



Letter



Combination of searches for pair-produced leptoquarks at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration ^{*}

ARTICLE INFO

Editor: M. Doser

ABSTRACT

A statistical combination of various searches for pair-produced leptoquarks is presented, using the full LHC Run 2 (2015–2018) data set of 139 fb^{-1} collected with the ATLAS detector from proton–proton collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV. All possible decays of the leptoquarks into quarks of the third generation and charged or neutral leptons of any generation are investigated. Since no significant deviations from the Standard Model expectation are observed in any of the individual analyses, combined exclusion limits are set on the production cross-sections for scalar and vector leptoquarks. The resulting lower bounds on leptoquark masses exceed those from the individual analyses by up to 100 GeV, depending on the signal hypothesis.

Contents

1. Introduction	1
2. Signal models	2
3. Experimental signatures	2
4. Statistical interpretation	3
5. Results	4
6. Conclusion	7
Declaration of competing interest	7
Data availability	7
Acknowledgements	8
References	8
The ATLAS Collaboration	9

1. Introduction

Leptoquarks (LQs) are hypothetical particles that carry both baryon and lepton quantum numbers ($B \neq 0$, $L \neq 0$). They are either scalar (spin zero) or vector (spin one) particles, carry colour and have a fractional electric charge. LQs therefore couple simultaneously to both quarks and leptons, providing a connection between the lepton and quark sectors, which appear to have similar structures. As such, LQs have already been discussed for many decades not only in unified theories [1–3] but also in technicolour [4–6] or composite models [7–9].

In the past decade, there has been renewed interest in LQs because of anomalies in various measurements of B -meson decays. While a recent reanalysis of data from the LHCb Collaboration has yielded results in agreement with lepton-flavour universality [10,11], other anomalies

such as in the $b \rightarrow s\mu\mu$ angular distribution or in charged-current $b \rightarrow c\ell\nu$ transitions remain [12–20].

This Letter combines searches from the ATLAS experiment for pair production of LQs that decay into a charged or neutral lepton and either a top or bottom quark. All analyses use the full Run 2 data set with an integrated luminosity of 139 fb^{-1} . This dataset was recorded between 2015 and 2018 with the ATLAS detector [21], when the Large Hadron Collider (LHC) collided protons at $\sqrt{s} = 13$ TeV.

LQs decay into a quark and lepton of the same or of different generations [22]. Third-generation scalar LQs have a charge of either $\pm 1/3$ (LQ_3^d) with decays into $\bar{b}\bar{\nu}_\tau$ or $\bar{t}\tau^+$ (and charge conjugate decays) or $\pm 2/3$ (LQ_3^u) with decays into $b\tau^+$ or $t\bar{\nu}_\tau$ (and charge conjugate decays). Mixed-generation scalar LQs can decay into a first- or second-generation lepton and a third-generation quark. Similarly to LQ_3 , they can have

^{*} E-mail address: atlas.publications@cern.ch.

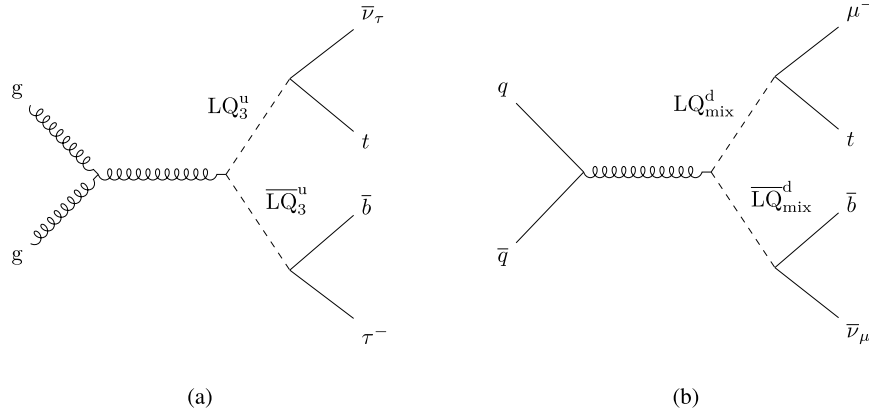


Fig. 1. Pair production of (a) up-type LQs of the third generation via gluon–gluon fusion with decays into a top quark and a neutrino or into a bottom quark and a τ -lepton, and of (b) down-type mixed LQs via quark–antiquark annihilation with decays into a top quark and a muon or into a bottom quark and a neutrino.

charge $\pm 1/3$ (LQ_{mix}^d) or $\pm 2/3$ (LQ_{mix}^u). Pairs of LQs would be produced at the LHC mainly via gluon–gluon fusion or quark–antiquark annihilation. These mechanisms are shown in Fig. 1, together with some example decays. The pair-production cross-section for scalar LQs depends only on the LQ mass (m_{LQ}).

This Letter considers nine independent searches that between them are sensitive to all decays into a bottom or top quark and any one of the charged or neutral leptons of all three generations. Sets of these analyses are combined to produce two-dimensional exclusion limits for both third-generation and mixed scalar LQs, as a function of m_{LQ} and branching ratio (B) to the charged lepton in order to obtain limits that are more stringent than those from the individual analyses. A limited set of searches is also interpreted in vector LQ models [23]. The pair-production cross-section for vector LQs depends not only on m_{LQ} but also on the coupling to gluons. An additional coupling of Yang–Mills type to gluons is either present or absent (“minimal coupling”) [24].

It should be noted that because the ATLAS analyses included here do not have any requirements on the LQ charge, the results for decays to a charged lepton are also valid for LQs with charge $\pm 4/3$, e.g. with decays into $\bar{b}\tau^+$, or charge $\pm 5/3$, e.g. with decays into $\tau\tau^+$.

2. Signal models

Simulated events with pair-produced scalar up-type and down-type LQs were generated at next-to-leading order (NLO) in quantum chromodynamics (QCD) with MADGRAPH5_AMC@NLO 2.6.0 [25]. The method described in Ref. [26] is used, in which fixed-order NLO QCD calculations [27,28] are interfaced to PYTHIA 8.230 [29] for the parton shower (PS) and hadronisation. Parton luminosities were provided by the five-flavour scheme NNPDF3.ONLO [30] parton distribution functions with $\alpha_s = 0.118$, and the underlying event (UE) was modelled with the A14 set of tuned parameters [31]. MADSPIN [32] was used for the decay of the LQ. The branching ratio of LQ decays to a charged lepton is controlled by the model parameter β , so for $\beta = 0$ there are only decays into a neutrino and a quark, and for $\beta = 1$ there are only decays into a charged lepton and a quark. However, for equal couplings to charged and neutral leptons, i.e. $\beta = 0.5$, B differs from 0.5 due to the sizeable top-quark mass [33]. Signal samples were mostly produced for a model parameter of $\beta = 0.5$, and target branching fractions B were obtained by reweighting the samples using generator-level information, as described in Ref [33]. The coupling strength parameter λ was set to 0.3, resulting in a LQ width of about 0.2 % of its mass [22,34].

Signal cross-sections for scalar LQs were obtained from a calculation of the pair production of scalar coloured particles, e.g. the supersymmetric partner of the top quark. Such particles have the same production modes (except lepton t-channel contributions) and their pair-production cross-section depends only on their mass. These cross-sections are computed at approximate next-to-next-to-leading order

(NNLO) in QCD with resummation of next-to-next-to-leading logarithmic (NNLL) soft gluon terms [35–38]. Lepton t -channel contributions are neglected and may lead to corrections at the percent level [39].

In addition to scalar LQs, two models of vector LQs are investigated. Simulated events with pair-produced U_1 and \tilde{U}_1 LQs were generated at leading order (LO) in QCD with MADGRAPH5_AMC@NLO, handling PDFs and the UE in the same way as for scalar LQs. For U_1 LQs, a simplified model [23] is used, neglecting further degrees of freedom relevant for the ultraviolet (UV) completion of the model. The samples were produced with a coupling strength parameter of $g_U = 3.0$, leading to a signal width of approximately 11 % [40]. The large value of g_U is motivated by a suppression of the production cross-section for additional mediators in an UV-complete model, which might otherwise be in tension with existing LHC Z' limits [24]. The coupling to gluons is determined through the chosen value of the model parameter κ , where $\kappa = 0$ corresponds to the Yang–Mills coupling scenario (U_1^{YM}) and $\kappa = 1$ to the minimal coupling scenario (U_1^{MC}). The coupling strength to left- and right-handed quarks and leptons of the various generations is determined by the model parameters $\beta_{L/R}$. While right-handed couplings are assumed to vanish in this analysis, β_L is set to unity, resulting in equal coupling strengths of U_1 LQs to top quarks and neutrinos or bottom quarks and charged leptons of a certain generation. Conversely, \tilde{U}_1 LQs [24,41] carry an electric charge of $\pm 5/3$, and thus only decays into a top quark and τ -lepton are allowed. Couplings of \tilde{U}_1 to the Standard Model gluon are governed by the model parameter κ_t . Additional couplings of \tilde{U}_1 to the heavy gluon g' , required for the UV completion of the model, depend on the model parameter κ_s . The choice of $\kappa_t = \kappa_s = 0$ corresponds to the Yang–Mills scenario (\tilde{U}_1^{YM}), whereas $\kappa_t = \kappa_s = -1$ gives the minimal coupling scenario (\tilde{U}_1^{MC}). Since production via an intermediate g' contributes only in quark-initiated processes, which are subdominant compared to gluon–gluon fusion, the pair-production cross-section of \tilde{U}_1 LQs depends only very slightly on the heavy-gluon mass, which is assumed to vanish in this analysis. No higher-order cross-section computations are available for the U_1 and \tilde{U}_1 models. Therefore, the cross-sections computed at LO by MADGRAPH5_AMC@NLO are used in the analysis.

Additional details of the Monte Carlo simulation and the estimation of background processes in the individual analyses can be found in the respective publications.

3. Experimental signatures

In the following, each of the analyses contributing to the combined results is described briefly, with further details available in the references. The final state in all analyses is reconstructed from electrons [42], muons [43], hadronically decaying τ -leptons (τ_{had}) [44], jets and missing transverse momentum (with magnitude E_T^{miss}) [45].

Different quality criteria, isolation requirements and transverse momentum (p_T) thresholds are applied in each analysis because of the different backgrounds present. No attempt is made to distinguish between a leptonically decaying τ -lepton and a prompt electron or muon (ℓ). Jets are reconstructed from energy deposits in the calorimeter system [46] or from particle-flow objects [47,48], using the anti- k_r algorithm [49,50] with a radius parameter of 0.4 by default. Jets can be categorised as b -tagged (i.e. as “ b -jets”) if they satisfy the requirements of a multivariate algorithm [51–53]. In order to better reconstruct high- p_T top quarks, jets with a larger radius-parameter value are used in some analyses, with the top-quark decay products reconstructed from jet substructure information.

In most of the analyses, one or both LQs have a neutrino in the final state, so they cannot be fully reconstructed. Various methods are employed to separate background from signal, such as the usage of event-level variables designed to identify one or more missing particles, or multivariate techniques that combine several final-state variables in an optimised way. In addition to signal-enriched regions, also called signal regions (SRs), control regions (CRs) are defined for the purpose of constraining major background processes. CRs and SRs are designed to be mutually exclusive.

Third-generation quarks and leptons

$t\nu b\tau$ [54]: The main selection requirements for this search are one τ_{had} , two b -jets, and large E_T^{miss} , allowing searches in the $\text{LQ}_3^u \rightarrow t\nu$ or $b\tau$ and $\text{LQ}_3^d \rightarrow t\tau$ or $b\nu$ channels. The p_T of the τ_{had} is used as the discriminant. This channel is also interpreted in the U_1^{YM} and U_1^{MC} models.

$b\tau b\tau$ [55]: This search targets the $\text{LQ}_3^u \rightarrow b\tau$ channel by selecting events with either two or one τ_{had} and one light charged lepton (arising from a leptonic τ decay), together with one or more b -jets. The discriminant is the output of a parameterised neural network [56], which uses as input various kinematic variables including the partially reconstructed LQ masses. This channel is also interpreted in the U_1^{YM} and U_1^{MC} models.

$t\tau t\tau$ [57]: The search targets the $\text{LQ}_3^d \rightarrow t\tau$ channel. Events are selected by requiring between one and three light charged leptons, at least one τ_{had} and two or more jets, one of which is b -tagged. The phase space of interest is divided into seven mutually exclusive SRs, based on the light charged-lepton and τ_{had} multiplicities. In each SR, the effective mass, m_{eff} , defined as the scalar sum of E_T^{miss} and the transverse momenta of all reconstructed leptons and jets is used as the discriminant. This channel is also reinterpreted in the U_1^{YM} and U_1^{MC} models.

Third-generation quarks and first- or second-generation leptons

$t\nu b\ell$ [40]: The strategy of this search is to select events with one light charged lepton, large E_T^{miss} and four or more jets, of which at least one must be b -tagged. It is therefore sensitive to the $\text{LQ}_{\text{mix}}^u \rightarrow t\nu$, $b\ell$ or $b\mu$ and $\text{LQ}_{\text{mix}}^d \rightarrow b\nu$, $t\ell$ or $t\mu$ channels. The discriminant is the output of a neural network with kinematic variables as input. This channel is also interpreted in the U_1^{YM} and U_1^{MC} models.

$b\ell b\ell$ [58]: This analysis targets either the $\text{LQ}_{\text{mix}}^u \rightarrow b\ell$ or $b\mu$ channels. Events are required to contain exactly two electrons or two muons with opposite electric charges and at least two jets. Events are then categorised according to the multiplicity of the b -tagged jets. LQ candidates are identified by choosing the combination of leptons and jets resulting in the smallest difference between the two lepton–jet invariant masses. The average mass of the two LQ candidates serves as the discriminant.

$t\ell t\ell$ (2ℓ) [59]: The search targets the $\text{LQ}_{\text{mix}}^d \rightarrow t\ell$ or $t\mu$ channels. The analysis is optimised for signal events with both top quarks decaying hadronically by requiring exactly two opposite-sign same-flavour leptons and two $R = 1.0$ jets containing the top decay products. A boosted decision tree classifier (BDT) is trained to separate signal events from background events. In addition to variables calculated from the p_T of leptons and jets as well as E_T^{miss} , observables obtained using recursive jigsaw reconstruction techniques [60] serve as input to the BDT. The BDT output score is used as the discriminant in the SRs.

$t\ell t\ell$ ($\geq 3\ell$) [61]: Complementing the $t\ell t\ell$ (2ℓ) analysis, this search targets the same signal hypotheses in final states with at least three light charged leptons. In addition, events are required to have at least two reconstructed jets, at least one of which must be b -tagged. The SR is split on the basis of lepton multiplicity, and m_{eff} is used as the discriminant.

Third-generation quarks and neutrinos

$t\nu t\nu$ [62]: The search for pair-produced scalar partners of the top quark in final states consisting of two hadronically decaying top quarks and large E_T^{miss} is also interpreted as a search for pair-produced LQs, primarily targeting the $\text{LQ}_3^u \rightarrow t\nu$ channel. The main selection requirements in the SR are four jets, two of which are b -tagged, no charged leptons, and large E_T^{miss} . Top candidates are reconstructed using jets with $R = 1.2$. Two such top candidates are required, and the SR is subdivided according to both the mass of the top candidate with lower transverse momentum and the kinematic variable m_{T2,χ^2} [63], which is a transverse mass suited to the case where there are two missing particles. For this publication, this channel is also reinterpreted in the LQ_{mix}^u , U_1^{YM} and U_1^{MC} models.

