Search for the production of single vector-like and excited quarks in the Wt final state in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

The ATLAS collaboration

E-mail: atlas.publications@cern.ch

ABSTRACT: A search for vector-like quarks and excited quarks in events containing a top quark and a W boson in the final state is reported here. The search is based on $20.3\,\text{fb}^{-1}$ of proton-proton collision data taken at the LHC at a centre-of-mass energy of $8\,\text{TeV}$ recorded by the ATLAS detector. Events with one or two leptons, and one, two or three jets are selected with the additional requirement that at least one jet contains a b-quark. Single-lepton events are also required to contain at least one large-radius jet from the hadronic decay of a high-p_{T} W boson or a top quark. No significant excess over the expected background is observed and upper limits on the cross-section times branching ratio for different vector-like quark and excited-quark model masses are derived. For the excited-quark production and decay to Wt with unit couplings, quarks with masses below $1500\,\text{GeV}$ are excluded and coupling-dependent limits are set.

Contents

1 Introduction

The number of quark generations known within the Standard Model (SM) is three and the existence of additional heavy quarks similar to those in the SM is strongly constrained by the discovery of the Higgs boson at the Large Hadron Collider (LHC) [1–3]. Additional quarks that have non-SM Higgs couplings, in particular vector-like quarks (VLQs), remain popular, especially in models which address the naturalness question [4, 5]. New quarks can have right and left handed couplings to the W boson and are color triplets [6]. VLQs appear in several extensions of the SM, such as extra dimensions [7], supersymmetry [8], composite Higgs [9, 10] and little Higgs [11] models, in which they cancel top-quark loop contributions to the Higgs mass [12]. Depending on the model, VLQs can be realized in different multiplets, such as in singlets, doublets and triplets [13].

This paper describes a search for singly produced vector-like quarks with charge $\pm\frac{1}{3}$ of the elementary charge, e. Two models are considered: the single production of a VLQ via the t-channel exchange of a Z boson in a composite Higgs model [10, 14] (called B), and the single production of a VLQ that also has excited-quark couplings [15] (called b^*). Only final states in which the B or b^* decay into Wt are considered. The corresponding leading-order (LO) Feynman diagrams for these processes are shown in figure 1.
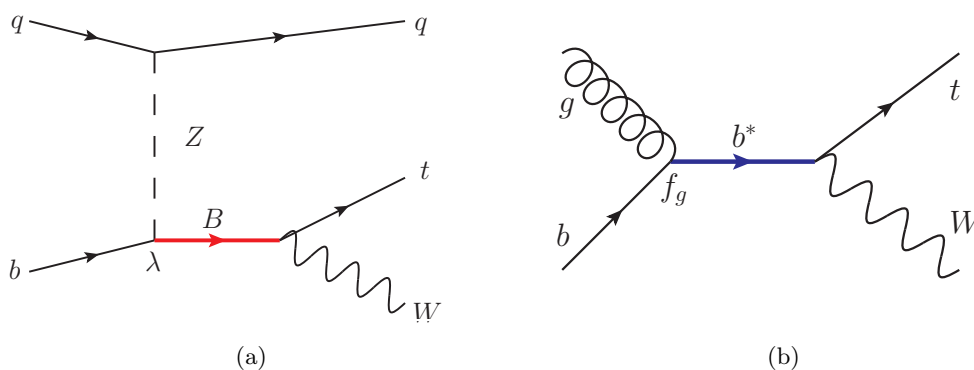
Figure 1. Leading-order Feynman diagrams for the production and decay of (a) a single B together with a light quark and (b) a single b^*.

m_B [GeV]	$\sigma \times \mathrm{BR}(B \to Wt)$ [fb]	
	$\lambda = 2$	$\lambda = 3$
400	710	—
600	220	250
800	52	97
1000	15	30
1200	4.8	10.2
1400	1.7	3.6

Table 1. Cross-section times branching ratio for $pp \to Bq \to Wt$ for different B masses and coupling values λ at a centre-of-mass energy of $\sqrt{s} = 8$ TeV [10, 14]. For $\lambda \cdot v/\sqrt{2} > m_B - m_b$ with the vacuum-expectation value v and the mass of the b-quark m_b one gets an unphysical b-quark mass. This is denoted in the table by "—".

The cross-section for singlet B production is proportional to the square of the bZB coupling strength λ. The production via Higgs-boson exchange is also possible, although the Z-induced process is dominant. The B can decay into Zb, Hb and Wt with the branching ratios given by the VLQ couplings[1] for singlet B. The light quark in the final state gives rise to a forward jet. The cross-section for singlet B production with subsequent decay to Wt has been calculated in the TS-10 model [10, 14], a four-dimensional version of a model with composite fermions in a 10 representation of SO(5). The cross-section is given in table 1 for two values of the coupling parameter λ, for which the 2×2 mass mixing matrix of the b-quark and the B has been diagonalised. The largest value of λ for which the B decay width is still smaller than the experimental mass resolution is $\lambda = 3$. A top-quark mass of 172.5 GeV is assumed throughout.

In addition to the Zb, Hb and Wt couplings, the b^* also has a chromomagnetic coupling f_g to a gluon and a b-quark [15–17], making it both a vector-like quark and an excited quark [18]. Complete models of VLQs usually contain other particles and interactions which result in an effective chromomagnetic coupling. Examples of such models are

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[1]At high singlet B masses they are roughly 1:1:2 [6].

$m_{b^*}[\text{ GeV}]$	$\sigma \times \text{BR}(b^* \to Wt)$ [fb]	
	$f_{\text{L(R)}} = 1, f_{\text{R(L)}} = 0$	$f_{\text{L}} = f_{\text{R}} = 1$
400	115×10^3	196×10^3
600	18.3×10^3	35×10^3
800	3.9×10^3	7.5×10^3
1000	1.0×10^3	2.0×10^3
1200	310	610
1400	110	210
1800	16	30

Table 2. Cross-section times branching ratio for $b^* \to Wt$ for different b^* masses and b^*Wt couplings [15] at a centre-of-mass energy $\sqrt{s} = 8$ TeV. Here $f_g = 1$ is assumed.

technicolour [19, 20], topcolour [21, 22], extra dimension models [23, 24] or models with a heavy partner of the gluon [25], which gives rise to the effective gb coupling. The strength of the coupling is assumed to be $f_g = 1$ in this paper unless otherwise indicated. The b^* in the VLQ case has $f_{\text{L}} = f_{\text{R}} = 1$, but it is also allowed to have purely left-handed ($f_{\text{L}} = 1$, $f_{\text{R}} = 0$) or purely right-handed ($f_{\text{L}} = 0$, $f_{\text{R}} = 1$) couplings to the top quark. The cross-sections times branching ratios for the production of b^* with decay to Wt for these three coupling scenarios are given in table 2. For purely left-handed couplings the cross-sections are the same as those for purely right-handed couplings. However, for VLQ-like couplings the cross-sections are not exactly the sum of the individual contributions since setting both couplings to 1 modifies the b^* decay branching ratios. In the following, $f_{\text{L}} = f_{\text{R}} = 1$ is assumed unless stated otherwise.

After the decay of B/b^* into Wt, the top quark decays into a b-quark and another W boson. At least one of the W bosons is required to decay leptonically (to an electron or muon, and the corresponding neutrino). Events are separated into dilepton and single-lepton signatures. A hadronically decaying W boson or top quark is identified by clustering its decay products into a single jet since for high B/b^* masses the W boson and top quark are boosted. The clustering requirement is the main change in the analysis strategy for the single-lepton channel compared to the search for single-b^* production in the complete 7 TeV LHC dataset collected by ATLAS [26]. It increases the sensitivity to high B and b^* masses, where the top quark and W boson have large transverse momentum.

Searches for a VLQ with charge $\pm\frac{1}{3}e$ have also been performed by ATLAS in final states with Z-bosons using data at $\sqrt{s} = 8$ TeV, and exploiting both pair production and single production and resulted in limits in the range 685 to 755 GeV [27]. Searches for pair production of VLQs, assuming strong interactions similar to those in the SM, have also been performed by ATLAS [28–30] in data at $\sqrt{s} = 8$ TeV and by CMS [31, 32] at $\sqrt{s} = 7$ TeV, and resulted in limits in the ranges 760 to 900 GeV and 625 to 675 GeV, respectively. Recently, the CMS collaboration set lower limits on pair-produced vector-like B quark mass in the range 740 to 900 GeV, for different combinations of the B quark branching fractions [33] and on left-handed, right-handed, and vector-like b^* quark masses decaying to Wt in the range 1390 to 1530 GeV [34], using data at $\sqrt{s} = 8$ TeV. A search

for b^* has been performed by ATLAS with the full 7 TeV LHC dataset and a limit on the b^* mass for couplings $f_g = f_L = f_R = 1$ was set at 1.03 TeV [26]. All limits are given at 95% credibility level (CL). This search for the single production of $B \to Wt$ is the first for a B in this final state and using the novelty approach for boosted event topologies. While searches for pair production currently dominate the limits, single production becomes more competitive for higher quark masses, due to the reduced kinematic phase-space constraints and the larger dataset.

In the analysis presented here, six different single-lepton and dilepton signal regions (SR) are defined, which were optimised to maximise the expected significance for the B/b^* models considered. This analysis is also complementary to the search of dijet mass resonances in ATLAS with data at $\sqrt{s} = 8$ TeV, which probes the qg final state [35]. The main processes contributing to the background after applying all selection cuts are from top-quark pair $(t\bar{t})$ production and single top-quark production in association with a W boson. Other background contributions are from W- or Z-boson production in association with jets. Smaller contributions arise from diboson production processes and processes where a jet is misidentified as a lepton. To estimate these SM backgrounds in a consistent and robust fashion, corresponding control regions (CR) are defined for each of the signal regions. They are chosen to be non-overlapping with the SR selections in order to provide independent data samples enriched in particular background sources. The shape of the discriminating variable, the invariant mass for the single-lepton channel and transverse mass for the dilepton channel, is used in a binned likelihood fit to test for the presence of a signal. The systematic uncertainties and the MC statistical uncertainties on the expected values are included in the fit as nuisance parameters. These additional degrees of freedom allow the modelling of the backgrounds to be improved based on data, increasing the sensitivity to the signal. Correlations of a given nuisance parameter across the various regions, between the various backgrounds, and possibly the signal, are also taken into account. A background-only fit is used to determine the compatibility of the observed event yield in each SR with the corresponding SM background expectation. The improved *post-fit* model resulting from this fit is used throughout this paper for the presentation of control distributions. The observed and expected upper limits at 95% CL on the number of events from VLQ phenomena for each signal region are derived using a Bayesian approach.

2 ATLAS detector

The ATLAS experiment [36] at the LHC is a multi-purpose particle detector with a forward-backward symmetric cylindrical geometry and a near 4π coverage in solid angle.[2] It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic (EM) and hadron calorimeters, and a muon spec-

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

trometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic energy measurements with high granularity. A hadronic (iron/scintillator-tile) calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The end-cap and forward regions are instrumented with LAr calorimeters for both the EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and is based on three large air-core toroid superconducting magnets with eight coils each. It includes a system of precision tracking chambers up to $|\eta| = 2.7$ and fast detectors for triggering at $|\eta| < 2.4$. A three-level trigger system is used to select events of interest. The first-level trigger is implemented in hardware and uses a subset of the detector information, while the other two levels are software-based, and the last trigger level uses the full detector information.

3 Data and simulated samples

The dataset used for this analysis was collected in 2012 by the ATLAS detector at the LHC, and corresponds to an integrated luminosity of $20.3\,\text{fb}^{-1}$ of proton-proton collisions at a centre-of-mass energy $\sqrt{s} = 8$ TeV. Events are required to have passed at least a single-electron or single-muon trigger. The electron and muon triggers impose a transverse momentum (p_T) threshold of 24 GeV along with isolation requirements on the lepton. To recover efficiency for higher-p_T leptons, the isolated-lepton triggers are complemented by triggers without isolation requirements but with a higher p_T threshold of 60 GeV (36 GeV) for electrons (muons).

Events are accepted if they contain at least one reconstructed primary vertex (PV). A reconstructed PV candidate is required to have at least five associated tracks of $p_\text{T} > 400\,\text{MeV}$, consistent with originating from the beam collision region in the x-y plane. The PV is chosen as the vertex candidate with the largest sum of the squared transverse momenta of its associated tracks among all candidates.

The B signal is simulated with PROTOS v2.2 [6], interfaced to PYTHIA v6.4 [37] for hadronisation and underlying events. The MSTW2008NLO68CL [38, 39] parton distribution function (PDF) set is used. The production kinematics and decay properties do not depend on the coupling λ. The b^* signal is simulated at LO in QCD with the matrix-element generator MADGRAPH5 v1.5.12 [40] and interfaced to PYTHIA v8.175 [41] for hadronisation. The MSTW2008NLO68CL PDF set is used. The couplings are set to $f_g = f_\text{L} = 1$, $f_\text{R} = 0$ for the left-handed samples, and $f_g = f_\text{R} = 1$, $f_\text{L} = 0$ for the right-handed ones. For both signal models, samples are generated with the mass of the new quark set to values from 400 GeV to 1800 GeV. The PROTOS B sample is generated by the diagram $gq \to Bbq$ and the factorisation and renormalisation scales are set dynamically to the square of the momentum transfer of the virtual Z boson for the light quark line and to the p_T of the extra b-quark for the gluon splitting line. In the MADGRAPH5 samples, the scales are set to the mass of the generated resonance particle. Since for most of the analysis presented here it is assumed that $f_\text{L} = f_\text{R} = 1$, left- and right-handed samples are added together and scaled to the appropriate theory cross-section times branching fraction.

Top-quark pair and single top-quark events in the t, s and Wt channels are simulated using the next-to-leading-order (NLO) generator POWHEG-BOX v1_r2129, v1_r1556 and v1_r2092, respectively [42, 43]. The CT10 [44] PDF set is used and PYTHIA v6.4 [37] performs the hadronisation. The top-quark background samples are initially normalised to their theory predictions. The $t\bar{t}$ predicted cross-section is $\sigma_{t\bar{t}} = 253^{+13}_{-15}$ pb, computed at next-to-next-to-leading-order (NNLO) in QCD, including resummation of next-to-next-to-leading logarithmic (NNLL) soft gluon terms with TOP++2.0 [45–51]. The single-top predicted cross-sections are $\sigma_t = 87.8^{+3.4}_{-1.9}$ pb [52] and $\sigma_{Wt} = 22.4 \pm 1.5$ pb [53], computed at NLO with NNLL corrections.

The ALPGEN v2.14 LO generator [54], interfaced to PYTHIA v6.4, is used to generate W+jets and Z+jets events, with the CTEQ6L1 [55] PDF set. A parton-jet matching scheme is employed to avoid double-counting of partonic configurations generated by both the matrix-element calculation and the parton shower [56]. The samples are generated separately for W/Z with light-quark jets (W+light-jets, Z+light-jets) and heavy-quark jets (Wbb+jets, Wcc+jets, Wc+jets, Zbb+jets, Zcc+jets). Overlap between the events in samples with heavy quarks generated from the matrix-element calculation and those generated from parton-shower evolution in the samples with light-quark jets is avoided via an algorithm based on the angular separation between the extra heavy quarks, Q: if $\Delta R(Q, Q') > 0.4$, the matrix-element prediction is used, otherwise the parton-shower prediction is used. Diboson events (WW, WZ, ZZ) are generated with ALPGEN interfaced to HERWIG v6.52 [57] for hadronisation and JIMMY v4.31 [58] for the modelling of the underlying event, with the CTEQ6L1 PDF set.

After event generation, most signal and all background samples are passed through the full simulation of the ATLAS detector [59] based on GEANT4 [60] and reconstructed using the same procedure as for collision data. A faster simulation [61] is used for the signal samples in the dilepton selection and for samples selected to assess systematic uncertainties. All samples are simulated with additional proton-proton interactions in the same bunch crossing ("pile-up") and reweighted to have the same distribution of the mean number of interactions per bunch-crossing as the data.

4   Event selection and background estimation

Two types of events are selected: those in which the prompt W boson and the one from the top quark both decay leptonically (dilepton final state), and those in which only one W boson decays leptonically and the other one decays hadronically (lepton+jets final state). Only electrons and muons are considered for the leptonic W decay. The events are separated into orthogonal categories based on the decay signature of the two W bosons, as illustrated in figure 2. Full details of the methods used to assign events to the categories shown in figure 2(a) and 2(b) are given below.

4.1   Object reconstruction

Electron candidates are reconstructed from energy clusters in the EM calorimeter and matched to tracks in the inner detector. Selected electrons must have a transverse en-
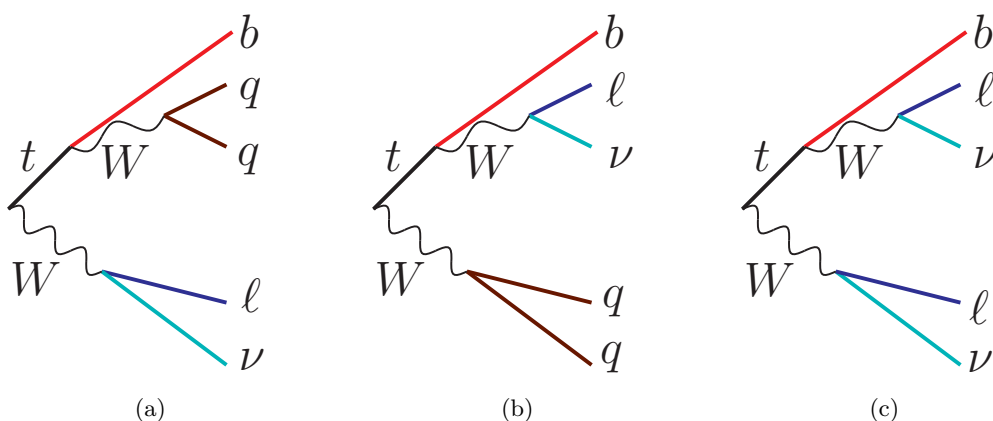
Figure 2. Final-state categories: (a) one lepton and a hadronic top-quark decay, (b) one lepton and a hadronic W-boson decay and (c) dilepton.

ergy $E_{\mathrm{T}} = E_{\mathrm{cluster}}/\cosh(\eta_{\mathrm{track}}) > 25$ GeV and $|\eta_{\mathrm{cluster}}| < 2.47$, where E_{cluster} and η_{cluster} indicate the electromagnetic cluster energy and pseudorapidity, respectively, and η_{track} the track pseudorapidity [62]. A veto is placed on electrons in the transition region between the barrel and end-cap calorimeter, $1.37 < |\eta_{\mathrm{cluster}}| < 1.52$. The electron track is required to originate less than 2 mm along the z-axis (longitudinal impact parameter) from the selected event primary vertex. The three main sources of background for high-E_{T} isolated electrons are hadrons misidentified as electrons, photon conversions and electrons originating from secondary vertices in decays of heavy-flavour hadrons (non-prompt electrons). In order to suppress the background from these sources, it is required that there is little calorimeter activity in the region surrounding the electron candidate. Two isolation variables are defined for this purpose: the energy deposited around the electron candidate in the calorimeter with a cone size of $\Delta R = 0.2$, and the sum of the transverse momenta of all tracks in a cone of size $\Delta R = 0.3$ around the electron candidate. Efficiencies and purities of the identification and isolation requirements are corrected with appropriate scale factors to match the simulation to the data. They depend on the η and the E_{T} of the electron.

