

Search for supersymmetry at $\sqrt{s} = 13$ TeV in final states with jets and two same-sign leptons or three leptons with the ATLAS detector

ATLAS Collaboration*

CERN, 1211 Geneva 23, Switzerland

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Abstract A search for strongly produced supersymmetric particles is conducted using signatures involving multiple energetic jets and either two isolated leptons (e or μ) with the same electric charge or at least three isolated leptons. The search also utilises b -tagged jets, missing transverse momentum and other observables to extend its sensitivity. The analysis uses a data sample of proton–proton collisions at $\sqrt{s} = 13$ TeV recorded with the ATLAS detector at the Large Hadron Collider in 2015 corresponding to a total integrated luminosity of 3.2 fb^{-1} . No significant excess over the Standard Model expectation is observed. The results are interpreted in several simplified supersymmetric models and extend the exclusion limits from previous searches. In the context of exclusive production and simplified decay modes, gluino masses are excluded at 95 % confidence level up to 1.1–1.3 TeV for light neutralinos (depending on the decay channel), and bottom squark masses are also excluded up to 540 GeV. In the former scenarios, neutralino masses are also excluded up to 550–850 GeV for gluino masses around 1 TeV.

1 Introduction

Supersymmetry (SUSY) [1–6] is one of the most studied frameworks to extend the Standard Model (SM) beyond the electroweak scale; a general review can be found in Ref. [7]. In its minimal realisation (MSSM) [8,9] it predicts a new bosonic (fermionic) partner for each fundamental SM fermion (boson), as well as an additional Higgs doublet. If R -parity is conserved [10] the lightest supersymmetric particle (LSP) is stable and is typically the lightest neutralino¹ $\tilde{\chi}_1^0$. Only such scenarios are considered in this paper. In many models, the LSP can be a viable dark matter candidate [11,12] and produce collider signatures with large missing transverse momentum.

In order to address the SM hierarchy problem with SUSY models [13–16], TeV-scale masses are required [17,18] for the partners of the gluons (gluinos \tilde{g}) and of the top quark chiral degrees of freedom (top squarks \tilde{t}_L and \tilde{t}_R), due to the large top Yukawa coupling. The latter also favours significant \tilde{t}_L – \tilde{t}_R mixing, so that the lighter mass eigenstate \tilde{t}_1 is in many scenarios lighter than the other squarks [19,20]. Bottom squarks may also be light, being bound to top squarks by $SU(2)_L$ invariance. This leads to potentially large production cross-sections for gluino pairs ($\tilde{g}\tilde{g}$), top–antitop squark pairs ($\tilde{t}_1\tilde{t}_1^*$) and bottom–antibottom squark pairs ($\tilde{b}_1\tilde{b}_1^*$) at the Large Hadron Collider (LHC) [21]. Production of isolated leptons may arise in the cascade decays of those superpartners to SM quarks and neutralinos $\tilde{\chi}_1^0$, via intermediate neutralinos $\tilde{\chi}_{2,3,4}^0$ or charginos $\tilde{\chi}_{1,2}^\pm$ that in turn lead to W , Z or Higgs bosons, or to lepton superpartners (sleptons). Lighter third-generation squarks would also enhance $\tilde{g} \rightarrow t\tilde{t}_1^*$ or $\tilde{g} \rightarrow b\tilde{b}_1^*$ branching ratios over the generic decays involving light-flavour squarks, favouring the production of heavy flavour quarks and, in the case of top quarks, additional leptons.

This paper presents a search for SUSY in final states with two leptons (electrons or muons) of the same electric charge (referred to as same-sign (SS) leptons) [22] or three leptons (3L) in any charge combination, jets and missing transverse momentum (\vec{p}_T^{miss} , whose magnitude is referred to as E_T^{miss}). It is an extension to $\sqrt{s} = 13$ TeV of an earlier search performed by ATLAS with $\sqrt{s} = 8$ TeV data [23], and uses the data collected by the ATLAS experiment [24] in proton–proton (pp) collisions during 2015. Despite the much lower integrated luminosity collected at $\sqrt{s} = 13$ TeV compared to that collected at $\sqrt{s} = 8$ TeV, a similar or improved sensitivity at $\sqrt{s} = 13$ TeV is expected due to the much larger cross-sections predicted for the production of SUSY particles with

¹ The SUSY partners of the Higgs and electroweak gauge bosons mix to form the mass eigenstates known as charginos ($\tilde{\chi}_l^\pm$, $l = 1, 2$ ordered by increasing mass) and neutralinos ($\tilde{\chi}_m^0$, $m = 1, \dots, 4$ ordered by increasing mass).

* e-mail: atlas.publications@cern.ch

masses at the TeV scale. A similar search for SUSY in this topology was also performed by the CMS Collaboration [25] at $\sqrt{s} = 8$ TeV. While the same-sign leptons signature is present in many scenarios of physics beyond the SM (BSM), SM processes leading to such final states have very small cross-sections. Compared to many other BSM searches, analyses based on same-sign leptons therefore allow the use of looser kinematic requirements (for example, on E_T^{miss} or the momentum of jets and leptons), preserving sensitivity to scenarios with small mass differences between gluinos/squarks and the LSP, or in which R -parity is not conserved [23].

The sensitivity to a wide range of models is illustrated by the interpretation of the results in the context of four different SUSY benchmark processes that may lead to same-sign or three-lepton signatures. The first two scenarios focus on gluino pair production with generic decays into light quarks and multiple leptons, either involving light sleptons, $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_2^0 \rightarrow q\bar{q}\ell\ell^* \rightarrow q\bar{q}\ell^+\ell^-\tilde{\chi}_1^0$ (Fig. 1a), or mediated by a cascade involving $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$, $\tilde{g} \rightarrow q\bar{q}'\tilde{\chi}_1^\pm \rightarrow q\bar{q}'W^\pm\tilde{\chi}_2^0 \rightarrow q\bar{q}'W^\pm Z\tilde{\chi}_1^0$ (Fig. 1b). The other two scenarios are motivated by the expectation that the third-generation squarks are lighter than the other squarks and target the direct production of $\tilde{b}_1\tilde{b}_1^*$ pairs with subsequent chargino-mediated $\tilde{b}_1 \rightarrow tW^-\tilde{\chi}_1^0$ decays (Fig. 1c) or the production of $\tilde{g}\tilde{g}$ pairs decaying as $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ via an off-shell top squark (Fig. 1d).

Four signal regions (SRs) are designed to achieve good sensitivity for these SUSY scenarios, mainly characterised by the number of b -tagged jets or reconstructed leptons. They are detailed in Sect. 4, preceded by descriptions of the experimental apparatus (Sect. 2) and the simulated samples (Sect. 3). Section 5 is devoted to the estimation of the contribution from SM processes to the signal regions, validated by comparisons with data in dedicated regions. The results are presented in Sect. 6, together with the statistical tests used to interpret the results in the context of the SUSY benchmark scenarios. Finally, Sect. 7 summarises the main conclusions of this paper.

2 The ATLAS detector

The ATLAS experiment [24] is a multi-purpose particle detector with a forward-backward symmetric cylindrical geometry and nearly 4π coverage in solid angle.¹ The inter-

¹ ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z -axis along the beam pipe. The x -axis points from the IP to the centre of the LHC ring, and the y -axis points 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 $\eta = -\ln \tan(\theta/2)$. Rapidity is defined as $y = 0.5 \ln [(E + p_z)/(E - p_z)]$ where E denotes the energy and p_z is the component of the momentum along the beam direction.

action point is surrounded by an inner detector (ID), a calorimeter system, and a muon spectrometer.

The ID provides precision tracking of charged particles for pseudorapidities $|\eta| < 2.5$ and is surrounded by a superconducting solenoid providing a 2 T axial magnetic field. It consists of pixel and silicon-microstrip detectors inside a transition radiation tracker. One significant upgrade for the $\sqrt{s} = 13$ TeV running period is the presence of the Insertable B-Layer [26], an additional pixel layer close to the interaction point, which provides high-resolution hits at small radius to improve the tracking performance.

In the pseudorapidity region $|\eta| < 3.2$, high-granularity lead/liquid-argon (LAr) electromagnetic (EM) sampling calorimeters are used. A steel/scintillator tile calorimeter measures hadron energies for $|\eta| < 1.7$. The endcap and forward regions, spanning $1.5 < |\eta| < 4.9$, are instrumented with LAr calorimeters for both the EM and hadronic measurements.

The muon spectrometer consists of three large superconducting toroids with eight coils each, a system of trigger and precision-tracking chambers, which provide triggering and tracking capabilities in the ranges $|\eta| < 2.4$ and $|\eta| < 2.7$, respectively.

A two-level trigger system is used to select events. The first-level trigger is implemented in hardware and uses a subset of the detector information. This is followed by the software-based High-Level Trigger stage, which can run offline reconstruction and calibration software, reducing the event rate to about 1 kHz.

3 Dataset and simulated event samples

The data were collected by the ATLAS detector during 2015 with a peak instantaneous luminosity of $L = 5.2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, a bunch spacing of 25 ns, and a mean number of additional pp interactions per bunch crossing (pile-up) in the dataset of $\langle \mu \rangle = 14$. After the application of beam, detector and data quality requirements, the integrated luminosity considered in this analysis corresponds to 3.2 fb^{-1} with an uncertainty of $\pm 5\%$. The luminosity and its uncertainty are derived following a methodology similar to that detailed in Ref. [27] from a preliminary calibration of the luminosity scale using a pair of x - y beam separation scans performed in August 2015.

Monte Carlo (MC) simulated event samples are used to aid in the estimation of the background from SM processes and to model the SUSY signal. The MC samples are processed through an ATLAS detector simulation [28] based on GEANT4 [29] or a fast simulation using a parameterisation of the calorimeter response and GEANT4 for the other parts of the detector [30] and are reconstructed in the same manner as the data.

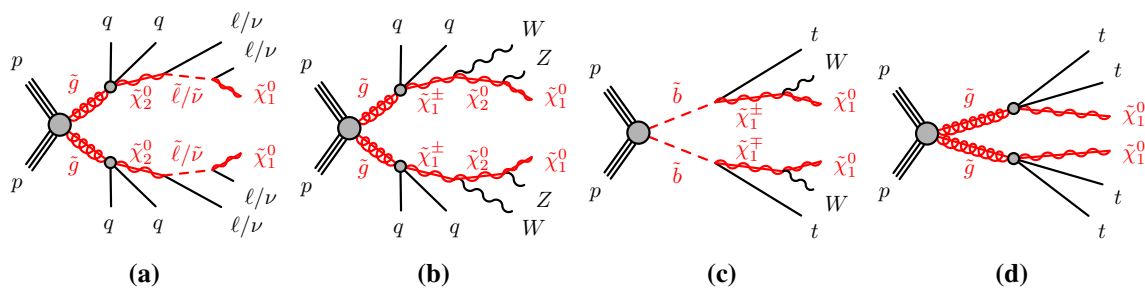


Fig. 1 SUSY processes featuring gluino (a, b, d) or bottom squark (c) pair production considered in this analysis

Diboson processes with four charged leptons (ℓ), three charged leptons and one neutrino, or two charged leptons and two neutrinos are simulated using the SHERPA v2.1.1 generator [31], and are described in detail in Ref. [32]. The matrix elements contain the doubly resonant WW , WZ and ZZ processes and all other diagrams with four or six electroweak vertices (such as same-electric-charge W boson production in association with two jets, $W^\pm W^\pm jj$). Fully leptonic triboson processes (WWW , WWZ , WZZ and ZZZ) with up to six charged leptons are also simulated using SHERPA v2.1.1 and described in Ref. [32]. The 4ℓ and $2\ell + 2\nu$ processes are calculated at next-to-leading order (NLO) for up to one additional parton; final states with two and three additional partons are calculated at leading order (LO). The $WWZ \rightarrow 4\ell + 2\nu$ or $2\ell + 4\nu$ processes are calculated at LO with up to two additional partons. The $3\ell + 1\nu$ process is calculated at NLO and up to three extra partons at LO using the Comix [33] and OpenLoops [34] matrix element generators and merged with the SHERPA parton shower [35] using the ME+PS@NLO prescription [36]. The $WWW/WZZ \rightarrow 3\ell + 3\nu$, $WZZ \rightarrow 5\ell + 1\nu$, $ZZZ \rightarrow 6\ell + 0\nu$, $4\ell + 2\nu$ or $2\ell + 4\nu$ processes are calculated with the same configuration but with up to only two extra partons at LO. The CT10 [37] parton distribution function (PDF) set is used for all SHERPA samples in conjunction with a dedicated tuning of the parton shower parameters developed by the SHERPA authors. The generator cross-sections (at NLO for most of the processes) are used when normalising these backgrounds.

Samples of $t\bar{t}V$ (with $V = W$ and Z , including non-resonant Z/γ^* contributions) and $t\bar{t}WW$ production are generated at LO with MADGRAPH v2.2.2 [38] interfaced to the PYTHIA 8.186 [39] parton shower model, with up to two ($t\bar{t}W$), one ($t\bar{t}Z$) or no ($t\bar{t}WW$) extra partons included in the matrix element; they are described in detail in Ref. [40]. MADGRAPH is also used to simulate the tZ , $t\bar{t}\bar{t}$ and $t\bar{t}t$ processes. The A14 set of tuned parameters (tune) [41] is used together with the NNPDF23LO PDF set [42]. The $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}WW$ and $t\bar{t}\bar{t}$ events are normalised to their NLO cross-section [43] while the generator cross-section is used for tZ and $t\bar{t}t$.

Production of a Higgs boson in association with a $t\bar{t}$ pair is simulated using AMC@NLO [43] (in MADGRAPH v2.2.2) interfaced to HERWIG 2.7.1 [44]. The UEEE5 underlying-event tune is used together with the CTEQ6L1 [45] (matrix element) and CT10 [37] (parton shower) PDF sets. Simulated samples of SM Higgs boson production in association with a W or Z boson are produced with PYTHIA 8.186, using the A14 tune and the NNPDF23LO PDF set. Events are normalised with cross-sections calculated at NLO [46].

The signal SUSY processes are generated from LO matrix elements with up to two extra partons, using the MADGRAPH v2.2.3 generator interfaced to PYTHIA 8.186 with the A14 tune for the modelling of the SUSY decay chain, parton showering, hadronisation and the description of the underlying event. Parton luminosities are provided by the NNPDF23LO PDF set. Jet-parton matching is realised following the CKKW-L prescription [47], with a matching scale set to one quarter of the pair-produced superpartner mass. Signal cross-sections are calculated to NLO in the strong coupling constant, adding the resummation of soft gluon emission at next-to-leading-logarithmic accuracy (NLO+NLL) [48–52]. The nominal cross-section and the uncertainty are taken from an envelope of cross-section predictions using different PDF sets and factorisation and renormalisation scales, as described in Ref. [53]. The production cross-section of gluino pairs with a mass of 1.2 TeV is 86 fb at $\sqrt{s} = 13$ TeV (compared with 4.4 fb at $\sqrt{s} = 8$ TeV), while the production cross-section of pairs of bottom squarks with a mass of 500 GeV is 520 fb at $\sqrt{s} = 13$ TeV (compared with 86 fb at $\sqrt{s} = 8$ TeV).

In all MC samples, except those produced by SHERPA, the EVTGEN v1.2.0 program [54] is used to model the properties of the bottom and charm hadron decays. To simulate the effects of additional pp collisions in the same and nearby bunch crossings, additional interactions are generated using the soft QCD processes of PYTHIA 8.186 with the A2 tune [55] and the MSTW2008LO PDF [56], and overlaid onto the simulated hard scatter event. The Monte Carlo samples are reweighted so that the distribution of the number of reconstructed vertices matches the distribution observed in the data.

4 Event selection

Candidate events are required to have a reconstructed vertex [57], with at least two associated tracks with $p_T > 400$ MeV, and the vertex with the highest sum of squared transverse momentum of the tracks is considered as primary vertex. In order to perform background estimations using data, two categories of electrons and muons are defined: “candidate” and “signal” (the latter being a subset of the “candidate” leptons satisfying tighter selection criteria).

Electron candidates are reconstructed from an isolated electromagnetic calorimeter energy deposit matched to an ID track and are required to have $|\eta| < 2.47$, a transverse momentum $p_T > 10$ GeV, and to pass a loose likelihood-based identification requirement [58,59]. The likelihood input variables include measurements of calorimeter shower shapes and measurements of track properties from the ID. Candidates within the transition region between the barrel and endcap electromagnetic calorimeters, $1.37 < |\eta| < 1.52$, are removed. The track matched with the electron must have a significance of the transverse impact parameter with respect to the reconstructed primary vertex, d_0 , of $|d_0|/\sigma(d_0) < 5$.

Muon candidates are reconstructed in the region $|\eta| < 2.5$ from muon spectrometer tracks matching ID tracks. All muons must have $p_T > 10$ GeV and must pass the medium identification requirements defined in Ref. [60], based on selections on the number of hits in the different ID and muon spectrometer subsystems, and the significance of the charge to momentum ratio q/p [60].

Jets are reconstructed with the anti- k_r algorithm [61] with radius parameter $R = 0.4$, using three-dimensional energy clusters in the calorimeter [62] as input. All jets must have $p_T > 20$ GeV and $|\eta| < 2.8$. Jets are calibrated as described in Ref. [63]. In order to reduce the effects of pile-up, for jets with $p_T < 50$ GeV and $|\eta| < 2.4$ a significant fraction of the tracks associated with each jet must have an origin compatible with the primary vertex, as defined by the jet vertex tagger [64]. Furthermore, for all jets the expected average energy contribution from pile-up clusters is subtracted according to the jet area [63].

Identification of jets containing b -hadrons (b -tagging) is performed with the MV2c20 algorithm, a multivariate discriminant making use of track impact parameters and reconstructed secondary vertices [65,66]. A requirement is chosen corresponding to a 70% average efficiency obtained for b -jets in simulated $t\bar{t}$ events. The rejection factors for light-quark jets, c -quark jets and hadronically decaying τ leptons in simulated $t\bar{t}$ events are approximately 440, 8 and 26, respectively [66]. Jets with $|\eta| < 2.5$ which satisfy this b -tagging requirement are identified as b -jets. To compensate for differences between data and MC simulation in the b -tagging

efficiencies and mis-tag rates, correction factors are applied to the simulated samples [66].

After object identification, overlaps between objects are resolved. Any jet within a distance $\Delta R_y = \sqrt{(\Delta y)^2 + (\Delta\phi)^2} = 0.2$ of an electron candidate is discarded, unless the jet has a value of the MV2c20 discriminant larger than the value corresponding to approximately an 80% b -tagging efficiency, in which case the electron is discarded since it is likely originating from a semileptonic b -hadron decay. Any remaining electron within $\Delta R_y = 0.4$ of a jet is discarded. Muons within $\Delta R_y = 0.4$ of a jet are also removed. However, if the jet has fewer than three associated tracks, the muon is kept and the jet is discarded instead to avoid inefficiencies for high-energy muons undergoing significant energy loss in the calorimeter.

Signal electrons must satisfy a tight likelihood-based identification requirement [58,59] and have $|\eta| < 2$ to reduce the impact of electron charge mis-identification. Signal muons must fulfil the requirement of $|d_0|/\sigma(d_0) < 3$. The track associated to the signal leptons must have a longitudinal impact parameter with respect to the reconstructed primary vertex, z_0 , satisfying $|z_0 \sin\theta| < 0.5$ mm. Isolation requirements are applied to both the signal electrons and muons. The scalar sum of the p_T of tracks within a variable-size cone around the lepton, excluding its own track, must be less than 6% of the lepton p_T . The track isolation cone radius for electrons (muons) $\Delta R_\eta = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ is given by the smaller of $\Delta R_\eta = 10$ GeV/ p_T and $\Delta R_\eta = 0.2$ (0.3), that is, a cone of size 0.2 (0.3) at low p_T but narrower for high- p_T leptons. In addition, in the case of electrons the energy of calorimeter energy clusters in a cone of $\Delta R_\eta = 0.2$ around the electron (excluding the deposition from the electron itself) must be less than 6% of the electron p_T . Simulated events are corrected to account for minor differences in the lepton trigger, reconstruction and identification efficiencies between data and MC simulation.

The missing transverse momentum \vec{p}_T^{miss} is defined as the negative vector sum of the transverse momenta of all identified physics objects (electrons, photons, muons, jets) and an additional soft term. The soft term is constructed from all tracks that are not associated with any physics object, and that are associated with the primary vertex. In this way, the E_T^{miss} is adjusted for the best calibration of the jets and the other identified physics objects above, while maintaining pile-up independence in the soft term [67,68].

Events are selected using a combination (logical OR) of dilepton and E_T^{miss} triggers, the latter being used only for events with $E_T^{\text{miss}} > 250$ GeV. The trigger-level requirements on E_T^{miss} and the leading and subleading lepton p_T are looser than those applied offline to ensure that trigger efficiencies are constant in the relevant phase space. Events of interest are selected if they contain at least two signal leptons with $p_T > 20$ GeV. If the event contains exactly two

Table 1 Summary of the event selection criteria for the signal regions (see text for details)

Signal region	$N_{\text{lept}}^{\text{signal}}$	$N_{b\text{-jets}}^{20}$	N_{jets}^{50}	$E_{\text{T}}^{\text{miss}}$ (GeV)	m_{eff} (GeV)
SR0b3j	≥ 3	$= 0$	≥ 3	> 200	> 550
SR0b5j	≥ 2	$= 0$	≥ 5	> 125	> 650
SR1b	≥ 2	≥ 1	≥ 4	> 150	> 550
SR3b	≥ 2	≥ 3	–	> 125	> 650

signal leptons, they are required to have the same electric charge.

