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Combination of searches for invisible decays of the Higgs boson using 139 fb^{-1} of proton-proton collision data at √s = 13 TeV collected with the ATLAS experiment

The ATLAS Collaboration

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Combination of searches for invisible decays of the Higgs boson using 139 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13$ TeV collected with the ATLAS experiment

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ABSTRACT

Many extensions of the Standard Model predict the production of dark matter particles at the LHC. Sufficiently light dark matter particles may be produced in decays of the Higgs boson that would appear invisible to the detector. This Letter presents a statistical combination of searches for $H \rightarrow$ invisible decays where multiple production modes of the Standard Model Higgs boson are considered. These searches are performed with the ATLAS detector using 139 fb^{-1} of proton–proton collisions at a centre–of–mass energy of $\sqrt{s} = 13$ TeV at the LHC. In combination with the results at $\sqrt{s} = 7$ TeV and 8 TeV, an upper limit on the $H \rightarrow$ invisible branching ratio of 0.107 (0.077) at the 95% confidence level is observed (expected). These results are also interpreted in the context of models where the 125 GeV Higgs boson acts as a portal to dark matter, and limits are set on the scattering cross-section of weakly interacting massive particles and nucleons.

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Contents

1. Introduction . . . 1
2. Combination inputs . . . 2
2.1. VBF + $E_{\mathrm{T}}^{\mathrm{miss}}$ search . . . 2
2.2. $Z(\rightarrow \ell\ell) + E_{\mathrm{T}}^{\mathrm{miss}}$ search . . . 3
2.3. $t\bar{t} + E_{\mathrm{T}}^{\mathrm{miss}}$ search . . . 3
2.4. VBF + $E_{\mathrm{T}}^{\mathrm{miss}} + \gamma$ search . . . 3
2.5. Jet + $E_{\mathrm{T}}^{\mathrm{miss}}$ search . . . 3
2.6. Run 1 combination . . . 4
3. Statistical model . . . 4
3.1. Uncertainty correlation in Run 2 combination . . . 4
3.2. Uncertainty correlation in Run 1 and Run 2 combination . . . 4
4. Results . . . 4
5. Comparison to direct dark matter detection experiments . . . 5
6. Conclusion . . . 6
Declaration of competing interest . . . 6
Data availability . . . 6
Acknowledgements . . . 6
References . . . 7
The ATLAS Collaboration . . . 8

1. Introduction

Compelling astrophysical evidence suggests that dark matter (DM) comprises most of the matter in the universe [1–4]. However,

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

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its nature is still unknown and poses one of the central questions in modern physics. A possible candidate for DM is a massive, stable and electrically neutral particle χ, interacting weakly with the known particles of the Standard Model (SM).

Several theoretical frameworks predict the production of DM particles in proton–proton collisions at the Large Hadron Collider (LHC) [5–7]. In a wide class of those models, the 125 GeV Higgs boson [8,9] acts as a portal between a dark sector and the SM sector, either through Yukawa-type couplings to fermionic DM, or other mechanisms [10–23]. If kinematically allowed, pairs of DM particles can then be produced via the decay of the Higgs boson. The DM particles would traverse the detector without interacting and are inferred indirectly through the presence of missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$)[1] in the interaction. This decay channel is therefore called "invisible." In the SM, the branching fraction to invisible final states is about 0.1% [24] arising from the decay of the Higgs boson via $ZZ^* \to 4\nu$.

Direct searches for invisible decays of the Higgs boson were carried out with the ATLAS detector [25,26] during Run 1 of the LHC, using up to 4.7 fb^{-1} of pp collision data at a centre-of-mass energy of $\sqrt{s} = 7$ TeV and up to 20.3 fb^{-1} at 8 TeV. Various event topologies were considered: vector boson fusion (VBF) [27], production in association with a Z boson (ZH) that decays into a pair of electrons or muons [28], and with a W or Z boson that decays into hadrons [29]. A statistical combination of these ATLAS searches resulted in an observed (expected) upper limit at the 95% confidence level (CL) on the invisible Higgs boson branching ratio of $\mathcal{B}_{H\to\mathrm{inv}} < 0.25\ (0.27^{+0.10}_{-0.08})$ [30]. These searches were expanded with up to 36 fb^{-1} of Run 2 data and their combination, including Run 1 results, yielding an upper limit of $\mathcal{B}_{H\to\mathrm{inv}} < 0.26\ (0.17^{+0.07}_{-0.05})$ at the 95% CL [31]. A combination from the CMS experiment using a similar dataset reported an observed (expected) upper limit of 0.19 (0.15) [32].

More recently, new direct searches for invisible decays of the Higgs boson using the full Run 2 data of up to 139 fb^{-1} were performed, covering most of the Higgs boson production modes, by ATLAS [33–37] and CMS [38–40]. In both experiments the VBF final state is the most sensitive channel resulting in an upper limit of 0.145 (0.103) for ATLAS and 0.18 (0.12) for CMS.

A partial combination of the ATLAS VBF and ZH searches together with the analyses targetting visible decays of the Higgs boson was carried out [41] and its results reduce the observed (expected) upper limit on $\mathcal{B}_{H\to\mathrm{inv}}$ to 0.13 (0.08). Such a combination considers the impact of $\mathcal{B}_{H\to\mathrm{inv}}$ on the Higgs boson total decay width and simultaneously determines $\mathcal{B}_{H\to\mathrm{inv}}$, together with the coupling of the Higgs boson to all the SM particles as well as a potential contribution to undetected Higgs boson decays not generating missing transverse energy. The approach relies on a different set of assumptions to what is used in this letter.

This letter presents the statistical combination of all ATLAS direct searches for invisible decays of the Higgs boson using the full Run2 dataset. This includes the gluon–gluon fusion, VBF, ZH and ttH production modes, represented in Fig. 1 and assumes the production cross-sections of the Higgs boson does not deviate from the SM predictions [24,42–47]. In addition, a statistical combination with the combined Run 1 result [30] from ATLAS is included, yielding the most sensitive direct constraint to invisible Higgs boson decays in ATLAS.

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. The distance between two objects in η–ϕ space is $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. Transverse momentum is defined by $p_{\mathrm{T}} = p\sin\theta$.

2. Combination inputs

The inputs to the combination for the Run 2 result consist of searches for invisible decays of the Higgs boson, with the following production modes:

- VBF topology (VBF + $E_{\mathrm{T}}^{\mathrm{miss}}$) [33]
- associated production with a Z boson decaying into electrons or muons ($Z(\to \ell\ell) + E_{\mathrm{T}}^{\mathrm{miss}}$) [36]
- associated production with a $t\bar{t}$ pair, using all top-quark decay modes except those with hadronically decaying τ–leptons ($t\bar{t} + E_{\mathrm{T}}^{\mathrm{miss}}$) [48]
- VBF topology in association with an emitted photon (VBF + $E_{\mathrm{T}}^{\mathrm{miss}} + \gamma$) [34]
- gluon–gluon fusion, in association with a high p_{T} jet (Jet + $E_{\mathrm{T}}^{\mathrm{miss}}$) [37]

all of which use the full data sample, corresponding to an integrated luminosity of 139 fb^{-1}.

These analyses target different production modes of the Higgs boson and so their event selection criteria are made to be largely orthogonal by using different requirements on lepton, photon, jet and b-tagged jet multiplicity. The level of residual non-orthogonality was evaluated by considering both the data events and signal samples for all the Higgs boson production modes. The largest set of shared events is between the Jet + $E_{\mathrm{T}}^{\mathrm{miss}}$ and VBF + $E_{\mathrm{T}}^{\mathrm{miss}}$ searches, which select events with large missing transverse energy, no reconstructed leptons, and multiple jets in the final state. The number of overlapping events corresponds to 0.2% (1.5%) of the total data (expected signal Monte Carlo (MC) samples) events selected by the Jet + $E_{\mathrm{T}}^{\mathrm{miss}}$ analysis. The impact of the overlap on the final combined result is negligible, altering the upper limit on $\mathcal{B}_{H\to\mathrm{inv}}$ by less than 0.001. A brief overview of the Run 2 analyses and the inputs to the Run 1 combined result [30] is given below.

2.1. VBF + E_T^{miss} search

In the VBF production mode, the $H \to$ invisible signal is characterised by two jets with a large separation in pseudorapidity and missing transverse momentum arising from the invisible decays of the Higgs boson. The analysis targetting this signature selects events collected with a trigger selection based on the presence of $E_{\mathrm{T}}^{\mathrm{miss}}$. Events are further selected if their two jets with the highest p_{T} fulfill the VBF topology requirements: lying in opposite longitudinal hemispheres, being well separated in η, and not back-to-back in the transverse plane. In order to reduce the contribution from W, Z+jets and $t\bar{t}$ production, and to ensure orthogonality with the other analyses, events containing leptons or photon candidates, or two or more jets identified as b-tagged jets [49] are vetoed.

In this signature, the dominant background sources are $Z(\to \nu\nu)$ + jets and $W(\to \ell\nu)$ + jets production, where in the latter process the charged lepton ℓ is not detected or mis-identified. These backgrounds are evaluated simultaneously using high-statistics control regions in the 1-lepton and 2-leptons channels. A dedicated theoretical calculation at next-to-leading order in the phase space relevant for this analysis [50] allows the estimation of the total irreducible background with a precision of few-percent. The multijet background is directly estimated from data.

The final discrimination is obtained by splitting signal and control region events into 16 bins based on $E_{\mathrm{T}}^{\mathrm{miss}}$, the invariant mass of selected dijet pair, their separation in ϕ, and jet multiplicity to maximise the signal/background separation. Assuming the SM cross-section for the VBF production mode, an observed (expected) upper limit of 0.145 (0.103) at the 95% CL is placed on $\mathcal{B}_{H\to\mathrm{inv}}$.

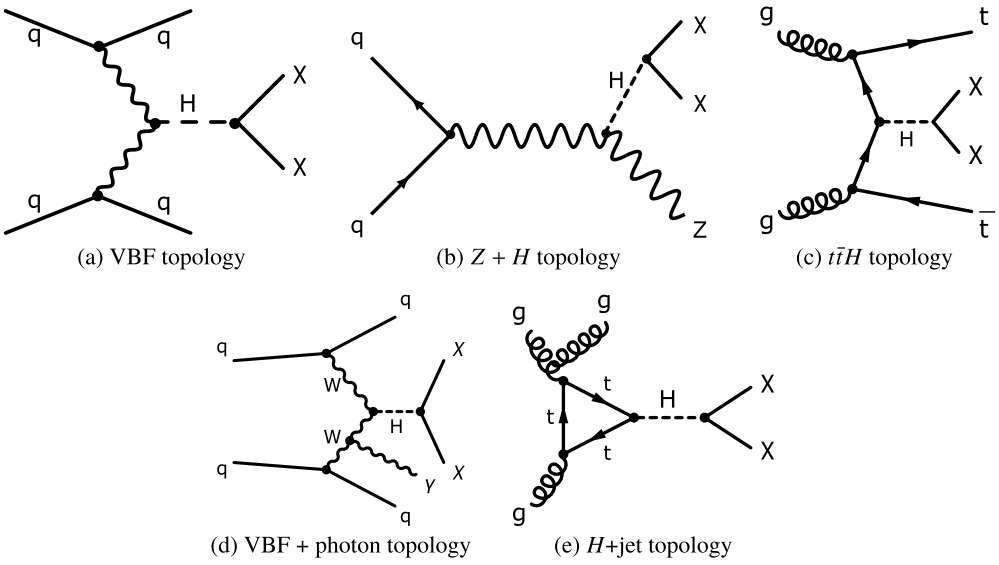

Fig. 1. Diagrams illustrating the Higgs boson production mode targetted for the Run 2 searches.

2.2. $Z(\rightarrow \ell\ell) + E_T^{miss}$ search

The search targetting the Higgs boson production in association with a Z boson selects events containing a pair of electrons or muons and significant missing transverse momentum. The two charged leptons are required to have an invariant mass within a narrow window around the Z boson mass for the events to satisfy the signal selection requirements.

The dominant backgrounds for this signature are ZZ, where one of the Z bosons decays into a neutrino–antineutrino pair, and WZ production. Contributions from $t\bar{t}$ and WW production are estimated from data, using events with two identified different-flavour charged leptons (electrons and muons).

