, *Electron and photon energy calibration with the ATLAS detector using LHC Run 1 data*, *Eur. Phys. J. C* **74** (2014) 3071 [[arXiv:1407.5063](#)] [[INSPIRE](#)].
- [80] ATLAS collaboration, *Measurement of the muon reconstruction performance of the ATLAS detector using 2011 and 2012 LHC proton-proton collision data*, *Eur. Phys. J. C* **74** (2014) 3130 [[arXiv:1407.3935](#)] [[INSPIRE](#)].
- [81] ATLAS collaboration, *Jet energy measurement and its systematic uncertainty in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, *Eur. Phys. J. C* **75** (2015) 17 [[arXiv:1406.0076](#)] [[INSPIRE](#)].
- [82] ATLAS collaboration, *Jet energy resolution in proton-proton collisions at $\sqrt{s} = 7$ TeV recorded in 2010 with the ATLAS detector*, *Eur. Phys. J. C* **73** (2013) 2306 [[arXiv:1210.6210](#)] [[INSPIRE](#)].
- [83] ATLAS collaboration, *Luminosity determination in pp collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector at the LHC*, *Eur. Phys. J. C* **71** (2011) 1630 [[arXiv:1101.2185](#)] [[INSPIRE](#)].
- [84] A.L. Read, *Presentation of search results: the CL_s technique*, *J. Phys. G* **28** (2002) 2693 [[INSPIRE](#)].
- [85] T. Junk, *Confidence level computation for combining searches with small statistics*, *Nucl. Instrum. Meth. A* **434** (1999) 435 [[hep-ex/9902006](#)] [[INSPIRE](#)].

- [86] G. Cowan, K. Cranmer, E. Gross and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics*, *Eur. Phys. J. C* **71** (2011) 1554 [Erratum *ibid.* **C 73** (2013) 2501] [[arXiv:1007.1727](#)] [[INSPIRE](#)].
- [87] W. Verkerke and D.P. Kirkby, *The RooFit toolkit for data modeling*, *eConf C* **0303241** (2003) MOLT007 [[physics/0306116](#)] [[INSPIRE](#)].
- [88] L. Moneta et al., *The RooStats project*, *PoS(ACAT2010)057* [[arXiv:1009.1003](#)] [[INSPIRE](#)].
- [89] C. Degrande et al., *Automatic computations at next-to-leading order in QCD for top-quark flavor-changing neutral processes*, *Phys. Rev. D* **91** (2015) 034024 [[arXiv:1412.5594](#)] [[INSPIRE](#)].
- [90] G. Durieux, F. Maltoni and C. Zhang, *Global approach to top-quark flavor-changing interactions*, *Phys. Rev. D* **91** (2015) 074017 [[arXiv:1412.7166](#)] [[INSPIRE](#)].
- [91] ATLAS collaboration, *ATLAS computing acknowledgements*, [ATL-GEN-PUB-2016-002](#) (2016).

The ATLAS collaboration

M. Aaboud^{137d}, G. Aad⁸⁸, B. Abbott¹¹⁵, O. Abdinov^{12,*}, B. Abeloos¹¹⁹, S.H. Abidi¹⁶¹, O.S. AbouZeid¹³⁹, N.L. Abraham¹⁵¹, H. Abramowicz¹⁵⁵, H. Abreu¹⁵⁴, Y. Abulaiti^{148a,148b}, B.S. Acharya^{167a,167b,a}, S. Adachi¹⁵⁷, L. Adamczyk^{41a}, J. Adelman¹¹⁰, M. Adersberger¹⁰², T. Adye¹³³, A.A. Affolder¹³⁹, Y. Afik¹⁵⁴, C. Agheorghiesei^{28c}, J.A. Aguilar-Saavedra^{128a,128f}, F. Ahmadov^{68,b}, G. Aielli^{135a,135b}, S. Akatsuka⁷¹, H. Akerstedt^{148a,148b}, T.P.A. Åkesson⁸⁴, E. Akilli⁵², A.V. Akimov⁹⁸, G.L. Alberghi^{22a,22b}, J. Albert¹⁷², P. Albicocco⁵⁰, M.J. Alconada Verzini⁷⁴, S. Alderweireldt¹⁰⁸, M. Aleksa³², I.N. Aleksandrov⁶⁸, C. Alexa^{28b}, G. Alexander¹⁵⁵, T. Alexopoulos¹⁰, M. Alhroob¹¹⁵, B. Ali¹³⁰, M. Aliev^{76a,76b}, G. Alimonti^{94a}, J. Alison³³, S.P. Alkire³⁸, C. Allaire¹¹⁹, B.M.M. Allbrooke¹⁵¹, B.W. Allen¹¹⁸, P.P. Allport¹⁹, A. Aloisio^{106a,106b}, A. Alonso³⁹, F. Alonso⁷⁴, C. Alpigiani¹⁴⁰, A.A. Alshehri⁵⁶, M.I. Alstady⁸⁸, B. Alvarez Gonzalez³², D. Álvarez Piqueras¹⁷⁰, M.G. Alviggi^{106a,106b}, B.T. Amadio¹⁶, Y. Amaral Coutinho^{26a}, C. Amelung²⁵, D. Amidei⁹², S.P. Amor Dos Santos^{128a,128c}, S. Amoroso³², C. Anastopoulos¹⁴¹, L.S. Ancu⁵², N. Andari¹⁹, T. Andeen¹¹, C.F. Anders^{60b}, J.K. Anders¹⁸, K.J. Anderson³³, A. Andreazza^{94a,94b}, V. Andrei^{60a}, S. Angelidakis³⁷, I. Angelozzi¹⁰⁹, A. Angerami³⁸, A.V. Anisenkov^{111,c}, A. Annovi^{126a}, C. Antel^{60a}, M. Antonelli⁵⁰, A. Antonov^{100,*}, D.J.A. Antrim¹⁶⁶, F. Anulli^{134a}, M. Aoki⁶⁹, L. Aperio Bella³², G. Arabidze⁹³, Y. Arai⁶⁹, J.P. Araque^{128a}, V. Araujo Ferraz^{26a}, A.T.H. Arce⁴⁸, R.E. Ardell⁸⁰, F.A. Arduh⁷⁴, J-F. Arguin⁹⁷, S. Argyropoulos⁶⁶, M. Arik^{20a}, A.J. Armbruster³², L.J. Armitage⁷⁹, O. Arnaez¹⁶¹, H. Arnold⁵¹, M. Arratia³⁰, O. Arslan²³, A. Artamonov^{99,*}, G. Artoni¹²², S. Artz⁸⁶, S. Asai¹⁵⁷, N. Asbah⁴⁵, A. Ashkenazi¹⁵⁵, L. Asquith¹⁵¹, K. Assamagan²⁷, R. Astalos^{146a}, R.J. Atkin^{147a}, M. Atkinson¹⁶⁹, N.B. Atlay¹⁴³, K. Augsten¹³⁰, G. Avolio³², B. Axen¹⁶, M.K. Ayoub^{35a}, G. Azuelos^{97,d}, A.E. Baas^{60a}, M.J. Baca¹⁹, H. Bachacou¹³⁸, K. Bachas^{76a,76b}, M. Backes¹²², P. Bagnaia^{134a,134b}, M. Bahmani⁴², H. Bahrasemani¹⁴⁴, J.T. Baines¹³³, M. Bajic³⁹, O.K. Baker¹⁷⁹, P.J. Bakker¹⁰⁹, D. Bakshi Gupta⁸², E.M. Baldin^{111,c}, P. Balek¹⁷⁵, F. Balli¹³⁸, W.K. Balunas¹²⁴, E. Banas⁴², A. Bandyopadhyay²³, Sw. Banerjee^{176,e}, A.A.E. Bannoura¹⁷⁷, L. Barak¹⁵⁵, E.L. Barberio⁹¹, D. Barberis^{53a,53b}, M. Barbero⁸⁸, T. Barillari¹⁰³, M-S Barisits⁶⁵, J.T. Barkeloo¹¹⁸, T. Barklow¹⁴⁵, N. Barlow³⁰, S.L. Barnes^{36b}, B.M. Barnett¹³³, R.M. Barnett¹⁶, Z. Barnovska-Blenessy^{36c}, A. Baroncelli^{136a}, G. Barone²⁵, A.J. Barr¹²², L. Barranco Navarro¹⁷⁰, F. Barreiro⁸⁵, J. Barreiro Guimarães da Costa^{35a}, R. Bartoldus¹⁴⁵, A.E. Barton⁷⁵, P. Bartos^{146a}, A. Basalaev¹²⁵, A. Bassalat¹¹⁹, R.L. Bates⁵⁶, S.J. Batista¹⁶¹, J.R. Batley³⁰, M. Battaglia¹³⁹, M. Bause^{134a,134b}, F. Bauer¹³⁸, K.T. Bauer¹⁶⁶, H.S. Bawa^{145,f}, J.B. Beacham¹¹³, M.D. Beattie⁷⁵, T. Beau⁸³, P.H. Beauchemin¹⁶⁵, P. Bechtel²³, H.P. Beck^{18,g}, H.C. Beck⁵⁸, K. Becker¹²², M. Becker⁸⁶, C. Becot¹¹², A.J. Beddall^{20e}, A. Beddall^{20b}, V.A. Bednyakov⁶⁸, M. Bedognetti¹⁰⁹, C.P. Bee¹⁵⁰, T.A. Beermann³², M. Begalli^{26a}, M. Begel²⁷, J.K. Behr⁴⁵, A.S. Bell⁸¹, G. Bella¹⁵⁵, L. Bellagamba^{22a}, A. Bellerive³¹, M. Bellomo¹⁵⁴, K. Belotskiy¹⁰⁰, O. Beltramello³², N.L. Belyaev¹⁰⁰, O. Benary^{155,*}, D. Bencheikroun^{137a}, M. Bender¹⁰², N. Benekos¹⁰, Y. Benhammou¹⁵⁵, E. Benhar Noccioli¹⁷⁹, J. Benitez⁶⁶, D.P. Benjamin⁴⁸, M. Benoit⁵², J.R. Bensinger²⁵, S. Bentvelsen¹⁰⁹, L. Beresford¹²², M. Beretta⁵⁰, D. Berge⁴⁵, E. Bergeas Kuutmann¹⁶⁸, N. Berger⁵, L.J. Bergsten²⁵, J. Beringer¹⁶, S. Berlendis⁵⁷, N.R. Bernard⁸⁹, G. Bernardi⁸³, C. Bernius¹⁴⁵, F.U. Bernlochner²³, T. Berry⁸⁰, P. Berta⁸⁶, C. Bertella^{35a}, G. Bertoli^{148a,148b}, I.A. Bertram⁷⁵, C. Bertsche⁴⁵, G.J. Besjes³⁹, O. Bessidskaia Bylund^{148a,148b}, M. Bessner⁴⁵, N. Besson¹³⁸, A. Bethani⁸⁷, S. Bethke¹⁰³, A. Betti²³, A.J. Bevan⁷⁹, J. Beyer¹⁰³, R.M. Bianchi¹²⁷, O. Biebel¹⁰², D. Biedermann¹⁷, R. Bielski⁸⁷, K. Bierwagen⁸⁶, N.V. Biesuz^{126a,126b}, M. Biglietti^{136a}, T.R.V. Billoud⁹⁷, H. Bilokon⁵⁰, M. Bindi⁵⁸, A. Bingul^{20b}, C. Bini^{134a,134b}, S. Biondi^{22a,22b}, T. Bisanz⁵⁸, C. Bittrich⁴⁷, D.M. Bjergaard⁴⁸, J.E. Black¹⁴⁵, K.M. Black²⁴, R.E. Blair⁶, T. Blazek^{146a}, I. Bloch⁴⁵, C. Blocker²⁵, A. Blue⁵⁶, U. Blumenschein⁷⁹, Dr. Blunier^{34a}, G.J. Bobbink¹⁰⁹, V.S. Bobrovnikov^{111,c}, S.S. Bocchetta⁸⁴, A. Bocci⁴⁸, C. Bock¹⁰², D. Boerner¹⁷⁷, D. Bogavac¹⁰², A.G. Bogdanchikov¹¹¹, C. Bohm^{148a}, V. Boisvert⁸⁰, P. Bokan^{168,h}, T. Bold^{41a}, A.S. Boldyrev¹⁰¹, A.E. Bolz^{60b}, M. Bomben⁸³, M. Bona⁷⁹, J.S. Bonilla¹¹⁸, M. Boonekamp¹³⁸, A. Borisov¹³², G. Borissov⁷⁵, J. Bortfeldt³², D. Bortoletto¹²², V. Bortolotto^{62a}, D. Boscherini^{22a}, M. Bosman¹³,