To maximise the sensitivity in different signal models, four overlapping signal regions are defined as shown in Table 1, with requirements on the number of signal leptons ($N_{\text{lept}}^{\text{signal}}$), the number of b -jets with $p_{\text{T}} > 20$ GeV ($N_{b\text{-jets}}^{20}$), the number of jets with $p_{\text{T}} > 50$ GeV regardless of their flavour (N_{jets}^{50}), $E_{\text{T}}^{\text{miss}}$ and the effective mass (m_{eff}), defined as the scalar sum of the p_{T} of the signal leptons and jets (regardless of their flavour) in the event plus the $E_{\text{T}}^{\text{miss}}$.

Each signal region is motivated by a different SUSY scenario. The SR0b3j and SR0b5j signal regions are sensitive to gluino-mediated and directly produced squarks of the first and second generations leading to final states particularly rich in leptons (Fig. 1a) or in jets (Fig. 1b), but with no enhancement of the production of b -quarks. Third-generation squark models resulting in final states with two b -quarks, such as direct bottom squark production (Fig. 1c), are targeted by the SR1b signal region. Finally, the signal region SR3b targets gluino-mediated top squark production resulting in final states with four b -quarks (Fig. 1d).

The values of acceptance times efficiency of the SR selections for the SUSY signal models in Fig. 1 typically range between 1 and 6% for $m_{\tilde{g}} = 1.2$ TeV or $m_{\tilde{b}_1} = 600$ GeV, and a light $\tilde{\chi}_1^0$.

5 Background estimation

Three main sources of SM background can be distinguished in this analysis. A first category consists of events with two same-sign prompt leptons or at least three prompt leptons, mainly from $t\bar{t}V$ and diboson processes. Other types of background events include those containing electrons with mis-measured charge, mainly from the production of top quark pairs, and those containing at least one non-prompt or fake lepton, which mainly originate from hadron decays in events containing top quarks or of W bosons in association with jets.

5.1 Background estimation methods

The estimation of the SM background processes with two same-sign prompt leptons or at least three prompt leptons

is performed using the MC samples described in Sect. 3. Since diboson and $t\bar{t}V$ events are the main backgrounds in the signal regions, dedicated validation regions with an enhanced contribution from these processes are defined to verify the background predictions (see Sect. 5.3).

Background events due to charge mis-identification, dominated by electrons having emitted a hard bremsstrahlung photon which subsequently converted to an electron–positron pair, are referred to as “charge-flip”. The probability of mis-identifying the charge of a muon is checked in both data and MC simulation, and found to be negligible in the kinematic range relevant to this analysis. The contribution of charge-flip events is estimated using data. The electron charge-flip probability is extracted in a $Z/\gamma^* \rightarrow ee$ data sample using a likelihood fit which takes as input the numbers of same-sign and opposite-sign electron pairs observed in the sample. The charge-flip probability is a free parameter of the fit and is extracted as a function of the electron p_{T} and η . The event yield of this background in the signal or validation regions is obtained by applying the measured charge-flip probability to data regions with the same kinematic requirements as the signal or validation regions but with opposite-sign lepton pairs.

The contribution from fake or non-prompt (FNP) leptons (such as hadrons mis-identified as leptons, leptons originating from heavy-flavour decays, and electrons from photon conversions) is also estimated from data with a matrix method similar to that described in Ref. [23]. In this method, two types of lepton identification criteria are defined: “tight”, corresponding to the signal lepton criteria described in Sect. 4, and “loose”, corresponding to candidate leptons. The matrix method relates the number of events containing prompt or FNP leptons to the number of observed events with tight or loose-not-tight leptons using the probability for loose prompt or FNP leptons to satisfy the tight criteria. The probability for loose prompt leptons to satisfy the tight selection criteria is obtained using a $Z/\gamma^* \rightarrow \ell\ell$ data sample and is modelled as a function of the lepton p_{T} and η . The probability for loose FNP leptons to satisfy the tight selection criteria is determined from data in a SS control region enriched in non-prompt leptons originating from heavy-flavour decays. This region contains events with at least one b -jet, one tight muon with $p_{\text{T}} > 40$ GeV (likely prompt) and an additional loose electron or muon (likely FNP). The contribution from prompt leptons and charge mis-measured electrons to this region is subtracted from the observed event yields.

The data-driven background estimates are cross-checked with an MC-based technique. In this method, the contributions from processes with FNP leptons and electron charge mis-identification are obtained from MC simulation and normalised to data in dedicated control regions at low jet multiplicity, low $E_{\text{T}}^{\text{miss}}$, and either with or without b -jets. The normalisation is performed using five multipliers: one to correct

Table 2 The main sources of systematic uncertainty on the SM background estimates for the four signal regions are shown and their values given as relative uncertainties in the expected signal region background event yields. The individual components can be correlated and therefore

do not necessarily add up in quadrature to the total systematic uncertainty. For reference, the total number of expected background events is also shown

	SR0b3j	SR0b5j	SR1b	SR3b
Diboson theoretical uncertainties	23 %	16 %	1 %	<1 %
$t\bar{t}V$ theoretical uncertainties	3 %	4 %	13 %	9 %
Other theoretical uncertainties	5 %	3 %	9 %	15 %
MC statistical uncertainties	11 %	14 %	3 %	6 %
Jet energy scale	12 %	11 %	6 %	5 %
Jet energy resolution	3 %	9 %	2 %	3 %
b -tagging	4 %	6 %	3 %	10 %
PDF	6 %	6 %	6 %	8 %
Fake/non-prompt leptons	18 %	20 %	18 %	21 %
Charge flip	–	1 %	3 %	8 %
Total background uncertainties	30 %	34 %	22 %	31 %
Total background events	1.5	0.88	4.5	0.80

the electron charge mis-identification rate, and four to correct the contributions from FNP electrons or muons originating from b -jets or light-flavour jets, respectively. In addition to the MC samples listed in Sect. 3, this method employs samples of top quark pair production generated with the POWHEG-Box v2 generator interfaced to PYTHIA 6.428 [69], as well as samples of simulated W +jets and Z +jets events generated with POWHEG-Box v2 interfaced to PYTHIA 8.186.

5.2 Systematic uncertainties on the background estimation

Table 2 summarises the contributions of the different sources of systematic uncertainty in the total SM background predictions in the signal regions.

The systematic uncertainties related to the same-sign prompt leptons background estimation arise from the accuracy of the theoretical and experimental modelling in the MC simulation. The primary sources of systematic uncertainties are related to the jet energy scale calibration, the jet energy resolution, b -tagging efficiency, and MC modelling and theoretical cross-section uncertainties. The cross-sections used to normalise the MC samples are varied according to the uncertainty in the cross-section calculation, that is, 6 % for diboson, 13 % for $t\bar{t}W$ and 12 % $t\bar{t}Z$ production [43]. Additional uncertainties are assigned to these backgrounds to account for the modelling of the kinematic distributions in the MC simulation. For $t\bar{t}W$ and $t\bar{t}Z$, the predictions from the MADGRAPH and SHERPA generators are compared, leading to a $\sim 30\%$ uncertainty for these processes after the SR selections. For dibosons, uncertainties are estimated by varying the renormalisation, factorisation and resummation scales used to generate these samples, leading to a $\sim 30\%$ uncertainty for these processes after the SR selections. For triboson,

$t\bar{t}h$, $t\bar{t}t\bar{t}$ and tZ production processes, which constitute a small background in all signal regions, a 50 % uncertainty on the event yields is assumed.

Uncertainties in the FNP lepton background estimate are assigned due to the limited number of data events with loose and tight leptons. In addition, systematic uncertainties of 50–60 % are assigned to the probabilities for loose FNP leptons to satisfy the tight signal criteria to account for potentially different FNP compositions (heavy flavour, light flavour or conversions) between the regions used to measure these probabilities and the SRs, as well as the contamination from prompt leptons in the former regions. This leads to overall FNP background uncertainties in the total background estimates of 18–21 % depending on the signal region.

For the charge-flip background prediction, the main uncertainties originate from the statistical uncertainty of the charge-flip probability measurements and the background contamination of the sample used to extract the charge-flip probability.

5.3 Validation of background estimates

To check the validity and robustness of the background estimates, the distributions of several discriminating variables in data are compared with the predicted background after various requirements on the number of jets and b -jets. Events are categorised based on the flavours of the selected leptons, and the different flavour channels are compared separately. Examples of such distributions are shown in Fig. 2a, c and illustrate that the predictions and data agree fairly well. The background estimates in a kinematic region close to the signal regions can also be observed in Fig. 3, which shows the

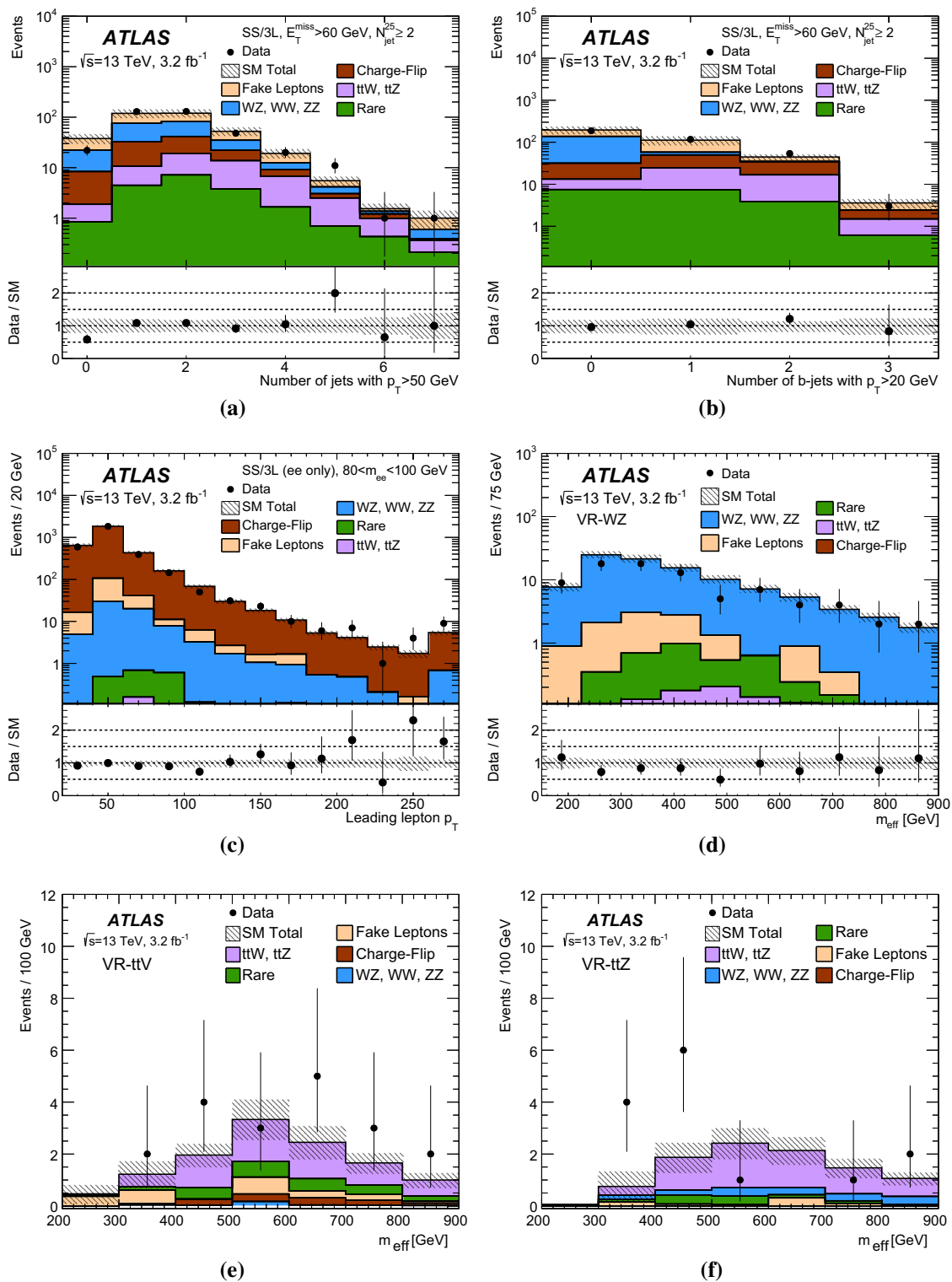


Fig. 2 Distributions of kinematic variables after a SS/3L selection including **a**, **b** $E_T^{\text{miss}} > 60 \text{ GeV}$ and $N_{\text{jet}}^{25} \geq 2$, **c** a b -jet veto and $80 < m_{\ell\ell} < 100 \text{ GeV}$, and **d-f** distributions in the validation regions. The statistical uncertainties in the background prediction are included in the uncertainty band, as well as the theory uncertainties for the backgrounds with prompt SS/3L, and the full systematic uncertainties for

data-driven backgrounds. The last bin includes overflows. The “Fake leptons” category corresponds to FNP leptons (see text), and the “Rare” category contains the contributions from associated production of $t\bar{t}$ with $h/WW/t/\bar{t}$, as well as tZ , Wh , Zh , and triboson production. The lower part of the figures **a-d** shows the ratio of data to the background prediction

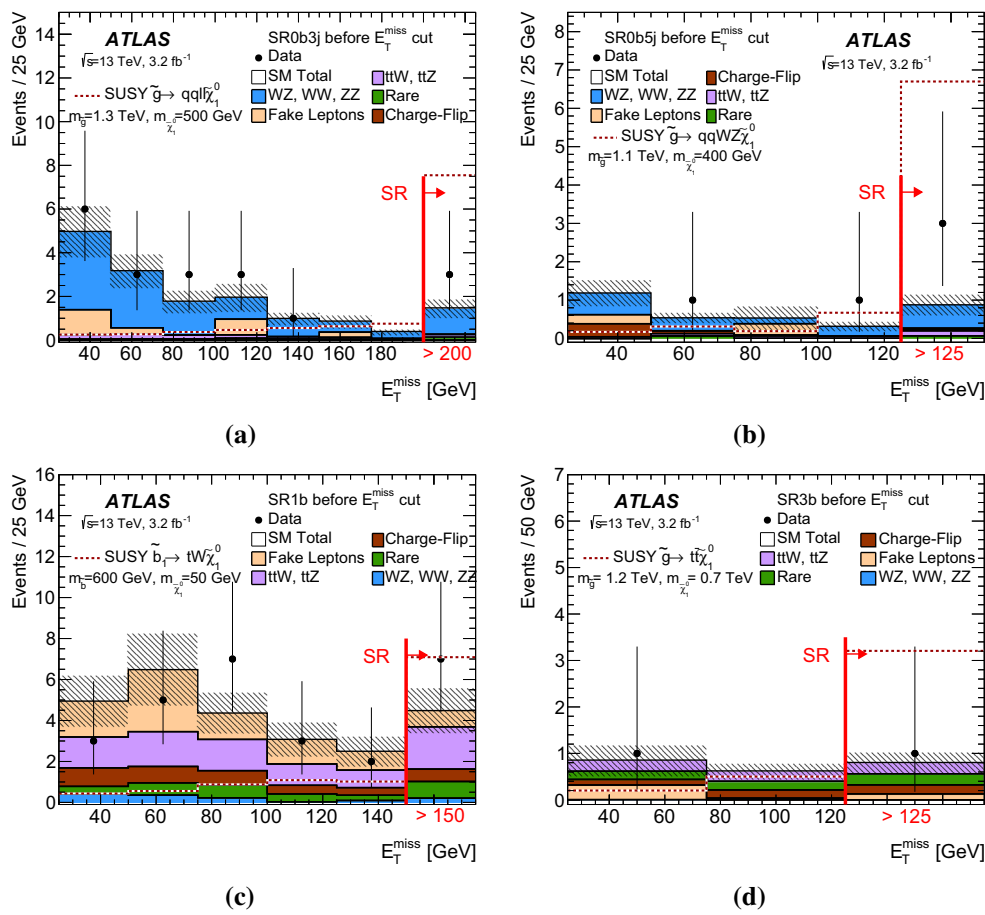


Fig. 3 Missing transverse momentum distributions after **a** SR0b3j, **b** SR0b5j, **c** SR1b and **d** SR3b selection, beside the E_T^{miss} requirement. The results in the signal regions are shown in the last (inclusive) bin of each plot. The statistical uncertainties in the background prediction are included in the uncertainty band, as well as the theory uncertainties

for the backgrounds with prompt SS/3L, and the full systematic uncertainties for data-driven backgrounds. The “Fake leptons” category corresponds to FNP leptons (see text), and the “Rare” category includes the contributions from associated production of $t\bar{t}$ with $h/WW/t/\bar{t}$, as well as tZ , Wh , Zh , and triboson production

E_T^{miss} distributions in the signal regions before applying the E_T^{miss} requirements.

Dedicated validation regions (VRs) are defined to test the estimate of the rare SM processes contributing to the signal regions, whose cross-sections have not yet been measured at $\sqrt{s} = 13$ TeV. The corresponding selections are summarised in Table 3. In these regions, upper bounds are placed on E_T^{miss} and m_{eff} to reduce signal contamination, and the small residual overlap with the signal regions is resolved by vetoing events that contribute to the signal regions. To further reduce contributions from electron charge mis-identification, events are also vetoed if one of the two leading leptons is an electron with $|\eta| > 1.37$, since contributions from charge-flip electrons are smaller in the central region due to the lower amount of crossed material. The purity of the targeted processes in these regions ranges from about 40 to 80 %. The VR-ttV and VR-ttZ regions overlap with each other, with 30 % of the ttV events in VR-ttV also present in VR-ttZ, and

the contributions from the $t\bar{t}Z$ and $t\bar{t}W$ processes is similar in VR-ttV.

The observed yields in these validation regions, compared with the background predictions and uncertainties, can be seen in Table 4, and the effective mass distributions are shown in Fig. 2d, f. There is fair agreement between data and the estimated background for the validation regions, with the largest deviations being observed in VR-ttV with a 1.5σ deviation.

6 Results

Figure 3 shows the data E_T^{miss} distributions after the signal region selections (beside that on E_T^{miss}) in data together with the expected contributions from all the SM backgrounds with their total statistical and systematic uncertainties. For illustration, a typical SUSY signal distribution corresponding to the most relevant benchmark scenario in each SR is displayed.

Table 3 Summary of the event selection in the validation regions. Requirements are placed on the number of signal leptons ($N_{\text{lept}}^{\text{signal}}$) and candidate leptons ($N_{\text{lept}}^{\text{cand}}$), the number of jets with $p_T > 25$ GeV (N_{jets}^{25}) or the number of b -jets with $p_T > 20$ GeV ($N_{b\text{-jets}}^{20}$). The three leading-

p_T leptons are referred to as $\ell_{1,2,3}$ with decreasing p_T and the two leading jets as $j_{1,2}$. Additional requirements are set on the invariant mass of the two leading electrons m_{ee} , the presence of SS leptons or a pair of same-flavour opposite-sign leptons (SFOS) and its invariant mass m_{SFOS}

	$N_{\text{lept}}^{\text{signal}}$ ($N_{\text{lept}}^{\text{cand}}$)	$N_{b\text{-jets}}^{20}$	N_{jets}^{25}	E_T^{miss} (GeV)	m_{eff} (GeV)	Other
VR-WW	=2 (=2) =1 SS pair	=0	≥ 2	35–200	300–900	$m(j_1 j_2) > 500$ GeV $p_T(j_2) > 40$ GeV $p_T(\ell_2) > 30$ GeV veto $80 < m_{ee} < 100$ GeV
VR-WZ	=3 (=3)	=0	1–3	30–200	<900	$p_T(\ell_3) > 30$ GeV
VR-ttV	≥ 2 (–) ≥ 1 SS pair	≥ 2	≥ 5 ($e^\pm e^\pm, e^\pm \mu^\pm$) ≥ 3 ($\mu^\pm \mu^\pm$)	20–200	200–900	$p_T(\ell_2) > 25$ GeV veto $\{E_T^{\text{miss}} > 125$ and $m_{\text{eff}} > 650$ GeV}
VR-ttZ	≥ 3 (–) ≥ 1 SFOS pair	≥ 1	≥ 4 (=1 b -jet) ≥ 3 (≥ 2 b -jets)	20–150	100–900	$p_T(\ell_2) > 25$ GeV $p_T(\ell_3) > 20$ GeV (if e) $80 < m_{\text{SFOS}} < 100$ GeV
All VRs	Veto events belonging to any SR, or if ℓ_1 or ℓ_2 is an electron with $ \eta > 1.37$ (except in VR-WZ)					

Table 4 The numbers of observed data and expected background events for the validation regions. The ‘‘Rare’’ category contains the contributions from associated production of $t\bar{t}$ with $h/WW/t/t\bar{t}$, as well as tZ , Wh , Zh , and triboson production. Background categories shown as

‘‘–’’ denote that they cannot contribute to a given region (charge flips or $W^\pm W^\pm jj$ in 3-lepton regions). The individual uncertainties can be correlated and therefore do not necessarily add up in quadrature to the total systematic uncertainty

	VR-WW	VR-WZ	VR-ttV	VR-ttZ
Observed events	4	82	19	14
Total background events	3.4 ± 0.8	98 ± 15	12.1 ± 2.7	9.7 ± 2.5
Fake/non-prompt leptons	0.6 ± 0.5	8 ± 6	2.1 ± 1.4	0.6 ± 1.0
Charge-flip	0.26 ± 0.05	–	1.14 ± 0.15	–
$t\bar{t}W$	0.05 ± 0.03	0.25 ± 0.09	2.4 ± 0.8	0.10 ± 0.03
$t\bar{t}Z$	0.02 ± 0.01	0.72 ± 0.26	3.9 ± 1.3	6.3 ± 2.1
WZ	1.0 ± 0.4	78 ± 13	0.19 ± 0.10	1.2 ± 0.4
$W^\pm W^\pm jj$	1.3 ± 0.5	–	0.02 ± 0.03	–
ZZ	0.02 ± 0.01	8.2 ± 2.8	0.12 ± 0.15	0.30 ± 0.19
Rare	0.10 ± 0.05	2.8 ± 1.4	2.3 ± 1.2	1.1 ± 0.6

The detailed yields for data and the different sources of SM background in the signal regions are presented in Table 5. The uncertainties amount to 22–34 % of the total background depending on the signal region. In all four SRs the number of data events exceeds the expectation but is consistent within the uncertainties, the smallest p -value for the SM-only hypothesis being 0.04 for SR0b5j. Out of the 14 events in the SRs, 2 of the events in SR1b and the 3 events in SR0b3j contain three leptons. None of those events contain three leptons of equal charge, or are present in more than one SR.