Beyond the signature selections, sensitivity for the $H \rightarrow$ invisible model is enhanced using a boosted decision tree (BDT) discriminator to improve the separation between signal and background. A profile likelihood fit to the BDT output distribution results in an observed (expected) upper limit on $\mathcal{B}_{H\rightarrow\text{inv}}$ of 0.185 (0.185) at the 95% CL, assuming the SM production cross-section for this process.

2.3. $t\bar{t} + E_T^{miss}$ search

The production mode of the Higgs boson in association with a top-quark pair is targetted by reinterpreting the combination of several searches for new phenomena in association with heavy flavour quarks [51–53]. The final states arising from this production mode are characterised by the presence of b-tagged jets and different charged lepton multiplicities, depending on the decay mode of the two W bosons from the $t\bar{t}$ decays. In addition, a relevant amount of $E_{\text{T}}^{\text{miss}}$ is present, coming from the invisible decay products of the Higgs boson and from neutrinos.

A targetted event selection is developed for each lepton multiplicity, resulting in different dominant background contributions from SM processes: $t\bar{t}$ and $Z(\rightarrow \nu\nu)+$jets in the 0-lepton channel, $t\bar{t}$ in the 1-lepton channel and ttZ in the 2-lepton channel. For all the combined analyses, background-enriched selections are defined in order to allow the data to aid in estimating the dominant backgrounds, and validation regions are used to verify the robustness of these estimates.

The combination of the three analyses of each lepton multiplicity, considered in this document as a single combined analysis, places an observed (expected) upper limit on $\mathcal{B}_{H\rightarrow\text{inv}}$ of 0.376 (0.295) at the 95% CL, assuming the SM production cross-section for this process.

2.4. $VBF + E_T^{miss} + \gamma$ search

The VBF topology is further investigated by a dedicated analysis targetting the final states with an emitted photon. The event signature is characterised by significant missing transverse momentum and one photon in the final state, in addition to a pair of forward jets. In the SM this topology can arise from $V\gamma$+jets production, where V is either a Z boson decaying into a neutrino pair or a W boson decaying leptonically, where the charged lepton is missed.
A dense neural network was designed and trained to separate such backgrounds from the $H \rightarrow$ invisible signal by using kinematic properties of the events. The residual SM contribution to the signal regions is estimated with the aid of specific control regions requiring the presence of electron or muon candidates, to set the normalisation of the MC simulation for $V\gamma$+jets processes. Assuming the SM production cross-section on the signal model, an observed (expected) upper limit on $\mathcal{B}_{H\rightarrow\text{inv}}$ of 0.375 (0.346) at the 95% CL is evaluated.

2.5. $Jet + E_T^{miss}$ search

The gluon–gluon fusion production mode of the Higgs boson is targetted by a search for new phenomena in events with at least one jet and large missing transverse momentum. Data are collected with a trigger selection based on the presence of $E_{\text{T}}^{\text{miss}}$ and events are vetoed if any charged lepton or photon is reconstructed.
The dominant SM background for this search arises from the irreducible process $Z \rightarrow \nu\nu$ or $W \rightarrow \ell\nu$ in association with jets, where the W boson decays into either hadronically decaying τ-leptons or undetected electrons or muons. Additional contributions include $t\bar{t}$ pair or single-top production, diboson production, and non-collision and multijet backgrounds. The estimate of the major SM processes in the analysis selection is based on a profile likelihood fit to the distribution of the p_{T} of the system recoiling against the jets reconstructed in the event, performed simultaneously in the signal region and in orthogonal control regions enriched with the targetted backgrounds. Assuming the SM cross-section for Higgs boson gluon–gluon fusion production, an observed (expected) upper limit on $\mathcal{B}_{H\rightarrow\text{inv}}$ of 0.329 (0.383) at the 95% CL is achieved.

2.6. Run 1 combination

The Run 1 ATLAS $H \to$ invisible combination utilises 4.7 fb^{-1} of pp collision data at $\sqrt{s} = 7$ TeV and 20.3 fb^{-1} at $\sqrt{s} = 8$ TeV [30]. This combination considers inputs from direct detection of $H \to$ invisible through Higgs bosons produced via VBF or in association with a vector boson V, where the vector boson decays either leptonically ($Z \to \ell\ell$) or hadronically ($W/Z \to jj$). All of the signal and control regions are utilized in a maximum-likelihood fit resulting in an observed (expected) upper limit of $\mathcal{B}_{H\to\text{inv}} < 0.252$ (0.265) at the 95% CL. The sensitivity is driven by the VBF channel.

3. Statistical model

The statistical combination of the analyses is performed by constructing the product of their respective likelihoods and maximising the resulting profile likelihood ratio [54]:

$$\Lambda(\beta;\theta) = \frac{L\left(\beta, \hat{\hat{\theta}}(\beta)\right)}{L\left(\hat{\beta}, \hat{\theta}\right)}$$

where β and θ are the parameter of interest and the nuisance parameters respectively. In the numerator, the nuisance parameters are set to their fitted values $\hat{\hat{\theta}}(\beta)$, which maximise the likelihood function for fixed values of the parameter of interest, β. In the denominator, both the parameter of interest and the nuisance parameters are set to the values $\hat{\beta}$ and $\hat{\theta}$ which jointly maximise the likelihood. This is done following the implementation described in Ref. [55,56], with $\mathcal{B}_{H\to\text{inv}}$ as the parameter of interest, β. Systematic uncertainties are modelled in the likelihood function as nuisance parameters, θ, constrained by Gaussian or log-normal probability density functions. Upper limits on $\mathcal{B}_{H\to\text{inv}}$ are determined following the CL_s formalism [57] using the profile likelihood ratio as a test statistic.

3.1. Uncertainty correlation in Run 2 combination

In the combination of Run 2 results, most experimental systematic uncertainties, as well as the uncertainty on the integrated luminosity and the modelling of additional pp collisions in the same and neighbouring bunch crossings (pile-up), are correlated across all search channels. The assessment of some of the uncertainties associated with the calibration of the jet energy scale (JES) and the jet energy resolution varies between the different analyses in terms of jet reconstruction algorithms and parameterisation choices. For this reason, the uncertainty components stemming from identical methodologies are presumed to be correlated, while the rest of the uncertainties are treated as uncorrelated. Finally, a few experimental systematic uncertainties that are tightly constrained in a given analysis are not correlated in order not to introduce any potential phase space specific biases. The impact of these assumptions on the combined result is estimated by using alternative correlation models and found to have an absolute effect on the $\mathcal{B}_{H\to\text{inv}}$ limit of the order of 0.003.

The uncertainties related to background predictions are considered to be uncorrelated among analyses due to the different nature of the leading backgrounds, the variety of kinematic phase space covered by the various analyses, and the usage of data-driven techniques. The systematic uncertainties in the prediction of Higgs boson production follow the recommendations in Ref. [24]. Variations connected to the choice of parton distribution functions (PDF) are considered as correlated among channels while effects of missing higher-order contributions (estimates through variations of factorisation and renormalisation scales) and parton shower/hadronisation models are considered independently for each Higgs boson production mode and therefore uncorrelated across the analyses.

3.2. Uncertainty correlation in Run 1 and Run 2 combination

The Run 2 result described above is combined with the Run 1 searches for $H \to$ invisible decays. The adopted correlation scheme follows closely the statistical combination of the partial Run 2 results with the Run 1 combination [31].

The correlation schemes of the individual Run 1 and Run 2 combinations are preserved when combined together. Due to the differences between the detector layouts and data-taking conditions, reconstruction algorithms, which are calibrated using data, and treatment of systematic uncertainties, the correlations between the two LHC runs are not clearly identifiable. Hence, no correlations between Run 1 and 2 are assumed for most instrumental uncertainties. Exceptions are made for uncertainties related to the modelling of the calorimeter response dependence on jet flavour and pile-up, the calibration of the JES across different η regions, and the uncertainties related to the JES of b-quark jets. Such components are treated as correlated given that the same methodology was applied to compute them in both of the datasets.

Background modelling uncertainties are considered to be uncorrelated in order to reflect improvements in the MC simulation tools and general theory predictions that have evolved significantly since Run 1, both on the side of the hard process simulation and on the side of the parton shower and hadronisation models. For similar reasons, the signal modelling uncertainties are considered uncorrelated between the Run 1 and Run 2 combinations.

The result of the combination shows little sensitivity to the exact correlation scheme between the Run 1 and Run 2 results due to the dominant weight of the latter.

4. Results

The value of twice the negative logarithmic profile likelihood ratio $-2\ln(\Lambda)(\mathcal{B}_{H\to\text{inv}};\theta)$ as a function of $\mathcal{B}_{H\to\text{inv}}$ of the individual analyses and of the combined Run 2 result are shown in Fig. 2 (left). The combined best-fit value for $\mathcal{B}_{H\to\text{inv}}$ is 0.04 ± 0.04. Good agreement among the best fit values of the individual analyses, reported in Table 1, is observed.

The best-fit values for $\mathcal{B}_{H\to\text{inv}}$ together with the 95% CL expected and observed upper limits for each individual Run 2 analysis and their combination are also shown in Table 1. An upper limit of 0.113 is observed for the combined Run 2 data, while an upper limit of 0.080 was expected in the case of no observed excess in data. Relative to the most sensitive single analysis, the VBF final state, the Run 2 combination brings a relative sensitivity improvement of 22%.

Overall, the leading systematic uncertainty of the result is due to the modelling uncertainties of the W/Z+jets prediction in the VBF + $E_{\text{T}}^{\text{miss}}$ search [33]. Subdominant uncertainties with similar contribution are related to the statistical precision of the data sample; the number of simulated MC events, in particular for the W/Z+jets process; the reconstruction and identification of jets and leptons; and the modelling of background processes other than from W/Z+jets production.

The observed $-2\ln(\Lambda)(\mathcal{B}_{H\to\text{inv}};\theta)$ scan of the combined Run 1+2 result is represented in Fig. 2 (right), alongside the individual Run 1 and Run 2 combinations. A best-fit value of $\mathcal{B}_{H\to\text{inv}} = 0.04 \pm 0.04$ is obtained for the Run 1+2 combination, corresponding to an observed (expected) upper limit of $\mathcal{B}_{H\to\text{inv}} < 0.107$ (0.077) at the 95% CL. The result is dominated by the

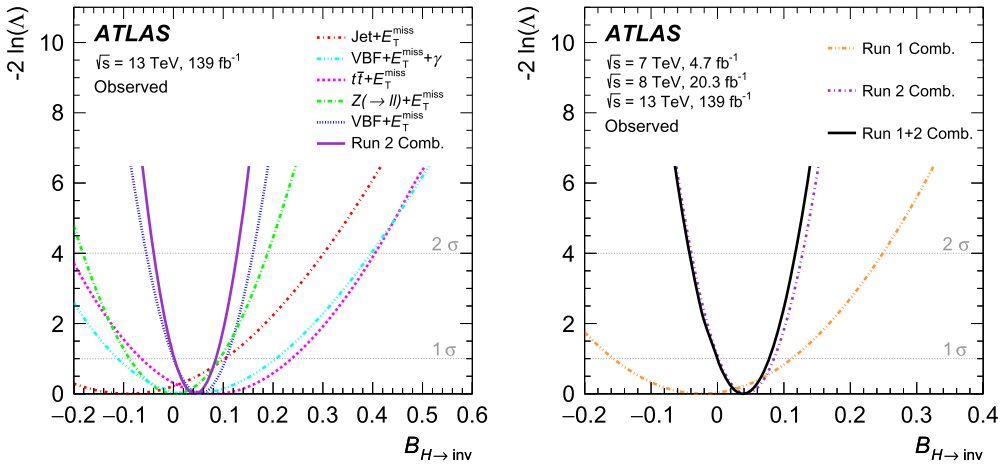

Fig. 2. The observed value of $-2\ln(\Lambda)$ as a function of $\mathcal{B}_{H\to\text{inv}}$ for the individual Run 2 analyses and their combination (left) and the Run 2 combination together with the Run 1 combination and the total Run 1+2 combination (right).

Table 1
Best fit value, observed and expected 95% upper limit on $\mathcal{B}_{H\to\text{inv}}$ for each individual Run 2 analysis, their combination, the Run 1 combination and the full Run 1+2 combination.

