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Aaboud, M.; The ATLAS Collaboration

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Search for High-Mass Resonances Decaying to $\tau\nu$ in pp Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector

M. Aaboud *et al.**
(ATLAS Collaboration)

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A search for high-mass resonances decaying to $\tau\nu$ using proton-proton collisions at $\sqrt{s} = 13$ TeV produced by the Large Hadron Collider is presented. Only τ -lepton decays with hadrons in the final state are considered. The data were recorded with the ATLAS detector and correspond to an integrated luminosity of 36.1 fb^{-1} . No statistically significant excess above the standard model expectation is observed; model-independent upper limits are set on the visible $\tau\nu$ production cross section. Heavy W' bosons with masses less than 3.7 TeV in the sequential standard model and masses less than 2.2–3.8 TeV depending on the coupling in the nonuniversal $G(221)$ model are excluded at the 95% credibility level.

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Heavy charged gauge bosons (W') appear frequently in theories of physics beyond the standard model (SM). They are often assumed to obey lepton universality, such as in the sequential standard model (SSM) [1], which predicts a W'_{SSM} boson with couplings identical to those of the SM W boson. However, this assumption is not required. In particular, models in which the W' boson couples preferentially to third-generation fermions may be linked to the high mass of the top quark [2–5] or to recent indications of lepton flavor universality violation in B meson decays [6,7]. An example is the nonuniversal $G(221)$ model (NU) [4,5], which exhibits a $SU(2)_l \times SU(2)_h \times U(1)$ gauge symmetry, where $SU(2)_l$ couples to *light* fermions (first two generations), $SU(2)_h$ couples to *heavy* fermions (third generation), and ϕ_{NU} is the mixing angle between them. The model predicts W'_{NU} and Z'_{NU} bosons which are approximately degenerate in mass and couple only to left-handed fermions. At leading order and neglecting sign, the W'_{NU} couplings to heavy (light) fermions are scaled by $\cot\phi_{\text{NU}}$ ($\tan\phi_{\text{NU}}$) relative to those of W'_{SSM} . Thus $\cot\phi_{\text{NU}} > 1$ corresponds to enhanced couplings to tau leptons while $\cot\phi_{\text{NU}} = 1$ yields W'_{NU} couplings identical to those of W'_{SSM} . For Z'_{NU} , the coupling to heavy (light) fermions is given by $g \cot\phi_{\text{NU}}$ ($g \tan\phi_{\text{NU}}$), where g is the SM weak coupling constant. At high values of $\cot\phi_{\text{NU}}$, the branching fraction of W'_{NU} to a tau lepton (τ) and a neutrino (ν) approaches 26%.

In this Letter, a search for high-mass resonances (0.5–5 TeV) decaying to $\tau\nu$ using proton-proton (pp) collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV produced by the Large Hadron Collider (LHC) is presented. The data were recorded with the ATLAS detector and correspond to an integrated luminosity of 36.1 fb^{-1} . Only τ decays with hadrons in the final state are considered; these account for 65% of the total τ branching fraction. A counting experiment is performed from events that pass a high transverse-mass threshold, optimized separately for each of the signal mass hypotheses.

A direct search for high-mass resonances decaying to $\tau\nu$ has been performed by the CMS Collaboration using 19.7 fb^{-1} of integrated luminosity at $\sqrt{s} = 8$ TeV [8]. The search excludes W'_{SSM} with a mass below 2.7 TeV at the 95% credibility level and W'_{NU} with a mass below 2.7–2.0 TeV for $\cot\phi_{\text{NU}}$ in the range 1.0–5.5. The most stringent limit on W'_{SSM} from searches in the $e\nu$ and $\mu\nu$ final states is 5.1 TeV from ATLAS [9] using 36.1 fb^{-1} of integrated luminosity at $\sqrt{s} = 13$ TeV.

The ATLAS experiment is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry [10,11]. It consists of an inner detector for charged-particle tracking in the pseudorapidity region $|\eta| < 2.5$, electromagnetic and hadronic calorimeters that provide energy measurements up to $|\eta| = 4.9$, and a muon spectrometer that covers $|\eta| < 2.7$. A two-level trigger system is used to select events [12].

Hadronic τ decays are composed of a neutrino and a set of visible decay products ($\tau_{\text{had-vis}}$), typically one or three charged pions and up to two neutral pions. The reconstruction of the visible decay products [13] is seeded by jets reconstructed from topological clusters of energy depositions [14] in the calorimeter. The $\tau_{\text{had-vis}}$ candidates must have a transverse momentum $p_T > 50 \text{ GeV}$, $|\eta| < 2.4$

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(excluding $1.37 < |\eta| < 1.52$), one or three associated tracks, and an electric charge of ± 1 . Only the candidate with the highest p_T in each event is selected. Hadronic τ decays are identified using boosted decision trees that exploit calorimetric shower shape and tracking information [15,16]. Loose criteria are used, which offer adequate rejection against quark- and gluon-initiated jets. Very loose criteria, with about one quarter of the rejection power, are used to create control regions. An additional dedicated veto is used to reduce the number of electrons misidentified as $\tau_{\text{had-vis}}$. The total efficiency for $\tau_{\text{had-vis}}$ is $\sim 60\%$ at $p_T = 100$ GeV and decreases to $\sim 30\%$ at $p_T = 2$ TeV, where the large boost and collimation of the decay products causes inefficiencies in the track reconstruction and association.

Events containing electron or muon candidates are rejected. Electron candidates [17–19] must have $p_T > 20$ GeV, $|\eta| < 2.47$ (excluding $1.37 < |\eta| < 1.52$) and must pass a loose likelihood-based identification selection. Muon candidates [20] are required to have $p_T > 20$ GeV, $|\eta| < 2.5$ and to pass a very loose muon identification requirement. The missing transverse momentum, with magnitude E_T^{miss} , is calculated as the negative vectorial sum of the p_T of all reconstructed and calibrated $\tau_{\text{had-vis}}$ candidates and jets [21–23]. A correction that accounts for momentum not associated with these reconstructed objects is calculated using inner-detector tracks that originate from the hard-scattering vertex [23]. The correction contributes no more than 5% on average in signal events.

Events are selected by triggers that require E_T^{miss} above thresholds of 70, 90, or 110 GeV depending on the data-taking period. To minimize uncertainties in the trigger efficiency, the offline reconstructed E_T^{miss} is required to be at least 150 GeV. At this threshold the trigger efficiency is 80% and increases to more than 98% above 250 GeV. This behavior is determined by the E_T^{miss} resolution of the trigger, which is lower than in the offline reconstruction. The events must satisfy criteria designed to reduce backgrounds from cosmic rays, single-beam-induced events and calorimeter noise [24] and they must contain a loose $\tau_{\text{had-vis}}$ candidate. To further suppress single-beam-induced background, the $\tau_{\text{had-vis}}$ must have at least one associated track with $p_T > 10$ GeV. The multijet background is further

suppressed by requiring that the $\tau_{\text{had-vis}}$ p_T and the E_T^{miss} are balanced: $0.7 < p_T^\tau/E_T^{\text{miss}} < 1.3$. The azimuthal angle between the $\tau_{\text{had-vis}}$ and the missing momentum, $\Delta\phi$, is required to be larger than 2.4. Finally, thresholds ranging from 0.25 to 1.8 TeV in steps of 0.05 TeV are placed on the transverse mass, m_T , where $m_T^2 \equiv 2p_T^\tau E_T^{\text{miss}}(1 - \cos \Delta\phi)$.

The background is divided into events where the selected $\tau_{\text{had-vis}}$ originates from a quark- or gluon-initiated jet (jet background) and those where it does not (nonjet background). The jet background originates primarily from $W/Z + \text{jets}$ and multijet production and is estimated using a data-driven technique. The nonjet background is estimated using simulation and originates primarily from $W \rightarrow \tau\nu$ production with additional minor contributions from $W/Z/\gamma^*$, $t\bar{t}$, single top-quark, and diboson (WW , WZ and ZZ) production (collectively called *others*).

The event generators and other software packages used to produce the simulated samples are summarized in Table I. The $W/Z/\gamma^*$ sample is artificially enhanced in high-mass events to improve statistical coverage in the scanned mass range. Particle interactions with the ATLAS detector are simulated with GEANT 4 [25,26] and contributions from additional pp interactions (pileup) are simulated using PYTHIA 8.186 and the MSTW2008LO parton distribution function (PDF) set [27]. Finally, the simulated events are processed through the same reconstruction software as the data. Corrections are applied to account for mismodeling of the momentum scales and resolutions of reconstructed objects, the $\tau_{\text{had-vis}}$ reconstruction and identification efficiency, the electron to $\tau_{\text{had-vis}}$ misidentification rate, and the E_T^{miss} trigger efficiency.

The simulated samples are normalized using the integrated luminosity of the collected data set and their theoretical cross sections. The $W/Z/\gamma^*$ cross sections are calculated as a function of the boson mass at next-to-next-to-leading order (NNLO) [49] using the CT14NNLO PDF set, including electroweak corrections at next-to-leading order (NLO) [50] using the MRST2004QED PDF set [51]. Uncertainties are taken from Ref. [52] and include variations of the PDF sets, scale, α_S , beam energy, and electroweak corrections. The variations amount to a $\sim 5\%$ total uncertainty in the $W/Z/\gamma^*$ cross section at low mass, increasing to 34% at 2 TeV. The $t\bar{t}$ and single top-quark production cross sections are

TABLE I. The event generators and other software packages used to generate the matrix-element process and model nonperturbative effects in the simulated event samples. The top-quark mass is set to 172.5 GeV.

Process	Matrix element	Nonperturbative	Refs.
$W/Z/\gamma^*$	POWHEG-BOX 2, CT10, PHOTOS++ 3.52	PYTHIA 8.186, AZNLO, CTEQ6L1, EVTGEN 1.2.0	[28–36]
$t\bar{t}$	POWHEG-BOX 2, CT10	PYTHIA 6.428, P2012, CTEQ6L1, EVTGEN 1.2.0	[37–39]
Single top	POWHEG-BOX 1, CT10f4, MADSPIN	PYTHIA 6.428, P2012, CTEQ6L1, EVTGEN 1.2.0	[40–43]
Diboson	SHERPA 2.1.1, CT10	SHERPA 2.1.1	[44–48]

calculated to at least NLO with an uncertainty of 3%–6% [53–56]. The diboson cross sections are calculated to NLO with an uncertainty of 10% [44,57].

The simulated samples are affected by uncertainties associated with the generation of the events, the detector simulation, and the determination of the integrated luminosity. Uncertainties related to the modeling of the hard scatter, radiation, and fragmentation are at most 2% of the total background estimate. Uncertainties in the detector simulation manifest themselves through the efficiency of reconstruction, identification and triggering algorithms, and through particle energy scales and resolutions. The effects of energy uncertainties are propagated to E_T^{miss} . The uncertainty in the $\tau_{\text{had-vis}}$ identification efficiency is 5%–6%, as determined from measurements of $Z \rightarrow \tau\tau$ events. An additional uncertainty that increases by 20%–25% per TeV is assigned to $\tau_{\text{had-vis}}$ candidates with $p_T > 150$ GeV in accord with studies of high- p_T jets [58]. The uncertainty in the $\tau_{\text{had-vis}}$ energy scale is 2%–3%. The probability for electrons to be misidentified as $\tau_{\text{had-vis}}$ is measured with a precision of 3%–14% [16]. The uncertainty in the E_T^{miss} trigger efficiency is negligible for $E_T^{\text{miss}} > 300$ GeV and can be as large as 10% for $E_T^{\text{miss}} < 300$ GeV. Uncertainties associated with reconstructed electrons, muons, and jets are found to have a very small impact. The uncertainty in the combined 2015 + 2016 integrated luminosity is 2.1%, derived following a methodology similar to that used in Ref. [59], and has a minor impact. The uncertainty related to the simulation of pileup is $\sim 1\%$.

The W' signal events are modeled by reweighting the W sample using a leading-order matrix-element calculation. Electroweak corrections for the W cross section and interference between W and W' are not included as they are model dependent. Uncertainties in the W' cross section are estimated in the same way as for W bosons. They are not included in the fitting procedure used to extract experimental cross-section limits, but are instead included when overlaying predicted model cross sections. Uncertainties in the W' acceptance due to PDF, scale, and α_s variations are negligible. In the NU model, the total decay width increases to 35% of the pole mass for large values of $\cot\phi_{\text{NU}}$, which decreases the signal acceptance as more events are produced at low mass. Decays to WZ and Wh are not considered in the calculation of the total W'_{NU} decay width as their impact is small ($< 7\%$) and model dependent. Values of $\cot\phi_{\text{NU}} > 5.5$ are not considered as the model is nonperturbative in this range.

The jet background contribution is estimated using events in three control regions (CR1, CR2, and CR3). The events must pass the selection for the signal region, except in CR1 and CR3 they must fail loose but pass very loose $\tau_{\text{had-vis}}$ identification and in CR2 and CR3 they must have $E_T^{\text{miss}} < 100$ GeV and the requirement on $p_T^{\tau}/E_T^{\text{miss}}$ is removed. The low- E_T^{miss} requirement yields high multijet purity in CR2 and CR3, while the very loose identification

preferentially rejects gluon-initiated jets over quark-initiated jets. This produces a similar fraction of quark-initiated jets in all control regions, which ensures minimal correlation between the identification and E_T^{miss} . The estimated jet contribution is defined as $N_{\text{jet}} = N_{\text{CR1}}N_{\text{CR2}}/N_{\text{CR3}}$. The nonjet contamination in CR1 (10%), CR2 (3.7%), and CR3 (0.5%) is subtracted using simulation. The transfer factor, $N_{\text{CR2}}/N_{\text{CR3}}$, is parametrized in $\tau_{\text{had-vis}} p_T$ and track multiplicity and is in the range 0.4–0.7 (0.15–0.3) for 1-track (3-track) $\tau_{\text{had-vis}}$. Systematic uncertainties are assigned to account for any residual correlation between the transfer factor and the E_T^{miss} and $p_T^{\tau}/E_T^{\text{miss}}$ selection criteria, which would arise if the jet composition was different in CR1 and CR3. They are evaluated by repeating the jet estimate with the following modified control region definitions: (a) altered very loose $\tau_{\text{had-vis}}$ identification criteria, (b) modified E_T^{miss} and $p_T^{\tau}/E_T^{\text{miss}}$ selection, and (c) CR2 and CR3 replaced by alternative control regions rich in $W(\rightarrow\mu\nu) + \text{jets}$ events. The corresponding variations define the dominant uncertainty in the jet background contribution, which ranges from 20% at $m_T = 0.2$ TeV to $^{+200\%}_{-60\%}$ at $m_T = 2$ TeV, where the jet background is subdominant. The uncertainty due to the subtraction of nonjet contamination in the control regions is negligible.

To reduce the impact of statistical fluctuations in the jet background estimate, a function $f(m_T) = m_T^{a+b \log m_T}$, where a and b are free parameters, is fitted to the estimate in the range $400 < m_T < 800$ GeV and is used to evaluate the jet background in the range $m_T > 500$ GeV. The impact of altering the fit range leads to an uncertainty that increases with m_T , reaching 50% at $m_T = 2$ TeV. The statistical uncertainty from the control regions is propagated using pseudoexperiments and also reaches 50% at $m_T = 2$ TeV.

Figure 1 shows the observed m_T distribution of the data after event selection, including the estimated SM background contributions and predictions for W'_{SSM} and W'_{NU} ($\cot\phi_{\text{NU}} = 5.5$) bosons with masses of 3 TeV. The number of observed events is consistent with the expected SM background. Therefore, upper limits are set on the production of a high-mass resonance decaying to $\tau\nu$. The statistical analysis uses a likelihood function constructed as the Poisson probability describing the total number of observed events given the signal-plus-background expectation. Systematic uncertainties in the expected number of events are incorporated into the likelihood via nuisance parameters constrained by Gaussian prior probability density distributions. Correlations between signal and background are taken into account. A signal-strength parameter, with a uniform prior probability density distribution, multiplies the expected signal. The dominant relative uncertainties in the expected signal and background contributions are shown in Fig. 2 as a function of the m_T threshold.

