Physics Letters B 770 (2017) 278–301

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Search for heavy gauge W′ bosons in events with an energetic lepton and large missing transverse momentum at $\sqrt{s} = 13$ TeV

The CMS Collaboration *

CERN, Switzerland

ARTICLE INFO

Article history:
Received 29 December 2016
Received in revised form 26 March 2017
Accepted 20 April 2017
Available online 25 April 2017
Editor: M. Doser

Keywords:
CMS
Physics
Exo
BSM searches
W′

ABSTRACT

A search is presented for W′ bosons in events with an electron or muon and large missing transverse momentum, using proton–proton collision data at $\sqrt{s} = 13$ TeV collected with the CMS detector in 2015 and corresponding to an integrated luminosity of 2.3 fb^{-1}. No evidence of an excess of events relative to the standard model expectations is observed. For a W′ boson described by the sequential standard model, upper limits at 95% confidence level are set on the product of the production cross section and branching fraction and lower limits are established on the new boson mass. Masses below 4.1 TeV are excluded combining electron and muon decay channels, significantly improving upon the results obtained with the 8 TeV data. Exclusion limits at 95% confidence level on the product of the W′ production cross section and branching fraction are also derived in combination with the 8 TeV data. Finally, exclusion limits are set for the production of generic W′ bosons decaying into this final state using a model-independent approach.

© 2017 The Author. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/). Funded by SCOAP[3].

1. Introduction

Many standard model (SM) extensions require additional heavy gauge bosons. In particular, the sequential standard model (SSM) [1] predicts the existence of a new massive boson, W′, exhibiting the same couplings as the SM W boson, i.e., with final states consisting either of a charged lepton and neutrino or a quark pair. If sufficiently massive, the decay channel $W' \to t\bar{b}$ is also allowed.

This Letter describes a search for deviations from the SM predictions in events with a charged lepton (electron or muon) and missing transverse momentum in the final state, proceeding as shown in Fig. 1. It is assumed that there is no interference between the production of the new particle and the production of the SM W boson. This would be the case, for example, if the W′ interacts via V + A coupling. Its decays to SM bosons (W, Z, H), which are model dependent, are neglected. Dedicated searches for W′ decays into bosons can be found in Refs. [2–4].

Similar searches have been carried out by experiments at the FNAL Tevatron [5,6]. The most stringent limits on the mass of an SSM W′ boson to date come from the CERN LHC experiments. Using an integrated luminosity of 19.7 fb^{-1} of proton–proton (pp) collisions at a center-of-mass energy of 8 TeV, CMS set a lower limit at 95% confidence level (CL) on the W′ boson mass of 3.22 TeV in the electron channel and 2.99 TeV in the muon channel [7]. Combining both channels resulted in an exclusion of W′ bosons with a mass less than 3.28 TeV. Similarly, for the combined channels at $\sqrt{s} = 8$ TeV, ATLAS excluded W′ bosons with masses less than 3.24 TeV [8].

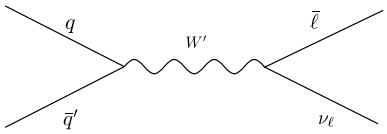

Fig. 1. Production and decay of an SSM W′ boson. The final state shown denotes both the $(\bar{\ell}\nu_\ell)$ state and its charge conjugate.

Because of the increase in the center-of-mass energy from 8 to 13 TeV, the parton luminosities associated with $q\bar{q}'$ interactions producing the W′ bosons increase by more than an order of magnitude in the high-mass region. Limits derived by ATLAS [9] using 3.2 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV exclude SSM W′ bosons with masses less than 4.07 TeV, for the combination of the electron and muon decay channels.

The results presented in this Letter are based on the analysis of 2.3 fb^{-1} of pp collision data collected with the CMS detector during 2015, at $\sqrt{s} = 13$ TeV. Limits are given both for the SSM interpretation, and for a generic W′, enabling constraints to be placed on a variety of other models.

* *E-mail address:* cms-publication-committee-chair@cern.ch.

http://dx.doi.org/10.1016/j.physletb.2017.04.043
0370-2693/© 2017 The Author. Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/). Funded by SCOAP[3].

2. The CMS detector

A detailed description of the CMS detector and the coordinate system used can be found in Ref. [10]. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are located the silicon pixel and strip tracker, measuring charged-particle trajectories in the pseudorapidity region $|\eta| < 2.5$, and the barrel and two endcap sections of the calorimeters ($|\eta| < 3$): a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL). Forward calorimeters extend the η coverage provided by the barrel and endcap detectors ($3 < |\eta| < 5$). Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid, in the range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. Additional detectors and upgraded electronics, installed before the beginning of the 13 TeV data collection period in 2015, have yielded improved reconstruction performance for muons relative to the 8 TeV data collection period in 2012.

The CMS experiment has a two-level trigger system. The level-1 (L1) trigger [11], composed of custom hardware processors, selects events of interest using information from the calorimeters and muon detectors and reduces the readout rate from the 40 MHz bunch-crossing frequency to a maximum of 100 kHz. The software based high-level trigger (HLT) [12] uses the full event information, including that from the inner tracker, to reduce the event rate to the 1 kHz that is recorded.

3. Analysis strategy and simulated samples

The analysis selects events with a high-energy charged lepton and large missing transverse momentum ($\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$), which may indicate the presence of a non-interacting particle (neutrino). The quantity $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ is defined as $-\sum \vec{p}_{\mathrm{T}}$ of all reconstructed particles with $E_{\mathrm{T}}^{\mathrm{miss}}$ being the magnitude of $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$.

The main discriminating variable used in the search is the transverse mass defined as $M_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}^{\ell}E_{\mathrm{T}}^{\mathrm{miss}}(1-\cos[\Delta\phi(\vec{p}_{\mathrm{T}}^{\,\ell}, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}})])}$, where $\vec{p}_{\mathrm{T}}^{\,\ell}$ is the lepton transverse momentum, p_{T}^{ℓ} is its magnitude, and $\Delta\phi(\vec{p}_{\mathrm{T}}^{\,\ell}, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}})$ is the difference in azimuthal angle between the lepton transverse momentum and missing transverse momentum vectors. A signal from very massive W′ bosons would appear at high M_{T} values.

The dominant and irreducible background is $\mathrm{W} \to \ell\nu$ with $\ell = \mathrm{e}, \mu, \tau$. The $\mathrm{W} \to \tau\nu$ process mostly contributes to the region of lower M_{T} values relative to decays into the other lepton channels, because of the momenta carried away by the two neutrinos from the tau decay. Possible interference between the production of W′ and SM W bosons is not considered. The existance of interference effects would change the total cross section and the shape of the M_{T} spectrum [7]. Other background processes are Drell–Yan (where one of the leptons is not reconstructed), $\mathrm{t\bar{t}}$ (semileptonic and dileptonic decay channels), single top quark, and dibosons (mainly WW production). The contributions from these processes are estimated from simulation.

To estimate the dominant SM W boson background, different $\mathrm{W} \to \ell\nu$ samples are used: an inclusive one generated at next-to-leading order (NLO) with MadGraph 5_aMC@NLO [13] describing the events with a W boson mass up to 200 GeV, and several exclusive samples, covering the boson high-mass region (from 200 GeV onwards), generated at leading order (LO) with pythia 8.2 [14], tune CUETP8M1 [15,16], and NNPDF3.0 parton distribution functions (PDF) [17]. A mass-dependent K factor, to account for higher order effects, is calculated using fewz 3.1 [18] at next-to-next-to-leading order (NNLO) QCD precision and mcsanc 1.01 [19] at NLO electroweak precision. The application of the K factor improves the description of the tail of the M_{T} distribution, the key element in this search.

