

Search for supersymmetry in final states with two same-sign or three leptons and jets using 36 fb^{-1} of $\sqrt{s} = 13 \text{ TeV}$ pp collision data with the ATLAS detector



The ATLAS collaboration

E-mail: atlas.publications@cern.ch

ABSTRACT: A search for strongly produced supersymmetric particles using signatures involving multiple energetic jets and either two isolated same-sign leptons (e or μ), or at least three isolated leptons, is presented. The analysis relies on the identification of b -jets and high missing transverse momentum to achieve good sensitivity. A data sample of proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$ recorded with the ATLAS detector at the Large Hadron Collider in 2015 and 2016, corresponding to a total integrated luminosity of 36.1 fb^{-1} , is used for the search. No significant excess over the Standard Model prediction is observed. The results are interpreted in several simplified supersymmetric models featuring R -parity conservation or R -parity violation, extending the exclusion limits from previous searches. In models considering gluino pair production, gluino masses are excluded up to 1.87 TeV at 95% confidence level. When bottom squarks are pair-produced and decay to a chargino and a top quark, models with bottom squark masses below 700 GeV and light neutralinos are excluded at 95% confidence level. In addition, model-independent limits are set on a possible contribution of new phenomena to the signal region yields.

KEYWORDS: Hadron-Hadron scattering (experiments), Supersymmetry

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1 Introduction

Supersymmetry (SUSY) [1–6] is one of the best-motivated extensions of the Standard Model (SM). A general review can be found in ref. [7]. In its minimal realization (the 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 [10] is conserved (RPC) the lightest supersymmetric particle (LSP) is stable and can be the lightest neutralino¹ $\tilde{\chi}_1^0$. In many models, the LSP can be a dark-matter candidate [11, 12] and produce signatures with large missing transverse momentum. If instead R -parity is violated (RPV), the LSP decay can generate events with high jet and lepton multiplicity. Both RPC and RPV scenarios can produce the final-state signatures considered in this article.

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 quarks (top squarks \tilde{t}_L and \tilde{t}_R), due to the large top Yukawa coupling.² The latter also favours significant \tilde{t}_L – \tilde{t}_R mixing, so that the mass eigenstate \tilde{t}_1 is lighter than all the

¹The SUSY partners of the Higgs and electroweak gauge bosons, the electroweakinos, 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).

²The partners of the left-handed (right-handed) quarks are labelled $\tilde{q}_{L(R)}$. In the case where there is significant L/R mixing (as is the case for third-generation squarks) the mass eigenstates of these squarks are labelled $\tilde{q}_{1,2}$ ordered by increasing mass.

other squarks in many scenarios [19, 20]. Bottom squarks (\tilde{b}_1) 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, $\tilde{\ell}$). Light third-generation squarks would also enhance gluino decays to top or bottom quarks relative to the generic decays involving light-flavour squarks, favouring the production of heavy-flavour quarks and, in the case of top quarks, additional isolated leptons.

This article 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, or three leptons (3L), jets and in some cases also missing transverse momentum, whose magnitude is referred to as E_T^{miss} . Only prompt decays of SUSY particles are considered. It is an extension of an earlier search performed by the ATLAS experiment [22] with $\sqrt{s} = 13$ TeV data [23], and uses the data collected in proton-proton (pp) collisions during 2015 and 2016. Similar searches for SUSY in this topology were also performed by the CMS experiment at $\sqrt{s} = 13$ TeV [24–26]. While the same-sign or three-lepton signatures are present in many scenarios of physics beyond the SM (BSM), SM processes leading to such final states have very small cross-sections. Compared to other BSM searches, analyses based on these signatures therefore allow the use of looser kinematic requirements (for example, on E_T^{miss} or on the momentum of jets and leptons), preserving sensitivity to scenarios with small mass differences between the produced gluinos/squarks and the LSP, or in which R -parity is not conserved. This sensitivity to a wide range of BSM physics processes is illustrated by the interpretation of the results in the context of twelve different SUSY simplified models [27–29] that may lead to same-sign or three-lepton signatures.

For RPC models, the first four scenarios studied focus on gluino pair production with decays into on-shell (figure 1a) or off-shell (figure 1b) top quarks, as well as on-shell light quarks. The latter are accompanied by a cascade decay involving a $\tilde{\chi}_1^\pm$ and a $\tilde{\chi}_2^0$ (figure 1c) or a $\tilde{\chi}_2^0$ and light sleptons (figure 1d). The other two RPC scenarios target the direct production of third-generation squark pairs with subsequent electroweakino-mediated decays (figures 1e and 1f). The former is characterized by final states with bottom squark pairs decaying to $t\bar{t}WW\tilde{\chi}_1^0\tilde{\chi}_1^0$. The latter, addressed here by looking at a final state with three same-sign leptons, is a model that could explain the slight excess seen in same-sign lepton signatures during Run 1 [30]. Finally, a full SUSY model with low fine-tuning, the non-universal Higgs model with two extra parameters (NUHM2) [31, 32], is also considered. When the soft-SUSY-breaking electroweakino mass, $m_{1/2}$, is in the range 300–800 GeV, the model mainly involves gluino pair production with gluinos decaying predominantly to $t\bar{t}\tilde{\chi}_1^0$ and $t\tilde{b}\tilde{\chi}_1^\pm$, giving rise to final states with two same-sign leptons and E_T^{miss} .

In the case of non-zero RPV couplings in the baryonic sector (λ''_{ijk}), as proposed in scenarios with minimal flavour violation [33–35], gluinos and squarks may decay directly to top quarks, leading to final states with same-sign leptons [36, 37] and b -quarks (figures 1g and 1h). Although these figures illustrate decay modes mediated by non-zero λ''_{313} (resp.

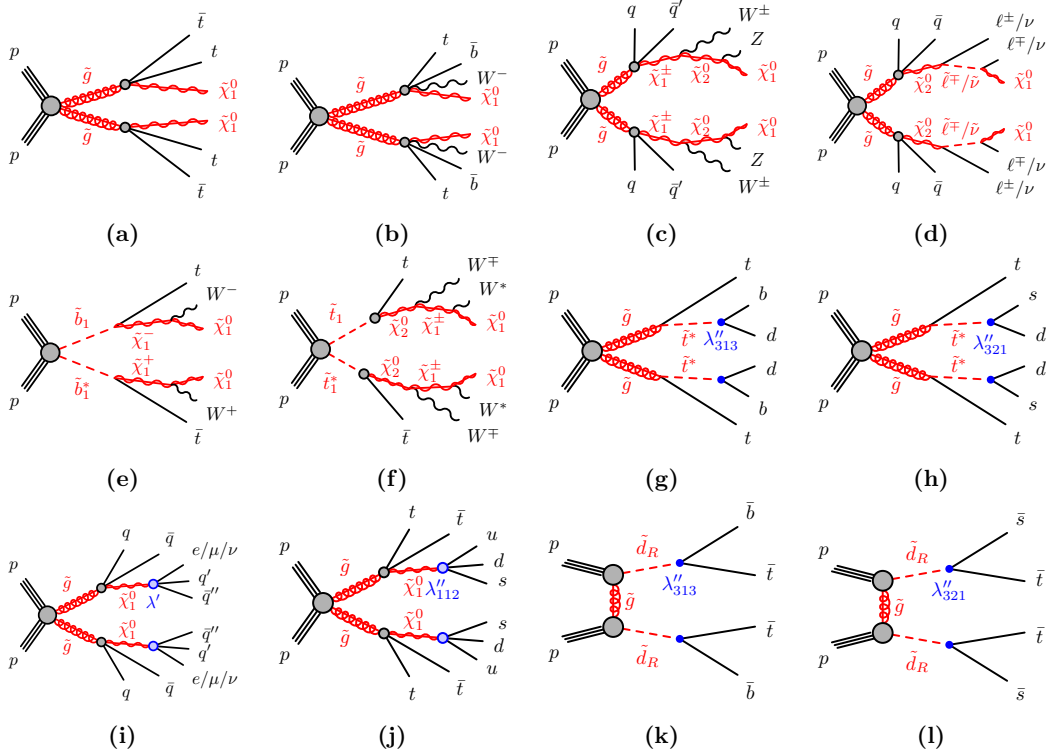


Figure 1. RPC SUSY processes featuring gluino ((a), (b), (c), (d)) or third-generation squark ((e), (f)) pair production studied in this analysis. RPV SUSY models considered are gluino pair production ((g), (h), (i), (j)) and t-channel production of down squark-rights ((k), (l)) which decay via baryon- or lepton-number violating couplings λ'' and λ' respectively. In the diagrams, $q \equiv u, d, c, s$ and $\ell \equiv e, \mu, \tau$. In figure 1d, $\tilde{\ell} \equiv \tilde{e}, \tilde{\mu}, \tilde{\tau}$ and $\tilde{\nu} \equiv \tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$. In figure 1f, the W^* labels indicate largely off-shell W bosons — the mass difference between $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ is around 1 GeV.

λ''_{321} couplings, the exclusion limits set for these scenarios also hold for non-zero λ''_{323} (resp. λ''_{311} or λ''_{322}), as these couplings lead to experimentally indistinguishable final states. Alternatively a gluino decaying to a neutralino LSP that further decays to SM particles via a non-zero RPV coupling in the leptonic sector, λ' , or in the baryonic sector λ'' , is also possible (figures 1i and 1j). Lower E_T^{miss} is expected in these scenarios, as there is no stable LSP, and the E_T^{miss} originates from neutrinos produced in the $\tilde{\chi}_1^0$ and top quark decays. Pair production of same-sign down squark-rights³ (figures 1k and 1l) is also considered. In all of these scenarios, antisquarks decay into the charge-conjugate final states of those indicated for the corresponding squarks, and gluinos decay with equal probabilities into the given final state or its charge conjugate.

2 ATLAS detector

The ATLAS experiment [22] is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and nearly 4π coverage in solid angle.⁴ The interaction

³These RPV baryon-number-violating couplings only apply to SU(2) singlets.

⁴ATLAS 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

point is surrounded by an inner detector (ID) for tracking, a calorimeter system, and a muon spectrometer (MS). The ID provides precision tracking of charged particles with pseudorapidities $|\eta| < 2.5$ and is surrounded by a superconducting solenoid providing a 2 T axial magnetic field. It consists of silicon pixel and silicon micro-strip 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 [38], an additional pixel layer close to the interaction point, which provides high-resolution hits at small radius to improve the tracking and vertexing performance. In the pseudorapidity region $|\eta| < 2.5$, high-granularity lead/liquid-argon electromagnetic 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 liquid-argon calorimeters for both the electromagnetic and hadronic measurements. The MS consists of three large superconducting toroids with eight coils each and 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 [39]. The first-level trigger is implemented in hardware. This is followed by the software-based high-level trigger, which can run algorithms similar to those used in the offline reconstruction software, reducing the event rate to about 1 kHz.

3 Data set and simulated event samples

The data used in this analysis were collected during 2015 and 2016 with a peak instantaneous luminosity of $L = 1.4 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. The mean number of pp interactions per bunch crossing (pile-up) in the data set is 24. After the application of beam, detector and data-quality requirements, the integrated luminosity considered corresponds to 36.1 fb^{-1} . The uncertainty in the combined 2015+2016 integrated luminosity is 3.2%. It is derived, following a methodology similar to that detailed in ref. [40], from a preliminary calibration of the luminosity scale using x - y beam-separation scans performed in August 2015 and May 2016.

Monte Carlo (MC) simulated event samples are used to model the SUSY signals and to estimate the irreducible SM background with two same-sign and/or three “prompt” leptons. Prompt leptons are produced directly in the hard-scattering process, or in the subsequent decays of W , Z and H bosons or prompt τ leptons. The reducible background, mainly arising from $t\bar{t}$ production, is estimated from the data as described in section 5.1. The MC samples were processed through a detailed ATLAS detector simulation [41] based on GEANT4 [42] or a fast simulation using a parameterization of the calorimeter response and GEANT4 for the ID and MS [43]. To simulate the effects of additional pp collisions in the same and nearby bunch crossings, inelastic interactions were generated using the soft

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. The transverse momentum p_T , the transverse energy E_T and the missing transverse momentum E_T^{miss} are defined in the x - y plane.

Physics process	Event generator	Parton shower	Cross-section normalization	PDF set	Set of tuned parameters
Signal					
RPC	MG5_AMC@NLO 2.2.3 [48]	PYTHIA 8.186 [44]	NLO+NLL	NNPDF2.3LO [49]	A14 [50]
RPV except figure 1j	MG5_AMC@NLO 2.2.3	PYTHIA 8.210	or	NNPDF2.3LO	A14
RPV figure 1j	HERWIG++ 2.7.1 [51]	HERWIG++ 2.7.1	NLO-Prospino2 [52–57]	CTEQ6L1 [58]	UEEE5 [59]
$t\bar{t} + X$					
$t\bar{t}W, t\bar{t}Z/\gamma^*$	MG5_AMC@NLO 2.2.2	PYTHIA 8.186	NLO [60]	NNPDF2.3LO	A14
$t\bar{t}H$	MG5_AMC@NLO 2.3.2	PYTHIA 8.186	NLO [60]	NNPDF2.3LO	A14
$4t$	MG5_AMC@NLO 2.2.2	PYTHIA 8.186	NLO [48]	NNPDF2.3LO	A14
Diboson					
ZZ, WZ	SHERPA 2.2.1 [61]	SHERPA 2.2.1	NLO [62]	NNPDF2.3LO	SHERPA default
Other (inc. $W^\pm W^\pm$)	SHERPA 2.1.1	SHERPA 2.1.1	NLO [62]	CT10 [63]	SHERPA default
Rare					
$t\bar{t}WW, t\bar{t}WZ$	MG5_AMC@NLO 2.2.2	PYTHIA 8.186	NLO [48]	NNPDF2.3LO	A14
$tZ, tWZ, t\bar{t}\bar{t}$	MG5_AMC@NLO 2.2.2	PYTHIA 8.186	LO	NNPDF2.3LO	A14
WH, ZH	MG5_AMC@NLO 2.2.2	PYTHIA 8.186	NLO [64]	NNPDF2.3LO	A14
Triboson	SHERPA 2.1.1	SHERPA 2.1.1	NLO [62]	CT10	SHERPA default

Table 1. Simulated signal and background event samples: the corresponding event generator, parton shower, cross-section normalization, PDF set and set of tuned parameters are shown for each sample. Because of their very small contribution to the signal-region background estimate, $t\bar{t}WW$, $t\bar{t}WZ$, tZ , tWZ , $t\bar{t}\bar{t}$, WH , ZH and triboson are summed and labelled “rare” in the following. NLO-Prospino2 refers to RPV down squark models of figures 1k and 1l, as well as the NUHM2 model.

strong-interaction processes of PYTHIA 8.186 [44] with a set of tuned parameters referred to as the A2 tune [45] and the MSTW2008LO parton distribution function (PDF) set [46]. These MC events were overlaid onto the simulated hard-scatter event and reweighted to match the pile-up conditions observed in the data. Table 1 presents, for all samples, the event generator, parton shower, cross-section normalization, PDF set and the set of tuned parameters for the modelling of the parton shower, hadronization and underlying event. In all MC samples, except those produced by the SHERPA event generator, the EVTGEN v1.2.0 program [47] was used to model the properties of bottom and charm hadron decays.

The SUSY signals from figure 1 are defined by an effective Lagrangian describing the interactions of a small number of new particles [27–29]. All SUSY particles not included in the decay of the pair-produced squarks and gluinos are effectively decoupled. These simplified models assume one production process and one decay channel with a 100% branching fraction. Apart from figure 1j, where events were generated with HERWIG++ [51], all simplified models were generated from leading-order (LO) matrix elements with up to two extra partons in the matrix element (only up to one for the $\tilde{g} \rightarrow q\bar{q}(\ell\ell/\nu\nu)\tilde{\chi}_1^0$ model) using MG5_AMC@NLO 2.2.3 [48] interfaced to PYTHIA 8 with the A14 tune [50] for the modelling of the parton shower, hadronization and underlying event. Jet-parton matching was realized following the CKKW-L prescription [65], with a matching scale set to one quarter of the pair-produced superpartner mass. All signal models were generated with prompt decays of the SUSY particles. Signal cross-sections were calculated at next-to-leading order (NLO) in the strong coupling constant, adding the resummation of soft-gluon emission at next-to-leading-logarithmic accuracy (NLO+NLL) [52–56], except for the RPV models of figures 1k and 1l and the NUHM2 model where NLO cross-sections were used [52, 66]. The nominal cross-sections and the uncertainties were taken from envelopes of cross-section pre-

dictions using different PDF sets and factorization and renormalization scales, as described in refs. [21, 57]. Typical pair-production cross-sections are: 4.7 ± 1.2 fb for gluinos with a mass of 1.7 TeV, 28 ± 4 fb for bottom squarks with a mass of 800 GeV, and 15.0 ± 2.0 fb for down squark-rights with a mass of 800 GeV and a gluino mass of 2.0 TeV.

The two dominant irreducible background processes are $t\bar{t}V$ (with V being a W or Z/γ^* boson) and diboson production with final states of four charged leptons ℓ ,⁵ three charged leptons and one neutrino, or two same-sign charged leptons and two neutrinos. The MC simulation samples for these are described in refs. [67] and [62], respectively. For diboson production, the matrix elements contain the doubly resonant diboson processes and all other diagrams with four or six electroweak vertices, such as $W^\pm W^\pm jj$, with one ($W^\pm W^\pm jj$) or two (WZ, ZZ) extra partons. NLO cross-sections for $t\bar{t}W$, $t\bar{t}Z/\gamma^*(\rightarrow \ell\ell)$,⁶ and leptonic diboson processes are respectively 0.60 pb [60], 0.12 pb and 6.0 pb [62]. The processes $t\bar{t}H$ and $4t$, with NLO cross-sections of 507.1 fb [60] and 9.2 fb [48] respectively, are also considered.

Other background processes, with small cross-sections and no significant contribution to any of the signal regions, are grouped into a category labelled “rare”. This category contains $t\bar{t}WW$ and $t\bar{t}WZ$ events generated with no extra parton in the matrix element, and tZ , tWZ , $t\bar{t}$, WH and ZH as well as triboson (WWW, WWZ, WZZ and ZZZ) production with fully leptonic decays, leading to up to six charged leptons. The processes WWW, WZZ and ZZZ were generated at NLO with additional LO matrix elements for up to two extra partons, while WWZ was generated at LO with up to two extra partons.

4 Event reconstruction and selection

Candidate events are required to have a reconstructed vertex [69] with at least two associated tracks with $p_T > 400$ MeV. The vertex with the largest Σp_T^2 of the associated tracks is chosen as the primary vertex of the event.

For the data-driven background estimations, two categories of electrons and muons are used: “candidate” and “signal” with the latter being a subset of the “candidate” leptons satisfying tighter selection criteria. Electron candidates are reconstructed from energy depositions in the electromagnetic calorimeter which were matched to an ID track and are required to have $|\eta| < 2.47$, $p_T > 10$ GeV, and pass the “Loose” likelihood-based identification requirement [70]. Candidates within the transition region between the barrel and endcap electromagnetic calorimeters, $1.37 < |\eta| < 1.52$, are not considered. The track matched with the electron must have a significance of the transverse impact parameter d_0 with respect to the reconstructed primary vertex 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 muon candidates must have $p_T > 10$ GeV and must pass the “Medium” identification requirements [71].

Jets are reconstructed with the anti- k_t algorithm [72] with radius parameter $R = 0.4$, using three-dimensional topological energy clusters in the calorimeter [73] as input. All jets

⁵All lepton flavours are included here and τ leptons subsequently decay leptonically or hadronically.

⁶This cross-section is computed using the configuration described in refs. [48, 68].

must have $p_T > 20$ GeV and $|\eta| < 2.8$. For all jets the expected average energy contribution from pile-up is subtracted according to the jet area [74, 75]. Jets are then calibrated as described in ref. [75]. In order to reduce the effects of pile-up, a significant fraction of the tracks in jets with $p_T < 60$ GeV and $|\eta| < 2.4$ must originate from the primary vertex, as defined by the jet vertex tagger (JVT) [76].

Identification of jets containing b -hadrons (b -tagging) is performed with the MV2c10 algorithm, a multivariate discriminant making use of track impact parameters and reconstructed secondary vertices [77, 78]. A requirement is chosen corresponding to a 70% average efficiency for tagging b -jets in simulated $t\bar{t}$ events. The rejection factors for light-quark/gluon jets, c -quark jets and $\tau \rightarrow \nu + \text{hadron}$ decays in simulated $t\bar{t}$ events are approximately 380, 12 and 54, respectively [78, 79]. Jets with $|\eta| < 2.5$ which satisfy the b -tagging and JVT requirements are identified as b -jets. Correction factors and uncertainties determined from data for the b -tagging efficiencies and mis-tag rates are applied to the simulated samples [78].

After the object identification, overlaps between the different objects are resolved. Any jet within a distance $\Delta R_y \equiv \sqrt{(\Delta y)^2 + (\Delta \phi)^2} = 0.2$ of a lepton candidate is discarded, unless the jet is b -tagged,⁷ in which case the lepton is discarded since it probably originated from a semileptonic b -hadron decay. Any remaining lepton within $\Delta R_y = \min\{0.4, 0.1 + 9.6 \text{ GeV}/p_T(\ell)\}$ of a jet is discarded. In the case of muons, the muon is retained and the jet is discarded if the jet has fewer than three associated tracks. This reduces inefficiencies for high-energy muons undergoing significant energy loss in the calorimeter.

Signal electrons must satisfy the ‘‘Medium’’ likelihood-based identification requirement [70]. In regions with large amounts of material in the tracker, an electron (positron) is more likely to emit a hard bremsstrahlung photon; if the photon subsequently converts to an asymmetric electron-positron pair, and the positron (electron) has high momentum and is reconstructed, the lepton charge can be misidentified (later referred to as ‘‘charge-flip’’). To reduce the impact of charge misidentification, signal electrons must satisfy $|\eta| < 2.0$. Furthermore, signal electrons that are likely to be reconstructed with an incorrect charge assignment are rejected using the electron cluster and track properties including the impact parameter, the curvature significance, the cluster width, and the quality of the matching between the cluster and its associated track, in terms of both energy and position. These variables, as well as the electron p_T and η , are combined into a single classifier using a boosted decision tree (BDT) algorithm. A selection requirement on the BDT output is chosen to achieve a rejection factor of 7-8 for electrons with a wrong charge assignment while selecting correctly measured electrons with an efficiency of 97%. Correction factors to account for differences in the selection efficiency between data and MC simulation are applied to the selected electrons in MC simulation. These correction factors are determined using $Z \rightarrow ee$ events [80].

Signal muons must fulfil the requirement $|d_0|/\sigma(d_0) < 3$. Tracks associated with the signal electrons or muons must have a longitudinal impact parameter z_0 with respect to the reconstructed primary vertex satisfying $|z_0 \sin \theta| < 0.5$ mm. Isolation requirements are

⁷In this case the b -tagging operating point corresponding to an efficiency of 85% is used.