Limits are set at the 95% credibility level (C.L.) using the Bayesian Analysis Toolkit [60]. Figure 3 shows the

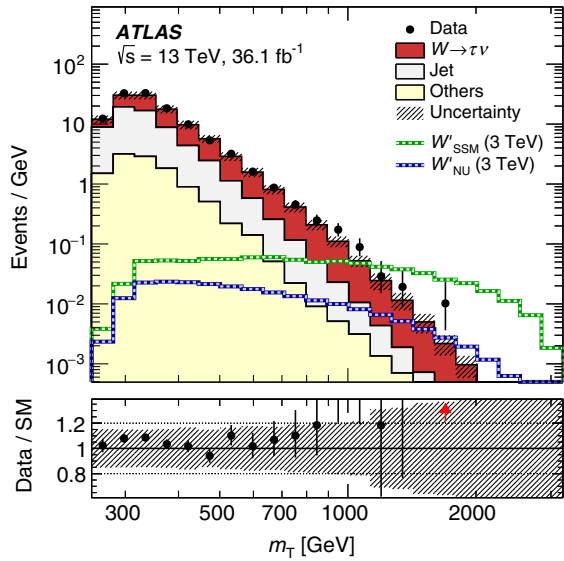


FIG. 1. Transverse mass distribution after the event selection. The total impact of the statistical and systematic uncertainties on the SM background is depicted by the hatched area. The ratio of the data to the estimated SM background is shown in the lower panel. The prediction for W'_{SSM} and W'_{NU} ($\cot\phi_{\text{NU}} = 5.5$) bosons with masses of 3 TeV are superimposed.

model-independent upper limits on the visible $\tau\nu$ production cross section, $\sigma(pp \rightarrow \tau\nu + X)\mathcal{A}\varepsilon$, as a function of the m_T threshold, where \mathcal{A} is the fiducial acceptance (including the m_T threshold) and ε is the reconstruction efficiency. Model-specific limits can be derived by evaluating σ , \mathcal{A} , and ε for the model in question and checking if the corresponding

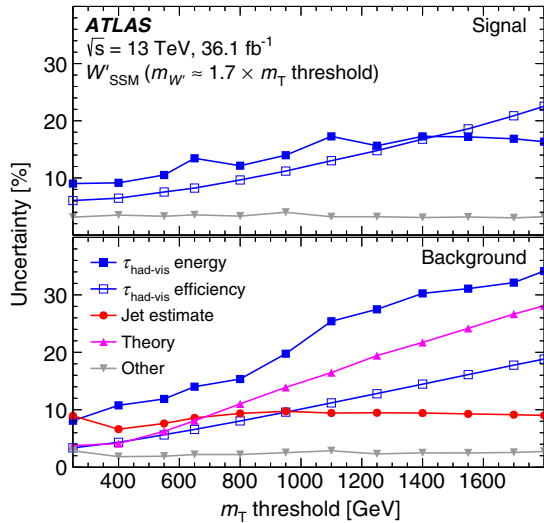


FIG. 2. Dominant relative uncertainties in the expected signal and background contributions as a function of the m_T threshold. For each threshold a W'_{SSM} boson with a mass of approximately 1.7 times the threshold is chosen. *Theory* includes uncertainties in the cross sections used to normalize the simulated samples and uncertainties associated with the modeling provided by the event generators. *Other* is the impact of all other uncertainties added in quadrature.

visible cross section is excluded at any m_T threshold. This allows the results to be reinterpreted for a broad range of models, regardless of their m_T distribution. Good agreement between the generated and reconstructed m_T distributions is found, indicating that a reliable calculation of the m_T threshold acceptance can be made at generator level. The reconstruction efficiency depends on m_T , $\varepsilon(m_T[\text{TeV}]) = 0.633 - 0.313m_T + 0.0688m_T^2 - 0.00575m_T^3$, ranging from 60% at 0.2 TeV to 7% at 5 TeV, and must be appropriately integrated out given the m_T distribution of the model. The relative uncertainty in the parametrized efficiency due to the choice of signal model is $\sim 10\%$. With these inputs the visible cross sections for W'_{SSM} and W'_{NU} bosons could be reproduced within 10% using only generator-level information. Data and details to facilitate reinterpretations can be found at Ref. [61].

Limits are also set on benchmark models by selecting the most sensitive m_T threshold for each W' mass hypothesis ($\sim 0.6m_{W'}$ up to a maximum of 1.45 TeV). The chosen threshold is found to have little dependence on the W' width. Figure 4(a) shows the 95% C.L. upper limit on the cross section times branching fraction as a function of $m_{W'}$ in the SSM. Heavy W'_{SSM} bosons with a mass lower than 3.7 TeV are excluded, with an expected exclusion limit of 3.8 TeV. Figure 4(b) shows the excluded region in the parameter space of the nonuniversal $G(221)$ model. Heavy W'_{NU} bosons with a mass lower than 2.2–3.8 TeV are excluded depending on $\cot\phi_{\text{NU}}$, thereby probing a significantly larger region of parameter space than previous searches [8]. The W'_{NU} limits are typically weaker than the W'_{SSM} limits as the increased W' width yields lower acceptances, while the enhancement in the decay rate cancels with the suppression in the production via first- and second-generation quarks. Limits from the ATLAS ee , $\mu\mu$, and $\tau\tau$ searches [58,62] are

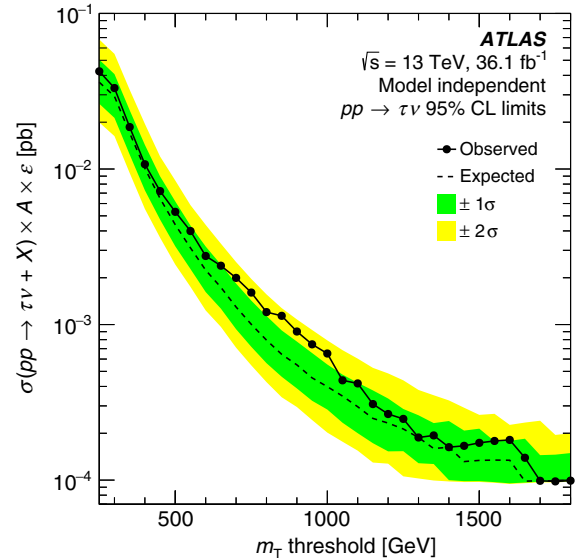


FIG. 3. The 95% C.L. upper limit on the visible $\tau\nu$ production cross section as a function of the m_T threshold.

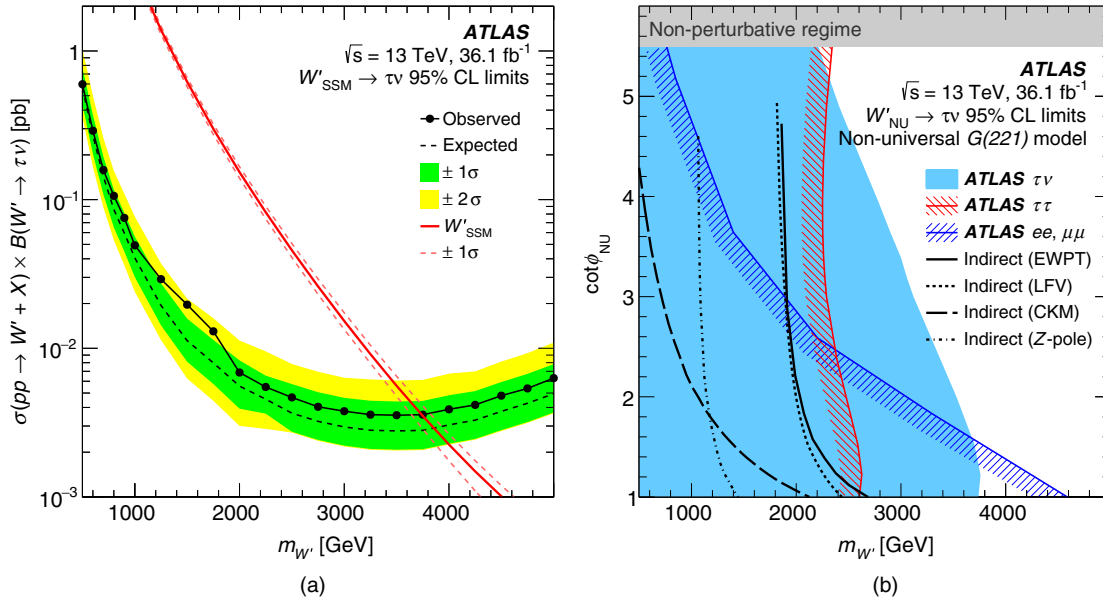


FIG. 4. (a) The 95% C.L. upper limit on the cross section times $\tau\nu$ branching fraction for W'_{SSM} . The W'_{SSM} cross section is overlaid where the additional lines represent the total theoretical uncertainty. (b) Excluded region for W'_{NU} . The 95% C.L. limits from the ATLAS $ee, \mu\mu$ [62], and $\tau\tau$ [58] searches and indirect limits at 95% C.L. from fits to electroweak precision measurements (EWPT) [63], lepton flavor violation (LFV) [64], CKM unitarity [65], and the original Z-pole data [2] are overlaid.

also overlaid, showing that the $\tau\nu$ search is complementary and extends the sensitivity over a large fraction of the parameter space. These results suggest that the $\tau\nu$ searches should be considered when placing limits on nonuniversal extended gauge groups, such as those seeking to explain lepton flavor violation in B meson decays.

In summary, a search for $W' \rightarrow \tau\nu$ in 36.1 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV recorded by the ATLAS detector at the LHC is presented. The channel where the τ decays hadronically is analyzed and no significant excess over the SM expectation is found. Upper limits are set on the visible cross section for $\tau\nu$ production, allowing interpretation in a broad range of models. Sequential standard model W'_{SSM} bosons with masses less than 3.7 TeV are excluded at 95% C.L., while nonuniversal $G(221)$ W'_{NU} bosons with masses less than 2.2–3.8 TeV are excluded depending on the model parameters.

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M. Aaboud,^{137d} G. Aad,⁸⁸ B. Abbott,¹¹⁵ O. Abdinov,^{12,a} B. Abeloos,¹¹⁹ S. H. Abidi,¹⁶¹ O. S. AbouZeid,¹³⁹ N. L. Abraham,¹⁵¹ H. Abramowicz,¹⁵⁵ H. Abreu,¹⁵⁴ Y. Abulaiti,⁶ B. S. Acharya,^{167a,167b,b} S. Adachi,¹⁵⁷ L. Adamczyk,^{41a} J. Adelman,¹¹⁰ M. Adersberger,¹⁰² T. Adye,¹³³ A. A. Affolder,¹³⁹ Y. Afik,¹⁵⁴ C. Agheorghiesei,^{28c} J. A. Aguilar-Saavedra,^{128a,128f} S. P. Ahlen,²⁴ F. Ahmadov,^{68,c} G. Aielli,^{135a,135b} S. Akatsuka,⁷¹ T. P. A. Åkesson,⁸⁴ E. Akilli,⁵² A. V. Akimov,⁹⁸ G. L. Alberghi,^{22a,22b} J. Albert,¹⁷² P. Albicocco,⁵⁰ M. J. Alconada Verzini,⁷⁴ S. Alderweireldt,¹⁰⁸ M. Aleksa,³² I. N. Aleksandrov,⁶⁸ C. Alexa,^{28b} G. Alexander,¹⁵⁵ T. Alexopoulos,¹⁰ M. Alhroob,¹¹⁵ B. Ali,¹³⁰ M. Aliev,^{76a,76b}

G. Alimonti,^{94a} J. Alison,³³ S. P. Alkire,¹⁴⁰ C. Allaire,¹¹⁹ B. M. M. Allbrooke,¹⁵¹ B. W. Allen,¹¹⁸ P. P. Allport,¹⁹
 A. Aloisio,^{106a,106b} A. Alonso,³⁹ F. Alonso,⁷⁴ C. Alpigliani,¹⁴⁰ A. A. Alshehri,⁵⁶ M. I. Alstary,⁸⁸ B. Alvarez Gonzalez,³²
 D. Álvarez Piqueras,¹⁷⁰ M. G. Alviggi,^{106a,106b} B. T. Amadio,¹⁶ Y. Amaral Coutinho,^{26a} L. Ambroz,¹²² C. Amelung,²⁵
 D. Amidei,⁹² S. P. Amor Dos Santos,^{128a,128c} S. Amoroso,³² C. S. Amrouche,⁵² C. Anastopoulos,¹⁴¹ L. S. Ancu,⁵²
 N. Andari,¹⁹ T. Andeen,¹¹ C. F. Anders,^{60b} J. K. Anders,¹⁸ K. J. Anderson,³³ A. Andreazza,^{94a,94b} V. Andrei,^{60a}
 S. Angelidakis,³⁷ I. Angelozzi,¹⁰⁹ A. Angerami,³⁸ A. V. Anisenkov,^{111,d} A. Annovi,^{126a} C. Antel,^{60a} M. T. Anthony,¹⁴¹
 M. Antonelli,⁵⁰ D. J. Antrim,¹⁶⁶ F. Anulli,^{134a} M. Aoki,⁶⁹ L. Aperio Bella,³² G. Arabidze,⁹³ Y. Arai,⁶⁹ J. P. Araque,^{128a}
 V. Araujo Ferraz,^{26a} R. Araujo Pereira,^{26a} A. T. H. Arce,⁴⁸ R. E. Ardell,⁸⁰ F. A. Arduh,⁷⁴ J-F. Arguin,⁹⁷ S. Argyropoulos,⁶⁶
 A. J. Armbruster,³² L. J. Armitage,⁷⁹ O. Arnaez,¹⁶¹ H. Arnold,¹⁰⁹ M. Arratia,³⁰ O. Arslan,²³ A. Artamonov,^{99,a} G. Artoni,¹²²
 S. Artz,⁸⁶ S. Asai,¹⁵⁷ N. Asbah,⁴⁵ A. Ashkenazi,¹⁵⁵ E. M. Asimakopoulou,¹⁶⁸ L. Asquith,¹⁵¹ K. Assamagan,²⁷ R. Astalos,^{146a}
 R. J. Atkin,^{147a} M. Atkinson,¹⁶⁹ N. B. Atlay,¹⁴³ K. Augsten,¹³⁰ G. Avolio,³² R. Avramidou,^{36a} B. Axen,¹⁶ M. K. Ayoub,^{35a}
 G. Azuelos,^{97,e} A. E. Baas,^{60a} M. J. Baca,¹⁹ H. Bachacou,¹³⁸ K. Bachas,^{76a,76b} M. Backes,¹²² P. Bagnaia,^{134a,134b}
 M. Bahmani,⁴² H. Bahrasemani,¹⁴⁴ J. T. Baines,¹³³ M. Bajic,³⁹ O. K. Baker,¹⁷⁹ P. J. Bakker,¹⁰⁹ D. Bakshi Gupta,⁸²
 E. M. Baldin,^{111,d} P. Balek,¹⁷⁵ F. Balli,¹³⁸ W. K. Balunas,¹²⁴ E. Banas,⁴² A. Bandyopadhyay,²³ Sw. Banerjee,^{176,f}
 A. A. E. Bannoura,¹⁷⁷ L. Barak,¹⁵⁵ W. M. Barbe,³⁷ E. L. Barberio,⁹¹ D. Barberis,^{53a,53b} M. Barbero,⁸⁸ T. Barillari,¹⁰³
 M-S Barisits,³² J. T. Barkeloo,¹¹⁸ T. Barklow,¹⁴⁵ N. Barlow,³⁰ R. Barnea,¹⁵⁴ S. L. Barnes,^{36c} B. M. Barnett,¹³³
 R. M. Barnett,¹⁶ Z. Barnovska-Blenessy,^{36a} A. Baroncelli,^{136a} G. Barone,²⁵ A. J. Barr,¹²² L. Barranco Navarro,¹⁷⁰
 F. Barreiro,⁸⁵ J. Barreiro Guimarães da Costa,^{35a} R. Bartoldus,¹⁴⁵ A. E. Barton,⁷⁵ P. Bartos,^{146a} A. BasalaeV,¹²⁵
 A. Bassalat,^{119,g} R. L. Bates,⁵⁶ S. J. Batista,¹⁶¹ J. R. Batley,³⁰ M. Battaglia,¹³⁹ M. Bauce,^{134a,134b} F. Bauer,¹³⁸ K. T. Bauer,¹⁶⁶
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 C. P. Bee,¹⁵⁰ T. A. Beermann,³² M. Begalli,^{26a} M. Begel,²⁷ A. Behera,¹⁵⁰ J. K. Behr,⁴⁵ A. S. Bell,⁸¹ G. Bella,¹⁵⁵
 L. Bellagamba,^{22a} A. Bellerive,³¹ M. Bellomo,¹⁵⁴ K. Belotskiy,¹⁰⁰ N. L. Belyaev,¹⁰⁰ O. Benary,^{155,a} D. BencheKroun,^{137a}
 M. Bender,¹⁰² N. Benekos,¹⁰ Y. Benhammou,¹⁵⁵ E. Benhar Nocchioli,¹⁷⁹ J. Benitez,⁶⁶ D. P. Benjamin,⁴⁸ M. Benoit,⁵²
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 P. Berta,⁸⁶ C. Bertella,^{35a} G. Bertoli,^{148a,148b} I. A. Bertram,⁷⁵ C. Bertsche,⁴⁵ G. J. Besjes,³⁹ O. Bessidskaia Bylund,^{148a,148b}
 M. Bessner,⁴⁵ N. Besson,¹³⁸ A. Bethani,⁸⁷ S. Bethke,¹⁰³ A. Betti,²³ A. J. Bevan,⁷⁹ J. Beyer,¹⁰³ R. M. Bianchi,¹²⁷ O. Biebel,¹⁰²
 D. Biedermann,¹⁷ R. Bielski,⁸⁷ K. Bierwagen,⁸⁶ N. V. Biesuz,^{126a,126b} M. Biglietti,^{136a} T. R. V. Billoud,⁹⁷ M. Bindi,⁵⁸
 A. Bingul,^{20b} C. Bini,^{134a,134b} S. Biondi,^{22a,22b} T. Bisanz,⁵⁸ C. Bittrich,⁴⁷ D. M. Bjergaard,⁴⁸ J. E. Black,¹⁴⁵ K. M. Black,²⁴
 R. E. Blair,⁶ T. Blazek,^{146a} I. Bloch,⁴⁵ C. Blocker,²⁵ A. Blue,⁵⁶ U. Blumenschein,⁷⁹ Dr. Blunier,^{34a} G. J. Bobbink,¹⁰⁹
 V. S. Bobrovnikov,^{111,d} S. S. Bocchetta,⁸⁴ A. Bocci,⁴⁸ C. Bock,¹⁰² D. Boerner,¹⁷⁷ D. Bogavac,¹⁰² A. G. Bogdanchikov,¹¹¹
 C. Bohm,^{148a} V. Boisvert,⁸⁰ P. Bokan,^{168,j} T. Bold,^{41a} A. S. Boldyrev,¹⁰¹ A. E. Bolz,^{60b} M. Bomben,⁸³ M. Bona,⁷⁹
 J. S. Bonilla,¹¹⁸ M. Boonekamp,¹³⁸ A. Borisov,¹³² G. BorissoV,⁷⁵ J. Bortfeldt,³² D. Bortoletto,¹²² V. Bortolotto,^{135a,135b}
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 C. Bourdarios,¹¹⁹ S. K. Boutle,⁵⁶ A. Boveia,¹¹³ J. Boyd,³² I. R. Boyko,⁶⁸ A. J. Bozson,⁸⁰ J. Bracinik,¹⁹ N. Brahimi,⁸⁸
 A. Brandt,⁸ G. Brandt,¹⁷⁷ O. Brandt,^{60a} F. Braren,⁴⁵ U. Bratzler,¹⁵⁸ B. Brau,⁸⁹ J. E. Brau,¹¹⁸ W. D. Breaden Madden,⁵⁶
 K. Brendlinger,⁴⁵ A. J. Brennan,⁹¹ L. Brenner,⁴⁵ R. Brenner,¹⁶⁸ S. Bressler,¹⁷⁵ D. L. Briglin,¹⁹ T. M. Bristow,⁴⁹ D. Britton,⁵⁶
 D. Britzger,^{60b} I. Brock,²³ R. Brock,⁹³ G. Brooijmans,³⁸ T. Brooks,⁸⁰ W. K. Brooks,^{34b} E. Brost,¹¹⁰ J. H. Broughton,¹⁹
 P. A. Bruckman de Renstrom,⁴² D. Bruncko,^{146b} A. Bruni,^{22a} G. Bruni,^{22a} L. S. Bruni,¹⁰⁹ S. Bruno,^{135a,135b} BH Brunt,³⁰
 M. Bruschi,^{22a} N. Bruscino,¹²⁷ P. Bryant,³³ L. Bryngemark,⁴⁵ T. Buanes,¹⁵ Q. Buat,³² P. Buchholz,¹⁴³ A. G. Buckley,⁵⁶
 I. A. Budagov,⁶⁸ F. Buehrer,⁵¹ M. K. Bugge,¹²¹ O. Bulekov,¹⁰⁰ D. Bullock,⁸ T. J. Burch,¹¹⁰ S. Burdin,⁷⁷ C. D. Burgard,¹⁰⁹
 A. M. Burger,⁵ B. Burghgrave,¹¹⁰ K. Burka,⁴² S. Burke,¹³³ I. Burmeister,⁴⁶ J. T. P. Burr,¹²² D. Büscher,⁵¹ V. Büscher,⁸⁶
 E. Buschmann,⁵⁸ P. Bussey,⁵⁶ J. M. Butler,²⁴ C. M. Buttar,⁵⁶ J. M. Butterworth,⁸¹ P. Butti,³² W. Buttinger,³² A. Buzatu,¹⁵³
 A. R. Buzykaev,^{111,d} G. Cabras,^{22a,22b} S. Cabrera Urbán,¹⁷⁰ D. Caforio,¹³⁰ H. Cai,¹⁶⁹ V. M. M. Cairo,² O. Cakir,^{4a}
 N. Calace,⁵² P. Calafiura,¹⁶ A. Calandri,⁸⁸ G. Calderini,⁸³ P. Calfayan,⁶⁴ G. Callea,^{40a,40b} L. P. Caloba,^{26a}
 S. Calvente Lopez,⁸⁵ D. Calvet,³⁷ S. Calvet,³⁷ T. P. Calvet,¹⁵⁰ M. Calvetti,^{126a,126b} R. Camacho Toro,³³ S. Camarda,³²
 P. Camarri,^{135a,135b} D. Cameron,¹²¹ R. Caminal Armadans,⁸⁹ C. Camincher,⁵⁷ S. Campana,³² M. Campanelli,⁸¹
 A. Camplani,^{94a,94b} A. Campoverde,¹⁴³ V. Canale,^{106a,106b} M. Cano Bret,^{36c} J. Cantero,¹¹⁶ T. Cao,¹⁵⁵ Y. Cao,¹⁶⁹

