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The ATLAS Collaboration

DOI
10.1007/JHEP11(2016)112

Publication date
2016

Document Version
Final published version

Published in
The Journal of High Energy Physics

Published for SISSA by Springer

Received: June 8, 2016
Revised: September 28, 2016
Accepted: November 10, 2016
Published: November 21, 2016

Search for the Standard Model Higgs boson produced by vector-boson fusion and decaying to bottom quarks in $\sqrt{s} = 8$ TeV pp collisions with the ATLAS detector

JHEP11(2016)112

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Abstract: A search with the ATLAS detector is presented for the Standard Model Higgs boson produced by vector-boson fusion and decaying to a pair of bottom quarks, using 20.2 fb^{-1} of LHC proton-proton collision data at $\sqrt{s} = 8$ TeV. The signal is searched for as a resonance in the invariant mass distribution of a pair of jets containing b-hadrons in vector-boson-fusion candidate events. The yield is measured to be -0.8 ± 2.3 times the Standard Model cross-section for a Higgs boson mass of 125 GeV. The upper limit on the cross-section times the branching ratio is found to be 4.4 times the Standard Model cross-section at the 95% confidence level, consistent with the expected limit value of 5.4 (5.7) in the background-only (Standard Model production) hypothesis.

Keywords: Hadron-Hadron scattering (experiments), Higgs physics, proton-proton scattering

ArXiv ePrint: 1606.02181

doi:10.1007/JHEP11(2016)112

Contents

1 Introduction

Since the ATLAS and CMS collaborations reported the observation [1, 2] of a new particle with a mass of about 125 GeV and with properties consistent with those expected for the Higgs boson in the Standard Model (SM) [3–5], more precise measurements have strengthened the hypothesis that the new particle is indeed the Higgs boson [6–9]. These measurements were performed primarily in the bosonic decay modes of the new particle: $H \to \gamma\gamma$, ZZ, W^+W^-. It is essential to study whether it also directly decays into fermions as predicted by the SM. Recently CMS and ATLAS reported evidence for the $H \to \tau^+\tau^-$ decay mode at a significance level of 3.4 and 4.5 standard deviations, respectively [10–12], and the combination of these results qualifies as an observation [13]. However, the $H \to b\bar{b}$ decay mode has not yet been observed [14–19], and the only direct evidence of its existence so far has been obtained by the CDF and D0 collaborations [14] at the Tevatron collider.

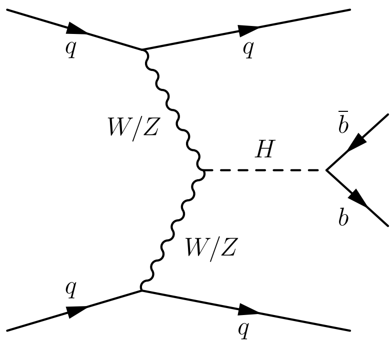

Figure 1. An example Feynman diagram illustrating vector-boson-fusion production of the Higgs boson and its decay to a $b\bar{b}$ pair.

The production processes of Higgs bosons at the LHC include gluon fusion ($gg \to H$, denoted ggF), vector-boson fusion ($qq \to qqH$, denoted VBF), Higgs-strahlung ($q\bar{q}' \to WH, ZH$, denoted WH/ZH or jointly VH), and production in association with a top-quark pair ($gg \to t\bar{t}H$, denoted $t\bar{t}H$). While an inclusive observation of the SM Higgs boson decaying to a $b\bar{b}$ pair is difficult in hadron collisions because of the overwhelming background from multijet production, the VH, VBF, and $t\bar{t}H$ processes offer viable options for the observation of the $b\bar{b}$ decay channel. As reported in refs. [15–19], the leptonic decays of vector bosons, the kinematic properties of the production process, and the identification of top quarks are used to reduce the background for VH, VBF, and $t\bar{t}H$, respectively.

This article presents a search for VBF production of the SM Higgs boson in the $b\bar{b}$ decay mode (VBF signal or VBF Higgs hereafter) using data recorded with the ATLAS detector in proton-proton collisions at a centre-of-mass energy $\sqrt{s} = 8$ TeV. The signal is searched for as a resonance in the invariant mass distribution (m_{bb}) of a pair of jets containing b-hadrons (b-jets) in vector-boson-fusion candidates. Events are selected by requiring four energetic jets generated from the $qqH \to qqb\bar{b}$ process as illustrated in figure 1: two light-quark jets (VBF jets) at a small angle with respect to the beam line and two b-jets from the Higgs boson decay in more central regions. Higgs bosons are colour singlets with no colour line to the bottom quarks; thus little QCD radiation and hadronic activity is expected between the two VBF jets, creating a rapidity gap between them. This feature is used to distinguish signal events from multijet events, which form the dominant background with a non-resonant contribution to the m_{bb} distribution. Another relevant background source arises from the decay of a Z boson to $b\bar{b}$ in association with two jets ($Z \to b\bar{b}$ or Z hereafter). This results in a resonant contribution to the m_{bb} distribution.

To improve the sensitivity, a multivariate analysis (MVA) is used to exploit the topology of the VBF Higgs final state. An alternative analysis is performed using kinematic cuts and the m_{bb} distribution. The selected sample contains a minor contribution from Higgs boson events produced via the ggF process in association with two jets. These events exhibit an m_{bb} distribution similar to that of VBF Higgs events, and are treated as signal in this analysis. The possible contribution of VH production to the signal was also studied but found to be negligible compared to VBF and ggF Higgs production for this analysis.

2 The ATLAS detector

The ATLAS experiment uses a multi-purpose particle detector [20] with a forward-backward symmetric cylindrical geometry and a near 4π coverage in solid angle.[1] It consists of an inner tracking detector (ID) surrounded by a thin superconducting solenoid providing a 2 T magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer (MS). The ID consists of silicon pixel and microstrip tracking detectors covering the pseudorapidity range $|\eta| < 2.5$, and a transition radiation detector in the region $|\eta| < 2.0$. Lead/liquid-argon (LAr) sampling calorimeters in the region $|\eta| < 3.2$ provide electromagnetic energy measurements with high granularity. A hadron (steel/scintillator-tile) calorimeter covers the range $|\eta| < 1.7$. The end-cap and forward regions are instrumented with LAr calorimeters for both the electromagnetic and hadronic energy measurements up to $|\eta| = 4.9$. The MS surrounds the calorimeters and is based on three large air-core toroid superconducting magnets with eight coils each. It includes a system of tracking chambers covering $|\eta| < 2.7$ and fast detectors for triggering in the range $|\eta| < 2.4$. The ATLAS trigger system [21] consists of three levels: the first (L1) is a hardware-based system, and the second and third levels are software-based systems which are collectively referred to as the high-level trigger (HLT).

3 Data and simulation samples

The data used in this analysis were collected by the ATLAS experiment at a centre-of-mass energy of 8 TeV during 2012, and correspond to an integrated luminosity of 20.2 fb^{-1} recorded in stable beam conditions and with all relevant sub-detectors providing high-quality data.

Events are primarily selected by a trigger requiring four jets with transverse momentum $p_T > 15$ GeV at L1 and $p_T > 35$ GeV in the HLT, two of which must be identified as b-jets by a dedicated HLT b-tagging algorithm (HLT b-jets). This trigger was available during the entire 2012 data-taking period. Two triggers designed to enhance the acceptance for VBF $H \to b\bar{b}$ events (VBF Higgs triggers) were added during the 2012 data-taking period. They require either three L1 jets with $p_T > 15$ GeV where one jet is in the forward region ($|\eta| > 3.2$), or two L1 jets in the forward region with $p_T > 15$ GeV. These criteria are completed by the requirement of at least one HLT b-jet with $p_T > 35$ GeV. The VBF Higgs triggers were used for a data sample corresponding to an integrated luminosity of 4.4 fb^{-1}, resulting in an approximately 25% increase of the signal acceptance.

VBF and ggF Higgs boson signal events and Z boson background events are modelled by Monte Carlo (MC) simulations. The signal samples with a Higgs boson mass of 125 GeV are generated by POWHEG [22–24], which calculates the VBF and ggF Higgs production processes up to next-to-leading order (NLO) in α_S. Samples of Z boson + jets events

[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 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 $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

JHEP11(2016)112

are generated using MadGraph5 [25], where the associated jets are produced via strong or electroweak (EW) processes including VBF, and the matrix elements are calculated for up to and including three partons at leading order. For all simulated samples, the NLO CT10 parton distribution functions (PDF) [26] are used. The parton shower and the hadronisation are modelled by Pythia8 [27], with the AU2 set of tuned parameters [28, 29] for the underlying event.

The VBF Higgs predictions are normalised to a cross-section calculation that includes full NLO QCD and EW corrections and approximate next-to-next-to-leading-order (NNLO) QCD corrections [30]. The NLO EW corrections also affect the p_{T} shape of the Higgs boson [31]. The p_{T} shape is reweighted, based on the shape difference between Hawk calculations without and with NLO EW corrections included [32, 33].

The overall normalisation of the ggF process is taken from a calculation at NNLO in QCD that includes soft-gluon resummation up to next-to-next-to-leading logarithmic terms (NNLL) [30]. Corrections to the shape of the generated p_{T} distribution of Higgs bosons are applied to match the distribution from the NNLO calculation with the NNLL corrections provided by the Hres program [34, 35]. In this calculation, the effects of finite masses of the top and bottom quarks are included and dynamic renormalisation and factorisation scales are used. A reweighting is derived such that the inclusive Higgs p_{T} spectrum matches the Hres prediction, and the Higgs p_{T} spectrum of events with at least two jets matches the the Minlo hjj [36] prediction, the most recent calculation in this phase space.

The ATLAS simulation [37] of the detector is used for all MC events based on the Geant4 program [38] except for the response of the calorimeters, for which a parameterised simulation [39] is used. All simulated events are generated with a range of minimum-bias interactions overlaid on the hard-scattering interaction to account for multiple pp interactions that occur in the same or neighbouring bunch crossings (pile-up). The simulated events are processed with the same reconstruction algorithms as the data. Corrections are applied to the simulated samples to account for differences between data and simulation in the trigger and reconstruction efficiencies and in pile-up contributions.

4 Object reconstruction

Charged-particle tracks are reconstructed with a p_{T} threshold of 400 MeV. Event vertices are formed from these tracks and are required to have at least three tracks. The primary vertex is chosen as the vertex with the largest $\Sigma\, p_{\mathrm{T}}^2$ of the associated tracks.

Jets are reconstructed from topological clusters of energy deposits, after noise suppression, in the calorimeters [40] using the anti-k_t algorithm [41] with a radius parameter $R = 0.4$. Jet energies are corrected for the contribution of pile-up interactions using a jet-area-based technique [42], and calibrated using p_{T}- and η-dependent correction factors determined from MC simulations and in-situ data measurements of Z+jet, γ+jet and multijet events [43, 44]. To suppress jets from pile-up interactions, which are mainly at low p_{T}, a jet vertex tagger [45], based on tracking and vertexing information, is applied to jets with $p_{\mathrm{T}} < 50$ GeV and $|\eta| < 2.4$.

JHEP11(2016)112

Process	Cross-section × BR [pb]	Acceptance
VBF $H \to b\bar{b}$	0.9	6.9 $\times 10^{-3}$
ggF $H \to b\bar{b}$	11.1	4.2 $\times 10^{-4}$
$Z \to b\bar{b}$ + 1, 2, or 3 partons	5.9 $\times 10^{2}$	3.1 $\times 10^{-4}$

Table 1. Cross-sections times branching ratios (BRs) used for the VBF and ggF $H \to b\bar{b}$ and $Z \to b\bar{b}$ MC generation, and acceptances of the pre-selection criteria for simulated samples.

The b-jets are identified (b-tagged) by exploiting the relatively long lifetime and large mass of b-hadrons. The b-tagging methods are based on the presence of tracks with a large impact parameter with respect to the primary vertex, and secondary decay vertices. This information is combined into a single neural-network discriminant [46]. This analysis uses a b-tagging criterion that, in simulated $t\bar{t}$ events, provides an average efficiency of 70% for b-jets and a c-jet (light-jet) mis-tag rate less than 20% (1%).