Muon candidates are reconstructed by matching muon spectrometer hits to inner-detector tracks, using the complete track information from both detectors and accounting for scattering and energy loss in the ATLAS detector material. Selected muons have a transverse momentum greater than 25 GeV and a pseudorapidity of $|\eta| < 2.5$. The muon track longitudinal impact parameter with respect to the primary vertex is required to be less than 2 mm. Isolation criteria are applied in order to reduce background contamination from events in which a muon is produced at a secondary vertex in the decay of a heavy-flavour quark (non-prompt muon). The ratio of the summed p_{T} of tracks within a cone of variable size $\Delta R = 10$ GeV$/p_{\mathrm{T}}^{\mu}$ to the p_{T} of the muon is required to be less than 0.05 [63]. Efficiencies and purities of the identification and isolation requirements are corrected with appropriate scale factors to match the simulation to the data; they depend on η and ϕ of the muon.

Jets are reconstructed using the anti-k_t algorithm [64], applied to clusters of calorimeter cells that are topologically connected and calibrated to the hadronic energy scale [65]

using a local calibration scheme [66]. Jet energies are calibrated using energy- and η-dependent correction factors derived from simulation, and with residual corrections from in-situ measurements [67]. Events with jets built from noisy calorimeter cells or non-collision background processes are removed [68].

In this paper jets reconstructed with two different radius parameters are used. Small-R jets (also denoted simply by "jets" or j_4) have a radius parameter of 0.4 and are required to have $p_T > 25$ GeV and $|\eta| < 4.5$. Small-R jets from additional simultaneous pp interactions are rejected by an additional requirement: the ratio of the scalar sum of the p_T of tracks associated with the jet and the primary vertex to the scalar sum of the p_T of all tracks associated with the jet must be at least 0.5 for jets with $p_T < 50$ GeV and $|\eta| < 2.4$. Large-R jets (j_{10}) have a radius parameter of 1.0 [68] and are subject to a trimming procedure [69] to minimise the impact of energy depositions from pile-up interactions. The trimming algorithm reconstructs constituent jets with the k_t algorithm [70–72] with a radius parameter of 0.3 from the clusters belonging to the original large-R jet. Constituent jets contributing less than 5% of the large-R jet p_T are removed. The remaining energy depositions are used to calculate the kinematic and substructure properties of the large-R jet. The masses of the large-R jets ($m_{j_{10}}$) are calibrated to their particle-level values [67, 73, 74]. In the analysis, large-R jets are required to have $p_T > 200$ GeV and $|\eta| < 2.0$.

Since the reconstruction of jets and electrons is partially based on the same energy clusters, the closest small-R jet overlapping with electron candidates within a cone of size $\Delta R = 0.2$ is removed. Since electrons from prompt W-boson decays should be isolated from jet activity, electrons that are still within less than $\Delta R = 0.4$ of a jet are removed. Similarly, prompt muons should be isolated from jet activity, so that beside the muon-isolation criteria above, selected muons must not overlap with a reconstructed jet within a radius of size $\Delta R = 0.4$.

Small-R jets containing b-quarks (b-quark jets) from the top-quark decay are identified using a combination of multivariate algorithms (b-tagging) [75]. These algorithms exploit the long lifetime of B hadrons and the properties of the resulting displaced and reconstructed secondary vertex. The working point of the algorithm is chosen such that b-quark jets in simulated $t\bar{t}$ events are tagged with an average efficiency of 70% and a rejection factor for light-flavour jets of ~ 100.

The missing transverse momentum vector, $\vec{E}_T^{\text{miss}}$, is calculated as the negative vector sum over all the calorimeter cells in the event, and is further refined by applying object-level corrections for the contributions which arise from identified photons, leptons and jets [76]. In the analysis the magnitude, E_T^{miss}, of the missing transverse momentum vector is used.

4.2 Single-lepton event selection and background estimation

In the single-lepton final state, the selected events have exactly one isolated lepton (electron or muon) and exactly two or three small-R central jets ($|\eta| < 2.5$), exactly one of which is b-tagged. Events with two jets are included in order to select events where the two jets from the W boson are merged at larger boost. Events are also required to have at least one large-R jet with $p_T^{j_{10}} > 200$ GeV and $m_{j_{10}} > 50$ GeV. If several massive large-R jets are found, the one with the highest p_T is considered. Requirements on the
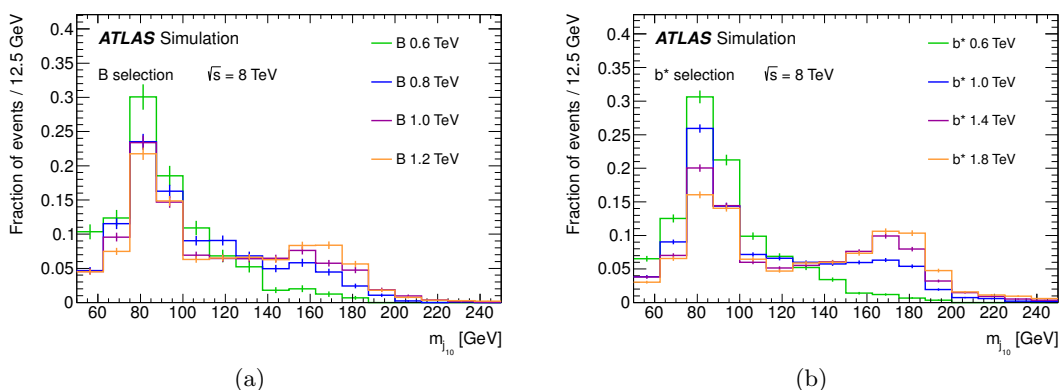
Figure 3. Comparison of the leading large-R jet mass for various simulated (a) B and (b) b^* signal masses before applying any requirement on angular distances which later define the signal regions. The distributions are normalised to unity.
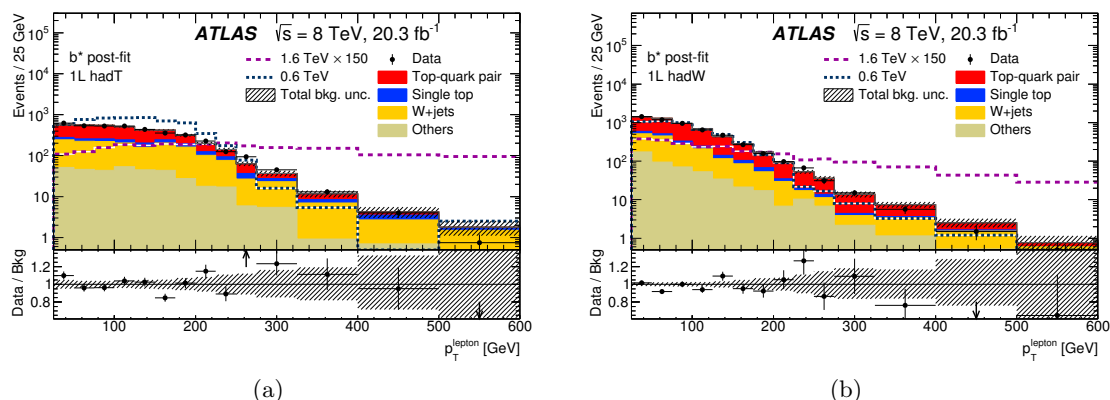
missing transverse momentum and the transverse mass of the lepton–E_T^{miss} system[3] of $E_T^{miss} > 20$ GeV and $m_T(\ell, E_T^{miss}) + E_T^{miss} > 60$ GeV, respectively, reduce the fraction of selected events originating from non-prompt or misidentified leptons. A requirement on the azimuthal angle between the large-R jet and the lepton, $\Delta\phi(\ell, j_{10}) > 1.5$, increases the signal-to-background ratio, because in signal events large-R jets from boosted hadronic top-quark (W-boson) decays recoil against the leptonic decay of the other W boson (top quark) as shown in figure 2(a) and 2(b). Figure 3 shows the mass distribution of the leading large-R jet at this selection level for various simulated B (left) and b^* (right) signal masses studied in this paper.

Angular correlations are used to select single-lepton events and to categorise them in the different signal regions: if the smallest distance between the lepton and any small-R jet satisfies $\Delta R(\ell, j_4) > 1.5$, and if the largest distance between the leading (highest p_T) large-R jet and any small-R jet satisfies $\Delta R(j_4, j_{10}) < 2.0$, events are assigned to the 1L hadronic top region (*1L hadT*, see figure 2(a)). However, if the smallest distance between the lepton and any small-R jet is $\Delta R(\ell, j_4) < 1.5$ and the largest distance between the leading large-R jet and any small-R jet is $\Delta R(j_4, j_{10}) > 2.0$, the event is assigned to the 1L hadronic W category (*1L hadW*, see figure 2(b)). If an event cannot be assigned to any of the two categories, it is rejected.

For the B and b^* signal regions the same selection cuts are applied, except that for the B signal regions at least one additional forward small-R jet ($2.5 < |\eta| < 4.5$) is required. The selection with (without) forward-jet requirement is referred to as B (b^*) selection.

Figure 4 presents the distributions of the lepton transverse momentum for the b^* selection of the single-lepton analysis for the predicted SM background processes, for data events and two b^* signal masses studied in this paper in the *1L hadT* (left) and *1L hadW* (right) regions. The transverse momentum distribution of the leading (highest p_T) forward

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[3]The transverse mass is defined as $m_T(\ell, E_T^{miss}) = \sqrt{2p_T(\ell)E_T^{miss}[1 - \cos\Delta\phi(p_T(\ell), E_T^{miss})]}$, where p_T denotes the magnitude of the lepton transverse momentum, and $\Delta\phi(p_T(\ell), E_T^{miss})$ the azimuthal difference between the missing transverse momentum and the lepton direction.

Figure 4. Distributions of the lepton transverse momentum in the b^* selection of the single-lepton analysis for the data, SM background processes and two b^* signal masses in the (a) b^* *1L hadT* and (b) b^* *1L hadW* signal regions. The signal distributions are scaled to the theory cross-sections multiplied by the indicated factor for better visibility and the background processes are normalised to their post-fit normalisation. The uncertainty band includes statistical and all systematic uncertainties. The last bin includes the overflow.
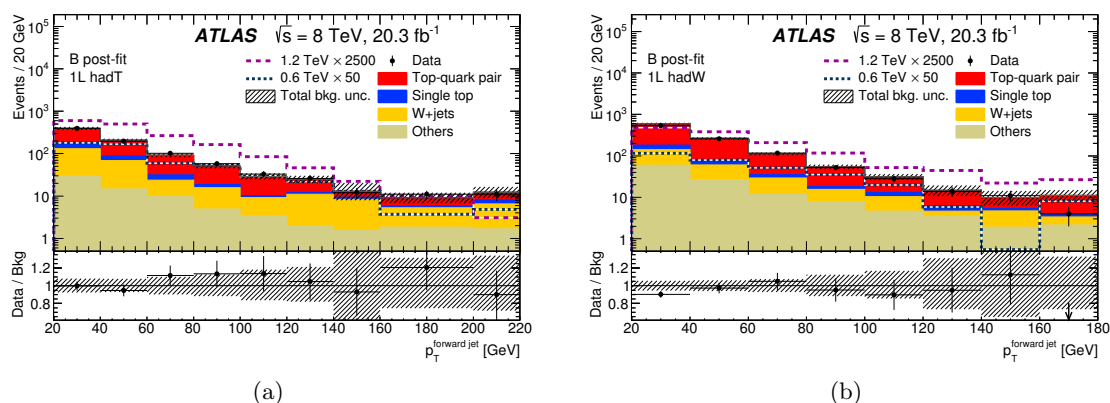
Figure 5. Distributions of the leading forward-jet transverse momentum in the B selection of the single-lepton analysis for the data events, SM background processes and two B signal masses in the (a) B *1L hadT* and (b) B *1L hadW* signal region. The signal distributions are scaled to the theory cross-sections multiplied by the indicated factor for better visibility and the background processes are normalised to their post-fit normalisation. The uncertainty band includes statistical and all systematic uncertainties. The last bin includes the overflow.

jet after applying all selection criteria in the two B signal regions is shown in figure 5. The background processes are normalised to the post-fit event yields (see section 6) and the data agrees with the SM expectation within the statistical and systematic uncertainties band in both figures.

The main background processes with a single-lepton signature arise from top-quark pair and W+jets production, with smaller contributions from single top-quark production, multijet, Z+jets and diboson events. The normalisation of W+jets processes as well as the $t\bar{t}$ and single-top Wt-processes is improved by constraining the predicted yields to match

the data in appropriate control regions enriched in W and $t\bar{t}$ events, respectively. Two control regions (CRs) for each signal region are defined for this purpose. The selection for the W-enriched region is the same as for the signal region, except that each event is required to have exactly zero b-tagged jets. The selection for the $t\bar{t}$ control regions is the same as for the signal regions, except that only events with two or more b-tagged jets are selected. The multijet processes are estimated with a data-driven matrix method described in reference [77]. The remaining background processes, such as single top-quark production, Z+jets and diboson processes are estimated using simulations. The contamination of the $t\bar{t}$ control regions by b^* and B signals with masses of $m \geq 1000$ GeV is at most 16% and 0.9%, respectively, and in the W-enriched control regions at most 2.2% and 0.1%, respectively.

The invariant mass calculated from the four-momenta of the lepton, all (two or three) central small-R jets and the missing transverse momentum is used to discriminate the signal from the background processes in the statistical analysis. Since the longitudinal component of the neutrino momentum is not reconstructed, it is set to zero. Figure 6 shows the reconstructed mass distribution for the b^* selection (top row) and for the B selection (bottom row) in the *1L hadT* (left side) and the *1L hadW* (right side) signal region. Further kinematic distributions, such as the leading large-R jet mass in the b^* signal regions and the leading large-R jet transverse momentum in the B signal regions, are presented in figure 7. All SM background processes in figure 4–7 are normalised to the post-fit normalisation that is discussed in section 6. The figures show good agreement between the data and the SM background processes. The total number of data events and the event yields after fitting the background-only hypotheses to data (as explained in section 6), together with their systematic uncertainties in the B and b^* signal regions, are listed in tables 3 and 4.

The post-fit normalisation is consistent with the pre-fit expectation within uncertainties: the normalisation of the top-quark background differs by 5–10%, the normalisation of W+jets processes in the SRs is consistent with 1.0, except for the *1L hadW* B signal region, where it decreases to 0.65 ± 0.11.

Figure 8 presents the distributions of the discriminant in the single-lepton channel (reconstructed mass) together with their statistical and systematic uncertainties in the b^* W+jets control regions (top row) and in the B $t\bar{t}$ control regions (bottom row) for the *1L hadT* category (left side) and the *1L hadW* category (right side).

4.3 Dilepton event selection and background estimation

Events in the dilepton final state are required to have exactly one electron and one muon with opposite charge as well as one or two central small-R jets ($|\eta| < 2.5$), exactly one of which is required to be b-tagged. Since same-flavour $Z \to \ell\ell$ ($\ell = e, \mu$) events are already suppressed by the opposite-flavour lepton requirement, no $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement is applied. For the b^* signal, it was found that the angular distance between the jet and the lepton is smaller than that in background process events, so an additional requirement is made on the smallest value of angle ϕ between the leading small-R jet (j_0) and the leptons, $\Delta\phi_{\min}(\ell, j_0) < 0.9$.
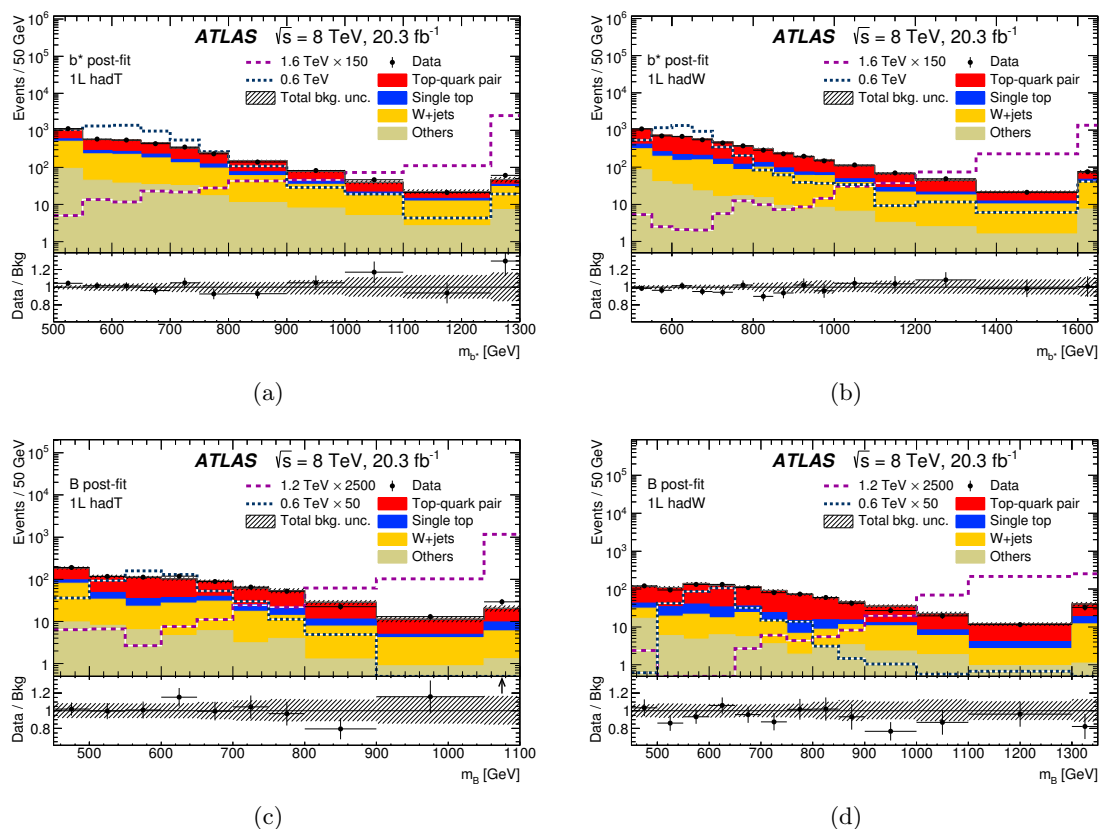
Figure 6. Distributions of the reconstructed mass in the b^* (top row) and B (bottom row) selection of the single-lepton analysis for the SM background processes, data and two b^* (top row) or B (bottom row) signal masses in the (a) b^* *1L hadT*, (b) b^* *1L hadW*, (c) B *1L hadT* and (d) B *1L hadW* signal regions. The signal distributions are scaled to the theory cross-sections multiplied by the indicated factor for better visibility and the background processes are normalised to their post-fit normalisation. The uncertainty band includes statistical and all systematic uncertainties. The first and last bin include the underflow and overflow, respectively. The binning of the figures is the same as used in the binned likelihood fit function.