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 size for electrons (muons) $\Delta R_\eta \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ is given by the smaller of $\Delta R_\eta = 10 \text{ GeV}/p_T$ and $\Delta R_\eta = 0.2$ (0.3). In addition, in the case of electrons the calorimeter energy clusters in a cone of $\Delta R_\eta = 0.2$ around the electron (excluding the deposit from the electron itself) must be less than 6% of the electron p_T . Simulated events are corrected to account for differences in the lepton trigger, reconstruction, identification and isolation efficiencies between data and MC simulation.

The missing transverse momentum is defined as the negative vector sum of the transverse momenta of all identified candidate objects (electrons, photons [81], muons and jets) and an additional soft term. The soft term is constructed from all tracks associated with the primary vertex but not with any physics object. In this way, the E_T^{miss} is adjusted for the best calibration of the jets and the other identified physics objects listed above, while maintaining approximate pile-up independence in the soft term [82, 83].

Events are selected using a combination of dilepton and E_T^{miss} triggers, the latter being used only for events with $E_T^{\text{miss}} > 250 \text{ GeV}$. 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. The event selection requires at least two signal leptons with $p_T > 20 \text{ GeV}$ (apart from two signal regions where the lower bound on the subleading lepton p_T is 10 GeV).⁸ If the event contains exactly two signal leptons, they must have the same electric charge. In order to reject detector noise and non-collision backgrounds (including those from cosmic rays, beam-gas and beam-halo interactions), events are discarded if they contain any jet not satisfying basic quality criteria [84, 85].

To maximize the sensitivity to the signal models of figure 1, 19 non-exclusive⁹ signal regions (SRs) are defined in table 2. The SRs are named in the form $SNLMbX$, where S indicates if the signal region is targeting an RPC or RPV model, N indicates the number of leptons required, M the number of b -jets required, and X indicates the severity of the E_T^{miss} or m_{eff} requirements (Soft, Medium or Hard). All signal regions, except Rpv2L0b, allow any number of additional leptons in addition to a $e^\pm e^\pm$, $e^\pm \mu^\pm$ or $\mu^\pm \mu^\pm$ pair. Signal regions with a three lepton selection can either require any lepton charge combination (Rpc3L0bH, Rpc3L0bS) or that all three leptons have the same charge (Rpc3LSS1b). The other requirements used to define the SRs are the number of signal leptons ($N_{\text{leptons}}^{\text{signal}}$), number of b -jets with $p_T > 20 \text{ GeV}$ ($N_{b\text{-jets}}$), number of jets with p_T above 25, 40 or 50 GeV, regardless of their flavour (N_{jets}), E_T^{miss} , the effective mass (m_{eff}) and the charge of the signal leptons. The m_{eff} variable is defined as the scalar sum of the p_T of the signal leptons, jets and the E_T^{miss} . For SRs where the Z +jets background is important (Rpc3LSS1b, Rpv2L0b and Rpv2L2bH), events in which the invariant mass of two same-sign electrons is close to the Z boson mass are vetoed. For SRs targeting the production of down squark pairs (Rpv2L1bS, Rpv2L2bS, Rpv2L1bM), only events with at least two

⁸To ensure that the trigger efficiency is constant for selected events where the subleading lepton p_T lies between 10 and 20 GeV only the E_T^{miss} trigger is used in this case.

⁹Each signal region partially overlaps with at least one other signal region.

Signal region	$N_{\text{leptons}}^{\text{signal}}$	$N_{b\text{-jets}}$	N_{jets}	$p_{\text{T}}^{\text{jet}}$ [GeV]	$E_{\text{T}}^{\text{miss}}$ [GeV]	m_{eff} [GeV]	$E_{\text{T}}^{\text{miss}}/m_{\text{eff}}$	Other	Targeted Signal
Rpc2L2bS	$\geq 2\text{SS}$	≥ 2	≥ 6	> 25	> 200	> 600	> 0.25	—	Figure 1a
Rpc2L2bH	$\geq 2\text{SS}$	≥ 2	≥ 6	> 25	—	> 1800	> 0.15	—	Figure 1a, NUHM2
Rpc2Lsoft1b	$\geq 2\text{SS}$	≥ 1	≥ 6	> 25	> 100	—	> 0.3	$20,10 < p_{\text{T}}^{\ell_1}, p_{\text{T}}^{\ell_2} < 100 \text{ GeV}$	Figure 1b
Rpc2Lsoft2b	$\geq 2\text{SS}$	≥ 2	≥ 6	> 25	> 200	> 600	> 0.25	$20,10 < p_{\text{T}}^{\ell_1}, p_{\text{T}}^{\ell_2} < 100 \text{ GeV}$	Figure 1b
Rpc2L0bS	$\geq 2\text{SS}$	$= 0$	≥ 6	> 25	> 150	—	> 0.25	—	Figure 1c
Rpc2L0bH	$\geq 2\text{SS}$	$= 0$	≥ 6	> 40	> 250	> 900	—	—	Figure 1c
Rpc3L0bS	≥ 3	$= 0$	≥ 4	> 40	> 200	> 600	—	—	Figure 1d
Rpc3L0bH	≥ 3	$= 0$	≥ 4	> 40	> 200	> 1600	—	—	Figure 1d
Rpc3L1bS	≥ 3	≥ 1	≥ 4	> 40	> 200	> 600	—	—	Other
Rpc3L1bH	≥ 3	≥ 1	≥ 4	> 40	> 200	> 1600	—	—	Other
Rpc2L1bS	$\geq 2\text{SS}$	≥ 1	≥ 6	> 25	> 150	> 600	> 0.25	—	Figure 1e
Rpc2L1bH	$\geq 2\text{SS}$	≥ 1	≥ 6	> 25	> 250	—	> 0.2	—	Figure 1e
Rpc3LSS1b	$\geq \ell^\pm \ell^\pm \ell^\pm$	≥ 1	—	—	—	—	—	veto $81 < m_{e^\pm e^\pm} < 101 \text{ GeV}$	Figure 1f
Rpv2L1bH	$\geq 2\text{SS}$	≥ 1	≥ 6	> 50	—	> 2200	—	—	Figures 1g, 1h
Rpv2L0b	$= 2\text{SS}$	$= 0$	≥ 6	> 40	—	> 1800	—	veto $81 < m_{e^\pm e^\pm} < 101 \text{ GeV}$	Figure 1i
Rpv2L2bH	$\geq 2\text{SS}$	≥ 2	≥ 6	> 40	—	> 2000	—	veto $81 < m_{e^\pm e^\pm} < 101 \text{ GeV}$	Figure 1j
Rpv2L2bS	$\geq \ell^- \ell^-$	≥ 2	≥ 3	> 50	—	> 1200	—	—	Figure 1k
Rpv2L1bS	$\geq \ell^- \ell^-$	≥ 1	≥ 4	> 50	—	> 1200	—	—	Figure 1l
Rpv2L1bM	$\geq \ell^- \ell^-$	≥ 1	≥ 4	> 50	—	> 1800	—	—	Figure 1l

Table 2. Summary of the signal region definitions. Unless explicitly stated in the table, at least two signal leptons with $p_{\text{T}} > 20 \text{ GeV}$ and same charge (SS) are required in each signal region. Requirements are placed on the number of signal leptons ($N_{\text{leptons}}^{\text{signal}}$), the number of b -jets with $p_{\text{T}} > 20 \text{ GeV}$ ($N_{b\text{-jets}}$), the number of jets (N_{jets}) above a certain p_{T} threshold ($p_{\text{T}}^{\text{jet}}$), $E_{\text{T}}^{\text{miss}}$, m_{eff} and/or $E_{\text{T}}^{\text{miss}}/m_{\text{eff}}$. The last column indicates the targeted signal model. The Rpc3L1b and Rpc3L1bH SRs are not motivated by a particular signal model and can be seen as a natural extension of the Rpc3L0b SRs with the same kinematic selections but requiring at least one b -jet.

negatively charged leptons are considered, as the down squarks decay exclusively to top antiquarks. Finally, SRs targeting signal scenarios with lepton p_{T} spectra softer than typical background processes impose an upper bound on the leptons' p_{T} . The last column of table 2 indicates the targeted signal model. The Rpc3L1b and Rpc3L1bH SRs are not motivated by a particular signal model and can be seen as a natural extension of the Rpc3L0b SRs with the same kinematic selections but requiring at least one b -jet.

The values of acceptance times efficiency of the SR selections for the RPC SUSY signal models, with masses near the exclusion limit, typically range between 0.5% and 7% for models with a light $\tilde{\chi}_1^0$ and between 0.5 and 2% for models with a heavy $\tilde{\chi}_1^0$. For RPV SUSY signal models, these values are in the range 0.2-4%. To increase the signal efficiency for the SUSY models with low-energy leptons (figure 1b), the p_{T} threshold of leptons is relaxed from 20 GeV to 10 GeV in the SR definition.

5 Background estimation

Two main sources of SM background can be distinguished in this analysis. The first category is the reducible background, which includes events containing electrons with mis-measured charge, mainly from the production of top quark pairs, and events containing

at least one fake or non-prompt (FNP) lepton. The FNP lepton mainly originates from heavy-flavour hadron decays in events containing top quarks, or W or Z bosons. Hadrons misidentified as leptons, electrons from photon conversions and leptons from pion or kaon decays in flight are other possible sources. Data-driven methods used for the estimation of this reducible background in the signal and validation regions are described in section 5.1.

The second background category is the irreducible background from events with two same-sign prompt leptons or at least three prompt leptons and is estimated using the MC simulation samples. Since diboson and $t\bar{t}V$ events are the main irreducible backgrounds in the signal regions, dedicated validation regions (VR) with an enhanced contribution from these processes, and small signal contamination, are defined to verify the background predictions from the simulation (section 5.2). Section 5.3 discusses the systematic uncertainties considered when performing the background estimation in the signal and validation regions.

5.1 Reducible background estimation methods

Charge misidentification is only relevant for electrons. The contribution of charge-flip events to the SR/VR is estimated using the 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 a window of 10 GeV around the Z boson mass. The charge-flip probability is a free parameter of the fit and is extracted as a function of the electron p_T and η . These probabilities are around 0.5% (1%) and 0.1% (0.2%) for the candidate and signal electrons for $|\eta| < 1.37$ ($|\eta| > 1.52$), respectively. The former is used only in the FNP lepton background estimation. The event yield of the charge-flip electron background in the signal or validation regions is obtained by multiplying the measured charge-flip probability with the number of events in data regions with the same kinematic requirements as the signal or validation regions but with opposite-sign lepton pairs.

Two data-driven methods are used to estimate the FNP lepton background, referred to as the “matrix method” and the “MC template method”. The estimates from these methods are combined to give the final estimate. These two methods are described below.

The first estimation of the FNP lepton background is performed with a matrix method similar to that described in ref. [86]. Two types of lepton identification criteria are defined: “tight”, corresponding to the signal lepton criteria described in section 4, and “loose”, corresponding to candidate leptons after object overlap removal and the charge-flip BDT selection described also in section 4. 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 (ε) 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 efficiencies for electrons (muons) rise from 60% (80%) at low p_T to almost 100% at p_T above 50 GeV — apart from endcap electrons, for which they reach only 95%. The probability for loose FNP leptons to satisfy the tight selection criteria (FNP lepton rate, f) is determined from data in SS control regions enriched in non-prompt leptons mostly originating from heavy-flavour hadron decays in single-lepton $t\bar{t}$ events. These regions

contain events with at least one b -jet, one well-isolated muon (referred to as the “tag”), and an additional loose electron or muon which is used for the measurement. The rates f are measured as a function of p_T after subtracting the small contribution from prompt-lepton processes predicted by simulation and the data-driven estimation of events with electron charge-flip.¹⁰ For electrons, and muons with $|\eta| < 2.3$, f is constant at around 10% for $p_T < 30$ GeV (20% for muons with $|\eta| > 2.3$) and increases at higher p_T . With these values of ε and f , the method has been demonstrated to correctly estimate the FNP lepton background.

The second method for FNP lepton estimation is the MC template method described in details in refs. [86, 87]. It relies on the correct modelling of the kinematic distributions of the FNP leptons and charge-flipped electron processes in $t\bar{t}$ and V +jets samples. These samples were simulated with the POWHEG-BOX generator [88–91] and the parton shower and hadronization performed by either PYTHIA 6.428 [92] ($t\bar{t}$) or PYTHIA 8.186 (V +jets). The FNP leptons are classified in five categories, namely electrons and muons originating from b - and light-quark jets as well as electrons from photon conversions. Normalization factors for each of the five sources are adjusted to match the observed data in dedicated control regions. Events are selected with at least two same-sign signal leptons, $E_T^{\text{miss}} > 40$ GeV, two or more jets, and are required not to belong to the SRs. They are further split into regions with or without b -jets and with different lepton flavours of the same-sign lepton pair, giving a total of six control regions. The global normalization factors applied to the MC samples for estimating the reducible background in each SR vary from 1.2 ± 1.1 to 2.9 ± 2.0 , where the errors account for statistical uncertainties and uncertainties related to the choice of event generator (see section 5.3).

Since the FNP lepton predictions from the MC template and matrix methods in the signal and validation regions are consistent with each other, a weighted average of the two results is used. With this approach, the combined estimate is always dominated by systematic uncertainties, which is not always the case when only the matrix method is used due to small number of events in the control regions. To check the validity and robustness of the FNP lepton estimate, 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. Examples of such distributions are shown in figure 2, and illustrate that the data are described by the prediction within uncertainties. The apparent disagreement for m_{eff} above 1 TeV in figure 2d is covered by the large theory uncertainty for the diboson background, which is not shown but amounts to about 30% for m_{eff} above 1 TeV.

5.2 Validation of irreducible background estimates

Dedicated validation regions are defined to verify the estimate of the $t\bar{t}V$, WZ and $W^\pm W^\pm$ background in the signal regions. The corresponding selections are summarized in table 3. The overlap with the signal regions is resolved by removing events that are selected in the signal regions. The purity of the targeted background processes in these regions ranges from 35% to 65%. The expected signal contamination is generally below 5% for models near

¹⁰For muons with $p_T < 20$ GeV, f is parameterized as a function of p_T and η .

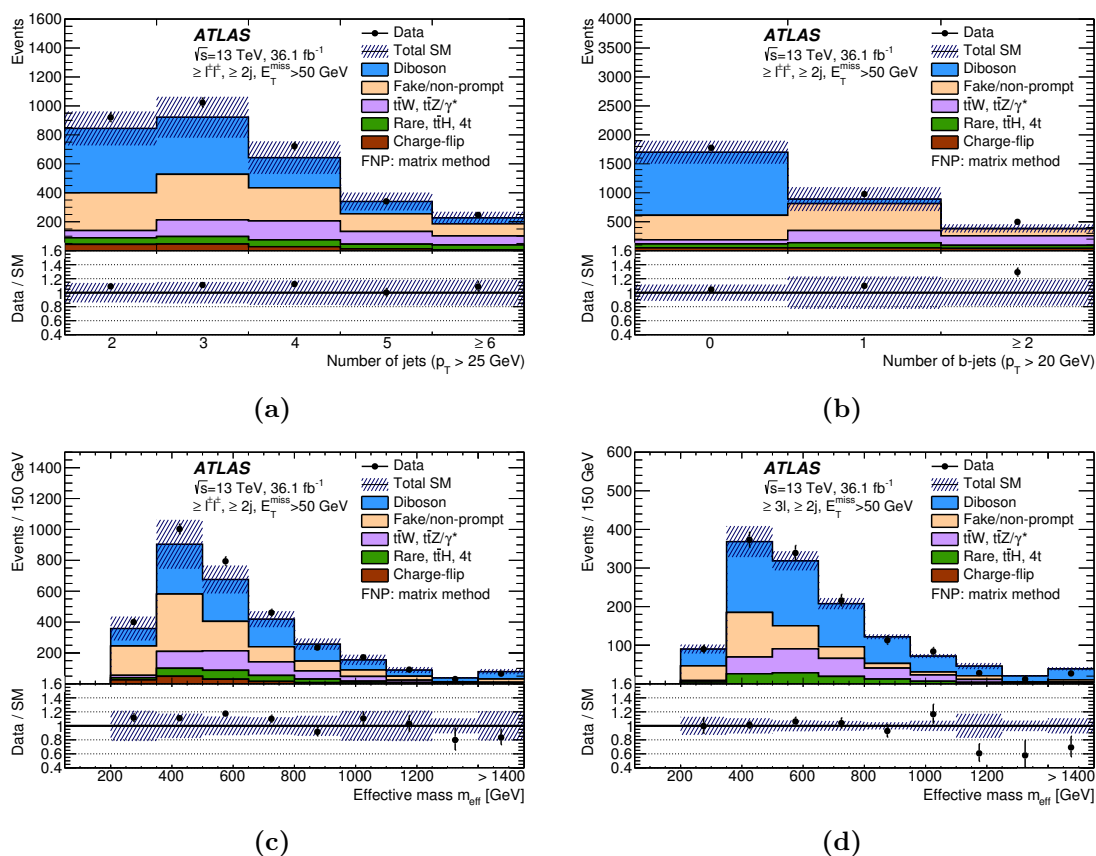


Figure 2. Distributions of (a) the number of jets, (b) the number of b -tagged jets and (c), (d) the effective mass. The distributions are made after requiring at least two jets ($p_T > 40$ GeV) and $E_T^{\text{miss}} > 50$ GeV, as well as at least two same-sign leptons (a, b, c) or three leptons (d). The uncertainty bands include the statistical uncertainties for the background prediction as well as the systematic uncertainties for fake- or non-prompt-lepton backgrounds (using the matrix method) and charge-flip electrons. Not included are theoretical uncertainties in the irreducible background contributions. The rare category is defined in the text.

the limit of exclusion in $t\bar{t}Z$, WZ and W^+W^\pm VRs and about 20% in the $t\bar{t}W$ VR. The observed yields, compared with the background predictions and uncertainties, are shown in table 4. There is good agreement between data and the estimated background in all the validation regions.

5.3 Systematic uncertainties

Statistical uncertainties due to the number of data events in the loose and tight lepton control regions are considered in the FNP lepton background estimate. In the matrix method, the systematic uncertainties mainly come from potentially different compositions of b -jets, light-quark jets and photon conversions between the signal regions and the regions where the FNP lepton rates are measured. The uncertainty coming from the prompt-lepton contamination in the FNP lepton control regions is also considered. Overall, the uncertainty in the FNP lepton rate f amounts to 30% at low p_T , and can reach 85% for muons with

Validation Region	$N_{\text{leptons}}^{\text{signal}}$	$N_{b\text{-jets}}$	N_{jets}	$p_{\text{T}}^{\text{jet}}$ [GeV]	$E_{\text{T}}^{\text{miss}}$ [GeV]	m_{eff} [GeV]	Other
$t\bar{t}W$	$= 2SS$	≥ 1	$\geq 4 (e^{\pm}e^{\pm}, e^{\pm}\mu^{\pm})$ $\geq 3 (\mu^{\pm}\mu^{\pm})$	> 40 > 25	> 45	> 550	$p_{\text{T}}^{\ell_2} > 40 \text{ GeV}$ $\sum p_{\text{T}}^{b\text{-jet}} / \sum p_{\text{T}}^{\text{jet}} > 0.25$
$t\bar{t}Z$	≥ 3 $\geq 1 \text{ SFOS pair}$	≥ 1	≥ 3	> 35	—	> 450	$81 < m_{\text{SFOS}} < 101 \text{ GeV}$
$WZ4j$	$= 3$	$= 0$	≥ 4	> 25	—	> 450	$E_{\text{T}}^{\text{miss}} / \sum p_{\text{T}}^{\ell} < 0.7$
$WZ5j$	$= 3$	$= 0$	≥ 5	> 25	—	> 450	$E_{\text{T}}^{\text{miss}} / \sum p_{\text{T}}^{\ell} < 0.7$
$W^{\pm}W^{\pm}jj$	$= 2SS$	$= 0$	≥ 2	> 50	> 55	> 650	veto $81 < m_{e^{\pm}e^{\pm}} < 101 \text{ GeV}$ $p_{\text{T}}^{\ell_2} > 30 \text{ GeV}$ $\Delta R_{\eta}(\ell_{1,2}, j) > 0.7$ $\Delta R_{\eta}(\ell_1, \ell_2) > 1.3$
All VRs	Veto events belonging to any SR						

Table 3. Summary of the event selection in the validation regions (VRs). Requirements are placed on the number of signal leptons ($N_{\text{leptons}}^{\text{signal}}$), the number of b -jets with $p_{\text{T}} > 20 \text{ GeV}$ ($N_{b\text{-jets}}$) or the number of jets (N_{jets}) above a certain p_{T} threshold ($p_{\text{T}}^{\text{jet}}$). The two leading- p_{T} leptons are referred to as $\ell_{1,2}$ with decreasing p_{T} . Additional requirements are set on $E_{\text{T}}^{\text{miss}}$, m_{eff} , the invariant mass of the two leading electrons $m_{e^{\pm}e^{\pm}}$, the presence of SS leptons or a pair of same-flavour opposite-sign leptons (SFOS) and its invariant mass m_{SFOS} . A minimum angular separation between the leptons and the jets ($\Delta R_{\eta}(\ell_{1,2}, j)$) and between the two leptons ($\Delta R_{\eta}(\ell_1, \ell_2)$) is imposed in the $W^{\pm}W^{\pm}jj$ VR. For the two WZ VRs the selection also relies on the ratio of the $E_{\text{T}}^{\text{miss}}$ in the event to the sum of p_{T} of all signal leptons p_{T} ($E_{\text{T}}^{\text{miss}} / \sum p_{\text{T}}^{\ell}$). The ratio of the scalar sum of the p_{T} of all b -jets to that of all jets in the event ($\sum p_{\text{T}}^{b\text{-jet}} / \sum p_{\text{T}}^{\text{jet}}$) is used in the $t\bar{t}W$ VR selection.

Validation Region	$t\bar{t}W$	$t\bar{t}Z$	$WZ4j$	$WZ5j$	$W^{\pm}W^{\pm}jj$
$t\bar{t}Z/\gamma^*$	6.2 ± 0.9	123 ± 17	17.8 ± 3.5	10.1 ± 2.3	1.06 ± 0.22
$t\bar{t}W$	19.0 ± 2.9	1.71 ± 0.27	1.30 ± 0.32	0.45 ± 0.14	4.1 ± 0.8
$t\bar{t}H$	5.8 ± 1.2	3.6 ± 1.8	1.8 ± 0.6	0.96 ± 0.34	0.69 ± 0.14
$4t$	1.02 ± 0.22	0.27 ± 0.14	0.04 ± 0.02	0.03 ± 0.02	0.03 ± 0.02
$W^{\pm}W^{\pm}$	0.5 ± 0.4	—	—	—	26 ± 14
WZ	1.4 ± 0.8	29 ± 17	200 ± 110	70 ± 40	27 ± 14
ZZ	0.04 ± 0.03	5.5 ± 3.1	22 ± 12	9 ± 5	0.53 ± 0.30
Rare	2.2 ± 0.5	26 ± 13	7.3 ± 2.1	3.0 ± 1.0	1.8 ± 0.5
Fake/non-prompt leptons	18 ± 16	22 ± 14	49 ± 31	17 ± 12	13 ± 10
Charge-flip electrons	3.4 ± 0.5	—	—	—	1.74 ± 0.22
Total SM background	57 ± 16	212 ± 35	300 ± 130	110 ± 50	77 ± 31
Observed	71	209	257	106	99

Table 4. The numbers of observed data and expected background events in the validation regions. The rare category is defined in the text. Background categories with yields shown as “—” do not contribute to a given region (e.g. charge flips in three-lepton regions) or their estimates are below 0.01 events. The displayed yields include all statistical and systematic uncertainties described in section 5.3.