5 Event pre-selection

Events with exactly four jets, each with $p_{\mathrm{T}} > 50$ GeV and $|\eta| < 4.5$, are retained. The four jets are ordered in η such that $\eta_1 < \eta_2 < \eta_3 < \eta_4$. The jets associated with η_1 and η_4 are labelled as VBF jets (or $J1$ and $J2$). The other two jets associated with η_2 and η_3 (Higgs jets or $b1$ and $b2$) are required to be within the tracker acceptance ($|\eta| < 2.5$), and to be identified as b-jets. The two Higgs jets must be matched to the HLT b-jets for events satisfying the primary trigger; for events satisfying the VBF Higgs triggers, one of the two Higgs jets is required to be matched to an HLT b-jet. The 50 GeV cut on jet p_{T} shapes the m_{bb} distribution for non-resonant backgrounds, creating a peak near 130 GeV, which makes the extraction of a signal difficult. This shaping is removed by requiring the p_{T} of the $b\bar{b}$ system to exceed 100 GeV. Table 1 summarises the acceptances of these pre-selection criteria, for the VBF and ggF Higgs MC events [30, 47] and the Z MC events.

For the pre-selected events, corrections are applied to improve the b-jet energy measurements. If muons with $p_{\mathrm{T}} > 4$ GeV and $|\eta| < 2.5$ are found within a b-jet, the four-momentum of the muon closest to the jet axis is added to that of the jet (after correcting for the expected energy deposited by the muon in the calorimeter material). Such muons are reconstructed by combining measurements from the ID and MS systems, and are required to satisfy tight muon identification quality criteria [48]. In addition, a p_{T}-dependent correction of up to 5% is applied to account for biases in the response due to resolution effects. This correction is determined from simulated WH/ZH events following ref. [15].

6 Multivariate analysis

A Boosted Decision Tree [49, 50] (BDT) method, as implemented in the Toolkit for Multivariate Data Analysis package [51], is used to exploit the characteristics of VBF production. The BDT is trained to discriminate between VBF Higgs signal events and non-resonant background events modelled using the data in the sideband regions of the m_{bb} distribution ($70 < m_{bb} < 90$ GeV and $150 < m_{bb} < 190$ GeV).

The input variables of the BDT are chosen to exploit the difference in topologies between signal events and background events while keeping them as uncorrelated as possible with m_{bb}, to ensure that the sideband regions provide a good description of the non-resonant background in the signal region. In order of decreasing discrimination power, which is determined by removing variables one by one from the analysis, the variables are: the jet widths of VBF jets having $|\eta| < 2.1$ (the jet width is defined as the p_{T}-weighted angular distance of the jet constituents from the jet axis, and is set to zero if $|\eta| > 2.1$), which differs on average for quark and gluon jets; the scalar sum of the p_{T} of additional jets with $p_{\mathrm{T}} > 20$ GeV in the region $|\eta| < 2.5$, $\Sigma p_{\mathrm{T}}^{\mathrm{jets}}$; the invariant mass of the two VBF jets, m_{JJ}; the η separation between the two VBF jets, $\Delta\eta_{JJ}$; the maximum $|\eta|$ of the two VBF jets, $\max(|\eta_{J1}|, |\eta_{J2}|)$; the separation between the $|\eta|$ average of the VBF jets and that of the Higgs jets, $(|\eta_{J1}| + |\eta_{J2}|)/2 - (|\eta_{b1}| + |\eta_{b2}|)/2$; and the cosine of the polar angle of the cross product of the VBF jets momenta, $\cos\theta$, which is sensitive to the production mechanism.

Figures 2 and 3 show the distributions of the BDT input variables in the data and the simulated samples for the VBF $H \to b\bar{b}$, ggF $H \to b\bar{b}$, and $Z \to b\bar{b}$ events that satisfy the pre-selection criteria. The BDT responses to the pre-selected data and simulated events are compared in figure 4. As expected, the BDT response to the VBF Higgs signal sample is significantly different from its response to the data, which are primarily multijet events, and also from its response to the Z and ggF Higgs samples.

7 Invariant mass spectrum of the two b-jets

The signal is estimated using a fit to the m_{bb} distribution in the range $70 < m_{bb} < 300$ GeV. The contributions to the distribution include $H \to b\bar{b}$ events, from either VBF or ggF production; $Z \to b\bar{b}$ events produced in association with jets; and non-resonant processes such as multijet, $t\bar{t}$, single top, and W+jets production. In order to better exploit the MVA discrimination power, the fit is performed simultaneously in four categories based on the BDT output. The boundaries of the four categories, shown in table 2, were optimised by minimising the relative statistical uncertainties, $\sqrt{N_{\mathrm{sig}} + N_{\mathrm{bg}}}/N_{\mathrm{sig}}$, where N_{sig} and N_{bg} are the expected numbers of signal and background events, respectively. Table 2 shows, for each category, the total number of events observed in the data and the number of Higgs events expected from the VBF and ggF production processes, along with the number of Z events expected in the entire mass range. The categories in table 2 are listed in order of increasing sensitivity.

The shapes of the m_{bb} distributions for Higgs and Z boson events are taken from simulation. Their shapes in the four categories are found to be comparable; therefore the inclusive shapes are used. The m_{bb} shapes for VBF and ggF Higgs boson events are similar, as expected. In order to minimise the effects of the limited MC sample size, the resulting m_{bb} histograms for Higgs and Z events are smoothed using the 353QH algorithm [52]. The m_{bb} distributions used in the fit are shown in figure 5. The Higgs yield is left free to vary. The Z yield is constrained to the SM prediction within its theoretical uncertainty (see section 8.3).

JHEP11(2016)112

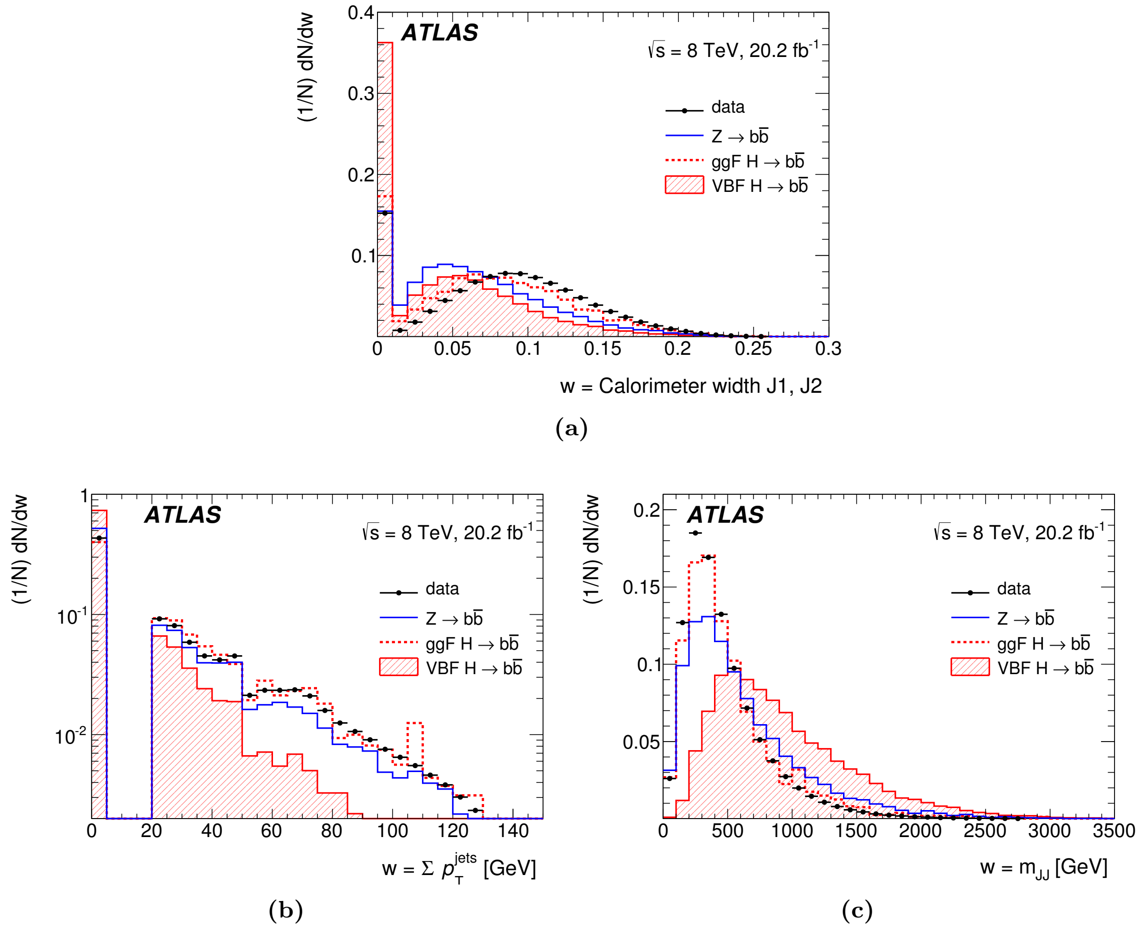

Figure 2. Distributions of the BDT input variables from the data (points) and the simulated samples for VBF $H \to b\bar{b}$ events (shaded histograms), ggF $H \to b\bar{b}$ events (open dashed histograms) and $Z \to b\bar{b}$ events (open solid histograms). The pre-selection criteria are applied to these samples. The variables are: (a) the jet widths for the VBF jets having $|\eta| < 2.1$ (the jet width is set at zero if $|\eta| > 2.1$); (b) the scalar sum of the p_{T} of additional jets with $p_{\mathrm{T}} > 20$ GeV in the region $|\eta| < 2.5$, $\Sigma p_{\mathrm{T}}^{\mathrm{jets}}$ (the peak at zero represents events without additional jets); and (c) the invariant mass of the two VBF jets, m_{JJ}.

Process	Pre-selection	Category I (−0.08 to 0.01)	Category II (0.01 to 0.06)	Category III (0.06 to 0.09)	Category IV (> 0.09)
VBF $H \to b\bar{b}$	130	39	33	23	19
ggF $H \to b\bar{b}$	94	31	8.5	3.8	1.6
$Z \to b\bar{b}$	3700	1100	350	97	49
Data	554302	176073	46912	15015	6493

Table 2. Expected numbers of events for VBF and ggF $H \to b\bar{b}$ and $Z \to b\bar{b}$ processes, and the observed numbers of events in data with $70 < m_{bb} < 300$ GeV, after the pre-selection criteria are applied, in the four categories of the BDT response. The categories are listed in order of increasing sensitivity. The values in the parentheses represent the boundaries of each BDT category.