Analysis	Best fit $\mathcal{B}_{H\to\text{inv}}$	Observed 95% U.L.	Expected 95% U.L.
Jet + $E_{\text{T}}^{\text{miss}}$	$-0.09^{+0.19}_{-0.20}$	0.329	$0.383^{+0.157}_{-0.107}$
VBF + $E_{\text{T}}^{\text{miss}}$ + γ	$0.04^{+0.17}_{-0.15}$	0.375	$0.346^{+0.151}_{-0.097}$
$t\bar{t}$ + $E_{\text{T}}^{\text{miss}}$	0.08 ± 0.15	0.376	$0.295^{+0.125}_{-0.083}$
$Z(\to \ell\ell)$ + $E_{\text{T}}^{\text{miss}}$	0.00 ± 0.09	0.185	$0.185^{+0.078}_{-0.052}$
VBF + $E_{\text{T}}^{\text{miss}}$	0.05 ± 0.05	0.145	$0.103^{+0.041}_{-0.028}$
Run 2 Comb.	0.04 ± 0.04	0.113	$0.080^{+0.031}_{-0.022}$
Run 1 Comb.	$-0.02^{+0.14}_{-0.13}$	0.252	$0.265^{+0.105}_{-0.074}$
Run 1+2 Comb.	0.04 ± 0.04	0.107	$0.077^{+0.030}_{-0.022}$

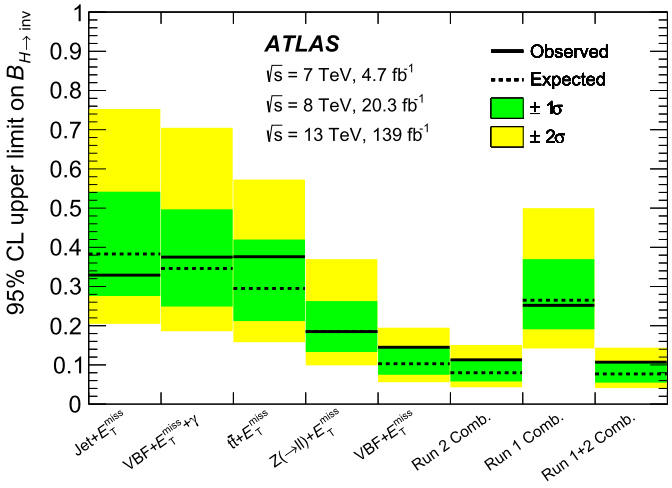

Fig. 3. The observed and expected upper limits on $\mathcal{B}_{H\to\text{inv}}$ at 95% CL for the Run 2 analyses targetting the Jet + $E_{\text{T}}^{\text{miss}}$, VBF + $E_{\text{T}}^{\text{miss}}$ + γ, $t\bar{t}$ + $E_{\text{T}}^{\text{miss}}$, $Z(\to \ell\ell)$ + $E_{\text{T}}^{\text{miss}}$, VBF + $E_{\text{T}}^{\text{miss}}$ final states and their combination, the Run 1 combination and the full Run 1+2 result; the 1σ and 2σ contours of the expected limit distribution are also shown.

Run 2 analysis with the addition of Run 1 combination improving the expected relative sensitivity by 4%.

The overall picture of the most relevant sources of uncertainty in the Run 1 + Run 2 combination is very similar to that of the Run 2 combination. The upper limit would improve by 50% if all sources of systematic uncertainties were ignored.

The upper limits for each individual Run 2 analysis, their combination, the Run 1 combination and the overall Run 1+2 combined result are summarised in Fig. 3. The current combination improves the constraints on $\mathcal{B}_{H\to\text{inv}}$ by more than a factor of two as compared to the previous ATLAS combination from Run 1 and partial Run 2 results [31].

5. Comparison to direct dark matter detection experiments

The combined observed Run 1+2 upper limit on $\mathcal{B}_{H\to\text{inv}}$ can be converted into a limit on the spin-independent scattering cross-section of a weakly interacting massive particle (WIMP) and a nucleon [13,18,58,59] ($\sigma_{\text{WIMP-Nucleon}}$), to allow the comparison of the results with the ones from experiments based on different detector technologies. The translation is performed in the context of Higgs portal models [15,60] using an effective field theory framework, where the mediator of new interactions is assumed to be above the TeV-level and therefore well above the scale probed at the Higgs boson mass. The approach assumes that Higgs boson decays into a pair of WIMP particles are kinematically possible ($m_{\text{WIMP}} < m_H/2$) and that the WIMP particle is either a scalar, a Majorana fermion, or a vector-like state.[2] In addition, in the case of vectorial DM states, various ultraviolet-complete (UV) models were proposed [62–64]. In such scenarios, the vector DM candidate is introduced as a gauge field of a U(1)′ group which extends the SM symmetry group and a dark Higgs sector is added to generate the vector boson mass via the Higgs spontaneous symmetry breaking mechanism. This adds at least two free parameters to the model: the mass m_2 of the additional dark Higgs boson and its mixing angle α with the SM Higgs boson.

The constraint from the combined observed Run 1+2 exclusion limit of $\mathcal{B}_{H\to\text{inv}} < 0.093$ at 90% CL is compared to the results from representative direct DM detection experiments [65–68] in Fig. 4. The excluded $\sigma_{\text{WIMP-Nucleon}}$ values range from 10^{-45} cm^2 to 10^{-42} cm^2 in the scalar WIMP scenario. In the Majorana fermion WIMP case, the effective coupling is reduced by a factor m_H^2 [27], excluding cross-section values down to 2×10^{-47} cm^2 for low WIMP masses; $\sigma_{\text{WIMP-Nucleon}}$ values down to 10^{-54} cm^2 can be excluded for the vector WIMP hypothesis. For UV-complete models, Fig. 4 also shows the upper limit cross-section behaviour for a mixing

[2] The value of $f_N = 0.308 \pm 0.018$ [61] is used as nuclear form factor.

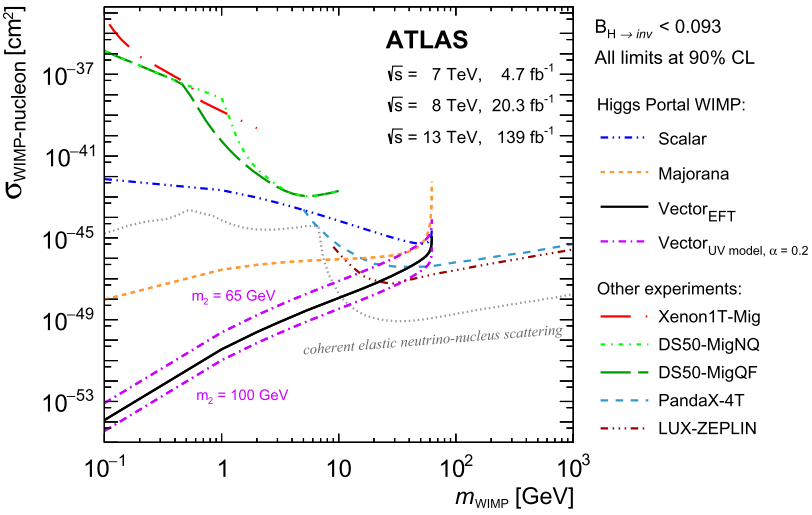

Fig. 4. Upper limit at the 90% CL on the spin-independent WIMP-nucleon scattering cross-section as a function of the WIMP mass for direct detection experiments and the interpretation of the $H \rightarrow$ invisible combination result in the context of Higgs portal models considering scalar, Majorana and vector WIMP hypotheses. For the vector case, results from UV-complete models are shown (pink curves) for two representative values for the mass of the predicted Dark Higgs particle (m_2) and a mixing angle α=0.2. The uncertainties from the nuclear form factor are smaller than the line thickness. Direct detection results are taken from Refs. [65–68]. The neutrino floor for coherent elastic neutrino-nucleus scattering (dotted gray line) is taken from Refs. [69,70], which assume that germanium is the target over the whole WIMP mass range. The regions above the limit contours are excluded in the range shown in the plot.

angle $\alpha = 0.2$ and for masses of the dark Higgs particle equal to 65 GeV and 100 GeV corresponding to the worst and best limit for a scan of m_2 in the range [65, 1000] GeV [64]. This comparison illustrates the complementarity in coverage by the direct-detection experiments and the searches at colliders, such as the presented analysis.

6. Conclusion

In summary, searches for invisible decays of the Higgs boson using 139 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV recorded in Run 2 of the LHC in several Higgs boson production topologies were statistically combined assuming SM Higgs boson production. An upper limit on the invisible Higgs boson branching ratio of $\mathcal{B}_{H\rightarrow \text{inv}} < 0.113$ ($0.080^{+0.031}_{-0.022}$) is observed (expected) at the 95% CL. A statistical combination of this result with the combination of $H \rightarrow$ invisible searches using up to 4.7 fb^{-1} of pp collision data at $\sqrt{s} = 7$ TeV and up to 20.3 fb^{-1} at 8 TeV collected in Run 1 of the LHC yields an observed (expected) upper limit of $\mathcal{B}_{H\rightarrow \text{inv}} < 0.107$ ($0.077^{+0.030}_{-0.022}$) at the 95% CL. The combined Run 1+2 result is translated into upper limits on the WIMP-nucleon scattering cross-section for Higgs portal models. The derived limits on $\sigma_{\text{WIMP-Nucleon}}$ range down to 10^{-45} cm^2 (scalar), 2×10^{-47} cm^2 (Majorana) and 10^{-54} cm^2 (vector), highlighting the complementarity of DM searches at the LHC and direct detection experiments.

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://hepdata.cedar.ac.uk)