$p_T > 40$ GeV, and 50% for electrons with $p_T > 20$ GeV; these values are driven respectively by the dependency of the isolation of non-prompt muons on the kinematic properties of the jets which emit them, and the uncertainty in the proportion of non-prompt electrons from heavy-flavoured hadron decays with respect to other sources of FNP electrons (mainly converted photons). The uncertainties in the prompt-lepton efficiency ε are much smaller. The uncertainties in the FNP lepton background estimated with the matrix method in each VR and SR are then evaluated by propagating the f and ε uncertainties. In the MC template method, the systematic uncertainty is obtained by changing the generator from POWHEG-BOX to SHERPA and propagating uncertainties from the control region fit to the global normalization scale factors applied to the MC samples. The uncertainties in these scale factors are in the range 75–80%, depending on the SRs. When combining the results of the MC template method and the matrix method to obtain the final estimate, systematic uncertainties are propagated assuming conservatively a full correlation between the two methods.

The uncertainty in the electron charge-flip probability mainly originates from the number of events in the regions used in the charge-flip probability measurement and the uncertainty related to the background subtraction from the Z boson's mass peak. The relative error in the charge-flip rate is below 20% (30%) for signal (candidate) electrons with p_T above 20 GeV.

The systematic uncertainties related to the estimated background from same-sign prompt leptons arise from the experimental uncertainties (jet energy scale calibration, jet energy resolution and b -tagging efficiency) as well as theoretical modelling and theoretical cross-section uncertainties. The statistical uncertainty of the simulated event samples is also taken into account.

The cross-sections used to normalize the MC samples are varied according to the uncertainty in the cross-section calculation, which is 13% for $t\bar{t}W$, 12% for $t\bar{t}Z$ production [60], 6% for diboson production [62], 8% for $t\bar{t}H$ [60] and 30% for $4t$ [48]. Additional uncertainties are assigned to some of these backgrounds to account for the theoretical modelling of the kinematic distributions in the MC simulation. For $t\bar{t}W$ and $t\bar{t}Z$, the predictions from the MG5_AMC@NLO and SHERPA generators are compared, and the renormalization and factorization scales used to generate these samples are varied independently within a factor of two, leading to a 15–35% uncertainty in the expected SR yields for these processes. For diboson production, uncertainties are estimated by varying the QCD and matching scales, as well as the parton shower recoil scheme, leading to a 30–40% uncertainty for these processes after the SR selections. For $t\bar{t}H$, $4t$ and rare production processes, a 50% uncertainty in their total contribution is assigned.

6 Results and interpretation

Figure 3a shows the event yields for data and the expected background contributions in all signal regions. Detailed information about the yields can be found in table 5. In all 19 SRs the number of observed data events is consistent with the expected background within the uncertainties. The contributions listed in the rare category are dominated by triboson,

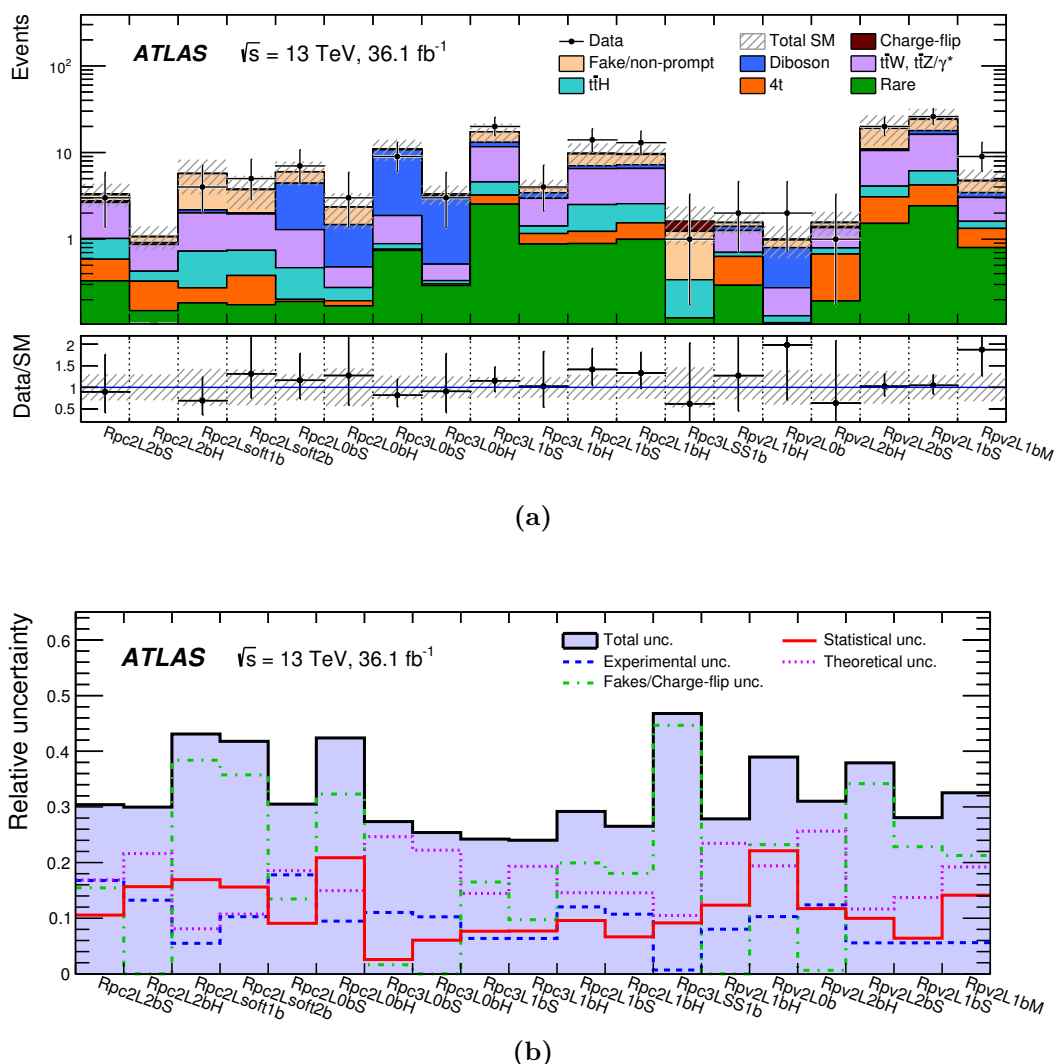


Figure 3. Comparison of (a) the observed and expected event yields in each signal region and (b) the relative uncertainties in the total background yield estimate. For the latter, “statistical uncertainty” corresponds to reducible and irreducible background statistical uncertainties. The background predictions correspond to those presented in table 5 and the rare category is explained in the text.

tWZ and $t\bar{t}WW$ production:¹¹ the triboson processes generally dominate in the SRs with no b -jets, while tWZ and $t\bar{t}WW$ dominate in the SRs with one and two b -jets, respectively.

Figure 3b summarizes the contributions from the different sources of systematic uncertainty to the total SM background predictions in the signal regions. The uncertainties amount to 25–50% of the total background depending on the signal region, dominated by systematic uncertainties coming from the reducible background or the theory.

In the absence of any significant deviation from the SM predictions, upper limits on possible BSM contributions to the signal regions are derived, as well as exclusion limits

¹¹Contributions from WH , ZH , tZ and $t\bar{t}t$ production never represent more than 20% of the rare background.

Signal Region	Rpc2L2bS	Rpc2L2bH	Rpc2Lsoft1b	Rpc2Lsoft2b	Rpc2L0bS	Rpc2L0bH
$t\bar{t}W, t\bar{t}Z\gamma^*$	1.6 ± 0.4	0.44 ± 0.14	1.3 ± 0.4	1.21 ± 0.33	0.82 ± 0.31	0.20 ± 0.10
$t\bar{t}H$	0.43 ± 0.25	0.10 ± 0.06	0.45 ± 0.24	0.36 ± 0.21	0.27 ± 0.15	0.08 ± 0.07
$4t$	0.26 ± 0.13	0.18 ± 0.09	0.09 ± 0.05	0.21 ± 0.11	0.01 ± 0.01	0.02 ± 0.02
Diboson	0.10 ± 0.10	0.04 ± 0.02	0.17 ± 0.09	0.05 ± 0.03	3.1 ± 1.4	1.0 ± 0.5
Rare	0.33 ± 0.18	0.15 ± 0.09	0.18 ± 0.10	0.17 ± 0.10	0.19 ± 0.11	0.17 ± 0.10
Fake/non-prompt leptons	0.5 ± 0.6	0.15 ± 0.15	3.5 ± 2.4	1.7 ± 1.5	1.6 ± 1.0	0.9 ± 0.9
Charge-flip electrons	0.10 ± 0.01	0.02 ± 0.01	0.08 ± 0.02	0.08 ± 0.02	0.05 ± 0.01	0.01 ± 0.01
Total Background	3.3 ± 1.0	1.08 ± 0.32	5.8 ± 2.5	3.8 ± 1.6	6.0 ± 1.8	2.4 ± 1.0
Observed	3	0	4	5	7	3
S_{obs}^{95}	5.5	3.6	6.3	7.7	8.3	6.1
S_{exp}^{95}	$5.6^{+2.2}_{-1.5}$	$3.9^{+1.4}_{-0.4}$	$7.1^{+2.5}_{-1.5}$	$6.2^{+2.6}_{-1.5}$	$7.5^{+2.6}_{-1.8}$	$5.3^{+2.1}_{-1.3}$
σ_{vis} [fb]	0.15	0.10	0.17	0.21	0.23	0.17
p_0 (Z)	0.71 (-)	0.91 (-)	0.69 (-)	0.30 (0.5 σ)	0.36 (0.4 σ)	0.35 (0.4 σ)

Signal Region	Rpc3L0bS	Rpc3L0bH	Rpc3L1bS	Rpc3L1bH	Rpc2L1bS	Rpc2L1bH	Rpc3LSS1b
$t\bar{t}W, t\bar{t}Z\gamma^*$	0.98 ± 0.25	0.18 ± 0.08	7.1 ± 1.1	1.54 ± 0.28	4.0 ± 1.0	4.0 ± 0.9	—
$t\bar{t}H$	0.12 ± 0.08	0.03 ± 0.02	1.4 ± 0.7	0.25 ± 0.14	1.3 ± 0.7	1.0 ± 0.6	0.22 ± 0.12
$4t$	0.02 ± 0.01	0.01 ± 0.01	0.7 ± 0.4	0.28 ± 0.15	0.34 ± 0.17	0.54 ± 0.28	—
Diboson	8.9 ± 2.9	2.6 ± 0.8	1.4 ± 0.5	0.48 ± 0.17	0.5 ± 0.3	0.7 ± 0.3	—
Rare	0.7 ± 0.4	0.29 ± 0.16	2.5 ± 1.3	0.9 ± 0.5	0.9 ± 0.5	1.0 ± 0.6	0.12 ± 0.07
Fake/non-prompt leptons	0.23 ± 0.23	0.15 ± 0.15	4.2 ± 3.1	0.5 ± 0.5	2.5 ± 2.2	2.3 ± 1.9	0.9 ± 0.7
Charge-flip electrons	—	—	—	—	0.25 ± 0.04	0.25 ± 0.05	0.39 ± 0.08
Total Background	11.0 ± 3.0	3.3 ± 0.8	17 ± 4	3.9 ± 0.9	9.8 ± 2.9	9.8 ± 2.6	1.6 ± 0.8
Observed	9	3	20	4	14	13	1
S_{obs}^{95}	8.3	5.4	14.7	6.1	13.7	12.4	3.9
S_{exp}^{95}	$9.3^{+3.1}_{-2.3}$	$5.5^{+2.2}_{-1.5}$	$12.6^{+5.1}_{-3.4}$	$5.9^{+2.2}_{-1.8}$	$10.0^{+3.7}_{-2.6}$	$9.7^{+3.4}_{-2.6}$	$4.0^{+1.8}_{-0.3}$
σ_{vis} [fb]	0.23	0.15	0.41	0.17	0.38	0.34	0.11
p_0 (Z)	0.72 (-)	0.85 (-)	0.32 (0.5 σ)	0.46 (0.1 σ)	0.17 (1.0 σ)	0.21 (0.8 σ)	0.56 (-)

Signal Region	Rpv2L1bH	Rpv2L0b	Rpv2L2bH	Rpv2L2bS	Rpv2L1bS	Rpv2L1bM
$t\bar{t}W, t\bar{t}Z\gamma^*$	0.56 ± 0.14	0.14 ± 0.08	0.56 ± 0.15	6.5 ± 1.3	10.1 ± 1.7	1.4 ± 0.5
$t\bar{t}H$	0.07 ± 0.05	0.02 ± 0.02	0.12 ± 0.07	1.0 ± 0.5	1.9 ± 1.0	0.28 ± 0.15
$4t$	0.34 ± 0.17	0.01 ± 0.01	0.48 ± 0.24	1.6 ± 0.8	1.8 ± 0.9	0.53 ± 0.27
Diboson	0.14 ± 0.06	0.52 ± 0.21	0.04 ± 0.02	0.42 ± 0.16	1.7 ± 0.6	0.42 ± 0.15
Rare	0.29 ± 0.17	0.10 ± 0.06	0.19 ± 0.13	1.5 ± 0.8	2.4 ± 1.2	0.8 ± 0.4
Fake/non-prompt leptons	0.15 ± 0.15	0.18 ± 0.31	0.15 ± 0.15	8 ± 7	6 ± 6	1.3 ± 1.2
Charge-flip electrons	0.02 ± 0.01	0.03 ± 0.02	0.03 ± 0.01	0.46 ± 0.08	0.74 ± 0.12	0.10 ± 0.02
Total Background	1.6 ± 0.4	1.0 ± 0.4	1.6 ± 0.5	19 ± 7	25 ± 7	4.8 ± 1.6
Observed	2	2	1	20	26	9
S_{obs}^{95}	4.8	5.2	3.9	17.5	18.1	11.4
S_{exp}^{95}	$4.1^{+1.9}_{-0.4}$	$4.0^{+1.7}_{-0.3}$	$4.1^{+1.8}_{-0.4}$	$16.8^{+5.2}_{-4.2}$	$17.2^{+5.9}_{-4.2}$	$7.3^{+2.5}_{-1.8}$
σ_{vis} [fb]	0.13	0.14	0.11	0.48	0.50	0.31
p_0 (Z)	0.33 (0.4 σ)	0.19 (0.9 σ)	0.55 (-)	0.48 (0.1 σ)	0.44 (0.2 σ)	0.07 (1.5 σ)

Table 5. Numbers of events observed in the signal regions compared with the expected backgrounds. The rare category is defined in the text. Background categories with yields shown as a “—” do not contribute to a given region (e.g. charge flips in three-lepton regions) or their estimates are below 0.01. The 95% confidence level (CL) upper limits are shown on the observed and expected numbers of BSM events, S_{obs}^{95} and S_{exp}^{95} (as well as the $\pm 1\sigma$ excursions from the expected limit), respectively. The 95% CL upper limits on the visible cross-section (σ_{vis}) are also given. Finally, the p-values (p_0) give the probabilities to observe a deviation from the predicted background at least as large as that in the data. The number of equivalent Gaussian standard deviations (Z) is also shown when $p_0 < 0.5$.

on the masses of SUSY particles in the benchmark scenarios of figure 1. The HistFitter framework [93], which utilizes a profile-likelihood-ratio test [94], is used to establish 95% confidence intervals using the CL_s prescription [95]. The likelihood is built as the product of a Poisson probability density function describing the observed number of events in the signal region and, to constrain the nuisance parameters associated with the systematic uncertainties, Gaussian distributions whose widths correspond to the sizes of these uncertainties; Poisson distributions are used instead for MC simulation statistical uncertainties. Correlations of a given nuisance parameter between the backgrounds and the signal are taken into account when relevant. The hypothesis tests are performed for each of the signal regions independently.

Table 5 presents 95% confidence level (CL) observed (expected) model-independent upper limits on the number of BSM events, S_{obs}^{95} (S_{exp}^{95}), that may contribute to the signal regions. Normalizing these by the integrated luminosity L of the data sample, they can be interpreted as upper limits on the visible BSM cross-section (σ_{vis}), defined as $\sigma_{\text{vis}} = \sigma_{\text{prod}} \times A \times \epsilon = S_{\text{obs}}^{95}/L$, where σ_{prod} is the production cross-section, A the acceptance and ϵ the reconstruction efficiency. The largest deviation of the data from the background prediction corresponds to an excess of 1.5 standard deviations in the Rpv2L1bM SR.

Exclusion limits at 95% CL are also set on the masses of the superpartners involved in the SUSY benchmark scenarios considered. Apart from the NUHM2 model, simplified models are used, corresponding to a single production mode and with 100% branching ratio to a specific decay chain, with the masses of the SUSY particles not involved in the process set to very high values. Figures 4, 5 and 6 show the exclusion limits in all the models considered in figure 1 and the NUHM2 model. The assumptions about the decay chain considered for the different SUSY particles are stated above each figure. For each region of the signal parameter space, the SR with the best expected sensitivity is chosen.

For the RPC models, the limits set are compared with the existing limits set by other ATLAS SUSY searches [23, 96]. For the models shown in figure 4, the mass limits on gluinos and bottom squarks are up to 400 GeV higher than the previous limits, reflecting the improvements in the signal region definitions as well as the increase in integrated luminosity. Gluinos with masses up to 1.75 TeV are excluded in scenarios with a light $\tilde{\chi}_1^0$ in figure 4a. This limit is extended to 1.87 TeV when $\tilde{\chi}_2^0$ and slepton masses are in-between the gluino and the $\tilde{\chi}_1^0$ masses (figure 4c). More generally, gluino masses below 1.57 TeV and bottom squarks with masses below 700 GeV are excluded in models with a massless LSP. The “compressed” regions, where SUSY particle masses are close to each other, are also better covered and LSP masses up to 1200 and 250 GeV are excluded in the gluino and bottom squark pair-production models, respectively. Of particular interest is the observed exclusion of models producing gluino pairs with an off-shell top quark in the decay (figure 1b), see figure 4a. In this case, models are excluded for mass differences between the gluino and neutralino of 205 GeV (only 35 GeV larger than the minimum mass difference for decays into two on-shell W bosons and two b -quarks) for a gluino mass below 0.9 TeV. The Rpc3LSS1b SR allows the exclusion of top squarks with masses below 700 GeV when the top squark decays to a top quark and a cascade of electroweakinos $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^\pm W^\mp \rightarrow W^* W^\mp \tilde{\chi}_1^0$ (see figure 4e for the conditions on the sparticle masses).

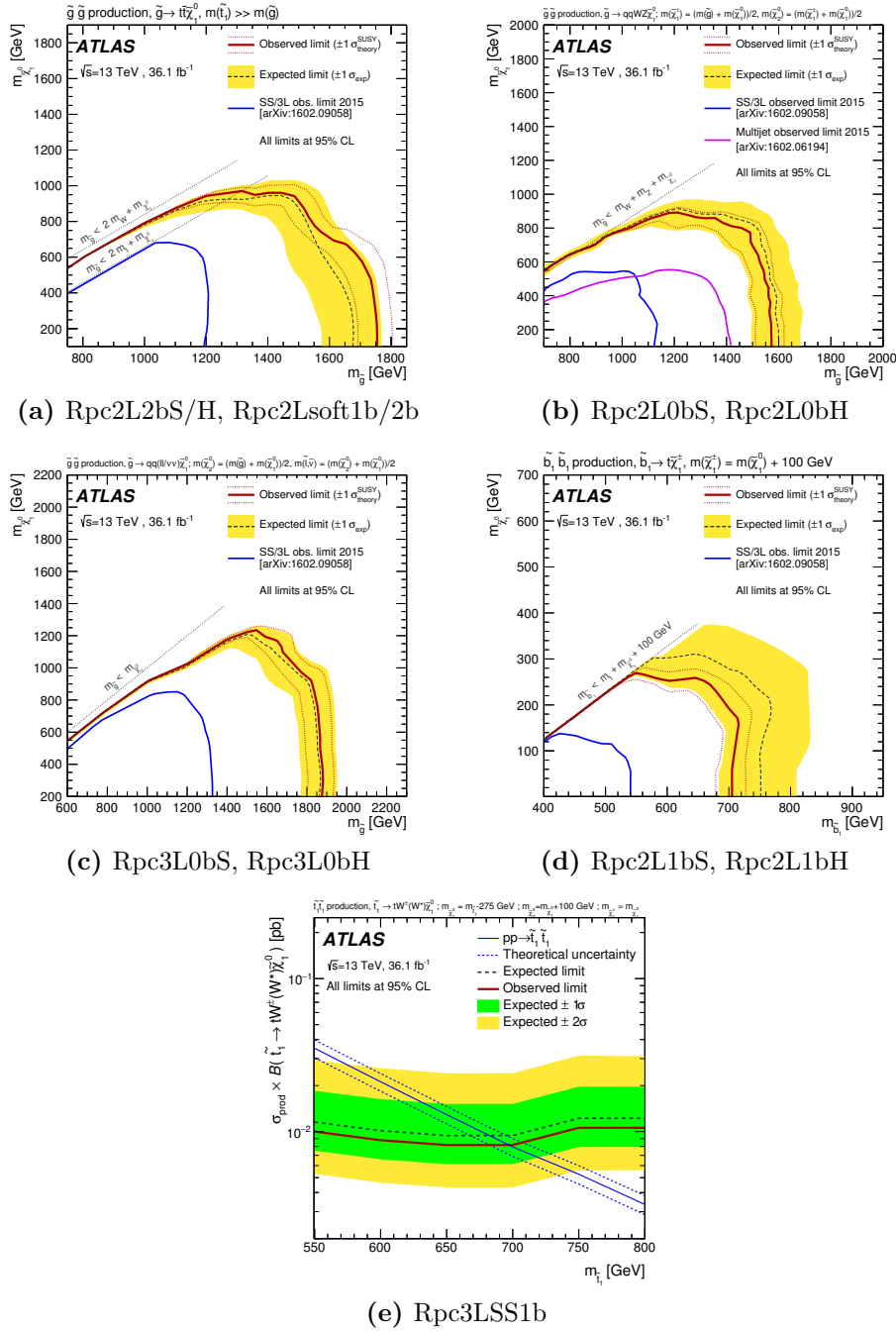


Figure 4. Observed and expected exclusion limits on the \tilde{g} , \tilde{b}_1 , \tilde{t}_1 and $\tilde{\chi}_1^0$ masses in the context of RPC SUSY scenarios with simplified mass spectra. The signal regions used to obtain the limits are specified in the subtitle of each scenario. All limits are computed at 95% CL. 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. The contours of the band around the expected limit are the $\pm 1\sigma$ results ($\pm 2\sigma$ is also considered in figure (e), including all uncertainties except the theoretical uncertainties in the signal cross-section). In figures (a)–(d), the diagonal line indicates the kinematic limit for the decays in each specified scenario and results are compared with the observed limits obtained by previous ATLAS searches [23, 96].