JHEP11(2016)112

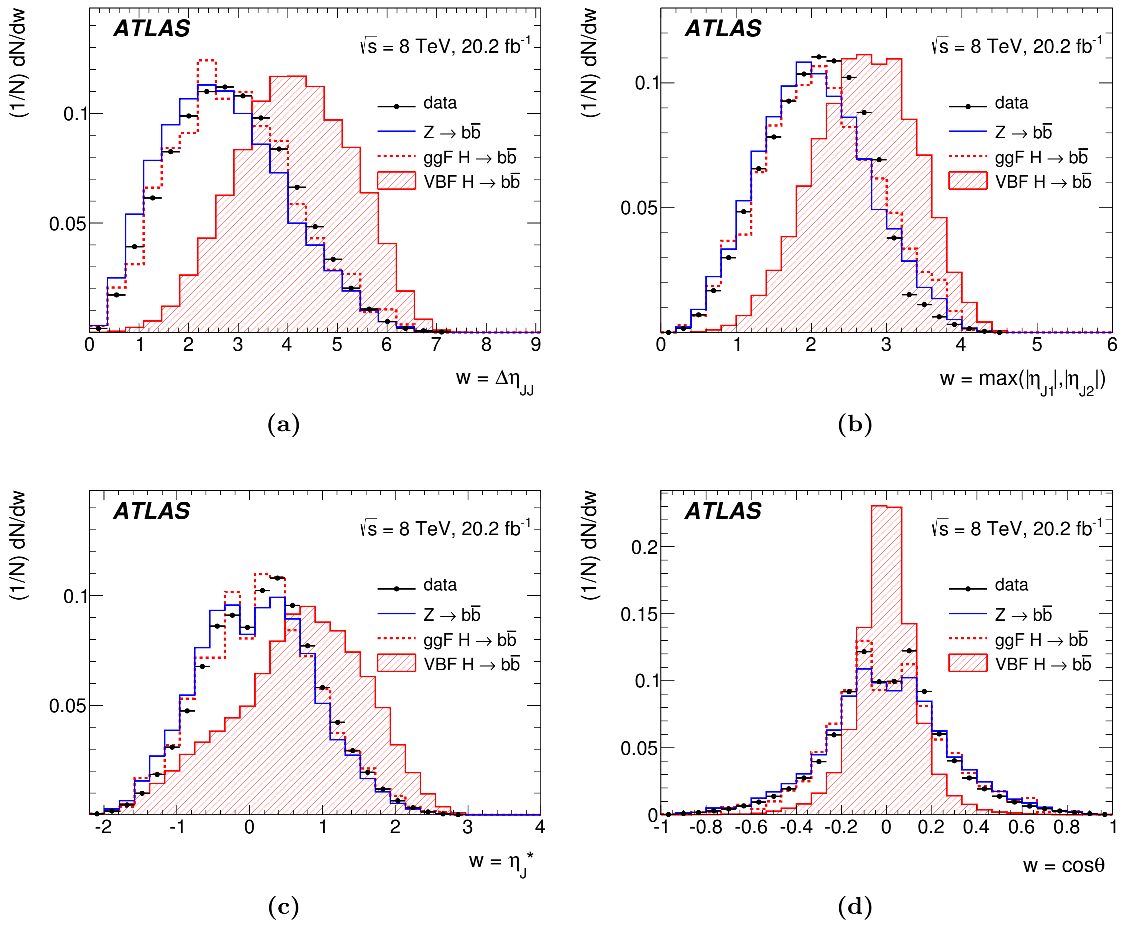

Figure 3. Distributions of the BDT input variables from the data (points) and the simulated samples for VBF $H \to b\bar{b}$ events (shaded histograms), ggF $H \to b\bar{b}$ events (open dashed histograms) and $Z \to b\bar{b}$ events (open solid histograms). The pre-selection criteria are applied to these samples. The variables are: (a) the η separation between the two VBF jets, $\Delta\eta_{JJ}$; (b) the maximum $|\eta|$ of the two VBF jets, $\max(|\eta_{J1}|, |\eta_{J2}|)$; (c) the separation between the $|\eta|$ average of the VBF jets and that of the Higgs jets, $\eta_J^* = (|\eta_{J1}| + |\eta_{J2}|)/2 - (|\eta_{b1}| + |\eta_{b2}|)/2$; and (d) the cosine of the polar angle of the cross product of the VBF jets momenta, $\cos\theta$.

A data-driven method is used to model the m_{bb} distribution of the non-resonant background. Data in the sidebands of the m_{bb} distribution are fit simultaneously to a function which is then interpolated to the signal region. The analytic forms considered are Bernstein polynomials [53], combinations of exponential functions, and combinations of Bernstein polynomials and exponential functions with various numbers of coefficients, and functions with a χ^2 probability greater than 0.05, that do not introduce a bias, are selected. For each form, the minimum number of coefficients is determined by performing an F-test, and the corresponding function is chosen as a candidate function. The fitted signal strength is measured for each candidate function using toy samples. The function giving the smallest bias is used as the nominal distribution. The function giving the second smallest bias is

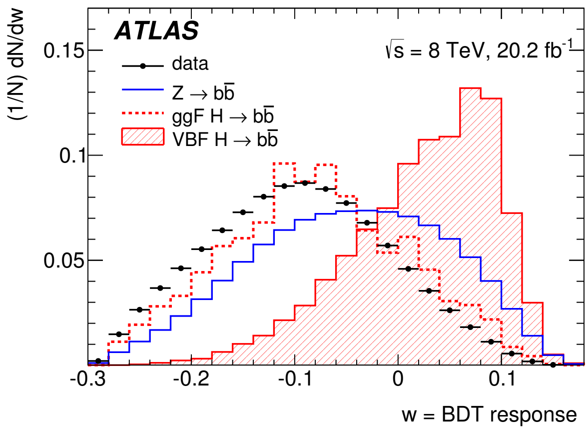

Figure 4. Distributions of the BDT response to the data (points) and to the simulated samples for VBF $H \to b\bar{b}$ events (shaded histogram), ggF $H \to b\bar{b}$ events (open dashed histogram) and $Z \to b\bar{b}$ events (open solid histogram). The pre-selection criteria are applied to these samples.

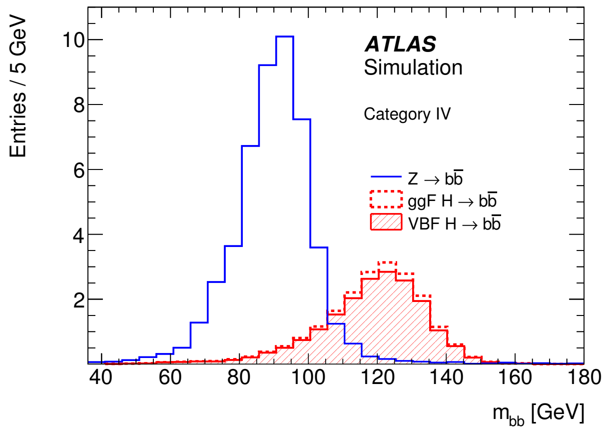

Figure 5. Simulated invariant mass distributions of two b-jets from decays of Higgs bosons, summed for VBF (shaded histogram) and ggF (open dashed histogram) production, as well as from decays of Z bosons (open solid histogram), normalised to the expected contributions in category IV, which gives the highest sensitivity.

taken as an alternative distribution, and is used to estimate the systematic uncertainty due to the choice of analytic function. The shapes of the m_{bb} distributions are observed to be different in the four categories. Bernstein polynomials of different degrees, fourth-order in category I and third-order in the higher-sensitivity categories, are found to best describe the m_{bb} shape of the non-resonant background. The nominal and alternative functions are summarised in table 3.

8 Sources of systematic uncertainty

This section discusses sources of systematic uncertainty: experimental uncertainties, uncertainties on the modelling of the non-resonant background, and theoretical uncertainties

JHEP11(2016)112

	category I	category II	category III	category IV
Nominal	4^{th} Pol.	3^{rd} Pol.	3^{rd} Pol.	3^{rd} Pol.
Alternative	2^{nd} Pol. $\times$ exponential	3 exponentials	2 exponentials	exponential

Table 3. Nominal and alternative functions describing the non-resonant background in the four BDT categories. The fourth-, third-, and second-order Bernstein polynomials are referred to as 4^{th} Pol., 3^{rd} Pol., and 2^{nd} Pol.

on the Higgs and Z processes. The uncertainties can affect the normalisation and the kinematic distributions individually or both together.

8.1 Experimental uncertainties

The dominant experimental uncertainties on the Higgs signal yield arise from the statistical uncertainty due to the finite size of the MC samples, the jet energy scale uncertainty, and the b-jet triggering and tagging, contributing 15%, 10–20%, and 10% respectively, to the total uncertainty on the Higgs yield. Limited MC sizes affect the normalisation via the acceptance of the signal events and the shape of the signal m_{bb} distribution. Several sources contribute to the uncertainty on the jet energy scale [44]. They include the in situ jet calibration, pile-up-dependent corrections and the flavour composition of jets in different event classes. The shape of the m_{bb} distribution for the Higgs signal and the Z background is affected by the jet energy scale uncertainty. Moreover, the change in the jet energy modifies the value of the BDT output and can cause migration of events between BDT categories. The b-jet trigger and tagging efficiencies are another source of systematic uncertainty, contributing 10% to the total uncertainty. They are calibrated using multijet events containing a muon and $t\bar{t}$ events, respectively [54]. The uncertainty on the jet energy resolution contributes about 4%. The uncertainty on the integrated luminosity, 1.9% [55], is included, but is negligible compared to the other uncertainties mentioned above.

8.2 Modelling uncertainties on the m_{bb} shape of the non-resonant background

The uncertainties on the shape of the m_{bb} distribution for the non-resonant background is the largest source of systematic uncertainty, contributing about 80% to the total uncertainty on the Higgs yield. The dominant contributions to this source come from the limited number of events in the m_{bb} sidebands of the data used for the fit to the nominal function, and from the choice of the function. For the latter, an alternative function is chosen for each BDT region, as described in section 7 and listed in table 3. Pseudo-data are generated using the nominal functions and are fit simultaneously in the four BDT categories with nominal and alternative functions. The bin-by-bin differences in the background yield predicted by the two alternative descriptions are used to estimate, by means of an eigenvector decomposition, the corresponding systematic uncertainties.

8.3 Theoretical uncertainties

The uncertainties on the MC modelling of the Higgs signal events contribute about 10% to the total uncertainty on the Higgs yield. The sources for these uncertainties are higher order

JHEP11(2016)112

QCD corrections, the modelling of the underlying event and the parton shower, the PDFs, and the $H \to b\bar{b}$ branching ratio. An uncertainty on higher order QCD corrections for the cross-sections and acceptances is estimated by varying the factorisation and renormalisation scales, μ_{F} and μ_{R}, independently by a factor of two around the nominal values [31] with the constraint $0.5 \leq \mu_{\mathrm{F}}/\mu_{\mathrm{R}} \leq 2$. Higher order corrections to the p_{T} spectrum of the Higgs boson (described in section 3) are an additional source of the modelling uncertainties. This uncertainty is estimated by comparing the results between LO and NLO calculations for VBF production and by varying the factorisation and renormalisation scales for ggF production. Uncertainties related to the simulation of the underlying event and the parton shower are estimated by comparing distributions obtained using POWHEG+PYTHIA8 and POWHEG+HERWIG [56]. The uncertainties on the acceptance due to uncertainties in the PDFs are estimated by studying the change in the acceptance when different PDF sets such as MSTW2008NLO [57] and NNPDF2.3 [58] are used or the CT10 PDF set parameters are varied within their uncertainties. The largest variation in acceptance is taken as a systematic uncertainty. The uncertainty on the $H \to b\bar{b}$ branching ratio, 3.2% [47], is also accounted for.

The uncertainty on higher order QCD corrections to the $Z \to b\bar{b}$ yield is estimated by varying the factorisation and renormalisation scales around the nominal value in the manner described above. It is found to be about 40-50%, depending on the BDT category, out of which about 25% is correlated. These correlated and uncorrelated uncertainties are used to constrain the Z yield in the fit. This process results in about 20-25% to the total uncertainty on the Higgs yield.

9 Statistical procedure and results

A statistical fitting procedure based on the RooStats framework [59, 60] is used to estimate the Higgs signal strength, μ, from the data, where μ is the ratio of the measured signal yield to the SM prediction. A binned likelihood function is constructed as the product of Poisson-probability terms of the bins in the m_{bb} distributions, and of the four different BDT categories.

The impact of systematic uncertainties on the signal and background expectations, presented in section 8, is described by a vector of nuisance parameters (NPs), $\vec{\theta}$. The expected numbers of signal and background events in each bin and category are functions of $\vec{\theta}$. For each NP with an a priori constraint, the prior is taken into account as a Gaussian constraint in the likelihood. The NPs associated with uncertainties in the shape and normalisation of the non-resonant background events, which do not have priors, are determined from the data.