M. D. M. Capeans Garrido,³² I. Caprini,^{28b} M. Caprini,^{28b} M. Capua,^{40a,40b} R. M. Carbone,³⁸ R. Cardarelli,^{135a} F. Cardillo,⁵¹
 I. Carli,¹³¹ T. Carli,³² G. Carlino,^{106a} B. T. Carlson,¹²⁷ L. Carminati,^{94a,94b} R. M. D. Carney,^{148a,148b} S. Caron,¹⁰⁸
 E. Carquin,^{34b} S. Carrá,^{94a,94b} G. D. Carrillo-Montoya,³² D. Casadei,^{147b} M. P. Casado,^{13,k} A. F. Casha,¹⁶¹ M. Casolino,¹³
 D. W. Casper,¹⁶⁶ R. Castelijin,¹⁰⁹ V. Castillo Gimenez,¹⁷⁰ N. F. Castro,^{128a,128e} A. Catinaccio,³² J. R. Catmore,¹²¹ A. Cattai,³²
 J. Caudron,²³ V. Cavaliere,²⁷ E. Cavallaro,¹³ D. Cavalli,^{94a} M. Cavalli-Sforza,¹³ V. Cavasinni,^{126a,126b} E. Celebi,^{20d}
 F. Ceradini,^{136a,136b} L. Cerda Alberich,¹⁷⁰ A. S. Cerqueira,^{26b} A. Cerri,¹⁵¹ L. Cerrito,^{135a,135b} F. Cerutti,¹⁶ A. Cervelli,^{22a,22b}
 S. A. Cetin,^{20d} A. Chafaq,^{137a} D. Chakraborty,¹¹⁰ S. K. Chan,⁵⁹ W. S. Chan,¹⁰⁹ Y. L. Chan,^{62a} P. Chang,¹⁶⁹ J. D. Chapman,³⁰
 D. G. Charlton,¹⁹ C. C. Chau,³¹ C. A. Chavez Barajas,¹⁵¹ S. Che,¹¹³ A. Chegwiddden,⁹³ S. Chekanov,⁶ S. V. Chekulaev,^{163a}
 G. A. Chelkov,^{68,1} M. A. Chelstowska,³² C. Chen,^{36a} C. Chen,⁶⁷ H. Chen,²⁷ J. Chen,^{36a} J. Chen,³⁸ S. Chen,^{35b} S. Chen,¹²⁴
 X. Chen,^{35c,m} Y. Chen,⁷⁰ Y.-H. Chen,⁴⁵ H. C. Cheng,⁹² H. J. Cheng,^{35a,35d} A. Cheplakov,⁶⁸ E. Cheremushkina,¹³²
 R. Cherkaoui El Moursli,^{137e} E. Cheu,⁷ K. Cheung,⁶³ L. Chevalier,¹³⁸ V. Chiarella,⁵⁰ G. Chiarelli,^{126a} G. Chiodini,^{76a}
 A. S. Chisholm,³² A. Chitan,^{28b} I. Chiu,¹⁵⁷ Y. H. Chiu,¹⁷² M. V. Chizhov,⁶⁸ K. Choi,⁶⁴ A. R. Chomont,¹¹⁹ S. Chouridou,¹⁵⁶
 Y. S. Chow,¹⁰⁹ V. Christodoulou,⁸¹ M. C. Chu,^{62a} J. Chudoba,¹²⁹ A. J. Chuinard,⁹⁰ J. J. Chwastowski,⁴² L. Chytka,¹¹⁷
 D. Cinca,⁴⁶ V. Cindro,⁷⁸ I. A. Cioară,²³ A. Ciocio,¹⁶ F. Ciroto,^{106a,106b} Z. H. Citron,¹⁷⁵ M. Citterio,^{94a} A. Clark,⁵²
 M. R. Clark,³⁸ P. J. Clark,⁴⁹ R. N. Clarke,¹⁶ C. Clement,^{148a,148b} Y. Coadou,⁸⁸ M. Cobal,^{167a,167c} A. Coccaro,^{53a,53b}
 J. Cochran,⁶⁷ L. Colasurdo,¹⁰⁸ B. Cole,³⁸ A. P. Colijn,¹⁰⁹ J. Collot,⁵⁷ P. Conde Muiño,^{128a,128b} E. Coniavitis,⁵¹
 S. H. Connell,^{147b} I. A. Connelly,⁸⁷ S. Constantinescu,^{28b} F. Conventi,^{106a,n} A. M. Cooper-Sarkar,¹²² F. Cormier,¹⁷¹
 K. J. R. Cormier,¹⁶¹ M. Corradi,^{134a,134b} E. E. Corrigan,⁸⁴ F. Corriveau,^{90,o} A. Cortes-Gonzalez,³² M. J. Costa,¹⁷⁰
 D. Costanzo,¹⁴¹ G. Cottin,³⁰ G. Cowan,⁸⁰ B. E. Cox,⁸⁷ J. Crane,⁸⁷ K. Cranmer,¹¹² S. J. Crawley,⁵⁶ R. A. Creager,¹²⁴
 G. Cree,³¹ S. Crépe-Renaudin,⁵⁷ F. Crescioli,⁸³ M. Cristinziani,²³ V. Croft,¹¹² G. Crosetti,^{40a,40b} A. Cueto,⁸⁵
 T. Cuhadar Donszelmann,¹⁴¹ A. R. Cukierman,¹⁴⁵ M. Curatolo,⁵⁰ J. Cúth,⁸⁶ S. Czekierda,⁴² P. Czodrowski,³²
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 M. F. Daneri,²⁹ N. P. Dang,^{176,f} N. S. Dann,⁸⁷ M. Danninger,¹⁷¹ V. Dao,³² G. Darbo,^{53a} S. Darmora,⁸ O. Dartsis,⁵
 A. Dattagupta,¹¹⁸ T. Daubney,⁴⁵ W. Davey,²³ C. David,⁴⁵ T. Davidek,¹³¹ D. R. Davis,⁴⁸ E. Dawe,⁹¹ I. Dawson,¹⁴¹ K. De,⁸
 R. de Asmundis,^{106a} A. De Benedetti,¹¹⁵ S. De Castro,^{22a,22b} S. De Cecco,⁸³ N. De Groot,¹⁰⁸ P. de Jong,¹⁰⁹ H. De la Torre,⁹³
 F. De Lorenzi,⁶⁷ A. De Maria,⁵⁸ D. De Pedis,^{134a} A. De Salvo,^{134a} U. De Sanctis,^{135a,135b} A. De Santo,¹⁵¹
 K. De Vasconcelos Corga,⁸⁸ J. B. De Vivie De Regie,¹¹⁹ C. Debenedetti,¹³⁹ D. V. Dedovich,⁶⁸ N. Dehghanian,³
 M. Del Gaudio,^{40a,40b} J. Del Peso,⁸⁵ D. Delgove,¹¹⁹ F. Deliot,¹³⁸ C. M. Delitzsch,⁷ A. Dell'Acqua,³² L. Dell'Asta,²⁴
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 A. Di Ciaccio,^{135a,135b} L. Di Ciaccio,⁵ W. K. Di Clemente,¹²⁴ C. Di Donato,^{106a,106b} A. Di Girolamo,³² B. Di Micco,^{136a,136b}
 R. Di Nardo,³² K. F. Di Petrillo,⁵⁹ A. Di Simone,⁵¹ R. Di Sipio,¹⁶¹ D. Di Valentino,³¹ C. Diaconu,⁸⁸ M. Diamond,¹⁶¹
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 A. Dimitrievska,¹⁶ J. Dingfelder,²³ F. Dittus,³² F. Djama,⁸⁸ T. Djobava,^{54b} J. I. Djuvsland,^{60a} M. A. B. do Vale,^{26c}
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 J. Duarte-Campderros,¹⁵⁵ F. Dubinin,⁹⁸ A. Dubreuil,⁵² E. Duchovni,¹⁷⁵ G. Duckeck,¹⁰² A. Ducourthial,⁸³ O. A. Ducu,^{97,p}
 D. Duda,¹⁰⁹ A. Dudarev,³² A. Chr. Dudder,⁸⁶ E. M. Duffield,¹⁶ L. Dufлот,¹¹⁹ M. Dührssen,³² C. Dulsen,¹⁷⁷ M. Dumancic,¹⁷⁵
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 T. Eifert,³² G. Eigen,¹⁵ K. Einsweiler,¹⁶ T. Ekelof,¹⁶⁸ M. El Kacimi,^{137c} R. El Kosseifi,⁸⁸ V. Ellajosyula,⁸⁸ M. Ellert,¹⁶⁸
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 M. B. Epland,⁴⁸ J. Erdmann,⁴⁶ A. Ereditato,¹⁸ S. Errede,¹⁶⁹ M. Escalier,¹¹⁹ C. Escobar,¹⁷⁰ B. Esposito,⁵⁰ O. Estrada Pastor,¹⁷⁰
 A. I. Etiennevre,¹³⁸ E. Etzion,¹⁵⁵ H. Evans,⁶⁴ A. Ezhilov,¹²⁵ M. Ezzi,^{137e} F. Fabbri,^{22a,22b} L. Fabbri,^{22a,22b} V. Fabiani,¹⁰⁸
 G. Facini,⁸¹ R. M. Fakhrutdinov,¹³² S. Falciano,^{134a} P. J. Falke,⁵ S. Falke,⁵ J. Faltova,¹³¹ Y. Fang,^{35a} M. Fanti,^{94a,94b}
 A. Farbin,⁸ A. Farilla,^{136a} E. M. Farina,^{123a,123b} T. Farooque,⁹³ S. Farrell,¹⁶ S. M. Farrington,¹⁷³ P. Farthouat,³² F. Fassi,^{137e}
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W. Fedorko,¹⁷¹ M. Feickert,⁴³ S. Feigl,¹²¹ L. Feligioni,⁸⁸ C. Feng,^{36b} E. J. Feng,³² M. Feng,⁴⁸ M. J. Fenton,⁵⁶
A. B. Fenyuk,¹³² L. Feremenga,⁸ J. Ferrando,⁴⁵ A. Ferrari,¹⁶⁸ P. Ferrari,¹⁰⁹ R. Ferrari,^{123a} D. E. Ferreira de Lima,^{60b}
A. Ferrer,¹⁷⁰ D. Ferrere,⁵² C. Ferretti,⁹² F. Fiedler,⁸⁶ A. Filipčić,⁷⁸ F. Filthaut,¹⁰⁸ M. Fincke-Keeler,¹⁷² K. D. Finelli,²⁴
M. C. N. Fiolhais,^{128a,128c,s} L. Fiorini,¹⁷⁰ C. Fischer,¹³ J. Fischer,¹⁷⁷ W. C. Fisher,⁹³ N. Flaschel,⁴⁵ I. Fleck,¹⁴³
P. Fleischmann,⁹² R. R. M. Fletcher,¹²⁴ T. Flick,¹⁷⁷ B. M. Flierl,¹⁰² L. M. Flores,¹²⁴ L. R. Flores Castillo,^{62a} N. Fomin,¹⁵
G. T. Forcolin,⁸⁷ A. Formica,¹³⁸ F. A. Förster,¹³ A. Forti,⁸⁷ A. G. Foster,¹⁹ D. Fournier,¹¹⁹ H. Fox,⁷⁵ S. Fracchia,¹⁴¹
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M. Fraternali,^{123a,123b} D. Freeborn,⁸¹ S. M. Fressard-Batraneanu,³² B. Freund,⁹⁷ W. S. Freund,^{26a} D. Froidevaux,³²
J. A. Frost,¹²² C. Fukunaga,¹⁵⁸ T. Fusayasu,¹⁰⁴ J. Fuster,¹⁷⁰ O. Gabizon,¹⁵⁴ A. Gabrielli,^{22a,22b} A. Gabrielli,¹⁶ G. P. Gach,^{41a}
S. Gadatsch,⁵² S. Gadomski,⁸⁰ P. Gadow,¹⁰³ G. Gagliardi,^{53a,53b} L. G. Gagnon,⁹⁷ C. Galea,^{28b} B. Galhardo,^{128a,128c}
E. J. Gallas,¹²² B. J. Gallop,¹³³ P. Gallus,¹³⁰ G. Galster,³⁹ R. Gamboa Goni,⁷⁹ K. K. Gan,¹¹³ S. Ganguly,¹⁷⁵ Y. Gao,⁷⁷
Y. S. Gao,^{145,h} F. M. Garay Walls,^{34a} C. García,¹⁷⁰ J. E. García Navarro,¹⁷⁰ J. A. García Pascual,^{35a} M. Garcia-Sciveres,¹⁶
R. W. Gardner,³³ N. Garelli,¹⁴⁵ V. Garonne,¹²¹ K. Gasnikova,⁴⁵ A. Gaudiello,^{53a,53b} G. Gaudio,^{123a} I. L. Gavrilenko,⁹⁸
A. Gavriluk,⁹⁹ C. Gay,¹⁷¹ G. Gaycken,²³ E. N. Gazis,¹⁰ C. N. P. Gee,¹³³ J. Geisen,⁵⁸ M. Geisen,⁸⁶ M. P. Geisler,^{60a}
K. Gellerstedt,^{148a,148b} C. Gemme,^{53a} M. H. Genest,⁵⁷ C. Geng,⁹² S. Gentile,^{134a,134b} C. Gentsos,¹⁵⁶ S. George,⁸⁰
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S. Gkaitatzis,¹⁵⁶ I. Gkialas,^{9,t} E. L. Gkoukousis,¹³ P. Gkoutoumis,¹⁰ L. K. Gladilin,¹⁰¹ C. Glasman,⁸⁵ J. Glatzer,¹³
P. C. F. Glaysher,⁴⁵ A. Glazov,⁴⁵ M. Goblirsch-Kolb,²⁵ J. Godlewski,⁴² S. Goldfarb,⁹¹ T. Golling,⁵² D. Golubkov,¹³²
A. Gomes,^{128a,128b} R. Gonçalves,^{128a} R. Goncalves Gama,^{26b} G. Gonella,⁵¹ L. Gonella,¹⁹ A. Gongadze,⁶⁸ F. Gonnella,¹⁹
J. L. Gonski,⁵⁹ S. González de la Hoz,¹⁷⁰ S. Gonzalez-Sevilla,⁵² L. Goossens,³² P. A. Gorbounov,⁹⁹ H. A. Gordon,²⁷
B. Gorini,³² E. Gorini,^{76a,76b} A. Gorišek,⁷⁸ A. T. Goshaw,⁴⁸ C. Gössling,⁴⁶ M. I. Gostkin,⁶⁸ C. A. Gottardo,²³ C. R. Goudet,¹¹⁹
D. Goujdami,^{137c} A. G. Goussiou,¹⁴⁰ N. Govender,^{147b,u} C. Goy,⁵ E. Gozani,¹⁵⁴ I. Grabowska-Bold,^{41a} P. O. J. Gradin,¹⁶⁸
E. C. Graham,⁷⁷ J. Gramling,¹⁶⁶ E. Gramstad,¹²¹ S. Grancagnolo,¹⁷ V. Gratchev,¹²⁵ P. M. Gravila,^{28f} C. Gray,⁵⁶ H. M. Gray,¹⁶
Z. D. Greenwood,^{82,v} C. Greife,²³ K. Gregersen,⁸¹ I. M. Gregor,⁴⁵ P. Grenier,¹⁴⁵ K. Grevtsov,⁴⁵ J. Griffiths,⁸ A. A. Grillo,¹³⁹
K. Grimm,¹⁴⁵ S. Grinstein,^{13,w} Ph. Gris,³⁷ J.-F. Grivaz,¹¹⁹ S. Groh,⁸⁶ E. Gross,¹⁷⁵ J. Grosse-Knetter,⁵⁸ G. C. Grossi,⁸²
Z. J. Grout,⁸¹ A. Grummer,¹⁰⁷ L. Guan,⁹² W. Guan,¹⁷⁶ J. Guenther,³² A. Guerguichon,¹¹⁹ F. Guescini,^{163a} D. Guest,¹⁶⁶
O. Gueta,¹⁵⁵ R. Gugel,⁵¹ B. Gui,¹¹³ T. Guillemain,⁵ S. Guindon,³² U. Gul,⁵⁶ C. Gumpert,³² J. Guo,^{36c} W. Guo,⁹² Y. Guo,^{36a,x}
R. Gupta,⁴³ S. Gurbuz,^{20a} G. Gustavino,¹¹⁵ B. J. Gutelman,¹⁵⁴ P. Gutierrez,¹¹⁵ N. G. Gutierrez Ortiz,⁸¹ C. Gutschow,⁸¹
C. Guyot,¹³⁸ M. P. Guzik,^{41a} C. Gwenlan,¹²² C. B. Gwilliam,⁷⁷ A. Haas,¹¹² C. Haber,¹⁶ H. K. Hadavand,⁸ N. Haddad,^{137e}
A. Hadeef,⁸⁸ S. Hageböck,²³ M. Hagihara,¹⁶⁴ H. Hakobyan,^{180a} M. Haleem,¹⁷⁸ J. Haley,¹¹⁶ G. Halladjian,⁹³
G. D. Hallewell,⁸⁸ K. Hamacher,¹⁷⁷ P. Hamal,¹¹⁷ K. Hamano,¹⁷² A. Hamilton,^{147a} G. N. Hamity,¹⁴¹ K. Han,^{36a,y} L. Han,^{36a}
S. Han,^{35a,35d} K. Hanagaki,^{69,z} M. Hance,¹³⁹ D. M. Handl,¹⁰² B. Haney,¹²⁴ R. Hankache,⁸³ P. Hanke,^{60a} E. Hansen,⁸⁴
J. B. Hansen,³⁹ J. D. Hansen,³⁹ M. C. Hansen,²³ P. H. Hansen,³⁹ K. Hara,¹⁶⁴ A. S. Hard,¹⁷⁶ T. Harenberg,¹⁷⁷ S. Harkusha,⁹⁵
P. F. Harrison,¹⁷³ N. M. Hartmann,¹⁰² Y. Hasegawa,¹⁴² A. Hasib,⁴⁹ S. Hassani,¹³⁸ S. Haug,¹⁸ R. Hauser,⁹³ L. Hauswald,⁴⁷
L. B. Havener,³⁸ M. Havranek,¹³⁰ C. M. Hawkes,¹⁹ R. J. Hawkins,³² D. Hayden,⁹³ C. Hayes,¹⁵⁰ C. P. Hays,¹²² J. M. Hays,⁷⁹
H. S. Hayward,⁷⁷ S. J. Haywood,¹³³ M. P. Heath,⁴⁹ V. Hedberg,⁸⁴ L. Heelan,⁸ S. Heer,²³ K. K. Heidegger,⁵¹ S. Heim,⁴⁵
T. Heim,¹⁶ B. Heinemann,^{45,aa} J. J. Heinrich,¹⁰² L. Heinrich,¹¹² C. Heinz,⁵⁵ J. Hejbal,¹²⁹ L. Helary,³² A. Held,¹⁷¹
S. Hellesund,¹²¹ S. Hellman,^{148a,148b} C. Helsen,³² R. C. W. Henderson,⁷⁵ Y. Heng,¹⁷⁶ S. Henkelmann,¹⁷¹
A. M. Henriques Correia,³² G. H. Herbert,¹⁷ H. Herde,²⁵ V. Herget,¹⁷⁸ Y. Hernández Jiménez,^{147c} H. Herr,⁸⁶ G. Herten,⁵¹
R. Hertenberger,¹⁰² L. Hervas,³² T. C. Herwig,¹²⁴ G. G. Hesketh,⁸¹ N. P. Hessey,^{163a} J. W. Hetherly,⁴³ S. Higashino,⁶⁹
E. Higón-Rodríguez,¹⁷⁰ K. Hildebrand,³³ E. Hill,¹⁷² J. C. Hill,³⁰ K. H. Hiller,⁴⁵ S. J. Hillier,¹⁹ M. Hils,⁴⁷ I. Hinchliffe,¹⁶
M. Hirose,⁵¹ D. Hirschbuehl,¹⁷⁷ B. Hiti,⁷⁸ O. Hladik,¹²⁹ D. R. Hlaluku,^{147c} X. Hoad,⁴⁹ J. Hobbs,¹⁵⁰ N. Hod,^{163a}
M. C. Hodgkinson,¹⁴¹ A. Hoecker,³² M. R. Hoferkamp,¹⁰⁷ F. Hoenig,¹⁰² D. Hohn,²³ D. Hohov,¹¹⁹ T. R. Holmes,³³
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Y. Horii,¹⁰⁵ A. J. Horton,¹⁴⁴ L. A. Horyn,³³ J.-Y. Hostachy,⁵⁷ A. Hostiuc,¹⁴⁰ S. Hou,¹⁵³ A. Hoummada,^{137a} J. Howarth,⁸⁷
J. Hoya,⁷⁴ M. Hrabovsky,¹¹⁷ J. Hrdinka,³² I. Hristova,¹⁷ J. Hrivnac,¹¹⁹ T. Hryn'ova,⁵ A. Hrynevich,⁹⁶ P. J. Hsu,⁶³
S.-C. Hsu,¹⁴⁰ Q. Hu,²⁷ S. Hu,^{36c} Y. Huang,^{35a} Z. Hubacek,¹³⁰ F. Hubaut,⁸⁸ M. Huebner,²³ F. Hugging,²³ T. B. Huffman,¹²²