$b\nu b\nu$ [64]: The search for scalar partners of the bottom quark in events with no light charged leptons, two b -tagged jets and large E_T^{miss} also targets pair-produced LQs in the $\text{LQ}_3^d \rightarrow b\nu$ channel. However, since there is neither a requirement on additional jets nor explicit τ reconstruction the search also has sensitivity to the $\text{LQ}_3^d \rightarrow t\tau$ channel. A cut-based approach is used for high values of a specific mass reconstructed in the presence of neutrinos, m_{CT} [65]. The SR is subdivided into regions depending on m_{CT} and m_{eff} . At lower values of m_{CT} a BDT is used as the discriminant, with input variables based on the kinematics of the final-state jets and E_T^{miss} . For this publication, this channel is also reinterpreted in the LQ_{mix}^d models.

A summary of the channels considered in this Letter, together with which interpretations are made and the main selection requirements, is given in Table 1.

4. Statistical interpretation

The statistical combination of the different searches follows the same formalism as the individual analyses. Simultaneous binned profile-likelihood fits to CRs and SRs, steered by the `cabinetry` library [66,67], are performed, and a modified frequentist method, the CL_s method [68] as implemented in `pyhf` [69,70], is used to set exclusion limits on various signal hypotheses. Systematic uncertainties are accounted for by including them in the fits via nuisance parameters (NPs). The binned likelihood function $\mathcal{L}(\mu, \theta)$ is constructed as the product of Poisson probability terms over all bins considered in the analysis and a number of Gaussian or log-normal priors for the NPs associated with systematic uncertainties. It depends on the signal strength parameter, μ , a multiplicative factor applied to the theoretical signal production cross-section, and on θ , a set of NPs including a number of unconstrained multiplicative factors for the major background processes as well as those entering the Gaussian and log-normal priors, which adjust the expectations for signal and background according to the corresponding systematic uncertainties.

Table 1

Overview of the individual analyses, together with the models used to interpret them and the main object selections in the signal region: number of electrons or muons (N_e), number of hadronically decaying τ -leptons ($N_{\tau_{\text{had}}}$) and number of b -jets ($N_{b\text{jets}}$). All analyses interpreted in the same model are combined except for U_1 in the $t\nu b\ell$ final state, where no other channels are available for combination.

Interpretation		Scalar				Vector		Signal Region		
Search		LQ ₃ ^u	LQ ₃ ^d	LQ _{mix} ^u	LQ _{mix} ^d	$U_1^{\text{YM/MC}}$	$\tilde{U}_1^{\text{YM/MC}}$	N_e	$N_{\tau_{\text{had}}}$	$N_{b\text{jets}}$
Final State	Citation									
$t\nu b\tau$	[54]	✓	✓	–	–	✓	–	0	1	≥ 2
$b\tau b\tau$	[55]	✓	–	–	–	✓	–	{0, 1}	{1, 2}	{1, 2}
$t\tau t\tau$	[57]	–	✓	–	–	–	✓	{1, 2, 3}	≥ 1	≥ 1
$t\nu b\ell$	[40]	–	–	✓	✓	✓	–	1	–	≥ 1
$b\ell b\ell$	[58]	–	–	✓	–	–	–	2	–	{0, 1, 2}
$t\ell t\ell$ (2ℓ)	[59]	–	–	–	✓	–	–	2	–	–
$t\ell t\ell$ ($\geq 3\ell$)	[61]	–	–	–	✓	–	–	{3, 4}	–	≥ 2
$t\nu t\nu$	[62]	✓	–	✓	–	✓	–	0	0	≥ 2
$b\nu b\nu$	[64]	–	✓	–	✓	–	–	0	–	≥ 2

The test statistic used to determine the exclusion limits is based on the profile likelihood ratio

$$t_\mu = -2 \ln \frac{\mathcal{L}(\mu, \hat{\theta})}{\mathcal{L}(\hat{\mu}, \hat{\theta})},$$

where $\hat{\mu}$ and $\hat{\theta}$ are the values of the parameters that maximise the likelihood function, and $\hat{\theta}$ are the values of the NPs that maximise the likelihood function for a given value of μ . Upper limits on the signal production cross-section are derived for each of the signal scenarios considered in this analysis. For a given signal scenario, values of the production cross-section (parameterised by μ) yielding $\text{CL}_s < 0.05$, where CL_s is computed using the asymptotic approximation [71], are excluded at $\geq 95\%$ confidence level (CL).

The sensitivity of each individual analysis entering the combination is limited primarily by statistical uncertainties. As such, systematic uncertainties do not have a major impact in the combined analysis, and therefore assumptions about their correlation across the different analyses do not affect the results significantly. Detector-related uncertainties are assumed to be correlated across analyses, unless that is not valid because of different approaches to event reconstruction or a different choice of correlation model in individual analyses. Similarly, uncertainties in the modelling of the signal process are only assumed to be correlated when parameterised in the same way in individual analyses. However, treating these uncertainties as fully uncorrelated yields a difference of at most 5% on the cross-section limit. Uncertainties in the modelling and normalisation of background processes are assumed to be uncorrelated between analyses, since the phase spaces of interest and background estimation techniques can differ significantly. As is standard in ATLAS searches, theory uncertainties affecting the signal acceptance are considered when setting exclusion limits, but those affecting the production cross-section are not.

In each combination, the SRs and CRs defined for the individual searches are generally statistically independent between the various analyses, due to the selection requirements on the multiplicity and flavour of the charged leptons. Additional criteria are used in the one-lepton CRs in the (otherwise zero-lepton) $t\nu t\nu$ channel, such as the requirement that the lepton p_T is below the threshold used in the SRs and CRs of the other channels. Residual overlaps caused by the use of different lepton identification criteria were found to be negligible in all cases except between one of the six SRs of the $t\nu t\nu$ analysis and the SR of the $t\nu b\tau$ analysis. Since this SR in the $t\nu t\nu$ analysis does not significantly affect the sensitivity for LQ signal processes, it is removed from the combination. Other overlaps between SRs of different analyses do not exceed 7% (2%), as estimated with Monte Carlo signal samples (data), and have negligible impact on the results presented in this Letter. Similarly, statistical overlaps between CRs in one analysis and SRs

or CRs in other analyses have negligible impact on the results and are therefore ignored.

5. Results

No significant deviations from the Standard Model expectation are observed in any of the analysis channels considered in this Letter, and good agreement is also found in the combined background-only fits to data. Upper limits on the cross-sections for LQ pair production are calculated at 95% CL using simultaneous signal-plus-background fits to the CRs and SRs, in which the background normalisations and possible signal contributions are determined. Such limits on the cross-sections are evaluated for a wide range of values for the branching ratio of LQs into charged leptons. Comparisons with theoretical cross-section predictions provide mass exclusion limits.

The exclusion limits for scalar third-generation up-type LQs obtained from the combined analysis are shown in Fig. 2(a) on top of an overlay of the limits from the three individual analyses. As discussed in Section 4 the limits are dominated by statistical uncertainties. As an example, at $\mathcal{B} = 0.4$ and a LQ mass of 1.3 TeV the dominating systematic uncertainties on the cross-section are due to background modelling (7%) and signal modelling (4%). Compared to the individual searches, the exclusion reach is improved by up to 100 GeV for intermediate values of \mathcal{B} , where more than one individual analysis provides sensitivity. Similar observations are made in the case of scalar third-generation down-type LQs, where the exclusion limits improve by up to 70 GeV as shown in Fig. 2(b).

The combined exclusion limits also show improvement with respect to the three individual analyses sensitive to scalar up-type LQs decaying into a third-generation quark and a first- or second-generation lepton. This is especially true for low and intermediate values of \mathcal{B} . The corresponding exclusion contours are shown in Fig. 3 for decays to a muon (a) or an electron (b), with improvements in the observed exclusion limits of up to 80 GeV and 90 GeV, respectively.

In the case of scalar down-type LQs decaying into a third-generation quark and a first- or second-generation lepton, improvements in sensitivity are observed across the whole range of \mathcal{B} , since a total of four individual analysis channels are combined here, generally also resulting in higher exclusion limits when the LQ is assumed to decay exclusively into a top quark and a charged lepton. Corresponding results are shown in Fig. 4, with the combination improving the exclusion limits by up to 60 GeV for decays to a muon and by up to 80 GeV for decays to an electron. For LQs decaying into a top quark and a muon with $\mathcal{B} \approx 1$, the observed combined lower limit on the LQ mass is slightly weaker than the one observed in $t\mu t\mu$ ($\geq 3\ell$) since a worse-than-expected limit is observed in $t\mu t\mu$ (2ℓ).

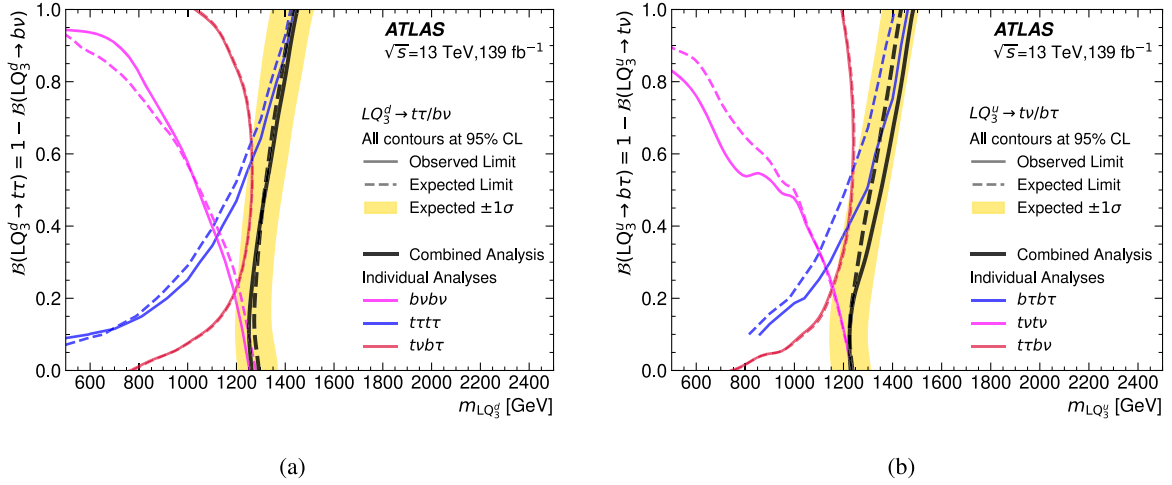


Fig. 2. Expected and observed 95 % CL exclusion limits on the LQ mass as a function of the branching ratio to a charged lepton. Limits are presented for third-generation (a) up-type and (b) down-type LQs decaying into a third-generation quark and lepton. The full β parameter space is not evaluated for some analyses if they have limited sensitivity.

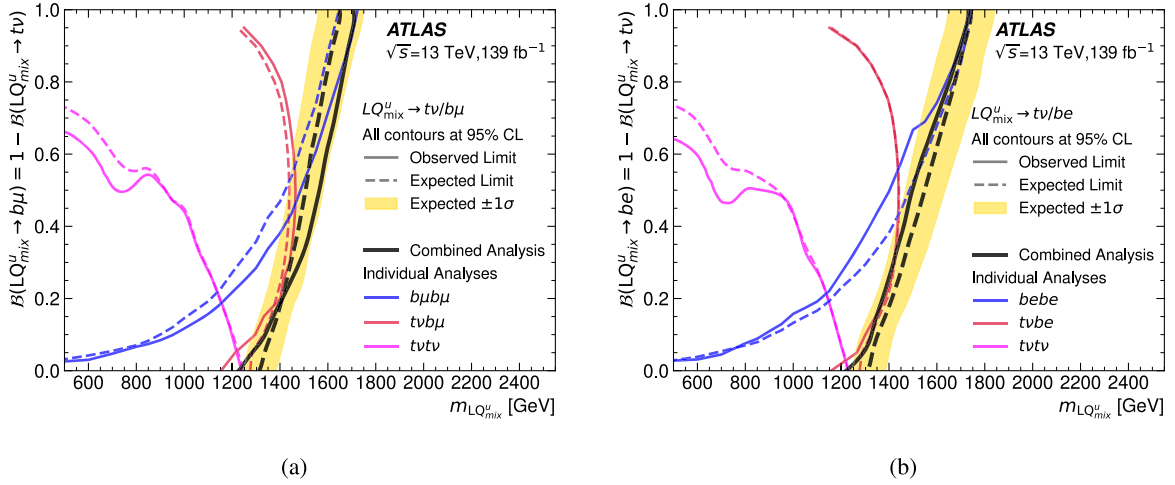


Fig. 3. Expected and observed 95 % CL exclusion limits on the LQ mass as a function of the branching ratio to a charged lepton. Limits are presented for up-type scalar LQs decaying into a third-generation quark and (a) a muon or (b) an electron. The full β parameter space is not evaluated for some analyses if they have limited sensitivity.

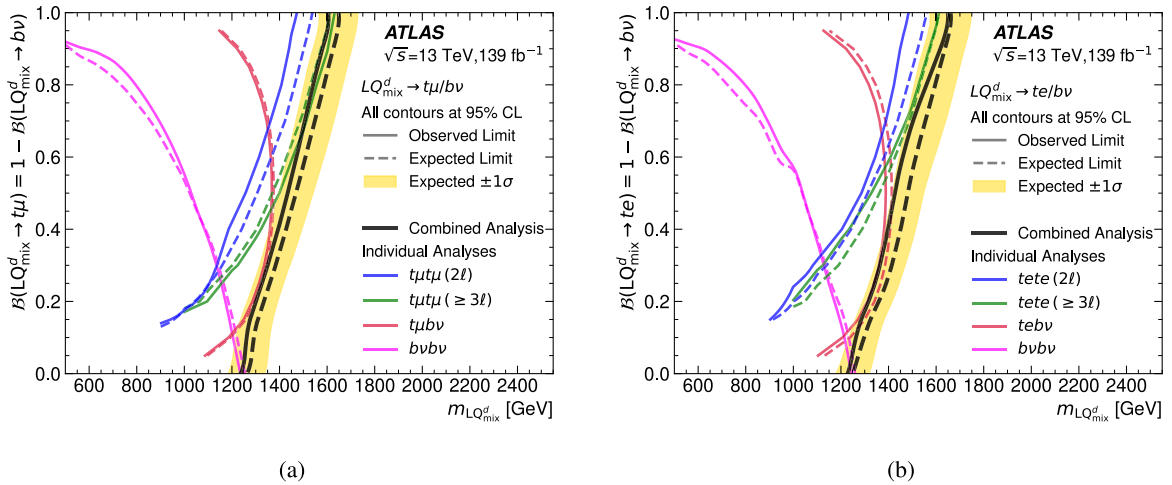


Fig. 4. Expected and observed 95 % CL exclusion limits on the LQ mass as a function of the branching ratio to a charged lepton. Limits are presented for down-type scalar LQs decaying into a third-generation quark and (a) a muon or (b) an electron. The full β parameter space is not evaluated for some analyses if they have limited sensitivity.