In the absence of any significant deviations from the SM predictions, upper limits on possible BSM contributions to the signal regions are computed, in particular in the context of the SUSY benchmark scenarios described in Sect. 1. The HistFitter framework [70], which utilises a profile-likelihood-ratio test [71], is used to establish 95 %

confidence intervals using the CL_s prescription [72]. The likelihood is built as the product of a Poisson probability density function describing the observed number of events in the signal region and Gaussian distributions constraining the nuisance parameters associated with the systematic uncertainties whose widths correspond to the sizes of these uncertainties; Poisson distributions are used instead for MC statistical uncertainties. Correlations of a given nuisance parameter across the different sources of backgrounds and the signal are taken into account when relevant. The statistical tests are performed independently for each of the signal regions.

Table 6 presents 95 % confidence level (CL) model-independent upper limits on the number of BSM events, N_{BSM} , that may contribute to the signal regions. Normalising these by the integrated luminosity L of the data sample, they can be interpreted as upper limits on the visible BSM cross-

Table 5 The number of observed data events and expected background contributions in the signal regions. The p -value of the observed events for the background-only hypothesis is denoted by $p(s = 0)$. The ‘‘Rare’’ category contains the contributions from associated production of $t\bar{t}$ with $h/WW/t/t\bar{t}$, as well as tZ , Wh , Zh , and triboson production.

	SR0b3j	SR0b5j	SR1b	SR3b
Observed events	3	3	7	1
Total background events	1.5 ± 0.4	0.88 ± 0.29	4.5 ± 1.0	0.80 ± 0.25
$p(s = 0)$	0.13	0.04	0.15	0.36
Fake/non-prompt leptons	<0.2	0.05 ± 0.18	0.8 ± 0.8	0.13 ± 0.17
Charge-flip	–	0.02 ± 0.01	0.60 ± 0.12	0.19 ± 0.06
$t\bar{t}W$	0.02 ± 0.01	0.08 ± 0.04	1.1 ± 0.4	0.10 ± 0.05
$t\bar{t}Z$	0.10 ± 0.04	0.05 ± 0.03	0.92 ± 0.31	0.14 ± 0.06
WZ	1.2 ± 0.4	0.48 ± 0.20	0.18 ± 0.11	<0.02
$W^\pm W^\pm jj$	–	0.12 ± 0.07	0.03 ± 0.02	<0.01
ZZ	<0.03	<0.04	<0.03	<0.03
Rare	0.14 ± 0.08	0.07 ± 0.05	0.8 ± 0.4	0.24 ± 0.14

Background categories shown as ‘‘–’’ denote that they cannot contribute to a given region (charge flips or $W^\pm W^\pm jj$ in 3-lepton regions). The individual uncertainties can be correlated and therefore do not necessarily add up in quadrature to the total systematic uncertainty

Table 6 Signal model-independent upper limits on the number of BSM events (N_{BSM}) and the visible signal cross-section (σ_{vis}) in the four SRs. The numbers (in parentheses) give the observed (expected under the SM hypothesis) 95 % CL upper limits. Calculations are performed with

	SR0b3j	SR0b5j	SR1b	SR3b
$N_{\text{BSM}}^{\text{obs}} (N_{\text{BSM}}^{\text{exp}})$	5.9 (4.1 $^{+1.6}_{-0.8}$)	6.4 (3.6 $^{+1.2}_{-1.1}$)	8.8 (6.0 $^{+2.6}_{-1.6}$)	3.8 (3.7 $^{+1.1}_{-0.5}$)
$\sigma_{\text{vis}}^{\text{obs}}$ [fb]	1.8	2.0	2.8	1.2

pseudo-experiments. The $\pm 1\sigma$ variations on the expected limit due to the statistical and systematic uncertainties in the background prediction are also shown

section σ_{vis} , defined as the product $\sigma_{\text{prod}} \times A \times \epsilon = N_{\text{BSM}}/L$ of production cross-section, acceptance and reconstruction efficiency.

Exclusion limits are also set on the masses of the superpartners involved in the four SUSY benchmark scenarios considered in this analysis. Simplified models corresponding to a single production mode and with 100% branching ratio to a specific decay chain are used, with the masses of the SUSY particles not involved in the process set to very high values. Figure 4 shows the limits on the mass of the $\tilde{\chi}_1^0$ as a function of the \tilde{g} or \tilde{b}_1 mass. In some cases, the new limits set by this analysis can be compared with the existing limits set by the combination of ATLAS SUSY searches with 8 TeV data [73, 74]. For parts of the parameter space, the sensitivity reached with the 13 TeV dataset exceeds that of the 8 TeV dataset, and additional parameter space regions can be excluded, especially for large neutralino masses.

Signal models featuring gluino pair production with a subsequent gluino decay via $\tilde{\chi}_2^0$ and light sleptons ($\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_2^0 \rightarrow q\bar{q}(\ell\bar{\ell}^*/\nu\bar{\nu}^*) \rightarrow q\bar{q}(\ell^+\ell^-/\nu\nu)\tilde{\chi}_1^0$) are probed using SR0b3j (Fig. 4a). In this simplified model, the gluinos decay into $u\bar{u}$, $d\bar{d}$, $s\bar{s}$ or $c\bar{c}$ with equal probabilities, and the six types of leptons are also produced in the $\tilde{\chi}_2^0$ decays with equal probabilities. The $\tilde{\chi}_2^0$ mass is set to $m_{\tilde{\chi}_2^0} =$

$(m_{\tilde{g}} + m_{\tilde{\chi}_1^0})/2$, with the $\tilde{\ell}$ and $\tilde{\nu}$ masses set to $m_{\tilde{\ell},\tilde{\nu}} = (m_{\tilde{\chi}_2^0} + m_{\tilde{\chi}_1^0})/2$. Gluino masses up to $m_{\tilde{g}} \approx 1.3$ TeV for a light $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^0$ masses up to $m_{\tilde{\chi}_1^0} \approx 850$ GeV for gluinos with $m_{\tilde{g}} \approx 1.1$ TeV are excluded in this scenario.

Similarly, models with gluino production with a subsequent two-step gluino decay via $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ ($\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^\pm \rightarrow q\bar{q}W\tilde{\chi}_2^0 \rightarrow q\bar{q}WZ\tilde{\chi}_1^0$) are probed with SR0b5j (Fig. 4b). In this simplified model, the gluinos decay into $u\bar{u}$, $d\bar{d}$, $s\bar{s}$ or $c\bar{c}$ with equal probabilities. The $\tilde{\chi}_1^\pm$ mass is set to $m_{\tilde{\chi}_1^\pm} = (m_{\tilde{g}} + m_{\tilde{\chi}_1^0})/2$ and the $\tilde{\chi}_2^0$ mass is set to $m_{\tilde{\chi}_2^0} = (m_{\tilde{\chi}_1^\pm} + m_{\tilde{\chi}_1^0})/2$; W and Z bosons produced in the decay chain are not necessarily on-shell. The exclusion limits in this scenario reach $m_{\tilde{g}} \approx 1.1$ TeV (for light $\tilde{\chi}_1^0$) and $m_{\tilde{\chi}_1^0} \approx 550$ GeV (for $m_{\tilde{g}} \approx 1.0$ TeV).

Exclusion limits in a simplified model of bottom squark production with chargino-mediated $\tilde{b}_1 \rightarrow tW^-\tilde{\chi}_1^0$ decays are obtained with SR1b (Fig. 4c). In this model the $\tilde{\chi}_1^\pm$ mass is set to $m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0} + 100$ GeV. The limits can reach mass values of $m_{\tilde{b}_1} \approx 540$ GeV for a light $\tilde{\chi}_1^0$, while $m_{\tilde{\chi}_1^0} \lesssim 140$ GeV are also excluded for $m_{\tilde{b}_1} \approx 425$ GeV, significantly extending the previous limits obtained at $\sqrt{s} = 8$ TeV [74]

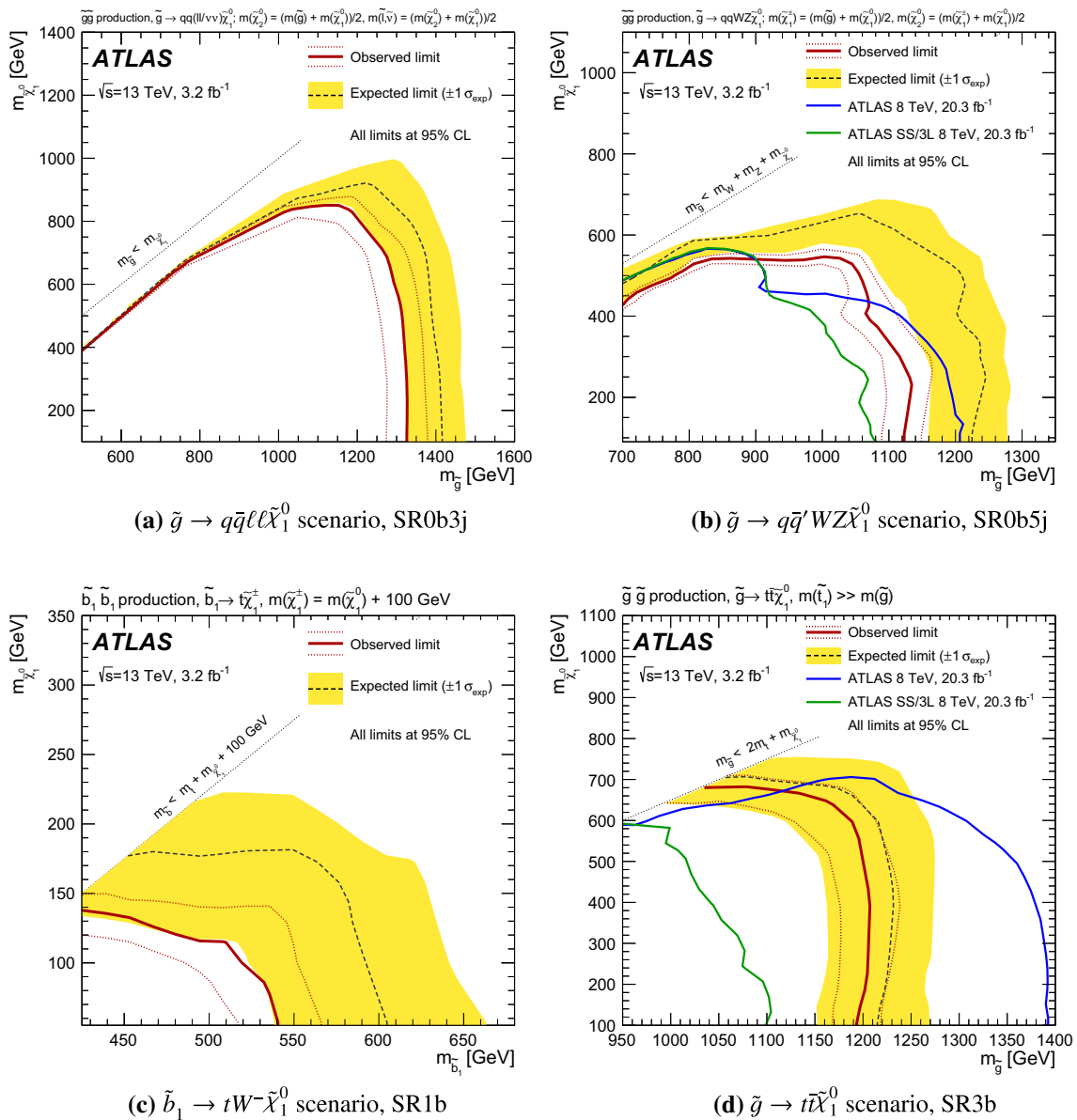


Fig. 4 Observed and expected exclusion limits on the \tilde{g} , \tilde{b}_1 and $\tilde{\chi}_1^0$ masses in the context of SUSY scenarios with simplified mass spectra featuring $\tilde{g}\tilde{g}$ or $\tilde{b}_1\tilde{b}_1^*$ pair production with exclusive decay modes. The signal region used to obtain the limits is specified for each scenario. The contours of the band around the expected limit are the $\pm 1\sigma$ results, including all uncertainties except theoretical uncertainties on the signal cross-section. The *dotted lines* around the observed limit illustrate the

change in the observed limit as the nominal signal cross-section is scaled up and down by the theoretical uncertainty. All limits are computed at 95% CL. The *diagonal lines* indicate the kinematic limit for the decays in each specified scenario. For figures **b**, **d** Results are compared with the observed limits obtained by previous ATLAS searches [23, 73, 74]. For figures **a**, **c** a direct comparison with earlier searches is not possible, due to differing model assumptions

which excluded $m_{\tilde{b}_1} \lesssim 470 \text{ GeV}$ for $m_{\tilde{\chi}_1^0} \approx 60 \text{ GeV}$ for a similar model.

Finally, SR3b is used to set limits on masses in a simplified model with gluino pair production and $\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$ decays via an off-shell top squark (Fig. 4d). In that case, gluino masses of $m_{\tilde{g}} \lesssim 1.2 \text{ TeV}$ are excluded for $m_{\tilde{\chi}_1^0} \lesssim 600 \text{ GeV}$, and $\tilde{\chi}_1^0$ masses up to $m_{\tilde{\chi}_1^0} \approx 680 \text{ GeV}$ are also excluded for $m_{\tilde{g}} \approx 1.05 \text{ TeV}$.

7 Conclusion

A search for supersymmetry in events with exactly two same-sign leptons or at least three leptons, multiple jets, b -jets and E_T^{miss} is presented. The analysis is performed with proton-proton collision data at $\sqrt{s} = 13 \text{ TeV}$ collected with the ATLAS detector at the Large Hadron Collider corresponding to an integrated luminosity of 3.2 fb^{-1} . With no significant excess over the Standard Model expectation observed,

results are interpreted in the framework of simplified models featuring gluino and bottom squark production. In the $\tilde{g}\tilde{g}$ simplified models considered, $m_{\tilde{g}} \lesssim 1.1\text{--}1.3$ TeV and $m_{\tilde{\chi}_1^0} \lesssim 550\text{--}850$ GeV are excluded at 95% confidence level depending on the model parameters. Bottom squark masses of $m_{\tilde{b}_1} \lesssim 540$ GeV are also excluded for a light $\tilde{\chi}_1^0$ in a $\tilde{b}_1\tilde{b}_1^*$ simplified model with $\tilde{b}_1 \rightarrow tW^-\tilde{\chi}_1^0$. These results are complementary to those of previous searches and extend the exclusion limits they set.

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G. Aad⁸⁶, B. Abbott¹¹³, J. Abdallah¹⁵¹, O. Abdinov¹¹, B. Abeloos¹¹⁷, R. Aben¹⁰⁷, M. Abolins⁹¹, O. S. AbouZeid¹³⁷, H. Abramowicz¹⁵³, H. Abreu¹⁵², R. Abreu¹¹⁶, Y. Abulaiti^{146a,146b}, B. S. Acharya^{163a,163b,a}, L. Adamczyk^{39a}, D. L. Adams²⁶, J. Adelman¹⁰⁸, S. Adomeit¹⁰⁰, T. Adye¹³¹, A. A. Affolder⁷⁵, T. Agatonovic-Jovin¹³, J. Agricola⁵⁵, J. A. Aguilar-Saavedra^{126a,126f}, S. P. Ahlen²³, F. Ahmadov^{66,b}, G. Aielli^{133a,133b}, H. Akerstedt^{146a,146b}, T. P. A. Åkesson⁸², A. V. Akimov⁹⁶, G. L. Alberghi^{21a,21b}, J. Albert¹⁶⁸, S. Albrand⁵⁶, M. J. Alconada Verzini⁷², M. Aleksa³¹, I. N. Aleksandrov⁶⁶, C. Alexa^{27b}, G. Alexander¹⁵³, T. Alexopoulos¹⁰, M. Alhroob¹¹³, G. Alimonti^{92a}, J. Alison³², S. P. Alkire³⁶, B. M. M. Allbrooke¹⁴⁹, B. W. Allen¹¹⁶, P. P. Allport¹⁸, A. Aloisio^{104a,104b}, A. Alonso³⁷, F. Alonso⁷², C. Alpigiani¹³⁸, B. Alvarez Gonzalez³¹, D. Álvarez Piqueras¹⁶⁶, M. G. Alvigi^{104a,104b}, B. T. Amadio¹⁵, K. Amako⁶⁷, Y. Amaral Coutinho^{25a}, C. Amelung²⁴, D. Amidei⁹⁰, S. P. Amor Dos Santos^{126a,126c}, A. Amorim^{126a,126b}, S. Amoroso³¹, N. Amram¹⁵³, G. Amundsen²⁴, C. Anastopoulos¹³⁹, L. S. Ancu⁵⁰, N. Andari¹⁰⁸, T. Andeen³², C. F. Anders^{59b}, G. Anders³¹, J. K. Anders⁷⁵, K. J. Anderson³², A. Andreazza^{92a,92b}, V. Andrei^{59a}, S. Angelidakis⁹, I. Angelozzi¹⁰⁷, P. Anger⁴⁵, A. Angerami³⁶, F. Anghinolfi³¹, A. V. Anisenkov^{109,c}, N. Anjos¹², A. Annovi^{124a,124b}, M. Antonelli⁴⁸, A. Antonov⁹⁸, J. Antos^{144b}, F. Anulli^{132a}, M. Aoki⁶⁷, L. Aperio Bella¹⁸, G. Arabidze⁹¹, Y. Arai⁶⁷, J. P. Araque^{126a}, A. T. H. Arce⁴⁶, F. A. Arduh⁷², J-F. Arguin⁹⁵, S. Argyropoulos⁶⁴, M. Arik^{19a}, A. J. Armbruster³¹, L. J. Armitage⁷⁷, O. Arnaez³¹, H. Arnold⁴⁹, M. Arratia²⁹, O. Arslan²², A. Artamonov⁹⁷, G. Artoni¹²⁰, S. Artz⁸⁴, S. Asai¹⁵⁵, N. Asbah⁴³, A. Ashkenazi¹⁵³, B. Åsman^{146a,146b}, L. Asquith¹⁴⁹, K. Assamagan²⁶, R. Astalos^{144a}, M. Atkinson¹⁶⁵, N. B. Atlay¹⁴¹, K. Augsten¹²⁸, G. Avolio³¹, B. Axen¹⁵, M. K. Ayoub¹¹⁷, G. Azuelos^{95,d}, M. A. Baak³¹, A. E. Baas^{59a}, M. J. Baca¹⁸, H. Bachacou¹³⁶, K. Bachas^{74a,74b}, M. Backes³¹, M. Backhaus³¹, P. Bagiacchi^{132a,132b}, P. Bagnaia^{132a,132b}, Y. Bai^{34a}, J. T. Baines¹³¹, O. K. Baker¹⁷⁵, E. M. Baldwin^{109,c}, P. Balek¹²⁹, T. Balestri¹⁴⁸, F. Balli¹³⁶, W. K. Balunas¹²², E. Banas⁴⁰, Sw. Banerjee^{172,e}, A. A. E. Bannoura¹⁷⁴, L. Barak³¹, E. L. Barberio⁸⁹, D. Barberis^{51a,51b}, M. Barbero⁸⁶, T. Barillari¹⁰¹, M. Barisonzi^{163a,163b}, T. Barklow¹⁴³, N. Barlow²⁹, S. L. Barnes⁸⁵, B. M. Barnett¹³¹, R. M. Barnett¹⁵, Z. Barnovska⁵, A. Baroncelli^{134a}, G. Barone²⁴, A. J. Barr¹²⁰, L. Barranco Navarro¹⁶⁶, F. Barreiro⁸³, J. Barreiro Guimarães da Costa^{34a}, R. Bartoldus¹⁴³, A. E. Barton⁷³, P. Bartos^{144a}, A. Basalae¹²³, A. Bassalat¹¹⁷, A. Basye¹⁶⁵, R. L. Bates⁵⁴, S. J. Batista¹⁵⁸, J. R. Batley²⁹, M. Battaglia¹³⁷, M. Bauc^{132a,132b}, F. Bauer¹³⁶, H. S. Bawa^{143,f}, J. B. Beacham¹¹¹, M. D. Beattie⁷³, T. Beau⁸¹, P. H. Beauchemin¹⁶¹, P. Bechtel²², H. P. Beck^{17,g}, K. Becker¹²⁰, M. Becker⁸⁴, M. Beckingham¹⁶⁹, C. Becot¹¹⁰, A. J. Beddall^{19e}, A. Beddall^{19b}, V. A. Bednyakov⁶⁶, M. Bedognetti¹⁰⁷, C. P. Bee¹⁴⁸, L. J. Beamster¹⁰⁷, T. A. Beermann³¹, M. Begel²⁶, J. K. Behr¹²⁰, C. Belanger-Champagne⁸⁸, A. S. Bell⁷⁹, G. Bella¹⁵³, L. Bellagamba^{21a}, A. Bellerive³⁰, M. Bellomo⁸⁷, K. Belotskiy⁹⁸, O. Beltramello³¹, N. L. Belyaev⁹⁸, O. Benary¹⁵³, D. Bencheikroun^{135a}, M. Bender¹⁰⁰, K. Bendtz^{146a,146b}, N. Benekos¹⁰, Y. Benhammou¹⁵³, E. Benhar Nocchioli¹⁷⁵, J. Benitez⁶⁴, J. A. Benitez Garcia^{159b}, D. P. Benjamin⁴⁶, J. R. Bensinger²⁴, S. Bentvelsen¹⁰⁷, L. Beresford¹²⁰, M. Beretta⁴⁸, D. Berge¹⁰⁷, E. Bergeas Kuutmann¹⁶⁴, N. Berger⁵, F. Berghaus¹⁶⁸, J. Beringer¹⁵, S. Berlendis⁵⁶, N. R. Bernard⁸⁷, C. Bernius¹¹⁰, F. U. Bernlochner²², T. Berry⁷⁸, P. Berta¹²⁹, C. Bertella⁸⁴, G. Bertoli^{146a,146b}, F. Bertolucci^{124a,124b}, I. A. Bertram⁷³, C. Bertsche¹¹³, D. Bertsche¹¹³, G. J. Besjes³⁷, O. Bessidskaia Bylund^{146a,146b}, M. Bessner⁴³, N. Besson¹³⁶, C. Betancourt⁴⁹, S. Bethke¹⁰¹, A. J. Bevan⁷⁷, W. Bhimji¹⁵, R. M. Bianchi¹²⁵, L. Bianchini²⁴, M. Bianco³¹, O. Biebel¹⁰⁰, D. Biedermann¹⁶, R. Bielski⁸⁵, N. V. Biesuz^{124a,124b}, M. Biglietti^{134a}, J. Bilbao De Mendizabal⁵⁰, H. Bilokon⁴⁸,