For the B signal, events are required to have exactly one central b-tagged jet from the top-quark decay and one small-R jet with $1.5 < |\eta| < 4.5$ from the light quark. If this additional jet is in the range of $|\eta| < 2.5$, then it is required not to be b-tagged. Events are also allowed to contain up to one additional untagged jet with $|\eta| < 1.5$.

Events with one central jet and two central jets have different background compositions and are considered as separate signal regions *2L 1jet 1tag* and *2L 2jet 1tag*, respectively. A $t\bar{t}$ control region *2L 2jet 2tag* is defined by requiring exactly two central b-tagged small-R jets. The contamination by B and b^* signals with $m = 1000$ GeV is at most 0.3%.

The main background processes with a dilepton signature arise from top-quark pair, single top-quark and diboson production, with smaller contributions from non-prompt lepton and Z+jets events. The Z+jets background, which arises from Z-boson decays to tau leptons that subsequently decay into an electron and a muon, is taken from simulation samples. The non-prompt lepton background process arises from events where one or two jets are misidentified as leptons. This background includes mainly multijet processes as
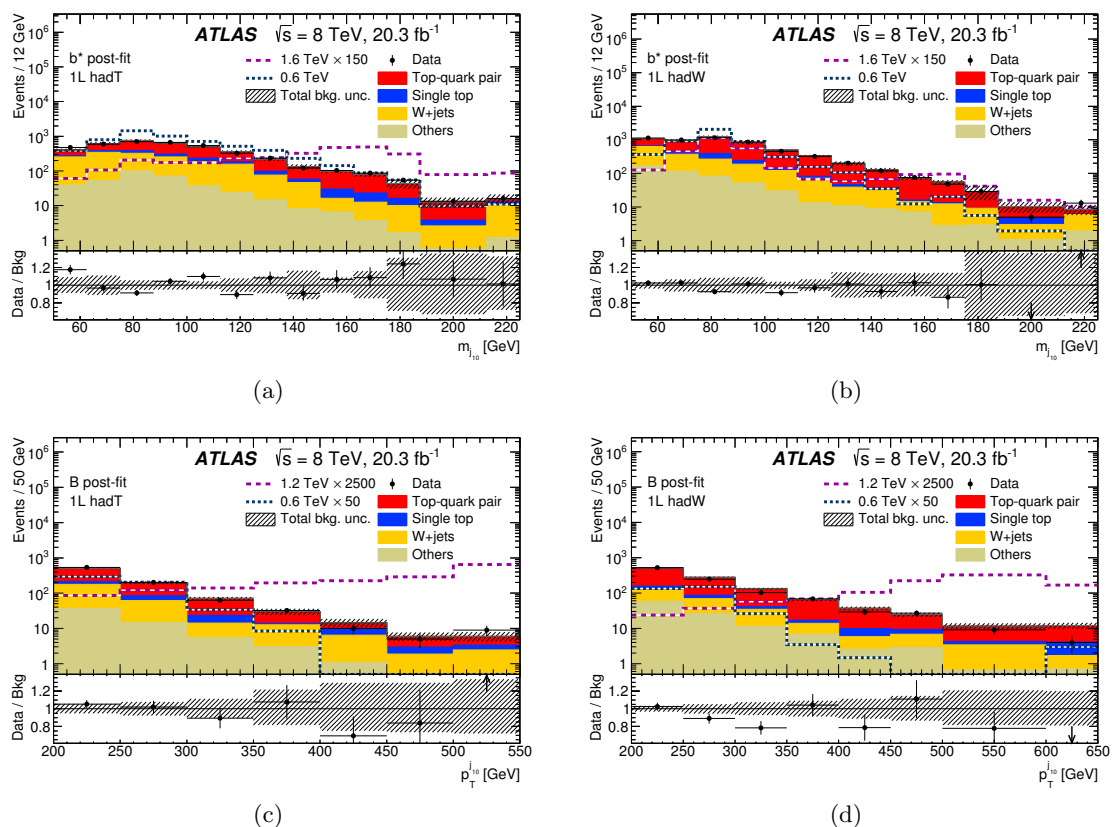
Figure 7. Distributions of the leading large-R jet mass in the b^* selection (top row) and distributions of the leading large-R transverse momentum in the B selection (bottom row) of the single-lepton analysis for the SM background processes, data and two b^* (top row) or B (bottom row) signal masses in the (a),(c) *1L hadT* and (b),(d) *1L hadW* signal regions. The signal distributions are scaled to the theory cross-sections multiplied by the indicated factor for better visibility and the background processes are normalised to their post-fit normalisation. The uncertainty band includes statistical and all systematic uncertainties. The last bin includes the overflow.

well as processes with a single-lepton final state ($t\bar{t}$ single-lepton channel, single top-quark other than Wt-channel, W+jets). It is estimated with the data-driven matrix method [77] as described in section 4.2. The event yields in each of the signal regions after fitting the background-only hypothesis to data are shown in table 3 and 4. For each process the post-fit normalisation is compatible with the pre-fit normalisation.

Selected kinematic distributions, such as the p_{T} of the leading lepton and the $E_{\mathrm{T}}^{\mathrm{miss}}$, for the dilepton events in the signal regions *2L 1jet 1tag* and *2L 2jet 1tag* are shown in figure 9. The background processes are normalised to post-fit event yields and their sum models the data well. The transverse mass (m_{T}) of the system formed by the leptons, the leading jet and the $E_{\mathrm{T}}^{\mathrm{miss}}$ is used as the final discriminating distribution.

The distributions of m_{T} for the different B and b^* signal and control regions are shown in figure 10 and figure 11, respectively. The distributions show the bin widths used in the statistical analysis. The control region distributions for various kinematic variables as well as the event yields show good agreement between data and MC simulation.
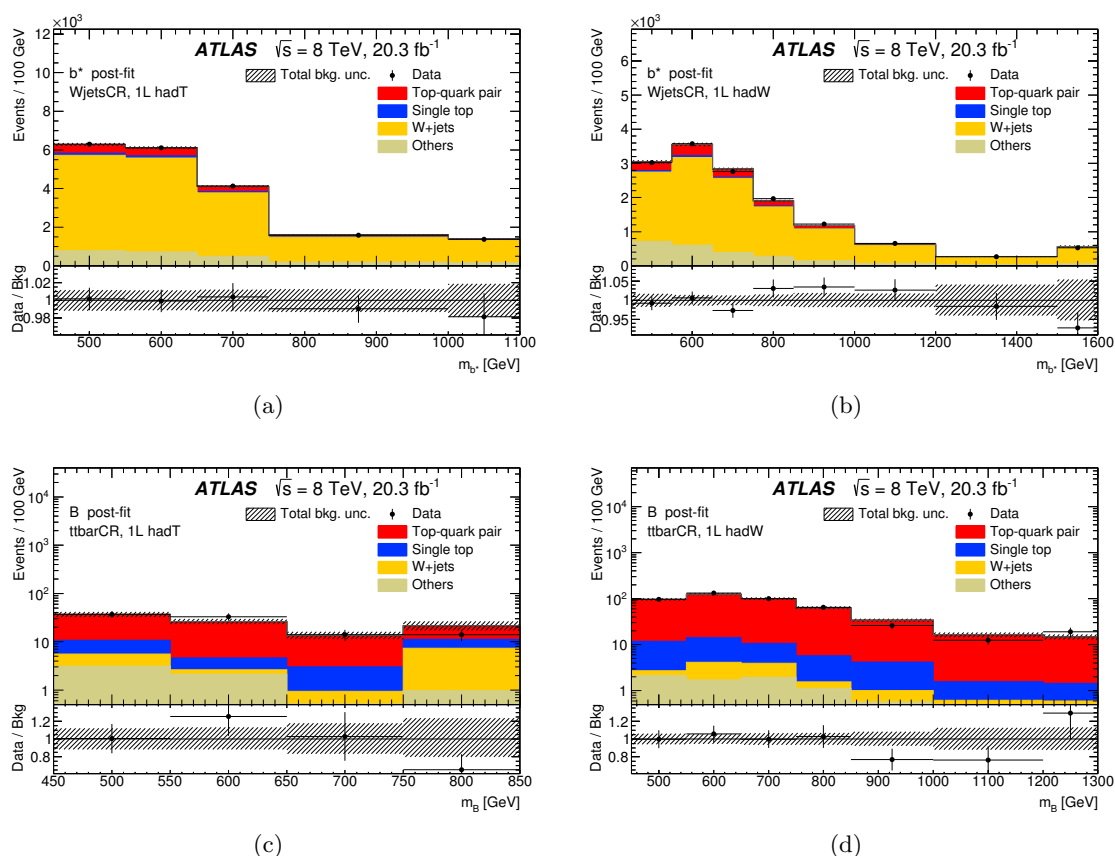
Figure 8. Distributions of the reconstructed mass in the b^* (top row) and B (bottom row) selection of the single-lepton analysis for the SM background processes and data events in the (a), (c) *1L hadT* and (b), (d) *1L hadW* W+jets control region (top row) and $t\bar{t}$ control region (bottom row). The background processes are normalised to their post-fit normalisation. The uncertainty band includes statistical and all systematic uncertainties. The first and last bin include the underflow and overflow, respectively. The binning of the figures is the same as used in the binned likelihood fit function.

5 Systematic uncertainties

Systematic uncertainties affect the yield and acceptance estimates as well as the shape of the discriminant distributions of the signal and background processes. They are included as nuisance parameters in the statistical analysis and both normalisation and shape variations are considered (except for the theoretical cross section uncertainty and the PDF uncertainties). Sources of uncertainty include the modelling of the detector, properties of reconstructed objects, theoretical modelling of the signals and backgrounds, as well as the uncertainty of the prediction arising from the limited size of the simulated event samples.

5.1 Experimental uncertainties

Experimental sources of systematic uncertainty arise from the reconstruction and measurement of jets [67, 74, 78–80], leptons [62, 81] and $E_{\mathrm{T}}^{\mathrm{miss}}$ [76]. The impact of the uncertainty in the jet-energy scale (JES) is evaluated for both the small-R and large-R jets. For large-R jets, additional uncertainties associated with the scale and resolution of the jet mass

Process	1L hadT	1L hadW	2L 1jet 1tag	2L 2jet 1tag
$t\bar{t}$	483(27)	746(34)	2480(40)	1457(34)
Single t	94(13)	125(13)	276(23)	81(9)
W+jets	220(40)	152(27)	—	—
WW, WZ, ZZ, Z+jets	22(7)	30(11)	15(5)	5(4)
Non-prompt lepton	18(11)	28(14)	6(4)	1.9(15)
Signal $m_B = 500$ GeV	12.0(19)	10.4(16)	13.8(9)	4.1(4)
Signal $m_B = 600$ GeV	22.4(22)	13.4(15)	7.9(4)	2.34(25)
Signal $m_B = 700$ GeV	16.7(13)	10.6(8)	4.06(25)	1.33(11)
Signal $m_B = 800$ GeV	11.1(7)	7.3(5)	2.35(14)	0.69(6)
Signal $m_B = 1000$ GeV	3.62(29)	2.78(16)	0.64(4)	0.205(19)
Signal $m_B = 1200$ GeV	1.40(9)	1.09(7)	0.188(14)	0.073(7)
Total bkg.	835(34)	1081(35)	2780(40)	1544(35)
Data	856	1018	2760	1548

Table 3. Event yields in the signal regions for the B analysis after the fit of the background-only hypothesis (as explained in section 6). The uncertainties include statistical and systematic uncertainties. The uncertainties on the background composition are much larger than the uncertainty on the sum of the backgrounds, which is strongly constrained by the data. The numbers of the B signal events are evaluated using the respective theory cross-sections and branching ratios for $\lambda = 2$.

Process	1L hadT	1L hadW	2L 1jet 1tag	2L 2jet 1tag
$t\bar{t}$	1860(60)	3390(120)	1160(40)	1409(33)
Single t	368(33)	520(40)	253(26)	97(10)
W+jets	1360(140)	1290(120)	—	—
WW, WZ, ZZ, Z+jets	230(100)	180(50)	13(4)	3.0(16)
Non-prompt lepton	60(40)	100(40)	6(4)	2.0(14)
Signal $m_{b^*} = 600$ GeV	5800(270)	4890(230)	800(50)	493(27)
Signal $m_{b^*} = 800$ GeV	2240(90)	1640(70)	215(14)	142(7)
Signal $m_{b^*} = 1000$ GeV	661(30)	591(26)	55.0(34)	44.1(25)
Signal $m_{b^*} = 1200$ GeV	209(10)	196(10)	16.2(12)	14.2(10)
Signal $m_{b^*} = 1400$ GeV	68.5(32)	63.4(31)	4.8(4)	4.20(34)
Signal $m_{b^*} = 1600$ GeV	23.8(12)	21.2(10)	1.41(15)	1.35(14)
Signal $m_{b^*} = 1800$ GeV	8.7(5)	7.3(4)	0.49(8)	0.48(8)
Total bkg.	3880(70)	5480(70)	1436(33)	1511(34)
Data	3933	5380	1448	1502

Table 4. Event yields in the signal regions for the b^* analysis after the fit of the background-only hypothesis (as explained in section 6). The uncertainties include statistical and systematic uncertainties. The uncertainties on the background composition are much larger than the uncertainty on the sum of the backgrounds, which is strongly constrained by the data. The numbers of the b^* signal events are evaluated using the respective theory cross-sections and branching ratios. The couplings are assumed to be $f_{\mathrm{L}} = f_{\mathrm{R}} = 1$.
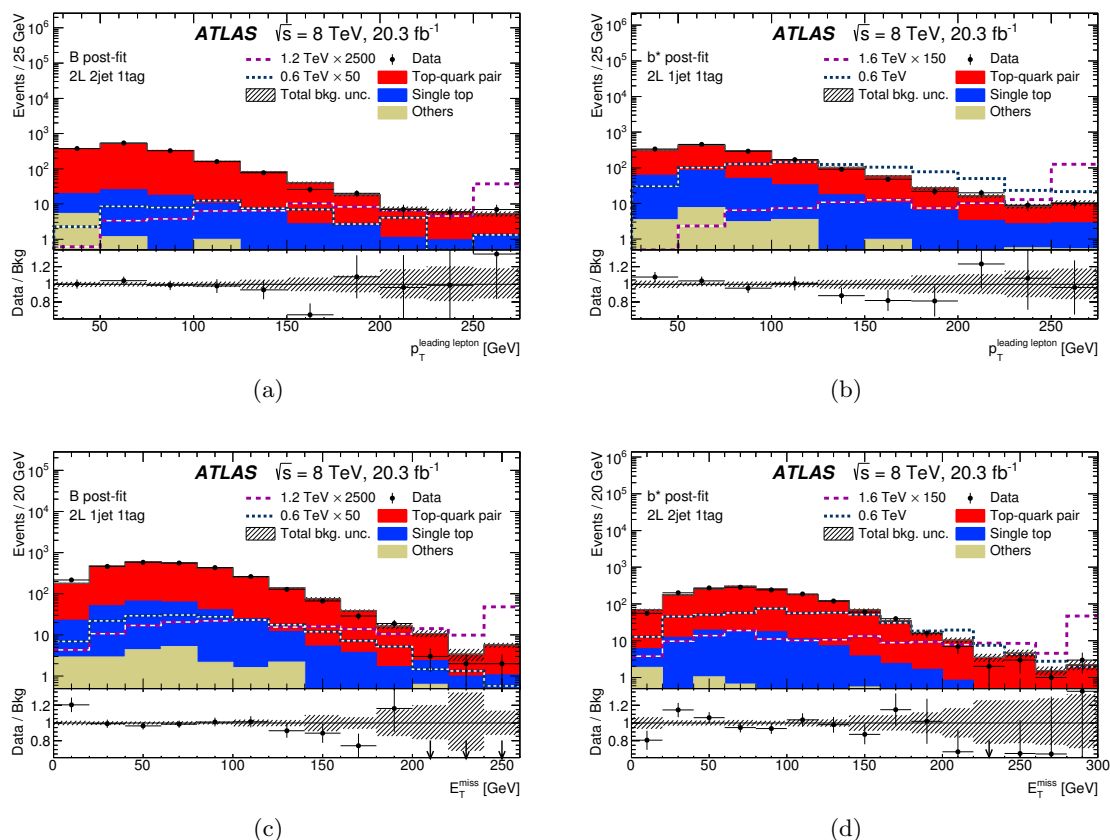
Figure 9. Distributions of kinematic variables in different signal regions of the dilepton selection for SM background processes and data, overlaid with two corresponding signal distributions: (a) leading lepton p_T in the *2L 2jet 1tag* region after the B selection and (b) in the *2L 1jet 1tag* region after the b^* selection, (c) E_T^{miss} in the *2L 1jet 1tag* region after the B selection and (d) in the *2L 2jet 1tag* region after the b^* selection. The signal distributions are scaled to the theory cross-sections multiplied by the indicated factor for better visibility and the background processes are normalised to their post-fit normalisation. The uncertainty band includes statistical and all systematic uncertainties. The last bin includes the overflow.

are included. The E_T^{miss} has additional uncertainty contributions due to the modelling of energy deposits not associated with any reconstructed object. Further uncertainties arise from the lepton trigger, reconstruction, energy scale and resolution as well as from the lepton and jet identification efficiency modelling. Uncertainties on the b-tagging efficiency and mistag rates are estimated from data [82].