High mass Drell–Yan and $\mathrm{t\bar{t}}$ samples are generated with powheg(v2) [20–24], an event generator at NLO, with parton showering and hadronization described by pythia 8.2, using the CUETP8M1 tune and NNPDF3.0 PDF set. The $\mathrm{t\bar{t}}$ category includes both semileptonic and dileptonic decay modes samples. Single top quark production is generated inclusively with powheg(v2) in the tW-channel and with MadGraph5_aMC@NLO matched to pythia8.2 using the FXFX algorithm [25], in the s- and t-channels. Diboson (WW, WZ, and ZZ) production is generated with pythia 8.2, tune CUETP8M1, and the NNPDF2.3LO PDF set [26].

Background from jets misidentified as electrons (referred to as QCD multijet background in what follows) is largely rejected by the analysis selection criteria described in the next section, and the residual contribution is estimated from data by using a control region defined by the electron isolation and the ratio $p_{\mathrm{T}}^{\ell}/E_{\mathrm{T}}^{\mathrm{miss}}$. This method of estimating the QCD multijet contribution was already used in our previous analysis [7] and is based on four regions (isolated and non-isolated signal and background events) to estimate the normalization and provide the template data. The probability to misidentify jets as muons is negligible.

For the signal events, the generation of SSM $\mathrm{W}' \to \ell\nu$ samples for the electron and muon decay channels is performed with pythia 8.2 at LO, tune CUETP8M1, and the NNPDF3.0 PDF set. A W′ mass-dependent K factor is applied based on NNLO QCD cross sections as calculated with fewz 3.1. The K factor varies from 1.3 to 1.1 for the range of W′ masses studied in this analysis, namely from 0.4 to 5.8 TeV. The NNLO corrections decrease with W′ boson masses up to around 4.5 TeV. For higher W′ masses, the phase space for production in pp collisions at 13 TeV decreases, leading to a growing fraction of new bosons produced off mass-shell, towards lower masses. In those cases, the K factor increases and becomes similar to the low-mass values. The product of the NNLO signal production cross section and branching fraction, $\sigma_{\mathrm{W}'}\mathcal{B}(\mathrm{W}' \to \ell\nu)$, with $\ell = \mathrm{e}$ or μ, strongly depends on the W′ mass, varying from 111 pb for $M(\mathrm{W}') = 0.4$ TeV to 0.151 fb for $M(\mathrm{W}') = 5.8$ TeV. For the benchmark masses of $M(\mathrm{W}') = 2.4$ and 3.6 TeV, used later for illustration, the values are 59.8 and 4.4 fb, respectively. The width of the SSM W′ is a function of its mass.

All generated signal and background events are processed through a full simulation of the CMS detector based on Geant4 [27], and including an emulation of the trigger. The simulated events are reconstructed with the same code used to reconstruct the data.

The simulation of particle production from additional collisions in the same or nearby bunch crossing (pileup) is included in all event samples by superimposing minimum bias interactions onto the simulated events, with a frequency distribution matching that observed in data. The average number of interactions per bunch crossing in the selected data is 10.

4. Object identification and event selection

Events with at least one high-p_{T} lepton are selected using inclusive lepton triggers. Single-electron triggers with transverse energy thresholds of 105 or 115 GeV and loose electron identification criteria are used. The single-muon triggers require $p_{\mathrm{T}} > 45$ GeV for a muon pseudorapidity, $|\eta| < 2.1$, or $p_{\mathrm{T}} > 50$ GeV for $|\eta| < 2.4$ (the limit of coverage of the muon detectors). The relatively high electron trigger threshold is required in order to suppress non-prompt

electrons and misidentified jets. The offline reconstructed p_T must be greater than 130 (53) GeV in the electron (muon) channel, where the trigger efficiency reaches a plateau of 0.99 (0.96) relative to the full analysis requirements described in the following.

Leptons and $\vec{p}_T^{\,miss}$ are reconstructed using a particle-flow technique [28,29], an algorithm that combines measurements from all components of the CMS detector in order to reconstruct and identify individual particles in the event. Requirements for identifying good quality and energetic leptons are applied, optimized for high-p_T values where the analysis has the largest sensitivity to the expected signals. Events containing calorimeter noise or large E_T^{miss} due to instrumental effects, such as beam halo or jets near nonfunctioning channels in the calorimeters [30], are not used. The primary vertex in the event is defined as the vertex with the highest $\sum p_T^2$, where the sum is over the tracks associated to it.

Electrons are reconstructed from electromagnetic energy deposits (clusters) in the ECAL acceptance region (barrel, $|\eta| < 1.444$, endcaps, $1.566 < |\eta| < 2.5$) matched to a track in the silicon tracker [31]. The transverse energy of a localized cluster is defined as $E_T = E \sin\theta$, with θ the polar angle relative to the beam axis, and where the cluster energy E includes any deposits consistent with bremsstrahlung emission. The electron identification, optimized for high-p_T values [32,33], includes requirements on the isolation and on the variables describing the electromagnetic shower shape. The electron isolation is computed using the sum of three terms, based on tracker, ECAL, and HCAL information, after correction for the contributions expected from detector noise and pileup. The electron isolation in the tracker is ensured by requiring the scalar p_T sum of all tracks, within a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ centered around the track of the electron candidate and originating from the primary vertex, to be less than 5 GeV. The ECAL isolation is defined as the E_T sum of the energy deposits within a cone of $\Delta R = 0.3$ around the electron candidate to be less than 3% of the electron E_T. The HCAL isolation considers the sum of energy deposits in the hadronic calorimeter within a cone of $\Delta R = 0.15$ around the electron direction which must be less than 5% of the electron energy deposit in the ECAL. In each case the sums exclude the electron candidate itself. In order to differentiate between electrons and photon conversions, the electron track is required to have no more than one hit missing in the pixel layers, and the transverse distance to the primary vertex must be less than 0.02 (0.05) cm in the barrel (endcap). The electron momenta for electrons with $p_T \approx 45$ GeV from $Z \to ee$ decays are estimated by combining energy measurements in the ECAL with momentum measurements in the tracker. For high-energy electrons the momentum scale and resolution are dominated entirely by the energy measurement in the ECAL. The discriminating variable in this search, M_T, is more sensitive to variations of energy scale than to uncertainty in energy resolution. The energy scale has therefore been checked using high-mass offshell dielectron events coming from Z-boson decays.

Muons are reconstructed by combining the information from the tracker and the muon systems [34,35]. Each muon is required to have at least one hit in the pixel detector, hits in at least four layers of the strip tracker, and segments in two or more muon detector chambers. Since consecutive layers in the muon system are separated by thick layers of steel, the latter requirement significantly reduces the amount of hadronic *punch-through*. To reduce background from cosmic ray muons, each muon is required to have a transverse impact parameter less than 0.02 cm and a longitudinal distance parameter less than 0.5 cm. Both parameters are defined relative to the primary vertex. In order to suppress muons with mismeasured p_T, an additional requirement $\sigma_{p_T}/p_T < 0.3$ is applied, where σ_{p_T} is the uncertainty in the p_T from the track reconstruction. Muon isolation requires that the scalar p_T sum of all tracks originating from the interaction vertex within a cone of $\Delta R = 0.3$ around its direction, excluding the muon track, be less than 10% of the muon p_T. The muon p_T reconstruction is optimized for the high-p_T region and its performance has been studied using both high-energy cosmic ray muons and dimuons from high-p_T Z boson decays [33]. The relative p_T resolution for muons with $p_T < 200$ GeV is 1.3–2.0% in the barrel and better than 6% in the endcaps. For high-p_T muons (p_T up to 1 TeV) the relative resolution in the barrel is better than 10%.