M. Bindi⁵⁵, S. Binet¹¹⁷, A. Bingul^{19b}, C. Bini^{132a,132b}, S. Biondi^{21a,21b}, D. M. Bjergaard⁴⁶, C. W. Black¹⁵⁰, J. E. Black¹⁴³, K. M. Black²³, D. Blackburn¹³⁸, R. E. Blair⁶, J.-B. Blanchard¹³⁶, J. E. Blanco⁷⁸, T. Blazek^{144a}, I. Bloch⁴³, C. Blocker²⁴, W. Blum^{84,*}, U. Blumenschein⁵⁵, S. Blunier^{33a}, G. J. Bobbink¹⁰⁷, V. S. Bobrovnikov^{109,c}, S. S. Bocchetta⁸², A. Bocci⁴⁶, C. Bock¹⁰⁰, M. Boehler⁴⁹, D. Boerner¹⁷⁴, J. A. Bogaerts³¹, D. Bogavac¹³, A. G. Bogdanchikov¹⁰⁹, C. Bohm^{146a}, V. Boisvert⁷⁸, T. Bold^{39a}, V. Boldea^{27b}, A. S. Boldyrev^{163a,163c}, M. Bomben⁸¹, M. Bona⁷⁷, M. Boonekamp¹³⁶, A. Borisov¹³⁰, G. Borissov⁷³, J. Bortfeldt¹⁰⁰, D. Bortoletto¹²⁰, V. Bortolotto^{61a,61b,61c}, K. Bos¹⁰⁷, D. Boscherini^{21a}, M. Bosman¹², J. D. Bossio Sola²⁸, J. Boudreau¹²⁵, J. Bouffard², E. V. Bouhova-Thacker⁷³, D. Boumediene³⁵, C. Bourdarios¹¹⁷, N. Bousson¹¹⁴, S. K. Boutle⁵⁴, A. Boveia³¹, J. Boyd³¹, I. R. Boyko⁶⁶, J. Bracinik¹⁸, A. Brandt⁸, G. Brandt⁵⁵, O. Brandt^{59a}, U. Bratzler¹⁵⁶, B. Brau⁸⁷, J. E. Brau¹¹⁶, H. M. Braun^{174,*}, W. D. Breaden Madden⁵⁴, K. Brendlinger¹²², A. J. Brennan⁸⁹, L. Brenner¹⁰⁷, R. Brenner¹⁶⁴, S. Bressler¹⁷¹, T. M. Bristow⁴⁷, D. Britton⁵⁴, D. Britzger⁴³, F. M. Brochu²⁹, I. Brock²², R. Brock⁹¹, G. Brooijmans³⁶, T. Brooks⁷⁸, W. K. Brooks^{33b}, J. Brosamer¹⁵, E. Brost¹¹⁶, J.H Broughton¹⁸, P. A. Bruckman de Renstrom⁴⁰, D. Bruncko^{144b}, R. Bruneliere⁴⁹, A. Bruni^{21a}, G. Bruni^{21a}, BH Brunt²⁹, M. Bruschi^{21a}, N. Bruscinò²², P. Bryant³², L. Bryngemark⁸², T. Buanes¹⁴, Q. Buat¹⁴², P. Buchholz¹⁴¹, A. G. Buckley⁵⁴, I. A. Budagov⁶⁶, F. Buehrer⁴⁹, M. K. Bugge¹¹⁹, O. Bulekov⁹⁸, D. Bullock⁸, H. Burckhart³¹, S. Burdin⁷⁵, C. D. Burgard⁴⁹, B. Burghgrave¹⁰⁸, K. Burka⁴⁰, S. Burke¹³¹, I. Burmeister⁴⁴, E. Busato³⁵, D. Büscher⁴⁹, V. Büscher⁸⁴, P. Bussey⁵⁴, J. M. Butler²³, A. I. Butt³, C. M. Buttar⁵⁴, J. M. Butterworth⁷⁹, P. Butti¹⁰⁷, W. Buttinger²⁶, A. Buzatu⁵⁴, A. R. Buzykaev^{109,c}, S. Cabrera Urbán¹⁶⁶, D. Caforio¹²⁸, V. M. Cairo^{38a,38b}, O. Cakir^{4a}, N. Calace⁵⁰, P. Calafiura¹⁵, A. Calandri⁸⁶, G. Calderini⁸¹, P. Calfayan¹⁰⁰, L. P. Caloba^{25a}, D. Calvet³⁵, S. Calvet³⁵, T. P. Calvet⁸⁶, R. Camacho Toro³², S. Camarda³¹, P. Camarri^{133a,133b}, D. Cameron¹¹⁹, R. Caminal Armadans¹⁶⁵, C. Camincher⁵⁶, S. Campana³¹, M. Campanelli⁷⁹, A. Campoverde¹⁴⁸, V. Canale^{104a,104b}, A. Canepa^{159a}, M. Cano Bret^{34e}, J. Cantero⁸³, R. Cantrill^{126a}, T. Cao⁴¹, M. D. M. Capeans Garrido³¹, I. Caprini^{27b}, M. Caprini^{27b}, M. Capua^{38a,38b}, R. Caputo⁸⁴, R. M. Carbone³⁶, R. Cardarelli^{133a}, F. Cardillo⁴⁹, T. Carli³¹, G. Carlino^{104a}, L. Carminati^{92a,92b}, S. Caron¹⁰⁶, E. Carquin^{33a}, G. D. Carrillo-Montoya³¹, J. R. Carter²⁹, J. Carvalho^{126a,126c}, D. Casadei⁷⁹, M. P. Casado^{12,h}, M. Casolino¹², D. W. Casper¹⁶², E. Castaneda-Miranda^{145a}, A. Castelli¹⁰⁷, V. Castillo Gimenez¹⁶⁶, N. F. Castro^{126a,i}, A. Catinaccio³¹, J. R. Catmore¹¹⁹, A. Cattai³¹, J. Caudron⁸⁴, V. Cavaliere¹⁶⁵, D. Cavalli^{92a}, M. Cavalli-Sforza¹², V. Cavasinni^{124a,124b}, F. Ceradini^{134a,134b}, L. Cerda Alberich¹⁶⁶, B. C. Cerio⁴⁶, A. S. Cerqueira^{25b}, A. Cerri¹⁴⁹, L. Cerrito⁷⁷, F. Cerutti¹⁵, M. Cerv³¹, A. Cervelli¹⁷, S. A. Cetin^{19d}, A. Chafaq^{135a}, D. Chakraborty¹⁰⁸, I. Chalupkova¹²⁹, S. K. Chan⁵⁸, Y. L. Chan^{61a}, P. Chang¹⁶⁵, J. D. Chapman²⁹, D. G. Charlton¹⁸, A. Chatterjee⁵⁰, C. C. Chau¹⁵⁸, C. A. Chavez Barajas¹⁴⁹, S. Che¹¹¹, S. Cheatham⁷³, A. Chegwidan⁹¹, S. Chekanov⁶, S. V. Chekulaev^{159a}, G. A. Chelkov^{66,j}, M. A. Chelstowska⁹⁰, C. Chen⁶⁵, H. Chen²⁶, K. Chen¹⁴⁸, S. Chen^{34c}, S. Chen¹⁵⁵, X. Chen^{34f}, Y. Chen⁶⁸, H. C. Cheng⁹⁰, H.J Cheng^{34a}, Y. Cheng³², A. Cheplakov⁶⁶, E. Cheremushkina¹³⁰, R. Cherkaoui El Moursli^{135e}, V. Chernyatin^{26,*}, E. Cheu⁷, L. Chevalier¹³⁶, V. Chiarella⁴⁸, G. Chiarelli^{124a,124b}, G. Chiodini^{74a}, A. S. Chisholm¹⁸, A. Chitan^{27b}, M. V. Chizhov⁶⁶, K. Choi⁶², A. R. Chomont³⁵, S. Chouridou⁹, B. K. B. Chow¹⁰⁰, V. Christodoulou⁷⁹, D. Chromek-Burckhart³¹, J. Chudoba¹²⁷, A. J. Chuinard⁸⁸, J. J. Chwastowski⁴⁰, L. Chytka¹¹⁵, G. Ciapetti^{132a,132b}, A. K. Ciftci^{4a}, D. Cinca⁵⁴, V. Cindro⁷⁶, I. A. Cioara²², A. Ciocio¹⁵, F. Ciroto^{104a,104b}, Z. H. Citron¹⁷¹, M. Ciubancan^{27b}, A. Clark⁵⁰, B. L. Clark⁵⁸, P. J. Clark⁴⁷, R. N. Clarke¹⁵, C. Clement^{146a,146b}, Y. Coadou⁸⁶, M. Cobal^{163a,163c}, A. Coccaro⁵⁰, J. Cochran⁶⁵, L. Coffey²⁴, L. Colasurdo¹⁰⁶, B. Cole³⁶, S. Cole¹⁰⁸, A. P. Colijn¹⁰⁷, J. Collot⁵⁶, T. Colombo³¹, G. Compostella¹⁰¹, P. Conde Muñio^{126a,126b}, E. Coniavitis⁴⁹, S. H. Connell^{145b}, I. A. Connelly⁷⁸, V. Consorti⁴⁹, S. Constantinescu^{27b}, C. Conta^{121a,121b}, G. Conti³¹, F. Conventi^{104a,k}, M. Cooke¹⁵, B. D. Cooper⁷⁹, A. M. Cooper-Sarkar¹²⁰, T. Cornelissen¹⁷⁴, M. Corradi^{132a,132b}, F. Corriveau^{88,l}, A. Corso-Radu¹⁶², A. Cortes-Gonzalez¹², G. Cortiana¹⁰¹, G. Costa^{92a}, M. J. Costa¹⁶⁶, D. Costanzo¹³⁹, G. Cottin²⁹, G. Cowan⁷⁸, B. E. Cox⁸⁵, K. Cranmer¹¹⁰, S. J. Crawley⁵⁴, G. Cree³⁰, S. Crépe-Renaudin⁵⁶, F. Crescioli⁸¹, W. A. Cribbs^{146a,146b}, M. Crispin Ortuzar¹²⁰, M. Cristinziani²², V. Croft¹⁰⁶, G. Crosetti^{38a,38b}, T. Cuhadar Donszelmann¹³⁹, J. Cummings¹⁷⁵, M. Curatolo⁴⁸, J. Cúth⁸⁴, C. Cuthbert¹⁵⁰, H. Czirr¹⁴¹, P. Czodrowski³, S. D'Auria⁵⁴, M. D'Onofrio⁷⁵, M. J. Da Cunha Sargedas De Sousa^{126a,126b}, C. Da Via⁸⁵, W. Dabrowski^{39a}, T. Dai⁹⁰, O. Dale¹⁴, F. Dallaire⁹⁵, C. Dallapiccola⁸⁷, M. Dam³⁷, J. R. Dandoy³², N. P. Dang⁴⁹, A. C. Daniells¹⁸, N. S. Dann⁸⁵, M. Danninger¹⁶⁷, M. Dano Hoffmann¹³⁶, V. Dao⁴⁹, G. Darbo^{51a}, S. Darmora⁸, J. Dassoulas³, A. Dattagupta⁶², W. Davey²², C. David¹⁶⁸, T. Davidek¹²⁹, M. Davies¹⁵³, P. Davison⁷⁹, Y. Davygora^{59a}, E. Dawe⁸⁹, I. Dawson¹³⁹, R. K. Daya-Ishmukhametova⁸⁷, K. De⁸, R. de Asmundis^{104a}, A. De Benedetti¹¹³, S. De Castro^{21a,21b}, S. De Cecco⁸¹, N. De Groot¹⁰⁶, P. de Jong¹⁰⁷, H. De la Torre⁸³, F. De Lorenzi⁶⁵, D. De Pedis^{132a}, A. De Salvo^{132a}, U. De Sanctis¹⁴⁹, A. De Santo¹⁴⁹, J. B. De Vivie De Regie¹¹⁷, W. J. Dearnaley⁷³, R. Debe²⁶, C. Debenedetti¹³⁷, D. V. Dedovich⁶⁶, I. Deigaard¹⁰⁷, J. Del Peso⁸³, T. Del Prete^{124a,124b}, D. Delgove¹¹⁷, F. Deliot¹³⁶, C. M. Delitzsch⁵⁰, M. Deliyergiyev⁷⁶, A. Dell'Acqua³¹, L. Dell'Asta²³, M. Dell'Orso^{124a,124b}, M. Della Pietra^{104a,k}, D. della Volpe⁵⁰, M. Delmastro⁵, P. A. Delsart⁵⁶, C. Deluca¹⁰⁷, D. A. DeMarco¹⁵⁸, S. Demers¹⁷⁵, M. Demichev⁶⁶, A. Demilly⁸¹, S. P. Denisov¹³⁰,