E. W. Hughes,³⁸ M. Huhtinen,³² R. F. H. Hunter,³¹ P. Huo,¹⁵⁰ A. M. Hupe,³¹ N. Huseynov,^{68,c} J. Huston,⁹³ J. Huth,⁵⁹ R. Hyneman,⁹² G. Iacobucci,⁵² G. Iakovidis,²⁷ I. Ibragimov,¹⁴³ L. Iconomidou-Fayard,¹¹⁹ Z. Idrissi,^{137e} P. Iengo,³² R. Ignazzi,³⁹ O. Igonkina,^{109,bb} R. Iguchi,¹⁵⁷ T. Iizawa,¹⁷⁴ Y. Ikegami,⁶⁹ M. Ikeno,⁶⁹ D. Iliadis,¹⁵⁶ N. Ilic,¹⁴⁵ F. Iltzsche,⁴⁷ G. Introzzi,^{123a,123b} M. Iodice,^{136a} K. Iordanidou,³⁸ V. Ippolito,^{134a,134b} M. F. Isacson,¹⁶⁸ N. Ishijima,¹²⁰ M. Ishino,¹⁵⁷ M. Ishitsuka,¹⁵⁹ C. Issever,¹²² S. Istin,^{20a} F. Ito,¹⁶⁴ J. M. Iturbe Ponce,^{62a} R. Iuppa,^{162a,162b} A. Ivina,¹⁷⁵ H. Iwasaki,⁶⁹ J. M. Izen,⁴⁴ V. Izzo,^{106a} S. Jabbar,³ P. Jacka,¹²⁹ P. Jackson,¹ R. M. Jacobs,²³ V. Jain,² G. Jakel,¹⁷⁷ K. B. Jakobi,⁸⁶ K. Jakobs,⁵¹ S. Jakobsen,⁶⁵ T. Jakoubek,¹²⁹ D. O. Jamin,¹¹⁶ D. K. Jana,⁸² R. Jansky,⁵² J. Janssen,²³ M. Janus,⁵⁸ P. A. Janus,^{41a} G. Jarlskog,⁸⁴ N. Javadov,^{68,c} T. Javůrek,⁵¹ M. Javurkova,⁵¹ F. Jeanneau,¹³⁸ L. Jeanty,¹⁶ J. Jejelava,^{54a,cc} A. Jelinskas,¹⁷³ P. Jenni,^{51,dd} J. Jeong,⁴⁵ C. Jeske,¹⁷³ S. Jézéquel,⁵ H. Ji,¹⁷⁶ J. Jia,¹⁵⁰ H. Jiang,⁶⁷ Y. Jiang,^{36a} Z. Jiang,¹⁴⁵ S. Jiggins,⁵¹ F. A. Jimenez Morales,³⁷ J. Jimenez Pena,¹⁷⁰ S. Jin,^{35b} A. Jinaru,^{28b} O. Jinnouchi,¹⁵⁹ H. Jivan,^{147c} P. Johansson,¹⁴¹ K. A. Johns,⁷ C. A. Johnson,⁶⁴ W. J. Johnson,¹⁴⁰ K. Jon-And,^{148a,148b} R. W. L. Jones,⁷⁵ S. D. Jones,¹⁵¹ S. Jones,⁷ T. J. Jones,⁷⁷ J. Jongmanns,^{60a} P. M. Jorge,^{128a,128b} J. Jovicevic,^{163a} X. Ju,¹⁷⁶ J. J. Junggeburth,¹⁰³ A. Juste Rozas,^{13,w} A. Kaczmarek,⁴² M. Kado,¹¹⁹ H. Kagan,¹¹³ M. Kagan,¹⁴⁵ T. Kaji,¹⁷⁴ E. Kajomovitz,¹⁵⁴ C. W. Kalderon,⁸⁴ A. Kaluza,⁸⁶ S. Kama,⁴³ A. Kamenshchikov,¹³² L. Kanjir,⁷⁸ Y. Kano,¹⁵⁷ V. A. Kantserov,¹⁰⁰ J. Kanzaki,⁶⁹ B. Kaplan,¹¹² L. S. Kaplan,¹⁷⁶ D. Kar,^{147c} K. Karakostas,¹⁰ N. Karastathis,¹⁰ M. J. Kareem,^{163b} E. Karentzos,¹⁰ S. N. Karpov,⁶⁸ Z. M. Karpova,⁶⁸ V. Kartvelishvili,⁷⁵ A. N. Karyukhin,¹³² K. Kasahara,¹⁶⁴ L. Kashif,¹⁷⁶ R. D. Kass,¹¹³ A. Kastanas,¹⁴⁹ Y. Kataoka,¹⁵⁷ C. Kato,¹⁵⁷ A. Katre,⁵² J. Katzy,⁴⁵ K. Kawade,⁷⁰ K. Kawagoe,⁷³ T. Kawamoto,¹⁵⁷ G. Kawamura,⁵⁸ E. F. Kay,⁷⁷ V. F. Kazanin,^{111,d} R. Keeler,¹⁷² R. Kehoe,⁴³ J. S. Keller,³¹ E. Kellermann,⁸⁴ J. J. Kempster,¹⁹ J. Kendrick,¹⁹ O. Kepka,¹²⁹ B. P. Kerševan,⁷⁸ S. Kersten,¹⁷⁷ R. A. Keyes,⁹⁰ M. Khader,¹⁶⁹ F. Khalil-zada,¹² A. Khanov,¹¹⁶ A. G. Kharlamov,^{111,d} T. Kharlamova,^{111,d} A. Khodinov,¹⁶⁰ T. J. Khoo,⁵² V. Khovanskiy,^{99,a} E. Khramov,⁶⁸ J. Khubua,^{54b,ee} S. Kido,⁷⁰ M. Kiehn,⁵² C. R. Kilby,⁸⁰ H. Y. Kim,⁸ S. H. Kim,¹⁶⁴ Y. K. Kim,³³ N. Kimura,^{167a,167c} O. M. Kind,¹⁷ B. T. King,⁷⁷ D. Kirchmeier,⁴⁷ J. Kirk,¹³³ A. E. Kiryunin,¹⁰³ T. Kishimoto,¹⁵⁷ D. Kisielewska,^{41a} V. Kitali,⁴⁵ O. Kivernyk,⁵ E. Kladiva,^{146b,a} T. Klapdor-Kleingrothaus,⁵¹ M. H. Klein,⁹² M. Klein,⁷⁷ U. Klein,⁷⁷ K. Kleinknecht,⁸⁶ P. Klimek,¹¹⁰ A. Klimentov,²⁷ R. Klingenberg,^{46,a} T. Klingl,²³ T. Klioutchnikova,³² F. F. Klitzner,¹⁰² E.-E. Kluge,^{60a} P. Kluit,¹⁰⁹ S. Kluth,¹⁰³ E. Kneringer,⁶⁵ E. B. F. G. Knoops,⁸⁸ A. Knue,⁵¹ A. Kobayashi,¹⁵⁷ D. Kobayashi,⁷³ T. Kobayashi,¹⁵⁷ M. Kobel,⁴⁷ M. Kocian,¹⁴⁵ P. Kodys,¹³¹ T. Koffas,³¹ E. Koffeman,¹⁰⁹ N. M. Köhler,¹⁰³ T. Koi,¹⁴⁵ M. Kolb,^{60b} I. Koletsou,⁵ T. Kondo,⁶⁹ N. Kondrashova,^{36c} K. Köneke,⁵¹ A. C. König,¹⁰⁸ T. Kono,^{69,ff} R. Konoplich,^{112,gg} N. Konstantinidis,⁸¹ B. Konya,⁸⁴ R. Kopeliansky,⁶⁴ S. Koperny,^{41a} K. Korcyl,⁴² K. Kordas,¹¹⁹ A. Korn,⁸¹ I. Korolkov,¹³ E. V. Korolkova,¹⁴¹ O. Kortner,¹⁰³ S. Kortner,¹⁰³ T. Kosek,¹³¹ V. V. Kostyukhin,²³ A. Kotwal,⁴⁸ A. Koulouris,¹⁰ A. Kourkoumeli-Charalampidi,^{123a,123b} C. Kourkoumelis,⁹ E. Kourlitis,¹⁴¹ V. Kouskoura,²⁷ A. B. Kowalewska,⁴² R. Kowalewski,¹⁷² T. Z. Kowalski,^{41a} C. Kozakai,¹⁵⁷ W. Kozanecki,¹³⁸ A. S. Kozhin,¹³² V. A. Kramarenko,¹⁰¹ G. Kramberger,⁷⁸ D. Krasnopevtsev,¹⁰⁰ M. W. Krasny,⁸³ A. Krasznahorkay,³² D. Krauss,¹⁰³ J. A. Kremer,^{41a} J. Kretzschmar,⁷⁷ K. Kreutzfeldt,⁵⁵ P. Krieger,¹⁶¹ K. Krizka,¹⁶ K. Kroeninger,⁴⁶ H. Kroha,¹⁰³ J. Kroll,¹²⁹ J. Kroll,¹²⁴ J. Kroseberg,²³ J. Krstic,¹⁴ U. Kruchonak,⁶⁸ H. Krüger,²³ N. Krumnack,⁶⁷ M. C. Kruse,⁴⁸ T. Kubota,⁹¹ S. Kuday,^{4b} J. T. Kuechler,¹⁷⁷ S. Kuehn,³² A. Kugel,^{60a} F. Kuger,¹⁷⁸ T. Kuhl,⁴⁵ V. Kukhtin,⁶⁸ R. Kukla,⁸⁸ Y. Kulchitsky,⁹⁵ S. Kuleshov,^{34b} Y. P. Kulinich,¹⁶⁹ M. Kuna,⁵⁷ T. Kunigo,⁷¹ A. Kupco,¹²⁹ T. Kupfer,⁴⁶ O. Kuprash,¹⁵⁵ H. Kurashige,⁷⁰ L. L. Kurchaninov,^{163a} Y. A. Kurochkin,⁹⁵ M. G. Kurth,^{35a,35d} E. S. Kuwertz,¹⁷² M. Kuze,¹⁵⁹ J. Kvita,¹¹⁷ T. Kwan,¹⁷² A. La Rosa,¹⁰³ J. L. La Rosa Navarro,^{26d} L. La Rotonda,^{40a,40b} F. La Ruffa,^{40a,40b} C. Lacasta,¹⁷⁰ F. Lacava,^{134a,134b} J. Lacey,⁴⁵ D. P. J. Lack,⁸⁷ H. Lacker,¹⁷ D. Lacour,⁸³ E. Ladygin,⁶⁸ R. Lafaye,⁵ B. Laforge,⁸³ S. Lai,⁵⁸ S. Lammers,⁶⁴ W. Lampl,⁷ E. Lançon,²⁷ U. Landgraf,⁵¹ M. P. J. Landon,⁷⁹ M. C. Lanfermann,⁵² V. S. Lang,⁴⁵ J. C. Lange,¹³ R. J. Langenberg,³² A. J. Lankford,¹⁶⁶ F. Lanni,²⁷ K. Lantzsch,²³ A. Lanza,^{123a} A. Lapertosa,^{53a,53b} S. Laplace,⁸³ J. F. Laporte,¹³⁸ T. Lari,^{94a} F. Lasagni Manghi,^{22a,22b} M. Lassnig,³² T. S. Lau,^{62a} A. Laudrain,¹¹⁹ A. T. Law,¹³⁹ P. Laycock,⁷⁷ M. Lazzaroni,^{94a,94b} B. Le,⁹¹ O. Le Dortz,⁸³ E. Le Guirriec,⁸⁸ E. P. Le Quilleuc,¹³⁸ M. LeBlanc,⁷ T. LeCompte,⁶ F. Ledroit-Guillon,⁵⁷ C. A. Lee,²⁷ G. R. Lee,^{34a} S. C. Lee,¹⁵³ L. Lee,⁵⁹ B. Lefebvre,⁹⁰ M. Lefebvre,¹⁷² F. Legger,¹⁰² C. Leggett,¹⁶ G. Lehmann Miotto,³² W. A. Leight,⁴⁵ A. Leisos,^{156,hh} M. A. L. Leite,^{26d} R. Leitner,¹³¹ D. Lellouch,¹⁷⁵ B. Lemmer,⁵⁸ K. J. C. Leney,⁸¹ T. Lenz,²³ B. Lenzi,³² R. Leone,⁷ S. Leone,^{126a} C. Leonidopoulos,⁴⁹ G. Lerner,¹⁵¹ C. Leroy,⁹⁷ R. Les,¹⁶¹ A. A. J. Lesage,¹³⁸ C. G. Lester,³⁰ M. Levchenko,¹²⁵ J. Levêque,⁵ D. Levin,⁹² L. J. Levinson,¹⁷⁵ M. Levy,¹⁹ D. Lewis,⁷⁹ B. Li,^{36a,x} C.-Q. Li,^{36a} H. Li,^{36b} L. Li,^{36c} Q. Li,^{35a,35d} Q. Li,^{36a} S. Li,^{36c,36d} X. Li,^{36c} Y. Li,¹⁴³ Z. Liang,^{35a} B. Liberti,^{135a} A. Liblong,¹⁶¹ K. Lie,^{62c} A. Limosani,¹⁵² C. Y. Lin,³⁰ K. Lin,⁹³ S. C. Lin,¹⁸² T. H. Lin,⁸⁶ R. A. Linck,⁶⁴ B. E. Lindquist,¹⁵⁰ A. E. Lioni,⁵² E. Lipeles,¹²⁴ A. Lipniacka,¹⁵ M. Lisovyi,^{60b} T. M. Liss,^{169,ii} A. Lister,¹⁷¹ A. M. Litke,¹³⁹ J. D. Little,⁸ B. Liu,⁶ B. Liu,⁶⁷ H. Liu,⁹² H. Liu,²⁷