The test statistic q_μ is constructed according to the profile-likelihood ratio:

$$q_\mu = 2\ln(\mathcal{L}(\mu, \vec{\theta}_\mu)/\mathcal{L}(\hat{\mu}, \hat{\vec{\theta}})), \tag{9.1}$$

where $\hat{\mu}$ and $\hat{\vec{\theta}}$ are the parameters that maximise the likelihood, and $\vec{\theta}_\mu$ are the nuisance parameter values that maximise the likelihood for a given μ. This test statistic is used

Source of uncertainty		Uncertainty on μ	
		MVA	Cut-based
Experimental uncertainties	Detector-related	$+0.2/-0.3$	$+1.6/-1.2$
	MC statistics	±0.4	±0.1
Theoretical uncertainties	MC signal modelling	±0.1	±1.3
	Z yield	$+0.6/-0.5$	±1.4
Non-resonant background modelling	Choice of function	±1.0	±1.0
	Sideband statistics	±1.7	±3.7
Statistical uncertainties		±1.3	
Total		±2.3	$+4.6/-4.4$

Table 4. Summary of uncertainties on the Higgs signal strength for the MVA analysis, and for the cut-based analysis. They are estimated at the central values of the signal strength, $\mu = -0.8$ and -5.2 for the MVA and cut-based analyses, respectively. The two systematic uncertainties accounting for non-resonant background modelling are strongly correlated. Their combined value for the MVA analysis is 1.8.

both to measure the compatibility of the background-only model with the data, and to determine exclusion intervals using the CL_S method [61, 62].

The robustness of the fit is validated by generating pseudo-data and estimating the number of signal events for various values of μ. The results of the fit in the four categories are shown in figure 6. The Z yield is constrained to the SM prediction within its theoretical uncertainty, using four independent constraints in the four BDT regions (uncorrelated terms) and a common constraint (correlated term) as described in section 8.3. The ratios of Z yields to the SM predictions (μ_Z) are found to be compatible in all of the four BDT regions. Combined over the four categories, the fit further constrains μ_Z to 0.7 ± 0.2.

The combined Higgs signal strength is -0.8 ± 2.3, where the uncertainty includes both the statistical (±1.3) and systematic ($+1.8/-1.9$) components. The breakdown of the systematic uncertainty on the estimated signal strength is given in table 4. The correlation coefficient between the combined μ and the combined μ_Z is found to be 0.22. In the absence of a signal, the limit on the Higgs signal strength at 95% confidence level (CL) is expected to be 5.4. When Standard Model production is assumed, the expected limit is found to be 5.7. The observed limit is 4.4.

The compatibility between the measured Z yield and its SM prediction is alternatively tested by removing its a priori constraint from the fit. In this case a value of $\mu_Z = 0.3 \pm 0.3$ is extracted from the fit, to be compared to the theory prediction of 1.0 ± 0.4. The absence of the Z constraint modifies the combined Higgs signal strength slightly, to -0.5 ± 2.3.

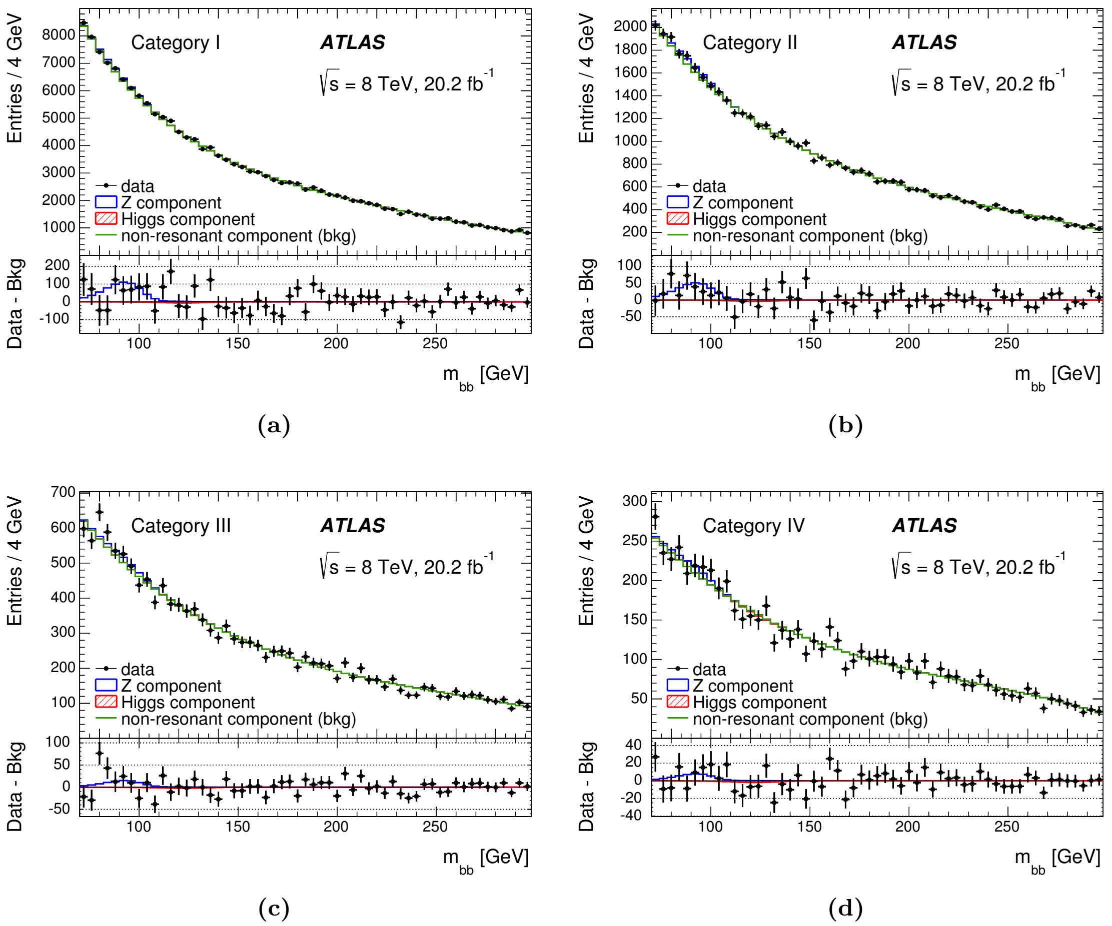

Figure 6. Results of the profile-likelihood fit to the m_{bb} distributions in the four BDT categories. The points represent the data, and the histograms represent the non-resonant background, Z, and Higgs contributions. In the lower panels, the data after subtraction of the non-resonant background (points) are compared with the fit to the Z (open histogram) and Higgs (shaded histogram) contributions.

10 Cut-based analysis

An alternative analysis is performed based on kinematic cuts. While the MVA performs a simultaneous fit to the m_{bb} distributions of the four samples categorised by the BDT response, the cut-based analysis performs a fit to one m_{bb} distribution of the entire sample in the mass range between 70 GeV and 300 GeV. Events are required to satisfy kinematic criteria featuring the VBF Higgs final state. Events must not have any additional jet with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.4$, and must satisfy $|\Delta\eta_{JJ}| > 3.0$ and $m_{JJ} > 650$ GeV. Figure 7 shows the m_{bb} distribution of 32906 events in the data that satisfy the selection criteria. The number of signal events in the data is expected to be 68.8, with about 15% coming from ggF production. This can be compared to 158.9 events in the MVA, as obtained by summing the corresponding numbers in table 2 over the four categories, where about 28% comes from ggF production.

JHEP11(2016)112

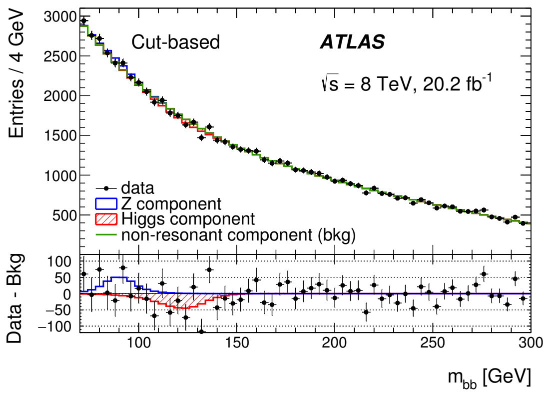

Figure 7. Distribution of m_{bb} for events selected in the cut-based analysis. The points represent the data, and the histograms represent the non-resonant background, Z, and Higgs contributions. In the lower panel, the data after subtraction of the non-resonant background (points) are compared with the fit to the Z (open histogram) and Higgs (shaded histogram) contributions. The Higgs yield extracted from the fit is consistent with zero.

The cut-based analysis uses an unbinned maximum likelihood fit. The resonance shapes of the m_{bb} distributions for the Higgs and Z events are determined by a fit to a Bukin function [63] using MC events. The analytic functions describing the non-resonant background are studied by using events that satisfy the pre-selection criteria described in section 5. A fourth-order polynomial is chosen as the nominal function and a fifth-order polynomial is chosen as the alternative function.

The Higgs yield is left free to vary, but the Z yield is fixed to its SM prediction. The robustness of the fit is validated by generating pseudo-data and constructing pulls of the estimated number of Higgs events for various values of μ. The fit results are presented in figure 7. The Higgs signal strength is measured to be $\mu = -5.2 \pm 3.7(\text{stat.})^{+2.7}_{-2.5}(\text{syst.})$, where the statistical uncertainty includes the statistical uncertainty on the non-resonant background modelling (see table 4). The sources of systematic uncertainty are the same as those for the MVA analysis as described in section 8 and are summarised in table 4. The uncertainties on μ are estimated as the changes in μ when the sources are varied within their uncertainties. Higher-order corrections to the Z samples and to the signal samples, the choice of function describing the non-resonant background, and the jet energy scale are the dominant sources of systematic uncertainty, each contributing about 40–50% to the total systematic uncertainty on the Higgs signal strength. The magnitudes of experimental and theoretical uncertianties are scaled with the central value of μ, as illustrated in table 4 except for the case of the MC statistical uncertainty. This is due to the fact that the MVA divides the MC samples into four categories, and uses the signal m_{bb} distribution directly in the fit as a template while the cut-based analysis uses an interpolated function. The upper limit on the strength is found to be 5.4 at the 95% CL, which can be compared to the expected limit values of 8.5 in the background-only hypothesis and 9.5 if Standard Model production is assumed. These results are consistent with those of the MVA. As expected, the cut-based analysis is less sensitive than the MVA.

JHEP11(2016)112

11 Summary

A search for the Standard Model Higgs boson produced by vector-boson fusion and decaying into a pair of bottom quarks is presented. The dataset analysed corresponds to an integrated luminosity of 20.2 fb^{-1} from pp collisions at $\sqrt{s} = 8$ TeV, recorded by the ATLAS experiment during Run 1 of the LHC. Events are selected using the distinct final state of the VBF $H \to b\bar{b}$ signal, which is the presence of four energetic jets: two b-jets from the Higgs boson decay in the central region of the detector and two jets in the forward/backward region. To improve the sensitivity, a multivariate analysis is used, exploiting the topology of the VBF Higgs final state and the properties of jets. The signal yield is estimated by performing a fit to the invariant mass distribution of the two b-jets in the range $70 < m_{bb} < 300$ GeV and assuming a Higgs boson mass of 125 GeV. The ratio of the Higgs signal yield to the SM prediction is measured to be $\mu = -0.8 \pm 1.3(\text{stat.})^{+1.8}_{-1.9}(\text{syst.}) = -0.8 \pm 2.3$. The upper limit on μ is observed to be $\mu = 4.4$ at the 95% CL, which should be compared to the expected limits of 5.4 in the background-only hypothesis and 5.7 if Standard Model production is assumed. An alternative analysis is performed using kinematic selection criteria and provides consistent results: $\mu = -5.2^{+4.6}_{-4.4}$ and a 95% CL upper limit of 5.4.

Acknowledgments

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

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, the Canada Council, CANARIE, CRC, Compute Canada, FQRNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, FP7, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d'Avenir Labex and Idex, ANR, Région Auvergne and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF; BSF, GIF and Minerva, Israel; BRF, Norway;

JHEP11(2016)112

Generalitat de Catalunya, Generalitat Valenciana, Spain; the Royal Society and Leverhulme Trust, United Kingdom.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (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. [64].