D. Denysiuk¹³⁶, D. Derendarz⁴⁰, J. E. Derkaoui^{135d}, F. Derue⁸¹, P. Dervan⁷⁵, K. Desch²², C. Deterre⁴³, K. Dette⁴⁴, P. O. Deviveiros³¹, A. Dewhurst¹³¹, S. Dhaliwal²⁴, A. Di Ciaccio^{133a,133b}, L. Di Ciaccio⁵, W. K. Di Clemente¹²², C. Di Donato^{132a,132b}, A. Di Girolamo³¹, B. Di Girolamo³¹, B. Di Micco^{134a,134b}, R. Di Nardo⁴⁸, A. Di Simone⁴⁹, R. Di Sipio¹⁵⁸, D. Di Valentino³⁰, C. Diaconu⁸⁶, M. Diamond¹⁵⁸, F. A. Dias⁴⁷, M. A. Diaz^{33a}, E. B. Diehl⁹⁰, J. Dietrich¹⁶, S. Diglio⁸⁶, A. Dimitrievska¹³, J. Dingfelder²², P. Dita^{27b}, S. Dita^{27b}, F. Dittus³¹, F. Djama⁸⁶, T. Djobava^{52b}, J. I. Djuvsland^{59a}, M. A. B. do Vale^{25c}, D. Dobos³¹, M. Dobre^{27b}, C. Doglioni⁸², T. Dohmae¹⁵⁵, J. Dolejsi¹²⁹, Z. Dolezal¹²⁹, B. A. Dolgoshein^{98,*}, M. Donadelli^{25d}, S. Donati^{124a,124b}, P. Dondero^{121a,121b}, J. Donini³⁵, J. Dopke¹³¹, A. Doria^{104a}, M. T. Dova⁷², A. T. Doyle⁵⁴, E. Drechsler⁵⁵, M. Dris¹⁰, Y. Du^{34d}, J. Duarte-Campderros¹⁵³, E. Duchovni¹⁷¹, G. Duckeck¹⁰⁰, O. A. Ducu^{27b}, D. Duda¹⁰⁷, A. Dudarev³¹, L. Dufлот¹¹⁷, L. Duguid⁷⁸, M. Dührssen³¹, M. Dunford^{59a}, H. Duran Yildiz^{4a}, M. Düren⁵³, A. Durglishvili^{52b}, D. Duschinger⁴⁵, B. Dutta⁴³, M. Dyndal^{39a}, C. Eckardt⁴³, K. M. Ecker¹⁰¹, R. C. Edgar⁹⁰, W. Edson², N. C. Edwards⁴⁷, T. Eifert³¹, G. Eigen¹⁴, K. Einsweiler¹⁵, T. Ekelof¹⁶⁴, M. El Kacimi^{135c}, V. Ellajosyula⁸⁶, M. Ellert¹⁶⁴, S. Elles⁵, F. Ellinghaus¹⁷⁴, A. A. Elliot¹⁶⁸, N. Ellis³¹, J. Elmsheuser¹⁰⁰, M. Elsing³¹, D. Emelianov¹³¹, Y. Enari¹⁵⁵, O. C. Endner⁸⁴, M. Endo¹¹⁸, J. S. Ennis¹⁶⁹, J. Erdmann⁴⁴, A. Ereditato¹⁷, G. Ernis¹⁷⁴, J. Ernst², M. Ernst²⁶, S. Errede¹⁶⁵, E. Ertel⁸⁴, M. Escalier¹¹⁷, H. Esch⁴⁴, C. Escobar¹²⁵, B. Esposito⁴⁸, A. I. Etievre¹³⁶, E. Etzion¹⁵³, H. Evans⁶², A. Ezhilov¹²³, F. Fabbri^{21a,21b}, L. Fabbri^{21a,21b}, G. Facini³², R. M. Fakhrutdinov¹³⁰, S. Falciano^{132a}, R. J. Falla⁷⁹, J. Faltova¹²⁹, Y. Fang^{34a}, M. Fanti^{92a,92b}, A. Farbin⁸, A. Farilla^{134a}, C. Farina¹²⁵, T. Farooque¹², S. Farrell¹⁵, S. M. Farrington¹⁶⁹, P. Farthouat³¹, F. Fassi^{135c}, P. Fassnacht³¹, D. Fassouliotis⁹, M. Fauci Giannelli⁷⁸, A. Favareto^{51a,51b}, W. J. Fawcett¹²⁰, L. Fayard¹¹⁷, O. L. Fedin^{123,m}, W. Fedorko¹⁶⁷, S. Feigl¹¹⁹, L. Feligioni⁸⁶, C. Feng^{34d}, E. J. Feng³¹, H. Feng⁹⁰, A. B. Fenyuk¹³⁰, L. Feremenga⁸, P. Fernandez Martinez¹⁶⁶, S. Fernandez Perez¹², J. Ferrando⁵⁴, A. Ferrari¹⁶⁴, P. Ferrari¹⁰⁷, R. Ferrari^{121a}, D. E. Ferreira de Lima⁵⁴, A. Ferrer¹⁶⁶, D. Ferrere⁵⁰, C. Ferretti⁹⁰, A. Ferretto Parodi^{51a,51b}, F. Fiedler⁸⁴, A. Filipčič⁷⁶, M. Filipuzzi⁴³, F. Filthaut¹⁰⁶, M. Fincke-Keeler¹⁶⁸, K. D. Finelli¹⁵⁰, M. C. N. Fiolhais^{126a,126c}, L. Fiorini¹⁶⁶, A. Firan⁴¹, A. Fischer², C. Fischer¹², J. Fischer¹⁷⁴, W. C. Fisher⁹¹, N. Flaschel⁴³, I. Fleck¹⁴¹, P. Fleischmann⁹⁰, G. T. Fletcher¹³⁹, G. Fletcher⁷⁷, R. R. M. Fletcher¹²², T. Flick¹⁷⁴, A. Floderus⁸², L. R. Flores Castillo^{61a}, M. J. Flowerdew¹⁰¹, G. T. Forcolin⁸⁵, A. Formica¹³⁶, A. Forti⁸⁵, A. G. Foster¹⁸, D. Fournier¹¹⁷, H. Fox⁷³, S. Fracchia¹², P. Francavilla⁸¹, M. Franchini^{21a,21b}, D. Francis³¹, L. Franconi¹¹⁹, M. Franklin⁵⁸, M. Frate¹⁶², M. Fraternali^{121a,121b}, D. Freeborn⁷⁹, S. M. Fressard-Batraneanu³¹, F. Friedrich⁴⁵, D. Froidevaux³¹, J. A. Frost¹²⁰, C. Fukunaga¹⁵⁶, E. Fullana Torregrosa⁸⁴, T. Fusayasu¹⁰², J. Fuster¹⁶⁶, C. Gabaldon⁵⁶, O. Gabizon¹⁷⁴, A. Gabrielli^{21a,21b}, A. Gabrielli¹⁵, G. P. Gach^{39a}, S. Gadatsch³¹, S. Gadomski⁵⁰, G. Gagliardi^{51a,51b}, L. G. Gagnon⁹⁵, P. Gagnon⁶², C. Galea¹⁰⁶, B. Galhardo^{126a,126c}, E. J. Gallas¹²⁰, B. J. Gallop¹³¹, P. Gallus¹²⁸, G. Galster³⁷, K. K. Gan¹¹¹, J. Gao^{34b,86}, Y. Gao⁴⁷, Y. S. Gao^{143,f}, F. M. Garay Walls⁴⁷, C. García¹⁶⁶, J. E. García Navarro¹⁶⁶, M. Garcia-Sciveres¹⁵, R. W. Gardner³², N. Garelli¹⁴³, V. Garonne¹¹⁹, A. Gascon Bravo⁴³, C. Gatti⁴⁸, A. Gaudiello^{51a,51b}, G. Gaudio^{121a}, B. Gaur¹⁴¹, L. Gauthier⁹⁵, I. L. Gavrilenko⁹⁶, C. Gay¹⁶⁷, G. Gaycken²², E. N. Gazis¹⁰, Z. Gece¹⁶⁷, C. N. P. Gee¹³¹, Ch. Geich-Gimbel²², M. P. Geisler^{59a}, C. Gemme^{51a}, M. H. Genest⁵⁶, C. Geng^{34b,n}, S. Gentile^{132a,132b}, S. George⁷⁸, D. Gerbaudo¹⁶², A. Gershon¹⁵³, S. Ghasemi¹⁴¹, H. Ghazlane^{135b}, B. Giacobbe^{21a}, S. Giagu^{132a,132b}, P. Giannetti^{124a,124b}, B. Gibbard²⁶, S. M. Gibson⁷⁸, M. Gignac¹⁶⁷, M. Gilchriese¹⁵, T. P. S. Gillam²⁹, D. Gillberg³⁰, G. Gilles¹⁷⁴, D. M. Gingrich^{3,d}, N. Giokaris⁹, M. P. Giordani^{163a,163c}, F. M. Giorgi^{21a}, F. M. Giorgi¹⁶, P. F. Giraud¹³⁶, P. Giromini⁵⁸, D. Giugni^{92a}, C. Giuliani¹⁰¹, M. Giulini^{59b}, B. K. Gjelsten¹¹⁹, S. Gkaitatzis¹⁵⁴, I. Gkialas¹⁵⁴, E. L. Gkoukousis¹¹⁷, L. K. Gladilin⁹⁹, C. Glasman⁸³, J. Glatzer³¹, P. C. F. Glaysheer⁴⁷, A. Glazov⁴³, M. Goblirsch-Kolb¹⁰¹, J. Godlewski⁴⁰, S. Goldfarb⁹⁰, T. Golling⁵⁰, D. Golubkov¹³⁰, A. Gomes^{126a,126b,126d}, R. Gonçalves^{126a}, J. Goncalves Pinto Firmino Da Costa¹³⁶, L. Gonella¹⁸, A. Gongadze⁶⁶, S. González de la Hoz¹⁶⁶, G. Gonzalez Parra¹², S. Gonzalez-Sevilla⁵⁰, L. Goossens³¹, P. A. Gorbounov⁹⁷, H. A. Gordon²⁶, I. Gorelov¹⁰⁵, B. Gorini³¹, E. Gorini^{74a,74b}, A. Gorišek⁷⁶, E. Gornicki⁴⁰, A. T. Goshaw⁴⁶, C. Gössling⁴⁴, M. I. Gostkin⁶⁶, C. R. Goudet¹¹⁷, D. Goujdami^{135c}, A. G. Goussiou¹³⁸, N. Govender^{145b}, E. Gozani¹⁵², L. Graber⁵⁵, I. Grabowska-Bold^{39a}, P. O. J. Gradin¹⁶⁴, P. Grafström^{21a,21b}, J. Gramling⁵⁰, E. Gramstad¹¹⁹, S. Grancagnolo¹⁶, V. Gratchev¹²³, H. M. Gray³¹, E. Graziani^{134a}, Z. D. Greenwood^{80,o}, C. Grefe²², K. Gregersen⁷⁹, I. M. Gregor⁴³, P. Grenier¹⁴³, K. Grevtsov⁵, J. Griffiths⁸, A. A. Grillo¹³⁷, K. Grimm⁷³, S. Grinstein^{12,p}, Ph. Gris³⁵, J.-F. Grivaz¹¹⁷, S. Groh⁸⁴, J. P. Grohs⁴⁵, E. Gross¹⁷¹, J. Grosse-Knetter⁵⁵, G. C. Grossi⁸⁰, Z. J. Grout¹⁴⁹, L. Guan⁹⁰, W. Guan¹⁷², J. Guenther¹²⁸, F. Guescini⁵⁰, D. Guest¹⁶², O. Gueta¹⁵³, E. Guido^{51a,51b}, T. Guillemain⁵, S. Guindon², U. Gul⁵⁴, C. Gumpert³¹, J. Guo^{34e}, Y. Guo^{34b,n}, S. Gupta¹²⁰, G. Gustavino^{132a,132b}, P. Gutierrez¹¹³, N. G. Gutierrez Ortiz⁷⁹, C. Gutsche⁴⁵, C. Guyot¹³⁶, C. Gwenlan¹²⁰, C. B. Gwilliam⁷⁵, A. Haas¹¹⁰, C. Haber¹⁵, H. K. Hadavand⁸, N. Haddad^{135e}, A. Hadeef⁸⁶, P. Haefner²², S. Hageböck²², Z. Hajduk⁴⁰, H. Hakobyan^{176,*}, M. Haleem⁴³, J. Haley¹¹⁴, D. Hall¹²⁰, G. Halladjian⁹¹, G. D. Hallewell⁸⁶, K. Hamacher¹⁷⁴, P. Hamal¹¹⁵, K. Hamano¹⁶⁸, A. Hamilton^{145a}, G. N. Hamity¹³⁹, P. G. Hamnett⁴³, L. Han^{34b}, K. Hanagaki^{67,q}, K. Hanawa¹⁵⁵, M. Hance¹³⁷, B. Haney¹²², P. Hanke^{59a}, R. Hanna¹³⁶, J. B. Hansen³⁷, J. D. Hansen³⁷, M. C. Hansen²², P. H. Hansen³⁷, K. Hara¹⁶⁰, A. S. Hard¹⁷², T. Harenberg¹⁷⁴,

F. Hariri¹¹⁷, S. Harkusha⁹³, R. D. Harrington⁴⁷, P. F. Harrison¹⁶⁹, F. Hartjes¹⁰⁷, M. Hasegawa⁶⁸, Y. Hasegawa¹⁴⁰, A. Hasib¹¹³, S. Hassani¹³⁶, S. Haug¹⁷, R. Hauser⁹¹, L. Hauswald⁴⁵, M. Havranek¹²⁷, C. M. Hawkes¹⁸, R. J. Hawkins³¹, A. D. Hawkins⁸², D. Hayden⁹¹, C. P. Hays¹²⁰, J. M. Hays⁷⁷, H. S. Hayward⁷⁵, S. J. Haywood¹³¹, S. J. Head¹⁸, T. Heck⁸⁴, V. Hedberg⁸², L. Heelan⁸, S. Heim¹²², T. Heim¹⁵, B. Heinemann¹⁵, J. J. Heinrich¹⁰⁰, L. Heinrich¹¹⁰, C. Heinz⁵³, J. Hejbal¹²⁷, L. Helary²³, S. Hellman^{146a,146b}, C. Helsen³¹, J. Henderson¹²⁰, R. C. W. Henderson⁷³, Y. Heng¹⁷², S. Henkelmann¹⁶⁷, A. M. Henriques Correia³¹, S. Henrot-Versille¹¹⁷, G. H. Herbert¹⁶, Y. Hernández Jiménez¹⁶⁶, G. Herten⁴⁹, R. Hertenberger¹⁰⁰, L. Hervas³¹, G. G. Hesketh⁷⁹, N. P. Hessey¹⁰⁷, J. W. Hetherly⁴¹, R. Hickling⁷⁷, E. Higón-Rodríguez¹⁶⁶, E. Hill¹⁶⁸, J. C. Hill²⁹, K. H. Hiller⁴³, S. J. Hillier¹⁸, I. Hinchliffe¹⁵, E. Hines¹²², R. R. Hinman¹⁵, M. Hirose¹⁵⁷, D. Hirschbuehl¹⁷⁴, J. Hobbs¹⁴⁸, N. Hod¹⁰⁷, M. C. Hodgkinson¹³⁹, P. Hodgson¹³⁹, A. Hoecker³¹, M. R. Hoferkamp¹⁰⁵, F. Hoenic¹⁰⁰, M. Hohlfeld⁸⁴, D. Hohn²², T. R. Holmes¹⁵, M. Homann⁴⁴, T. M. Hong¹²⁵, B. H. Hooberman¹⁶⁵, W. H. Hopkins¹¹⁶, Y. Horii¹⁰³, A. J. Horton¹⁴², J.-Y. Hostachy⁵⁶, S. Hou¹⁵¹, A. Houmada^{135a}, J. Howard¹²⁰, J. Howarth⁴³, M. Hrabovsky¹¹⁵, I. Hristova¹⁶, J. Hrivnac¹¹⁷, T. Hryn'ova⁵, A. Hrynevich⁹⁴, C. Hsu^{145c}, P. J. Hsu^{151,r}, S.-C. Hsu¹³⁸, D. Hu³⁶, Q. Hu^{34b}, Y. Huang⁴³, Z. Hubacek¹²⁸, F. Hubaut⁸⁶, F. Huegging²², T. B. Huffman¹²⁰, E. W. Hughes³⁶, G. Hughes⁷³, M. Huhtinen³¹, T. A. Hülsing⁸⁴, N. Huseynov^{66,b}, J. Huston⁹¹, J. Huth⁵⁸, G. Iacobucci⁵⁰, G. Iakovidis²⁶, I. Ibragimov¹⁴¹, L. Iconomidou-Fayard¹¹⁷, E. Ideal¹⁷⁵, Z. Idrissi^{135c}, P. Iengo³¹, O. Igonkina¹⁰⁷, T. Iizawa¹⁷⁰, Y. Ikegami⁶⁷, M. Ikeno⁶⁷, Y. Ilchenko^{32,s}, D. Iliadis¹⁵⁴, N. Ilic¹⁴³, T. Ince¹⁰¹, G. Introzzi^{121a,121b}, P. Ioannou^{9,*}, M. Iodice^{134a}, K. Iordanidou³⁶, V. Ippolito⁵⁸, A. Irls Quiles¹⁶⁶, C. Isaksson¹⁶⁴, M. Ishino⁶⁹, M. Ishitsuka¹⁵⁷, R. Ishmukhametov¹¹¹, C. Issever¹²⁰, S. Istin^{19a}, F. Ito¹⁶⁰, J. M. Iturbe Ponce⁸⁵, R. Iuppa^{133a,133b}, J. Ivarsson⁸², W. Iwanski⁴⁰, H. Iwasaki⁶⁷, J. M. Izen⁴², V. Izzo^{104a}, S. Jabbar³, B. Jackson¹²², M. Jackson⁷⁵, P. Jackson¹, V. Jain², K. B. Jakobi⁸⁴, K. Jakobs⁴⁹, S. Jakobsen³¹, T. Jakoubek¹²⁷, D. O. Jamin¹¹⁴, D. K. Jana⁸⁰, E. Jansen⁷⁹, R. Jansky⁶³, J. Janssen²², M. Janus⁵⁵, G. Jarlskog⁸², N. Javadov^{66,b}, T. Javůrek⁴⁹, F. Jeanneau¹³⁶, L. Jeanty¹⁵, J. Jejelava^{52a,t}, G.-Y. Jeng¹⁵⁰, D. Jennens⁸⁹, P. Jenni^{49,u}, J. Jentsch⁴⁴, C. Jeske¹⁶⁹, S. Jézéquel⁵, H. Ji¹⁷², J. Jia¹⁴⁸, H. Jiang⁶⁵, Y. Jiang^{34b}, S. Jiggins⁷⁹, J. Jimenez Pena¹⁶⁶, S. Jin^{34a}, A. Jinaru^{27b}, O. Jinnouchi¹⁵⁷, P. Johansson¹³⁹, K. A. Johns⁷, W. J. Johnson¹³⁸, K. Jon-And^{146a,146b}, G. Jones¹⁶⁹, R. W. L. Jones⁷³, S. Jones⁷, T. J. Jones⁷⁵, J. Jongmanns^{59a}, P. M. Jorge^{126a,126b}, J. Jovicevic^{159a}, X. Ju¹⁷², A. Juste Rozas^{12,p}, M. K. Köhler¹⁷¹, A. Kaczmarska⁴⁰, M. Kado¹¹⁷, H. Kagan¹¹¹, M. Kagan¹⁴³, S. J. Kahn⁸⁶, E. Kajomovitz⁴⁶, C. W. Kalderon¹²⁰, A. Kaluza⁸⁴, S. Kama⁴¹, A. Kamenshchikov¹³⁰, N. Kanaya¹⁵⁵, S. Kaneti²⁹, V. A. Kantserov⁹⁸, J. Kanzaki⁶⁷, B. Kaplan¹¹⁰, L. S. Kaplan¹⁷², A. Kapliy³², D. Kar^{145c}, K. Karakostas¹⁰, A. Karamaoun³, N. Karastathis¹⁰, M. J. Kareem⁵⁵, E. Karentzos¹⁰, M. Karnevskiy⁸⁴, S. N. Karpov⁶⁶, Z. M. Karpova⁶⁶, K. Karthik¹¹⁰, V. Kartvelishvili⁷³, A. N. Karyukhin¹³⁰, K. Kasahara¹⁶⁰, L. Kashif¹⁷², R. D. Kass¹¹¹, A. Kastanas¹⁴, Y. Kataoka¹⁵⁵, C. Kato¹⁵⁵, A. Katre⁵⁰, J. Katzy⁴³, K. Kawagoe⁷¹, T. Kawamoto¹⁵⁵, G. Kawamura⁵⁵, S. Kazama¹⁵⁵, V. F. Kazanin^{109,c}, R. Keeler¹⁶⁸, R. Kehoe⁴¹, J. S. Keller⁴³, J. J. Kempster⁷⁸, K. Kentaro¹⁰³, H. Keoshkerian⁸⁵, O. Kepka¹²⁷, B. P. Kerševan⁷⁶, S. Kersten¹⁷⁴, R. A. Keyes⁸⁸, F. Khalil-zada¹¹, H. Khandanyan^{146a,146b}, A. Khanov¹¹⁴, A. G. Kharlamov^{109,c}, T. J. Khoo²⁹, V. Khovanskii⁹⁷, E. Khramov⁶⁶, J. Khubua^{52b,v}, S. Kido⁶⁸, H. Y. Kim⁸, S. H. Kim¹⁶⁰, Y. K. Kim³², N. Kimura¹⁵⁴, O. M. Kind¹⁶, B. T. King⁷⁵, M. King¹⁶⁶, S. B. King¹⁶⁷, J. Kirk¹³¹, A. E. Kiryunin¹⁰¹, T. Kishimoto⁶⁸, D. Kisielewska^{39a}, F. Kiss⁴⁹, K. Kiuchi¹⁶⁰, O. Kivernyk¹³⁶, E. Kladiva^{144b}, M. H. Klein³⁶, M. Klein⁷⁵, U. Klein⁷⁵, K. Kleinknecht⁸⁴, P. Klimek^{146a,146b}, A. Klimentov²⁶, R. Klingenberg⁴⁴, J. A. Klinger¹³⁹, T. Klioutchnikova³¹, E.-E. Kluge^{59a}, P. Kluit¹⁰⁷, S. Kluth¹⁰¹, J. Knapik⁴⁰, E. Kneringer⁶³, E. B. F. G. Knoops⁸⁶, A. Knue⁵⁴, A. Kobayashi¹⁵⁵, D. Kobayashi¹⁵⁷, T. Kobayashi¹⁵⁵, M. Kobel⁴⁵, M. Kocian¹⁴³, P. Kodys¹²⁹, T. Koffas³⁰, E. Koffeman¹⁰⁷, L. A. Kogan¹²⁰, T. Kohriki⁶⁷, T. Koi¹⁴³, H. Kolanoski¹⁶, M. Kolb^{59b}, I. Koletsou⁵, A. A. Komar^{96,*}, Y. Komori¹⁵⁵, T. Kondo⁶⁷, N. Kondrashova⁴³, K. Köneke⁴⁹, A. C. König¹⁰⁶, T. Kono^{67,w}, R. Konoplich^{110,x}, N. Konstantinidis⁷⁹, R. Kopeliansky⁶², S. Koperny^{39a}, L. Köpke⁸⁴, A. K. Kopp⁴⁹, K. Korcyl⁴⁰, K. Kordas¹⁵⁴, A. Korn⁷⁹, A. A. Korol^{109,c}, I. Korolkov¹², E. V. Korolkova¹³⁹, O. Kortner¹⁰¹, S. Kortner¹⁰¹, T. Kosek¹²⁹, V. V. Kostyukhin²², V. M. Kotov⁶⁶, A. Kotwal⁴⁶, A. Kourkoumeli-Charalampidi¹⁵⁴, C. Kourkoumelis⁹, V. Kouskoura²⁶, A. Koutsman^{159a}, A. B. Kowalewska⁴⁰, R. Kowalewski¹⁶⁸, T. Z. Kowalski^{39a}, W. Kozanecki¹³⁶, A. S. Kozhin¹³⁰, V. A. Kramarenko⁹⁹, G. Kramberger⁷⁶, D. Krasnopeltsev⁹⁸, M. W. Krasny⁸¹, A. Krasznahorkay³¹, J. K. Kraus²², A. Kravchenko²⁶, M. Kretz^{59c}, J. Kretzschmar⁷⁵, K. Kreutzfeldt⁵³, P. Krieger¹⁵⁸, K. Krizka³², K. Kroeninger⁴⁴, H. Kroha¹⁰¹, J. Kroll¹²², J. Kroseberg²², J. Krstic¹³, U. Kruchonak⁶⁶, H. Krüger²², N. Krumnack⁶⁵, A. Kruse¹⁷², M. C. Kruse⁴⁶, M. Kruskal²³, T. Kubota⁸⁹, H. Kucuk⁷⁹, S. Kuday^{4b}, J. T. Kuechler¹⁷⁴, S. Kuehn⁴⁹, A. Kugel^{59c}, F. Kuger¹⁷³, A. Kuhl¹³⁷, T. Kuhl⁴³, V. Kukhtin⁶⁶, R. Kukla¹³⁶, Y. Kulchitsky⁹³, S. Kuleshov^{33b}, M. Kuna^{132a,132b}, T. Kunigo⁶⁹, A. Kupco¹²⁷, H. Kurashige⁶⁸, Y. A. Kurochkin⁹³, V. Kus¹²⁷, E. S. Kuwertz¹⁶⁸, M. Kuze¹⁵⁷, J. Kvita¹¹⁵, T. Kwan¹⁶⁸, D. Kyriazopoulos¹³⁹, A. La Rosa¹⁰¹, J. L. La Rosa Navarro^{25d}, L. La Rotonda^{38a,38b}, C. Lacasta¹⁶⁶, F. Lacava^{132a,132b}, J. Lacey³⁰, H. Lacker¹⁶, D. Lacour⁸¹, V. R. Lacuesta¹⁶⁶, E. Ladygin⁶⁶, R. Lafaye⁵, B. Laforge⁸¹, T. Lagouri¹⁷⁵, S. Lai⁵⁵, S. Lammers⁶², W. Lampf⁷, E. Lançon¹³⁶, U. Landgraf⁴⁹, M. P. J. Landon⁷⁷, V. S. Lang^{59a}, J. C. Lange¹², A. J. Lankford¹⁶², F. Lanni²⁶, K. Lantzsch²², A. Lanza^{121a}, S. Laplace⁸¹,