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The ATLAS Collaboration

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G. Bella [151], L. Bellagamba [23b], A. Bellerive [34], P. Bellos [20], K. Beloborodov [37], N.L. Belyaev [37], D. Benchekroun [35a], F. Bendebba [35a], Y. Benhammou [151], M. Benoit [29], J.R. Bensinger [26], S. Bentvelsen [114], L. Beresford [48], M. Beretta [53], E. Bergeaas Kuutmann [160], N. Berger [4], B. Bergmann [132], J. Beringer [17a], S. Berlendis [7], G. Bernardi [5], C. Bernius [143], F.U. Bernlochner [24], T. Berry [95], P. Berta [133], A. Berthold [50], I.A. Bertram [91], S. Bethke [110], A. Betti [75a,75b], A.J. Bevan [94], M. Bhamjee [33c], S. Bhatta [145], D.S. Bhattacharya [165], P. Bhattarai [26], V.S. Bhopatkar [121], R. Bi [29,ad], R.M. Bianchi [129], O. Biebel [109], R. Bielski [123], M. Biglietti [77a], T.R.V. Billoud [132], M. Bindi [55], A. Bingul [21b], C. Bini [75a,75b], A. Biondini [92], C.J. Birch-sykes [101], G.A. Bird [20,134], M. Birman [168], M. Biros [133], T. Bisanz [36], E. Bisceglie [43b,43a], D. Biswas [169], A. Bitadze [101], K. Bjørke [125], I. Bloch [48], C. Blocker [26], A. Blue [59], U. Blumenschein [94], J. Blumenthal [100], G.J. Bobbink [114], V.S. Bobrovnikov [37], M. Boehler [54], D. Bogavac [36], A.G. Bogdanchikov [37], C. Bohm [47a], V. Boisvert [95], P. Bokan [48], T. Bold [85a], M. Bomben [5], M. Bona [94], M. Boonekamp [135], C.D. Booth [95], A.G. Borbély [59], H.M. Borecka-Bielska [108], L.S. Borgna [96], G. Borissov [91], D. Bortoletto [126], D. Boscherini [23b], M. Bosman [13], J.D. Bossio Sola [36], K. Bouaouda [35a], N. Bouchhar [162], J. Boudreau [129], E.V. Bouhova-Thacker [91], D. Boumediene [40], R. Bouquet [5], A. Boveia [119], J. Boyd [36], D. Boye [29], I.R. Boyko [38], J. Bracinik [20], N. Brahimi [62d], G. Brandt [170], O. Brandt [32], F. Braren [48], B. Brau [103], J.E. Brau [123], K. Brendlinger [48], R. Brener [168], L. Brenner [114], R. Brenner [160], S. Bressler [168], D. Britton [59], D. Britzger [110], I. Brock [24], G. Brooijmans [41], W.K. Brooks [137f], E. Brost [29], L.M. Brown [164], T.L. Bruckler [126], P.A. Bruckman de Renstrom [86], B. Brüers [48], D. Bruncko [28b,*], A. Bruni [23b], G. Bruni [23b], M. Bruschi [23b], N. Bruscino [75a,75b], T. Buanes [16], Q. Buat [138], A.G. Buckley [59], I.A. Budagov [38,*], M.K. Bugge [125], O. Bulekov [37], B.A. Bullard [143], S. Burdin [92], C.D. Burgard [49], A.M. Burger [40], B. Burghgrave [8], O. Burlayenko [54], J.T.P. Burr [32], C.D. Burton [11], J.C. Burzynski [142], E.L. Busch [41], V. Büscher [100], P.J. Bussey [59], J.M. Butler [25], C.M. Buttar [59], J.M. Butterworth [96], W. Buttinger [134], C.J. Buxo Vazquez [107], A.R. Buzykaev [37], G. Cabras [23b], S. Cabrera Urbán [162], D. Caforio [58], H. Cai [129], Y. Cai [14a,14e], V.M.M. Cairo [36], O. Cakir [3a], N. Calace [36], P. Calafiura [17a], G. Calderini [127], P. Calfayan [68], G. Callea [59], L.P. Caloba [82b], D. Calvet [40], S. Calvet [40], T.P. Calvet [102], M. Calvetti [74a,74b], R. Camacho Toro [127], S. Camarda [36], D. Camarero Munoz [26], P. Camarri [76a,76b], M.T. Camerlingo [72a,72b], D. Cameron [125], C. Camincher [164], M. Campanelli [96], A. Camplani [42], V. Canale [72a,72b], A. Canesse [104], M. Cano Bret [80], J. Cantero [162], Y. Cao [161], F. Capocasa [26], M. Capua [43b,43a], A. Carbone [71a,71b], R. Cardarelli [76a], J.C.J. Cardenas [8], F. Cardillo [162], T. Carli [36], G. Carlino [72a], J.I. Carlotto [13], B.T. Carlson [129,q], E.M. Carlson [164,156a], L. Carminati [71a,71b], M. Carnesale [75a,75b], S. Caron [113], E. Carquin [137f], S. Carrá [71a,71b], G. Carratta [23b,23a], F. Carrio Argos [33g], J.W.S. Carter [155], T.M. Carter [52], M.P. Casado [13,i], A.F. Casha [155], M. Caspar [48], E.G. Castiglia [171], F.L. Castillo [63a], L. Castillo Garcia [13], V. Castillo Gimenez [162], N.F. Castro [130a,130e], A. Catinaccio [36], J.R. Catmore [125], V. Cavaliere [29], N. Cavalli [23b,23a], V. Cavasinni [74a,74b], E. Celebi [21a], F. Celli [126], M.S. Centonze [70a,70b], K. Cerny [122], A.S. Cerqueira [82a], A. Cerri [146], L. Cerrito [76a,76b], F. Cerutti [17a], A. Cervelli [23b], G. Cesarini [53], S.A. Cetin [21d], Z. Chadi [35a], D. Chakraborty [115], M. Chala [130f], J. Chan [169], W.Y. Chan [153], J.D. Chapman [32], B. Chargeishvili [149b], D.G. Charlton [20], T.P. Charman [94], M. Chatterjee [19], C. Chauhan [133], S. Chekanov [6], S.V. Chekulaev [156a], G.A. Chelkov [38,a], A. Chen [106], B. Chen [151], B. Chen [164], H. Chen [14c], H. Chen [29], J. Chen [62c], J. Chen [142], S. Chen [153], S.J. Chen [14c], X. Chen [62c], X. Chen [14b,aa], Y. Chen [62a], C.L. Cheng [169], H.C. Cheng [64a], S. Cheong [143], A. Cheplakov [38], E. Cheremushkina [48], E. Cherepanova [114], R. Cherkaoui El Moursli [35e], E. Cheu [7], K. Cheung [65], L. Chevalier [135], V. Chiarella [53], G. Chiarelli [74a], N. Chiedde [102], G. Chiodini [70a], A.S. Chisholm [20], A. Chitan [27b], M. Chitishvili [162], M.V. Chizhov [38], K. Choi [11], A.R. Chomont [75a,75b], Y. Chou [103], E.Y.S. Chow [114], T. Chowdhury [33g], L.D. Christopher [33g], K.L. Chu [64a], M.C. Chu [64a], X. Chu [14a,14e], J. Chudoba [131], J.J. Chwastowski [86], D. Cieri [110], K.M. Ciesla [85a], V. Cindro [93], A. Ciocio [17a], F. Cirotto [72a,72b], Z.H. Citron [168], M. Citterio [71a], D.A. Ciubotaru [27b], B.M. Ciungu [155], A. Clark [56], P.J. Clark [52], J.M. Clavijo Columbie [48], S.E. Clawson [101], C. Clement [47a,47b], J. Clercx [48], L. Clissa [23b,23a], Y. Coadou [102], M. Cobal [69a,69c], A. Coccaro [57b], R.F. Coelho Barrue [130a], R. Coelho Lopes De Sa [103], S. Coelli [71a], H. Cohen [151], A.E.C. Coimbra [71a,71b], B. Cole [41], J. Collot [60], P. Conde Muiño [130a,130g], M.P. Connell [33c], S.H. Connell [33c], I.A. Connelly [59], E.I. Conroy [126], F. Conventi [72a,ac], H.G. Cooke [20], A.M. Cooper-Sarkar [126], F. Cormier [163], L.D. Corpe [36], M. Corradi [75a,75b], F. Corriveau [104,v], A. Cortes-Gonzalez [18], M.J. Costa [162], F. Costanza [4], D. Costanzo [139], B.M. Cote [119], G. Cowan [95], K. Cranmer [117], S. Crépé-Renaudin [60], F. Crescioli [127], M. Cristinziani [141], M. Cristoforetti [78a,78b,c], V. Croft [114], G. Crosetti [43b,43a], A. Cueto [36], T. Cuhadar Donszelmann [159], H. Cui [14a,14e], Z. Cui [7], W.R. Cunningham [59], F. Curcio [43b,43a], P. Czodrowski [36], M.M. Czurylo [63b],

