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Search for Higgs boson decays into a pair of light bosons in the $bb\mu\mu$ final state in pp collision at $\sqrt{s} = 13$ TeV with the ATLAS detector

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ABSTRACT

A search for decays of the Higgs boson into a pair of new spin-zero particles, $H \to aa$, where the a-bosons decay into a b-quark pair and a muon pair, is presented. The search uses 36.1 fb^{-1} of proton–proton collision data at $\sqrt{s} = 13$ TeV recorded by the ATLAS experiment at the LHC in 2015 and 2016. No significant deviation from the Standard Model prediction is observed. Upper limits at 95% confidence level are placed on the branching ratio $(\sigma_H/\sigma_{\mathrm{SM}}) \times \mathcal{B}(H \to aa \to bb\mu\mu)$, ranging from 1.2×10^{-4} to 8.4×10^{-4} in the a-boson mass range of 20–60 GeV. Model-independent limits are set on the visible production cross-section times the branching ratio to the $bb\mu\mu$ final state for new physics, $\sigma_{\mathrm{vis}}(X) \times \mathcal{B}(X \to bb\mu\mu)$, ranging from 0.1 fb to 0.73 fb for $m_{\mu\mu}$ between 18 and 62 GeV.

1. Introduction

The discovery of the Standard Model (SM) Higgs boson [1,2] has opened up new avenues to search for physics beyond the SM (BSM) with perspectives to search for non-SM or "exotic" decays of the Higgs boson. Such searches could provide unique access to hidden-sector particles that are singlets under the SM gauge transformations [3]. Exotic decays of the Higgs boson are predicted by many new-physics models [3,4], including those with an extended Higgs sector [5–9], dark matter (DM) models [10–14], models with a first-order electroweak phase transition [15,16] and theories with neutral naturalness [17,18]. These models have also been used to explain the observations of a γ-ray excess from the galactic centre (GC) by the Fermi Large Area Telescope [19,20]. For example, a model for the GC γ-ray excess was proposed in which 30 GeV DM particles pair-annihilate dominantly through a CP-odd scalar mediator that subsequently decays into SM fermions [13]. If the mediator is sufficiently lighter than the SM Higgs boson (H) then H decay into the mediator pair can be observed at the LHC.

Existing measurements constrain the BSM or "exotic" branching ratio ($\mathcal{B}$) of the 125 GeV Higgs boson decays to less than approximately 34% at 95% confidence level [21]. Due to the narrow width (~ 4 MeV) of the Higgs boson, even a small non-SM coupling of $\mathcal{O}(10^{-2})$ can lead to $\mathcal{O}(10\%)$ branching ratio into BSM states. This potentially large $\mathcal{B}(H \to \text{BSM states})$ motivates direct searches for exotic H decays.

The analysis presented in this Letter performs the search in the $bb\mu\mu$ final state. The a-boson can be either a scalar or a pseudoscalar under parity transformations, since the decay mode considered in this search is not sensitive to the difference in coupling. Assuming that the a-boson mixes with the SM Higgs boson and inherits its Yukawa couplings to fermions, the largest branching ratio is expected to be to the heaviest fermions accessible by kinematics ($2m_a < m_H$), where m_a and m_H are the a-boson and Higgs boson masses. For $m_a \gtrsim 10$ GeV this means the a-boson would decay preferentially into bb. However, in models with enhanced lepton couplings such as the Type-III 2HDM [22], the $a \to \mu\mu$ branching ratio can also be relatively large. Additionally, the sensitivity of a given channel does not depend only on the expected signal rate in a particular model, but also on the efficiency for triggering and reconstructing events of interest. The presence of a clean dimuon resonance provides a distinctive signature that can be used for triggering and precision mass reconstruction, which helps to suppress background.

Searches for the Higgs boson with a mass of 125 GeV decaying into two spin-zero particles, $H \to aa$, have been performed in various final states in ATLAS and CMS [23–29]. The CMS search with $\sqrt{s} = 8$ TeV data in the $bb\mu\mu$ final state set 95% CL limits on $(\sigma_H/\sigma_{\mathrm{SM}}) \times \mathcal{B}(H \to aa \to bb\mu\mu)$ between 2×10^{-4} and 8×10^{-4} in the a-boson mass range of 25–62.5 GeV [25]. In Type-III 2HDM+S scenario with tan $\beta = 2$ [4], where tan β denotes the ratio of the vacuum expectation values of the two Higgs fields, these limits translate into upper limits on $(\sigma_H/\sigma_{\mathrm{SM}}) \times \mathcal{B}(H \to aa)$ ranging between 13% and 50%. Some of the most stringent limits up to date for Type-III 2HDM+S with tan $\beta = 2$ come from the CMS search with $\sqrt{s} = 13$ TeV data in the $bb\tau\tau$ final state, setting the up-

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per limits on $(\sigma_H/\sigma_{SM}) \times \mathcal{B}(H \to aa)$ between 4% and 26% in the a-boson mass range of 15–60 GeV [28].

2. Data and simulation

The search presented in this Letter is based on the 36.1 fb^{-1} dataset of proton–proton collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV recorded by the ATLAS experiment at the LHC during 2015 and 2016. The ATLAS experiment [30] is 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 solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer. Events are collected with single-muon triggers requiring the muon p_{T} to be above 24 or 26 GeV, depending on the data-taking period. The trigger efficiency for the signal events with the muon p_{T} on the trigger plateau is about 80%.

Simulated events are used to model the signal and SM backgrounds processes. Higgs boson production through the gluon–gluon fusion (ggF) and vector-boson fusion (VBF) processes was modelled at next-to-leading order (NLO) using Powheg-Box v2 [31–33] interfaced with Pythia 8.186 [34] using the AZNLO set of tuned parameters [35] for the simulation of the $bb\mu\mu$ decay of the Higgs boson, as well as for parton showering and hadronisation. The ggF Higgs boson production rate is normalised to the total cross-section predicted by a next-to-next-to-next-to-leading-order QCD calculation with NLO electroweak corrections applied [36–40]. The VBF production rate is normalised to an approximate next-to-next-to-leading-order (NNLO) QCD cross-section with NLO electroweak corrections applied [41–44]. Five mass points were simulated in the range $m_a = 20$–60 GeV in steps of 10 GeV for both ggF and VBF production.

Sherpa 2.2.1 [45] with the NNPDF3.0 [46] set of parton distribution functions (PDF) was used for the generation of Drell–Yan, W+jets and diboson (WW, WZ, ZZ) backgrounds. Cross-sections were calculated at NNLO QCD accuracy for $Z^{(*)}/\gamma^* +$ jets and $W +$ jets production [47] and at NLO including LO contributions with two additional partons for the diboson processes [45,48,49]. The $t\bar{t}$ and single-top-quark samples were generated with Powheg-Box v2 [32] using the CT10 PDF set [50] interfaced with Pythia v6.428 [51] and the Perugia 2012 set of tuned parameters [52] for the parton shower. The mass of the top quark (m_t) was set to 172.5 GeV. The parameter h_{damp} in Powheg, used to regulate the high-p_{T} radiation, was set to m_t for improved agreement between data and simulation in the high p_{T} region [53]. The cross-section of $t\bar{t}$ was calculated at NNLO in QCD including resummation of next-to-next-to-leading logarithmic (NNLL) soft gluon terms [54,55]. The cross-section for single-top-quark production was calculated with the prescriptions in Refs. [56,57]. The production of $t\bar{t}$ pairs in association with W/Z bosons (denoted by $t\bar{t}V$) was modelled with samples generated at LO using MadGraph5_aMC@NLO v2.2.2 [58] and showered with Pythia v8.186. The samples are normalised to NLO cross-sections [59,60].

Additional pp collisions generated with Pythia v8.186 were overlaid to model the effects of additional interactions in the same and neighbouring bunch crossings (pile-up) for all simulated events. The pile-up simulation used the A2 set of tuned parameters [61] and the MSTW2008LO PDF set [62]. All the samples were processed through the full ATLAS detector simulation [63] based on GEANT4 [64] and processed with the same reconstruction algorithm as used for data.

3. Selection criteria

Interaction vertices from proton–proton collisions are reconstructed from at least two tracks with transverse momentum (p_{T}) larger than 0.4 GeV, and are required to be consistent with the beamspot envelope. The primary vertex (PV) is identified as the one with the largest $\sum p_{\mathrm{T}}^2$ of associated tracks [65].

Muon candidates are reconstructed using the information from the inner detector and the muon spectrometer [66]. They are required to satisfy "medium" identification criteria [66], be matched to the PV and have $p_{\mathrm{T}} > 7$ GeV and $|\eta| < 2.7$. Additionally, the muons must satisfy the following criteria: the projected longitudinal impact parameter $|z_0 \sin\theta|$ must be less than 0.5 mm and the ratio of the transverse impact parameter d_0 to its estimated uncertainty σ_{d_0}, $|d_0/\sigma_{d_0}|$, must be less than 3. Finally, the selected muons must fulfil requirements on the scalar sum of p_{T} of additional inner detector tracks and on the sum of the E_{T} of calorimeter topological clusters [67] in a cone of size $\Delta R = 0.2$ around the muon to ensure they satisfy "tight" isolation criteria [66]. These requirements select signal muons with an identification efficiency of ∼94% and isolation efficiency ranging between ∼91% for $m_a = 20$ GeV and ∼95% for $m_a = 60$ GeV.

Jets are reconstructed using the anti-k_t algorithm [68] implemented in the FastJet package [69] with a radius parameter $R = 0.4$ applied to topological clusters of energy deposits in calorimeter cells. Jets from pile-up are suppressed with the use of tracking information as detailed in Ref. [70]. All selected jets are required to have $p_{\mathrm{T}} > 20$ GeV, $|\eta| < 2.5$ and must pass quality requirements defined to minimise the impact of detector effects, beam backgrounds and cosmic rays.

Jets consistent with the hadronisation of a b-quark (b-jets) are identified using a multivariate discriminant [71,72]. This analysis uses the 77% b-jet identification efficiency working point for which the purity of the b-tagged sample is approximately 95%, while the probability of misidentifying a jet initiated by a charm quark as a b-jet is approximately 16%, as determined from a sample of simulated $t\bar{t}$ events.

In order to reject non-prompt muons from the decay of hadrons within a jet, an overlap removal algorithm is applied. If a jet is found within $\Delta R = 0.4$ of the muon candidate, the overlap is resolved in the following way: if there are more than two tracks with $p_{\mathrm{T}} > 500$ MeV associated with the jet then the muon is removed from the event, otherwise the muon is retained and the jet is removed.

The missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$) used in the analysis is calculated as the magnitude of the negative vector sum ($\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$) of the transverse momenta of all selected and calibrated objects in the event and the additional "soft" term that takes into account tracks not associated with any of the these objects [73]. The "soft" term is calculated from inner detector tracks matched to the PV and included to achieve a better $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution.

Events are required to have exactly two b-tagged jets with $p_{\mathrm{T}} > 20$ GeV and exactly two reconstructed muons of opposite charge, with the leading muon having $p_{\mathrm{T}} > 27$ GeV to be in the maximum-efficiency regime of the trigger and the subleading muon having $p_{\mathrm{T}} > 7$ GeV. The dimuon invariant mass ($m_{\mu\mu}$) is required to be between 16 GeV and 64 GeV. The upper bound on $m_{\mu\mu}$ is defined by the assumption that the 125 GeV Higgs boson decays into two

[1] The ATLAS Collaboration 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 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 beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