To reduce the Drell–Yan background in each decay channel, events with additional electrons (muons) of $p_T > 35$ (25) GeV and in $|\eta| < 2.5(2.4)$ are rejected.

Once events containing a high-p_T lepton are selected, the two-body decay kinematics of the $W' \to \ell\nu$ process is exploited to further reduce the background, by applying two additional requirements, $|\Delta\phi(\vec{p}_T^{\,\ell}, \vec{p}_T^{\,miss})| > 2.5$ and $0.4 < p_T^{\ell}/E_T^{miss} < 1.5$.

The signal efficiency for the selection procedure, with no requirement on the reconstructed M_T in the event, is determined from simulated samples and is maximal ($\approx$0.80 for both decay channels) for a W′ boson of mass 1.5 TeV and decreases gradually for larger and smaller masses down to ≈ 0.65.

5. Systematic uncertainties

The sources of systematic uncertainties of experimental nature can be divided into those that are channel-specific and those that are common to the electron and muon channels. For each source of uncertainty, upper and lower values are propagated to the kinematic quantities of the different objects (e, μ, and E_T^{miss}) in each event, the selection re-applied, and new M_T values obtained, which are considered in the statistical analysis of the data, as presented in the next section.

Mismeasurements of the electron energy scale and resolution are typically small and do not change the M_T shape significantly. The systematic uncertainty in the electron energy scale was taken to be 2% [33]. For the electron energy resolution, an additional Gaussian smearing of 2% is applied to the one from MC simulation, to match the measurements performed on data using dielectron events from Z boson decays. The uncertainty in the electron identification efficiency when extrapolated to high E_T is 4% (6%) in the barrel (endcaps). Scale factors are applied to the simulation samples to account for possible differences between data and simulation for trigger efficiency. They are determined with an uncertainty of 0.2% (0.5%) for barrel (endcaps), and are consistent with unity for the electrons.

In the muon decay channel, the p_T scale is sensitive to an imperfect modeling of the alignment in the tracker or muon systems. Studies are performed on the curvature of muon tracks in different regions of η and ϕ using high-p_T cosmic ray data and dimuon events from collisions, together with the corresponding simulation samples. They indicate the absence of a significant curvature bias. The uncertainties associated with these results are taken as contributions to the overall systematic uncertainties. For the central region ($|\eta| < 1.2$) the bias uncertainty is 0.03/TeV and in the forward region ($1.2 < |\eta| < 2.4$) the bias uncertainty is 0.04/TeV. These uncertainties are propagated to the muon p_T assignment and consequently, to the M_T distribution. The p_T resolution at high-p_T values in data is well reproduced by the simulation and no further correction is applied. Muon trigger and identification efficiencies measured in data are consistent with those from simulated samples within the precision of the efficiency measurement allowed by the amount of data collected at high p_T. Uncertainties on the extrapolation to high p_T values are assigned, which increase from 3% for $p_T < 500$ GeV to 8.5% for $p_T > 1$ TeV.

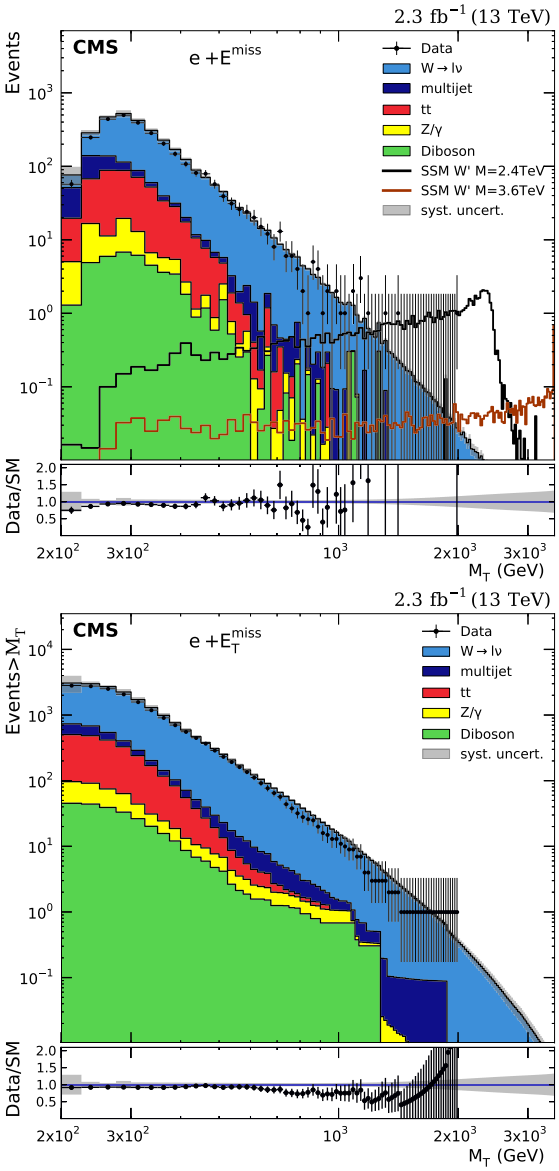

Fig. 2. Distributions for data and expected SM backgrounds in the electron channel: transverse mass M_T (upper) and the associated integral distribution (total number of events above a given value of M_T) (lower). The expected signals from the decays of W′ bosons with masses $M(W') = 2.4$ and 3.6 TeV are also shown in the upper figure. The lower panels show the ratio of data to SM predictions, where the band centered around unity indicates the systematic uncertainty in the expected background, excluding the 2.7% uncertainty in the luminosity.