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JHEP11(2016)112

The ATLAS collaboration

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JHEP11(2016)112

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JHEP11(2016)112

A. Cortes-Gonzalez[13], G. Cortiana[102], G. Costa[93a], M.J. Costa[167], D. Costanzo[140], G. Cottin[30], G. Cowan[79], B.E. Cox[86], K. Cranmer[111], S.J. Crawley[55], G. Cree[31], S. Crépé-Renaudin[57], F. Crescioli[82], W.A. Cribbs[147a,147b], M. Crispin Ortuzar[121], M. Cristinziani[23], V. Croft[107], G. Crosetti[39a,39b], T. Cuhadar Donszelmann[140], J. Cummings[176], M. Curatolo[49], J. Cúth[85], C. Cuthbert[151], H. Czirr[142], P. Czodrowski[3], G. D'amen[22a,22b], S. D'Auria[55], M. D'Onofrio[76], M.J. Da Cunha Sargedas De Sousa[127a,127b], C. Da Via[86], W. Dabrowski[40a], T. Dado[145a], T. Dai[91], O. Dale[15], F. Dallaire[96], C. Dallapiccola[88], M. Dam[38], J.R. Dandoy[33], N.P. Dang[50], A.C. Daniells[19], N.S. Dann[86], M. Danninger[168], M. Dano Hoffmann[137], V. Dao[50], G. Darbo[52a], S. Darmora[8], J. Dassoulas[3], A. Dattagupta[63], W. Davey[23], C. David[169], T. Davidek[130], M. Davies[154], P. Davison[80], E. Dawe[90], I. Dawson[140], R.K. Daya-Ishmukhametova[88], K. De[8], R. de Asmundis[105a], A. De Benedetti[114], S. De Castro[22a,22b], S. De Cecco[82], N. De Groot[107], P. de Jong[108], H. De la Torre[84], F. De Lorenzi[66], A. De Maria[56], D. De Pedis[133a], A. De Salvo[133a], U. De Sanctis[150], A. De Santo[150], J.B. De Vivie De Regie[118], W.J. Dearnaley[74], R. Debbe[27], C. Debenedetti[138], D.V. Dedovich[67], N. Dehghanian[3], I. Deigaard[108], M. Del Gaudio[39a,39b], J. Del Peso[84], T. Del Prete[125a,125b], D. Delgove[118], F. Deliot[137], C.M. Delitzsch[51], M. Deliyergiyev[77], A. Dell'Acqua[32], L. Dell'Asta[24], M. Dell'Orso[125a,125b], M. Della Pietra[105a,k], D. della Volpe[51], M. Delmastro[5], P.A. Delsart[57], C. Deluca[108], D.A. DeMarco[159], S. Demers[176], M. Demichev[67], A. Demilly[82], S.P. Denisov[131], D. Denysiuk[137], D. Derendarz[41], J.E. Derkaoui[136d], F. Derue[82], P. Dervan[76], K. Desch[23], C. Deterre[44], K. Dette[45], P.O. Deviveiros[32], A. Dewhurst[132], S. Dhaliwal[25], A. Di Ciaccio[134a,134b], L. Di Ciaccio[5], W.K. Di Clemente[123], C. Di Donato[133a,133b], A. Di Girolamo[32], B. Di Girolamo[32], B. Di Micco[135a,135b], R. Di Nardo[32], A. Di Simone[50], R. Di Sipio[159], D. Di Valentino[31], C. Diaconu[87], M. Diamond[159], F.A. Dias[48], M.A. Diaz[34a], E.B. Diehl[91], J. Dietrich[17], S. Diglio[87], A. Dimitrievska[14], J. Dingfelder[23], P. Dita[28b], S. Dita[28b], F. Dittus[32], F. Djama[87], T. Djobava[53b], J.I. Djuvsland[60a], M.A.B. do Vale[26c], D. Dobos[32], M. Dobre[28b], C. Doglioni[83], T. Dohmae[156], J. Dolejsi[130], Z. Dolezal[130], B.A. Dolgoshein[99,*], M. Donadelli[26d], S. Donati[125a,125b], P. Dondero[122a,122b], J. Donini[36], J. Dopke[132], A. Doria[105a], M.T. Dova[73], A.T. Doyle[55], E. Drechsler[56], M. Dris[10], Y. Du[35d], J. Duarte-Campderros[154], E. Duchovni[172], G. Duckeck[101], O.A. Ducu[96,m], D. Duda[108], A. Dudarev[32], E.M. Duffield[16], L. Duflot[118], L. Duguid[79], M. Dührssen[32], M. Dumancic[172], M. Dunford[60a], H. Duran Yildiz[4a], M. Düren[54], A. Durglishvili[53b], D. Duschinger[46], B. Dutta[44], M. Dyndal[44], C. Eckardt[44], K.M. Ecker[102], R.C. Edgar[91], N.C. Edwards[48], T. Eifert[32], G. Eigen[15], K. Einsweiler[16], T. Ekelof[165], M. El Kacimi[136c], V. Ellajosyula[87], M. Ellert[165], S. Elles[5], F. Ellinghaus[175], A.A. Elliot[169], N. Ellis[32], J. Elmsheuser[27], M. Elsing[32], D. Emeliyanov[132], Y. Enari[156], O.C. Endner[85], M. Endo[119], J.S. Ennis[170], J. Erdmann[45], A. Ereditato[18], G. Ernis[175], J. Ernst[2], M. Ernst[27], S. Errede[166], E. Ertel[85], M. Escalier[118], H. Esch[45], C. Escobar[126], B. Esposito[49], A.I. Etienvre[137], E. Etzion[154], H. Evans[63], A. Ezhilov[124], F. Fabbri[22a,22b], L. Fabbri[22a,22b], G. Facini[33], R.M. Fakhrutdinov[131], S. Falciano[133a], R.J. Falla[80], J. Faltova[130], Y. Fang[35a], M. Fanti[93a,93b], A. Farbin[8], A. Farilla[135a], C. Farina[126], T. Farooque[13], S. Farrell[16], S.M. Farrington[170], P. Farthouat[32], F. Fassi[136e], P. Fassnacht[32], D. Fassouliotis[9], M. Faucci Giannelli[79], A. Favareto[52a,52b], W.J. Fawcett[121], L. Fayard[118], O.L. Fedin[124,n], W. Fedorko[168], S. Feigl[120], L. Feligioni[87], C. Feng[35d], E.J. Feng[32], H. Feng[91], A.B. Fenyuk[131], L. Feremenga[8], P. Fernandez Martinez[167], S. Fernandez Perez[13], J. Ferrando[55], A. Ferrari[165], P. Ferrari[108], R. Ferrari[122a], D.E. Ferreira de Lima[60b], A. Ferrer[167], D. Ferrere[51], C. Ferretti[91], A. Ferretto Parodi[52a,52b], F. Fiedler[85], A. Filipčič[77], M. Filipuzzi[44], F. Filthaut[107], M. Fincke-Keeler[169], K.D. Finelli[151], M.C.N. Fiolhais[127a,127c], L. Fiorini[167], A. Firan[42], A. Fischer[2], C. Fischer[13], J. Fischer[175], W.C. Fisher[92], N. Flaschel[44], I. Fleck[142], P. Fleischmann[91], G.T. Fletcher[140], R.R.M. Fletcher[123], T. Flick[175], A. Floderus[83], L.R. Flores Castillo[62a], M.J. Flowerdew[102], G.T. Forcolin[86], A. Formica[137], A. Forti[86],

JHEP11(2016)112

A.G. Foster[19], D. Fournier[118], H. Fox[74], S. Fracchia[13], P. Francavilla[82], M. Franchini[22a,22b], D. Francis[32], L. Franconi[120], M. Franklin[59], M. Frate[163], M. Fraternali[122a,122b], D. Freeborn[80], S.M. Fressard-Batraneanu[32], F. Friedrich[46], D. Froidevaux[32], J.A. Frost[121], C. Fukunaga[157], E. Fullana Torregrosa[85], T. Fusayasu[103], J. Fuster[167], C. Gabaldon[57], O. Gabizon[175], A. Gabrielli[22a,22b], A. Gabrielli[16], G.P. Gach[40a], S. Gadatsch[32], S. Gadomski[51], G. Gagliardi[52a,52b], L.G. Gagnon[96], P. Gagnon[63], C. Galea[107], B. Galhardo[127a,127c], E.J. Gallas[121], B.J. Gallop[132], P. Gallus[129], G. Galster[38], K.K. Gan[112], J. Gao[35b,87], Y. Gao[48], Y.S. Gao[144,f], F.M. Garay Walls[48], C. García[167], J.E. García Navarro[167], M. Garcia-Sciveres[16], R.W. Gardner[33], N. Garelli[144], V. Garonne[120], A. Gascon Bravo[44], C. Gatti[49], A. Gaudiello[52a,52b], G. Gaudio[122a], B. Gaur[142], L. Gauthier[96], I.L. Gavrilenko[97], C. Gay[168], G. Gaycken[23], E.N. Gazis[10], Z. Gecse[168], C.N.P. Gee[132], Ch. Geich-Gimbel[23], M. Geisen[85], M.P. Geisler[60a], C. Gemme[52a], M.H. Genest[57], C. Geng[35b,o], S. Gentile[133a,133b], S. George[79], D. Gerbaudo[13], A. Gershon[154], S. Ghasemi[142], H. Ghazlane[136b], M. Ghneimat[23], B. Giacobbe[22a], S. Giagu[133a,133b], P. Giannetti[125a,125b], B. Gibbard[27], S.M. Gibson[79], M. Gignac[168], M. Gilchriese[16], T.P.S. Gillam[30], D. Gillberg[31], G. Gilles[175], D.M. Gingrich[3,d], N. Giokaris[9], M.P. Giordani[164a,164c], F.M. Giorgi[22a], F.M. Giorgi[17], P.F. Giraud[137], P. Giromini[59], D. Giugni[93a], F. Giuli[121], C. Giuliani[102], M. Giulini[60b], B.K. Gjelsten[120], S. Gkaitatzis[155], I. Gkialas[155], E.L. Gkougkousis[118], L.K. Gladilin[100], C. Glasman[84], J. Glatzer[32], P.C.F. Glaysher[48], A. Glazov[44], M. Goblirsch-Kolb[102], J. Godlewski[41], S. Goldfarb[91], T. Golling[51], D. Golubkov[131], A. Gomes[127a,127b,127d], R. Gonçalo[127a], J. Goncalves Pinto Firmino Da Costa[137], L. Gonella[19], A. Gongadze[67], S. González de la Hoz[167], G. Gonzalez Parra[13], S. Gonzalez-Sevilla[51], L. Goossens[32], P.A. Gorbounov[98], H.A. Gordon[27], I. Gorelov[106], B. Gorini[32], E. Gorini[75a,75b], A. Gorišek[77], E. Gornicki[41], A.T. Goshaw[47], C. Gössling[45], M.I. Gostkin[67], C.R. Goudet[118], D. Goujdami[136c], A.G. Goussiou[139], N. Govender[146b,p], E. Gozani[153], L. Graber[56], I. Grabowska-Bold[40a], P.O.J. Gradin[57], P. Grafström[22a,22b], J. Gramling[51], E. Gramstad[120], S. Grancagnolo[17], V. Gratchev[124], P.M. Gravila[28e], H.M. Gray[32], E. Graziani[135a], Z.D. Greenwood[81,q], C. Grefe[23], K. Gregersen[80], I.M. Gregor[44], P. Grenier[144], K. Grevtsov[5], J. Griffiths[8], A.A. Grillo[138], K. Grimm[74], S. Grinstein[13,r], Ph. Gris[36], J.-F. Grivaz[118], S. Groh[85], J.P. Grohs[46], E. Gross[172], J. Grosse-Knetter[56], G.C. Grossi[81], Z.J. Grout[150], L. Guan[91], W. Guan[173], J. Guenther[129], F. Guescini[51], D. Guest[163], O. Gueta[154], E. Guido[52a,52b], T. Guillemin[5], S. Guindon[2], U. Gul[55], C. Gumpert[32], J. Guo[35e], Y. Guo[35b,o], S. Gupta[121], G. Gustavino[133a,133b], P. Gutierrez[114], N.G. Gutierrez Ortiz[80], C. Gutschow[46], C. Guyot[137], C. Gwenlan[121], C.B. Gwilliam[76], A. Haas[111], C. Haber[16], H.K. Hadavand[8], N. Haddad[136e], A. Hadef[87], P. Haefner[23], S. Hageböck[23], Z. Hajduk[41], H. Hakobyan[177,*], M. Haleem[44], J. Haley[115], G. Halladjian[92], G.D. Hallewell[87], K. Hamacher[175], P. Hamal[116], K. Hamano[169], A. Hamilton[146a], G.N. Hamity[140], P.G. Hamnett[44], L. Han[35b], K. Hanagaki[68,s], K. Hanawa[156], M. Hance[138], B. Haney[123], P. Hanke[60a], R. Hanna[137], J.B. Hansen[38], J.D. Hansen[38], M.C. Hansen[23], P.H. Hansen[38], K. Hara[161], A.S. Hard[173], T. Harenberg[175], F. Hariri[118], S. Harkusha[94], R.D. Harrington[48], P.F. Harrison[170], F. Hartjes[108], N.M. Hartmann[101], M. Hasegawa[69], Y. Hasegawa[141], A. Hasib[114], S. Hassani[137], S. Haug[18], R. Hauser[92], L. Hauswald[46], M. Havranek[128], C.M. Hawkes[19], R.J. Hawkings[32], D. Hayden[92], C.P. Hays[121], J.M. Hays[78], H.S. Hayward[76], S.J. Haywood[132], S.J. Head[19], T. Heck[85], V. Hedberg[83], L. Heelan[8], S. Heim[123], T. Heim[16], B. Heinemann[16], J.J. Heinrich[101], L. Heinrich[111], C. Heinz[54], J. Hejbal[128], L. Helary[24], S. Hellman[147a,147b], C. Helsens[32], J. Henderson[121], R.C.W. Henderson[74], Y. Heng[173], S. Henkelmann[168], A.M. Henriques Correia[32], S. Henrot-Versille[118], G.H. Herbert[17], Y. Hernández Jiménez[167], G. Herten[50], R. Hertenberger[101], L. Hervas[32], G.G. Hesketh[80], N.P. Hessey[108], J.W. Hetherly[42], R. Hickling[78], E. Higón-Rodriguez[167], E. Hill[169], J.C. Hill[30], K.H. Hiller[44], S.J. Hillier[19],