M.J. Da Cunha Sargedas De Sousa [62a], J.V. Da Fonseca Pinto [82b], C. Da Via [101], W. Dabrowski [85a], T. Dado [49], S. Dahbi [33g], T. Dai [106], C. Dallapiccola [103], M. Dam [42], G. D'amen [29], V. D'Amico [109], J. Damp [100], J.R. Dandoy [128], M.F. Daneri [30], M. Danninger [142], V. Dao [36], G. Darbo [57b], S. Darmora [6], S.J. Das [29], S. D'Auria [71a,71b], C. David [156b], T. Davidek [133], B. Davis-Purcell [34], I. Dawson [94], K. De [8], R. De Asmundis [72a], N. De Biase [48], S. De Castro [23b,23a], N. De Groot [113], P. de Jong [114], H. De la Torre [107], A. De Maria [14c], A. De Salvo [75a], U. De Sanctis [76a,76b], A. De Santo [146], J.B. De Vivie De Regie [60], D.V. Dedovich [38], J. Degens [114], A.M. Deiana [44], F. Del Corso [23b,23a], J. Del Peso [99], F. Del Rio [63a], F. Deliot [135], C.M. Delitzsch [49], M. Della Pietra [72a,72b], D. Della Volpe [56], A. Dell'Acqua [36], L. Dell'Asta [71a,71b], M. Delmastro [4], P.A. Delsart [60], S. Demers [171], M. Demichev [38], S.P. Denisov [37], L. D'Eramo [115], D. Derendarz [86], F. Derue [127], P. Dervan [92], K. Desch [24], K. Dette [155], C. Deutsch [24], F.A. Di Bello [57b,57a], A. Di Ciaccio [76a,76b], L. Di Ciaccio [4], A. Di Domenico [75a,75b], C. Di Donato [72a,72b], A. Di Girolamo [36], G. Di Gregorio [5], A. Di Luca [78a,78b], B. Di Micco [77a,77b], R. Di Nardo [77a,77b], C. Diaconu [102], F.A. Dias [114], T. Dias Do Vale [142], M.A. Diaz [137a,137b], F.G. Diaz Capriles [24], M. Didenko [162], E.B. Diehl [106], L. Diehl [54], S. Díez Cornell [48], C. Diez Pardos [141], C. Dimitriadi [24,160], A. Dimitrievska [17a], J. Dingfelder [24], I-M. Dinu [27b], S.J. Dittmeier [63b], F. Dittus [36], F. Djama [102], T. Djobava [149b], J.I. Djuvsland [16], C. Doglioni [101,98], J. Dolejsi [133], Z. Dolezal [133], M. Donadelli [82c], B. Dong [107], J. Donini [40], A. D'Onofrio [77a,77b], M. D'Onofrio [92], J. Dopke [134], A. Doria [72a], M.T. Dova [90], A.T. Doyle [59], M.A. Draguet [126], E. Drechsler [142], E. Dreyer [168], I. Drivas-koulouris [10], A.S. Drobac [158], M. Drozdova [56], D. Du [62a], T.A. du Pree [114], F. Dubinin [37], M. Dubovsky [28a], E. Duchovni [168], G. Duckeck [109], O.A. Ducu [27b], D. Duda [110], A. Dudarev [36], E.R. Duden [26], M. D'uffizi [101], L. Duflot [66], M. Dührssen [36], C. Dülsen [170], A.E. Dumitriu [27b], M. Dunford [63a], S. Dungs [49], K. Dunne [47a,47b], A. Duperrin [102], H. Duran Yildiz [3a], M. Düren [58], A. Durglishvili [149b], B.L. Dwyer [115], G.I. Dyckes [17a], M. Dyndal [85a], S. Dysch [101], B.S. Dziedzic [86], Z.O. Earnshaw [146], B. Eckerova [28a], S. Eggebrecht [55], M.G. Eggleston [51], E. Egidio Purcino De Souza [127], L.F. Ehrke [56], G. Eigen [16], K. Einsweiler [17a], T. Ekelof [160], P.A. Ekman [98], Y. El Ghazali [35b], H. El Jarrari [35e,148], A. El Moussaouy [35a], V. Ellajosyula [160], M. Ellert [160], F. Ellinghaus [170], A.A. Elliot [94], N. Ellis [36], J. Elmsheuser [29], M. Elsing [36], D. Emeliyanov [134], Y. Enari [153], I. Ene [17a], S. Epari [13], J. Erdmann [49], P.A. Erland [86], M. Errenst [170], M. Escalier [66], C. Escobar [162], E. Etzion [151], G. Evans [130a], H. Evans [68], M.O. Evans [146], A. Ezhilov [37], S. Ezzarqtouni [35a], F. Fabbri [59], L. Fabbri [23b,23a], G. Facini [96], V. Fadeyev [136], R.M. Fakhrutdinov [37], S. Falciano [75a], L.F. Falda Ulhoa Coelho [36], P.J. Falke [24], S. Falke [36], J. Faltova [133], C. Fan [161], Y. Fan [14a], Y. Fang [14a,14e], M. Fanti [71a,71b], M. Faraj [69a,69b], Z. Farazpay [97], A. Farbin [8], A. Farilla [77a], T. Farooque [107], S.M. Farrington [52], F. Fassi [35e], D. Fassouliotis [9], M. Faucci Giannelli [76a,76b], W.J. Fawcett [32], L. Fayard [66], P. Federic [133], P. Federicova [131], O.L. Fedin [37,a], G. Fedotov [37], M. Feickert [169], L. Feligioni [102], A. Fell [139], D.E. Fellers [123], C. Feng [62b], M. Feng [14b], Z. Feng [114], M.J. Fenton [159], A.B. Fenyuk [37], L. Ferencz [48], R.A.M. Ferguson [91], S.I. Fernandez Luengo [137f], M.J.V. Fernoux [102], J. Ferrando [48], A. Ferrari [160], P. Ferrari [114,113], R. Ferrari [73a], D. Ferrere [56], C. Ferretti [106], F. Fiedler [100], A. Filipčič [93], E.K. Filmer [1], F. Filthaut [113], M.C.N. Fiolhais [130a,130c,b], L. Fiorini [162], W.C. Fisher [107], T. Fitschen [101], I. Fleck [141], P. Fleischmann [106], T. Flick [170], L. Flores [128], M. Flores [33d], L.R. Flores Castillo [64a], F.M. Follega [78a,78b], N. Fomin [16], J.H. Foo [155], B.C. Forland [68], A. Formica [135], A.C. Forti [101], E. Fortin [36], A.W. Fortman [61], M.G. Foti [17a], L. Fountas [9], D. Fournier [66], H. Fox [91], P. Francavilla [74a,74b], S. Francescato [61], S. Franchellucci [56], M. Franchini [23b,23a], S. Franchino [63a], D. Francis [36], L. Franco [113], L. Franconi [48], M. Franklin [61], G. Frattari [26], A.C. Freegard [94], W.S. Freund [82b], Y.Y. Frid [151], N. Fritzsche [50], A. Froch [54], D. Froidevaux [36], J.A. Frost [126], Y. Fu [62a], M. Fujimoto [118], E. Fullana Torregrosa [162,*], E. Furtado De Simas Filho [82b], J. Fuster [162], A. Gabrielli [23b,23a], A. Gabrielli [155], P. Gadow [48], G. Gagliardi [57b,57a], L.G. Gagnon [17a], E.J. Gallas [126], B.J. Gallop [134], K.K. Gan [119], S. Ganguly [153], J. Gao [62a], Y. Gao [52], F.M. Garay Walls [137a,137b], B. Garcia [29,ad], C. García [162], J.E. García Navarro [162], M. Garcia-Sciveres [17a], R.W. Gardner [39], D. Garg [80], R.B. Garg [143], C.A. Garner [155], S.J. Gasiorowski [138], P. Gaspar [82b], G. Gaudio [73a], V. Gautam [13], P. Gauzzi [75a,75b], I.L. Gavrilenko [37], A. Gavrilyuk [37], C. Gay [163], G. Gaycken [48], E.N. Gazis [10], A.A. Geanta [27b,27e], C.M. Gee [136], C. Gemme [57b], M.H. Genest [60], S. Gentile [75a,75b], S. George [95], W.F. George [20], T. Geralis [46], L.O. Gerlach [55], P. Gessinger-Befurt [36], M.E. Geyik [170], M. Ghneimat [141], K. Ghorbanian [94], A. Ghosal [141], A. Ghosh [159], A. Ghosh [7], B. Giacobbe [23b], S. 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L.K. Gladilin [37], C. Glasman [99], G.R. Gledhill [123], M. Glisic [123], I. Gnesi [43b,f], Y. Go [29,ad], M. Goblirsch-Kolb [36], B. Gocke [49], D. Godin [108], B. Gokturk [21a], S. Goldfarb [105], T. Golling [56], M.G.D. Gololo [33g], D. Golubkov [37], J.P. Gombas [107], A. Gomes [130a,130b], G. Gomes Da Silva [141], A.J. Gomez Delegido [162], R. Gonçalo [130a,130c], G. Gonella [123], L. Gonella [20], A. Gongadze [38], F. Gonnella [20], J.L. Gonski [41], S. González de la Hoz [162], S. Gonzalez Fernandez [13], R. Gonzalez Lopez [92], C. Gonzalez Renteria [17a], R. Gonzalez Suarez [160], S. Gonzalez-Sevilla [56], G.R. Gonzalvo Rodriguez [162], R.Y. González Andana [52], L. Goossens [36], P.A. Gorbounov [37], B. Gorini [36], E. Gorini [70a,70b], A. Gorišek [93], T.C. Gosart [128], A.T. Goshaw [51], M.I. Gostkin [38], S. Goswami [121], C.A. Gottardo [36], M. Gouighri [35b], V. Goumarre [48], A.G. Goussiou [138], N. Govender [33c], I. Grabowska-Bold [85a], K. Graham [34], E. Gramstad [125], S. Grancagnolo [70a,70b], M. Grandi [146], V. Gratchev [37,*], P.M. Gravila [27f], F.G. Gravili [70a,70b], H.M. Gray [17a], M. Greco [70a,70b], C. Grefe [24], I.M. Gregor [48], P. Grenier [143], C. Grieco [13], A.A. Grillo [136], K. Grimm [31,l], S. Grinstein [13,s], J.-F. Grivaz [66], E. Gross [168], J. Grosse-Knetter [55], C. Grud [106], J.C. Grundy [126], L. Guan [106], W. Guan [169], C. Gubbels [163], J.G.R. Guerrero Rojas [162], G. Guerrieri [69a,69b], F. Guescini [110], R. Gugel [100], J.A.M. Guhit [106], A. Guida [48], T. Guillemin [4], E. Guilloton [166,134], S. Guindon [36], F. Guo [14a,14e], J. Guo [62c], L. Guo [66], Y. Guo [106], R. Gupta [48], S. Gurbuz [24], S.S. Gurdasani [54], G. Gustavino [36], M. Guth [56], P. Gutierrez [120], L.F. Gutierrez Zagazeta [128], C. Gutschow [96], C. Gwenlan [126], C.B. Gwilliam [92], E.S. Haaland [125], A. Haas [117], M. Habedank [48], C. Haber [17a], H.K. Hadavand [8], A. Hadef [100], S. Hadzic [110], E.H. Haines [96], M. Haleem [165], J. Haley [121], J.J. Hall [139], G.D. Hallewell [102], L. Halser [19], K. Hamano [164], H. Hamdaoui [35e], M. Hamer [24], G.N. Hamity [52], E.J. Hampshire [95], J. Han [62b], K. Han [62a], L. Han [14c], L. Han [62a], S. Han [17a], Y.F. Han [155], K. Hanagaki [83], M. Hance [136], D.A. Hangal [41,z], H. Hanif [142], M.D. Hank [128], R. Hankache [101], J.B. Hansen [42], J.D. Hansen [42], P.H. Hansen [42], K. Hara [157], D. Harada [56], T. Harenberg [170], S. Harkusha [37], Y.T. Harris [126], N.M. Harrison [119], P.F. Harrison [166], N.M. Hartman [143], N.M. Hartmann [109], Y. Hasegawa [140], A. Hasib [52], S. Haug [19], R. Hauser [107], M. Havranek [132], C.M. Hawkes [20], R.J. Hawkings [36], S. Hayashida [111], D. Hayden [107], C. Hayes [106], R.L. Hayes [114], C.P. Hays [126], J.M. Hays [94], H.S. Hayward [92], F. He [62a], Y. He [154], Y. He [127], N.B. Heatley [94], V. Hedberg [98], A.L. Heggelund [125], N.D. Hehir [94], C. Heidegger [54], K.K. Heidegger [54], W.D. Heidorn [81], J. Heilman [34], S. Heim [48], T. Heim [17a], J.G. Heinlein [128], J.J. Heinrich [123], L. Heinrich [110], J. Hejbal [131], L. Helary [48], A. Held [169], S. Hellesund [16], C.M. Helling [163], S. Hellman [47a,47b], C. Helsens [36], R.C.W. Henderson [91], L. Henkelmann [32], A.M. Henriques Correia [36], H. Herde [98], Y. Hernández Jiménez [145], L.M. Herrmann [24], T. Herrmann [50], G. Herten [54], R. Hertenberger [109], L. Hervas [36], N.P. Hessey [156a], H. Hibi [84], S.J. Hillier [20], F. Hinterkeuser [24], M. Hirose [124], S. Hirose [157], D. Hirschbuehl [170], T.G. Hitchings [101], B. Hiti [93], J. Hobbs [145], R. Hobincu [27e], N. Hod [168], M.C. Hodgkinson [139], B.H. Hodkinson [32], A. Hoecker [36], J. Hofer [48], T. Holm [24], M. Holzbock [110], L.B.A.H. Hommels [32], B.P. Honan [101], J. Hong [62c], T.M. Hong [129], J.C. Honig [54], B.H. Hooberman [161], W.H. Hopkins [6], Y. Horii [111], S. Hou [148], A.S. Howard [93], J. Howarth [59], J. Hoya [6], M. Hrabovsky [122], A. Hrynevich [48], T. Hryn'ova [4], P.J. Hsu [65], S.-C. Hsu [138], Q. Hu [41], Y.F. Hu [14a,14e], D.P. Huang [96], S. Huang [64b], X. Huang [14c], Y. Huang [62a], Y. Huang [14a], Z. Huang [101], Z. Hubacek [132], M. Huebner [24], F. Huegging [24], T.B. Huffman [126], M. Huhtinen [36], S.K. Huiberts [16], R. Hulsken [104], N. Huseynov [12,a], J. Huston [107], J. Huth [61], R. Hyneman [143], G. Iacobucci [56], G. Iakovidis [29], I. Ibragimov [141], L. Iconomidou-Fayard [66], P. Iengo [72a,72b], R. Iguchi [153], T. Iizawa [56], Y. Ikegami [83], A. Ilg [19], N. Ilic [155], H. Imam [35a], T. Ingebretsen Carlson [47a,47b], G. Introzzi [73a,73b], M. Iodice [77a], V. Ippolito [75a,75b], M. Ishino [153], W. Islam [169], C. Issever [18,48], S. Istin [21a], H. Ito [167], J.M. Iturbe Ponce [64a], R. Iuppa [78a,78b], A. Ivina [168], J.M. Izen [45], V. Izzo [72a], P. Jacka [131,132], P. Jackson [1], R.M. Jacobs [48], B.P. Jaeger [142], C.S. Jagfeld [109], P. Jain [54], G. Jäkel [170], K. Jakobs [54], T. Jakoubek [168], J. Jamieson [59], K.W. Janas [85a], A.E. Jaspan [92], M. Javurkova [103], F. Jeanneau [135], L. Jeanty [123], J. Jejelava [149a,y], P. Jenni [54,g], C.E. Jessiman [34], S. Jézéquel [4], C. Jia [62b], J. Jia [145], X. Jia [61], X. Jia [14a,14e], Z. Jia [14c], Y. Jiang [62a], S. Jiggins [48], J. Jimenez Pena [110], S. Jin [14c], A. Jinaru [27b], O. Jinnouchi [154], P. Johansson [139], K.A. Johns [7], J.W. Johnson [136], D.M. Jones [32], E. Jones [166], P. Jones [32], R.W.L. Jones [91], T.J. Jones [92], R. Joshi [119], J. Jovicevic [15], X. Ju [17a], J.J. Junggeburth [36], T. Junkermann [63a], A. Juste Rozas [13,s], S. Kabana [137e], A. Kaczmarska [86], M. Kado [110], H. Kagan [119], M. Kagan [143], A. Kahn [41], A. Kahn [128], C. Kahra [100], T. Kaji [167], E. Kajomovitz [150], N. Kakati [168], C.W. Kalderon [29], A. Kamenshchikov [155], S. Kanayama [154], N.J. Kang [136], D. Kar [33g], K. Karava [126], M.J. Kareem [156b], E. Karentzos [54], I. Karkanias [152,e], S.N. Karpov [38], Z.M. Karpova [38], V. Kartvelishvili [91], A.N. Karyukhin [37], E. Kasimi [152,e], J. Katzy [48], S. Kaur [34], K. Kawade [140], T. Kawamoto [135], G. Kawamura [55], E.F. Kay [164], F.I. Kaya [158], S. Kazakos [13], V.F. Kazanin [37], Y. Ke [145],