The largest detector-specific uncertainties for the single-lepton channel arise from large-R jet-energy scale uncertainties (10–18% effect on the predicted background yield), large R-jet energy and mass resolution uncertainties (2–5%), small-R jet-energy scale uncertainties (3–5%) and the b-tagging uncertainties (1–3%), depending on the signal region and analysis selection. The expected yield of events with non-prompt leptons is subject to uncertainties in the real and non-prompt lepton efficiencies and they sum to a 2–18% uncertainty on the total SM background in the defined signal regions.
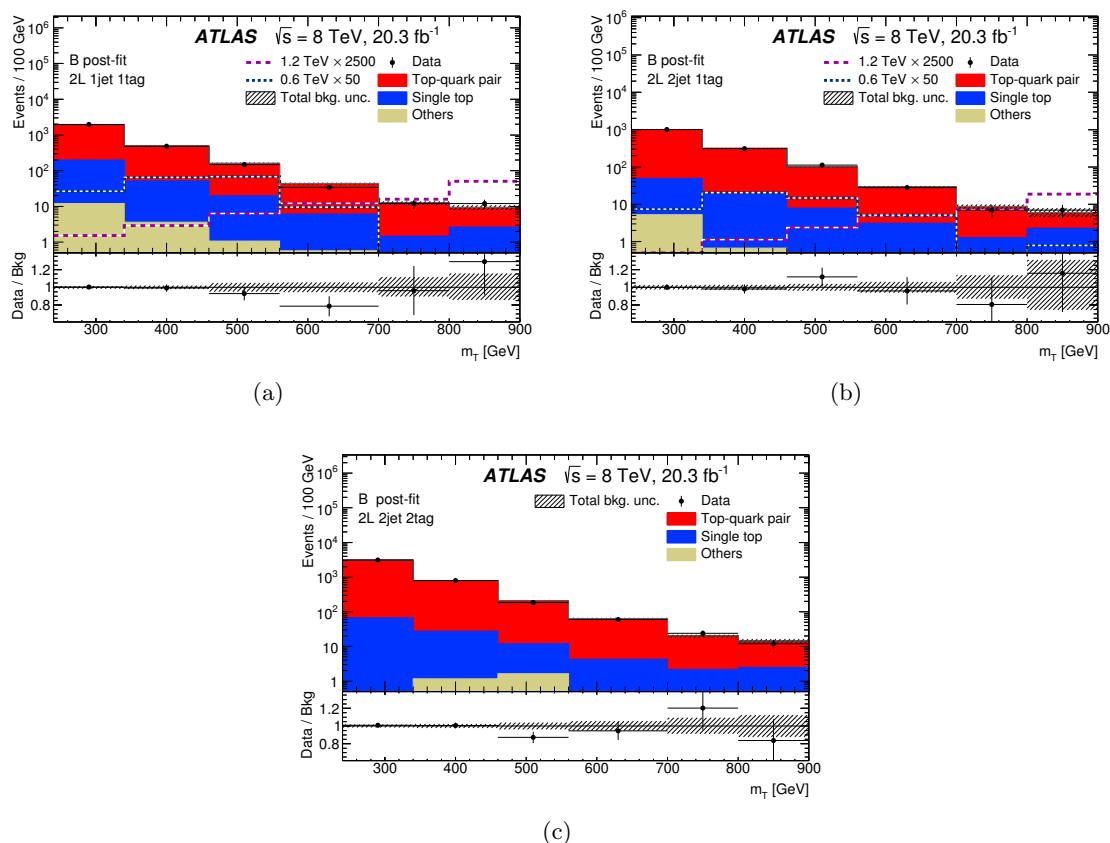
Figure 10. Distributions of the discriminant variable, transverse mass, m_T, in the dilepton channel for data and SM background processes in the (a) *2L 1jet 1tag* signal region, (b) *2L 2jet 1tag* signal region and (c) *2L 2jet 2tag* control region using the B selection. The two B signal distributions that are included for the signal region distributions are scaled to the theory cross-sections multiplied by the indicated factor for better visibility. The background processes are normalised to their post-fit normalisation. The uncertainty band includes statistical and all systematic uncertainties. The first and the last bin contain the underflow and overflow, respectively. The binning of the figures is the same as used in the binned likelihood fit function.

For the dilepton channel, the relative impact of a particular systematic uncertainty is similar for the signal and background and for the different signal regions. Significant variations on the acceptance come from the b-tagging uncertainty (2–5%), electron identification uncertainty (2–3%) and from JES uncertainties related to pile-up (1–2%).

5.2 Modelling of theoretical uncertainties

Theoretical uncertainties are evaluated for the signal as well as for the background processes. The evaluation of the PDF uncertainty follows the PDF4LHC prescription [83] using three different PDF sets (CT10, MSTW2008NLO68CL and NNPDF20 [84]). The uncertainty on top-quark pair production due to initial- and final-state radiation is evaluated using the ALPGEN LO generator, with the CTEQ6L1 PDF set and interfaced with PYTHIA v6.426. The renormalisation scale associated with the strong coupling α_S in the
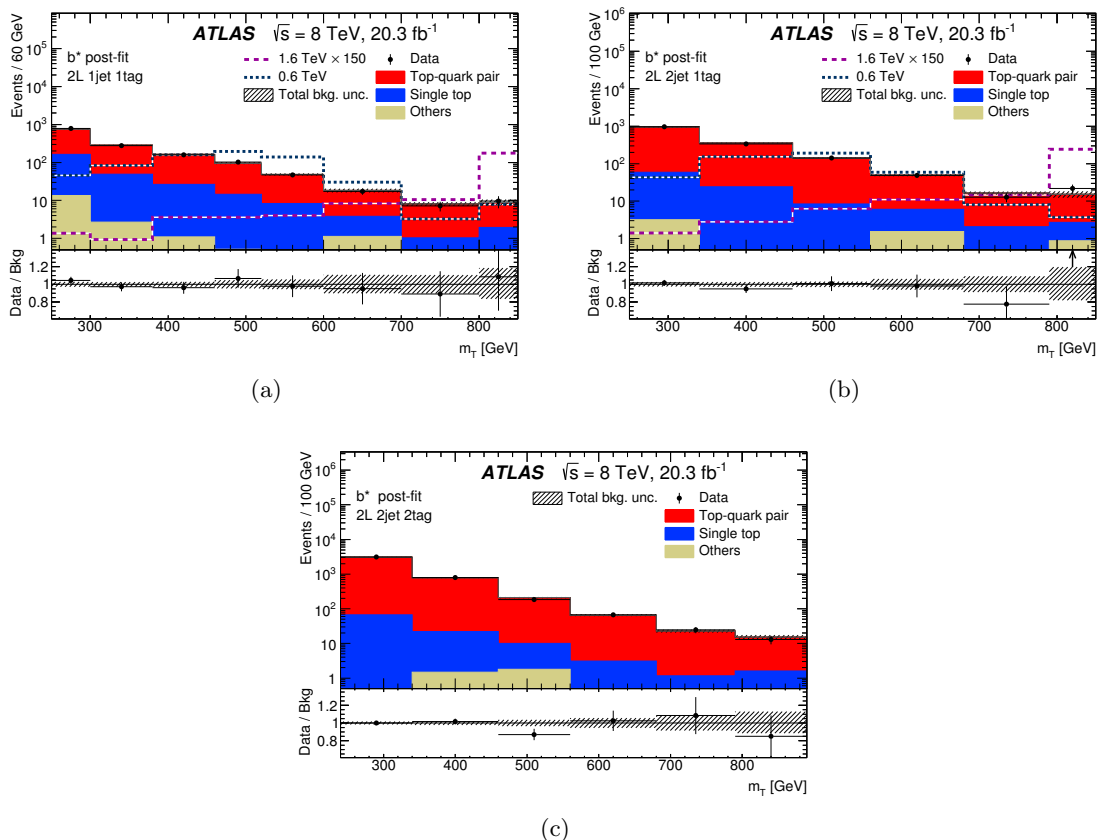
Figure 11. Distributions of the discriminant variable, transverse mass, m_{T}, in the dilepton channel for data and SM background processes in the (a) *2L 1jet 1tag* signal region, (b) *2L 2jet 1tag* signal region and (c) *2L 2jet 2tag* control region using the b^* selection. For the signal region distributions, the two included b^* signal distributions are scaled to the theory cross-sections multiplied by the indicated factor for better visibility. The background processes are normalised to their post-fit normalisation. The uncertainty band includes statistical and all systematic uncertainties. The first and the last bin contain the underflow and overflow, respectively. The binning of the figures is the same as used in the binned likelihood fit function.

matrix-element calculation is varied by factors of 2 and 0.5, and at the same time the amount of radiation is decreased or increased in a range compatible with data by choosing the appropriate variation of the PYTHIA Perugia 2012 tune [85].

The uncertainty on the top-quark pair and single top-quark Wt processes due to the choice of generator and parton shower is evaluated by comparing the nominal simulation samples to POWHEG-BOX and MC@NLO v4.06 [86, 87] samples interfaced with HERWIG v6.52.

For background estimates based on simulations, the largest sources of uncertainty in the single-lepton analysis are due to varying the parameters controlling the initial-state radiation model (2.5–5%), the PDF sets (1–3%) and renormalisation and factorisation scales (1–7%). Differences for heavy-flavour and light-flavour components of the W+jets background processes in the signal and control regions lead to a systematic uncertainty of 4–5%.

For the dilepton analysis, the initial- and final-state radiation uncertainty has an impact on the selection efficiency of 5–17%. The impact of the other theoretical uncertainties on the total background rate is 1–8%, depending on the signal region and signal or background sample.

The normalisation of the $t\bar{t}$, single-top t-channel and Wt backgrounds has an uncertainty of $^{+5.1}_{-5.9}$% [50, 51], $^{+3.9}_{-2.2}$% and 6.8% [53], respectively. The diboson and W/Z+jets background processes have an uncertainty of 5% and 4% [88], respectively, with an additional 24% for each additional jet [89, 90].

The uncertainty on the luminosity of ± 2.8% [91] affects the normalisation of the signal and the background processes estimated from theory predictions.

6   Statistical analysis and results

The distributions of m_B and m_{b^*} in the single-lepton channel and m_T in the dilepton channel are sensitive to resonant production of B and b^*, respectively. A binned likelihood fit is performed in order to test for the presence of a signal. A separate fit is performed for each signal hypothesis, i.e. B/b^* with fixed mass and couplings. Let N_i be the observed number of events in bin i, B_i the predicted number of background events, S_i the predicted number of signal events assuming a cross-section of 1 pb, and μ the signal-strength parameter, which measures the signal cross-section in units of pb. The likelihood function is constructed as the product of Poisson likelihood terms, each of the form $\mathrm{Pois}(N_i; \mu S_i + B_i)$, over all bins of the $m_B/m_{b^*}/m_T$ distributions in the signal and control regions. The one-sided 95% CL upper limit on μ, and therefore the signal cross-section, is constructed in a Bayesian approach[4] with a positive semidefinite flat prior for μ. The expected limits are derived by fitting to the nominal background estimate [94].

The likelihood function also depends on a set of nuisance parameters, which encode the adjustments of the expectations due to the systematic uncertainties discussed in section 5. The prior for each of the nuisance parameters is taken to be the normal distribution, where a value of 0 corresponds to the nominal prediction, and ± 1 to the symmetric variation by one standard deviation. The uncertainties on the expected numbers of events in each bin (S_i, B_i) are propagated to μ through these parameters. They also allow the control regions to improve the description of the data, and to reduce the impact of systematic uncertainties in the signal region. The strongest reduction is achieved for the normalisation uncertainty on the W+jets background, which becomes 10% after the fit, compared to the about 40% before the fit. The largest uncertainties are due to the JES, the b-tagging, and the background normalisation, where the latter is dominant for small masses. Table 5 shows the normalisation variation from the largest systematic uncertainties before and after the fit. The posterior distribution of the nuisance parameters after the fit of the background-only ($\mu = 0$) hypothesis to the data is used to compute post-fit event yields, to normalise the distributions in the control plots, and to check for agreement between data and the background prediction in many variables. Given that the best-fit values of

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[4]The posterior density function is sampled using the Bayesian Analysis Toolkit [92], interfaced to RooStats [93].

	b^*		B	
	Pre-fit [%]	Post-fit [%]	Pre-fit [%]	Post-fit [%]
Jet uncertainties	14.0	6.5	12.0	6.2
b-tagging uncertainties	3.3	3.0	2.8	2.5
Lepton uncertainties	1.6	1.5	1.6	1.6
Fake-lepton uncertainties	2.6	2.4	2.9	2.6
Theory uncertainties				
• Top-quark pair	3.2	1.8	9.4	3.4
• W+jets	9.1	3.6	9.6	4.9
• Single top	0.0	0.0	0.1	0.1
• Diboson	0.5	0.5	0.2	0.2
• Z+jets	0.5	0.5	0.7	0.7

Table 5. Relative effects of the systematic uncertainties on the total background estimate in the signal regions, before and after fitting. The jet uncertainties include large-R jet uncertainties and other jet uncertainties such as jet energy scale and resolution. The lower part of the table shows how the theoretical uncertainties on individual backgrounds affect the sum of all backgrounds.

the nuisance parameters were found to be compatible between the individual regions, the nuisance parameters are treated as fully correlated between the regions.

The post-fit event yields for the B and b^* signal regions together with their systematic uncertainties are listed in the tables 3 and 4. For illustration, the number of events for some signal hypotheses are also presented, each normalised to the predicted cross-section times branching ratio.

The maximum local deviation of the observed data from the expected background is 1.4 standard deviations, seen in the last bin of the b^* *1L hadT* signal region (figure 6(a)). The value is computed using a moving-window algorithm [95] that compares data to the improved background estimate in the signal regions. Given the absence of a significant excess, limits are set on the production cross-section of both B and b^* multiplied by the branching ratio of the decay to Wt.

The resulting expected and observed limits at the 95% CL on cross-section times branching ratio are presented as functions of the B (figure 12(a)) and b^* (figure 12(b)) mass, and are compared to the theory predictions. No large deviations of the observed limits from the expected limits are found. The observed limits for high masses are slightly worse than expected, because the corresponding fits are sensitive to the mild excess in the last bin of the signal region in the single-lepton channel (see above).

The observed (expected) mass limit is defined by the intersection of the theory line with the observed (expected) cross-section limit. For the B production, no limit on the mass and only limits on the cross-section times branching ratio can be set. For b^* production with couplings of $f_g = f_L = f_R = 1$, the cross-section limits are translated into an observed (expected) lower limit on the b^* mass of 1500 GeV (1660 GeV).

The cross-section is parameterised as a function of the couplings f_g and $f_{L,R}$ to extract the limits on these couplings for several mass hypotheses. The resulting contours are shown in figure 13.
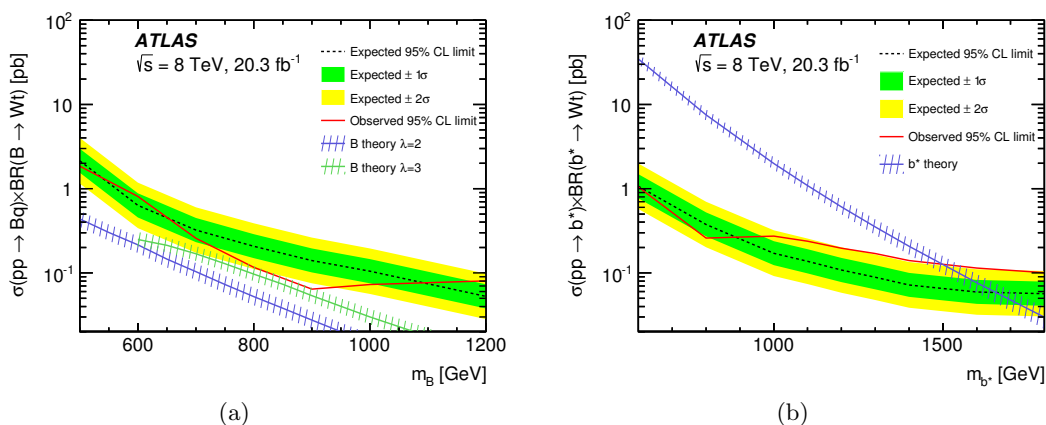
Figure 12. Expected (dashed black line) and observed (solid red line) 95% CL limits on the (a) B and the (b) b^* production cross-sections times branching fractions plotted against the mass. The uncertainty band around the expected limit indicates the variations by ± 1 and ± 2 standard deviations. The single-lepton and the dilepton channels are combined. Also shown are the theory predictions, which for B are for two different coupling values λ in the mass range where these are valid. The couplings $f_g = f_L = f_R = 1$ are assumed for the b^* theory predictions. For both the b^* and the B signals, the uncertainty in the theory band includes the scale and the PDF uncertainties.
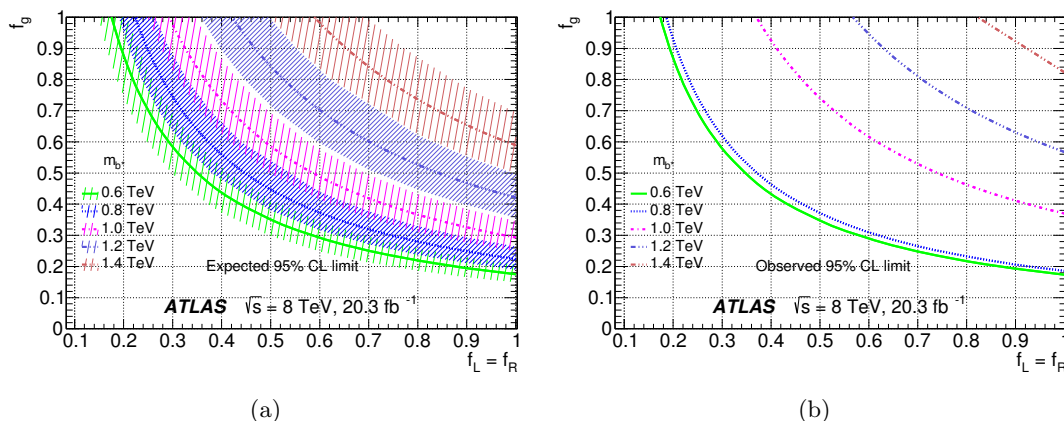
Figure 13. Expected (a) and observed (b) limit contours at the 95% CL as a function of the coupling parameters for several choices of m_{b^*}. The surrounding shaded bands correspond to ± 1 standard derivations around the expected limits. For a given mass, couplings above the corresponding contour line are excluded.

7 Conclusion

A search for the production of singly produced fourth-generation vector-like quarks and excited quarks with charge $\pm \frac{1}{3}e$ (down-type) in which the B, produced via the weak interaction, and b^* produced via the strong interaction with chromomagnetic couplings, decay into Wt has been performed using $20.3\,\mathrm{fb}^{-1}$ of $\sqrt{s} = 8$ TeV proton-proton collision data delivered by the Large Hadron Collider and recorded with the ATLAS detector. Final states

with one or two leptons and with one, two or three jets are considered. The observations are consistent with the Standard Model expectations. Limits are set for B and b^* models by combining the results from the single-lepton and dilepton channels. The b^* models with $f_g = f_L = f_R = 1$ and decay to Wt are excluded up to masses of 1500 GeV at 95% CL. Upper limits on the production cross-sections times branching ratios for different vector-like B and excited b^* quark masses are also provided. The b^* limit is an improvement over the previous ATLAS result and yields similar exclusion limits as the recent CMS result. The cross section limit on the single production of vector-like B quarks extends the set of existing B searches into the Wt final state using a novel approach for boosted event topologies.