C. Lapoire³¹, J. F. Laporte¹³⁶, T. Lari^{92a}, F. Lasagni Manghi^{21a,21b}, M. Lassnig³¹, P. Laurelli⁴⁸, W. Lavrijsen¹⁵, A. T. Law¹³⁷, P. Laycock⁷⁵, T. Lazovich⁵⁸, M. Lazzaroni^{92a,92b}, O. Le Dortz⁸¹, E. Le Guirriec⁸⁶, E. Le Menedeu¹², E. P. Le Quilleuc¹³⁶, M. LeBlanc¹⁶⁸, T. LeCompte⁶, F. Ledroit-Guillon⁵⁶, C. A. Lee²⁶, S. C. Lee¹⁵¹, L. Lee¹, G. Lefebvre⁸¹, M. Lefebvre¹⁶⁸, F. Legger¹⁰⁰, C. Leggett¹⁵, A. Lehan⁷⁵, G. Lehmann Miotto³¹, X. Lei⁷, W. A. Leight³⁰, A. Leisos^{154,y}, A. G. Leister¹⁷⁵, M. A. L. Leite^{25d}, R. Leitner¹²⁹, D. Lellouch¹⁷¹, B. Lemmer⁵⁵, K. J. C. Leney⁷⁹, T. Lenz²², B. Lenzi³¹, R. Leone⁷, S. Leone^{124a,124b}, C. Leonidopoulos⁴⁷, S. Leontsinis¹⁰, G. Lerner¹⁴⁹, C. Leroy⁹⁵, A. A. J. Lesage¹³⁶, C. G. Lester²⁹, M. Levchenko¹²³, J. Levêque⁵, D. Levin⁹⁰, L. J. Levinson¹⁷¹, M. Levy¹⁸, A. M. Leyko²², M. Leyton⁴², B. Li^{34b,z}, H. Li¹⁴⁸, H. L. Li³², L. Li⁴⁶, L. Li^{34e}, Q. Li^{34a}, S. Li⁴⁶, X. Li⁸⁵, Y. Li¹⁴¹, Z. Liang¹³⁷, H. Liao³⁵, B. Liberti^{133a}, A. Liblong¹⁵⁸, P. Lichard³¹, K. Lie¹⁶⁵, J. Liebal²², W. Liebig¹⁴, C. Limbach²², A. Limosani¹⁵⁰, S. C. Lin^{151,aa}, T. H. Lin⁸⁴, B. E. Lindquist¹⁴⁸, E. Lipeles¹²², A. Lipniacka¹⁴, M. Lisovyi^{59b}, T. M. Liss¹⁶⁵, D. Lissauer²⁶, A. Lister¹⁶⁷, A. M. Litke¹³⁷, B. Liu^{151,ab}, D. Liu¹⁵¹, H. Liu⁹⁰, H. Liu²⁶, J. Liu⁸⁶, J. B. Liu^{34b}, K. Liu⁸⁶, L. Liu¹⁶⁵, M. Liu⁴⁶, M. Liu^{34b}, Y. L. Liu^{34b}, Y. Liu^{34b}, M. Livan^{121a,121b}, A. Lleres⁵⁶, J. Llorente Merino⁸³, S. L. Lloyd⁷⁷, F. Lo Sterzo¹⁵¹, E. Lobodzinska⁴³, P. Loch⁷, W. S. Lockman¹³⁷, F. K. Loebinger⁸⁵, A. E. Loevschall-Jensen³⁷, K. M. Loew²⁴, A. Loginov¹⁷⁵, T. Lohse¹⁶, K. Lohwasser⁴³, M. Lokajicek¹²⁷, B. A. Long²³, J. D. Long¹⁶⁵, R. E. Long⁷³, L. Longo^{74a,74b}, K. A.Looper¹¹¹, L. Lopes^{126a}, D. Lopez Mateos⁵⁸, B. Lopez Paredes¹³⁹, I. Lopez Paz¹², A. Lopez Solis⁸¹, J. Lorenz¹⁰⁰, N. Lorenzo Martinez⁶², M. Losada²⁰, P. J. Lösel¹⁰⁰, X. Lou^{34a}, A. Lounis¹¹⁷, J. Love⁶, P. A. Love⁷³, H. Lu^{61a}, N. Lu⁹⁰, H. J. Lubatti¹³⁸, C. Luci^{132a,132b}, A. Lucotte⁵⁶, C. Luedtke⁴⁹, F. Luehring⁶², W. Lukas⁶³, L. Luminari^{132a}, O. Lundberg^{146a,146b}, B. Lund-Jensen¹⁴⁷, D. Lynn²⁶, R. Lysak¹²⁷, E. Lytken⁸², V. Lyubushkin⁶⁶, H. Ma²⁶, L. L. Ma^{34d}, G. Maccarrone⁴⁸, A. Macchiolo¹⁰¹, C. M. Macdonald¹³⁹, B. Maček⁷⁶, J. Machado Miguens^{122,126b}, D. Madaffari⁸⁶, R. Madar³⁵, H. J. Maddocks¹⁶⁴, W. F. Mader⁴⁵, A. Madsen⁴³, J. Maeda⁶⁸, S. Maeland¹⁴, T. Maeno²⁶, A. Maevskiy⁹⁹, E. Magradze⁵⁵, J. Mahlstedt¹⁰⁷, C. Maiani¹¹⁷, C. Maidantchik^{25a}, A. A. Maier¹⁰¹, T. Maier¹⁰⁰, A. Maio^{126a,126b,126d}, S. Majewski¹¹⁶, Y. Makida⁶⁷, N. Makovec¹¹⁷, B. Malaescu⁸¹, Pa. Malecki⁴⁰, V. P. Maleev¹²³, F. Malek⁵⁶, U. Mallik⁶⁴, D. Malon⁶, C. Malone¹⁴³, S. Maltezos¹⁰, V. M. Malyshev¹⁰⁹, S. Malyukov³¹, J. Mamuzic⁴³, G. Mancini⁴⁸, B. Mandelli³¹, L. Mandelli^{92a}, I. Mandić⁷⁶, J. Maneira^{126a,126b}, L. Manhaes de Andrade Filho^{25b}, J. Manjarres Ramos^{159b}, A. Mann¹⁰⁰, B. Mansoulie¹³⁶, R. Mantifel⁸⁸, M. Mantoani⁵⁵, S. Manzoni^{92a,92b}, L. Mapelli³¹, G. Marceca²⁸, L. March⁵⁰, G. Marchiori⁸¹, M. Marcisovsky¹²⁷, M. Marjanovic¹³, D. E. Marley⁹⁰, F. Marroquim^{25a}, S. P. Marsden⁸⁵, Z. Marshall¹⁵, L. F. Marti¹⁷, S. Marti-Garcia¹⁶⁶, B. Martin⁹¹, T. A. Martin¹⁶⁹, V. J. Martin⁴⁷, B. Martin dit Latour¹⁴, M. Martinez^{12,p}, S. Martin-Haugh¹³¹, V. S. Martoiu^{27b}, A. C. Martyniuk⁷⁹, M. Marx¹³⁸, F. Marzano^{132a}, A. Marzin³¹, L. Masetti⁸⁴, T. Mashimo¹⁵⁵, R. Mashinistov⁹⁶, J. Masik⁸⁵, A. L. Maslennikov^{109,c}, I. Massa^{21a,21b}, L. Massa^{21a,21b}, P. Mastrandrea⁵, A. Mastroberardino^{38a,38b}, T. Masubuchi¹⁵⁵, P. Mättig¹⁷⁴, J. Mattmann⁸⁴, J. Maurer^{27b}, S. J. Maxfield⁷⁵, D. A. Maximov^{109,c}, R. Mazini¹⁵¹, S. M. Mazza^{92a,92b}, N. C. Mc Fadden¹⁰⁵, G. Mc Goldrick¹⁵⁸, S. P. Mc Kee⁹⁰, A. McCann⁹⁰, R. L. McCarthy¹⁴⁸, T. G. McCarthy³⁰, L. I. McClymont⁷⁹, K. W. McFarlane^{57,*}, J. A. McFayden⁷⁹, G. Mchedlidze⁵⁵, S. J. McMahon¹³¹, R. A. McPherson^{168,1}, M. Medinnis⁴³, S. Meehan¹³⁸, S. Mehlhase¹⁰⁰, A. Mehta⁷⁵, K. Meier^{59a}, C. Meineck¹⁰⁰, B. Meirose⁴², B. R. Mellado Garcia^{145c}, F. Meloni¹⁷, A. Mengarelli^{21a,21b}, S. Menke¹⁰¹, E. Meoni¹⁶¹, K. M. Mercurio⁵⁸, S. Mergelmeyer¹⁶, P. Mermod⁵⁰, L. Merola^{104a,104b}, C. Meroni^{92a}, F. S. Merritt³², A. Messina^{132a,132b}, J. Metcalfe⁶, A. S. Mete¹⁶², C. Meyer⁸⁴, C. Meyer¹²², J-P. Meyer¹³⁶, J. Meyer¹⁰⁷, H. Meyer Zu Theenhausen^{59a}, R. P. Middleton¹³¹, S. Miglioranzi^{163a,163c}, L. Mijović²², G. Mikenberg¹⁷¹, M. Mikesikova¹²⁷, M. Mikuz⁷⁶, M. Milesi⁸⁹, A. Milic³¹, D. W. Miller³², C. Mills⁴⁷, A. Milov¹⁷¹, D. A. Milstead^{146a,146b}, A. A. Minaenko¹³⁰, Y. Minami¹⁵⁵, I. A. Minashvili⁶⁶, A. I. Mincer¹¹⁰, B. Mindur^{39a}, M. Mineev⁶⁶, Y. Ming¹⁷², L. M. Mir¹², K. P. Mistry¹²², T. Mitani¹⁷⁰, J. Mitrevski¹⁰⁰, V. A. Mitsou¹⁶⁶, A. Miucci⁵⁰, P. S. Miyagawa¹³⁹, J. U. Mjörnmark⁸², T. Moa^{146a,146b}, K. Mochizuki⁸⁶, S. Mohapatra³⁶, W. Mohr⁴⁹, S. Molander^{146a,146b}, R. Moles-Valls²², R. Monden⁶⁹, M. C. Mondragon⁹¹, K. Mönig⁴³, J. Monk³⁷, E. Monnier⁸⁶, A. Montalbano¹⁴⁸, J. Montejo Berlingen³¹, F. Monticelli⁷², S. Monzani^{92a,92b}, R. W. Moore³, N. Morange¹¹⁷, D. Moreno²⁰, M. Moreno Llácer⁵⁵, P. Morettini^{51a}, D. Mori¹⁴², T. Mori¹⁵⁵, M. Morii⁵⁸, M. Morinaga¹⁵⁵, V. Morisbak¹¹⁹, S. Moritz⁸⁴, A. K. Morley¹⁵⁰, G. Mornacchi³¹, J. D. Morris⁷⁷, S. S. Mortensen³⁷, L. Morvaj¹⁴⁸, M. Mosidze^{52b}, J. Moss¹⁴³, K. Motohashi¹⁵⁷, R. Mount¹⁴³, E. Mountricha²⁶, S. V. Mouraviev^{96,*}, E. J. W. Moyses⁸⁷, S. Muanza⁸⁶, R. D. Mudd¹⁸, F. Mueller¹⁰¹, J. Mueller¹²⁵, R. S. P. Mueller¹⁰⁰, T. Mueller²⁹, D. Muenstermann⁷³, P. Mullen⁵⁴, G. A. Mullier¹⁷, F. J. Munoz Sanchez⁸⁵, J. A. Murillo Quijada¹⁸, W. J. Murray^{169,131}, H. Musheghyan⁵⁵, A. G. Myagkov^{130,ac}, M. Myska¹²⁸, B. P. Nachman¹⁴³, O. Nackenhorst⁵⁰, J. Nadal⁵⁵, K. Nagai¹²⁰, R. Nagai^{67,w}, Y. Nagai⁸⁶, K. Nagano⁶⁷, Y. Nagasaka⁶⁰, K. Nagata¹⁶⁰, M. Nagel¹⁰¹, E. Nagy⁸⁶, A. M. Nairz³¹, Y. Nakahama³¹, K. Nakamura⁶⁷, T. Nakamura¹⁵⁵, I. Nakano¹¹², H. Namasivayam⁴², R. F. Naranjo Garcia⁴³, R. Narayan³², D. I. Narrias Villar^{59a}, I. Naryshkin¹²³, T. Naumann⁴³, G. Navarro²⁰, R. Nayyar⁷, H. A. Neal⁹⁰, P. Yu. Nechaeva⁹⁶, T. J. Neep⁸⁵, P. D. Nef¹⁴³, A. Negri^{121a,121b}, M. Negrini^{21a}, S. Nektarijevic¹⁰⁶, C. Nellist¹¹⁷, A. Nelson¹⁶², S. Nemecek¹²⁷, P. Nemethy¹¹⁰, A. A. Nepomuceno^{25a}, M. Nessi^{31,ad}, M. S. Neubauer¹⁶⁵, M. Neumann¹⁷⁴,

R. M. Neves¹¹⁰, P. Nevski²⁶, P. R. Newman¹⁸, D. H. Nguyen⁶, R. B. Nickerson¹²⁰, R. Nicolaidou¹³⁶, B. Nicquevert³¹, J. Nielsen¹³⁷, A. Nikiforov¹⁶, V. Nikolaenko^{130,ac}, I. Nikolic-Audit⁸¹, K. Nikolopoulos¹⁸, J. K. Nilsen¹¹⁹, P. Nilsson²⁶, Y. Ninomiya¹⁵⁵, A. Nisati^{132a}, R. Nisius¹⁰¹, T. Nobe¹⁵⁵, L. Nodulman⁶, M. Nomachi¹¹⁸, I. Nomidis³⁰, T. Nooney⁷⁷, S. Norberg¹¹³, M. Nordberg³¹, N. Norjoharuddeen¹²⁰, O. Novgorodova⁴⁵, S. Nowak¹⁰¹, M. Nozaki⁶⁷, L. Nozka¹¹⁵, K. Ntekas¹⁰, E. Nurse⁷⁹, F. Nuti⁸⁹, F. O'grady⁷, D. C. O'Neil¹⁴², A. A. O'Rourke⁴³, V. O'Shea⁵⁴, F. G. Oakham^{30,d}, H. Oberlack¹⁰¹, T. Obermann²², J. Ocariz⁸¹, A. Ochi⁶⁸, I. Ochoa³⁶, J. P. Ochoa-Ricoux^{33a}, S. Oda⁷¹, S. Odaka⁶⁷, H. Ogren⁶², A. Oh⁸⁵, S. H. Oh⁴⁶, C. C. Ohm¹⁵, H. Ohman¹⁶⁴, H. Oide³¹, H. Okawa¹⁶⁰, Y. Okumura³², T. Okuyama⁶⁷, A. Olariu^{27b}, L. F. Oleiro Seabra^{126a}, S. A. Olivares Pino⁴⁷, D. Oliveira Damazio²⁶, A. Olszewski⁴⁰, J. Olszowska⁴⁰, A. Onofre^{126a,126e}, K. Onogi¹⁰³, P. U. E. Onyisi^{32,s}, C. J. Oram^{159a}, M. J. Oreglia³², Y. Oren¹⁵³, D. Orestano^{134a,134b}, N. Orlando^{61b}, R. S. Orr¹⁵⁸, B. Osculati^{51a,51b}, R. Ospanov⁸⁵, G. Otero y Garzon²⁸, H. Otono⁷¹, M. Ouchrif^{135d}, F. Ould-Saada¹¹⁹, A. Ouraou¹³⁶, K. P. Oussoren¹⁰⁷, Q. Ouyang^{34a}, A. Ovcharova¹⁵, M. Owen⁵⁴, R. E. Owen¹⁸, V. E. Ozcan^{19a}, N. Ozturk⁸, K. Pachal¹⁴², A. Pacheco Pages¹², C. Padilla Aranda¹², M. Pagáčová⁴⁹, S. Pagan Griso¹⁵, F. Paige²⁶, P. Pais⁸⁷, K. Pajchel¹¹⁹, G. Palacino^{159b}, S. Palestini³¹, M. Palka^{39b}, D. Pallin³⁵, A. Palma^{126a,126b}, E. St. Panagiotopoulou¹⁰, C. E. Pandini⁸¹, J. G. Panduro Vazquez⁷⁸, P. Pani^{146a,146b}, S. Panitkin²⁶, D. Pantea^{27b}, L. Paolozzi⁵⁰, Th. D. Papadopoulou¹⁰, K. Papageorgiou¹⁵⁴, A. Paramonov⁶, D. Paredes Hernandez¹⁷⁵, M. A. Parker²⁹, K. A. Parker¹³⁹, F. Parodi^{51a,51b}, J. A. Parsons³⁶, U. Parzefall⁴⁹, V. R. Pascuzzi¹⁵⁸, E. Pasqualucci^{132a}, S. Passaggio^{51a}, F. Pastore^{134a,134b,*}, Fr. Pastore⁷⁸, G. Pásztor³⁰, S. Pataraiia¹⁷⁴, N. D. Patel¹⁵⁰, J. R. Pater⁸⁵, T. Pauly³¹, J. Pearce¹⁶⁸, B. Pearson¹¹³, L. E. Pedersen³⁷, M. Pedersen¹¹⁹, S. Pedraza Lopez¹⁶⁶, R. Pedro^{126a,126b}, S. V. Peleganchuk^{109,c}, D. Pelikan¹⁶⁴, O. Penc¹²⁷, C. Peng^{34a}, H. Peng^{34b}, J. Penwell⁶², B. S. Peralva^{25b}, M. M. Perego¹³⁶, D. V. Perepelitsa²⁶, E. Perez Codina^{159a}, L. Perini^{92a,92b}, H. Pernegger³¹, S. Perrella^{104a,104b}, R. Peschke⁴³, V. D. Peshekhonov⁶, K. Peters³¹, R. F. Y. Peters⁸⁵, B. A. Petersen³¹, T. C. Petersen³⁷, E. Petit⁵⁶, A. Petridis¹, C. Petridou¹⁵⁴, P. Petroff¹¹⁷, E. Petrolu^{132a}, M. Petrov¹²⁰, F. Petrucci^{134a,134b}, N. E. Pettersson¹⁵⁷, A. Peyaud¹³⁶, R. Pezoa^{33b}, P. W. Phillips¹³¹, G. Piacquadio¹⁴³, E. Pianori¹⁶⁹, A. Picazio⁸⁷, E. Piccaro⁷⁷, M. Piccinini^{21a,21b}, M. A. Pickering¹²⁰, R. Piegaiia²⁸, J. E. Pilcher³², A. D. Pilkington⁸⁵, A. W. J. Pin⁸⁵, J. Pina^{126a,126b,126d}, M. Pinamonti^{163a,163c,ae}, J. L. Pinfold³, A. Pingel³⁷, S. Pires⁸¹, H. Pirumov⁴³, M. Pitt¹⁷¹, L. Plazak^{144a}, M.-A. Pleier²⁶, V. Pleskot⁸⁴, E. Plotnikova⁶⁶, P. Plucinski^{146a,146b}, D. Pluth⁶⁵, R. Poettgen^{146a,146b}, L. Poggioli¹¹⁷, D. Pohl²², G. Polesello^{121a}, A. Poley⁴³, A. Policicchio^{38a,38b}, R. Polifka¹⁵⁸, A. Polini^{21a}, C. S. Pollard⁵⁴, V. Polychronakos²⁶, K. Pommès³¹, L. Pontecorvo^{132a}, B. G. Pope⁹¹, G. A. Popeneciu^{27c}, D. S. Popovic¹³, A. Poppleton³¹, S. Pospisil¹²⁸, K. Potamianos¹⁵, I. N. Potrap⁶⁶, C. J. Potter²⁹, C. T. Potter¹¹⁶, G. Poulard³¹, J. Poveda³¹, V. Pozdnyakov⁶⁶, M. E. Pozo Astigarraga³¹, P. Pralavorio⁸⁶, A. Pranko¹⁵, S. Prell⁶⁵, D. Price⁸⁵, L. E. Price⁶, M. Primavera^{74a}, S. Prince⁸⁸, M. Proissl⁴⁷, K. Prokofiev^{61c}, F. Prokoshin^{33b}, S. Protopopescu²⁶, J. Proudfoot⁶, M. Przybycien^{39a}, D. Puudu^{134a,134b}, D. Poldon¹⁴⁸, M. Purohit^{26,af}, P. Puzo¹¹⁷, J. Qian⁹⁰, G. Qin⁵⁴, Y. Qin⁸⁵, A. Quadt⁵⁵, W. B. Quayle^{163a,163b}, M. Queitsch-Maitland⁸⁵, D. Quilty⁵⁴, S. Raddum¹¹⁹, V. Radeka²⁶, V. Radescu^{59b}, S. K. Radhakrishnan¹⁴⁸, P. Radloff¹¹⁶, P. Rados⁸⁹, F. Ragusa^{92a,92b}, G. Rahal¹⁷⁷, S. Rajagopalan²⁶, M. Rammensee³¹, C. Rangel-Smith¹⁶⁴, M. G. Ratti^{92a,92b}, F. Rauscher¹⁰⁰, S. Rave⁸⁴, T. Ravenscroft⁵⁴, M. Raymond³¹, A. L. Read¹¹⁹, N. P. Readioff⁷⁵, D. M. Rebuffi^{121a,121b}, A. Redelbach¹⁷³, G. Redlinger²⁶, R. Reece¹³⁷, K. Reeves⁴², L. Rehnisch¹⁶, J. Reichert¹²², H. Reisin²⁸, C. Rembser³¹, H. Ren^{34a}, M. Rescigno^{132a}, S. Resconi^{92a}, O. L. Rezanova^{109,c}, P. Reznicek¹²⁹, R. Rezvani⁹⁵, R. Richter¹⁰¹, S. Richter⁷⁹, E. Richter-Was^{39b}, O. Ricken²², M. Ridel⁸¹, P. Rieck¹⁶, C. J. Riegel¹⁷⁴, J. Rieger⁵⁵, O. Rifki¹¹³, M. Rijssenbeek¹⁴⁸, A. Rimoldi^{121a,121b}, L. Rinaldi^{21a}, B. Ristic⁵⁰, E. Ritsch³¹, I. Riu¹², F. Rizatdinova¹¹⁴, E. Rizvi⁷⁷, C. Rizzi¹², S. H. Robertson^{88,1}, A. Robichaud-Veronneau⁸⁸, D. Robinson²⁹, J. E. M. Robinson⁴³, A. Robson⁵⁴, C. Roda^{124a,124b}, Y. Rodina⁸⁶, A. Rodriguez Perez¹², D. Rodriguez Rodriguez¹⁶⁶, S. Roe³¹, C. S. Rogan⁵⁸, O. Røhne¹¹⁹, A. Romaniouk⁹⁸, M. Romano^{21a,21b}, S. M. Romano Saez³⁵, E. Romero Adam¹⁶⁶, N. Rompotis¹³⁸, M. Ronzani⁴⁹, L. Roos⁸¹, E. Ros¹⁶⁶, S. Rosati^{132a}, K. Rosbach⁴⁹, P. Rose¹³⁷, O. Rosenthal¹⁴¹, V. Rossetti^{146a,146b}, E. Rossi^{104a,104b}, L. P. Rossi^{51a}, J. H. N. Rosten²⁹, R. Rosten¹³⁸, M. Rotaru^{27b}, I. Roth¹⁷¹, J. Rothberg¹³⁸, D. Rousseau¹¹⁷, C. R. Royon¹³⁶, A. Rozanov⁸⁶, Y. Rozen¹⁵², X. Ruan^{145c}, F. Rubbo¹⁴³, I. Rubinskiy⁴³, V. I. Rud⁹⁹, M. S. Rudolph¹⁵⁸, F. Rühr⁴⁹, A. Ruiz-Martinez³¹, Z. Rurikova⁴⁹, N. A. Rusakovich⁶⁶, A. Ruschke¹⁰⁰, H. L. Russell¹³⁸, J. P. Rutherford⁷, N. Ruthmann³¹, Y. F. Ryabov¹²³, M. Rybar¹⁶⁵, G. Rybkin¹¹⁷, S. Ryu⁶, A. Ryzhov¹³⁰, A. F. Saavedra¹⁵⁰, G. Sabato¹⁰⁷, S. Sacerdoti²⁸, H. F.-W. Sadrozinski¹³⁷, R. Sadykov⁶⁶, F. Safai Tehrani^{132a}, P. Saha¹⁰⁸, M. Sahinsoy^{59a}, M. Saimpert¹³⁶, T. Saito¹⁵⁵, H. Sakamoto¹⁵⁵, Y. Sakurai¹⁷⁰, G. Salamanna^{134a,134b}, A. Salamon^{133a,133b}, J. E. Salazar Loyola^{33b}, D. Salek¹⁰⁷, P. H. Sales De Bruin¹³⁸, D. Saliagic¹⁰¹, A. Salnikov¹⁴³, J. Salt¹⁶⁶, D. Salvatore^{38a,38b}, F. Salvatore¹⁴⁹, A. Salvucci^{61a}, A. Salzburger³¹, D. Sammel⁴⁹, D. Sampsonidis¹⁵⁴, A. Sanchez^{104a,104b}, J. Sánchez¹⁶⁶, V. Sanchez Martinez¹⁶⁶, H. Sandaker¹¹⁹, R. L. Sandbach⁷⁷, H. G. Sander⁸⁴, M. P. Sanders¹⁰⁰, M. Sandhoff¹⁷⁴, C. Sandoval²⁰, R. Sandstroem¹⁰¹, D. P. C. Sankey¹³¹, M. Sannino^{51a,51b}, A. Sansoni⁴⁸, C. Santoni³⁵, R. Santonico^{133a,133b}, H. Santos^{126a}, I. Santoyo Castillo¹⁴⁹, K. Sapp¹²⁵, A. Saproinov⁶⁶, J. G. Saraiva^{126a,126d}, B. Sarrazin²², O. Sasaki⁶⁷,