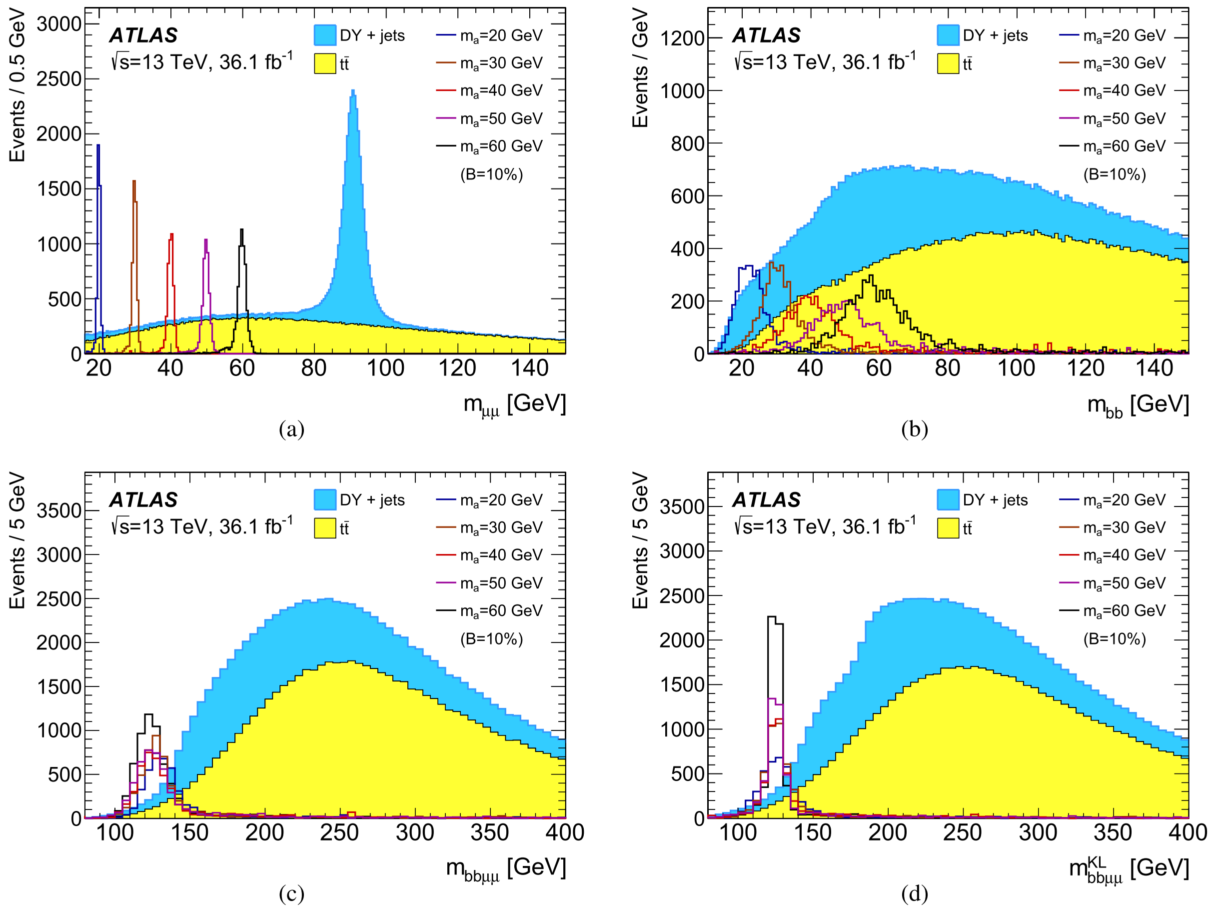


Fig. 1. The (a) $m_{\mu\mu}$, (b) m_{bb} before the KL fit, (c) $m_{bb\mu\mu}$ before and (d) $m^{\mathrm{KL}}_{bb\mu\mu}$ after the KL fit for events after the preselection stage, but removing the upper bound on $m_{\mu\mu}$. The $t\bar{t}$ contribution is modelled with the simulated sample normalised to the theoretical cross-section. The Drell–Yan contribution is taken from data templates (described in the text) and normalised to the total yield predicted by the Drell–Yan simulation. The signal distributions for all five simulated m_a are also shown assuming the SM Higgs boson cross-section (including ggF, VBF and VH production) and $\mathcal{B}(H \to aa \to bb\mu\mu) = 10\%$. The branching ratio in this and all subsequent figures is chosen so as to give good visibility on the plot.

on-shell particles of equal masses, while the lower bound is motivated by the kinematics of the a-boson decays. For lower values of m_a, most of the signal jets fall below the reconstruction threshold and the jets tend to overlap geometrically in the detector so that the sensitivity of the analysis to the $H \to aa$ signal decreases. This set of selection criteria is referred to as the "preselection".

Signal events are characterised by the invariant mass of the two b-jets (m_{bb}) being equal, within the detector resolution, to the dimuon invariant mass and the four-object mass ($m_{bb\mu\mu}$) being approximately 125 GeV. One side of the $H \to aa$ decay ($a \to \mu\mu$) is measured with approximately ten times better resolution than the other side of the decay ($a \to bb$), as shown in Figs. 1(a) and 1(b).

A kinematic-likelihood (KL) fit [74] exploiting the symmetry of $H \to aa$ decays is performed to test the compatibility of an event with the $m_{bb} \simeq m_{\mu\mu}$ hypothesis and improve the $m_{bb\mu\mu}$ resolution in signal events. The KL fit finds the energies of the leading ($\hat{E}_{b_1}$) and subleading ($\hat{E}_{b_2}$) b-jets that maximise the likelihood for an event with measured leading and subleading b-jet energies E_{b_1} and E_{b_2} and with dimuon invariant mass $m_{\mu\mu}$. The likelihood is defined as follows,

$$L = W(\hat{E}_{b_1}, E_{b_1}) \cdot W(\hat{E}_{b_2}, E_{b_2}) \cdot F_{\mathrm{BW}}(m^{\mathrm{KL}}_{bb}, m_{\mu\mu}),$$

where m^{KL}_{bb} is the dijet invariant mass computed from the b-jet four-momenta corresponding to $\hat{E}_{b_1}$ and $\hat{E}_{b_2}$, W is the transfer function of the b-jets, and F_{BW} is a Breit–Wigner function centred on $m_{\mu\mu}$ with a width that is small compared to the m_{bb} resolution. The transfer function $W(\hat{E}_{b_1}, E_{b_1})$ is a double Gaussian probability density function derived from simulated events as a function of jet p_{T} and η using the difference between true and reconstructed energies. The fit determines a maximum-likelihood value of L (denoted by $\ln(L^{\max})$), which quantifies how well an event fits to the constraints. The b-jet momenta determined by the fit are used to recompute the four-body mass denoted $m^{\mathrm{KL}}_{bb\mu\mu}$. As seen in Fig. 1(d), the resolution of the $m^{\mathrm{KL}}_{bb\mu\mu}$ distribution for the signal is improved by up to a factor of two compared to the pre-fit $m_{bb\mu\mu}$ shown in Fig. 1(c), while the background shape within the $m_{bb\mu\mu}$ signal peak remains almost unchanged with the yields rising by ∼20%. This allows the analysis to place tighter constraints on the difference between the reconstructed invariant mass of the $bb\mu\mu$ system and m_H, rejecting more background events and obtaining higher signal significance.

Two criteria based on the kinematic likelihood fit are applied to select signal-like events and reject background events that do not fit the $m_{bb} = m_{\mu\mu}$ constraint well: $|m^{\mathrm{KL}}_{bb\mu\mu} - m_H| < 15$ GeV and $\ln(L^{\max}) > -8$. Finally, the $E_{\mathrm{T}}^{\mathrm{miss}} < 60$ GeV requirement rejects a large portion of $t\bar{t}$ pairs where both top quarks decay semileptonically, while retaining most of the signal events. Adding these three requirements after the preselection stage defines the signal-enhanced region (SR). A search for a localised excess above the expected background is performed in multiple $m_{\mu\mu}$ bins of the SR

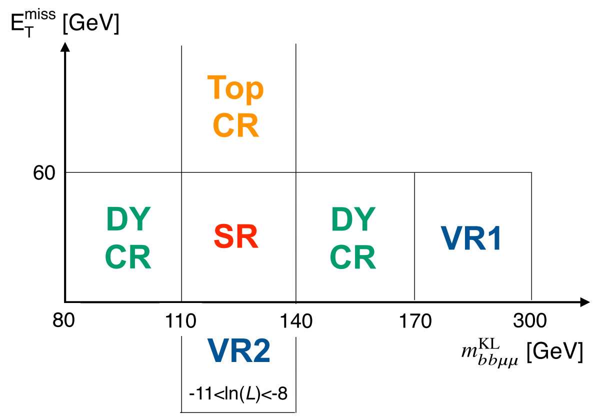


Fig. 2. Illustration of the signal, control and validation regions used in the analysis. The E_T^{miss} requirement in the VR2 region is the same as in the SR. The corresponding DY-template regions are defined in the same way except that the two-b-tag requirement is changed to a zero-b-tag requirement.

centred around the hypothesised m_a. A bin width of 2 GeV is chosen for $16 < m_{\mu\mu} \leq 40$ GeV, 3 GeV for $40 < m_{\mu\mu} < 50$ GeV and 4 GeV for $50 \leq m_{\mu\mu} < 64$ GeV respectively, in order to maximise the sensitivity.

4. Backgrounds

The dominant backgrounds in the signal region are Drell–Yan (DY) dimuon events in association with b-quarks and pair production of top quarks where both W bosons from top quarks decay into muons. Each of the dominant backgrounds amounts to approximately 50% of the total background in the SR. Two control regions (CR) are defined to constrain the contributions of the dominant backgrounds in the signal region. They are chosen such that they have negligible signal contamination, but are kinematically close to the SR to reduce model dependence. The top control region (TCR) is defined by applying the same selection criteria as for the signal region, but inverting the requirement on the missing transverse momentum to $E_T^{miss} > 60$ GeV. According to the simulation, approximately 95% of the events in TCR originate from $t\bar{t}$ production. The Higgs boson mass sidebands of the signal region are used as the Drell–Yan control region (DYCR): the constraint on the $bb\mu\mu$ invariant mass after the KL fit is inverted to $80 < m^{KL}_{bb\mu\mu} < 110$ GeV or $140 < m^{KL}_{bb\mu\mu} < 170$ GeV. The DYCR consists of about 50% DY events and about 50% $t\bar{t}$ events.

The shapes of the $t\bar{t}$ kinematic variables are modelled using simulated events, while the distributions for the Drell–Yan process are taken from data templates as described below. The $t\bar{t}$ simulated sample and the DY templates are normalised in profile likelihood fits to the data. In one fit variant, the two background normalisations are simultaneously determined from the event yields in the TCR and DYCR assuming no presence of signal. In a second variant, the two background normalisations and the signal strength are determined using the event yields measured in the TCR, DYCR, and a given signal window. Two validation regions are defined to compare the number of observed events with the number of SM events predicted by the fit. One validation region (VR1) is defined in the high tail of the $bb\mu\mu$ invariant mass distribution, $170 < m^{KL}_{bb\mu\mu} < 300$ GeV, while for the second validation region (VR2) only the requirement on the $\ln(L^{max})$ is changed relative to the SR, $-11 < \ln(L) < -8$. All the analysis regions are illustrated in Fig. 2.

The DY templates for each of the kinematic variables considered in a particular region of the analysis (SR, CR or VR) are taken from the data in a corresponding template region (DYTR). For each analysis region the associated DYTR is defined by changing the two-b-tag requirement (present in every SR, CR and VR) to a zero-b-tag requirement, while keeping all other selection requirements the same. All the DYTR are > 90% pure in DY events. The small contribution from non-DY backgrounds, namely $t\bar{t}$, dibosons, W + jets, single-top and $t\bar{t}V$, is subtracted from the data in a DYTR using the simulated samples, and the remaining data events are assigned to the DY template. To construct b-jet-based variables, such as m_{bb} and $m_{bb\mu\mu}$, in a DYTR the two leading non-tagged jets are taken and used in the computation instead of the b-jets.

It is verified in both the simulation and the data that the shapes of all the muon-based variables (most importantly $m_{\mu\mu}$) are consistent between the sample with no b-tagged jets and the sample with two b-tagged jets. To account for differences in jet kinematics between the DYTR dominated by light-flavour jets and the corresponding analysis region dominated by heavy-flavour jets, an event-reweighting based on the leading jet p_T is applied to the events in the DYTR. The event weights are derived in the data after the preselection as the ratio of the leading b-tagged jet p_T in the two-b-tag sample to the leading jet p_T in the sample with zero b-tags. An improvement in the modelling of jet-based kinematic variables after the reweighting is verified both in simulation and in data in the DYCR, while the shape of the $m_{\mu\mu}$ distribution remains unchanged.

Minor backgrounds include diboson production, W boson production in association with b-jets (with one non-prompt muon satisfying the isolation criteria) and production of a single top quark or $t\bar{t}$ pair in association with a vector boson. The contribution of the minor backgrounds in the signal region is at the percent level. They are estimated using simulation normalised to the best available theory prediction.

5. Systematic uncertainties

Dominant sources of experimental systematic uncertainty are the calibration and resolution of jet energies and muon momenta, the measurement of the b-tagging efficiency and the measurement of the scale and resolution of the soft term of the missing transverse momentum. Each of these uncertainties affects the $t\bar{t}$ yields by up to 14% in any of the $m_{\mu\mu}$ bins of the signal region. Other experimental uncertainties have a sub-percent effect on the expected yields. These include the uncertainties in the measurement of muon identification and isolation efficiencies and the uncertainties associated with the integrated luminosity and the simulation of pile-up interactions. The uncertainty in the combined 2015 + 2016 integrated luminosity is 2.1%. It is derived, following a methodology similar to that detailed in Ref. [75], from a calibration of the luminosity scale using x–y beam-separation scans performed in August 2015 and May 2016.

Four sources of theoretical uncertainty in the modelling of the $t\bar{t}$ process are considered in the analysis. As the $t\bar{t}$ simulation is normalised to the data in TCR, all of these uncertainties are applied to the acceptance ratio between TCR and SR. Hadronisation and parton-showering model uncertainties are estimated using a sample generated with POWHEG and showered by HERWIG++ v2.7.1 and comparing it with the nominal POWHEG sample showered with PYTHIA v6.428. The uncertainty due to the choice of the event generator is estimated by comparing the expected yields obtained using a $t\bar{t}$ sample generated with aMC@NLO and one that is generated with POWHEG. Both samples are showered with HERWIG++ v2.7.1. The event generator and hadronisation/parton-showering uncertainties are found to have the largest effect among all the uncertainties affecting the total $t\bar{t}$ expectation in the signal region: ∼18% and ∼16%, respectively. Systematic uncertainties in the modelling of initial- and final-state radiation (ISR and FSR) are assessed with Powheg samples showered with two alternative settings of Pythia v6.428. The first of these uses the PERUGIA2012radHi tune and has the renormalisation and factorisation scales set to twice the nominal value, resulting in more radiation in the final state. In addition, it has h_{damp} set to $2 \times m_t$. The second sample, using the PERUGIA2012radLo tune, has $h_{\text{damp}} = m_t$ and the renormalisation and factorisation scales are set to half of their nominal values, resulting in less radiation in the event. This uncertainty has about a 5% effect on the final $t\bar{t}$ yields. Finally, the uncertainties due to the choice of PDF are evaluated by taking the maximum difference in the acceptance ratio between TCR and SR obtained with the nominal CT10 set and the alternative PDF4LHC15 set [76]. The PDF uncertainty has up to a 2% effect on the final $t\bar{t}$ yields.