Acknowledgments

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S. Campana[30], M. Campanelli[78], A. Campoverde[148], V. Canale[104a,104b], A. Canepa[159a],
M. Cano Bret[33e], J. Cantero[82], R. Cantrill[126a], T. Cao[40], M.D.M. Capeans Garrido[30],
I. Caprini[26b], M. Caprini[26b], M. Capua[37a,37b], R. Caputo[83], R.M. Carbone[35],
R. Cardarelli[133a], F. Cardillo[48], T. Carli[30], G. Carlino[104a], L. Carminati[91a,91b],
S. Caron[106], E. Carquin[32a], G.D. Carrillo-Montoya[30], J.R. Carter[28], J. Carvalho[126a,126c],
D. Casadei[78], M.P. Casado[12], M. Casolino[12], E. Castaneda-Miranda[145a], A. Castelli[107],
V. Castillo Gimenez[167], N.F. Castro[126a,g], P. Catastini[57], A. Catinaccio[30],
J.R. Catmore[119], A. Cattai[30], J. Caudron[83], V. Cavaliere[165], D. Cavalli[91a],
M. Cavalli-Sforza[12], V. Cavasinni[124a,124b], F. Ceradini[134a,134b], B.C. Cerio[45], K. Cerny[129],
A.S. Cerqueira[24b], A. Cerri[149], L. Cerrito[76], F. Cerutti[15], M. Cerv[30], A. Cervelli[17],
S.A. Cetin[19c], A. Chafaq[135a], D. Chakraborty[108], I. Chalupkova[129], Y.L. Chan[60a],
P. Chang[165], J.D. Chapman[28], D.G. Charlton[18], C.C. Chau[158], C.A. Chavez Barajas[149],
S. Cheatham[152], A. Chegwidden[90], S. Chekanov[6], S.V. Chekulaev[159a], G.A. Chelkov[65,h],
M.A. Chelstowska[89], C. Chen[64], H. Chen[25], K. Chen[148], L. Chen[33d,i], S. Chen[33c],
S. Chen[155], X. Chen[33f], Y. Chen[67], H.C. Cheng[89], Y. Cheng[31], A. Cheplakov[65],
E. Cheremushkina[130], R. Cherkaoui El Moursli[135e], V. Chernyatin[25,*], E. Cheu[7],
L. Chevalier[136], V. Chiarella[47], G. Chiarelli[124a,124b], G. Chiodini[73a], A.S. Chisholm[18],
R.T. Chislett[78], A. Chitan[26b], M.V. Chizhov[65], K. Choi[61], S. Chouridou[9],
B.K.B. Chow[100], V. Christodoulou[78], D. Chromek-Burckhart[30], J. Chudoba[127],
A.J. Chuinard[87], J.J. Chwastowski[39], L. Chytka[115], G. Ciapetti[132a,132b], A.K. Ciftci[4a],
D. Cinca[53], V. Cindro[75], I.A. Cioara[21], A. Ciocio[15], F. Cirotto[104a,104b], Z.H. Citron[172],
M. Ciubancan[26b], A. Clark[49], B.L. Clark[57], P.J. Clark[46], R.N. Clarke[15],
C. Clement[146a,146b], Y. Coadou[85], M. Cobal[164a,164c], A. Coccaro[49], J. Cochran[64],
L. Coffey[23], J.G. Cogan[143], L. Colasurdo[106], B. Cole[35], S. Cole[108], A.P. Colijn[107],
J. Collot[55], T. Colombo[58c], G. Compostella[101], P. Conde Muiño[126a,126b], E. Coniavitis[48],
S.H. Connell[145b], I.A. Connelly[77], V. Consorti[48], S. Constantinescu[26b], C. Conta[121a,121b],
G. Conti[30], F. Conventi[104a,j], M. Cooke[15], B.D. Cooper[78], A.M. Cooper-Sarkar[120],
T. Cornelissen[175], M. Corradi[20a], F. Corriveau[87,k], A. Corso-Radu[163],
A. Cortes-Gonzalez[12], G. Cortiana[101], G. Costa[91a], M.J. Costa[167], D. Costanzo[139],

D. Côté[8], G. Cottin[28], G. Cowan[77], B.E. Cox[84], K. Cranmer[110], G. Cree[29],
S. Crépé-Renaudin[55], F. Crescioli[80], W.A. Cribbs[146a,146b], M. Crispin Ortuzar[120],
M. Cristinziani[21], V. Croft[106], G. Crosetti[37a,37b], T. Cuhadar Donszelmann[139],
J. Cummings[176], M. Curatolo[47], J. Cúth[83], C. Cuthbert[150], H. Czirr[141], P. Czodrowski[3],
S. D'Auria[53], M. D'Onofrio[74], M.J. Da Cunha Sargedas De Sousa[126a,126b], C. Da Via[84],
W. Dabrowski[38a], A. Dafinca[120], T. Dai[89], O. Dale[14], F. Dallaire[95], C. Dallapiccola[86],
M. Dam[36], J.R. Dandoy[31], N.P. Dang[48], A.C. Daniells[18], M. Danninger[168],
M. Dano Hoffmann[136], V. Dao[48], G. Darbo[50a], S. Darmora[8], J. Dassoulas[3],
A. Dattagupta[61], W. Davey[21], C. David[169], T. Davidek[129], E. Davies[120,l], M. Davies[153],
P. Davison[78], Y. Davygora[58a], E. Dawe[88], I. Dawson[139], R.K. Daya-Ishmukhametova[86],
K. De[8], R. de Asmundis[104a], A. De Benedetti[113], S. De Castro[20a,20b], S. De Cecco[80],
N. De Groot[106], P. de Jong[107], H. De la Torre[82], F. De Lorenzi[64], D. De Pedis[132a],
A. De Salvo[132a], U. De Sanctis[149], A. De Santo[149], J.B. De Vivie De Regie[117],
W.J. Dearnaley[72], R. Debbe[25], C. Debenedetti[137], D.V. Dedovich[65], I. Deigaard[107],
J. Del Peso[82], T. Del Prete[124a,124b], D. Delgove[117], F. Deliot[136], C.M. Delitzsch[49],
M. Deliyergiyev[75], A. Dell'Acqua[30], L. Dell'Asta[22], M. Dell'Orso[124a,124b],
M. Della Pietra[104a,j], D. della Volpe[49], M. Delmastro[5], P.A. Delsart[55], C. Deluca[107],
D.A. DeMarco[158], S. Demers[176], M. Demichev[65], A. Demilly[80], S.P. Denisov[130],
D. Derendarz[39], J.E. Derkaoui[135d], F. Derue[80], P. Dervan[74], K. Desch[21], C. Deterre[42],
K. Dette[43], P.O. Deviveiros[30], A. Dewhurst[131], S. Dhaliwal[23], A. Di Ciaccio[133a,133b],
L. Di Ciaccio[5], A. Di Domenico[132a,132b], C. Di Donato[104a,104b], A. Di Girolamo[30],
B. Di Girolamo[30], A. Di Mattia[152], B. Di Micco[134a,134b], R. Di Nardo[47], A. Di Simone[48],
R. Di Sipio[158], D. Di Valentino[29], C. Diaconu[85], M. Diamond[158], F.A. Dias[46],
M.A. Diaz[32a], E.B. Diehl[89], J. Dietrich[16], S. Diglio[85], A. Dimitrievska[13], J. Dingfelder[21],
P. Dita[26b], S. Dita[26b], F. Dittus[30], F. Djama[85], T. Djobava[51b], J.I. Djuvsland[58a],
M.A.B. do Vale[24c], D. Dobos[30], M. Dobre[26b], C. Doglioni[81], T. Dohmae[155], J. Dolejsi[129],
Z. Dolezal[129], B.A. Dolgoshein[98,*], M. Donadelli[24d], S. Donati[124a,124b],
P. Dondero[121a,121b], J. Donini[34], J. Dopke[131], A. Doria[104a], M.T. Dova[71], A.T. Doyle[53],
E. Drechsler[54], M. Dris[10], E. Dubreuil[34], E. Duchovni[172], G. Duckeck[100],
O.A. Ducu[26b,85], D. Duda[107], A. Dudarev[30], L. Duflot[117], L. Duguid[77], M. Dührssen[30],
M. Dunford[58a], H. Duran Yildiz[4a], M. Düren[52], A. Durglishvili[51b], D. Duschinger[44],
B. Dutta[42], M. Dyndal[38a], C. Eckardt[42], K.M. Ecker[101], R.C. Edgar[89], W. Edson[2],
N.C. Edwards[46], W. Ehrenfeld[21], T. Eifert[30], G. Eigen[14], K. Einsweiler[15], T. Ekelof[166],
M. El Kacimi[135c], M. Ellert[166], S. Elles[5], F. Ellinghaus[175], A.A. Elliot[169], N. Ellis[30],
J. Elmsheuser[100], M. Elsing[30], D. Emeliyanov[131], Y. Enari[155], O.C. Endner[83],
M. Endo[118], J. Erdmann[43], A. Ereditato[17], G. Ernis[175], J. Ernst[2], M. Ernst[25],
S. Errede[165], E. Ertel[83], M. Escalier[117], H. Esch[43], C. Escobar[125], B. Esposito[47],
A.I. Etienvre[136], E. Etzion[153], H. Evans[61], A. Ezhilov[123], L. Fabbri[20a,20b], G. Facini[31],
R.M. Fakhrutdinov[130], S. Falciano[132a], R.J. Falla[78], J. Faltova[129], Y. Fang[33a],
M. Fanti[91a,91b], A. Farbin[8], A. Farilla[134a], T. Farooque[12], S. Farrell[15], S.M. Farrington[170],
P. Farthouat[30], F. Fassi[135e], P. Fassnacht[30], D. Fassouliotis[9], M. Faucci Giannelli[77],
A. Favareto[50a,50b], L. Fayard[117], O.L. Fedin[123,m], W. Fedorko[168], S. Feigl[30], L. Feligioni[85],
C. Feng[33d], E.J. Feng[30], H. Feng[89], A.B. Fenyuk[130], L. Feremenga[8],
P. Fernandez Martinez[167], S. Fernandez Perez[30], J. Ferrando[53], A. Ferrari[166],
P. Ferrari[107], R. Ferrari[121a], D.E. Ferreira de Lima[53], A. Ferrer[167], D. Ferrere[49],
C. Ferretti[89], A. Ferretto Parodi[50a,50b], M. Fiascaris[31], F. Fiedler[83], A. Filipčič[75],
M. Filipuzzi[42], F. Filthaut[106], M. Fincke-Keeler[169], K.D. Finelli[150],
M.C.N. Fiolhais[126a,126c], L. Fiorini[167], A. Firan[40], A. Fischer[2], C. Fischer[12], J. Fischer[175],
W.C. Fisher[90], N. Flaschel[42], I. Fleck[141], P. Fleischmann[89], G.T. Fletcher[139],
G. Fletcher[76], R.R.M. Fletcher[122], T. Flick[175], A. Floderus[81], L.R. Flores Castillo[60a],
M.J. Flowerdew[101], A. Formica[136], A. Forti[84], D. Fournier[117], H. Fox[72], S. Fracchia[12],
P. Francavilla[80], M. Franchini[20a,20b], D. Francis[30], L. Franconi[119], M. Franklin[57],

M. Frate[163], M. Fraternali[121a,121b], D. Freeborn[78], S.T. French[28], F. Friedrich[44],
D. Froidevaux[30], J.A. Frost[120], C. Fukunaga[156], E. Fullana Torregrosa[83], B.G. Fulsom[143],
T. Fusayasu[102], J. Fuster[167], C. Gabaldon[55], O. Gabizon[175], A. Gabrielli[20a,20b],
A. Gabrielli[15], G.P. Gach[18], S. Gadatsch[30], S. Gadomski[49], G. Gagliardi[50a,50b],
P. Gagnon[61], C. Galea[106], B. Galhardo[126a,126c], E.J. Gallas[120], B.J. Gallop[131],
P. Gallus[128], G. Galster[36], K.K. Gan[111], J. Gao[33b,85], Y. Gao[46], Y.S. Gao[143,e],
F.M. Garay Walls[46], F. Garberson[176], C. García[167], J.E. García Navarro[167],
M. Garcia-Sciveres[15], R.W. Gardner[31], N. Garelli[143], V. Garonne[119], C. Gatti[47],
A. Gaudiello[50a,50b], G. Gaudio[121a], B. Gaur[141], L. Gauthier[95], P. Gauzzi[132a,132b],
I.L. Gavrilenko[96], C. Gay[168], G. Gaycken[21], E.N. Gazis[10], P. Ge[33d], Z. Gecse[168],
C.N.P. Gee[131], Ch. Geich-Gimbel[21], M.P. Geisler[58a], C. Gemme[50a], M.H. Genest[55],
S. Gentile[132a,132b], M. George[54], S. George[77], D. Gerbaudo[163], A. Gershon[153],
S. Ghasemi[141], H. Ghazlane[135b], B. Giacobbe[20a], S. Giagu[132a,132b], V. Giangiobbe[12],
P. Giannetti[124a,124b], B. Gibbard[25], S.M. Gibson[77], M. Gignac[168], M. Gilchriese[15],
T.P.S. Gillam[28], D. Gillberg[30], G. Gilles[34], D.M. Gingrich[3,d], N. Giokaris[9],
M.P. Giordani[164a,164c], F.M. Giorgi[20a], F.M. Giorgi[16], P.F. Giraud[136], P. Giromini[47],
D. Giugni[91a], C. Giuliani[101], M. Giulini[58b], B.K. Gjelsten[119], S. Gkaitatzis[154],
I. Gkialas[154], E.L. Gkougkousis[117], L.K. Gladilin[99], C. Glasman[82], J. Glatzer[30],
P.C.F. Glaysher[46], A. Glazov[42], M. Goblirsch-Kolb[101], J.R. Goddard[76], J. Godlewski[39],
S. Goldfarb[89], T. Golling[49], D. Golubkov[130], A. Gomes[126a,126b,126d], R. Gonçalo[126a],
J. Goncalves Pinto Firmino Da Costa[136], L. Gonella[21], S. González de la Hoz[167],
G. Gonzalez Parra[12], S. Gonzalez-Sevilla[49], L. Goossens[30], P.A. Gorbounov[97],
H.A. Gordon[25], I. Gorelov[105], B. Gorini[30], E. Gorini[73a,73b], A. Gorišek[75], E. Gornicki[39],
A.T. Goshaw[45], C. Gössling[43], M.I. Gostkin[65], D. Goujdami[135c], A.G. Goussiou[138],
N. Govender[145b], E. Gozani[152], H.M.X. Grabas[137], L. Graber[54], I. Grabowska-Bold[38a],
P.O.J. Gradin[166], P. Grafström[20a,20b], K-J. Grahn[42], J. Gramling[49], E. Gramstad[119],
S. Grancagnolo[16], V. Gratchev[123], H.M. Gray[30], E. Graziani[134a], Z.D. Greenwood[79,n],
C. Grefe[21], K. Gregersen[78], I.M. Gregor[42], P. Grenier[143], J. Griffiths[8], A.A. Grillo[137],
K. Grimm[72], S. Grinstein[12,o], Ph. Gris[34], J.-F. Grivaz[117], J.P. Grohs[44], A. Grohsjean[42],
E. Gross[172], J. Grosse-Knetter[54], G.C. Grossi[79], Z.J. Grout[149], L. Guan[89],
J. Guenther[128], F. Guescini[49], D. Guest[163], O. Gueta[153], E. Guido[50a,50b], T. Guillemin[117],
S. Guindon[2], U. Gul[53], C. Gumpert[44], J. Guo[33e], Y. Guo[33b,p], S. Gupta[120],
G. Gustavino[132a,132b], P. Gutierrez[113], N.G. Gutierrez Ortiz[78], C. Gutschow[44],
C. Guyot[136], C. Gwenlan[120], C.B. Gwilliam[74], A. Haas[110], C. Haber[15], H.K. Hadavand[8],
N. Haddad[135e], P. Haefner[21], S. Hageböck[21], Z. Hajduk[39], H. Hakobyan[177], M. Haleem[42],
J. Haley[114], D. Hall[120], G. Halladjian[90], G.D. Hallewell[85], K. Hamacher[175], P. Hamal[115],
K. Hamano[169], A. Hamilton[145a], G.N. Hamity[139], P.G. Hamnett[42], L. Han[33b],
K. Hanagaki[66,q], K. Hanawa[155], M. Hance[137], B. Haney[122], P. Hanke[58a], R. Hanna[136],
J.B. Hansen[36], J.D. Hansen[36], M.C. Hansen[21], P.H. Hansen[36], K. Hara[160], A.S. Hard[173],
T. Harenberg[175], F. Hariri[117], S. Harkusha[92], R.D. Harrington[46], P.F. Harrison[170],
F. Hartjes[107], M. Hasegawa[67], Y. Hasegawa[140], A. Hasib[113], S. Hassani[136], S. Haug[17],
R. Hauser[90], L. Hauswald[44], M. Havranek[127], C.M. Hawkes[18], R.J. Hawkings[30],
A.D. Hawkins[81], T. Hayashi[160], D. Hayden[90], C.P. Hays[120], J.M. Hays[76],
H.S. Hayward[74], S.J. Haywood[131], S.J. Head[18], T. Heck[83], V. Hedberg[81], L. Heelan[8],
S. Heim[122], T. Heim[175], B. Heinemann[15], L. Heinrich[110], J. Hejbal[127], L. Helary[22],
S. Hellman[146a,146b], D. Hellmich[21], C. Helsens[12], J. Henderson[120], R.C.W. Henderson[72],
Y. Heng[173], C. Hengler[42], S. Henkelmann[168], A. Henrichs[176], A.M. Henriques Correia[30],
S. Henrot-Versille[117], G.H. Herbert[16], Y. Hernández Jiménez[167], G. Herten[48],
R. Hertenberger[100], L. Hervas[30], G.G. Hesketh[78], N.P. Hessey[107], J.W. Hetherly[40],
R. Hickling[76], E. Higón-Rodriguez[167], E. Hill[169], J.C. Hill[28], K.H. Hiller[42], S.J. Hillier[18],
I. Hinchliffe[15], E. Hines[122], R.R. Hinman[15], M. Hirose[157], D. Hirschbuehl[175], J. Hobbs[148],
N. Hod[107], M.C. Hodgkinson[139], P. Hodgson[139], A. Hoecker[30], M.R. Hoeferkamp[105],