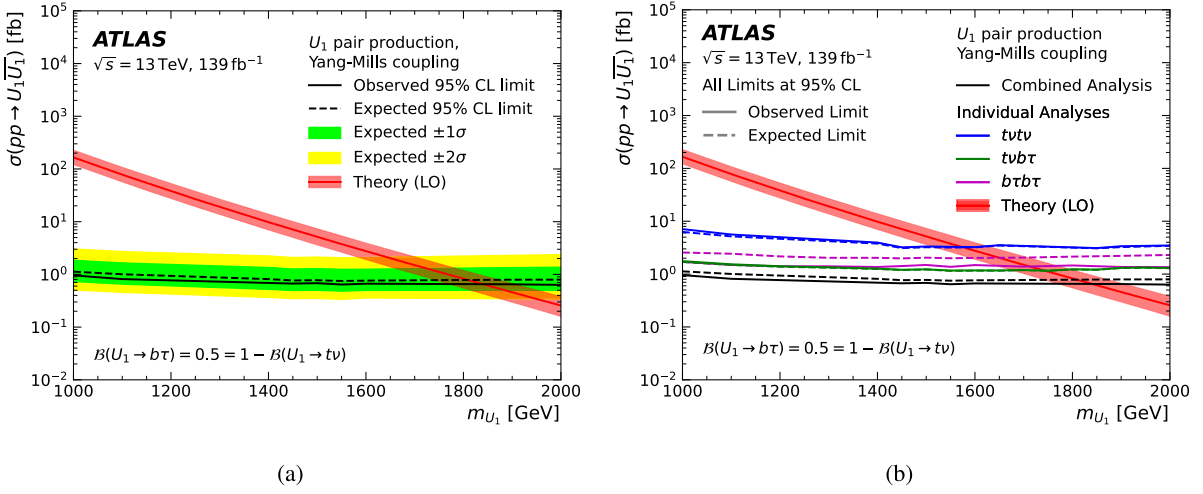


Fig. 5. Expected and observed 95 % CL exclusion limits on the U_1^{YM} production cross-section as a function of the LQ mass, with a branching ratio of 0.5 to a τ -lepton. The limits obtained from the combined analysis, including uncertainty bands, are presented in (a), whereas (b) shows the limits obtained from the individual analyses for comparison. The theoretical prediction and its $\pm 1\sigma$ uncertainty due to variations of the parton distribution functions, the strong coupling parameter and the renormalisation and factorisation scales are shown in red.

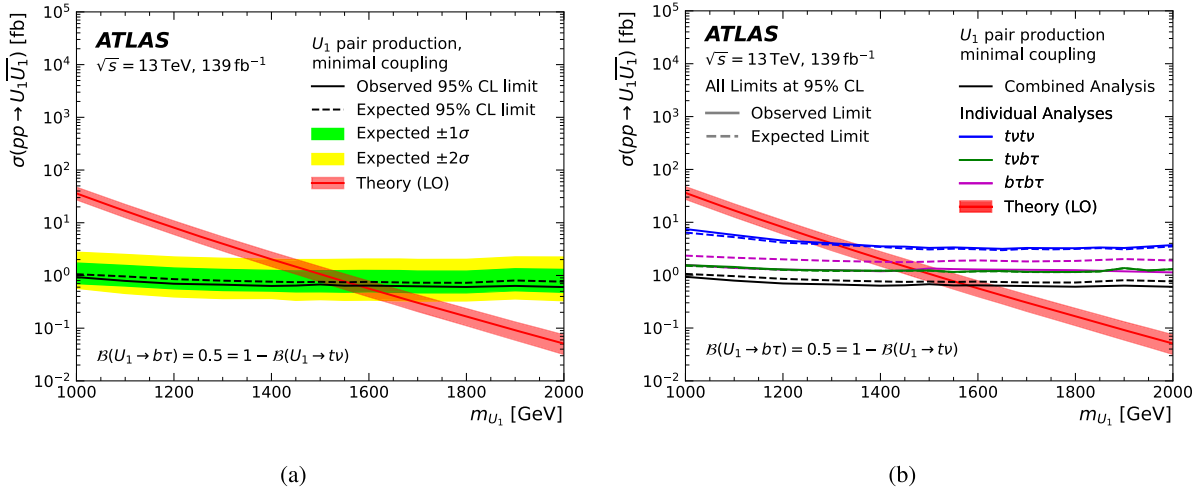


Fig. 6. Expected and observed 95 % CL exclusion limits on the U_1^{MC} production cross-section as a function of the LQ mass with a branching ratio of 0.5 to a τ -lepton. The limits obtained from the combined analysis, including uncertainty bands, are presented in (a), whereas (b) shows the limits obtained from the individual analyses for comparison. The theoretical prediction and its $\pm 1\sigma$ uncertainty due to variations of the parton distribution functions, the strong coupling parameter and the renormalisation and factorisation scales are shown in red.

In addition to mass exclusion limits for scalar LQs, limits on the production cross-section of U_1 vector LQs decaying into a third-generation quark and lepton are provided, assuming $\beta = 0.5$. The results of combining the three contributing analyses are shown in Fig. 5 and Fig. 6 for U_1^{YM} and U_1^{MC} , respectively. The observed (expected) lower limits on the U_1 mass are 1840 GeV (1810 GeV) for U_1^{YM} and 1580 GeV (1560 GeV) for U_1^{MC} . For these signal hypotheses, the combined expected limits are primarily driven by the searches in the $tvb\tau$ final state as expected. The combined observed limits are slightly higher than the expected ones, mainly due to the $b\tau b\tau$ channel showing similar behaviour, and are improved by 70 GeV (U_1^{YM}) and 80 GeV (U_1^{MC}) compared to the individual analyses.

Finally, the search in $t\tau t\tau$ final states is reinterpreted in the \tilde{U}_1 vector LQ model. Since \tilde{U}_1 carries an electric charge of $\pm 5/3$, it decays exclusively into a top quark and a τ -lepton. The resulting upper limits on the production cross-section are shown in Fig. 7, with observed (expected) lower limits on the \tilde{U}_1 mass of 1810 GeV (1810 GeV) and 1540 GeV (1530 GeV) for \tilde{U}_1^{YM} and \tilde{U}_1^{MC} , respectively.

Table 2 summarises the lower limits on the LQ mass obtained in this analysis at $\beta = 0.0, 0.5, 1.0$, including four additional limits [40] on U_1 vector LQs that decay into a third-generation quark and a first- or second-generation lepton, where no other channels are available for a combination. Since the analyses are not sensitive to the quark charge, the results shown for scalar LQs with $\beta = 1$, i.e. the last column and first six rows of Table 2, are also valid for scalar LQs with charge $\pm 4/3$ and be , $b\mu$ or $b\tau$ decays or with charge $\pm 5/3$ and te , $t\mu$, or $t\tau$ decays.

A comparison to results from the CMS collaboration is not directly possible for results on vector LQs [72–74] due to the different models used by ATLAS and CMS. For the pair production of scalar LQs the individual limits are already better than the CMS limits [72–76]¹ at $\beta = 0.0, 0.5, 1.0$ for all decay channels. The limits shown in Figs. 2 to 4 therefore constitute the best limits to date for any value of β .

¹ After submission of this paper a new result from the CMS Collaboration has been reported [77], yielding results on the search for scalar and vector LQs in the $b\mu b\mu$ final state.

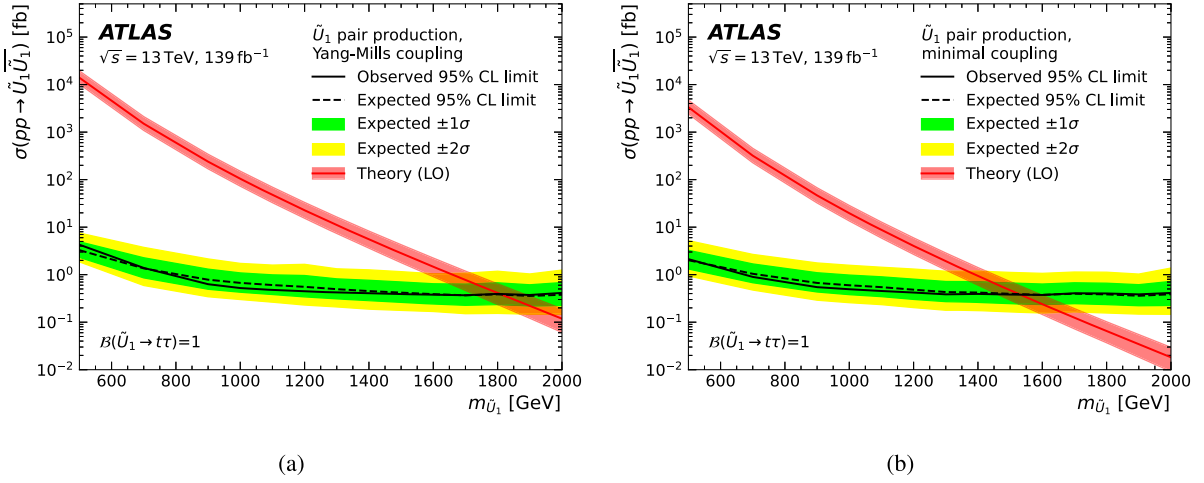


Fig. 7. Expected and observed 95 % CL exclusion limits on the \tilde{U}_1 production cross-section as a function of the LQ mass with a branching ratio of 1.0 to a τ -lepton. Limits are presented for (a) \tilde{U}_1^{YM} and (b) \tilde{U}_1^{MC} . The theoretical prediction and its $\pm 1\sigma$ uncertainty due to variations of the parton distribution functions, the strong coupling parameter and the renormalisation and factorisation scales are shown in red.

Table 2

Expected and observed 95 % CL lower limits on the LQ mass at branching ratios to a charged lepton of $B = 0.0, 0.5, 1.0$ for the signal hypotheses considered in this analysis, including four additional limits [40] on the U_1 vector LQs decaying into a third-generation quark and a first- or second-generation lepton, where no other channels are available for a combination.

	$B = 0.0$		$B = 0.5$		$B = 1.0$	
	95 % CL Limit [GeV]		95 % CL Limit [GeV]		95 % CL Limit [GeV]	
	Observed	Expected	Observed	Expected	Observed	Expected
$LQ_3^u \rightarrow tv/b\tau$	1240	1240^{+70}_{-90}	1340	1300^{+70}_{-80}	1480	1440^{+70}_{-80}
$LQ_3^d \rightarrow t\tau/b\nu$	1260	1260^{+80}_{-80}	1360	1340^{+60}_{-70}	1520	1470^{+70}_{-70}
$LQ_{\text{mix}}^u \rightarrow tv/b\mu$	1230	1310^{+70}_{-70}	1570	1510^{+70}_{-70}	1710	1650^{+90}_{-90}
$LQ_{\text{mix}}^u \rightarrow tv/be$	1230	1310^{+70}_{-70}	1510	1550^{+80}_{-80}	1730	1740^{+90}_{-100}
$LQ_{\text{mix}}^d \rightarrow t\mu/b\nu$	1240	1260^{+70}_{-80}	1430	1470^{+70}_{-70}	1600	1650^{+80}_{-80}
$LQ_{\text{mix}}^d \rightarrow te/b\nu$	1230	1250^{+70}_{-70}	1450	1500^{+70}_{-70}	1650	1660^{+90}_{-90}
$U_1^{\text{YM}} \rightarrow tv/b\tau$	-	-	1840	1810^{+80}_{-90}	-	-
$U_1^{\text{MC}} \rightarrow tv/b\tau$	-	-	1580	1560^{+70}_{-70}	-	-
$U_1^{\text{YM}} \rightarrow tv/b\mu$	-	-	1980	1930^{+50}_{-60}	-	-
$U_1^{\text{MC}} \rightarrow tv/b\mu$	-	-	1710	1660^{+50}_{-50}	-	-
$U_1^{\text{YM}} \rightarrow tv/be$	-	-	1900	1930^{+50}_{-70}	-	-
$U_1^{\text{MC}} \rightarrow tv/be$	-	-	1620	1650^{+50}_{-60}	-	-
$\tilde{U}_1^{\text{YM}} \rightarrow t\tau$	-	-	-	-	1810	1810^{+80}_{-70}
$\tilde{U}_1^{\text{MC}} \rightarrow t\tau$	-	-	-	-	1540	1530^{+90}_{-60}

6. Conclusion

A statistical combination of searches for pair-produced leptoquarks that decay into a third-generation quark (t or b) and any charged or neutral lepton is presented. The analysis exploits the full data sample recorded with the ATLAS detector in Run 2 of the LHC, corresponding to 139 fb^{-1} of proton–proton collisions at $\sqrt{s} = 13 \text{ TeV}$. No significant deviation from the Standard Model expectation is observed. At 95% CL the lower limits on the masses of scalar LQs are found to range from 1230 to 1730 GeV, depending on branching ratio, leptoquark charge and lepton flavour. The combined analyses extend the mass exclusion range by up to 100 GeV compared to the previous best individual analyses. For any combination of these parameters the ATLAS limits constitute the best limits to date.

Limits are also placed on some benchmark models of vector LQs. In the U_1^{MC} model, where the coupling to gluons is minimal, LQs are excluded in the mass range below 1580 to 1710 GeV for $B = 0.5$, depending on LQ flavour. For the Yang–Mills model U_1^{YM} , LQs are excluded in

the mass range below 1840 to 1980 GeV for $B = 0.5$, depending on LQ flavour. The combined analysis extends the mass exclusion range by up to 80 GeV compared to the best individual analyses. Vector LQs with charge $\pm 5/3$ and $t\tau$ decays are excluded up to 1540 GeV for \tilde{U}_1^{MC} and up to 1810 GeV for \tilde{U}_1^{YM} .

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data for this manuscript are not available. The values in the plots and tables associated to this article are stored in HEPDATA (<https://www.hepdata.net/>).

Acknowledgements

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

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF/SFU (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [78].

We gratefully acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; ANID, Chile; CAS, MOST and NSFC, China; Minciencias, Colombia; MEYS CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF and MPG, Germany; GSRI, Greece; RGC and Hong Kong SAR, China; ISF and Benozio Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MEiN, Poland; FCT, Portugal; MNE/IFA, Romania; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DSI/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taipei; TENMAK, Türkiye; STFC, United Kingdom; DOE and NSF, United States of America.

Individual groups and members have received support from BCKDF, Canarie, CRC and DRAC, Canada; CERN-CZ, PRIMUS 21/SCI/017 and UNCE SCI/013, Czech Republic; COST, ERC, ERDF, Horizon 2020, ICSC-NextGenerationEU and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex, Investissements d’Avenir Idex and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and MINERVA, Israel; Norwegian Financial Mechanism 2014-2021, Norway; NCN and NAWA, Poland; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom.