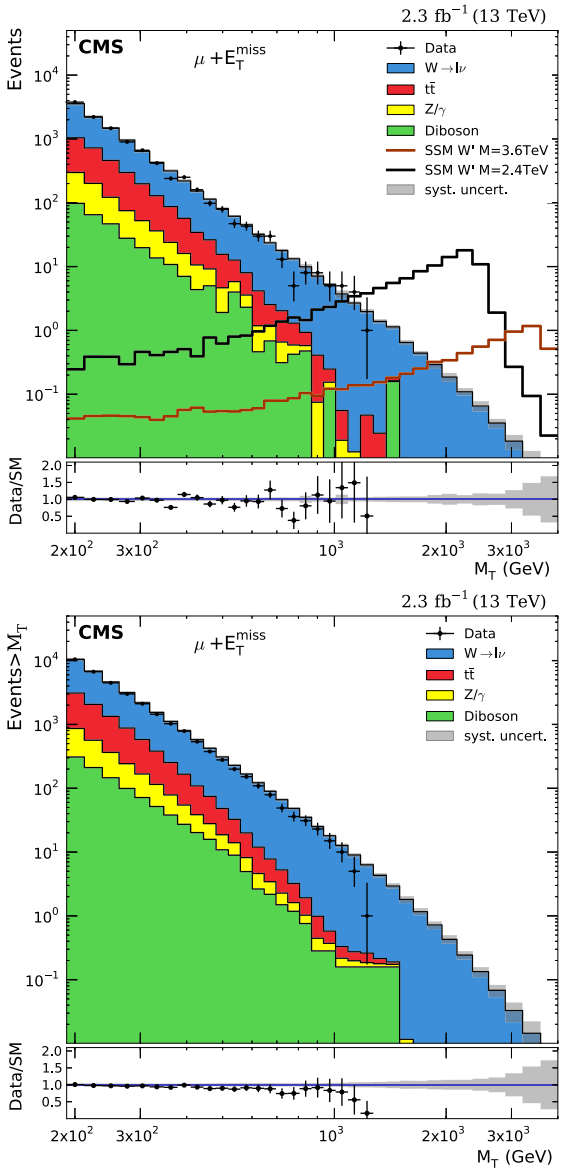

Fig. 3. Distributions for data and expected SM backgrounds in the muon channel: transverse mass M_T (upper) and the associated integral distribution (total number of events above a given value of M_T) (lower). The expected signals from the decays of W′ bosons with masses $M(W') = 2.4$ and 3.6 TeV are also shown in the upper figure. The lower panels show the ratio of data to SM predictions, where the band centered around unity indicates the systematic uncertainty in the expected background, excluding the 2.7% uncertainty in the luminosity.

The sources of uncertainty in the lepton p_T translate directly into the E_T^{miss} calculation, which in the sample of events selected is mainly determined by the high p_T of the lepton. As events are allowed to include an arbitrary number of jets, which may originate from initial state radiation, systematic uncertainties in the jet energy scale and resolution are propagated to the E_T^{miss} variable.

Common to both the electron and muon channels are the uncertainties on the total integrated luminosity (2.7%) [36] and in the reweighting procedure applied to simulated samples to match the pileup in data (5%). The application of K factors accounting for higher-order corrections, both for the signals and the background, is also affected by systematic uncertainties. The uncertainty in the signal K factor arises from the choice of PDF and α_S. The combined uncertainty is evaluated using the PDF4LHC prescription [37], where in the computation of each PDF set the strong coupling constant is varied. Uncertainties from different PDF sets and α_S variation are added in quadrature. For the background K factor, a uniform uncertainty of 5%, stemming from the NNLO corrections, is applied in addition to a mass-dependent uncertainty. The latter is determined by comparing the results from the two possible procedures for combining the QCD and electroweak corrections: additive or factorized methods [7]. The theoretical uncertainty related to the choice of the PDF set in the background modeling is estimated using the PDF4LHC prescription and dominates the total uncertainty at high M_T in both decay channels.

6. Results

Fig. 2 shows the distribution of transverse mass M_T (upper) and the associated integral distribution (total number of events above a given value of M_T) (lower) for the electron decay channel for

Table 1
Numbers of events in the electron decay channel integrated above M_T thresholds of 500, 1000, and 1500 GeV, for data, SM background, and signals with $M(W') = 2.4$ and 3.6 TeV. The uncertainties include systematic and statistical uncertainties, but do not include the 2.7% uncertainty in the integrated luminosity.

	$M_T > 500$ GeV	$M_T > 1000$ GeV	$M_T > 1500$ GeV
Data	230	11	1
SM background	246 ± 18	14.3 ± 1.2	1.9 ± 0.2
SSM $M(W') = 2.4$ TeV	66.1 ± 5.5	58.4 ± 5.2	46.3 ± 4.4
SSM $M(W') = 3.6$ TeV	5.5 ± 0.7	4.9 ± 0.7	4.3 ± 0.6

Table 2
Numbers of events in the muon decay channel integrated above M_T thresholds of 500, 1000, and 1500 GeV, for data, SM background, and signals with $M(W') = 2.4$ and 3.6 TeV. The uncertainties include statistical and systematic uncertainties, but do not include the 2.7% uncertainty in the integrated luminosity.

	$M_T > 500$ GeV	$M_T > 1000$ GeV	$M_T > 1500$ GeV
Data	229	11	0
SM background	255 ± 20	12.8 ± 1.2	1.8 ± 0.2
SSM $M(W') = 2.4$ TeV	95.1 ± 5.2	83.2 ± 5.0	64.1 ± 6.0
SSM $M(W') = 3.6$ TeV	6.4 ± 0.5	5.7 ± 0.5	5.0 ± 0.5

$M_T > 200$ GeV. The corresponding distributions are presented for the muon channel in Fig. 3 for $M_T > 120$ GeV, where the lower trigger p_T threshold enables the extension of the distribution to lower transverse masses. The increasing bin size at high M_T values in the muon distribution reflects the degrading muon p_T resolution. The highest M_T value observed in the electron (muon) channel is 2.0 (1.2) TeV. The expected signals from the decay of W′ bosons with masses $M(W') = 2.4$ and 3.6 TeV are also shown. The lower panels in the M_T distributions present the data-to-prediction ratios and indicate reasonable agreement between data and SM expectations.

Tables 1 and 2 summarize the number of events expected from SM processes, compared to data, when integrating above three representative M_T thresholds (500, 1000, and 1500 GeV) for the electron and muon decay channels, respectively. Also shown are the number of expected signal events for W′ signals with mass $M(W') = 2.4$ and 3.6 TeV.

6.1. Exclusion limits on SSM W′ bosons

Upper limits on the product $\sigma_{W'}\mathcal{B}(W' \to \ell\nu)$, with $\ell = e$ or μ, are determined using a Bayesian approach with a uniform prior probability distribution for the signal cross section in the context of SSM W′ boson production [38]. A shape analysis (binned likelihood) is performed where the likelihood function is based on probability density functions described by the M_T distributions for the expected background processes, signals, and data. Systematic uncertainties discussed in Section 5 in the expected signal and background yields are included through nuisance parameters with log-normal prior distributions.

Expected and observed 95% CL limits as a function of W′ mass are shown in Fig. 4 in the electron (upper) and muon (lower) channels, for $M(W') > 400$ GeV. The SSM W′ NNLO cross section as a function of the W′ mass is also displayed, together with the uncertainty associated with the choice of PDF and α_S, which is shown as a shaded band. With the present data sample, SSM W′ resonances of masses less than 3.6 TeV (3.6 TeV expected) in the electron channel and less than 3.9 TeV (3.8 TeV expected) in the muon channel are excluded at 95% CL. These results provide tighter limits than those obtained from Run 1 data [7]. The combination of the electron and muon channels, which have comparable sensitivity, improves the limit such that the production of SSM W′ bosons with masses below 4.1 TeV (4.0 TeV expected) are excluded at 95% CL, as shown in Fig. 5. In making this combination, all systematic uncertainties that are common to both channels are assumed to be fully correlated.