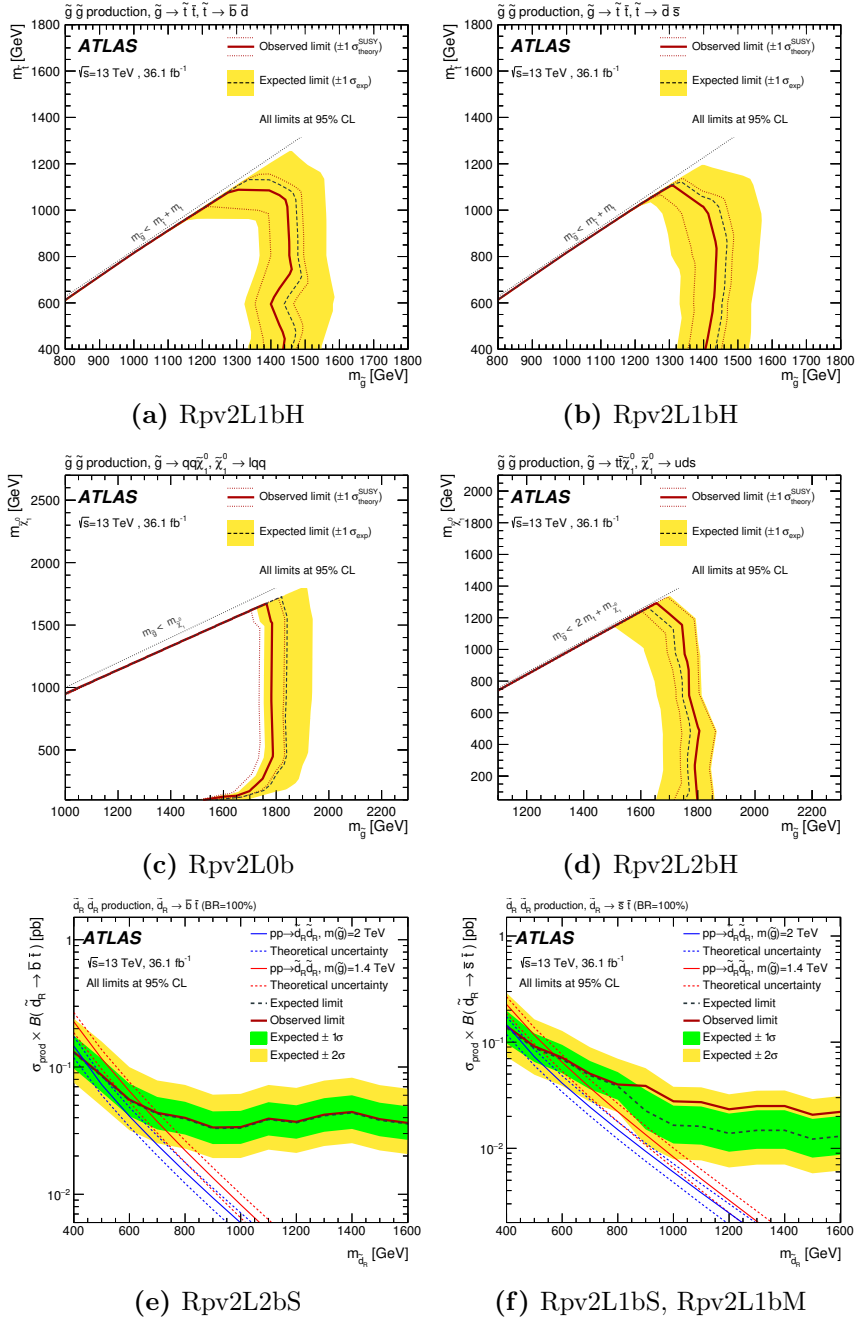


Figure 5. Observed and expected exclusion limits on the \tilde{g} , \tilde{t}_1 , \tilde{d}_R and $\tilde{\chi}_1^0$ masses in the context of RPV SUSY scenarios with simplified mass spectra featuring $\tilde{g}\tilde{g}$ or $\tilde{d}_R\tilde{d}_R$ pair production with exclusive decay modes. The signal regions used to obtain the limits are specified in the subtitle of each scenario. All limits are computed at 95% CL. 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. The contours of the band around the expected limit are the $\pm 1\sigma$ results, including all uncertainties except theoretical uncertainties in the signal cross-section ($\pm 2\sigma$ is also considered in figures 5e and 5f). In figures 5a–5d, the diagonal line indicates the kinematic limit for the decays in each specified scenario. For figures 5e and 5f, theoretical production cross-sections are shown for two different gluino masses in red (1.4 TeV) and blue (2.0 TeV).

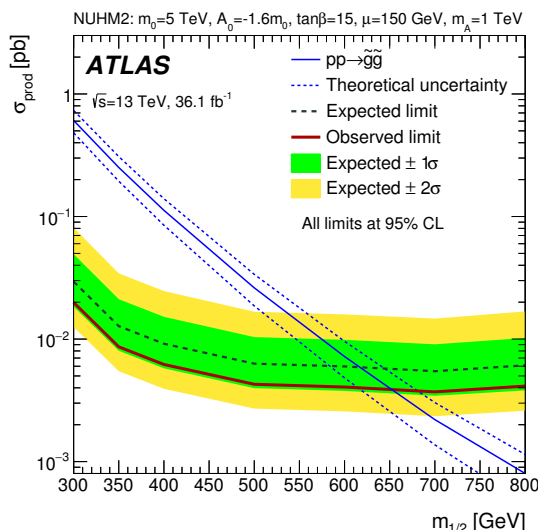


Figure 6. Observed and expected exclusion limits as a function of $m_{1/2}$ in the NUHM2 model [31, 32]. The signal region Rpc2L2bH is used to obtain the limits. The contours of the green (yellow) band around the expected limit are the $\pm 1\sigma$ ($\pm 2\sigma$) results, including all uncertainties. The limits are computed at 95% CL.

For the RPV models with gluino pair production (figures 5a–5d), a generic exclusion of gluinos with masses below 1.3 TeV is obtained. Weaker exclusion limits, typically around 500 GeV, are obtained in models with pair production of \tilde{d}_R (figures 5e, 5f).

Finally, in the NUHM2 model with low fine-tuning, values of the parameter $m_{1/2}$ below 615 GeV are excluded, corresponding to gluino masses below 1500 GeV (figure 6).

7 Conclusion

A search for supersymmetry in events with two same-sign leptons or at least three leptons, multiple jets, b -jets and large E_T^{miss} and/or large m_{eff} is presented. The analysis is performed with proton-proton collision data at $\sqrt{s} = 13$ TeV collected in 2015 and 2016 with the ATLAS detector at the Large Hadron Collider corresponding to an integrated luminosity of 36.1 fb^{-1} . With no significant excess over the Standard Model prediction observed, results are interpreted in the framework of simplified models featuring gluino and squark production in R -parity-conserving and R -parity-violating scenarios. Lower limits on particle masses are derived at 95% confidence level. In the $\tilde{g}\tilde{g}$ simplified RPC models considered, gluinos with masses up to 1.87 TeV are excluded in scenarios with a light $\tilde{\chi}_1^0$. RPC models with bottom squark masses below 700 GeV are also excluded in a $\tilde{b}_1\tilde{b}_1^*$ simplified model with $\tilde{b}_1 \rightarrow tW^-\tilde{\chi}_1^0$ and a light $\tilde{\chi}_1^0$. In RPV scenarios, masses of down squark-rights are probed up to $m_{\tilde{d}_R} \approx 500$ GeV. All models with gluino masses below 1.3 TeV are excluded, greatly extending the previous exclusion limits obtained within this search. Model-independent limits on the cross-section of a possible signal contribution to the signal regions are set.

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M. Aaboud^{137d}, G. Aad⁸⁸, B. Abbott¹¹⁵, O. Abidinov^{12,*}, B. Abeloos¹¹⁹, S.H. Abidi¹⁶¹, O.S. AbouZeid¹³⁹, N.L. Abraham¹⁵¹, H. Abramowicz¹⁵⁵, H. Abreu¹⁵⁴, R. Abreu¹¹⁸, Y. Abulaiti^{148a,148b}, B.S. Acharya^{167a,167b,a}, S. Adachi¹⁵⁷, L. Adamczyk^{41a}, J. Adelman¹¹⁰, M. Adersberger¹⁰², T. Adye¹³³, A.A. Affolder¹³⁹, Y. Afik¹⁵⁴, T. Agatonovic-Jovin¹⁴, C. Agheorghiesei^{28c}, J.A. Aguilar-Saavedra^{128a,128f}, S.P. Ahlen²⁴, F. Ahmadov^{68,b}, G. Aielli^{135a,135b}, S. Akatsuka⁷¹, H. Akerstedt^{148a,148b}, T.P.A. Åkesson⁸⁴, E. Akilli⁵², A.V. Akimov⁹⁸, G.L. Alberghi^{22a,22b}, J. Albert¹⁷², P. Albicocco⁵⁰, M.J. Alconada Verzini⁷⁴, S.C. Alderweireldt¹⁰⁸, M. Aleksa³², I.N. Aleksandrov⁶⁸, C. Alexa^{28b}, G. Alexander¹⁵⁵, T. Alexopoulos¹⁰, M. Alhroob¹¹⁵, B. Ali¹³⁰, M. Aliev^{76a,76b}, G. Alimonti^{94a}, J. Alison³³, S.P. Alkire³⁸, B.M.M. Allbrooke¹⁵¹, B.W. Allen¹¹⁸, P.P. Allport¹⁹, A. Aloisio^{106a,106b}, A. Alonso³⁹, F. Alonso⁷⁴, C. Alpigiani¹⁴⁰, A.A. Alshehri⁵⁶, M.I. Alstaty⁸⁸, B. Alvarez Gonzalez³², D. Álvarez Piqueras¹⁷⁰, M.G. Alviggi^{106a,106b}, B.T. Amadio¹⁶, Y. Amaral Coutinho^{26a}, C. Amelung²⁵, D. Amidei⁹², S.P. Amor Dos Santos^{128a,128c}, S. Amoroso³², G. Amundsen²⁵, C. Anastopoulos¹⁴¹, L.S. Ancu⁵², N. Andari¹⁹, T. Andeen¹¹, C.F. Anders^{60b}, J.K. Anders⁷⁷, K.J. Anderson³³, A. Andreazza^{94a,94b}, V. Andrei^{60a}, S. Angelidakis³⁷, I. Angelozzi¹⁰⁹, A. Angerami³⁸, A.V. Anisenkov^{111,c}, N. Anjos¹³, A. Annovi^{126a,126b}, C. Antel^{60a}, M. Antonelli⁵⁰, A. Antonov^{100,*}, D.J. Antrim¹⁶⁶, F. Anulli^{134a}, M. Aoki⁶⁹, L. Aperio Bella³², G. Arabidze⁹³, Y. Arai⁶⁹, J.P. Araque^{128a}, V. Araujo Ferraz^{26a}, A.T.H. Arce⁴⁸, R.E. Ardell⁸⁰, F.A. Arduh⁷⁴, J-F. Arguin⁹⁷, S. Argyropoulos⁶⁶, M. Arik^{20a}, A.J. Armbruster³², L.J. Armitage⁷⁹, O. Arnaez¹⁶¹, H. Arnold⁵¹, M. Arratia³⁰, O. Arslan²³, A. Artamonov^{99,*}, G. Artoni¹²², S. Artz⁸⁶, S. Asai¹⁵⁷, N. Asbah⁴⁵, A. Ashkenazi¹⁵⁵, L. Asquith¹⁵¹, K. Assamagan²⁷, R. Astalos^{146a}, M. Atkinson¹⁶⁹, N.B. Atlay¹⁴³, K. Augsten¹³⁰, G. Avolio³², B. Axen¹⁶, M.K. Ayoub¹¹⁹, G. Azuelos^{97,d}, A.E. Baas^{60a}, M.J. Baca¹⁹, H. Bachacou¹³⁸, K. Bachas^{76a,76b}, M. Backes¹²², P. Bagnaia^{134a,134b}, M. Bahmani⁴², H. Bahrasemani¹⁴⁴, J.T. Baines¹³³, M. Bajic³⁹, O.K. Baker¹⁷⁹, E.M. Baldin^{111,c}, P. Balek¹⁷⁵, F. Balli¹³⁸, W.K. Balunas¹²⁴, E. Banas⁴², A. Bandyopadhyay²³, Sw. Banerjee^{176,e}, A.A.E. Bannoura¹⁷⁸, L. Barak¹⁵⁵, E.L. Barberio⁹¹, D. Barberis^{53a,53b}, M. Barbero⁸⁸, T. Barillari¹⁰³, M-S Barisits³², J.T. Barkeloo¹¹⁸, T. Barklow¹⁴⁵, N. Barlow³⁰, S.L. Barnes^{36c}, B.M. Barnett¹³³, R.M. Barnett¹⁶, Z. Barnovska-Blenessy^{36a}, A. Baroncelli^{136a}, G. Barone²⁵, A.J. Barr¹²², L. Barranco Navarro¹⁷⁰, F. Barreiro⁸⁵, J. Barreiro Guimarães da Costa^{35a}, R. Bartoldus¹⁴⁵, A.E. Barton⁷⁵, P. Bartos^{146a}, A. Basalae¹²⁵, A. Bassalat^{119,f}, R.L. Bates⁵⁶, S.J. Batista¹⁶¹, J.R. Batley³⁰, M. Battaglia¹³⁹, M. Bause^{134a,134b}, F. Bauer¹³⁸, H.S. Bawa^{145,g}, J.B. Beacham¹¹³, M.D. Beattie⁷⁵, T. Beau⁸³, P.H. Beauchemin¹⁶⁵, P. Bechtel²³, H.P. Beck^{18,h}, H.C. Beck⁵⁷, K. Becker¹²², M. Becker⁸⁶, C. Becot¹¹², A.J. Beddall^{20e}, A. Beddall^{20b}, V.A. Bednyakov⁶⁸, M. Bedognetti¹⁰⁹, C.P. Bee¹⁵⁰, T.A. Beermann³², M. Begalli^{26a}, M. Beger²⁷, J.K. Behr⁴⁵, A.S. Bell⁸¹, G. Bella¹⁵⁵, L. Bellagamba^{22a}, A. Bellerive³¹, M. Bellomo¹⁵⁴, K. Belotskiy¹⁰⁰, O. Beltramello³², N.L. Belyaev¹⁰⁰, O. Benary^{155,*}, D. Benchekroun^{137a}, M. Bender¹⁰², K. Bendtz^{148a,148b}, N. Benekos¹⁰, Y. Benhammou¹⁵⁵, E. Benhar Nocchioli¹⁷⁹, J. Benitez⁶⁶, D.P. Benjamin⁴⁸, M. Benoit⁵², J.R. Bensinger²⁵, S. Bentvelsen¹⁰⁹, L. Beresford¹²², M. Beretta⁵⁰, D. Berge¹⁰⁹, E. Bergeas Kuutmann¹⁶⁸, N. Berger⁵, J. Beringer¹⁶, S. Berlendis⁵⁸, N.R. Bernard⁸⁹, G. Bernardi⁸³, C. Bernius¹⁴⁵, F.U. Bernlochner²³, T. Berry⁸⁰, P. Berta⁸⁶, C. Bertella^{35a}, G. Bertoli^{148a,148b}, F. Bertolucci^{126a,126b}, I.A. Bertram⁷⁵, C. Bertsche⁴⁵, D. Bertsche¹¹⁵, G.J. Besjes³⁹, O. Bessidskaia Bylund^{148a,148b}, M. Bessner⁴⁵, N. Besson¹³⁸, A. Bethani⁸⁷, S. Bethke¹⁰³, A.J. Bevan⁷⁹, J. Beyer¹⁰³, R.M. Bianchi¹²⁷, O. Biebel¹⁰², D. Biedermann¹⁷, R. Bielski⁸⁷, K. Bierwagen⁸⁶, N.V. Biesuz^{126a,126b}, M. Biglietti^{136a}, T.R.V. Billoud⁹⁷, H. Bilokon⁵⁰, M. Bindi⁵⁷, A. Bingul^{20b}, C. Bini^{134a,134b}, S. Biondi^{22a,22b}, T. Bisanz⁵⁷, C. Bittrich⁴⁷, D.M. Bjergaard⁴⁸, J.E. Black¹⁴⁵, K.M. Black²⁴, R.E. Blair⁶,

T. Blazek^{146a}, I. Bloch⁴⁵, C. Blocker²⁵, A. Blue⁵⁶, W. Blum^{86,*}, U. Blumenschein⁷⁹, S. Blunier^{34a}, G.J. Bobbink¹⁰⁹, V.S. Bobrovnikov^{111,c}, S.S. Bocchetta⁸⁴, A. Bocci⁴⁸, C. Bock¹⁰², M. Boehler⁵¹, D. Boerner¹⁷⁸, D. Bogavac¹⁰², A.G. Bogdanchikov¹¹¹, C. Boehm^{148a}, V. Boisvert⁸⁰, P. Bokan^{168,i}, T. Bold^{41a}, A.S. Boldyrev¹⁰¹, A.E. Bolz^{60b}, M. Bomben⁸³, M. Bona⁷⁹, M. Boonekamp¹³⁸, A. Borisov¹³², G. Borissov⁷⁵, J. Bortfeldt³², D. Bortoletto¹²², V. Bortolotto^{62a}, D. Boscherini^{22a}, M. Bosman¹³, J.D. Bossio Sola²⁹, J. Boudreau¹²⁷, J. Bouffard², E.V. Bouhova-Thacker⁷⁵, D. Boumediene³⁷, C. Bourdarios¹¹⁹, S.K. Boutle⁵⁶, A. Boveia¹¹³, J. Boyd³², I.R. Boyko⁶⁸, J. Bracinik¹⁹, A. Brandt⁸, G. Brandt⁵⁷, O. Brandt^{60a}, U. Bratzler¹⁵⁸, B. Brau⁸⁹, J.E. Brau¹¹⁸, W.D. Breaden Madden⁵⁶, K. Brendlinger⁴⁵, A.J. Brennan⁹¹, L. Brenner¹⁰⁹, R. Brenner¹⁶⁸, S. Bressler¹⁷⁵, D.L. Briglin¹⁹, T.M. Bristow⁴⁹, D. Britton⁵⁶, D. Britzger⁴⁵, F.M. Brochu³⁰, I. Brock²³, R. Brock⁹³, G. Brooijmans³⁸, T. Brooks⁸⁰, W.K. Brooks^{34b}, J. Brosamer¹⁶, E. Brost¹¹⁰, J.H. Broughton¹⁹, P.A. Bruckman de Renstrom⁴², D. Bruncko^{146b}, A. Bruni^{22a}, G. Bruni^{22a}, L.S. Bruni¹⁰⁹, B.H. Brunt³⁰, M. Bruschi^{22a}, N. Bruscino²³, P. Bryant³³, L. Bryngemark⁴⁵, T. Buanes¹⁵, Q. Buat¹⁴⁴, P. Buchholz¹⁴³, A.G. Buckley⁵⁶, I.A. Budagov⁶⁸, F. Buehrer⁵¹, M.K. Bugge¹²¹, O. Bulekov¹⁰⁰, D. Bullock⁸, T.J. Burch¹¹⁰, S. Burdin⁷⁷, C.D. Burgard⁵¹, A.M. Burger⁵, B. Burghgrave¹¹⁰, K. Burka⁴², S. Burke¹³³, I. Burmeister⁴⁶, J.T.P. Burr¹²², E. Busato³⁷, D. Büscher⁵¹, V. Büscher⁸⁶, P. Bussey⁵⁶, J.M. Butler²⁴, C.M. Buttar⁵⁶, J.M. Butterworth⁸¹, P. Butti³², W. Buttinger²⁷, A. Buzatu¹⁵³, A.R. Buzykaev^{111,c}, S. Cabrera Urbán¹⁷⁰, D. Caforio¹³⁰, V.M. Cairo^{40a,40b}, O. Cakir^{4a}, N. Calace⁵², P. Calafiura¹⁶, A. Calandri⁸⁸, G. Calderini⁸³, P. Calfayan⁶⁴, G. Callea^{40a,40b}, L.P. Caloba^{26a}, S. Calvente Lopez⁸⁵, D. Calvet³⁷, S. Calvet³⁷, T.P. Calvet⁸⁸, R. Camacho Toro³³, S. Camarda³², P. Camarri^{135a,135b}, D. Cameron¹²¹, R. Caminal Armadans¹⁶⁹, C. Camincher⁵⁸, S. Campana³², M. Campanelli⁸¹, A. Camplani^{94a,94b}, A. Campoverde¹⁴³, V. Canale^{106a,106b}, M. Cano Bret^{36c}, J. Cantero¹¹⁶, T. Cao¹⁵⁵, M.D.M. Capeans Garrido³², I. Caprini^{28b}, M. Caprini^{28b}, M. Capua^{40a,40b}, R.M. Carbone³⁸, R. Cardarelli^{135a}, F. Cardillo⁵¹, I. Carli¹³¹, T. Carli³², G. Carlino^{106a}, B.T. Carlson¹²⁷, L. Carminati^{94a,94b}, R.M.D. Carney^{148a,148b}, S. Caron¹⁰⁸, E. Carquin^{34b}, S. Carrá^{94a,94b}, G.D. Carrillo-Montoya³², D. Casadei¹⁹, M.P. Casado^{13,j}, M. Casolino¹³, D.W. Casper¹⁶⁶, R. Castelijin¹⁰⁹, V. Castillo Gimenez¹⁷⁰, N.F. Castro^{128a,k}, A. Catinaccio³², J.R. Catmore¹²¹, A. Cattai³², J. Caudron²³, V. Cavaliere¹⁶⁹, E. Cavallaro¹³, D. Cavalli^{94a}, M. Cavalli-Sforza¹³, V. Cavasinni^{126a,126b}, E. Celebi^{20d}, F. Ceradini^{136a,136b}, L. Cerda Alberich¹⁷⁰, A.S. Cerqueira^{26b}, A. Cerri¹⁵¹, L. Cerrito^{135a,135b}, F. Cerutti¹⁶, A. Cervelli¹⁸, S.A. Cetin^{20d}, A. Chafaq^{137a}, D. Chakraborty¹¹⁰, S.K. Chan⁵⁹, W.S. Chan¹⁰⁹, Y.L. Chan^{62a}, P. Chang¹⁶⁹, J.D. Chapman³⁰, D.G. Charlton¹⁹, C.C. Chau³¹, C.A. Chavez Barajas¹⁵¹, S. Che¹¹³, S. Cheatham^{167a,167c}, A. Chegwiddden⁹³, S. Chekanov⁶, S.V. Chekulaev^{163a}, G.A. Chelkov^{68,l}, M.A. Chelstowska³², C. Chen⁶⁷, H. Chen²⁷, J. Chen^{36a}, S. Chen^{35b}, S. Chen¹⁵⁷, X. Chen^{35c,m}, Y. Chen⁷⁰, H.C. Cheng⁹², H.J. Cheng^{35a,35d}, A. Cheplakov⁶⁸, E. Cheremushkina¹³², R. Cherkaoui El Moursli^{137e}, E. Cheu⁷, K. Cheung⁶³, L. Chevalier¹³⁸, V. Chiarella⁵⁰, G. Chiarelli^{126a,126b}, G. Chiodini^{76a}, A.S. Chisholm³², A. Chitan^{28b}, Y.H. Chiu¹⁷², M.V. Chizhov⁶⁸, K. Choi⁶⁴, A.R. Chomont³⁷, S. Chouridou¹⁵⁶, Y.S. Chow^{62a}, V. Christodoulou⁸¹, M.C. Chu^{62a}, J. Chudoba¹²⁹, A.J. Chuinard⁹⁰, J.J. Chwastowski⁴², L. Chytka¹¹⁷, A.K. Ciftci^{4a}, D. Cinca⁴⁶, V. Cindro⁷⁸, I.A. Cioara²³, C. Ciocca^{22a,22b}, A. Ciocio¹⁶, F. Ciotto^{106a,106b}, Z.H. Citron¹⁷⁵, M. Citterio^{94a}, M. Ciubancan^{28b}, A. Clark⁵², B.L. Clark⁵⁹, M.R. Clark³⁸, P.J. Clark⁴⁹, R.N. Clarke¹⁶, C. Clement^{148a,148b}, Y. Coadou⁸⁸, M. Cokal^{167a,167c}, A. Coccaro⁵², J. Cochran⁶⁷, L. Colasurdo¹⁰⁸, B. Cole³⁸, A.P. Colijn¹⁰⁹, J. Collot⁵⁸, T. Colombo¹⁶⁶, P. Conde Muño^{128a,128b}, E. Coniavitis⁵¹, S.H. Connell^{147b}, I.A. Connelly⁸⁷, S. Constantinescu^{28b}, G. Conti³², F. Conventi^{106a,n}, M. Cooke¹⁶, A.M. Cooper-Sarkar¹²², F. Cormier¹⁷¹, K.J.R. Cormier¹⁶¹, M. Corradi^{134a,134b}, F. Corriveau^{90,o}, A. Cortes-Gonzalez³², G. Cortiana¹⁰³, G. Costa^{94a}, M.J. Costa¹⁷⁰,