J.D. Bossio Sola²⁹, J. Boudreau¹²⁷, E.V. Bouhova-Thacker⁷⁵, D. Boumediene³⁷, C. Bourdarios¹¹⁹, S.K. Boutle⁵⁶, A. Boveia¹¹³, J. Boyd³², I.R. Boyko⁶⁸, A.J. Bozson⁸⁰, J. Bracinik¹⁹, A. Brandt⁸, G. Brandt¹⁷⁷, O. Brandt^{60a}, F. Braren⁴⁵, U. Bratzler¹⁵⁸, B. Brau⁸⁹, J.E. Brau¹¹⁸, W.D. Breaden Madden⁵⁶, K. Brendlinger⁴⁵, A.J. Brennan⁹¹, L. Brenner¹⁰⁹, R. Brenner¹⁶⁸, S. Bressler¹⁷⁵, D.L. Briglin¹⁹, T.M. Bristow⁴⁹, D. Britton⁵⁶, D. Britzger^{60b}, I. Brock²³, R. Brock⁹³, G. Brooijmans³⁸, T. Brooks⁸⁰, W.K. Brooks^{34b}, E. Brost¹¹⁰, J.H. Broughton¹⁹, P.A. Bruckman de Renstrom⁴², D. Bruncko^{146b}, A. Bruni^{22a}, G. Bruni^{22a}, L.S. Bruni¹⁰⁹, S. Bruno^{135a,135b}, B.H. Brunt³⁰, M. Bruschi^{22a}, N. Bruscino¹²⁷, P. Bryant³³, L. Bryngemark⁴⁵, T. Buanes¹⁵, Q. Buat¹⁴⁴, P. Buchholz¹⁴³, A.G. Buckley⁵⁶, I.A. Budagov⁶⁸, F. Buehrer⁵¹, M.K. Bugge¹²¹, O. Bulekov¹⁰⁰, D. Bullock⁸, T.J. Burch¹¹⁰, S. Burdin⁷⁷, C.D. Burgard¹⁰⁹, A.M. Burger⁵, B. Burghgrave¹¹⁰, K. Burka⁴², S. Burke¹³³, I. Burmeister⁴⁶, J.T.P. Burr¹²², D. Büscher⁵¹, V. Büscher⁸⁶, E. Buschmann⁵⁸, P. Bussey⁵⁶, J.M. Butler²⁴, C.M. Buttar⁵⁶, J.M. Butterworth⁸¹, P. Butti³², W. Buttinger²⁷, A. Buzatu¹⁵³, A.R. Buzykaev^{111,c}, S. Cabrera Urbán¹⁷⁰, D. Caforio¹³⁰, H. Cai¹⁶⁹, V.M.M. Cairo², O. Cakir^{4a}, N. Calace⁵², P. Calafiura¹⁶, A. Calandri⁸⁸, G. Calderini⁸³, P. Calfayan⁶⁴, G. Callea^{40a,40b}, L.P. Caloba^{26a}, S. Calvente Lopez⁸⁵, D. Calvet³⁷, S. Calvet³⁷, T.P. Calvet⁸⁸, R. Camacho Toro³³, S. Camarda³², P. Camarri^{135a,135b}, D. Cameron¹²¹, R. Caminal Armadans⁸⁹, C. Camincher⁵⁷, S. Campana³², M. Campanelli⁸¹, A. Camplani^{94a,94b}, A. Campoverde¹⁴³, V. Canale^{106a,106b}, M. Cano Bret^{36b}, J. Cantero¹¹⁶, T. Cao¹⁵⁵, M.D.M. Capeans Garrido³², I. Caprini^{28b}, M. Caprini^{28b}, M. Capua^{40a,40b}, R.M. Carbone³⁸, R. Cardarelli^{135a}, F. Cardillo⁵¹, I. Carli¹³¹, T. Carli³², G. Carlino^{106a}, B.T. Carlson¹²⁷, L. Carminati^{94a,94b}, R.M.D. Carney^{148a,148b}, S. Caron¹⁰⁸, E. Carquin^{34b}, S. Carrá^{94a,94b}, G.D. Carrillo-Montoya³², D. Casadei¹⁹, M.P. Casado^{13,i}, A.F. Casha¹⁶¹, M. Casolino¹³, D.W. Casper¹⁶⁶, R. Castelijns¹⁰⁹, V. Castillo Gimenez¹⁷⁰, N.F. Castro^{128a}, A. Catinaccio³², J.R. Catmore¹²¹, A. Cattai³², J. Caudron²³, V. Cavaliere¹⁶⁹, E. Cavallaro¹³, D. Cavalli^{94a}, M. Cavalli-Sforza¹³, V. Cavasinni^{126a,126b}, E. Celebi^{20d}, F. Ceradini^{136a,136b}, L. Cerda Alberich¹⁷⁰, A.S. Cerqueira^{26b}, A. Cerri¹⁵¹, L. Cerrito^{135a,135b}, F. Cerutti¹⁶, A. Cervelli^{22a,22b}, S.A. Cetin^{20d}, A. Chafaq^{137a}, DC Chakraborty¹¹⁰, S.K. Chan⁵⁹, W.S. Chan¹⁰⁹, Y.L. Chan^{62a}, P. Chang¹⁶⁹, J.D. Chapman³⁰, D.G. Charlton¹⁹, C.C. Chau³¹, C.A. Chavez Barajas¹⁵¹, S. Che¹¹³, S. Cheatham^{167a,167c}, A. Chegwiddden⁹³, S. Chekanov⁶, S.V. Chekulaev^{163a}, G.A. Chelkov^{68,j}, M.A. Chelstowska³², C. Chen^{36c}, C. Chen⁶⁷, H. Chen²⁷, J. Chen^{36c}, J. Chen³⁸, S. Chen^{35b}, S. Chen¹⁵⁷, X. Chen^{35c,k}, Y. Chen⁷⁰, H.C. Cheng⁹², H.J. Cheng^{35a,35d}, A. Cheplakov⁶⁸, E. Cheremushkina¹³², R. Cherkaoui El Moursli^{137e}, E. Cheu⁷, K. Cheung⁶³, L. Chevalier¹³⁸, V. Chiarella⁵⁰, G. Chiarelli^{126a}, G. Chiodini^{76a}, A.S. Chisholm³², A. Chitan^{28b}, Y.H. Chiu¹⁷², M.V. Chizhov⁶⁸, K. Choi⁶⁴, A.R. Chomont³⁷, S. Chouridou¹⁵⁶, Y.S. Chow¹⁰⁹, V. Christodoulou⁸¹, M.C. Chu^{62a}, J. Chudoba¹²⁹, A.J. Chuinard⁹⁰, J.J. Chwastowski⁴², L. Chytka¹¹⁷, A.K. Ciftci^{4a}, D. Cinca⁴⁶, V. Cindro⁷⁸, I.A. Cioară²³, A. Ciocio¹⁶, F. Cirotto^{106a,106b}, Z.H. Citron¹⁷⁵, M. Citterio^{94a}, M. Ciubancan^{28b}, A. Clark⁵², M.R. Clark³⁸, P.J. Clark⁴⁹, R.N. Clarke¹⁶, C. Clement^{148a,148b}, Y. Coadou⁸⁸, M. Cobal^{167a,167c}, A. Coccaro⁵², J. Cochran⁶⁷, L. Colasurdo¹⁰⁸, B. Cole³⁸, A.P. Colijn¹⁰⁹, J. Collot⁵⁷, P. Conde Muiño^{128a,128b}, E. Coniavitis⁵¹, S.H. Connell^{147b}, I.A. Connelly⁸⁷, S. Constantinescu^{28b}, G. Conti³², F. Conventi^{106a,l}, A.M. Cooper-Sarkar¹²², F. Cormier¹⁷¹, K.J.R. Cormier¹⁶¹, M. Corradi^{134a,134b}, E.E. Corrigan⁸⁴, F. Corriveau^{90,m}, A. Cortes-Gonzalez³², M.J. Costa¹⁷⁰, D. Costanzo¹⁴¹, G. Cottin³⁰, G. Cowan⁸⁰, B.E. Cox⁸⁷, K. Cranmer¹¹², S.J. Crawley⁵⁶, R.A. Creager¹²⁴, G. Cree³¹, S. Crépe-Renaudin⁵⁷, F. Crescioli⁸³, W.A. Cribbs^{148a,148b}, M. Cristinziani²³, V. Croft¹¹², G. Crosetti^{40a,40b}, A. Cueto⁸⁵, T. Cuhadar Donszelmann¹⁴¹, A.R. Cukierman¹⁴⁵, J. Cummings¹⁷⁹, M. Curatolo⁵⁰, J. Cúth⁸⁶, S. Czekierda⁴², P. Czodrowski³², G. D'amen^{22a,22b}, S. D'Auria⁵⁶, L. D'Eramo⁸³, M. D'Onofrio⁷⁷, M.J. Da Cunha Sargedas De Sousa^{128a,128b}, C. Da Via⁸⁷, W. Dabrowski^{41a}, T. Dado^{146a,h}, S. Dahbi^{137e}, T. Dai⁹², O. Dale¹⁵, F. Dallaire⁹⁷, C. Dallapiccola⁸⁹, M. Dam³⁹, J.R. Dandoy¹²⁴, M.F. Daneri²⁹, N.P. Dang^{176,e}, N.D. Dann⁸⁷, M. Danninger¹⁷¹, M. Dano Hoffmann¹³⁸, V. Dao³², G. Darbo^{53a}, S. Darmora⁸, J. Dassoulas³, A. Dattagupta¹¹⁸, T. Daubney⁴⁵, W. Davey²³, C. David⁴⁵, T. Davidek¹³¹, D.R. Davis⁴⁸, P. Davison⁸¹, E. Dawe⁹¹, I. Dawson¹⁴¹, K. De⁸,

R. de Asmundis^{106a}, A. De Benedetti¹¹⁵, S. De Castro^{22a,22b}, S. De Cecco⁸³, N. De Groot¹⁰⁸, P. de Jong¹⁰⁹, H. De la Torre⁹³, F. De Lorenzi⁶⁷, A. De Maria^{58,n}, D. De Pedis^{134a}, A. De Salvo^{134a}, U. De Sanctis^{135a,135b}, A. De Santo¹⁵¹, K. De Vasconcelos Corga⁸⁸, J.B. De Vivie De Regie¹¹⁹, R. Debbe²⁷, C. Debenedetti¹³⁹, D.V. Dedovich⁶⁸, N. Dehghanian³, I. Deigaard¹⁰⁹, M. Del Gaudio^{40a,40b}, J. Del Peso⁸⁵, D. Delgove¹¹⁹, F. Deliot¹³⁸, C.M. Delitzsch⁷, A. Dell'Acqua³², L. Dell'Asta²⁴, M. Della Pietra^{106a,106b}, D. della Volpe⁵², M. Delmastro⁵, C. Delporte¹¹⁹, P.A. Delsart⁵⁷, D.A. DeMarco¹⁶¹, S. Demers¹⁷⁹, M. Demichev⁶⁸, A. Demilly⁸³, S.P. Denisov¹³², D. Denysiuk¹³⁸, D. Derendarz⁴², J.E. Derkaoui^{137d}, F. Derue⁸³, P. Dervan⁷⁷, K. Desch²³, C. Deterre⁴⁵, K. Dette¹⁶¹, M.R. Devesa²⁹, P.O. Deviveiros³², A. Dewhurst¹³³, S. Dhaliwal²⁵, F.A. Di Bello⁵², A. Di Ciaccio^{135a,135b}, L. Di Ciaccio⁵, W.K. Di Clemente¹²⁴, C. Di Donato^{106a,106b}, A. Di Girolamo³², B. Di Girolamo³², B. Di Micco^{136a,136b}, R. Di Nardo³², K.F. Di Petrillo⁵⁹, A. Di Simone⁵¹, R. Di Sipio¹⁶¹, D. Di Valentino³¹, C. Diaconu⁸⁸, M. Diamond¹⁶¹, F.A. Dias³⁹, M.A. Diaz^{34a}, J. Dickinson¹⁶, E.B. Diehl⁹², J. Dietrich¹⁷, S. Díez Cornell⁴⁵, A. Dimitrievska¹⁶, J. Dingfelder²³, P. Dita^{28b}, S. Dita^{28b}, F. Dittus³², F. Djama⁸⁸, T. Djobava^{54b}, J.I. Djuvsland^{60a}, M.A.B. do Vale^{26c}, M. Dobre^{28b}, D. Dodsworth²⁵, C. Doglioni⁸⁴, J. Dolejsi¹³¹, Z. Dolezal¹³¹, M. Donadelli^{26d}, S. Donati^{126a,126b}, J. Donini³⁷, J. Dopke¹³³, A. Doria^{106a}, M.T. Dova⁷⁴, A.T. Doyle⁵⁶, E. Drechsler⁵⁸, E. Dreyer¹⁴⁴, M. Dris¹⁰, Y. Du^{36a}, J. Duarte-Campderros¹⁵⁵, F. Dubinin⁹⁸, A. Dubreuil⁵², E. Duchovni¹⁷⁵, G. Duckeck¹⁰², A. Ducourthial⁸³, O.A. Ducu^{97,o}, D. Duda¹⁰⁹, A. Dudarev³², A.Ch. Dudder⁸⁶, E.M. Duffield¹⁶, L. Duflo¹¹⁹, M. Dührssen³², C. Dülse¹⁷⁷, M. Dumancic¹⁷⁵, A.E. Dumitriu^{28b,p}, A.K. Duncan⁵⁶, M. Dunford^{60a}, A. Duperrin⁸⁸, H. Duran Yildiz^{4a}, M. Düren⁵⁵, A. Durglishvili^{54b}, D. Duschinger⁴⁷, B. Dutta⁴⁵, D. Duvnjak¹, M. Dyndal⁴⁵, B.S. Dziedzic⁴², C. Eckardt⁴⁵, K.M. Ecker¹⁰³, R.C. Edgar⁹², T. Eifert³², G. Eigen¹⁵, K. Einsweiler¹⁶, T. Ekelof¹⁶⁸, M. El Kacimi^{137c}, R. El Kosseifi⁸⁸, V. Ellajosyula⁸⁸, M. Ellert¹⁶⁸, S. Elles⁵, F. Ellinghaus¹⁷⁷, A.A. Elliot¹⁷², N. Ellis³², J. Elmsheuser²⁷, M. Elsing³², D. Emeliyanov¹³³, Y. Enari¹⁵⁷, J.S. Ennis¹⁷³, M.B. Epland⁴⁸, J. Erdmann⁴⁶, A. Ereditato¹⁸, M. Ernst²⁷, S. Errede¹⁶⁹, M. Escalier¹¹⁹, C. Escobar¹⁷⁰, B. Esposito⁵⁰, O. Estrada Pastor¹⁷⁰, A.I. Etiennevre¹³⁸, E. Etzion¹⁵⁵, H. Evans⁶⁴, A. Ezhilov¹²⁵, M. Ezzi^{137e}, F. Fabbri^{22a,22b}, L. Fabbri^{22a,22b}, V. Fabiani¹⁰⁸, G. Facini⁸¹, R.M. Fakhruddinov¹³², S. Falciano^{134a}, R.J. Falla⁸¹, J. Faltova¹³¹, Y. Fang^{35a}, M. Fanti^{94a,94b}, A. Farbin⁸, A. Farilla^{136a}, E.M. Farina^{123a,123b}, T. Farooque⁹³, S. Farrell¹⁶, S.M. Farrington¹⁷³, P. Farthouat³², F. Fassi^{137e}, P. Fassnacht³², D. Fassouliotis⁹, M. Fauci Giannelli⁴⁹, A. Favareto^{53a,53b}, W.J. Fawcett¹²², L. Fayard¹¹⁹, O.L. Fedin^{125,q}, W. Fedorko¹⁷¹, S. Feigl¹²¹, L. Feligioni⁸⁸, C. Feng^{36a}, E.J. Feng³², M. Feng⁴⁸, M.J. Fenton⁵⁶, A.B. Fenyuk¹³², L. Feremenga⁸, P. Fernandez Martinez¹⁷⁰, J. Ferrando⁴⁵, A. Ferrari¹⁶⁸, P. Ferrari¹⁰⁹, R. Ferrari^{123a}, D.E. Ferreira de Lima^{60b}, A. Ferrer¹⁷⁰, D. Ferrere⁵², C. Ferretti⁹², F. Fiedler⁸⁶, A. Filipčič⁷⁸, M. Filipuzzi⁴⁵, F. Filthaut¹⁰⁸, M. Fincke-Keeler¹⁷², K.D. Finelli²⁴, M.C.N. Fiolhais^{128a,128c,r}, L. Fiorini¹⁷⁰, C. Fischer¹³, J. Fischer¹⁷⁷, W.C. Fisher⁹³, N. Flaschel⁴⁵, I. Fleck¹⁴³, P. Fleischmann⁹², R.R.M. Fletcher¹²⁴, T. Flick¹⁷⁷, B.M. Flierl¹⁰², L.R. Flores Castillo^{62a}, N. Fomin¹⁵, G.T. Forcolin⁸⁷, A. Formica¹³⁸, F.A. Förster¹³, A.C. Forti⁸⁷, A.G. Foster¹⁹, D. Fournier¹¹⁹, H. Fox⁷⁵, S. Fracchia¹⁴¹, P. Francavilla^{126a,126b}, M. Franchini^{22a,22b}, S. Franchino^{60a}, D. Francis³², L. Franconi¹²¹, M. Franklin⁵⁹, M. Frate¹⁶⁶, M. Fraternali^{123a,123b}, D. Freeborn⁸¹, S.M. Fressard-Batraneanu³², B. Freund⁹⁷, W.S. Freund^{26a}, D. Froidevaux³², J.A. Frost¹²², C. Fukunaga¹⁵⁸, T. Fusayasu¹⁰⁴, J. Fuster¹⁷⁰, O. Gabizon¹⁵⁴, A. Gabrielli^{22a,22b}, A. Gabrielli¹⁶, G.P. Gach^{41a}, S. Gadatsch⁵², S. Gadomski⁸⁰, G. Gagliardi^{53a,53b}, L.G. Gagnon⁹⁷, C. Galea¹⁰⁸, B. Galhardo^{128a,128c}, E.J. Gallas¹²², B.J. Gallop¹³³, P. Gallus¹³⁰, G. Galster³⁹, K.K. Gan¹¹³, S. Ganguly¹⁷⁵, Y. Gao⁷⁷, Y.S. Gao^{145,f}, F.M. Garay Walls^{34a}, C. García¹⁷⁰, J.E. García Navarro¹⁷⁰, J.A. García Pascual^{35a}, M. Garcia-Sciveres¹⁶, R.W. Gardner³³, N. Garelli¹⁴⁵, V. Garonne¹²¹, K. Gasnikova⁴⁵, C. Gatti⁵⁰, A. Gaudiello^{53a,53b}, G. Gaudio^{123a}, I.L. Gavrilenko⁹⁸, C. Gay¹⁷¹, G. Gaycken²³, E.N. Gazis¹⁰, C.N.P. Gee¹³³, J. Geisen⁵⁸, M. Geisen⁸⁶, M.P. Geisler^{60a}, K. Gellerstedt^{148a,148b}, C. Gemme^{53a}, M.H. Genest⁵⁷, C. Geng⁹², S. Gentile^{134a,134b}, C. Gentsos¹⁵⁶, S. George⁸⁰, D. Gerbaudo¹³, G. Gessner⁴⁶, S. Ghasemi¹⁴³, M. Ghneimat²³, B. Giacobbe^{22a}, S. Giagu^{134a,134b}, N. Giangiacomi^{22a,22b}, P. Giannetti^{126a},