JHEP11(2016)112

I. Hinchliffe[16], E. Hines[123], R.R. Hinman[16], M. Hirose[158], D. Hirschbuehl[175], J. Hobbs[149], N. Hod[160a], M.C. Hodgkinson[140], P. Hodgson[140], A. Hoecker[32], M.R. Hoeferkamp[106], F. Hoenig[101], D. Hohn[23], T.R. Holmes[16], M. Homann[45], T.M. Hong[126], B.H. Hooberman[166], W.H. Hopkins[117], Y. Horii[104], A.J. Horton[143], J-Y. Hostachy[57], S. Hou[152], A. Hoummada[136a], J. Howarth[44], M. Hrabovsky[116], I. Hristova[17], J. Hrivnac[118], T. Hryn'ova[5], A. Hrynevich[95], C. Hsu[146c], P.J. Hsu[152,t], S.-C. Hsu[139], D. Hu[37], Q. Hu[35b], Y. Huang[44], Z. Hubacek[129], F. Hubaut[87], F. Huegging[23], T.B. Huffman[121], E.W. Hughes[37], G. Hughes[74], M. Huhtinen[32], T.A. Hülsing[85], P. Huo[149], N. Huseynov[67,b], J. Huston[92], J. Huth[59], G. Iacobucci[51], G. Iakovidis[27], I. Ibragimov[142], L. Iconomidou-Fayard[118], E. Ideal[176], Z. Idrissi[136e], P. Iengo[32], O. Igonkina[108,u], T. Iizawa[171], Y. Ikegami[68], M. Ikeno[68], Y. Ilchenko[11,v], D. Iliadis[155], N. Ilic[144], T. Ince[102], G. Introzzi[122a,122b], P. Ioannou[9,*], M. Iodice[135a], K. Iordanidou[37], V. Ippolito[59], M. Ishino[70], M. Ishitsuka[158], R. Ishmukhametov[112], C. Issever[121], S. Istin[20a], F. Ito[161], J.M. Iturbe Ponce[86], R. Iuppa[134a,134b], W. Iwanski[41], H. Iwasaki[68], J.M. Izen[43], V. Izzo[105a], S. Jabbar[3], B. Jackson[123], M. Jackson[76], P. Jackson[1], V. Jain[2], K.B. Jakobi[85], K. Jakobs[50], S. Jakobsen[32], T. Jakoubek[128], D.O. Jamin[115], D.K. Jana[81], E. Jansen[80], R. Jansky[64], J. Janssen[23], M. Janus[56], G. Jarlskog[83], N. Javadov[67,b], T. Javůrek[50], F. Jeanneau[137], L. Jeanty[16], J. Jejelava[53a,w], G.-Y. Jeng[151], D. Jennens[90], P. Jenni[50,x], J. Jentzsch[45], C. Jeske[170], S. Jézéquel[5], H. Ji[173], J. Jia[149], H. Jiang[66], Y. Jiang[35b], S. Jiggins[80], J. Jimenez Pena[167], S. Jin[35a], A. Jinaru[28b], O. Jinnouchi[158], P. Johansson[140], K.A. Johns[7], W.J. Johnson[139], K. Jon-And[147a,147b], G. Jones[170], R.W.L. Jones[74], S. Jones[7], T.J. Jones[76], J. Jongmanns[60a], P.M. Jorge[127a,127b], J. Jovicevic[160a], X. Ju[173], A. Juste Rozas[13,r], M.K. Köhler[172], A. Kaczmarska[41], M. Kado[118], H. Kagan[112], M. Kagan[144], S.J. Kahn[87], E. Kajomovitz[47], C.W. Kalderon[121], A. Kaluza[85], S. Kama[42], A. Kamenshchikov[131], N. Kanaya[156], S. Kaneti[30], L. Kanjir[77], V.A. Kantserov[99], J. Kanzaki[68], B. Kaplan[111], L.S. Kaplan[173], A. Kapliy[33], D. Kar[146c], K. Karakostas[10], A. Karamaoun[3], N. Karastathis[10], M.J. Kareem[56], E. Karentzos[10], M. Karnevskiy[85], S.N. Karpov[67], Z.M. Karpova[67], K. Karthik[111], V. Kartvelishvili[74], A.N. Karyukhin[131], K. Kasahara[161], L. Kashif[173], R.D. Kass[112], A. Kastanas[15], Y. Kataoka[156], C. Kato[156], A. Katre[51], J. Katzy[44], K. Kawagoe[72], T. Kawamoto[156], G. Kawamura[56], S. Kazama[156], V.F. Kazanin[110,c], R. Keeler[169], R. Kehoe[42], J.S. Keller[44], J.J. Kempster[79], K Kentaro[104], H. Keoshkerian[159], O. Kepka[128], B.P. Kerševan[77], S. Kersten[175], R.A. Keyes[89], F. Khalil-zada[12], A. Khanov[115], A.G. Kharlamov[110,c], T.J. Khoo[51], V. Khovanskiy[98], E. Khramov[67], J. Khubua[53b,y], S. Kido[69], H.Y. Kim[8], S.H. Kim[161], Y.K. Kim[33], N. Kimura[155], O.M. Kind[17], B.T. King[76], M. King[167], S.B. King[168], J. Kirk[132], A.E. Kiryunin[102], T. Kishimoto[69], D. Kisielewska[40a], F. Kiss[50], K. Kiuchi[161], O. Kivernyk[137], E. Kladiva[145b], M.H. Klein[37], M. Klein[76], U. Klein[76], K. Kleinknecht[85], P. Klimek[147a,147b], A. Klimentov[27], R. Klingenberg[45], J.A. Klinger[140], T. Klioutchnikova[32], E.-E. Kluge[60a], P. Kluit[108], S. Kluth[102], J. Knapik[41], E. Kneringer[64], E.B.F.G. Knoops[87], A. Knue[55], A. Kobayashi[156], D. Kobayashi[158], T. Kobayashi[156], M. Kobel[46], M. Kocian[144], P. Kodys[130], T. Koffas[31], E. Koffeman[108], T. Koi[144], H. Kolanoski[17], M. Kolb[60b], I. Koletsou[5], A.A. Komar[97,*], Y. Komori[156], T. Kondo[68], N. Kondrashova[44], K. Köneke[50], A.C. König[107], T. Kono[68,z], R. Konoplich[111,aa], N. Konstantinidis[80], R. Kopeliansky[63], S. Koperny[40a], L. Köpke[85], A.K. Kopp[50], K. Korcyl[41], K. Kordas[155], A. Korn[80], A.A. Korol[110,c], I. Korolkov[13], E.V. Korolkova[140], O. Kortner[102], S. Kortner[102], T. Kosek[130], V.V. Kostyukhin[23], A. Kotwal[47], A. Kourkoumeli-Charalampidi[155], C. Kourkoumelis[9], V. Kouskoura[27], A.B. Kowalewska[41], R. Kowalewski[169], T.Z. Kowalski[40a], C. Kozakai[156], W. Kozanecki[137], A.S. Kozhin[131], V.A. Kramarenko[100], G. Kramberger[77], D. Krasnopevtsev[99], M.W. Krasny[82], A. Krasznahorkay[32], J.K. Kraus[23], A. Kravchenko[27], M. Kretz[60c], J. Kretzschmar[76], K. Kreutzfeldt[54], P. Krieger[159], K. Krizka[33], K. Kroeninger[45], H. Kroha[102], J. Kroll[123], J. Kroseberg[23], J. Krstic[14], U. Kruchonak[67], H. Krüger[23],