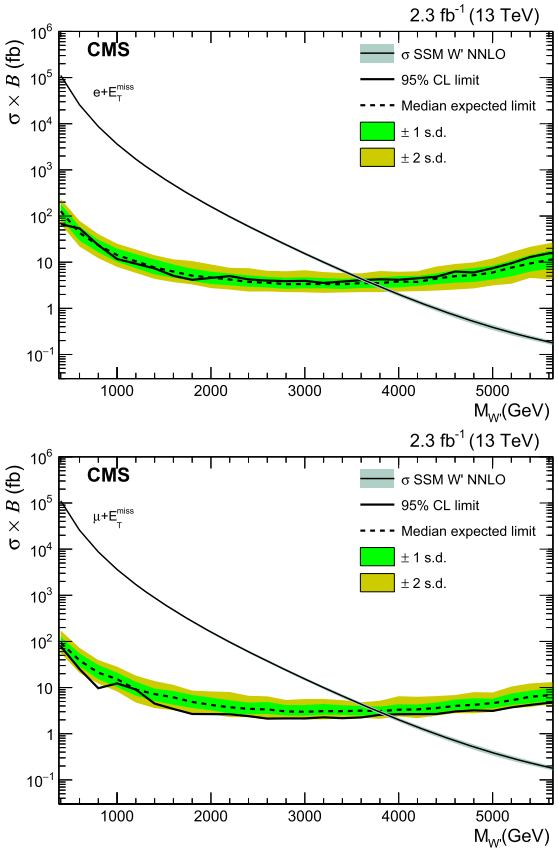

Fig. 4. Expected and observed 95% CL limits for the electron (upper) and muon (lower) decay channels. The expected (observed) limit is displayed as a dashed (solid) line and the associated inner (outer) bands represent the one (two) standard deviation (s.d.) uncertainties. The SSM W′ NNLO cross sections are displayed as a function of $M(W')$.

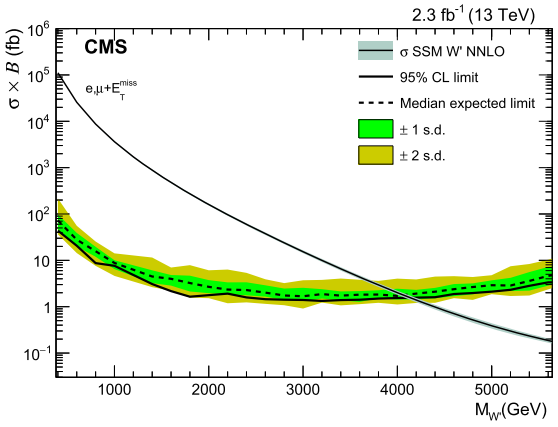

Fig. 5. Expected and observed 95% CL limits for the combination of the electron and muon decay channels. The expected (observed) limit is displayed as a dashed (solid) line and the associated inner (outer) bands represent the one (two) standard deviation (s.d.) uncertainties. The SSM W′ NNLO cross section is displayed as a function of $M(W')$.

6.2. Combination with Run 1 results

A similar search for a W′ boson in the electron and muon channels was performed using Run 1 data at 8 TeV center-of-mass en-

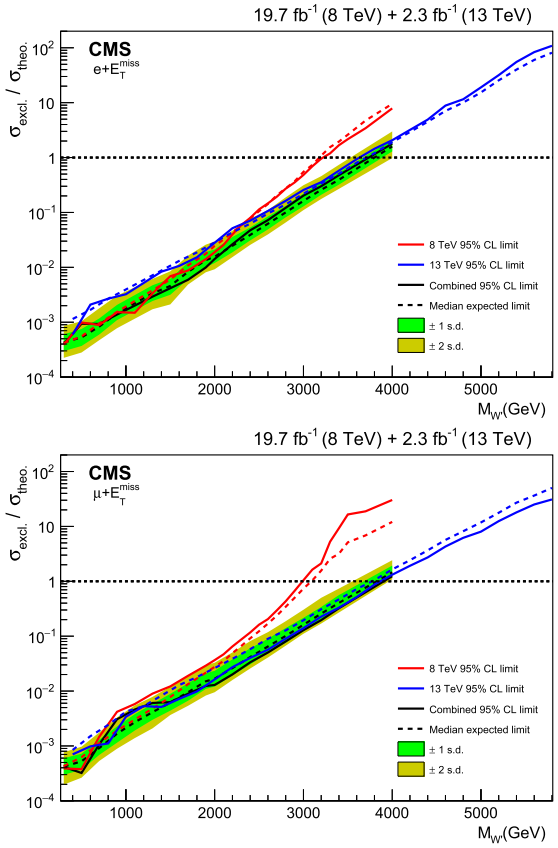

Fig. 6. Ratio of the cross section lower limit to the theoretical cross section shown in red (lighter curves) for the 8 TeV data, blue (darker curves) for the 13 TeV data, and black for the combined data sets in the electron (upper) and muon (lower) channels. The observed limits are shown with solid lines and expected limits with dashed lines. For the W′ mass range 400–4000 GeV, where the combination is limited by the 8 TeV data set, the one- and two-standard deviation (s.d.) uncertainty bands for the combined limits are shown in green and yellow, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ergy [7]. These results can be combined with the present analysis using the prescription from Ref. [39]. The systematic uncertainties are assumed to be uncorrelated between Run 1 and Run 2. The 95% CL limits on the product $\sigma_{W'}\mathcal{B}(W' \to \ell\nu)$ derived from the combination of data at $\sqrt{s} = 8$ and 13 TeV are presented in Fig. 6 for the electron (upper) and the muon (lower) decay channels. In this case, the cross sections are presented relative to the predicted NNLO cross section for the SSM W′ production at each center-of-mass energy. The sensitivity to exclude high-mass W′ bosons is dominated by the data set at $\sqrt{s} = 13$ TeV, and these data determine the limit exclusively for masses above 4 TeV. For W′ masses below 2.2 TeV, the higher integrated luminosity data set from the 8 TeV Run still makes the biggest contribution to the sensitivity. Considering both data sets, SSM W′ bosons with masses less than 3.7 (3.9) TeV are excluded in the electron (muon) channel. Combining both final state channels using the data at both center-of-mass energies the production of SSM W′ bosons with masses below 4.1 TeV is excluded at 95% CL.

6.3. Model-independent cross section limits

A cross section limit that is independent of the M_T dependence expected in any given model is determined by performing a single-bin counting experiment in a transverse mass range above a threshold, denoted M_T^{min}. The results for the electron and muon