D. Costanzo¹⁴¹, G. Cottin³⁰, G. Cowan⁸⁰, B.E. Cox⁸⁷, K. Cranmer¹¹², S.J. Crawley⁵⁶, R.A. Creager¹²⁴, G. Cree³¹, S. Crépe-Renaudin⁵⁸, F. Crescioli⁸³, W.A. Cribbs^{148a,148b}, M. Cristinziani²³, V. Croft¹⁰⁸, G. Crosetti^{40a,40b}, A. Cueto⁸⁵, T. Cuhadar Donszelmann¹⁴¹, A.R. Cukierman¹⁴⁵, J. Cummings¹⁷⁹, M. Curatolo⁵⁰, J. Cúth⁸⁶, S. Czekierda⁴², P. Czodrowski³², G. D'amen^{22a,22b}, S. D'Auria⁵⁶, L. D'eraimo⁸³, M. D'Onofrio⁷⁷, M.J. Da Cunha Sargedas De Sousa^{128a,128b}, C. Da Via⁸⁷, W. Dabrowski^{41a}, T. Dado^{146a}, T. Dai⁹², O. Dale¹⁵, F. Dallaire⁹⁷, C. Dallapiccola⁸⁹, M. Dam³⁹, J.R. Dandoy¹²⁴, M.F. Daneri²⁹, N.P. Dang¹⁷⁶, A.C. Daniells¹⁹, N.S. Dann⁸⁷, M. Danninger¹⁷¹, M. Dano Hoffmann¹³⁸, V. Dao¹⁵⁰, G. Darbo^{53a}, S. Darmora⁸, J. Dassoulas³, A. Dattagupta¹¹⁸, T. Daubney⁴⁵, W. Davey²³, C. David⁴⁵, T. Davidek¹³¹, D.R. Davis⁴⁸, P. Davison⁸¹, E. Dawe⁹¹, I. Dawson¹⁴¹, K. De⁸, R. de Asmundis^{106a}, A. De Benedetti¹¹⁵, S. De Castro^{22a,22b}, S. De Cecco⁸³, N. De Groot¹⁰⁸, P. de Jong¹⁰⁹, H. De la Torre⁹³, F. De Lorenzi⁶⁷, A. De Maria⁵⁷, D. De Pedis^{134a}, A. De Salvo^{134a}, U. De Sanctis^{135a,135b}, A. De Santo¹⁵¹, K. De Vasconcelos Corga⁸⁸, J.B. De Vivie De Regie¹¹⁹, R. Debbe²⁷, C. Debenedetti¹³⁹, D.V. Dedovich⁶⁸, N. Dehghanian³, I. Deigaard¹⁰⁹, M. Del Gaudio^{40a,40b}, J. Del Peso⁸⁵, D. Delgove¹¹⁹, F. Deliot¹³⁸, C.M. Delitzsch⁷, A. Dell'Acqua³², L. Dell'Asta²⁴, M. Dell'Orso^{126a,126b}, M. Della Pietra^{106a,106b}, D. della Volpe⁵², M. Delmastro⁵, C. Delporte¹¹⁹, P.A. Delsart⁵⁸, D.A. DeMarco¹⁶¹, S. Demers¹⁷⁹, M. Demichev⁶⁸, A. Demilly⁸³, S.P. Denisov¹³², D. Denysiuk¹³⁸, D. Derendarz⁴², J.E. Derkaoui^{137d}, F. Derue⁸³, P. Dervan⁷⁷, K. Desch²³, C. Deterre⁴⁵, K. Dette¹⁶¹, M.R. Devesa²⁹, P.O. Deviveiros³², A. Dewhurst¹³³, S. Dhaliwal²⁵, F.A. Di Bello⁵², A. Di Ciaccio^{135a,135b}, L. Di Ciaccio⁵, W.K. Di Clemente¹²⁴, C. Di Donato^{106a,106b}, A. Di Girolamo³², B. Di Girolamo³², B. Di Micco^{136a,136b}, R. Di Nardo³², K.F. Di Petrillo⁵⁹, A. Di Simone⁵¹, R. Di Sipio¹⁶¹, D. Di Valentino³¹, C. Diaconu⁸⁸, M. Diamond¹⁶¹, F.A. Dias³⁹, M.A. Diaz^{34a}, E.B. Diehl⁹², J. Dietrich¹⁷, S. Díez Cornell⁴⁵, A. Dimitrievska¹⁴, J. Dingfelder²³, P. Dita^{28b}, S. Dita^{28b}, F. Dittus³², F. Djama⁸⁸, T. Djobava^{54b}, J.I. Djuvsland^{60a}, M.A.B. do Vale^{26c}, D. Dobos³², M. Dobre^{28b}, C. Doglioni⁸⁴, J. Dolejsi¹³¹, Z. Dolezal¹³¹, M. Donadelli^{26d}, S. Donati^{126a,126b}, P. Dondero^{123a,123b}, J. Donini³⁷, J. Dopke¹³³, A. Doria^{106a}, M.T. Dova⁷⁴, A.T. Doyle⁵⁶, E. Drechsler⁵⁷, M. Dris¹⁰, Y. Du^{36b}, J. Duarte-Campderros¹⁵⁵, A. Dubreuil⁵², E. Duchovni¹⁷⁵, G. Duckeck¹⁰², A. Ducourthial⁸³, O.A. Ducu^{97,p}, D. Duda¹⁰⁹, A. Dudarev³², A.Ch. Dudder⁸⁶, E.M. Duffield¹⁶, L. Dufflot¹¹⁹, M. Dührssen³², C. Dulsen¹⁷⁸, M. Dumancic¹⁷⁵, A.E. Dumitriu^{28b}, A.K. Duncan⁵⁶, M. Dunford^{60a}, H. Duran Yildiz^{4a}, M. Düren⁵⁵, A. Durglishvili^{54b}, D. Duschinger⁴⁷, B. Dutta⁴⁵, D. Duvnjak¹, M. Dyndal⁴⁵, B.S. Dziejczak⁴², C. Eckardt⁴⁵, K.M. Ecker¹⁰³, R.C. Edgar⁹², T. Eifert³², G. Eigen¹⁵, K. Einsweiler¹⁶, T. Ekelof¹⁶⁸, M. El Kacimi^{137c}, R. El Kosseifi⁸⁸, V. Ellajosyula⁸⁸, M. Ellert¹⁶⁸, S. Elles⁵, F. Ellinghaus¹⁷⁸, A.A. Elliot¹⁷², N. Ellis³², J. Elmsheuser²⁷, M. Elsing³², D. Emeliyanov¹³³, Y. Enari¹⁵⁷, O.C. Endner⁸⁶, J.S. Ennis¹⁷³, J. Erdmann⁴⁶, A. Ereditato¹⁸, M. Ernst²⁷, S. Errede¹⁶⁹, M. Escalier¹¹⁹, C. Escobar¹⁷⁰, B. Esposito⁵⁰, O. Estrada Pastor¹⁷⁰, A.I. Etienne¹³⁸, E. Etzion¹⁵⁵, H. Evans⁶⁴, A. Ezhilov¹²⁵, M. Ezzi^{137e}, F. Fabbri^{22a,22b}, L. Fabbri^{22a,22b}, V. Fabiani¹⁰⁸, G. Facini⁸¹, R.M. Fakhruddinov¹³², S. Falciano^{134a}, R.J. Falla⁸¹, J. Faltova³², Y. Fang^{35a}, M. Fanti^{94a,94b}, A. Farbin⁸, A. Farilla^{136a}, C. Farina¹²⁷, E.M. Farina^{123a,123b}, T. Farooque⁹³, S. Farrell¹⁶, S.M. Farrington¹⁷³, P. Farthouat³², F. Fassi^{137e}, P. Fassnacht³², D. Fassouliotis⁹, M. Fauci Giannelli⁴⁹, A. Favareto^{53a,53b}, W.J. Fawcett¹²², L. Fayard¹¹⁹, O.L. Fedin^{125,q}, W. Fedorko¹⁷¹, S. Feigl¹²¹, L. Feligioni⁸⁸, C. Feng^{36b}, E.J. Feng³², H. Feng⁹², M.J. Fenton⁵⁶, A.B. Fenyuk¹³², L. Feremenga⁸, P. Fernandez Martinez¹⁷⁰, S. Fernandez Perez¹³, J. Ferrando⁴⁵, A. Ferrari¹⁶⁸, P. Ferrari¹⁰⁹, R. Ferrari^{123a}, D.E. Ferreira de Lima^{60b}, A. Ferrer¹⁷⁰, D. Ferrere⁵², C. Ferretti⁹², F. Fiedler⁸⁶, A. Filipčić⁷⁸, M. Filipuzzi⁴⁵, F. Filthaut¹⁰⁸, M. Fincke-Keeler¹⁷², K.D. Finelli¹⁵², M.C.N. Fiolhais^{128a,128c,r}, L. Fiorini¹⁷⁰, A. Fischer², C. Fischer¹³, J. Fischer¹⁷⁸, W.C. Fisher⁹³, N. Flaschel⁴⁵, I. Fleck¹⁴³, P. Fleischmann⁹², R.R.M. Fletcher¹²⁴, T. Flick¹⁷⁸,

B.M. Flierl¹⁰², L.R. Flores Castillo^{62a}, M.J. Flowerdew¹⁰³, G.T. Forcolin⁸⁷, A. Formica¹³⁸,
 F.A. Förster¹³, A. Forti⁸⁷, A.G. Foster¹⁹, D. Fournier¹¹⁹, H. Fox⁷⁵, S. Fracchia¹⁴¹,
 P. Francavilla⁸³, M. Franchini^{22a,22b}, S. Franchino^{60a}, D. Francis³², L. Franconi¹²¹, M. Franklin⁵⁹,
 M. Frate¹⁶⁶, M. Fraternali^{123a,123b}, D. Freeborn⁸¹, S.M. Fressard-Batraneanu³², B. Freund⁹⁷,
 D. Froidevaux³², J.A. Frost¹²², C. Fukunaga¹⁵⁸, T. Fusayasu¹⁰⁴, J. Fuster¹⁷⁰, C. Gabaldon⁵⁸,
 O. Gabizon¹⁵⁴, A. Gabrielli^{22a,22b}, A. Gabrielli¹⁶, G.P. Gach^{41a}, S. Gadatsch³², S. Gadomski⁸⁰,
 G. Gagliardi^{53a,53b}, L.G. Gagnon⁹⁷, C. Galea¹⁰⁸, B. Galhardo^{128a,128c}, E.J. Gallas¹²²,
 B.J. Gallop¹³³, P. Gallus¹³⁰, G. Galster³⁹, K.K. Gan¹¹³, S. Ganguly³⁷, Y. Gao⁷⁷, Y.S. Gao^{145,g},
 F.M. Garay Walls^{34a}, C. García¹⁷⁰, J.E. García Navarro¹⁷⁰, J.A. García Pascual^{35a},
 M. Garcia-Sciveres¹⁶, R.W. Gardner³³, N. Garelli¹⁴⁵, V. Garonne¹²¹, A. Gascon Bravo⁴⁵,
 K. Gasnikova⁴⁵, C. Gatti⁵⁰, A. Gaudiello^{53a,53b}, G. Gaudio^{123a}, I.L. Gavrilenko⁹⁸, C. Gay¹⁷¹,
 G. Gaycken²³, E.N. Gazis¹⁰, C.N.P. Gee¹³³, J. Geisen⁵⁷, M. Geisen⁸⁶, M.P. Geisler^{60a},
 K. Gellerstedt^{148a,148b}, C. Gemme^{53a}, M.H. Genest⁵⁸, C. Geng⁹², S. Gentile^{134a,134b},
 C. Gentsos¹⁵⁶, S. George⁸⁰, D. Gerbaudo¹³, A. Gershon¹⁵⁵, G. Geßner⁴⁶, S. Ghasemi¹⁴³,
 M. Ghneimat²³, B. Giacobbe^{22a}, S. Giagu^{134a,134b}, N. Giangiacomi^{22a,22b}, P. Giannetti^{126a,126b},
 S.M. Gibson⁸⁰, M. Gignac¹⁷¹, M. Gilchriese¹⁶, D. Gillberg³¹, G. Gilles¹⁷⁸, D.M. Gingrich^{3,d},
 M.P. Giordani^{167a,167c}, F.M. Giorgi^{22a}, P.F. Giraud¹³⁸, P. Giromini⁵⁹, G. Giugliarelli^{167a,167c},
 D. Giugni^{94a}, F. Giuli¹²², C. Giuliani¹⁰³, M. Giulini^{60b}, B.K. Gjelsten¹²¹, S. Gkaitatzis¹⁵⁶,
 I. Gkialas^{9,s}, E.L. Gkougkousis¹³, P. Gkoutoumis¹⁰, L.K. Gladilin¹⁰¹, C. Glasman⁸⁵,
 J. Glatzer¹³, P.C.F. Glaysher⁴⁵, A. Glazov⁴⁵, M. Goblirsch-Kolb²⁵, J. Godlewski⁴², S. Goldfarb⁹¹,
 T. Golling⁵², D. Golubkov¹³², A. Gomes^{128a,128b,128d}, R. Gonçalo^{128a}, R. Goncalves Gama^{26a},
 J. Goncalves Pinto Firmino Da Costa¹³⁸, G. Gonella⁵¹, L. Gonella¹⁹, A. Gongadze⁶⁸,
 S. González de la Hoz¹⁷⁰, S. Gonzalez-Sevilla⁵², L. Goossens³², P.A. Gorbounov⁹⁹,
 H.A. Gordon²⁷, I. Gorelov¹⁰⁷, B. Gorini³², E. Gorini^{76a,76b}, A. Gorišek⁷⁸, A.T. Goshaw⁴⁸,
 C. Gössling⁴⁶, M.I. Gostkin⁶⁸, C.A. Gottardo²³, C.R. Goudet¹¹⁹, D. Goujdami^{137c},
 A.G. Goussiou¹⁴⁰, N. Govender^{147b,t}, E. Gozani¹⁵⁴, L. Graber⁵⁷, I. Grabowska-Bold^{41a},
 P.O.J. Gradin¹⁶⁸, J. Gramling¹⁶⁶, E. Gramstad¹²¹, S. Grancagnolo¹⁷, V. Gratchev¹²⁵,
 P.M. Gravila^{28f}, C. Gray⁵⁶, H.M. Gray¹⁶, Z.D. Greenwood^{82,u}, C. Grefe²³, K. Gregersen⁸¹,
 I.M. Gregor⁴⁵, P. Grenier¹⁴⁵, K. Grevtsov⁵, J. Griffiths⁸, A.A. Grillo¹³⁹, K. Grimm⁷⁵,
 S. Grinstein^{13,v}, Ph. Gris³⁷, J.-F. Grivaz¹¹⁹, S. Groh⁸⁶, E. Gross¹⁷⁵, J. Grosse-Knetter⁵⁷,
 G.C. Grossi⁸², Z.J. Grout⁸¹, A. Grummer¹⁰⁷, L. Guan⁹², W. Guan¹⁷⁶, J. Guenther⁶⁵,
 F. Guescini^{163a}, D. Guest¹⁶⁶, O. Gueta¹⁵⁵, B. Gui¹¹³, E. Guido^{53a,53b}, T. Guillemin⁵,
 S. Guindon³², U. Gul⁵⁶, C. Gumpert³², J. Guo^{36c}, W. Guo⁹², Y. Guo^{36a,w}, R. Gupta⁴³,
 S. Gupta¹²², G. Gustavino¹¹⁵, B.J. Gutelman¹⁵⁴, P. Gutierrez¹¹⁵, N.G. Gutierrez Ortiz⁸¹,
 C. Gutsche⁸¹, C. Guyot¹³⁸, M.P. Guzik^{41a}, C. Gwenlan¹²², C.B. Gwilliam⁷⁷, A. Haas¹¹²,
 C. Haber¹⁶, H.K. Hadavand⁸, N. Haddad^{137e}, A. Hade⁸⁸, S. Hageböck²³, M. Hagihara¹⁶⁴,
 H. Hakobyan^{180,*}, M. Haleem⁴⁵, J. Haley¹¹⁶, G. Halladjian⁹³, G.D. Hallowell⁸⁸, K. Hamacher¹⁷⁸,
 P. Hamal¹¹⁷, K. Hamano¹⁷², A. Hamilton^{147a}, G.N. Hamity¹⁴¹, P.G. Hamnett⁴⁵, L. Han^{36a},
 S. Han^{35a,35d}, K. Hanagaki^{69,x}, K. Hanawa¹⁵⁷, M. Hance¹³⁹, B. Haney¹²⁴, P. Hanke^{60a},
 J.B. Hansen³⁹, J.D. Hansen³⁹, M.C. Hansen²³, P.H. Hansen³⁹, K. Hara¹⁶⁴, A.S. Hard¹⁷⁶,
 T. Harenberg¹⁷⁸, F. Hariri¹¹⁹, S. Harkusha⁹⁵, R.D. Harrington⁴⁹, P.F. Harrison¹⁷³,
 N.M. Hartmann¹⁰², Y. Hasegawa¹⁴², A. Hasib⁴⁹, S. Hassani¹³⁸, S. Haug¹⁸, R. Hauser⁹³,
 L. Hauswald⁴⁷, L.B. Havener³⁸, M. Havranek¹³⁰, C.M. Hawkes¹⁹, R.J. Hawkins³²,
 D. Hayakawa¹⁵⁹, D. Hayden⁹³, C.P. Hays¹²², J.M. Hays⁷⁹, H.S. Hayward⁷⁷, S.J. Haywood¹³³,
 S.J. Head¹⁹, T. Heck⁸⁶, V. Hedberg⁸⁴, L. Heelan⁸, S. Heer²³, K.K. Heidegger⁵¹, S. Heim⁴⁵,
 T. Heim¹⁶, B. Heinemann^{45,y}, J.J. Heinrich¹⁰², L. Heinrich¹¹², C. Heinz⁵⁵, J. Hejbal¹²⁹,
 L. Helary³², A. Held¹⁷¹, S. Hellman^{148a,148b}, C. Helsens³², R.C.W. Henderson⁷⁵, Y. Heng¹⁷⁶,
 S. Henkelmann¹⁷¹, A.M. Henriques Correia³², S. Henrot-Versille¹¹⁹, G.H. Herbert¹⁷, H. Herde²⁵,