The uncertainties in the theoretical cross-sections (described earlier in this Letter) are assigned to the minor backgrounds whose yields are taken directly from the simulation: dibosons (10%), single top (5%) and $t\bar{t}V$ (13%). A 100% uncertainty is applied to the $W+$jets process to account for the limited precision of the simulation when modelling the non-prompt muons satisfying the isolation criteria. Due to the minor contribution of the $W+$jets background to the analysis, this uncertainty has negligible effect. As these backgrounds have very small contributions to the SR, no theoretical uncertainties affecting the acceptance have been applied.

The systematic uncertainties applied to the data-driven DY template include the uncertainties in the shape of the template due to the background subtraction and different jet-flavour composition between the DYTR and SR. The uncertainty in the background subtraction is estimated from a comparison of the nominal template after the non-DY backgrounds are subtracted and the template where no subtraction is performed. The effect of this systematic uncertainty on the DY yields in the signal region is up to 4%. The uncertainty in the template shape due to the jet-flavour composition is assessed by comparing the nominal template extracted from the DYTR with zero b-tagged jets to the template extracted from the corresponding region, but with exactly one b-tagged jet. The average per-bin difference between the two templates in the $m_{\mu\mu}$ distribution is taken as an overall uncertainty in the shape, amounting to 14%.

The systematic uncertainties affecting the acceptance of the $H \to aa$ signal that correspond to the QCD scale uncertainties, the process of parton showering and hadronization and the choice of PDF set are evaluated. The renormalisation and factorisation scales are independently varied up and down from their nominal value by a factor of two and the largest resulting change is taken as the overall uncertainty due to the QCD scale. The parton-shower uncertainties are derived by independently shifting up and down the Pythia internal parameters that control the amount of ISR and FSR. Uncertainties due to the PDF are evaluated by taking the maximum difference between the yields obtained with the nominal PDF set and the alternative PDF4LHC15 and NNPDF3.0 PDF sets. The uncertainties due to the missing higher-order QCD corrections are applied to the ggF and VBF Higgs boson production cross-sections, amounting to 3.9% and 2.1%, respectively [36,77]. The uncertainties due to the choice of PDF and α_S are also applied to the Higgs boson cross-section, amounting to 3.2% for ggF and 0.4% for VBF production [36,77].

Additionally, the ggF signal sample is compared with the alternative sample generated using the NNLOPS approach [78]. The Higgs boson rapidity distribution in the original Powheg signal sample is found to be consistent with the one predicted by the NNLOPS calculations, while the Higgs boson transverse momentum ($p_T(H)$) distribution is found to be harder than the one obtained using the NNLOPS approach. A reweighting is derived as a function of $p_T(H)$ by fitting the ratio of the two generated p_T distributions with a continuous function. The ggF signal sample is then reweighted with this function to obtain the nominal signal prediction. A 2.5% difference in the SR event yields observed between the weighted and unweighted sample is applied as a systematic uncertainty in the modelling of $p_T(H)$.

The signal contribution of the Higgs boson produced in the association with a vector boson (VH) is taken into account by increasing the total cross-section of the ggF and VBF processes by an estimated 3.5% VH contribution. A 100% uncertainty is applied to this procedure to account for kinematic differences between the estimated VH contribution and the generated ggF and VBF processes. The contribution from other Higgs boson production processes is minor and therefore not included.

Table 1 shows a summary of the dominant post-fit systematic uncertainties in the total background and signal yields across multiple $m_{\mu\mu}$ bins of the signal region. All of the uncertainties shown in Table 1, except the normalisation and cross-section uncertainties, affect the shapes of the signal and background distributions and therefore the extrapolation of the predicted yields from the CRs to the SR.

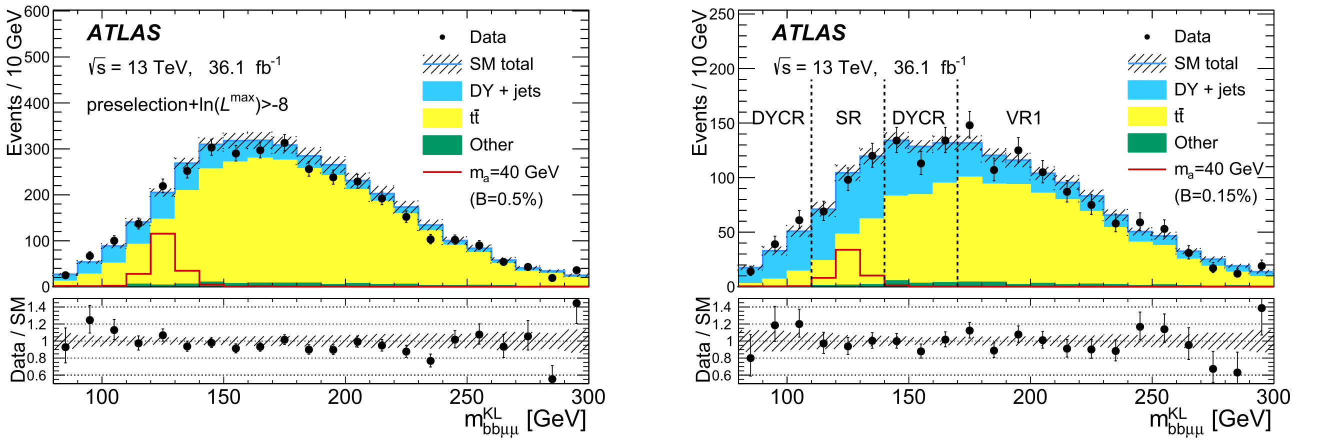
Table 1
Summary of the dominant post-fit systematic uncertainties on the background and signal yields. The uncertainties are expressed as a percentage of the total background (middle column) and signal (rightmost column) yields per $m_{\mu\mu}$ bin of the signal region. Shown are the uncertainties that exceed 2% in at least one $m_{\mu\mu}$ bin.

Source	Total background [%]	Signal [%]
DY: normalisation	9.3–15	–
DY: flavour composition	6.9–11	–
DY: background subtraction	0.4–2.4	–
$t\bar{t}$: hard-scatter generation	3.6–8.6	–
$t\bar{t}$: hadronisation/parton-shower	3.2–7.7	–
$t\bar{t}$: normalisation	2.1–5.0	–
$t\bar{t}$: ISR/FSR	1.0–2.4	–
MC statistics	2.4–4.9	2.3–4.6
b-tagging	0.6–1.5	17–19
Jet-energy resolution	0.3–2.9	5.2–8.4
Jet-energy scale	0.3–2.9	3.9–6.5
Muon-p_T resolution	0.1–2.2	0.3–1.2
Luminosity	<0.01	2.1
Signal: QCD scale	–	6
Signal: ISR/FSR	–	4
Signal: ggF cross-section		
- missing higher-order QCD	–	3.6–3.8
- PDF & α_S	–	2.8–3.0
Signal: VH contribution	–	3.5
Signal: $p_T(H)$ reweighting	–	2.3–2.5

6. Results

The expected SM background in each of the analysis regions is determined by a profile likelihood fit to the data. The numbers of observed and predicted events in each of the bins included in the likelihood are described by Poisson probability density functions. The systematic uncertainties are implemented as nuisance parameters constrained by Gaussian distributions with widths corresponding to the sizes of the uncertainties.

The background-only version of the fit is performed to verify that the post-fit background yields agree with the data in the VRs and SR. In this version of the fit, only the data in TCR and DYCR are used to constrain the $t\bar{t}$ and DY backgrounds and determine their normalisation factors. Both TCR and DYCR are considered as one bin each. The free fit parameters are the overall normalisation factors for the $t\bar{t}$ and Drell–Yan backgrounds. The derived $t\bar{t}$ (DY) normalisation factors are then applied to the number of $t\bar{t}$ (DY) events as predicted by the simulation (template) in any of the VR



(a) (b)

Fig. 3. The predicted and observed $m^{\mathrm{KL}}_{bb\mu\mu}$ distributions (a) after the preselection and the KL-fit $\ln(L^{\max}) > -8$ constraint and (b) across DYCR, SR and VR1 (shown separated by vertical dashed lines). Both are shown after the background-only fit and differ only in the $E_{\mathrm{T}}^{\mathrm{miss}} < 60$ GeV criterion being applied in (b). The signal distribution for $m_a = 40$ GeV is also shown assuming the SM Higgs boson cross-section (including ggF, VBF and VH production) and (a) $\mathcal{B}(H \to aa \to bb\mu\mu) = 0.5\%$ and (b) $\mathcal{B}(H \to aa \to bb\mu\mu) = 0.15\%$. The hashed bands show the total statistical and systematic uncertainties of the backgrounds.

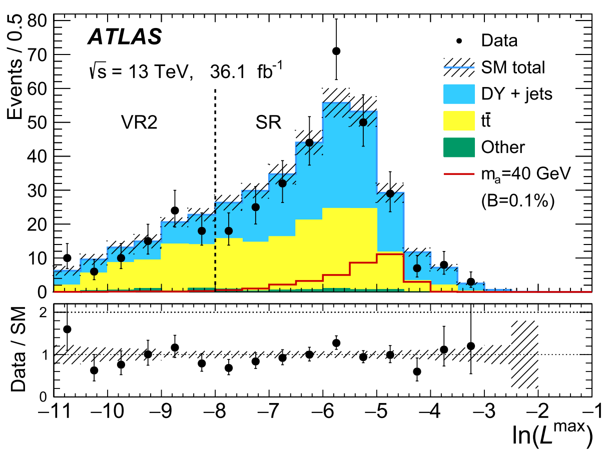


Fig. 4. The predicted and observed KL-fit $\ln(L^{\max})$ distribution across VR2 and SR (shown separated by a vertical dashed line) after the background-only fit. The signal distribution for $m_a = 40$ GeV is also shown assuming the SM Higgs boson cross-section (including ggF, VBF and VH production) and $\mathcal{B}(H \to aa \to bb\mu\mu) = 0.1\%$. The hashed bands show the total statistical and systematic uncertainties of the backgrounds.

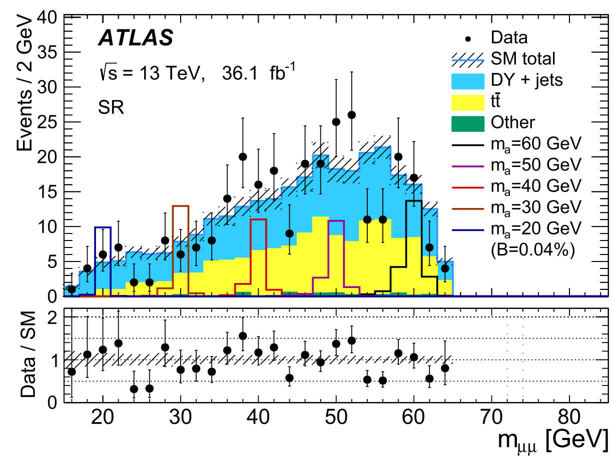


Fig. 5. The predicted and observed $m_{\mu\mu}$ distributions in the SR after the background-only fit. The signal distributions are also shown assuming the SM Higgs boson cross-section (including ggF, VBF and VH production) and $\mathcal{B}(H \to aa \to bb\mu\mu) = 0.04\%$. The hashed bands show the total statistical and systematic uncertainties of the backgrounds.

or SR bins. The post-fit distributions are shown in Figs. 3–5. Both the normalisation and the shapes of the predicted background distributions describe the data well in all of the analysis control and validation regions, as well as in the SR. The post-fit yields in five $m_{\mu\mu}$ bins of the SR, for which the signal sample was simulated, are shown in Table 2.

Since no significant deviation from the predicted background is observed in the signal region, upper limits on signal yields at 95% confidence level (CL) are set as a function of $m_{\mu\mu}$ using the CL$_s$ prescription [79,80]. A series of profile likelihood fits is applied to the data in order to test 36 hypotheses for the m_a value in steps half the size of the mass-bin width optimised in each $m_{\mu\mu}$ region. In each fit the likelihood function is based on the observed and predicted yields in a SR $m_{\mu\mu}$ bin corresponding to the m_a hypothesis under test and on the expected and measured yields in the TCR and DYCR. The profile likelihood is maximised to extract the best-fit values for the signal strength and the $t\bar{t}$ and DY normalisation factors.