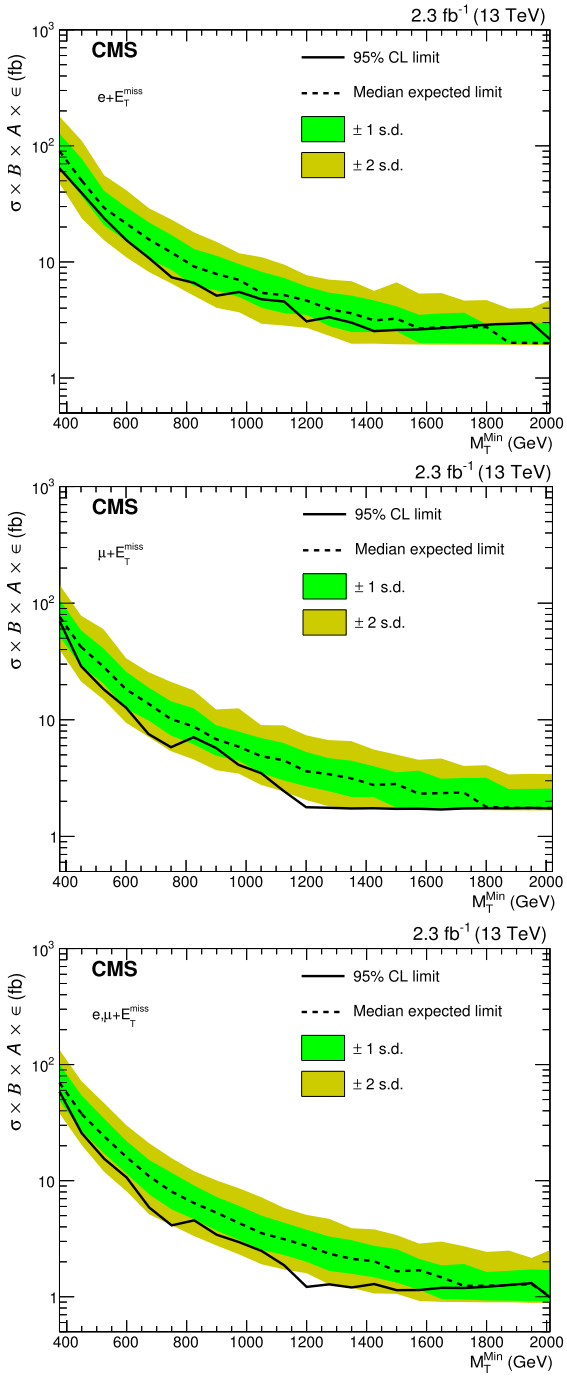

Fig. 7. Expected (dashed line) and observed (solid line) 95% CL limit for the model-independent cross section limit as a function of the lower M_T threshold, denoted M_T^{min}, for the electron channel (upper plot), the muon channel (middle plot), and the combined channels (lower plot). The inner (outer) bands represent the one- (two-)standard deviation (s.d.) uncertainties.

channels are shown in Fig. 7 along with the combination. Values of the product of cross section and branching fractions above the solid curve are excluded. The observed cross section limit includes the fiducial acceptance, A, defined by the lepton geometrical acceptance and the offline p_T thresholds (Section 4), as well as detector effects and kinematic selection (back-to-back topology), denoted as ϵ. Both quantities are evaluated relative to events generated with a transverse mass above the M_T^{min} threshold. The fiducial acceptance for very massive SSM W′ bosons is of the order

of 1, since the products of their decay are mainly emitted at very high angles relative to the beam direction.

In order to compare a specific new model to the given cross section limits, the effect of the threshold $M_{\mathrm{T}}^{\mathrm{min}}$ on the signal acceptance has to be taken into account by determining the ratio ($f_{M_{\mathrm{T}}}$) of the number of events with $M_{\mathrm{T}} > M_{\mathrm{T}}^{\mathrm{min}}$ to the number of events generated. For the M_{T} range shown in Fig. 7 the reconstruction efficiency is constant and the impact of the M_{T} resolution effect is negligible. Therefore $f_{M_{\mathrm{T}}}$ can be evaluated at generator level. For lower M_{T} a very small (<1%) difference is expected because of the single lepton trigger threshold (130 GeV for electrons, 50 GeV for muons).

A limit on the product of the cross section and branching fraction $(\sigma\,\mathcal{B}\,A\,\epsilon)_{\mathrm{excl}}$ can be obtained by dividing the excluded cross section of the model-independent limit $(\sigma\,\mathcal{B}\,A\,\epsilon)_{\mathrm{MI}}$ given in Fig. 7 by the calculated fraction $f_{M_{\mathrm{T}}}(M_{\mathrm{T}}^{\mathrm{min}})$:

$$(\sigma\,\mathcal{B}\,A\,\epsilon)_{\mathrm{excl}} = \frac{(\sigma\,\mathcal{B}\,A\,\epsilon)_{\mathrm{MI}}(M_{\mathrm{T}}^{\mathrm{min}})}{f_{M_{\mathrm{T}}}(M_{\mathrm{T}}^{\mathrm{min}})}.$$

Any deviation in the value of the product of the fiducial acceptance and signal efficiency of the new model from that applied to the W′ in Fig. 7 would need to be taken into consideration. The latter has a value of 0.83 ± 0.03, where the quoted uncertainty corresponds to the estimated variation as a function of $M_{\mathrm{T}}^{\mathrm{min}}$. For a predicted massive state decaying into two back-to-back leptons, thus having similar kinematic properties to those of a generic W′ boson, the deviation would be small and no additional correction would be required.

The validity of the model-independent limit procedure was checked by applying it to an SSM W′ boson of 3.6 TeV mass and the results obtained are consistent with those presented in Section 6.1 using the dedicated analysis. It should be noted that this approach corresponds to a single-bin limit, which is expected to be slightly less sensitive than that obtained from a dedicated analysis exploiting the full M_{T} shape.

7. Summary

A search has been performed for sequential standard model W′ bosons in final states containing a single energetic electron or muon and large missing transverse momentum, using proton–proton collision data at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 2.3 fb^{-1}. No deviation from the background expectations has been observed and exclusion limits at 95% confidence level have been extracted on the mass of a W′ boson. Masses below 3.6 (3.9) TeV are excluded in the electron (muon) decay channel analysis, significantly improving upon the results obtained with the $\sqrt{s} = 8$ TeV data. This search has been combined with the earlier one conducted at 8 TeV, where the sensitivity of the search is dominated by the 13 TeV data, yielding a lower mass limit of 4.1 TeV for W′ bosons when combining data from both decay channels and center-of-mass energies. Finally, generic limits on the production of W′ resonances with the same leptonic final states have been obtained using a model-independent approach.

Acknowledgements

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, RFBR and RAEP (Russia); MESTD (Serbia); SEIDI and CPAN (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TÜBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

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 Science 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 Scientific 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 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, 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.

References

[1] G. Altarelli, B. Mele, M. Ruiz-Altaba, Searching for new heavy vector bosons in $p\bar{p}$ colliders, Z. Phys. C 45 (1989) 109, http://dx.doi.org/10.1007/BF01556677.

[2] CMS Collaboration, Search for a W' or techni-ρ decaying into WZ in pp collisions at $\sqrt{s} = 7$ TeV, Phys. Rev. Lett. 109 (2012) 141801, http://dx.doi.org/10.1103/PhysRevLett.109.141801, arXiv:1206.0433.

[3] CMS Collaboration, Search for new resonances decaying via WZ to leptons in proton–proton collisions at $\sqrt{s} = 8$ TeV, Phys. Lett. B 740 (2015) 83, http://dx.doi.org/10.1016/j.physletb.2014.11.026, arXiv:1407.3476.

[4] ATLAS Collaboration, Searches for heavy diboson resonances in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, JHEP 09 (2016) 173, http://dx.doi.org/10.1007/JHEP09(2016)173, arXiv:1606.04833.

[5] V.M. Abazov, B. Abbott, D0 Collaboration, Search for W' bosons decaying to an electron and a neutrino with the D0 detector, Phys. Rev. Lett. 100 (2008) 031804, http://dx.doi.org/10.1103/PhysRevLett.100.031804, arXiv:0710.2966.

[6] T. Aaltonen, et al., CDF Collaboration, Search for a new heavy gauge boson W' with electron + missing transverse energy in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, Phys. Rev. D 83 (2011) 031102, http://dx.doi.org/10.1103/PhysRevD.83.031102, arXiv:1012.5145.

[7] CMS Collaboration, Search for physics beyond the standard model in final states with a lepton and missing transverse energy in proton–proton collisions at $\sqrt{s} = 8$ TeV, Phys. Rev. D 91 (2015) 092005, http://dx.doi.org/10.1103/PhysRevD.91.092005, arXiv:1408.2745.