V. Herget¹⁷⁷, Y. Hernández Jiménez^{147c}, H. Herr⁸⁶, G. Herten⁵¹, R. Hertenberger¹⁰², L. Hervas³², T.C. Herwig¹²⁴, G.G. Hesketh⁸¹, N.P. Hessey^{163a}, J.W. Hetherly⁴³, S. Higashino⁶⁹, E. Higón-Rodríguez¹⁷⁰, K. Hildebrand³³, E. Hill¹⁷², J.C. Hill³⁰, K.H. Hiller⁴⁵, S.J. Hillier¹⁹, M. Hils⁴⁷, I. Hinchliffe¹⁶, M. Hirose⁵¹, D. Hirschbuehl¹⁷⁸, B. Hiti⁷⁸, O. Hladik¹²⁹, X. Hoad⁴⁹, J. Hobbs¹⁵⁰, N. Hod^{163a}, M.C. Hodgkinson¹⁴¹, P. Hodgson¹⁴¹, A. Hoecker³², M.R. Hoferkamp¹⁰⁷, F. Hoenig¹⁰², D. Hohn²³, T.R. Holmes³³, M. Homann⁴⁶, S. Honda¹⁶⁴, T. Honda⁶⁹, T.M. Hong¹²⁷, B.H. Hooberman¹⁶⁹, W.H. Hopkins¹¹⁸, Y. Horii¹⁰⁵, A.J. Horton¹⁴⁴, J.-Y. Hostachy⁵⁸, S. Hou¹⁵³, A. Houmada^{137a}, J. Howarth⁸⁷, J. Hoya⁷⁴, M. Hrabovsky¹¹⁷, J. Hrdinka³², I. Hristova¹⁷, J. Hrivnac¹¹⁹, T. Hryn'ova⁵, A. Hrynevich⁹⁶, P.J. Hsu⁶³, S.-C. Hsu¹⁴⁰, Q. Hu^{36a}, S. Hu^{36c}, Y. Huang^{35a}, Z. Hubacek¹³⁰, F. Hubaut⁸⁸, F. Huegging²³, T.B. Huffman¹²², E.W. Hughes³⁸, G. Hughes⁷⁵, M. Huhtinen³², P. Huo¹⁵⁰, N. Huseynov^{68,b}, J. Huston⁹³, J. Huth⁵⁹, G. Iacobucci⁵², G. Iakovidis²⁷, I. Ibragimov¹⁴³, L. Iconomidou-Fayard¹¹⁹, Z. Idrissi^{137e}, P. Iengo³², O. Igonkina^{109,z}, T. Iizawa¹⁷⁴, Y. Ikegami⁶⁹, M. Ikeno⁶⁹, Y. Ilchenko^{11,aa}, D. Iliadis¹⁵⁶, N. Ilic¹⁴⁵, G. Introzzi^{123a,123b}, P. Ioannou^{9,*}, M. Iodice^{136a}, K. Iordanidou³⁸, V. Ippolito⁵⁹, M.F. Isacson¹⁶⁸, N. Ishijima¹²⁰, M. Ishino¹⁵⁷, M. Ishitsuka¹⁵⁹, C. Issever¹²², S. Istin^{20a}, F. Ito¹⁶⁴, J.M. Iturbe Ponce^{62a}, R. Iuppa^{162a,162b}, H. Iwasaki⁶⁹, J.M. Izen⁴⁴, V. Izzo^{106a}, S. Jabbar³, P. Jackson¹, R.M. Jacobs²³, V. Jain², K.B. Jakobi⁸⁶, K. Jakobs⁵¹, S. Jakobsen⁶⁵, T. Jakoubek¹²⁹, D.O. Jamin¹¹⁶, D.K. Jana⁸², R. Jansky⁵², J. Janssen²³, M. Janus⁵⁷, P.A. Janus^{41a}, G. Jarlskog⁸⁴, N. Javadov^{68,b}, T. Javůrek⁵¹, M. Javurkova⁵¹, F. Jeanneau¹³⁸, L. Jeanty¹⁶, J. Jejelava^{54a,ab}, A. Jelinskas¹⁷³, P. Jenni^{51,ac}, C. Jeske¹⁷³, S. Jézéquel⁵, H. Ji¹⁷⁶, J. Jia¹⁵⁰, H. Jiang⁶⁷, Y. Jiang^{36a}, Z. Jiang¹⁴⁵, S. Jiggins⁸¹, J. Jimenez Pena¹⁷⁰, S. Jin^{35a}, A. Jinaru^{28b}, O. Jinnouchi¹⁵⁹, H. Jivan^{147c}, P. Johansson¹⁴¹, K.A. Johns⁷, C.A. Johnson⁶⁴, W.J. Johnson¹⁴⁰, K. Jon-And^{148a,148b}, R.W.L. Jones⁷⁵, S.D. Jones¹⁵¹, S. Jones⁷, T.J. Jones⁷⁷, J. Jongmanns^{60a}, P.M. Jorge^{128a,128b}, J. Jovicevic^{163a}, X. Ju¹⁷⁶, A. Juste Rozas^{13,v}, M.K. Köhler¹⁷⁵, A. Kaczmarska⁴², M. Kado¹¹⁹, H. Kagan¹¹³, M. Kagan¹⁴⁵, S.J. Kahn⁸⁸, T. Kaji¹⁷⁴, E. Kajomovitz⁴⁸, C.W. Kalderon⁸⁴, A. Kaluza⁸⁶, S. Kama⁴³, A. Kamenshchikov¹³², N. Kanaya¹⁵⁷, L. Kanjir⁷⁸, V.A. Kantserov¹⁰⁰, J. Kanzaki⁶⁹, B. Kaplan¹¹², L.S. Kaplan¹⁷⁶, D. Kar^{147c}, K. Karakostas¹⁰, N. Karastathis¹⁰, M.J. Kareem⁵⁷, E. Karentzos¹⁰, S.N. Karpov⁶⁸, Z.M. Karpova⁶⁸, K. Karthik¹¹², V. Kartvelishvili⁷⁵, A.N. Karyukhin¹³², K. Kasahara¹⁶⁴, L. Kashif¹⁷⁶, R.D. Kass¹¹³, A. Kastanas¹⁴⁹, Y. Kataoka¹⁵⁷, C. Kato¹⁵⁷, A. Katre⁵², J. Katzy⁴⁵, K. Kawade⁷⁰, K. Kawagoe⁷³, T. Kawamoto¹⁵⁷, G. Kawamura⁵⁷, E.F. Kay⁷⁷, V.F. Kazanin^{111,c}, R. Keeler¹⁷², R. Kehoe⁴³, J.S. Keller³¹, E. Kellermann⁸⁴, J.J. Kempster⁸⁰, J. Kendrick¹⁹, H. Keoshkerian¹⁶¹, O. Kepka¹²⁹, B.P. Kerševan⁷⁸, S. Kersten¹⁷⁸, R.A. Keyes⁹⁰, M. Khader¹⁶⁹, F. Khalil-zada¹², A. Khanov¹¹⁶, A.G. Kharlamov^{111,c}, T. Kharlamova^{111,c}, A. Khodinov¹⁶⁰, T.J. Khoo⁵², V. Khovanskiy^{99,*}, E. Khramov⁶⁸, J. Khubua^{54b,ad}, S. Kido⁷⁰, C.R. Kilby⁸⁰, H.Y. Kim⁸, S.H. Kim¹⁶⁴, Y.K. Kim³³, N. Kimura¹⁵⁶, O.M. Kind¹⁷, B.T. King⁷⁷, D. Kirchmeier⁴⁷, J. Kirk¹³³, A.E. Kiryunin¹⁰³, T. Kishimoto¹⁵⁷, D. Kisielewska^{41a}, V. Kitali⁴⁵, O. Kivernyk⁵, E. Kladiva^{146b}, T. Klapdor-Kleingrothaus⁵¹, M.H. Klein⁹², M. Klein⁷⁷, U. Klein⁷⁷, K. Kleinknecht⁸⁶, P. Klimek¹¹⁰, A. Klimentov²⁷, R. Klingenberg⁴⁶, T. Klingl²³, T. Klioutchnikova³², E.-E. Kluge^{60a}, P. Kluit¹⁰⁹, S. Kluth¹⁰³, E. Kneringer⁶⁵, E.B.F.G. Knoops⁸⁸, A. Knue¹⁰³, A. Kobayashi¹⁵⁷, D. Kobayashi¹⁵⁹, T. Kobayashi¹⁵⁷, M. Kobel⁴⁷, M. Kocian¹⁴⁵, P. Kodys¹³¹, T. Koffas³¹, E. Koffeman¹⁰⁹, N.M. Köhler¹⁰³, T. Koi¹⁴⁵, M. Kolb^{60b}, I. Koletsou⁵, A.A. Komar^{98,*}, T. Kondo⁶⁹, N. Kondrashova^{36c}, K. Köneke⁵¹, A.C. König¹⁰⁸, T. Kono^{69,ae}, R. Konoplich^{112,af}, N. Konstantinidis⁸¹, R. Kopeliansky⁶⁴, S. Koperny^{41a}, A.K. Kopp⁵¹, K. Korcyl⁴², K. Kordas¹⁵⁶, A. Korn⁸¹, A.A. Korol^{111,c}, I. Korolkov¹³, E.V. Korolkova¹⁴¹, O. Kortner¹⁰³, S. Kortner¹⁰³, T. Kosek¹³¹, V.V. Kostyukhin²³, A. Kotwal⁴⁸, A. Koulouris¹⁰, A. Kourkoumeli-Charalampidi^{123a,123b}, C. Kourkoumelis⁹, E. Kourlitis¹⁴¹, V. Kouskoura²⁷, A.B. Kowalewska⁴², R. Kowalewski¹⁷², T.Z. Kowalski^{41a}, C. Kozakai¹⁵⁷, W. Kozanecki¹³⁸,

A.S. Kozhin¹³², V.A. Kramarenko¹⁰¹, G. Kramberger⁷⁸, D. Krasnopevtsev¹⁰⁰, M.W. Krasny⁸³,
 A. Krasznahorkay³², D. Krauss¹⁰³, J.A. Kremer^{41a}, J. Kretzschmar⁷⁷, K. Kretzfeldt⁵⁵,
 P. Krieger¹⁶¹, K. Krizka¹⁶, K. Kroeninger⁴⁶, H. Kroha¹⁰³, J. Kroll¹²⁹, J. Kroll¹²⁴, J. Kroseberg²³,
 J. Krstic¹⁴, U. Kruchonak⁶⁸, H. Krüger²³, N. Krumnack⁶⁷, M.C. Kruse⁴⁸, T. Kubota⁹¹,
 H. Kucuk⁸¹, S. Kuday^{4b}, J.T. Kuechler¹⁷⁸, S. Kuehn³², A. Kugel^{60a}, F. Kuger¹⁷⁷, T. Kuhl⁴⁵,
 V. Kukhtin⁶⁸, R. Kukla⁸⁸, Y. Kulchitsky⁹⁵, S. Kuleshov^{34b}, Y.P. Kulinich¹⁶⁹, M. Kuna^{134a,134b},
 T. Kunigo⁷¹, A. Kupco¹²⁹, T. Kupfer⁴⁶, O. Kuprash¹⁵⁵, H. Kurashige⁷⁰, L.L. Kurchaninov^{163a},
 Y.A. Kurochkin⁹⁵, M.G. Kurth^{35a,35d}, V. Kus¹²⁹, E.S. Kuwertz¹⁷², M. Kuze¹⁵⁹, J. Kvita¹¹⁷,
 T. Kwan¹⁷², D. Kyriazopoulos¹⁴¹, A. La Rosa¹⁰³, J.L. La Rosa Navarro^{26d}, L. La Rotonda^{40a,40b},
 F. La Ruffa^{40a,40b}, C. Lacasta¹⁷⁰, F. Lacava^{134a,134b}, J. Lacey⁴⁵, D.P.J. Lack⁸⁷, H. Lacker¹⁷,
 D. Lacour⁸³, E. Ladygin⁶⁸, R. Lafaye⁵, B. Laforge⁸³, T. Lagouri¹⁷⁹, S. Lai⁵⁷, S. Lammers⁶⁴,
 W. Lampl⁷, E. Lançon²⁷, U. Landgraf⁵¹, M.P.J. Landon⁷⁹, M.C. Lanfermann⁵², V.S. Lang⁴⁵,
 J.C. Lange¹³, R.J. Langenberg³², A.J. Lankford¹⁶⁶, F. Lanni²⁷, K. Lantzsch²³, A. Lanza^{123a},
 A. Lapertosa^{53a,53b}, S. Laplace⁸³, J.F. Laporte¹³⁸, T. Lari^{94a}, F. Lasagni Manghi^{22a,22b},
 M. Lassnig³², T.S. Lau^{62a}, P. Laurelli⁵⁰, W. Lavrijsen¹⁶, A.T. Law¹³⁹, P. Laycock⁷⁷,
 T. Lazovich⁵⁹, M. Lazzaroni^{94a,94b}, B. Le⁹¹, O. Le Dortz⁸³, E. Le Guirriec⁸⁸, E.P. Le Quilleuc¹³⁸,
 M. LeBlanc¹⁷², T. LeCompte⁶, F. Ledroit-Guillon⁵⁸, C.A. Lee²⁷, G.R. Lee^{133,ag}, S.C. Lee¹⁵³,
 L. Lee⁵⁹, B. Lefebvre⁹⁰, G. Lefebvre⁸³, M. Lefebvre¹⁷², F. Legger¹⁰², C. Leggett¹⁶,
 G. Lehmann Miotto³², X. Lei⁷, W.A. Leight⁴⁵, M.A.L. Leite^{26d}, R. Leitner¹³¹, D. Lellouch¹⁷⁵,
 B. Lemmer⁵⁷, K.J.C. Leney⁸¹, T. Lenz²³, B. Lenzi³², R. Leone⁷, S. Leone^{126a,126b},
 C. Leonidopoulos⁴⁹, G. Lerner¹⁵¹, C. Leroy⁹⁷, A.A.J. Lesage¹³⁸, C.G. Lester³⁰, M. Levchenko¹²⁵,
 J. Levêque⁵, D. Levin⁹², L.J. Levinson¹⁷⁵, M. Levy¹⁹, D. Lewis⁷⁹, B. Li^{36a,w}, Changqiao Li^{36a},
 H. Li¹⁵⁰, L. Li^{36c}, Q. Li^{35a,35d}, Q. Li^{36a}, S. Li⁴⁸, X. Li^{36c}, Y. Li¹⁴³, Z. Liang^{35a}, B. Liberti^{135a},
 A. Liblong¹⁶¹, K. Lie^{62c}, J. Liebal²³, W. Liebig¹⁵, A. Limosani¹⁵², S.C. Lin¹⁸², T.H. Lin⁸⁶,
 R.A. Linck⁶⁴, B.E. Lindquist¹⁵⁰, A.E. Lioni⁵², E. Lipeles¹²⁴, A. Lipniacka¹⁵, M. Lisovsky^{60b},
 T.M. Liss^{169,ah}, A. Lister¹⁷¹, A.M. Litke¹³⁹, B. Liu⁶⁷, H. Liu⁹², H. Liu²⁷, J.K.K. Liu¹²², J. Liu^{36b},
 J.B. Liu^{36a}, K. Liu⁸⁸, L. Liu¹⁶⁹, M. Liu^{36a}, Y. Liu^{35a,35d}, Y.L. Liu^{36a}, Y. Liu^{36a}, M. Livan^{123a,123b},
 A. Lleres⁵⁸, J. Llorente Merino^{35a}, S.L. Lloyd⁷⁹, C.Y. Lo^{62b}, F. Lo Sterzo¹⁵³, E.M. Lobodzinska⁴⁵,
 P. Loch⁷, F.K. Loebinger⁸⁷, A. Loesle⁵¹, K.M. Loew²⁵, A. Loginov^{179,*}, T. Lohse¹⁷,
 K. Lohwasser¹⁴¹, M. Lokajicek¹²⁹, B.A. Long²⁴, J.D. Long¹⁶⁹, R.E. Long⁷⁵, L. Longo^{76a,76b},
 K.A. Looper¹¹³, J.A. Lopez^{34b}, D. Lopez Mateos⁵⁹, I. Lopez Paz¹³, A. Lopez Solis⁸³, J. Lorenz¹⁰²,
 N. Lorenzo Martinez⁵, M. Losada²¹, P.J. Lösel¹⁰², X. Lou^{35a}, A. Lounis¹¹⁹, J. Love⁶, P.A. Love⁷⁵,
 H. Lu^{62a}, N. Lu⁹², Y.J. Lu⁶³, H.J. Lubatti¹⁴⁰, C. Luci^{134a,134b}, A. Lucotte⁵⁸, C. Luedtke⁵¹,
 F. Luehring⁶⁴, W. Lukas⁶⁵, L. Luminari^{134a}, O. Lundberg^{148a,148b}, B. Lund-Jensen¹⁴⁹,
 M.S. Lutz⁸⁹, P.M. Luzi⁸³, D. Lynn²⁷, R. Lysak¹²⁹, E. Lytken⁸⁴, F. Lyu^{35a}, V. Lyubushkin⁶⁸,
 H. Ma²⁷, L.L. Ma^{36b}, Y. Ma^{36b}, G. Maccarrone⁵⁰, A. Macchiolo¹⁰³, C.M. Macdonald¹⁴¹,
 B. Maček⁷⁸, J. Machado Miguens^{124,128b}, D. Madaffari¹⁷⁰, R. Madar³⁷, W.F. Mader⁴⁷,
 A. Madsen⁴⁵, J. Maeda⁷⁰, S. Maeland¹⁵, T. Maeno²⁷, A.S. Maevskiy¹⁰¹, V. Magerl⁵¹,
 J. Mahlstedt¹⁰⁹, C. Maiani¹¹⁹, C. Maidantchik^{26a}, A.A. Maier¹⁰³, T. Maier¹⁰²,
 A. Maio^{128a,128b,128d}, O. Majersky^{146a}, S. Majewski¹¹⁸, Y. Makida⁶⁹, N. Makovec¹¹⁹,
 B. Malaescu⁸³, Pa. Malecki⁴², V.P. Maleev¹²⁵, F. Malek⁵⁸, U. Mallik⁶⁶, D. Malon⁶, C. Malone³⁰,
 S. Maltezos¹⁰, S. Malyukov³², J. Mamuzic¹⁷⁰, G. Mancini⁵⁰, I. Mandić⁷⁸, J. Maneira^{128a,128b},
 L. Manhaes de Andrade Filho^{26b}, J. Manjarres Ramos⁴⁷, K.H. Mankinen⁸⁴, A. Mann¹⁰²,
 A. Manousos³², B. Mansoulie¹³⁸, J.D. Mansour^{35a}, R. Mantifel⁹⁰, M. Mantoani⁵⁷,
 S. Manzoni^{94a,94b}, L. Mapelli³², G. Marceca²⁹, L. March⁵², L. Marchese¹²², G. Marchiori⁸³,
 M. Marcisovsky¹²⁹, M. Marjanovic³⁷, D.E. Marley⁹², F. Marroquim^{26a}, S.P. Marsden⁸⁷,
 Z. Marshall¹⁶, M.U.F. Martensson¹⁶⁸, S. Marti-Garcia¹⁷⁰, C.B. Martin¹¹³, T.A. Martin¹⁷³,
 V.J. Martin⁴⁹, B. Martin dit Latour¹⁵, M. Martinez^{13,v}, V.I. Martinez Outschoorn¹⁶⁹,

S. Martin-Haugh¹³³, V.S. Martoiu^{28b}, A.C. Martyniuk⁸¹, A. Marzin³², L. Masetti⁸⁶,
 T. Mashimo¹⁵⁷, R. Mashinistov⁹⁸, J. Masik⁸⁷, A.L. Maslennikov^{111,c}, L. Massa^{135a,135b},
 P. Mastrandrea⁵, A. Mastroberardino^{40a,40b}, T. Masubuchi¹⁵⁷, P. Mättig¹⁷⁸, J. Maurer^{28b},
 S.J. Maxfield⁷⁷, D.A. Maximov^{111,c}, R. Mazini¹⁵³, I. Maznas¹⁵⁶, S.M. Mazza^{94a,94b},
 N.C. Mc Fadden¹⁰⁷, G. Mc Goldrick¹⁶¹, S.P. Mc Kee⁹², A. McCarn⁹², R.L. McCarthy¹⁵⁰,
 T.G. McCarthy¹⁰³, L.I. McClymont⁸¹, E.F. McDonald⁹¹, J.A. McFayden³², G. Mchedlidze⁵⁷,
 S.J. McMahan¹³³, P.C. McNamara⁹¹, C.J. McNicol¹⁷³, R.A. McPherson^{172,o}, S. Meehan¹⁴⁰,
 T.J. Megy⁵¹, S. Mehlhase¹⁰², A. Mehta⁷⁷, T. Meideck⁵⁸, K. Meier^{60a}, B. Meirose⁴⁴,
 D. Melini^{170,ai}, B.R. Mellado Garcia^{147c}, J.D. Mellenthin⁵⁷, M. Melo^{146a}, F. Meloni¹⁸,
 A. Melzer²³, S.B. Menary⁸⁷, L. Meng⁷⁷, X.T. Meng⁹², A. Mengarelli^{22a,22b}, S. Menke¹⁰³,
 E. Meoni^{40a,40b}, S. Mergelmeyer¹⁷, C. Merlassino¹⁸, P. Mermod⁵², L. Merola^{106a,106b},
 C. Meroni^{94a}, F.S. Merritt³³, A. Messina^{134a,134b}, J. Metcalfe⁶, A.S. Mete¹⁶⁶, C. Meyer¹²⁴,
 J-P. Meyer¹³⁸, J. Meyer¹⁰⁹, H. Meyer Zu Theenhausen^{60a}, F. Miano¹⁵¹, R.P. Middleton¹³³,
 S. Miglioranzì^{53a,53b}, L. Mijović⁴⁹, G. Mikenberg¹⁷⁵, M. Mikestikova¹²⁹, M. Mikuž⁷⁸, M. Milesi⁹¹,
 A. Milic¹⁶¹, D.A. Millar⁷⁹, D.W. Miller³³, C. Mills⁴⁹, A. Milov¹⁷⁵, D.A. Milstead^{148a,148b},
 A.A. Minaenko¹³², Y. Minami¹⁵⁷, I.A. Minashvili^{54b}, A.I. Mincer¹¹², B. Mindur^{41a}, M. Mineev⁶⁸,
 Y. Minegishi¹⁵⁷, Y. Ming¹⁷⁶, L.M. Mir¹³, K.P. Mistry¹²⁴, T. Mitani¹⁷⁴, J. Mitrevski¹⁰²,
 V.A. Mitsou¹⁷⁰, A. Miucci¹⁸, P.S. Miyagawa¹⁴¹, A. Mizukami⁶⁹, J.U. Mjörnmark⁸⁴,
 T. Mkrtchyan¹⁸⁰, M. Mlynarikova¹³¹, T. Moa^{148a,148b}, K. Mochizuki⁹⁷, P. Mogg⁵¹,
 S. Mohapatra³⁸, S. Molander^{148a,148b}, R. Moles-Valls²³, M.C. Mondragon⁹³, K. Mönig⁴⁵,
 J. Monk³⁹, E. Monnier⁸⁸, A. Montalbano¹⁵⁰, J. Montejo Berlingen³², F. Monticelli⁷⁴,
 S. Monzani^{94a,94b}, R.W. Moore³, N. Morange¹¹⁹, D. Moreno²¹, M. Moreno Llácer³²,
 P. Morettini^{53a}, S. Morgenstern³², D. Mori¹⁴⁴, T. Mori¹⁵⁷, M. Morii⁵⁹, M. Morinaga¹⁷⁴,
 V. Morisbak¹²¹, A.K. Morley³², G. Mornacchi³², J.D. Morris⁷⁹, L. Morvaj¹⁵⁰, P. Moschovakos¹⁰,
 M. Mosidze^{54b}, H.J. Moss¹⁴¹, J. Moss^{145,aj}, K. Motohashi¹⁵⁹, R. Mount¹⁴⁵, E. Mountricha²⁷,
 E.J.W. Moyse⁸⁹, S. Muanza⁸⁸, F. Mueller¹⁰³, J. Mueller¹²⁷, R.S.P. Mueller¹⁰²,
 D. Muenstermann⁷⁵, P. Mullen⁵⁶, G.A. Mullier¹⁸, F.J. Munoz Sanchez⁸⁷, W.J. Murray^{173,133},
 H. Mushheghyan³², M. Muškinja⁷⁸, A.G. Myagkov^{132,ak}, M. Myska¹³⁰, B.P. Nachman¹⁶,
 O. Nackenhurst⁵², K. Nagai¹²², R. Nagai^{69,ae}, K. Nagano⁶⁹, Y. Nagasaka⁶¹, K. Nagata¹⁶⁴,
 M. Nagel⁵¹, E. Nagy⁸⁸, A.M. Nairz³², Y. Nakahama¹⁰⁵, K. Nakamura⁶⁹, T. Nakamura¹⁵⁷,
 I. Nakano¹¹⁴, R.F. Naranjo Garcia⁴⁵, R. Narayan¹¹, D.I. Narrias Villar^{60a}, I. Naryshkin¹²⁵,
 T. Naumann⁴⁵, G. Navarro²¹, R. Nayyar⁷, H.A. Neal⁹², P.Yu. Nechaeva⁹⁸, T.J. Neep¹³⁸,
 A. Negri^{123a,123b}, M. Negrini^{22a}, S. Nektarijevic¹⁰⁸, C. Nellist¹¹⁹, A. Nelson¹⁶⁶, M.E. Nelson¹²²,
 S. Nemecek¹²⁹, P. Nemethy¹¹², M. Nessi^{32,al}, M.S. Neubauer¹⁶⁹, M. Neumann¹⁷⁸, P.R. Newman¹⁹,
 T.Y. Ng^{62c}, T. Nguyen Manh⁹⁷, R.B. Nickerson¹²², R. Nicolaidou¹³⁸, J. Nielsen¹³⁹,
 V. Nikolaenko^{132,ak}, I. Nikolic-Audit⁸³, K. Nikolopoulos¹⁹, J.K. Nilsen¹²¹, P. Nilsson²⁷,
 Y. Ninomiya¹⁵⁷, A. Nisati^{134a}, N. Nishu^{36c}, R. Nisius¹⁰³, I. Nitsche⁴⁶, T. Nitta¹⁷⁴, T. Nobe¹⁵⁷,
 Y. Noguchi⁷¹, M. Nomachi¹²⁰, I. Nomidis³¹, M.A. Nomura²⁷, T. Nooney⁷⁹, M. Nordberg³²,
 N. Norjoharuddeen¹²², O. Novgorodova⁴⁷, M. Nozaki⁶⁹, L. Nozka¹¹⁷, K. Ntekas¹⁶⁶, E. Nurse⁸¹,
 F. Nuti⁹¹, K. O'connor²⁵, D.C. O'Neil¹⁴⁴, A.A. O'Rourke⁴⁵, V. O'Shea⁵⁶, F.G. Oakham^{31,d},
 H. Oberlack¹⁰³, T. Obermann²³, J. Ocariz⁸³, A. Ochi⁷⁰, I. Ochoa³⁸, J.P. Ochoa-Ricoux^{34a},
 S. Oda⁷³, S. Odaka⁶⁹, A. Oh⁸⁷, S.H. Oh⁴⁸, C.C. Ohm¹⁶, H. Ohman¹⁶⁸, H. Oide^{53a,53b},
 H. Okawa¹⁶⁴, Y. Okumura¹⁵⁷, T. Okuyama⁶⁹, A. Olariu^{28b}, L.F. Oleiro Seabra^{128a},
 S.A. Olivares Pino^{34a}, D. Oliveira Damazio²⁷, A. Olszewski⁴², J. Olszowska⁴², A. Onofre^{128a,128e},
 K. Onogi¹⁰⁵, P.U.E. Onyisi^{11,aa}, H. Oppen¹²¹, M.J. Oreglia³³, Y. Oren¹⁵⁵, D. Orestano^{136a,136b},
 N. Orlando^{62b}, R.S. Orr¹⁶¹, B. Osculati^{53a,53b,*}, R. Ospanov^{36a}, G. Otero y Garzon²⁹,
 H. Otono⁷³, M. Ouchrif^{137d}, F. Ould-Saada¹²¹, A. Ouraou¹³⁸, K.P. Oussoren¹⁰⁹, Q. Ouyang^{35a},
 M. Owen⁵⁶, R.E. Owen¹⁹, V.E. Ozcan^{20a}, N. Ozturk⁸, K. Pachal¹⁴⁴, A. Pacheco Pages¹³,