J. K. K. Liu,¹²² J. B. Liu,^{36a} K. Liu,⁸³ M. Liu,^{36a} P. Liu,¹⁶ Y. L. Liu,^{36a} Y. Liu,^{36a} M. Livan,^{123a,123b} A. Lleres,⁵⁷
 J. Llorente Merino,^{35a} S. L. Lloyd,⁷⁹ C. Y. Lo,^{62b} F. Lo Sterzo,⁴³ E. M. Lobodzinska,⁴⁵ P. Loch,⁷ F. K. Loebinger,⁸⁷
 A. Loesle,⁵¹ K. M. Loew,²⁵ T. Lohse,¹⁷ K. Lohwasser,¹⁴¹ M. Lokajicek,¹²⁹ B. A. Long,²⁴ J. D. Long,¹⁶⁹ R. E. Long,⁷⁵
 L. Longo,^{76a,76b} K. A.Looper,¹¹³ J. A. Lopez,^{34b} I. Lopez Paz,¹³ A. Lopez Solis,⁸³ J. Lorenz,¹⁰² N. Lorenzo Martinez,⁵
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 L. Luminari,^{134a} B. Lund-Jensen,¹⁴⁹ M. S. Lutz,⁸⁹ P. M. Luzzi,⁸³ D. Lynn,²⁷ R. Lysak,¹²⁹ E. Lytken,⁸⁴ F. Lyu,^{35a}
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 J. Machado Miguens,^{124,128b} D. Madaffari,¹⁷⁰ R. Madar,³⁷ W. F. Mader,⁴⁷ A. Madsen,⁴⁵ N. Madysa,⁴⁷ J. Maeda,⁷⁰
 S. Maeland,¹⁵ T. Maeno,²⁷ A. S. Maevskiy,¹⁰¹ V. Magerl,⁵¹ C. Maidantchik,^{26a} T. Maier,¹⁰² A. Maio,^{128a,128b,128d}
 O. Majersky,^{146a} S. Majewski,¹¹⁸ Y. Makida,⁶⁹ N. Makovec,¹¹⁹ B. Malaescu,⁸³ Pa. Malecki,⁴² V. P. Maleev,¹²⁵ F. Malek,⁵⁷
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 J. Maneira,^{128a,128b} L. Manhaes de Andrade Filho,^{26b} J. Manjarres Ramos,⁴⁷ K. H. Mankinen,⁸⁴ A. Mann,¹⁰² A. Manousos,⁶⁵
 B. Mansoulie,¹³⁸ J. D. Mansour,^{35a} R. Mantifel,⁹⁰ M. Mantoani,⁵⁸ S. Manzoni,^{94a,94b} G. Marceca,²⁹ L. March,⁵²
 L. Marchese,¹²² G. Marchiori,⁸³ M. Marcisovsky,¹²⁹ C. A. Marin Tobon,³² M. Marjanovic,³⁷ D. E. Marley,⁹²
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 A. C. Martyniuk,⁸¹ A. Marzin,³² L. Masetti,⁸⁶ T. Mashimo,¹⁵⁷ R. Mashinistov,⁹⁸ J. Masik,⁸⁷ A. L. Maslennikov,^{111,d}
 L. H. Mason,⁹¹ L. Massa,^{135a,135b} P. Mastrandrea,⁵ A. Mastroberardino,^{40a,40b} T. Masubuchi,¹⁵⁷ P. Mättig,¹⁷⁷ J. Maurer,^{28b}
 S. J. Maxfield,⁷⁷ D. A. Maximov,^{111,d} R. Mazini,¹⁵³ I. Maznas,¹⁵⁶ S. M. Mazza,¹³⁹ N. C. Mc Fadden,¹⁰⁷ G. Mc Goldrick,¹⁶¹
 S. P. Mc Kee,⁹² A. McCarn,⁹² T. G. McCarthy,¹⁰³ L. I. McClymont,⁸¹ E. F. McDonald,⁹¹ J. A. Mcfayden,³² G. Mchedlidze,⁵⁸
 M. A. McKay,⁴³ K. D. McLean,¹⁷² S. J. McMahon,¹³³ P. C. McNamara,⁹¹ C. J. McNicol,¹⁷³ R. A. McPherson,^{172,o}
 Z. A. Meadows,⁸⁹ S. Meehan,¹⁴⁰ T. J. Megy,⁵¹ S. Mehlhase,¹⁰² A. Mehta,⁷⁷ T. Meideck,⁵⁷ K. Meier,^{60a} B. Meirose,⁴⁴
 D. Melini,^{170,ij} B. R. Mellado Garcia,^{147c} J. D. Mellenthin,⁵⁸ M. Melo,^{146a} F. Meloni,¹⁸ A. Melzer,²³ S. B. Menary,⁸⁷
 L. Meng,⁷⁷ X. T. Meng,⁹² A. Mengarelli,^{22a,22b} S. Menke,¹⁰³ E. Meoni,^{40a,40b} S. Mergelmeyer,¹⁷ C. Merlassino,¹⁸
 P. Mermod,⁵² L. Merola,^{106a,106b} C. Meroni,^{94a} F. S. Merritt,³³ A. Messina,^{134a,134b} J. Metcalfe,⁶ A. S. Mete,¹⁶⁶ C. Meyer,¹²⁴
 J-P. Meyer,¹³⁸ J. Meyer,¹⁵⁴ H. Meyer Zu Theenhausen,^{60a} F. Miano,¹⁵¹ R. P. Middleton,¹³³ L. Mijović,⁴⁹ G. Mikenberg,¹⁷⁵
 M. Mikestikova,¹²⁹ M. Mikuž,⁷⁸ M. Milesi,⁹¹ A. Milic,¹⁶¹ D. A. Millar,⁷⁹ D. W. Miller,³³ A. Milov,¹⁷⁵ D. A. Milstead,^{148a,148b}
 A. A. Minaenko,¹³² I. A. Minashvili,^{54b} A. I. Mincer,¹¹² B. Mindur,^{41a} M. Mineev,⁶⁸ Y. Minegishi,¹⁵⁷ Y. Ming,¹⁷⁶
 L. M. Mir,¹³ A. Mirto,^{76a,76b} K. P. Mistry,¹²⁴ T. Mitani,¹⁷⁴ J. Mitrevski,¹⁰² V. A. Mitsou,¹⁷⁰ A. Miucci,¹⁸ P. S. Miyagawa,¹⁴¹
 A. Mizukami,⁶⁹ J. U. Mjörnmark,⁸⁴ T. Mkrchyan,¹⁸⁰ M. Mlynarikova,¹³¹ T. Moa,^{148a,148b} K. Mochizuki,⁹⁷ P. Mogg,⁵¹
 S. Mohapatra,³⁸ S. Molander,^{148a,148b} R. Moles-Valls,²³ M. C. Mondragon,⁹³ K. Mönig,⁴⁵ J. Monk,³⁹ E. Monnier,⁸⁸
 A. Montalbano,¹⁴⁴ J. Montejo Berlingen,³² F. Monticelli,⁷⁴ S. Monzani,^{94a} R. W. Moore,³ N. Morange,¹¹⁹ D. Moreno,²¹
 M. Moreno Llácer,³² P. Moretini,^{53a} M. Morgenstern,¹⁰⁹ S. Morgenstern,³² D. Mori,¹⁴⁴ T. Mori,¹⁵⁷ M. Morii,⁵⁹
 M. Morinaga,¹⁷⁴ V. Morisbak,¹²¹ A. K. Morley,³² G. Mornacchi,³² J. D. Morris,⁷⁹ L. Morvaj,¹⁵⁰ P. Moschovakos,¹⁰
 M. Mosidze,^{54b} H. J. Moss,¹⁴¹ J. Moss,^{145,kk} K. Motohashi,¹⁵⁹ R. Mount,¹⁴⁵ E. Mountricha,²⁷ E. J. W. Moyse,⁸⁹ S. Muanza,⁸⁸
 F. Mueller,¹⁰³ J. Mueller,¹²⁷ R. S. P. Mueller,¹⁰² D. Muenstermann,⁷⁵ P. Mullen,⁵⁶ G. A. Mullier,¹⁸ F. J. Munoz Sanchez,⁸⁷
 P. Murin,^{146b} W. J. Murray,^{173,133} A. Murrone,^{94a,94b} M. Muškinja,⁷⁸ C. Mwewa,^{147a} A. G. Myagkov,^{132,ll} J. Myers,¹¹⁸
 M. Myska,¹³⁰ B. P. Nachman,¹⁶ O. Nackenhorst,⁴⁶ K. Nagai,¹²² R. Nagai,^{69,ff} K. Nagano,⁶⁹ Y. Nagasaka,⁶¹ K. Nagata,¹⁶⁴
 M. Nagel,⁵¹ E. Nagy,⁸⁸ A. M. Nairz,³² Y. Nakahama,¹⁰⁵ K. Nakamura,⁶⁹ T. Nakamura,¹⁵⁷ I. Nakano,¹¹⁴ F. Napolitano,^{60a}
 R. F. Naranjo Garcia,⁴⁵ R. Narayan,¹¹ D. I. Narrias Villar,^{60a} I. Naryshkin,¹²⁵ T. Naumann,⁴⁵ G. Navarro,²¹ R. Nayyar,⁷
 H. A. Neal,⁹² P. Yu. Nechaeva,⁹⁸ T. J. Neep,¹³⁸ A. Negri,^{123a,123b} M. Negrini,^{22a} S. Nektarijevic,¹⁰⁸ C. Nellist,⁵⁸
 M. E. Nelson,¹²² S. Nemecek,¹²⁹ P. Nemethy,¹¹² M. Nessi,^{32,mm} M. S. Neubauer,¹⁶⁹ M. Neumann,¹⁷⁷ P. R. Newman,¹⁹
 T. Y. Ng,^{62c} Y. S. Ng,¹⁷ H. D. N. Nguyen,⁸⁸ T. Nguyen Manh,⁹⁷ E. Nibigira,³⁷ R. B. Nickerson,¹²² R. Nicolaidou,¹³⁸
 J. Nielsen,¹³⁹ N. Nikiforou,¹¹ V. Nikolaenko,^{132,ll} I. Nikolic-Audit,⁸³ K. Nikolopoulos,¹⁹ P. Nilsson,²⁷ Y. Ninomiya,⁶⁹
 A. Nisati,^{134a} N. Nishu,^{36c} R. Nisius,¹⁰³ I. Nitsche,⁴⁶ T. Nitta,¹⁷⁴ T. Nobe,¹⁵⁷ Y. Noguchi,⁷¹ M. Nomachi,¹²⁰ I. Nomidis,³¹
 M. A. Nomura,²⁷ T. Nooney,⁷⁹ M. Nordberg,³² N. Norjoharuddeen,¹²² T. Novak,⁷⁸ O. Novgorodova,⁴⁷ R. Novotny,¹³⁰
 M. Nozaki,⁶⁹ L. Nozka,¹¹⁷ K. Ntekas,¹⁶⁶ E. Nurse,⁸¹ F. Nuti,⁹¹ K. O'Connor,²⁵ D. C. O'Neil,¹⁴⁴ A. A. O'Rourke,⁴⁵
 V. O'Shea,⁵⁶ F. G. Oakham,^{31,e} H. Oberlack,¹⁰³ T. Obermann,²³ J. Ocariz,⁸³ A. Ochi,⁷⁰ I. Ochoa,³⁸ J. P. Ochoa-Ricoux,^{34a}