S.M. Gibson⁸⁰, M. Gignac¹⁷¹, M. Gilchriese¹⁶, D. Gillberg³¹, G. Gilles¹⁷⁷, D.M. Gingrich^{3,d}, M.P. Giordani^{167a,167c}, F.M. Giorgi^{22a}, P.F. Giraud¹³⁸, P. Giromini⁵⁹, G. Giugliarelli^{167a,167c}, D. Giugni^{94a}, F. Giuli¹²², M. Giuliani^{60b}, B.K. Gjelsten¹²¹, S. Gkaitatzis¹⁵⁶, I. Gkialas^{9,s}, E.L. Gkougkousis¹³, P. Gkoutoumis¹⁰, L.K. Gladilin¹⁰¹, C. Glasman⁸⁵, J. Glatzer¹³, P.C.F. Glaysheer⁴⁵, A. Glazov⁴⁵, M. Goblirsch-Kolb²⁵, J. Godlewski⁴², S. Goldfarb⁹¹, T. Golling⁵², D. Golubkov¹³², A. Gomes^{128a,128b,128d}, R. Gonalo^{128a}, R. Goncalves Gama^{26a}, J. Goncalves Pinto Firmino Da Costa¹³⁸, G. Gonella⁵¹, L. Gonella¹⁹, A. Gongadze⁶⁸, F. Gonnella¹⁹, J.L. Gonski⁵⁹, S. Gonzalez de la Hoz¹⁷⁰, S. Gonzalez-Sevilla⁵², L. Goossens³², P.A. Gorbounov⁹⁹, H.A. Gordon²⁷, B. Gorini³², E. Gorini^{76a,76b}, A. Gorišek⁷⁸, A.T. Goshaw⁴⁸, C. Gossling⁴⁶, M.I. Gostkin⁶⁸, C.A. Gottardo²³, C.R. Goudet¹¹⁹, D. Goujdami^{137c}, A.G. Goussiou¹⁴⁰, N. Govender^{147b,t}, C. Goy⁵, E. Gozani¹⁵⁴, I. Grabowska-Bold^{41a}, P.O.J. Gradin¹⁶⁸, E.C. Graham⁷⁷, J. Gramling¹⁶⁶, E. Gramstad¹²¹, S. Grancagnolo¹⁷, V. Gratchev¹²⁵, P.M. Gravila^{28f}, C. Gray⁵⁶, H.M. Gray¹⁶, Z.D. Greenwood^{82,u}, C. Grefe²³, K. Gregersen⁸¹, I.M. Gregor⁴⁵, P. Grenier¹⁴⁵, K. Grevtsov⁵, J. Griffiths⁸, A.A. Grillo¹³⁹, K. Grimm⁷⁵, S. Grinstein^{13,v}, Ph. Gris³⁷, J.-F. Grivaz¹¹⁹, S. Groh⁸⁶, E. Gross¹⁷⁵, J. Grosse-Knetter⁵⁸, G.C. Grossi⁸², Z.J. Grout⁸¹, A. Grummer¹⁰⁷, L. Guan⁹², W. Guan¹⁷⁶, J. Guenther³², A. Guerguichon¹¹⁹, F. Guescini^{163a}, D. Guest¹⁶⁶, O. Gueta¹⁵⁵, R. Gugel⁵¹, B. Gui¹¹³, T. Guillemin⁵, S. Guindon³², U. Gul⁵⁶, C. Gumpert³², J. Guo^{36b}, W. Guo⁹², Y. Guo^{36c,w}, R. Gupta⁴³, S. Gurbuz^{20a}, G. Gustavino¹¹⁵, B.J. Gutelman¹⁵⁴, P. Gutierrez¹¹⁵, N.G. Gutierrez Ortiz⁸¹, C. Gutscheow⁸¹, C. Guyot¹³⁸, M.P. Guzik^{41a}, C. Gwenlan¹²², C.B. Gwilliam⁷⁷, A. Haas¹¹², C. Haber¹⁶, H.K. Hadavand⁸, N. Haddad^{137e}, A. Hadeef⁸⁸, S. Hagebock²³, M. Hagihara¹⁶⁴, H. Hakobyan^{180,*}, M. Haleem¹⁷⁸, J. Haley¹¹⁶, G. Halladjian⁹³, G.D. Hallewell⁸⁸, K. Hamacher¹⁷⁷, P. Hamal¹¹⁷, K. Hamano¹⁷², A. Hamilton^{147a}, G.N. Hamity¹⁴¹, P.G. Hamnett⁴⁵, K. Han^{36c,x}, L. Han^{36c}, S. Han^{35a,35d}, K. Hanagaki^{69,y}, M. Hance¹³⁹, D.M. Handl¹⁰², B. Haney¹²⁴, R. Hankache⁸³, P. Hanke^{60a}, E. Hansen⁸⁴, J.B. Hansen³⁹, J.D. Hansen³⁹, M.C. Hansen²³, P.H. Hansen³⁹, K. Hara¹⁶⁴, A.S. Hard¹⁷⁶, T. Harenberg¹⁷⁷, F. Hariri¹¹⁹, S. Harkusha⁹⁵, P.F. Harrison¹⁷³, N.M. Hartmann¹⁰², Y. Hasegawa¹⁴², A. Hasib⁴⁹, S. Hassani¹³⁸, S. Haug¹⁸, R. Hauser⁹³, L. Hauswald⁴⁷, L.B. Havener³⁸, M. Havranek¹³⁰, C.M. Hawkes¹⁹, R.J. Hawkings³², D. Hayden⁹³, C.P. Hays¹²², J.M. Hays⁷⁹, H.S. Hayward⁷⁷, S.J. Haywood¹³³, T. Heck⁸⁶, V. Hedberg⁸⁴, L. Heelan⁸, S. Heer²³, K.K. Heidegger⁵¹, S. Heim⁴⁵, T. Heim¹⁶, B. Heinemann^{45,z}, J.J. Heinrich¹⁰², L. Heinrich¹¹², C. Heinz⁵⁵, J. Hejbal¹²⁹, L. Helary³², A. Held¹⁷¹, S. Hellman^{148a,148b}, C. Helsens³², R.C.W. Henderson⁷⁵, Y. Heng¹⁷⁶, S. Henkelmann¹⁷¹, A.M. Henriques Correia³², G.H. Herbert¹⁷, H. Herde²⁵, V. Herget¹⁷⁸, Y. Hernandez Jimenez^{147c}, H. Herr⁸⁶, G. Herten⁵¹, R. Hertenberger¹⁰², L. Hervas³², T.C. Herwig¹²⁴, G.G. Hesketh⁸¹, N.P. Hessey^{163a}, J.W. Hetherly⁴³, S. Higashino⁶⁹, E. Higon-Rodriguez¹⁷⁰, K. Hildebrand³³, E. Hill¹⁷², J.C. Hill³⁰, K.H. Hiller⁴⁵, S.J. Hillier¹⁹, M. Hils⁴⁷, I. Hinchliffe¹⁶, M. Hirose⁵¹, D. Hirschbuehl¹⁷⁷, B. Hiti⁷⁸, O. Hladik¹²⁹, D.R. Hlaluku^{147c}, X. Hoad⁴⁹, J. Hobbs¹⁵⁰, N. Hod^{163a}, M.C. Hodgkinson¹⁴¹, P. Hodgson¹⁴¹, A. Hoecker³², M.R. Hoferkamp¹⁰⁷, F. Hoenig¹⁰², D. Hohn²³, D. Hohov¹¹⁹, T.R. Holmes³³, M. Holzbock¹⁰², M. Homann⁴⁶, S. Honda¹⁶⁴, T. Honda⁶⁹, T.M. Hong¹²⁷, B.H. Hooberman¹⁶⁹, W.H. Hopkins¹¹⁸, Y. Horii¹⁰⁵, A.J. Horton¹⁴⁴, J.-Y. Hostachy⁵⁷, A. Hostiuc¹⁴⁰, S. Hou¹⁵³, A. Hoummada^{137a}, J. Howarth⁸⁷, J. Hoya⁷⁴, M. Hrabovsky¹¹⁷, J. Hrdinka³², I. Hristova¹⁷, J. Hrivnac¹¹⁹, T. Hryn'ova⁵, A. Hrynevich⁹⁶, P.J. Hsu⁶³, S.-C. Hsu¹⁴⁰, Q. Hu²⁷, S. Hu^{36b}, Y. Huang^{35a}, Z. Hubacek¹³⁰, F. Hubaut⁸⁸, F. Huegging²³, T.B. Huffman¹²², E.W. Hughes³⁸, M. Huhtinen³², R.F.H. Hunter³¹, P. Huo¹⁵⁰, A.M. Hupe³¹, N. Huseynov^{68,b}, J. Huston⁹³, J. Huth⁵⁹, R. Hyneman⁹², G. Iacobucci⁵², G. Iakovidis²⁷, I. Ibragimov¹⁴³, L. Iconomidou-Fayard¹¹⁹, Z. Idrissi^{137e}, P. Iengo³², O. Igonkina^{109,aa}, T. Iizawa¹⁷⁴, Y. Ikegami⁶⁹, M. Ikeno⁶⁹, D. Iliadis¹⁵⁶, N. Ilic¹⁴⁵, F. Iltzsche⁴⁷, G. Introzzi^{123a,123b}, P. Ioannou^{9,*}, M. Iodice^{136a}, K. Iordanidou³⁸, V. Ippolito⁵⁹, M.F. Isacson¹⁶⁸, N. Ishijima¹²⁰, M. Ishino¹⁵⁷, M. Ishitsuka¹⁵⁹, C. Issever¹²², S. Istin^{20a,ab}, F. Ito¹⁶⁴, J.M. Iturbe Ponce^{62a}, R. Iuppa^{162a,162b}, H. Iwasaki⁶⁹, J.M. Izen⁴⁴, V. Izzo^{106a}, S. Jabbar³, P. Jackson¹, R.M. Jacobs²³, V. Jain², G. Jakel¹⁷⁷, K.B. Jakobi⁸⁶, K. Jakobs⁵¹, S. Jakobsen⁶⁵, T. Jakoubek¹²⁹, D.O. Jamin¹¹⁶, D.K. Jana⁸²,