In addition, individual members wish to acknowledge support from CERN: European Organization for Nuclear Research (CERN PJAS); Chile: Agencia Nacional de Investigación y Desarrollo (FONDECYT 1190886, FONDECYT 1210400, FONDECYT 1230987); China: National Natural Science Foundation of China (NSFC - 12175119, NSFC 12275265); European Union: European Research Council (ERC - 948254, ERC 101089007), Horizon 2020 Framework Programme (MUCCA - CHIST-ERA-19-XAI-00), Italian Center for High Performance Computing, Big Data and Quantum Computing (ICSC, NextGenerationEU); France: Agence Nationale de la Recherche (ANR-20-CE31-0013, ANR-21-CE31-0013, ANR-21-CE31-0022), Investissements d’Avenir Labex (ANR-11-LABX-0012); Germany: Baden-Württemberg Stiftung (BW Stiftung-Postdoc Eliteprogramme), Deutsche Forschungsgemeinschaft (DFG - 469666862, DFG - CR 312/5-1); Italy: Istituto Nazionale di Fisica Nucleare (ICSC, NextGenerationEU); Japan: Japan Society for the Promotion of Science (JSPS KAKENHI 22H01227, JSPS KAKENHI 22KK0227, JSPS KAKENHI JP21H05085, JSPS KAKENHI JP22H04944); Netherlands: Netherlands Organisation for Scientific Research (NWO Veni 2020 - VI.Veni.202.179); Norway: Research Council of Norway (RCN-314472); Poland: Polish National Agency for Academic Exchange (PPN/PPO/2020/1/00002/U/00001), Polish National Science Centre (NCN 2021/42/E/ST2/00350, NCN OPUS nr 2022/47/B/ST2/03059, NCN UMO-2019/34/E/ST2/00393, UMO-2020/37/B/ST2/01043, UMO-2021/40/C/ST2/00187, UMO-2022/47/O/ST2/00148); Slovenia: Slovenian Research Agency (ARIS grant J1-3010); Spain: BBVA Foundation (LEO22-1-603), Generalitat Valenciana (Artemisa, FEDER, IDIFEDER/2018/048), La Caixa Banking Foun-

















ation (LCF/BQ/PI20/11760025), Ministry of Science and Innovation (RYC2019-028510-I, RYC2020-030254-I), PROMETEO and GenT Programmes Generalitat Valenciana (CIDEAGENT/2019/023, CIDEAGENT/2019/027); Sweden: Swedish Research Council (VR 2018-00482, VR 2022-03845, VR 2022-04683), Knut and Alice Wallenberg Foundation (KAW 2017.0100, KAW 2018.0157, KAW 2018.0458, KAW 2019.0447); Switzerland: Swiss National Science Foundation (SNSF - PCEFP2_194658); United Kingdom: Leverhulme Trust (Leverhulme Trust RPG-2020-004); United States of America: Neubauer Family Foundation.

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The ATLAS Collaboration

G. Aad^{102, }, E. Aakvaag^{16, }, B. Abbott^{120, }, K. Abeling^{55, }, N.J. Abicht^{49, }, S.H. Abidi^{29, },
A. Aboulhorma^{35e, }, H. Abramowicz^{151, }, H. Abreu^{150, }, Y. Abulaiti^{117, }, B.S. Acharya^{69a,69b, },
C. Adam Bourdarios^{4, }, L. Adamczyk^{86a, }, S.V. Addepalli^{26, }, M.J. Addison^{101, }, J. Adelman^{115, },

A. Adiguzel ^{21c, [id](#)}, T. Adye ^{134, [id](#)}, A.A. Affolder ^{136, [id](#)}, Y. Afik ^{39, [id](#)}, M.N. Agaras ^{13, [id](#)}, J. Agarwala ^{73a,73b, [id](#)},
A. Aggarwal ^{100, [id](#)}, C. Agheorghiesei ^{27c, [id](#)}, A. Ahmad ^{36, [id](#)}, F. Ahmadov ^{38, [id](#), [z](#)}, W.S. Ahmed ^{104, [id](#)}, S. Ahuja ^{95, [id](#)},
X. Ai ^{62e, [id](#)}, G. Aielli ^{76a,76b, [id](#)}, A. Aikot ^{163, [id](#)}, M. Ait Tamlihat ^{35e, [id](#)}, B. Aitbenkikh ^{35a, [id](#)}, I. Aizenberg ^{169, [id](#)},
M. Akbiyik ^{100, [id](#)}, T.P.A. Åkesson ^{98, [id](#)}, A.V. Akimov ^{37, [id](#)}, D. Akiyama ^{168, [id](#)}, N.N. Akolkar ^{24, [id](#)}, S. Aktas ^{21a, [id](#)},
K. Al Houry ^{41, [id](#)}, G.L. Alberghi ^{23b, [id](#)}, J. Albert ^{165, [id](#)}, P. Albicocco ^{53, [id](#)}, G.L. Albouy ^{60, [id](#)}, S. Alderweireldt ^{52, [id](#)},
Z.L. Alegria ^{121, [id](#)}, M. Aleksa ^{36, [id](#)}, I.N. Aleksandrov ^{38, [id](#)}, C. Alexa ^{27b, [id](#)}, T. Alexopoulos ^{10, [id](#)}, F. Alfonsi ^{23b, [id](#)},
M. Algren ^{56, [id](#)}, M. Alhroob ^{141, [id](#)}, B. Ali ^{132, [id](#)}, H.M.J. Ali ^{91, [id](#)}, S. Ali ^{148, [id](#)}, S.W. Alibocus ^{92, [id](#)}, M. Aliev ^{33c, [id](#)},
G. Alimonti ^{71a, [id](#)}, W. Alkakh ^{55, [id](#)}, C. Allaire ^{66, [id](#)}, B.M.M. Allbrooke ^{146, [id](#)}, J.F. Allen ^{52, [id](#)},
C.A. Allendes Flores ^{137f, [id](#)}, P.P. Allport ^{20, [id](#)}, A. Aloisio ^{72a,72b, [id](#)}, F. Alonso ^{90, [id](#)}, C. Alpigliani ^{138, [id](#)},
M. Alvarez Estevez ^{99, [id](#)}, A. Alvarez Fernandez ^{100, [id](#)}, M. Alves Cardoso ^{56, [id](#)}, M.G. Alviggi ^{72a,72b, [id](#)}, M. Aly ^{101, [id](#)},
Y. Amaral Coutinho ^{83b, [id](#)}, A. Ambler ^{104, [id](#)}, C. Amelung ^{36, [id](#)}, M. Amerl ^{101, [id](#)}, C.G. Ames ^{109, [id](#)}, D. Amidei ^{106, [id](#)},
S.P. Amor Dos Santos ^{130a, [id](#)}, K.R. Amos ^{163, [id](#)}, V. Ananiev ^{125, [id](#)}, C. Anastopoulos ^{139, [id](#)}, T. Andeen ^{11, [id](#)},
J.K. Anders ^{36, [id](#)}, S.Y. Andread ^{47a,47b, [id](#)}, A. Andreatza ^{71a,71b, [id](#)}, S. Angelidakis ^{9, [id](#)}, A. Angerami ^{41, [id](#), [ac](#)},
A.V. Anisenkov ^{37, [id](#)}, A. Annovi ^{74a, [id](#)}, C. Antel ^{56, [id](#)}, M.T. Anthony ^{139, [id](#)}, E. Antipov ^{145, [id](#)}, M. Antonelli ^{53, [id](#)},
F. Anulli ^{75a, [id](#)}, M. Aoki ^{84, [id](#)}, T. Aoki ^{153, [id](#)}, J.A. Aparisi Pozo ^{163, [id](#)}, M.A. Aparo ^{146, [id](#)}, L. Aperio Bella ^{48, [id](#)},
C. Appelt ^{18, [id](#)}, A. Apyan ^{26, [id](#)}, S.J. Arbiol Val ^{87, [id](#)}, C. Arcangeletti ^{53, [id](#)}, A.T.H. Arce ^{51, [id](#)}, E. Arena ^{92, [id](#)},
J-F. Arguin ^{108, [id](#)}, S. Argyropoulos ^{54, [id](#)}, J.-H. Arling ^{48, [id](#)}, O. Arnaez ^{4, [id](#)}, H. Arnold ^{114, [id](#)}, G. Artoni ^{75a,75b, [id](#)},
H. Asada ^{111, [id](#)}, K. Asai ^{118, [id](#)}, S. Asai ^{153, [id](#)}, N.A. Asbah ^{36, [id](#)}, K. Assamagan ^{29, [id](#)}, R. Astalos ^{28a, [id](#)}, S. Atashi ^{159, [id](#)},
R.J. Atkin ^{33a, [id](#)}, M. Atkinson ^{162, [id](#)}, H. Atmani ^{35f, [id](#)}, P.A. Atmasiddha ^{128, [id](#)}, K. Augsten ^{132, [id](#)}, S. Auricchio ^{72a,72b, [id](#)},
A.D. Aurion ^{20, [id](#)}, V.A. Austrup ^{101, [id](#)}, G. Avolio ^{36, [id](#)}, K. Axiotis ^{56, [id](#)}, G. Azuelos ^{108, [id](#), [ag](#)}, D. Babal ^{28b, [id](#)},
H. Bachacou ^{135, [id](#)}, K. Bachas ^{152, [id](#), [q](#)}, A. Bachiu ^{34, [id](#)}, F. Backman ^{47a,47b, [id](#)}, A. Badea ^{39, [id](#)}, T.M. Baer ^{106, [id](#)},
P. Bagnaia ^{75a,75b, [id](#)}, M. Bahmani ^{18, [id](#)}, D. Bahner ^{54, [id](#)}, K. Bai ^{123, [id](#)}, A.J. Bailey ^{163, [id](#)}, V.R. Bailey ^{162, [id](#)},
J.T. Baines ^{134, [id](#)}, L. Baines ^{94, [id](#)}, O.K. Baker ^{172, [id](#)}, E. Bakos ^{15, [id](#)}, D. Bakshi Gupta ^{8, [id](#)}, V. Balakrishnan ^{120, [id](#)},
R. Balasubramanian ^{114, [id](#)}, E.M. Baldin ^{37, [id](#)}, P. Balek ^{86a, [id](#)}, E. Ballabene ^{23b,23a, [id](#)}, F. Balli ^{135, [id](#)}, L.M. Baltes ^{63a, [id](#)},
W.K. Balunas ^{32, [id](#)}, J. Balz ^{100, [id](#)}, E. Banas ^{87, [id](#)}, M. Bandieramonte ^{129, [id](#)}, A. Bandyopadhyay ^{24, [id](#)}, S. Bansal ^{24, [id](#)},
L. Barak ^{151, [id](#)}, M. Barakat ^{48, [id](#)}, E.L. Barberio ^{105, [id](#)}, D. Barberis ^{57b,57a, [id](#)}, M. Barbero ^{102, [id](#)}, M.Z. Barel ^{114, [id](#)},
K.N. Barends ^{33a, [id](#)}, T. Barillari ^{110, [id](#)}, M-S. Barisits ^{36, [id](#)}, T. Barklow ^{143, [id](#)}, P. Baron ^{122, [id](#)},
D.A. Baron Moreno ^{101, [id](#)}, A. Baroncelli ^{62a, [id](#)}, G. Barone ^{29, [id](#)}, A.J. Barr ^{126, [id](#)}, J.D. Barr ^{96, [id](#)}, F. Barreiro ^{99, [id](#)},
J. Barreiro Guimarães da Costa ^{14a, [id](#)}, U. Barron ^{151, [id](#)}, M.G. Barros Teixeira ^{130a, [id](#)}, S. Barsov ^{37, [id](#)},
F. Bartels ^{63a, [id](#)}, R. Bartoldus ^{143, [id](#)}, A.E. Barton ^{91, [id](#)}, P. Bartos ^{28a, [id](#)}, A. Basan ^{100, [id](#)}, M. Baselga ^{49, [id](#)},
A. Bassalat ^{66, [id](#), [b](#)}, M.J. Basso ^{156a, [id](#)}, C.R. Basson ^{101, [id](#)}, R.L. Bates ^{59, [id](#)}, S. Batlamous ^{35e, [id](#)}, B. Batool ^{141, [id](#)},
M. Battaglia ^{136, [id](#)}, D. Battulga ^{18, [id](#)}, M. Bauce ^{75a,75b, [id](#)}, M. Bauer ^{36, [id](#)}, P. Bauer ^{24, [id](#)}, L.T. Bazzano Hurrell ^{30, [id](#)},
J.B. Beacham ^{51, [id](#)}, T. Beau ^{127, [id](#)}, J.Y. Beaucamp ^{90, [id](#)}, P.H. Beauchemin ^{158, [id](#)}, P. Bechtel ^{24, [id](#)}, H.P. Beck ^{19, [id](#), [p](#)},
K. Becker ^{167, [id](#)}, A.J. Beddall ^{82, [id](#)}, V.A. Bednyakov ^{38, [id](#)}, C.P. Bee ^{145, [id](#)}, L.J. Beemster ^{15, [id](#)}, T.A. Beermann ^{36, [id](#)},
M. Begalli ^{83d, [id](#)}, M. Begel ^{29, [id](#)}, A. Behera ^{145, [id](#)}, J.K. Behr ^{48, [id](#)}, J.F. Beirer ^{36, [id](#)}, F. Beisiegel ^{24, [id](#)},
M. Belfkir ^{116b, [id](#)}, G. Bella ^{151, [id](#)}, L. Bellagamba ^{23b, [id](#)}, A. Bellerive ^{34, [id](#)}, P. Bellos ^{20, [id](#)}, K. Beloborodov ^{37, [id](#)},
D. Benchekroun ^{35a, [id](#)}, F. Bendebba ^{35a, [id](#)}, Y. Benhammou ^{151, [id](#)}, K.C. Benkendorfer ^{61, [id](#)}, L. Beresford ^{48, [id](#)},
M. Beretta ^{53, [id](#)}, E. Bergeas Kuutmann ^{161, [id](#)}, N. Berger ^{4, [id](#)}, B. Bergmann ^{132, [id](#)}, J. Beringer ^{17a, [id](#)},
G. Bernardi ^{5, [id](#)}, C. Bernius ^{143, [id](#)}, F.U. Bernlochner ^{24, [id](#)}, F. Bernon ^{36,102, [id](#)}, A. Berrocal Guardia ^{13, [id](#)},
T. Berry ^{95, [id](#)}, P. Berta ^{133, [id](#)}, A. Berthold ^{50, [id](#)}, S. Bethke ^{110, [id](#)}, A. Betti ^{75a,75b, [id](#)}, A.J. Bevan ^{94, [id](#)},
N.K. Bhalla ^{54, [id](#)}, M. Bhamjee ^{33c, [id](#)}, S. Bhatta ^{145, [id](#)}, D.S. Bhattacharya ^{166, [id](#)}, P. Bhattarai ^{143, [id](#)}, K.D. Bhide ^{54, [id](#)},
V.S. Bhopatkar ^{121, [id](#)}, R.M. Bianchi ^{129, [id](#)}, G. Bianco ^{23b,23a, [id](#)}, O. Biebel ^{109, [id](#)}, R. Bielski ^{123, [id](#)}, M. Biglietti ^{77a, [id](#)},