F. Hoenig[100], M. Hohlfeld[83], D. Hohn[21], T.R. Holmes[15], M. Homann[43], T.M. Hong[125],
W.H. Hopkins[116], Y. Horii[103], A.J. Horton[142], J-Y. Hostachy[55], S. Hou[151],
A. Hoummada[135a], J. Howard[120], J. Howarth[42], M. Hrabovsky[115], I. Hristova[16],
J. Hrivnac[117], T. Hryn'ova[5], A. Hrynevich[93], C. Hsu[145c], P.J. Hsu[151,r], S.-C. Hsu[138],
D. Hu[35], Q. Hu[33b], X. Hu[89], Y. Huang[42], Z. Hubacek[128], F. Hubaut[85], F. Huegging[21],
T.B. Huffman[120], E.W. Hughes[35], G. Hughes[72], M. Huhtinen[30], T.A. Hülsing[83],
N. Huseynov[65,b], J. Huston[90], J. Huth[57], G. Iacobucci[49], G. Iakovidis[25], I. Ibragimov[141],
L. Iconomidou-Fayard[117], E. Ideal[176], Z. Idrissi[135e], P. Iengo[30], O. Igonkina[107],
T. Iizawa[171], Y. Ikegami[66], K. Ikematsu[141], M. Ikeno[66], Y. Ilchenko[31,s], D. Iliadis[154],
N. Ilic[143], T. Ince[101], G. Introzzi[121a,121b], P. Ioannou[9], M. Iodice[134a], K. Iordanidou[35],
V. Ippolito[57], A. Irles Quiles[167], C. Isaksson[166], M. Ishino[68], M. Ishitsuka[157],
R. Ishmukhametov[111], C. Issever[120], S. Istin[19a], J.M. Iturbe Ponce[84], R. Iuppa[133a,133b],
J. Ivarsson[81], W. Iwanski[39], H. Iwasaki[66], J.M. Izen[41], V. Izzo[104a], S. Jabbar[3],
B. Jackson[122], M. Jackson[74], P. Jackson[1], M.R. Jaekel[30], V. Jain[2], K. Jakobs[48],
S. Jakobsen[30], T. Jakoubek[127], J. Jakubek[128], D.O. Jamin[114], D.K. Jana[79], E. Jansen[78],
R. Jansky[62], J. Janssen[21], M. Janus[54], G. Jarlskog[81], N. Javadov[65,b], T. Javůrek[48],
L. Jeanty[15], J. Jejelava[51a,t], G.-Y. Jeng[150], D. Jennens[88], P. Jenni[48,u], J. Jentzsch[43],
C. Jeske[170], S. Jézéquel[5], H. Ji[173], J. Jia[148], Y. Jiang[33b], S. Jiggins[78], J. Jimenez Pena[167],
S. Jin[33a], A. Jinaru[26b], O. Jinnouchi[157], M.D. Joergensen[36], P. Johansson[139],
K.A. Johns[7], W.J. Johnson[138], K. Jon-And[146a,146b], G. Jones[170], R.W.L. Jones[72],
T.J. Jones[74], J. Jongmanns[58a], P.M. Jorge[126a,126b], K.D. Joshi[84], J. Jovicevic[159a],
X. Ju[173], P. Jussel[62], A. Juste Rozas[12,o], M. Kaci[167], A. Kaczmarska[39], M. Kado[117],
H. Kagan[111], M. Kagan[143], S.J. Kahn[85], E. Kajomovitz[45], C.W. Kalderon[120], S. Kama[40],
A. Kamenshchikov[130], N. Kanaya[155], S. Kaneti[28], V.A. Kantserov[98], J. Kanzaki[66],
B. Kaplan[110], L.S. Kaplan[173], A. Kapliy[31], D. Kar[145c], K. Karakostas[10], A. Karamaoun[3],
N. Karastathis[10,107], M.J. Kareem[54], E. Karentzos[10], M. Karnevskiy[83], S.N. Karpov[65],
Z.M. Karpova[65], K. Karthik[110], V. Kartvelishvili[72], A.N. Karyukhin[130], K. Kasahara[160],
L. Kashif[173], R.D. Kass[111], A. Kastanas[14], Y. Kataoka[155], C. Kato[155], A. Katre[49],
J. Katzy[42], K. Kawade[103], K. Kawagoe[70], T. Kawamoto[155], G. Kawamura[54],
S. Kazama[155], V.F. Kazanin[109,c], R. Keeler[169], R. Kehoe[40], J.S. Keller[42],
J.J. Kempster[77], H. Keoshkerian[84], O. Kepka[127], B.P. Kerševan[75], S. Kersten[175],
R.A. Keyes[87], F. Khalil-zada[11], H. Khandanyan[146a,146b], A. Khanov[114],
A.G. Kharlamov[109,c], T.J. Khoo[28], V. Khovanskiy[97], E. Khramov[65], J. Khubua[51b,v],
S. Kido[67], H.Y. Kim[8], S.H. Kim[160], Y.K. Kim[31], N. Kimura[154], O.M. Kind[16],
B.T. King[74], M. King[167], S.B. King[168], J. Kirk[131], A.E. Kiryunin[101], T. Kishimoto[67],
D. Kisielewska[38a], F. Kiss[48], K. Kiuchi[160], O. Kivernyk[136], E. Kladiva[144b], M.H. Klein[35],
M. Klein[74], U. Klein[74], K. Kleinknecht[83], P. Klimek[146a,146b], A. Klimentov[25],
R. Klingenberg[43], J.A. Klinger[139], T. Klioutchnikova[30], E.-E. Kluge[58a], P. Kluit[107],
S. Kluth[101], J. Knapik[39], E. Kneringer[62], E.B.F.G. Knoops[85], A. Knue[53],
A. Kobayashi[155], D. Kobayashi[157], T. Kobayashi[155], M. Kobel[44], M. Kocian[143],
P. Kodys[129], T. Koffas[29], E. Koffeman[107], L.A. Kogan[120], S. Kohlmann[175], Z. Kohout[128],
T. Kohriki[66], T. Koi[143], H. Kolanoski[16], M. Kolb[58b], I. Koletsou[5], A.A. Komar[96,*],
Y. Komori[155], T. Kondo[66], N. Kondrashova[42], K. Köneke[48], A.C. König[106], T. Kono[66],
R. Konoplich[110,w], N. Konstantinidis[78], R. Kopeliansky[152], S. Koperny[38a], L. Köpke[83],
A.K. Kopp[48], K. Korcyl[39], K. Kordas[154], A. Korn[78], A.A. Korol[109,c], I. Korolkov[12],
E.V. Korolkova[139], O. Kortner[101], S. Kortner[101], T. Kosek[129], V.V. Kostyukhin[21],
V.M. Kotov[65], A. Kotwal[45], A. Kourkoumeli-Charalampidi[154], C. Kourkoumelis[9],
V. Kouskoura[25], A. Koutsman[159a], R. Kowalewski[169], T.Z. Kowalski[38a], W. Kozanecki[136],
A.S. Kozhin[130], V.A. Kramarenko[99], G. Kramberger[75], D. Krasnopevtsev[98],
M.W. Krasny[80], A. Krasznahorkay[30], J.K. Kraus[21], A. Kravchenko[25], S. Kreiss[110],
M. Kretz[58c], J. Kretzschmar[74], K. Kreutzfeldt[52], P. Krieger[158], K. Krizka[31],
K. Kroeninger[43], H. Kroha[101], J. Kroll[122], J. Kroseberg[21], J. Krstic[13], U. Kruchonak[65],

H. Krüger[21], N. Krumnack[64], A. Kruse[173], M.C. Kruse[45], M. Kruskal[22], T. Kubota[88],
H. Kucuk[78], S. Kuday[4b], S. Kuehn[48], A. Kugel[58c], F. Kuger[174], A. Kuhl[137], T. Kuhl[42],
V. Kukhtin[65], R. Kukla[136], Y. Kulchitsky[92], S. Kuleshov[32b], M. Kuna[132a,132b],
T. Kunigo[68], A. Kupco[127], H. Kurashige[67], Y.A. Kurochkin[92], V. Kus[127],
E.S. Kuwertz[169], M. Kuze[157], J. Kvita[115], T. Kwan[169], D. Kyriazopoulos[139],
A. La Rosa[137], J.L. La Rosa Navarro[24d], L. La Rotonda[37a,37b], C. Lacasta[167],
F. Lacava[132a,132b], J. Lacey[29], H. Lacker[16], D. Lacour[80], V.R. Lacuesta[167], E. Ladygin[65],
R. Lafaye[5], B. Laforge[80], T. Lagouri[176], S. Lai[54], L. Lambourne[78], S. Lammers[61],
C.L. Lampen[7], W. Lampl[7], E. Lançon[136], U. Landgraf[48], M.P.J. Landon[76], V.S. Lang[58a],
J.C. Lange[12], A.J. Lankford[163], F. Lanni[25], K. Lantzsch[21], A. Lanza[121a], S. Laplace[80],
C. Lapoire[30], J.F. Laporte[136], T. Lari[91a], F. Lasagni Manghi[20a,20b], M. Lassnig[30],
P. Laurelli[47], W. Lavrijsen[15], A.T. Law[137], P. Laycock[74], T. Lazovich[57], O. Le Dortz[80],
E. Le Guirriec[85], E. Le Menedeu[12], M. LeBlanc[169], T. LeCompte[6], F. Ledroit-Guillon[55],
C.A. Lee[145a], S.C. Lee[151], L. Lee[1], G. Lefebvre[80], M. Lefebvre[169], F. Legger[100],
C. Leggett[15], A. Lehan[74], G. Lehmann Miotto[30], X. Lei[7], W.A. Leight[29], A. Leisos[154,x],
A.G. Leister[176], M.A.L. Leite[24d], R. Leitner[129], D. Lellouch[172], B. Lemmer[54],
K.J.C. Leney[78], T. Lenz[21], B. Lenzi[30], R. Leone[7], S. Leone[124a,124b], C. Leonidopoulos[46],
S. Leontsinis[10], C. Leroy[95], C.G. Lester[28], M. Levchenko[123], J. Levêque[5], D. Levin[89],
L.J. Levinson[172], M. Levy[18], A. Lewis[120], A.M. Leyko[21], M. Leyton[41], B. Li[33b,y],
H. Li[148], H.L. Li[31], L. Li[45], L. Li[33e], S. Li[45], X. Li[84], Y. Li[33c,z], Z. Liang[137], H. Liao[34],
B. Liberti[133a], A. Liblong[158], P. Lichard[30], K. Lie[165], J. Liebal[21], W. Liebig[14],
C. Limbach[21], A. Limosani[150], S.C. Lin[151,aa], T.H. Lin[83], F. Linde[107], B.E. Lindquist[148],
J.T. Linnemann[90], E. Lipeles[122], A. Lipniacka[14], M. Lisovyi[58b], T.M. Liss[165],
D. Lissauer[25], A. Lister[168], A.M. Litke[137], B. Liu[151,ab], D. Liu[151], H. Liu[89], J. Liu[85],
J.B. Liu[33b], K. Liu[85], L. Liu[165], M. Liu[45], M. Liu[33b], Y. Liu[33b], M. Livan[121a,121b],
A. Lleres[55], J. Llorente Merino[82], S.L. Lloyd[76], F. Lo Sterzo[151], E. Lobodzinska[42],
P. Loch[7], W.S. Lockman[137], F.K. Loebinger[84], A.E. Loevschall-Jensen[36], K.M. Loew[23],
A. Loginov[176], T. Lohse[16], K. Lohwasser[42], M. Lokajicek[127], B.A. Long[22], J.D. Long[165],
R.E. Long[72], K.A. Looper[111], L. Lopes[126a], D. Lopez Mateos[57], B. Lopez Paredes[139],
I. Lopez Paz[12], J. Lorenz[100], N. Lorenzo Martinez[61], M. Losada[162], P.J. Lösel[100],
X. Lou[33a], A. Lounis[117], J. Love[6], P.A. Love[72], H. Lu[60a], N. Lu[89], H.J. Lubatti[138],
C. Luci[132a,132b], A. Lucotte[55], C. Luedtke[48], F. Luehring[61], W. Lukas[62], L. Luminari[132a],
O. Lundberg[146a,146b], B. Lund-Jensen[147], D. Lynn[25], R. Lysak[127], E. Lytken[81], H. Ma[25],
L.L. Ma[33d], G. Maccarrone[47], A. Macchiolo[101], C.M. Macdonald[139], B. Maček[75],
J. Machado Miguens[122,126b], D. Macina[30], D. Madaffari[85], R. Madar[34], H.J. Maddocks[72],
W.F. Mader[44], A. Madsen[166], J. Maeda[67], S. Maeland[14], T. Maeno[25], A. Maevskiy[99],
E. Magradze[54], K. Mahboubi[48], J. Mahlstedt[107], C. Maiani[136], C. Maidantchik[24a],
A.A. Maier[101], T. Maier[100], A. Maio[126a,126b,126d], S. Majewski[116], Y. Makida[66],
N. Makovec[117], B. Malaescu[80], Pa. Malecki[39], V.P. Maleev[123], F. Malek[55], U. Mallik[63],
D. Malon[6], C. Malone[143], S. Maltezos[10], V.M. Malyshev[109], S. Malyukov[30],
J. Mamuzic[42], G. Mancini[47], B. Mandelli[30], L. Mandelli[91a], I. Mandić[75], R. Mandrysch[63],
J. Maneira[126a,126b], A. Manfredini[101], L. Manhaes de Andrade Filho[24b],
J. Manjarres Ramos[159b], A. Mann[100], A. Manousakis-Katsikakis[9], B. Mansoulie[136],
R. Mantifel[87], M. Mantoani[54], L. Mapelli[30], L. March[145c], G. Marchiori[80],
M. Marcisovsky[127], C.P. Marino[169], M. Marjanovic[13], D.E. Marley[89], F. Marroquim[24a],
S.P. Marsden[84], Z. Marshall[15], L.F. Marti[17], S. Marti-Garcia[167], B. Martin[90],
T.A. Martin[170], V.J. Martin[46], B. Martin dit Latour[14], M. Martinez[12,o],
S. Martin-Haugh[131], V.S. Martoiu[26b], A.C. Martyniuk[78], M. Marx[138], F. Marzano[132a],
A. Marzin[30], L. Masetti[83], T. Mashimo[155], R. Mashinistov[96], J. Masik[84],
A.L. Maslennikov[109,c], I. Massa[20a,20b], L. Massa[20a,20b], P. Mastrandrea[5],
A. Mastroberardino[37a,37b], T. Masubuchi[155], P. Mättig[175], J. Mattmann[83], J. Maurer[26b],
S.J. Maxfield[74], D.A. Maximov[109,c], R. Mazini[151], S.M. Mazza[91a,91b], G. Mc Goldrick[158],

S.P. Mc Kee[89], A. McCarn[89], R.L. McCarthy[148], T.G. McCarthy[29], N.A. McCubbin[131],
K.W. McFarlane[56,*], J.A. Mcfayden[78], G. Mchedlidze[54], S.J. McMahon[131],
R.A. McPherson[169,k], M. Medinnis[42], S. Meehan[145a], S. Mehlhase[100], A. Mehta[74],
K. Meier[58a], C. Meineck[100], B. Meirose[41], B.R. Mellado Garcia[145c], F. Meloni[17],
A. Mengarelli[20a,20b], S. Menke[101], E. Meoni[161], K.M. Mercurio[57], S. Mergelmeyer[21],
P. Mermod[49], L. Merola[104a,104b], C. Meroni[91a], F.S. Merritt[31], A. Messina[132a,132b],
J. Metcalfe[25], A.S. Mete[163], C. Meyer[83], C. Meyer[122], J-P. Meyer[136], J. Meyer[107],
H. Meyer Zu Theenhausen[58a], R.P. Middleton[131], S. Miglioranzi[164a,164c], L. Mijović[21],
G. Mikenberg[172], M. Mikestikova[127], M. Mikuž[75], M. Milesi[88], A. Milic[30], D.W. Miller[31],
C. Mills[46], A. Milov[172], D.A. Milstead[146a,146b], A.A. Minaenko[130], Y. Minami[155],
I.A. Minashvili[65], A.I. Mincer[110], B. Mindur[38a], M. Mineev[65], Y. Ming[173], L.M. Mir[12],
K.P. Mistry[122], T. Mitani[171], J. Mitrevski[100], V.A. Mitsou[167], A. Miucci[49],
P.S. Miyagawa[139], J.U. Mjörnmark[81], T. Moa[146a,146b], K. Mochizuki[85], S. Mohapatra[35],
W. Mohr[48], S. Molander[146a,146b], R. Moles-Valls[21], R. Monden[68], K. Mönig[42],
C. Monini[55], J. Monk[36], E. Monnier[85], A. Montalbano[148], J. Montejo Berlingen[12],
F. Monticelli[71], S. Monzani[132a,132b], R.W. Moore[3], N. Morange[117], D. Moreno[162],
M. Moreno Llácer[54], P. Morettini[50a], D. Mori[142], T. Mori[155], M. Morii[57], M. Morinaga[155],
V. Morisbak[119], S. Moritz[83], A.K. Morley[150], G. Mornacchi[30], J.D. Morris[76],
S.S. Mortensen[36], A. Morton[53], L. Morvaj[103], M. Mosidze[51b], J. Moss[143],
K. Motohashi[157], R. Mount[143], E. Mountricha[25], S.V. Mouraviev[96,*], E.J.W. Moyse[86],
S. Muanza[85], R.D. Mudd[18], F. Mueller[101], J. Mueller[125], R.S.P. Mueller[100], T. Mueller[28],
D. Muenstermann[49], P. Mullen[53], G.A. Mullier[17], J.A. Murillo Quijada[18],
W.J. Murray[170,131], H. Musheghyan[54], E. Musto[152], A.G. Myagkov[130,ac], M. Myska[128],
B.P. Nachman[143], O. Nackenhorst[54], J. Nadal[54], K. Nagai[120], R. Nagai[157], Y. Nagai[85],
K. Nagano[66], A. Nagarkar[111], Y. Nagasaka[59], K. Nagata[160], M. Nagel[101], E. Nagy[85],
A.M. Nairz[30], Y. Nakahama[30], K. Nakamura[66], T. Nakamura[155], I. Nakano[112],
H. Namasivayam[41], R.F. Naranjo Garcia[42], R. Narayan[31], D.I. Narrias Villar[58a],
T. Naumann[42], G. Navarro[162], R. Nayyar[7], H.A. Neal[89], P.Yu. Nechaeva[96], T.J. Neep[84],
P.D. Nef[143], A. Negri[121a,121b], M. Negrini[20a], S. Nektarijevic[106], C. Nellist[117],
A. Nelson[163], S. Nemecek[127], P. Nemethy[110], A.A. Nepomuceno[24a], M. Nessi[30,ad],
M.S. Neubauer[165], M. Neumann[175], R.M. Neves[110], P. Nevski[25], P.R. Newman[18],
D.H. Nguyen[6], R.B. Nickerson[120], R. Nicolaidou[136], B. Nicquevert[30], J. Nielsen[137],
N. Nikiforou[35], A. Nikiforov[16], V. Nikolaenko[130,ac], I. Nikolic-Audit[80], K. Nikolopoulos[18],
J.K. Nilsen[119], P. Nilsson[25], Y. Ninomiya[155], A. Nisati[132a], R. Nisius[101], T. Nobe[155],
M. Nomachi[118], I. Nomidis[29], T. Nooney[76], S. Norberg[113], M. Nordberg[30],
O. Novgorodova[44], S. Nowak[101], M. Nozaki[66], L. Nozka[115], K. Ntekas[10],
G. Nunes Hanninger[88], T. Nunnemann[100], E. Nurse[78], F. Nuti[88], B.J. O'Brien[46],
F. O'grady[7], D.C. O'Neil[142], V. O'Shea[53], F.G. Oakham[29,d], H. Oberlack[101],
T. Obermann[21], J. Ocariz[80], A. Ochi[67], I. Ochoa[35], J.P. Ochoa-Ricoux[32a], S. Oda[70],
S. Odaka[66], H. Ogren[61], A. Oh[84], S.H. Oh[45], C.C. Ohm[15], H. Ohman[166], H. Oide[30],
W. Okamura[118], H. Okawa[160], Y. Okumura[31], T. Okuyama[66], A. Olariu[26b],
S.A. Olivares Pino[46], D. Oliveira Damazio[25], A. Olszewski[39], J. Olszowska[39],
A. Onofre[126a,126e], K. Onogi[103], P.U.E. Onyisi[31,s], C.J. Oram[159a], M.J. Oreglia[31],
Y. Oren[153], D. Orestano[134a,134b], N. Orlando[154], C. Oropeza Barrera[53], R.S. Orr[158],
B. Osculati[50a,50b], R. Ospanov[84], G. Otero y Garzon[27], H. Otono[70], M. Ouchrif[135d],
F. Ould-Saada[119], A. Ouraou[136], K.P. Oussoren[107], Q. Ouyang[33a], A. Ovcharova[15],
M. Owen[53], R.E. Owen[18], V.E. Ozcan[19a], N. Ozturk[8], K. Pachal[142], A. Pacheco Pages[12],
C. Padilla Aranda[12], M. Pagáčová[48], S. Pagan Griso[15], E. Paganis[139], F. Paige[25],
P. Pais[86], K. Pajchel[119], G. Palacino[159b], S. Palestini[30], M. Palka[38b], D. Pallin[34],
A. Palma[126a,126b], Y.B. Pan[173], E.St. Panagiotopoulou[10], C.E. Pandini[80],
J.G. Panduro Vazquez[77], P. Pani[146a,146b], S. Panitkin[25], D. Pantea[26b], L. Paolozzi[49],
Th.D. Papadopoulou[10], K. Papageorgiou[154], A. Paramonov[6], D. Paredes Hernandez[154],