R. Jansky⁵², J. Janssen²³, M. Janus⁵⁸, P.A. Janus^{41a}, G. Jarlskog⁸⁴, N. Javadov^{68,b}, T. Javůrek⁵¹, M. Javurkova⁵¹, F. Jeanneau¹³⁸, L. Jeanty¹⁶, J. Jejelava^{54a,ac}, A. Jelinskas¹⁷³, P. Jenni^{51,ad}, C. Jeske¹⁷³, S. Jézéquel⁵, H. Ji¹⁷⁶, J. Jia¹⁵⁰, H. Jiang⁶⁷, Y. Jiang^{36c}, Z. Jiang¹⁴⁵, S. Jiggins⁸¹, J. Jimenez Pena¹⁷⁰, S. Jin^{35b}, A. Jinaru^{28b}, O. Jinnouchi¹⁵⁹, H. Jivan^{147c}, P. Johansson¹⁴¹, K.A. Johns⁷, C.A. Johnson⁶⁴, W.J. Johnson¹⁴⁰, K. Jon-And^{148a,148b}, R.W.L. Jones⁷⁵, S.D. Jones¹⁵¹, S. Jones⁷, T.J. Jones⁷⁷, J. Jongmanns^{60a}, P.M. Jorge^{128a,128b}, J. Jovicevic^{163a}, X. Ju¹⁷⁶, A. Juste Rozas^{13,v}, A. Kaczmarek⁴², M. Kado¹¹⁹, H. Kagan¹¹³, M. Kagan¹⁴⁵, S.J. Kahn⁸⁸, T. Kajji¹⁷⁴, E. Kajomovitz¹⁵⁴, C.W. Kalderon⁸⁴, A. Kaluza⁸⁶, S. Kama⁴³, A. Kamenshchikov¹³², L. Kanjir⁷⁸, Y. Kano¹⁵⁷, V.A. Kantserov¹⁰⁰, J. Kanzaki⁶⁹, B. Kaplan¹¹², L.S. Kaplan¹⁷⁶, D. Kar^{147c}, K. Karakostas¹⁰, N. Karastathis¹⁰, M.J. Kareem^{163b}, E. Karentzos¹⁰, S.N. Karpov⁶⁸, Z.M. Karpova⁶⁸, V. Kartvelishvili⁷⁵, A.N. Karyukhin¹³², K. Kasahara¹⁶⁴, L. Kashif¹⁷⁶, R.D. Kass¹¹³, A. Kastanas¹⁴⁹, Y. Kataoka¹⁵⁷, C. Kato¹⁵⁷, A. Katre⁵², J. Katzy⁴⁵, K. Kawade⁷⁰, K. Kawagoe⁷³, T. Kawamoto¹⁵⁷, G. Kawamura⁵⁸, E.F. Kay⁷⁷, V.F. Kazanin^{111,c}, R. Keeler¹⁷², R. Kehoe⁴³, J.S. Keller³¹, E. Kellermann⁸⁴, J.J. Kempster⁸⁰, J. Kendrick¹⁹, H. Keoshkerian¹⁶¹, O. Kepka¹²⁹, B.P. Kerševan⁷⁸, S. Kersten¹⁷⁷, R.A. Keyes⁹⁰, M. Khader¹⁶⁹, F. Khalil-zada¹², A. Khanov¹¹⁶, A.G. Kharlamov^{111,c}, T. Kharlamova¹¹¹, A. Khodinov¹⁶⁰, T.J. Khoo⁵², V. Khovanskiy^{99,*}, E. Khramov⁶⁸, J. Khubua^{54b,ae}, S. Kido⁷⁰, M. Kiehn⁵², C.R. Kilby⁸⁰, H.Y. Kim⁸, S.H. Kim¹⁶⁴, Y.K. Kim³³, N. Kimura^{167a,167c}, O.M. Kind¹⁷, B.T. King⁷⁷, D. Kirchmeier⁴⁷, J. Kirk¹³³, A.E. Kiryunin¹⁰³, T. Kishimoto¹⁵⁷, D. Kisielewska^{41a}, V. Kitali⁴⁵, O. Kivernyk⁵, E. Kladiva^{146b}, T. Klapdor-Kleingrothaus⁵¹, M.H. Klein⁹², M. Klein⁷⁷, U. Klein⁷⁷, K. Kleinknecht⁸⁶, P. Klimek¹¹⁰, A. Klimentov²⁷, R. Klingenberg^{46,*}, T. Klingl²³, T. Klioutchnikova³², F.F. Klitzner¹⁰², P. Kluit¹⁰⁹, S. Kluth¹⁰³, E. Kneringer⁶⁵, E.B.F.G. Knoops⁸⁸, A. Knue⁵¹, A. Kobayashi¹⁵⁷, D. Kobayashi⁷³, T. Kobayashi¹⁵⁷, M. Kobel⁴⁷, M. Kocian¹⁴⁵, P. Kodys¹³¹, T. Koffas³¹, E. Koffeman¹⁰⁹, N.M. Köhler¹⁰³, T. Koi¹⁴⁵, M. Kolb^{60b}, I. Koletsou⁵, T. Kondo⁶⁹, N. Kondrashova^{36b}, K. Köneke⁵¹, A.C. König¹⁰⁸, T. Kono^{69,af}, R. Konoplich^{112,ag}, N. Konstantinidis⁸¹, B. Konya⁸⁴, R. Kopeliansky⁶⁴, S. Koperny^{41a}, K. Korcyl⁴², K. Kordas¹⁵⁶, A. Korn⁸¹, I. Korolkov¹³, E.V. Korolkova¹⁴¹, O. Kortner¹⁰³, S. Kortner¹⁰³, T. Kosek¹³¹, V.V. Kostyukhin²³, A. Kotwal⁴⁸, A. Koulouris¹⁰, A. Kourkouveli-Charalampidi^{123a,123b}, C. Kourkouvelis⁹, E. Kourlitis¹⁴¹, V. Kouskoura²⁷, A.B. Kowalewska⁴², R. Kowalewski¹⁷², T.Z. Kowalski^{41a}, C. Kozakai¹⁵⁷, W. Kozanecki¹³⁸, A.S. Kozhin¹³², V.A. Kramarenko¹⁰¹, G. Kramberger⁷⁸, D. Krasnopevtsev¹⁰⁰, M.W. Krasny⁸³, A. Krasznahorkay³², D. Krauss¹⁰³, J.A. Kremer^{41a}, J. Kretzschmar⁷⁷, K. Kreutzfeldt⁵⁵, P. Krieger¹⁶¹, K. Krizka¹⁶, K. Kroeninger⁴⁶, H. Kroha¹⁰³, J. Kroll¹²⁹, J. Kroll¹²⁴, J. Kroseberg²³, J. Krstic¹⁴, U. Kruchonak⁶⁸, H. Krüger²³, N. Krumnack⁶⁷, M.C. Kruse⁴⁸, T. Kubota⁹¹, H. Kucuk⁸¹, S. Kuday^{4b}, J.T. Kuechler¹⁷⁷, S. Kuehn³², A. Kugel^{60a}, F. Kuger¹⁷⁸, T. Kuhl⁴⁵, V. Kukhtin⁶⁸, R. Kukla⁸⁸, Y. Kulchitsky⁹⁵, S. Kuleshov^{34b}, Y.P. Kulinich¹⁶⁹, M. Kuna⁵⁷, T. Kunigo⁷¹, A. Kupco¹²⁹, T. Kupfer⁴⁶, O. Kuprash¹⁵⁵, H. Kurashige⁷⁰, L.L. Kurchaninov^{163a}, Y.A. Kurochkin⁹⁵, M.G. Kurth^{35a,35d}, E.S. Kuwertz¹⁷², M. Kuze¹⁵⁹, J. Kvita¹¹⁷, T. Kwan¹⁷², A. La Rosa¹⁰³, J.L. La Rosa Navarro^{26d}, L. La Rotonda^{40a,40b}, F. La Ruffa^{40a,40b}, C. Lacasta¹⁷⁰, F. Lacava^{134a,134b}, J. Lacey⁴⁵, D.P.J. Lack⁸⁷, H. Lacker¹⁷, D. Lacour⁸³, E. Ladygin⁶⁸, R. Lafaye⁵, B. Laforge⁸³, S. Lai⁵⁸, S. Lammers⁶⁴, W. Lampl⁷, E. Lançon²⁷, U. Landgraf⁵¹, M.P.J. Landon⁷⁹, M.C. Lanfermann⁵², V.S. Lang⁴⁵, J.C. Lange¹³, R.J. Langenberg³², A.J. Lankford¹⁶⁶, F. Lanni²⁷, K. Lantzsch²³, A. Lanza^{123a}, A. Lapertosa^{53a,53b}, S. Laplace⁸³, J.F. Laporte¹³⁸, T. Lari^{94a}, F. Lasagni Manghi^{22a,22b}, M. Lassnig³², T.S. Lau^{62a}, A. Laudrain¹¹⁹, P. Laurelli⁵⁰, A.T. Law¹³⁹, P. Laycock⁷⁷, M. Lazzaroni^{94a,94b}, B. Le⁹¹, O. Le Dortz⁸³, E. Le Guirriec⁸⁸, E.P. Le Quilleuc¹³⁸, M. LeBlanc⁷, T. LeCompte⁶, F. Ledroit-Guillon⁵⁷, C.A. Lee²⁷, G.R. Lee^{34a}, S.C. Lee¹⁵³, L. Lee⁵⁹, B. Lefebvre⁹⁰, G. Lefebvre⁸³, M. Lefebvre¹⁷², F. Legger¹⁰², C. Leggett¹⁶, G. Lehmann Miotto³², X. Lei⁷, W.A. Leight⁴⁵, M.A.L. Leite^{26d}, R. Leitner¹³¹, D. Lellouch¹⁷⁵, B. Lemmer⁵⁸, K.J.C. Leney⁸¹, T. Lenz²³, B. Lenzi³², R. Leone⁷, S. Leone^{126a}, C. Leonidopoulos⁴⁹, G. Lerner¹⁵¹, C. Leroy⁹⁷, R. Les¹⁶¹, A.A.J. Lesage¹³⁸, C.G. Lester³⁰, M. Levchenko¹²⁵, J. Levêque⁵, D. Levin⁹², L.J. Levinson¹⁷⁵, M. Levy¹⁹, D. Lewis⁷⁹, B. Li^{36c,w}, C.-Q. Li^{36c}, H. Li^{36a}, L. Li^{36b}, Q. Li^{35a,35d}, Q. Li^{36c}, S. Li⁴⁸, X. Li^{36b}, Y. Li¹⁴³, Z. Liang^{35a}, B. Liberti^{135a}, A. Liblong¹⁶¹, K. Lie^{62c},

A. Limosani¹⁵², C.Y. Lin³⁰, K. Lin⁹³, S.C. Lin¹⁸², T.H. Lin⁸⁶, R.A. Linck⁶⁴, B.E. Lindquist¹⁵⁰, A.L. Lioni⁵², E. Lipeles¹²⁴, A. Lipniacka¹⁵, M. Lisovsky^{60b}, T.M. Liss^{169,ah}, A. Lister¹⁷¹, A.M. Litke¹³⁹, B. Liu⁶⁷, H. Liu⁹², H. Liu²⁷, J.K.K. Liu¹²², J.B. Liu^{36c}, kliu Liu⁸³, L. Liu¹⁶⁹, M. Liu^{36c}, Y.L. Liu^{36c}, Y. Liu^{36c}, M. Livan^{123a,123b}, A. Lleres⁵⁷, J. Llorente Merino^{35a}, S.L. Lloyd⁷⁹, C.Y. Lo^{62b}, F. Lo Sterzo⁴³, E.M. Lobodzinska⁴⁵, P. Loch⁷, F.K. Loebinger⁸⁷, A. Loesle⁵¹, K.M. Loew²⁵, T. Lohse¹⁷, K. Lohwasser¹⁴¹, M. Lokajicek¹²⁹, B.A. Long²⁴, J.D. Long¹⁶⁹, R.E. Long⁷⁵, L. Longo^{76a,76b}, K.A. Looper¹¹³, J.A. Lopez^{34b}, I. Lopez Paz¹³, A. Lopez Solis⁸³, J. Lorenz¹⁰², N. Lorenzo Martinez⁵, M. Losada²¹, P.J. Lösel¹⁰², X. Lou^{35a}, A. Lounis¹¹⁹, J. Love⁶, P.A. Love⁷⁵, H. Lu^{62a}, N. Lu⁹², Y.J. Lu⁶³, H.J. Lubatti¹⁴⁰, C. Luci^{134a,134b}, A. Lucotte⁵⁷, C. Luedtke⁵¹, F. Luehring⁶⁴, W. Lukas⁶⁵, L. Luminari^{134a}, B. Lund-Jensen¹⁴⁹, M.S. Lutz⁸⁹, P.M. Luzi⁸³, D. Lynn²⁷, R. Lysak¹²⁹, E. Lytken⁸⁴, F. Lyu^{35a}, V. Lyubushkin⁶⁸, H. Ma²⁷, L.L. Ma^{36a}, Y. Ma^{36a}, G. Maccarrone⁵⁰, A. Macchiolo¹⁰³, C.M. Macdonald¹⁴¹, B. Maček⁷⁸, J. Machado Miguens¹²⁴, D. Madaffari¹⁷⁰, R. Madar³⁷, W.F. Mader⁴⁷, A. Madsen⁴⁵, N. Madysa⁴⁷, J. Maeda⁷⁰, S. Maeland¹⁵, T. Maeno²⁷, A.S. Maevskiy¹⁰¹, V. Magerl⁵¹, C. Maidantchik^{26a}, T. Maier¹⁰², A. Maio^{128a,128b,128d}, O. Majersky^{146a}, S. Majewski¹¹⁸, Y. Makida⁶⁹, N. Makovec¹¹⁹, B. Malaescu⁸³, Pa. Malecki⁴², V.P. Maleev¹²⁵, F. Malek⁵⁷, U. Mallik⁶⁶, D. Malon⁶, C. Malone³⁰, S. Maltezos¹⁰, S. Malyukov³², J. Mamuzic¹⁷⁰, G. Mancini⁵⁰, I. Mandić⁷⁸, J. Maneira^{128a,128b}, L. Manhaes de Andrade Filho^{26b}, J. Manjarres Ramos⁴⁷, K.H. Mankinen⁸⁴, A. Mann¹⁰², A. Manousos³², B. Mansoulie¹³⁸, J.D. Mansour^{35a}, R. Mantifel⁹⁰, M. Mantoani⁵⁸, S. Manzoni^{94a,94b}, L. Mapelli³², G. Marceca²⁹, L. March⁵², L. Marchese¹²², G. Marchiori⁸³, M. Marcisovsky¹²⁹, C.A. Marin Tobon³², M. Marjanovic³⁷, D.E. Marley⁹², F. Marroquim^{26a}, S.P. Marsden⁸⁷, Z. Marshall¹⁶, M.U.F. Martensson¹⁶⁸, S. Marti-Garcia¹⁷⁰, C.B. Martin¹¹³, T.A. Martin¹⁷³, V.J. Martin⁴⁹, B. Martin dit Latour¹⁵, M. Martinez^{13,v}, V.I. Martinez Outschoorn⁸⁹, S. Martin-Haugh¹³³, V.S. Martoiu^{28b}, A.C. Martyniuk⁸¹, A. Marzin³², L. Masetti⁸⁶, T. Mashimo¹⁵⁷, R. Mashinistov⁹⁸, J. Masik⁸⁷, A.L. Maslennikov^{111,c}, L.H. Mason⁹¹, L. Massa^{135a,135b}, P. Mastrandrea⁵, A. Mastroberardino^{40a,40b}, T. Masubuchi¹⁵⁷, P. Mättig¹⁷⁷, J. Maurer^{28b}, S.J. Maxfield⁷⁷, D.A. Maximov^{111,c}, R. Mazini¹⁵³, I. Maznas¹⁵⁶, S.M. Mazza^{94a,94b}, N.C. Mc Fadden¹⁰⁷, G. Mc Goldrick¹⁶¹, S.P. Mc Kee⁹², A. McCarn⁹², R.L. McCarthy¹⁵⁰, T.G. McCarthy¹⁰³, L.I. McClymont⁸¹, E.F. McDonald⁹¹, J.A. Mcfayden³², G. Mchedlidze⁵⁸, S.J. McMahon¹³³, P.C. McNamara⁹¹, C.J. McNicol¹⁷³, R.A. McPherson^{172,m}, Z.A. Meadows⁸⁹, S. Meehan¹⁴⁰, T. Megy⁵¹, S. Mehlhase¹⁰², A. Mehta⁷⁷, T. Meideck⁵⁷, B. Meirose⁴⁴, D. Melini^{170,ai}, B.R. Mellado Garcia^{147c}, J.D. Mellenthin⁵⁸, M. Melo^{146a}, F. Meloni¹⁸, A. Melzer²³, S.B. Menary⁸⁷, L. Meng⁷⁷, X.T. Meng⁹², A. Mengarelli^{22a,22b}, S. Menke¹⁰³, E. Meoni^{40a,40b}, S. Mergelmeyer¹⁷, C. Merlassino¹⁸, P. Mermod⁵², L. Merola^{106a,106b}, C. Meroni^{94a}, F.S. Merritt³³, A. Messina^{134a,134b}, J. Metcalfe⁶, A.S. Mete¹⁶⁶, C. Meyer¹²⁴, J-P. Meyer¹³⁸, J. Meyer¹⁰⁹, H. Meyer Zu Theenhausen^{60a}, F. Miano¹⁵¹, R.P. Middleton¹³³, S. Miglioranza^{53a,53b}, L. Mijović⁴⁹, G. Mikenberg¹⁷⁵, M. Mikestikova¹²⁹, M. Mikuž⁷⁸, M. Milesi⁹¹, A. Milic¹⁶¹, D.A. Millar⁷⁹, D.W. Miller³³, A. Milov¹⁷⁵, D.A. Milstead^{148a,148b}, A.A. Minaenko¹³², I.A. Minashvili^{54b}, A.I. Mincer¹¹², B. Mindur^{41a}, M. Mineev⁶⁸, Y. Minegishi¹⁵⁷, Y. Ming¹⁷⁶, L.M. Mir¹³, A. Mirto^{76a,76b}, K.P. Mistry¹²⁴, T. Mitani¹⁷⁴, J. Mitrevski¹⁰², V.A. Mitsou¹⁷⁰, A. Miucci¹⁸, P.S. Miyagawa¹⁴¹, A. Mizukami⁶⁹, J.U. Mjörnmark⁸⁴, T. Mkrtchyan¹⁸⁰, M. Mlynarikova¹³¹, T. Moa^{148a,148b}, K. Mochizuki⁹⁷, P. Mogg⁵¹, S. Mohapatra³⁸, S. Molander^{148a,148b}, R. Moles-Valls²³, M.C. Mondragon⁹³, K. Mönig⁴⁵, J. Monk³⁹, E. Monnier⁸⁸, A. Montalbano¹⁵⁰, J. Montejo Berlingen³², F. Monticelli⁷⁴, S. Monzani^{94a}, R.W. Moore³, N. Morange¹¹⁹, D. Moreno²¹, M. Moreno Llácer³², P. Morettini^{53a}, M. Morgenstern¹⁰⁹, S. Morgenstern³², D. Mori¹⁴⁴, T. Mori¹⁵⁷, M. Morii⁵⁹, M. Morinaga¹⁷⁴, V. Morisbak¹²¹, A.K. Morley³², G. Mornacchi³², J.D. Morris⁷⁹, L. Morvaj¹⁵⁰, P. Moschovakos¹⁰, M. Mosidze^{54b}, H.J. Moss¹⁴¹, J. Moss^{145,aj}, K. Motohashi¹⁵⁹, R. Mount¹⁴⁵, E. Mountricha²⁷, E.J.W. Moyse⁸⁹, S. Muanza⁸⁸, F. Mueller¹⁰³, J. Mueller¹²⁷, R.S.P. Mueller¹⁰², D. Muenstermann⁷⁵, P. Mullen⁵⁶, G.A. Mullier¹⁸, F.J. Munoz Sanchez⁸⁷, W.J. Murray^{173,133}, M. Muškinja⁷⁸, C. Mwewa^{147a}, A.G. Myagkov^{132,ak}, J. Myers¹¹⁸, M. Myska¹³⁰, B.P. Nachman¹⁶, O. Nackenhorst⁴⁶, K. Nagai¹²², R. Nagai^{69,af},

