



# Evidence for single top-quark production in the $s$ -channel in proton–proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector using the Matrix Element Method



ATLAS Collaboration\*

## ARTICLE INFO

### Article history:

Received 20 November 2015  
 Received in revised form 17 February 2016  
 Accepted 3 March 2016  
 Available online 8 March 2016  
 Editor: W.-D. Schlatter

## ABSTRACT

This Letter presents evidence for single top-quark production in the  $s$ -channel using proton–proton collisions at a centre-of-mass energy of 8 TeV with the ATLAS detector at the CERN Large Hadron Collider. The analysis is performed on events containing one isolated electron or muon, large missing transverse momentum and exactly two  $b$ -tagged jets in the final state. The analysed data set corresponds to an integrated luminosity of  $20.3 \text{ fb}^{-1}$ . The signal is extracted using a maximum-likelihood fit of a discriminant which is based on the matrix element method and optimized in order to separate single-top-quark  $s$ -channel events from the main background contributions, which are top-quark pair production and  $W$  boson production in association with heavy-flavour jets. The measurement leads to an observed signal significance of 3.2 standard deviations and a measured cross-section of  $\sigma_s = 4.8 \pm 0.8(\text{stat.})_{-1.3}^{+1.6}(\text{syst.}) \text{ pb}$ , which is consistent with the Standard Model expectation. The expected significance for the analysis is 3.9 standard deviations.

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## 1. Introduction

In proton–proton ( $pp$ ) collisions, top quarks are produced mainly in pairs via the strong interaction, but also singly via the electroweak interaction through a  $Wtb$  vertex. Therefore, single top-quark production provides a powerful probe for the electroweak couplings of the top quark. In the Standard Model (SM), three different production mechanisms are possible in leading-order (LO) QCD: an exchange of a virtual  $W$  boson either in the  $t$ -channel or in the  $s$ -channel (see Fig. 1), or the associated production of a top quark and a  $W$  boson. Among other interesting features,  $s$ -channel single top-quark production is sensitive to new particles proposed in several models of physics beyond the SM, such as charged Higgs boson or  $W'$  boson production [1]. It also plays an important role in indirect searches for new phenomena that could be modelled as anomalous couplings in an effective quantum field theory [2]. Furthermore,  $s$ -channel production, like the other two production channels, provides a direct determination of the absolute value of the Cabibbo–Kobayashi–Maskawa (CKM) matrix element  $V_{tb}$ .

Single top-quark production was first seen by the CDF and DØ collaborations in combined measurements of the  $s$ -channel and  $t$ -channel [3,4]. Recently, the  $s$ -channel alone was observed in a

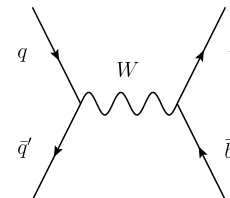


Fig. 1. Feynman diagram in leading-order QCD for the dominant hard scattering process in the  $s$ -channel of single top-quark production.

combination of the results from both collaborations [5]. At the Large Hadron Collider (LHC) [6] the production of single top quarks was observed both in the  $t$ -channel and in associated  $Wt$  production by the CMS [7,8] and ATLAS collaborations [9,10]. For the  $s$ -channel, results of a search at  $\sqrt{s} = 8$  TeV using an integrated luminosity of  $20.3 \text{ fb}^{-1}$  were published by ATLAS [11]. That analysis was based on a boosted decision tree (BDT) event classifier and led to an upper limit of 14.6 pb at the 95% confidence level. The obtained cross-section was  $\sigma_s^{\text{BDT}} = 5.0 \pm 4.3 \text{ pb}$  with an observed signal significance of  $1.3 \sigma$ .

Standard Model predictions are available for the production of single top quarks in next-to-leading-order (NLO) QCD [12–14] including resummed next-to-next-to-leading logarithmic (NNLL) corrections for soft gluon emissions [15–17]. For the  $s$ -channel the predicted total inclusive cross-section for  $pp$  collisions at a centre-

\* E-mail address: [atlas.publications@cern.ch](mailto:atlas.publications@cern.ch).

of-mass energy  $\sqrt{s} = 8$  TeV is  $\sigma_s^{\text{th}} = 5.61 \pm 0.22$  pb, while for the  $t$ -channel it is  $\sigma_t^{\text{th}} = 87.76_{-1.91}^{+3.44}$  pb, and  $\sigma_{Wt}^{\text{th}} = 22.37 \pm 1.52$  pb for associated  $Wt$  production. The given uncertainties include variations of the renormalization and factorization scales, as well as an estimate of the uncertainty of the parton distribution function (PDF) needed for the calculation.

In this Letter, a measurement of single top-quark  $s$ -channel production in  $pp$  collisions with  $\sqrt{s} = 8$  TeV at the LHC is presented. Each of the two other single-top-quark production processes,  $t$ -channel and  $Wt$  production, is treated as a background process assuming its cross-section as predicted by NLO+NNLL QCD calculations. In the SM the top quark decays almost exclusively into a  $W$  boson and a  $b$ -quark. This analysis considers only the leptonic decays ( $e$  or  $\mu$ ) of the  $W$  boson, since the fully hadronic final states are dominated by overwhelming multi-jet background. Some of the events containing a  $W$  boson decaying into a  $\tau$  lepton which subsequently decays leptonically are also selected. At LO the final state contains two jets with large transverse momenta: one jet originating from the decay of the top quark into a  $b$ -quark (“ $b$ -jet”), and another  $b$ -jet from the  $Wtb$  vertex producing the top quark. Thus the experimental signature consists of an isolated electron or muon, large missing transverse momentum,  $E_T^{\text{miss}}$ , due to the undetected neutrino from the  $W$  boson decay, and two jets with large transverse momentum,  $p_T$ , and which are both identified as containing  $b$ -hadrons (“ $b$ -tagged”). The electron and muon channels in this analysis are merged regardless of the lepton charge in order to measure the combined production cross-section of top quarks and top antiquarks.

In contrast to the aforementioned BDT-based analysis [11], the signal extraction in this analysis is based on the matrix element (ME) method [18,19]. The same data set is used in both analyses. This analysis takes advantage of enhanced simulation samples which reduce the statistical uncertainty and give a better description of the data. Furthermore, updated calibrations for the 2012 data are used, resulting in a reduction of systematic uncertainties. The event selection is improved by adding a veto on dileptonic events, which leads to a significant suppression of the background for top-quark pair ( $t\bar{t}$ ) production (see Section 5). The combination of all these measures results in a significant improvement in the sensitivity to the  $s$ -channel process. Approximately half of this improvement can be attributed to the change in method from BDT to ME. In particular, the BDT technique applied to this analysis is limited by the sample sizes available for the training, while the ME approach is not sensitive to this limitation.

## 2. The ATLAS detector

The ATLAS detector [20] is a multi-purpose detector consisting of a tracking system, calorimeters and an outer muon spectrometer. The inner tracking system contains a silicon pixel detector, a silicon microstrip tracker and a straw-tube transition radiation tracker. The system is surrounded by a thin solenoid magnet which produces a 2 T axial magnetic field, and it provides charged-particle tracking as well as particle identification in the pseudo-rapidity<sup>1</sup> region  $|\eta| < 2.5$ . The central calorimeter system covers the range of  $|\eta| < 1.7$  and is divided into a liquid-argon electromagnetic sampling calorimeter with high granularity and a hadron calorimeter consisting of steel/scintillator tiles. The endcap regions

are equipped with liquid-argon calorimeters for electromagnetic and hadronic energy measurements up to  $|\eta| = 4.9$ . The outer muon spectrometer is immersed in a toroidal magnetic field provided by air-core superconducting magnets and comprises tracking chambers for precise muon momentum measurements up to  $|\eta| = 2.7$  and trigger chambers covering the range  $|\eta| < 2.4$ . The combination of all these systems provides efficient and precise reconstruction of leptons and photons in the range  $|\eta| < 2.5$ . Jets and  $E_T^{\text{miss}}$  are reconstructed using energy deposits over the full coverage of the calorimeters,  $|\eta| < 4.9$ . A three-level trigger system [21] is used to reduce the recorded rate of uninteresting events and to select the events in question.

## 3. Data and simulation samples

The data for this analysis was collected with the ATLAS detector at the LHC in 2012 at a centre-of-mass energy of 8 TeV using single-electron or single-muon triggers. The applied trigger thresholds ensure a constant efficiency with respect to the energy of the lepton candidates used in this analysis. Each triggered event includes on average about 20 additional  $pp$  collisions (pile-up) from the same bunch-crossing. Only events recorded under stable beam conditions are selected and all events have to pass stringent data quality requirements and need to contain at least one reconstructed primary vertex with at least five associated tracks. The data used by this analysis corresponds to an integrated luminosity of  $20.3 \pm 0.6$  fb<sup>-1</sup> [22].

The samples used for the simulation of the single-top-quark  $s$ -channel signal events, as well as the ones for the  $t\bar{t}$ , single-top-quark  $t$ -channel and  $Wt$  backgrounds, were produced using the NLO generator POWHEG-Box (v1\_r2129) [23] with the CT10 PDFs [24]. The parton shower, hadronization and underlying event were simulated with PYTHIA (v6.42) [25] using the Perugia 2011C set of tuned parameters [26]. For generator, parton shower and fragmentation modeling studies, alternative simulation samples are employed. In case of the  $s$ -channel signal and the  $t$ -channel background the MADGRAPH5\_aMC@NLO (v2.0) generator was used [27], while for the  $t\bar{t}$  and  $Wt$  backgrounds it was the MC@NLO (v4.03) [28] generator. In both cases the CT10 PDFs were used and the generators were interfaced to HERWIG (v6.52) [29] for parton showering and hadronization, and JIMMY (v4.31) [30] for the underlying event. The impacts of scale variations as well as uncertainties on the initial and final state radiation (ISR/FSR) in signal events were studied using samples generated with the POWHEG-Box generator, again connected to PYTHIA, for various values of the factorization and renormalization scales.

The processes for  $W$  boson production in association with jets ( $W$ +jets) were modelled by the LO multi-parton SHERPA generator (v1.4.1) [31] together with CT10 PDF sets. This generator matches the parton shower to the multi-leg LO matrix elements by using the CKKW method [32]. The SHERPA generator was used for the complete event generation including the underlying event, using the default set of tuned parameters. The background contributions from  $Z$  boson production in association with jets ( $Z$ +jets) were simulated using the LO ALPGEN (v2.14) generator [33] coupled with PYTHIA (v6.42) and CTEQ6L1 PDF sets [34]. The latter is also used to test the  $W$ +jets modeling. The diboson processes ( $WW$ ,  $WZ$ ,  $ZZ$ ) were simulated using the HERWIG (v6.52) and JIMMY (v4.31) generators with the AUET2 tune [35] and the CTEQ6L1 PDF set. The single-boson and diboson samples were normalized to their production cross-sections calculated at next-to-next-to-leading order (NNLO) [36] and NLO [37], respectively. The multi-jet background was modelled by a data-driven method as described in Section 4.

Almost all the generated event samples were passed through the full ATLAS detector simulation [38] based on GEANT4 [39]

<sup>1</sup> 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 upward. Cylindrical coordinates  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$ .

and then processed with the same reconstruction chain as the data. The remaining samples, which consist of single-top-quark  $s$ - and  $t$ -channel samples for scale variation studies, as well as for  $t$ -channel and  $t\bar{t}$  modeling studies, are passed through the ATLAS-FAST2 simulation of the ATLAS detector, which uses a fast simulation for the calorimeters [40]. The simulated events were overlaid with additional minimum-bias events generated with PYTHIA to simulate the effect of additional  $pp$  interactions. All processes involving top quarks were generated using a top-quark mass of 172.5 GeV.

#### 4. Background estimation

The two most important backgrounds are  $t\bar{t}$  and  $W$ +jets production. The former is difficult to distinguish from the signal since  $t\bar{t}$  events contain real top-quark decays. In its dileptonic decay mode,  $t\bar{t}$  events can mimic the final-state signature of the signal if one of the two leptons escapes unidentified, whereas the semileptonic decay mode contributes to the selected samples if only two of its four jets are identified or if some jets are merged. The  $W$ +jets events can contribute to the background if they contain  $b$ -jets in the final state or due to mis-tagging of jets containing other quark flavours. Single top-quark  $t$ -channel production also leads to a sizeable background contribution, while associated  $Wt$  production has only a small effect.

A less significant background contribution is multi-jet production where jets, non-prompt leptons from heavy-flavour decays, or electrons from photon conversions are mis-identified as prompt isolated leptons. This background is estimated by using a data-driven matrix method [41], where the probability to mis-identify an isolated electron or muon in an event is obtained by exploiting sum rules based on disjoint control samples, one almost pure electron or muon sample and another containing a high fraction of mis-identified leptons due to a relaxed lepton-isolation criterion. For both decay channels the amount of multi-jet background is below 2% in the final selection. Other minor backgrounds are from  $Z$ +jets and diboson production.

Apart from the data-driven multi-jet background, all samples are normalized to their predicted cross-sections. The samples for single top-quark production are normalized to their NLO+NNLL predictions (see Section 1), while for all  $t\bar{t}$  samples a recent calculation with Top++ (v2.0) at NNLO in QCD including resummations of NNLL soft gluon terms of  $\sigma_{t\bar{t}}^{\text{th}} = 253_{-15}^{+13}$  pb is used for the normalization [42–47].

#### 5. Event reconstruction and selection

For the selection of  $s$ -channel final states, a single high- $p_T$  lepton, either electron or muon, exactly two  $b$ -tagged jets and a large amount of  $E_T^{\text{miss}}$  are required.

Electrons are reconstructed as energy deposits in the electromagnetic calorimeter matched to charged-particle tracks in the inner detector and must pass tight identification requirements [48,49]. The transverse momentum of the electrons must satisfy  $p_T > 30$  GeV and be in the central region with pseudorapidity  $|\eta| < 2.47$ , excluding the region  $1.37 < |\eta| < 1.52$ , which contains a large amount of inactive material. Muon candidates are identified using combined information from the inner detector and the muon spectrometer [50,51]. They are required to have  $p_T > 30$  GeV and  $|\eta| < 2.5$ . Both the electrons and muons must fulfill additional isolation requirements, as described in Ref. [41], in order to reduce contributions from non-prompt leptons originating from hadron decays, and fake leptons.

Jets are reconstructed by using the anti- $k_t$  algorithm [52] with a radius parameter of 0.4 for calorimeter energy clusters calibrated

with the local cluster weighting method [53]. For the jet calibration an energy- and  $\eta$ -dependent simulation-based scheme with in-situ corrections based on data [54] is employed. Only events containing exactly two jets with  $p_T > 40$  GeV for the leading jet and  $p_T > 30$  GeV for the second leading jet, as well as  $|\eta| < 2.5$  for both jets are selected. Events involving additional jets with  $p_T > 25$  GeV and  $|\eta| < 4.5$  are rejected. Both jets must be identified as  $b$ -jets. The identification is performed using a neural network which combines spatial and lifetime information from secondary vertices of tracks associated with the jets. The operating point of the tagging algorithm used in this analysis corresponds to a  $b$ -tagging efficiency of 70% and a rejection factor for light-flavour jets of about 140, while the rejection factor for charm jets is around 5 [55,56].

The missing transverse momentum is computed from the vector sum of all clusters of energy deposits in the calorimeter that are associated with reconstructed objects, and the transverse momenta of the reconstructed muons [57,58]. The energy deposits are calibrated at the corresponding energy scale of the parent object. Since  $E_T^{\text{miss}}$  is a measure for the undetectable neutrino originating from the top-quark decay, in this analysis only events with  $E_T^{\text{miss}} > 35$  GeV are accepted. Furthermore, the transverse mass<sup>2</sup> of the  $W$  boson,  $m_T^W$ , needs to be larger than 30 GeV to suppress multi-jet background.

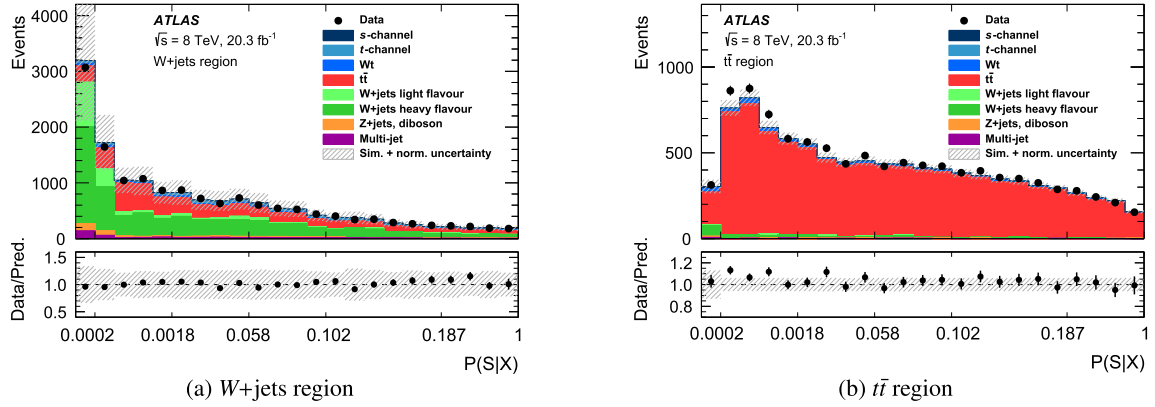
The main background at this stage of the selection originates from top-quark pair production, which is in turn dominated by dileptonic  $t\bar{t}$  events. To reduce this background, a veto is applied to all events containing an additional reconstructed electron or muon identified with loose criteria. The minimum required  $p_T$  of these leptons is 5 GeV. By this measure the  $t\bar{t}$  background is diminished by 30% while reducing the signal by less than half a per cent. After the application of all event selection criteria, a signal-to-background ratio of 4.6% is reached. The event yields for all samples in the signal region are collected in Table 1.

Apart from the signal region, two more regions are defined to validate the modeling, one validation region for  $t\bar{t}$  production and a control region for the  $W$ +jets background. The latter is used to constrain the normalization of the  $W$ +jets background in the final signal extraction, as explained in more detail in Section 8. The two regions are defined in the same way as the signal region, except that neither the veto on events with additional jets nor the one on dilepton events are applied. Top-quark pair production is enriched by selecting events containing exactly four jets with  $p_T > 25$  GeV, two of them  $b$ -tagged at the 70% working point. The  $W$ +jets control region is defined using a less stringent  $b$ -tag requirement (80% working point); in order to ensure that this region is disjoint from the signal region, it is required that at least one of the two jets fails to meet the signal region  $b$ -tagging criteria at the 70% working point.

#### 6. Matrix element method

The ME method directly uses theoretical calculations to compute a per-event signal probability. This technique was used for the observation of single top-quark production at the Tevatron [59, 3,4]. The discrimination between signal and background is based on the computation of likelihood values  $\mathcal{P}(X|H_{\text{proc}})$  for the hypothesis that a measured event with final state  $X$  is of a certain process type  $H_{\text{proc}}$ . Those likelihoods can be computed by

<sup>2</sup> The transverse mass,  $m_T^W$ , is computed from the lepton transverse momentum,  $p_T^\ell$ , and the difference in azimuthal angle,  $\Delta\phi$ , between the lepton and the missing transverse momentum as  $m_T^W = \sqrt{2E_T^{\text{miss}} p_T^\ell (1 - \cos(\Delta\phi(\hat{E}_T^{\text{miss}}, \hat{p}_T^\ell))}$ .



**Fig. 2.** ME discriminant for the (a)  $W$ +jets control region and (b) for the  $t\bar{t}$  validation region. Except for the data-driven multi-jet background all samples are scaled to their SM expectation. The hatched bands represent the predicted normalization uncertainty of all processes added in quadrature with the statistical uncertainty of the simulation. The lower panels show the relative difference between data and the prediction. Both histograms use the non-equidistant binning of the ME discriminant  $P(S|X)$  optimized for the signal region.

means of the factorization theorem from the corresponding partonic cross-sections of the hard scatter. The mapping between the hadronic measured final state and the parton state is implemented by transfer functions which take into account the detector resolution functions, the reconstruction and  $b$ -tagging efficiencies, as well as all possible permutations between the partons and the reconstructed objects.

The phase-space integration of the differential partonic cross-sections is performed using the Monte Carlo integration algorithm Vegas [60] from the CUBA program library [61]. The required PDF sets are taken from the LHAPDF5 package [62], while the computation of the scattering amplitudes is based on codes from the MCFM program [63]. The parameterizations of the ATLAS detector resolutions used for the transfer functions are those used in the KLfitter kinematic fit framework [64,65].

In total, eight different processes are considered for the computation of the likelihood values. For the  $s$ -channel signal, final states with two and three partons are included, while the single-top-quark  $t$ -channel process is modelled in the four-flavour scheme only. In the case of  $t\bar{t}$  production semileptonic and dileptonic processes are evaluated separately. The remaining background processes are  $W$  boson production with two associated light-flavour jets, with one light-flavour jet and one charm jet, and  $W+b\bar{b}$  production.

From the likelihood values of these processes the probability  $P(S|X)$  for a measured event  $X$  to be a signal event  $S$  can be computed with Bayes' theorem by

$$P(S|X) = \frac{\sum_i \alpha_{S_i} \mathcal{P}(X|S_i)}{\sum_i \alpha_{S_i} \mathcal{P}(X|S_i) + \sum_j \alpha_{B_j} \mathcal{P}(X|B_j)}. \quad (1)$$

Here,  $S_i$  and  $B_j$  denote all signal and background processes that are being considered. The *a priori* probabilities  $\alpha_{S_i}$  and  $\alpha_{B_j}$  are given by the expected fraction of events of each process in the set of selected events within the signal region. The value of  $P(S|X)$  is taken as the main discriminant in the signal extraction. The binning of the ME discriminant is optimized in the signal region utilizing a dedicated algorithm [66]. This results in a non-equidistant binning which exhibits wider bins in regions with a large signal contribution, while preserving a sufficiently large number of background events in each bin. In the following, all histograms showing the ME discriminant are drawn with a constant bin width causing a non-linear horizontal scale. Values of  $P(S|X)$  lower than 0.00015 are not taken into account for the signal extraction because of the large background domination in this range.

In order to validate the  $s$ -channel ME discriminant  $P(S|X)$  a comparison of the discriminant between data and the simulation is shown in Fig. 2 for the  $W$ +jets control region and the  $t\bar{t}$  validation region. For the latter, only the two  $b$ -tagged jets are considered for the ME discriminant computation. The normalization of each sample in Fig. 2 except for the data-driven multi-jet background is obtained by a similar fit to data as described in Sec. 8. The only difference is that here all samples, including the signal, are varied within their SM prediction uncertainty, while for the signal extraction fit the signal is allowed to float freely. In both regions the data is described well by the simulation.

## 7. Systematic uncertainties

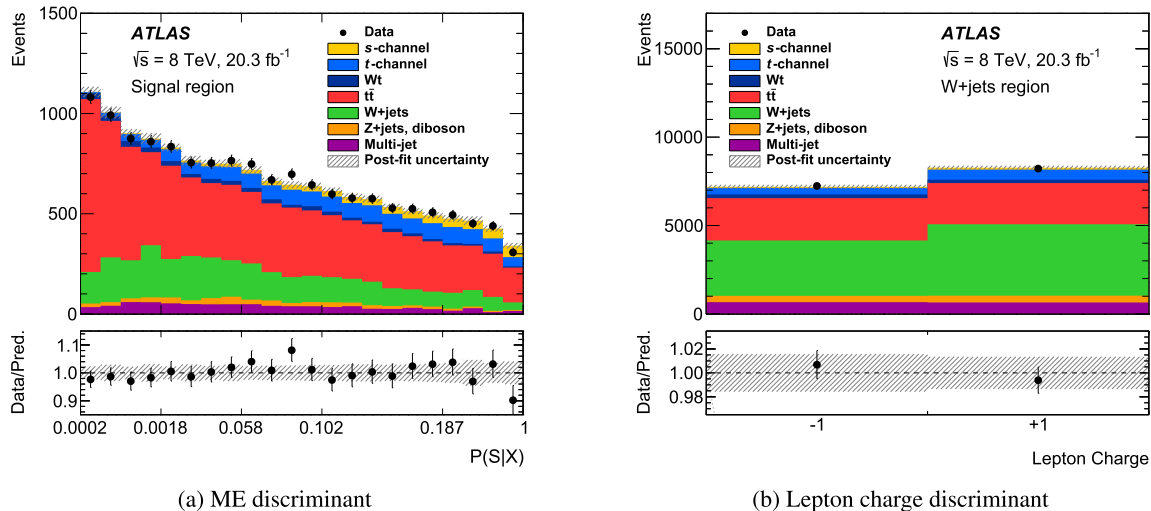
Apart from systematic effects in the signal acceptance and the background normalizations, the ME discriminant is subject to those systematic effects which change the four-momenta of the reconstructed objects. Therefore, systematic uncertainties such as the energy calibration of jets, electrons and muons are propagated through the whole analysis including the ME computation by variations in the modeling of the detector response.

The main sources of systematic uncertainties for jets are the energy scale, which is evaluated by a combination of in-situ techniques [54], the energy resolution [67] and the reconstruction efficiency [54]. For  $b$ ,  $c$  and light-flavour tagging of the jets the modeling of the respective efficiencies is taken into account [55,56]. The lepton uncertainties originate from trigger, identification and isolation efficiencies, as well as from their energy scale and resolution [49,51]. Both the energy scale and energy resolution uncertainties for the jets and leptons are transferred to the  $E_T^{\text{miss}}$  calculation. The impact of low- $p_T$  jets on  $E_T^{\text{miss}}$  and contributions from energy deposits in the calorimeters not associated with any reconstructed objects are considered as well.

Potential mis-modeling in the simulation of the signal and the main background processes is also taken into account in the evaluation of the systematic uncertainties. This includes contributions from the modeling of the hard process, the parton showers, hadronization and ISR/FSR. The uncertainty caused by the choice of renormalization and factorization scales is evaluated for the signal process and  $t\bar{t}$  production. All of these uncertainties are estimated by comparing simulation samples produced with different generators (see Section 3) or different parameter settings such as shower models or scales.

The normalization uncertainties of the different samples are taken from theory except for the multi-jet background, which is





**Fig. 3.** Post-fit distribution of (a) the ME discriminant in the signal region and (b) the lepton charge discriminant in the  $W$ +jets control region. All samples are scaled by the fit result utilizing all fit parameters. The hatched bands indicate the total uncertainty of the post-fit result including all correlations. The ME distributions are made using the optimized, non-equidistant binning which is also applied in the signal extraction fit.

estimated by a data-driven method. Uncertainties of 6%, 4% and 7% are assigned to  $t\bar{t}$ , single top-quark  $t$ -channel, and  $Wt$  production, respectively. For  $W$ +jets production, as well as for the combination of  $Z$ +jets and diboson production, an uncertainty of 60% each is considered [68,69]. The uncertainty for  $W$ +jets production is dominated by its heavy-flavour contribution. For the multi-jet background a normalization uncertainty of 50% is estimated.

The uncertainties associated with the PDFs are taken into account for all simulated samples by assessing a systematic uncertainty according to the PDF4LHC prescription [70], which makes use of the MSTW2008NLO [71], CT10, and NNPDF2.3 [72] sets. The uncertainty of the luminosity measurement is 2.8%, which was determined by dedicated beam-separation scans [22].

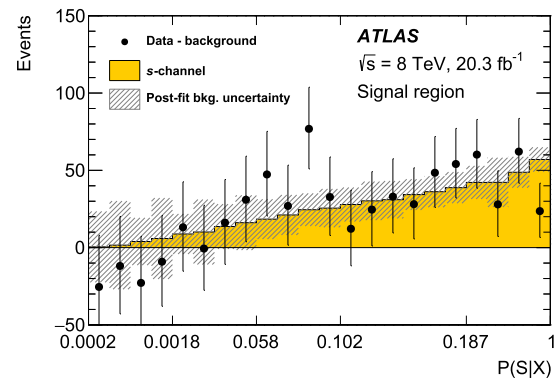
In addition to the impact of the systematic uncertainties on the signal acceptance and the background normalizations, their effect on the shape of the discriminant distributions is taken into account if it is significant. The significance is evaluated by performing  $\chi^2$  tests between the nominal and the systematically varied distributions made from uncorrelated event samples. Only a small fraction of all systematic uncertainties exhibit a significant shape effect. These are mainly the impact of the jet energy scale and resolution on the single-top-quark  $s$ - and  $t$ -channel samples.

For all simulation samples the effect of their limited size is included in the systematic uncertainty.

## 8. Signal extraction

The amount of signal in the selected data set is measured by means of a binned maximum-likelihood fit of the ME discriminant in the signal region. In order to better constrain the  $W$ +jets background, the lepton charge in the  $W$ +jets-enriched control region is used as an additional discriminant variable in the fit, as it exploits the charge asymmetry of the incoming partons participating in the  $W$ +jets processes. The likelihood function used in the fit consists of a Poisson term for the overall number of observed events, a product of probability densities of the discriminants taken over all bins of the distributions and a product of Gaussian constraint terms for the nuisance parameters which incorporate all statistical and systematic uncertainties in the fit. While all backgrounds are constrained by their given uncertainties, the signal strength  $\mu = \sigma_s/\sigma_s^{\text{th}}$  is a free parameter in the fit.

The significance of the fit result is obtained with a profile-likelihood-ratio test statistic which is used to determine how well



**Fig. 4.** Distribution of the ME discriminant in data in the signal region after the subtraction of all backgrounds (post-fit), showing the signal contribution. The error bars indicate the uncertainty of the measurement in each bin. The fitted distribution for the simulation of the signal is also shown together with its fit uncertainty for all backgrounds given by the hatched band. The binning is the same as the optimized, non-equidistant binning used in the fit.

the fit result agrees with the background-only hypothesis. Ensemble tests for all nuisance parameters are performed using the aforementioned likelihood function to get the expected distributions of the test statistic for the background-only and the signal-plus-background hypotheses. The significance is evaluated by integrating the probability density of the test statistic expected for the background-only hypothesis above the observed value. In a similar fashion the confidence interval of the measured signal strength can be estimated by studying its  $p$ -value dependence for the background-only hypothesis, as well as for the signal-plus-background hypothesis, by means of ensemble tests. The statistical evaluation used throughout this analysis is based on the RooStats framework [73].

## 9. Results

The results of the maximum-likelihood fit are presented in Fig. 3, which shows the two discriminant distributions used in the fit for all samples scaled by the fit results. For the ME discriminant the signal contribution in the data after the subtraction of all background samples is given in Fig. 4. After the fit, none of the nuisance parameters is biased or further constrained by the fit, ex-

**Table 1**

Pre-fit and post-fit event yields in the signal region for ME discriminant values larger than 0.00015. The post-fit uncertainty corresponds to the uncertainty of the maximum-likelihood fit including all correlations. The last column shows the ratio of post-fit to pre-fit results.

Process	Pre-fit	Post-fit	Post-fit / Pre-fit
Single-top $s$ -channel	610	540 ± 160	0.89
Single-top $t$ -channel	1230	1360 ± 160	1.10
Assoc. $Wt$ production	370	380 ± 50	1.02
$t\bar{t}$ production	8200	8100 ± 400	0.99
$W$ +jets	2600	3100 ± 500	1.17
$Z$ +jets & diboson	290	410 ± 280	1.40
Multi-jet	600	800 ± 400	1.28
Total expectation	13 980	14 670 ± 180	1.05
Data		14 677	

**Table 2**

Main statistical and systematic uncertainties contributing to the total uncertainty of the measured cross-section. The relative uncertainties reflect the influence of each systematic effect on the overall signal strength uncertainty. Apart from possible correlations between the systematic uncertainties, the total uncertainty contains several minor contributions which are all smaller than 1%.

Type	$\pm\Delta\sigma/\sigma$ [%]
Data statistics	16
MC statistics	12
Jet energy resolution	12
$t$ -channel generator choice	11
$b$ -tagging	8
$s$ -channel generator scale	7
$W$ +jets normalization	6
Luminosity	5
$t$ -channel normalization	5
Jet energy scale	5
PDF	3
Lepton identification	2
Electron energy scale	1
$t\bar{t}$ generator choice	1
Lepton trigger	1
Charm tagging	1
Other	<1
Total	34

cept for the  $W$ +jets normalization. Here, the rather conservative input uncertainty is halved by the fit to signal and the  $W$ +jets control regions. The observed signal strength obtained by the fit is  $\mu = 0.86^{+0.31}_{-0.28}$  with an observed (expected) significance of 3.2 (3.9) standard deviations. Table 1 summarizes the pre-fit and post-fit event yields for the signal and all backgrounds.

This analysis measures a cross-section of  $\sigma_s = 4.8 \pm 0.8(\text{stat.})^{+1.6}_{-1.3}(\text{syst.}) \text{ pb} = 4.8^{+1.8}_{-1.6} \text{ pb}$ . The main sources of uncertainty are collected in Table 2. The largest contribution arises from the limited sample sizes for data and the simulation. The jet energy resolution plays a major role, as well as the modeling of the single-top-quark  $t$ -channel background and scale variations for the signal. All other systematic effects are negligible.

The measured cross-section can be interpreted in terms of the CKM matrix element  $V_{tb}$ . The ratio of the measured cross-section to the prediction is equal to  $|f_{LV}V_{tb}|^2$ , where the form factor  $f_{LV}$  could be modified by new physics or radiative corrections through anomalous coupling contributions, for example those in Refs. [74–76]. The  $s$ -channel production and top quark decays through  $|V_{ts}|$  and  $|V_{td}|$  are assumed to be small. A lower limit on  $|V_{tb}|$  is obtained for  $f_{LV} = 1$  as in the SM, without assuming CKM unitarity [77,78]. The measured value of  $|f_{LV}V_{tb}|$  is  $0.93^{+0.18}_{-0.20}$ , and the corresponding lower limit on  $|V_{tb}|$  at the 95% confidence level is 0.5.

## 10. Conclusion

An analysis for  $s$ -channel single top-quark production in  $pp$  collisions at a centre-of-mass energy of 8 TeV recorded by the ATLAS detector at the LHC is presented. The analysed data set corresponds to an integrated luminosity of 20.3 fb<sup>-1</sup>. The selected events consist either of an electron or muon, two jets, both of which are identified to be induced by a  $b$ -quark, and large  $E_T^{\text{miss}}$ . In order to separate the signal from the large background contributions, a matrix element method discriminant is used. The signal is extracted from the data utilizing a profile likelihood fit, which leads to a measured cross-section of  $4.8^{+1.8}_{-1.6} \text{ pb}$ . The result, which is in agreement with the SM prediction, corresponds to an observed significance of 3.2 standard deviations, while the expected significance of the analysis is 3.9 standard deviations.

## Acknowledgements

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

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

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

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G. Aad<sup>85</sup>, B. Abbott<sup>113</sup>, J. Abdallah<sup>151</sup>, O. Abdinov<sup>11</sup>, R. Aben<sup>107</sup>, M. Abolins<sup>90</sup>, O.S. AbouZeid<sup>158</sup>, H. Abramowicz<sup>153</sup>, H. Abreu<sup>152</sup>, R. Abreu<sup>116</sup>, Y. Abulaiti<sup>146a,146b</sup>, B.S. Acharya<sup>164a,164b,a</sup>, L. Adamczyk<sup>38a</sup>, D.L. Adams<sup>25</sup>, J. Adelman<sup>108</sup>, S. Adomeit<sup>100</sup>, T. Adye<sup>131</sup>, A.A. Affolder<sup>74</sup>, T. Agatonovic-Jovin<sup>13</sup>, J. Agricola<sup>54</sup>, J.A. Aguilar-Saavedra<sup>126a,126f</sup>, S.P. Ahlen<sup>22</sup>, F. Ahmadov<sup>65,b</sup>, G. Aielli<sup>133a,133b</sup>, H. Akerstedt<sup>146a,146b</sup>, T.P.A. Åkesson<sup>81</sup>, A.V. Akimov<sup>96</sup>, G.L. Alberghi<sup>20a,20b</sup>, J. Albert<sup>169</sup>, S. Albrand<sup>55</sup>, M.J. Alconada Verzini<sup>71</sup>, M. Aleksa<sup>30</sup>, I.N. Aleksandrov<sup>65</sup>, C. Alexa<sup>26b</sup>, G. Alexander<sup>153</sup>, T. Alexopoulos<sup>10</sup>, M. Alhroob<sup>113</sup>, G. Alimonti<sup>91a</sup>, L. Alio<sup>85</sup>, J. Alison<sup>31</sup>, S.P. Alkire<sup>35</sup>, B.M.M. Allbrooke<sup>149</sup>, P.P. Allport<sup>18</sup>, A. Aloisio<sup>104a,104b</sup>, A. Alonso<sup>36</sup>, F. Alonso<sup>71</sup>, C. Alpigiani<sup>138</sup>, A. Altheimer<sup>35</sup>, B. Alvarez Gonzalez<sup>30</sup>, D. Álvarez Piqueras<sup>167</sup>, M.G. Alviggi<sup>104a,104b</sup>, B.T. Amadio<sup>15</sup>, K. Amako<sup>66</sup>, Y. Amaral Coutinho<sup>24a</sup>, C. Amelung<sup>23</sup>, D. Amidei<sup>89</sup>, S.P. Amor Dos Santos<sup>126a,126c</sup>, A. Amorim<sup>126a,126b</sup>, S. Amoroso<sup>48</sup>, N. Amram<sup>153</sup>, G. Amundsen<sup>23</sup>, C. Anastopoulos<sup>139</sup>, L.S. Ancu<sup>49</sup>, N. Andari<sup>108</sup>, T. Andeen<sup>35</sup>, C.F. Anders<sup>58b</sup>, G. Anders<sup>30</sup>, J.K. Anders<sup>74</sup>, K.J. Anderson<sup>31</sup>, A. Andreazza<sup>91a,91b</sup>, V. Andrei<sup>58a</sup>, S. Angelidakis<sup>9</sup>, I. Angelozzi<sup>107</sup>, P. Anger<sup>44</sup>, A. Angerami<sup>35</sup>, F. Anghinolfi<sup>30</sup>, A.V. Anisenkov<sup>109,c</sup>, N. Anjos<sup>12</sup>, A. Annovi<sup>124a,124b</sup>, M. Antonelli<sup>47</sup>, A. Antonov<sup>98</sup>, J. Antos<sup>144b</sup>, F. Anulli<sup>132a</sup>, M. Aoki<sup>66</sup>, L. Aperio Bella<sup>18</sup>, G. Arabidze<sup>90</sup>, Y. Arai<sup>66</sup>, J.P. Araque<sup>126a</sup>, A.T.H. Arce<sup>45</sup>, F.A. Arduh<sup>71</sup>, J-F. Arguin<sup>95</sup>, S. Argyropoulos<sup>63</sup>, M. Arik<sup>19a</sup>, A.J. Armbruster<sup>30</sup>, O. Arnaez<sup>30</sup>, H. Arnold<sup>48</sup>, M. Arratia<sup>28</sup>, O. Arslan<sup>21</sup>, A. Artamonov<sup>97</sup>, G. Artoni<sup>23</sup>, S. Artz<sup>83</sup>, S. Asai<sup>155</sup>, N. Asbah<sup>42</sup>, A. Ashkenazi<sup>153</sup>, B. Åsman<sup>146a,146b</sup>, L. Asquith<sup>149</sup>, K. Assamagan<sup>25</sup>, R. Astalos<sup>144a</sup>, M. Atkinson<sup>165</sup>, N.B. 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 H. Ten Kate<sup>30</sup>, P.K. Teng<sup>151</sup>, J.J. Teoh<sup>118</sup>, F. Tepel<sup>175</sup>, S. Terada<sup>66</sup>, K. Terashi<sup>155</sup>, J. Terron<sup>82</sup>, S. Terzo<sup>101</sup>,  
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 Yu.A. Tikhonov<sup>109,c</sup>, S. Timoshenko<sup>98</sup>, E. Tiouchichine<sup>85</sup>, P. Tipton<sup>176</sup>, S. Tisserant<sup>85</sup>, K. Todome<sup>157</sup>,  
 T. Todorov<sup>5,\*</sup>, S. Todorova-Nova<sup>129</sup>, J. Tojo<sup>70</sup>, S. Tokár<sup>144a</sup>, K. Tokushuku<sup>66</sup>, K. Tollefson<sup>90</sup>, E. Tolley<sup>57</sup>,  
 L. Tomlinson<sup>84</sup>, M. Tomoto<sup>103</sup>, L. Tompkins<sup>143,al</sup>, K. Toms<sup>105</sup>, E. Torrence<sup>116</sup>, H. Torres<sup>142</sup>,  
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I.M. Trigger<sup>159a</sup>, S. Trincas-Duvoid<sup>80</sup>, M.F. Tripiana<sup>12</sup>, W. Trischuk<sup>158</sup>, B. Trocme<sup>55</sup>, C. Troncon<sup>91a</sup>, M. Trottier-McDonald<sup>15</sup>, M. Trovatelli<sup>169</sup>, L. Truong<sup>164a,164c</sup>, M. Trzebinski<sup>39</sup>, A. Trzupek<sup>39</sup>, C. Tsarouchas<sup>30</sup>, J.C.-L. Tseng<sup>120</sup>, P.V. Tsiarshka<sup>92</sup>, D. Tsionou<sup>154</sup>, G. Tsipolitis<sup>10</sup>, N. Tsirintanis<sup>9</sup>, S. Tsiskaridze<sup>12</sup>, V. Tsiskaridze<sup>48</sup>, E.G. Tskhadadze<sup>51a</sup>, K.M. Tsui<sup>60a</sup>, I.I. Tsukerman<sup>97</sup>, V. Tsulaia<sup>15</sup>, S. Tsuno<sup>66</sup>, D. Tsybychev<sup>148</sup>, A. Tudorache<sup>26b</sup>, V. Tudorache<sup>26b</sup>, A.N. Tuna<sup>57</sup>, S.A. Tupputi<sup>20a,20b</sup>, S. Turchikhin<sup>99,aj</sup>, D. Turecek<sup>128</sup>, R. Turra<sup>91a,91b</sup>, A.J. Turvey<sup>40</sup>, P.M. Tuts<sup>35</sup>, A. Tykhonov<sup>49</sup>, M. 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Vickey Boeriu<sup>139</sup>, G.H.A. Viehhauser<sup>120</sup>, S. Viel<sup>15</sup>, R. Vigne<sup>62</sup>, M. Villa<sup>20a,20b</sup>, M. Villaplana Perez<sup>91a,91b</sup>, E. Vilucchi<sup>47</sup>, M.G. Vincker<sup>29</sup>, V.B. Vinogradov<sup>65</sup>, I. Vivarelli<sup>149</sup>, S. Vlachos<sup>10</sup>, D. Vladoiu<sup>100</sup>, M. Vlasak<sup>128</sup>, M. Vogel<sup>32a</sup>, P. Vokac<sup>128</sup>, G. Volpi<sup>124a,124b</sup>, M. Volpi<sup>88</sup>, H. von der Schmitt<sup>101</sup>, H. von Radziewski<sup>48</sup>, E. von Toerne<sup>21</sup>, V. Vorobel<sup>129</sup>, K. Vorobev<sup>98</sup>, M. Vos<sup>167</sup>, R. Voss<sup>30</sup>, J.H. Vosseveld<sup>74</sup>, N. Vranjes<sup>13</sup>, M. Vranjes Milosavljevic<sup>13</sup>, V. Vrba<sup>127</sup>, M. Vreeswijk<sup>107</sup>, R. Vuillermet<sup>30</sup>, I. Vukotic<sup>31</sup>, Z. Vykydal<sup>128</sup>, P. Wagner<sup>21</sup>, W. Wagner<sup>175</sup>, H. Wahlberg<sup>71</sup>, S. Wahrmund<sup>44</sup>, J. Wakabayashi<sup>103</sup>, J. Walder<sup>72</sup>, R. Walker<sup>100</sup>, W. Walkowiak<sup>141</sup>, C. Wang<sup>151</sup>, F. Wang<sup>173</sup>, H. Wang<sup>15</sup>, H. Wang<sup>40</sup>, J. Wang<sup>42</sup>, J. Wang<sup>150</sup>, K. Wang<sup>87</sup>, R. Wang<sup>6</sup>, S.M. Wang<sup>151</sup>, T. Wang<sup>21</sup>, T. Wang<sup>35</sup>, X. Wang<sup>176</sup>, C. Wanotayaroj<sup>116</sup>, A. Warburton<sup>87</sup>, C.P. Ward<sup>28</sup>, D.R. Wardrope<sup>78</sup>, A. Washbrook<sup>46</sup>, C. Wasicki<sup>42</sup>, P.M. Watkins<sup>18</sup>, A.T. Watson<sup>18</sup>, I.J. Watson<sup>150</sup>, M.F. Watson<sup>18</sup>, G. Watts<sup>138</sup>, S. Watts<sup>84</sup>, B.M. Waugh<sup>78</sup>, S. Webb<sup>84</sup>, M.S. Weber<sup>17</sup>, S.W. Weber<sup>174</sup>, J.S. Webster<sup>6</sup>, A.R. Weidberg<sup>120</sup>, B. Weinert<sup>61</sup>, J. Weingarten<sup>54</sup>, C. Weiser<sup>48</sup>, H. Weits<sup>107</sup>, P.S. Wells<sup>30</sup>, T. Wenaus<sup>25</sup>, T. Wengler<sup>30</sup>, S. Wenig<sup>30</sup>, N. Wermes<sup>21</sup>, M. Werner<sup>48</sup>, P. Werner<sup>30</sup>, M. Wessels<sup>58a</sup>, J. Wetter<sup>161</sup>, K. Whalen<sup>116</sup>, A.M. Wharton<sup>72</sup>, A. White<sup>8</sup>, M.J. White<sup>1</sup>, R. White<sup>32b</sup>, S. White<sup>124a,124b</sup>, D. Whiteson<sup>163</sup>, F.J. Wickens<sup>131</sup>, W. Wiedenmann<sup>173</sup>, M. Wielers<sup>131</sup>, P. Wienemann<sup>21</sup>, C. Wiglesworth<sup>36</sup>, L.A.M. Wiik-Fuchs<sup>21</sup>, A. Wildauer<sup>101</sup>, H.G. Wilkens<sup>30</sup>, H.H. Williams<sup>122</sup>, S. Williams<sup>107</sup>, C. Willis<sup>90</sup>, S. Willocq<sup>86</sup>, A. Wilson<sup>89</sup>, J.A. Wilson<sup>18</sup>, I. Wingerter-Seez<sup>5</sup>, F. Winklmeier<sup>116</sup>, B.T. Winter<sup>21</sup>, M. Wittgen<sup>143</sup>, J. Wittkowski<sup>100</sup>, S.J. Wollstadt<sup>83</sup>, M.W. Wolter<sup>39</sup>, H. Wolters<sup>126a,126c</sup>, B.K. Wosiek<sup>39</sup>, J. Wotschack<sup>30</sup>, M.J. Woudstra<sup>84</sup>, K.W. Wozniak<sup>39</sup>, M. Wu<sup>55</sup>, M. Wu<sup>31</sup>, S.L. Wu<sup>173</sup>, X. Wu<sup>49</sup>, Y. Wu<sup>89</sup>, T.R. Wyatt<sup>84</sup>, B.M. Wynne<sup>46</sup>, S. Xella<sup>36</sup>, D. Xu<sup>33a</sup>, L. Xu<sup>25</sup>, B. Yabsley<sup>150</sup>, S. Yacoob<sup>145a</sup>, R. Yakabe<sup>67</sup>, M. Yamada<sup>66</sup>, D. Yamaguchi<sup>157</sup>, Y. Yamaguchi<sup>118</sup>, A. Yamamoto<sup>66</sup>, S. Yamamoto<sup>155</sup>, T. Yamanaka<sup>155</sup>, K. Yamauchi<sup>103</sup>, Y. Yamazaki<sup>67</sup>, Z. Yan<sup>22</sup>, H. Yang<sup>33e</sup>, H. Yang<sup>173</sup>, Y. Yang<sup>151</sup>, W.-M. Yao<sup>15</sup>, Y.C. Yap<sup>80</sup>, Y. Yasu<sup>66</sup>, E. Yatsenko<sup>5</sup>, K.H. Yau Wong<sup>21</sup>, J. Ye<sup>40</sup>, S. Ye<sup>25</sup>, I. Yeletsikh<sup>65</sup>, A.L. Yen<sup>57</sup>, E. Yildirim<sup>42</sup>, K. Yorita<sup>171</sup>, R. Yoshida<sup>6</sup>, K. Yoshihara<sup>122</sup>, C. 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<sup>1</sup> Department of Physics, University of Adelaide, Adelaide, Australia



- <sup>2</sup> Physics Department, SUNY Albany, Albany NY, United States
- <sup>3</sup> Department of Physics, University of Alberta, Edmonton AB, Canada
- <sup>4</sup> <sup>(a)</sup> Department of Physics, Ankara University, Ankara; <sup>(b)</sup> Istanbul Aydin University, Istanbul; <sup>(c)</sup> Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
- <sup>5</sup> LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France
- <sup>6</sup> High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States
- <sup>7</sup> Department of Physics, University of Arizona, Tucson AZ, United States
- <sup>8</sup> Department of Physics, The University of Texas at Arlington, Arlington TX, United States
- <sup>9</sup> Physics Department, University of Athens, Athens, Greece
- <sup>10</sup> Physics Department, National Technical University of Athens, Zografou, Greece
- <sup>11</sup> Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
- <sup>12</sup> Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain
- <sup>13</sup> Institute of Physics, University of Belgrade, Belgrade, Serbia
- <sup>14</sup> Department for Physics and Technology, University of Bergen, Bergen, Norway
- <sup>15</sup> Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States
- <sup>16</sup> Department of Physics, Humboldt University, Berlin, Germany
- <sup>17</sup> Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
- <sup>18</sup> School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
- <sup>19</sup> <sup>(a)</sup> Department of Physics, Bogazici University, Istanbul; <sup>(b)</sup> Department of Physics Engineering, Gaziantep University, Gaziantep; <sup>(c)</sup> Department of Physics, Dogus University, Istanbul, Turkey
- <sup>20</sup> <sup>(a)</sup> INFN Sezione di Bologna; <sup>(b)</sup> Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
- <sup>21</sup> Physikalisches Institut, University of Bonn, Bonn, Germany
- <sup>22</sup> Department of Physics, Boston University, Boston MA, United States
- <sup>23</sup> Department of Physics, Brandeis University, Waltham MA, United States
- <sup>24</sup> <sup>(a)</sup> Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; <sup>(b)</sup> Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; <sup>(c)</sup> Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; <sup>(d)</sup> Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
- <sup>25</sup> Physics Department, Brookhaven National Laboratory, Upton NY, United States
- <sup>26</sup> <sup>(a)</sup> Transilvania University of Brasov, Brasov, Romania; <sup>(b)</sup> National Institute of Physics and Nuclear Engineering, Bucharest; <sup>(c)</sup> National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; <sup>(d)</sup> University Politehnica Bucharest, Bucharest; <sup>(e)</sup> West University in Timisoara, Timisoara, Romania
- <sup>27</sup> Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
- <sup>28</sup> Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
- <sup>29</sup> Department of Physics, Carleton University, Ottawa ON, Canada
- <sup>30</sup> CERN, Geneva, Switzerland
- <sup>31</sup> Enrico Fermi Institute, University of Chicago, Chicago IL, United States
- <sup>32</sup> <sup>(a)</sup> Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; <sup>(b)</sup> Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
- <sup>33</sup> <sup>(a)</sup> Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; <sup>(b)</sup> Department of Modern Physics, University of Science and Technology of China, Anhui; <sup>(c)</sup> Department of Physics, Nanjing University, Jiangsu; <sup>(d)</sup> School of Physics, Shandong University, Shandong; <sup>(e)</sup> Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai, China; <sup>(f)</sup> Physics Department, Tsinghua University, Beijing 100084, China
- <sup>34</sup> Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
- <sup>35</sup> Nevis Laboratory, Columbia University, Irvington NY, United States
- <sup>36</sup> Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
- <sup>37</sup> <sup>(a)</sup> INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; <sup>(b)</sup> Dipartimento di Fisica, Università della Calabria, Rende, Italy
- <sup>38</sup> <sup>(a)</sup> AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; <sup>(b)</sup> Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
- <sup>39</sup> Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
- <sup>40</sup> Physics Department, Southern Methodist University, Dallas TX, United States
- <sup>41</sup> Physics Department, University of Texas at Dallas, Richardson TX, United States
- <sup>42</sup> DESY, Hamburg and Zeuthen, Germany
- <sup>43</sup> Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
- <sup>44</sup> Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
- <sup>45</sup> Department of Physics, Duke University, Durham NC, United States
- <sup>46</sup> SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
- <sup>47</sup> INFN Laboratori Nazionali di Frascati, Frascati, Italy
- <sup>48</sup> Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
- <sup>49</sup> Section de Physique, Université de Genève, Geneva, Switzerland
- <sup>50</sup> <sup>(a)</sup> INFN Sezione di Genova; <sup>(b)</sup> Dipartimento di Fisica, Università di Genova, Genova, Italy
- <sup>51</sup> <sup>(a)</sup> E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi; <sup>(b)</sup> High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
- <sup>52</sup> II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
- <sup>53</sup> SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- <sup>54</sup> II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- <sup>55</sup> Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
- <sup>56</sup> Department of Physics, Hampton University, Hampton VA, United States
- <sup>57</sup> Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States
- <sup>58</sup> <sup>(a)</sup> Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; <sup>(b)</sup> Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
- <sup>59</sup> Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- <sup>60</sup> <sup>(a)</sup> Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; <sup>(b)</sup> Department of Physics, The University of Hong Kong, Hong Kong; <sup>(c)</sup> Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
- <sup>61</sup> Department of Physics, Indiana University, Bloomington IN, United States
- <sup>62</sup> Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- <sup>63</sup> University of Iowa, Iowa City IA, United States
- <sup>64</sup> Department of Physics and Astronomy, Iowa State University, Ames IA, United States
- <sup>65</sup> Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- <sup>66</sup> KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- <sup>67</sup> Graduate School of Science, Kobe University, Kobe, Japan
- <sup>68</sup> Faculty of Science, Kyoto University, Kyoto, Japan
- <sup>69</sup> Kyoto University of Education, Kyoto, Japan
- <sup>70</sup> Department of Physics, Kyushu University, Fukuoka, Japan
- <sup>71</sup> Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- <sup>72</sup> Physics Department, Lancaster University, Lancaster, United Kingdom

- 73 <sup>(a)</sup> INFN Sezione di Lecce; <sup>(b)</sup> 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
- 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 Física Teórica C-15, Universidad Autónoma 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
- 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
- 90 Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States
- 91 <sup>(a)</sup> INFN Sezione di Milano; <sup>(b)</sup> Dipartimento di Fisica, Università di Milano, Milano, Italy
- 92 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
- 93 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus
- 94 Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States
- 95 Group of Particle Physics, University of Montreal, Montreal QC, Canada
- 96 P.N. Lebedev Physical Institute of the Russian 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 <sup>(a)</sup> INFN Sezione di Napoli; <sup>(b)</sup> Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- 105 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States
- 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
- 109 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- 110 Department of Physics, New York University, New York NY, United States
- 111 Ohio State University, Columbus OH, United States
- 112 Faculty of Science, Okayama University, Okayama, Japan
- 113 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States
- 114 Department of Physics, Oklahoma State University, Stillwater OK, United States
- 115 Palacký University, RCPTM, Olomouc, Czech Republic
- 116 Center for High Energy Physics, University of Oregon, Eugene OR, United States
- 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 <sup>(a)</sup> INFN Sezione di Pavia; <sup>(b)</sup> Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- 122 Department of Physics, University of Pennsylvania, Philadelphia PA, United States
- 123 National Research Centre “Kurchatov Institute” B.P.Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
- 124 <sup>(a)</sup> INFN Sezione di Pisa; <sup>(b)</sup> Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- 125 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States
- 126 <sup>(a)</sup> Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa; <sup>(b)</sup> Faculdade de Ciências, Universidade de Lisboa, Lisboa; <sup>(c)</sup> Department of Physics, University of Coimbra, Coimbra; <sup>(d)</sup> Centro de Física Nuclear da Universidade de Lisboa, Lisboa; <sup>(e)</sup> Departamento de Física, Universidade do Minho, Braga; <sup>(f)</sup> Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); <sup>(g)</sup> Dep Física and CEFITEC of Faculdade de Ciências 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 <sup>(a)</sup> INFN Sezione di Roma; <sup>(b)</sup> Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- 133 <sup>(a)</sup> INFN Sezione di Roma Tor Vergata; <sup>(b)</sup> Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- 134 <sup>(a)</sup> INFN Sezione di Roma Tre; <sup>(b)</sup> Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- 135 <sup>(a)</sup> Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; <sup>(b)</sup> Centre National de l’Energie des Sciences Techniques Nucleaires, Rabat; <sup>(c)</sup> Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; <sup>(d)</sup> Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; <sup>(e)</sup> 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
- 138 Department of Physics, University of Washington, Seattle WA, United States
- 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
- 144 <sup>(a)</sup> Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; <sup>(b)</sup> Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- 145 <sup>(a)</sup> Department of Physics, University of Cape Town, Cape Town; <sup>(b)</sup> Department of Physics, University of Johannesburg, Johannesburg; <sup>(c)</sup> School of Physics, University of the Witwatersrand, Johannesburg, South Africa

- <sup>146</sup> <sup>(a)</sup> Department of Physics, Stockholm University; <sup>(b)</sup> The Oskar Klein Centre, Stockholm, Sweden
- <sup>147</sup> Physics Department, Royal Institute of Technology, Stockholm, Sweden
- <sup>148</sup> Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States
- <sup>149</sup> Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- <sup>150</sup> School of Physics, University of Sydney, Sydney, Australia
- <sup>151</sup> Institute of Physics, Academia Sinica, Taipei, Taiwan
- <sup>152</sup> Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
- <sup>153</sup> Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- <sup>154</sup> Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- <sup>155</sup> International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
- <sup>156</sup> Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- <sup>157</sup> Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- <sup>158</sup> Department of Physics, University of Toronto, Toronto ON, Canada
- <sup>159</sup> <sup>(a)</sup> TRIUMF, Vancouver BC; <sup>(b)</sup> Department of Physics and Astronomy, York University, Toronto ON, Canada
- <sup>160</sup> Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan
- <sup>161</sup> Department of Physics and Astronomy, Tufts University, Medford MA, United States
- <sup>162</sup> Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
- <sup>163</sup> Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States
- <sup>164</sup> <sup>(a)</sup> INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; <sup>(b)</sup> ICTP, Trieste; <sup>(c)</sup> Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- <sup>165</sup> Department of Physics, University of Illinois, Urbana IL, United States
- <sup>166</sup> Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
- <sup>167</sup> 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
- <sup>168</sup> Department of Physics, University of British Columbia, Vancouver BC, Canada
- <sup>169</sup> Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
- <sup>170</sup> Department of Physics, University of Warwick, Coventry, United Kingdom
- <sup>171</sup> Waseda University, Tokyo, Japan
- <sup>172</sup> Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
- <sup>173</sup> Department of Physics, University of Wisconsin, Madison WI, United States
- <sup>174</sup> Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
- <sup>175</sup> Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
- <sup>176</sup> Department of Physics, Yale University, New Haven CT, United States
- <sup>177</sup> Yerevan Physics Institute, Yerevan, Armenia
- <sup>178</sup> Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

- <sup>a</sup> Also at Department of Physics, King's College London, London, United Kingdom.
- <sup>b</sup> Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
- <sup>c</sup> Also at Novosibirsk State University, Novosibirsk, Russia.
- <sup>d</sup> Also at TRIUMF, Vancouver BC, Canada.
- <sup>e</sup> Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, United States of America.
- <sup>f</sup> Also at Department of Physics, California State University, Fresno CA, United States of America.
- <sup>g</sup> Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
- <sup>h</sup> Also at Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, Portugal.
- <sup>i</sup> Also at Tomsk State University, Tomsk, Russia.
- <sup>j</sup> Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.
- <sup>k</sup> Also at Università di Napoli Parthenope, Napoli, Italy.
- <sup>l</sup> Also at Institute of Particle Physics (IPP), Canada.
- <sup>m</sup> Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.
- <sup>n</sup> Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- <sup>o</sup> Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America.
- <sup>p</sup> Also at Louisiana Tech University, Ruston LA, United States of America.
- <sup>q</sup> Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
- <sup>r</sup> Also at Graduate School of Science, Osaka University, Osaka, Japan.
- <sup>s</sup> Also at Department of Physics, National Tsing Hua University, Taiwan.
- <sup>t</sup> Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America.
- <sup>u</sup> Also at Institute of Theoretical Physics, Iliia State University, Tbilisi, Georgia.
- <sup>v</sup> Also at CERN, Geneva, Switzerland.
- <sup>w</sup> Also at Georgian Technical University (GTU), Tbilisi, Georgia.
- <sup>x</sup> Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.
- <sup>y</sup> Also at Manhattan College, New York NY, United States of America.
- <sup>z</sup> Also at Hellenic Open University, Patras, Greece.
- <sup>aa</sup> Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.
- <sup>ab</sup> Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.
- <sup>ac</sup> Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.
- <sup>ad</sup> Also at School of Physics, Shandong University, Shandong, China.
- <sup>ae</sup> Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
- <sup>af</sup> Also at Section de Physique, Université de Genève, Geneva, Switzerland.
- <sup>ag</sup> Also at International School for Advanced Studies (SISSA), Trieste, Italy.
- <sup>ah</sup> Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America.
- <sup>ai</sup> Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.
- <sup>aj</sup> Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.
- <sup>ak</sup> Also at National Research Nuclear University MEPhI, Moscow, Russia.
- <sup>al</sup> Also at Department of Physics, Stanford University, Stanford CA, United States of America.
- <sup>am</sup> Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.
- <sup>an</sup> Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.
- \* Deceased.