J.M. Keaveney [33a], R. Keeler [164], G.V. Kehris [61], J.S. Keller [34], A.S. Kelly [96], D. Kelsey [146], J.J. Kempster [146], K.E. Kennedy [41], P.D. Kennedy [100], O. Kepka [131], B.P. Kerridge [166], S. Kersten [170], B.P. Kerševan [93], S. Keshri [66], L. Keszeghova [28a], S. Ketabchi Haghighat [155], M. Khandoga [127], A. Khanov [121], A.G. Kharlamov [37], T. Kharlamova [37], E.E. Khoda [138], T.J. Khoo [18], G. Khoriauli [165], J. Khubua [149b], Y.A.R. Khwaira [66], M. Kiehn [36], A. Kilgallon [123], D.W. Kim [47a,47b], Y.K. Kim [39], N. Kimura [96], A. Kirchhoff [55], C. Kirfel [24], J. Kirk [134], A.E. Kiryunin [110], T. Kishimoto [153], D.P. Kisliuk [155], C. Kitsaki [10], O. Kivernyk [24], M. Klassen [63a], C. Klein [34], L. Klein [165], M.H. Klein [106], M. Klein [92], S.B. Klein [56], U. Klein [92], P. Klimek [36], A. Klimentov [29], T. Klioutchnikova [36], P. Kluit [114], S. Kluth [110], E. Kneringer [79], T.M. Knight [155], A. Knue [54], R. Kobayashi [87], M. 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Kroll [128], K.S. Krowpman [107], U. Kruchonak [38], H. Krüger [24], N. Krumnack [81], M.C. Kruse [51], J.A. Krzysiak [86], O. Kuchinskaia [37], S. Kuday [3a], S. Kuehn [36], R. Kuesters [54], T. Kuhl [48], V. Kukhtin [38], Y. Kulchitsky [37,a], S. Kuleshov [137d,137b], M. Kumar [33g], N. Kumari [102], A. Kupco [131], T. Kupfer [49], A. Kupich [37], O. Kuprash [54], H. Kurashige [84], L.L. Kurchaninov [156a], O. Kurdysh [66], Y.A. Kurochkin [37], A. Kurova [37], M. Kuze [154], A.K. Kvam [103], J. Kvita [122], T. Kwan [104], N.G. Kyriacou [106], L.A.O. Laatu [102], C. Lacasta [162], F. Lacava [75a,75b], H. Lacker [18], D. Lacour [127], N.N. Lad [96], E. Ladygin [38], B. Laforge [127], T. Lagouri [137e], S. Lai [55], I.K. Lakomiec [85a], N. Lalloue [60], J.E. Lambert [120], S. Lammers [68], W. Lampl [7], C. Lampoudis [152,e], A.N. Lancaster [115], E. Lançon [29], U. Landgraf [54], M.P.J. Landon [94], V.S. Lang [54], R.J. Langenberg [103], A.J. Lankford [159], F. Lanni [36], K. 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Li [14c], H. Li [62b], J. Li [62c], K. Li [138], L. Li [62c], M. Li [14a,14e], Q.Y. Li [62a], S. Li [14a,14e], S. Li [62d,62c,d], T. Li [62b], X. Li [104], Z. Li [62b], Z. Li [126], Z. Li [104], Z. Li [92], Z. Li [14a,14e], Z. Liang [14a], M. Liberatore [48], B. Liberti [76a], K. Lie [64c], J. Lieber Marin [82b], H. Lien [68], K. Lin [107], R.A. Linck [68], R.E. Lindley [7], J.H. Lindon [2], A. Linss [48], E. Lipeles [128], A. Lipniacka [16], A. Lister [163], J.D. Little [4], B. Liu [14a], B.X. Liu [142], D. Liu [62d,62c], J.B. Liu [62a], J.K.K. Liu [32], K. Liu [62d,62c], M. Liu [62a], M.Y. Liu [62a], P. Liu [14a], Q. Liu [62d,138,62c], X. Liu [62a], Y. Liu [14c,14e], Y.L. Liu [106], Y.W. Liu [62a], J. Llorente Merino [142], S.L. Lloyd [94], E.M. Lobodzinska [48], P. Loch [7], S. Loffredo [76a,76b], T. Lohse [18], K. Lohwasser [139], E. Loiacono [48], M. Lokajicek [131], J.D. Lomas [20], J.D. Long [161], I. Longarini [159], L. Longo [70a,70b], R. Longo [161], I. Lopez Paz [67], A. Lopez Solis [48], J. Lorenz [109], N. Lorenzo Martinez [4], A.M. Lory [109], X. Lou [47a,47b], X. Lou [14a,14e], A. Lounis [66], J. Love [6], P.A. Love [91], G. Lu [14a,14e], M. Lu [80], S. Lu [128], Y.J. Lu [65], H.J. Lubatti [138], C. Luci [75a,75b], F.L. Lucio Alves [14c], A. Lucotte [60], F. Luehring [68], I. Luise [145], O. Lukianchuk [66], O. Lundberg [144], B. Lund-Jensen [144], N.A. Luongo [123], M.S. Lutz [151], D. Lynn [29], H. Lyons [92], R. Lysak [131], E. Lytken [98], V. Lyubushkin [38], T. Lyubushkina [38], M.M. Lyukova [145], H. Ma [29], L.L. Ma [62b], Y. Ma [96], D.M. Mac Donell [164], G. Maccarrone [53], J.C. MacDonald [139], R. Madar [40], W.F. Mader [50], J. Maeda [84], T. Maeno [29], M. Maerker [50], H. Maguire [139], A. Maio [130a,130b,130d], K. Maj [85a], O. Majersky [48], S. Majewski [123], N. Makovec [66], V. Maksimovic [15], B. Malaescu [127], Pa. Malecki [86], V.P. Maleev [37], F. Malek [60], D. Malito [43b,43a], U. Mallik [80], C. Malone [32], S. Maltezos [10], S. Malyukov [38], J. Mamuzic [13], G. Mancini [53], G. Manco [73a,73b], J.P. Mandalia [94], I. Mandić [93], L. Manhaes de Andrade Filho [82a], I.M. Maniatis [168], J. Manjarres Ramos [102], D.C. Mankad [168], A. Mann [109], B. Mansoulie [135], S. Manzoni [36], A. Marantis [152], G. Marchiori [5], M. Marcisovsky [131], C. Marcon [71a,71b], M. Marinescu [20], M. Marjanovic [120], E.J. Marshall [91], Z. Marshall [17a],

S. Marti-Garcia [162], T.A. Martin [166], V.J. Martin [52], B. Martin dit Latour [16], L. Martinelli [75a,75b], M. Martinez [13,s], P. Martinez Agullo [162], V.I. Martinez Outschoorn [103], P. Martinez Suarez [13], S. Martin-Haugh [134], V.S. Martoiu [27b], A.C. Martyniuk [96], A. Marzin [36], S.R. Maschek [110], D. Mascione [78a,78b], L. Masetti [100], T. Mashimo [153], J. Masik [101], A.L. Maslennikov [37], L. Massa [23b], P. Massarotti [72a,72b], P. Mastrandrea [74a,74b], A. Mastroberardino [43b,43a], T. Masubuchi [153], T. Mathisen [160], N. Matsuzawa [153], J. Maurer [27b], B. Maček [93], D.A. Maximov [37], R. Mazini [148], I. Maznas [152,e], M. Mazza [107], S.M. Mazza [136], C. Mc Ginn [29], J.P. Mc Gowan [104], S.P. Mc Kee [106], E.F. McDonald [105], A.E. McDougall [114], J.A. Mcfayden [146], R.P. McGovern [128], G. Mchedlidze [149b], R.P. Mckenzie [33g], T.C. Mclachlan [48], D.J. Mclaughlin [96], K.D. McLean [164], S.J. McMahon [134], P.C. McNamara [105], C.M. Mcpartland [92], R.A. McPherson [164,v], T. Megy [40], S. Mehlhase [109], A. Mehta [92], D. Melini [150], B.R. Mellado Garcia [33g], A.H. Melo [55], F. Meloni [48], A.M. Mendes Jacques Da Costa [101], H.Y. Meng [155], L. Meng [91], S. Menke [110], M. Mentink [36], E. Meoni [43b,43a], C. Merlassino [126], L. Merola [72a,72b], C. Meroni [71a], G. Merz [106], O. Meshkov [37], J. Metcalfe [6], A.S. Mete [6], C. Meyer [68], J-P. Meyer [135], R.P. Middleton [134], L. Mijović [52], G. Mikenberg [168], M. Mikestikova [131], M. Mikuž [93], H. Mildner [139], A. Milic [36], C.D. Milke [44], D.W. Miller [39], L.S. Miller [34], A. Milov [168], D.A. Milstead [47a,47b], T. Min [14c], A.A. Minaenko [37], I.A. Minashvili [149b], L. Mince [59], A.I. Mincer [117], B. Mindur [85a], M. Mineev [38], Y. Mino [87], L.M. Mir [13], M. Miralles Lopez [162], M. Mironova [17a], M.C. Missio [113], T. Mitani [167], A. Mitra [166], V.A. Mitsou [162], O. Miu [155], P.S. Miyagawa [94], Y. Miyazaki [89], A. Mizukami [83], T. Mkrtchyan [63a], M. Mlinarevic [96], T. Mlinarevic [96], M. Mlynarikova [36], S. Mobius [55], K. Mochizuki [108], P. Moder [48], P. Mogg [109], A.F. Mohammed [14a,14e], S. Mohapatra [41], G. Mokgatitswane [33g], B. Mondal [141], S. Mondal [132], G. Monig [146], K. Mönig [48], E. Monnier [102], L. Monsonis Romero [162], J. Montejo Berlingen [83], M. Montella [119], F. Monticelli [90], N. Morange [66], A.L. Moreira De Carvalho [130a], M. Moreno Llácer [162], C. Moreno Martinez [56], P. Morettini [57b], S. Morgenstern [36], M. Morii [61], M. Morinaga [153], A.K. Morley [36], F. Morodei [75a,75b], L. Morvaj [36], P. Moschovakos [36], B. Moser [36], M. Mosidze [149b], T. Moskalets [54], P. Moskvitina [113], J. Moss [31,m], E.J.W. Moyse [103], O. Mtintsilana [33g], S. Muanza [102], J. Mueller [129], D. Muenstermann [91], R. Müller [19], G.A. Mullier [160], J.J. Mullin [128], D.P. Mungo [155], J.L. Munoz Martinez [13], D. Munoz Perez [162], F.J. Munoz Sanchez [101], M. 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Parzefall [54], B. Pascual Dias [108], L. Pascual Dominguez [151], F. Pasquali [114], E. Pasqualucci [75a], S. Passaggio [57b],

F. Pastore [95], P. Pasuwan [47a,47b], P. Patel [86], U.M. Patel [51], J.R. Pater [101], T. Pauly [36], J. Pearkes [143], M. Pedersen [125], R. Pedro [130a], S.V. Peleganchuk [37], O. Penc [36], E.A. Pender [52], H. Peng [62a], K.E. Penski [109], M. Penzin [37], B.S. Peralva [82d], A.P. Pereira Peixoto [60], L. Pereira Sanchez [47a,47b], D.V. Perepelitsa [29,ad], E. Perez Codina [156a], M. Perganti [10], L. Perini [71a,71b,*], H. Pernegger [36], S. Perrella [36], A. Perrevoort [113], O. Perrin [40], K. Peters [48], R.F.Y. Peters [101], B.A. Petersen [36], T.C. Petersen [42], E. Petit [102], V. Petousis [132], C. Petridou [152,e], A. Petrukhin [141], M. Pettee [17a], N.E. Pettersson [36], A. Petukhov [37], K. Petukhova [133], A. Peyaud [135], R. Pezoa [137f], L. Pezzotti [36], G. Pezzullo [171], T.M. Pham [169], T. Pham [105], P.W. Phillips [134], M.W. Phipps [161], G. Piacquadio [145], E. Pianori [17a], F. Piazza [71a,71b], R. Piegaia [30], D. Pietreanu [27b], A.D. Pilkington [101], M. Pinamonti [69a,69c], J.L. Pinfold [2], B.C. Pinheiro Pereira [130a], C. Pitman Donaldson [96], D.A. Pizzi [34], L. Pizzimento [76a,76b], A. Pizzini [114], M.-A. Pleier [29], V. Plesanovs [54], V. Pleskot [133], E. Plotnikova [38], G. Poddar [4], R. Poettgen [98], L. Poggioli [127], D. Pohl [24], I. Pokharel [55], S. Polacek [133], G. Polesello [73a], A. Poley [142,156a], R. Polifka [132], A. Polini [23b], C.S. Pollard [166], Z.B. Pollock [119], V. Polychronakos [29], E. Pompa Pacchi [75a,75b], D. Ponomarenko [113], L. Pontecorvo [36], S. Popa [27a], G.A. Popeneciu [27d], D.M. Portillo Quintero [156a], S. Pospisil [132], P. Postolache [27c], K. Potamianos [126], P.P. Potepa [85a], I.N. Potrap [38], C.J. Potter [32], H. Potti [1], T. Poulsen [48], J. Poveda [162], M.E. Pozo Astigarraga [36], A. Prades Ibanez [162], M.M. Prapa [46], J. Pretel [54], D. Price [101], M. Primavera [70a], M.A. Principe Martin [99], R. Privara [122], M.L. Proffitt [138], N. 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Reynolds [17a], M. Rezaei Estabragh [170], O.L. Rezanova [37], P. Reznicek [133], N. Ribaric [91], E. Ricci [78a,78b], R. Richter [110], S. Richter [47a,47b], E. Richter-Was [85b], M. Ridel [127], S. Ridouani [35d], P. Rieck [117], P. Riedler [36], M. Rijssenbeek [145], A. Rimoldi [73a,73b], M. Rimoldi [48], L. Rinaldi [23b,23a], T.T. Rinn [29], M.P. Rinnagel [109], G. Ripellino [160], I. Riu [13], P. Rivadeneira [48], J.C. Rivera Vergara [164], F. Rizatdinova [121], E. Rizvi [94], C. Rizzi [56], B.A. Roberts [166], B.R. Roberts [17a], S.H. Robertson [104,v], M. Robin [48], D. Robinson [32], C.M. Robles Gajardo [137f], M. Robles Manzano [100], A. Robson [59], A. Rocchi [76a,76b], C. Roda [74a,74b], S. Rodriguez Bosca [63a], Y. Rodriguez Garcia [22a], A. Rodriguez Rodriguez [54], A.M. Rodríguez Vera [156b], S. Roe [36], J.T. Roemer [159], A.R. Roepe-Gier [136], J. Roggel [170], O. Røhne [125], R.A. Rojas [103], C.P.A. Roland [68], J. Roloff [29], A. Romaniouk [37], E. Romano [73a,73b], M. Romano [23b], A.C. Romero Hernandez [161], N. Rompotis [92], L. Roos [127], S. Rosati [75a], B.J. Rosser [39], E. Rossi [4], E. Rossi [72a,72b], L.P. Rossi [57b], L. Rossini [48], R. Rosten [119], M. Rotaru [27b], B. Rottler [54], C. Rougier [102], D. Rousseau [66], D. Rousso [32], A. Roy [161], S. Roy-Garand [155], A. Rozanov [102], Y. Rozen [150], X. Ruan [33g], A. Rubio Jimenez [162], A.J. Ruby [92], V.H. Ruelas Rivera [18], T.A. Ruggeri [1], A. Ruiz-Martinez [162], A. Rummler [36], Z. Rurikova [54], N.A. Rusakovich [38], H.L. Russell [164], J.P. Rutherfoord [7], K. Rybacki [91], M. Rybar [133], E.B. Rye [125], A. Ryzhov [37], J.A. Sabater Iglesias [56], P. Sabatini [162], L. Sabetta [75a,75b], H.F-W. Sadrozinski [136], F. Safai Tehrani [75a], B. Safarzadeh Samani [146], M. Safdari [143], S. Saha [104], M. Sahinsoy [110], M. Saimpert [135], M. Saito [153], T. Saito [153], D. Salamani [36], A. Salnikov [143], J. Salt [162], A. Salvador Salas [13], D. Salvatore [43b,43a], F. Salvatore [146], A. Salzburger [36], D. Sammel [54], D. Sampsonidis [152,e], D. Sampsonidou [123,62c], J. Sánchez [162], A. Sanchez Pineda [4], V. Sanchez Sebastian [162], H. Sandaker [125], C.O. Sander [48], J.A. Sandesara [103], M. Sandhoff [170], C. Sandoval [22b], D.P.C. Sankey [134], T. Sano [87], A. Sansoni [53], L. Santi [75a,75b], C. Santoni [40], H. Santos [130a,130b], S.N. Santpur [17a], A. Santra [168], K.A. Saoucha [139], J.G. Saraiva [130a,130d], J. Sardain [7], O. Sasaki [83], K. Sato [157], C. Sauer [63b], F. Sauerburger [54], E. Sauvan [4], P. Savard [155,ab], R. Sawada [153], C. Sawyer [134], L. Sawyer [97], I. Sayago Galvan [162], C. Sbarra [23b], A. Sbrizzi [23b,23a], T. Scanlon [96], J. Schaarschmidt [138], P. Schacht [110], D. Schaefer [39], U. Schäfer [100], A.C. Schaffer [66,44], D. Schaile [109], R.D. Schamberger [145], E. Schanet [109], C. Scharf [18], M.M. Schefer [19], V.A. Schegelsky [37], D. Scheirich [133], F. Schenck [18], M. Schernau [159], C. Scheulen [55], C. Schiavi [57b,57a], E.J. Schioppa [70a,70b], M. Schioppa [43b,43a], B. Schlag [143], K.E. Schleicher [54], S. Schlenker [36], J. Schmeing [170], M.A. Schmidt [170], K. Schmieden [100], C. Schmitt [100], S. Schmitt [48], L. Schoeffel [135], A. Schoening [63b],

P.G. Scholer [54], E. Schopf [126], M. Schott [100], J. Schovancova [36], S. Schramm [56], F. Schroeder [170], H-C. Schultz-Coulon [63a], M. Schumacher [54], B.A. Schumm [136], Ph. Schune [135], H.R. Schwartz [136], A. Schwartzman [143], T.A. Schwarz [106], Ph. Schwemling [135], R. Schwienhorst [107], A. Sciandra [136], G. Sciolla [26], F. Scuri [74a], F. Scutti [105], C.D. Sebastiani [92], K. Sedlaczek [49], P. Seema [18], S.C. Seidel [112], A. Seiden [136], B.D. Seidlitz [41], C. Seitz [48], J.M. Seixas [82b], G. Sekhniaidze [72a], S.J. Sekula [44], L. Selem [4], N. Semprini-Cesari [23b,23a], S. Sen [51], D. Sengupta [56], V. Senthilkumar [162], L. Serin [66], L. Serkin [69a,69b], M. Sessa [77a,77b], H. Severini [120], F. Sforza [57b,57a], A. Sfyrla [56], E. Shabalina [55], R. Shaheen [144], J.D. Shahinian [128], D. Shaked Renous [168], L.Y. Shan [14a], M. Shapiro [17a], A. Sharma [36], A.S. Sharma [163], P. Sharma [80], S. Sharma [48], P.B. Shatalov [37], K. Shaw [146], S.M. Shaw [101], Q. Shen [62c,5], P. Sherwood [96], L. Shi [96], C.O. Shimmin [171], Y. Shimogama [167], J.D. Shinner [95], I.P.J. Shipsey [126], S. Shirabe [60], M. Shiyakova [38], J. Shlomi [168], M.J. Shochet [39], J. Shojaii [105], D.R. Shope [125], S. Shrestha [119,ae], E.M. Shrif [33g], M.J. Shroff [164], P. Sicho [131], A.M. Sickles [161], E. Sideras Haddad [33g], A. Sidoti [23b], F. Siegert [50], Dj. Sijacki [15], R. Sikora [85a], F. Sili [90], J.M. Silva [20], M.V. Silva Oliveira [36], S.B. Silverstein [47a], S. Simion [66], R. Simoniello [36], E.L. Simpson [59], H. Simpson [146], L.R. Simpson [106], N.D. Simpson [98], S. Simsek [21d], S. Sindhu [55], P. Sinervo [155], S. Singh [142], S. Singh [155], S. Sinha [48], S. Sinha [33g], M. Sioli [23b,23a], I. Siral [36], S.Yu. Sivoklokov [37,*], J. Sjölin [47a,47b], A. Skaf [55], E. Skorda [98], P. Skubic [120], M. Slawinska [86], V. Smakhtin [168], B.H. Smart [134], J. Smiesko [36], S.Yu. Smirnov [37], Y. Smirnov [37], L.N. Smirnova [37,a], O. Smirnova [98], A.C. Smith [41], E.A. Smith [39], H.A. Smith [126], J.L. Smith [92], R. Smith [143], M. Smizanska [91], K. Smolek [132], A.A. Snesarev [37], H.L. Snoek [114], S. Snyder [29], R. Sobie [164,v], A. Soffer [151], C.A. Solans Sanchez [36], E.Yu. Soldatov [37], U. Soldevila [162], A.A. Solodkov [37], S. Solomon [54], A. Soloshenko [38], K. Solovieva [54], O.V. Solovyanov [40], V. Solovyev [37], P. Sommer [36], A. Sonay [13], W.Y. Song [156b], J.M. Sonneveld [114], A. Sopczak [132], A.L. Sopio [96], F. Sopkova [28b], V. Sothilingam [63a], S. Sottocornola [68], R. Soualah [116c], Z. Soumaimi [35e], D. South [48], S. Spagnolo [70a,70b], M. Spalla [110], D. Sperlich [54], G. Spigo [36], M. Spina [146], S. Spinali [91], D.P. Spiteri [59], M. Spousta [133], E.J. Staats [34], A. Stabile [71a,71b], R. Stamen [63a], M. Stamenkovic [114], A. Stampekis [20], M. Standke [24], E. Stanecka [86], M.V. Stange [50], B. Stanislaus [17a], M.M. Stanitzki [48], M. Stankaityte [126], B. Stapf [48], E.A. Starchenko [37], G.H. Stark [136], J. Stark [102], D.M. Starko [156b], P. Staroba [131], P. Starovoitov [63a], S. Stärz [104], R. Staszewski [86], G. Stavropoulos [46], J. Steentoft [160], P. Steinberg [29], B. Stelzer [142,156a], H.J. Stelzer [129], O. Stelzer-Chilton [156a], H. Stenzel [58], T.J. Stevenson [146], G.A. Stewart [36], J.R. Stewart [121], M.C. Stockton [36], G. Stoicea [27b], M. Stolarski [130a], S. Stonjek [110], A. Straessner [50], J. Strandberg [144], S. Strandberg [47a,47b], M. Strauss [120], T. Strebler [102], P. Strizenec [28b], R. Ströhmer [165], D.M. Strom [123], L.R. Strom [48], R. Stroynowski [44], A. Strubig [47a,47b], S.A. Stucci [29], B. Stugu [16], J. Stupak [120], N.A. Styles [48], D. Su [143], S. Su [62a], W. Su [62d,138,62c], X. Su [62a,66], K. Sugizaki [153], V.V. Sulin [37], M.J. Sullivan [92], D.M.S. Sultan [78a,78b], L. Sultanaliyeva [37], S. Sultansoy [3b], T. Sumida [87], S. Sun [106], S. Sun [169], O. Sunneborn Gudnadottir [160], M.R. Sutton [146], M. Svatos [131], M. Swiatlowski [156a], T. Swirski [165], I. Sykora [28a], M. Sykora [133], T. Sykora [133], D. Ta [100], K. Tackmann [48,t], A. Taffard [159], R. Tafirout [156a], J.S. Tafoya Vargas [66], R.H.M. Taibah [127], R. Takashima [88], E.P. Takeva [52], Y. Takubo [83], M. Talby [102], A.A. Talyshev [37], K.C. Tam [64b], N.M. Tamir [151], A. Tanaka [153], J. Tanaka [153], R. Tanaka [66], M. Tanasini [57b,57a], J. Tang [62c], Z. Tao [163], S. Tapia Araya [137f], S. Tapprogge [100], A. Tarek Abouelfadl Mohamed [107], S. Tarem [150], K. Tariq [62b], G. Tarna [102,27b], G.F. Tartarelli [71a], P. Tas [133], M. Tasevsky [131], E. Tassi [43b,43a], A.C. Tate [161], G. Tateno [153], Y. Tayalati [35e,u], G.N. Taylor [105], W. Taylor [156b], H. Teagle [92], A.S. Tee [169], R. Teixeira De Lima [143], P. Teixeira-Dias [95], J.J. Teoh [155], K. Terashi [153], J. Terron [99], S. Terzo [13], M. Testa [53], R.J. Teuscher [155,v], A. Thaler [79], O. Theiner [56], N. Themistokleous [52], T. Theveneaux-Pelzer [102], O. Thielmann [170], D.W. Thomas [95], J.P. Thomas [20], E.A. Thompson [17a], P.D. Thompson [20], E. Thomson [128], Y. Tian [55], V. Tikhomirov [37,a], Yu.A. Tikhonov [37], S. Timoshenko [37], E.X.L. Ting [1], P. Tipton [171], S.H. Tlou [33g], A. Tnourji [40], K. Todome [23b,23a], S. Todorova-Nova [133], S. Todt [50], M. Togawa [83], J. Tojo [89], S. Tokár [28a], K. Tokushuku [83], O. Toldaiev [68], R. Tombs [32], M. Tomoto [83,111], L. Tompkins [143], K.W. Topolnicki [85b], E. Torrence [123], H. Torres [102], E. Torró Pastor [162], M. Toscani [30], C. Tosciri [39], M. Tost [11], D.R. Tovey [139], A. Traeet [16], I.S. Trandafir [27b], T. Trefzger [165], A. Tricoli [29], I.M. Trigger [156a], S. Trincaz-Duvoid [127], D.A. Trischuk [26], B. Trocmé [60], C. Troncon [71a], L. Truong [33c], M. Trzebinski [86], A. Trzupek [86], F. Tsai [145], M. Tsai [106], A. Tsiamis [152,e], P.V. Tsiareshka [37], S. Tsigaridas [156a], A. Tsirigotis [152,r], V. Tsiskaridze [145], E.G. Tskhadadze [149a], M. Tsopoulou [152,e], Y. Tsujikawa [87], I.I. Tsukerman [37], V. Tsulaia [17a], S. Tsuno [83], O. Tsur [150], D. Tsybychev [145], Y. Tu [64b], A. Tudorache [27b], V. Tudorache [27b], A.N. Tuna [36], S. Turchikhin [38],

I. Turk Cakir [3a], R. Turra [71a], T. Turtuvshin [38,w], P.M. Tuts [41], S. Tzamarias [152,e], P. Tzanis [10], E. Tzovara [100], K. Uchida [153], F. Ukegawa [157], P.A. Ulloa Poblete [137c], E.N. Umaka [29], G. Unal [36], M. Unal [11], A. Undrus [29], G. Unel [159], J. Urban [28b], P. Urquijo [105], G. Usai [8], R. Ushioda [154], M. Usman [108], Z. Uysal [21b], L. Vacavant [102], V. Vacek [132], B. Vachon [104], K.O.H. Vadla [125], T. Vafeiadis [36], A. Vaitkus [96], C. Valderanis [109], E. Valdes Santurio [47a,47b], M. Valente [156a], S. Valentinetti [23b,23a], A. Valero [162], E. Valiente Moreno [162], A. Vallier [102], J.A. Valls Ferrer [162], D.R. Van Arneman [114], T.R. Van Daalen [138], P. Van Gemmeren [6], M. Van Rijnbach [125,36], S. Van Stroud [96], I. Van Vulpen [114], M. Vanadia [76a,76b], W. Vandelli [36], M. Vandenbroucke [135], E.R. Vandewall [121], D. Vannicola [151], L. Vannoli [57b,57a], R. Vari [75a], E.W. Varnes [7], C. Varni [17a], T. Varol [148], D. Varouchas [66], L. Varriale [162], K.E. Varvell [147], M.E. Vasile [27b], L. Vaslin [40], G.A. Vasquez [164], F. Vazeille [40], T. Vazquez Schroeder [36], J. Veatch [31], V. Vecchio [101], M.J. Veen [103], I. Veliscek [126], L.M. Veloce [155], F. Veloso [130a,130c], S. Veneziano [75a], A. Ventura [70a,70b], A. Verbytskyi [110], M. Verducci [74a,74b], C. Vergis [24], M. Verissimo De Araujo [82b], W. Verkerke [114], J.C. Vermeulen [114], C. Vernieri [143], P.J. Verschuuren [95], M. Vessella [103], M.C. Vetterli [142,ab], A. Vgenopoulos [152,e], N. Viaux Maira [137f], T. Vickey [139], O.E. Vickey Boeriu [139], G.H.A. Viehhauser [126], L. Vigani [63b], M. Villa [23b,23a], M. Villaplana Perez [162], E.M. Villhauer [52], E. Vilucchi [53], M.G. Vincter [34], G.S. Virdee [20], A. Vishwakarma [52], C. Vittori [36], I. Vivarelli [146], V. Vladimirov [166], E. Voevodina [110], F. Vogel [109], P. Vokac [132], J. Von Ahnen [48], E. Von Toerne [24], B. Vormwald [36], V. Vorobel [133], K. Vorobev [37], M. Vos [162], K. Voss [141], J.H. Vossebeld [92], M. Vozak [114], L. Vozdecky [94], N. Vranjes [15], M. Vranjes Milosavljevic [15], M. Vreeswijk [114], R. Vuillermet [36], O. Vujinovic [100], I. Vukotic [39], S. Wada [157], C. Wagner [103], J.M. Wagner [17a], W. Wagner [170], S. Wahdan [170], H. Wahlberg [90], R. Wakasa [157], M. Wakida [111], J. Walder [134], R. Walker [109], W. Walkowiak [141], A. Wall [128], A.Z. Wang [169], C. Wang [100], C. Wang [62c], H. Wang [17a], J. Wang [64a], R.-J. Wang [100], R. Wang [61], R. Wang [6], S.M. Wang [148], S. Wang [62b], T. Wang [62a], W.T. Wang [80], X. Wang [14c], X. Wang [161], X. Wang [62c], Y. Wang [62d], Y. Wang [14c], Z. Wang [106], Z. Wang [62d,51,62c], Z. Wang [106], A. Warburton [104], R.J. Ward [20], N. Warrack [59], A.T. Watson [20], H. Watson [59], M.F. Watson [20], G. Watts [138], B.M. Waugh [96], C. Weber [29], H.A. Weber [18], M.S. Weber [19], S.M. Weber [63a], C. Wei [62a], Y. Wei [126], A.R. Weidberg [126], E.J. Weik [117], J. Weingarten [49], M. Weirich [100], C. Weiser [54], C.J. Wells [48], T. Wenaus [29], B. Wendland [49], T. Wengler [36], N.S. Wenke [110], N. Wermes [24], M. Wessels [63a], K. Whalen [123], A.M. Wharton [91], A.S. White [61], A. White [8], M.J. White [1], D. Whiteson [159], L. Wickremasinghe [124], W. Wiedenmann [169], C. Wiel [50], M. Wielers [134], C. Wiglesworth [42], L.A.M. Wiik-Fuchs [54], D.J. Wilbern [120], H.G. Wilkens [36], D.M. Williams [41], H.H. Williams [128], S. Williams [32], S. Willocq [103], B.J. Wilson [101], P.J. Windischhofer [39], F. Winklmeier [123], B.T. Winter [54], J.K. Winter [101], M. Wittgen [143], M. Wobisch [97], R. Wölker [126], J. Wollrath [159], M.W. Wolter [86], H. Wolters [130a,130c], V.W.S. Wong [163], A.F. Wongel [48], S.D. Worm [48], B.K. Wosiek [86], K.W. Woźniak [86], K. Wraight [59], J. Wu [14a,14e], M. Wu [64a], M. Wu [113], S.L. Wu [169], X. Wu [56], Y. Wu [62a], Z. Wu [135,62a], J. Wuerzinger [110], T.R. Wyatt [101], B.M. Wynne [52], S. Xella [42], L. Xia [14c], M. Xia [14b], J. Xiang [64c], X. Xiao [106], M. Xie [62a], X. Xie [62a], S. Xin [14a,14e], J. Xiong [17a], I. Xiotidis [146], D. Xu [14a], H. Xu [62a], H. Xu [62a], L. Xu [62a], R. Xu [128], T. Xu [106], Y. Xu [14b], Z. Xu [62b], Z. Xu [14a], B. Yabsley [147], S. Yacoob [33a], N. Yamaguchi [89], Y. Yamaguchi [154], H. Yamauchi [157], T. Yamazaki [17a], Y. Yamazaki [84], J. Yan [62c], S. Yan [126], Z. Yan [25], H.J. Yang [62c,62d], H.T. Yang [62a], S. Yang [62a], T. Yang [64c], X. Yang [62a], X. Yang [14a], Y. Yang [44], Z. Yang [62a,106], W-M. Yao [17a], Y.C. Yap [48], H. Ye [14c], H. Ye [55], J. Ye [44], S. Ye [29], X. Ye [62a], Y. Yeh [96], I. Yeletskikh [38], B.K. Yeo [17a], M.R. Yexley [91], P. Yin [41], K. Yorita [167], S. Younas [27b], C.J.S. Young [54], C. Young [143], Y. Yu [62a], M. Yuan [106], R. Yuan [62b,k], L. Yue [96], M. Zaazoua [35e], B. Zabinski [86], E. Zaid [52], T. Zakareishvili [149b], N. Zakharchuk [34], S. Zambito [56], J.A. Zamora Saa [137d,137b], J. Zang [153], D. Zanzi [54], O. Zaplatilek [132], C. Zeitnitz [170], H. Zeng [14a], J.C. Zeng [161], D.T. Zenger Jr [26], O. Zenin [37], T. Ženiš [28a], S. Zenz [94], S. Zerradi [35a], D. Zerwas [66], M. Zhai [14a,14e], B. Zhang [14c], D.F. Zhang [139], J. Zhang [62b], J. Zhang [6], K. Zhang [14a,14e], L. Zhang [14c], P. Zhang [14a,14e], R. Zhang [169], S. Zhang [106], T. Zhang [153], X. Zhang [62c], X. Zhang [62b], Y. Zhang [62c,5], Z. Zhang [17a], Z. Zhang [66], H. Zhao [138], P. Zhao [51], T. Zhao [62b], Y. Zhao [136], Z. Zhao [62a], A. Zhemchugov [38], X. Zheng [62a], Z. Zheng [143], D. Zhong [161], B. Zhou [106], C. Zhou [169], H. Zhou [7], N. Zhou [62c], Y. Zhou [7], C.G. Zhu [62b], J. Zhu [106], Y. Zhu [62c], Y. Zhu [62a], X. Zhuang [14a], K. Zhukov [37], V. Zhulanov [37], N.I. Zimine [38], J. Zinsser [63b], M. Ziolkowski [141], L. Živković [15], A. Zoccoli [23b,23a], K. Zoch [56], T.G. Zorbas [139], O. Zormpa [46], W. Zou [41], L. Zwalinski [36]

[1] *Department of Physics, University of Adelaide, Adelaide; Australia*
[2] *Department of Physics, University of Alberta, Edmonton AB; Canada*

[3] [(a)] Department of Physics, Ankara University, Ankara; [(b)] Division of Physics, TOBB University of Economics and Technology, Ankara; Türkiye
[4] LAPP, Univ. Savoie Mont Blanc, CNRS/IN2P3, Annecy; France
[5] APC, Université Paris Cité, CNRS/IN2P3, Paris; France
[6] High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America
[7] Department of Physics, University of Arizona, Tucson AZ; United States of America
[8] Department of Physics, University of Texas at Arlington, Arlington TX; United States of America
[9] Physics Department, National and Kapodistrian University of Athens, Athens; Greece
[10] Physics Department, National Technical University of Athens, Zografou; Greece
[11] Department of Physics, University of Texas at Austin, Austin TX; United States of America
[12] Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan
[13] Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain
[14] [(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; [(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, Bogazici University, Istanbul; [(b)] Department of Physics Engineering, Gaziantep University, Gaziantep; [(c)] Department of Physics, Istanbul University, Istanbul; [(d)] Istinye University, Sariyer, Istanbul; Türkiye
[22] [(a)] Facultad de Ciencias y Centro de Investigaciónes, 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)] University Politehnica Bucharest, 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; 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] [(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
[83] KEK, High Energy Accelerator Research Organization, Tsukuba; Japan
[84] Graduate School of Science, Kobe University, Kobe; Japan
[85] [(a)] AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; [(b)] Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland
[86] Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland
[87] Faculty of Science, Kyoto University, Kyoto; Japan
[88] Kyoto University of Education, 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 Teorica 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; [(c)] University of Sharjah, Sharjah; 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. Javakhishvili 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] Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden
[161] Department of Physics, University of Illinois, Urbana IL; United States of America
[162] Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia – CSIC, Valencia; Spain
[163] Department of Physics, University of British Columbia, Vancouver BC; Canada
[164] Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada
[165] Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany
[166] Department of Physics, University of Warwick, Coventry; United Kingdom
[167] Waseda University, Tokyo; Japan
[168] Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel
[169] Department of Physics, University of Wisconsin, Madison WI; United States of America
[170] Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany
[171] 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 Borough of Manhattan Community College, City University of New York, New York NY; United States of America.
[c] Also at Bruno Kessler Foundation, Trento; Italy.
[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 Fisica de la Universitat Autonoma 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 and Astronomy, Michigan State University, East Lansing MI; United States of America.
[l] Also at Department of Physics, California State University, East Bay; United States of America.
[m] Also at Department of Physics, California State University, Sacramento; United States of America.
[n] Also at Department of Physics, King's College London, London; United Kingdom.
[o] Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
[p] Also at Department of Physics, University of Thessaly; Greece.
[q] Also at Department of Physics, Westmont College, Santa Barbara; United States of America.
[r] Also at Hellenic Open University, Patras; Greece.
[s] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
[t] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
[u] Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.
[v] Also at Institute of Particle Physics (IPP); Canada.
[w] Also at Institute of Physics and Technology, Ulaanbaatar; Mongolia.
[x] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
[y] Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.
[z] Also at Lawrence Livermore National Laboratory, Livermore; United States of America.
[aa] Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
[ab] Also at TRIUMF, Vancouver BC; Canada.
[ac] Also at Università di Napoli Parthenope, Napoli; Italy.
[ad] Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America.
[ae] Also at Washington College, Maryland; United States of America.
[af] Also at Physics Department, An-Najah National University, Nablus; Palestine.
* Deceased.