S. Oda,⁷³ S. Odaka,⁶⁹ A. Oh,⁸⁷ S. H. Oh,⁴⁸ C. C. Ohm,¹⁴⁹ H. Ohman,¹⁶⁸ H. Oide,^{53a,53b} H. Okawa,¹⁶⁴ Y. Okazaki,⁷¹ Y. Okumura,¹⁵⁷ T. Okuyama,⁶⁹ A. Olariu,^{28b} L. F. Oleiro Seabra,^{128a} S. A. Olivares Pino,^{34a} D. Oliveira Damazio,²⁷ J. L. Oliver,¹ M. J. R. Olsson,³³ A. Olszewski,⁴² J. Olszowska,⁴² A. Onofre,^{128a,128e} K. Onogi,¹⁰⁵ P. U. E. Onyisi,^{11,nn} H. Oppen,¹²¹ M. J. Oreglia,³³ Y. Oren,¹⁵⁵ D. Orestano,^{136a,136b} E. C. Orgill,⁸⁷ N. Orlando,^{62b} R. S. Orr,¹⁶¹ B. Osculati,^{53a,53b,a} R. Ospanov,^{36a} G. Otero y Garzon,²⁹ H. Otono,⁷³ M. Ouchrif,^{137d} F. Ould-Saada,¹²¹ A. Ouraou,¹³⁸ K. P. Oussoren,¹⁰⁹ Q. Ouyang,^{35a} M. Owen,⁵⁶ R. E. Owen,¹⁹ V. E. Ozcan,^{20a} N. Ozturk,⁸ K. Pachal,¹⁴⁴ A. Pacheco Pages,¹³ L. Pacheco Rodriguez,¹³⁸ C. Padilla Aranda,¹³ S. Pagan Griso,¹⁶ M. Paganini,¹⁷⁹ F. Paige,²⁷ G. Palacino,⁶⁴ S. Palazzo,^{40a,40b} S. Palestini,³² M. Palka,^{41b} D. Pallin,³⁷ I. Panagoulas,¹⁰ C. E. Pandini,⁵² J. G. Panduro Vazquez,⁸⁰ P. Pani,³² L. Paolozzi,⁵² Th. D. Papadopoulou,¹⁰ K. Papageorgiou,⁹¹ A. Paramonov,⁶ D. Paredes Hernandez,^{62b} B. Parida,^{36c} A. J. Parker,⁷⁵ M. A. Parker,³⁰ K. A. Parker,⁴⁵ F. Parodi,^{53a,53b} J. A. Parsons,³⁸ U. Parzefall,⁵¹ V. R. Pascuzzi,¹⁶¹ J. M. Pasner,¹³⁹ E. Pasqualucci,^{134a} S. Passaggio,^{53a} Fr. Pastore,⁸⁰ P. Pasuwan,^{148a,148b} S. Patariaia,⁸⁶ J. R. Pater,⁸⁷ A. Pathak,^{176,f} T. Pauly,³² B. Pearson,¹⁰³ S. Pedraza Lopez,¹⁷⁰ R. Pedro,^{128a,128b} S. V. Peleganchuk,^{111,d} O. Penc,¹²⁹ C. Peng,^{35a,35d} H. Peng,^{36a} J. Penwell,⁶⁴ B. S. Peralva,^{26b} M. M. Perego,¹³⁸ A. P. Pereira Peixoto,^{128a} D. V. Perepelitsa,²⁷ F. Peri,¹⁷ L. Perini,^{94a,94b} H. Pernegger,³² S. Perrella,^{106a,106b} V. D. Peshekhonov,^{68,a} K. Peters,⁴⁵ R. F. Y. Peters,⁸⁷ B. A. Petersen,³² T. C. Petersen,³⁹ E. Petit,⁵⁷ A. Petridis,¹ C. Petridou,¹⁵⁶ P. Petroff,¹¹⁹ E. Petrolo,^{134a} M. Petrov,¹²² F. Petrucci,^{136a,136b} N. E. Pettersson,⁸⁹ A. Peyaud,¹³⁸ R. Pezoa,^{34b} T. Pham,⁹¹ F. H. Phillips,⁹³ P. W. Phillips,¹³³ G. Piacquadio,¹⁵⁰ E. Pianori,¹⁷³ A. Picazio,⁸⁹ M. A. Pickering,¹²² R. Piegaia,²⁹ J. E. Pilcher,³³ A. D. Pilkington,⁸⁷ M. Pinamonti,^{135a,135b} J. L. Pinfold,³ M. Pitt,¹⁷⁵ M.-A. Pleier,²⁷ V. Pleskot,¹³¹ E. Plotnikova,⁶⁸ D. Pluth,⁶⁷ P. Podberezko,¹¹¹ R. Poettgen,⁸⁴ R. Poggi,^{123a,123b} L. Poggioli,¹¹⁹ I. Pogrebnyak,⁹³ D. Pohl,²³ I. Pokharel,⁵⁸ G. Polesello,^{123a} A. Poley,⁴⁵ A. Policicchio,^{40a,40b} R. Polifka,³² A. Polini,^{22a} C. S. Pollard,⁴⁵ V. Polychronakos,²⁷ D. Ponomarenko,¹⁰⁰ L. Pontecorvo,^{134a} G. A. Popeneciu,^{28d} D. M. Portillo Quintero,⁸³ S. Pospisil,¹³⁰ K. Potamianos,⁴⁵ I. N. Potrap,⁶⁸ C. J. Potter,³⁰ H. Potti,¹¹ T. Poulsen,⁸⁴ J. Poveda,³² M. E. Pozo Astigarraga,³² P. Pralavorio,⁸⁸ S. Prell,⁶⁷ D. Price,⁸⁷ M. Primavera,^{76a} S. Prince,⁹⁰ N. Proklova,¹⁰⁰ K. Prokofiev,^{62c} F. Prokoshin,^{34b} S. Protopopescu,²⁷ J. Proudfoot,⁶ M. Przybycien,^{41a} A. Puri,¹⁶⁹ P. Puzo,¹¹⁹ J. Qian,⁹² Y. Qin,⁸⁷ A. Quadt,⁵⁸ M. Queitsch-Maitland,⁴⁵ A. Qureshi,¹ S. K. Radhakrishnan,¹⁵⁰ P. Rados,⁹¹ F. Ragusa,^{94a,94b} G. Rahal,¹⁸¹ J. A. Raine,⁸⁷ S. Rajagopalan,²⁷ T. Rashid,¹¹⁹ S. Raspopov,⁵ M. G. Ratti,^{94a,94b} D. M. Rauch,⁴⁵ F. Rauscher,¹⁰² S. Rave,⁸⁶ B. Ravina,¹⁴¹ I. Ravinovich,¹⁷⁵ J. H. Rawling,⁸⁷ M. Raymond,³² A. L. Read,¹²¹ N. P. Readioff,⁵⁷ M. Reale,^{76a,76b} D. M. Rebutzi,^{123a,123b} A. Redelbach,¹⁷⁸ G. Redlinger,²⁷ R. Reece,¹³⁹ R. G. Reed,^{147c} K. Reeves,⁴⁴ L. Rehnisch,¹⁷ J. Reichert,¹²⁴ A. Reiss,⁸⁶ C. Rembser,³² H. Ren,^{35a,35d} M. Rescigno,^{134a} S. Resconi,^{94a} E. D. Resseguie,¹²⁴ S. Rettie,¹⁷¹ E. Reynolds,¹⁹ O. L. Rezanova,^{111,d} P. Reznicek,¹³¹ R. Richter,¹⁰³ S. Richter,⁸¹ E. Richter-Was,^{41b} O. Ricken,²³ M. Ridel,⁸³ P. Rieck,¹⁰³ C. J. Riegel,¹⁷⁷ O. Rifki,⁴⁵ M. Rijssenbeek,¹⁵⁰ A. Rimoldi,^{123a,123b} M. Rimoldi,¹⁸ L. Rinaldi,^{22a} G. Ripellino,¹⁴⁹ B. Ristić,³² E. Ritsch,³² I. Riu,¹³ J. C. Rivera Vergara,^{34a} F. Rizatdinova,¹¹⁶ E. Rizvi,⁷⁹ C. Rizzi,¹³ R. T. Roberts,⁸⁷ S. H. Robertson,^{90,o} A. Robichaud-Veronneau,⁹⁰ D. Robinson,³⁰ J. E. M. Robinson,⁴⁵ A. Robson,⁵⁶ E. Rocco,⁸⁶ C. Roda,^{126a,126b} Y. Rodina,^{88,oo} S. Rodriguez Bosca,¹⁷⁰ A. Rodriguez Perez,¹³ D. Rodriguez Rodriguez,¹⁷⁰ A. M. Rodríguez Vera,^{163b} S. Roe,³² C. S. Rogan,⁵⁹ O. Røhne,¹²¹ R. Röhrig,¹⁰³ C. P. A. Roland,⁶⁴ J. Roloff,⁵⁹ A. Romaniouk,¹⁰⁰ M. Romano,^{22a,22b} E. Romero Adam,¹⁷⁰ N. Rompotis,⁷⁷ M. Ronzani,¹¹² L. Roos,⁸³ S. Rosati,^{134a} K. Rosbach,⁵¹ P. Rose,¹³⁹ N.-A. Rosien,⁵⁸ E. Rossi,^{106a,106b} L. P. Rossi,^{53a} L. Rossini,^{94a,94b} J. H. N. Rosten,³⁰ R. Rosten,¹⁴⁰ M. Rotaru,^{28b} J. Rothberg,¹⁴⁰ D. Rousseau,¹¹⁹ D. Roy,^{147c} A. Rozanov,⁸⁸ Y. Rozen,¹⁵⁴ X. Ruan,^{147c} F. Rubbo,¹⁴⁵ F. Rühr,⁵¹ A. Ruiz-Martinez,³¹ Z. Rurikova,⁵¹ N. A. Rusakovich,⁶⁸ H. L. Russell,⁹⁰ J. P. Rutherford,⁷ N. Ruthmann,³² E. M. Rüttinger,⁴⁵ Y. F. Ryabov,¹²⁵ M. Rybar,¹⁶⁹ G. Rybkin,¹¹⁹ S. Ryu,⁶ A. Ryzhov,¹³² G. F. Rzehorz,⁵⁸ A. F. Saavedra,¹⁵² P. Sabatini,⁵⁸ G. Sabato,¹⁰⁹ S. Sacerdoti,¹¹⁹ H. F.-W. Sadrozinski,¹³⁹ R. Sadykov,⁶⁸ F. Safai Tehrani,^{134a} P. Saha,¹¹⁰ M. Sahinsoy,^{60a} M. Saimpert,⁴⁵ M. Saito,¹⁵⁷ T. Saito,¹⁵⁷ H. Sakamoto,¹⁵⁷ D. Salamani,⁵² G. Salamanna,^{136a,136b} J. E. Salazar Loyola,^{34b} D. Salek,¹⁰⁹ P. H. Sales De Bruin,¹⁶⁸ D. Salihagic,¹⁰³ A. Salnikov,¹⁴⁵ J. Salt,¹⁷⁰ D. Salvatore,^{40a,40b} F. Salvatore,¹⁵¹ A. Salvucci,^{62a,62b,62c} A. Salzburger,³² D. Sammel,⁵¹ D. Sampsonidis,¹⁵⁶ D. Sampsonidou,¹⁵⁶ J. Sánchez,¹⁷⁰ A. Sanchez Pineda,^{167a,167c} H. Sandaker,¹²¹ C. O. Sander,⁴⁵ M. Sandhoff,¹⁷⁷ C. Sandoval,²¹ D. P. C. Sankey,¹³³ M. Sannino,^{53a,53b} Y. Sano,¹⁰⁵ A. Sansoni,⁵⁰ C. Santoni,³⁷ H. Santos,^{128a} I. Santoyo Castillo,¹⁵¹ A. Sapronov,⁶⁸ J. G. Saraiva,^{128a,128b,128d} O. Sasaki,⁶⁹ K. Sato,¹⁶⁴ E. Sauvan,⁵ P. Savard,^{161,e} N. Savic,¹⁰³ R. Sawada,¹⁵⁷ C. Sawyer,¹³³ L. Sawyer,^{82,v} C. Sbarra,^{22a} A. Sbrizzi,^{22a,22b} T. Scanlon,⁸¹ D. A. Scannicchio,¹⁶⁶ J. Schaarschmidt,¹⁴⁰ P. Schacht,¹⁰³ B. M. Schachtner,¹⁰² D. Schaefer,³³ L. Schaefer,¹²⁴ J. Schaeffer,⁸⁶ S. Schaepe,³² U. Schäfer,⁸⁶ A. C. Schaffer,¹¹⁹ D. Schaile,¹⁰² R. D. Schamberger,¹⁵⁰ V. A. Schegelsky,¹²⁵ D. Scheirich,¹³¹ F. Schenck,¹⁷ M. Schernau,¹⁶⁶ C. Schiavi,^{53a,53b} S. Schier,¹³⁹ L. K. Schildgen,²³ Z. M. Schillaci,²⁵