[8] ATLAS Collaboration, Search for new particles in events with one lepton and missing transverse momentum in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector, JHEP 09 (2014) 037, http://dx.doi.org/10.1007/JHEP09(2014)037, arXiv:1407.7494.

[9] ATLAS Collaboration, Search for new resonances in events with one lepton and missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, Phys. Lett. B 762 (2016) 334, http://dx.doi.org/10.1016/j.physletb.2016.09.040, arXiv:1606.03977.
[10] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. 3 (2008) S08004, http://dx.doi.org/10.1088/1748-0221/3/08/S08004.
[11] CMS Collaboration, The TriDAS Project Technical Design Report, vol. I: The trigger systems, CMS TDR CERN/LHCC 2000-038. CERN, 2000, https://cdsweb.cern.ch/record/706847/.
[12] CMS Collaboration, The TriDAS Project Technical Design Report, vol. II: Data Acquisition and High-Level Trigger, CMS TDR CERN/LHCC 2002-026. CERN, 2002, http://cds.cern.ch/record/578006.
[13] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.S. Shao, T. Stelzer, P. Torrielli, M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, JHEP 07 (2014) 079, http://dx.doi.org/10.1007/JHEP07(2014)079, arXiv:1405.0301.
[14] T. Sjöstrand, S. Ask, J.R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C.O. Rasmussen, P.Z. Skands, An introduction to PYTHIA 8.2, Comput. Phys. Commun. 191 (2015) 159, http://dx.doi.org/10.1016/j.cpc.2015.01.024, arXiv:1410.3012.
[15] P. Skands, S. Carrazza, J. Rojo, Tuning PYTHIA 8.1: the Monash 2013 Tune, Eur. Phys. J. C 74 (2014) 3024, http://dx.doi.org/10.1140/epjc/s10052-014-3024-y, arXiv:1404.5630.
[16] CMS Collaboration, Event generator tunes obtained from underlying event and multiparton scattering measurements, Eur. Phys. J. C 76 (2016) 115, http://dx.doi.org/10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.
[17] R.D. Ball, V. Bertone, S. Carrazza, C.S. Deans, L. Del Debbio, S. Forte, A. Guffanti, N.P. Hartland, J.I. Latorre, J. Rojo, M. Ubiali, NNPDF Collaboration, Parton distributions for the LHC Run II, JHEP 04 (2015) 040, http://dx.doi.org/10.1007/JHEP04(2015)040, arXiv:1410.8849.
[18] Y. Li, F. Petriello, Combining QCD and electroweak corrections to dilepton production in FEWZ, Phys. Rev. D 86 (2012) 094034, http://dx.doi.org/10.1103/PhysRevD.86.094034, arXiv:1208.5967.
[19] S.G. Bondarenko, A.A. Sapronov, NLO EW and QCD proton–proton cross section calculations with mcsanc-v1.01, Comput. Phys. Commun. 184 (2013) 2343, http://dx.doi.org/10.1016/j.cpc.2013.05.010, arXiv:1301.3687.
[20] L. Barze, G. Montagna, P. Nason, O. Nicrosini, F. Piccinini, A. Vicini, Neutral current Drell–Yan with combined QCD and electroweak corrections in the POWHEG BOX, Eur. Phys. J. C 73 (2013) 2474, http://dx.doi.org/10.1140/epjc/s10052-013-2474-y, arXiv:1302.4606.
[21] S. Alioli, P. Nason, C. Oleari, E. Re, Powheg (v2): a general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX, JHEP 06 (2010) 043, http://dx.doi.org/10.1007/JHEP06(2010)043, arXiv:1002.2581.
[22] S. Alioli, P. Nason, C. Oleari, E. Re, NLO single-top production matched with shower in POWHEG: s- and t-channel contributions, JHEP 09 (2009) 111, http://dx.doi.org/10.1088/1126-6708/2009/09/111, arXiv:0907.4076, Erratum: http://dx.doi.org/10.1007/JHEP02(2010)011.
[23] E. Re, Single-top Wt-channel production matched with parton showers using the POWHEG method, Eur. Phys. J. C 71 (2011) 1547, http://dx.doi.org/10.1140/epjc/s10052-011-1547-z, arXiv:1009.2450.
[24] J.M. Campbell, R.K. Ellis, P. Nason, E. Re, Top-pair production and decay at NLO matched with parton showers, JHEP 04 (2015) 114, http://dx.doi.org/10.1007/JHEP04(2015)114, arXiv:1412.1828.
[25] R. Frederix, S. Frixione, Merging meets matching in MC@NLO, JHEP 12 (2012) 061, http://dx.doi.org/10.1007/JHEP12(2012)061, arXiv:1209.6215.
[26] R.D. Ball, V. Bertone, S. Carrazza, C.S. Deans, L. Del Debbio, S. Forte, A. Guffanti, N.P. Hartland, J.I. Latorre, J. Rojo, M. Ubiali, NNPDF Collaboration, Parton distributions with LHC data, Nucl. Phys. B 867 (2013) 244, http://dx.doi.org/10.1016/j.nuclphysb.2012.10.003, arXiv:1207.1303.
[27] S. Agostinelli, et al., GEANT4 Collaboration, GEANT4—a simulation toolkit, Nucl. Instrum. Methods A 506 (2003) 250, http://dx.doi.org/10.1016/S0168-9002(03)01368-8.
[28] CMS Collaboration, Particle-flow Event Reconstruction in CMS and Performance for Jets, Taus, and $E_{\mathrm{T}}^{\mathrm{miss}}$, CMS Physics Analysis Summary CMS-PAS-PFT-09–001, 2009, http://cdsweb.cern.ch/record/1194487.
[29] CMS Collaboration, Commissioning of the Particle-Flow Event Reconstruction with the First LHC Collisions Recorded in the CMS Detector, CMS Physics Analysis Summary CMS-PAS-PFT-10–001, 2010, http://cdsweb.cern.ch/record/1247373.
[30] CMS Collaboration, Performance of Missing Energy Reconstruction in 13 TeV pp Collision Data Using the CMS Detector, CMS Physics Analysis Summary CMS-PAS-JME-16–004, 2016, http://cdsweb.cern.ch/record/2205284.
[31] CMS Collaboration, Performance of electron reconstruction and selection with the CMS detector in proton–proton collisions at $\sqrt{s} = 8$ TeV, J. Instrum. 10 (2015) P06005, http://dx.doi.org/10.1088/1748-0221/10/06/P06005, arXiv:1502.02701.
[32] CMS Collaboration, Search for physics beyond the standard model in dilepton mass spectra in proton–proton collisions at $\sqrt{s} = 8$ TeV, JHEP 04 (2015) 025, http://dx.doi.org/10.1007/JHEP04(2015)025, arXiv:1412.6302.
[33] CMS Collaboration, Search for narrow resonances in dilepton mass spectra in proton–proton collisions at $\sqrt{s} = 13$ TeV and combination with $\sqrt{s} = 8$ TeV data, Phys. Lett. B 768 (2017) 57–80, http://dx.doi.org/10.1016/j.physletb.2017.02.010, arXiv:1609.05391.
[34] CMS Collaboration, Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV, J. Instrum. 7 (2012) P10002, http://dx.doi.org/10.1088/1748-0221/7/10/P10002, arXiv:1206.4071.
[35] CMS Collaboration, The performance of CMS muon detector in proton–proton collision at $\sqrt{s} = 7$ TeV at the LHC, J. Instrum. 8 (2013) P11002, http://dx.doi.org/10.1088/1748-0221/8/11/P11002, arXiv:1306.6905.
[36] CMS Collaboration, CMS Luminosity Measurement for the 2015 Data Taking Period, CMS Physics Analysis Summary CMS-PAS-LUM-15–001, 2015, http://cdsweb.cern.ch/record/2138682.
[37] J. Butterworth, et al., PDF4LHC recommendations for LHC Run II, J. Phys. G 43 (2016) 023001, http://dx.doi.org/10.1088/0954-3899/43/2/023001, arXiv:1510.03865.
[38] G. Cowan, Statistics, in: K. Nakamura, et al. (Eds.), Particle Data Group, in: Review of Particle Physics, vol. 37, 2010, p. 075021.
[39] ATLAS Collaboration, CMS Collaboration, LHC Higgs Combination Group, Procedure for the LHC Higgs Boson Search Combination in Summer 2011, Technical Report ATL-PHYS-PUB-2011-011, CMS NOTE 2011/005, 2011, https://cds.cern.ch/record/1375842.