C.S. Billingsley⁴⁴, M. Bindi^{55, [id](#)}, A. Bingul^{21b, [id](#)}, C. Bini^{75a,75b, [id](#)}, A. Biondini^{92, [id](#)}, C.J. Birch-sykes^{101, [id](#)}, G.A. Bird^{32, [id](#)}, M. Birman^{169, [id](#)}, M. Biroš^{133, [id](#)}, S. Biryukov^{146, [id](#)}, T. Bisanz^{49, [id](#)}, E. Bisceglie^{43b,43a, [id](#)}, J.P. Biswal^{134, [id](#)}, D. Biswas^{141, [id](#)}, K. Bjørke^{125, [id](#)}, I. Bloch^{48, [id](#)}, A. Blue^{59, [id](#)}, U. Blumenschein^{94, [id](#)}, J. Blumenthal^{100, [id](#)}, V.S. Bobrovnikov^{37, [id](#)}, M. Boehler^{54, [id](#)}, B. Boehm^{166, [id](#)}, D. Bogavac^{36, [id](#)}, A.G. Bogdanchikov^{37, [id](#)}, C. Boehm^{47a, [id](#)}, V. Boisvert^{95, [id](#)}, P. Bokan^{36, [id](#)}, T. Bold^{86a, [id](#)}, M. Bomben^{5, [id](#)}, M. Bona^{94, [id](#)}, M. Boonekamp^{135, [id](#)}, C.D. Booth^{95, [id](#)}, A.G. Borbély^{59, [id](#)}, I.S. Bordulev^{37, [id](#)}, H.M. Borecka-Bielska^{108, [id](#)}, G. Borissov^{91, [id](#)}, D. Bortoletto^{126, [id](#)}, D. Boscherini^{23b, [id](#)}, M. Bosman^{13, [id](#)}, J.D. Bossio Sola^{36, [id](#)}, K. Bouaouda^{35a, [id](#)}, N. Bouchhar^{163, [id](#)}, J. Boudreau^{129, [id](#)}, E.V. Bouhova-Thacker^{91, [id](#)}, D. Boumediene^{40, [id](#)}, R. Bouquet^{57b,57a, [id](#)}, A. Boveia^{119, [id](#)}, J. Boyd^{36, [id](#)}, D. Boye^{29, [id](#)}, I.R. Boyko^{38, [id](#)}, J. Bracinik^{20, [id](#)}, N. Brahimi^{4, [id](#)}, G. Brandt^{171, [id](#)}, O. Brandt^{32, [id](#)}, F. Braren^{48, [id](#)}, B. Brau^{103, [id](#)}, J.E. Brau^{123, [id](#)}, R. Brenner^{169, [id](#)}, L. Brenner^{114, [id](#)}, R. Brenner^{161, [id](#)}, S. Bressler^{169, [id](#)}, D. Britton^{59, [id](#)}, D. Britzger^{110, [id](#)}, I. Brock^{24, [id](#)}, G. Brooijmans^{41, [id](#)}, E. Brost^{29, [id](#)}, L.M. Brown^{165, [id](#)}, L.E. Bruce^{61, [id](#)}, T.L. Bruckler^{126, [id](#)}, P.A. Bruckman de Renstrom^{87, [id](#)}, B. Brüers^{48, [id](#)}, A. Bruni^{23b, [id](#)}, G. Bruni^{23b, [id](#)}, M. Bruschi^{23b, [id](#)}, N. Bruscino^{75a,75b, [id](#)}, T. Buanes^{16, [id](#)}, Q. Buat^{138, [id](#)}, D. Buchin^{110, [id](#)}, A.G. Buckley^{59, [id](#)}, O. Bulekov^{37, [id](#)}, B.A. Bullard^{143, [id](#)}, S. Burdin^{92, [id](#)}, C.D. Burgard^{49, [id](#)}, A.M. Burger^{36, [id](#)}, B. Burghgrave^{8, [id](#)}, O. Burlayenko^{54, [id](#)}, J.T.P. Burr^{32, [id](#)}, C.D. Burton^{11, [id](#)}, J.C. Burzynski^{142, [id](#)}, E.L. Busch^{41, [id](#)}, V. Büscher^{100, [id](#)}, P.J. Bussey^{59, [id](#)}, J.M. Butler^{25, [id](#)}, C.M. Buttar^{59, [id](#)}, J.M. Butterworth^{96, [id](#)}, W. Buttinger^{134, [id](#)}, C.J. Buxo Vazquez^{107, [id](#)}, A.R. Buzykaev^{37, [id](#)}, S. Cabrera Urbán^{163, [id](#)}, L. Cadamuro^{66, [id](#)}, D. Caforio^{58, [id](#)}, H. Cai^{129, [id](#)}, Y. Cai^{14a,14c, [id](#)}, Y. Cai^{14c, [id](#)}, V.M.M. Cairo^{36, [id](#)}, O. Cakir^{3a, [id](#)}, N. Calace^{36, [id](#)}, P. Calafiura^{17a, [id](#)}, G. Calderini^{127, [id](#)}, P. Calfayan^{68, [id](#)}, G. Callea^{59, [id](#)}, L.P. Caloba^{83b, [id](#)}, D. Calvet^{40, [id](#)}, S. Calvet^{40, [id](#)}, M. Calvetti^{74a,74b, [id](#)}, R. Camacho Toro^{127, [id](#)}, S. Camarda^{36, [id](#)}, D. Camarero Munoz^{26, [id](#)}, P. Camarri^{76a,76b, [id](#)}, M.T. Camerlingo^{72a,72b, [id](#)}, D. Cameron^{36, [id](#)}, C. Camincher^{165, [id](#)}, M. Campanelli^{96, [id](#)}, A. Camplani^{42, [id](#)}, V. Canale^{72a,72b, [id](#)}, A.C. Canbay^{3a, [id](#)}, J. Cantero^{163, [id](#)}, Y. Cao^{162, [id](#)}, F. Capocasa^{26, [id](#)}, M. Capua^{43b,43a, [id](#)}, A. Carbone^{71a,71b, [id](#)}, R. Cardarelli^{76a, [id](#)}, J.C.J. Cardenas^{8, [id](#)}, F. Cardillo^{163, [id](#)}, G. Carducci^{43b,43a, [id](#)}, T. Carli^{36, [id](#)}, G. Carlino^{72a, [id](#)}, J.I. Carlotto^{13, [id](#)}, B.T. Carlson^{129, [id](#)}, E.M. Carlson^{165,156a, [id](#)}, L. Carminati^{71a,71b, [id](#)}, A. Carnelli^{135, [id](#)}, M. Carnesale^{75a,75b, [id](#)}, S. Caron^{113, [id](#)}, E. Carquin^{137f, [id](#)}, S. Carrá^{71a, [id](#)}, G. Carratta^{23b,23a, [id](#)}, A.M. Carroll^{123, [id](#)}, T.M. Carter^{52, [id](#)}, M.P. Casado^{13, [id](#)}, M. Caspar^{48, [id](#)}, F.L. Castillo^{4, [id](#)}, L. Castillo Garcia^{13, [id](#)}, V. Castillo Gimenez^{163, [id](#)}, N.F. Castro^{130a,130c, [id](#)}, A. Catinaccio^{36, [id](#)}, J.R. Catmore^{125, [id](#)}, T. Cavaliere^{4, [id](#)}, V. Cavaliere^{29, [id](#)}, N. Cavalli^{23b,23a, [id](#)}, Y.C. Cekmecelioglu^{48, [id](#)}, E. Celebi^{21a, [id](#)}, F. Celli^{126, [id](#)}, M.S. Centonze^{70a,70b, [id](#)}, V. Cepaitis^{56, [id](#)}, K. Cerny^{122, [id](#)}, A.S. Cerqueira^{83a, [id](#)}, A. Cerri^{146, [id](#)}, L. Cerrito^{76a,76b, [id](#)}, F. Cerutti^{17a, [id](#)}, B. Cervato^{141, [id](#)}, A. Cervelli^{23b, [id](#)}, G. Cesarini^{53, [id](#)}, S.A. Cetin^{82, [id](#)}, D. Chakraborty^{115, [id](#)}, J. Chan^{17a, [id](#)}, W.Y. Chan^{153, [id](#)}, J.D. Chapman^{32, [id](#)}, E. Chapon^{135, [id](#)}, B. Chargeishvili^{149b, [id](#)}, D.G. Charlton^{20, [id](#)}, M. Chatterjee^{19, [id](#)}, C. Chauhan^{133, [id](#)}, Y. Che^{14c, [id](#)}, S. Chekanov^{6, [id](#)}, S.V. Chekulaev^{156a, [id](#)}, G.A. Chelkov^{38, [id](#)}, A. Chen^{106, [id](#)}, B. Chen^{151, [id](#)}, B. Chen^{165, [id](#)}, H. Chen^{14c, [id](#)}, H. Chen^{29, [id](#)}, J. Chen^{62c, [id](#)}, J. Chen^{142, [id](#)}, M. Chen^{126, [id](#)}, S. Chen^{153, [id](#)}, S.J. Chen^{14c, [id](#)}, X. Chen^{62c,135, [id](#)}, X. Chen^{14b, [id](#)}, Y. Chen^{62a, [id](#)}, C.L. Cheng^{170, [id](#)}, H.C. Cheng^{64a, [id](#)}, S. Cheong^{143, [id](#)}, A. Cheplakov^{38, [id](#)}, E. Cheremushkina^{48, [id](#)}, E. Cherepanova^{114, [id](#)}, R. Cherkaoui El Moursli^{35e, [id](#)}, E. Cheu^{7, [id](#)}, K. Cheung^{65, [id](#)}, L. Chevalier^{135, [id](#)}, V. Chiarella^{53, [id](#)}, G. Chiarelli^{74a, [id](#)}, N. Chiedde^{102, [id](#)}, G. Chiodini^{70a, [id](#)}, A.S. Chisholm^{20, [id](#)}, A. Chitan^{27b, [id](#)}, M. Chitishvili^{163, [id](#)}, M.V. Chizhov^{38, [id](#)}, K. Choi^{11, [id](#)}, Y. Chou^{138, [id](#)}, E.Y.S. Chow^{113, [id](#)}, K.L. Chu^{169, [id](#)}, M.C. Chu^{64a, [id](#)}, X. Chu^{14a,14c, [id](#)}, J. Chudoba^{131, [id](#)}, J.J. Chwastowski^{87, [id](#)}, D. Cieri^{110, [id](#)}, K.M. Ciesla^{86a, [id](#)}, V. Cindro^{93, [id](#)}, A. Ciocio^{17a, [id](#)}, F. Ciotto^{72a,72b, [id](#)}, Z.H. Citron^{169, [id](#)}, M. Citterio^{71a, [id](#)}, D.A. Ciubotaru^{27b, [id](#)}, A. Clark^{56, [id](#)}, P.J. Clark^{52, [id](#)}, C. Clarry^{155, [id](#)}, J.M. Clavijo Columbie^{48, [id](#)}, S.E. Clawson^{48, [id](#)}, C. Clement^{47a,47b, [id](#)}, J. Clercx^{48, [id](#)}, Y. Coadou^{102, [id](#)}, M. Cobal^{69a,69c, [id](#)}, A. Coccaro^{57b, [id](#)}, R.F. Coelho Barrue^{130a, [id](#)},