Y. Sasaki¹⁵⁵, K. Sato¹⁶⁰, G. Sauvage^{5,*}, E. Sauvan⁵, G. Savage⁷⁸, P. Savard^{158,d}, C. Sawyer¹³¹, L. Sawyer^{80,o}, J. Saxon³², C. Sbarra^{21a}, A. Sbrizzi^{21a,21b}, T. Scanlon⁷⁹, D. A. Scannicchio¹⁶², M. Scarcella¹⁵⁰, V. Scarfone^{38a,38b}, J. Schaarschmidt¹⁷¹, P. Schacht¹⁰¹, D. Schaefer³¹, R. Schaefer⁴³, J. Schaeffer⁸⁴, S. Schaepe²², S. Schaezel^{59b}, U. Schäfer⁸⁴, A. C. Schaffer¹¹⁷, D. Schaile¹⁰⁰, R. D. Schamberger¹⁴⁸, V. Scharf^{59a}, V. A. Schegelsky¹²³, D. Scheirich¹²⁹, M. Schernau¹⁶², C. Schiavi^{51a,51b}, C. Schillo⁴⁹, M. Schioppa^{38a,38b}, S. Schlenker³¹, K. Schmieden³¹, C. Schmitt⁸⁴, S. Schmitt⁴³, S. Schmitz⁸⁴, B. Schneider^{159a}, Y. J. Schnellbach⁷⁵, U. Schnoor⁴⁹, L. Schoeffel¹³⁶, A. Schoening^{59b}, B. D. Schoenrock⁹¹, E. Schopf²², A. L. S. Schorlemmer⁴⁴, M. Schott⁸⁴, D. Schouten^{159a}, J. Schovancova⁸, S. Schramm⁵⁰, M. Schreyer¹⁷³, N. Schuh⁸⁴, M. J. Schultens²², H.-C. Schultz-Coulon^{59a}, H. Schulz¹⁶, M. Schumacher⁴⁹, B. A. Schumm¹³⁷, Ph. Schune¹³⁶, C. Schwanenberger⁸⁵, A. Schwartzman¹⁴³, T. A. Schwarz⁹⁰, Ph. Schwegler¹⁰¹, H. Schweiger⁸⁵, Ph. Schwemling¹³⁶, R. Schwienhorst⁹¹, J. Schwindling¹³⁶, T. Schwindt²², G. Sciolla²⁴, F. Scuri^{124a,124b}, F. Scutti⁸⁹, J. Searcy⁹⁰, P. Seema²², S. C. Seidel¹⁰⁵, A. Seiden¹³⁷, F. Seifert¹²⁸, J. M. Seixas^{25a}, G. Sekhniaidze^{104a}, K. Sekhon⁹⁰, S. J. Sekula⁴¹, D. M. Seliverstov^{123,*}, N. Semprini-Cesari^{21a,21b}, C. Serfon¹¹⁹, L. Serin¹¹⁷, L. Serkin^{163a,163b}, M. Sessa^{134a,134b}, R. Seuster^{159a}, H. Severini¹¹³, T. Sfiligoi⁷⁶, F. Sforza³¹, A. Sfyrila⁵⁰, E. Shabalina⁵⁵, N. W. Shaikh^{146a,146b}, L. Y. Shan^{34a}, R. Shang¹⁶⁵, J. T. Shank²³, M. Shapiro¹⁵, P. B. Shatalov⁹⁷, K. Shaw^{163a,163b}, S. M. Shaw⁸⁵, A. Shcherbakova^{146a,146b}, C. Y. Shehu¹⁴⁹, P. Sherwood⁷⁹, L. Shi^{151,ag}, S. Shimizu⁶⁸, C. O. Shimmin¹⁶², M. Shimojima¹⁰², M. Shiyakova^{66,ah}, A. Shmeleva⁹⁶, D. Shoaleh Saadi⁹⁵, M. J. Shochet³², S. Shojaii^{92a,92b}, S. Shrestha¹¹¹, E. Shulga⁹⁸, M. A. Shupe⁷, P. Sicho¹²⁷, P. E. Sidebo¹⁴⁷, O. Sidiropoulou¹⁷³, D. Sidorov¹¹⁴, A. Sidoti^{21a,21b}, F. Siegert⁴⁵, Dj. Sijacki¹³, J. Silva^{126a,126d}, S. B. Silverstein^{146a}, V. Simak¹²⁸, O. Simard⁵, Lj. Simic¹³, S. Simion¹¹⁷, E. Simioni⁸⁴, B. Simmons⁷⁹, D. Simon³⁵, M. Simon⁸⁴, P. Sinervo¹⁵⁸, N. B. Sinev¹¹⁶, M. Sioli^{21a,21b}, G. Siragusa¹⁷³, S. Yu. Sivoklokov⁹⁹, J. Sjölin^{146a,146b}, T. B. Sjurson¹⁴, M. B. Skinner⁷³, H. P. Skottowe⁵⁸, P. Skubic¹¹³, M. Slater¹⁸, T. Slavicek¹²⁸, M. Slawinska¹⁰⁷, K. Sliwa¹⁶¹, R. Slovak¹²⁹, V. Smakhtin¹⁷¹, B. H. Smart⁵, L. Smestad¹⁴, S. Yu. Smirnov⁹⁸, Y. Smirnov⁹⁸, L. N. Smirnova^{99,ai}, O. Smirnova⁸², M. N. K. Smith³⁶, R. W. Smith³⁶, M. Smizanska⁷³, K. Smolek¹²⁸, A. A. Snesarev⁹⁶, G. Snidero⁷⁷, S. Snyder²⁶, R. Sobie^{168,1}, F. Socher⁴⁵, A. Soffer¹⁵³, D. A. Soh^{151,ag}, G. Sokhranyii⁷⁶, C. A. Solans Sanchez³¹, M. Solar¹²⁸, E. Yu. Soldatov⁹⁸, U. Soldevila¹⁶⁶, A. A. Solodkov¹³⁰, A. Soloshenko⁶⁶, O. V. Solovyanov¹³⁰, V. Solovyev¹²³, P. Sommer⁴⁹, H. Son¹⁶¹, H. Y. Song^{34b,z}, A. Sood¹⁵, A. Sopczak¹²⁸, V. Sopko¹²⁸, V. Sorin¹², D. Sosa^{59b}, C. L. Sotiropoulou^{124a,124b}, R. Soualah^{163a,163c}, A. M. Soukharev^{109,c}, D. South⁴³, B. C. Sowden⁷⁸, S. Spagnolo^{74a,74b}, M. Spalla^{124a,124b}, M. Spangenberg¹⁶⁹, F. Spanò⁷⁸, D. Sperlich¹⁶, F. Spettel¹⁰¹, R. Spighi^{21a}, G. Spigo³¹, L. A. Spiller⁸⁹, M. Spousta¹²⁹, R. D. St. Denis^{54,*}, A. Stabile^{92a}, J. Stahlman¹²², R. Stamen^{59a}, S. Stamm¹⁶, E. Stanecka⁴⁰, R. W. Stanek⁶, C. Stancu^{134a}, M. Stancu-Bellu⁴³, M. M. Stanitzki⁴³, S. Stapnes¹¹⁹, E. A. Starchenko¹³⁰, G. H. Stark³², J. Stark⁵⁶, P. Staroba¹²⁷, P. Starovoitov^{59a}, S. Stärz³¹, R. Staszewski⁴⁰, P. Steinberg²⁶, B. Stelzer¹⁴², H. J. Stelzer³¹, O. Stelzer-Chilton^{159a}, H. Stenzel⁵³, G. A. Stewart⁵⁴, J. A. Stillings²², M. C. Stockton⁸⁸, M. Stoebe⁸⁸, G. Stoica^{27b}, P. Stolte⁵⁵, S. Stonjek¹⁰¹, A. R. Stradling⁸, A. Straessner⁴⁵, M. E. Stramaglia¹⁷, J. Strandberg¹⁴⁷, S. Strandberg^{146a,146b}, A. Strandlie¹¹⁹, M. Strauss¹¹³, P. Strizeneč^{144b}, R. Ströhmer¹⁷³, D. M. Strom¹¹⁶, R. Stroynowski⁴¹, A. Strubig¹⁰⁶, S. A. Stucci¹⁷, B. Stugu¹⁴, N. A. Styles⁴³, D. Su¹⁴³, J. Su¹²⁵, R. Subramaniam⁸⁰, S. Suchek^{59a}, Y. Sugaya¹¹⁸, M. Suk¹²⁸, V. V. Sulin⁹⁶, S. Sultansoy^{4c}, T. Sumida⁶⁹, S. Sun⁵⁸, X. Sun^{34a}, J. E. Sundermann⁴⁹, K. Suruliz¹⁴⁹, G. Susinno^{38a,38b}, M. R. Sutton¹⁴⁹, S. Suzuki⁶⁷, M. Svatos¹²⁷, M. Swiatlowski³², I. Sykora^{144a}, T. Sykora¹²⁹, D. Ta⁴⁹, C. Taccini^{134a,134b}, K. Tackmann⁴³, J. Taenzer¹⁵⁸, A. Taffard¹⁶², R. Tafirout^{159a}, N. Taiblum¹⁵³, H. Takai²⁶, R. Takashima⁷⁰, H. Takeda⁶⁸, T. Takeshita¹⁴⁰, Y. Takubo⁶⁷, M. Talby⁸⁶, A. A. Talyshev^{109,c}, J. Y. C. Tam¹⁷³, K. G. Tan⁸⁹, J. Tanaka¹⁵⁵, R. Tanaka¹¹⁷, S. Tanaka⁶⁷, B. B. Tannenwald¹¹¹, S. Tapia Araya^{33b}, S. Tapprogge⁸⁴, S. Tarem¹⁵², G. F. Tartarelli^{92a}, P. Tas¹²⁹, M. Tasevsky¹²⁷, T. Tashiro⁶⁹, E. Tassi^{38a,38b}, A. Tavares Delgado^{126a,126b}, Y. Tayalati^{135d}, A. C. Taylor¹⁰⁵, G. N. Taylor⁸⁹, P. T. E. Taylor⁸⁹, W. Taylor^{159b}, F. A. Teischinger³¹, P. Teixeira-Dias⁷⁸, K. K. Temming⁴⁹, D. Temple¹⁴², H. Ten Kate³¹, P. K. Teng¹⁵¹, J. J. Teoh¹¹⁸, F. Tepel¹⁷⁴, S. Terada⁶⁷, K. Terashi¹⁵⁵, J. Terron⁸³, S. Terzo¹⁰¹, M. Testa⁴⁸, R. J. Teuscher^{158,1}, T. Theveneaux-Pelzer⁸⁶, J. P. Thomas¹⁸, J. Thomas-Wilsker⁷⁸, E. N. Thompson³⁶, P. D. Thompson¹⁸, R. J. Thompson⁸⁵, A. S. Thompson⁵⁴, L. A. Thomsen¹⁷⁵, E. Thomson¹²², M. Thomson²⁹, M. J. Tibbetts¹⁵, R. E. Tiesse Torres⁸⁶, V. O. Tikhomirov^{96,aj}, Yu. A. Tikhonov^{109,c}, S. Timoshenko⁹⁸, P. Tipton¹⁷⁵, S. Tisserant⁸⁶, K. Todome¹⁵⁷, T. Todorov^{5,*}, S. Todorova-Nova¹²⁹, J. Tojo⁷¹, S. Tokár^{144a}, K. Tokushuku⁶⁷, E. Tolley⁵⁸, L. Tomlinson⁸⁵, M. Tomoto¹⁰³, L. Tompkins^{143,ak}, K. Toms¹⁰⁵, B. Tong⁵⁸, P. Tornambe⁴⁹, E. Torrence¹¹⁶, H. Torres¹⁴², E. Torró Pastor¹³⁸, J. Toth^{86,al}, F. Touchard⁸⁶, D. R. Tovey¹³⁹, T. Trefzger¹⁷³, L. Tremblet³¹, H. Trepanier⁹⁵, A. Tricoli³¹, I. M. Trigger^{159a}, S. Trincaz-Duvold⁸¹, M. F. Tripiana¹², W. Trischuk¹⁵⁸, B. Trocme⁵⁶, A. Trofymov⁴³, C. Troncon^{92a}, M. Trotter-McDonald¹⁵, M. Trovatelli¹⁶⁸, L. Truong^{163a,163b}, M. Trzebinski⁴⁰, A. Trzupek⁴⁰, J. C.-L. Tseng¹²⁰, P. V. Tsiarehshka⁹³, G. Tsipolitis¹⁰, N. Tsirintanis⁹, S. Tsiskaridze¹², V. Tsiskaridze⁴⁹, E. G. Tskhadadze^{52a}, K. M. Tsui^{61a}, I. I. Tsukerman⁹⁷, V. Tsulaia¹⁵, S. Tsuno⁶⁷, D. Tsybychev¹⁴⁸, A. Tudorache^{27b}, V. Tudorache^{27b}, A. N. Tuna⁵⁸, S. A. Tupputi^{21a,21b}, S. Turchikhin^{99,ai}, D. Turecek¹²⁸, D. Turgeman¹⁷¹, R. Turra^{92a,92b}, A. J. Turvey⁴¹, P. M. Tuts³⁶, M. Tylmad^{146a,146b}, M. Tyndel¹³¹, G. Uccielli^{21a,21b}, I. Ueda¹⁵⁵, R. Ueno³⁰