N. Krumnack[66], A. Kruse[173], M.C. Kruse[47], M. Kruskal[24], T. Kubota[90], H. Kucuk[80], S. Kuday[4b], J.T. Kuechler[175], S. Kuehn[50], A. Kugel[60c], F. Kuger[174], A. Kuhl[138], T. Kuhl[44], V. Kukhtin[67], R. Kukla[137], Y. Kulchitsky[94], S. Kuleshov[34b], M. Kuna[133a,133b], T. Kunigo[70], A. Kupco[128], H. Kurashige[69], Y.A. Kurochkin[94], V. Kus[128], E.S. Kuwertz[169], M. Kuze[158], J. Kvita[116], T. Kwan[169], D. Kyriazopoulos[140], A. La Rosa[102], J.L. La Rosa Navarro[26d], L. La Rotonda[39a,39b], C. Lacasta[167], F. Lacava[133a,133b], J. Lacey[31], H. Lacker[17], D. Lacour[82], V.R. Lacuesta[167], E. Ladygin[67], R. Lafaye[5], B. Laforge[82], T. Lagouri[176], S. Lai[56], S. Lammers[63], W. Lampl[7], E. Lançon[137], U. Landgraf[50], M.P.J. Landon[78], V.S. Lang[60a], J.C. Lange[13], A.J. Lankford[163], F. Lanni[27], K. Lantzsch[23], A. Lanza[122a], S. Laplace[82], C. Lapoire[32], J.F. Laporte[137], T. Lari[93a], F. Lasagni Manghi[22a,22b], M. Lassnig[32], P. Laurelli[49], W. Lavrijsen[16], A.T. Law[138], P. Laycock[76], T. Lazovich[59], M. Lazzaroni[93a,93b], B. Le[90], O. Le Dortz[82], E. Le Guirriec[87], E.P. Le Quilleuc[137], M. LeBlanc[169], T. LeCompte[6], F. Ledroit-Guillon[57], C.A. Lee[27], S.C. Lee[152], L. Lee[1], G. Lefebvre[82], M. Lefebvre[169], F. Legger[101], C. Leggett[16], A. Lehan[76], G. Lehmann Miotto[32], X. Lei[7], W.A. Leight[31], A. Leisos[155,ab], A.G. Leister[176], M.A.L. Leite[26d], R. Leitner[130], D. Lellouch[172], B. Lemmer[56], K.J.C. Leney[80], T. Lenz[23], B. Lenzi[32], R. Leone[7], S. Leone[125a,125b], C. Leonidopoulos[48], S. Leontsinis[10], G. Lerner[150], C. Leroy[96], A.A.J. Lesage[137], C.G. Lester[30], M. Levchenko[124], J. Levêque[5], D. Levin[91], L.J. Levinson[172], M. Levy[19], D. Lewis[78], A.M. Leyko[23], M. Leyton[43], B. Li[35b,o], H. Li[149], H.L. Li[33], L. Li[47], L. Li[35e], Q. Li[35a], S. Li[47], X. Li[86], Y. Li[142], Z. Liang[35a], B. Liberti[134a], A. Liblong[159], P. Lichard[32], K. 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Manhaes de Andrade Filho[26b], J. Manjarres Ramos[160b], A. Mann[101], A. Manousos[32], B. Mansoulie[137], J.D. Mansour[35a], R. Mantifel[89], M. Mantoani[56], S. Manzoni[93a,93b], L. Mapelli[32], G. Marceca[29], L. March[51], G. Marchiori[82], M. Marcisovsky[128], M. Marjanovic[14], D.E. Marley[91], F. Marroquim[26a], S.P. Marsden[86], Z. Marshall[16], S. Marti-Garcia[167], B. Martin[92], T.A. Martin[170], V.J. Martin[48], B. Martin dit Latour[15], M. Martinez[13,r], S. Martin-Haugh[132], V.S. Martoiu[28b], A.C. Martyniuk[80], M. Marx[139], A. Marzin[32], L. Masetti[85], T. Mashimo[156], R. Mashinistov[97], J. Masik[86], A.L. Maslennikov[110,c], I. Massa[22a,22b], L. Massa[22a,22b], P. Mastrandrea[5], A. Mastroberardino[39a,39b], T. Masubuchi[156], P. Mättig[175], J. Mattmann[85], J. Maurer[28b], S.J. Maxfield[76], D.A. Maximov[110,c], R. Mazini[152], S.M. Mazza[93a,93b], N.C. Mc Fadden[106], G. Mc Goldrick[159], S.P. Mc Kee[91], A. McCarn[91], R.L. McCarthy[149], T.G. McCarthy[31], L.I. McClymont[80], E.F. McDonald[90], K.W. McFarlane[58,*], J.A. Mcfayden[80], G. Mchedlidze[56], S.J. McMahon[132], R.A. McPherson[169,l], M. Medinnis[44], S. Meehan[139], S. Mehlhase[101], A. Mehta[76], K. Meier[60a], C. Meineck[101], B. Meirose[43], D. Melini[167], B.R. Mellado Garcia[146c], M. Melo[145a], F. Meloni[18], A. Mengarelli[22a,22b], S. Menke[102], E. Meoni[162], S. Mergelmeyer[17], P. Mermod[51], L. Merola[105a,105b], C. Meroni[93a], F.S. Merritt[33], A. Messina[133a,133b], J. Metcalfe[6], A.S. Mete[163], C. Meyer[85], C. Meyer[123], J-P. Meyer[137], J. Meyer[108], H. Meyer Zu Theenhausen[60a], F. Miano[150], R.P. Middleton[132], S. Miglioranzi[52a,52b], L. Mijović[23], G. Mikenberg[172], M. Mikestikova[128], M. Mikuž[77], M. Milesi[90], A. Milic[64], D.W. Miller[33], C. Mills[48], A. Milov[172], D.A. Milstead[147a,147b], A.A. Minaenko[131], Y. Minami[156], I.A. Minashvili[67], A.I. Mincer[111], B. Mindur[40a], M. Mineev[67], Y. Ming[173], L.M. Mir[13], K.P. Mistry[123], T. Mitani[171], J. Mitrevski[101], V.A. Mitsou[167], A. Miucci[51], P.S. Miyagawa[140], J.U. Mjörnmark[83], T. Moa[147a,147b], K. Mochizuki[96], S. Mohapatra[37], S. Molander[147a,147b], R. Moles-Valls[23], R. Monden[70], M.C. Mondragon[92], K. Mönig[44], J. Monk[38], E. Monnier[87], A. Montalbano[149], J. Montejo Berlingen[32], F. Monticelli[73], S. Monzani[93a,93b], R.W. Moore[3], N. Morange[118], D. Moreno[21], M. Moreno Llácer[56], P. Morettini[52a], D. Mori[143], T. Mori[156], M. Morii[59], M. Morinaga[156], V. Morisbak[120], S. Moritz[85], A.K. Morley[151], G. Mornacchi[32], J.D. Morris[78], S.S. Mortensen[38], L. Morvaj[149], M. Mosidze[53b], J. Moss[144], K. Motohashi[158], R. Mount[144], E. Mountricha[27], S.V. Mouraviev[97,*], E.J.W. Moyse[88], S. Muanza[87], R.D. Mudd[19], F. Mueller[102], J. Mueller[126], R.S.P. Mueller[101], T. Mueller[30], D. Muenstermann[74], P. Mullen[55], G.A. Mullier[18], F.J. Munoz Sanchez[86], J.A. Murillo Quijada[19], W.J. Murray[170,132], H. Musheghyan[56], M. Muškinja[77], A.G. Myagkov[131,ae], M. Myska[129], B.P. Nachman[144], O. Nackenhorst[51], K. Nagai[121], R. Nagai[68,z], K. Nagano[68], Y. Nagasaka[61], K. Nagata[161], M. Nagel[50], E. Nagy[87], A.M. Nairz[32], Y. Nakahama[32], K. Nakamura[68], T. Nakamura[156], I. Nakano[113], H. Namasivayam[43], R.F. Naranjo Garcia[44], R. Narayan[11], D.I. Narrias Villar[60a], I. Naryshkin[124], T. Naumann[44], G. Navarro[21], R. Nayyar[7], H.A. Neal[91], P.Yu. Nechaeva[97], T.J. Neep[86], P.D. Nef[144], A. Negri[122a,122b], M. Negrini[22a], S. Nektarijevic[107], C. Nellist[118], A. Nelson[163], S. Nemecek[128], P. Nemethy[111], A.A. Nepomuceno[26a], M. Nessi[32,af], M.S. Neubauer[166], M. Neumann[175], R.M. Neves[111], P. Nevski[27], P.R. Newman[19], D.H. Nguyen[6], T. Nguyen Manh[96], R.B. Nickerson[121], R. Nicolaidou[137], J. Nielsen[138], A. Nikiforov[17], V. Nikolaenko[131,ae], I. Nikolic-Audit[82], K. Nikolopoulos[19], J.K. Nilsen[120], P. Nilsson[27], Y. Ninomiya[156], A. Nisati[133a], R. Nisius[102], T. Nobe[156], L. Nodulman[6], M. Nomachi[119], I. Nomidis[31], T. Nooney[78], S. Norberg[114], M. Nordberg[32], N. Norjoharuddeen[121], O. Novgorodova[46], S. Nowak[102], M. Nozaki[68], L. Nozka[116], K. Ntekas[10], E. Nurse[80], F. Nuti[90], F. O'grady[7], D.C. O'Neil[143], A.A. O'Rourke[44], V. O'Shea[55], F.G. Oakham[31,d], H. Oberlack[102], T. Obermann[23], J. Ocariz[82], A. Ochi[69], I. Ochoa[37], J.P. Ochoa-Ricoux[34a], S. Oda[72], S. Odaka[68], H. Ogren[63], A. Oh[86], S.H. Oh[47], C.C. Ohm[16], H. Ohman[165], H. Oide[32], H. Okawa[161], Y. Okumura[33], T. Okuyama[68], A. Olariu[28b], L.F. Oleiro Seabra[127a], S.A. Olivares Pino[48], D. Oliveira Damazio[27], A. Olszewski[41], J. Olszowska[41], A. Onofre[127a,127e], K. Onogi[104], P.U.E. Onyisi[11,v], M.J. Oreglia[33], Y. Oren[154], D. Orestano[135a,135b], N. Orlando[62b], R.S. Orr[159], B. Osculati[52a,52b], R. Ospanov[86], G. Otero y Garzon[29], H. Otono[72], M. Ouchrif[136d], F. Ould-Saada[120], A. Ouraou[137], K.P. Oussoren[108], Q. Ouyang[35a], M. Owen[55], R.E. Owen[19], V.E. Ozcan[20a], N. Ozturk[8], K. Pachal[143], A. Pacheco Pages[13], C. Padilla Aranda[13], M. Pagáčová[50], S. Pagan Griso[16], F. Paige[27], P. Pais[88], K. Pajchel[120], G. Palacino[160b], S. Palestini[32], M. Palka[40b], D. Pallin[36], A. Palma[127a,127b], E.St. Panagiotopoulou[10], C.E. Pandini[82], J.G. Panduro Vazquez[79], P. Pani[147a,147b], S. Panitkin[27], D. Pantea[28b], L. Paolozzi[51], Th.D. Papadopoulou[10], K. Papageorgiou[155], A. Paramonov[6], D. Paredes Hernandez[176], A.J. Parker[74], M.A. Parker[30], K.A. Parker[140], F. Parodi[52a,52b], J.A. Parsons[37], U. Parzefall[50], V.R. Pascuzzi[159], E. Pasqualucci[133a], S. Passaggio[52a], Fr. Pastore[79], G. Pásztor[31,ag], S. Pataraia[175], J.R. Pater[86], T. Pauly[32], J. Pearce[169],