L. Pacheco Rodriguez¹³⁸, C. Padilla Aranda¹³, S. Pagan Griso¹⁶, M. Paganini¹⁷⁹, F. Paige²⁷,
 G. Palacino⁶⁴, S. Palazzo^{40a,40b}, S. Palestini³², M. Palka^{41b}, D. Pallin³⁷, E.St. Panagiotopoulou¹⁰,
 I. Panagoulas¹⁰, C.E. Pandini^{126a,126b}, J.G. Panduro Vazquez⁸⁰, P. Pani³², S. Panitkin²⁷,
 D. Pantea^{28b}, L. Paolozzi⁵², Th.D. Papadopoulou¹⁰, K. Papageorgiou^{9,s}, A. Paramonov⁶,
 D. Paredes Hernandez¹⁷⁹, A.J. Parker⁷⁵, M.A. Parker³⁰, K.A. Parker⁴⁵, F. Parodi^{53a,53b},
 J.A. Parsons³⁸, U. Parzefall⁵¹, V.R. Pascuzzi¹⁶¹, J.M. Pasner¹³⁹, E. Pasqualucci^{134a},
 S. Passaggio^{53a}, Fr. Pastore⁸⁰, S. Pataraja⁸⁶, J.R. Pater⁸⁷, T. Pauly³², B. Pearson¹⁰³,
 S. Pedraza Lopez¹⁷⁰, R. Pedro^{128a,128b}, S.V. Peleganchuk^{111,c}, O. Penc¹²⁹, C. Peng^{35a,35d},
 H. Peng^{36a}, J. Penwell⁶⁴, B.S. Peralva^{26b}, M.M. Perego¹³⁸, D.V. Perepelitsa²⁷, F. Peri¹⁷,
 L. Perini^{94a,94b}, H. Pernegger³², S. Perrella^{106a,106b}, R. Peschke⁴⁵, V.D. Peshekhonov^{68,*},
 K. Peters⁴⁵, R.F.Y. Peters⁸⁷, B.A. Petersen³², T.C. Petersen³⁹, E. Petit⁵⁸, A. Petridis¹,
 C. Petridou¹⁵⁶, P. Petroff¹¹⁹, E. Petrolo^{134a}, M. Petrov¹²², F. Petrucci^{136a,136b}, N.E. Pettersson⁸⁹,
 A. Peyaud¹³⁸, R. Pezoa^{34b}, F.H. Phillips⁹³, P.W. Phillips¹³³, G. Piacquadio¹⁵⁰, E. Pianori¹⁷³,
 A. Picazio⁸⁹, E. Piccaro⁷⁹, M.A. Pickering¹²², R. Piegai²⁹, J.E. Pilcher³³, A.D. Pilkington⁸⁷,
 A.W.J. Pin⁸⁷, M. Pinamonti^{135a,135b}, J.L. Pinfold³, H. Pirumov⁴⁵, M. Pitt¹⁷⁵, L. Plazak^{146a},
 M.-A. Pleier²⁷, V. Pleskot⁸⁶, E. Plotnikova⁶⁸, D. Pluth⁶⁷, P. Podberczko¹¹¹, R. Poettgen⁸⁴,
 R. Poggi^{123a,123b}, L. Poggioli¹¹⁹, I. Pogrebnyak⁹³, D. Pohl²³, G. Polesello^{123a}, A. Poley⁴⁵,
 A. Policicchio^{40a,40b}, R. Polifka³², A. Polini^{22a}, C.S. Pollard⁵⁶, V. Polychronakos²⁷, K. Pommès³²,
 D. Ponomarenko¹⁰⁰, L. Pontecorvo^{134a}, G.A. Popeneciu^{28d}, S. Pospisil¹³⁰, K. Potamianos¹⁶,
 I.N. Potrap⁶⁸, C.J. Potter³⁰, H. Potti¹¹, T. Poulsen⁸⁴, J. Poveda³², M.E. Pozo Astigarraga³²,
 P. Pralavorio⁸⁸, A. Pranko¹⁶, S. Prell⁶⁷, D. Price⁸⁷, M. Primavera^{76a}, S. Prince⁹⁰, N. Proklova¹⁰⁰,
 K. Prokofiev^{62c}, F. Prokoshin^{34b}, S. Protopopescu²⁷, J. Proudfoot⁶, M. Przybycien^{41a}, A. Puri¹⁶⁹,
 P. Puzo¹¹⁹, J. Qian⁹², G. Qin⁵⁶, Y. Qin⁸⁷, A. Quadt⁵⁷, M. Queitsch-Maitland⁴⁵, D. Quilty⁵⁶,
 S. Raddum¹²¹, V. Radeka²⁷, V. Radescu¹²², S.K. Radhakrishnan¹⁵⁰, P. Radloff¹¹⁸, P. Rados⁹¹,
 F. Ragusa^{94a,94b}, G. Rahal¹⁸¹, J.A. Raine⁸⁷, S. Rajagopalan²⁷, C. Rangel-Smith¹⁶⁸, T. Rashid¹¹⁹,
 S. Raspopov⁵, M.G. Ratti^{94a,94b}, D.M. Rauch⁴⁵, F. Rauscher¹⁰², S. Rave⁸⁶, I. Ravinovich¹⁷⁵,
 J.H. Rawling⁸⁷, M. Raymond³², A.L. Read¹²¹, N.P. Readioff⁵⁸, M. Reale^{76a,76b},
 D.M. Rebuzzi^{123a,123b}, A. Redelbach¹⁷⁷, G. Redlinger²⁷, R. Reece¹³⁹, R.G. Reed^{147c}, K. Reeves⁴⁴,
 L. Rehnisch¹⁷, J. Reichert¹²⁴, A. Reiss⁸⁶, C. Rembser³², H. Ren^{35a,35d}, M. Rescigno^{134a},
 S. Resconi^{94a}, E.D. Resseguie¹²⁴, S. Rettie¹⁷¹, E. Reynolds¹⁹, O.L. Rezanova^{111,c}, P. Reznicek¹³¹,
 R. Rezvani⁹⁷, R. Richter¹⁰³, S. Richter⁸¹, E. Richter-Was^{41b}, O. Ricken²³, M. Ridel⁸³, P. Rieck¹⁰³,
 C.J. Riegel¹⁷⁸, J. Rieger⁵⁷, O. Rifki¹¹⁵, M. Rijssenbeek¹⁵⁰, A. Rimoldi^{123a,123b}, M. Rimoldi¹⁸,
 L. Rinaldi^{22a}, G. Ripellino¹⁴⁹, B. Ristić³², E. Ritsch³², I. Riu¹³, F. Rizatdinova¹¹⁶, E. Rizvi⁷⁹,
 C. Rizzi¹³, R.T. Roberts⁸⁷, S.H. Robertson^{90,o}, A. Robichaud-Veronneau⁹⁰, D. Robinson³⁰,
 J.E.M. Robinson⁴⁵, A. Robson⁵⁶, E. Rocco⁸⁶, C. Roda^{126a,126b}, Y. Rodina^{88,am},
 S. Rodriguez Bosca¹⁷⁰, A. Rodriguez Perez¹³, D. Rodriguez Rodriguez¹⁷⁰, S. Roe³², C.S. Rogan⁵⁹,
 O. Røhne¹²¹, J. Roloff⁵⁹, A. Romaniouk¹⁰⁰, M. Romano^{22a,22b}, S.M. Romano Saez³⁷,
 E. Romero Adam¹⁷⁰, N. Rompotis⁷⁷, M. Ronzani⁵¹, L. Roos⁸³, S. Rosati^{134a}, K. Rosbach⁵¹,
 P. Rose¹³⁹, N.-A. Rosien⁵⁷, E. Rossi^{106a,106b}, L.P. Rossi^{53a}, J.H.N. Rosten³⁰, R. Rosten¹⁴⁰,
 M. Rotaru^{28b}, J. Rothberg¹⁴⁰, D. Rousseau¹¹⁹, A. Rozanov⁸⁸, Y. Rozen¹⁵⁴, X. Ruan^{147c},
 F. Rubbo¹⁴⁵, F. Rühr⁵¹, A. Ruiz-Martinez³¹, Z. Rurikova⁵¹, N.A. Rusakovich⁶⁸, H.L. Russell⁹⁰,
 J.P. Rutherford⁷, N. Ruthmann³², Y.F. Ryabov¹²⁵, M. Rybar¹⁶⁹, G. Rybkin¹¹⁹, S. Ryu⁶,
 A. Ryzhov¹³², G.F. Rzehorz⁵⁷, A.F. Saavedra¹⁵², G. Sabato¹⁰⁹, S. Sacerdoti²⁹,
 H.F.W. Sadrozinski¹³⁹, R. Sadykov⁶⁸, F. Safai Tehrani^{134a}, P. Saha¹¹⁰, M. Sahinsoy^{60a},
 M. Saimpert⁴⁵, M. Saito¹⁵⁷, T. Saito¹⁵⁷, H. Sakamoto¹⁵⁷, Y. Sakurai¹⁷⁴, G. Salamanna^{136a,136b},
 J.E. Salazar Loyola^{34b}, D. Salek¹⁰⁹, P.H. Sales De Bruin¹⁶⁸, D. Salihagic¹⁰³, A. Salmikov¹⁴⁵,
 J. Salt¹⁷⁰, D. Salvatore^{40a,40b}, F. Salvatore¹⁵¹, A. Salvucci^{62a,62b,62c}, A. Salzburger³²,
 D. Sammel⁵¹, D. Sampsonidis¹⁵⁶, D. Sampsonidou¹⁵⁶, J. Sánchez¹⁷⁰, V. Sanchez Martinez¹⁷⁰,

A. Sanchez Pineda^{167a,167c}, H. Sandaker¹²¹, R.L. Sandbach⁷⁹, C.O. Sander⁴⁵, M. Sandhoff¹⁷⁸,
 C. Sandoval²¹, D.P.C. Sankey¹³³, M. Sannino^{53a,53b}, Y. Sano¹⁰⁵, A. Sansoni⁵⁰, C. Santoni³⁷,
 H. Santos^{128a}, I. Santoyo Castillo¹⁵¹, A. Sapronov⁶⁸, J.G. Saraiva^{128a,128d}, B. Sarrazin²³,
 O. Sasaki⁶⁹, K. Sato¹⁶⁴, E. Sauvan⁵, G. Savage⁸⁰, P. Savard^{161,d}, N. Savic¹⁰³, C. Sawyer¹³³,
 L. Sawyer^{82,u}, J. Saxon³³, C. Sbarra^{22a}, A. Sbrizzi^{22a,22b}, T. Scanlon⁸¹, D.A. Scannicchio¹⁶⁶,
 J. Schaarschmidt¹⁴⁰, P. Schacht¹⁰³, B.M. Schachtner¹⁰², D. Schaefer³², L. Schaefer¹²⁴,
 R. Schaefer⁴⁵, J. Schaeffer⁸⁶, S. Schaep²³, S. Schaetzel^{160b}, U. Schäfer⁸⁶, A.C. Schaffer¹¹⁹,
 D. Schaile¹⁰², R.D. Schamberger¹⁵⁰, V.A. Schegelsky¹²⁵, D. Scheirich¹³¹, M. Schernau¹⁶⁶,
 C. Schiavi^{53a,53b}, S. Schier¹³⁹, L.K. Schildgen²³, C. Schillo⁵¹, M. Schioppa^{40a,40b}, S. Schlenker³²,
 K.R. Schmidt-Sommerfeld¹⁰³, K. Schmieden³², C. Schmitt⁸⁶, S. Schmitt⁴⁵, S. Schmitz⁸⁶,
 U. Schnoor⁵¹, L. Schoeffel¹³⁸, A. Schoening^{60b}, B.D. Schoenrock⁹³, E. Schopf²³, M. Schott⁸⁶,
 J.F.P. Schouwenberg¹⁰⁸, J. Schovancova³², S. Schramm⁵², N. Schuh⁸⁶, A. Schulte⁸⁶,
 M.J. Schultens²³, H.-C. Schultz-Coulon^{60a}, H. Schulz¹⁷, M. Schumacher⁵¹, B.A. Schumm¹³⁹,
 Ph. Schune¹³⁸, A. Schwartzman¹⁴⁵, T.A. Schwarz⁹², H. Schweiger⁸⁷, Ph. Schwemling¹³⁸,
 R. Schwienhorst⁹³, J. Schwindling¹³⁸, A. Sciandra²³, G. Sciolla²⁵, M. Scornajenghi^{40a,40b},
 F. Scuri^{126a,126b}, F. Scutti⁹¹, J. Searcy⁹², P. Seema²³, S.C. Seidel¹⁰⁷, A. Seiden¹³⁹, J.M. Seixas^{26a},
 G. Sekhniaidze^{106a}, K. Sekhon⁹², S.J. Sekula⁴³, N. Semprini-Cesari^{22a,22b}, S. Senkin³⁷,
 C. Serfon¹²¹, L. Serin¹¹⁹, L. Serkin^{167a,167b}, M. Sessa^{136a,136b}, R. Seuster¹⁷², H. Severini¹¹⁵,
 T. Sfiligoj⁷⁸, F. Sforza¹⁶⁵, A. Sfyrla⁵², E. Shabalina⁵⁷, N.W. Shaikh^{148a,148b}, L.Y. Shan^{35a},
 R. Shang¹⁶⁹, J.T. Shank²⁴, M. Shapiro¹⁶, P.B. Shatalov⁹⁹, K. Shaw^{167a,167b}, S.M. Shaw⁸⁷,
 A. Shcherbakova^{148a,148b}, C.Y. Shehu¹⁵¹, Y. Shen¹¹⁵, N. Sherafati³¹, P. Sherwood⁸¹, L. Shi^{153,an},
 S. Shimizu⁷⁰, C.O. Shimmin¹⁷⁹, M. Shimojima¹⁰⁴, I.P.J. Shipsey¹²², S. Shirabe⁷³,
 M. Shiyakova^{68,ao}, J. Shlomi¹⁷⁵, A. Shmeleva⁹⁸, D. Shoaleh Saadi⁹⁷, M.J. Shochet³³,
 S. Shojaii^{94a,94b}, D.R. Shope¹¹⁵, S. Shrestha¹¹³, E. Shulga¹⁰⁰, M.A. Shupe⁷, P. Sicho¹²⁹,
 A.M. Sickles¹⁶⁹, P.E. Sidebo¹⁴⁹, E. Sideras Haddad^{147c}, O. Sidiropoulou¹⁷⁷, A. Sidoti^{22a,22b},
 F. Siegert⁴⁷, Dj. Sijacki¹⁴, J. Silva^{128a,128d}, S.B. Silverstein^{148a}, V. Simak¹³⁰, L. Simic¹⁴,
 S. Simion¹¹⁹, E. Simioni⁸⁶, B. Simmons⁸¹, M. Simon⁸⁶, P. Sinervo¹⁶¹, N.B. Sinev¹¹⁸,
 M. Sioli^{22a,22b}, G. Siragusa¹⁷⁷, I. Siral⁹², S.Yu. Sivoklokov¹⁰¹, J. Sjölin^{148a,148b}, M.B. Skinner⁷⁵,
 P. Skubic¹¹⁵, M. Slater¹⁹, T. Slavicek¹³⁰, M. Slawinska⁴², K. Sliwa¹⁶⁵, R. Slovak¹³¹,
 V. Smakhtin¹⁷⁵, B.H. Smart⁵, J. Smiesko^{146a}, N. Smirnov¹⁰⁰, S.Yu. Smirnov¹⁰⁰, Y. Smirnov¹⁰⁰,
 L.N. Smirnova^{101,ap}, O. Smirnova⁸⁴, J.W. Smith⁵⁷, M.N.K. Smith³⁸, R.W. Smith³⁸,
 M. Smizanska⁷⁵, K. Smolek¹³⁰, A.A. Snesarev⁹⁸, I.M. Snyder¹¹⁸, S. Snyder²⁷, R. Sobie^{172,o},
 F. Socher⁴⁷, A.M. Soffa¹⁶⁶, A. Soffer¹⁵⁵, A. Søggaard⁴⁹, D.A. Soh¹⁵³, G. Sokhrannyi⁷⁸,
 C.A. Solans Sanchez³², M. Solar¹³⁰, E.Yu. Soldatov¹⁰⁰, U. Soldevila¹⁷⁰, A.A. Solodkov¹³²,
 A. Soloshenko⁶⁸, O.V. Solovyanov¹³², V. Solovyev¹²⁵, P. Sommer⁵¹, H. Son¹⁶⁵, A. Sopczak¹³⁰,
 D. Sosa^{60b}, C.L. Sotiropoulou^{126a,126b}, R. Soualah^{167a,167c}, A.M. Soukharev^{111,c}, D. South⁴⁵,
 B.C. Sowden⁸⁰, S. Spagnolo^{76a,76b}, M. Spalla^{126a,126b}, M. Spangenberg¹⁷³, F. Spanò⁸⁰,
 D. Sperlich¹⁷, F. Spettel¹⁰³, T.M. Spieker^{60a}, R. Spighi^{22a}, G. Spigo³², L.A. Spiller⁹¹,
 M. Spousta¹³¹, R.D. St. Denis^{56,*}, A. Stabile^{94a}, R. Stamen^{60a}, S. Stamm¹⁷, E. Stanecka⁴²,
 R.W. Stanek⁶, C. Stanescu^{136a}, M.M. Stanitzki⁴⁵, B.S. Stapf¹⁰⁹, S. Stapnes¹²¹,
 E.A. Starchenko¹³², G.H. Stark³³, J. Stark⁵⁸, S.H. Stark³⁹, P. Staroba¹²⁹, P. Starovoitov^{60a},
 S. Stärz³², R. Staszewski⁴², P. Steinberg²⁷, B. Stelzer¹⁴⁴, H.J. Stelzer³², O. Stelzer-Chilton^{163a},
 H. Stenzel⁵⁵, G.A. Stewart⁵⁶, M.C. Stockton¹¹⁸, M. Stoebe⁹⁰, G. Stoicea^{28b}, P. Stolte⁵⁷,
 S. Stonjek¹⁰³, A.R. Stradling⁸, A. Straessner⁴⁷, M.E. Stramaglia¹⁸, J. Strandberg¹⁴⁹,
 S. Strandberg^{148a,148b}, M. Strauss¹¹⁵, P. Strizeneč^{146b}, R. Ströhmer¹⁷⁷, D.M. Strom¹¹⁸,
 R. Stroynowski⁴³, A. Strubig⁴⁹, S.A. Stucci²⁷, B. Stugu¹⁵, N.A. Styles⁴⁵, D. Su¹⁴⁵, J. Su¹²⁷,
 S. Suchek^{60a}, Y. Sugaya¹²⁰, M. Suk¹³⁰, V.V. Sulin⁹⁸, DMS Sultan^{162a,162b}, S. Sultansoy^{4c},
 T. Sumida⁷¹, S. Sun⁵⁹, X. Sun³, K. Suruliz¹⁵¹, C.J.E. Suster¹⁵², M.R. Sutton¹⁵¹, S. Suzuki⁶⁹,