R. Coelho Lopes De Sa ^{103, [ib](#)}, S. Coelli ^{71a, [ib](#)}, B. Cole ^{41, [ib](#)}, J. Collot ^{60, [ib](#)}, P. Conde Muiño ^{130a,130g, [ib](#)},
M.P. Connell ^{33c, [ib](#)}, S.H. Connell ^{33c, [ib](#)}, E.I. Conroy ^{126, [ib](#)}, F. Conventi ^{72a, [ib](#), [ah](#)}, H.G. Cooke ^{20, [ib](#)},
A.M. Cooper-Sarkar ^{126, [ib](#)}, A. Cordeiro Oudot Choi ^{127, [ib](#)}, L.D. Corpe ^{40, [ib](#)}, M. Corradi ^{75a,75b, [ib](#)},
F. Corrivau ^{104, [ib](#), [x](#)}, A. Cortes-Gonzalez ^{18, [ib](#)}, M.J. Costa ^{163, [ib](#)}, F. Costanza ^{4, [ib](#)}, D. Costanzo ^{139, [ib](#)},
B.M. Cote ^{119, [ib](#)}, G. Cowan ^{95, [ib](#)}, K. Cranmer ^{170, [ib](#)}, D. Cremonini ^{23b,23a, [ib](#)}, S. Crépé-Renaudin ^{60, [ib](#)},
F. Crescioli ^{127, [ib](#)}, M. Cristinziani ^{141, [ib](#)}, M. Cristoforetti ^{78a,78b, [ib](#)}, V. Croft ^{114, [ib](#)}, J.E. Crosby ^{121, [ib](#)},
G. Crosetti ^{43b,43a, [ib](#)}, A. Cueto ^{99, [ib](#)}, T. Cuhadar Donszelmann ^{159, [ib](#)}, H. Cui ^{14a,14c, [ib](#)}, Z. Cui ^{7, [ib](#)},
W.R. Cunningham ^{59, [ib](#)}, F. Curcio ^{43b,43a, [ib](#)}, P. Czodrowski ^{36, [ib](#)}, M.M. Czurylo ^{63b, [ib](#)},
M.J. Da Cunha Sargedas De Sousa ^{57b,57a, [ib](#)}, J.V. Da Fonseca Pinto ^{83b, [ib](#)}, C. Da Via ^{101, [ib](#)}, W. Dabrowski ^{86a, [ib](#)},
T. Dado ^{49, [ib](#)}, S. Dahbi ^{33g, [ib](#)}, T. Dai ^{106, [ib](#)}, D. Dal Santo ^{19, [ib](#)}, C. Dallapiccola ^{103, [ib](#)}, M. Dam ^{42, [ib](#)}, G. D’amen ^{29, [ib](#)},
V. D’Amico ^{109, [ib](#)}, J. Damp ^{100, [ib](#)}, J.R. Dandoy ^{34, [ib](#)}, M. Danninger ^{142, [ib](#)}, V. Dao ^{36, [ib](#)}, G. Darbo ^{57b, [ib](#)},
S. Darmora ^{6, [ib](#)}, S.J. Das ^{29, [ib](#), [ai](#)}, S. D’Auria ^{71a,71b, [ib](#)}, A. D’avanzo ^{130a, [ib](#)}, C. David ^{33a, [ib](#)}, T. Davidek ^{133, [ib](#)},
B. Davis-Purcell ^{34, [ib](#)}, I. Dawson ^{94, [ib](#)}, H.A. Day-hall ^{132, [ib](#)}, K. De ^{8, [ib](#)}, R. De Asmundis ^{72a, [ib](#)}, N. De Biase ^{48, [ib](#)},
S. De Castro ^{23b,23a, [ib](#)}, N. De Groot ^{113, [ib](#)}, P. de Jong ^{114, [ib](#)}, H. De la Torre ^{115, [ib](#)}, A. De Maria ^{14c, [ib](#)},
A. De Salvo ^{75a, [ib](#)}, U. De Sanctis ^{76a,76b, [ib](#)}, F. De Santis ^{70a,70b, [ib](#)}, A. De Santo ^{146, [ib](#)}, J.B. De Vivie De Regie ^{60, [ib](#)},
D.V. Dedovich ^{38, [ib](#)}, J. Degens ^{114, [ib](#)}, A.M. Deiana ^{44, [ib](#)}, F. Del Corso ^{23b,23a, [ib](#)}, J. Del Peso ^{99, [ib](#)}, F. Del Rio ^{63a, [ib](#)},
L. Delagrangé ^{127, [ib](#)}, F. Deliot ^{135, [ib](#)}, C.M. Delitzsch ^{49, [ib](#)}, M. Della Pietra ^{72a,72b, [ib](#)}, D. Della Volpe ^{56, [ib](#)},
A. Dell’Acqua ^{36, [ib](#)}, L. Dell’Asta ^{71a,71b, [ib](#)}, M. Delmastro ^{4, [ib](#)}, P.A. Delsart ^{60, [ib](#)}, S. Demers ^{172, [ib](#)}, M. Demichev ^{38, [ib](#)},
S.P. Denisov ^{37, [ib](#)}, L. D’Eramo ^{40, [ib](#)}, D. Derendarz ^{87, [ib](#)}, F. Derue ^{127, [ib](#)}, P. Dervan ^{92, [ib](#)}, K. Desch ^{24, [ib](#)},
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 K.Y. Fung^{64a, [id](#)}, E. Furtado De Simas Filho^{83b, [id](#)}, M. Furukawa^{153, [id](#)}, J. Fuster^{163, [id](#)}, A. Gabrielli^{23b,23a, [id](#)},
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 C. García^{163, [id](#)}, A. Garcia Alonso^{114, [id](#)}, A.G. Garcia Caffaro^{172, [id](#)}, J.E. García Navarro^{163, [id](#)},
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 J.M. Gargan⁵², C.A. Garner¹⁵⁵, C.M. Garvey^{33a, [id](#)}, P. Gaspar^{83b, [id](#)}, V.K. Gassmann¹⁵⁸, G. Gaudio^{73a, [id](#)},
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 M. Ghani^{167, [id](#)}, M. Ghneimat^{141, [id](#)}, K. Ghorbanian^{94, [id](#)}, A. Ghosal^{141, [id](#)}, A. Ghosh^{159, [id](#)}, A. Ghosh^{7, [id](#)},
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 L. Ginabat^{127, [id](#)}, D.M. Gingrich^{2, [id](#), [ag](#)}, M.P. Giordani^{69a,69c, [id](#)}, P.F. Giraud^{135, [id](#)}, G. Giugliarelli^{69a,69c, [id](#)},
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 R. Gonzalez Lopez^{92, [id](#)}, C. Gonzalez Renteria^{17a, [id](#)}, M.V. Gonzalez Rodrigues^{48, [id](#)}, R. Gonzalez Suarez^{161, [id](#)},
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Heidegger ^{54, [ib](#)}, W.D. Heidorn ^{81, [ib](#)}, J. Heilman ^{34, [ib](#)}, S. Heim ^{48, [ib](#)}, T. Heim ^{17a, [ib](#)}, J.G. Heinlein ^{128, [ib](#)}, J.J. Heinrich ^{123, [ib](#)}, L. Heinrich ^{110, [ib](#)},^{ae} J. Hejbal ^{131, [ib](#)}, A. Held ^{170, [ib](#)}, S. Hellesund ^{16, [ib](#)}, C.M. Helling ^{164, [ib](#)}, S. Hellman ^{47a,47b, [ib](#)}, R.C.W. Henderson ^{91, [ib](#)}, L. Henkelmann ^{32, [ib](#)}, A.M. Henriques Correia ^{36, [ib](#)}, H. Herde ^{98, [ib](#)}, Y. Hernández Jiménez ^{145, [ib](#)}, L.M. Herrmann ^{24, [ib](#)}, T. Herrmann ^{50, [ib](#)}, G. Herten ^{54, [ib](#)}, R. Hertenberger ^{109, [ib](#)}, L. Hervas ^{36, [ib](#)}, M.E. Hesping ^{100, [ib](#)}, N.P. Hessey ^{156a, [ib](#)}, E. Hill ^{155, [ib](#)}, S.J. Hillier ^{20, [ib](#)}, J.R. Hinds ^{107, [ib](#)}, F. Hinterkeuser ^{24, [ib](#)}, M. Hirose ^{124, [ib](#)}, S. Hirose ^{157, [ib](#)}, D. Hirschbuehl ^{171, [ib](#)}, T.G. Hitchings ^{101, [ib](#)}, B. Hiti ^{93, [ib](#)}, J. 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Ju ^{17a, [ib](#)}, J.J. Jungeburth ^{103, [ib](#)}, T. Junkermann ^{63a, [ib](#)}, A. Juste Rozas ^{13, [ib](#)},^t M.K. Juzek ^{87, [ib](#)}, S. Kabana ^{137e, [ib](#)}, A. Kaczmarska ^{87, [ib](#)}, M. Kado ^{110, [ib](#)}, H. Kagan ^{119, [ib](#)}, M. Kagan ^{143, [ib](#)}, A. Kahn ^{41, [ib](#)}, A. Kahn ^{128, [ib](#)}, C. Kahra ^{100, [ib](#)}, T. Kaji ^{153, [ib](#)}, E. Kajomovitz ^{150, [ib](#)}, N. Kakati ^{169, [ib](#)}, I. Kalaitzidou ^{54, [ib](#)}, C.W. Kalderon ^{29, [ib](#)}, N.J. Kang ^{136, [ib](#)}, D. Kar ^{33g, [ib](#)}, K. Karava ^{126, [ib](#)}, M.J. Kareem ^{156b, [ib](#)}, E. Karentzos ^{54, [ib](#)}, I. Karkanias ^{152, [ib](#)}, O. Karkout ^{114, [ib](#)}, S.N. Karpov ^{38, [ib](#)}, Z.M. Karpova ^{38, [ib](#)}, V. Kartvelishvili ^{91, [ib](#)}, A.N. Karyukhin ^{37, [ib](#)}, E. Kasimi ^{152, [ib](#)}, J. Katzy ^{48, [ib](#)}, S. Kaur ^{34, [ib](#)}, K. Kawade ^{140, [ib](#)}, M.P. Kawale ^{120, [ib](#)}, C. Kawamoto ^{88, [ib](#)}, T. 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V.F. Kazanin ^{37, [ib](#)}, Y. Ke ^{145, [ib](#)}, J.M. Keaveney ^{33a, [ib](#)}, R. Keeler ^{165, [ib](#)}, G.V. Kehris ^{61, [ib](#)}, J.S. Keller ^{34, [ib](#)}, A.S. Kelly ⁹⁶, J.J. Kempster ^{146, [ib](#)}, P.D. Kennedy ^{100, [ib](#)}, O. Kepka ^{131, [ib](#)}, B.P. Kerridge ^{134, [ib](#)}, S. Kersten ^{171, [ib](#)}, B.P. Kerševan ^{93, [ib](#)}, S. Keshri ^{66, [ib](#)}, L. Keszeghova ^{28a, [ib](#)}, S. Ketabchi Haghghat ^{155, [ib](#)}, R.A. Khan ^{129, [ib](#)}, A. Khanov ^{121, [ib](#)}, A.G. Kharlamov ^{37, [ib](#)}, T. Kharlamova ^{37, [ib](#)}, E.E. Khoda ^{138, [ib](#)}, M. Kholodenko ^{37, [ib](#)}, T.J. Khoo ^{18, [ib](#)}, G. Khoriali ^{166, [ib](#)}, J. Khubua ^{149b, [ib](#)}, Y.A.R. Khwaira ^{66, [ib](#)}, B. Kibirige ^{33g}, A. Kilgallon ^{123, [ib](#)}, D.W. Kim ^{47a,47b, [ib](#)}, Y.K. Kim ^{39, [ib](#)}, N. Kimura ^{96, [ib](#)}, M.K. Kingston ^{55, [ib](#)}, A. Kirchoff ^{55, [ib](#)}, C. Kirfel ^{24, [ib](#)}, F. Kirfel ^{24, [ib](#)}, J. 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Lister ^{164, [ib](#)}, J.D. Little ^{4, [ib](#)}, B. Liu ^{14a, [ib](#)}

B.X. Liu ^{142, [id](#)}, D. Liu ^{62d,62c, [id](#)}, J.B. Liu ^{62a, [id](#)}, J.K.K. Liu ^{32, [id](#)}, K. Liu ^{62d,62c, [id](#)}, M. Liu ^{62a, [id](#)}, M.Y. Liu ^{62a, [id](#)},
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 I.M. Maniatis ^{169, [id](#)}, J. Manjarres Ramos ^{102, [id](#),^{ab}}, D.C. Mankad ^{169, [id](#)}, A. Mann ^{109, [id](#)}, S. Manzoni ^{36, [id](#)},
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 M. Marinescu ^{20, [id](#)}, S. Marium ^{48, [id](#)}, M. Marjanovic ^{120, [id](#)}, E.J. Marshall ^{91, [id](#)}, Z. Marshall ^{17a, [id](#)},
 S. Marti-Garcia ^{163, [id](#)}, T.A. Martin ^{167, [id](#)}, V.J. Martin ^{52, [id](#)}, B. Martin dit Latour ^{16, [id](#)}, L. Martinelli ^{75a,75b, [id](#)},
 M. Martinez ^{13, [id](#),^r}, P. Martinez Agullo ^{163, [id](#)}, V.I. Martinez Outschoorn ^{103, [id](#)}, P. Martinez Suarez ^{13, [id](#)},
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 L. Masetti ^{100, [id](#)}, T. Mashimo ^{153, [id](#)}, J. Masik ^{101, [id](#)}, A.L. Maslennikov ^{37, [id](#)}, P. Massarotti ^{72a,72b, [id](#)},
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 M. Mazza ^{107, [id](#)}, S.M. Mazza ^{136, [id](#)}, E. Mazzeo ^{71a,71b, [id](#)}, C. Mc Ginn ^{29, [id](#)}, J.P. Mc Gowan ^{104, [id](#)}, S.P. Mc Kee ^{106, [id](#)},
 C.C. McCracken ^{164, [id](#)}, E.F. McDonald ^{105, [id](#)}, A.E. McDougall ^{114, [id](#)}, J.A. MCFayden ^{146, [id](#)}, R.P. McGovern ^{128, [id](#)},
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 C.M. Mcpartland ^{92, [id](#)}, R.A. McPherson ^{165, [id](#),^x}, S. Mehlhase ^{109, [id](#)}, A. Mehta ^{92, [id](#)}, D. Melini ^{163, [id](#)},
 B.R. Mellado Garcia ^{33g, [id](#)}, A.H. Melo ^{55, [id](#)}, F. Meloni ^{48, [id](#)}, A.M. Mendes Jacques Da Costa ^{101, [id](#)},
 H.Y. Meng ^{155, [id](#)}, L. Meng ^{91, [id](#)}, S. Menke ^{110, [id](#)}, M. Mentink ^{36, [id](#)}, E. Meoni ^{43b,43a, [id](#)}, G. Mercado ^{115, [id](#)},
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 J-P. Meyer ^{135, [id](#)}, R.P. Middleton ^{134, [id](#)}, L. Mijović ^{52, [id](#)}, G. Mikenberg ^{169, [id](#)}, M. Mikesstikova ^{131, [id](#)},
 M. Mikuž ^{93, [id](#)}, H. Mildner ^{100, [id](#)}, A. Milic ^{36, [id](#)}, D.W. Miller ^{39, [id](#)}, E.H. Miller ^{143, [id](#)}, L.S. Miller ^{34, [id](#)},
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 S. Mohapatra ^{41, [id](#)}, G. Mokgatitswane ^{33g, [id](#)}, L. Moleri ^{169, [id](#)}, B. Mondal ^{141, [id](#)}, S. Mondal ^{132, [id](#)}, K. Mönig ^{48, [id](#)},
 E. Monnier ^{102, [id](#)}, L. Monsonis Romero ¹⁶³, J. Montejo Berlingen ^{13, [id](#)}, M. Montella ^{119, [id](#)}, F. Montekali ^{77a,77b, [id](#)},
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 M. Moreno Llácer ^{163, [id](#)}, C. Moreno Martinez ^{56, [id](#)}, P. Morettini ^{57b, [id](#)}, S. Morgenstern ^{36, [id](#)}, M. Morii ^{61, [id](#)},