Model-dependent limits are set on $(\sigma_H/\sigma_{\mathrm{SM}}) \times \mathcal{B}(H \to aa \to bb\mu\mu)$ assuming the signal acceptance × efficiency as given by the simulation. The signal acceptance × efficiency varies between 1.3% and 2.5% for ggF production and between 0.94% and 3.2% for VBF Higgs boson production. To obtain the signal yield for masses for which no events were simulated, the acceptance × efficiency is interpolated with spline functions between the five simulated points. All signal-related uncertainties are taken into account in the likelihood, with an additional 3% interpolation uncertainty applied to the intermediate masses. The limits are set in the $20 \le m_a \le 60$ GeV range for which the signal samples were simulated and range between 2×10^{-4} and 10^{-3} (see Fig. 6(a)).

A model-independent fit that does not include any prediction for the signal yields in SRs and CRs is also performed. The upper limit on the number of BSM events for each mass bin of the SR is translated to a 95% CL upper bound on the visible cross-section for new physics times branching ratio into $bb\mu\mu$ final state (including the KL fit constraint on $m_{bb} \sim m_{\mu\mu}$ and the four-object invariant mass constraint $m^{\mathrm{KL}}_{bb\mu\mu} \sim m_H$), $\sigma_{\mathrm{vis}}(X) \times \mathcal{B}(X \to bb\mu\mu)$. The visible cross-section is defined as the product of the production cross-section and acceptance × efficiency ($\sigma_{\mathrm{vis}}(X) = \sigma_{\mathrm{prod}}(X) \times \epsilon_X$) of a potential signal after all the analysis selection criteria have been

Table 2
Total and individual background yields in five representative $m_{\mu\mu}$ bins of the signal region. The yields are the post-fit values as determined by the background-only fit. The uncertainties shown include all systematic uncertainties and the statistical MC uncertainty. $W+$jets contribution in the SR is found to be negligible and is therefore not shown in the table.

$m_{\mu\mu}$ bin [GeV]	[19–21]	[29–31]	[39–41]	[48–52]	[58–62]
Observed events	6	6	16	48	29
Total background	4.84 ± 0.97	7.8 ± 1.2	13.7 ± 2.2	37.9 ± 5.1	30.8 ± 4.2
$t\bar{t}$	0.96 ± 0.29	3.08 ± 0.74	6.6 ± 1.5	18.1 ± 4.3	14.8 ± 3.3
DY	3.88 ± 0.92	4.5 ± 1.1	7.1 ± 1.7	19.0 ± 4.5	15.5 ± 3.6
Dibosons	< 0.01	< 0.01	$0.02^{+0.04}_{-0.02}$	0.26 ± 0.16	0.3 ± 0.1
Single top	< 0.01	0.2 ± 0.2	< 0.01	$0.65^{+0.97}_{-0.65}$	$0.09^{+0.19}_{-0.09}$
$t\bar{t}V$	< 0.01	< 0.01	< 0.01	$0.01^{+0.02}_{-0.01}$	0.05 ± 0.03

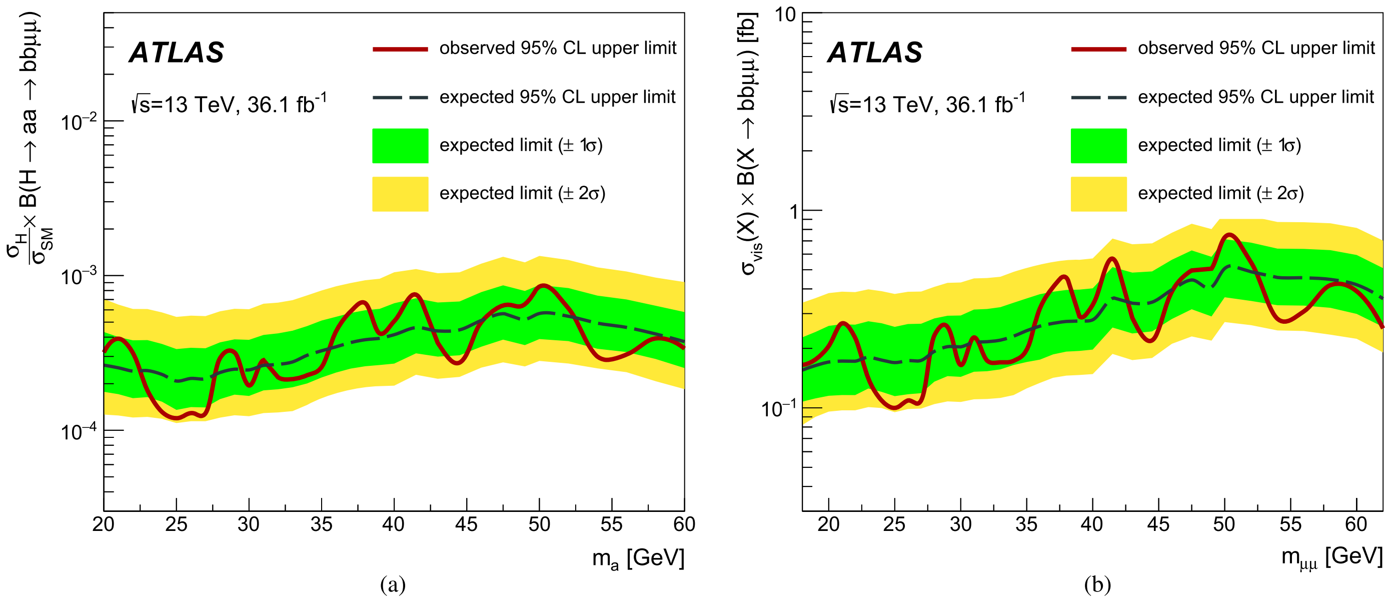


Fig. 6. The (a) observed and expected upper limits at the 95% confidence level on $\mathcal{B}(H \to aa \to bb\mu\mu)$ given the SM Higgs boson production cross-section in the ggF, VBF and VH modes and (b) model-independent upper limits on the visible cross-section for new physics times branching ratio to the $bb\mu\mu$ final state $\sigma_{\text{vis}}(X) \times \mathcal{B}(X \to bb\mu\mu)$.

applied. The limits range from 0.1 fb to 0.73 fb, depending on the dimuon mass, and are shown in Fig. 6(b). The most significant excess of data over the SM prediction is found at $m_{\mu\mu} = 38$ GeV, with a local significance of 1.6 standard deviations.

7. Conclusions

In summary, a search for exotic decays of the Higgs boson into two spin-zero particles in the $bb\mu\mu$ final state is presented. The analysis uses 36.1 fb^{-1} of pp collision data collected by ATLAS during the 2015 and 2016 runs of the LHC at $\sqrt{s} = 13$ TeV. The search for a narrow dimuon resonance is performed over the range 18 GeV $\leq m_{\mu\mu} \leq 62$ GeV using mass bins that are 2, 3 or 4 GeV wide depending on $m_{\mu\mu}$. No significant excess of the data above the SM prediction is observed. Upper limits are set on $(\sigma_H/\sigma_{\text{SM}}) \times \mathcal{B}(H \to aa \to bb\mu\mu)$ and range between 1.2×10^{-4} and 8.4×10^{-4}, depending on m_a. In Type-III 2HDM+S scenario with $\tan\beta = 2$ these limits translate into upper limits on $(\sigma_H/\sigma_{\text{SM}}) \times \mathcal{B}(H \to aa)$ ranging between 7% and 47%. The same analysis, implementing all selection criteria including $m_{bb} \sim m_{\mu\mu}$ and $m^{\text{KL}}_{bb\mu\mu} \sim m_H$ constraints, is used to set the model-independent limits on the visible cross-section for new physics times branching ratio to the $bb\mu\mu$ final state ($\sigma_{\text{vis}}(X) \times \mathcal{B}(X \to bb\mu\mu)$), ranging from 0.1 fb to 0.73 fb, depending on the dimuon mass.

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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 [hep-ex].
[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 [hep-ex].
[3] D. Curtin, et al., Exotic decays of the 125 GeV Higgs boson, Phys. Rev. D 90 (2014) 075004, arXiv:1312.4992 [hep-ph].
[4] D. Curtin, R. Essig, Y.-M. Zhong, Uncovering light scalars with exotic Higgs decays to $b\bar{b}\mu^+\mu^-$, arXiv:1412.4779 [hep-ph].
[5] B.A. Dobrescu, K.T. Matchev, Light axion within the next-to-minimal supersymmetric standard model, J. High Energy Phys. 09 (2000) 031, arXiv:hep-ph/0008192.
[6] U. Ellwanger, J.F. Gunion, C. Hugonie, S. Moretti, Towards a no lose theorem for NMSSM Higgs discovery at the LHC, arXiv:hep-ph/0305109, 2003.
[7] R. Dermisek, J.F. Gunion, Escaping the large fine-tuning and little hierarchy problems in the next to minimal supersymmetric model and $h \to aa$ decays, Phys. Rev. Lett. 95 (2005) 041801, arXiv:hep-ph/0502105.
[8] S. Chang, R. Dermisek, J.F. Gunion, N. Weiner, Nonstandard Higgs boson decays, Annu. Rev. Nucl. Part. Sci. 58 (2008) 75, arXiv:0801.4554 [hep-ph].
[9] D.E. Morrissey, A. Pierce, Modified Higgs boson phenomenology from gauge or gaugino mediation in the next-to-minimal supersymmetric standard model, Phys. Rev. D 78 (2008) 075029, arXiv:0807.2259 [hep-ph].
[10] V. Silveira, A. Zee, Scalar phantoms, Phys. Lett. B 161 (1985) 136.
[11] M. Pospelov, A. Ritz, M.B. Voloshin, Secluded WIMP dark matter, Phys. Lett. B 662 (2008) 53, arXiv:0711.4866 [hep-ph].
[12] P. Draper, T. Liu, C.E.M. Wagner, L.-T. Wang, H. Zhang, Dark light-Higgs bosons, Phys. Rev. Lett. 106 (2011) 121805, arXiv:1009.3963 [hep-ph].
[13] S. Ipek, D. McKeen, A.E. Nelson, Renormalizable model for the galactic center gamma-ray excess from dark matter annihilation, Phys. Rev. D 90 (2014) 055021, arXiv:1404.3716 [hep-ph].
[14] A. Martin, J. Shelton, J. Unwin, Fitting the galactic center gamma-ray excess with cascade annihilations, Phys. Rev. D 90 (2014) 103513, arXiv:1405.0272 [hep-ph].
[15] S. Profumo, M.J. Ramsey-Musolf, G. Shaughnessy, Singlet Higgs phenomenology and the electroweak phase transition, J. High Energy Phys. 08 (2007) 010, arXiv:0705.2425 [hep-ph].
[16] N. Blinov, J. Kozaczuk, D.E. Morrissey, C. Tamarit, Electroweak baryogenesis from exotic electroweak symmetry breaking, Phys. Rev. D 92 (2015) 035012, arXiv:1504.05195 [hep-ph].
[17] N. Craig, A. Katz, M. Strassler, R. Sundrum, Naturalness in the dark at the LHC, J. High Energy Phys. 07 (2015) 105, arXiv:1501.05310 [hep-ph].
[18] D. Curtin, C.B. Verhaaren, Discovering uncolored naturalness in exotic Higgs decays, J. High Energy Phys. 12 (2015) 072, arXiv:1506.06141 [hep-ph].
[19] M. Ajello, et al., Fermi-LAT observations of high-energy γ-ray emission toward the galactic center, Astrophys. J. 819 (2016) 44, arXiv:1511.02938 [astro-ph.HE].
[20] C. Boehm, M.J. Dolan, C. McCabe, M. Spannowsky, C.J. Wallace, Extended gamma-ray emission from coy dark matter, J. Cosmol. Astropart. Phys. 1405 (2014) 009, arXiv:1401.6458 [hep-ph].
[21] ATLAS and CMS Collaborations, Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s} = 7$ and 8 TeV, J. High Energy Phys. 08 (2016) 045, arXiv:1606.02266 [hep-ex].
[22] G. Branco, et al., Theory and phenomenology of two-Higgs-doublet models, Phys. Rep. 516 (2012) 1, arXiv:1106.0034 [hep-ph].
[23] ATLAS Collaboration, Search for Higgs bosons decaying to aa in the $\mu\mu\tau\tau$ final state in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS experiment, Phys. Rev. D 92 (2015) 052002, arXiv:1505.01609 [hep-ex].
[24] CMS Collaboration, A search for pair production of new light bosons decaying into muons, Phys. Lett. B 752 (2016) 146, arXiv:1506.00424 [hep-ex].
[25] CMS Collaboration, Search for light bosons in decays of the 125 GeV Higgs boson in proton–proton collisions at $\sqrt{s} = 8$ TeV, J. High Energy Phys. 10 (2017) 076, arXiv:1701.02032 [hep-ex].
[26] ATLAS Collaboration, Search for Higgs boson decays to beyond-the-Standard-Model light bosons in four-lepton events with the ATLAS detector at $\sqrt{s} = 13$ TeV, arXiv:1802.03388 [hep-ex], 2018.
[27] ATLAS Collaboration, Search for Higgs boson decays into pairs of light (pseudo)scalar particles in the $\gamma\gamma jj$ final state in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Lett. B 782 (2018) 750, arXiv:1803.11145 [hep-ex].
[28] CMS Collaboration, Search for an exotic decay of the Higgs boson to a pair of light pseudoscalars in the final state with two b quarks and two τ leptons in proton–proton collisions at $\sqrt{s} = 13$ TeV, arXiv:1805.10191 [hep-ex], 2018.
[29] ATLAS Collaboration, Search for the Higgs boson produced in association with a vector boson and decaying into two spin-zero particles in the $H \to aa \to 4b$ channel in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, arXiv:1806.07355 [hep-ex], 2018.
[30] ATLAS Collaboration, The ATLAS experiment at the CERN large hadron collider, J. Instrum. 3 (2008) S08003.
[31] P. Nason, A new method for combining NLO QCD with shower Monte Carlo algorithms, J. High Energy Phys. 11 (2004) 040, arXiv:hep-ph/0409146.
[32] S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method, J. High Energy Phys. 11 (2007) 070, arXiv:0709.2092 [hep-ph].
[33] S. Alioli, P. Nason, C. Oleari, E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX, J. High Energy Phys. 1006 (2010) 043, arXiv:1002.2581 [hep-ph].
[34] T. Sjöstrand, et al., An introduction to PYTHIA 8.2, Comput. Phys. Commun. 191 (2015) 159, arXiv:1410.3012 [hep-ph].
[35] ATLAS Collaboration, Measurement of the Z/γ^* boson transverse momentum distribution in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector, J. High Energy Phys. 09 (2014) 145, arXiv:1406.3660 [hep-ex].
[36] D. de Florian, et al., Handbook of LHC Higgs cross sections: 4. Deciphering the nature of the Higgs sector, arXiv:1610.07922 [hep-ph], 2016.
[37] C. Anastasiou, C. Duhr, F. Dulat, F. Herzog, B. Mistlberger, Higgs boson gluon-fusion production in QCD at three loops, Phys. Rev. Lett. 114 (2015) 212001, arXiv:1503.06056 [hep-ph].
[38] C. Anastasiou, et al., High precision determination of the gluon fusion Higgs boson cross-section at the LHC, J. High Energy Phys. 05 (2016) 058, arXiv:1602.00695 [hep-ph].
[39] S. Actis, G. Passarino, C. Sturm, S. Uccirati, NLO electroweak corrections to Higgs boson production at hadron colliders, Phys. Lett. B 670 (2008) 12, arXiv:0809.1301 [hep-ph].
[40] C. Anastasiou, R. Boughezal, F. Petriello, Mixed QCD-electroweak corrections to Higgs boson production in gluon fusion, J. High Energy Phys. 04 (2009) 003, arXiv:0811.3458 [hep-ph].
[41] J.R. Andersen, et al., in: S. Heinemeyer, C. Mariotti, G. Passarino, R. Tanaka (Eds.), Handbook of LHC Higgs Cross Sections: 3. Higgs Properties, 2013, arXiv:1307.1347 [hep-ph].
[42] M. Ciccolini, A. Denner, S. Dittmaier, Strong and electroweak corrections to the production of a Higgs boson + 2 jets via weak interactions at the large hadron collider, Phys. Rev. Lett. 99 (2007) 161803, arXiv:0707.0381 [hep-ph].
[43] M. Ciccolini, A. Denner, S. Dittmaier, Electroweak and QCD corrections to Higgs production via vector-boson fusion at the LHC, Phys. Rev. D 77 (2008) 013002, arXiv:0710.4749 [hep-ph].
[44] P. Bolzoni, F. Maltoni, S.-O. Moch, M. Zaro, Higgs boson production via vector-boson fusion at next-to-next-to-leading order in QCD, Phys. Rev. Lett. 105 (2010) 011801, arXiv:1003.4451 [hep-ph].
[45] T. Gleisberg, et al., Event generation with SHERPA 1.1, J. High Energy Phys. 02 (2009) 007, arXiv:0811.4622 [hep-ph].
[46] R.D. Ball, et al., Parton distributions for the LHC Run II, J. High Energy Phys. 04 (2015) 040, arXiv:1410.8849 [hep-ph].
[47] C. Anastasiou, L.J. Dixon, K. Melnikov, F. Petriello, High precision QCD at hadron colliders: electroweak gauge boson rapidity distributions at NNLO, Phys. Rev. D 69 (2004) 094008, arXiv:hep-ph/0312266 [hep-ph].
[48] S. Höche, F. Krauss, S. Schumann, F. Siegert, NLO matrix elements and truncated showers, J. High Energy Phys. 08 (2011) 123, arXiv:1009.1127 [hep-ph].
[49] J.M. Campbell, R.K. Ellis, C. Williams, Vector boson pair production at the LHC, J. High Energy Phys. 07 (2011) 018, arXiv:1105.0020 [hep-ph].
[50] H.-L. Lai, M. Guzzi, J. Huston, Z. Li, P.M. Nadolsky, et al., New parton distributions for collider physics, Phys. Rev. D 82 (2010) 074024, arXiv:1007.2241 [hep-ph].
[51] T. Sjöstrand, S. Mrenna, P.Z. Skands, PYTHIA 6.4 physics and manual, J. High Energy Phys. 05 (2006) 026, arXiv:hep-ph/0603175.
[52] P.Z. Skands, Tuning Monte Carlo generators: the Perugia tunes, Phys. Rev. D 82 (2010) 074018, arXiv:1005.3457 [hep-ph].