M. Svatos¹²⁹, M. Swiatlowski³³, S.P. Swift², I. Sykora^{146a}, T. Sykora¹³¹, D. Ta⁵¹, K. Tackmann⁴⁵,
 J. Taenzer¹⁵⁵, A. Taffard¹⁶⁶, R. Tafirout^{163a}, E. Tahirovic⁷⁹, N. Taiblum¹⁵⁵, H. Takai²⁷,
 R. Takashima⁷², E.H. Takasugi¹⁰³, T. Takeshita¹⁴², Y. Takubo⁶⁹, M. Talby⁸⁸, A.A. Talyshev^{111,c},
 J. Tanaka¹⁵⁷, M. Tanaka¹⁵⁹, R. Tanaka¹¹⁹, S. Tanaka⁶⁹, R. Tanioka⁷⁰, B.B. Tannenwald¹¹³,
 S. Tapia Araya^{34b}, S. Tapprogge⁸⁶, S. Tarem¹⁵⁴, G.F. Tartarelli^{94a}, P. Tas¹³¹, M. Tasevsky¹²⁹,
 T. Tashiro⁷¹, E. Tassi^{40a,40b}, A. Tavares Delgado^{128a,128b}, Y. Tayalati^{137e}, A.C. Taylor¹⁰⁷,
 A.J. Taylor⁴⁹, G.N. Taylor⁹¹, P.T.E. Taylor⁹¹, W. Taylor^{163b}, P. Teixeira-Dias⁸⁰, D. Temple¹⁴⁴,
 H. Ten Kate³², P.K. Teng¹⁵³, J.J. Teoh¹²⁰, F. Tepel¹⁷⁸, S. Terada⁶⁹, K. Terashi¹⁵⁷, J. Terron⁸⁵,
 S. Terzo¹³, M. Testa⁵⁰, R.J. Teuscher^{161,o}, T. Theveneaux-Pelzer⁸⁸, F. Thiele³⁹, J.P. Thomas¹⁹,
 J. Thomas-Wilsker⁸⁰, P.D. Thompson¹⁹, A.S. Thompson⁵⁶, L.A. Thomsen¹⁷⁹, E. Thomson¹²⁴,
 M.J. Tibbetts¹⁶, R.E. Ticse Torres⁸⁸, V.O. Tikhomirov^{98,aq}, Yu.A. Tikhonov^{111,c},
 S. Timoshenko¹⁰⁰, P. Tipton¹⁷⁹, S. Tisserant⁸⁸, K. Todome¹⁵⁹, S. Todorova-Nova⁵, S. Todt⁴⁷,
 J. Tojo⁷³, S. Tokár^{146a}, K. Tokushuku⁶⁹, E. Tolley¹¹³, L. Tomlinson⁸⁷, M. Tomoto¹⁰⁵,
 L. Tompkins^{145,ar}, K. Toms¹⁰⁷, B. Tong⁵⁹, P. Tornambe⁵¹, E. Torrence¹¹⁸, H. Torres⁴⁷,
 E. Torró Pastor¹⁴⁰, J. Toth^{88,as}, F. Touchard⁸⁸, D.R. Tovey¹⁴¹, C.J. Treado¹¹², T. Trefzger¹⁷⁷,
 F. Tresoldi¹⁵¹, A. Tricoli²⁷, I.M. Trigger^{163a}, S. Trincaz-Duvoid⁸³, M.F. Tripiana¹³,
 W. Trischuk¹⁶¹, B. Trocme⁵⁸, A. Trofymov⁴⁵, C. Troncon^{94a}, M. Trottier-McDonald¹⁶,
 M. Trovatelli¹⁷², L. Truong^{147b}, M. Trzebinski⁴², A. Trzupek⁴², K.W. Tsang^{62a}, J.C-L. Tseng¹²²,
 P.V. Tsiarehka⁹⁵, G. Tsipolitis¹⁰, N. Tsirintanis⁹, S. Tsiskaridze¹³, V. Tsiskaridze⁵¹,
 E.G. Tskhadadze^{54a}, K.M. Tsui^{62a}, I.I. Tsukerman⁹⁹, V. Tsulaia¹⁶, S. Tsuno⁶⁹, D. Tsybychev¹⁵⁰,
 Y. Tu^{62b}, A. Tudorache^{28b}, V. Tudorache^{28b}, T.T. Tulbure^{28a}, A.N. Tuna⁵⁹, S.A. Tupputi^{22a,22b},
 S. Turchikhin⁶⁸, D. Turgeman¹⁷⁵, I. Turk Cakir^{4b,at}, R. Turra^{94a}, P.M. Tuts³⁸, G. Ucchielli^{22a,22b},
 I. Ueda⁶⁹, M. Ughetto^{148a,148b}, F. Ukegawa¹⁶⁴, G. Unal³², A. Undrus²⁷, G. Unel¹⁶⁶,
 F.C. Ungaro⁹¹, Y. Unno⁶⁹, C. Unverdorben¹⁰², J. Urban^{146b}, P. Urquijo⁹¹, P. Urrejola⁸⁶,
 G. Usai⁸, J. Usui⁶⁹, L. Vacavant⁸⁸, V. Vacek¹³⁰, B. Vachon⁹⁰, K.O.H. Vadla¹²¹, A. Vaidya⁸¹,
 C. Valderanis¹⁰², E. Valdes Santurio^{148a,148b}, M. Valente⁵², S. Valentineti^{22a,22b}, A. Valero¹⁷⁰,
 L. Valéry¹³, S. Valkar¹³¹, A. Vallier⁵, J.A. Valls Ferrer¹⁷⁰, W. Van Den Wollenberg¹⁰⁹,
 H. van der Graaf¹⁰⁹, P. van Gemmeren⁶, J. Van Nieuwkoop¹⁴⁴, I. van Vulpen¹⁰⁹,
 M.C. van Woerden¹⁰⁹, M. Vanadia^{135a,135b}, W. Vandelli³², A. Vaniachine¹⁶⁰, P. Vankov¹⁰⁹,
 G. Vardanyan¹⁸⁰, R. Vari^{134a}, E.W. Varnes⁷, C. Varni^{53a,53b}, T. Varol⁴³, D. Varouchas¹¹⁹,
 A. Vartapetian⁸, K.E. Varvell¹⁵², J.G. Vasquez¹⁷⁹, G.A. Vasquez^{34b}, F. Vazeille³⁷,
 T. Vazquez Schroeder⁹⁰, J. Veatch⁵⁷, V. Veeraraghavan⁷, L.M. Veloce¹⁶¹, F. Veloso^{128a,128c},
 S. Veneziano^{134a}, A. Ventura^{76a,76b}, M. Venturi¹⁷², N. Venturi³², A. Venturini²⁵, V. Vercesi^{123a},
 M. Verducci^{136a,136b}, W. Verkerke¹⁰⁹, A.T. Vermeulen¹⁰⁹, J.C. Vermeulen¹⁰⁹, M.C. Vetterli^{144,d},
 N. Viaux Maira^{34b}, O. Viazlo⁸⁴, I. Vichou^{169,*}, T. Vickey¹⁴¹, O.E. Vickey Boeriu¹⁴¹,
 G.H.A. Viehhauser¹²², S. Viel¹⁶, L. Vigani¹²², M. Villa^{22a,22b}, M. Villaplana Perez^{94a,94b},
 E. Vilucchi⁵⁰, M.G. Vincter³¹, V.B. Vinogradov⁶⁸, A. Vishwakarma⁴⁵, C. Vittori^{22a,22b},
 I. Vivarelli¹⁵¹, S. Vlachos¹⁰, M. Vogel¹⁷⁸, P. Vokac¹³⁰, G. Volpi¹³, H. von der Schmitt¹⁰³,
 E. von Toerne²³, V. Vorobel¹³¹, K. Vorobev¹⁰⁰, M. Vos¹⁷⁰, R. Voss³², J.H. Vosseveld⁷⁷,
 N. Vranjes¹⁴, M. Vranjes Milosavljevic¹⁴, V. Vrba¹³⁰, M. Vreeswijk¹⁰⁹, R. Vuillermet³²,
 I. Vukotic³³, P. Wagner²³, W. Wagner¹⁷⁸, J. Wagner-Kuhr¹⁰², H. Wahlberg⁷⁴, S. Wahrenmund⁴⁷,
 J. Walder⁷⁵, R. Walker¹⁰², W. Walkowiak¹⁴³, V. Wallangen^{148a,148b}, C. Wang^{35b}, C. Wang^{36b,au},
 F. Wang¹⁷⁶, H. Wang¹⁶, H. Wang³, J. Wang⁴⁵, J. Wang¹⁵², Q. Wang¹¹⁵, R. Wang⁶,
 S.M. Wang¹⁵³, T. Wang³⁸, W. Wang^{153,av}, W. Wang^{36a,aw}, Z. Wang^{36c}, C. Wanotayaroj¹¹⁸,
 A. Warburton⁹⁰, C.P. Ward³⁰, D.R. Wardrope⁸¹, A. Washbrook⁴⁹, P.M. Watkins¹⁹,
 A.T. Watson¹⁹, M.F. Watson¹⁹, G. Watts¹⁴⁰, S. Watts⁸⁷, B.M. Waugh⁸¹, A.F. Webb¹¹,
 S. Webb⁸⁶, M.S. Weber¹⁸, S.W. Weber¹⁷⁷, S.A. Weber³¹, J.S. Webster⁶, A.R. Weidberg¹²²,
 B. Weinert⁶⁴, J. Weingarten⁵⁷, M. Weirich⁸⁶, C. Weiser⁵¹, H. Weits¹⁰⁹, P.S. Wells³², T. Wenaus²⁷,

T. Wengler³², S. Wenig³², N. Wermes²³, M.D. Werner⁶⁷, P. Werner³², M. Wessels^{60a}, T.D. Weston¹⁸, K. Whalen¹¹⁸, N.L. Whallon¹⁴⁰, A.M. Wharton⁷⁵, A.S. White⁹², A. White⁸, M.J. White¹, R. White^{34b}, D. Whiteson¹⁶⁶, B.W. Whitmore⁷⁵, F.J. Wickens¹³³, W. Wiedenmann¹⁷⁶, M. Wielers¹³³, C. Wiglesworth³⁹, L.A.M. Wiik-Fuchs⁵¹, A. Wildauer¹⁰³, F. Wilk⁸⁷, H.G. Wilkens³², H.H. Williams¹²⁴, S. Williams¹⁰⁹, C. Willis⁹³, S. Willocq⁸⁹, J.A. Wilson¹⁹, I. Wingerter-Seez⁵, E. Winkels¹⁵¹, F. Winklmeier¹¹⁸, O.J. Winston¹⁵¹, B.T. Winter²³, M. Wittgen¹⁴⁵, M. Wobisch^{82,u}, T.M.H. Wolf¹⁰⁹, R. Wolff⁸⁸, M.W. Wolter⁴², H. Wolters^{128a,128c}, V.W.S. Wong¹⁷¹, S.D. Worm¹⁹, B.K. Wosiek⁴², J. Wotschack³², K.W. Wozniak⁴², M. Wu³³, S.L. Wu¹⁷⁶, X. Wu⁵², Y. Wu⁹², T.R. Wyatt⁸⁷, B.M. Wynne⁴⁹, S. Xella³⁹, Z. Xi⁹², L. Xia^{35c}, D. Xu^{35a}, L. Xu²⁷, T. Xu¹³⁸, B. Yabsley¹⁵², S. Yacoob^{147a}, D. Yamaguchi¹⁵⁹, Y. Yamaguchi¹⁵⁹, A. Yamamoto⁶⁹, S. Yamamoto¹⁵⁷, T. Yamanaka¹⁵⁷, F. Yamane⁷⁰, M. Yamatani¹⁵⁷, Y. Yamazaki⁷⁰, Z. Yan²⁴, H. Yang^{36c}, H. Yang¹⁶, Y. Yang¹⁵³, Z. Yang¹⁵, W-M. Yao¹⁶, Y.C. Yap⁸³, Y. Yasu⁶⁹, E. Yatsenko⁵, K.H. Yau Wong²³, J. Ye⁴³, S. Ye²⁷, I. Yeletsikh⁶⁸, E. Yigitbasi²⁴, E. Yildirim⁸⁶, K. Yorita¹⁷⁴, K. Yoshihara¹²⁴, C. Young¹⁴⁵, C.J.S. Young³², J. Yu⁸, J. Yu⁶⁷, S.P.Y. Yuen²³, I. Yusuf^{30,ax}, B. Zabinski⁴², G. Zacharis¹⁰, R. Zaidan¹³, A.M. Zaitsev^{132,ak}, N. Zakharchuk⁴⁵, J. Zalieckas¹⁵, A. Zaman¹⁵⁰, S. Zambito⁵⁹, D. Zanzi⁹¹, C. Zeitnitz¹⁷⁸, G. Zemaityte¹²², A. Zemla^{41a}, J.C. Zeng¹⁶⁹, Q. Zeng¹⁴⁵, O. Zenin¹³², T. Ženiš^{146a}, D. Zerwas¹¹⁹, D. Zhang⁹², F. Zhang¹⁷⁶, G. Zhang^{36a,aw}, H. Zhang¹¹⁹, J. Zhang⁶, L. Zhang⁵¹, L. Zhang^{36a}, M. Zhang¹⁶⁹, P. Zhang^{35b}, R. Zhang²³, R. Zhang^{36a,au}, X. Zhang^{36b}, Y. Zhang^{35a,35d}, Z. Zhang¹¹⁹, X. Zhao⁴³, Y. Zhao^{36b,ay}, Z. Zhao^{36a}, A. Zhemchugov⁶⁸, B. Zhou⁹², C. Zhou¹⁷⁶, L. Zhou⁴³, M. Zhou^{35a,35d}, M. Zhou¹⁵⁰, N. Zhou^{35c}, C.G. Zhu^{36b}, H. Zhu^{35a}, J. Zhu⁹², Y. Zhu^{36a}, X. Zhuang^{35a}, K. Zhukov⁹⁸, A. Zibell¹⁷⁷, D. Zieminska⁶⁴, N.I. Zimine⁶⁸, C. Zimmermann⁸⁶, S. Zimmermann⁵¹, Z. Zinonos¹⁰³, M. Zinser⁸⁶, M. Ziolkowski¹⁴³, L. Živković¹⁴, G. Zoernig¹⁷⁶, A. Zoccoli^{22a,22b}, R. Zou³³, M. zur Nedden¹⁷, L. Zwalinski³²

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

² Physics Department, SUNY Albany, Albany NY, U.S.A.

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

⁴ ^(a) Department of Physics, Ankara University, Ankara; ^(b) Istanbul Aydin University, Istanbul; ^(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, U.S.A.

⁷ Department of Physics, University of Arizona, Tucson AZ, U.S.A.

⁸ Department of Physics, The University of Texas at Arlington, Arlington TX, U.S.A.

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

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

¹¹ Department of Physics, The University of Texas at Austin, Austin TX, U.S.A.

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

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

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

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

¹⁶ Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, U.S.A.

¹⁷ Department of Physics, Humboldt University, Berlin, Germany

¹⁸ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

¹⁹ School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

²⁰ ^(a) Department of Physics, Bogazici University, Istanbul; ^(b) Department of Physics Engineering, Gaziantep University, Gaziantep; ^(d) Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul; ^(e) Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey

- 21 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
- 22 ^(a) INFN Sezione di Bologna; ^(b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
- 23 Physikalisches Institut, University of Bonn, Bonn, Germany
- 24 Department of Physics, Boston University, Boston MA, U.S.A.
- 25 Department of Physics, Brandeis University, Waltham MA, U.S.A.
- 26 ^(a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; ^(b) Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; ^(c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; ^(d) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
- 27 Physics Department, Brookhaven National Laboratory, Upton NY, U.S.A.
- 28 ^(a) Transilvania University of Brasov, Brasov; ^(b) Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; ^(c) Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi; ^(d) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; ^(e) University Politehnica Bucharest, Bucharest; ^(f) West University in Timisoara, Timisoara, Romania
- 29 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
- 30 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- 31 Department of Physics, Carleton University, Ottawa ON, Canada
- 32 CERN, Geneva, Switzerland
- 33 Enrico Fermi Institute, University of Chicago, Chicago IL, U.S.A.
- 34 ^(a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; ^(b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- 35 ^(a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; ^(b) Department of Physics, Nanjing University, Jiangsu; ^(c) Physics Department, Tsinghua University, Beijing 100084; ^(d) University of Chinese Academy of Science (UCAS), Beijing, China
- 36 ^(a) Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Anhui; ^(b) School of Physics, Shandong University, Shandong; ^(c) Department of Physics and Astronomy, Key Laboratory for Particle Physics, Astrophysics and Cosmology, Ministry of Education; Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai(also at PKU-CHEP), China
- 37 Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
- 38 Nevis Laboratory, Columbia University, Irvington NY, U.S.A.
- 39 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
- 40 ^(a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; ^(b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
- 41 ^(a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; ^(b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
- 42 Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
- 43 Physics Department, Southern Methodist University, Dallas TX, U.S.A.
- 44 Physics Department, University of Texas at Dallas, Richardson TX, U.S.A.
- 45 DESY, Hamburg and Zeuthen, Germany
- 46 Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- 47 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- 48 Department of Physics, Duke University, Durham NC, U.S.A.
- 49 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- 50 INFN e Laboratori Nazionali di Frascati, Frascati, Italy
- 51 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
- 52 Departement de Physique Nucleaire et Corpusculaire, Université de Genève, Geneva, Switzerland
- 53 ^(a) INFN Sezione di Genova; ^(b) Dipartimento di Fisica, Università di Genova, Genova, Italy
- 54 ^(a) E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi; ^(b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

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

- ⁹⁷ Group of Particle Physics, University of Montreal, Montreal QC, Canada
⁹⁸ P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
⁹⁹ Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
¹⁰⁰ National Research Nuclear University MEPhI, Moscow, Russia
¹⁰¹ D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
¹⁰² Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
¹⁰³ Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
¹⁰⁴ Nagasaki Institute of Applied Science, Nagasaki, Japan
¹⁰⁵ Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
¹⁰⁶ ^(a) INFN Sezione di Napoli; ^(b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
¹⁰⁷ Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, U.S.A.
¹⁰⁸ Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
¹⁰⁹ Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
¹¹⁰ Department of Physics, Northern Illinois University, DeKalb IL, U.S.A.
¹¹¹ Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
¹¹² Department of Physics, New York University, New York NY, U.S.A.
¹¹³ Ohio State University, Columbus OH, U.S.A.
¹¹⁴ Faculty of Science, Okayama University, Okayama, Japan
¹¹⁵ Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, U.S.A.
¹¹⁶ Department of Physics, Oklahoma State University, Stillwater OK, U.S.A.
¹¹⁷ Palacký University, RCPTM, Olomouc, Czech Republic
¹¹⁸ Center for High Energy Physics, University of Oregon, Eugene OR, U.S.A.
¹¹⁹ LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
¹²⁰ Graduate School of Science, Osaka University, Osaka, Japan
¹²¹ Department of Physics, University of Oslo, Oslo, Norway
¹²² Department of Physics, Oxford University, Oxford, United Kingdom
¹²³ ^(a) INFN Sezione di Pavia; ^(b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
¹²⁴ Department of Physics, University of Pennsylvania, Philadelphia PA, U.S.A.
¹²⁵ National Research Centre “Kurchatov Institute” B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
¹²⁶ ^(a) INFN Sezione di Pisa; ^(b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
¹²⁷ Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, U.S.A.
¹²⁸ ^(a) Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa; ^(b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; ^(c) Department of Physics, University of Coimbra, Coimbra; ^(d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; ^(e) Departamento de Física, Universidade do Minho, Braga; ^(f) Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada; ^(g) Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
¹²⁹ Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
¹³⁰ Czech Technical University in Prague, Praha, Czech Republic
¹³¹ Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
¹³² State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia
¹³³ Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
¹³⁴ ^(a) INFN Sezione di Roma; ^(b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
¹³⁵ ^(a) INFN Sezione di Roma Tor Vergata; ^(b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
¹³⁶ ^(a) INFN Sezione di Roma Tre; ^(b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy

- 137 (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies -
 Université Hassan II, Casablanca; (b) Centre National de l'Energie des Sciences Techniques
 Nucleaires, Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech;
 (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) Faculté des
 sciences, Université Mohammed V, Rabat, Morocco
- 138 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
- 139 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA,
 U.S.A.
- 140 Department of Physics, University of Washington, Seattle WA, U.S.A.
- 141 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- 142 Department of Physics, Shinshu University, Nagano, Japan
- 143 Department Physik, Universität Siegen, Siegen, Germany
- 144 Department of Physics, Simon Fraser University, Burnaby BC, Canada
- 145 SLAC National Accelerator Laboratory, Stanford CA, U.S.A.
- 146 (a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b)
 Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of
 Sciences, Kosice, Slovak Republic
- 147 (a) Department of Physics, University of Cape Town, Cape Town; (b) Department of Physics,
 University of Johannesburg, Johannesburg; (c) School of Physics, University of the Witwatersrand,
 Johannesburg, South Africa
- 148 (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden
- 149 Physics Department, Royal Institute of Technology, Stockholm, Sweden
- 150 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY,
 U.S.A.
- 151 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- 152 School of Physics, University of Sydney, Sydney, Australia
- 153 Institute of Physics, Academia Sinica, Taipei, Taiwan
- 154 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
- 155 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv,
 Israel
- 156 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- 157 International Center for Elementary Particle Physics and Department of Physics, The University of
 Tokyo, Tokyo, Japan
- 158 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- 159 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- 160 Tomsk State University, Tomsk, Russia
- 161 Department of Physics, University of Toronto, Toronto ON, Canada
- 162 (a) INFN-TIFPA; (b) University of Trento, Trento, Italy
- 163 (a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto
 ON, Canada
- 164 Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science
 and Engineering, University of Tsukuba, Tsukuba, Japan
- 165 Department of Physics and Astronomy, Tufts University, Medford MA, U.S.A.
- 166 Department of Physics and Astronomy, University of California Irvine, Irvine CA, U.S.A.
- 167 (a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; (b) ICTP, Trieste; (c) Dipartimento
 di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- 168 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
- 169 Department of Physics, University of Illinois, Urbana IL, U.S.A.
- 170 Instituto de Fisica Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Spain
- 171 Department of Physics, University of British Columbia, Vancouver BC, Canada
- 172 Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada

- ¹⁷³ Department of Physics, University of Warwick, Coventry, United Kingdom
¹⁷⁴ Waseda University, Tokyo, Japan
¹⁷⁵ Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
¹⁷⁶ Department of Physics, University of Wisconsin, Madison WI, U.S.A.
¹⁷⁷ Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
¹⁷⁸ Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
¹⁷⁹ Department of Physics, Yale University, New Haven CT, U.S.A.
¹⁸⁰ Yerevan Physics Institute, Yerevan, Armenia
¹⁸¹ Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France
¹⁸² Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
- ^a Also at Department of Physics, King's College London, London, United Kingdom
^b Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
^c Also at Novosibirsk State University, Novosibirsk, Russia
^d Also at TRIUMF, Vancouver BC, Canada
^e Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, U.S.A.
^f Also at Physics Department, An-Najah National University, Nablus, Palestine
^g Also at Department of Physics, California State University, Fresno CA, U.S.A.
^h Also at Department of Physics, University of Fribourg, Fribourg, Switzerland
ⁱ Also at II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
^j Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
^k Also at Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, Portugal
^l Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
^m Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China
ⁿ Also at Università di Napoli Parthenope, Napoli, Italy
^o Also at Institute of Particle Physics (IPP), Canada
^p Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
^q Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia
^r Also at Borough of Manhattan Community College, City University of New York, New York City, U.S.A.
^s Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece
^t Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa
^u Also at Louisiana Tech University, Ruston LA, U.S.A.
^v Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
^w Also at Department of Physics, The University of Michigan, Ann Arbor MI, U.S.A.
^x Also at Graduate School of Science, Osaka University, Osaka, Japan
^y Also at Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
^z Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
^{aa} Also at Department of Physics, The University of Texas at Austin, Austin TX, U.S.A.
^{ab} Also at Institute of Theoretical Physics, Iliia State University, Tbilisi, Georgia
^{ac} Also at CERN, Geneva, Switzerland
^{ad} Also at Georgian Technical University (GTU), Tbilisi, Georgia
^{ae} Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan
^{af} Also at Manhattan College, New York NY, U.S.A.

- ^{ag} Also at Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
- ^{ah} Also at The City College of New York, New York NY, U.S.A.
- ^{ai} Also at Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Portugal
- ^{aj} Also at Department of Physics, California State University, Sacramento CA, U.S.A.
- ^{ak} Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
- ^{al} Also at Departement de Physique Nucleaire et Corpusculaire, Université de Genève, Geneva, Switzerland
- ^{am} Also at Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain
- ^{an} Also at School of Physics, Sun Yat-sen University, Guangzhou, China
- ^{ao} Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria
- ^{ap} Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
- ^{aq} Also at National Research Nuclear University MEPhI, Moscow, Russia
- ^{ar} Also at Department of Physics, Stanford University, Stanford CA, U.S.A.
- ^{as} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
- ^{at} Also at Giresun University, Faculty of Engineering, Turkey
- ^{au} Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- ^{av} Also at Department of Physics, Nanjing University, Jiangsu, China
- ^{aw} Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
- ^{ax} Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia
- ^{ay} Also at LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
- * Deceased