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I.R. Sotarriva Alvarez ^{154, [id](#)}, V. Sothilingam ^{63a}, O.J. Soto Sandoval ^{137c,137b, [id](#)}, S. Sottocornola ^{68, [id](#)},
R. Soualah ^{160, [id](#)}, Z. Soumami ^{35c, [id](#)}, D. South ^{48, [id](#)}, N. Soybelman ^{169, [id](#)}, S. Spagnolo ^{70a,70b, [id](#)}, M. Spalla ^{110, [id](#)},
D. Sperlich ^{54, [id](#)}, G. Spigo ^{36, [id](#)}, S. Spinali ^{91, [id](#)}, D.P. Spiteri ^{59, [id](#)}, M. Spusta ^{133, [id](#)}, E.J. Staats ^{34, [id](#)},
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M.M. Stanitzki ^{48, [id](#)}, B. Stapf ^{48, [id](#)}, E.A. Starchenko ^{37, [id](#)}, G.H. Stark ^{136, [id](#)}, J. Stark ^{102, [id](#), [ab](#)}, P. Staroba ^{131, [id](#)},
P. Starovoitov ^{63a, [id](#)}, S. Stärz ^{104, [id](#)}, R. Staszewski ^{87, [id](#)}, G. Stavropoulos ^{46, [id](#)}, J. Steentoft ^{161, [id](#)}, P. Steinberg ^{29, [id](#)},
B. Stelzer ^{142,156a, [id](#)}, H.J. Stelzer ^{129, [id](#)}, O. Stelzer-Chilton ^{156a, [id](#)}, H. Stenzel ^{58, [id](#)}, T.J. Stevenson ^{146, [id](#)},
G.A. Stewart ^{36, [id](#)}, J.R. Stewart ^{121, [id](#)}, M.C. Stockton ^{36, [id](#)}, G. Stoicea ^{27b, [id](#)}, M. Stolarski ^{130a, [id](#)}, S. Stonjek ^{110, [id](#)},
A. Straessner ^{50, [id](#)}, J. Strandberg ^{144, [id](#)}, S. Strandberg ^{47a,47b, [id](#)}, M. Stratmann ^{171, [id](#)}, M. Strauss ^{120, [id](#)},
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W. Su ^{62d, [id](#)}, X. Su ^{62a, [id](#)}, K. Sugizaki ^{153, [id](#)}, V.V. Sulin ^{37, [id](#)}, M.J. Sullivan ^{92, [id](#)}, D.M.S. Sultan ^{126, [id](#)},
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M. Swiatlowski ^{156a, [id](#)}, T. Swirski ^{166, [id](#)}, I. Sykora ^{28a, [id](#)}, M. Sykora ^{133, [id](#)}, T. Sykora ^{133, [id](#)}, D. Ta ^{100, [id](#)},
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 G.N. Taylor ^{105, [id](#)}, W. Taylor ^{156b, [id](#)}, A.S. Tee ^{170, [id](#)}, R. Teixeira De Lima ^{143, [id](#)}, P. Teixeira-Dias ^{95, [id](#)},
 J.J. Teoh ^{155, [id](#)}, K. Terashi ^{153, [id](#)}, J. Terron ^{99, [id](#)}, S. Terzo ^{13, [id](#)}, M. Testa ^{53, [id](#)}, R.J. Teuscher ^{155, [id](#), [x](#)}, A. Thaler ^{79, [id](#)},
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 S.H. Tlou ^{33g, [id](#)}, A. Tnourji ^{40, [id](#)}, K. Todome ^{154, [id](#)}, S. Todorova-Nova ^{133, [id](#)}, S. Todt ⁵⁰, M. Togawa ^{84, [id](#)},
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 L. Tompkins ^{143, [id](#), [n](#)}, K.W. Topolnicki ^{86b, [id](#)}, E. Torrence ^{123, [id](#)}, H. Torres ^{102, [id](#), [ab](#)}, E. Torró Pastor ^{163, [id](#)},
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 P.V. Tsiareshka ³⁷, S. Tsigaridas ^{156a, [id](#)}, A. Tsigotis ^{152, [id](#), [s](#)}, V. Tsiskaridze ^{155, [id](#)}, E.G. Tskhadadze ^{149a, [id](#)},
 M. Tsooulou ^{152, [id](#)}, Y. Tsujikawa ^{88, [id](#)}, I.I. Tsukerman ^{37, [id](#)}, V. Tsulaia ^{17a, [id](#)}, S. Tsuno ^{84, [id](#)}, K. Tsuru ^{118, [id](#)},
 D. Tsybychev ^{145, [id](#)}, Y. Tu ^{64b, [id](#)}, A. Tudorache ^{27b, [id](#)}, V. Tudorache ^{27b, [id](#)}, A.N. Tuna ^{61, [id](#)}, S. Turchikhin ^{57b,57a, [id](#)},
 I. Turk Cakir ^{3a, [id](#)}, R. Turra ^{71a, [id](#)}, T. Turtuvshin ^{38, [id](#), [y](#)}, P.M. Tuts ^{41, [id](#)}, S. Tzamarias ^{152, [id](#), [e](#)}, P. Tzanis ^{10, [id](#)},
 E. Tzovara ^{100, [id](#)}, F. Ukegawa ^{157, [id](#)}, P.A. Ulloa Poblete ^{137c,137b, [id](#)}, E.N. Umaka ^{29, [id](#)}, G. Unal ^{36, [id](#)}, M. Unal ^{11, [id](#)},
 A. Undrus ^{29, [id](#)}, G. Unel ^{159, [id](#)}, J. Urban ^{28b, [id](#)}, P. Urquijo ^{105, [id](#)}, P. Urrejola ^{137a, [id](#)}, G. Usai ^{8, [id](#)}, R. Ushioda ^{154, [id](#)},
 M. Usman ^{108, [id](#)}, Z. Uysal ^{82, [id](#)}, V. Vacek ^{132, [id](#)}, B. Vachon ^{104, [id](#)}, K.O.H. Vadla ^{125, [id](#)}, T. Vafeiadis ^{36, [id](#)},
 A. Vaitkus ^{96, [id](#)}, C. Valderanis ^{109, [id](#)}, E. Valdes Santurio ^{47a,47b, [id](#)}, M. Valente ^{156a, [id](#)}, S. Valentineti ^{23b,23a, [id](#)},
 A. Valero ^{163, [id](#)}, E. Valiente Moreno ^{163, [id](#)}, A. Vallier ^{102, [id](#), [ab](#)}, J.A. Valls Ferrer ^{163, [id](#)}, D.R. Van Arneman ^{114, [id](#)},
 T.R. Van Daalen ^{138, [id](#)}, A. Van Der Graaf ^{49, [id](#)}, P. Van Gemmeren ^{6, [id](#)}, M. Van Rijnbach ^{125, [id](#)}, S. Van Stroud ^{96, [id](#)},
 I. Van Vulpen ^{114, [id](#)}, M. Vanadia ^{76a,76b, [id](#)}, W. Vandelli ^{36, [id](#)}, E.R. Vandewall ^{121, [id](#)}, D. Vannicola ^{151, [id](#)},
 L. Vannoli ^{57b,57a, [id](#)}, R. Vari ^{75a, [id](#)}, E.W. Varnes ^{7, [id](#)}, C. Varni ^{17b, [id](#)}, T. Varol ^{148, [id](#)}, D. Varouchas ^{66, [id](#)},
 L. Varriale ^{163, [id](#)}, K.E. Varvell ^{147, [id](#)}, M.E. Vasile ^{27b, [id](#)}, L. Vaslin ⁸⁴, G.A. Vasquez ^{165, [id](#)}, A. Vasyukov ^{38, [id](#)},
 R. Vavricka ¹⁰⁰, F. Vazeille ^{40, [id](#)}, T. Vazquez Schroeder ^{36, [id](#)}, J. Veatch ^{31, [id](#)}, V. Vecchio ^{101, [id](#)}, M.J. Veen ^{103, [id](#)},
 I. Veliscek ^{126, [id](#)}, L.M. Veloce ^{155, [id](#)}, F. Veloso ^{130a,130c, [id](#)}, S. Veneziano ^{75a, [id](#)}, A. Ventura ^{70a,70b, [id](#)},
 S. Ventura Gonzalez ^{135, [id](#)}, A. Verbytskyi ^{110, [id](#)}, M. Verducci ^{74a,74b, [id](#)}, C. Vergis ^{24, [id](#)},
 M. Verissimo De Araujo ^{83b, [id](#)}, W. Verkerke ^{114, [id](#)}, J.C. Vermeulen ^{114, [id](#)}, C. Vernieri ^{143, [id](#)}, M. Vessella ^{103, [id](#)},
 M.C. Vetterli ^{142, [id](#), [ag](#)}, A. Vgenopoulos ^{152, [id](#), [e](#)}, N. Viaux Maira ^{137f, [id](#)}, T. Vickey ^{139, [id](#)}, O.E. Vickey Boeriu ^{139, [id](#)},
 G.H.A. Viehhauser ^{126, [id](#)}, L. Vigani ^{63b, [id](#)}, M. Villa ^{23b,23a, [id](#)}, M. Villaplana Perez ^{163, [id](#)}, E.M. Villhauer ⁵²,
 E. Vilucchi ^{53, [id](#)}, M.G. Vincter ^{34, [id](#)}, G.S. Virdee ^{20, [id](#)}, A. Vishwakarma ^{52, [id](#)}, A. Visibile ¹¹⁴, C. Vittori ^{36, [id](#)},
 I. Vivarelli ^{23b,23a, [id](#)}, E. Voevodina ^{110, [id](#)}, F. Vogel ^{109, [id](#)}, J.C. Voigt ^{50, [id](#)}, P. Vokac ^{132, [id](#)}, Yu. Volkotrub ^{86a, [id](#)},
 J. Von Ahnen ^{48, [id](#)}, E. Von Toerne ^{24, [id](#)}, B. Vormwald ^{36, [id](#)}, V. Vorobel ^{133, [id](#)}, K. Vorobev ^{37, [id](#)}, M. Vos ^{163, [id](#)},
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 C. Wagner ¹⁰³, J.M. Wagner ^{17a, [id](#)}, W. Wagner ^{171, [id](#)}, S. Wahdan ^{171, [id](#)}, H. Wahlberg ^{90, [id](#)}, M. Wakida ^{111, [id](#)},

J. Walder^{134, [ID](#)}, R. Walker^{109, [ID](#)}, W. Walkowiak^{141, [ID](#)}, A. Wall^{128, [ID](#)}, E.J. Wallin^{98, [ID](#)}, T. Wamorkar^{6, [ID](#)},
A.Z. Wang^{136, [ID](#)}, C. Wang^{100, [ID](#)}, C. Wang^{11, [ID](#)}, H. Wang^{17a, [ID](#)}, J. Wang^{64c, [ID](#)}, R.-J. Wang^{100, [ID](#)}, R. Wang^{61, [ID](#)},
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X. Wang^{162, [ID](#)}, X. Wang^{62c, [ID](#)}, Y. Wang^{62d, [ID](#)}, Y. Wang^{14c, [ID](#)}, Z. Wang^{106, [ID](#)}, Z. Wang^{62d,51,62c, [ID](#)}, Z. Wang^{106, [ID](#)},
A. Warburton^{104, [ID](#)}, R.J. Ward^{20, [ID](#)}, N. Warrack^{59, [ID](#)}, S. Waterhouse^{95, [ID](#)}, A.T. Watson^{20, [ID](#)}, H. Watson^{59, [ID](#)},
M.F. Watson^{20, [ID](#)}, E. Watton^{59,134, [ID](#)}, G. Watts^{138, [ID](#)}, B.M. Waugh^{96, [ID](#)}, C. Weber^{29, [ID](#)}, H.A. Weber^{18, [ID](#)},
M.S. Weber^{19, [ID](#)}, S.M. Weber^{63a, [ID](#)}, C. Wei^{62a, [ID](#)}, Y. Wei^{126, [ID](#)}, A.R. Weidberg^{126, [ID](#)}, E.J. Weik^{117, [ID](#)},
J. Weingarten^{49, [ID](#)}, M. Weirich^{100, [ID](#)}, C. Weiser^{54, [ID](#)}, C.J. Wells^{48, [ID](#)}, T. Wenaus^{29, [ID](#)}, B. Wendland^{49, [ID](#)},
T. Wengler^{36, [ID](#)}, N.S. Wenke¹¹⁰, N. Wermes^{24, [ID](#)}, M. Wessels^{63a, [ID](#)}, A.M. Wharton^{91, [ID](#)}, A.S. White^{61, [ID](#)},
A. White^{8, [ID](#)}, M.J. White^{1, [ID](#)}, D. Whiteson^{159, [ID](#)}, L. Wickremasinghe^{124, [ID](#)}, W. Wiedenmann^{170, [ID](#)},
M. Wielers^{134, [ID](#)}, C. Wiglesworth^{42, [ID](#)}, D.J. Wilbern¹²⁰, H.G. Wilkens^{36, [ID](#)}, D.M. Williams^{41, [ID](#)},
H.H. Williams¹²⁸, S. Williams^{32, [ID](#)}, S. Willocq^{103, [ID](#)}, B.J. Wilson^{101, [ID](#)}, P.J. Windischhofer^{39, [ID](#)}, F.I. Winkel^{30, [ID](#)},
F. Winklmeier^{123, [ID](#)}, B.T. Winter^{54, [ID](#)}, J.K. Winter^{101, [ID](#)}, M. Wittgen¹⁴³, M. Wobisch^{97, [ID](#)}, Z. Wolffs^{114, [ID](#)},
J. Wollrath¹⁵⁹, M.W. Wolter^{87, [ID](#)}, H. Wolters^{130a,130c, [ID](#)}, E.L. Woodward^{41, [ID](#)}, S.D. Worm^{48, [ID](#)}, B.K. Wosiek^{87, [ID](#)},
K.W. Woźniak^{87, [ID](#)}, S. Wozniowski^{55, [ID](#)}, K. Wraight^{59, [ID](#)}, C. Wu^{20, [ID](#)}, M. Wu^{14d, [ID](#)}, M. Wu^{113, [ID](#)}, S.L. Wu^{170, [ID](#)},
X. Wu^{56, [ID](#)}, Y. Wu^{62a, [ID](#)}, Z. Wu^{135, [ID](#)}, J. Wuerzinger^{110, [ID](#)},^{ae}, T.R. Wyatt^{101, [ID](#)}, B.M. Wynne^{52, [ID](#)}, S. Xella^{42, [ID](#)},
L. Xia^{14c, [ID](#)}, M. Xia^{14b, [ID](#)}, J. Xiang^{64c, [ID](#)}, M. Xie^{62a, [ID](#)}, X. Xie^{62a, [ID](#)}, S. Xin^{14a,14c, [ID](#)}, A. Xiong^{123, [ID](#)}, J. Xiong^{17a, [ID](#)},
D. Xu^{14a, [ID](#)}, H. Xu^{62a, [ID](#)}, L. Xu^{62a, [ID](#)}, R. Xu^{128, [ID](#)}, T. Xu^{106, [ID](#)}, Y. Xu^{14b, [ID](#)}, Z. Xu^{52, [ID](#)}, Z. Xu^{14c}, B. Yabsley^{147, [ID](#)},
S. Yacoob^{33a, [ID](#)}, Y. Yamaguchi^{154, [ID](#)}, E. Yamashita^{153, [ID](#)}, H. Yamauchi^{157, [ID](#)}, T. Yamazaki^{17a, [ID](#)},
Y. Yamazaki^{85, [ID](#)}, J. Yan^{62c}, S. Yan^{59, [ID](#)}, Z. Yan^{103, [ID](#)}, H.J. Yang^{62c,62d, [ID](#)}, H.T. Yang^{62a, [ID](#)}, S. Yang^{62a, [ID](#)},
T. Yang^{64c, [ID](#)}, X. Yang^{36, [ID](#)}, X. Yang^{14a, [ID](#)}, Y. Yang^{44, [ID](#)}, Y. Yang^{62a}, Z. Yang^{62a, [ID](#)}, W.-M. Yao^{17a, [ID](#)}, H. Ye^{14c, [ID](#)},
H. Ye^{55, [ID](#)}, J. Ye^{14a, [ID](#)}, S. Ye^{29, [ID](#)}, X. Ye^{62a, [ID](#)}, Y. Yeh^{96, [ID](#)}, I. Yeletsikh^{38, [ID](#)}, B.K. Yeo^{17b, [ID](#)}, M.R. Yexley^{96, [ID](#)},
P. Yin^{41, [ID](#)}, K. Yorita^{168, [ID](#)}, S. Younas^{27b, [ID](#)}, C.J.S. Young^{36, [ID](#)}, C. Young^{143, [ID](#)}, C. Yu^{14a,14c, [ID](#)}, Y. Yu^{62a, [ID](#)},
M. Yuan^{106, [ID](#)}, R. Yuan^{62b, [ID](#)}, L. Yue^{96, [ID](#)}, M. Zaazoua^{62a, [ID](#)}, B. Zabinski^{87, [ID](#)}, E. Zaid⁵², Z.K. Zak^{87, [ID](#)},
T. Zakareishvili^{163, [ID](#)}, N. Zakharchuk^{34, [ID](#)}, S. Zambito^{56, [ID](#)}, J.A. Zamora Saa^{137d,137b, [ID](#)}, J. Zang^{153, [ID](#)},
D. Zanzi^{54, [ID](#)}, O. Zaplatilek^{132, [ID](#)}, C. Zeitnitz^{171, [ID](#)}, H. Zeng^{14a, [ID](#)}, J.C. Zeng^{162, [ID](#)}, D.T. Zenger Jr^{26, [ID](#)},
O. Zenin^{37, [ID](#)}, T. Ženiš^{28a, [ID](#)}, S. Zenz^{94, [ID](#)}, S. Zerradi^{35a, [ID](#)}, D. Zerwas^{66, [ID](#)}, M. Zhai^{14a,14c, [ID](#)}, D.F. Zhang^{139, [ID](#)},
J. Zhang^{62b, [ID](#)}, J. Zhang^{6, [ID](#)}, K. Zhang^{14a,14c, [ID](#)}, L. Zhang^{14c, [ID](#)}, P. Zhang^{14a,14c, [ID](#)}, R. Zhang^{170, [ID](#)}, S. Zhang^{106, [ID](#)},
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J. Zheng^{14c, [ID](#)}, K. Zheng^{162, [ID](#)}, X. Zheng^{62a, [ID](#)}, Z. Zheng^{143, [ID](#)}, D. Zhong^{162, [ID](#)}, B. Zhou^{106, [ID](#)}, H. Zhou^{7, [ID](#)},
N. Zhou^{62c, [ID](#)}, Y. Zhou^{14c, [ID](#)}, Y. Zhou⁷, C.G. Zhu^{62b, [ID](#)}, J. Zhu^{106, [ID](#)}, Y. Zhu^{62c, [ID](#)}, Y. Zhu^{62a, [ID](#)}, X. Zhuang^{14a, [ID](#)},
K. Zhukov^{37, [ID](#)}, N.I. Zimine^{38, [ID](#)}, J. Zinsser^{63b, [ID](#)}, M. Ziolkowski^{141, [ID](#)}, L. Živković^{15, [ID](#)}, A. Zoccoli^{23b,23a, [ID](#)},
K. Zoch^{61, [ID](#)}, T.G. Zorbass^{139, [ID](#)}, O. Zormpa^{46, [ID](#)}, W. Zou^{41, [ID](#)}, L. Zwalinski^{36, [ID](#)}