K. Nagano⁶⁹, Y. Nagasaka⁶¹, K. Nagata¹⁶⁴, M. Nagel⁵¹, E. Nagy⁸⁸, A.M. Nairz³²,
Y. Nakahama¹⁰⁵, K. Nakamura⁶⁹, T. Nakamura¹⁵⁷, I. Nakano¹¹⁴, R.F. Naranjo Garcia⁴⁵,
R. Narayan¹¹, D.I. Narrias Villar^{60a}, I. Naryshkin¹²⁵, T. Naumann⁴⁵, G. Navarro²¹, R. Nayyar⁷,
H.A. Neal⁹², P.Yu. Nechaeva⁹⁸, T.J. Neep¹³⁸, A. Negri^{123a,123b}, M. Negrini^{22a}, S. Nektarijevic¹⁰⁸,
C. Nellist⁵⁸, A. Nelson¹⁶⁶, M.E. Nelson¹²², S. Nemecek¹²⁹, P. Nemethy¹¹², M. Nessi^{32,al},
M.S. Neubauer¹⁶⁹, M. Neumann¹⁷⁷, P.R. Newman¹⁹, T.Y. Ng^{62c}, Y.S. Ng¹⁷, T. Nguyen Manh⁹⁷,
R.B. Nickerson¹²², R. Nicolaidou¹³⁸, J. Nielsen¹³⁹, N. Nikiforou¹¹, V. Nikolaenko^{132,ak},
I. Nikolic-Audit⁸³, K. Nikolopoulos¹⁹, P. Nilsson²⁷, Y. Ninomiya⁶⁹, A. Nisati^{134a}, N. Nishu^{36b},
R. Nisius¹⁰³, I. Nitsche⁴⁶, T. Nitta¹⁷⁴, T. Nobe¹⁵⁷, Y. Noguchi⁷¹, M. Nomachi¹²⁰, I. Nomidis³¹,
M.A. Nomura²⁷, T. Nooney⁷⁹, M. Nordberg³², N. Norjoharuddeen¹²², O. Novgorodova⁴⁷,
R. Novotny¹³⁰, M. Nozaki⁶⁹, L. Nozka¹¹⁷, K. Ntekas¹⁶⁶, E. Nurse⁸¹, F. Nuti⁹¹, K. O'Connor²⁵,
D.C. O'Neil¹⁴⁴, A.A. O'Rourke⁴⁵, V. O'Shea⁵⁶, F.G. Oakham^{31,d}, H. Oberlack¹⁰³,
T. Obermann²³, J. Ocariz⁸³, A. Ochi⁷⁰, I. Ochoa³⁸, J.P. Ochoa-Ricoux^{34a}, S. Oda⁷³, S. Odaka⁶⁹,
A. Oh⁸⁷, S.H. Oh⁴⁸, C.C. Ohm¹⁴⁹, H. Ohman¹⁶⁸, H. Oide^{53a,53b}, H. Okawa¹⁶⁴, Y. Okumura¹⁵⁷,
T. Okuyama⁶⁹, A. Olariu^{28b}, L.F. Oleiro Seabra^{128a}, S.A. Olivares Pino^{34a},
D. Oliveira Damazio²⁷, J.L. Oliver¹, M.J.R. Olsson³³, A. Olszewski⁴², J. Olszowska⁴²,
A. Onofre^{128a,128e}, K. Onogi¹⁰⁵, P.U.E. Onyisi^{11,am}, H. Oppen¹²¹, M.J. Oreglia³³, Y. Oren¹⁵⁵,
D. Orestano^{136a,136b}, E.C. Orgill⁸⁷, N. Orlando^{62b}, R.S. Orr¹⁶¹, B. Osculati^{53a,53b,*},
R. Ospanov^{36c}, G. Otero y Garzon²⁹, H. Otono⁷³, M. Ouchrif^{137d}, F. Ould-Saada¹²¹,
A. Ouraou¹³⁸, K.P. Oussoren¹⁰⁹, Q. Ouyang^{35a}, M. Owen⁵⁶, R.E. Owen¹⁹, V.E. Ozcan^{20a},
N. Ozturk⁸, K. Pachal¹⁴⁴, A. Pacheco Pages¹³, L. Pacheco Rodriguez¹³⁸, C. Padilla Aranda¹³,
S. Pagan Griso¹⁶, M. Paganini¹⁷⁹, F. Paige²⁷, G. Palacino⁶⁴, S. Palazzo^{40a,40b}, S. Palestini³²,
M. Palka^{41b}, D. Pallin³⁷, E.St. Panagiotopoulou¹⁰, I. Panagoulas¹⁰, C.E. Pandini⁵²,
J.G. Panduro Vazquez⁸⁰, P. Pani³², S. Panitkin²⁷, D. Pantea^{28b}, L. Paolozzi⁵²,
Th.D. Papadopoulou¹⁰, K. Papageorgiou^{9,s}, A. Paramonov⁶, D. Paredes Hernandez^{62b},
A.J. Parker⁷⁵, M.A. Parker³⁰, K.A. Parker⁴⁵, F. Parodi^{53a,53b}, J.A. Parsons³⁸, U. Parzefall⁵¹,
V.R. Pascuzzi¹⁶¹, J.M.P. Pasner¹³⁹, E. Pasqualucci^{134a}, S. Passaggio^{53a}, Fr. Pastore⁸⁰,
S. Pataria⁸⁶, J.R. Pater⁸⁷, T. Pauly³², B. Pearson¹⁰³, S. Pedraza Lopez¹⁷⁰, R. Pedro^{128a,128b},
S.V. Peleganchuk^{111,c}, O. Penc¹²⁹, C. Peng^{35a,35d}, H. Peng^{36c}, J. Penwell⁶⁴, B.S. Peralva^{26b},
M.M. Perego¹³⁸, D.V. Perepelitsa²⁷, F. Peri¹⁷, L. Perini^{94a,94b}, H. Pernegger³², S. Perrella^{106a,106b},
V.D. Peshekhonov^{68,*}, K. Peters⁴⁵, R.F.Y. Peters⁸⁷, B.A. Petersen³², T.C. Petersen³⁹, E. Petit⁵⁷,
A. Petridis¹, C. Petridou¹⁵⁶, P. Petroff¹¹⁹, E. Petrolo^{134a}, M. Petrov¹²², F. Petrucci^{136a,136b},
N.E. Pettersson⁸⁹, A. Peyaud¹³⁸, R. Pezoa^{34b}, T. Pham⁹¹, F.H. Phillips⁹³, P.W. Phillips¹³³,
G. Piacquadio¹⁵⁰, E. Pianori¹⁷³, A. Picazio⁸⁹, M.A. Pickering¹²², R. Piegai²⁹, J.E. Pilcher³³,
A.D. Pilkington⁸⁷, M. Pinamonti^{135a,135b}, J.L. Pinfold³, M. Pitt¹⁷⁵, M.-A. Pleier²⁷, V. Pleskot⁸⁶,
E. Plotnikova⁶⁸, D. Pluth⁶⁷, P. Podberezko¹¹¹, R. Poettgen⁸⁴, R. Poggi^{123a,123b}, L. Poggioli¹¹⁹,
I. Pogrebnyak⁹³, D. Pohl²³, I. Pokharel⁵⁸, G. Polesello^{123a}, A. Poley⁴⁵, A. Policicchio^{40a,40b},
R. Polifka³², A. Polini^{22a}, C.S. Pollard⁴⁵, V. Polychronakos²⁷, K. Pommès³², D. Ponomarenko¹⁰⁰,
L. Pontecorvo^{134a}, G.A. Popeneciu^{28d}, D.M. Portillo Quintero⁸³, S. Pospisil¹³⁰, K. Potamianos⁴⁵,
I.N. Potrap⁶⁸, C.J. Potter³⁰, H. Potti¹¹, T. Poulsen⁸⁴, J. Poveda³², M.E. Pozo Astigarraga³²,
P. Pralavorio⁸⁸, S. Prell⁶⁷, D. Price⁸⁷, M. Primavera^{76a}, S. Prince⁹⁰, N. Proklova¹⁰⁰,
K. Prokofiev^{62c}, F. Prokoshin^{34b}, S. Protopopescu²⁷, J. Proudfoot⁶, M. Przybycien^{41a}, A. Puri¹⁶⁹,
P. Puzo¹¹⁹, J. Qian⁹², Y. Qin⁸⁷, A. Quadt⁵⁸, M. Queitsch-Maitland⁴⁵, V. Radeka²⁷,
S.K. Radhakrishnan¹⁵⁰, P. Rados⁹¹, F. Ragusa^{94a,94b}, G. Rahal¹⁸¹, J.A. Raine⁸⁷,
S. Rajagopalan²⁷, T. Rashid¹¹⁹, S. Raspopov⁵, M.G. Ratti^{94a,94b}, D.M. Rauch⁴⁵, F. Rauscher¹⁰²,
S. Rave⁸⁶, I. Ravinovich¹⁷⁵, J.H. Rawling⁸⁷, M. Raymond³², A.L. Read¹²¹, N.P. Readioff⁵⁷,
M. Reale^{76a,76b}, D.M. Rebuzzi^{123a,123b}, A. Redelbach¹⁷⁸, G. Redlinger²⁷, R. Reece¹³⁹,
R.G. Reed^{147c}, K. Reeves⁴⁴, L. Rehnisch¹⁷, J. Reichert¹²⁴, A. Reiss⁸⁶, C. Rembser³²,
H. Ren^{35a,35d}, M. Rescigno^{134a}, S. Resconi^{94a}, E.D. Resseguie¹²⁴, S. Rettie¹⁷¹, E. Reynolds¹⁹,
O.L. Rezanova^{111,c}, P. Reznicek¹³¹, R. Richter¹⁰³, S. Richter⁸¹, E. Richter-Was^{41b}, O. Ricken²³,
M. Ridel⁸³, P. Rieck¹⁰³, C.J. Riegel¹⁷⁷, O. Rifki¹¹⁵, M. Rijssenbeek¹⁵⁰, A. Rimoldi^{123a,123b},
M. Rimoldi¹⁸, L. Rinaldi^{22a}, G. Ripellino¹⁴⁹, B. Ristić³², E. Ritsch³², I. Riu¹³,