M. Ughetto^{146a,146b}, F. Ukegawa¹⁶⁰, G. Unal³¹, A. Undrus²⁶, G. Unel¹⁶², F. C. Ungaro⁸⁹, Y. Unno⁶⁷, C. Unverdorben¹⁰⁰, J. Urban^{144b}, P. Urquijo⁸⁹, P. Urrejola⁸⁴, G. Usai⁸, A. Usanova⁶³, L. Vacavant⁸⁶, V. Vacek¹²⁸, B. Vachon⁸⁸, C. Valderanis⁸⁴, E. Valdes Santurio^{146a,146b}, N. Valencic¹⁰⁷, S. Valentineti^{21a,21b}, A. Valero¹⁶⁶, L. Valery¹², S. Valkar¹²⁹, S. Vallecorsa⁵⁰, J. A. Valls Ferrer¹⁶⁶, W. Van Den Wollenberg¹⁰⁷, P. C. Van Der Deijl¹⁰⁷, R. van der Geer¹⁰⁷, H. van der Graaf¹⁰⁷, N. van Eldik¹⁵², P. van Gemmeren⁶, J. Van Nieuwkoop¹⁴², I. van Vulpen¹⁰⁷, M. C. van Woerden³¹, M. Vanadia^{132a,132b}, W. Vandelli³¹, R. Vanguri¹²², A. Vaniachine⁶, P. Vankov¹⁰⁷, G. Vardanyan¹⁷⁶, R. Vari^{132a}, E. W. Varnes⁷, T. Varol⁴¹, D. Varouchas⁸¹, A. Vartapetian⁸, K. E. Varvell¹⁵⁰, F. Vazeille³⁵, T. Vazquez Schroeder⁸⁸, J. Veatch⁷, L. M. Veloce¹⁵⁸, F. Veloso^{126a,126c}, S. Veneziano^{132a}, A. Ventura^{74a,74b}, M. Venturi¹⁶⁸, N. Venturi¹⁵⁸, A. Venturini²⁴, V. Vercesi^{121a}, M. Verducci^{132a,132b}, W. Verkerke¹⁰⁷, J. C. Vermeulen¹⁰⁷, A. Vest^{45.am}, M. C. Vetterli^{142.d}, O. Viazlo⁸², I. Vichou¹⁶⁵, T. Vickey¹³⁹, O. E. Vickey Boeriu¹³⁹, G. H. A. Viehhauser¹²⁰, S. Viel¹⁵, R. Vigne⁶³, M. Villa^{21a,21b}, M. Villaplana Perez^{92a,92b}, E. Vilucchi⁴⁸, M. G. Vincter³⁰, V. B. Vinogradov⁶⁶, C. Vittori^{21a,21b}, I. Vivarelli¹⁴⁹, S. Vlachos¹⁰, M. Vlasak¹²⁸, M. Vogel¹⁷⁴, P. Vokac¹²⁸, G. Volpi^{124a,124b}, M. Volpi⁸⁹, H. von der Schmitt¹⁰¹, E. von Toerne²², V. Vorobel¹²⁹, K. Vorobev⁹⁸, M. Vos¹⁶⁶, R. Voss³¹, J. H. Vosseveld⁷⁵, N. Vranjes¹³, M. Vranjes Milosavljevic¹³, V. Vrba¹²⁷, M. Vreeswijk¹⁰⁷, R. Vuillermet³¹, I. Vukotic³², Z. Vykydal¹²⁸, P. Wagner²², W. Wagner¹⁷⁴, H. Wahlberg⁷², S. Wahrmund⁴⁵, J. Wakabayashi¹⁰³, J. Walder⁷³, R. Walker¹⁰⁰, W. Walkowiak¹⁴¹, V. Wallangen^{146a,146b}, C. Wang¹⁵¹, C. Wang^{34d,86}, F. Wang¹⁷², H. Wang¹⁵, H. Wang⁴¹, J. Wang⁴³, J. Wang¹⁵⁰, K. Wang⁸⁸, R. Wang⁶, S. M. Wang¹⁵¹, T. Wang²², T. Wang³⁶, X. Wang¹⁷⁵, C. Wanotayaroj¹¹⁶, A. Warburton⁸⁸, C. P. Ward²⁹, D. R. Wardrope⁷⁹, A. Washbrook⁴⁷, P. M. Watkins¹⁸, A. T. Watson¹⁸, I. J. Watson¹⁵⁰, M. F. Watson¹⁸, G. Watts¹³⁸, S. Watts⁸⁵, B. M. Waugh⁷⁹, S. Webb⁸⁴, M. S. Weber¹⁷, S. W. Weber¹⁷³, J. S. Webster⁶, A. R. Weidberg¹²⁰, B. Weinert⁶², J. Weingarten⁵⁵, C. Weiser⁴⁹, H. Weits¹⁰⁷, P. S. Wells³¹, T. Wenaus²⁶, T. Wengler³¹, S. Wenig³¹, N. Wermes²², M. Werner⁴⁹, P. Werner³¹, M. Wessels^{59a}, J. Wetter¹⁶¹, K. Whalen¹¹⁶, N. L. Whallon¹³⁸, A. M. Wharton⁷³, A. White⁸, M. J. White¹, R. White^{33b}, S. White^{124a,124b}, D. Whiteson¹⁶², F. J. Wickens¹³¹, W. Wiedenmann¹⁷², M. Wielers¹³¹, P. Wienemann²², C. Wiglesworth³⁷, L. A. M. Wiik-Fuchs²², A. Wildauer¹⁰¹, H. G. Wilkens³¹, H. H. Williams¹²², S. Williams¹⁰⁷, C. Willis⁹¹, S. Willocq⁸⁷, J. A. Wilson¹⁸, I. Wingerter-Seetz⁵, F. Winklmeier¹¹⁶, O. J. Winston¹⁴⁹, B. T. Winter²², M. Wittgen¹⁴³, J. Wittkowski¹⁰⁰, S. J. Wollstadt⁸⁴, M. W. Wolter⁴⁰, H. Wolters^{126a,126c}, B. K. Wosiek⁴⁰, J. Wotschack³¹, M. J. Woudstra⁸⁵, K. W. Wozniak⁴⁰, M. Wu⁵⁶, M. Wu³², S. L. Wu¹⁷², X. Wu⁵⁰, Y. Wu⁹⁰, T. R. Wyatt⁸⁵, B. M. Wynne⁴⁷, S. Xella³⁷, D. Xu^{34a}, L. Xu²⁶, B. Yabsley¹⁵⁰, S. Yacoob^{145a}, R. Yakabe⁶⁸, D. Yamaguchi¹⁵⁷, Y. Yamaguchi¹¹⁸, A. Yamamoto⁶⁷, S. Yamamoto¹⁵⁵, T. Yamanaka¹⁵⁵, K. Yamauchi¹⁰³, Y. Yamazaki⁶⁸, Z. Yan²³, H. Yang^{34e}, H. Yang¹⁷², Y. Yang¹⁵¹, Z. Yang¹⁴, W-M. Yao¹⁵, Y. C. Yap⁸¹, Y. Yasu⁶⁷, E. Yatsenko⁵, K. H. Yau Wong²², J. Ye⁴¹, S. Ye²⁶, I. Yeletsikh⁶⁶, A. L. Yen⁵⁸, E. Yildirim⁴³, K. Yorita¹⁷⁰, R. Yoshida⁶, K. Yoshihara¹²², C. Young¹⁴³, C. J. S. Young³¹, S. Youssef²³, D. R. Yu¹⁵, J. Yu⁸, J. M. Yu⁹⁰, J. Yu⁶⁵, L. Yuan⁶⁸, S. P. Y. Yuen²², I. Yusuff^{29.an}, B. Zabinski⁴⁰, R. Zaidan^{34d}, A. M. Zaitsev^{130.ac}, N. Zakharchuk⁴³, J. Zalieckas¹⁴, A. Zaman¹⁴⁸, S. Zambito⁵⁸, L. Zanello^{132a,132b}, D. Zanzi⁸⁹, C. Zeitnitz¹⁷⁴, M. Zeman¹²⁸, A. Zemla^{39a}, J. C. Zeng¹⁶⁵, Q. Zeng¹⁴³, K. Zengel²⁴, O. Zenin¹³⁰, T. Ženiš^{144a}, D. Zerwas¹¹⁷, D. Zhang⁹⁰, F. Zhang¹⁷², G. Zhang^{34b,z}, H. Zhang^{34c}, J. Zhang⁶, L. Zhang⁴⁹, R. Zhang²², R. Zhang^{34b,ao}, X. Zhang^{34d}, Z. Zhang¹¹⁷, X. Zhao⁴¹, Y. Zhao^{34d,117}, Z. Zhao^{34b}, A. Zhemchugov⁶⁶, J. Zhong¹²⁰, B. Zhou⁹⁰, C. Zhou⁴⁶, L. Zhou³⁶, L. Zhou⁴¹, M. Zhou¹⁴⁸, N. Zhou^{34f}, C. G. Zhu^{34d}, H. Zhu^{34a}, J. Zhu⁹⁰, Y. Zhu^{34b}, X. Zhuang^{34a}, K. Zhukov⁹⁶, A. Zibell¹⁷³, D. Zieminska⁶², N. I. Zimine⁶⁶, C. Zimmermann⁸⁴, S. Zimmermann⁴⁹, Z. Zinonos⁵⁵, M. Zinser⁸⁴, M. Ziolkowski¹⁴¹, L. Živković¹³, G. Zobernig¹⁷², A. Zoccoli^{21a,21b}, M. zur Nedden¹⁶, G. Zurzolo^{104a,104b}, L. Zwalinski³¹

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

² Physics Department, SUNY Albany, Albany, NY, USA

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

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

⁵ LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France

⁶ High Energy Physics Division, Argonne National Laboratory, Argonne, IL, USA

⁷ Department of Physics, University of Arizona, Tucson, AZ, USA

⁸ Department of Physics, The University of Texas at Arlington, Arlington, TX, USA

⁹ Physics Department, University of Athens, Athens, Greece

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

¹¹ Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

¹² Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain

¹³ Institute of Physics, University of Belgrade, Belgrade, Serbia

- ¹⁴ Department for Physics and Technology, University of Bergen, Bergen, Norway
- ¹⁵ Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, USA
- ¹⁶ Department of Physics, Humboldt University, Berlin, Germany
- ¹⁷ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
- ¹⁸ School of Physics and Astronomy, University of Birmingham, Birmingham, UK
- ¹⁹ ^(a)Department of Physics, Bogazici University, Istanbul, Turkey; ^(b)Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey; ^(c)Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey; ^(d)Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
- ²⁰ Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
- ²¹ ^(a)INFN Sezione di Bologna, Bologna, Italy; ^(b)Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
- ²² Physikalisches Institut, University of Bonn, Bonn, Germany
- ²³ Department of Physics, Boston University, Boston, MA, USA
- ²⁴ Department of Physics, Brandeis University, Waltham, MA, USA
- ²⁵ ^(a)Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil; ^(b)Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil; ^(c)Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil; ^(d)Instituto de Fisica, Universidade de Sao Paulo, São Paulo, Brazil
- ²⁶ Physics Department, Brookhaven National Laboratory, Upton, NY, USA
- ²⁷ ^(a)Transilvania University of Brasov, Brasov, Romania; ^(b)National Institute of Physics and Nuclear Engineering, Bucharest, Romania; ^(c)Physics Department, National Institute for Research and Development of Isotopic and Molecular Technologies, Cluj Napoca, Romania; ^(d)University Politehnica Bucharest, Bucharest, Romania; ^(e)West University in Timisoara, Timisoara, Romania
- ²⁸ Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
- ²⁹ Cavendish Laboratory, University of Cambridge, Cambridge, UK
- ³⁰ Department of Physics, Carleton University, Ottawa, ON, Canada
- ³¹ CERN, Geneva, Switzerland
- ³² Enrico Fermi Institute, University of Chicago, Chicago, IL, USA
- ³³ ^(a)Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile; ^(b)Departamento de Física, Universidad Técnica Federico Santa María, Valparaiso, Chile
- ³⁴ ^(a)Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China; ^(b)Department of Modern Physics, University of Science and Technology of China, Hefei, Anhui, China; ^(c)Department of Physics, Nanjing University, Nanjing, Jiangsu, China; ^(d)School of Physics, Shandong University, Jinan, Shandong, China; ^(e)Shanghai Key Laboratory for Particle Physics and Cosmology, Department of Physics and Astronomy, Shanghai Jiao Tong University (also affiliated with PKU-CHEP), Shanghai, China; ^(f)Physics Department, Tsinghua University, Beijing 100084, China
- ³⁵ Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
- ³⁶ Nevis Laboratory, Columbia University, Irvington, NY, USA
- ³⁷ Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
- ³⁸ ^(a)INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Frascati, Italy; ^(b)Dipartimento di Fisica, Università della Calabria, Rende, Italy
- ³⁹ ^(a)Faculty of Physics and Applied Computer Science, AGH University of Science and Technology, Kraków, Poland; ^(b)Marian Smoluchowski Institute of Physics, Jagiellonian University, Kraków, Poland
- ⁴⁰ Institute of Nuclear Physics, Polish Academy of Sciences, Kraków, Poland
- ⁴¹ Physics Department, Southern Methodist University, Dallas, TX, USA
- ⁴² Physics Department, University of Texas at Dallas, Richardson, TX, USA
- ⁴³ DESY, Hamburg and Zeuthen, Germany
- ⁴⁴ Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- ⁴⁵ Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- ⁴⁶ Department of Physics, Duke University, Durham, NC, USA
- ⁴⁷ SUPA-School of Physics and Astronomy, University of Edinburgh, Edinburgh, UK
- ⁴⁸ INFN Laboratori Nazionali di Frascati, Frascati, Italy
- ⁴⁹ Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany

- 50 Section de Physique, Université de Genève, Geneva, Switzerland
- 51 ^(a)INFN Sezione di Genova, Genoa, Italy; ^(b)Dipartimento di Fisica, Università di Genova, Genoa, Italy
- 52 ^(a)E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi, Georgia; ^(b)High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- 53 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- 54 SUPA-School of Physics and Astronomy, University of Glasgow, Glasgow, UK
- 55 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- 56 Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
- 57 Department of Physics, Hampton University, Hampton, VA, USA
- 58 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, USA
- 59 ^(a)Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany; ^(b)Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany; ^(c)ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
- 60 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- 61 ^(a)Department of Physics, The Chinese University of Hong Kong, Shatin, NT, Hong Kong; ^(b)Department of Physics, The University of Hong Kong, Pokfulam, Hong Kong; ^(c)Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
- 62 Department of Physics, Indiana University, Bloomington, IN, USA
- 63 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- 64 University of Iowa, Iowa City, IA, USA
- 65 Department of Physics and Astronomy, Iowa State University, Ames, IA, USA
- 66 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- 67 KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- 68 Graduate School of Science, Kobe University, Kobe, Japan
- 69 Faculty of Science, Kyoto University, Kyoto, Japan
- 70 Kyoto University of Education, Kyoto, Japan
- 71 Department of Physics, Kyushu University, Fukuoka, Japan
- 72 Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- 73 Physics Department, Lancaster University, Lancaster, UK
- 74 ^(a)INFN Sezione di Lecce, Lecce, Italy; ^(b)Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- 75 Oliver Lodge Laboratory, University of Liverpool, Liverpool, UK
- 76 Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- 77 School of Physics and Astronomy, Queen Mary University of London, London, UK
- 78 Department of Physics, Royal Holloway University of London, Surrey, UK
- 79 Department of Physics and Astronomy, University College London, London, UK
- 80 Louisiana Tech University, Ruston, LA, USA
- 81 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- 82 Fysiska institutionen, Lunds universitet, Lund, Sweden
- 83 Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- 84 Institut für Physik, Universität Mainz, Mainz, Germany
- 85 School of Physics and Astronomy, University of Manchester, Manchester, UK
- 86 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- 87 Department of Physics, University of Massachusetts, Amherst, MA, USA
- 88 Department of Physics, McGill University, Montreal, QC, Canada
- 89 School of Physics, University of Melbourne, Melbourne, VIC, Australia
- 90 Department of Physics, The University of Michigan, Ann Arbor, MI, USA
- 91 Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA
- 92 ^(a)INFN Sezione di Milano, Milan, Italy; ^(b)Dipartimento di Fisica, Università di Milano, Milan, Italy
- 93 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
- 94 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
- 95 Group of Particle Physics, University of Montreal, Montreal, QC, Canada
- 96 P.N. Lebedev Physical Institute of the Russian, Academy of Sciences, Moscow, Russia

- 97 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- 98 National Research Nuclear University MEPhI, Moscow, Russia
- 99 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- 100 Fakultät für Physik, Ludwig-Maximilians-Universität München, Munich, Germany
- 101 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Munich, Germany
- 102 Nagasaki Institute of Applied Science, Nagasaki, Japan
- 103 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- 104 ^(a)INFN Sezione di Napoli, Naples, Italy; ^(b)Dipartimento di Fisica, Università di Napoli, Naples, Italy
- 105 Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, USA
- 106 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, The Netherlands
- 107 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, The Netherlands
- 108 Department of Physics, Northern Illinois University, De Kalb, IL, USA
- 109 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- 110 Department of Physics, New York University, New York, NY, USA
- 111 Ohio State University, Columbus, OH, USA
- 112 Faculty of Science, Okayama University, Okayama, Japan
- 113 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, USA
- 114 Department of Physics, Oklahoma State University, Stillwater, OK, USA
- 115 Palacký University, RCPTM, Olomouc, Czech Republic
- 116 Center for High Energy Physics, University of Oregon, Eugene, OR, USA
- 117 LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris Saclay, Orsay, France
- 118 Graduate School of Science, Osaka University, Osaka, Japan
- 119 Department of Physics, University of Oslo, Oslo, Norway
- 120 Department of Physics, Oxford University, Oxford, UK
- 121 ^(a)INFN Sezione di Pavia, Pavia, Italy; ^(b)Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- 122 Department of Physics, University of Pennsylvania, Philadelphia, PA, USA
- 123 National Research Centre “Kurchatov Institute” B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
- 124 ^(a)INFN Sezione di Pisa, Pisa, Italy; ^(b)Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- 125 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, USA
- 126 ^(a)Laboratório de Instrumentação e Física Experimental de Partículas-LIP, Lisbon, Portugal; ^(b)Faculdade de Ciências, Universidade de Lisboa, Lisbon, Portugal; ^(c)Department of Physics, University of Coimbra, Coimbra, Portugal; ^(d)Centro de Física Nuclear da Universidade de Lisboa, Lisbon, Portugal; ^(e)Departamento de Física, Universidade do Minho, Braga, Portugal; ^(f)Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain; ^(g)Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- 127 Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
- 128 Czech Technical University in Prague, Prague, Czech Republic
- 129 Faculty of Mathematics and Physics, Charles University in Prague, Prague, Czech Republic
- 130 State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia
- 131 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, UK
- 132 ^(a)INFN Sezione di Roma, Rome, Italy; ^(b)Dipartimento di Fisica, Sapienza Università di Roma, Rome, Italy
- 133 ^(a)INFN Sezione di Roma Tor Vergata, Rome, Italy; ^(b)Dipartimento di Fisica, Università di Roma Tor Vergata, Rome, Italy
- 134 ^(a)INFN Sezione di Roma Tre, Rome, Italy; ^(b)Dipartimento di Matematica e Fisica, Università Roma Tre, Rome, Italy
- 135 ^(a)Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies-Université Hassan II, Casablanca, Morocco; ^(b)Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat, Morocco; ^(c)Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Marrakech, Morocco; ^(d)Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco; ^(e)Faculté des Sciences, Université Mohammed V, Rabat, Morocco
- 136 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France

- 137 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, USA
138 Department of Physics, University of Washington, Seattle, WA, USA
139 Department of Physics and Astronomy, University of Sheffield, Sheffield, UK
140 Department of Physics, Shinshu University, Nagano, Japan
141 Fachbereich Physik, Universität Siegen, Siegen, Germany
142 Department of Physics, Simon Fraser University, Burnaby, BC, Canada
143 SLAC National Accelerator Laboratory, Stanford, CA, USA
144 ^(a)Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic; ^(b)Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
145 ^(a)Department of Physics, University of Cape Town, Cape Town, South Africa; ^(b)Department of Physics, University of Johannesburg, Johannesburg, South Africa; ^(c)School of Physics, University of the Witwatersrand, Johannesburg, South Africa
146 ^(a)Department of Physics, Stockholm University, Stockholm, Sweden; ^(b)The Oskar Klein Centre, Stockholm, Sweden
147 Physics Department, Royal Institute of Technology, Stockholm, Sweden
148 Departments of Physics and Astronomy and Chemistry, Stony Brook University, Stony Brook, NY, USA
149 Department of Physics and Astronomy, University of Sussex, Brighton, UK
150 School of Physics, University of Sydney, Sydney, Australia
151 Institute of Physics, Academia Sinica, Taipei, Taiwan
152 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
153 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
154 Department of Physics, Aristotle University of Thessaloniki, Thessaloníki, Greece
155 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
156 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
157 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
158 Department of Physics, University of Toronto, Toronto, ON, Canada
159 ^(a)TRIUMF, Vancouver, BC, Canada; ^(b)Department of Physics and Astronomy, York University, Toronto, ON, Canada
160 Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan
161 Department of Physics and Astronomy, Tufts University, Medford, MA, USA
162 Department of Physics and Astronomy, University of California Irvine, Irvine, CA, USA
163 ^(a)INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy; ^(b)ICTP, Trieste, Italy; ^(c)Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
164 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
165 Department of Physics, University of Illinois, Urbana, IL, USA
166 Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
167 Department of Physics, University of British Columbia, Vancouver, BC, Canada
168 Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada
169 Department of Physics, University of Warwick, Coventry, UK
170 Waseda University, Tokyo, Japan
171 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
172 Department of Physics, University of Wisconsin, Madison, WI, USA
173 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
174 Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
175 Department of Physics, Yale University, New Haven, CT, USA
176 Yerevan Physics Institute, Yerevan, Armenia
177 Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
- ^a Also at Department of Physics, King's College London, London, UK
^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, USA
- ^f Also at Department of Physics, California State University, Fresno, CA, USA
- ^g Also at Department of Physics, University of Fribourg, Fribourg, Switzerland
- ^h Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
- ⁱ Also at Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, Porto, Portugal
- ^j Also at Tomsk State University, Tomsk, Russia
- ^k Also at Università di Napoli Parthenope, Naples, Italy
- ^l Also at Institute of Particle Physics (IPP), Canada
- ^m Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia
- ⁿ Also at Department of Physics, The University of Michigan, Ann Arbor, MI, USA
- ^o Also at Louisiana Tech University, Ruston, LA, USA
- ^p Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
- ^q Also at Graduate School of Science, Osaka University, Osaka, Japan
- ^r Also at Department of Physics, National Tsing Hua University, Taiwan
- ^s Also at Department of Physics, The University of Texas at Austin, Austin, TX, USA
- ^t Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia
- ^u Also at CERN, Geneva, Switzerland
- ^v Also at Georgian Technical University (GTU), Tbilisi, Georgia
- ^w Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan
- ^x Also at Manhattan College, New York, NY, USA
- ^y Also at Hellenic Open University, Patras, Greece
- ^z Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
- ^{aa} Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
- ^{ab} Also at School of Physics, Shandong University, Shandong, China
- ^{ac} Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
- ^{ad} Also at Section de Physique, Université de Genève, Geneva, Switzerland
- ^{ae} Also at International School for Advanced Studies (SISSA), Trieste, Italy
- ^{af} Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, USA
- ^{ag} Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China
- ^{ah} Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria
- ^{ai} Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- ^{aj} Also at National Research Nuclear University MEPhI, Moscow, Russia
- ^{ak} Also at Department of Physics, Stanford University, Stanford, CA, USA
- ^{al} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
- ^{am} Also at Flensburg University of Applied Sciences, Flensburg, Germany
- ^{an} Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia
- ^{ao} Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- * Deceased