E. J. Schioppa,³² M. Schioppa,^{40a,40b} K. E. Schleicher,⁵¹ S. Schlenker,³² K. R. Schmidt-Sommerfeld,¹⁰³ K. Schmieden,³² C. Schmitt,⁸⁶ S. Schmitt,⁴⁵ S. Schmitz,⁸⁶ U. Schnoor,⁵¹ L. Schoeffel,¹³⁸ A. Schoening,^{60b} E. Schopf,²³ M. Schott,⁸⁶ J. F. P. Schouwenberg,¹⁰⁸ J. Schovancova,³² S. Schramm,⁵² N. Schuh,⁸⁶ A. Schulte,⁸⁶ H.-C. Schultz-Coulon,^{60a} M. Schumacher,⁵¹ B. A. Schumm,¹³⁹ Ph. Schune,¹³⁸ A. Schwartzman,¹⁴⁵ T. A. Schwarz,⁹² H. Schweiger,⁸⁷ Ph. Schwemling,¹³⁸ R. Schwienhorst,⁹³ J. Schwindling,¹³⁸ A. Sciandra,²³ G. Sciolla,²⁵ M. Scornajenghi,^{40a,40b} F. Scuri,^{126a} F. Scutti,⁹¹ L. M. Scyboz,¹⁰³ J. Searcy,⁹² C. D. Sebastiani,^{134a,134b} P. Seema,²³ S. C. Seidel,¹⁰⁷ A. Seiden,¹³⁹ J. M. Seixas,^{26a} G. Sekhniaidze,^{106a} K. Sekhon,⁹² S. J. Sekula,⁴³ N. Semprini-Cesari,^{22a,22b} S. Senkin,³⁷ C. Serfon,¹²¹ L. Serin,¹¹⁹ L. Serkin,^{167a,167b} M. Sessa,^{136a,136b} H. Severini,¹¹⁵ T. Šfiligoj,⁷⁸ F. Sforza,¹⁶⁵ A. Sfyrta,⁵² E. Shabalina,⁵⁸ J. D. Shahinian,¹³⁹ N. W. Shaikh,^{148a,148b} L. Y. Shan,^{35a} R. Shang,¹⁶⁹ J. T. Shank,²⁴ M. Shapiro,¹⁶ A. Sharma,¹²² A. S. Sharma,¹ P. B. Shatalov,⁹⁹ K. Shaw,^{167a,167b} S. M. Shaw,⁸⁷ A. Shcherbakova,¹²⁵ C. Y. Shehu,¹⁵¹ Y. Shen,¹¹⁵ N. Sherafati,³¹ A. D. Sherman,²⁴ P. Sherwood,⁸¹ L. Shi,^{153,pp} S. Shimizu,⁷⁰ C. O. Shimmin,¹⁷⁹ M. Shimojima,¹⁰⁴ I. P. J. Shipsey,¹²² S. Shirabe,⁷³ M. Shiyakova,^{68,qq} J. Shlomi,¹⁷⁵ A. Shmeleva,⁹⁸ D. Shoaleh Saadi,⁹⁷ M. J. Shochet,³³ S. Shojaii,⁹¹ D. R. Shope,¹¹⁵ S. Shrestha,¹¹³ E. Shulga,¹⁰⁰ P. Sicho,¹²⁹ A. M. Sickles,¹⁶⁹ P. E. Sidebo,¹⁴⁹ E. Sideras Haddad,^{147c} O. Sidiropoulou,¹⁷⁸ A. Sidoti,^{22a,22b} F. Siegert,⁴⁷ Dj. Sijacki,¹⁴ J. Silva,^{128a,128b,128d} M. Silva Jr.,¹⁷⁶ S. B. Silverstein,^{148a} L. Simic,⁶⁸ S. Simion,¹¹⁹ E. Simioni,⁸⁶ B. Simmons,⁸¹ M. Simon,⁸⁶ P. Sinervo,¹⁶¹ N. B. Sinev,¹¹⁸ M. Sioli,^{22a,22b} G. Siragusa,¹⁷⁸ I. Siral,⁹² S. Yu. Sivoklokov,¹⁰¹ J. Sjölin,^{148a,148b} M. B. Skinner,⁷⁵ P. Skubic,¹¹⁵ M. Slater,¹⁹ T. Slavicek,¹³⁰ M. Slawinska,⁴² K. Sliwa,¹⁶⁵ R. Slovak,¹³¹ V. Smakhtin,¹⁷⁵ B. H. Smart,⁵ J. Smiesko,^{146a} N. Smirnov,¹⁰⁰ S. Yu. Smirnov,¹⁰⁰ Y. Smirnov,¹⁰⁰ L. N. Smirnova,^{101,rr} O. Smirnova,⁸⁴ J. W. Smith,⁵⁸ M. N. K. Smith,³⁸ R. W. Smith,³⁸ M. Smizanska,⁷⁵ K. Smolek,¹³⁰ A. A. Snesarev,⁹⁸ I. M. Snyder,¹¹⁸ S. Snyder,²⁷ R. Sobie,^{172,o} F. Socher,⁴⁷ A. M. Soffa,¹⁶⁶ A. Soffer,¹⁵⁵ A. Sjøgaard,⁴⁹ D. A. Soh,¹⁵³ G. Sokhrannyi,⁷⁸ C. A. Solans Sanchez,³² M. Solar,¹³⁰ E. Yu. Soldatov,¹⁰⁰ U. Soldevila,¹⁷⁰ A. A. Solodkov,¹³² A. Soloshenko,⁶⁸ O. V. Solovyanov,¹³² V. Solovyev,¹²⁵ P. Sommer,¹⁴¹ H. Son,¹⁶⁵ W. Song,¹³³ A. Sopczak,¹³⁰ F. Sopkova,^{146b} D. Sosa,^{60b} C. L. Sotiropoulou,^{126a,126b} S. Sottocornola,^{123a,123b} R. Soualah,^{167a,167c} A. M. Soukharev,^{111,d} D. South,⁴⁵ B. C. Sowden,⁸⁰ S. Spagnolo,^{76a,76b} M. Spalla,¹⁰³ M. Spangenberg,¹⁷³ F. Spanò,⁸⁰ D. Sperlich,¹⁷ F. Spettel,¹⁰³ T. M. Spieker,^{60a} R. Spighi,^{22a} G. Spigo,³² L. A. Spiller,⁹¹ M. Spousta,¹³¹ A. Stabile,^{94a,94b} R. Stamen,^{60a} S. Stamm,¹⁷ E. Stanecka,⁴² R. W. Stanek,⁶ C. Stanescu,^{136a} M. M. Stanitzki,⁴⁵ B. S. Stapf,¹⁰⁹ S. Stapnes,¹²¹ E. A. Starchenko,¹³² G. H. Stark,³³ J. Stark,⁵⁷ S. H. Stark,³⁹ P. Staroba,¹²⁹ P. Starovoitov,^{60a} S. Stärz,³² R. Staszewski,⁴² M. Stegler,⁴⁵ P. Steinberg,²⁷ B. Stelzer,¹⁴⁴ H. J. Stelzer,³² O. Stelzer-Chilton,^{163a} H. Stenzel,⁵⁵ T. J. Stevenson,⁷⁹ G. A. Stewart,³² M. C. Stockton,¹¹⁸ G. Stoicea,^{28b} P. Stolte,⁵⁸ S. Stonjek,¹⁰³ A. Straessner,⁴⁷ J. Strandberg,¹⁴⁹ S. Strandberg,^{148a,148b} M. Strauss,¹¹⁵ P. Strizenec,^{146b} R. Ströhmer,¹⁷⁸ D. M. Strom,¹¹⁸ R. Stroynowski,⁴³ A. Strubig,⁴⁹ S. A. Stucci,²⁷ B. Stugu,¹⁵ J. Stupak,¹¹⁵ N. A. Styles,⁴⁵ D. Su,¹⁴⁵ J. Su,¹²⁷ S. Suchek,^{60a} Y. Sugaya,¹²⁰ M. Suk,¹³⁰ V. V. Sulin,⁹⁸ DMS Sultan,⁵² S. Sultansoy,^{4c} T. Sumida,⁷¹ S. Sun,⁹² X. Sun,³ K. Suruliz,¹⁵¹ C. J. E. Suster,¹⁵² M. R. Sutton,¹⁵¹ S. Suzuki,⁶⁹ M. Svatos,¹²⁹ M. Swiatlowski,³³ S. P. Swift,² A. Sydorenko,⁸⁶ I. Sykora,^{146a} T. Sykora,¹³¹ D. Ta,⁸⁶ K. Tackmann,⁴⁵ J. Taenzer,¹⁵⁵ A. Taffard,¹⁶⁶ R. Tafirout,^{163a} E. Tahirovic,⁷⁹ N. Taiblum,¹⁵⁵ H. Takai,²⁷ R. Takashima,⁷² E. H. Takasugi,¹⁰³ K. Takeda,⁷⁰ T. Takeshita,¹⁴² Y. Takubo,⁶⁹ M. Talby,⁸⁸ A. A. Talyshev,^{111,d} J. Tanaka,¹⁵⁷ M. Tanaka,¹⁵⁹ R. Tanaka,¹¹⁹ R. Tanioka,⁷⁰ B. B. Tannenwald,¹¹³ S. Tapia Araya,^{34b} S. Tapprogge,⁸⁶ A. T. Tarek Abouelfadl Mohamed,⁸³ S. Tarem,¹⁵⁴ G. Tarna,^{28b,q} G. F. Tartarelli,^{94a} P. Tas,¹³¹ M. Tasevsky,¹²⁹ T. Tashiro,⁷¹ E. Tassi,^{40a,40b} A. Tavares Delgado,^{128a,128b} Y. Tayalati,^{137e} A. C. Taylor,¹⁰⁷ A. J. Taylor,⁴⁹ G. N. Taylor,⁹¹ P. T. E. Taylor,⁹¹ W. Taylor,^{163b} P. Teixeira-Dias,⁸⁰ D. Temple,¹⁴⁴ H. Ten Kate,³² P. K. Teng,¹⁵³ J. J. Teoh,¹²⁰ F. Tepel,¹⁷⁷ S. Terada,⁶⁹ K. Terashi,¹⁵⁷ J. Terron,⁸⁵ S. Terzo,¹³ M. Testa,⁵⁰ R. J. Teuscher,^{161,o} S. J. Thais,¹⁷⁹ T. Thevenaux-Pelzer,⁴⁵ F. Thiele,³⁹ J. P. Thomas,¹⁹ P. D. Thompson,¹⁹ A. S. Thompson,⁵⁶ L. A. Thomsen,¹⁷⁹ E. Thomson,¹²⁴ Y. Tian,³⁸ R. E. Ticse Torres,⁵⁸ V. O. Tikhomirov,^{98,ss} Yu. A. Tikhonov,^{111,d} S. Timoshenko,¹⁰⁰ P. Tipton,¹⁷⁹ S. Tisserant,⁸⁸ K. Todome,¹⁵⁹ S. Todorova-Nova,⁵ S. Todt,⁴⁷ J. Tojo,⁷³ S. Tokár,^{146a} K. Tokushuku,⁶⁹ E. Tolley,¹¹³ M. Tomoto,¹⁰⁵ L. Tompkins,^{145,tt} K. Toms,¹⁰⁷ B. Tong,⁵⁹ P. Tornambe,⁵¹ E. Torrence,¹¹⁸ H. Torres,⁴⁷ E. Torró Pastor,¹⁴⁰ C. Toscirci,¹²² J. Toth,^{88,uu} F. Touchard,⁸⁸ D. R. Tovey,¹⁴¹ C. J. Treado,¹¹² T. Trefzger,¹⁷⁸ F. Tresoldi,¹⁵¹ A. Tricoli,²⁷ I. M. Trigger,^{163a} S. Trincaz-Duvold,⁸³ M. F. Tripiana,¹³ W. Trischuk,¹⁶¹ B. Trocmé,⁵⁷ A. Trofymov,⁴⁵ C. Troncon,^{94a} M. Trovatelli,¹⁷² F. Trovato,¹⁵¹ L. Truong,^{147b} M. Trzebinski,⁴² A. Trzupek,⁴² F. Tsai,⁴⁵ K. W. Tsang,^{62a} J. C.-L. Tseng,¹²² P. V. Tsiarehka,⁹⁵ N. Tsirintanis,⁹ S. Tsiskaridze,¹³ V. Tsiskaridze,¹⁵⁰ E. G. Tskhadadze,^{54a} I. I. Tsukerman,⁹⁹ V. Tsulaia,¹⁶ S. Tsuno,⁶⁹ D. Tsybychev,¹⁵⁰ Y. Tu,^{62b} A. Tudorache,^{28b} V. Tudorache,^{28b} T. T. Tulbure,^{28a} A. N. Tuna,⁵⁹ S. Turchikhin,⁶⁸ D. Turgeman,¹⁷⁵ I. Turk Cakir,^{4b,vv} R. Turra,^{94a} P. M. Tuts,³⁸ G. Uccielli,^{22a,22b} I. Ueda,⁶⁹ M. Ughetto,^{148a,148b} F. Ukegawa,¹⁶⁴ G. Unal,³² A. Undrus,²⁷ G. Unel,¹⁶⁶ F. C. Ungaro,⁹¹

Y. Unno,⁶⁹ K. Uno,¹⁵⁷ J. Urban,^{146b} P. Urquijo,⁹¹ P. Urrejola,⁸⁶ G. Usai,⁸ J. Usui,⁶⁹ L. Vacavant,⁸⁸ V. Vacek,¹³⁰ B. Vachon,⁹⁰ K. O. H. Vadla,¹²¹ A. Vaidya,⁸¹ C. Valderanis,¹⁰² E. Valdes Santurio,^{148a,148b} M. Valente,⁵² S. Valentinetti,^{22a,22b} A. Valero,¹⁷⁰ L. Valéry,⁴⁵ R. A. Vallance,¹⁹ A. Vallier,⁵ J. A. Valls Ferrer,¹⁷⁰ T. R. Van Daalen,¹³ W. Van Den Wollenberg,¹⁰⁹ H. van der Graaf,¹⁰⁹ P. van Gemmeren,⁶ J. Van Nieuwkoop,¹⁴⁴ I. van Vulpen,¹⁰⁹ M. C. van Woerden,¹⁰⁹ M. Vanadia,^{135a,135b} W. Vandelli,³² A. Vaniachine,¹⁶⁰ P. Vankov,¹⁰⁹ R. Vari,^{134a} E. W. Varnes,⁷ C. Varni,^{53a,53b} T. Varol,⁴³ D. Varouchas,¹¹⁹ A. Vartapetian,⁸ K. E. Varvell,¹⁵² J. G. Vasquez,¹⁷⁹ G. A. Vasquez,^{34b} F. Vazeille,³⁷ D. Vazquez Furelos,¹³ T. Vazquez Schroeder,⁹⁰ J. Veatch,⁵⁸ V. Vecchio,^{136a,136b} L. M. Veloce,¹⁶¹ F. Veloso,^{128a,128c} S. Veneziano,^{134a} A. Ventura,^{76a,76b} M. Venturi,¹⁷² N. Venturi,³² V. Vercesi,^{123a} M. Verducci,^{136a,136b} C. Vergis,²³ W. Verkerke,¹⁰⁹ A. T. Vermeulen,¹⁰⁹ J. C. Vermeulen,¹⁰⁹ M. C. Vetterli,^{144,e} N. Viaux Maira,^{34b} O. Viazlo,⁸⁴ I. Vichou,^{169,a} T. Vickey,¹⁴¹ O. E. Vickey Boeriu,¹⁴¹ G. H. A. Viehhauser,¹²² S. Viel,¹⁶ L. Vigani,¹²² M. Villa,^{22a,22b} M. Villaplana Perez,^{94a,94b} E. Vilucchi,⁵⁰ M. G. Vincker,³¹ V. B. Vinogradov,⁶⁸ A. Vishwakarma,⁴⁵ C. Vittori,^{22a,22b} I. Vivarelli,¹⁵¹ S. Vlachos,¹⁰ M. Vogel,¹⁷⁷ P. Vokac,¹³⁰ G. Volpi,¹³ S. E. von Buddenbrock,^{147c} E. von Toerne,²³ V. Vorobel,¹³¹ K. Vorobev,¹⁰⁰ M. Vos,¹⁷⁰ J. H. Vossebeld,⁷⁷ N. Vranjes,¹⁴ M. Vranjes Milosavljevic,¹⁴ V. Vrba,¹³⁰ M. Vreeswijk,¹⁰⁹ R. Vuillermet,³² I. Vukotic,³³ P. Wagner,²³ W. Wagner,¹⁷⁷ J. Wagner-Kuhr,¹⁰² H. Wahlberg,⁷⁴ S. Wahrenmund,⁴⁷ K. Wakamiya,⁷⁰ J. Walder,⁷⁵ R. Walker,¹⁰² W. Walkowiak,¹⁴³ V. Wallangen,^{148a,148b} A. M. Wang,⁵⁹ C. Wang,^{36b,q} F. Wang,¹⁷⁶ H. Wang,¹⁶ H. Wang,³ J. Wang,^{60b} J. Wang,¹⁵² Q. Wang,¹¹⁵ R.-J. Wang,⁸³ R. Wang,^{36a} R. Wang,⁶ S. M. Wang,¹⁵³ T. Wang,³⁸ W. Wang,^{153,ww} W. Wang,^{36a,xx} Y. Wang,^{36a} Z. Wang,^{36c} C. Wanotayaroj,⁴⁵ A. Warburton,⁹⁰ C. P. Ward,³⁰ D. R. Wardrope,⁸¹ A. Washbrook,⁴⁹ P. M. Watkins,¹⁹ A. T. Watson,¹⁹ M. F. Watson,¹⁹ G. Watts,¹⁴⁰ S. Watts,⁸⁷ B. M. Waugh,⁸¹ A. F. Webb,¹¹ S. Webb,⁸⁶ C. Weber,¹⁷⁹ M. S. Weber,¹⁸ S. M. Weber,^{60a} S. A. Weber,³¹ J. S. Webster,⁶ A. R. Weidberg,¹²² B. Weinert,⁶⁴ J. Weingarten,⁵⁸ M. Weirich,⁸⁶ C. Weiser,⁵¹ P. S. Wells,³² T. Wenaus,²⁷ T. Wengler,³² S. Wenig,³² N. Wermes,²³ M. D. Werner,⁶⁷ P. Werner,³² M. Wessels,^{60a} T. D. Weston,¹⁸ K. Whalen,¹¹⁸ N. L. Whallon,¹⁴⁰ A. M. Wharton,⁷⁵ A. S. White,⁹² A. White,⁸ M. J. White,¹ R. White,^{34b} D. Whiteson,¹⁶⁶ B. W. Whitmore,⁷⁵ F. J. Wickens,¹³³ W. Wiedenmann,¹⁷⁶ M. Wielers,¹³³ C. Wiglesworth,³⁹ L. A. M. Wiik-Fuchs,⁵¹ A. Wildauer,¹⁰³ F. Wilk,⁸⁷ H. G. Wilkens,³² H. H. Williams,¹²⁴ S. Williams,³⁰ C. Willis,⁹³ S. Willocq,⁸⁹ J. A. Wilson,¹⁹ I. Wingerter-Seez,⁵ E. Winkels,¹⁵¹ F. Winklmeier,¹¹⁸ O. J. Winston,¹⁵¹ B. T. Winter,²³ M. Wittgen,¹⁴⁵ M. Wobisch,^{82,v} A. Wolf,⁸⁶ T. M. H. Wolf,¹⁰⁹ R. Wolff,⁸⁸ M. W. Wolter,⁴² H. Wolters,^{128a,128c} V. W. S. Wong,¹⁷¹ N. L. Woods,¹³⁹ S. D. Worm,¹⁹ B. K. Wosiek,⁴² K. W. Wozniak,⁴² K. Wraight,⁵⁶ M. Wu,³³ S. L. Wu,¹⁷⁶ X. Wu,⁵² Y. Wu,^{36a} T. R. Wyatt,⁸⁷ B. M. Wynne,⁴⁹ S. Xella,³⁹ Z. Xi,⁹² L. Xia,^{35c} D. Xu,^{35a} H. Xu,^{36a} L. Xu,²⁷ T. Xu,¹³⁸ W. Xu,⁹² B. Yabsley,¹⁵² S. Yacoob,^{147a} K. Yajima,¹²⁰ D. P. Yallup,⁸¹ D. Yamaguchi,¹⁵⁹ Y. Yamaguchi,¹⁵⁹ A. Yamamoto,⁶⁹ T. Yamanaka,¹⁵⁷ F. Yamane,⁷⁰ M. Yamatani,¹⁵⁷ T. Yamazaki,¹⁵⁷ Y. Yamazaki,⁷⁰ Z. Yan,²⁴ H. Yang,^{36c,36d} H. Yang,¹⁶ S. Yang,⁶⁶ Y. Yang,¹⁵³ Y. Yang,¹⁵⁷ Z. Yang,¹⁵ W.-M. Yao,¹⁶ Y. C. Yap,⁴⁵ Y. Yasu,⁶⁹ E. Yatsenko,⁵ K. H. Yau Wong,²³ J. Ye,⁴³ S. Ye,²⁷ I. Yeletsikh,⁶⁸ E. Yigitbasi,²⁴ E. Yildirim,⁸⁶ K. Yorita,¹⁷⁴ K. Yoshihara,¹²⁴ C. Young,¹⁴⁵ C. J. S. Young,³² J. Yu,⁸ J. Yu,⁶⁷ X. Yue,^{60a} S. P. Y. Yuen,²³ I. Yusuf,^{30,yy} B. Zabinski,⁴² G. Zacharis,¹⁰ R. Zaidan,¹³ A. M. Zaitsev,^{132,ll} N. Zakharchuk,⁴⁵ J. Zalieckas,¹⁵ S. Zambito,⁵⁹ D. Zanzi,³² C. Zeitnitz,¹⁷⁷ G. Zemaityte,¹²² J. C. Zeng,¹⁶⁹ Q. Zeng,¹⁴⁵ O. Zenin,¹³² T. Ženiš,^{146a} D. Zerwas,¹¹⁹ M. Zgubič,¹²² D. Zhang,^{36b} D. Zhang,⁹² F. Zhang,¹⁷⁶ G. Zhang,^{36a,xx} H. Zhang,^{35b} J. Zhang,⁶ L. Zhang,⁵¹ L. Zhang,^{36a} M. Zhang,¹⁶⁹ P. Zhang,^{35b} R. Zhang,²³ R. Zhang,^{36a,q} X. Zhang,^{36b} Y. Zhang,^{35a,35d} Z. Zhang,¹¹⁹ X. Zhao,⁴³ Y. Zhao,^{36b,y} Z. Zhao,^{36a} A. Zhemchugov,⁶⁸ B. Zhou,⁹² C. Zhou,¹⁷⁶ L. Zhou,⁴³ M. Zhou,^{35a,35d} M. Zhou,¹⁵⁰ N. Zhou,^{36c} Y. Zhou,⁷ C. G. Zhu,^{36b} H. Zhu,^{36a} H. Zhu,^{35a} J. Zhu,⁹² Y. Zhu,^{36a} X. Zhuang,^{35a} K. Zhukov,⁹⁸ V. Zhulanov,^{111,zz} A. Zibell,¹⁷⁸ D. Zieminska,⁶⁴ N. I. Zimine,⁶⁸ S. Zimmermann,⁵¹ Z. Zinonos,¹⁰³ M. Zinser,⁸⁶ M. Ziolkowski,¹⁴³ L. Živković,¹⁴ G. Zobernig,¹⁷⁶ A. Zoccoli,^{22a,22b} K. Zoch,⁵⁸ T. G. Zorbas,¹⁴¹ R. Zou,³³ M. zur Nedden,¹⁷ and L. Zwalinski³²

