JHEP07(2020)108

Search for the $HH \to b\bar{b}b\bar{b}$ process via vector-boson fusion production using proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS collaboration

E-mail: atlas.publications@cern.ch

ABSTRACT: A search for Higgs boson pair production via vector-boson fusion (VBF) in the $b\bar{b}b\bar{b}$ final state is carried out with the ATLAS experiment using $126\,\text{fb}^{-1}$ of proton-proton collision data delivered at $\sqrt{s} = 13$ TeV by the Large Hadron Collider. This search is sensitive to VBF production of additional heavy bosons that may decay into Higgs boson pairs, and in a non-resonant topology it can constrain the quartic coupling between the Higgs bosons and vector bosons. No significant excess relative to the Standard Model expectation is observed, and limits on the production cross-section are set at the 95% confidence level for a heavy scalar resonance in the context of an extended Higgs sector, and for non-resonant Higgs boson pair production. Interpretation in terms of the coupling between a Higgs boson pair and two vector bosons is also provided: coupling values normalised to the Standard Model expectation of $\kappa_{2V} < -0.76$ and $\kappa_{2V} > 2.90$ are excluded at the 95% confidence level in data.

Contents

1 Introduction

The Higgs boson (H) was discovered by the ATLAS and CMS collaborations in 2012 [1, 2] using proton-proton (pp) collisions at the Large Hadron Collider (LHC). The measured properties have so far been found to be in agreement with the Standard Model (SM) predictions. The production of a pair of Higgs bosons (HH) is a rare process in the SM with a cross-section about 1000 times smaller than the single Higgs boson production cross-section, but various theories beyond the SM (BSM) predict cross-sections for HH production that are significantly higher than the SM prediction. Spin-0 resonances, with narrow or broad width, that decay into Higgs boson pairs, appear in BSM scenarios [3, 4]. Enhanced non-resonant Higgs boson pair production is predicted by many models, for example those featuring light coloured scalars [5] or new contact interactions, such as direct $t\bar{t}HH$ vertices [6, 7].
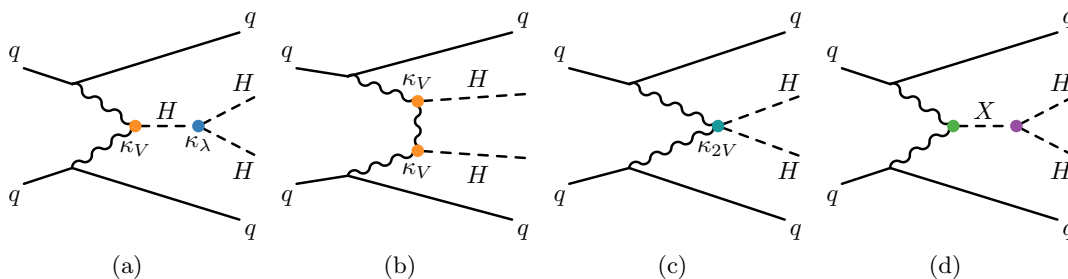
Figure 1. Tree-level Feynman diagrams contributing to Higgs boson pair production via VBF. Diagrams (a), (b) and (c) illustrate the non-resonant production modes scaling with $\kappa_V\kappa_\lambda$, κ_V^2 and κ_{2V}, respectively. Diagram (d) illustrates the resonant production mode.

Previous searches for Higgs boson pair production in the $b\bar{b}b\bar{b}$ channel were carried out in the gluon-gluon fusion (ggF) production mode by the ATLAS and CMS collaborations [8–12], and limits were set for resonant and non-resonant production. Statistical combinations of search results for HH in various decay channels were also performed by the two experiments [13, 14], profiting from the sensitivity of several final states.

This paper focuses on searches for Higgs boson pair production via vector-boson fusion (VBF), through diagrams such as those presented in figure 1, and using the dominant $H \to b\bar{b}$ decay mode [15]. The VBF process ($pp \to HHjj$) is characterised by the presence of two jets (j) with a large rapidity gap resulting from quarks from which a vector boson (V) is radiated. In the SM, three different types of couplings are involved in HH production via VBF: the Higgs boson self-coupling (HHH), the Higgs-boson-vector-boson coupling (VVH) and the quartic (di-vector-boson-di-Higgs-boson, or $VVHH$) coupling. The coupling modifiers κ_λ, κ_V and κ_{2V} control the strength of the HHH, VVH and $VVHH$ couplings with respect to the SM value, respectively, and are normalised so that they are equal 1 in the SM. A deviation of these coupling modifiers from their SM expectations could lead to enhanced HH production. While searches in the ggF mode are more sensitive to deviations in κ_λ, the VBF topology has unique sensitivity to κ_{2V} [15] because the ggF mode does not involve the $VVHH$ interaction. For resonant production, two classes of signals are tested to perform a generic inclusive search for resonances with masses m_X in the range 260–1000 GeV. The first signal class is representative of a broad resonance with width typically 10-20% of the signal mass; it corresponds to a heavy scalar of the 2HDM Type II model [16] and is obtained by setting the ratio of vacuum expectation values of the two Higgs doublets $\tan(\beta) = 2.0$ and $\sin(\beta - \alpha) = 0.6$, where α is the mixing angle between the two CP-even Higgs bosons. The second class features a narrow resonance with a fixed width of 4 MeV.

2 ATLAS detector

The ATLAS experiment [17–19] at the LHC operates a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a near 4π coverage in solid angle.[1] It consists of an inner tracking detector surrounded by a thin superconducting

---

[1]ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre

solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition-radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity. A hadronic steel/scintillator-tile calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for both the EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and incorporates three large air-core toroidal superconducting magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 Tm across most of the detector. The muon spectrometer includes a system of precision tracking chambers and fast detectors for triggering [20]. A two-level trigger system is used to select events. The first-level trigger is implemented in hardware and uses a subset of the detector information to reduce the accepted rate to at most 100 kHz. This is followed by the software-based high-level trigger (HLT), which reduces the accepted event rate to 1 kHz on average.

3   Data and simulated samples

This search is performed using data collected by the ATLAS experiment between 2016 and 2018 in $\sqrt{s} = 13$ TeV LHC pp collisions, which correspond to an integrated luminosity of 126 fb^{-1}. Only events recorded during stable beam conditions and when the detector components relevant to the analysis were operating normally are considered [21]. During the 2016 data-taking, a fraction of the data was affected by an inefficiency in the vertex reconstruction in the HLT, which reduced the efficiency of the algorithms used to identify jets originating from b-hadron decays; those events were not retained for further analysis. This reduces the integrated luminosity of the 2016 dataset to 24.3 fb^{-1}.

Simulated Monte Carlo (MC) event samples are used to model signal production and the backgrounds from top-quark-pair ($t\bar{t}$) production. The dominant process arises from multijet production, and is modelled using data-driven techniques.

Events with a generic scalar resonance produced via VBF and decaying into $HH \rightarrow b\bar{b}b\bar{b}$ were generated with POWHEG-BOX v2 [22–24] interfaced to PYTHIA 8.186 [25] for parton showering and hadronisation, with the Higgs boson mass fixed to 125 GeV [26]. The NNPDF23LO parton distribution function (PDF) set [27] and the A14 set of tuned parameters [28] for underlying-event simulation were used. Resonant signal samples were produced with masses ranging from 260 GeV to 1000 GeV.

Non-resonant production of Higgs boson pairs was simulated with MAD-GRAPH5_AMC@NLO [29]. The Higgs boson self-coupling and the couplings of the Higgs boson to vector bosons were set to their SM values, while the κ_{2V} coupling modifier was varied. Samples with κ_{2V} equal to 0.0, 0.5, 1.0, 1.5, 2.0, and 4.0 were generated at leading order (LO). Interference between various diagrams contributing to the non-resonant signal

---

of the LHC ring, and the y-axis points upwards. 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 $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

is considered in the simulation. A linear combination of three samples is used to derive distributions for a finer granularity of κ_{2V} values, following a technique used to generate κ_λ distributions [13]. A particular choice of three samples is done based on the κ_{2V} range of the generated distributions to avoid large weights and to reduce statistical uncertainties. The cross-section of the VBF HH process, evaluated at next-to-next-to-next-to-leading order (N^{3}LO) in QCD, is 1.73 ± 0.04 fb in the SM [30–33]. The N^{3}LO to LO cross-section ratio at the SM value is calculated and this factor is applied to the cross-sections at each κ_{2V} point.

To estimate the contribution from ggF HH production with two additional jets that can mimic the VBF HH topology, the SM non-resonant production of Higgs boson pairs via ggF was simulated with MadGraph5_aMC@NLO using the CT10 PDF set [34] and the FTapprox method [35] to include finite top-quark mass effects. In this sample, the generation of $pp \rightarrow H +$ parton is done at next-to-leading order (NLO). Parton showers and hadronisation were simulated with Herwig 7.0.4 [36]. Interference effects with other SM processes are found to be marginal and are ignored. The cross-section is evaluated at next-to-next-to-leading order (NNLO) with the resummation at next-to-next-to-leading-logarithm (NNLL) accuracy and including top-quark mass effects at NLO [35, 37–42]; it is equal to $31.05^{+1.40}_{-1.99}$ fb. The uncertainty includes the variations of the factorisation and renormalisation scales, PDF and α_S.

The generation of $t\bar{t}$ events was performed with Powheg-Box v2 [43] using the NNPDF3.0NLO [44] PDF set. The parton showers, hadronisation, and underlying event were simulated using Pythia 8.230 [45] with the NNPDF23LO PDF set and the corresponding A14 set of tuned underlying-event parameters. The predicted $t\bar{t}$ production cross-section is $831.8^{+19.8}_{-29.2} \pm 35.1$ pb as calculated with the Top++ 2.0 program to NNLO in perturbative QCD, including soft-gluon resummation to NNLL accuracy [46], and assuming a top-quark mass of 172.5 GeV. The first uncertainty comes from the independent variations of the factorisation and renormalisation scales, while the second one is associated with variations in the PDF and α_S, following the PDF4LHC prescription with the MSTW2008 68% CL NNLO, CT10 NNLO and NNPDF2.3 5f FFN PDF sets [27, 47–49].

For all simulated events, c-hadron and b-hadron decays were handled by EvtGen 1.2.0 [50]. To simulate the impact of multiple pp interactions that occur within the same or nearby bunch crossings (pile-up), minimum-bias events generated with Pythia 8.186 using the NNPDF2.3LO set of PDFs and the A3 set of tuned parameters [51] were overlaid on the hard-scatter process. The detector response was simulated with Geant 4 [52, 53], and the events were processed with the same reconstruction software as that was used for the data.

4 Event reconstruction

Events are required to have at least one reconstructed primary vertex with at least two associated tracks, each with transverse momentum $p_T > 0.4$ GeV. For events with more than one primary-vertex candidate, the one with the largest track $\sum p_T^2$ is chosen as the hard-scatter primary vertex.

Jets are reconstructed from three-dimensional topological clusters of energy deposits in the calorimeter [54] with the anti-k_t algorithm [55] implemented in the FASTJET package [56] with radius parameter $R = 0.4$. Clusters are calibrated at the EM scale [57] and their energy is corrected for additional energy deposits from pile-up interactions using an area-based correction [58]. Subsequently, calibration using p_T- and η-dependent factors derived from simulation is applied, followed by the global sequential calibration [57]. The latter reduces the flavour dependence of the calibration and energy leakage effects. The final calibration is based on in situ measurements in collision data [57]. To preferentially reject jets originating from pile-up interactions, a multivariate classification algorithm (jet vertex tagger) based on tracking information [59] is used for jets with $p_T < 60$ GeV and $|\eta| < 2.4$. The selected working point provides an inclusive hard-scatter process efficiency of about 97% in that kinematic region. The efficiency in the simulation is corrected to match that measured in data. Events having jets consistent with noise in the calorimeter or non-collision backgrounds are vetoed [57].

Jets containing b-hadrons are identified using a multivariate algorithm (MV2c10) [60, 61], which exploits information about the jet kinematics, the impact parameters of tracks associated with the jet and the presence of displaced vertices to form the decision. The b-tagging requirements result in an efficiency of 70% for jets with $p_T > 20$ GeV containing b-hadrons, and the misidentification rate is 0.3% (11.2%) for light-flavour (charm) jets. These were determined in a sample of simulated $t\bar{t}$ events. For all simulated events the b-tagging efficiencies are corrected to match those measured in data [60, 62, 63].

To further correct the b-jet energy for effects that are not considered in the default calibration, a jet energy regression is used. The method uses a boosted decision tree (BDT) algorithm implemented in TMVA [64]. The BDT training is performed using variables the b-jet energy resolution is sensitive to: MV2c10 score, energy leakage outside the jet cone, pile-up contamination, hard radiation from the original parton, and energy loss through semileptonic b-hadron decays. Both the training and the validation are performed with simulated $t\bar{t}$ samples, resulting in approximately 10% improvement in the jet energy resolution. The performance of the jet energy regression is validated in $Z(\to \mu\mu) + b/b\bar{b}$ events in data and no mismodelling is found. The $H \to b\bar{b}$ mass peak is found to be closer to 125 GeV and the standard deviation divided by the mean of the mass distribution is improved by about 25% for the $m_X = 600$ GeV signal sample.

5 Event selection

Events are selected using a combination of b-jet triggers, with the lowest jet transverse energy, E_T, threshold at 35 GeV, jet $|\eta| < 2.5$ and one or two b-tagged jets. The b-jet trigger efficiency is measured in data, and the simulated events are corrected to match the measured trigger efficiency.

To select events compatible with VBF production of Higgs boson pairs decaying into four b-quarks, exactly four central b-tagged jets with $p_T > 40$ GeV and $|\eta| < 2.0$ and at least two forward jets with $p_T > 30$ GeV and $|\eta| > 2.0$ are required. Events with more than four central jets are vetoed in case more than four jets fulfil the b-tagging requirement. To

	Selections		
VBF topology	At least two jets with $p_{\mathrm{T}} > 30$, $|\eta| > 2.0$	Two highest-p_{T} jets with opposite sign η	
		$\left|\Delta\eta_{jj}^{\mathrm{VBF}}\right| > 5.0$ and $m_{jj}^{\mathrm{VBF}} > 1000$	
Signal topology	Exactly 4 b-tagged jets with $p_{\mathrm{T}} > 40$, $|\eta| < 2.0$		
	If $m_{4b} < 1250$	$\frac{360}{m_{4b}} - 0.5 < \Delta R_{bb}^{\mathrm{lead}} < \frac{653}{m_{4b}} + 0.475$	
		$\frac{235}{m_{4b}} \quad\quad < \Delta R_{bb}^{\mathrm{subl}} < \frac{875}{m_{4b}} + 0.35$	
	If $m_{4b} \geq 1250$	$\Delta R_{bb}^{\mathrm{lead}} < 1$	
		$\Delta R_{bb}^{\mathrm{subl}} < 1$	
	Pairs with minimum $D_{HH} = \sqrt{(m_{2b}^{\mathrm{lead}})^2 + (m_{2b}^{\mathrm{subl}})^2}\left|\sin\left(\tan^{-1}\left(\frac{m_{2b}^{\mathrm{subl}}}{m_{2b}^{\mathrm{lead}}}\right) - \tan^{-1}\left(\frac{116.5}{123.7}\right)\right)\right|$		
Background rejection	Multijet	$|\Delta\eta_{HH}| < 1.5$	
		$|\Sigma_i \vec{p}_{\mathrm{T}i}| < 60$, where $i = b$-jets and VBF-jets	
		$p_{\mathrm{T},H}^{\mathrm{lead}} > 0.5 m_{4b} - 103$	
		$p_{\mathrm{T},H}^{\mathrm{subl}} > 0.33 m_{4b} - 73$	
	$t\bar{t}$	Veto if $X_{Wt} = \sqrt{\left(\frac{m_W - 80.4}{0.1 m_W}\right)^2 + \left(\frac{m_t - 172.5}{0.1 m_t}\right)^2} \leq 1.5$	
Region definition	Signal region (SR)	$X_{HH} = \sqrt{\left(\frac{m_{2b}^{\mathrm{lead}} - 123.7}{11.6}\right)^2 + \left(\frac{m_{2b}^{\mathrm{subl}} - 116.5}{18.1}\right)^2} < 1.6$	
	Validation region (veto SR)	$\sqrt{\left(m_{2b}^{\mathrm{lead}} - 123.7\right)^2 + \left(m_{2b}^{\mathrm{subl}} - 116.5\right)^2} < 30$	
	Sideband region (veto SR, VR)	$\sqrt{\left(m_{2b}^{\mathrm{lead}} - 123.7\right)^2 + \left(m_{2b}^{\mathrm{subl}} - 116.5\right)^2} < 45$	

Table 1. Summary of the selection criteria for capturing the VBF topology, identifying $HH \to b\bar{b}b\bar{b}$ decays, and suppressing background events. Possible remnants of the VBF process are identified using the two highest-p_{T} forward jets. Labels "lead" and "subl" refer to the leading and subleading Higgs boson candidates (ordered in p_{T}), respectively. The definitions of the different analysis regions are also provided. The transverse momenta and masses are expressed in GeV.

form Higgs boson candidates, b-tagged jets are used, and the forward jets are considered as possible remnants of the VBF process. The Higgs boson reconstruction procedure is the same as the one described in ref. [8], except that the usage of the jet energy regression changes the numerical values in the signal region definition described below. A summary of the selection criteria is provided in table 1.

5.1 VBF-jets selection

The two highest-p_{T} forward jets with opposite sign of η are considered as remnants of the VBF production process if the absolute value of the pseudorapidity separation between them, $\left|\Delta\eta_{jj}^{\mathrm{VBF}}\right|$, exceeds 5.0 and their invariant mass, m_{jj}^{VBF}, is greater than 1000 GeV.

5.2 Signal kinematics selection

The four central b-tagged jets are considered in three possible combinations of two-jet pairings. Their invariant mass, m_{4b}, is used to define criteria to select signal-like events. The following ΔR requirements must be satisfied; these reflect the correlation of m_{4b} with

the Lorentz boost of the Higgs bosons and the angle between their decay products in the laboratory frame:

$$\left.\begin{array}{l} \dfrac{360 \text{ GeV}}{m_{4b}} - 0.5 < \Delta R_{bb}^{\text{lead}} < \dfrac{653 \text{ GeV}}{m_{4b}} + 0.475 \\[2ex] \dfrac{235 \text{ GeV}}{m_{4b}} \qquad < \Delta R_{bb}^{\text{subl}} < \dfrac{875 \text{ GeV}}{m_{4b}} + 0.35 \end{array}\right\} \quad \text{if } m_{4b} < 1250 \text{ GeV},$$

$$\left.\begin{array}{l} \Delta R_{bb}^{\text{lead}} < 1 \\[1ex] \Delta R_{bb}^{\text{subl}} < 1 \end{array}\right\} \quad \text{if } m_{4b} \geq 1250 \text{ GeV},$$

where $\Delta R_{bb}^{\text{lead}}$ and $\Delta R_{bb}^{\text{subl}}$ are the angular distances between the jets that form, respectively, the leading and subleading Higgs boson candidates (ordered in p_{T}). These criteria are optimised for both non-resonant and resonant Higgs boson pair production, and the numerical values are chosen to maximise the signal sensitivity.