J.C. Rivera Vergara^{34a}, F. Rizatdinova¹¹⁶, E. Rizvi⁷⁹, C. Rizzi¹³, R.T. Roberts⁸⁷, S.H. Robertson^{90,m}, A. Robichaud-Veronneau⁹⁰, D. Robinson³⁰, J.E.M. Robinson⁴⁵, A. Robson⁵⁶, E. Rocco⁸⁶, C. Roda^{126a,126b}, Y. Rodina^{88,an}, S. Rodriguez Bosca¹⁷⁰, A. Rodriguez Perez¹³, D. Rodriguez Rodriguez¹⁷⁰, A.M. Rodríguez Vera^{163b}, S. Roe³², C.S. Rogan⁵⁹, O. Røhne¹²¹, R. Röhrig¹⁰³, J. Roloff⁵⁹, A. Romaniouk¹⁰⁰, M. Romano^{22a,22b}, S.M. Romano Saez³⁷, E. Romero Adam¹⁷⁰, N. Rompotis⁷⁷, M. Ronzani⁵¹, L. Roos⁸³, S. Rosati^{134a}, K. Rosbach⁵¹, P. Rose¹³⁹, N.-A. Rosien⁵⁸, E. Rossi^{106a,106b}, L.P. Rossi^{53a}, J.H.N. Rosten³⁰, R. Rosten¹⁴⁰, M. Rotaru^{28b}, J. Rothberg¹⁴⁰, D. Rousseau¹¹⁹, D. Roy^{147c}, A. Rozanov⁸⁸, Y. Rozen¹⁵⁴, X. Ruan^{147c}, F. Rubbo¹⁴⁵, F. Rühr⁵¹, A. Ruiz-Martinez³¹, Z. Rurikova⁵¹, N.A. Rusakovich⁶⁸, H.L. Russell⁹⁰, J.P. Rutherford⁷, N. Ruthmann³², E.M. Rüttinger⁴⁵, Y.F. Ryabov¹²⁵, M. Rybar¹⁶⁹, G. Rybkin¹¹⁹, S. Ryu⁶, A. Ryzhov¹³², G.F. Rzehorz⁵⁸, G. Sabato¹⁰⁹, S. Sacerdoti²⁹, H.F.W. Sadrozinski¹³⁹, R. Sadykov⁶⁸, F. Safai Tehrani^{134a}, P. Saha¹¹⁰, M. Sahinsoy^{60a}, M. Saimpert⁴⁵, M. Saito¹⁵⁷, T. Saito¹⁵⁷, H. Sakamoto¹⁵⁷, G. Salamanna^{136a,136b}, J.E. Salazar Loyola^{34b}, D. Salek¹⁰⁹, P.H. Sales De Bruin¹⁶⁸, D. Salihagic¹⁰³, A. Salnikov¹⁴⁵, J. Salt¹⁷⁰, D. Salvatore^{40a,40b}, F. Salvatore¹⁵¹, A. Salvucci^{62a,62b,62c}, A. Salzburger³², D. Sammel⁵¹, D. Sampsonidis¹⁵⁶, D. Sampsonidou¹⁵⁶, J. Sánchez¹⁷⁰, A. Sanchez Pineda^{167a,167c}, H. Sandaker¹²¹, R.L. Sandbach⁷⁹, C.O. Sander⁴⁵, M. Sandhoff¹⁷⁷, C. Sandoval²¹, D.P.C. Sankey¹³³, M. Sannino^{53a,53b}, Y. Sano¹⁰⁵, A. Sansoni⁵⁰, C. Santoni³⁷, H. Santos^{128a}, I. Santoyo Castillo¹⁵¹, A. Saponov⁶⁸, J.G. Saraiva^{128a,128d}, O. Sasaki⁶⁹, K. Sato¹⁶⁴, E. Sauvan⁵, G. Savage⁸⁰, P. Savard^{161,d}, N. Savic¹⁰³, R. Sawada¹⁵⁷, C. Sawyer¹³³, L. Sawyer^{82,u}, C. Sbarra^{22a}, A. Sbrizzi^{22a,22b}, T. Scanlon⁸¹, D.A. Scannicchio¹⁶⁶, J. Schaarschmidt¹⁴⁰, P. Schacht¹⁰³, B.M. Schachtner¹⁰², D. Schaefer³³, L. Schaefer¹²⁴, J. Schaeffer⁸⁶, S. Schaepe³², U. Schäfer⁸⁶, A.C. Schaffer¹¹⁹, D. Schaile¹⁰², R.D. Schamberger¹⁵⁰, V.A. Schegelsky¹²⁵, D. Scheirich¹³¹, F. Schenck¹⁷, M. Schernau¹⁶⁶, C. Schiavi^{53a,53b}, S. Schier¹³⁹, L.K. Schildgen²³, C. Schillo⁵¹, E.J. Schioppa³², M. Schioppa^{40a,40b}, K.E. Schleicher⁵¹, S. Schlenker³², K.R. Schmidt-Sommerfeld¹⁰³, K. Schmieden³², C. Schmitt⁸⁶, S. Schmitt⁴⁵, S. Schmitz⁸⁶, U. Schnoor⁵¹, L. Schoeffel¹³⁸, A. Schoening^{60b}, B.D. Schoenrock⁹³, E. Schopf²³, M. Schott⁸⁶, J.F.P. Schouwenberg¹⁰⁸, J. Schovancova³², S. Schramm⁵², N. Schuh⁸⁶, A. Schulte⁸⁶, H.-C. Schultz-Coulon^{60a}, M. Schumacher⁵¹, B.A. Schumm¹³⁹, Ph. Schune¹³⁸, A. Schwartzman¹⁴⁵, T.A. Schwarz⁹², H. Schweiger⁸⁷, Ph. Schwemling¹³⁸, R. Schwienhorst⁹³, A. Sciandra²³, G. Sciolla²⁵, M. Scornajenghi^{40a,40b}, F. Scuri^{126a}, F. Scutti⁹¹, L.M. Scyboz¹⁰³, J. Searcy⁹², P. Seema²³, S.C. Seidel¹⁰⁷, A. Seiden¹³⁹, J.M. Seixas^{26a}, G. Sekhniaidze^{106a}, K. Sekhon⁹², S.J. Sekula⁴³, N. Semprini-Cesari^{22a,22b}, S. Senkin³⁷, C. Serfon¹²¹, L. Serin¹¹⁹, L. Serkin^{167a,167b}, M. Sessa^{136a,136b}, H. Severini¹¹⁵, T. Šfiligoj⁷⁸, F. Sforza¹⁶⁵, A. Sfyrly⁵², E. Shabalina⁵⁸, N.W. Shaikh^{148a,148b}, L.Y. Shan^{35a}, R. Shang¹⁶⁹, J.T. Shank²⁴, M. Shapiro¹⁶, P.B. Shatalov⁹⁹, K. Shaw^{167a,167b}, S.M. Shaw⁸⁷, A. Shcherbakova^{148a,148b}, C.Y. Shehu¹⁵¹, Y. Shen¹¹⁵, N. Sherafati³¹, A.D. Sherman²⁴, P. Sherwood⁸¹, L. Shi^{153,ao}, S. Shimizu⁷⁰, C.O. Shimmin¹⁷⁹, M. Shimojima¹⁰⁴, I.P.J. Shipsey¹²², S. Shirabe⁷³, M. Shiyakova^{68,ap}, J. Shlomi¹⁷⁵, A. Shmeleva⁹⁸, D. Shoaleh Saadi⁹⁷, M.J. Shochet³³, S. Shojaii⁹¹, D.R. Shope¹¹⁵, S. Shrestha¹¹³, E. Shulga¹⁰⁰, M.A. Shupe⁷, P. Sicho¹²⁹, A.M. Sickles¹⁶⁹, P.E. Sidebo¹⁴⁹, E. Sideras Haddad^{147c}, O. Sidiropoulou¹⁷⁸, A. Sidoti^{22a,22b}, F. Siegert⁴⁷, Dj. Sijacki¹⁴, J. Silva^{128a,128d}, M. Silva Jr.¹⁷⁶, S.B. Silverstein^{148a}, V. Simak¹³⁰, L. Simic⁶⁸, S. Simion¹¹⁹, E. Simioni⁸⁶, B. Simmons⁸¹, M. Simon⁸⁶, P. Sinervo¹⁶¹, N.B. Sinev¹¹⁸, M. Sioli^{22a,22b}, G. Siragusa¹⁷⁸, I. Siral⁹², S.Yu. Sivoklokov¹⁰¹, J. Sjölin^{148a,148b}, M.B. Skinner⁷⁵, P. Skubic¹¹⁵, M. Slater¹⁹, T. Slavicek¹³⁰, M. Slawinska⁴², K. Sliwa¹⁶⁵, R. Slovak¹³¹, V. Smakhtin¹⁷⁵, B.H. Smart⁵, J. Smiesko^{146a}, N. Smirnov¹⁰⁰, S.Yu. Smirnov¹⁰⁰, Y. Smirnov¹⁰⁰, L.N. Smirnova^{101,aq}, O. Smirnova⁸⁴, J.W. Smith⁵⁸, M.N.K. Smith³⁸, R.W. Smith³⁸, M. Smizanska⁷⁵, K. Smolek¹³⁰, A.A. Snesarev⁹⁸, I.M. Snyder¹¹⁸, S. Snyder²⁷, R. Sobie^{172,m}, F. Socher⁴⁷, A.M. Soffa¹⁶⁶, A. Soffer¹⁵⁵, A. Søggaard⁴⁹, D.A. Soh¹⁵³, G. Sokhrannyi⁷⁸, C.A. Solans Sanchez³², M. Solar¹³⁰, E.Yu. Soldatov¹⁰⁰, U. Soldevila¹⁷⁰, A.A. Solodkov¹³², A. Soloshenko⁶⁸, O.V. Solovyanov¹³², V. Solovyev¹²⁵, P. Sommer¹⁴¹, H. Son¹⁶⁵, W. Song¹³³, A. Sopczak¹³⁰, D. Sosa^{60b}, C.L. Sotiropoulou^{126a,126b}, S. Sottocornola^{123a,123b}, R. Soualah^{167a,167c}, A.M. Soukharev^{111,c}, D. South⁴⁵, B.C. Sowden⁸⁰,