M.A. Parker[28], K.A. Parker[139], F. Parodi[50a,50b], J.A. Parsons[35], U. Parzefall[48],
E. Pasqualucci[132a], S. Passaggio[50a], F. Pastore[134a,134b,*], Fr. Pastore[77], G. Pásztor[29],
S. Pataraia[175], N.D. Patel[150], J.R. Pater[84], T. Pauly[30], J. Pearce[169], B. Pearson[113],
L.E. Pedersen[36], M. Pedersen[119], S. Pedraza Lopez[167], R. Pedro[126a,126b],
S.V. Peleganchuk[109,c], D. Pelikan[166], O. Penc[127], C. Peng[33a], H. Peng[33b], B. Penning[31],
J. Penwell[61], D.V. Perepelitsa[25], E. Perez Codina[159a], M.T. Pérez García-Estañ[167],
L. Perini[91a,91b], H. Pernegger[30], S. Perrella[104a,104b], R. Peschke[42], V.D. Peshekhonov[65],
K. Peters[30], R.F.Y. Peters[84], B.A. Petersen[30], T.C. Petersen[36], E. Petit[42], A. Petridis[1],
C. Petridou[154], P. Petroff[117], E. Petrolo[132a], F. Petrucci[134a,134b], N.E. Pettersson[157],
R. Pezoa[32b], P.W. Phillips[131], G. Piacquadio[143], E. Pianori[170], A. Picazio[49], E. Piccaro[76],
M. Piccinini[20a,20b], M.A. Pickering[120], R. Piegaia[27], D.T. Pignotti[111], J.E. Pilcher[31],
A.D. Pilkington[84], A.W.J. Pin[84], J. Pina[126a,126b,126d], M. Pinamonti[164a,164c,ae],
J.L. Pinfold[3], A. Pingel[36], S. Pires[80], H. Pirumov[42], M. Pitt[172], C. Pizio[91a,91b],
L. Plazak[144a], M.-A. Pleier[25], V. Pleskot[129], E. Plotnikova[65], P. Plucinski[146a,146b],
D. Pluth[64], R. Poettgen[146a,146b], L. Poggioli[117], D. Pohl[21], G. Polesello[121a], A. Poley[42],
A. Policicchio[37a,37b], R. Polifka[158], A. Polini[20a], C.S. Pollard[53], V. Polychronakos[25],
K. Pommès[30], L. Pontecorvo[132a], B.G. Pope[90], G.A. Popeneciu[26c], D.S. Popovic[13],
A. Poppleton[30], S. Pospisil[128], K. Potamianos[15], I.N. Potrap[65], C.J. Potter[149],
C.T. Potter[116], G. Poulard[30], J. Poveda[30], V. Pozdnyakov[65], P. Pralavorio[85],
A. Pranko[15], S. Prasad[30], S. Prell[64], D. Price[84], L.E. Price[6], M. Primavera[73a],
S. Prince[87], M. Proissl[46], K. Prokofiev[60c], F. Prokoshin[32b], E. Protopapadaki[136],
S. Protopopescu[25], J. Proudfoot[6], M. Przybycien[38a], E. Ptacek[116], D. Puddu[134a,134b],
E. Pueschel[86], D. Puldon[148], M. Purohit[25,af], P. Puzo[117], J. Qian[89], G. Qin[53], Y. Qin[84],
A. Quadt[54], D.R. Quarrie[15], W.B. Quayle[164a,164b], M. Queitsch-Maitland[84], D. Quilty[53],
S. Raddum[119], V. Radeka[25], V. Radescu[42], S.K. Radhakrishnan[148], P. Radloff[116],
P. Rados[88], F. Ragusa[91a,91b], G. Rahal[178], S. Rajagopalan[25], M. Rammensee[30],
C. Rangel-Smith[166], F. Rauscher[100], S. Rave[83], T. Ravenscroft[53], M. Raymond[30],
A.L. Read[119], N.P. Readioff[74], D.M. Rebuzzi[121a,121b], A. Redelbach[174], G. Redlinger[25],
R. Reece[137], K. Reeves[41], L. Rehnisch[16], J. Reichert[122], H. Reisin[27], C. Rembser[30],
H. Ren[33a], A. Renaud[117], M. Rescigno[132a], S. Resconi[91a], O.L. Rezanova[109,c],
P. Reznicek[129], R. Rezvani[95], R. Richter[101], S. Richter[78], E. Richter-Was[38b], O. Ricken[21],
M. Ridel[80], P. Rieck[16], C.J. Riegel[175], J. Rieger[54], O. Rifki[113], M. Rijssenbeek[148],
A. Rimoldi[121a,121b], L. Rinaldi[20a], B. Ristić[49], E. Ritsch[30], I. Riu[12], F. Rizatdinova[114],
E. Rizvi[76], S.H. Robertson[87,k], A. Robichaud-Veronneau[87], D. Robinson[28],
J.E.M. Robinson[42], A. Robson[53], C. Roda[124a,124b], S. Roe[30], O. Røhne[119], S. Rolli[161],
A. Romaniouk[98], M. Romano[20a,20b], S.M. Romano Saez[34], E. Romero Adam[167],
N. Rompotis[138], M. Ronzani[48], L. Roos[80], E. Ros[167], S. Rosati[132a], K. Rosbach[48],
P. Rose[137], P.L. Rosendahl[14], O. Rosenthal[141], V. Rossetti[146a,146b], E. Rossi[104a,104b],
L.P. Rossi[50a], J.H.N. Rosten[28], R. Rosten[138], M. Rotaru[26b], I. Roth[172], J. Rothberg[138],
D. Rousseau[117], C.R. Royon[136], A. Rozanov[85], Y. Rozen[152], X. Ruan[145c], F. Rubbo[143],
I. Rubinskiy[42], V.I. Rud[99], C. Rudolph[44], M.S. Rudolph[158], F. Rühr[48],
A. Ruiz-Martinez[30], Z. Rurikova[48], N.A. Rusakovich[65], A. Ruschke[100], H.L. Russell[138],
J.P. Rutherfoord[7], N. Ruthmann[30], Y.F. Ryabov[123], M. Rybar[165], G. Rybkin[117],
N.C. Ryder[120], A.F. Saavedra[150], G. Sabato[107], S. Sacerdoti[27], A. Saddique[3],
H.F-W. Sadrozinski[137], R. Sadykov[65], F. Safai Tehrani[132a], P. Saha[108], M. Sahinsoy[58a],
M. Saimpert[136], T. Saito[155], H. Sakamoto[155], Y. Sakurai[171], G. Salamanna[134a,134b],
A. Salamon[133a], J.E. Salazar Loyola[32b], M. Saleem[113], D. Salek[107],
P.H. Sales De Bruin[138], D. Salihagic[101], A. Salnikov[143], J. Salt[167], D. Salvatore[37a,37b],
F. Salvatore[149], A. Salvucci[60a], A. Salzburger[30], D. Sammel[48], D. Sampsonidis[154],
A. Sanchez[104a,104b], J. Sánchez[167], V. Sanchez Martinez[167], H. Sandaker[119],
R.L. Sandbach[76], H.G. Sander[83], M.P. Sanders[100], M. Sandhoff[175], C. Sandoval[162],
R. Sandstroem[101], D.P.C. Sankey[131], M. Sannino[50a,50b], A. Sansoni[47], C. Santoni[34],

R. Santonico[133a,133b], H. Santos[126a], I. Santoyo Castillo[149], K. Sapp[125], A. Sapronov[65],
J.G. Saraiva[126a,126d], B. Sarrazin[21], O. Sasaki[66], Y. Sasaki[155], K. Sato[160], G. Sauvage[5,*],
E. Sauvan[5], G. Savage[77], P. Savard[158,d], C. Sawyer[131], L. Sawyer[79,n], J. Saxon[31],
C. Sbarra[20a], A. Sbrizzi[20a,20b], T. Scanlon[78], D.A. Scannicchio[163], M. Scarcella[150],
V. Scarfone[37a,37b], J. Schaarschmidt[172], P. Schacht[101], D. Schaefer[30], R. Schaefer[42],
J. Schaeffer[83], S. Schaepe[21], S. Schaetzel[58b], U. Schäfer[83], A.C. Schaffer[117], D. Schaile[100],
R.D. Schamberger[148], V. Scharf[58a], V.A. Schegelsky[123], D. Scheirich[129], M. Schernau[163],
C. Schiavi[50a,50b], C. Schillo[48], M. Schioppa[37a,37b], S. Schlenker[30], K. Schmieden[30],
C. Schmitt[83], S. Schmitt[58b], S. Schmitt[42], B. Schneider[159a], Y.J. Schnellbach[74],
U. Schnoor[44], L. Schoeffel[136], A. Schoening[58b], B.D. Schoenrock[90], E. Schopf[21],
A.L.S. Schorlemmer[54], M. Schott[83], D. Schouten[159a], J. Schovancova[8], S. Schramm[49],
M. Schreyer[174], N. Schuh[83], M.J. Schultens[21], H.-C. Schultz-Coulon[58a], H. Schulz[16],
M. Schumacher[48], B.A. Schumm[137], Ph. Schune[136], C. Schwanenberger[84],
A. Schwartzman[143], T.A. Schwarz[89], Ph. Schwegler[101], H. Schweiger[84],
Ph. Schwemling[136], R. Schwienhorst[90], J. Schwindling[136], T. Schwindt[21], F.G. Sciacca[17],
E. Scifo[117], G. Sciolla[23], F. Scuri[124a,124b], F. Scutti[21], J. Searcy[89], G. Sedov[42],
E. Sedykh[123], P. Seema[21], S.C. Seidel[105], A. Seiden[137], F. Seifert[128], J.M. Seixas[24a],
G. Sekhniaidze[104a], K. Sekhon[89], S.J. Sekula[40], D.M. Seliverstov[123,*],
N. Semprini-Cesari[20a,20b], C. Serfon[30], L. Serin[117], L. Serkin[164a,164b], T. Serre[85],
M. Sessa[134a,134b], R. Seuster[159a], H. Severini[113], T. Sfiligoj[75], F. Sforza[30], A. Sfyrla[30],
E. Shabalina[54], M. Shamim[116], L.Y. Shan[33a], R. Shang[165], J.T. Shank[22], M. Shapiro[15],
P.B. Shatalov[97], K. Shaw[164a,164b], S.M. Shaw[84], A. Shcherbakova[146a,146b], C.Y. Shehu[149],
P. Sherwood[78], L. Shi[151,ag], S. Shimizu[67], C.O. Shimmin[163], M. Shimojima[102],
M. Shiyakova[65], A. Shmeleva[96], D. Shoaleh Saadi[95], M.J. Shochet[31], S. Shojaii[91a,91b],
S. Shrestha[111], E. Shulga[98], M.A. Shupe[7], S. Shushkevich[42], P. Sicho[127], P.E. Sidebo[147],
O. Sidiropoulou[174], D. Sidorov[114], A. Sidoti[20a,20b], F. Siegert[44], Dj. Sijacki[13],
J. Silva[126a,126d], Y. Silver[153], S.B. Silverstein[146a], V. Simak[128], O. Simard[5], Lj. Simic[13],
S. Simion[117], E. Simioni[83], B. Simmons[78], D. Simon[34], P. Sinervo[158], N.B. Sinev[116],
M. Sioli[20a,20b], G. Siragusa[174], A.N. Sisakyan[65,*], S.Yu. Sivoklokov[99], J. Sjölin[146a,146b],
T.B. Sjursen[14], M.B. Skinner[72], H.P. Skottowe[57], P. Skubic[113], M. Slater[18],
T. Slavicek[128], M. Slawinska[107], K. Sliwa[161], V. Smakhtin[172], B.H. Smart[46],
L. Smestad[14], S.Yu. Smirnov[98], Y. Smirnov[98], L.N. Smirnova[99,ah], O. Smirnova[81],
M.N.K. Smith[35], R.W. Smith[35], M. Smizanska[72], K. Smolek[128], A.A. Snesarev[96],
G. Snidero[76], S. Snyder[25], R. Sobie[169,k], F. Socher[44], A. Soffer[153], D.A. Soh[151,ag],
G. Sokhrannyi[75], C.A. Solans[30], M. Solar[128], J. Solc[128], E.Yu. Soldatov[98], U. Soldevila[167],
A.A. Solodkov[130], A. Soloshenko[65], O.V. Solovyanov[130], V. Solovyev[123], P. Sommer[48],
H.Y. Song[33b,y], N. Soni[1], A. Sood[15], A. Sopczak[128], B. Sopko[128], V. Sopko[128], V. Sorin[12],
D. Sosa[58b], M. Sosebee[8], C.L. Sotiropoulou[124a,124b], R. Soualah[164a,164c],
A.M. Soukharev[109,c], D. South[42], B.C. Sowden[77], S. Spagnolo[73a,73b], M. Spalla[124a,124b],
M. Spangenberg[170], F. Spanò[77], W.R. Spearman[57], D. Sperlich[16], F. Spettel[101],
R. Spighi[20a], G. Spigo[30], L.A. Spiller[88], M. Spousta[129], R.D. St. Denis[53,*], A. Stabile[91a],
S. Staerz[44], J. Stahlman[122], R. Stamen[58a], S. Stamm[16], E. Stanecka[39], C. Stanescu[134a],
M. Stanescu-Bellu[42], M.M. Stanitzki[42], S. Stapnes[119], E.A. Starchenko[130], J. Stark[55],
P. Staroba[127], P. Starovoitov[58a], R. Staszewski[39], P. Steinberg[25], B. Stelzer[142],
H.J. Stelzer[30], O. Stelzer-Chilton[159a], H. Stenzel[52], G.A. Stewart[53], J.A. Stillings[21],
M.C. Stockton[87], M. Stoebe[87], G. Stoicea[26b], P. Stolte[54], S. Stonjek[101], A.R. Stradling[8],
A. Straessner[44], M.E. Stramaglia[17], J. Strandberg[147], S. Strandberg[146a,146b],
A. Strandlie[119], E. Strauss[143], M. Strauss[113], P. Strizenec[144b], R. Ströhmer[174],
D.M. Strom[116], R. Stroynowski[40], A. Strubig[106], S.A. Stucci[17], B. Stugu[14], N.A. Styles[42],
D. Su[143], J. Su[125], R. Subramaniam[79], A. Succurro[12], S. Suchek[58a], Y. Sugaya[118],
M. Suk[128], V.V. Sulin[96], S. Sultansoy[4c], T. Sumida[68], S. Sun[57], X. Sun[33a],
J.E. Sundermann[48], K. Suruliz[149], G. Susinno[37a,37b], M.R. Sutton[149], S. Suzuki[66],