[53] ATLAS Collaboration, Comparison of Monte Carlo generator predictions for gap fraction and jet multiplicity observables in $t\bar{t}$ events, ATL-PHYS-PUB-2014-005, url: https://cds.cern.ch/record/1703034, 2014.
[54] M. Czakon, P. Fiedler, A. Mitov, Total top-quark pair-production cross section at hadron colliders through O(α_S^4), Phys. Rev. Lett. 110 (2013) 252004, arXiv:1303.6254 [hep-ph].
[55] M. Czakon, A. Mitov, Top++: a program for the calculation of the top-pair cross-section at hadron colliders, Comput. Phys. Commun. 185 (2014) 2930, arXiv:1112.5675 [hep-ph].
[56] N. Kidonakis, Next-to-next-to-leading-order collinear and soft gluon corrections for t-channel single top quark production, Phys. Rev. D 83 (2011) 091503, arXiv:1103.2792 [hep-ph].
[57] N. Kidonakis, Two-loop soft anomalous dimensions for single top quark associated production with a W- or H, Phys. Rev. D 82 (2010) 054018, arXiv:1005.4451 [hep-ph].
[58] 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, J. High Energy Phys. 07 (2014) 079, arXiv:1405.0301 [hep-ph].
[59] A. Lazopoulos, T. McElmurry, K. Melnikov, F. Petriello, Next-to-leading order QCD corrections to $t\bar{t}Z$ production at the LHC, Phys. Lett. B 666 (2008) 62, arXiv:0804.2220 [hep-ph].
[60] J.M. Campbell, R.K. Ellis, $t\bar{t}W$ production and decay at NLO, J. High Energy Phys. 07 (2012) 052, arXiv:1204.5678 [hep-ph].
[61] ATLAS Collaboration, Summary of ATLAS Pythia 8 tunes, ATL-PHYS-PUB-2012-003, url: https://cds.cern.ch/record/1474107, 2012.
[62] A. Martin, W. Stirling, R. Thorne, G. Watt, Parton distributions for the LHC, Eur. Phys. J. C 63 (2009) 189, arXiv:0901.0002 [hep-ph].
[63] ATLAS Collaboration, The ATLAS simulation infrastructure, Eur. Phys. J. C 70 (2010) 823, arXiv:1005.4568 [physics.ins-det].
[64] S. Agostinelli, et al., GEANT4 – a simulation toolkit, Nucl. Instrum. Methods A 506 (2003) 250.
[65] ATLAS Collaboration, Vertex reconstruction performance of the ATLAS detector at $\sqrt{s} = 13$ TeV, ATL-PHYS-PUB-2015-026, url: https://cds.cern.ch/record/2037717, 2015.
[66] ATLAS Collaboration, Muon reconstruction performance of the ATLAS detector in proton–proton collision data at $\sqrt{s} = 13$ TeV, Eur. Phys. J. C 76 (2016) 292, arXiv:1603.05598 [hep-ex].
[67] ATLAS Collaboration, Topological cell clustering in the ATLAS calorimeters and its performance in LHC Run 1, Eur. Phys. J. C 77 (2017) 490, arXiv:1603.02934 [hep-ex].
[68] M. Cacciari, G.P. Salam, G. Soyez, The anti-k_t jet clustering algorithm, J. High Energy Phys. 04 (2008) 063, arXiv:0802.1189 [hep-ph].
[69] M. Cacciari, G.P. Salam, G. Soyez, FastJet user manual, Eur. Phys. J. C 72 (2012) 1896, arXiv:1111.6097 [hep-ph].
[70] 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 [hep-ex].
[71] ATLAS Collaboration, Performance of b-jet identification in the ATLAS experiment, J. Instrum. 11 (2016) P04008, arXiv:1512.01094 [hep-ex].
[72] ATLAS Collaboration, Optimisation of the ATLAS b-tagging performance for the 2016 LHC Run, ATL-PHYS-PUB-2016-012, url: https://cds.cern.ch/record/2160731, 2016.
[73] ATLAS Collaboration, Performance of missing transverse momentum reconstruction with the ATLAS detector using proton–proton collisions at $\sqrt{s} = 13$ TeV, arXiv:1802.08168 [hep-ex], 2017.
[74] J. Erdmann, et al., A likelihood-based reconstruction algorithm for top-quark pairs and the KLFitter framework, Nucl. Instrum. Methods A 748 (2014) 18, arXiv:1312.5595 [hep-ex].
[75] ATLAS Collaboration, Luminosity determination in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector at the LHC, Eur. Phys. J. C 76 (2016) 653, arXiv:1608.03953 [hep-ex].
[76] J. Butterworth, et al., PDF4LHC recommendations for LHC Run II, J. Phys. G 43 (2016) 023001, arXiv:1510.03865 [hep-ph].
[77] LHC Higgs Cross Section Working Group, Handbook of LHC Higgs cross sections: 3. Higgs properties, arXiv:1307.1347 [hep-ph], 2013.
[78] K. Hamilton, P. Nason, E. Re, G. Zanderighi, NNLOPS simulation of Higgs boson production, J. High Energy Phys. 10 (2013) 222, arXiv:1309.0017 [hep-ph].
[79] T. Junk, Confidence level computation for combining searches with small statistics, Nucl. Instrum. Methods A 434 (1999) 435, arXiv:hep-ex/9902006.
[80] A.L. Read, Presentation of search results: the CLs technique, J. Phys. G 28 (2002) 2693.
[81] ATLAS Collaboration, ATLAS Computing Acknowledgements, ATL-GEN-PUB-2016-002, url: https://cds.cern.ch/record/2202407.