S. Spagnolo^{76a,76b}, M. Spalla^{126a,126b}, M. Spangenberg¹⁷³, F. Spanò⁸⁰, D. Sperlich¹⁷, F. Spettel¹⁰³, T.M. Spieker^{60a}, R. Spighi^{22a}, G. Spigo³², L.A. Spiller⁹¹, M. Spousta¹³¹, R.D. St. Denis^{56,*}, A. Stabile^{94a,94b}, R. Stamen^{60a}, S. Stamm¹⁷, E. Stanecka⁴², R.W. Stanek⁶, C. Stanescu^{136a}, M.M. Stanitzki⁴⁵, B.S. Stapf¹⁰⁹, S. Stapnes¹²¹, E.A. Starchenko¹³², G.H. Stark³³, J. Stark⁵⁷, S.H. Stark³⁹, P. Staroba¹²⁹, P. Starovoitov^{60a}, S. Stärz³², R. Staszewski⁴², M. Stegler⁴⁵, P. Steinberg²⁷, B. Stelzer¹⁴⁴, H.J. Stelzer³², O. Stelzer-Chilton^{163a}, H. Stenzel⁵⁵, T.J. Stevenson⁷⁹, G.A. Stewart³², M.C. Stockton¹¹⁸, G. Stoicea^{28b}, P. Stolte⁵⁸, S. Stonjek¹⁰³, A. Straessner⁴⁷, M.E. Stramaglia¹⁸, J. Strandberg¹⁴⁹, S. Strandberg^{148a,148b}, M. Strauss¹¹⁵, P. Strizenec^{146b}, R. Ströhmer¹⁷⁸, D.M. Strom¹¹⁸, R. Stroynowski⁴³, A. Strubig⁴⁹, S.A. Stucci²⁷, B. Stugu¹⁵, N.A. Styles⁴⁵, D. Su¹⁴⁵, J. Su¹²⁷, S. Suchek^{60a}, Y. Sugaya¹²⁰, M. Suk¹³⁰, V.V. Sulin⁹⁸, D.M.S. Sultan⁵², S. Sultansoy^{4c}, T. Sumida⁷¹, S. Sun⁹², X. Sun³, K. Suruliz¹⁵¹, C.J.E. Suster¹⁵², M.R. Sutton¹⁵¹, S. Suzuki⁶⁹, M. Svatos¹²⁹, M. Swiatkowski³³, S.P. Swift², A. Sydorenko⁸⁶, I. Sykora^{146a}, T. Sykora¹³¹, D. Ta⁵¹, K. Tackmann⁴⁵, J. Taenzer¹⁵⁵, A. Taffard¹⁶⁶, R. Tafirout^{163a}, E. Tahirovic⁷⁹, N. Taiblum¹⁵⁵, H. Takai²⁷, R. Takashima⁷², E.H. Takasugi¹⁰³, K. Takeda⁷⁰, T. Takeshita¹⁴², Y. Takubo⁶⁹, M. Talby⁸⁸, A.A. Talyshev^{111,c}, J. Tanaka¹⁵⁷, M. Tanaka¹⁵⁹, R. Tanaka¹¹⁹, R. Tanioka⁷⁰, B.B. Tannenwald¹¹³, S. Tapia Araya^{34b}, S. Tapprogge⁸⁶, S. Tarem¹⁵⁴, G.F. Tartarelli^{94a}, P. Tas¹³¹, M. Tasevsky¹²⁹, T. Tashiro⁷¹, E. Tassi^{40a,40b}, A. Tavares Delgado^{128a,128b}, Y. Tayalati^{137e}, A.C. Taylor¹⁰⁷, A.J. Taylor⁴⁹, G.N. Taylor⁹¹, P.T.E. Taylor⁹¹, W. Taylor^{163b}, P. Teixeira-Dias⁸⁰, D. Temple¹⁴⁴, H. Ten Kate³², P.K. Teng¹⁵³, J.J. Teoh¹²⁰, F. Tepel¹⁷⁷, S. Terada⁶⁹, K. Terashi¹⁵⁷, J. Terron⁸⁵, S. Terzo¹³, M. Testa⁵⁰, R.J. Teuscher^{161,m}, S.J. Thais¹⁷⁹, T. Theveneaux-Pelzer⁴⁵, F. Thiele³⁹, J.P. Thomas¹⁹, J. Thomas-Wilsker⁸⁰, P.D. Thompson¹⁹, A.S. Thompson⁵⁶, L.A. Thomsen¹⁷⁹, E. Thomson¹²⁴, Y. Tian³⁸, R.E. Ticse Torres⁵⁸, V.O. Tikhomirov^{98,ar}, Yu.A. Tikhonov^{111,c}, S. Timoshenko¹⁰⁰, P. Tipton¹⁷⁹, S. Tisserant⁸⁸, K. Todome¹⁵⁹, S. Todorova-Nova⁵, S. Todt⁴⁷, J. Tojo⁷³, S. Tokár^{146a}, K. Tokushuku⁶⁹, E. Tolley¹¹³, L. Tomlinson⁸⁷, M. Tomoto¹⁰⁵, L. Tompkins^{145,as}, K. Toms¹⁰⁷, B. Tong⁵⁹, P. Tornambe⁵¹, E. Torrence¹¹⁸, H. Torres⁴⁷, E. Torró Pastor¹⁴⁰, J. Toth^{88,at}, F. Touchard⁸⁸, D.R. Tovey¹⁴¹, C.J. Treado¹¹², T. Trefzger¹⁷⁸, F. Tresoldi¹⁵¹, A. Tricoli²⁷, I.M. Trigger^{163a}, S. Trincas-Duvold⁸³, M.F. Tripiana¹³, W. Trischuk¹⁶¹, B. Trocme⁵⁷, A. Trofymov⁴⁵, C. Troncon^{94a}, M. Trovatelli¹⁷², L. Truong^{147b}, M. Trzebinski⁴², A. Trzupek⁴², K.W. Tsang^{62a}, J.C.-L. Tseng¹²², P.V. Tsireshka⁹⁵, N. Tsirintanis⁹, S. Tsiskaridze¹³, V. Tsiskaridze⁵¹, E.G. Tskhadadze^{54a}, I.I. Tsukerman⁹⁹, V. Tsulaia¹⁶, S. Tsuno⁶⁹, D. Tsybychev¹⁵⁰, Y. Tu^{62b}, A. Tudorache^{28b}, V. Tudorache^{28b}, T.T. Tulbure^{28a}, A.N. Tuna⁵⁹, S. Turchikhin⁶⁸, D. Turgeman¹⁷⁵, I. Turk Cakir^{4b,au}, R. Turra^{94a}, P.M. Tuts³⁸, G. Uccielli^{22a,22b}, I. Ueda⁶⁹, M. Ughetto^{148a,148b}, F. Ukegawa¹⁶⁴, G. Unal³², A. Undrus²⁷, G. Unel¹⁶⁶, F.C. Ungaro⁹¹, Y. Unno⁶⁹, K. Uno¹⁵⁷, J. Urban^{146b}, P. Urquijo⁹¹, P. Urrejola⁸⁶, G. Usai⁸, J. Usui⁶⁹, L. Vacavant⁸⁸, V. Vacek¹³⁰, B. Vachon⁹⁰, K.O.H. Vadla¹²¹, A. Vaidya⁸¹, C. Valderanis¹⁰², E. Valdes Santurio^{148a,148b}, M. Valente⁵², S. Valentinetti^{22a,22b}, A. Valero¹⁷⁰, L. Valéry¹³, A. Vallier⁵, J.A. Valls Ferrer¹⁷⁰, W. Van Den Wollenberg¹⁰⁹, H. van der Graaf¹⁰⁹, P. van Gemmeren⁶, J. Van Nieuwkoop¹⁴⁴, I. van Vulpen¹⁰⁹, M.C. van Woerden¹⁰⁹, M. Vanadia^{135a,135b}, W. Vandelli³², A. Vaniachine¹⁶⁰, P. Vankov¹⁰⁹, R. Vari^{134a}, E.W. Varnes⁷, C. Varni^{53a,53b}, T. Varol⁴³, D. Varouchas¹¹⁹, A. Vartapetian⁸, K.E. Varvell¹⁵², J.G. Vasquez¹⁷⁹, G.A. Vasquez^{34b}, F. Vazeille³⁷, D. Vazquez Furelos¹³, T. Vazquez Schroeder⁹⁰, J. Veatch⁵⁸, V. Veeraraghavan⁷, L.M. Veloce¹⁶¹, F. Veloso^{128a,128c}, S. Veneziano^{134a}, A. Ventura^{76a,76b}, M. Venturi¹⁷², N. Venturi³², V. Vercesi^{123a}, M. Verducci^{136a,136b}, W. Verkerke¹⁰⁹, A.T. Vermeulen¹⁰⁹, J.C. Vermeulen¹⁰⁹, M.C. Vetterli^{144,d}, N. Viaux Maira^{34b}, O. Viazlo⁸⁴, I. Vichou^{169,*}, T. Vickey¹⁴¹, O.E. Vickey Boeriu¹⁴¹, G.H.A. Viehhauser¹²², S. Viel¹⁶, L. Vigani¹²², M. Villa^{22a,22b}, M. Villaplana Perez^{94a,94b}, E. Vilucchi⁵⁰, M.G. Vinciter³¹, V.B. Vinogradov⁶⁸, A. Vishwakarma⁴⁵, C. Vittori^{22a,22b}, I. Vivarelli¹⁵¹, S. Vlachos¹⁰, M. Vogel¹⁷⁷, P. Vokac¹³⁰, G. Volpi¹³, S.E. von Buddenbrock^{147c}, E. von Toerne²³, V. Vorobel¹³¹, K. Vorobev¹⁰⁰, M. Vos¹⁷⁰, R. Voss³², J.H. Vosseveld⁷⁷, N. Vranjes¹⁴, M. Vranjes Milosavljevic¹⁴, V. Vrba¹³⁰, M. Vreeswijk¹⁰⁹, R. Vuillermet³², I. Vukotic³³, P. Wagner²³, W. Wagner¹⁷⁷, J. Wagner-Kuhr¹⁰², H. Wahlberg⁷⁴, S. Wahrmund⁴⁷, K. Wakamiya⁷⁰, J. Walder⁷⁵, R. Walker¹⁰², W. Walkowiak¹⁴³,

V. Wallangen^{148a,148b}, A.M. Wang⁵⁹, C. Wang^{36a,p}, F. Wang¹⁷⁶, H. Wang¹⁶, H. Wang³, J. Wang^{60b}, J. Wang¹⁵², Q. Wang¹¹⁵, R.-J. Wang⁸³, R. Wang⁶, S.M. Wang¹⁵³, T. Wang³⁸, W. Wang^{153,av}, W. Wang^{36c,aw}, Z. Wang^{36b}, C. Wanotayaroj⁴⁵, A. Warburton⁹⁰, C.P. Ward³⁰, D.R. Wardrope⁸¹, A. Washbrook⁴⁹, P.M. Watkins¹⁹, A.T. Watson¹⁹, M.F. Watson¹⁹, G. Watts¹⁴⁰, S. Watts⁸⁷, B.M. Waugh⁸¹, A.F. Webb¹¹, S. Webb⁸⁶, M.S. Weber¹⁸, S.M. Weber^{60a}, S.A. Weber³¹, J.S. Webster⁶, A.R. Weidberg¹²², B. Weinert⁶⁴, J. Weingarten⁵⁸, M. Weirich⁸⁶, C. Weiser⁵¹, P.S. Wells³², T. Wenaus²⁷, T. Wengler³², S. Wenig³², N. Vermes²³, M.D. Werner⁶⁷, P. Werner³², M. Wessels^{60a}, T.D. Weston¹⁸, K. Whalen¹¹⁸, N.L. Whallon¹⁴⁰, A.M. Wharton⁷⁵, A.S. White⁹², A. White⁸, M.J. White¹, R. White^{34b}, D. Whiteson¹⁶⁶, B.W. Whitmore⁷⁵, F.J. Wickens¹³³, W. Wiedenmann¹⁷⁶, M. Wielers¹³³, C. Wigglesworth³⁹, L.A.M. Wiik-Fuchs⁵¹, A. Wildauer¹⁰³, F. Wilk⁸⁷, H.G. Wilkens³², H.H. Williams¹²⁴, S. Williams³⁰, C. Willis⁹³, S. Willocq⁸⁹, J.A. Wilson¹⁹, I. Wingerter-Seez⁵, E. Winkels¹⁵¹, F. Winklmeier¹¹⁸, O.J. Winston¹⁵¹, B.T. Winter²³, M. Wittgen¹⁴⁵, M. Wobisch^{82,u}, A. Wolf⁸⁶, T.M.H. Wolf¹⁰⁹, R. Wolff⁸⁸, M.W. Wolter⁴², H. Wolters^{128a,128c}, V.W.S. Wong¹⁷¹, N.L. Woods¹³⁹, S.D. Worm¹⁹, B.K. Wosiek⁴², J. Wotschack³², K.W. Woźniak⁴², M. Wu³³, S.L. Wu¹⁷⁶, X. Wu⁵², Y. Wu^{36c}, T.R. Wyatt⁸⁷, B.M. Wynne⁴⁹, S. Xella³⁹, Z. Xi⁹², L. Xia^{35c}, D. Xu^{35a}, L. Xu²⁷, T. Xu¹³⁸, W. Xu⁹², B. Yabsley¹⁵², S. Yacoob^{147a}, K. Yajima¹²⁰, D.P. Yallup⁸¹, D. Yamaguchi¹⁵⁹, Y. Yamaguchi¹⁵⁹, A. Yamamoto⁶⁹, T. Yamanaka¹⁵⁷, F. Yamane⁷⁰, M. Yamatani¹⁵⁷, T. Yamazaki¹⁵⁷, Y. Yamazaki⁷⁰, Z. Yan²⁴, H. Yang^{36b}, H. Yang¹⁶, S. Yang⁶⁶, Y. Yang¹⁵³, Z. Yang¹⁵, W.-M. Yao¹⁶, Y.C. Yap⁴⁵, Y. Yasu⁶⁹, E. Yatsenko⁵, K.H. Yau Wong²³, J. Ye⁴³, S. Ye²⁷, I. Yeletsikh⁶⁸, E. Yigitbasi²⁴, E. Yildirim⁸⁶, K. Yorita¹⁷⁴, K. Yoshihara¹²⁴, C. Young¹⁴⁵, C.J.S. Young³², J. Yu⁸, J. Yu⁶⁷, S.P.Y. Yuen²³, I. Yusuf^{30,ax}, B. Zabinski⁴², G. Zacharis¹⁰, R. Zaidan¹³, A.M. Zaitsev^{132,ak}, N. Zakharchuk⁴⁵, J. Zalieckas¹⁵, A. Zaman¹⁵⁰, S. Zambito⁵⁹, D. Zanzi³², C. Zeitnitz¹⁷⁷, G. Zemaityte¹²², J.C. Zeng¹⁶⁹, Q. Zeng¹⁴⁵, O. Zenin¹³², T. Ženis^{146a}, D. Zerwas¹¹⁹, D. Zhang^{36a}, D. Zhang⁹², F. Zhang¹⁷⁶, G. Zhang^{36c,aw}, H. Zhang¹¹⁹, J. Zhang⁶, L. Zhang⁵¹, L. Zhang^{36c}, M. Zhang¹⁶⁹, P. Zhang^{35b}, R. Zhang²³, R. Zhang^{36c,p}, X. Zhang^{36a}, Y. Zhang^{35a,35d}, Z. Zhang¹¹⁹, X. Zhao⁴³, Y. Zhao^{36a,x}, Z. Zhao^{36c}, A. Zhemchugov⁶⁸, B. Zhou⁹², C. Zhou¹⁷⁶, L. Zhou⁴³, M. Zhou^{35a,35d}, M. Zhou¹⁵⁰, N. Zhou^{36b}, Y. Zhou⁷, C.G. Zhu^{36a}, H. Zhu^{35a}, J. Zhu⁹², Y. Zhu^{36c}, X. Zhuang^{35a}, K. Zhukov⁹⁸, A. Zibell¹⁷⁸, D. Ziemska⁶⁴, N.I. Zimine⁶⁸, S. Zimmermann⁵¹, Z. Zinonos¹⁰³, M. Zinser⁸⁶, M. Ziolkowski¹⁴³, L. Živković¹⁴, G. Zobernig¹⁷⁶, A. Zoccoli^{22a,22b}, R. Zou³³, M. zur Nedden¹⁷, L. Zwalinski³²

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

² Physics Department, SUNY Albany, Albany NY, United States of America

³ Department of Physics, University of Alberta, Edmonton AB, Canada

⁴ Department of Physics^(a), Ankara University, Ankara; Istanbul Aydin University^(b), Istanbul; Division of Physics^(c), TOBB University of Economics and Technology, Ankara, Turkey

⁵ LAPP, Univ. Grenoble Alpes, Univ. Savoie Mont Blanc, CNRS/IN2P3, Annecy, France