M. Svatos[127], M. Swiatlowski[143], I. Sykora[144a], T. Sykora[129], D. Ta[48], C. Taccini[134a,134b],
K. Tackmann[42], J. Taenzer[158], A. Taffard[163], R. Tafirout[159a], N. Taiblum[153], H. Takai[25],
R. Takashima[69], H. Takeda[67], T. Takeshita[140], Y. Takubo[66], M. Talby[85],
A.A. Talyshev[109,c], J.Y.C. Tam[174], K.G. Tan[88], J. Tanaka[155], R. Tanaka[117], S. Tanaka[66],
B.B. Tannenwald[111], N. Tannoury[21], S. Tapia Araya[32b], S. Tapprogge[83], S. Tarem[152],
F. Tarrade[29], G.F. Tartarelli[91a], P. Tas[129], M. Tasevsky[127], T. Tashiro[68], E. Tassi[37a,37b],
A. Tavares Delgado[126a,126b], Y. Tayalati[135d], F.E. Taylor[94], G.N. Taylor[88],
P.T.E. Taylor[88], W. Taylor[159b], F.A. Teischinger[30], M. Teixeira Dias Castanheira[76],
P. Teixeira-Dias[77], K.K. Temming[48], D. Temple[142], H. Ten Kate[30], P.K. Teng[151],
J.J. Teoh[118], F. Tepel[175], S. Terada[66], K. Terashi[155], J. Terron[82], S. Terzo[101], M. Testa[47],
R.J. Teuscher[158,k], T. Theveneaux-Pelzer[34], J.P. Thomas[18], J. Thomas-Wilsker[77],
E.N. Thompson[35], P.D. Thompson[18], R.J. Thompson[84], A.S. Thompson[53],
L.A. Thomsen[176], E. Thomson[122], M. Thomson[28], R.P. Thun[89,*], M.J. Tibbetts[15],
R.E. Ticse Torres[85], V.O. Tikhomirov[96,ai], Yu.A. Tikhonov[109,c], S. Timoshenko[98],
E. Tiouchichine[85], P. Tipton[176], S. Tisserant[85], K. Todome[157], T. Todorov[5,*],
S. Todorova-Nova[129], J. Tojo[70], S. Tokár[144a], K. Tokushuku[66], K. Tollefson[90], E. Tolley[57],
L. Tomlinson[84], M. Tomoto[103], L. Tompkins[143,aj], K. Toms[105], E. Torrence[116],
H. Torres[142], E. Torró Pastor[138], J. Toth[85,ak], F. Touchard[85], D.R. Tovey[139],
T. Trefzger[174], L. Tremblet[30], A. Tricoli[30], I.M. Trigger[159a], S. Trincaz-Duvoid[80],
M.F. Tripiana[12], W. Trischuk[158], B. Trocmé[55], C. Troncon[91a], M. Trottier-McDonald[15],
M. Trovatelli[169], L. Truong[164a,164c], M. Trzebinski[39], A. Trzupek[39], C. Tsarouchas[30],
J.C-L. Tseng[120], P.V. Tsiareshka[92], D. Tsionou[154], G. Tsipolitis[10], N. Tsirintanis[9],
S. Tsiskaridze[12], V. Tsiskaridze[48], E.G. Tskhadadze[51a], K.M. Tsui[60a], I.I. Tsukerman[97],
V. Tsulaia[15], S. Tsuno[66], D. Tsybychev[148], A. Tudorache[26b], V. Tudorache[26b],
A.N. Tuna[57], S.A. Tupputi[20a,20b], S. Turchikhin[99,ah], D. Turecek[128], R. Turra[91a,91b],
A.J. Turvey[40], P.M. Tuts[35], A. Tykhonov[49], M. Tylmad[146a,146b], M. Tyndel[131],
I. Ueda[155], R. Ueno[29], M. Ughetto[146a,146b], M. Ugland[14], F. Ukegawa[160], G. Unal[30],
A. Undrus[25], G. Unel[163], F.C. Ungaro[48], Y. Unno[66], C. Unverdorben[100], J. Urban[144b],
P. Urquijo[88], P. Urrejola[83], G. Usai[8], A. Usanova[62], L. Vacavant[85], V. Vacek[128],
B. Vachon[87], C. Valderanis[83], N. Valencic[107], S. Valentinetti[20a,20b], A. Valero[167],
L. Valery[12], S. Valkar[129], S. Vallecorsa[49], J.A. Valls Ferrer[167], W. Van Den Wollenberg[107],
P.C. Van Der Deijl[107], R. van der Geer[107], H. van der Graaf[107], N. van Eldik[152],
P. van Gemmeren[6], J. Van Nieuwkoop[142], I. van Vulpen[107], M.C. van Woerden[30],
M. Vanadia[132a,132b], W. Vandelli[30], R. Vanguri[122], A. Vaniachine[6], F. Vannucci[80],
G. Vardanyan[177], R. Vari[132a], E.W. Varnes[7], T. Varol[40], D. Varouchas[80],
A. Vartapetian[8], K.E. Varvell[150], F. Vazeille[34], T. Vazquez Schroeder[87], J. Veatch[7],
L.M. Veloce[158], F. Veloso[126a,126c], T. Velz[21], S. Veneziano[132a], A. Ventura[73a,73b],
D. Ventura[86], M. Venturi[169], N. Venturi[158], A. Venturini[23], V. Vercesi[121a],
M. Verducci[132a,132b], W. Verkerke[107], J.C. Vermeulen[107], A. Vest[44], M.C. Vetterli[142,d],
O. Viazlo[81], I. Vichou[165], T. Vickey[139], O.E. Vickey Boeriu[139], G.H.A. Viehhauser[120],
S. Viel[15], R. Vigne[62], M. Villa[20a,20b], M. Villaplana Perez[91a,91b], E. Vilucchi[47],
M.G. Vincter[29], V.B. Vinogradov[65], I. Vivarelli[149], F. Vives Vaque[3], S. Vlachos[10],
D. Vladoiu[100], M. Vlasak[128], M. Vogel[32a], P. Vokac[128], G. Volpi[124a,124b], M. Volpi[88],
H. von der Schmitt[101], H. von Radziewski[48], E. von Toerne[21], V. Vorobel[129],
K. Vorobev[98], M. Vos[167], R. Voss[30], J.H. Vossebeld[74], N. Vranjes[13],
M. Vranjes Milosavljevic[13], V. Vrba[127], M. Vreeswijk[107], R. Vuillermet[30], I. Vukotic[31],
Z. Vykydal[128], P. Wagner[21], W. Wagner[175], H. Wahlberg[71], S. Wahrmund[44],
J. Wakabayashi[103], J. Walder[72], R. Walker[100], W. Walkowiak[141], C. Wang[151],
F. Wang[173], H. Wang[15], H. Wang[40], J. Wang[42], J. Wang[150], K. Wang[87], R. Wang[6],
S.M. Wang[151], T. Wang[21], T. Wang[35], X. Wang[176], C. Wanotayaroj[116], A. Warburton[87],
C.P. Ward[28], D.R. Wardrope[78], A. Washbrook[46], C. Wasicki[42], P.M. Watkins[18],
A.T. Watson[18], I.J. Watson[150], M.F. Watson[18], G. Watts[138], S. Watts[84], B.M. Waugh[78],

S. Webb[84], M.S. Weber[17], S.W. Weber[174], J.S. Webster[31], A.R. Weidberg[120],
B. Weinert[61], J. Weingarten[54], C. Weiser[48], H. Weits[107], P.S. Wells[30], T. Wenaus[25],
T. Wengler[30], S. Wenig[30], N. Wermes[21], M. Werner[48], P. Werner[30], M. Wessels[58a],
J. Wetter[161], K. Whalen[116], A.M. Wharton[72], A. White[8], M.J. White[1], R. White[32b],
S. White[124a,124b], D. Whiteson[163], F.J. Wickens[131], W. Wiedenmann[173], M. Wielers[131],
P. Wienemann[21], C. Wiglesworth[36], L.A.M. Wiik-Fuchs[21], A. Wildauer[101],
H.G. Wilkens[30], H.H. Williams[122], S. Williams[107], C. Willis[90], S. Willocq[86], A. Wilson[89],
J.A. Wilson[18], I. Wingerter-Seez[5], F. Winklmeier[116], B.T. Winter[21], M. Wittgen[143],
J. Wittkowski[100], S.J. Wollstadt[83], M.W. Wolter[39], H. Wolters[126a,126c], B.K. Wosiek[39],
J. Wotschack[30], M.J. Woudstra[84], K.W. Wozniak[39], M. Wu[55], M. Wu[31], S.L. Wu[173],
X. Wu[49], Y. Wu[89], T.R. Wyatt[84], B.M. Wynne[46], S. Xella[36], D. Xu[33a], L. Xu[25],
B. Yabsley[150], S. Yacoob[145a], R. Yakabe[67], M. Yamada[66], D. Yamaguchi[157],
Y. Yamaguchi[118], A. Yamamoto[66], S. Yamamoto[155], T. Yamanaka[155], K. Yamauchi[103],
Y. Yamazaki[67], Z. Yan[22], H. Yang[33e], H. Yang[173], Y. Yang[151], W-M. Yao[15], Y.C. Yap[80],
Y. Yasu[66], E. Yatsenko[5], K.H. Yau Wong[21], J. Ye[40], S. Ye[25], I. Yeletskikh[65], A.L. Yen[57],
E. Yildirim[42], K. Yorita[171], R. Yoshida[6], K. Yoshihara[122], C. Young[143], C.J.S. Young[30],
S. Youssef[22], D.R. Yu[15], J. Yu[8], J.M. Yu[89], J. Yu[114], L. Yuan[67], S.P.Y. Yuen[21],
A. Yurkewicz[108], I. Yusuff[28,al], B. Zabinski[39], R. Zaidan[63], A.M. Zaitsev[130,ac],
J. Zalieckas[14], A. Zaman[148], S. Zambito[57], L. Zanello[132a,132b], D. Zanzi[88], C. Zeitnitz[175],
M. Zeman[128], A. Zemla[38a], Q. Zeng[143], K. Zengel[23], O. Zenin[130], T. Ženiš[144a],
D. Zerwas[117], D. Zhang[89], F. Zhang[173], G. Zhang[33b], H. Zhang[33c], J. Zhang[6], L. Zhang[48],
R. Zhang[21], R. Zhang[33b,i], X. Zhang[33d], Z. Zhang[117], X. Zhao[40], Y. Zhao[33d,117],
Z. Zhao[33b], A. Zhemchugov[65], J. Zhong[120], B. Zhou[89], C. Zhou[45], L. Zhou[35], L. Zhou[40],
M. Zhou[148], N. Zhou[33f], C.G. Zhu[33d], H. Zhu[33a], J. Zhu[89], Y. Zhu[33b], X. Zhuang[33a],
K. Zhukov[96], A. Zibell[174], D. Zieminska[61], N.I. Zimine[65], C. Zimmermann[83],
S. Zimmermann[48], Z. Zinonos[54], M. Zinser[83], M. Ziolkowski[141], L. Živković[13],
G. Zobernig[173], A. Zoccoli[20a,20b], M. zur Nedden[16], G. Zurzolo[104a,104b], L. Zwalinski[30]

1 Department of Physics, University of Adelaide, Adelaide, Australia
2 Physics Department, SUNY Albany, Albany NY, United States of America
3 Department of Physics, University of Alberta, Edmonton AB, Canada
4 (a) Department of Physics, Ankara University, Ankara; (b) Istanbul Aydin University, Istanbul; (c) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
5 LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France
6 High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America
7 Department of Physics, University of Arizona, Tucson AZ, United States of America
8 Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America
9 Physics Department, University of Athens, Athens, Greece
10 Physics Department, National Technical University of Athens, Zografou, Greece
11 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
12 Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
13 Institute of Physics, University of Belgrade, Belgrade, Serbia
14 Department for Physics and Technology, University of Bergen, Bergen, Norway
15 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
16 Department of Physics, Humboldt University, Berlin, Germany
17 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19 (a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics Engineering, Gaziantep University, Gaziantep; (c) Department of Physics, Dogus University, Istanbul, Turkey

20 [(a)] INFN Sezione di Bologna; [(b)] Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy

21 Physikalisches Institut, University of Bonn, Bonn, Germany

22 Department of Physics, Boston University, Boston MA, United States of America

23 Department of Physics, Brandeis University, Waltham MA, United States of America

24 [(a)] Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; [(b)] Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; [(c)] Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; [(d)] Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil

25 Physics Department, Brookhaven National Laboratory, Upton NY, United States of America

26 [(a)] Transilvania University of Brasov, Brasov; [(b)] National Institute of Physics and Nuclear Engineering, Bucharest; [(c)] National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; [(d)] University Politehnica Bucharest, Bucharest; [(e)] West University in Timisoara, Timisoara, Romania

27 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina

28 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

29 Department of Physics, Carleton University, Ottawa ON, Canada

30 CERN, Geneva, Switzerland

31 Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America

32 [(a)] Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; [(b)] Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

33 [(a)] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; [(b)] Department of Modern Physics, University of Science and Technology of China, Anhui; [(c)] Department of Physics, Nanjing University, Jiangsu; [(d)] School of Physics, Shandong University, Shandong; [(e)] Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai; [(f)] Physics Department, Tsinghua University, Beijing 100084, China

34 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France

35 Nevis Laboratory, Columbia University, Irvington NY, United States of America

36 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark

37 [(a)] INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; [(b)] Dipartimento di Fisica, Università della Calabria, Rende, Italy

38 [(a)] AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; [(b)] Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland

39 Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland

40 Physics Department, Southern Methodist University, Dallas TX, United States of America

41 Physics Department, University of Texas at Dallas, Richardson TX, United States of America

42 DESY, Hamburg and Zeuthen, Germany

43 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany

44 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany

45 Department of Physics, Duke University, Durham NC, United States of America

46 SUPA — School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

47 INFN Laboratori Nazionali di Frascati, Frascati, Italy

48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany

49 Section de Physique, Université de Genève, Geneva, Switzerland

50 [(a)] INFN Sezione di Genova; [(b)] Dipartimento di Fisica, Università di Genova, Genova, Italy

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

52 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany

53 SUPA — School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom

54 II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany

[55] Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France

[56] Department of Physics, Hampton University, Hampton VA, United States of America

[57] Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America

[58] [a] Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [b] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [c] ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany

[59] Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan

[60] [a] Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; [b] Department of Physics, The University of Hong Kong, Hong Kong; [c] Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China

[61] Department of Physics, Indiana University, Bloomington IN, United States of America

[62] Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria

[63] University of Iowa, Iowa City IA, United States of America

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

[65] Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia

[66] KEK, High Energy Accelerator Research Organization, Tsukuba, Japan

[67] Graduate School of Science, Kobe University, Kobe, Japan

[68] Faculty of Science, Kyoto University, Kyoto, Japan

[69] Kyoto University of Education, Kyoto, Japan

[70] Department of Physics, Kyushu University, Fukuoka, Japan

[71] Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina

[72] Physics Department, Lancaster University, Lancaster, United Kingdom

[73] [a] INFN Sezione di Lecce; [b] Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy

[74] Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom

[75] Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia

[76] School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom

[77] Department of Physics, Royal Holloway University of London, Surrey, United Kingdom

[78] Department of Physics and Astronomy, University College London, London, United Kingdom

[79] Louisiana Tech University, Ruston LA, United States of America

[80] Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France

[81] Fysiska institutionen, Lunds universitet, Lund, Sweden

[82] Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain

[83] Institut für Physik, Universität Mainz, Mainz, Germany

[84] School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom

[85] CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France

[86] Department of Physics, University of Massachusetts, Amherst MA, United States of America

[87] Department of Physics, McGill University, Montreal QC, Canada

[88] School of Physics, University of Melbourne, Victoria, Australia

[89] Department of Physics, The University of Michigan, Ann Arbor MI, United States of America

[90] Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America

[91] [a] INFN Sezione di Milano; [b] Dipartimento di Fisica, Università di Milano, Milano, Italy

[92] B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus

[93] National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus

[94] Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America

[95] Group of Particle Physics, University of Montreal, Montreal QC, Canada

[96] P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia

[97] Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia

[98] National Research Nuclear University MEPhI, Moscow, Russia

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

[100] Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany

[101] Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany

[102] Nagasaki Institute of Applied Science, Nagasaki, Japan

[103] Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan

[104] [a] INFN Sezione di Napoli; [b] Dipartimento di Fisica, Università di Napoli, Napoli, Italy

[105] Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America

[106] Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands

[107] Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands

[108] Department of Physics, Northern Illinois University, DeKalb IL, United States of America

[109] Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia

[110] Department of Physics, New York University, New York NY, United States of America

[111] Ohio State University, Columbus OH, United States of America

[112] Faculty of Science, Okayama University, Okayama, Japan

[113] Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America

[114] Department of Physics, Oklahoma State University, Stillwater OK, United States of America

[115] Palacký University, RCPTM, Olomouc, Czech Republic

[116] Center for High Energy Physics, University of Oregon, Eugene OR, United States of America

[117] LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France

[118] Graduate School of Science, Osaka University, Osaka, Japan

[119] Department of Physics, University of Oslo, Oslo, Norway

[120] Department of Physics, Oxford University, Oxford, United Kingdom

[121] [a] INFN Sezione di Pavia; [b] Dipartimento di Fisica, Università di Pavia, Pavia, Italy

[122] Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America

[123] National Research Centre "Kurchatov Institute" B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia

[124] [a] INFN Sezione di Pisa; [b] Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy

[125] Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America

[126] [a] Laboratório de Instrumentação e Física Experimental de Partículas — LIP, Lisboa; [b] Faculdade de Ciências, Universidade de Lisboa, Lisboa; [c] Department of Physics, University of Coimbra, Coimbra; [d] Centro de Física Nuclear da Universidade de Lisboa, Lisboa; [e] Departamento de Fisica, Universidade do Minho, Braga; [f] Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); [g] Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal

[127] Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic

[128] Czech Technical University in Prague, Praha, Czech Republic

[129] Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic

[130] State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia

[131] Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom

[132] [a] INFN Sezione di Roma; [b] Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy

[133] [a] INFN Sezione di Roma Tor Vergata; [b] Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy

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

135 (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies — Université Hassan II, Casablanca; (b) Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) Faculté des sciences, Université Mohammed V, Rabat, Morocco

136 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France

137 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America

138 Department of Physics, University of Washington, Seattle WA, United States of America

139 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom

140 Department of Physics, Shinshu University, Nagano, Japan

141 Fachbereich Physik, Universität Siegen, Siegen, Germany

142 Department of Physics, Simon Fraser University, Burnaby BC, Canada

143 SLAC National Accelerator Laboratory, Stanford CA, United States of America

144 (a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic

145 (a) Department of Physics, University of Cape Town, Cape Town; (b) Department of Physics, University of Johannesburg, Johannesburg; (c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa

146 (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden

147 Physics Department, Royal Institute of Technology, Stockholm, Sweden

148 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America

149 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom

150 School of Physics, University of Sydney, Sydney, Australia

151 Institute of Physics, Academia Sinica, Taipei, Taiwan

152 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel

153 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel

154 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece

155 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan

156 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan

157 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan

158 Department of Physics, University of Toronto, Toronto ON, Canada

159 (a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON, Canada

160 Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan

161 Department of Physics and Astronomy, Tufts University, Medford MA, United States of America

162 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

163 Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America

164 (a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; (b) ICTP, Trieste; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy

165 Department of Physics, University of Illinois, Urbana IL, United States of America

166 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

167 Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain

168 Department of Physics, University of British Columbia, Vancouver BC, Canada

169 Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada

170 Department of Physics, University of Warwick, Coventry, United Kingdom

171 Waseda University, Tokyo, Japan

172 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel

173 Department of Physics, University of Wisconsin, Madison WI, United States of America

174 Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany

175 Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany

176 Department of Physics, Yale University, New Haven CT, United States of America

177 Yerevan Physics Institute, Yerevan, Armenia

178 Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

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

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

[c] Also at Novosibirsk State University, Novosibirsk, Russia

[d] Also at TRIUMF, Vancouver BC, Canada

[e] Also at Department of Physics, California State University, Fresno CA, United States of America

[f] Also at Department of Physics, University of Fribourg, Fribourg, Switzerland

[g] Also at Departamento de Fisica e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal

[h] Also at Tomsk State University, Tomsk, Russia

[i] Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France

[j] Also at Universita di Napoli Parthenope, Napoli, Italy

[k] Also at Institute of Particle Physics (IPP), Canada

[l] Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom

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

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

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

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

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

[r] Also at Department of Physics, National Tsing Hua University, Taiwan

[s] Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America

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

[u] Also at CERN, Geneva, Switzerland

[v] Also at Georgian Technical University (GTU),Tbilisi, Georgia

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

[x] Also at Hellenic Open University, Patras, Greece

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

[z] Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France

[aa] Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan

[ab] Also at School of Physics, Shandong University, Shandong, China

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

[ad] Also at Section de Physique, Université de Genève, Geneva, Switzerland

[ae] Also at International School for Advanced Studies (SISSA), Trieste, Italy

[af] Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America

^{ag} Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China
^{ah} Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
^{ai} Also at National Research Nuclear University MEPhI, Moscow, Russia
^{aj} Also at Department of Physics, Stanford University, Stanford CA, United States of America
^{ak} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
^{al} Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia
* Deceased