Out of the possible pairings fulfilling the previous selection, the combination that leads to pairs with a dijet mass closest to the SM Higgs boson mass should be the optimal choice. However, due to energy loss through semileptonic b-hadron decays, this criterion is relaxed. The mass values of 123.7 GeV for the leading Higgs boson candidate and 116.5 GeV for the subleading Higgs boson candidate are found to maximise the signal significance for a resonance with a mass of 600 GeV, which lies in the middle of the covered mass range. The same target values are used for all other signal hypotheses. For a given pairing, the quantity D_{HH} that corresponds to the distance of the leading and subleading Higgs boson candidate masses, in the $(m_{2b}^{\text{lead}}, m_{2b}^{\text{subl}})$ plane, from the line connecting $(0 \text{ GeV}, 0 \text{ GeV})$ and $(123.7 \text{ GeV}, 116.5 \text{ GeV})$, can be computed as:

$$D_{HH} = \sqrt{(m_{2b}^{\text{lead}})^2 + (m_{2b}^{\text{subl}})^2} \left| \sin\left(\tan^{-1}\left(\frac{m_{2b}^{\text{subl}}}{m_{2b}^{\text{lead}}} \right) - \tan^{-1}\left(\frac{116.5 \text{ GeV}}{123.7 \text{ GeV}} \right) \right) \right|.$$

The pairing with the smallest value of D_{HH} is chosen. Studies based on simulation indicate that for SM non-resonant HH production the correct pairs are identified in at least 83% of the signal events, while for broad resonances the corresponding fraction is greater than 91%.

5.3 Selection for background suppression

In order to enhance the sensitivity to signal, various requirements are applied to suppress the background. The magnitude of the vector sum of the transverse momenta of the selected four b-jets and the two VBF-jets tends to peak at lower values for signal events than for multijet events. Consequently, it is required to be less than 60 GeV. The pseudorapidity difference between the reconstructed Higgs boson candidates, $|\Delta \eta_{HH}|$, is required to be below 1.5, and mass-dependent requirements on the transverse momenta of the leading and subleading Higgs boson candidates, respectively $p_{\text{T},H}^{\text{lead}}$ and $p_{\text{T},H}^{\text{subl}}$, are:

$$p_{\text{T},H}^{\text{lead}} > 0.5 m_{4b} - 103 \text{ GeV},$$

$$p_{\text{T},H}^{\text{subl}} > 0.33 m_{4b} - 73 \text{ GeV}.$$

The resulting dijet pairs are still dominated by multijet events. To further increase the search sensitivity, the dijet masses are required to fulfil:

$$X_{HH} = \sqrt{\left(\frac{m_{2b}^{\text{lead}} - 123.7 \text{ GeV}}{11.6 \text{ GeV}}\right)^2 + \left(\frac{m_{2b}^{\text{subl}} - 116.5 \text{ GeV}}{18.1 \text{ GeV}}\right)^2} < 1.6, \qquad (5.1)$$

where 11.6 GeV and 18.1 GeV are the experimental widths of the simulated leading and subleading Higgs boson candidates, respectively. The mass resolution of the subleading Higgs boson candidate is worse because it is composed of the lower p_{T} jets. These values are derived using a 600 GeV resonant signal sample and are similar for other signal samples.

Additional requirements are imposed to reduce the number of hadronically decaying $t\bar{t}$ events by vetoing candidate events compatible with a top-quark decay. The jet with the highest b-tagging score is considered as the b-jet originating from a top-quark decay and the remaining central jets are considered to stem from the W-boson decay. Since the top quarks are expected to be produced centrally, only central jets are tested. All possible two-jet combinations in the event are tested and the selected combination is the one with the smallest value of X_{Wt}, defined as:

$$X_{Wt} = \sqrt{\left(\frac{m_W - 80.4 \text{ GeV}}{0.1 m_W}\right)^2 + \left(\frac{m_t - 172.5 \text{ GeV}}{0.1 m_t}\right)^2},$$

where m_W and m_t are the reconstructed invariant masses of the W-boson and top-quark candidates, respectively. The event is vetoed if $X_{Wt} \leq 1.5$. This requirement reduces the $t\bar{t}$ contamination by about 50% with negligible impact on the signal efficiency.

All requirements listed above define the signal region (SR). The number of selected signal events divided by the number of generated events after each selection step (cumulative acceptance times efficiency) is shown in figure 2 for the non-resonant signal as a function of the κ_{2V} coupling modifier and for the resonant signal models as a function of the generated mass. The acceptance times efficiency increases as a function of the resonance mass, while for the non-resonant signal a significant drop is observed at $\kappa_{2V} = 1$. The trigger and jet selection requirements cause the drop for κ_{2V} values around 1, while the smaller acceptance times efficiency for low-mass resonances is due to the softer p_{T} spectrum of b-jets.

To estimate the background and to validate the background estimation technique, two regions orthogonal to the SR are used: the sideband region (SB) and the validation region (VR). The events in the SB and VR must fail the requirement defined in eq. (5.1) and fulfil

$$\sqrt{\left(m_{2b}^{\text{lead}} - 123.7 \text{ GeV}\right)^2 + \left(m_{2b}^{\text{subl}} - 116.5 \text{ GeV}\right)^2} < 30 \text{ GeV}$$

requirement in the VR and

$$30 \text{ GeV} < \sqrt{\left(m_{2b}^{\text{lead}} - 123.7 \text{ GeV}\right)^2 + \left(m_{2b}^{\text{subl}} - 116.5 \text{ GeV}\right)^2} < 45 \text{ GeV}$$

requirement in the SB. The m_{2b} distributions of the leading versus subleading Higgs boson candidates for the non-resonant signal and the multijet background are shown in figure 3, together with the contours of the SR, VR and SB.
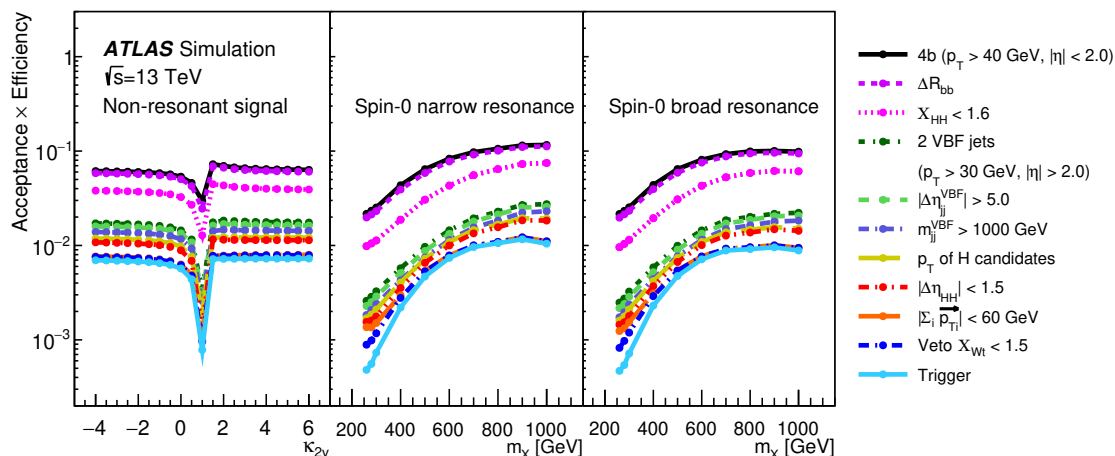
Figure 2. Cumulative acceptance times efficiency at each stage of the event selection, as detailed in section 5. The number of events surviving the selection divided by the number of generated events is reported separately for the non-resonant signal as a function of the κ_{2V} coupling modifier and for the narrow- and broad-width resonance production hypotheses as a function of the generated mass.
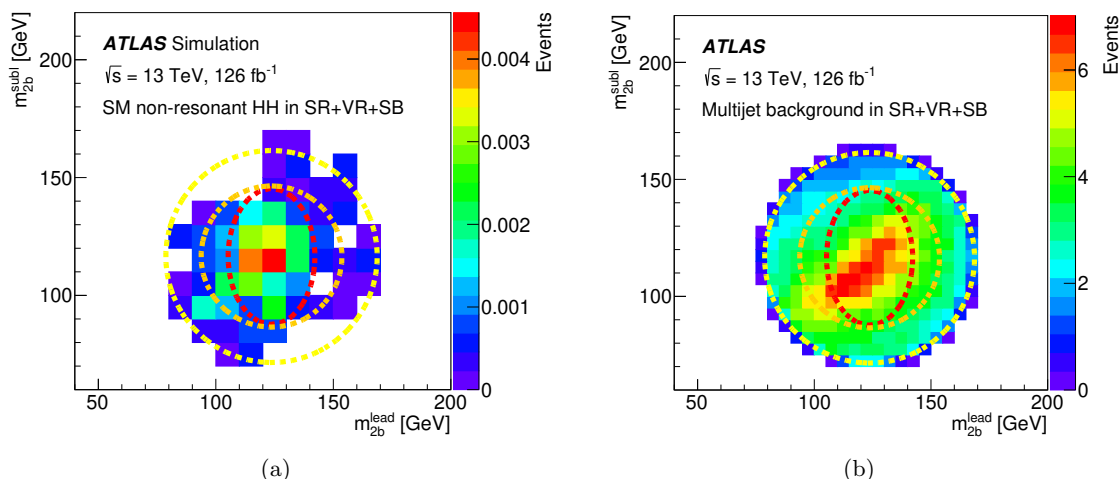

Figure 3. Two-dimensional mass regions used in the analysis. The signal region is inside the inner (red) dashed curve, the validation region is outside the signal region and within the intermediate (orange) circle, and the sideband is outside the validation region and within the outer (yellow) circle. The regions are shown for (a) simulated events from the SM non-resonant HH process and (b) the estimated multijet background.

6 Background estimation

After the event selection described in section 5, the background is dominated by multijet and $t\bar{t}$ events. The multijet events constitute about 95% of the total background and are modelled using data. The remaining 5% are $t\bar{t}$ events, which are modelled using simulation. The normalisation of the all-hadronic $t\bar{t}$ background is determined from data, whereas the non-all-hadronic $t\bar{t}$ background is normalised to the SM prediction. In the SM, the contribution of the HH pairs produced via ggF is small compared to other backgrounds

and three times larger than for the VBF production. Thus HH production via ggF is treated as a background in this analysis and is fixed to the SM prediction. Other minor backgrounds with contributions below 0.5% are neglected. The background estimation technique is the same as in ref. [8].

6.1 Multijet background

The data-driven multijet background estimation uses data events with lower b-jet multiplicity and reweights them to model events with higher b-jet multiplicity. The multijet events are selected using the same trigger and selection requirements as those used in the SR, except for the b-tagging requirement. In particular, the SR requires at least four b-jets ("four-tag sample"). To derive a background estimate for this region, events with at least four central jets, but with only two of them b-tagged ("two-tag sample"), are used. The events in the two-tag sample are reweighted by applying a product of two event weights. The first event weight corrects for the additional b-tagged jet activity and the second event weight corrects for the kinematic differences caused by requiring additional b-tagged jets. These differences can arise for a variety of reasons: the b-tagging efficiency varies as a function of jet p_{T} and η; the various multijet processes contribute with different fractions in each sample; and the fraction of events accepted by each trigger path changes. The reweighting is performed using one-dimensional distributions and is iterated until the weights converge to stable values. Details of the reweighting procedure can be found in ref. [8]. The weights are derived in the SB using the procedure described above and validated in the VR.

6.2 $t\bar{t}$ background

The shape of the $t\bar{t}$ background is modelled using simulation. The $t\bar{t}$ events are expected to contain two b-jets from the decay of two top quarks and additional jets stemming from the hadronic W-boson decay or additional quarks or gluons produced together with two top quarks. To reduce the statistical uncertainty, simulated $t\bar{t}$ events in the two-tag region, corrected by the kinematic weights derived for the multijet background, are also used. The procedure is validated in the SB, and good agreement is observed between the corrected two-tag sample and the four-tag sample within the uncertainties. Samples for all-hadronic and non-all-hadronic $t\bar{t}$ decays are handled separately.

6.3 Background normalisation

The normalisations of multijet and all-hadronic $t\bar{t}$ backgrounds are derived simultaneously by fitting the X_{Wt} distribution to data in the SB. The X_{Wt} distribution differs for the two backgrounds: the region of $X_{Wt} < 0.75$ is enriched in all-hadronic $t\bar{t}$ events and the region $X_{Wt} > 0.75$ is enriched in multijet events. The normalisation of the non-all-hadronic $t\bar{t}$ background is fixed to its SM prediction in the fit due to its small contribution to the total yields. Two parameters are used in the normalisation fit: f_{multijet} and $f_{\mathrm{all\text{-}had.}\ t\bar{t}}$. The f_{multijet} parameter scales the multijet yield from the two-tag to the four-tag sideband region after the reweighting described in section 6.1. The $f_{\mathrm{all\text{-}had.}\ t\bar{t}}$ parameter corrects the normalisation of all-hadronic $t\bar{t}$ yields in the four-tag sideband region. The fit results are cross-checked in the VR, where the same results are obtained within statistical uncertainties.

7 Systematic uncertainties

Background normalisation uncertainties are propagated from the fit, described in the previous section, which determines the multijet and all-hadronic $t\bar{t}$ yields. The statistical uncertainty of the multijet and all-hadronic $t\bar{t}$ normalisation parameters is accounted for, including their correlations. Two nuisance parameters are defined in the final fit described in section 8 by calculating two eigenvectors from the covariance matrix of the normalisation fit. Furthermore, the normalisation of the multijet background estimate is verified in the VR, where agreement with data is found; its statistical uncertainty in the VR is thus applied as a normalisation systematic uncertainty of the multijet background.

Two shape uncertainties for the multijet background modelling are evaluated using data from the VR. The multijet modelling uncertainty is related to the level of agreement between the data and the background model in this region. To evaluate this uncertainty, the m_{4b} distribution is split into low and high mass regions at 400 GeV and a linear fit to the ratio of this distribution between data and the sum of all backgrounds is performed in both mass regions. Studies show that the ratio, which appears to be constant, can be sufficiently well described by a straight-line fit, and that the change in the result is marginal for other splitting points. The $+1\sigma$ variation of the slope of the fitted line and the $+1\sigma$ variation of the fitted line with inverted slope are used as up and down variations of the uncertainty in the background shape. The yield of the varied multijet templates is fixed to its nominal value. The varied templates are derived separately for the low- and high-m_{4b} mass regions, the corresponding systematics are treated as uncorrelated in the final fit. The kinematic reweighting uncertainty is assessed by deriving an alternative multijet template using the same procedure as in the nominal case, but using data from the VR. This difference between the multijet templates derived in the SB and the VR is symmetrised around the nominal template, keeping the yield fixed to its nominal value.

The shape modelling uncertainty of the $t\bar{t}$ background is evaluated by comparing the nominal $t\bar{t}$ template derived using the two-tag sample as described in section 6 and a $t\bar{t}$ template derived using the four-tag sample after the basic preselection requirements defined in section 5. A straight-line fit to the ratio of the two-tag to four-tag m_{4b} templates is performed. With a procedure similar to the one applied for the multijet shape uncertainties, the up and down variations around the nominal $t\bar{t}$ template are extracted using a straight-line fit to the $+1\sigma$ variation of the slope of the fitted line and the $+1\sigma$ variation of the fitted line with inverted slope, while keeping the yield fixed to its nominal value. This uncertainty is derived separately for the non-all-hadronic (using MC) and all-hadronic (using data) $t\bar{t}$ samples and is not correlated in the fit between these two samples.

Theoretical uncertainties in the ggF background yield are evaluated by varying the renormalisation and factorisation scales and from the uncertainty associated with the choice of PDF set. The resulting variation of the expected ggF background yield is about 10%. When considering the same sources of theoretical uncertainty for the VBF HH signal, its acceptance times efficiency varies by 3%.

The experimental uncertainties listed below affect only MC samples. The uncertainties in the jet energy resolution and scale are evaluated at $\sqrt{s} = 13$ TeV using in situ measure-

ment techniques described in ref. [57]. The sources of uncertainty in these measurements are treated as fully correlated between the p_T and mass scales. The resolution uncertainty is evaluated in measurements documented in ref. [65] and is assessed by applying an additional smearing to these observables. The flavour tagging efficiency and its uncertainty for b- and c-jets is estimated in $t\bar{t}$ events, while the light-jet misidentification rate and uncertainty is determined using dijet events [60, 62, 63]. In addition, an uncertainty in the b-jet trigger efficiency is derived from the per-jet online b-tagging measurements [66]. The uncertainty in the integrated luminosity is 1.7% [67], obtained using the LUCID-2 detector [68] for the primary luminosity measurements.

8   Results

Following the statistical procedures outlined in ref. [1], a test statistic based on the profile likelihood ratio [69] is used to test hypothesised values σ_{VBF} of the cross-section of the signal model in units of fb. This test statistic extracts the information about the signal cross-section from a likelihood fit to the data. The likelihood function includes all parameters which describe the systematic uncertainties and their correlations discussed in section 7. As no significant excess over the background prediction is observed, exclusion limits are computed using the asymptotic formula [69]. The exclusion limits are based on the CL$_s$ method [70], where a value of σ_{VBF} is regarded as excluded at the 95% confidence level (CL) when CL$_s$ is smaller than 5%. The accuracy of the asymptotic approximation is verified with sampling distributions generated using pseudo-experiments.

The mass of the four selected b-jets, m_{4b}, in the SR is used as the final discriminant for limit setting. Figure 4 shows the distribution of data and the SM background after the background-only fit in the SR and VR. In addition, the signal prediction for the narrow-width resonance hypothesis with $m_X = 800$ GeV and the non-resonant signal at $\kappa_{2V} = 3$ are shown in the SR.

Upper limits on the cross-section are set for all tested models. Figure 5 shows the 95% CL upper limits for resonant HH production via VBF as a function of the resonance mass m_X for narrow- and broad-width resonance hypotheses. The significance of the excess over the background-only prediction is quantified using the local p_0-value, defined as the probability of the background-only model to produce a signal-like fluctuation at least as large as that observed in the data. The most extreme p_0-value corresponds to a local significance of 1.5 standard deviations at 550 GeV.

The expected and observed limits on SM non-resonant HH production via VBF are given in table 2. Limits are also calculated as a function of κ_{2V}, as presented in figure 6. The observed excluded region corresponds to $\kappa_{2V} < -0.76$ and $\kappa_{2V} > 2.90$, while the expected exclusion is $\kappa_{2V} < -0.91$ and $\kappa_{2V} > 3.11$. For κ_{2V} values deviating from the SM prediction, growing non-cancellation effects result in a harder m_{HH} spectrum, and thereby higher-p_T b-jets, which in turn lead to increased signal acceptance times efficiency as shown in figure 2. This search is therefore not sensitive to the region close to the SM prediction, corresponding to $\kappa_{2V} = 1$.

Table 3 summarises the relative impact of the uncertainties on the best-fit signal cross-section for two different narrow-width resonance production hypotheses, with masses equal
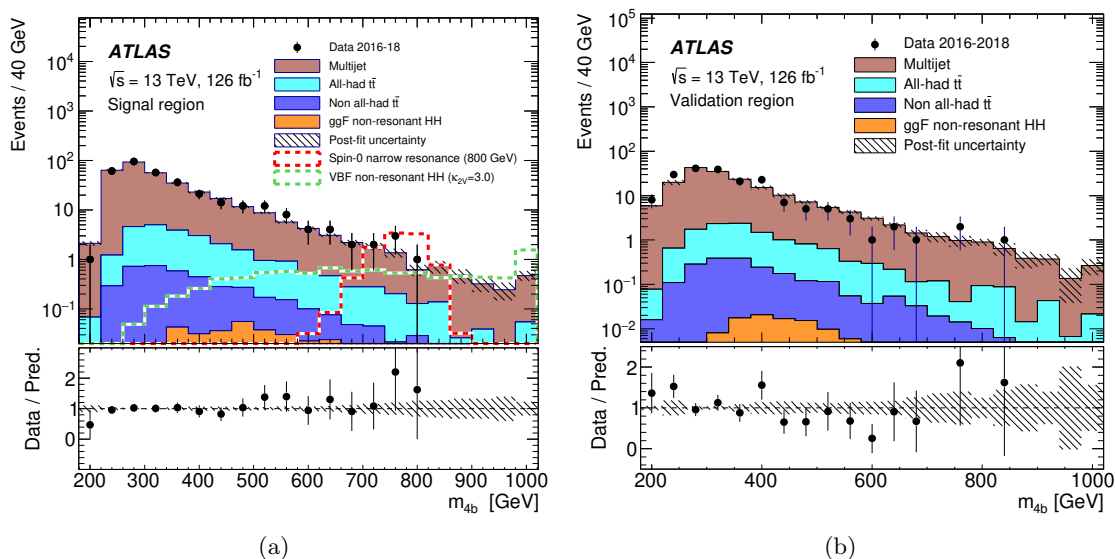
Figure 4. Post-fit mass distribution of the HH candidates in the (a) signal and (b) validation regions. The expected background is shown after the profile-likelihood fit to data with the background-only hypothesis; the narrow-width resonant signal at 800 GeV and the non-resonant signal at $\kappa_{2V} = 3$ are overlaid in the signal region, both normalised to the corresponding observed upper limits on the cross-section. The lower panel shows the ratio of the observed data to the estimated SM background. The distribution of events is shown per mass interval corresponding to the bin width of 40 GeV, while the overflow events are included in the last bin.

Figure 5. Observed and expected 95% CL upper limits on the production cross-section for resonant HH production via VBF as a function of the mass m_X. The (a) narrow- and (b) broad-width resonance hypotheses are presented.

to 300 GeV and 800 GeV. Only major sources of systematic uncertainty are quoted along with the impact of the statistical uncertainty. The uncertainties of similar nature are grouped into unique categories and the fit is performed independently for the two hypothesised signals. The systematic uncertainties related to the multijet background estimate have the largest impact on the result.

	Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
σ_{VBF} [fb]	1460	510	690	950	1330	1780
$\sigma_{\mathrm{VBF}}/\sigma_{\mathrm{VBF}}^{\mathrm{SM}}$	840	290	400	550	770	1030

Table 2. Upper limits at 95% CL for SM non-resonant HH production via VBF in fb (first row) and normalised to its SM expectation, $\sigma_{\mathrm{VBF}}^{\mathrm{SM}}$ (second row). Uncertainties related to the branching ratio of the $H \to b\bar{b}$ decay are not considered.
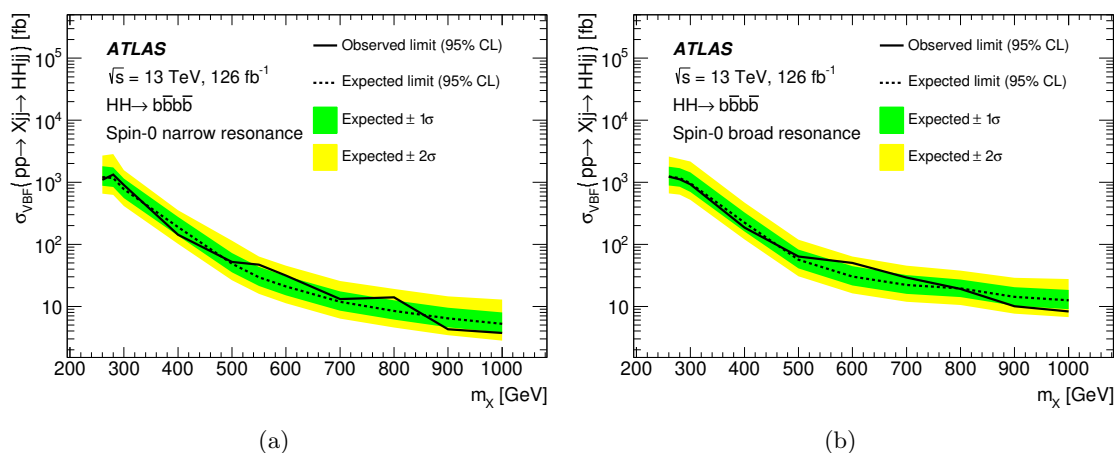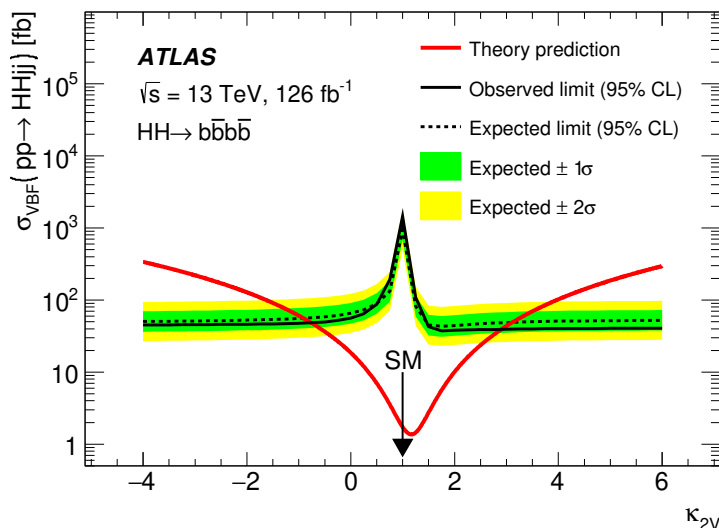

Figure 6. Observed and expected 95% CL upper limits on the production cross-section for non-resonant HH production via VBF as a function of the di-vector-boson-di-Higgs-boson coupling modifier κ_{2V}. The theory prediction of the cross-section as a function of κ_{2V} is also shown. More details on the predicted cross-section can be found in section 3.

Source	$m_X = 300$ GeV	Source	$m_X = 800$ GeV
Multijet normalisation	46%	Multijet modelling	44%
Jet energy resolution	26%	Jet energy resolution	23%
Multijet modelling	18%	Jet energy scale	19%
Multijet kinematic reweighting	17%	Multijet kinematic reweighting	9%
$t\bar{t}$ modelling	11%	Multijet normalisation	7%
Jet energy scale	10%	$t\bar{t}$ modelling	6%
Total systematic uncertainty	64%	Total systematic uncertainty	57%
Statistical uncertainty	77%	Statistical uncertainty	82%

Table 3. Dominant relative uncertainties in the best-fit signal cross-section $\sigma_{\mathrm{VBF}}^{\mathrm{best\ fit}}(pp \to Xjj \to HHjj)$ of hypothesised resonant HH signal production. The leading sources of systematic uncertainty, the total systematic uncertainty and the data statistical uncertainty are provided. Two mass points are selected: $m_X = 300$ GeV with the best-fit cross-section of 140 fb and $m_X = 800$ GeV with 4.7 fb, which correspond to the low and high mass regions. The groups of uncertainties do not add up in quadrature to the total uncertainty, because only the dominant uncertainties are shown and also due to correlations between the uncertainties.

9 Conclusion

A search for both resonant and non-resonant production of pairs of Standard Model Higgs bosons via vector-boson fusion has been carried out in the $b\bar{b}b\bar{b}$ channel. The analysed data were collected from $\sqrt{s} = 13$ TeV proton-proton collisions by the ATLAS detector at the LHC in 2016-2018 and correspond to an integrated luminosity of 126 fb^{-1}. Results for resonant HH production are reported in the mass range 260–1000 GeV. The largest deviation from the background-only hypothesis is observed at 550 GeV with a local significance of 1.5 standard deviations. Upper limits on the production cross-section are set for narrow- and broad-width scalar resonances at 95% CL. Limits are also set on the cross-section for non-resonant HH production, and as a function of the di-vector-boson-di-Higgs-boson coupling modifier, κ_{2V}. The observed 95% CL upper limit on the SM non-resonant HH production cross-section is 1460 fb, compatible with the expected limit at a level below two standard deviations. The observed excluded region corresponds to $\kappa_{2V} < -0.76$ and $\kappa_{2V} > 2.90$, while the expected exclusion is $\kappa_{2V} < -0.91$ and $\kappa_{2V} > 3.11$.

(Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (U.K.) and BNL (U.S.A.), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in ref. [71].

References

[1] ATLAS collaboration, *Observation of a new particle in the search for the standard model Higgs boson with the ATLAS detector at the LHC*, *Phys. Lett. B* **716** (2012) 1 [arXiv:1207.7214] [ɪɴSPIRE].

[2] CMS collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, *Phys. Lett. B* **716** (2012) 30 [arXiv:1207.7235] [ɪɴSPIRE].

[3] T.D. Lee, *A theory of spontaneous t violation*, *Phys. Rev. D* **8** (1973) 1226 [ɪɴSPIRE].

[4] G.C. Branco et al., *Theory and phenomenology of two-Higgs-doublet models*, *Phys. Rept.* **516** (2012) 1 [arXiv:1106.0034] [ɪɴSPIRE].

[5] G.D. Kribs and A. Martin, *Enhanced di-Higgs Production through Light colored scalars*, *Phys. Rev. D* **86** (2012) 095023 [arXiv:1207.4496] [ɪɴSPIRE].

[6] R. Grober and M. Muhlleitner, *Composite Higgs boson pair production at the LHC*, *JHEP* **06** (2011) 020 [arXiv:1012.1562] [ɪɴSPIRE].

[7] R. Contino et al., *Anomalous couplings in double Higgs production*, *JHEP* **08** (2012) 154 [arXiv:1205.5444] [ɪɴSPIRE].

[8] ATLAS collaboration, *Search for pair production of Higgs bosons in the $b\bar{b}b\bar{b}$ final state using proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *JHEP* **01** (2019) 030 [arXiv:1804.06174] [ɪɴSPIRE].

[9] CMS collaboration, *Search for resonant pair production of Higgs bosons decaying to bottom quark-antiquark pairs in proton-proton collisions at 13 TeV*, *JHEP* **08** (2018) 152 [arXiv:1806.03548] [ɪɴSPIRE].

[10] CMS collaboration, *Search for a massive resonance decaying to a pair of Higgs bosons in the four b quark final state in proton-proton collisions at $\sqrt{s} = 13$ TeV*, *Phys. Lett. B* **781** (2018) 244 [arXiv:1710.04960] [ɪɴSPIRE].

[11] CMS collaboration, *Search for production of Higgs boson pairs in the four b quark final state using large-area jets in proton-proton collisions at $\sqrt{s} = 13$ TeV*, *JHEP* **01** (2019) 040 [arXiv:1808.01473] [ɪɴSPIRE].

[12] CMS collaboration, *Search for nonresonant Higgs boson pair production in the $b\bar{b}$ final state at $\sqrt{s} = 13$ TeV*, *JHEP* **04** (2019) 112 [arXiv:1810.11854] [ɪɴSPIRE].

[13] ATLAS collaboration, *Combination of searches for Higgs boson pairs in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *Phys. Lett. B* **800** (2020) 135103 [arXiv:1906.02025] [ɪɴSPIRE].

[14] CMS collaboration, *Combination of searches for Higgs boson pair production in proton-proton collisions at $\sqrt{s} = 13$ TeV*, *Phys. Rev. Lett.* **122** (2019) 121803 [arXiv:1811.09689] [ɪɴSPIRE].

[15] F. Bishara, R. Contino and J. Rojo, *Higgs pair production in vector-boson fusion at the LHC and beyond*, *Eur. Phys. J. C* **77** (2017) 481 [arXiv:1611.03860] [INSPIRE].

[16] B. Coleppa, F. Kling and S. Su, *Constraining type II 2HDM in light of LHC Higgs searches*, *JHEP* **01** (2014) 161 [arXiv:1305.0002] [INSPIRE].

[17] ATLAS collaboration, *The ATLAS experiment at the CERN Large Hadron Collider*, 2008 *JINST* **3** S08003 [INSPIRE].

[18] ATLAS collaboration, *ATLAS Insertable B-Layer technical design report*, ATLAS-TDR-19 (2010).

[19] ATLAS IBL collaboration, *Production and integration of the ATLAS Insertable B-Layer*, 2018 *JINST* **13** T05008 [arXiv:1803.00844] [INSPIRE].

[20] ATLAS collaboration, *Performance of the ATLAS trigger system in 2015*, *Eur. Phys. J. C* **77** (2017) 317 [arXiv:1611.09661] [INSPIRE].

[21] ATLAS collaboration, *ATLAS data quality operations and performance for 2015–2018 data-taking*, 2020 *JINST* **15** P04003 [arXiv:1911.04632] [INSPIRE].

[22] P. Nason, *A new method for combining NLO QCD with shower Monte Carlo algorithms*, *JHEP* **11** (2004) 040 [hep-ph/0409146] [INSPIRE].

[23] S. Frixione, P. Nason and C. Oleari, *Matching NLO QCD computations with parton shower simulations: the POWHEG method*, *JHEP* **11** (2007) 070 [arXiv:0709.2092] [INSPIRE].

[24] S. Alioli, P. Nason, C. Oleari and E. Re, *A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX*, *JHEP* **06** (2010) 043 [arXiv:1002.2581] [INSPIRE].

[25] T. Sjöstrand, S. Mrenna and P.Z. Skands, *A brief introduction to PYTHIA 8.1*, *Comput. Phys. Commun.* **178** (2008) 852 [arXiv:0710.3820] [INSPIRE].

[26] ATLAS, CMS collaboration, *Combined measurement of the Higgs boson mass in pp collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS and CMS experiments*, *Phys. Rev. Lett.* **114** (2015) 191803 [arXiv:1503.07589] [INSPIRE].

[27] R.D. Ball et al., *Parton distributions with LHC data*, *Nucl. Phys. B* **867** (2013) 244 [arXiv:1207.1303] [INSPIRE].

[28] *ATLAS PYTHIA 8 tunes to 7 TeV datas*, ATL-PHYS-PUB-2014-021 (2014).

[29] J. Alwall et al., *The automated computation of tree-level and next-to-leading order differential cross sections and their matching to parton shower simulations*, *JHEP* **07** (2014) 079 [arXiv:1405.0301] [INSPIRE].

[30] J. Baglio et al., *The measurement of the Higgs self-coupling at the LHC: theoretical status*, *JHEP* **04** (2013) 151 [arXiv:1212.5581] [INSPIRE].

[31] L.-S. Ling et al., *NNLO QCD corrections to Higgs pair production via vector boson fusion at hadron colliders*, *Phys. Rev. D* **89** (2014) 073001 [arXiv:1401.7754] [INSPIRE].

[32] F.A. Dreyer and A. Karlberg, *Vector-Boson Fusion Higgs Pair Production at N^3LO*, *Phys. Rev. D* **98** (2018) 114016 [arXiv:1811.07906] [INSPIRE].

[33] F.A. Dreyer and A. Karlberg, *Fully differential vector-boson fusion Higgs pair production at next-to-next-to-leading order*, *Phys. Rev. D* **99** (2019) 074028 [arXiv:1811.07918] [INSPIRE].

[34] H.-L. Lai et al., *New parton distributions for collider physics*, *Phys. Rev. D* **82** (2010) 074024 [arXiv:1007.2241] [INSPIRE].

[35] M. Grazzini et al., *Higgs boson pair production at NNLO with top quark mass effects*, [*JHEP*](https://...) [**05** (2018) 059](https://...) [[arXiv:1803.02463](https://arxiv.org/abs/1803.02463)] [ɪɴSPIRE].

[36] J. Bellm et al., *HERWIG 7.0/HERWIG++ 3.0 release note*, [*Eur. Phys. J. C* **76** (2016) 196](https://...) [[arXiv:1512.01178](https://arxiv.org/abs/1512.01178)] [ɪɴSPIRE].

[37] S. Dawson, S. Dittmaier and M. Spira, *Neutral Higgs boson pair production at hadron colliders: QCD corrections*, [*Phys. Rev. D* **58** (1998) 115012](https://...) [[hep-ph/9805244](https://arxiv.org/abs/hep-ph/9805244)] [ɪɴSPIRE].

[38] S. Borowka et al., *Higgs boson pair production in gluon fusion at next-to-leading order with full top-quark mass dependence*, [*Phys. Rev. Lett.* **117** (2016) 012001](https://...) [*Erratum ibid.* **117** (2016) 079901] [[arXiv:1604.06447](https://arxiv.org/abs/1604.06447)] [ɪɴSPIRE].

[39] J. Baglio et al., *Gluon fusion into Higgs pairs at NLO QCD and the top mass scheme*, [*Eur. Phys. J. C* **79** (2019) 459](https://...) [[arXiv:1811.05692](https://arxiv.org/abs/1811.05692)] [ɪɴSPIRE].

[40] D. de Florian and J. Mazzitelli, *Higgs boson pair production at next-to-next-to-leading order in QCD*, [*Phys. Rev. Lett.* **111** (2013) 201801](https://...) [[arXiv:1309.6594](https://arxiv.org/abs/1309.6594)] [ɪɴSPIRE].

[41] D.Y. Shao, C.S. Li, H.T. Li and J. Wang, *Threshold resummation effects in Higgs boson pair production at the LHC*, [*JHEP* **07** (2013) 169](https://...) [[arXiv:1301.1245](https://arxiv.org/abs/1301.1245)] [ɪɴSPIRE].

[42] D. de Florian and J. Mazzitelli, *Higgs pair production at next-to-next-to-leading logarithmic accuracy at the LHC*, [*JHEP* **09** (2015) 053](https://...) [[arXiv:1505.07122](https://arxiv.org/abs/1505.07122)] [ɪɴSPIRE].

[43] S. Frixione, P. Nason and G. Ridolfi, *A positive-weight next-to-leading-order Monte Carlo for heavy flavour hadroproduction*, [*JHEP* **09** (2007) 126](https://...) [[arXiv:0707.3088](https://arxiv.org/abs/0707.3088)] [ɪɴSPIRE].

[44] NNPDF collaboration, *Parton distributions for the LHC Run II*, [*JHEP* **04** (2015) 040](https://...) [[arXiv:1410.8849](https://arxiv.org/abs/1410.8849)] [ɪɴSPIRE].

[45] T. Sjöstrand et al., *An introduction to PYTHIA 8.2*, [*Comput. Phys. Commun.* **191** (2015) 159](https://...) [[arXiv:1410.3012](https://arxiv.org/abs/1410.3012)] [ɪɴSPIRE].

[46] M. Czakon and A. Mitov, *Top++: a program for the calculation of the top-pair cross-section at hadron colliders*, [*Comput. Phys. Commun.* **185** (2014) 2930](https://...) [[arXiv:1112.5675](https://arxiv.org/abs/1112.5675)] [ɪɴSPIRE].

[47] M. Botje et al., *The PDF4LHC working group interim recommendations*, [arXiv:1101.0538](https://arxiv.org/abs/1101.0538) [ɪɴSPIRE].

[48] A.D. Martin, W.J. Stirling, R.S. Thorne and G. Watt, *Uncertainties on α_s in global PDF analyses and implications for predicted hadronic cross sections*, [*Eur. Phys. J. C* **64** (2009) 653](https://...) [[arXiv:0905.3531](https://arxiv.org/abs/0905.3531)] [ɪɴSPIRE].

[49] J. Gao et al., *CT10 next-to-next-to-leading order global analysis of QCD*, [*Phys. Rev. D* **89** (2014) 033009](https://...) [[arXiv:1302.6246](https://arxiv.org/abs/1302.6246)] [ɪɴSPIRE].

[50] D.J. Lange, *The EvtGen particle decay simulation package*, [*Nucl. Instrum. Meth. A* **462** (2001) 152](https://...) [ɪɴSPIRE].

[51] ATLAS collaboration, *The PYTHIA 8 A3 tune description of ATLAS minimum bias and inelastic measurements incorporating the Donnachie-Landshoff diffractive model*, [ATL-PHYS-PUB-2016-017](https://...) (2016).

[52] GEANT4 collaboration, *GEANT4 — A simulation toolkit*, [*Nucl. Instrum. Meth. A* **506** (2003) 250](https://...) [ɪɴSPIRE].

[53] ATLAS collaboration, *The ATLAS simulation infrastructure*, [*Eur. Phys. J. C* **70** (2010) 823](https://...) [[arXiv:1005.4568](https://arxiv.org/abs/1005.4568)] [ɪɴSPIRE].

[54] ATLAS collaboration, *Topological cell clustering in the ATLAS calorimeters and its performance in LHC Run 1*, [*Eur. Phys. J. C* **77** (2017) 490](https://...) [[arXiv:1603.02934](https://arxiv.org/abs/1603.02934)] [ɪɴSPIRE].

[55] M. Cacciari, G.P. Salam and G. Soyez, *The anti-k_t jet clustering algorithm*, *JHEP* **04** (2008) 063 [arXiv:0802.1189] [InSPIRE].

[56] M. Cacciari, G.P. Salam and G. Soyez, *FastJet user manual*, *Eur. Phys. J. C* **72** (2012) 1896 [arXiv:1111.6097] [InSPIRE].

[57] ATLAS collaboration, *Jet energy scale measurements and their systematic uncertainties in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *Phys. Rev. D* **96** (2017) 072002 [arXiv:1703.09665] [InSPIRE].

[58] M. Cacciari, G.P. Salam and G. Soyez, *The catchment area of jets*, *JHEP* **04** (2008) 005 [arXiv:0802.1188] [InSPIRE].

[59] ATLAS collaboration, *Performance of pile-up mitigation techniques for jets in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector*, *Eur. Phys. J. C* **76** (2016) 581 [arXiv:1510.03823] [InSPIRE].

[60] ATLAS collaboration, *ATLAS b-jet identification performance and efficiency measurement with $t\bar{t}$ events in pp collisions at $\sqrt{s} = 13$ TeV*, *Eur. Phys. J. C* **79** (2019) 970 [arXiv:1907.05120] [InSPIRE].

[61] ATLAS collaboration, *Optimisation and performance studies of the ATLAS b-tagging algorithms for the 2017-18 LHC run*, Tech. Rep. ATL-PHYS-PUB-2017-013, CERN, Geneva (Jul, 2017).

[62] ATLAS collaboration, *Measurement of b-tagging efficiency of c-jets in $t\bar{t}$ events using a likelihood approach with the ATLAS detector*, ATLAS-CONF-2018-001 (2018).

[63] ATLAS collaboration, *Calibration of light-flavour b-jet mistagging rates using ATLAS proton-proton collision data at $\sqrt{s} = 13$ TeV*, Tech. Rep. ATLAS-CONF-2018-006, CERN, Geneva (Apr, 2018).

[64] A. Hoecker et al., *TMVA — Toolkit for Multivariate Data Analysis*, physics/0703039.

[65] ATLAS collaboration, *Jet energy resolution in proton-proton collisions at $\sqrt{s} = 7$ TeV recorded in 2010 with the ATLAS detector*, *Eur. Phys. J. C* **73** (2013) 2306 [arXiv:1210.6210] [InSPIRE].

[66] ATLAS collaboration, *Search for resonances in the mass distribution of jet pairs with one or two jets identified as b-jets in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *Phys. Rev. D* **98** (2018) 032016 [arXiv:1805.09299] [InSPIRE].

[67] ATLAS collaboration, *Luminosity determination in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC*, ATLAS-CONF-2019-021 (2019).

[68] G. Avoni et al., *The new LUCID-2 detector for luminosity measurement and monitoring in ATLAS*, 2018 *JINST* **13** P07017 [InSPIRE].

[69] G. Cowan, K. Cranmer, E. Gross and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics*, *Eur. Phys. J. C* **71** (2011) 1554 [*Erratum ibid.* **73** (2013) 2501] [arXiv:1007.1727] [InSPIRE].

[70] A.L. Read, *Presentation of search results: the CL_s technique*, [InSPIRE].

[71] ATLAS collaboration, *ATLAS computing acknowledgements*, ATL-SOFT-PUB-2020-001 (2020).

The ATLAS collaboration

G. Aad[102], B. Abbott[129], D.C. Abbott[103], A. Abed Abud[71a,71b], K. Abeling[53],
D.K. Abhayasinghe[94], S.H. Abidi[167], O.S. AbouZeid[40], N.L. Abraham[156], H. Abramowicz[161],
H. Abreu[160], Y. Abulaiti[6], B.S. Acharya[67a,67b,o], B. Achkar[53], S. Adachi[163], L. Adam[100],
C. Adam Bourdarios[5], L. Adamczyk[84a], L. Adamek[167], J. Adelman[121], M. Adersberger[114],
A. Adiguzel[12c], S. Adorni[54], T. Adye[144], A.A. Affolder[146], Y. Afik[160], C. Agapopoulou[65],
M.N. Agaras[38], A. Aggarwal[119], C. Agheorghiesei[27c], J.A. Aguilar-Saavedra[140f,140a,aj],
F. Ahmadov[80], W.S. Ahmed[104], X. Ai[18], G. Aielli[74a,74b], S. Akatsuka[86], T.P.A. Åkesson[97],
E. Akilli[54], A.V. Akimov[111], K. Al Khoury[65], G.L. Alberghi[23b,23a], J. Albert[176],
M.J. Alconada Verzini[161], S. Alderweireldt[36], M. Aleksa[36], I.N. Aleksandrov[80], C. Alexa[27b],
D. Alexandre[19], T. Alexopoulos[10], A. Alfonsi[120], F. Alfonsi[23b,23a], M. Alhroob[129], B. Ali[142],
M. Aliev[155], G. Alimonti[69a], J. Alison[37], S.P. Alkire[148], C. Allaire[65], B.M.M. Allbrooke[156],
B.W. Allen[132], P.P. Allport[21], A. Aloisio[70a,70b], A. Alonso[40], F. Alonso[89], C. Alpigiani[148],
A.A. Alshehri[57], M. Alvarez Estevez[99], D. Álvarez Piqueras[174], M.G. Alviggi[70a,70b],
Y. Amaral Coutinho[81b], A. Ambler[104], L. Ambroz[135], C. Amelung[26], D. Amidei[106],
S.P. Amor Dos Santos[140a], S. Amoroso[46], C.S. Amrouche[54], F. An[79], C. Anastopoulos[149],
N. Andari[145], T. Andeen[11], C.F. Anders[61b], J.K. Anders[20], A. Andreazza[69a,69b], V. Andrei[61a],
C.R. Anelli[176], S. Angelidakis[38], A. Angerami[39], A.V. Anisenkov[122b,122a], A. Annovi[72a],
C. Antel[61a], M.T. Anthony[149], E. Antipov[130], M. Antonelli[51], D.J.A. Antrim[171], F. Anulli[73a],
M. Aoki[82], J.A. Aparisi Pozo[174], L. Aperio Bella[15a], G. Arabidze[107], J.P. Araque[140a],
V. Araujo Ferraz[81b], R. Araujo Pereira[81b], C. Arcangeletti[51], A.T.H. Arce[49], F.A. Arduh[89],
J-F. Arguin[110], S. Argyropoulos[78], J.-H. Arling[46], A.J. Armbruster[36], A. Armstrong[171],
O. Arnaez[167], H. Arnold[120], Z.P. Arrubarrena Tame[114], G. Artoni[135], S. Artz[100], S. Asai[163],
N. Asbah[59], E.M. Asimakopoulou[172], L. Asquith[156], J. Assahsah[35d], K. Assamagan[29],
R. Astalos[28a], R.J. Atkin[33a], M. Atkinson[173], N.B. Atlay[19], H. Atmani[65], K. Augsten[142],
G. Avolio[36], R. Avramidou[60a], M.K. Ayoub[15a], A.M. Azoulay[168b], G. Azuelos[110,aw],
H. Bachacou[145], K. Bachas[68a,68b], M. Backes[135], F. Backman[45a,45b], P. Bagnaia[73a,73b],
M. Bahmani[85], H. Bahrasemani[152], A.J. Bailey[174], V.R. Bailey[173], J.T. Baines[144], M. Bajic[40],
C. Bakalis[10], O.K. Baker[183], P.J. Bakker[120], D. Bakshi Gupta[8], S. Balaji[157], E.M. Baldin[122b,122a],
P. Balek[180], F. Balli[145], W.K. Balunas[135], J. Balz[100], E. Banas[85], A. Bandyopadhyay[24],
Sw. Banerjee[181,j], A.A.E. Bannoura[182], L. Barak[161], W.M. Barbe[38], E.L. Barberio[105],
D. Barberis[55b,55a], M. Barbero[102], G. Barbour[95], T. Barillari[115], M-S. Barisits[36], J. Barkeloo[132],
T. Barklow[153], R. Barnea[160], S.L. Barnes[60c], B.M. Barnett[144], R.M. Barnett[18],
Z. Barnovska-Blenessy[60a], A. Baroncelli[60a], G. Barone[29], A.J. Barr[135], L. Barranco Navarro[45a,45b],
F. Barreiro[99], J. Barreiro Guimarães da Costa[15a], S. Barsov[138], R. Bartoldus[153], G. Bartolini[102],
A.E. Barton[90], P. Bartos[28a], A. Basalaev[46], A. Bassalat[65,aq], M.J. Basso[167], R.L. Bates[57],
S. Batlamous[35e], J.R. Batley[32], B. Batool[151], M. Battaglia[146], M. Bauce[73a,73b], F. Bauer[145],
K.T. Bauer[171], H.S. Bawa[31,m], J.B. Beacham[49], T. Beau[136], P.H. Beauchemin[170], F. Becherer[52],
P. Bechtle[24], H.C. Beck[53], H.P. Beck[20,s], K. Becker[52], M. Becker[100], C. Becot[46], A. Beddall[12d],
A.J. Beddall[12a], V.A. Bednyakov[80], M. Bedognetti[120], C.P. Bee[155], T.A. Beermann[182],
M. Begalli[81b], M. Begel[29], A. Behera[155], J.K. Behr[46], F. Beisiegel[24], A.S. Bell[95], G. Bella[161],
L. Bellagamba[23b], A. Bellerive[34], P. Bellos[9], K. Beloborodov[122b,122a], K. Belotskiy[112],
N.L. Belyaev[112], D. Benchekroun[35a], N. Benekos[10], Y. Benhammou[161], D.P. Benjamin[6],
M. Benoit[54], J.R. Bensinger[26], S. Bentvelsen[120], L. Beresford[135], M. Beretta[51], D. Berge[46],
E. Bergeaas Kuutmann[172], N. Berger[5], B. Bergmann[142], L.J. Bergsten[26], J. Beringer[18],
S. Berlendis[7], G. Bernardi[136], C. Bernius[153], F.U. Bernlochner[24], T. Berry[94], P. Berta[100],
C. Bertella[15a], I.A. Bertram[90], O. Bessidskaia Bylund[182], N. Besson[145], A. Bethani[101],

S. Bethke[115], A. Betti[42], A.J. Bevan[93], J. Beyer[115], D.S. Bhattacharya[177], P. Bhattarai[26],
R. Bi[139], R.M. Bianchi[139], O. Biebel[114], D. Biedermann[19], R. Bielski[36], K. Bierwagen[100],
N.V. Biesuz[72a,72b], M. Biglietti[75a], T.R.V. Billoud[110], M. Bindi[53], A. Bingul[12d], C. Bini[73a,73b],
S. Biondi[23b,23a], M. Birman[180], T. Bisanz[53], J.P. Biswal[161], D. Biswas[181,j], A. Bitadze[101],
C. Bittrich[48], K. Bjørke[134], K.M. Black[25], T. Blazek[28a], I. Bloch[46], C. Blocker[26], A. Blue[57],
U. Blumenschein[93], G.J. Bobbink[120], V.S. Bobrovnikov[122b,122a], S.S. Bocchetta[97], A. Bocci[49],
D. Boerner[46], D. Bogavac[14], A.G. Bogdanchikov[122b,122a], C. Bohm[45a], V. Boisvert[94],
P. Bokan[53,172], T. Bold[84a], A.S. Boldyrev[113], A.E. Bolz[61b], M. Bomben[136], M. Bona[93],
J.S. Bonilla[132], M. Boonekamp[145], C.D. Booth[94], H.M. Borecka-Bielska[91], A. Borisov[123],
G. Borissov[90], J. Bortfeldt[36], D. Bortoletto[135], D. Boscherini[23b], M. Bosman[14],
J.D. Bossio Sola[104], K. Bouaouda[35a], J. Boudreau[139], E.V. Bouhova-Thacker[90], D. Boumediene[38],
S.K. Boutle[57], A. Boveia[127], J. Boyd[36], D. Boye[33c,ar], I.R. Boyko[80], A.J. Bozson[94], J. Bracinik[21],
N. Brahimi[102], G. Brandt[182], O. Brandt[32], F. Braren[46], B. Brau[103], J.E. Brau[132],
W.D. Breaden Madden[57], K. Brendlinger[46], L. Brenner[46], R. Brenner[172], S. Bressler[180],
B. Brickwedde[100], D.L. Briglin[21], D. Britton[57], D. Britzger[115], I. Brock[24], R. Brock[107],
G. Brooijmans[39], W.K. Brooks[147d], E. Brost[121], J.H Broughton[21], P.A. Bruckman de Renstrom[85],
D. Bruncko[28b], A. Bruni[23b], G. Bruni[23b], L.S. Bruni[120], S. Bruno[74a,74b], M. Bruschi[23b],
N. Bruscino[139], P. Bryant[37], L. Bryngemark[97], T. Buanes[17], Q. Buat[36], P. Buchholz[151],
A.G. Buckley[57], I.A. Budagov[80], M.K. Bugge[134], F. Bührer[52], O. Bulekov[112], T.J. Burch[121],
S. Burdin[91], C.D. Burgard[120], A.M. Burger[130], B. Burghgrave[8], J.T.P. Burr[46], C.D. Burton[11],
J.C. Burzynski[103], V. Büscher[100], E. Buschmann[53], P.J. Bussey[57], J.M. Butler[25], C.M. Buttar[57],
J.M. Butterworth[95], P. Butti[36], W. Buttinger[36], C.J. Buxo Vazquez[107], A. Buzatu[158],
A.R. Buzykaev[122b,122a], G. Cabras[23b,23a], S. Cabrera Urbán[174], D. Caforio[56], H. Cai[173],
V.M.M. Cairo[153], O. Cakir[4a], N. Calace[36], P. Calafiura[18], A. Calandri[102], G. Calderini[136],
P. Calfayan[66], G. Callea[57], L.P. Caloba[81b], A. Caltabiano[74a,74b], S. Calvente Lopez[99],
D. Calvet[38], S. Calvet[38], T.P. Calvet[155], M. Calvetti[72a,72b], R. Camacho Toro[136], S. Camarda[36],
D. Camarero Munoz[99], P. Camarri[74a,74b], D. Cameron[134], R. Caminal Armadans[103],
C. Camincher[36], S. Campana[36], M. Campanelli[95], A. Camplani[40], A. Campoverde[151],
V. Canale[70a,70b], A. Canesse[104], M. Cano Bret[60c], J. Cantero[130], T. Cao[161], Y. Cao[173],
M.D.M. Capeans Garrido[36], M. Capua[41b,41a], R. Cardarelli[74a], F. Cardillo[149], G. Carducci[41b,41a],
I. Carli[143], T. Carli[36], G. Carlino[70a], B.T. Carlson[139], L. Carminati[69a,69b], R.M.D. Carney[45a,45b],
S. Caron[119], E. Carquin[147d], S. Carrá[46], J.W.S. Carter[167], M.P. Casado[14,e], A.F. Casha[167],
D.W. Casper[171], R. Castelijn[120], F.L. Castillo[174], V. Castillo Gimenez[174], N.F. Castro[140a,140e],
A. Catinaccio[36], J.R. Catmore[134], A. Cattai[36], J. Caudron[24], V. Cavaliere[29], E. Cavallaro[14],
M. Cavalli-Sforza[14], V. Cavasinni[72a,72b], E. Celebi[12b], F. Ceradini[75a,75b], L. Cerda Alberich[174],
K. Cerny[131], A.S. Cerqueira[81a], A. Cerri[156], L. Cerrito[74a,74b], F. Cerutti[18], A. Cervelli[23b,23a],
S.A. Cetin[12b], Z. Chadi[35a], D. Chakraborty[121], S.K. Chan[59], W.S. Chan[120], W.Y. Chan[91],
J.D. Chapman[32], B. Chargeishvili[159b], D.G. Charlton[21], T.P. Charman[93], C.C. Chau[34], S. Che[127],
S. Chekanov[6], S.V. Chekulaev[168a], G.A. Chelkov[80,ao], M.A. Chelstowska[36], B. Chen[79],
C. Chen[60a], C.H. Chen[79], H. Chen[29], J. Chen[60a], J. Chen[39], S. Chen[137], S.J. Chen[15c],
X. Chen[15b,av], Y. Chen[83], Y-H. Chen[46], H.C. Cheng[63a], H.J. Cheng[15a], A. Cheplakov[80],
E. Cheremushkina[123], R. Cherkaoui El Moursli[35e], E. Cheu[7], K. Cheung[64], T.J.A. Chevalérias[145],
L. Chevalier[145], V. Chiarella[51], G. Chiarelli[72a], G. Chiodini[68a], A.S. Chisholm[21], A. Chitan[27b],
I. Chiu[163], Y.H. Chiu[176], M.V. Chizhov[80], K. Choi[66], A.R. Chomont[73a,73b], S. Chouridou[162],
Y.S. Chow[120], M.C. Chu[63a], X. Chu[15a,15d], J. Chudoba[141], A.J. Chuinard[104], J.J. Chwastowski[85],
L. Chytka[131], D. Cieri[115], K.M. Ciesla[85], D. Cinca[47], V. Cindro[92], I.A. Cioară[27b], A. Ciocio[18],
F. Cirotto[70a,70b], Z.H. Citron[180,k], M. Citterio[69a], D.A. Ciubotaru[27b], B.M. Ciungu[167],
A. Clark[54], M.R. Clark[39], P.J. Clark[50], C. Clement[45a,45b], Y. Coadou[102], M. Cobal[67a,67c],

A. Coccaro[55b], J. Cochran[79], H. Cohen[161], A.E.C. Coimbra[36], L. Colasurdo[119], B. Cole[39],
A.P. Colijn[120], J. Collot[58], P. Conde Muiño[140a,f], E. Coniavitis[52], S.H. Connell[33c],
I.A. Connelly[57], S. Constantinescu[27b], F. Conventi[70a,ax], A.M. Cooper-Sarkar[135], F. Cormier[175],
K.J.R. Cormier[167], L.D. Corpe[95], M. Corradi[73a,73b], E.E. Corrigan[97], F. Corriveau[104,af],
M.J. Costa[174], F. Costanza[5], D. Costanzo[149], G. Cowan[94], J.W. Cowley[32], J. Crane[101],
K. Cranmer[125], S.J. Crawley[57], R.A. Creager[137], S. Crépé-Renaudin[58], F. Crescioli[136],
M. Cristinziani[24], V. Croft[120], G. Crosetti[41b,41a], A. Cueto[5], T. Cuhadar Donszelmann[149],
A.R. Cukierman[153], W.R. Cunningham[57], S. Czekierda[85], P. Czodrowski[36],
M.J. Da Cunha Sargedas De Sousa[60b], J.V. Da Fonseca Pinto[81b], C. Da Via[101], W. Dabrowski[84a],
T. Dado[28a], S. Dahbi[35e], T. Dai[106], C. Dallapiccola[103], M. Dam[40], G. D'amen[29],
V. D'Amico[75a,75b], J. Damp[100], J.R. Dandoy[137], M.F. Daneri[30], N.P. Dang[181,j], N.S. Dann[101],
M. Danninger[175], V. Dao[36], G. Darbo[55b], O. Dartsi[5], A. Dattagupta[132], T. Daubney[46],
S. D'Auria[69a,69b], W. Davey[24], C. David[46], T. Davidek[143], D.R. Davis[49], I. Dawson[149], K. De[8],
R. De Asmundis[70a], M. De Beurs[120], S. De Castro[23b,23a], S. De Cecco[73a,73b], N. De Groot[119],
P. de Jong[120], H. De la Torre[107], A. De Maria[15c], D. De Pedis[73a], A. De Salvo[73a],
U. De Sanctis[74a,74b], M. De Santis[74a,74b], A. De Santo[156], K. De Vasconcelos Corga[102],
J.B. De Vivie De Regie[65], C. Debenedetti[146], D.V. Dedovich[80], A.M. Deiana[42],
M. Del Gaudio[41b,41a], J. Del Peso[99], Y. Delabat Diaz[46], D. Delgove[65], F. Deliot[145,r],
C.M. Delitzsch[7], M. Della Pietra[70a,70b], D. Della Volpe[54], A. Dell'Acqua[36], L. Dell'Asta[74a,74b],
M. Delmastro[5], C. Delporte[65], P.A. Delsart[58], D.A. DeMarco[167], S. Demers[183], M. Demichev[80],
G. Demontigny[110], S.P. Denisov[123], D. Denysiuk[120], L. D'Eramo[136], D. Derendarz[85],
J.E. Derkaoui[35d], F. Derue[136], P. Dervan[91], K. Desch[24], C. Deterre[46], K. Dette[167], C. Deutsch[24],
M.R. Devesa[30], P.O. Deviveiros[36], A. Dewhurst[144], F.A. Di Bello[54], A. Di Ciaccio[74a,74b],
L. Di Ciaccio[5], W.K. Di Clemente[137], C. Di Donato[70a,70b], A. Di Girolamo[36],
G. Di Gregorio[72a,72b], B. Di Micco[75a,75b], R. Di Nardo[103], K.F. Di Petrillo[59], R. Di Sipio[167],
D. Di Valentino[34], C. Diaconu[102], F.A. Dias[40], T. Dias Do Vale[140a], M.A. Diaz[147a],
J. Dickinson[18], E.B. Diehl[106], J. Dietrich[19], S. Díez Cornell[46], A. Dimitrievska[18], W. Ding[15b],
J. Dingfelder[24], F. Dittus[36], F. Djama[102], T. Djobava[159b], J.I. Djuvsland[17], M.A.B. Do Vale[81c],
M. Dobre[27b], D. Dodsworth[26], C. Doglioni[97], J. Dolejsi[143], Z. Dolezal[143], M. Donadelli[81d],
B. Dong[60c], J. Donini[38], A. D'onofrio[93], M. D'Onofrio[91], J. Dopke[144], A. Doria[70a], M.T. Dova[89],
A.T. Doyle[57], E. Drechsler[152], E. Dreyer[152], T. Dreyer[53], A.S. Drobac[170], D. Du[60b], Y. Duan[60b],
F. Dubinin[111], M. Dubovsky[28a], A. Dubreuil[54], E. Duchovni[180], G. Duckeck[114], A. Ducourthial[136],
O.A. Ducu[110], D. Duda[115], A. Dudarev[36], A.C. Dudder[100], E.M. Duffield[18], L. Duflot[65],
M. Dührssen[36], C. Dülsen[182], M. Dumancic[180], A.E. Dumitriu[27b], A.K. Duncan[57], M. Dunford[61a],
A. Duperrin[102], H. Duran Yildiz[4a], M. Düren[56], A. Durglishvili[159b], D. Duschinger[48], B. Dutta[46],
D. Duvnjak[1], G.I. Dyckes[137], M. Dyndal[36], S. Dysch[101], B.S. Dziedzic[85], K.M. Ecker[115],
R.C. Edgar[106], M.G. Eggleston[49], T. Eifert[36], G. Eigen[17], K. Einsweiler[18], T. Ekelof[172],
H. El Jarrari[35e], M. El Kacimi[35c], R. El Kosseifi[102], V. Ellajosyula[172], M. Ellert[172],
F. Ellinghaus[182], A.A. Elliot[93], N. Ellis[36], J. Elmsheuser[29], M. Elsing[36], D. Emeliyanov[144],
A. Emerman[39], Y. Enari[163], M.B. Epland[49], J. Erdmann[47], A. Ereditato[20], M. Errenst[36],
M. Escalier[65], C. Escobar[174], O. Estrada Pastor[174], E. Etzion[161], H. Evans[66], A. Ezhilov[138],
F. Fabbri[57], L. Fabbri[23b,23a], V. Fabiani[119], G. Facini[95], R.M. Faisca Rodrigues Pereira[140a],
R.M. Fakhrutdinov[123], S. Falciano[73a], P.J. Falke[5], S. Falke[5], J. Faltova[143], Y. Fang[15a], Y. Fang[15a],
G. Fanourakis[44], M. Fanti[69a,69b], M. Faraj[67a,67c,u], A. Farbin[8], A. Farilla[75a], E.M. Farina[71a,71b],
T. Farooque[107], S. Farrell[18], S.M. Farrington[50], P. Farthouat[36], F. Fassi[35e], P. Fassnacht[36],
D. Fassouliotis[9], M. Faucci Giannelli[50], W.J. Fawcett[32], L. Fayard[65], O.L. Fedin[138,p],
W. Fedorko[175], A. Fehr[20], M. Feickert[42], L. Feligioni[102], A. Fell[149], C. Feng[60b], E.J. Feng[36],
M. Feng[49], M.J. Fenton[57], A.B. Fenyuk[123], J. Ferrando[46], A. Ferrante[173], A. Ferrari[172],

P. Ferrari[120], R. Ferrari[71a], D.E. Ferreira de Lima[61b], A. Ferrer[174], D. Ferrere[54], C. Ferretti[106],
F. Fiedler[100], A. Filipčič[92], F. Filthaut[119], K.D. Finelli[25], M.C.N. Fiolhais[140a,140c,a], L. Fiorini[174],
F. Fischer[114], W.C. Fisher[107], I. Fleck[151], P. Fleischmann[106], R.R.M. Fletcher[137], T. Flick[182],
B.M. Flierl[114], L. Flores[137], L.R. Flores Castillo[63a], F.M. Follega[76a,76b], F. Fomin[17], J.H. Foo[167],
G.T. Forcolin[76a,76b], A. Formica[145], F.A. Förster[14], A.C. Forti[101], A.G. Foster[21], M.G. Foti[135],
D. Fournier[65], H. Fox[90], P. Francavilla[72a,72b], S. Francescato[73a,73b], M. Franchini[23b,23a],
S. Franchino[61a], D. Francis[36], L. Franconi[20], M. Franklin[59], A.N. Fray[93], P.M. Freeman[21],
B. Freund[110], W.S. Freund[81b], E.M. Freundlich[47], D.C. Frizzell[129], D. Froidevaux[36], J.A. Frost[135],
C. Fukunaga[164], E. Fullana Torregrosa[174], E. Fumagalli[55b,55a], T. Fusayasu[116], J. Fuster[174],
A. Gabrielli[23b,23a], A. Gabrielli[18], G.P. Gach[84a], S. Gadatsch[54], P. Gadow[115], G. Gagliardi[55b,55a],
L.G. Gagnon[110], C. Galea[27b], B. Galhardo[140a], G.E. Gallardo[135], E.J. Gallas[135], B.J. Gallop[144],
G. Galster[40], R. Gamboa Goni[93], K.K. Gan[127], S. Ganguly[180], J. Gao[60a], Y. Gao[50], Y.S. Gao[31,m],
C. García[174], J.E. García Navarro[174], J.A. García Pascual[15a], C. Garcia-Argos[52],
M. Garcia-Sciveres[18], R.W. Gardner[37], N. Garelli[153], S. Gargiulo[52], V. Garonne[134],
A. Gaudiello[55b,55a], G. Gaudio[71a], I.L. Gavrilenko[111], A. Gavrilyuk[124], C. Gay[175], G. Gaycken[46],
E.N. Gazis[10], A.A. Geanta[27b], C.M. Gee[146], C.N.P. Gee[144], J. Geisen[53], M. Geisen[100],
C. Gemme[55b], M.H. Genest[58], C. Geng[106], S. Gentile[73a,73b], S. George[94], T. Geralis[44],
L.O. Gerlach[53], P. Gessinger-Befurt[100], G. Gessner[47], S. Ghasemi[151], M. Ghasemi Bostanabad[176],
A. Ghosh[65], A. Ghosh[78], B. Giacobbe[23b], S. Giagu[73a,73b], N. Giangiacomi[23b,23a], P. Giannetti[72a],
A. Giannini[70a,70b], G. Giannini[14], S.M. Gibson[94], M. Gignac[146], D. Gillberg[34], G. Gilles[182],
D.M. Gingrich[3,aw], M.P. Giordani[67a,67c], F.M. Giorgi[23b], P.F. Giraud[145], G. Giugliarelli[67a,67c],
D. Giugni[69a], F. Giuli[74a,74b], S. Gkaitatzis[162], I. Gkialas[9,h], E.L. Gkougkousis[14],
P. Gkountoumis[10], L.K. Gladilin[113], C. Glasman[99], J. Glatzer[14], P.C.F. Glaysher[46], A. Glazov[46],
G.R. Gledhill[132], M. Goblirsch-Kolb[26], D. Godin[110], S. Goldfarb[105], T. Golling[54], D. Golubkov[123],
A. Gomes[140a,140b], R. Goncalves Gama[53], R. Gonçalo[140a], G. Gonella[52], L. Gonella[21],
A. Gongadze[80], F. Gonnella[21], J.L. Gonski[59], S. González de la Hoz[174], S. Gonzalez-Sevilla[54],
G.R. Gonzalvo Rodriguez[174], L. Goossens[36], P.A. Gorbounov[124], H.A. Gordon[29], B. Gorini[36],
E. Gorini[68a,68b], A. Gorišek[92], A.T. Goshaw[49], M.I. Gostkin[80], C.A. Gottardo[119], M. Gouighri[35b],
D. Goujdami[35c], A.G. Goussiou[148], N. Govender[33c], C. Goy[5], E. Gozani[160], I. Grabowska-Bold[84a],
E.C. Graham[91], J. Gramling[171], E. Gramstad[134], S. Grancagnolo[19], M. Grandi[156],
V. Gratchev[138], P.M. Gravila[27f], F.G. Gravili[68a,68b], C. Gray[57], H.M. Gray[18], C. Grefe[24],
K. Gregersen[97], I.M. Gregor[46], P. Grenier[153], K. Grevtsov[46], C. Grieco[14], N.A. Grieser[129],
A.A. Grillo[146], K. Grimm[31,l], S. Grinstein[14,aa], J.-F. Grivaz[65], S. Groh[100], E. Gross[180],
J. Grosse-Knetter[53], Z.J. Grout[95], C. Grud[106], A. Grummer[118], L. Guan[106], W. Guan[181],
J. Guenther[36], A. Guerguichon[65], J.G.R. Guerrero Rojas[174], F. Guescini[115], D. Guest[171],
R. Gugel[52], T. Guillemin[5], S. Guindon[36], U. Gul[57], J. Guo[60c], W. Guo[106], Y. Guo[60a,t], Z. Guo[102],
R. Gupta[46], S. Gurbuz[12c], G. Gustavino[129], M. Guth[52], P. Gutierrez[129], C. Gutschow[95],
C. Guyot[145], C. Gwenlan[135], C.B. Gwilliam[91], A. Haas[125], C. Haber[18], H.K. Hadavand[8],
N. Haddad[35e], A. Hadef[60a], S. Hageböck[36], M. Haleem[177], J. Haley[130], G. Halladjian[107],
G.D. Hallewell[102], K. Hamacher[182], P. Hamal[131], K. Hamano[176], H. Hamdaoui[35e],
G.N. Hamity[149], K. Han[60a,z], L. Han[60a], S. Han[15a], Y.F. Han[167], K. Hanagaki[82,x], M. Hance[146],
D.M. Handl[114], B. Haney[137], R. Hankache[136], E. Hansen[97], J.B. Hansen[40], J.D. Hansen[40],
M.C. Hansen[24], P.H. Hansen[40], E.C. Hanson[101], K. Hara[169], T. Harenberg[182], S. Harkusha[108],
P.F. Harrison[178], N.M. Hartmann[114], Y. Hasegawa[150], A. Hasib[50], S. Hassani[145], S. Haug[20],
R. Hauser[107], L.B. Havener[39], M. Havranek[142], C.M. Hawkes[21], R.J. Hawkings[36], D. Hayden[107],
C. Hayes[155], R.L. Hayes[175], C.P. Hays[135], J.M. Hays[93], H.S. Hayward[91], S.J. Haywood[144],
F. He[60a], M.P. Heath[50], V. Hedberg[97], L. Heelan[8], S. Heer[24], K.K. Heidegger[52], W.D. Heidorn[79],
J. Heilman[34], S. Heim[46], T. Heim[18], B. Heinemann[46,as], J.J. Heinrich[132], L. Heinrich[36],

C. Heinz[56], J. Hejbal[141], L. Helary[61b], A. Held[175], S. Hellesund[134], C.M. Helling[146],
S. Hellman[45a,45b], C. Helsens[36], R.C.W. Henderson[90], Y. Heng[181], S. Henkelmann[175],
A.M. Henriques Correia[36], G.H. Herbert[19], H. Herde[26], V. Herget[177], Y. Hernández Jiménez[33e],
H. Herr[100], M.G. Herrmann[114], T. Herrmann[48], G. Herten[52], R. Hertenberger[114], L. Hervas[36],
T.C. Herwig[137], G.G. Hesketh[95], N.P. Hessey[168a], A. Higashida[163], S. Higashino[82],
E. Higón-Rodriguez[174], K. Hildebrand[37], E. Hill[176], J.C. Hill[32], K.K. Hill[29], K.H. Hiller[46],
S.J. Hillier[21], M. Hils[48], I. Hinchliffe[18], F. Hinterkeuser[24], M. Hirose[133], S. Hirose[52],
D. Hirschbuehl[182], B. Hiti[92], O. Hladik[141], D.R. Hlaluku[33e], X. Hoad[50], J. Hobbs[155], N. Hod[180],
M.C. Hodgkinson[149], A. Hoecker[36], F. Hoenig[114], D. Hohn[52], D. Hohov[65], T.R. Holmes[37],
M. Holzbock[114], L.B.A.H. Hommels[32], S. Honda[169], T.M. Hong[139], J.C. Honig[52], A. Hönle[115],
B.H. Hooberman[173], W.H. Hopkins[6], Y. Horii[117], P. Horn[48], L.A. Horyn[37], S. Hou[158],
A. Hoummada[35a], J. Howarth[101], J. Hoya[89], M. Hrabovsky[131], J. Hrdinka[77], I. Hristova[19],
J. Hrivnac[65], A. Hrynevich[109], T. Hryn'ova[5], P.J. Hsu[64], S.-C. Hsu[148], Q. Hu[29], S. Hu[60c],
Y.F. Hu[15a,15d], D.P. Huang[95], Y. Huang[60a], Y. Huang[15a], Z. Hubacek[142], F. Hubaut[102],
M. Huebner[24], F. Huegging[24], T.B. Huffman[135], M. Huhtinen[36], R.F.H. Hunter[34], P. Huo[155],
A.M. Hupe[34], N. Huseynov[80,ah], J. Huston[107], J. Huth[59], R. Hyneman[106], S. Hyrych[28a],
G. Iacobucci[54], G. Iakovidis[29], I. Ibragimov[151], L. Iconomidou-Fayard[65], Z. Idrissi[35e], P. Iengo[36],
R. Ignazzi[40], O. Igonkina[120,ac,*], R. Iguchi[163], T. Iizawa[54], Y. Ikegami[82], M. Ikeno[82], D. Iliadis[162],
N. Ilic[119,167,af], F. Iltzsche[48], G. Introzzi[71a,71b], M. Iodice[75a], K. Iordanidou[168a],
V. Ippolito[73a,73b], M.F. Isacson[172], M. Ishino[163], W. Islam[130], C. Issever[19,46], S. Istin[160],
F. Ito[169], J.M. Iturbe Ponce[63a], R. Iuppa[76a,76b], A. Ivina[180], H. Iwasaki[82], J.M. Izen[43], V. Izzo[70a],
P. Jacka[141], P. Jackson[1], R.M. Jacobs[24], B.P. Jaeger[152], V. Jain[2], G. Jäkel[182], K.B. Jakobi[100],
K. Jakobs[52], T. Jakoubek[141], J. Jamieson[57], K.W. Janas[84a], R. Jansky[54], J. Janssen[24],
M. Janus[53], P.A. Janus[84a], G. Jarlskog[97], N. Javadov[80,ah], T. Javůrek[36], M. Javurkova[52],
F. Jeanneau[145], L. Jeanty[132], J. Jejelava[159a,ai], A. Jelinskas[178], P. Jenni[52,b], J. Jeong[46],
N. Jeong[46], S. Jézéquel[5], H. Ji[181], J. Jia[155], H. Jiang[79], Y. Jiang[60a], Z. Jiang[153,q], S. Jiggins[52],
F.A. Jimenez Morales[38], J. Jimenez Pena[115], S. Jin[15c], A. Jinaru[27b], O. Jinnouchi[165], H. Jivan[33e],
P. Johansson[149], K.A. Johns[7], C.A. Johnson[66], K. Jon-And[45a,45b], R.W.L. Jones[90], S.D. Jones[156],
S. Jones[7], T.J. Jones[91], J. Jongmanns[61a], P.M. Jorge[140a], J. Jovicevic[36], X. Ju[18],
J.J. Junggeburth[115], A. Juste Rozas[14,aa], A. Kaczmarska[85], M. Kado[73a,73b], H. Kagan[127],
M. Kagan[153], A. Kahn[39], C. Kahra[100], T. Kaji[179], E. Kajomovitz[160], C.W. Kalderon[97],
A. Kaluza[100], A. Kamenshchikov[123], M. Kaneda[163], L. Kanjir[92], Y. Kano[117], V.A. Kantserov[112],
J. Kanzaki[82], L.S. Kaplan[181], D. Kar[33e], K. Karava[135], M.J. Kareem[168b], S.N. Karpov[80],
Z.M. Karpova[80], V. Kartvelishvili[90], A.N. Karyukhin[123], L. Kashif[181], R.D. Kass[127],
A. Kastanas[45a,45b], C. Kato[60d,60c], J. Katzy[46], K. Kawade[150], K. Kawagoe[88], T. Kawaguchi[117],
T. Kawamoto[163], G. Kawamura[53], E.F. Kay[176], V.F. Kazanin[122b,122a], R. Keeler[176], R. Kehoe[42],
J.S. Keller[34], E. Kellermann[97], D. Kelsey[156], J.J. Kempster[21], J. Kendrick[21], K.E. Kennedy[39],
O. Kepka[141], S. Kersten[182], B.P. Kerševan[92], S. Ketabchi Haghighat[167], M. Khader[173],
F. Khalil-Zada[13], M. Khandoga[145], A. Khanov[130], A.G. Kharlamov[122b,122a],
T. Kharlamova[122b,122a], E.E. Khoda[175], A. Khodinov[166], T.J. Khoo[54], E. Khramov[80],
J. Khubua[159b], S. Kido[83], M. Kiehn[54], C.R. Kilby[94], Y.K. Kim[37], N. Kimura[95], O.M. Kind[19],
B.T. King[91,*], D. Kirchmeier[48], J. Kirk[144], A.E. Kiryunin[115], T. Kishimoto[163], D.P. Kisliuk[167],
V. Kitali[46], O. Kivernyk[5], T. Klapdor-Kleingrothaus[52], M. Klassen[61a], M.H. Klein[106], M. Klein[91],
U. Klein[91], K. Kleinknecht[100], P. Klimek[121], A. Klimentov[29], T. Klingl[24], T. Klioutchnikova[36],
F.F. Klitzner[114], P. Kluit[120], S. Kluth[115], E. Kneringer[77], E.B.F.G. Knoops[102], A. Knue[52],
D. Kobayashi[88], T. Kobayashi[163], M. Kobel[48], M. Kocian[153], P. Kodys[143], P.T. Koenig[24],
T. Koffas[34], N.M. Köhler[36], T. Koi[153], M. Kolb[61b], I. Koletsou[5], T. Komarek[131], T. Kondo[82],
N. Kondrashova[60c], K. Köneke[52], A.C. König[119], T. Kono[126], R. Konoplich[125,an],

V. Konstantinides[95], N. Konstantinidis[95], B. Konya[97], R. Kopeliansky[66], S. Koperny[84a],
K. Korcyl[85], K. Kordas[162], G. Koren[161], A. Korn[95], I. Korolkov[14], E.V. Korolkova[149],
N. Korotkova[113], O. Kortner[115], S. Kortner[115], T. Kosek[143], V.V. Kostyukhin[166],
A. Kotsokechagia[65], A. Kotwal[49], A. Koulouris[10], A. Kourkoumeli-Charalampidi[71a,71b],
C. Kourkoumelis[9], E. Kourlitis[149], V. Kouskoura[29], A.B. Kowalewska[85], R. Kowalewski[176],
C. Kozakai[163], W. Kozanecki[145], A.S. Kozhin[123], V.A. Kramarenko[113], G. Kramberger[92],
D. Krasnopevtsev[60a], M.W. Krasny[136], A. Krasznahorkay[36], D. Krauss[115], J.A. Kremer[84a],
J. Kretzschmar[91], P. Krieger[167], F. Krieter[114], A. Krishnan[61b], K. Krizka[18], K. Kroeninger[47],
H. Kroha[115], J. Kroll[141], J. Kroll[137], K.S. Krowpman[107], J. Krstic[16], U. Kruchonak[80],
H. Krüger[24], N. Krumnack[79], M.C. Kruse[49], J.A. Krzysiak[85], T. Kubota[105], O. Kuchinskaia[166],
S. Kuday[4b], J.T. Kuechler[46], S. Kuehn[36], A. Kugel[61a], T. Kuhl[46], V. Kukhtin[80], R. Kukla[102],
Y. Kulchitsky[108,ak], S. Kuleshov[147d], Y.P. Kulinich[173], M. Kuna[58], T. Kunigo[86], A. Kupco[141],
T. Kupfer[47], O. Kuprash[52], H. Kurashige[83], L.L. Kurchaninov[168a], Y.A. Kurochkin[108],
A. Kurova[112], M.G. Kurth[15a,15d], E.S. Kuwertz[36], M. Kuze[165], A.K. Kvam[148], J. Kvita[131],
T. Kwan[104], A. La Rosa[115], L. La Rotonda[41b,41a], F. La Ruffa[41b,41a], C. Lacasta[174],
F. Lacava[73a,73b], D.P.J. Lack[101], H. Lacker[19], D. Lacour[136], E. Ladygin[80], R. Lafaye[5],
B. Laforge[136], T. Lagouri[33e], S. Lai[53], S. Lammers[66], W. Lampl[7], C. Lampoudis[162], E. Lançon[29],
U. Landgraf[52], M.P.J. Landon[93], M.C. Lanfermann[54], V.S. Lang[46], J.C. Lange[53],
R.J. Langenberg[36], A.J. Lankford[171], F. Lanni[29], K. Lantzsch[24], A. Lanza[71a], A. Lapertosa[55b,55a],
S. Laplace[136], J.F. Laporte[145], T. Lari[69a], F. Lasagni Manghi[23b,23a], M. Lassnig[36], T.S. Lau[63a],
A. Laudrain[65], A. Laurier[34], M. Lavorgna[70a,70b], S.D. Lawlor[94], M. Lazzaroni[69a,69b], B. Le[105],
E. Le Guirriec[102], M. LeBlanc[7], T. LeCompte[6], F. Ledroit-Guillon[58], A.C.A. Lee[95], C.A. Lee[29],
G.R. Lee[17], L. Lee[59], S.C. Lee[158], S.J. Lee[34], S. Lee[79], B. Lefebvre[168a], H.P. Lefebvre[94],
M. Lefebvre[176], F. Legger[114], C. Leggett[18], K. Lehmann[152], N. Lehmann[182],
G. Lehmann Miotto[36], W.A. Leight[46], A. Leisos[162,y], M.A.L. Leite[81d], C.E. Leitgeb[114],
R. Leitner[143], D. Lellouch[180,*], K.J.C. Leney[42], T. Lenz[24], B. Lenzi[36], R. Leone[7], S. Leone[72a],
C. Leonidopoulos[50], A. Leopold[136], G. Lerner[156], C. Leroy[110], R. Les[167], C.G. Lester[32],
M. Levchenko[138], J. Levêque[5], D. Levin[106], L.J. Levinson[180], D.J. Lewis[21], B. Li[15b], B. Li[106],
C-Q. Li[60a], F. Li[60c], H. Li[60a], H. Li[60b], J. Li[60c], K. Li[153], L. Li[60c], M. Li[15a,15d], Q. Li[15a,15d],
Q.Y. Li[60a], S. Li[60d,60c], X. Li[46], Y. Li[46], Z. Li[60b], Z. Liang[15a], B. Liberti[74a], A. Liblong[167],
K. Lie[63c], S. Lim[29], C.Y. Lin[32], K. Lin[107], T.H. Lin[100], R.A. Linck[66], J.H. Lindon[21],
A.L. Lionti[54], E. Lipeles[137], A. Lipniacka[17], M. Lisovyi[61b], T.M. Liss[173,au], A. Lister[175],
A.M. Litke[146], J.D. Little[8], B. Liu[79], B.L. Liu[6], H.B. Liu[29], H. Liu[106], J.B. Liu[60a], J.K.K. Liu[135],
K. Liu[136], M. Liu[60a], P. Liu[18], Y. Liu[15a,15d], Y.L. Liu[106], Y.W. Liu[60a], M. Livan[71a,71b],
A. Lleres[58], J. Llorente Merino[152], S.L. Lloyd[93], C.Y. Lo[63b], F. Lo Sterzo[42], E.M. Lobodzinska[46],
P. Loch[7], S. Loffredo[74a,74b], T. Lohse[19], K. Lohwasser[149], M. Lokajicek[141], J.D. Long[173],
R.E. Long[90], L. Longo[36], K.A. Looper[127], J.A. Lopez[147d], I. Lopez Paz[101], A. Lopez Solis[149],
J. Lorenz[114], N. Lorenzo Martinez[5], M. Losada[22a], P.J. Lösel[114], A. Lösle[52], X. Lou[46], X. Lou[15a],
A. Lounis[65], J. Love[6], P.A. Love[90], J.J. Lozano Bahilo[174], M. Lu[60a], Y.J. Lu[64], H.J. Lubatti[148],
C. Luci[73a,73b], A. Lucotte[58], C. Luedtke[52], F. Luehring[66], I. Luise[136], L. Luminari[73a],
B. Lund-Jensen[154], M.S. Lutz[103], D. Lynn[29], H. Lyons[91], R. Lysak[141], E. Lytken[97], F. Lyu[15a],
V. Lyubushkin[80], T. Lyubushkina[80], H. Ma[29], L.L. Ma[60b], Y. Ma[60b], G. Maccarrone[51],
A. Macchiolo[115], C.M. Macdonald[149], J. Machado Miguens[137], D. Madaffari[174], R. Madar[38],
W.F. Mader[48], N. Madysa[48], J. Maeda[83], T. Maeno[29], M. Maerker[48], A.S. Maevskiy[113],
V. Magerl[52], N. Magini[79], D.J. Mahon[39], C. Maidantchik[81b], T. Maier[114], A. Maio[140a,140b,140d],
K. Maj[84a], O. Majersky[28a], S. Majewski[132], Y. Makida[82], N. Makovec[65], B. Malaescu[136],
Pa. Malecki[85], V.P. Maleev[138], F. Malek[58], U. Mallik[78], D. Malon[6], C. Malone[32], S. Maltezos[10],
S. Malyukov[80], J. Mamuzic[174], G. Mancini[51], I. Mandić[92], L. Manhaes de Andrade Filho[81a],

I.M. Maniatis[162], J. Manjarres Ramos[48], K.H. Mankinen[97], A. Mann[114], A. Manousos[77],
B. Mansoulie[145], I. Manthos[162], S. Manzoni[120], A. Marantis[162], G. Marceca[30], L. Marchese[135],
G. Marchiori[136], M. Marcisovsky[141], L. Marcoccia[74a,74b], C. Marcon[97], C.A. Marin Tobon[36],
M. Marjanovic[129], Z. Marshall[18], M.U.F. Martensson[172], S. Marti-Garcia[174], C.B. Martin[127],
T.A. Martin[178], V.J. Martin[50], B. Martin dit Latour[17], L. Martinelli[75a,75b], M. Martinez[14,aa],
V.I. Martinez Outschoorn[103], S. Martin-Haugh[144], V.S. Martoiu[27b], A.C. Martyniuk[95],
A. Marzin[36], S.R. Maschek[115], L. Masetti[100], T. Mashimo[163], R. Mashinistov[111], J. Masik[101],
A.L. Maslennikov[122b,122a], L. Massa[74a,74b], P. Massarotti[70a,70b], P. Mastrandrea[72a,72b],
A. Mastroberardino[41b,41a], T. Masubuchi[163], D. Matakias[10], A. Matic[114], P. Mättig[24],
J. Maurer[27b], B. Maček[92], D.A. Maximov[122b,122a], R. Mazini[158], I. Maznas[162], S.M. Mazza[146],
S.P. Mc Kee[106], T.G. McCarthy[115], W.P. McCormack[18], E.F. McDonald[105], J.A. Mcfayden[36],
G. Mchedlidze[159b], M.A. McKay[42], K.D. McLean[176], S.J. McMahon[144], P.C. McNamara[105],
C.J. McNicol[178], R.A. McPherson[176,af], J.E. Mdhluli[33e], Z.A. Meadows[103], S. Meehan[36],
T. Megy[52], S. Mehlhase[114], A. Mehta[91], T. Meideck[58], B. Meirose[43], D. Melini[174],
B.R. Mellado Garcia[33e], J.D. Mellenthin[53], M. Melo[28a], F. Meloni[46], A. Melzer[24], S.B. Menary[101],
E.D. Mendes Gouveia[140a,140e], L. Meng[36], X.T. Meng[106], S. Menke[115], E. Meoni[41b,41a],
S. Mergelmeyer[19], S.A.M. Merkt[139], C. Merlassino[20], P. Mermod[54], L. Merola[70a,70b],
C. Meroni[69a], O. Meshkov[113,111], J.K.R. Meshreki[151], A. Messina[73a,73b], J. Metcalfe[6],
A.S. Mete[171], C. Meyer[66], J. Meyer[160], J-P. Meyer[145], H. Meyer Zu Theenhausen[61a], F. Miano[156],
M. Michetti[19], R.P. Middleton[144], L. Mijović[50], G. Mikenberg[180], M. Mikestikova[141], M. Mikuž[92],
H. Mildner[149], M. Milesi[105], A. Milic[167], D.A. Millar[93], D.W. Miller[37], A. Milov[180],
D.A. Milstead[45a,45b], R.A. Mina[153,q], A.A. Minaenko[123], M. Miñano Moya[174], I.A. Minashvili[159b],
A.I. Mincer[125], B. Mindur[84a], M. Mineev[80], Y. Minegishi[163], L.M. Mir[14], A. Mirto[68a,68b],
K.P. Mistry[137], T. Mitani[179], J. Mitrevski[114], V.A. Mitsou[174], M. Mittal[60c], O. Miu[167],
A. Miucci[20], P.S. Miyagawa[149], A. Mizukami[82], J.U. Mjörnmark[97], T. Mkrtchyan[184],
M. Mlynarikova[143], T. Moa[45a,45b], K. Mochizuki[110], P. Mogg[52], S. Mohapatra[39], R. Moles-Valls[24],
M.C. Mondragon[107], K. Mönig[46], J. Monk[40], E. Monnier[102], A. Montalbano[152],
J. Montejo Berlingen[36], M. Montella[95], F. Monticelli[89], S. Monzani[69a], N. Morange[65],
D. Moreno[22a], M. Moreno Llácer[174], C. Moreno Martinez[14], P. Morettini[55b], M. Morgenstern[120],
S. Morgenstern[48], D. Mori[152], M. Morii[59], M. Morinaga[179], V. Morisbak[134], A.K. Morley[36],
G. Mornacchi[36], A.P. Morris[95], L. Morvaj[155], P. Moschovakos[36], B. Moser[120], M. Mosidze[159b],
T. Moskalets[145], H.J. Moss[149], J. Moss[31,n], E.J.W. Moyse[103], S. Muanza[102], J. Mueller[139],
R.S.P. Mueller[114], D. Muenstermann[90], G.A. Mullier[97], D.P. Mungo[69a,69b],
J.L. Munoz Martinez[14], F.J. Munoz Sanchez[101], P. Murin[28b], W.J. Murray[178,144],
A. Murrone[69a,69b], M. Muškinja[18], C. Mwewa[33a], A.G. Myagkov[123,ao], J. Myers[132], M. Myska[142],
B.P. Nachman[18], O. Nackenhorst[47], A.Nag Nag[48], K. Nagai[135], K. Nagano[82], Y. Nagasaka[62],
M. Nagel[52], J.L. Nagle[29], E. Nagy[102], A.M. Nairz[36], Y. Nakahama[117], K. Nakamura[82],
T. Nakamura[163], I. Nakano[128], H. Nanjo[133], F. Napolitano[61a], R.F. Naranjo Garcia[46],
R. Narayan[42], I. Naryshkin[138], T. Naumann[46], G. Navarro[22a], P.Y. Nechaeva[111], F. Nechansky[46],
T.J. Neep[21], A. Negri[71a,71b], M. Negrini[23b], C. Nellist[53], M.E. Nelson[135], S. Nemecek[141],
P. Nemethy[125], M. Nessi[36,d], M.S. Neubauer[173], M. Neumann[182], P.R. Newman[21], Y.S. Ng[19],
Y.W.Y. Ng[171], B. Ngair[35e], H.D.N. Nguyen[102], T. Nguyen Manh[110], E. Nibigira[38],
R.B. Nickerson[135], R. Nicolaidou[145], D.S. Nielsen[40], J. Nielsen[146], N. Nikiforou[11],
V. Nikolaenko[123,ao], I. Nikolic-Audit[136], K. Nikolopoulos[21], P. Nilsson[29], H.R. Nindhito[54],
Y. Ninomiya[82], A. Nisati[73a], N. Nishu[60c], R. Nisius[115], I. Nitsche[47], T. Nitta[179], T. Nobe[163],
Y. Noguchi[86], I. Nomidis[136], M.A. Nomura[29], M. Nordberg[36], N. Norjoharuddeen[135], T. Novak[92],
O. Novgorodova[48], R. Novotny[142], L. Nozka[131], K. Ntekas[171], E. Nurse[95], F.G. Oakham[34,aw],
H. Oberlack[115], J. Ocariz[136], A. Ochi[83], I. Ochoa[39], J.P. Ochoa-Ricoux[147a], K. O'Connor[26],

S. Oda[88], S. Odaka[82], S. Oerdek[53], A. Ogrodnik[84a], A. Oh[101], S.H. Oh[49], C.C. Ohm[154],
H. Oide[165], M.L. Ojeda[167], H. Okawa[169], Y. Okazaki[86], M.W. O'Keefe[91], Y. Okumura[163],
T. Okuyama[82], A. Olariu[27b], L.F. Oleiro Seabra[140a], S.A. Olivares Pino[147a],
D. Oliveira Damazio[29], J.L. Oliver[1], M.J.R. Olsson[171], A. Olszewski[85], J. Olszowska[85],
D.C. O'Neil[152], A.P. O'neill[135], A. Onofre[140a,140e], P.U.E. Onyisi[11], H. Oppen[134], M.J. Oreglia[37],
G.E. Orellana[89], D. Orestano[75a,75b], N. Orlando[14], R.S. Orr[167], V. O'Shea[57], R. Ospanov[60a],
G. Otero y Garzon[30], H. Otono[88], P.S. Ott[61a], M. Ouchrif[35d], J. Ouellette[29], F. Ould-Saada[134],
A. Ouraou[145], Q. Ouyang[15a], M. Owen[57], R.E. Owen[21], V.E. Ozcan[12c], N. Ozturk[8], J. Pacalt[131],
H.A. Pacey[32], K. Pachal[49], A. Pacheco Pages[14], C. Padilla Aranda[14], S. Pagan Griso[18],
M. Paganini[183], G. Palacino[66], S. Palazzo[50], S. Palestini[36], M. Palka[84b], D. Pallin[38],
I. Panagoulias[10], C.E. Pandini[36], J.G. Panduro Vazquez[94], P. Pani[46], G. Panizzo[67a,67c],
L. Paolozzi[54], C. Papadatos[110], K. Papageorgiou[9,h], S. Parajuli[43], A. Paramonov[6],
D. Paredes Hernandez[63b], S.R. Paredes Saenz[135], B. Parida[166], T.H. Park[167], A.J. Parker[31],
M.A. Parker[32], F. Parodi[55b,55a], E.W. Parrish[121], J.A. Parsons[39], U. Parzefall[52],
L. Pascual Dominguez[136], V.R. Pascuzzi[167], J.M.P. Pasner[146], F. Pasquali[120], E. Pasqualucci[73a],
S. Passaggio[55b], F. Pastore[94], P. Pasuwan[45a,45b], S. Pataraia[100], J.R. Pater[101], A. Pathak[181,j],
T. Pauly[36], B. Pearson[115], M. Pedersen[134], L. Pedraza Diaz[119], R. Pedro[140a], T. Peiffer[53],
S.V. Peleganchuk[122b,122a], O. Penc[141], H. Peng[60a], B.S. Peralva[81a], M.M. Perego[65],
A.P. Pereira Peixoto[140a], D.V. Perepelitsa[29], F. Peri[19], L. Perini[69a,69b], H. Pernegger[36],
S. Perrella[70a,70b], K. Peters[46], R.F.Y. Peters[101], B.A. Petersen[36], T.C. Petersen[40], E. Petit[102],
A. Petridis[1], C. Petridou[162], P. Petroff[65], F. Petrucci[75a,75b], M. Pettee[183],
N.E. Pettersson[103], K. Petukhova[143], A. Peyaud[145], R. Pezoa[147d], L. Pezzotti[71a,71b], T. Pham[105],
F.H. Phillips[107], P.W. Phillips[144], M.W. Phipps[173], G. Piacquadio[155], E. Pianori[18], A. Picazio[103],
R.H. Pickles[101], R. Piegaia[30], D. Pietreanu[27b], J.E. Pilcher[37], A.D. Pilkington[101],
M. Pinamonti[74a,74b], J.L. Pinfold[3], M. Pitt[161], L. Pizzimento[74a,74b], M.-A. Pleier[29], V. Pleskot[143],
E. Plotnikova[80], P. Podberezko[122b,122a], R. Poettgen[97], R. Poggi[54], L. Poggioli[65],
I. Pogrebnyak[107], D. Pohl[24], I. Pokharel[53], G. Polesello[71a], A. Poley[18], A. Policicchio[73a,73b],
R. Polifka[143], A. Polini[23b], C.S. Pollard[46], V. Polychronakos[29], D. Ponomarenko[112],
L. Pontecorvo[36], S. Popa[27a], G.A. Popeneciu[27d], L. Portales[5], D.M. Portillo Quintero[58],
S. Pospisil[142], K. Potamianos[46], I.N. Potrap[80], C.J. Potter[32], H. Potti[11], T. Poulsen[97],
J. Poveda[36], T.D. Powell[149], G. Pownall[46], M.E. Pozo Astigarraga[36], P. Pralavorio[102], S. Prell[79],
D. Price[101], M. Primavera[68a], S. Prince[104], M.L. Proffitt[148], N. Proklova[112], K. Prokofiev[63c],
F. Prokoshin[80], S. Protopopescu[29], J. Proudfoot[6], M. Przybycien[84a], D. Pudzha[138], A. Puri[173],
P. Puzo[65], J. Qian[106], Y. Qin[101], A. Quadt[53], M. Queitsch-Maitland[46], A. Qureshi[1], M. Racko[28a],
P. Rados[105], F. Ragusa[69a,69b], G. Rahal[98], J.A. Raine[54], S. Rajagopalan[29], A. Ramirez Morales[93],
K. Ran[15a,15d], T. Rashid[65], S. Raspopov[5], D.M. Rauch[46], F. Rauscher[114], S. Rave[100],
B. Ravina[149], I. Ravinovich[180], J.H. Rawling[101], M. Raymond[36], A.L. Read[134], N.P. Readioff[58],
M. Reale[68a,68b], D.M. Rebuzzi[71a,71b], A. Redelbach[177], G. Redlinger[29], K. Reeves[43],
L. Rehnisch[19], J. Reichert[137], D. Reikher[161], A. Reiss[100], A. Rej[151], C. Rembser[36], M. Renda[27b],
M. Rescigno[73a], S. Resconi[69a], E.D. Resseguie[137], S. Rettie[175], E. Reynolds[21],
O.L. Rezanova[122b,122a], P. Reznicek[143], E. Ricci[76a,76b], R. Richter[115], S. Richter[46],
E. Richter-Was[84b], O. Ricken[24], M. Ridel[136], P. Rieck[115], O. Rifki[46], M. Rijssenbeek[155],
A. Rimoldi[71a,71b], M. Rimoldi[46], L. Rinaldi[23b], G. Ripellino[154], I. Riu[14], J.C. Rivera Vergara[176],
F. Rizatdinova[130], E. Rizvi[93], C. Rizzi[36], R.T. Roberts[101], S.H. Robertson[104,af], M. Robin[46],
D. Robinson[32], J.E.M. Robinson[46], C.M. Robles Gajardo[147d], A. Robson[57], A. Rocchi[74a,74b],
E. Rocco[100], C. Roda[72a,72b], S. Rodriguez Bosca[174], A. Rodriguez Perez[14],
D. Rodriguez Rodriguez[174], A.M. Rodríguez Vera[168b], S. Roe[36], O. Røhne[134], R. Röhrig[115],
R.A. Rojas[147d], C.P.A. Roland[66], J. Roloff[29], A. Romaniouk[112], M. Romano[23b,23a],

N. Rompotis[91], M. Ronzani[125], L. Roos[136], S. Rosati[73a], K. Rosbach[52], G. Rosin[103],
B.J. Rosser[137], E. Rossi[46], E. Rossi[75a,75b], E. Rossi[70a,70b], L.P. Rossi[55b], L. Rossini[69a,69b],
R. Rosten[14], M. Rotaru[27b], J. Rothberg[148], D. Rousseau[65], G. Rovelli[71a,71b], A. Roy[11], D. Roy[33e],
A. Rozanov[102], Y. Rozen[160], X. Ruan[33e], F. Rühr[52], A. Ruiz-Martinez[174], A. Rummler[36],
Z. Rurikova[52], N.A. Rusakovich[80], H.L. Russell[104], L. Rustige[38,47], J.P. Rutherfoord[7],
E.M. Rüttinger[149], M. Rybar[39], G. Rybkin[65], E.B. Rye[134], A. Ryzhov[123], J.A. Sabater Iglesias[46],
P. Sabatini[53], G. Sabato[120], S. Sacerdoti[65], H.F-W. Sadrozinski[146], R. Sadykov[80],
F. Safai Tehrani[73a], B. Safarzadeh Samani[156], P. Saha[121], S. Saha[104], M. Sahinsoy[61a], A. Sahu[182],
M. Saimpert[46], M. Saito[163], T. Saito[163], H. Sakamoto[163], A. Sakharov[125,an], D. Salamani[54],
G. Salamanna[75a,75b], J.E. Salazar Loyola[147d], A. Salnikov[153], J. Salt[174], D. Salvatore[41b,41a],
F. Salvatore[156], A. Salvucci[63a,63b,63c], A. Salzburger[36], J. Samarati[36], D. Sammel[52],
D. Sampsonidis[162], D. Sampsonidou[162], J. Sánchez[174], A. Sanchez Pineda[67a,36,67c],
H. Sandaker[134], C.O. Sander[46], I.G. Sanderswood[90], M. Sandhoff[182], C. Sandoval[22a],
D.P.C. Sankey[144], M. Sannino[55b,55a], Y. Sano[117], A. Sansoni[51], C. Santoni[38], H. Santos[140a,140b],
S.N. Santpur[18], A. Santra[174], A. Sapronov[80], J.G. Saraiva[140a,140d], O. Sasaki[82], K. Sato[169],
F. Sauerburger[52], E. Sauvan[5], P. Savard[167,aw], N. Savic[115], R. Sawada[163], C. Sawyer[144],
L. Sawyer[96,al], C. Sbarra[23b], A. Sbrizzi[23a], T. Scanlon[95], J. Schaarschmidt[148], P. Schacht[115],
B.M. Schachtner[114], D. Schaefer[37], L. Schaefer[137], J. Schaeffer[100], S. Schaepe[36], U. Schäfer[100],
A.C. Schaffer[65], D. Schaile[114], R.D. Schamberger[155], N. Scharmberg[101], V.A. Schegelsky[138],
D. Scheirich[143], F. Schenck[19], M. Schernau[171], C. Schiavi[55b,55a], S. Schier[146], L.K. Schildgen[24],
Z.M. Schillaci[26], E.J. Schioppa[36], M. Schioppa[41b,41a], K.E. Schleicher[52], S. Schlenker[36],
K.R. Schmidt-Sommerfeld[115], K. Schmieden[36], C. Schmitt[100], S. Schmitt[46], S. Schmitz[100],
J.C. Schmoeckel[46], U. Schnoor[52], L. Schoeffel[145], A. Schoening[61b], P.G. Scholer[52], E. Schopf[135],
M. Schott[100], J.F.P. Schouwenberg[119], J. Schovancova[36], S. Schramm[54], F. Schroeder[182],
A. Schulte[100], H-C. Schultz-Coulon[61a], M. Schumacher[52], B.A. Schumm[146], Ph. Schune[145],
A. Schwartzman[153], T.A. Schwarz[106], Ph. Schwemling[145], R. Schwienhorst[107], A. Sciandra[146],
G. Sciolla[26], M. Scodeggio[46], M. Scornajenghi[41b,41a], F. Scuri[72a], F. Scutti[105], L.M. Scyboz[115],
C.D. Sebastiani[73a,73b], P. Seema[19], S.C. Seidel[118], A. Seiden[146], B.D. Seidlitz[29], T. Seiss[37],
J.M. Seixas[81b], G. Sekhniaidze[70a], K. Sekhon[106], S.J. Sekula[42], N. Semprini-Cesari[23b,23a],
S. Sen[49], C. Serfon[77], L. Serin[65], L. Serkin[67a,67b], M. Sessa[60a], H. Severini[129], T. Šfiligoj[92],
F. Sforza[55b,55a], A. Sfyrla[54], E. Shabalina[53], J.D. Shahinian[146], N.W. Shaikh[45a,45b],
D. Shaked Renous[180], L.Y. Shan[15a], J.T. Shank[25], M. Shapiro[18], A. Sharma[135], A.S. Sharma[1],
P.B. Shatalov[124], K. Shaw[156], S.M. Shaw[101], A. Shcherbakova[138], M. Shehade[180], Y. Shen[129],
A.D. Sherman[25], P. Sherwood[95], L. Shi[158,at], S. Shimizu[82], C.O. Shimmin[183], Y. Shimogama[179],
M. Shimojima[116], I.P.J. Shipsey[135], S. Shirabe[88], M. Shiyakova[80,ad], J. Shlomi[180], A. Shmeleva[111],
M.J. Shochet[37], J. Shojaii[105], D.R. Shope[129], S. Shrestha[127], E.M. Shrif[33e], E. Shulga[180],
P. Sicho[141], A.M. Sickles[173], P.E. Sidebo[154], E. Sideras Haddad[33e], O. Sidiropoulou[36],
A. Sidoti[23b,23a], F. Siegert[48], Dj. Sijacki[16], M.Jr. Silva[181], M.V. Silva Oliveira[81a],
S.B. Silverstein[45a], S. Simion[65], E. Simioni[100], R. Simoniello[100], S. Simsek[12b], P. Sinervo[167],
V. Sinetckii[113,111], N.B. Sinev[132], M. Sioli[23b,23a], I. Siral[106], S.Yu. Sivoklokov[113], J. Sjölin[45a,45b],
E. Skorda[97], P. Skubic[129], M. Slawinska[85], K. Sliwa[170], R. Slovak[143], V. Smakhtin[180],
B.H. Smart[144], J. Smiesko[28a], N. Smirnov[112], S.Yu. Smirnov[112], Y. Smirnov[112],
L.N. Smirnova[113,v], O. Smirnova[97], J.W. Smith[53], M. Smizanska[90], K. Smolek[142],
A. Smykiewicz[85], A.A. Snesarev[111], H.L. Snoek[120], I.M. Snyder[132], S. Snyder[29], R. Sobie[176,af],
A. Soffer[161], A. Søgaard[50], F. Sohns[53], C.A. Solans Sanchez[36], E.Yu. Soldatov[112], U. Soldevila[174],
A.A. Solodkov[123], A. Soloshenko[80], O.V. Solovyanov[123], V. Solovyev[138], P. Sommer[149], H. Son[170],
W. Song[144], W.Y. Song[168b], A. Sopczak[142], F. Sopkova[28b], C.L. Sotiropoulou[72a,72b],
S. Sottocornola[71a,71b], R. Soualah[67a,67c,g], A.M. Soukharev[122b,122a], D. South[46],

S. Spagnolo[68a,68b], M. Spalla[115], M. Spangenberg[178], F. Spanò[94], D. Sperlich[52], T.M. Spieker[61a],
R. Spighi[23b], G. Spigo[36], M. Spina[156], D.P. Spiteri[57], M. Spousta[143], A. Stabile[69a,69b],
B.L. Stamas[121], R. Stamen[61a], M. Stamenkovic[120], E. Stanecka[85], B. Stanislaus[135],
M.M. Stanitzki[46], M. Stankaityte[135], B. Stapf[120], E.A. Starchenko[123], G.H. Stark[146], J. Stark[58],
S.H. Stark[40], P. Staroba[141], P. Starovoitov[61a], S. Stärz[104], R. Staszewski[85], G. Stavropoulos[44],
M. Stegler[46], P. Steinberg[29], A.L. Steinhebel[132], B. Stelzer[152], H.J. Stelzer[139],
O. Stelzer-Chilton[168a], H. Stenzel[56], T.J. Stevenson[156], G.A. Stewart[36], M.C. Stockton[36],
G. Stoicea[27b], M. Stolarski[140a], S. Stonjek[115], A. Straessner[48], J. Strandberg[154],
S. Strandberg[45a,45b], M. Strauss[129], P. Strizenec[28b], R. Ströhmer[177], D.M. Strom[132],
R. Stroynowski[42], A. Strubig[50], S.A. Stucci[29], B. Stugu[17], J. Stupak[129], N.A. Styles[46], D. Su[153],
S. Suchek[61a], V.V. Sulin[111], M.J. Sullivan[91], D.M.S. Sultan[54], S. Sultansoy[4c], T. Sumida[86],
S. Sun[106], X. Sun[3], K. Suruliz[156], C.J.E. Suster[157], M.R. Sutton[156], S. Suzuki[82], M. Svatos[141],
M. Swiatlowski[37], S.P. Swift[2], T. Swirski[177], A. Sydorenko[100], I. Sykora[28a], M. Sykora[143],
T. Sykora[143], D. Ta[100], K. Tackmann[46,ab], J. Taenzer[161], A. Taffard[171], R. Tafirout[168a],
H. Takai[29], R. Takashima[87], K. Takeda[83], T. Takeshita[150], E.P. Takeva[50], Y. Takubo[82],
M. Talby[102], A.A. Talyshev[122b,122a], N.M. Tamir[161], J. Tanaka[163], M. Tanaka[165], R. Tanaka[65],
S. Tapia Araya[173], S. Tapprogge[100], A. Tarek Abouelfadl Mohamed[136], S. Tarem[160], K. Tariq[60b],
G. Tarna[27b,c], G.F. Tartarelli[69a], P. Tas[143], M. Tasevsky[141], T. Tashiro[86], E. Tassi[41b,41a],
A. Tavares Delgado[140a,140b], Y. Tayalati[35e], A.J. Taylor[50], G.N. Taylor[105], W. Taylor[168b],
A.S. Tee[90], R. Teixeira De Lima[153], P. Teixeira-Dias[94], H. Ten Kate[36], J.J. Teoh[120], S. Terada[82],
K. Terashi[163], J. Terron[99], S. Terzo[14], M. Testa[51], R.J. Teuscher[167,af], S.J. Thais[183],
T. Theveneaux-Pelzer[46], F. Thiele[40], D.W. Thomas[94], J.O. Thomas[42], J.P. Thomas[21],
A.S. Thompson[57], P.D. Thompson[21], L.A. Thomsen[183], E. Thomson[137], E.J. Thorpe[93],
R.E. Ticse Torres[53], V.O. Tikhomirov[111,ap], Yu.A. Tikhonov[122b,122a], S. Timoshenko[112],
P. Tipton[183], S. Tisserant[102], K. Todome[23b,23a], S. Todorova-Nova[5], S. Todt[48], J. Tojo[88],
S. Tokár[28a], K. Tokushuku[82], E. Tolley[127], K.G. Tomiwa[33e], M. Tomoto[117], L. Tompkins[153,q],
B. Tong[59], P. Tornambe[103], E. Torrence[132], H. Torres[48], E. Torró Pastor[148], C. Tosciri[135],
J. Toth[102,ae], D.R. Tovey[149], A. Traeet[17], C.J. Treado[125], T. Trefzger[177], F. Tresoldi[156],
A. Tricoli[29], I.M. Trigger[168a], S. Trincaz-Duvoid[136], D.A. Trischuk[175], W. Trischuk[167],
B. Trocmé[58], A. Trofymov[145], C. Troncon[69a], M. Trovatelli[176], F. Trovato[156], L. Truong[33c],
M. Trzebinski[85], A. Trzupek[85], F. Tsai[46], J.C-L. Tseng[135], P.V. Tsiareshka[108,ak],
A. Tsirigotis[162,y], V. Tsiskaridze[155], E.G. Tskhadadze[159a], M. Tsopoulou[162], I.I. Tsukerman[124],
V. Tsulaia[18], S. Tsuno[82], D. Tsybychev[155], Y. Tu[63b], A. Tudorache[27b], V. Tudorache[27b],
T.T. Tulbure[27a], A.N. Tuna[59], S. Turchikhin[80], D. Turgeman[180], I. Turk Cakir[4b,w], R.J. Turner[21],
R.T. Turra[69a], P.M. Tuts[39], S. Tzamarias[162], E. Tzovara[100], G. Ucchielli[47], K. Uchida[163],
I. Ueda[82], M. Ughetto[45a,45b], F. Ukegawa[169], G. Unal[36], A. Undrus[29], G. Unel[171], F.C. Ungaro[105],
Y. Unno[82], K. Uno[163], J. Urban[28b], P. Urquijo[105], G. Usai[8], Z. Uysal[12d], V. Vacek[142],
B. Vachon[104], K.O.H. Vadla[134], A. Vaidya[95], C. Valderanis[114], E. Valdes Santurio[45a,45b],
M. Valente[54], S. Valentinetti[23b,23a], A. Valero[174], L. Valéry[46], R.A. Vallance[21], A. Vallier[36],
J.A. Valls Ferrer[174], T.R. Van Daalen[14], P. Van Gemmeren[6], I. Van Vulpen[120], M. Vanadia[74a,74b],
W. Vandelli[36], E.R. Vandewall[130], A. Vaniachine[166], D. Vannicola[73a,73b], R. Vari[73a],
E.W. Varnes[7], C. Varni[55b,55a], T. Varol[158], D. Varouchas[65], K.E. Varvell[157], M.E. Vasile[27b],
G.A. Vasquez[176], J.G. Vasquez[183], F. Vazeille[38], D. Vazquez Furelos[14], T. Vazquez Schroeder[36],
J. Veatch[53], V. Vecchio[75a,75b], M.J. Veen[120], L.M. Veloce[167], F. Veloso[140a,140c], S. Veneziano[73a],
A. Ventura[68a,68b], N. Venturi[36], A. Verbytskyi[115], V. Vercesi[71a], M. Verducci[72a,72b],
C.M. Vergel Infante[79], C. Vergis[24], W. Verkerke[120], A.T. Vermeulen[120], J.C. Vermeulen[120],
M.C. Vetterli[152,aw], N. Viaux Maira[147d], M. Vicente Barreto Pinto[54], T. Vickey[149],
O.E. Vickey Boeriu[149], G.H.A. Viehhauser[135], L. Vigani[61b], M. Villa[23b,23a],