(ATLAS Collaboration)

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

²Physics Department, SUNY Albany, Albany New York, USA

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

^{4a}Department of Physics, Ankara University, Ankara, Turkey

^{4b}Istanbul Aydin University, Istanbul, Turkey

^{4c}Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey

- ⁵LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France
- ⁶High Energy Physics Division, Argonne National Laboratory, Argonne Illinois, USA
- ⁷Department of Physics, University of Arizona, Tucson Arizona, USA
- ⁸Department of Physics, The University of Texas at Arlington, Arlington Texas, USA
- ⁹Physics Department, National and Kapodistrian University of Athens, Athens, Greece
- ¹⁰Physics Department, National Technical University of Athens, Zografou, Greece
- ¹¹Department of Physics, The University of Texas at Austin, Austin Texas, USA
- ¹²Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- ¹³Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain
- ¹⁴Institute of Physics, University of Belgrade, Belgrade, Serbia
- ¹⁵Department for Physics and Technology, University of Bergen, Bergen, Norway
- ¹⁶Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley California, USA
- ¹⁷Department of Physics, Humboldt University, Berlin, Germany
- ¹⁸Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
- ¹⁹School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
- ^{20a}Department of Physics, Bogazici University, Istanbul, Turkey
- ^{20b}Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
- ^{20d}Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
- ^{20c}Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
- ²¹Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
- ^{22a}INFN Sezione di Bologna, Bologna, Italy
- ^{22b}Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
- ²³Physikalisches Institut, University of Bonn, Bonn, Germany
- ²⁴Department of Physics, Boston University, Boston Massachusetts, USA
- ²⁵Department of Physics, Brandeis University, Waltham Massachusetts, USA
- ^{26a}Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
- ^{26b}Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil
- ^{26c}Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei, Brazil
- ^{26d}Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
- ²⁷Physics Department, Brookhaven National Laboratory, Upton New York, USA
- ^{28a}Transilvania University of Brasov, Brasov, Romania
- ^{28b}Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
- ^{28c}Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania
- ^{28d}National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca, Romania
- ^{28e}University Politehnica Bucharest, Bucharest, Romania
- ^{28f}West University in Timisoara, Timisoara, Romania
- ²⁹Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
- ³⁰Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- ³¹Department of Physics, Carleton University, Ottawa Ontario, Canada
- ³²CERN, Geneva, Switzerland
- ³³Enrico Fermi Institute, University of Chicago, Chicago Illinois, USA
- ^{34a}Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
- ^{34b}Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- ^{35a}Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
- ^{35b}Department of Physics, Nanjing University, Jiangsu, China
- ^{35c}Physics Department, Tsinghua University, Beijing, China
- ^{35d}University of Chinese Academy of Science (UCAS), Beijing, China
- ^{36a}Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Anhui, China
- ^{36b}School of Physics, Shandong University, Shandong, China
- ^{36c}School 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, China
- ^{36d}Tsung-Dao Lee Institute, Shanghai, China
- ³⁷Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
- ³⁸Nevis Laboratory, Columbia University, Irvington New York, USA
- ³⁹Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
- ^{40a}INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
- ^{40b}Dipartimento di Fisica, Università della Calabria, Rende, Italy
- ^{41a}AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland

- ^{41b}Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
- ⁴²Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
- ⁴³Physics Department, Southern Methodist University, Dallas Texas, USA
- ⁴⁴Physics Department, University of Texas at Dallas, Richardson Texas, USA
- ⁴⁵DESY, Hamburg and Zeuthen, Germany
- ⁴⁶Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- ⁴⁷Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- ⁴⁸Department of Physics, Duke University, Durham North Carolina, USA
- ⁴⁹SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- ⁵⁰INFN e Laboratori Nazionali di Frascati, Frascati, Italy
- ⁵¹Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
- ⁵²Departement de Physique Nucleaire et Corpusculaire, Université de Genève, Geneva, Switzerland
- ^{53a}INFN Sezione di Genova, Genova, Italy
- ^{53b}Dipartimento di Fisica, Università di Genova, Genova, Italy
- ^{54a}E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
- ^{54b}High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- ⁵⁵II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- ⁵⁶SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- ⁵⁷Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
- ⁵⁸II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- ⁵⁹Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge Massachusetts, USA
- ^{60a}Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- ^{60b}Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
- ⁶¹Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- ^{62a}Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
- ^{62b}Department of Physics, The University of Hong Kong, Hong Kong, China
- ^{62c}Department of Physics and Institute for Advanced Study, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
- ⁶³Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
- ⁶⁴Department of Physics, Indiana University, Bloomington Indiana, USA
- ⁶⁵Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- ⁶⁶University of Iowa, Iowa City Iowa, USA
- ⁶⁷Department of Physics and Astronomy, Iowa State University, Ames Iowa, USA
- ⁶⁸Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- ⁶⁹KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- ⁷⁰Graduate School of Science, Kobe University, Kobe, Japan
- ⁷¹Faculty of Science, Kyoto University, Kyoto, Japan
- ⁷²Kyoto University of Education, Kyoto, Japan
- ⁷³Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan
- ⁷⁴Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- ⁷⁵Physics Department, Lancaster University, Lancaster, United Kingdom
- ^{76a}INFN Sezione di Lecce, Lecce, Italy
- ^{76b}Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- ⁷⁷Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- ⁷⁸Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
- ⁷⁹School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- ⁸⁰Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- ⁸¹Department of Physics and Astronomy, University College London, London, United Kingdom
- ⁸²Louisiana Tech University, Ruston Louisiana, USA
- ⁸³Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- ⁸⁴Fysiska institutionen, Lunds universitet, Lund, Sweden
- ⁸⁵Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- ⁸⁶Institut für Physik, Universität Mainz, Mainz, Germany
- ⁸⁷School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- ⁸⁸CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- ⁸⁹Department of Physics, University of Massachusetts, Amherst Massachusetts, USA
- ⁹⁰Department of Physics, McGill University, Montreal Québec, Canada
- ⁹¹School of Physics, University of Melbourne, Victoria, Australia
- ⁹²Department of Physics, The University of Michigan, Ann Arbor Michigan, USA

- ⁹³*Department of Physics and Astronomy, Michigan State University, East Lansing Michigan, USA*
- ^{94a}*INFN Sezione di Milano, Milano, Italy*
- ^{94b}*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 Québec, 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*
- ^{106a}*INFN Sezione di Napoli, Napoli, Italy*
- ^{106b}*Dipartimento di Fisica, Università di Napoli, Napoli, Italy*
- ¹⁰⁷*Department of Physics and Astronomy, University of New Mexico, Albuquerque New Mexico, USA*
- 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 Illinois, USA*
- ¹¹¹*Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia*
- ¹¹²*Department of Physics, New York University, New York New York, USA*
- ¹¹³*Ohio State University, Columbus Ohio, USA*
- ¹¹⁴*Faculty of Science, Okayama University, Okayama, Japan*
- ¹¹⁵*Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman Oklahoma, USA*
- ¹¹⁶*Department of Physics, Oklahoma State University, Stillwater Oklahoma, USA*
- ¹¹⁷*Palacký University, RCPTM, Olomouc, Czech Republic*
- ¹¹⁸*Center for High Energy Physics, University of Oregon, Eugene Oregon, USA*
- 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*
- ^{123a}*INFN Sezione di Pavia, Italy*
- ^{123b}*Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
- ¹²⁴*Department of Physics, University of Pennsylvania, Philadelphia Pennsylvania, USA*
- ¹²⁵*National Research Centre “Kurchatov Institute” B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia*
- ^{126a}*INFN Sezione di Pisa, Pisa, Italy*
- ^{126b}*Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
- ¹²⁷*Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh Pennsylvania, USA*
- ^{128a}*Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa, Portugal*
- ^{128b}*Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal*
- ^{128c}*Department of Physics, University of Coimbra, Coimbra, Portugal*
- ^{128d}*Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal*
- ^{128e}*Departamento de Física, Universidade do Minho, Braga, Portugal*
- ^{128f}*Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Spain*
- ^{128g}*Dep Física and CEFITEC de 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*
- ^{134a}*INFN Sezione di Roma, Roma, Italy*
- ^{134b}*Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy*
- ^{135a}*INFN Sezione di Roma Tor Vergata, Roma, Italy*
- ^{135b}*Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*
- ^{136a}*INFN Sezione di Roma Tre, Roma, Italy*
- ^{136b}*Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy*
- ^{137a}*Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca, Morocco*
- ^{137b}*Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat, Morocco*

- ^{137c}*Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco*
^{137d}*Faculté des Sciences, Université Mohamed Premier and LTPM, Oujda, Morocco*
^{137e}*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 California, USA*
- ¹⁴⁰*Department of Physics, University of Washington, Seattle Washington, USA*
- 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 British Columbia, Canada*
- ¹⁴⁵*SLAC National Accelerator Laboratory, Stanford California, USA*
- ^{146a}*Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava, Slovak Republic*
- ^{146b}*Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic*
- ^{147a}*Department of Physics, University of Cape Town, Cape Town, South Africa*
- ^{147b}*Department of Physics, University of Johannesburg, Johannesburg, South Africa*
- ^{147c}*School of Physics, University of the Witwatersrand, Johannesburg, South Africa*
- ^{148a}*Department of Physics, Stockholm University, Sweden*
- ^{148b}*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 New York, USA*
- 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 Ontario, Canada*
- ^{162a}*INFN-TIFPA, Trento, Italy*
- ^{162b}*University of Trento, Trento, Italy*
- ^{163a}*TRIUMF, Vancouver British Columbia, Canada*
- ^{163b}*Department of Physics and Astronomy, York University, Toronto Ontario, 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 Massachusetts, USA*
- ¹⁶⁶*Department of Physics and Astronomy, University of California Irvine, Irvine California, USA*
- ^{167a}*INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy*
- ^{167b}*ICTP, Trieste, Italy*
- ^{167c}*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 Illinois, USA*
- ¹⁷⁰*Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Spain*
- ¹⁷¹*Department of Physics, University of British Columbia, Vancouver British Columbia, Canada*
- ¹⁷²*Department of Physics and Astronomy, University of Victoria, Victoria British Columbia, 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 Wisconsin, USA*
- ¹⁷⁷*Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany*
- ¹⁷⁸*Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany*
- ¹⁷⁹*Department of Physics, Yale University, New Haven Connecticut, USA*
- 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*

- ^aDeceased.
- ^bAlso at Department of Physics, King's College London, London, United Kingdom.
- ^cAlso at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
- ^dAlso at Novosibirsk State University, Novosibirsk, Russia.
- ^eAlso at TRIUMF, Vancouver BC, Canada.
- ^fAlso at Department of Physics & Astronomy, University of Louisville, Louisville, KY, USA.
- ^gAlso at Physics Department, An-Najah National University, Nablus, Palestine.
- ^hAlso at Department of Physics, California State University, Fresno CA, USA.
- ⁱAlso at Department of Physics, University of Fribourg, Fribourg, Switzerland.
- ^jAlso at II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany.
- ^kAlso at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
- ^lAlso at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
- ^mAlso at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.
- ⁿAlso at Università di Napoli Parthenope, Napoli, Italy.
- ^oAlso at Institute of Particle Physics (IPP), Canada.
- ^pAlso at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.
- ^qAlso at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
- ^rAlso at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- ^sAlso at Borough of Manhattan Community College, City University of New York, New York City, USA.
- ^tAlso at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
- ^uAlso at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.
- ^vAlso at Louisiana Tech University, Ruston LA, USA.
- ^wAlso at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
- ^xAlso at Department of Physics, The University of Michigan, Ann Arbor MI, USA.
- ^yAlso at LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.
- ^zAlso at Graduate School of Science, Osaka University, Osaka, Japan.
- ^{aa}Also at Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany.
- ^{bb}Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.
- ^{cc}Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
- ^{dd}Also at CERN, Geneva, Switzerland.
- ^{ee}Also at Georgian Technical University (GTU), Tbilisi, Georgia.
- ^{ff}Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.
- ^{gg}Also at Manhattan College, New York NY, USA.
- ^{hh}Also at Hellenic Open University, Patras, Greece.
- ⁱⁱAlso at The City College of New York, New York NY, USA.
- ^{jj}Also at Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Spain.
- ^{kk}Also at Department of Physics, California State University, Sacramento CA, USA.
- ^{ll}Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
- ^{mmm}Also at Departement de Physique Nucleaire et Corpusculaire, Université de Genève, Geneva, Switzerland.
- ⁿⁿAlso at Department of Physics, The University of Texas at Austin, Austin TX, USA.
- ^{oo}Also at Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain.
- ^{pp}Also at School of Physics, Sun Yat-sen University, Guangzhou, China.
- ^{qq}Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.
- ^{rr}Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia.
- ^{ss}Also at National Research Nuclear University MEPhI, Moscow, Russia.
- ^{tt}Also at Department of Physics, Stanford University, Stanford CA, USA.
- ^{uu}Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
- ^{vv}Also at Giresun University, Faculty of Engineering, Turkey.
- ^{ww}Also at Department of Physics, Nanjing University, Jiangsu, China.
- ^{xx}Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
- ^{yy}Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.
- ^{zz}Also at Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia.