Published for SISSA by Springer

Received: *July 23, 2016*
Accepted: *November 6, 2016*
Published: *November 24, 2016*

Measurement of electroweak production of a W boson and two forward jets in proton-proton collisions at $\sqrt{s} = 8$ TeV



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Abstract: A measurement is presented of the cross section for the electroweak production of a W boson in association with two jets in proton-proton collisions at a center-of-mass energy of 8 TeV. The data set was collected with the CMS detector and corresponds to an integrated luminosity of 19.3 fb^{-1}. The measured fiducial cross section for W bosons decaying to electrons or muons and for $p_{\mathrm{T}}^{\mathrm{j1}} > 60$ GeV, $p_{\mathrm{T}}^{\mathrm{j2}} > 50$ GeV, $|\eta^{\mathrm{j}}| < 4.7$, and $m_{\mathrm{jj}} > 1000$ GeV is $0.42 \pm 0.04\,(\mathrm{stat}) \pm 0.09\,(\mathrm{syst}) \pm 0.01\,(\mathrm{lumi})$ pb. This result is consistent with the standard model leading-order prediction of $0.50 \pm 0.02\,(\mathrm{scale}) \pm 0.02\,(\mathrm{PDF})$ pb obtained with MadGraph5_aMC@NLO 2.1 interfaced to pythia 6.4. This is the first cross section measurement for this process.

Keywords: Electroweak interaction, Hadron-Hadron scattering (experiments)

ArXiv ePrint: 1607.06975

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Article funded by SCOAP^3.

doi:10.1007/JHEP11(2016)147

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1 Introduction

The production of a W or Z boson in association with two jets via the t-channel exchange of an electroweak gauge boson (EW production) plays an important role in testing the gauge sector of the standard model (SM), in particular, aspects of gauge boson self interactions. This process is characterized by the presence of two jets with a large separation in rapidity [1, 2]. Experimental studies of this topology are challenging because of large backgrounds and require a precise understanding of extra quark and gluon emissions computed in quantum chromodynamics (QCD) [3].

Three classes of EW diagrams for $\ell\nu$ production in association with two jets are shown in figure 1: a W boson radiating from a quark line (left), a W boson produced through vector boson fusion (VBF) processes involving a W boson and a Z boson (center), and a multiperipheral diagram with no s-channel W boson (right). These diagrams represent the EW signal in this analysis.

The study of the EW W+2-jets process is part of a more general investigation of the SM VBF process. These EW processes have been used to investigate the rapidity gaps at hadron colliders [1, 2], as a probe of triple-gauge-boson couplings [4, 5], and as a background to Higgs boson measurements in the VBF channel [6–9].

At the LHC, the EW production of a Z boson in association with forward and backward jets has been investigated by the CMS Collaboration at a center-of-mass energy of 7 TeV [3] (8 TeV [10]). The ATLAS Collaboration has published similar results at $\sqrt{s} = 8$ TeV [11].

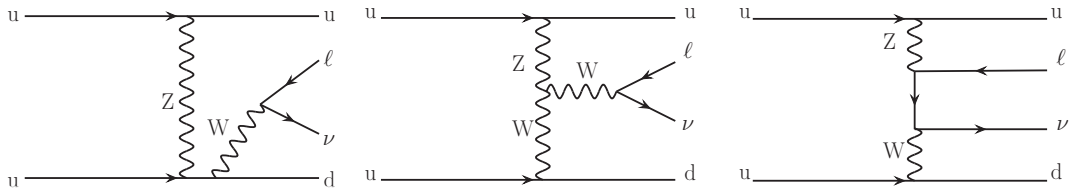


Figure 1. Representative diagrams for EW $\ell\nu$jj productions at the LHC: (left) bremsstrahlung, (center) VBF, and (right) multiperipheral processes.

The EW production of events with a same-sign W boson pair plus two jets was recently studied by the ATLAS Collaboration [12] and the CMS Collaboration [13] at 8 TeV.

This paper presents a measurement of the EW W+2-jets production cross section. The fiducial cross section is calculated for W bosons decaying to electrons or muons and for $p_{\mathrm{T}}^{\mathrm{j1}} > 60\,\mathrm{GeV}$, $p_{\mathrm{T}}^{\mathrm{j2}} > 50\,\mathrm{GeV}$, $|\eta^{\mathrm{j}}| < 4.7$, and $m_{\mathrm{jj}} > 1000\,\mathrm{GeV}$. The interference term between EW W+2-jets and QCD W+2-jets is neglected in the calculation of the fiducial cross section, and is considered as a source of systematic uncertainty. The data set corresponds to an integrated luminosity of 19.2 (19.3) fb^{-1} collected by the CMS experiment in the electron (muon) channel at $\sqrt{s} = 8\,\mathrm{TeV}$.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity [14] coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

The silicon tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$. It consists of 1440 silicon pixel and 15 148 silicon strip detector modules and is located in the 3.8 T field of the superconducting solenoid. For nonisolated particles of $1 < p_{\mathrm{T}} < 10\,\mathrm{GeV}$ and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_{T} and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [15]

The electron momentum is estimated by combining the energy measurement in the ECAL with the momentum measurement in the tracker. The momentum resolution for electrons with transverse momentum $p_{\mathrm{T}} \approx 45\,\mathrm{GeV}$ from $\mathrm{Z} \to \mathrm{ee}$ decays ranges from 1.7% for nonshowering electrons in the barrel region to 4.5% for showering electrons in the endcaps [16]. The electron objects in the transition region between the barrel and endcap ($1.44 < |\eta| < 1.57$) are less precise.

Muons are measured in the range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. Matching muons to tracks measured in the silicon tracker results in a relative p_{T} resolution for muons with $20 < p_{\mathrm{T}} < 100\,\mathrm{GeV}$ of 1.3–2.0% in the barrel and better than 6% in the endcaps. The p_{T} resolution in the barrel is better than 10% for muons with p_{T} up to 1 TeV [17].

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The HCAL, when combined with the ECAL, measures jets with energy resolution amounting typically to 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV. The forward calorimeter modules extend the coverage of hadronic jets to $|\eta| = 5.0$.

The missing transverse momentum vector $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ is defined as the projection on the plane perpendicular to the beams of the negative vector sum of the momenta of all reconstructed particles in an event. Its magnitude is referred to as $E_{\mathrm{T}}^{\mathrm{miss}}$. The CMS detector is nearly hermetic, allowing for precise measurements of $E_{\mathrm{T}}^{\mathrm{miss}}$.

The first level of the CMS trigger system, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select the events of interest in a fixed time interval of less than 4 μs. The high-level trigger processor farm further decreases the event rate from around 100 kHz to less than 1 kHz, before data storage.

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in ref. [14].

3 Simulated samples

Signal and background samples are simulated using standard packages. The Monte Carlo (MC) event generator MadGraph5_aMC@NLO 2.1 [18] is used to simulate the EW W($\to$ eν, $\mu\nu$, $\tau\nu$)+2-jets events. Alternative EW W($\to \ell\nu$) samples for systematic studies, where ℓ = e, μ, as well as QCD induced W+jets, $\mathrm{t\bar{t}}$, and Drell-Yan (DY) background events are simulated using MadGraph5 [19]. Single top quark production is modeled with powheg 1.0 [20–24]. Diboson samples (WW, WZ, ZZ) are generated with pythia 6.4 [25]. All samples are generated using the CTEQ6L1 [26] parton distribution function (PDF) set, except for the powheg single top quark sample, for which the CTEQ6M [26] PDF set is used. The parton showering and matching, hadronization, and underlying event simulation for all samples are performed by pythia 6, with the parameters of the underlying event set to the Z2* tune [27, 28]. The tauola 2.7 generator [29] is used to simulate τ lepton decays. For systematic uncertainty studies the alternative signal sample is also interfaced with herwig++ [30], which has different parton shower and hadronization models than pythia.

The QCD induced W+jets events, which is the main background, are generated with up to four partons using matrix element (ME) calculations. The ME-parton-shower matching scale is taken to be 10 GeV [31], and the factorization and renormalization scales are both dynamically set to $(M_{\mathrm{W}}^2 + p_{\mathrm{T,W}}^2 + \Sigma p_{\mathrm{T,j}}^2)^{1/2}$, where $M_{\mathrm{W}} = 80.4$ GeV is the W boson mass [32] and $\Sigma p_{\mathrm{T,j}}^2$ is the sum over the generated jets. The signal events are generated with the same factorization and renormalization scales.

Alternative $\mathrm{t\bar{t}}$ samples are generated with powheg 1.0 and mc@nlo 3.4 [33, 34]. The $\mathrm{t\bar{t}}$ sample generated with powheg 1.0 is interfaced with pythia 6. The PDF set used for this sample is CT10 [35]. The $\mathrm{t\bar{t}}$ sample generated with mc@nlo 3.4 is interfaced with herwig [36, 37]. The PDF set used for this sample is CTEQ6M.

The cross sections for the signal samples are calculated at leading order (LO) using MadGraph5_aMC@NLO 2.1. The cross sections for the QCD W+jets and DY samples are normalized to the next-to-next-to-leading-order (NNLO) prediction calculated with fewz 3.1 [38]. A data-driven method is used to normalize the QCD W+jets sample as described

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in section 5. The cross section for inclusive $t\bar{t}$ sample is normalized to the next-to-next-to-leading-logarithm prediction from the Top++v2.0 generator [39]. The cross section for the single top quark production process is obtained from Hathor v2.1 [40, 41], which is accurate up to next-to-leading-order (NLO). The cross sections for diboson samples are normalized to the NLO prediction calculated with MCFM 6.6 [42].

A Geant4-based simulation [43] of the CMS detector is used in the production of all simulated samples. Additional proton-proton interactions within a bunch crossing (pileup) are added to the simulation to match those observed in data. During this data-taking period the mean number of interactions per bunch crossing was 21. Simulated events are corrected for efficiency differences relative to data using a tag-and-probe method [44].

4 Event reconstruction and selection

A common event reconstruction algorithm and selection criteria are applied to data and simulated events. The event signature is an isolated lepton (electron or muon), two jets, and $E_{\mathrm{T}}^{\mathrm{miss}}$. Candidate events are collected with single-lepton triggers, which require an isolated electron (muon) with a p_{T} threshold of 27 (24) GeV. The overall trigger efficiency is 90% (94%) for the electron (muon) data, with a small dependence on p_{T} and η.

The analysis relies on a particle-flow (PF) technique [45, 46] that reconstructs various particles in the event (charged and neutral hadrons, electrons, muons, and photons) by optimally combining information from various CMS subdetectors.

Electrons are reconstructed from the combination of the tracker and the corresponding ECAL cluster information, and must pass electron identification requirements according to a multivariate identification technique [16]. Muons are reconstructed by fitting trajectories based on hits in the silicon tracker and in the outer muon system. Lepton candidates are required to originate from the primary vertex of the event, which is chosen to be the vertex with the highest value of $\sum p_{\mathrm{T}}^2$, where the sum is performed over all associated charged particle tracks.

Charged leptons from W boson decays are expected to be isolated from other activity in the event. Leptons are required to fulfill a requirement on their relative isolation, which is defined as the ratio of the p_{T} sum of all other PF candidates reconstructed in a cone $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ (0.4) around the candidate electron (muon) to the p_{T} of the candidate, and is corrected for contributions from pileup. The $\Delta\eta$ and $\Delta\phi$ are the differences in pseudorapidity and in azimuthal angle, respectively. For electrons, the isolation selection is tuned together with the multivariate identification requirement to give an signal efficiency of 80% independent of η. Electrons are required to have a relative isolation smaller than 0.11, 0.18, and 0.15 for $|\eta|$ ranges of 0.00–0.80, 0.80–1.48, and 1.48–2.50. Muons are required to have a relative isolation smaller than 0.12 over the entire $|\eta| < 2.1$ range used in the analysis. The efficiency of the selection requirements for muons originating from W boson decays is approximately 96%. To reduce the contribution from the DY production, the events are required to have no more than one isolated lepton in the final state.

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Jets are reconstructed from PF candidates using the anti-k_{T} clustering algorithm [47, 48] with a distance parameter 0.5. Charged particles not originating from the primary vertex are not considered for jet clustering [49]. Jets from pileup are identified and removed with a pileup jet identification algorithm [50], based on both vertex information and jet shape information. A jet quality requirement, primarily based on the energy ratio between the charged and neutral hadrons within the jet cone [51], is also applied in order to remove jets originating from calorimeter noise. Jets overlapping within $\Delta R = 0.3$ with identified leptons are not considered.

Pileup collisions and the underlying event can contribute to the energy of the reconstructed jets. A correction based on the projected area of a jet on the front face of the calorimeter is used to subtract the extra energy deposited in the jet coming from pileup [49, 52]. Furthermore, jet energy corrections are applied to account for the nonlinear energy response of the calorimeters and for other instrumental effects. These corrections are based on in situ measurements using dijet, γ+jet, and Z+jet data samples [53].

Electrons (muons) are required to have p_{T} greater than 30 (25) GeV and $|\eta| < 2.5$ (2.1). The electrons found in the transition region between the barrel and endcap ($1.44 < |\eta| < 1.57$) are not considered. Events are required to have at least two jets with $p_{\mathrm{T}} > 60\,\mathrm{GeV}$ (leading) and $p_{\mathrm{T}} > 50\,\mathrm{GeV}$ (subleading), both with $|\eta| < 4.7$.

To measure the W boson momentum an accurate $E_{\mathrm{T}}^{\mathrm{miss}}$ measurement is essential. We use $E_{\mathrm{T}}^{\mathrm{miss}}$ measured in the event with the full PF reconstruction [54] and require $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ (25) GeV in the electron (muon) channel to distinguish the W boson signal from multijet backgrounds. The leptonically decaying W boson is reconstructed by combining the kinematic information from the selected lepton with $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$. The unmeasurable p_z component of the neutrino can be estimated by assuming that the lepton and the $E_{\mathrm{T}}^{\mathrm{miss}}$ arise from a W boson with the nominal mass of 80.4 GeV. A quadratic equation for the neutrino p_z component is obtained that can be solved up to a two-fold ambiguity. In the case of two real solutions, the neutrino p_z solution that is closer to the charged lepton p_z is selected. In the case of two imaginary solutions, the common real part of the solutions is selected.

To reduce the background from events that do not contain $\mathrm{W} \to \ell\nu$ decays, we require that the transverse mass of the W boson candidate exceed 30 GeV. The transverse mass of the leptonically decaying W boson is defined as $\sqrt{2p_{\mathrm{T}}^{\ell}E_{\mathrm{T}}^{\mathrm{miss}}[1-\cos(\Delta\phi_{\ell,\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}})]}$, where $\Delta\phi_{\ell,\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}}$ is the azimuthal angle between the lepton and the $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ directions. In order to further improve the signal over background ratio, two additional requirements are used: the Zeppenfeld variable [1], defined as $|y_{\mathrm{W}} - (y_{\mathrm{j1}} + y_{\mathrm{j2}})/2|$, where y represents rapidity, must be less than 1.2; the invariant mass m_{jj} of the jet pair is required to be greater than 1000 GeV.

Table 1 provides a summary of the selection requirements.

5 Background estimation and signal extraction

The EW $\mathrm{W}(\to \tau\nu)$+2-jets events, with the τ leptons decaying to electrons or muons, have signatures similar to those for signal events and they represent 4% (5%) of the signal sample in the electron (muon) channel as estimated from simulation. When calculating the fiducial cross section we require that the W boson decays to e or μ only, so τ events are not included as part of the signal.

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$W \to \ell\nu$ Lepton requirements	Jet requirements
Single lepton trigger	$p_T^{j1} > 60\,\text{GeV}$, $p_T^{j2} > 50\,\text{GeV}$
High-quality lepton ID and isolation	$\lvert y_W - (y_{j1} + y_{j2})/2 \rvert < 1.2$
Electron (muon) $p_T > 30$ (25) GeV	$m_{jj} > 1000\,\text{GeV}$
$E_T^{miss} > 30$ (25) GeV for electron (muon) channels	
W transverse mass $> 30\,\text{GeV}$	
Veto second lepton	

Table 1. Summary of selection criteria.

A boosted decision tree (BDT) technique is used to distinguish between signal and background events and an unbinned maximum-likelihood fit to the m_{jj} distribution is used to extract the number of signal events as described below.

The BDT technique is implemented in the Toolkit for multivariate data analysis (TMVA) [55]. The adaptive boost algorithm (AdaBoost) [56] is used in the BDT training, which gives larger weights for decision trees with lower misclassification errors. For good BDT performance, variables well-modeled by simulation are required. The following input variables are used: lepton η, $\Delta\eta$ between jets, $\Delta\eta$ and $\Delta\phi$ between the W boson and each jet, and the W boson p_T.

The BDT is trained with simulated samples to discriminate the EW W($\to$ eν, $\mu\nu$, $\tau\nu$)+2-jets signal from the QCD W+jets events, which is the main background; selected simulated events with $m_{jj} > 260\,\text{GeV}$ are used. The lower required m_{jj} value provides a larger sample of events that help avoid over-training the BDT. Studies give no indication of a bias as a function of the minimum m_{jj}. On average the EW events have higher BDT values than the background events. The QCD W+jet simulation overestimates the event yield in the data set, and therefore a data-to-MC scaling factor is extracted as follows. The other background contributions are fixed to their simulated yields while the normalization of the QCD W+jets simulated events is scaled so that the total number of events in simulation equals that in the data set for BDT values less than 0.1. The fit is performed for events with $m_{jj} > 1000\,\text{GeV}$. The normalization uncertainties of the other backgrounds are considered as a source of systematic uncertainty. Systematic uncertainties related to the remaining discrepancy between data and simulation and to the contamination from signal in the BDT <0.1 region, especially in the muon channel as shown in figure 2, are discussed in section 6. The resulting W+jets normalization factors are $0.71 \pm 0.02\,(\text{stat}) \pm 0.03\,(\text{syst})$ and $0.70 \pm 0.02\,(\text{stat}) \pm 0.05\,(\text{syst})$ for the electron and muon channels, respectively. These normalization factors are applied in addition to the NNLO K factor of approximately 1.24, mentioned in section 3. The scale factor relative to LO is thus around 0.87, which agrees with the result in [57] and has also been verified with MCFM. Finally, similar numbers are found in another CMS analysis involving the VBF topology [58]. The QCD W+jets normalization scale factors are used later in the fit to the m_{jj} distributions when extracting the number of signal events.

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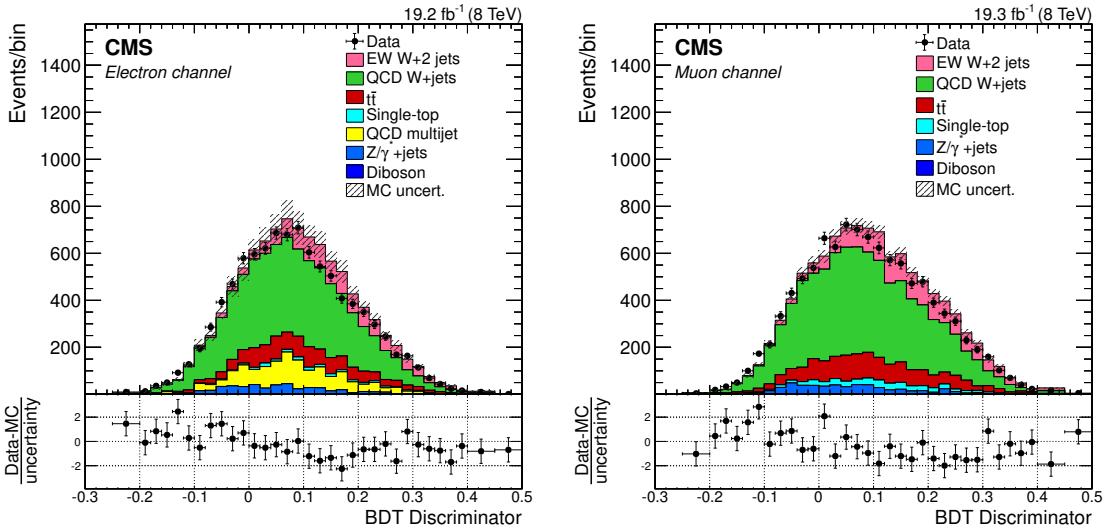


Figure 2. Comparison of the distributions of BDT discriminant output for data and simulation in the electron (left) and muon (right) channels with $m_{\mathrm{jj}} > 1000\,\mathrm{GeV}$. The simulated QCD W+jets sample is multiplied by the normalization scale factors and the simulated signal sample is multiplied by the signal strength.

Figure 2 shows the BDT output distributions for the electron and muon channels, with the simulated QCD W+jets sample multiplied by the normalization scale factors described above and the simulated signal sample multiplied by the signal strength we obtain later in this section. The uncertainty band includes the statistical uncertainty of the simulated samples, the integrated luminosity uncertainty, and a systematic uncertainty in the QCD background due to misidentified electrons (to be discussed below). The distributions of the difference between data and simulation divided by the uncertainty, where the uncertainty is computed at each point by combining the uncertainties in data and in simulation, are also shown in these plots.

The distributions of the leading jet p_{T} and the $\Delta\eta$ between the two jets for data and simulation after the lepton and jet selection requirements are shown in figures 3 and 4, respectively, with the QCD W+jets MC sample multiplied by the normalization scale factors described above.

Taking into account the QCD W+jet background normalization, the extraction of the signal yield is performed using an unbinned maximum-likelihood fit to the m_{jj} distribution in data. The signal strength μ_{signal}, which is defined as the ratio of the extracted signal yield and the expected yield predicted by the LO SM calculation, is the free parameter in the fit.

We employ a parametric function to model the m_{jj} distributions for the signal and each of the background contributions listed in table 2. Only dijet masses greater than 1000 GeV are used in the fit, as indicated by the study in ref. [1]. Based on the simulation we expect the m_{jj} distributions to be well-described by the two parameter power law function

$$\mathcal{F} = \frac{1}{m_{\mathrm{jj}}^{\,a_0 + a_1 \ln\left(m_{\mathrm{jj}}/8000\right)}}, \tag{5.1}$$

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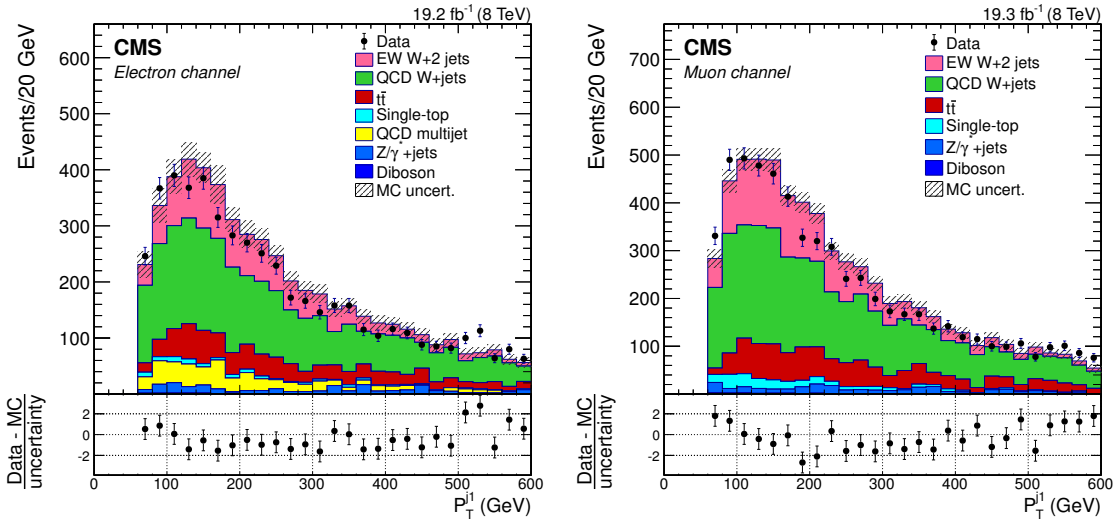


Figure 3. Comparison of the distributions of the leading jet p_{T} between data and simulation for the electron (left) and muon (right) channels with $m_{\mathrm{jj}} > 1000\,\mathrm{GeV}$.

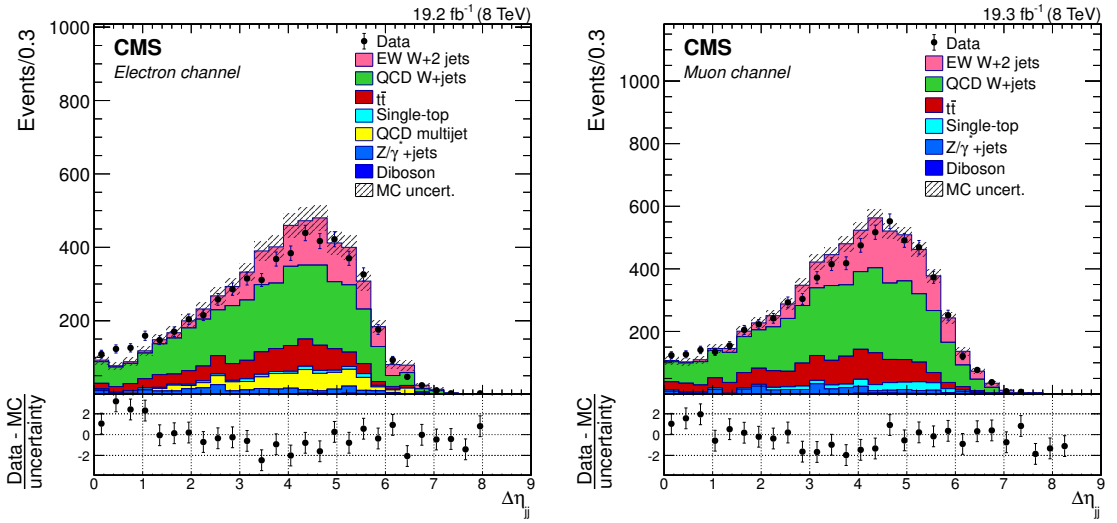


Figure 4. Comparison of the distributions of $\Delta\eta$ between the two leading jets between data and simulation for the electron (left) and muon (right) channels with $m_{\mathrm{jj}} > 1000\,\mathrm{GeV}$.

where a_0 and a_1 are obtained from the simulation and m_{jj} is in GeV. Separate fits are performed to the simulated distribution for the signal and each of the background contributions. This function provides a good description of the signal and background shapes.

The normalization of the EW W($\to$ eν, $\mu\nu$, $\tau\nu$)+2-jets contribution is a free parameter in the fit to the m_{jj} distribution, while the shape parameters are fixed to the MC prediction. The effect of QCD NLO corrections for the EW W($\to \ell\nu$)+2-jets process is tested by modifying the shape parameters in order to reproduce the prediction of VBFNLO 2.6 [59]; the resulting variation in the evaluated signal strength is below 1%.

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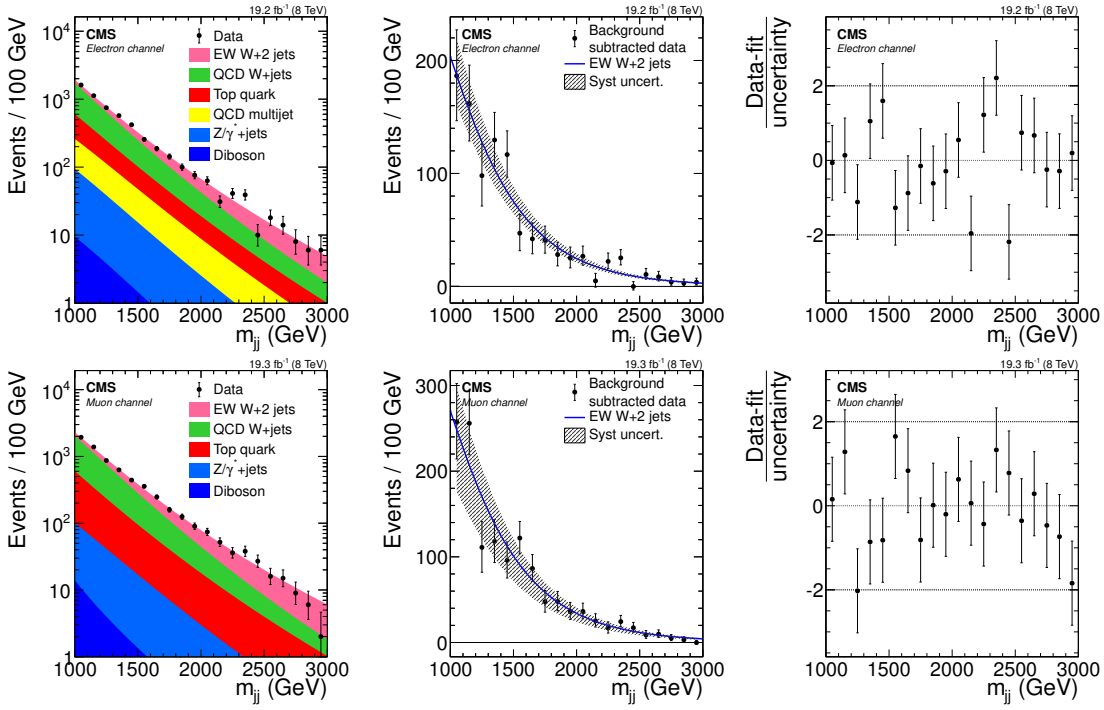


Figure 5. Distribution of the two-jet invariant mass m_{jj} for electron (upper) and muon (lower) channels. Fitted projections of signal and background processes are plotted as shaded regions (left plots). The m_{jj} distributions are shown after subtraction of all components except the EW W+2-jets process (center plots). Finally, the (data − fit)/uncertainty distributions are shown (right plots). Here the error bars represent the statistical uncertainties of the data.

The QCD W+jets background shape parameters are left free during the m_{jj} fit to data because of the poor agreement between data and simulation for this background. The normalization of the QCD W+jets background is fixed to the fit result from the BDT distribution, as described above.

Multijet events can be misidentified as signal because of the nonnegligible probability of jets to be misidentified as electrons. The fraction of fake electrons in the single electron data passing the selection described in section 4 is obtained from an independent two-component fit to the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution following ref. [44]. The normalization and shape parameters are fixed in the fit. We conservatively assume a 50% uncertainty in the QCD multijet yield when fitting the data.

The top quark background is a combination of $\mathrm{t\bar{t}}$ and single top quark processes with the simulated samples normalized according to the known cross sections. The shape parameters are obtained from the simulation and fixed during the fit. The top quark background normalization is assumed to have a Gaussian probability density function with a width of 7% [39].

Other background processes, such as diboson production and DY, are minor and are represented by their components with the corresponding normalization fixed in the fit. The shape parameters are obtained from simulation and are also fixed.

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Process	Electrons		Muons	
Data	5481		6514	
	Pre-fit	Measured ratio	Pre-fit	Measured ratio
W+jets	3913	0.71 (fixed)	5084	0.70 (fixed)
Top quark	933	1.00 ± 0.07	1357	1.00 ± 0.07
QCD multijet	510	fixed to $E_{\mathrm{T}}^{\mathrm{miss}}$ fit in data	—	—
DY+jets	236	1.00 (fixed)	256	1.00 (fixed)
Diboson	26	1.00 (fixed)	29	1.00 (fixed)
Total backgrounds	4488		5179	
Data − backgrounds	993		1335	
EW W+2-jets	1195	0.83 ± 0.08	1541	0.87 ± 0.08

Table 2. The expected event yields and the ratio of the measured and expected yields extracted from the maximum-likelihood fit to data.

Figure 5 (left) shows the observed m_{jj} distributions for the electron and muon channels, together with the fitted projections of the contribution of the signal and background processes described by the two-parameter power law function. The shapes of the different fit components look similar, nonetheless, their slopes are different. Figure 5 (center) shows the m_{jj} distribution after subtracting all SM background contributions. Figure 5 (right) presents the distributions of the difference between the m_{jj} values in data and from the fit, divided by the data uncertainty. The yields of the various SM components, as determined by the fit, are reported in table 2. The resulting signal strengths μ_{signal} are $0.83 \pm 0.08\,(\mathrm{stat})$ and $0.87 \pm 0.08\,(\mathrm{stat})$ for electron and muon channels, respectively. While a simple counting of events in table 2 can determine the number of EW W+2-jets events, the fitting procedure includes the distribution of figure 5 and allows us to use the shape parameters when calculating event yields.

This approach produces an acceptable model of the data (figure 5 left) and allows us to extract the EW W+2-jets signal (figure 5 center). In figure 5 right the mean value of the pull distribution is −0.04 (0.03), consistent with zero in the electron (muon) channel, and the pull variance is 0.90 (0.87), consistent with unity in the electron (muon) channel.

6 Systematic uncertainties

Systematic uncertainties arising from the jet energy scale and resolution are estimated by varying the calibration parameters up and down by one standard deviation in the simulation and evaluating the impact on the cross sections [53].

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A different parametric function is used to model the QCD W+jets shape to estimate the potential influence of the choice of parametric function in the fit result, and it is considered as a source of systematic uncertainty. To estimate the systematic uncertainty from the disagreement between data and simulation in the BDT output distributions, we divide the sideband in BDT (BDT < 0.1) used to estimate the scale factor for the QCD W+jets normalization into two roughly equally populated regions (BDT < 0.02, $0.02 <$ BDT < 0.1). We recompute the scale factor using these two subsamples and propagate the variation in the normalization to the final result. The uncertainty with respect to the QCD W+jets normalization is 4.9% (7.1%) in the electron (muon) channel. The uncertainty propagated to the cross section is 12.9% (16.6%) in the electron (muon) channel. The uncertainty on the normalization is then added in quadrature with the shape uncertainty as shown in table 3.

Background $\mathrm{t\bar{t}}$ samples produced with different generators and parton shower models (MC@NLO + HERWIG and POWHEG + PYTHIA) are used as alternative to the default $\mathrm{t\bar{t}}$ MADGRAPH shapes. We also select a $\mathrm{t\bar{t}}$ enriched phase space to compare the $\mathrm{t\bar{t}}$ sample produced with MADGRAPH with data. Reasonable agreement is found between the MADGRAPH $\mathrm{t\bar{t}}$ sample and data.

The EW W($\to \ell\nu$)+2-jets and QCD W($\to \ell\nu$)+2-jets processes have a positive interference term, which is neglected. In order to estimate the effect of the interference, two additional samples are generated using MADGRAPH:

- QCD W($\to \ell\nu$)+2-jets sample (strong process only),
- EW W($\to \ell\nu$)+2-jets + QCD W($\to \ell\nu$)+2-jets + interference effect sample (mixture of EW and strong processes).

We subtract the QCD and EW processes from the mixture sample to estimate the effect of the interference. The contribution of the interference effect is considered as an additional background with a fixed shape and normalization. The true EW signal strength is ≈12% smaller than the apparent signal strength because the interference is positive.

The fraction of jets faking electrons is varied by ±50% in the electron channel to estimate the uncertainty. A small difference in $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution [54] between data and simulation affects the signal acceptance at the 0.5% level. We also consider systematic uncertainties in the trigger efficiency (1%) and in the lepton reconstruction and selection efficiencies (2%) [44]. The uncertainty in the luminosity measurement is 2.6% [60]. Finally, we calculated the acceptance for the fiducial region with HERWIG++ signal samples, resulting in a 1.7% change in the measured cross section.

The systematic uncertainties are summarized in table 3.

7 Results

The fiducial EW W+2-jets cross section is calculated for W bosons decaying to electrons or muons and for $p_{\mathrm{T}}{}^{\mathrm{j1}} > 60\,\mathrm{GeV}$, $p_{\mathrm{T}}{}^{\mathrm{j2}} > 50\,\mathrm{GeV}$, $|\eta^{\mathrm{j}}| < 4.7$, and $m_{\mathrm{jj}} > 1000\,\mathrm{GeV}$. Here we include neutrinos in our definition of generator jets, which are reconstructed in the same manner as the PF jets mentioned above, but now at generator level.

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Source of uncertainty	Electrons	Muons
Integrated luminosity	2.6%	
Jet energy scale	5.4%	7.3%
Jet energy resolution	2.2%	3.7%
QCD W+jets shape and normalization	13.0%	16.7%
Top quark background shape and normalization	5.5%	6.0%
Interference effect	14.4%	13.8%
Jets faking electrons fraction (electron channel)	4.4%	—
Lepton trigger efficiency	0.9%	1.0%
Lepton selection efficiency	1.8%	2.0%
Pileup	<1%	<1%
Fiducial acceptance	1.7%	1.7%
Total (without integrated luminosity)	21.6%	24.1%

Table 3. Sources of systematic uncertainties and the magnitude of their effect on the fiducial cross section.

The fiducial cross section is computed as

$$\sigma_{\text{fiducial}} = \sigma_{\text{generator}} \mu_{\text{signal}} \epsilon_{\text{acceptance}}, \tag{7.1}$$

where $\sigma_{\text{generator}}$ is the generator level cross section, μ_{signal} is the signal strength, and $\epsilon_{\text{acceptance}}$ is the acceptance evaluated with the EW W($\to e\nu, \mu\nu, \tau\nu$)+2-jets sample.

To calculate $\epsilon_{\text{acceptance}}$, we divide the number of events in the fiducial region by the total number of generated events which results in an value of 0.0448. The uncertainty due to the limited size of the simulated sample is 0.7%. The fiducial selections are different from the selections used for the measurement (as summarized in table 1), for which the acceptance is 0.0128. The uncertainty due to the limited size of the simulated sample is 1.3%.

We use the best linear unbiased estimate method [61, 62] to combine the results in the electron and muon channels, assuming that the statistical uncertainties are uncorrelated and the systematic uncertainties are 100% correlated between the two channels. Because in this case the (fully correlated) systematic uncertainties are much larger than the statistical uncertainties, the method yields a statistical uncertainty for the combined result that is not much smaller than the statistical uncertainties for the individual channels. The results are summarized in table 4, and are in agreement with the SM LO prediction of $0.50 \pm 0.02\,(\text{scale}) \pm 0.02\,(\text{PDF})$ pb obtained from MadGraph5_aMC@NLO 2.1 interfaced to pythia 6.4. The statistical significance of the observation is approximately four standard deviations.

8 Summary

A measurement has been performed of the cross section for the electroweak production of W bosons produced in association with two forward jets in proton-proton collisions.

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Channel	Measured cross section
Electron	$0.41 \pm 0.04\,(\text{stat}) \pm 0.09\,(\text{syst}) \pm 0.01\,(\text{lumi})\,\text{pb}$
Muon	$0.43 \pm 0.04\,(\text{stat}) \pm 0.10\,(\text{syst}) \pm 0.01\,(\text{lumi})\,\text{pb}$
Combined	$0.42 \pm 0.04\,(\text{stat}) \pm 0.09\,(\text{syst}) \pm 0.01\,(\text{lumi})\,\text{pb}$

Table 4. The measured values for the EW W($\to \ell\nu$)+2-jets fiducial cross section.

The W bosons were identified through their decay to electrons and muons. The data set was collected by the CMS experiment and corresponds to an integrated luminosity of $19.2\,(19.3) \pm 0.5\,\text{fb}^{-1}$ in the electron (muon) channel at $\sqrt{s} = 8\,\text{TeV}$. The measured value of the fiducial electroweak W+2-jets cross section, for W bosons decaying to electrons or muons and for $p_{\text{T}}^{\text{j1}} > 60\,\text{GeV}$, $p_{\text{T}}^{\text{j2}} > 50\,\text{GeV}$, $|\eta^{\text{j}}| < 4.7$, and $m_{\text{jj}} > 1000\,\text{GeV}$, is $0.42 \pm 0.04\,(\text{stat}) \pm 0.09\,(\text{syst}) \pm 0.01\,(\text{lumi})\,\text{pb}$, consistent with the SM LO prediction of $0.50 \pm 0.02\,(\text{scale}) \pm 0.02\,(\text{PDF})\,\text{pb}$ obtained via MadGraph5_aMC@nlo 2.1 interfaced with pythia 6.4. This is the first measurement of the cross section for electroweak W+2-jets production.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS and RFBR (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (U.S.A.).

Individuals have received support from the Marie-Curie program and the European Research Council and EPLANET (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Sci-

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ence Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2013/11/B/ST2/04202, 2014/13/B/ST2/02543 and 2014/15/B/ST2/03998, Sonata-bis 2012/07/E/ST2/01406; the Thalis and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the National Priorities Research Program by Qatar National Research Fund; the Programa Clarín-COFUND del Principado de Asturias; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); and the Welch Foundation, contract C-1845.

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9: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France
10: Also at Joint Institute for Nuclear Research, Dubna, Russia
11: Also at Helwan University, Cairo, Egypt
12: Now at Zewail City of Science and Technology, Zewail, Egypt
13: Also at British University in Egypt, Cairo, Egypt
14: Now at Ain Shams University, Cairo, Egypt
15: Also at Université de Haute Alsace, Mulhouse, France
16: Also at Tbilisi State University, Tbilisi, Georgia
17: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
18: Also at University of Hamburg, Hamburg, Germany
19: Also at Brandenburg University of Technology, Cottbus, Germany
20: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
21: Also at Eötvös Loránd University, Budapest, Hungary
22: Also at University of Debrecen, Debrecen, Hungary
23: Also at Wigner Research Centre for Physics, Budapest, Hungary
24: Also at Indian Institute of Science Education and Research, Bhopal, India
25: Also at University of Visva-Bharati, Santiniketan, India
26: Now at King Abdulaziz University, Jeddah, Saudi Arabia
27: Also at University of Ruhuna, Matara, Sri Lanka
28: Also at Isfahan University of Technology, Isfahan, Iran
29: Also at University of Tehran, Department of Engineering Science, Tehran, Iran

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30: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
31: Also at Università degli Studi di Siena, Siena, Italy
32: Also at Purdue University, West Lafayette, U.S.A.
33: Now at Hanyang University, Seoul, Korea
34: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
35: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
36: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
37: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
38: Also at Institute for Nuclear Research, Moscow, Russia
39: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
40: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
41: Also at California Institute of Technology, Pasadena, U.S.A.
42: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
43: Also at INFN Sezione di Roma; Università di Roma, Roma, Italy
44: Also at National Technical University of Athens, Athens, Greece
45: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
46: Also at National and Kapodistrian University of Athens, Athens, Greece
47: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
48: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
49: Also at Adiyaman University, Adiyaman, Turkey
50: Also at Mersin University, Mersin, Turkey
51: Also at Cag University, Mersin, Turkey
52: Also at Piri Reis University, Istanbul, Turkey
53: Also at Gaziosmanpasa University, Tokat, Turkey
54: Also at Ozyegin University, Istanbul, Turkey
55: Also at Izmir Institute of Technology, Izmir, Turkey
56: Also at Marmara University, Istanbul, Turkey
57: Also at Kafkas University, Kars, Turkey
58: Also at Istanbul Bilgi University, Istanbul, Turkey
59: Also at Yildiz Technical University, Istanbul, Turkey
60: Also at Hacettepe University, Ankara, Turkey
61: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
62: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
63: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
64: Also at Utah Valley University, Orem, U.S.A.
65: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
66: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
67: Also at Argonne National Laboratory, Argonne, U.S.A.
68: Also at Erzincan University, Erzincan, Turkey
69: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
70: Also at Texas A&M University at Qatar, Doha, Qatar
71: Also at Kyungpook National University, Daegu, Korea

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