M. Villaplana Perez[69a,69b], E. Vilucchi[51], M.G. Vincter[34], G.S. Virdee[21], A. Vishwakarma[46],
C. Vittori[23b,23a], I. Vivarelli[156], M. Vogel[182], P. Vokac[142], S.E. von Buddenbrock[33e],
E. Von Toerne[24], V. Vorobel[143], K. Vorobev[112], M. Vos[174], J.H. Vossebeld[91], M. Vozak[101],
N. Vranjes[16], M. Vranjes Milosavljevic[16], V. Vrba[142], M. Vreeswijk[120], R. Vuillermet[36],
I. Vukotic[37], P. Wagner[24], W. Wagner[182], J. Wagner-Kuhr[114], S. Wahdan[182], H. Wahlberg[89],
V.M. Walbrecht[115], J. Walder[90], R. Walker[114], S.D. Walker[94], W. Walkowiak[151],
V. Wallangen[45a,45b], A.M. Wang[59], C. Wang[60c], C. Wang[60b], F. Wang[181], H. Wang[18], H. Wang[3],
J. Wang[63a], J. Wang[157], J. Wang[61b], P. Wang[42], Q. Wang[129], R.-J. Wang[100], R. Wang[60a],
R. Wang[6], S.M. Wang[158], W.T. Wang[60a], W. Wang[15c,ag], W.X. Wang[60a,ag], Y. Wang[60a,am],
Z. Wang[60c], C. Wanotayaroj[46], A. Warburton[104], C.P. Ward[32], D.R. Wardrope[95], N. Warrack[57],
A. Washbrook[50], A.T. Watson[21], M.F. Watson[21], G. Watts[148], B.M. Waugh[95], A.F. Webb[11],
S. Webb[100], C. Weber[183], M.S. Weber[20], S.A. Weber[34], S.M. Weber[61a], A.R. Weidberg[135],
J. Weingarten[47], M. Weirich[100], C. Weiser[52], P.S. Wells[36], T. Wenaus[29], T. Wengler[36],
S. Wenig[36], N. Wermes[24], M.D. Werner[79], M. Wessels[61a], T.D. Weston[20], K. Whalen[132],
N.L. Whallon[148], A.M. Wharton[90], A.S. White[106], A. White[8], M.J. White[1], D. Whiteson[171],
B.W. Whitmore[90], W. Wiedenmann[181], M. Wielers[144], N. Wieseotte[100], C. Wiglesworth[40],
L.A.M. Wiik-Fuchs[52], F. Wilk[101], H.G. Wilkens[36], L.J. Wilkins[94], H.H. Williams[137],
S. Williams[32], C. Willis[107], S. Willocq[103], J.A. Wilson[21], I. Wingerter-Seez[5], E. Winkels[156],
F. Winklmeier[132], O.J. Winston[156], B.T. Winter[52], M. Wittgen[153], M. Wobisch[96], A. Wolf[100],
T.M.H. Wolf[120], R. Wolff[102], R. Wölker[135], J. Wollrath[52], M.W. Wolter[85], H. Wolters[140a,140c],
V.W.S. Wong[175], N.L. Woods[146], S.D. Worm[21], B.K. Wosiek[85], K.W. Woźniak[85], K. Wraight[57],
S.L. Wu[181], X. Wu[54], Y. Wu[60a], T.R. Wyatt[101], B.M. Wynne[50], S. Xella[40], Z. Xi[106], L. Xia[178],
X. Xiao[106], I. Xiotidis[156], D. Xu[15a], H. Xu[60a,c], L. Xu[29], T. Xu[145], W. Xu[106], Z. Xu[60b], Z. Xu[153],
B. Yabsley[157], S. Yacoob[33a], K. Yajima[133], D.P. Yallup[95], D. Yamaguchi[165], Y. Yamaguchi[165],
A. Yamamoto[82], M. Yamatani[163], T. Yamazaki[163], Y. Yamazaki[83], Z. Yan[25], H.J. Yang[60c,60d],
H.T. Yang[18], S. Yang[78], X. Yang[60b,58], Y. Yang[163], W-M. Yao[18], Y.C. Yap[46], Y. Yasu[82],
E. Yatsenko[60c,60d], J. Ye[42], S. Ye[29], I. Yeletskikh[80], M.R. Yexley[90], E. Yigitbasi[25], K. Yorita[179],
K. Yoshihara[137], C.J.S. Young[36], C. Young[153], J. Yu[79], R. Yuan[60b,i], X. Yue[61a], S.P.Y. Yuen[24],
M. Zaazoua[35e], B. Zabinski[85], G. Zacharis[10], E. Zaffaroni[54], J. Zahreddine[136], A.M. Zaitsev[123,ao],
T. Zakareishvili[159b], N. Zakharchuk[34], S. Zambito[59], D. Zanzi[36], D.R. Zaripovas[57], S.V. Zeißner[47],
C. Zeitnitz[182], G. Zemaityte[135], J.C. Zeng[173], O. Zenin[123], T. Ženiš[28a], D. Zerwas[65],
M. Zgubič[135], B. Zhang[15c], D.F. Zhang[15b], G. Zhang[15b], H. Zhang[15c], J. Zhang[6], L. Zhang[15c],
L. Zhang[60a], M. Zhang[173], R. Zhang[24], X. Zhang[60b], Y. Zhang[15a,15d], Z. Zhang[63a], Z. Zhang[65],
P. Zhao[49], Y. Zhao[60b], Z. Zhao[60a], A. Zhemchugov[80], Z. Zheng[106], D. Zhong[173], B. Zhou[106],
C. Zhou[181], M.S. Zhou[15a,15d], M. Zhou[155], N. Zhou[60c], Y. Zhou[7], C.G. Zhu[60b], C. Zhu[15a,15d],
H.L. Zhu[60a], H. Zhu[15a], J. Zhu[106], Y. Zhu[60a], X. Zhuang[15a], K. Zhukov[111], V. Zhulanov[122b,122a],
D. Zieminska[66], N.I. Zimine[80], S. Zimmermann[52], Z. Zinonos[115], M. Ziolkowski[151], L. Živković[16],
G. Zobernig[181], A. Zoccoli[23b,23a], K. Zoch[53], T.G. Zorbas[149], R. Zou[37], L. Zwalinski[36]

1   *Department of Physics, University of Adelaide, Adelaide; Australia*
2   *Physics Department, SUNY Albany, Albany NY; United States of America*
3   *Department of Physics, University of Alberta, Edmonton AB; Canada*
4   *Department of Physics$^{(a)}$, Ankara University, Ankara; Istanbul Aydin University$^{(b)}$, Application
     and Research Center for Advanced Studies, Istanbul; Division of Physics$^{(c)}$, TOBB University of
     Economics and Technology, Ankara; Turkey*
5   *LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; 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 *Bahcesehir University[a], Faculty of Engineering and Natural Sciences, Istanbul; Istanbul Bilgi University[b], Faculty of Engineering and Natural Sciences, Istanbul; Department of Physics[c], Bogazici University, Istanbul; Department of Physics Engineering[d], Gaziantep University, Gaziantep; Turkey*

13 *Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan*

14 *Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain*

15 *Institute of High Energy Physics[a], Chinese Academy of Sciences, Beijing; Physics Department[b], Tsinghua University, Beijing; Department of Physics[c], Nanjing University, Nanjing; University of Chinese Academy of Science (UCAS)[d], Beijing; China*

16 *Institute of Physics, University of Belgrade, Belgrade; Serbia*

17 *Department for Physics and Technology, University of Bergen, Bergen; Norway*

18 *Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA; United States of America*

19 *Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany*

20 *Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland*

21 *School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom*

22 *Facultad de Ciencias y Centro de Investigaciónes[a], Universidad Antonio Nariño, Bogotá; Departamento de Física[b], Universidad Nacional de Colombia, Bogotá, Colombia; Colombia*

23 *INFN Bologna and Universita' di Bologna[a], Dipartimento di Fisica; INFN Sezione di Bologna[b]; 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 *Transilvania University of Brasov[a], Brasov; Horia Hulubei National Institute of Physics and Nuclear Engineering[b], Bucharest; Department of Physics[c], Alexandru Ioan Cuza University of Iasi, Iasi; National Institute for Research and Development of Isotopic and Molecular Technologies[d], Physics Department, Cluj-Napoca; University Politehnica Bucharest[e], Bucharest; West University in Timisoara[f], Timisoara; Romania*

28 *Faculty of Mathematics[a], Physics and Informatics, Comenius University, Bratislava; Department of Subnuclear Physics[b], 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 *Departamento de Física, Universidad de Buenos Aires, Buenos Aires; Argentina*

31 *California State University, CA; United States of America*

32 *Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom*

33 *Department of Physics[a], University of Cape Town, Cape Town; iThemba Labs[b], Western Cape; Department of Mechanical Engineering Science[c], University of Johannesburg, Johannesburg; University of South Africa[d], Department of Physics, Pretoria; School of Physics[e], University of the Witwatersrand, Johannesburg; South Africa*

34 *Department of Physics, Carleton University, Ottawa ON; Canada*

35 *Faculté des Sciences Ain Chock[a], Réseau Universitaire de Physique des Hautes Energies — Université Hassan II, Casablanca; Faculté des Sciences[b], Université Ibn-Tofail, Kénitra; Faculté des Sciences Semlalia[c], Université Cadi Ayyad, LPHEA-Marrakech; Faculté des Sciences[d], Université Mohamed Premier and LPTPM, Oujda; Faculté des sciences[e], Université Mohammed V, Rabat; Morocco*

36 *CERN, Geneva; Switzerland*

37 *Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America*

³⁸ *LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France*

³⁹ *Nevis Laboratory, Columbia University, Irvington NY; United States of America*

⁴⁰ *Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark*

⁴¹ *Dipartimento di Fisica^(a), Università della Calabria, Rende; INFN Gruppo Collegato di Cosenza^(b), Laboratori Nazionali di Frascati; Italy*

⁴² *Physics Department, Southern Methodist University, Dallas TX; United States of America*

⁴³ *Physics Department, University of Texas at Dallas, Richardson TX; United States of America*

⁴⁴ *National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece*

⁴⁵ *Department of Physics^(a), Stockholm University; Oskar Klein Centre^(b), Stockholm; Sweden*

⁴⁶ *Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany*

⁴⁷ *Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund; Germany*

⁴⁸ *Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany*

⁴⁹ *Department of Physics, Duke University, Durham NC; United States of America*

⁵⁰ *SUPA — School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom*

⁵¹ *INFN e Laboratori Nazionali di Frascati, Frascati; Italy*

⁵² *Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany*

⁵³ *II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany*

⁵⁴ *Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland*

⁵⁵ *Dipartimento di Fisica^(a), Università di Genova, Genova; INFN Sezione di Genova^(b); Italy*

⁵⁶ *II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany*

⁵⁷ *SUPA — School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom*

⁵⁸ *LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France*

⁵⁹ *Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America*

⁶⁰ *Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics^(a), University of Science and Technology of China, Hefei; Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE)^(b), Shandong University, Qingdao; School of Physics and Astronomy^(c), Shanghai Jiao Tong University, KLPPAC-MoE, SKLPPC, Shanghai; Tsung-Dao Lee Institute^(d), Shanghai; China*

⁶¹ *Kirchhoff-Institut für Physik^(a), Ruprecht-Karls-Universität Heidelberg, Heidelberg; Physikalisches Institut^(b), Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany*

⁶² *Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima; Japan*

⁶³ *Department of Physics^(a), Chinese University of Hong Kong, Shatin, N.T., Hong Kong; Department of Physics^(b), University of Hong Kong, Hong Kong; Department of Physics and Institute for Advanced Study^(c), Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong; China*

⁶⁴ *Department of Physics, National Tsing Hua University, Hsinchu; Taiwan*

⁶⁵ *IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France*

⁶⁶ *Department of Physics, Indiana University, Bloomington IN; United States of America*

⁶⁷ *INFN Gruppo Collegato di Udine^(a), Sezione di Trieste, Udine; ICTP^(b), Trieste; Dipartimento Politecnico di Ingegneria e Architettura^(c), Università di Udine, Udine; Italy*

⁶⁸ *INFN Sezione di Lecce^(a); Dipartimento di Matematica e Fisica^(b), Università del Salento, Lecce; Italy*

⁶⁹ *INFN Sezione di Milano^(a); Dipartimento di Fisica^(b), Università di Milano, Milano; Italy*

⁷⁰ *INFN Sezione di Napoli^(a); Dipartimento di Fisica^(b), Università di Napoli, Napoli; Italy*

⁷¹ *INFN Sezione di Pavia^(a); Dipartimento di Fisica^(b), Università di Pavia, Pavia; Italy*

⁷² *INFN Sezione di Pisa^(a); Dipartimento di Fisica E. Fermi^(b), Università di Pisa, Pisa; Italy*

⁷³ *INFN Sezione di Roma^(a); Dipartimento di Fisica^(b), Sapienza Università di Roma, Roma; Italy*

⁷⁴ *INFN Sezione di Roma Tor Vergata^(a); Dipartimento di Fisica^(b), Università di Roma Tor Vergata, Roma; Italy*

⁷⁵ *INFN Sezione di Roma Tre^(a); Dipartimento di Matematica e Fisica^(b), Università Roma Tre, Roma; Italy*

[76] *INFN-TIFPA$^{(a)}$; Università degli Studi di Trento$^{(b)}$, Trento; Italy*

[77] *Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck; Austria*

[78] *University of Iowa, Iowa City IA; United States of America*

[79] *Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America*

[80] *Joint Institute for Nuclear Research, Dubna; Russia*

[81] *Departamento de Engenharia Elétrica$^{(a)}$, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora; Universidade Federal do Rio De Janeiro COPPE/EE/IF$^{(b)}$, Rio de Janeiro; Universidade Federal de São João del Rei (UFSJ)$^{(c)}$, São João del Rei; Instituto de Física$^{(d)}$, Universidade de São Paulo, São Paulo; Brazil*

[82] *KEK, High Energy Accelerator Research Organization, Tsukuba; Japan*

[83] *Graduate School of Science, Kobe University, Kobe; Japan*

[84] *AGH University of Science and Technology$^{(a)}$, Faculty of Physics and Applied Computer Science, Krakow; Marian Smoluchowski Institute of Physics$^{(b)}$, Jagiellonian University, Krakow; Poland*

[85] *Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland*

[86] *Faculty of Science, Kyoto University, Kyoto; Japan*

[87] *Kyoto University of Education, Kyoto; Japan*

[88] *Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka; Japan*

[89] *Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina*

[90] *Physics Department, Lancaster University, Lancaster; United Kingdom*

[91] *Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom*

[92] *Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia*

[93] *School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom*

[94] *Department of Physics, Royal Holloway University of London, Egham; United Kingdom*

[95] *Department of Physics and Astronomy, University College London, London; United Kingdom*

[96] *Louisiana Tech University, Ruston LA; United States of America*

[97] *Fysiska institutionen, Lunds universitet, Lund; Sweden*

[98] *Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne; France*

[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] *B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk; Belarus*

[109] *Research Institute for Nuclear Problems of Byelorussian State University, Minsk; Belarus*

[110] *Group of Particle Physics, University of Montreal, Montreal QC; Canada*

[111] *P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow; Russia*

[112] *National Research Nuclear University MEPhI, Moscow; Russia*

[113] *D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow; Russia*

[114] *Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany*

[115] *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany*

[116] *Nagasaki Institute of Applied Science, Nagasaki; Japan*

[117] *Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan*

118 *Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America*

119 *Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen; Netherlands*

120 *Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands*

121 *Department of Physics, Northern Illinois University, DeKalb IL; United States of America*

122 *Budker Institute of Nuclear Physics and NSU$^{(a)}$, SB RAS, Novosibirsk; Novosibirsk State University Novosibirsk$^{(b)}$; Russia*

123 *Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino; Russia*

124 *Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of National Research Centre "Kurchatov Institute", Moscow; Russia*

125 *Department of Physics, New York University, New York NY; United States of America*

126 *Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan*

127 *Ohio State University, Columbus OH; United States of America*

128 *Faculty of Science, Okayama University, Okayama; Japan*

129 *Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America*

130 *Department of Physics, Oklahoma State University, Stillwater OK; United States of America*

131 *Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc; Czech Republic*

132 *Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America*

133 *Graduate School of Science, Osaka University, Osaka; Japan*

134 *Department of Physics, University of Oslo, Oslo; Norway*

135 *Department of Physics, Oxford University, Oxford; United Kingdom*

136 *LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Paris; France*

137 *Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America*

138 *Konstantinov Nuclear Physics Institute of National Research Centre "Kurchatov Institute", PNPI, St. Petersburg; Russia*

139 *Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America*

140 *Laboratório de Instrumentação e Física Experimental de Partículas — LIP$^{(a)}$, Lisboa; Departamento de Física$^{(b)}$, Faculdade de Ciências, Universidade de Lisboa, Lisboa; Departamento de Física$^{(c)}$, Universidade de Coimbra, Coimbra; Centro de Física Nuclear da Universidade de Lisboa$^{(d)}$, Lisboa; Departamento de Física$^{(e)}$, Universidade do Minho, Braga; Departamento de Física Teórica y del Cosmos$^{(f)}$, Universidad de Granada, Granada (Spain); Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia$^{(g)}$, Universidade Nova de Lisboa, Caparica; Instituto Superior Técnico$^{(h)}$, Universidade de Lisboa, Lisboa; Portugal*

141 *Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic*

142 *Czech Technical University in Prague, Prague; Czech Republic*

143 *Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic*

144 *Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom*

145 *IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France*

146 *Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America*

147 *Departamento de Física$^{(a)}$, Pontificia Universidad Católica de Chile, Santiago; Universidad Andres Bello$^{(b)}$, Department of Physics, Santiago; Instituto de Alta Investigación$^{(c)}$, Universidad de Tarapacá; Departamento de Física$^{(d)}$, Universidad Técnica Federico Santa María, Valparaíso; Chile*

148 *Department of Physics, University of Washington, Seattle WA; United States of America*

149 *Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom*

150 *Department of Physics, Shinshu University, Nagano; Japan*

151 *Department Physik, Universität Siegen, Siegen; Germany*

152 *Department of Physics, Simon Fraser University, Burnaby BC; Canada*

153 *SLAC National Accelerator Laboratory, Stanford CA; United States of America*

154 *Physics Department, Royal Institute of Technology, Stockholm; Sweden*

155 *Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America*

156 *Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom*

157 *School of Physics, University of Sydney, Sydney; Australia*

158 *Institute of Physics, Academia Sinica, Taipei; Taiwan*

159 *E. Andronikashvili Institute of Physics[(a)], Iv. Javakhishvili Tbilisi State University, Tbilisi; High Energy Physics Institute[(b)], Tbilisi State University, Tbilisi; Georgia*

160 *Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel*

161 *Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel*

162 *Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece*

163 *International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan*

164 *Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo; Japan*

165 *Department of Physics, Tokyo Institute of Technology, Tokyo; Japan*

166 *Tomsk State University, Tomsk; Russia*

167 *Department of Physics, University of Toronto, Toronto ON; Canada*

168 *TRIUMF[(a)], Vancouver BC; Department of Physics and Astronomy[(b)], York University, Toronto ON; Canada*

169 *Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan*

170 *Department of Physics and Astronomy, Tufts University, Medford MA; United States of America*

171 *Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America*

172 *Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden*

173 *Department of Physics, University of Illinois, Urbana IL; United States of America*

174 *Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia — CSIC, Valencia; Spain*

175 *Department of Physics, University of British Columbia, Vancouver BC; Canada*

176 *Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada*

177 *Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany*

178 *Department of Physics, University of Warwick, Coventry; United Kingdom*

179 *Waseda University, Tokyo; Japan*

180 *Department of Particle Physics, Weizmann Institute of Science, Rehovot; Israel*

181 *Department of Physics, University of Wisconsin, Madison WI; United States of America*

182 *Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany*

183 *Department of Physics, Yale University, New Haven CT; United States of America*

184 *Yerevan Physics Institute, Yerevan; Armenia*

[a] *Also at Borough of Manhattan Community College, City University of New York, New York NY; United States of America*

[b] *Also at CERN, Geneva; Switzerland*

[c] *Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France*

[d] *Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland*

[e] *Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona; Spain*

[f] *Also at Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal*

[g] Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah; United Arab Emirates

[h] Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece

[i] Also at Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America

[j] Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY; United States of America

[k] Also at Department of Physics, Ben Gurion University of the Negev, Beer Sheva; Israel

[l] Also at Department of Physics, California State University, East Bay; United States of America

[m] Also at Department of Physics, California State University, Fresno; United States of America

[n] Also at Department of Physics, California State University, Sacramento; United States of America

[o] Also at Department of Physics, King's College London, London; United Kingdom

[p] Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg; Russia

[q] Also at Department of Physics, Stanford University, Stanford CA; United States of America

[r] Also at Department of Physics, University of Adelaide, Adelaide; Australia

[s] Also at Department of Physics, University of Fribourg, Fribourg; Switzerland

[t] Also at Department of Physics, University of Michigan, Ann Arbor MI; United States of America

[u] Also at Dipartimento di Matematica, Informatica e Fisica, Università di Udine, Udine; Italy

[v] Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow; Russia

[w] Also at Giresun University, Faculty of Engineering, Giresun; Turkey

[x] Also at Graduate School of Science, Osaka University, Osaka; Japan

[y] Also at Hellenic Open University, Patras; Greece

[z] Also at IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France

[aa] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain

[ab] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany

[ac] Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen; Netherlands

[ad] Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria

[ae] Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest; Hungary

[af] Also at Institute of Particle Physics (IPP), Vancouver; Canada

[ag] Also at Institute of Physics, Academia Sinica, Taipei; Taiwan

[ah] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan

[ai] Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia

[aj] Also at Instituto de Fisica Teorica, IFT-UAM/CSIC, Madrid; Spain

[ak] Also at Joint Institute for Nuclear Research, Dubna; Russia

[al] Also at Louisiana Tech University, Ruston LA; United States of America

[am] Also at LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Paris; France

[an] Also at Manhattan College, New York NY; United States of America

[ao] Also at Moscow Institute of Physics and Technology State University, Dolgoprudny; Russia

[ap] Also at National Research Nuclear University MEPhI, Moscow; Russia

[aq] Also at Physics Department, An-Najah National University, Nablus; Palestine

[ar] Also at Physics Dept, University of South Africa, Pretoria; South Africa

[as] Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany

[at] Also at School of Physics, Sun Yat-sen University, Guangzhou; China

[au] Also at The City College of New York, New York NY; United States of America

[av] Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China

[aw] Also at TRIUMF, Vancouver BC; Canada

[ax] Also at Universita di Napoli Parthenope, Napoli; Italy

[*] Deceased