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N. Flaschel [44], I. Fleck [148], P. Fleischmann [103], R.R.M. Fletcher [134], T. Flick [179], B.M. Flierl [112], L.M. Flores [134], L.R. Flores Castillo [61a], F.M. Follega [73a,73b], N. Fomin [17], G.T. Forcolin [98], A. Formica [142], F.A. Förster [14], A.C. Forti [98], A.G. Foster [21], D. Fournier [129], H. Fox [87], S. Fracchia [146], P. Francavilla [69a,69b], M. Franchini [23b,23a], S. Franchino [59a], D. Francis [35], L. Franconi [131], M. Franklin [57], M. Frate [168], M. Fraternali [68a,68b], D. Freeborn [92], S.M. Fressard-Batraneanu [35], B. Freund [107], W.S. Freund [78b], D.C. Frizzell [125], D. Froidevaux [35], J.A. Frost [132], C. Fukunaga [161], E. Fullana Torregrosa [171], T. Fusayasu [114], J. Fuster [171], O. Gabizon [157], A. Gabrielli [23b,23a], A. Gabrielli [18], G.P. Gach [81a], S. Gadatsch [52], P. Gadow [113], G. Gagliardi [53b,53a], L.G. Gagnon [107], C. Galea [27b], B. Galhardo [137a,137c], E.J. Gallas [132], B.J. Gallop [141], P. Gallus [139], G. Galster [39], R. Gamboa Goni [90], K.K. Gan [123], S. Ganguly [177], J. Gao [58a], Y. Gao [88], Y.S. Gao [150,n], C. García [171], J.E. García Navarro [171], J.A. García Pascual [15a], M. Garcia-Sciveres [18], R.W. Gardner [36], N. Garelli [150], V. Garonne [131], K. Gasnikova [44], A. Gaudiello [53b,53a], G. Gaudio [68a], I.L. Gavrilenko [108], A. Gavrilyuk [109], C. Gay [172], G. Gaycken [24], E.N. Gazis [10], C.N.P. Gee [141], J. Geisen [51], M. Geisen [97], M.P. Geisler [59a], K. Gellerstedt [43a,43b], C. Gemme [53b], M.H. Genest [56], C. Geng [103], S. Gentile [70a,70b], S. George [91], D. Gerbaudo [14], G. Gessner [45], S. Ghasemi [148], M. Ghasemi Bostanabad [173], M. Ghneimat [24], B. Giacobbe [23b], S. Giagu [70a,70b], N. Giangiacomi [23b,23a], P. Giannetti [69a], A. Giannini [67a,67b], S.M. Gibson [91], M. Gignac [143], D. Gillberg [33], G. Gilles [179], D.M. Gingrich [3,aw], M.P. Giordani [64a,64c], F.M. Giorgi [23b], P.F. Giraud [142], P. Giromini [57], G. Giugliarelli [64a,64c], D. Giugni [66a], F. Giuli [132], M. Giulini [59b], S. Gkaitatzis [159], I. Gkialas [9,k], E.L. Gkougkousis [14], P. Gkountoumis [10], L.K. Gladilin [111], C. Glasman [96], J. Glatzer [14], P.C.F. Glaysher [44], A. Glazov [44], M. Goblirsch-Kolb [26], J. Godlewski [82], S. Goldfarb [102], T. Golling [52], D. Golubkov [121], A. Gomes [137a,137b], R. Goncalves Gama [78a], R. Gonçalo [137a], G. Gonella [50], L. Gonella [21], A. Gongadze [77], F. Gonnella [21], J.L. Gonski [57], S. González de la Hoz [171], S. Gonzalez-Sevilla [52], L. Goossens [35], P.A. Gorbounov [109], H.A. Gordon [29], B. Gorini [35], E. Gorini [65a,65b], A. Gorišek [89], A.T. Goshaw [47], C. Gössling [45], M.I. Gostkin [77], C.A. Gottardo [24], C.R. Goudet [129], D. Goujdami [34c], A.G. Goussiou [145], N. Govender [32b,c], C. Goy [5], E. Gozani [157], I. Grabowska-Bold [81a], P.O.J. Gradin [169], E.C. Graham [88], J. Gramling [168], E. Gramstad [131], S. Grancagnolo [19], V. Gratchev [135], P.M. Gravila [27f], F.G. Gravili [65a,65b], C. Gray [55], H.M. Gray [18], Z.D. Greenwood [93,al], C. Grefe [24], K. Gregersen [94], I.M. Gregor [44], P. Grenier [150], K. Grevtsov [44], N.A. Grieser [125], J. Griffiths [8], A.A. Grillo [143], K. Grimm [150,b], S. Grinstein [14,aa], Ph. Gris [37], J.-F. Grivaz [129], S. Groh [97], E. Gross [177], J. Grosse-Knetter [51], G.C. Grossi [93], Z.J. Grout [92], C. Grud [103], A. Grummer [116], L. Guan [103], W. Guan [178], J. Guenther [35], A. Guerguichon [129], F. Guescini [165a], D. Guest [168], R. Gugel [50], B. Gui [123], T. Guillemin [5], S. Guindon [35], U. Gul [55], C. Gumpert [35], J. Guo [58c], W. Guo [103], Y. Guo [58a,t], Z. Guo [99], R. Gupta [41], S. Gurbuz [12c], G. Gustavino [125], B.J. Gutelman [157], P. Gutierrez [125], C. Gutschow [92], C. Guyot [142], M.P. Guzik [81a], C. Gwenlan [132], C.B. Gwilliam [88], A. Haas [122], C. Haber [18], H.K. Hadavand [8], N. Haddad [34e], A. Hadef [58a], S. Hageböck [24], M. Hagihara [166], H. Hakobyan [181,*], M. Haleem [174], J. Haley [126], G. Halladjian [104], G.D. Hallewell [99], K. Hamacher [179], P. Hamal [127], K. Hamano [173], A. Hamilton [32a], G.N. Hamity [146], K. Han [58a,ak], L. Han [58a], S. Han [15d], K. Hanagaki [79,w], M. Hance [143], D.M. Handl [112], B. Haney [134], R. Hankache [133], P. Hanke [59a], E. Hansen [94], J.B. Hansen [39], J.D. Hansen [39], M.C. Hansen [24], P.H. Hansen [39], K. Hara [166], A.S. Hard [178], T. Harenberg [179], S. Harkusha [105], P.F. Harrison [175], N.M. Hartmann [112], Y. Hasegawa [147], A. Hasib [48], S. Hassani [142], S. Haug [20], R. Hauser [104], L. Hauswald [46], L.B. Havener [38], M. Havranek [139], C.M. Hawkes [21], R.J. Hawkings [35], D. Hayden [104], C. Hayes [152], C.P. Hays [132], J.M. Hays [90], H.S. Hayward [88], S.J. Haywood [141], M.P. Heath [48], V. Hedberg [94], L. Heelan [8], S. Heer [24], K.K. Heidegger [50], J. Heilman [33], S. Heim [44], T. Heim [18], B. Heinemann [44,ar], J.J. Heinrich [112], L. Heinrich [122], C. Heinz [54], J. Hejbal [138], L. Helary [35], A. Held [172], S. Hellesund [131], S. Hellman [43a,43b], C. Helsens [35], R.C.W. Henderson [87], Y. Heng [178], S. Henkelmann [172], A.M. Henriques Correia [35], G.H. Herbert [19], H. Herde [26], V. Herget [174], Y. Hernández Jiménez [32c], H. Herr [97], M.G. Herrmann [112], G. Herten [50], R. Hertenberger [112], L. Hervas [35], T.C. Herwig [134], G.G. Hesketh [92], N.P. Hessey [165a], J.W. Hetherly [41], S. Higashino [79], E. Higón-Rodriguez [171], K. Hildebrand [36], E. Hill [173], J.C. Hill [31], K.K. Hill [29], K.H. Hiller [44], S.J. Hillier [21], M. Hils [46], I. Hinchliffe [18], M. Hirose [130], D. Hirschbuehl [179], B. Hiti [89], O. Hladik [138], D.R. Hlaluku [32c], X. Hoad [48], J. Hobbs [152], N. Hod [165a], M.C. Hodgkinson [146], A. Hoecker [35], M.R. Hoeferkamp [116], F. Hoenig [112], D. Hohn [24], D. Hohov [129], T.R. Holmes [36], M. Holzbock [112], M. Homann [45], S. Honda [166], T. Honda [79], T.M. Hong [136], A. Hönle [113], B.H. Hooberman [170], W.H. Hopkins [128], Y. Horii [115], P. Horn [46], A.J. Horton [149], L.A. Horyn [36], J-Y. Hostachy [56], A. Hostiuc [145], S. Hou [155], A. Hoummada [34a], J. Howarth [98], J. Hoya [86], M. Hrabovsky [127], J. Hrdinka [35], I. Hristova [19], J. Hrivnac [129], A. Hrynevich [106], T. Hryn'ova [5], P.J. Hsu [62], S.-C. Hsu [145], Q. Hu [29], S. Hu [58c], Y. Huang [15a], Z. Hubacek [139], F. Hubaut [99], M. Huebner [24], F. Huegging [24], T.B. Huffman [132], E.W. Hughes [38], M. Huhtinen [35], R.F.H. Hunter [33], P. Huo [152], A.M. Hupe [33], N. Huseynov [77,ag], J. Huston [104], J. Huth [57], R. Hyneman [103], G. Iacobucci [52], G. Iakovidis [29], I. Ibragimov [148], L. Iconomidou-Fayard [129], Z. Idrissi [34e], P. Iengo [35], R. Ignazzi [39], O. Igonkina [118,ac], R. Iguchi [160], T. Iizawa [52], Y. Ikegami [79], M. Ikeno [79], D. Iliadis [159], N. Ilic [117], F. Iltzsche [46], G. Introzzi [68a,68b], M. Iodice [72a], K. Iordanidou [38], V. Ippolito [70a,70b], M.F. Isacson [169], N. Ishijima [130], M. Ishino [160], M. Ishitsuka [162], W. Islam [126], C. Issever [132], S. Istin [12c,aq], F. Ito [166], J.M. Iturbe Ponce [61a], R. Iuppa [73a,73b], A. Ivina [177], H. Iwasaki [79], J.M. Izen [42], V. Izzo [67a], P. Jacka [138], P. Jackson [1], R.M. Jacobs [24], V. Jain [2], G. Jäkel [179], K.B. Jakobi [97], K. Jakobs [50], S. Jakobsen [74], T. Jakoubek [138], D.O. Jamin [126], D.K. Jana [93], R. Jansky [52], J. Janssen [24], M. Janus [51], P.A. Janus [81a], G. Jarlskog [94], N. Javadov [77,ag], T. Javůrek [35], M. Javurkova [50], F. Jeanneau [142], L. Jeanty [18], J. Jejelava [156a,ah], A. Jelinskas [175], P. Jenni [50,d], J. Jeong [44], S. Jézéquel [5], H. Ji [178], J. Jia [152], H. Jiang [76], Y. Jiang [58a], Z. Jiang [150,r], S. Jiggins [50], F.A. Jimenez Morales [37], J. Jimenez Pena [171], S. Jin [15c], A. Jinaru [27b], O. Jinnouchi [162], H. Jivan [32c], P. Johansson [146], K.A. Johns [7], C.A. Johnson [63], W.J. Johnson [145], K. Jon-And [43a,43b], R.W.L. Jones [87], S.D. Jones [153], S. Jones [7], T.J. Jones [88], J. Jongmanns [59a], P.M. Jorge [137a,137b], J. Jovicevic [165a], X. Ju [18], J.J. Junggeburth [113], A. Juste Rozas [14,aa], A. Kaczmarska [82], M. Kado [129], H. Kagan [123], M. Kagan [150], T. Kaji [176], E. Kajomovitz [157], C.W. Kalderon [94], A. Kaluza [97], S. Kama [41], A. Kamenshchikov [121], L. Kanjir [89], Y. Kano [160], V.A. Kantserov [110], J. Kanzaki [79], B. Kaplan [122], L.S. Kaplan [178], D. Kar [32c], M.J. Kareem [165b], E. Karentzos [10], S.N. Karpov [77], Z.M. Karpova [77], V. Kartvelishvili [87], A.N. Karyukhin [121], L. Kashif [178], R.D. Kass [123], A. Kastanas [151], Y. Kataoka [160], C. Kato [58d,58c], J. Katzy [44], K. Kawade [80], K. Kawagoe [85], T. Kawamoto [160], G. Kawamura [51], E.F. Kay [88], V.F. Kazanin [120b,120a], R. Keeler [173], R. Kehoe [41], J.S. Keller [33], E. Kellermann [94], J.J. Kempster [21], J. Kendrick [21], O. Kepka [138], S. Kersten [179], B.P. Kerševan [89], R.A. Keyes [101], M. Khader [170], F. Khalil-Zada [13], A. Khanov [126], A.G. Kharlamov [120b,120a], T. Kharlamova [120b,120a], E.E. Khoda [172], A. Khodinov [163], T.J. Khoo [52], E. Khramov [77], J. Khubua [156b], S. Kido [80], M. Kiehn [52], C.R. Kilby [91], Y.K. Kim [36], N. Kimura [64a,64c], O.M. Kind [19], B.T. King [88], D. Kirchmeier [46], J. Kirk [141], A.E. Kiryunin [113], T. Kishimoto [160], D. Kisielewska [81a], V. Kitali [44], O. Kivernyk [5], E. Kladiva [28b,*], T. Klapdor-Kleingrothaus [50], M.H. Klein [103], M. Klein [88], U. Klein [88], K. Kleinknecht [97], P. Klimek [119], A. Klimentov [29], R. Klingenberg [45,*], T. Klingl [24], T. Klioutchnikova [35], F.F. Klitzner [112], P. Kluit [118], S. Kluth [113], E. Kneringer [74], E.B.F.G. Knoops [99], A. Knue [50], A. Kobayashi [160], D. Kobayashi [85], T. Kobayashi [160], M. Kobel [46], M. Kocian [150], P. Kodys [140], P.T. Koenig [24], T. Koffas [33], E. Koffeman [118], N.M. Köhler [113], T. Koi [150], M. Kolb [59b], I. Koletsou [5], T. Kondo [79], N. Kondrashova [58c], K. Köneke [50], A.C. König [117], T. Kono [79], R. Konoplich [122,an], V. Konstantinides [92], N. Konstantinidis [92], B. Konya [94], R. Kopeliansky [63], S. Koperny [81a], K. Korcyl [82], K. Kordas [159], G. Koren [158], A. Korn [92], I. Korolkov [14], E.V. Korolkova [146], N. Korotkova [111], O. Kortner [113], S. Kortner [113], T. Kosek [140], V.V. Kostyukhin [24], A. Kotwal [47], A. Koulouris [10], A. Kourkoumeli-Charalampidi [68a,68b], C. Kourkoumelis [9], E. Kourlitis [146], V. Kouskoura [29], A.B. Kowalewska [82], R. Kowalewski [173], T.Z. Kowalski [81a], C. Kozakai [160], W. Kozanecki [142], A.S. Kozhin [121], V.A. Kramarenko [111], G. Kramberger [89], D. Krasnopevtsev [58a], M.W. Krasny [133], A. Krasznahorkay [35], D. Krauss [113], J.A. Kremer [81a], J. Kretzschmar [88], P. Krieger [164], K. Krizka [18], K. Kroeninger [45], H. Kroha [113], J. Kroll [138], J. Kroll [134], J. Krstic [16], U. Kruchonak [77], H. Krüger [24], N. Krumnack [76], M.C. Kruse [47], T. Kubota [102], S. Kuday [4b], J.T. Kuechler [179], S. Kuehn [35], A. Kugel [59a], F. Kuger [174], T. Kuhl [44], V. Kukhtin [77], R. Kukla [99], Y. Kulchitsky [105], S. Kuleshov [144b], Y.P. Kulinich [170], M. Kuna [56], T. Kunigo [83], A. Kupco [138], T. Kupfer [45], O. Kuprash [158], H. Kurashige [80], L.L. Kurchaninov [165a], Y.A. Kurochkin [105], M.G. Kurth [15d], E.S. Kuwertz [35], M. Kuze [162], J. Kvita [127], T. Kwan [101], A. La Rosa [113], J.L. La Rosa Navarro [78d], L. La Rotonda [40b,40a], F. La Ruffa [40b,40a], C. Lacasta [171], F. Lacava [70a,70b], J. Lacey [44], D.P.J. Lack [98], H. Lacker [19], D. Lacour [133], E. Ladygin [77], R. Lafaye [5], B. Laforge [133], T. Lagouri [32c], S. Lai [51], S. Lammers [63], W. Lampl [7], E. Lançon [29], U. Landgraf [50], M.P.J. Landon [90], M.C. Lanfermann [52], V.S. Lang [44], J.C. Lange [14], R.J. Langenberg [35], A.J. Lankford [168], F. Lanni [29], K. Lantzsch [24], A. Lanza [68a], A. Lapertosa [53b,53a], S. Laplace [133], J.F. Laporte [142], T. Lari [66a], F. Lasagni Manghi [23b,23a], M. Lassnig [35], T.S. Lau [61a], A. Laudrain [129], M. Lavorgna [67a,67b], A.T. Law [143], P. Laycock [88], M. Lazzaroni [66a,66b], B. Le [102], O. Le Dortz [133], E. Le Guirriec [99], E.P. Le Quilleuc [142], M. LeBlanc [7], T. LeCompte [6], F. Ledroit-Guillon [56], C.A. Lee [29], G.R. Lee [144a], L. Lee [57], S.C. Lee [155], B. Lefebvre [101], M. Lefebvre [173], F. Legger [112], C. Leggett [18], K. Lehmann [149], N. Lehmann [179], G. Lehmann Miotto [35], W.A. Leight [44], A. Leisos [159,x], M.A.L. Leite [78d], R. Leitner [140], D. Lellouch [177], B. Lemmer [51], K.J.C. Leney [92], T. Lenz [24], B. Lenzi [35], R. Leone [7], S. Leone [69a], C. Leonidopoulos [48], G. Lerner [153], C. Leroy [107], R. Les [164], A.A.J. Lesage [142], C.G. Lester [31], M. Levchenko [135], J. Levêque [5], D. Levin [103], L.J. Levinson [177], D. Lewis [90], B. Li [103], C-Q. Li [58a,am], H. Li [58b], L. Li [58c], Q. Li [15d], Q.Y. Li [58a], S. Li [58d,58c], X. Li [58c], Y. Li [148], Z. Liang [15a], B. Liberti [71a], A. Liblong [164], K. Lie [61c], S. Liem [118], A. Limosani [154], C.Y. Lin [31], K. Lin [104], T.H. Lin [97], R.A. Linck [63], J.H. Lindon [21], B.E. Lindquist [152], A.L. Lionti [52], E. Lipeles [134], A. Lipniacka [17], M. Lisovyi [59b], T.M. Liss [170,at], A. Lister [172], A.M. Litke [143], J.D. Little [8], B. Liu [76], B.L Liu [6], H.B. Liu [29], H. Liu [103], J.B. Liu [58a], J.K.K. Liu [132], K. Liu [133], M. Liu [58a], P. Liu [18], Y. Liu [15a], Y.L. Liu [58a], Y.W. Liu [58a], M. Livan [68a,68b], A. Lleres [56], J. Llorente Merino [15a], S.L. Lloyd [90], C.Y. Lo [61b], F. Lo Sterzo [41], E.M. Lobodzinska [44], P. Loch [7], T. Lohse [19], K. Lohwasser [146], M. Lokajicek [138], B.A. Long [25], J.D. Long [170], R.E. Long [87], L. Longo [65a,65b], K.A. Looper [123], J.A. Lopez [144b], I. Lopez Paz [14], A. Lopez Solis [146], J. Lorenz [112], N. Lorenzo Martinez [5], M. Losada [22], P.J. Lösel [112], A. Lösle [50], X. Lou [44], X. Lou [15a], A. Lounis [129], J. Love [6], P.A. Love [87], J.J. Lozano Bahilo [171], H. Lu [61a], M. Lu [58a], N. Lu [103], Y.J. Lu [62], H.J. Lubatti [145], C. Luci [70a,70b], A. Lucotte [56], C. Luedtke [50], F. Luehring [63], I. Luise [133], L. Luminari [70a], B. Lund-Jensen [151], M.S. Lutz [100], P.M. Luzi [133], D. Lynn [29], R. Lysak [138], E. Lytken [94], F. Lyu [15a], V. Lyubushkin [77], H. Ma [29], L.L. Ma [58b], Y. Ma [58b], G. Maccarrone [49], A. Macchiolo [113], C.M. Macdonald [146], J. Machado Miguens [134,137b], D. Madaffari [171], R. Madar [37], W.F. Mader [46], A. Madsen [44], N. Madysa [46], J. Maeda [80], K. Maekawa [160], S. Maeland [17], T. Maeno [29], A.S. Maevskiy [111], V. Magerl [50], C. Maidantchik [78b], T. Maier [112], A. Maio [137a,137b,137d], O. Majersky [28a], S. Majewski [128], Y. Makida [79], N. Makovec [129], B. Malaescu [133], Pa. Malecki [82], V.P. Maleev [135], F. Malek [56], U. Mallik [75], D. Malon [6], C. Malone [31], S. Maltezos [10], S. Malyukov [35], J. Mamuzic [171], G. Mancini [49], I. Mandić [89], J. Maneira [137a], L. Manhaes de Andrade Filho [78a], J. Manjarres Ramos [46], K.H. Mankinen [94], A. Mann [112], A. Manousos [74], B. Mansoulie [142], J.D. Mansour [15a], M. Mantoani [51], S. Manzoni [66a,66b], G. Marceca [30], L. March [52], L. Marchese [132], G. Marchiori [133], M. Marcisovsky [138], C.A. Marin Tobon [35], M. Marjanovic [37], D.E. Marley [103], F. Marroquim [78b], Z. Marshall [18], M.U.F Martensson [169], S. Marti-Garcia [171], C.B. Martin [123], T.A. Martin [175], V.J. Martin [48], B. Martin dit Latour [17], M. Martinez [14,aa], V.I. Martinez Outschoorn [100], S. Martin-Haugh [141], V.S. Martoiu [27b], A.C. Martyniuk [92], A. Marzin [35], L. Masetti [97], T. Mashimo [160], R. Mashinistov [108], J. Masik [98], A.L. Maslennikov [120b,120a], L.H. Mason [102], L. Massa [71a,71b], P. Massarotti [67a,67b], P. Mastrandrea [5], A. Mastroberardino [40b,40a], T. Masubuchi [160], P. Mättig [179], J. Maurer [27b], B. Maček [89], S.J. Maxfield [88], D.A. Maximov [120b,120a], R. Mazini [155], I. Maznas [159], S.M. Mazza [143], N.C. Mc Fadden [116], G. Mc Goldrick [164], S.P. Mc Kee [103], A. McCarn [103], T.G. McCarthy [113], L.I. McClymont [92], E.F. McDonald [102], J.A. Mcfayden [35], G. Mchedlidze [51], M.A. McKay [41], K.D. McLean [173], S.J. McMahon [141], P.C. McNamara [102], C.J. McNicol [175], R.A. McPherson [173,ae], J.E. Mdhluli [32c], Z.A. Meadows [100], S. Meehan [145], T.M. Megy [50], S. Mehlhase [112], A. Mehta [88], T. Meideck [56], B. Meirose [42], D. Melini [171,h], B.R. Mellado Garcia [32c], J.D. Mellenthin [51], M. Melo [28a], F. Meloni [44], A. Melzer [24], S.B. Menary [98], E.D. Mendes Gouveia [137a], L. Meng [88], X.T. Meng [103], A. Mengarelli [23b,23a], S. Menke [113], E. Meoni [40b,40a], S. Mergelmeyer [19], C. Merlassino [20], P. Mermod [52], L. Merola [67a,67b], C. Meroni [66a], F.S. Merritt [36], A. Messina [70a,70b], J. Metcalfe [6], A.S. Mete [168], C. Meyer [134], J. Meyer [157], J-P. Meyer [142], H. Meyer Zu Theenhausen [59a], F. Miano [153], R.P. Middleton [141], L. Mijović [48], G. Mikenberg [177], M. Mikestikova [138], M. Mikuž [89], M. Milesi [102], A. Milic [164], D.A. Millar [90], D.W. Miller [36], A. Milov [177], D.A. Milstead [43a,43b], A.A. Minaenko [121], M. Miñano Moya [171], I.A. Minashvili [156b], A.I. Mincer [122], B. Mindur [81a], M. Mineev [77], Y. Minegishi [160], Y. Ming [178], L.M. Mir [14], A. Mirto [65a,65b], K.P. Mistry [134], T. Mitani [176], J. Mitrevski [112], V.A. Mitsou [171], A. Miucci [20], P.S. Miyagawa [146], A. Mizukami [79], J.U. Mjörnmark [94], T. Mkrtchyan [181], M. Mlynarikova [140], T. Moa [43a,43b], K. Mochizuki [107], P. Mogg [50], S. Mohapatra [38], S. Molander [43a,43b], R. Moles-Valls [24], M.C. Mondragon [104], K. Mönig [44], J. Monk [39], E. Monnier [99], A. Montalbano [149], J. Montejo Berlingen [35], F. Monticelli [86], S. Monzani [66a], N. Morange [129], D. Moreno [22], M. Moreno Llácer [35], P. Morettini [53b], M. Morgenstern [118], S. Morgenstern [46], D. Mori [149], M. Morii [57], M. Morinaga [176], V. Morisbak [131], A.K. Morley [35], G. Mornacchi [35], A.P. Morris [92], J.D. Morris [90], L. Morvaj [152], P. Moschovakos [10], M. Mosidze [156b], H.J. Moss [146], J. Moss [150,o], K. Motohashi [162], R. Mount [150], E. Mountricha [35], E.J.W. Moyse [100], S. Muanza [99], F. Mueller [113], J. Mueller [136], R.S.P. Mueller [112], D. Muenstermann [87], G.A. Mullier [20], F.J. Munoz Sanchez [98], P. Murin [28b], W.J. Murray [175,141], A. Murrone [66a,66b], M. Muškinja [89], C. Mwewa [32a], A.G. Myagkov [121,ao], J. Myers [128], M. Myska [139], B.P. Nachman [18], O. Nackenhorst [45], K. Nagai [132], K. Nagano [79], Y. Nagasaka [60], M. Nagel [50], E. Nagy [99], A.M. Nairz [35], Y. Nakahama [115], K. Nakamura [79], T. Nakamura [160], I. Nakano [124], H. Nanjo [130], F. Napolitano [59a], R.F. Naranjo Garcia [44], R. Narayan [11], D.I. Narrias Villar [59a], I. Naryshkin [135], T. Naumann [44], G. Navarro [22], R. Nayyar [7], H.A. Neal [103,*], P.Y. Nechaeva [108], T.J. Neep [142], A. Negri [68a,68b], M. Negrini [23b], S. Nektarijevic [117], C. Nellist [51], M.E. Nelson [132], S. Nemecek [138], P. Nemethy [122], M. Nessi [35,f], M.S. Neubauer [170], M. Neumann [179], P.R. Newman [21], T.Y. Ng [61c], Y.S. Ng [19], H.D.N. Nguyen [99], T. Nguyen Manh [107], E. Nibigira [37], R.B. Nickerson [132], R. Nicolaidou [142], J. Nielsen [143], N. Nikiforou [11], V. Nikolaenko [121,ao], I. Nikolic-Audit [133], K. Nikolopoulos [21], P. Nilsson [29], Y. Ninomiya [79], A. Nisati [70a], N. Nishu [58c], R. Nisius [113], I. Nitsche [45], T. Nitta [176], T. Nobe [160], Y. Noguchi [83], M. Nomachi [130], I. Nomidis [133], M.A. Nomura [29], T. Nooney [90], M. Nordberg [35], N. Norjoharuddeen [132], T. Novak [89], O. Novgorodova [46], R. Novotny [139], L. Nozka [127], K. Ntekas [168], E. Nurse [92], F. Nuti [102], F.G. Oakham [33,aw], H. Oberlack [113], T. Obermann [24], J. Ocariz [133], A. Ochi [80], I. Ochoa [38], J.P. Ochoa-Ricoux [144a], K. O'Connor [26], S. Oda [85], S. Odaka [79], S. Oerdek [51], A. Oh [98], S.H. Oh [47], C.C. Ohm [151], H. Oide [53b,53a], M.L. Ojeda [164], H. Okawa [166], Y. Okazaki [83], Y. Okumura [160], T. Okuyama [79], A. Olariu [27b], L.F. Oleiro Seabra [137a], S.A. Olivares Pino [144a], D. Oliveira Damazio [29], J.L. Oliver [1], M.J.R. Olsson [36], A. Olszewski [82], J. Olszowska [82], D.C. O'Neil [149], A. Onofre [137a,137e], K. Onogi [115], P.U.E. Onyisi [11], H. Oppen [131], M.J. Oreglia [36], Y. Oren [158], D. Orestano [72a,72b], E.C. Orgill [98], N. Orlando [61b], A.A. O'Rourke [44], R.S. Orr [164], B. Osculati [53b,53a,*], V. O'Shea [55], R. Ospanov [58a], G. Otero y Garzon [30], H. Otono [85], M. Ouchrif [34d], F. Ould-Saada [131], A. Ouraou [142], Q. Ouyang [15a], M. Owen [55], R.E. Owen [21], V.E. Ozcan [12c], N. Ozturk [8], J. Pacalt [127], H.A. Pacey [31], K. Pachal [149], A. Pacheco Pages [14], L. Pacheco Rodriguez [142], C. Padilla Aranda [14], S. Pagan Griso [18], M. Paganini [180], G. Palacino [63], S. Palazzo [40b,40a], S. Palestini [35], M. Palka [81b], D. Pallin [37], I. Panagoulias [10], C.E. Pandini [35], J.G. Panduro Vazquez [91], P. Pani [35], G. Panizzo [64a,64c], L. Paolozzi [52], T.D. Papadopoulou [10], K. Papageorgiou [9,k], A. Paramonov [6], D. Paredes Hernandez [61b], S.R. Paredes Saenz [132], B. Parida [58c], A.J. Parker [87], K.A. Parker [44], M.A. Parker [31], F. Parodi [53b,53a], J.A. Parsons [38], U. Parzefall [50], V.R. Pascuzzi [164], J.M.P. Pasner [143], E. Pasqualucci [70a], S. Passaggio [53b], F. Pastore [91], P. Pasuwan [43a,43b], S. Pataraia [97], J.R. Pater [98], A. Pathak [178,l], T. Pauly [35], B. Pearson [113], M. Pedersen [131], L. Pedraza Diaz [117], R. Pedro [137a,137b], S.V. Peleganchuk [120b,120a], O. Penc [138], C. Peng [15d], H. Peng [58a], B.S. Peralva [78a], M.M. Perego [142], A.P. Pereira Peixoto [137a], D.V. Perepelitsa [29], F. Peri [19], L. Perini [66a,66b], H. Pernegger [35], S. Perrella [67a,67b], V.D. Peshekhonov [77,*], K. Peters [44], R.F.Y. Peters [98], B.A. Petersen [35], T.C. Petersen [39], E. Petit [56], A. Petridis [1], C. Petridou [159], P. Petroff [129], M. Petrov [132], F. Petrucci [72a,72b], M. Pettee [180], N.E. Pettersson [100], A. Peyaud [142], R. Pezoa [144b], T. Pham [102], F.H. Phillips [104], P.W. Phillips [141], G. Piacquadio [152], E. Pianori [18], A. Picazio [100], M.A. Pickering [132], R.H. Pickles [98], R. Piegaia [30], J.E. Pilcher [36], A.D. Pilkington [98], M. Pinamonti [71a,71b], J.L. Pinfold [3], M. Pitt [177], M.-A. Pleier [29], V. Pleskot [140], E. Plotnikova [77], D. Pluth [76], P. Podberezko [120b,120a], R. Poettgen [94], R. Poggi [52], L. Poggioli [129], I. Pogrebnyak [104], D. Pohl [24], I. Pokharel [51], G. Polesello [68a], A. Poley [18], A. Policicchio [70a,70b], R. Polifka [35], A. Polini [23b], C.S. Pollard [44], V. Polychronakos [29], D. Ponomarenko [110], L. Pontecorvo [35], G.A. Popeneciu [27d], D.M. Portillo Quintero [133], S. Pospisil [139], K. Potamianos [44], I.N. Potrap [77], C.J. Potter [31], H. Potti [11], T. Poulsen [94], J. Poveda [35], T.D. Powell [146], M.E. Pozo Astigarraga [35], P. Pralavorio [99], S. Prell [76], D. Price [98], M. Primavera [65a], S. Prince [101], N. Proklova [110], K. Prokofiev [61c], F. Prokoshin [144b], S. Protopopescu [29], J. Proudfoot [6], M. Przybycien [81a], A. Puri [170], P. Puzo [129], J. Qian [103], Y. Qin [98], A. Quadt [51], M. Queitsch-Maitland [44], A. Qureshi [1], P. Rados [102], F. Ragusa [66a,66b], G. Rahal [95], J.A. Raine [52], S. Rajagopalan [29], A. Ramirez Morales [90], T. Rashid [129], S. Raspopov [5], M.G. Ratti [66a,66b], D.M. Rauch [44], F. Rauscher [112], S. Rave [97], B. Ravina [146], I. Ravinovich [177], J.H. Rawling [98], M. Raymond [35], A.L. Read [131], N.P. Readioff [56], M. Reale [65a,65b], D.M. Rebuzzi [68a,68b], A. Redelbach [174], G. Redlinger [29], R. Reece [143], R.G. Reed [32c], K. Reeves [42], L. Rehnisch [19], J. Reichert [134], A. Reiss [97], C. Rembser [35], H. Ren [15d], M. Rescigno [70a], S. Resconi [66a], E.D. Resseguie [134], S. Rettie [172], E. Reynolds [21], O.L. Rezanova [120b,120a], P. Reznicek [140], E. Ricci [73a,73b], R. Richter [113], S. Richter [92], E. Richter-Was [81b], O. Ricken [24], M. Ridel [133], P. Rieck [113], C.J. Riegel [179], O. Rifki [44], M. Rijssenbeek [152], A. Rimoldi [68a,68b], M. Rimoldi [20], L. Rinaldi [23b], G. Ripellino [151], B. Ristić [87], E. Ritsch [35], I. Riu [14], J.C. Rivera Vergara [144a], F. Rizatdinova [126], E. Rizvi [90], C. Rizzi [14], R.T. Roberts [98], S.H. Robertson [101,ae], D. Robinson [31], J.E.M. Robinson [44], A. Robson [55], E. Rocco [97], C. Roda [69a,69b], Y. Rodina [99], S. Rodriguez Bosca [171], A. Rodriguez Perez [14], D. Rodriguez Rodriguez [171], A.M. Rodríguez Vera [165b], S. Roe [35], C.S. Rogan [57], O. Røhne [131], R. Röhrig [113], C.P.A. Roland [63], J. Roloff [57], A. Romaniouk [110], M. Romano [23b,23a], N. Rompotis [88], M. Ronzani [122], L. Roos [133], S. Rosati [70a], K. Rosbach [50], P. Rose [143], N-A. Rosien [51], E. Rossi [44], E. Rossi [67a,67b], L.P. Rossi [53b], L. Rossini [66a,66b], J.H.N. Rosten [31], R. Rosten [14], M. Rotaru [27b], J. Rothberg [145], D. Rousseau [129], D. Roy [32c], A. Rozanov [99], Y. Rozen [157], X. Ruan [32c], F. Rubbo [150], F. Rühr [50], A. Ruiz-Martinez [171], Z. Rurikova [50], N.A. Rusakovich [77], H.L. Russell [101], J.P. Rutherfoord [7], E.M. Rüttinger [44,m], Y.F. Ryabov [135], M. Rybar [170], G. Rybkin [129], S. Ryu [6], A. Ryzhov [121], G.F. Rzehorz [51], P. Sabatini [51], G. Sabato [118], S. Sacerdoti [129], H.F-W. Sadrozinski [143], R. Sadykov [77], F. Safai Tehrani [70a], P. Saha [119], M. Sahinsoy [59a], A. Sahu [179], M. Saimpert [44], M. Saito [160], T. Saito [160], H. Sakamoto [160], A. Sakharov [122,an], D. Salamani [52], G. Salamanna [72a,72b], J.E. Salazar Loyola [144b], D. Salek [118], P.H. Sales De Bruin [169], D. Salihagic [113], A. Salnikov [150], J. Salt [171], D. Salvatore [40b,40a], F. Salvatore [153], A. Salvucci [61a,61b,61c], A. Salzburger [35], J. Samarati [35], D. Sammel [50], D. Sampsonidis [159], D. Sampsonidou [159], J. Sánchez [171], A. Sanchez Pineda [64a,64c], H. Sandaker [131], C.O. Sander [44], M. Sandhoff [179], C. Sandoval [22], D.P.C. Sankey [141], M. Sannino [53b,53a], Y. Sano [115], A. Sansoni [49], C. Santoni [37], H. Santos [137a], I. Santoyo Castillo [153], A. Santra [171], A. Sapronov [77], J.G. Saraiva [137a,137d], O. Sasaki [79], K. Sato [166], E. Sauvan [5], P. Savard [164,aw], N. Savic [113], R. Sawada [160], C. Sawyer [141], L. Sawyer [93,al], C. Sbarra [23b], A. Sbrizzi [23a], T. Scanlon [92], J. Schaarschmidt [145], P. Schacht [113], B.M. Schachtner [112], D. Schaefer [36], L. Schaefer [134], J. Schaeffer [97], S. Schaepe [35], U. Schäfer [97], A.C. Schaffer [129], D. Schaile [112], R.D. Schamberger [152], N. Scharmberg [98], V.A. Schegelsky [135], D. Scheirich [140], F. Schenck [19], M. Schernau [168], C. Schiavi [53b,53a], S. Schier [143], L.K. Schildgen [24], Z.M. Schillaci [26], E.J. Schioppa [35], M. Schioppa [40b,40a], K.E. Schleicher [50], S. Schlenker [35], K.R. Schmidt-Sommerfeld [113], K. Schmieden [35], C. Schmitt [97], S. Schmitt [44], S. Schmitz [97], J.C. Schmoeckel [44], U. Schnoor [50], L. Schoeffel [142], A. Schoening [59b], E. Schopf [24], M. Schott [97], J.F.P. Schouwenberg [117], J. Schovancova [35], S. Schramm [52], A. Schulte [97], H-C. Schultz-Coulon [59a], M. Schumacher [50], B.A. Schumm [143], Ph. Schune [142], A. Schwartzman [150], T.A. Schwarz [103], H. Schweiger [98], Ph. Schwemling [142], R. Schwienhorst [104], A. Sciandra [24], G. Sciolla [26], M. Scornajenghi [40b,40a], F. Scuri [69a], F. Scutti [102], L.M. Scyboz [113], J. Searcy [103], C.D. Sebastiani [70a,70b], P. Seema [24], S.C. Seidel [116], A. Seiden [143], T. Seiss [36], J.M. Seixas [78b], G. Sekhniaidze [67a], K. Sekhon [103], S.J. Sekula [41], N. Semprini-Cesari [23b,23a], S. Sen [47], S. Senkin [37], C. Serfon [131], L. Serin [129], L. Serkin [64a,64b], M. Sessa [72a,72b], H. Severini [125], F. Sforza [167], A. Sfyrla [52], E. Shabalina [51], J.D. Shahinian [143], N.W. Shaikh [43a,43b], L.Y. Shan [15a], R. Shang [170], J.T. Shank [25], M. Shapiro [18], A.S. Sharma [1], A. Sharma [132], P.B. Shatalov [109], K. Shaw [153], S.M. Shaw [98], A. Shcherbakova [135], Y. Shen [125], N. Sherafati [33], A.D. Sherman [25], P. Sherwood [92], L. Shi [155,as], S. Shimizu [79], C.O. Shimmin [180], M. Shimojima [114], I.P.J. Shipsey [132], S. Shirabe [85], M. Shiyakova [77], J. Shlomi [177], A. Shmeleva [108], D. Shoaleh Saadi [107], M.J. Shochet [36], S. Shojaii [102], D.R. Shope [125], S. Shrestha [123], E. Shulga [110], P. Sicho [138], A.M. Sickles [170], P.E. Sidebo [151], E. Sideras Haddad [32c], O. Sidiropoulou [35], A. Sidoti [23b,23a], F. Siegert [46], Dj. Sijacki [16], J. Silva [137a], M. Silva Jr. [178], M.V. Silva Oliveira [78a], S.B. Silverstein [43a], L. Simic [77], S. Simion [129], E. Simioni [97], M. Simon [97], R. Simoniello [97], P. Sinervo [164], N.B. Sinev [128], M. Sioli [23b,23a], G. Siragusa [174], I. Siral [103], S.Yu. Sivoklokov [111], J. Sjölin [43a,43b], P. Skubic [125], M. Slater [21], T. Slavicek [139], M. Slawinska [82], K. Sliwa [167], R. Slovak [140], V. Smakhtin [177], B.H. Smart [5], J. Smiesko [28a], N. Smirnov [110], S.Yu. Smirnov [110], Y. Smirnov [110], L.N. Smirnova [111], O. Smirnova [94], J.W. Smith [51], M.N.K. Smith [38], M. Smizanska [87], K. Smolek [139], A. Smykiewicz [82], A.A. Snesarev [108], I.M. Snyder [128], S. Snyder [29], R. Sobie [173,ae], A.M. Soffa [168], A. Soffer [158], A. Søgaard [48], D.A. Soh [155], G. Sokhrannyi [89], C.A. Solans Sanchez [35], M. 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