B. Pearson[114], L.E. Pedersen[38], M. Pedersen[120], S. Pedraza Lopez[167], R. Pedro[127a,127b], S.V. Peleganchuk[110,c], D. Pelikan[165], O. Penc[128], C. Peng[35a], H. Peng[35b], J. Penwell[63], B.S. Peralva[26b], M.M. Perego[137], D.V. Perepelitsa[27], E. Perez Codina[160a], L. Perini[93a,93b], H. Pernegger[32], S. Perrella[105a,105b], R. Peschke[44], V.D. Peshekhonov[67], K. Peters[44], R.F.Y. Peters[86], B.A. Petersen[32], T.C. Petersen[38], E. Petit[57], A. Petridis[1], C. Petridou[155], P. Petroff[118], E. Petrolo[133a], M. Petrov[121], F. Petrucci[135a,135b], N.E. Pettersson[88], A. Peyaud[137], R. Pezoa[34b], P.W. Phillips[132], G. Piacquadio[144], E. Pianori[170], A. Picazio[88], E. Piccaro[78], M. Piccinini[22a,22b], M.A. Pickering[121], R. Piegaia[29], J.E. Pilcher[33], A.D. Pilkington[86], A.W.J. Pin[86], M. Pinamonti[164a,164c,ah], J.L. Pinfold[3], A. Pingel[38], S. Pires[82], H. Pirumov[44], M. Pitt[172], L. Plazak[145a], M.-A. Pleier[27], V. Pleskot[85], E. Plotnikova[67], P. Plucinski[92], D. Pluth[66], R. Poettgen[147a,147b], L. Poggioli[118], D. Pohl[23], G. Polesello[122a], A. Poley[44], A. Policicchio[39a,39b], R. Polifka[159], A. Polini[22a], C.S. Pollard[55], V. Polychronakos[27], K. Pommès[32], L. Pontecorvo[133a], B.G. Pope[92], G.A. Popeneciu[28c], D.S. Popovic[14], A. Poppleton[32], S. Pospisil[129], K. Potamianos[16], I.N. Potrap[67], C.J. Potter[30], C.T. Potter[117], G. Poulard[32], J. Poveda[32], V. Pozdnyakov[67], M.E. Pozo Astigarraga[32], P. Pralavorio[87], A. Pranko[16], S. Prell[66], D. Price[86], L.E. Price[6], M. Primavera[75a], S. Prince[89], M. Proissl[48], K. Prokofiev[62c], F. Prokoshin[34b], S. Protopopescu[27], J. Proudfoot[6], M. Przybycien[40a], D. Puddu[135a,135b], D. Puldon[149], M. Purohit[27,ai], P. Puzo[118], J. Qian[91], G. Qin[55], Y. Qin[86], A. Quadt[56], W.B. Quayle[164a,164b], M. Queitsch-Maitland[86], D. Quilty[55], S. Raddum[120], V. Radeka[27], V. Radescu[60b], S.K. Radhakrishnan[149], P. Radloff[117], P. Rados[90], F. Ragusa[93a,93b], G. Rahal[178], J.A. Raine[86], S. Rajagopalan[27], M. Rammensee[32], C. Rangel-Smith[165], M.G. Ratti[93a,93b], F. Rauscher[101], S. Rave[85], T. Ravenscroft[55], I. Ravinovich[172], M. Raymond[32], A.L. Read[120], N.P. Readioff[76], M. Reale[75a,75b], D.M. Rebuzzi[122a,122b], A. Redelbach[174], G. Redlinger[27], R. Reece[138], K. Reeves[43], L. Rehnisch[17], J. Reichert[123], H. Reisin[29], C. Rembser[32], H. Ren[35a], M. Rescigno[133a], S. Resconi[93a], O.L. Rezanova[110,c], P. Reznicek[130], R. Rezvani[96], R. Richter[102], S. Richter[80], E. Richter-Was[40b], O. Ricken[23], M. Ridel[82], P. Rieck[17], C.J. Riegel[175], J. Rieger[56], O. Rifki[114], M. Rijssenbeek[149], A. Rimoldi[122a,122b], M. Rimoldi[18], L. Rinaldi[22a], B. Ristić[51], E. Ritsch[32], I. Riu[13], F. Rizatdinova[115], E. Rizvi[78], C. Rizzi[13], S.H. Robertson[89,l], A. Robichaud-Veronneau[89], D. Robinson[30], J.E.M. Robinson[44], A. Robson[55], C. Roda[125a,125b], Y. Rodina[87], A. Rodriguez Perez[13], D. Rodriguez Rodriguez[167], S. Roe[32], C.S. Rogan[59], O. Røhne[120], A. Romaniouk[99], M. Romano[22a,22b], S.M. Romano Saez[36], E. Romero Adam[167], N. Rompotis[139], M. Ronzani[50], L. Roos[82], E. Ros[167], S. Rosati[133a], K. Rosbach[50], P. Rose[138], O. Rosenthal[142], N.-A. Rosien[56], V. Rossetti[147a,147b], E. Rossi[105a,105b], L.P. Rossi[52a], J.H.N. Rosten[30], R. Rosten[139], M. Rotaru[28b], I. Roth[172], J. Rothberg[139], D. Rousseau[118], C.R. Royon[137], A. Rozanov[87], Y. Rozen[153], X. Ruan[146c], F. Rubbo[144], M.S. Rudolph[159], F. Rühr[50], A. Ruiz-Martinez[31], Z. Rurikova[50], N.A. Rusakovich[67], A. Ruschke[101], H.L. Russell[139], J.P. Rutherfoord[7], N. Ruthmann[32], Y.F. Ryabov[124], M. Rybar[166], G. Rybkin[118], S. Ryu[6], A. Ryzhov[131], G.F. Rzehorz[56], A.F. Saavedra[151], G. Sabato[108], S. Sacerdoti[29], H.F-W. Sadrozinski[138], R. Sadykov[67], F. Safai Tehrani[133a], P. Saha[109], M. Sahinsoy[60a], M. Saimpert[137], T. Saito[156], H. Sakamoto[156], Y. Sakurai[171], G. Salamanna[135a,135b], A. Salamon[134a,134b], J.E. Salazar Loyola[34b], D. Salek[108], P.H. Sales De Bruin[139], D. Salihagic[102], A. Salnikov[144], J. Salt[167], D. Salvatore[39a,39b], F. Salvatore[150], A. Salvucci[62a], A. Salzburger[32], D. Sammel[50], D. Sampsonidis[155], A. Sanchez[105a,105b], J. Sánchez[167], V. Sanchez Martinez[167], H. Sandaker[120], R.L. Sandbach[78], H.G. Sander[85], M. Sandhoff[175], C. Sandoval[21], R. Sandstroem[102], D.P.C. Sankey[132], M. Sannino[52a,52b], A. Sansoni[49], C. Santoni[36], R. Santonico[134a,134b], H. Santos[127a], I. Santoyo Castillo[150], K. Sapp[126], A. Sapronov[67], J.G. Saraiva[127a,127d], B. Sarrazin[23], O. Sasaki[68], Y. Sasaki[156], K. Sato[161], G. Sauvage[5,*], E. Sauvan[5], G. Savage[79], P. Savard[159,d], C. Sawyer[132], L. Sawyer[81,q], J. Saxon[33], C. Sbarra[22a],

A. Sbrizzi[22a,22b], T. Scanlon[80], D.A. Scannicchio[163], M. Scarcella[151], V. Scarfone[39a,39b], J. Schaarschmidt[172], P. Schacht[102], B.M. Schachtner[101], D. Schaefer[32], R. Schaefer[44], J. Schaeffer[85], S. Schaepe[23], S. Schaetzel[60b], U. Schäfer[85], A.C. Schaffer[118], D. Schaile[101], R.D. Schamberger[149], V. Scharf[60a], V.A. Schegelsky[124], D. Scheirich[130], M. Schernau[163], C. Schiavi[52a,52b], S. Schier[138], C. Schillo[50], M. Schioppa[39a,39b], S. Schlenker[32], K.R. Schmidt-Sommerfeld[102], K. Schmieden[32], C. Schmitt[85], S. Schmitt[44], S. Schmitz[85], B. Schneider[160a], U. Schnoor[50], L. Schoeffel[137], A. Schoening[60b], B.D. Schoenrock[92], E. Schopf[23], M. Schott[85], J. Schovancova[8], S. Schramm[51], M. Schreyer[174], N. Schuh[85], M.J. Schultens[23], H.-C. Schultz-Coulon[60a], H. Schulz[17], M. Schumacher[50], B.A. Schumm[138], Ph. Schune[137], A. Schwartzman[144], T.A. Schwarz[91], Ph. Schwegler[102], H. Schweiger[86], Ph. Schwemling[137], R. Schwienhorst[92], J. Schwindling[137], T. Schwindt[23], G. Sciolla[25], F. Scuri[125a,125b], F. Scutti[90], J. Searcy[91], P. Seema[23], S.C. Seidel[106], A. Seiden[138], F. Seifert[129], J.M. Seixas[26a], G. Sekhniaidze[105a], K. Sekhon[91], S.J. Sekula[42], D.M. Seliverstov[124,*], N. Semprini-Cesari[22a,22b], C. Serfon[120], L. Serin[118], L. Serkin[164a,164b], M. Sessa[135a,135b], R. Seuster[169], H. Severini[114], T. Sfiligoj[77], F. Sforza[32], A. Sfyrla[51], E. Shabalina[56], N.W. Shaikh[147a,147b], L.Y. Shan[35a], R. Shang[166], J.T. Shank[24], M. Shapiro[16], P.B. Shatalov[98], K. Shaw[164a,164b], S.M. Shaw[86], A. Shcherbakova[147a,147b], C.Y. Shehu[150], P. Sherwood[80], L. Shi[152,aj], S. Shimizu[69], C.O. Shimmin[163], M. Shimojima[103], M. Shiyakova[67,ak], A. Shmeleva[97], D. Shoaleh Saadi[96], M.J. Shochet[33], S. Shojaii[93a,93b], S. Shrestha[112], E. Shulga[99], M.A. Shupe[7], P. Sicho[128], A.M. Sickles[166], P.E. Sidebo[148], O. Sidiropoulou[174], D. Sidorov[115], A. Sidoti[22a,22b], F. Siegert[46], Dj. Sijacki[14], J. Silva[127a,127d], S.B. Silverstein[147a], V. Simak[129], O. Simard[5], Lj. Simic[14], S. Simion[118], E. Simioni[85], B. Simmons[80], D. Simon[36], M. Simon[85], P. Sinervo[159], N.B. Sinev[117], M. Sioli[22a,22b], G. Siragusa[174], S.Yu. Sivoklokov[100], J. Sjölin[147a,147b], T.B. Sjursen[15], M.B. Skinner[74], H.P. Skottowe[59], P. Skubic[114], M. Slater[19], T. Slavicek[129], M. Slawinska[108], K. Sliwa[162], R. Slovak[130], V. Smakhtin[172], B.H. Smart[5], L. Smestad[15], J. Smiesko[145a], S.Yu. Smirnov[99], Y. Smirnov[99], L.N. Smirnova[100,al], O. Smirnova[83], M.N.K. Smith[37], R.W. Smith[37], M. Smizanska[74], K. Smolek[129], A.A. Snesarev[97], S. Snyder[27], R. Sobie[169,l], F. Socher[46], A. Soffer[154], D.A. Soh[152], G. Sokhrannyi[77], C.A. Solans Sanchez[32], M. Solar[129], E.Yu. Soldatov[99], U. Soldevila[167], A.A. Solodkov[131], A. Soloshenko[67], O.V. Solovyanov[131], V. Solovyev[124], P. Sommer[50], H. Son[162], H.Y. Song[35b,am], A. Sood[16], A. Sopczak[129], V. Sopko[129], V. Sorin[13], D. Sosa[60b], C.L. Sotiropoulou[125a,125b], R. Soualah[164a,164c], A.M. Soukharev[110,c], D. South[44], B.C. Sowden[79], S. Spagnolo[75a,75b], M. Spalla[125a,125b], M. Spangenberg[170], F. Spanò[79], D. Sperlich[17], F. Spettel[102], R. Spighi[22a], G. Spigo[32], L.A. Spiller[90], M. Spousta[130], R.D. St. Denis[55,*], A. Stabile[93a], R. Stamen[60a], S. Stamm[17], E. Stanecka[41], R.W. Stanek[6], C. Stanescu[135a], M. Stanescu-Bellu[44], M.M. Stanitzki[44], S. Stapnes[120], E.A. Starchenko[131], G.H. Stark[33], J. Stark[57], P. Staroba[128], P. Starovoitov[60a], S. Stärz[32], R. Staszewski[41], P. Steinberg[27], B. Stelzer[143], H.J. Stelzer[32], O. Stelzer-Chilton[160a], H. Stenzel[54], G.A. Stewart[55], J.A. Stillings[23], M.C. Stockton[89], M. Stoebe[89], G. Stoicea[28b], P. Stolte[56], S. Stonjek[102], A.R. Stradling[8], A. Straessner[46], M.E. Stramaglia[18], J. Strandberg[148], S. Strandberg[147a,147b], A. Strandlie[120], M. Strauss[114], P. Strizenec[145b], R. Ströhmer[174], D.M. Strom[117], R. Stroynowski[42], A. Strubig[107], S.A. Stucci[18], B. Stugu[15], N.A. Styles[44], D. Su[144], J. Su[126], R. Subramaniam[81], S. Suchek[60a], Y. Sugaya[119], M. Suk[129], V.V. Sulin[97], S. Sultansoy[4c], T. Sumida[70], S. Sun[59], X. Sun[35a], J.E. Sundermann[50], K. Suruliz[150], G. Susinno[39a,39b], M.R. Sutton[150], S. Suzuki[68], M. Svatos[128], M. Swiatlowski[33], I. Sykora[145a], T. Sykora[130], D. Ta[50], C. Taccini[135a,135b], K. Tackmann[44], J. Taenzer[159], A. Taffard[163], R. Tafirout[160a], N. Taiblum[154], H. Takai[27], R. Takashima[71], T. Takeshita[141], Y. Takubo[68], M. Talby[87], A.A. Talyshev[110,c], K.G. Tan[90], J. Tanaka[156], R. Tanaka[118], S. Tanaka[68], B.B. Tannenwald[112], S. Tapia Araya[34b], S. Tapprogge[85], S. Tarem[153], G.F. Tartarelli[93a], P. Tas[130], M. Tasevsky[128], T. Tashiro[70],

JHEP11(2016)112

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JHEP11(2016)112

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JHEP11(2016)112

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JHEP11(2016)112

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JHEP11(2016)112

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JHEP11(2016)112

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JHEP11(2016)112

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JHEP11(2016)112