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

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

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

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

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

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

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

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

¹⁴ Institute of Physics, University of Belgrade, Belgrade, Serbia

¹⁵ Department for Physics and Technology, University of Bergen, Bergen, Norway

¹⁶ Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America

- ¹⁷ Department of Physics, Humboldt University, Berlin, Germany
- ¹⁸ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
- ¹⁹ School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
- ²⁰ Department of Physics^(a), Bogazici University, Istanbul; Department of Physics Engineering^(b), Gaziantep University, Gaziantep; Istanbul Bilgi University^(d), Faculty of Engineering and Natural Sciences, Istanbul; Bahcesehir University^(e), Faculty of Engineering and Natural Sciences, Istanbul, Turkey
- ²¹ Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
- ²² INFN Sezione di Bologna; ^(b) Dipartimento di Fisica e Astronomia^(a), Università di Bologna, Bologna, Italy
- ²³ Physikalisches Institut, University of Bonn, Bonn, Germany
- ²⁴ Department of Physics, Boston University, Boston MA, United States of America
- ²⁵ Department of Physics, Brandeis University, Waltham MA, United States of America
- ²⁶ Universidade Federal do Rio De Janeiro COPPE/EE/IF^(a), Rio de Janeiro; Electrical Circuits Department^(b), Federal University of Juiz de Fora (UFJF), Juiz de Fora; Federal University of Sao Joao del Rei (UFSJ)^(c), Sao Joao del Rei; Instituto de Fisica^(d), Universidade de Sao Paulo, Sao Paulo, Brazil
- ²⁷ Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
- ²⁸ Transilvania University of Brasov^(a), Brasov; Horia Hulubei National Institute of Physics and Nuclear Engineering; ^(c) Department of Physics^(b), Alexandru Ioan Cuza University of Iasi, Iasi; National Institute for Research and Development of Isotopic and Molecular Technologies^(d), Physics Department, Cluj Napoca; University Politehnica Bucharest^(e), Bucharest; West University in Timisoara^(f), Timisoara, Romania
- ²⁹ Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
- ³⁰ Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- ³¹ Department of Physics, Carleton University, Ottawa ON, Canada
- ³² CERN, Geneva, Switzerland
- ³³ Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
- ³⁴ Departamento de Física^(a), Pontificia Universidad Católica de Chile, Santiago; Departamento de Física^(b), Universidad Técnica Federico Santa María, Valparaíso, Chile
- ³⁵ Institute of High Energy Physics^(a), Chinese Academy of Sciences, Beijing; Department of Physics^(b), Nanjing University, Jiangsu; Physics Department^(c), Tsinghua University, Beijing; University of Chinese Academy of Science (UCAS)^(d), Beijing, China
- ³⁶ School of Physics^(a), Shandong University, Shandong; School of Physics and Astronomy^(b), Key Laboratory for Particle Physics, Astrophysics and Cosmology, Ministry of Education; Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University; Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics^(c), University of Science and Technology of China, Anhui, China
- ³⁷ Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
- ³⁸ Nevis Laboratory, Columbia University, Irvington NY, United States of America
- ³⁹ Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
- ⁴⁰ INFN Gruppo Collegato di Cosenza^(a), Laboratori Nazionali di Frascati; Dipartimento di Fisica^(b), Università della Calabria, Rende, Italy
- ⁴¹ AGH University of Science and Technology^(a), Faculty of Physics and Applied Computer Science, Krakow; Marian Smoluchowski Institute of Physics^(b), Jagiellonian University, Krakow, Poland
- ⁴² Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
- ⁴³ Physics Department, Southern Methodist University, Dallas TX, United States of America
- ⁴⁴ Physics Department, University of Texas at Dallas, Richardson TX, United States of America
- ⁴⁵ DESY, Hamburg and Zeuthen, Germany
- ⁴⁶ Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- ⁴⁷ Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany

- ⁴⁸ Department of Physics, Duke University, Durham NC, United States of America
⁴⁹ SUPA — School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
⁵⁰ INFN e Laboratori Nazionali di Frascati, Frascati, Italy
⁵¹ Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
⁵² Departement de Physique Nucleaire et Corpusculaire, Université de Genève, Geneva, Switzerland
⁵³ INFN Sezione di Genova; ^(b) Dipartimento di Fisica^(a), Università di Genova, Genova, Italy
⁵⁴ E. Andronikashvili Institute of Physics^(a), Iv. Javakhishvili Tbilisi State University, Tbilisi; High Energy Physics Institute^(b), Tbilisi State University, Tbilisi, Georgia
⁵⁵ II. Physikalisches Institut, Justus-Liebig-Universität Germany
⁵⁶ SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
⁵⁷ LPSC, Université Grenoble Alpes, CNRS-IN2P3, Grenoble INP, Grenoble, France
⁵⁸ II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
⁵⁹ Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America
⁶⁰ Kirchhoff-Institut für Physik^(a), Ruprecht-Karls-Universität Heidelberg, Heidelberg; Physikalisches Institut^(b), Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
⁶¹ Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
⁶² Department of Physics^(a), The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; Department of Physics^(b), The University of Hong Kong, Hong Kong; Department of Physics and Institute for Advanced Study^(c), The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
⁶³ Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
⁶⁴ Department of Physics, Indiana University, Bloomington IN, United States of America
⁶⁵ Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
⁶⁶ University of Iowa, Iowa City IA, United States of America
⁶⁷ Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America
⁶⁸ Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
⁶⁹ KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
⁷⁰ Graduate School of Science, Kobe University, Kobe, Japan
⁷¹ Faculty of Science, Kyoto University, Kyoto, Japan
⁷² Kyoto University of Education, Kyoto, Japan
⁷³ Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan
⁷⁴ Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
⁷⁵ Physics Department, Lancaster University, Lancaster, United Kingdom
⁷⁶ INFN Sezione di Lecce; ^(b) Dipartimento di Matematica e Fisica^(a), Università del Salento, Lecce, Italy
⁷⁷ Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
⁷⁸ Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
⁷⁹ School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
⁸⁰ Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
⁸¹ Department of Physics and Astronomy, University College London, London, United Kingdom
⁸² Louisiana Tech University, Ruston LA, United States of America
⁸³ Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
⁸⁴ Fysiska institutionen, Lunds universitet, Lund, Sweden
⁸⁵ Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain
⁸⁶ Institut für Physik, Universität Mainz, Mainz, Germany
⁸⁷ School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
⁸⁸ CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France

- ⁸⁹ Department of Physics, University of Massachusetts, Amherst MA, United States of America
- ⁹⁰ Department of Physics, McGill University, Montreal QC, Canada
- ⁹¹ School of Physics, University of Melbourne, Victoria, Australia
- ⁹² Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
- ⁹³ Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America
- ⁹⁴ INFN Sezione di Milano; ^(b) Dipartimento di Fisica^(a), Università di Milano, Milano, Italy
- ⁹⁵ B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
- ⁹⁶ Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Republic of Belarus
- ⁹⁷ Group of Particle Physics, University of Montreal, Montreal QC, Canada
- ⁹⁸ P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
- ⁹⁹ Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- ¹⁰⁰ National Research Nuclear University MEPhI, Moscow, Russia
- ¹⁰¹ D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- ¹⁰² Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- ¹⁰³ Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- ¹⁰⁴ Nagasaki Institute of Applied Science, Nagasaki, Japan
- ¹⁰⁵ Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- ¹⁰⁶ INFN Sezione di Napoli; ^(b) Dipartimento di Fisica^(a), Università di Napoli, Napoli, Italy
- ¹⁰⁷ Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
- ¹⁰⁸ Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- ¹⁰⁹ Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- ¹¹⁰ Department of Physics, Northern Illinois University, DeKalb IL, United States of America
- ¹¹¹ Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- ¹¹² Department of Physics, New York University, New York NY, United States of America
- ¹¹³ Ohio State University, Columbus OH, United States of America
- ¹¹⁴ Faculty of Science, Okayama University, Okayama, Japan
- ¹¹⁵ Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America
- ¹¹⁶ Department of Physics, Oklahoma State University, Stillwater OK, United States of America
- ¹¹⁷ Palacký University, RCPTM, Olomouc, Czech Republic
- ¹¹⁸ Center for High Energy Physics, University of Oregon, Eugene OR, United States of America
- ¹¹⁹ LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
- ¹²⁰ Graduate School of Science, Osaka University, Osaka, Japan
- ¹²¹ Department of Physics, University of Oslo, Oslo, Norway
- ¹²² Department of Physics, Oxford University, Oxford, United Kingdom
- ¹²³ INFN Sezione di Pavia; ^(b) Dipartimento di Fisica^(a), Università di Pavia, Pavia, Italy
- ¹²⁴ Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America
- ¹²⁵ National Research Centre "Kurchatov Institute" B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
- ¹²⁶ INFN Sezione di Pisa; ^(b) Dipartimento di Fisica E. Fermi^(a), Università di Pisa, Pisa, Italy
- ¹²⁷ Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America
- ¹²⁸ Laboratório de Instrumentação e Física Experimental de Partículas — LIP^(a), Lisboa; Faculdade de Ciências^(b), Universidade de Lisboa, Lisboa; Department of Physics^(c), University of Coimbra, Coimbra; Centro de Física Nuclear da Universidade de Lisboa^(d), Lisboa; Departamento de

- Fisica^(e), Universidade do Minho, Braga, Portugal; Departamento de Fisica Teorica y del Cosmos^(f), Universidad de Granada, Granada, Spain; Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia^(g), Universidade Nova de Lisboa, Caparica, Portugal
- ¹²⁹ Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- ¹³⁰ Czech Technical University in Prague, Praha, Czech Republic
- ¹³¹ Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
- ¹³² State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia
- ¹³³ Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- ¹³⁴ INFN Sezione di Roma; ^(b) Dipartimento di Fisica^(a), Sapienza Università di Roma, Roma, Italy
- ¹³⁵ INFN Sezione di Roma Tor Vergata; ^(b) Dipartimento di Fisica^(a), Università di Roma Tor Vergata, Roma, Italy
- ¹³⁶ INFN Sezione di Roma Tre; ^(b) Dipartimento di Matematica e Fisica^(a), Università Roma Tre, Roma, Italy
- ¹³⁷ Faculté des Sciences Ain Chock^(a), Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; Centre National de l'Energie des Sciences Techniques Nucleaires^(b), Rabat; Faculté des Sciences Semlalia^(c), Université Cadi Ayyad, LPHEA-Marrakech; Faculté des Sciences^(d), Université Mohamed Premier and LTPM, Oujda; Faculté des sciences^(e), Université Mohammed V, Rabat, Morocco
- ¹³⁸ Institut de Recherches sur les Lois Fondamentales de l'Univers, DSM/IRFU, CEA Saclay, Gif-sur-Yvette, France
- ¹³⁹ Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America
- ¹⁴⁰ Department of Physics, University of Washington, Seattle WA, United States of America
- ¹⁴¹ Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- ¹⁴² Department of Physics, Shinshu University, Nagano, Japan
- ¹⁴³ Department Physik, Universität Siegen, Siegen, Germany
- ¹⁴⁴ Department of Physics, Simon Fraser University, Burnaby BC, Canada
- ¹⁴⁵ SLAC National Accelerator Laboratory, Stanford CA, United States of America
- ¹⁴⁶ Faculty of Mathematics^(a), Physics and Informatics, Comenius University, Bratislava; Department of Subnuclear Physics^(b), Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- ¹⁴⁷ Department of Physics^(a), University of Cape Town, Cape Town; Department of Mechanical Engineering Science^(b), University of Johannesburg, Johannesburg; School of Physics^(c), University of the Witwatersrand, Johannesburg, South Africa
- ¹⁴⁸ Department of Physics^(a), Stockholm University; The Oskar Klein Centre^(b), Stockholm, Sweden
- ¹⁴⁹ Physics Department, Royal Institute of Technology, Stockholm, Sweden
- ¹⁵⁰ Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY, United States of America
- ¹⁵¹ Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- ¹⁵² School of Physics, University of Sydney, Sydney, Australia
- ¹⁵³ Institute of Physics, Academia Sinica, Taipei, Taiwan
- 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, The University of Tokyo, Tokyo, Japan
- ¹⁵⁸ Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- ¹⁵⁹ Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- ¹⁶⁰ Tomsk State University, Tomsk, Russia
- ¹⁶¹ Department of Physics, University of Toronto, Toronto ON, Canada
- ¹⁶² INFN-TIFPA; ^(b) University of Trento^(a), Trento, Italy

- ¹⁶³ TRIUMF^(a), Vancouver BC; Department of Physics and Astronomy^(b), York University, Toronto ON, Canada
- ¹⁶⁴ Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
- ¹⁶⁵ Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
- ¹⁶⁶ Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
- ¹⁶⁷ INFN Gruppo Collegato di Udine^(a), Sezione di Trieste, Udine; ICTP^(b), Trieste; Dipartimento di Chimica^(c), Fisica e Ambiente, Università di Udine, Udine, Italy
- ¹⁶⁸ Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
- ¹⁶⁹ Department of Physics, University of Illinois, Urbana IL, United States of America
- ¹⁷⁰ Instituto de Fisica Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Spain
- ¹⁷¹ Department of Physics, University of British Columbia, Vancouver BC, Canada
- ¹⁷² Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
- ¹⁷³ Department of Physics, University of Warwick, Coventry, United Kingdom
- ¹⁷⁴ Waseda University, Tokyo, Japan
- ¹⁷⁵ Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
- ¹⁷⁶ Department of Physics, University of Wisconsin, Madison WI, United States of America
- ¹⁷⁷ Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
- ¹⁷⁸ Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
- ¹⁷⁹ Department of Physics, Yale University, New Haven CT, United States of America
- ¹⁸⁰ Yerevan Physics Institute, Yerevan, Armenia
- ¹⁸¹ Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
- ¹⁸² Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
- ^a Also at Department of Physics, King's College London, London, United Kingdom
- ^b Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- ^c Also at Novosibirsk State University, Novosibirsk, Russia
- ^d Also at TRIUMF, Vancouver BC, Canada
- ^e Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY, United States of America
- ^f Also at Department of Physics, California State University, Fresno CA, United States of America
- ^g Also at Department of Physics, University of Fribourg, Fribourg, Switzerland
- ^h Also at II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- ⁱ Also at Departament de Fisica de la Universitat Autònoma de Barcelona, Barcelona, Spain
- ^j Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
- ^k Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China
- ^l Also at Università di Napoli Parthenope, Napoli, Italy
- ^m Also at Institute of Particle Physics (IPP), Canada
- ⁿ Also at Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- ^o Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Romania
- ^p Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- ^q Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia
- ^r Also at Borough of Manhattan Community College, City University of New York, New York City, United States of America
- ^s Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece
- ^t Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa

- ^u Also at Louisiana Tech University, Ruston LA, United States of America
- ^v Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
- ^w Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
- ^x Also at LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
- ^y Also at Graduate School of Science, Osaka University, Osaka, Japan
- ^z Also at Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
- ^{aa} Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- ^{ab} Also at Near East University, Nicosia, North Cyprus, Mersin 10, Turkey
- ^{ac} Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia
- ^{ad} Also at CERN, Geneva, Switzerland
- ^{ae} Also at Georgian Technical University (GTU), Tbilisi, Georgia
- ^{af} Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan
- ^{ag} Also at Manhattan College, New York NY, United States of America
- ^{ah} Also at The City College of New York, New York NY, United States of America
- ^{ai} Also at Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Spain
- ^{aj} Also at Department of Physics, California State University, Sacramento CA, United States of America
- ^{ak} Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
- ^{al} Also at Departement de Physique Nucleaire et Corpusculaire, Université de Genève, Geneva, Switzerland
- ^{am} Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America
- ^{an} Also at Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain
- ^{ao} Also at School of Physics, Sun Yat-sen University, Guangzhou, China
- ^{ap} Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria
- ^{aq} Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
- ^{ar} Also at National Research Nuclear University MEPhI, Moscow, Russia
- ^{as} Also at Department of Physics, Stanford University, Stanford CA, United States of America
- ^{at} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
- ^{au} Also at Giresun University, Faculty of Engineering, Turkey
- ^{av} Also at Department of Physics, Nanjing University, Jiangsu, China
- ^{aw} Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
- ^{ax} Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia
- * Deceased