¹ Department of Physics, University of Adelaide, Adelaide; Australia² Department of Physics, University of Alberta, Edmonton AB; Canada³ (a) Department of Physics, Ankara University, Ankara; (b) Division of Physics, TOBB University of Economics and Technology, Ankara; Türkiye⁴ LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; France⁵ APC, Université Paris Cité, CNRS/IN2P3, Paris; France⁶ High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America⁷ Department of Physics, University of Arizona, Tucson AZ; United States of America⁸ Department of Physics, University of Texas at Arlington, Arlington TX; United States of America⁹ Physics Department, National and Kapodistrian University of Athens, Athens; Greece¹⁰ Physics Department, National Technical University of Athens, Zografou; Greece¹¹ Department of Physics, University of Texas at Austin, Austin TX; United States of America¹² Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan¹³ Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain¹⁴ (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Physics Department, Tsinghua University, Beijing; (c) Department of Physics, Nanjing University, Nanjing; (d) School of Science, Shenzhen Campus of Sun Yat-sen University China; (e) University of Chinese Academy of Science (UCAS), Beijing; China

- ¹⁵ Institute of Physics, University of Belgrade, Belgrade; Serbia
- ¹⁶ Department for Physics and Technology, University of Bergen, Bergen; Norway
- ¹⁷ ^(a) Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA; ^(b) University of California, Berkeley CA; United States of America
- ¹⁸ Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany
- ¹⁹ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland
- ²⁰ School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom
- ²¹ ^(a) Department of Physics, Bogaziçi University, Istanbul; ^(b) Department of Physics Engineering, Gaziantep University, Gaziantep; ^(c) Department of Physics, Istanbul University, Istanbul; Türkiye
- ²² ^(a) Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogotá; ^(b) Departamento de Física, Universidad Nacional de Colombia, Bogotá; Colombia
- ²³ ^(a) Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna; ^(b) INFN Sezione di Bologna; Italy
- ²⁴ Physikalisches Institut, Universität Bonn, Bonn; Germany
- ²⁵ Department of Physics, Boston University, Boston MA; United States of America
- ²⁶ Department of Physics, Brandeis University, Waltham MA; United States of America
- ²⁷ ^(a) Transilvania University of Brasov, Brasov; ^(b) Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; ^(c) Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi; ^(d) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca; ^(e) National University of Science and Technology Politehnica, Bucharest; ^(f) West University in Timisoara, Timisoara; ^(g) Faculty of Physics, University of Bucharest, Bucharest; Romania
- ²⁸ ^(a) Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava; ^(b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic
- ²⁹ Physics Department, Brookhaven National Laboratory, Upton NY; United States of America
- ³⁰ Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires; Argentina
- ³¹ California State University, CA; United States of America
- ³² Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom
- ³³ ^(a) Department of Physics, University of Cape Town, Cape Town; ^(b) iThemba Labs, Western Cape; ^(c) Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg; ^(d) National Institute of Physics, University of the Philippines Diliman (Philippines); ^(e) University of South Africa, Department of Physics, Pretoria; ^(f) University of Zululand, KwaDlangezwa; ^(g) School of Physics, University of the Witwatersrand, Johannesburg; South Africa
- ³⁴ Department of Physics, Carleton University, Ottawa ON; Canada
- ³⁵ ^(a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca; ^(b) Faculté des Sciences, Université Ibn-Tofail, Kénitra; ^(c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA, Marrakech; ^(d) LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda; ^(e) Faculté des sciences, Université Mohammed V, Rabat; ^(f) Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco
- ³⁶ CERN, Geneva; Switzerland
- ³⁷ Affiliated with an institute covered by a cooperation agreement with CERN
- ³⁸ Affiliated with an international laboratory covered by a cooperation agreement with CERN
- ³⁹ Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America
- ⁴⁰ LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France
- ⁴¹ Nevis Laboratory, Columbia University, Irvington NY; United States of America
- ⁴² Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark
- ⁴³ ^(a) Dipartimento di Fisica, Università della Calabria, Rende; ^(b) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy
- ⁴⁴ Physics Department, Southern Methodist University, Dallas TX; United States of America
- ⁴⁵ Physics Department, University of Texas at Dallas, Richardson TX; United States of America
- ⁴⁶ National Centre for Scientific Research “Demokritos”, Agia Paraskevi; Greece
- ⁴⁷ ^(a) Department of Physics, Stockholm University; ^(b) Oskar Klein Centre, Stockholm; Sweden
- ⁴⁸ Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany
- ⁴⁹ Fakultät Physik, Technische Universität Dortmund, Dortmund; Germany
- ⁵⁰ Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany
- ⁵¹ Department of Physics, Duke University, Durham NC; United States of America
- ⁵² SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom
- ⁵³ INFN e Laboratori Nazionali di Frascati, Frascati; Italy
- ⁵⁴ Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany
- ⁵⁵ II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany
- ⁵⁶ Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland
- ⁵⁷ ^(a) Dipartimento di Fisica, Università di Genova, Genova; ^(b) INFN Sezione di Genova; Italy
- ⁵⁸ II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany
- ⁵⁹ SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom
- ⁶⁰ LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France
- ⁶¹ Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America
- ⁶² ^(a) Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; ^(b) Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao; ^(c) School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai; ^(d) Tsung-Dao Lee Institute, Shanghai; ^(e) School of Physics and Microelectronics, Zhengzhou University; China
- ⁶³ ^(a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; ^(b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany
- ⁶⁴ ^(a) Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong; ^(b) Department of Physics, University of Hong Kong, Hong Kong; ^(c) Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong; China
- ⁶⁵ Department of Physics, National Tsing Hua University, Hsinchu; Taiwan
- ⁶⁶ IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France
- ⁶⁷ Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona; Spain
- ⁶⁸ Department of Physics, Indiana University, Bloomington IN; United States of America
- ⁶⁹ ^(a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; ^(b) ICTP, Trieste; ^(c) Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine; Italy
- ⁷⁰ ^(a) INFN Sezione di Lecce; ^(b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy
- ⁷¹ ^(a) INFN Sezione di Milano; ^(b) Dipartimento di Fisica, Università di Milano, Milano; Italy
- ⁷² ^(a) INFN Sezione di Napoli; ^(b) Dipartimento di Fisica, Università di Napoli, Napoli; Italy
- ⁷³ ^(a) INFN Sezione di Pavia; ^(b) Dipartimento di Fisica, Università di Pavia, Pavia; Italy
- ⁷⁴ ^(a) INFN Sezione di Pisa; ^(b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy
- ⁷⁵ ^(a) INFN Sezione di Roma; ^(b) Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy
- ⁷⁶ ^(a) INFN Sezione di Roma Tor Vergata; ^(b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy
- ⁷⁷ ^(a) INFN Sezione di Roma Tre; ^(b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy
- ⁷⁸ ^(a) INFN-TIFPA; ^(b) Università degli Studi di Trento, Trento; Italy
- ⁷⁹ Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria
- ⁸⁰ University of Iowa, Iowa City IA; United States of America
- ⁸¹ Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America
- ⁸² Istinye University, Sariyer, Istanbul; Türkiye

- ⁸³ ^(a) Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora; ^(b) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; ^(c) Instituto de Física, Universidade de São Paulo, São Paulo; ^(d) Rio de Janeiro State University, Rio de Janeiro; Brazil
- ⁸⁴ KEK, High Energy Accelerator Research Organization, Tsukuba; Japan
- ⁸⁵ Graduate School of Science, Kobe University, Kobe; Japan
- ⁸⁶ ^(a) AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow; ^(b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland
- ⁸⁷ Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland
- ⁸⁸ Faculty of Science, Kyoto University, Kyoto; Japan
- ⁸⁹ Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka; Japan
- ⁹⁰ Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina
- ⁹¹ Physics Department, Lancaster University, Lancaster; United Kingdom
- ⁹² Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom
- ⁹³ Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia
- ⁹⁴ School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom
- ⁹⁵ Department of Physics, Royal Holloway University of London, Egham; United Kingdom
- ⁹⁶ Department of Physics and Astronomy, University College London, London; United Kingdom
- ⁹⁷ Louisiana Tech University, Ruston LA; United States of America
- ⁹⁸ Fysiska institutionen, Lunds universitet, Lund; Sweden
- ⁹⁹ Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain
- ¹⁰⁰ Institut für Physik, Universität Mainz, Mainz; Germany
- ¹⁰¹ School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom
- ¹⁰² CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France
- ¹⁰³ Department of Physics, University of Massachusetts, Amherst MA; United States of America
- ¹⁰⁴ Department of Physics, McGill University, Montreal QC; Canada
- ¹⁰⁵ School of Physics, University of Melbourne, Victoria; Australia
- ¹⁰⁶ Department of Physics, University of Michigan, Ann Arbor MI; United States of America
- ¹⁰⁷ Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America
- ¹⁰⁸ Group of Particle Physics, University of Montreal, Montreal QC; Canada
- ¹⁰⁹ Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany
- ¹¹⁰ Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany
- ¹¹¹ Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan
- ¹¹² Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America
- ¹¹³ Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands
- ¹¹⁴ Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands
- ¹¹⁵ Department of Physics, Northern Illinois University, DeKalb IL; United States of America
- ¹¹⁶ ^(a) New York University Abu Dhabi, Abu Dhabi; ^(b) United Arab Emirates University, Al Ain; United Arab Emirates
- ¹¹⁷ Department of Physics, New York University, New York NY; United States of America
- ¹¹⁸ Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan
- ¹¹⁹ Ohio State University, Columbus OH; United States of America
- ¹²⁰ Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America
- ¹²¹ Department of Physics, Oklahoma State University, Stillwater OK; United States of America
- ¹²² Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic
- ¹²³ Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America
- ¹²⁴ Graduate School of Science, Osaka University, Osaka; Japan
- ¹²⁵ Department of Physics, University of Oslo, Oslo; Norway
- ¹²⁶ Department of Physics, Oxford University, Oxford; United Kingdom
- ¹²⁷ LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris; France
- ¹²⁸ Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America
- ¹²⁹ Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America
- ¹³⁰ ^(a) Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa; ^(b) Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa; ^(c) Departamento de Física, Universidade de Coimbra, Coimbra; ^(d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; ^(e) Departamento de Física, Universidade do Minho, Braga; ^(f) Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain); ^(g) Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal
- ¹³¹ Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic
- ¹³² Czech Technical University in Prague, Prague; Czech Republic
- ¹³³ Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic
- ¹³⁴ Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom
- ¹³⁵ IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France
- ¹³⁶ Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America
- ¹³⁷ ^(a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; ^(b) Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago; ^(c) Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena; ^(d) Universidad Andres Bello, Department of Physics, Santiago; ^(e) Instituto de Alta Investigación, Universidad de Tarapacá, Arica; ^(f) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile
- ¹³⁸ Department of Physics, University of Washington, Seattle WA; United States of America
- ¹³⁹ Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom
- ¹⁴⁰ Department of Physics, Shinshu University, Nagano; Japan
- ¹⁴¹ Department Physik, Universität Siegen, Siegen; Germany
- ¹⁴² Department of Physics, Simon Fraser University, Burnaby BC; Canada
- ¹⁴³ SLAC National Accelerator Laboratory, Stanford CA; United States of America
- ¹⁴⁴ Department of Physics, Royal Institute of Technology, Stockholm; Sweden
- ¹⁴⁵ Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America
- ¹⁴⁶ Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom
- ¹⁴⁷ School of Physics, University of Sydney, Sydney; Australia
- ¹⁴⁸ Institute of Physics, Academia Sinica, Taipei; Taiwan
- ¹⁴⁹ ^(a) E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi; ^(b) High Energy Physics Institute, Tbilisi State University, Tbilisi; ^(c) University of Georgia, Tbilisi; Georgia
- ¹⁵⁰ Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel
- ¹⁵¹ Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel
- ¹⁵² Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece
- ¹⁵³ International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan
- ¹⁵⁴ Department of Physics, Tokyo Institute of Technology, Tokyo; Japan
- ¹⁵⁵ Department of Physics, University of Toronto, Toronto ON; Canada
- ¹⁵⁶ ^(a) TRIUMF, Vancouver BC; ^(b) Department of Physics and Astronomy, York University, Toronto ON; Canada

- ¹⁵⁷ Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan
¹⁵⁸ Department of Physics and Astronomy, Tufts University, Medford MA; United States of America
¹⁵⁹ Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America
¹⁶⁰ University of Sharjah, Sharjah; United Arab Emirates
¹⁶¹ Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden
¹⁶² Department of Physics, University of Illinois, Urbana IL; United States of America
¹⁶³ Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia – CSIC, Valencia; Spain
¹⁶⁴ Department of Physics, University of British Columbia, Vancouver BC; Canada
¹⁶⁵ Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada
¹⁶⁶ Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany
¹⁶⁷ Department of Physics, University of Warwick, Coventry; United Kingdom
¹⁶⁸ Waseda University, Tokyo; Japan
¹⁶⁹ Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel
¹⁷⁰ Department of Physics, University of Wisconsin, Madison WI; United States of America
¹⁷¹ Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany
¹⁷² Department of Physics, Yale University, New Haven CT; United States of America

- ^a Also Affiliated with an institute covered by a cooperation agreement with CERN.
^b Also at An-Najah National University, Nablus; Palestine.
^c Also at Borough of Manhattan Community College, City University of New York, New York NY; United States of America.
^d Also at Center for High Energy Physics, Peking University; China.
^e Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki; Greece.
^f Also at Centro Studi e Ricerche Enrico Fermi; Italy.
^g Also at CERN, Geneva; Switzerland.
^h Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
ⁱ Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona; Spain.
^j Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
^k Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva; Israel.
^l Also at Department of Physics, California State University, Sacramento; United States of America.
^m Also at Department of Physics, King's College London, London; United Kingdom.
ⁿ Also at Department of Physics, Stanford University, Stanford CA; United States of America.
^o Also at Department of Physics, Stellenbosch University; South Africa.
^p Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
^q Also at Department of Physics, University of Thessaly; Greece.
^r Also at Department of Physics, Westmont College, Santa Barbara; United States of America.
^s Also at Hellenic Open University, Patras; Greece.
^t Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
^u Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
^v Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria.
^w Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.
^x Also at Institute of Particle Physics (IPP); Canada.
^y Also at Institute of Physics and Technology, Mongolian Academy of Sciences, Ulaanbaatar; Mongolia.
^z Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
^{aa} Also at Institute of Theoretical Physics, Ilija State University, Tbilisi; Georgia.
^{ab} Also at L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse; France.
^{ac} Also at Lawrence Livermore National Laboratory, Livermore; United States of America.
^{ad} Also at National Institute of Physics, University of the Philippines Diliman (Philippines); Philippines.
^{ae} Also at Technical University of Munich, Munich; Germany.
^{af} Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
^{ag} Also at TRIUMF, Vancouver BC; Canada.
^{ah} Also at Università di Napoli Parthenope, Napoli; Italy.
^{ai} Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America.
^{aj} Also at Washington College, Chestertown, MD; United States of America.
^{ak} Also at Yeditepe University, Physics Department, Istanbul; Türkiye.
^{*} Deceased.