The CMS Collaboration

V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, M. Flechl, M. Friedl, R. Frühwirth [1], V.M. Ghete, C. Hartl, N. Hörmann, J. Hrubec, M. Jeitler [1], A. König, I. Krätschmer, D. Liko, T. Matsushita, I. Mikulec, D. Rabady, N. Rad, B. Rahbaran, H. Rohringer, J. Schieck [1], J. Strauss, W. Waltenberger, C.-E. Wulz [1]

Institut für Hochenergiephysik, Wien, Austria

O. Dvornikov, V. Makarenko, V. Zykunov

Institute for Nuclear Problems, Minsk, Belarus

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

National Centre for Particle and High Energy Physics, Minsk, Belarus

S. Alderweireldt, E.A. De Wolf, X. Janssen, J. Lauwers, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Universiteit Antwerpen, Antwerpen, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, N. Daci, I. De Bruyn, K. Deroover, S. Lowette, S. Moortgat, L. Moreels, A. Olbrechts, Q. Python, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Vrije Universiteit Brussel, Brussel, Belgium

H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, G. Karapostoli, T. Lenzi, A. Léonard, J. Luetic, T. Maerschalk, A. Marinov, A. Randle-conde, T. Seva, C. Vander Velde, P. Vanlaer, R. Yonamine, F. Zenoni, F. Zhang [2]

Université Libre de Bruxelles, Bruxelles, Belgium

A. Cimmino, T. Cornelis, D. Dobur, A. Fagot, G. Garcia, M. Gul, I. Khvastunov, D. Poyraz, S. Salva, R. Schöfbeck, A. Sharma, M. Tytgat, W. Van Driessche, E. Yazgan, N. Zaganidis

Ghent University, Ghent, Belgium

H. Bakhshiansohi, C. Beluffi [3], O. Bondu, S. Brochet, G. Bruno, A. Caudron, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, A. Jafari, P. Jez, M. Komm, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, C. Nuttens, K. Piotrzkowski, L. Quertenmont, M. Selvaggi, M. Vidal Marono, S. Wertz

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

N. Beliy

Université de Mons, Mons, Belgium

W.L. Aldá Júnior, F.L. Alves, G.A. Alves, L. Brito, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato [4], A. Custódio, E.M. Da Costa, G.G. Da Silveira [5], D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, D. Matos Figueiredo, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, A. Santoro, A. Sznajder, E.J. Tonelli Manganote [4], A. Vilela Pereira

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

S. Ahuja [a], C.A. Bernardes [b], S. Dogra [a], T.R. Fernandez Perez Tomei [a], E.M. Gregores [b], P.G. Mercadante [b], C.S. Moon [a], S.F. Novaes [a], Sandra S. Padula [a], D. Romero Abad [b], J.C. Ruiz Vargas [a]

[a] *Universidade Estadual Paulista, São Paulo, Brazil*
[b] *Universidade Federal do ABC, São Paulo, Brazil*

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, M. Rodozov, S. Stoykova, G. Sultanov, M. Vutova

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

A. Dimitrov, I. Glushkov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria

W. Fang [6]

Beihang University, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen [7], T. Cheng, C.H. Jiang, D. Leggat, Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, H. Zhang, J. Zhao

Institute of High Energy Physics, Beijing, China

Y. Ban, G. Chen, Q. Li, S. Liu, Y. Mao, S.J. Qian, D. Wang, Z. Xu

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

C. Avila, A. Cabrera, L.F. Chaparro Sierra, C. Florez, J.P. Gomez, C.F. González Hernández, J.D. Ruiz Alvarez, J.C. Sanabria

Universidad de Los Andes, Bogota, Colombia

N. Godinovic, D. Lelas, I. Puljak, P.M. Ribeiro Cipriano, T. Sculac

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, S. Micanovic, L. Sudic, T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, D. Tsiakkouri

University of Cyprus, Nicosia, Cyprus

M. Finger [8], M. Finger Jr. [8]

Charles University, Prague, Czech Republic

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

A.A. Abdelalim [9,10], Y. Mohammed [11], E. Salama [12,13]

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

B. Calpas, M. Kadastik, M. Murumaa, L. Perrini, M. Raidal, A. Tiko, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, J. Pekkanen, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

J. Härkönen, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, J. Tuominiemi, E. Tuovinen, L. Wendland

Helsinki Institute of Physics, Helsinki, Finland

J. Talvitie, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, C. Favaro, F. Ferri, S. Ganjour, S. Ghosh, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, I. Kucher, E. Locci, M. Machet, J. Malcles, J. Rander, A. Rosowsky, M. Titov, A. Zghiche

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

A. Abdulsalam, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, E. Chapon, C. Charlot, O. Davignon, R. Granier de Cassagnac, M. Jo, S. Lisniak, P. Miné, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, S. Regnard, R. Salerno, Y. Sirois, T. Strebler, Y. Yilmaz, A. Zabi

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

J.-L. Agram [14], J. Andrea, A. Aubin, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, N. Chanon, C. Collard, E. Conte [14], X. Coubez, J.-C. Fontaine [14], D. Gelé, U. Goerlach, A.-C. Le Bihan, K. Skovpen, P. Van Hove

Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS-IN2P3, France

S. Gadrat

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France

S. Beauceron, C. Bernet, G. Boudoul, E. Bouvier, C.A. Carrillo Montoya, R. Chierici, D. Contardo, B. Courbon, P. Depasse, H. El Mamouni, J. Fan, J. Fay, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov [15], D. Sabes, V. Sordini, M. Vander Donckt, P. Verdier, S. Viret

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

T. Toriashvili [16]

Georgian Technical University, Tbilisi, Georgia

Z. Tsamalaidze [8]

Tbilisi State University, Tbilisi, Georgia

C. Autermann, S. Beranek, L. Feld, A. Heister, M.K. Kiesel, K. Klein, M. Lipinski, A. Ostapchuk, M. Preuten, F. Raupach, S. Schael, C. Schomakers, J. Schulz, T. Verlage, H. Weber, V. Zhukov [15]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

A. Albert, F.F. Bispinck, M. Brodski, E. Dietz-Laursonn, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, M. Hamer, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, M. Olschewski, K. Padeken, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, L. Sonnenschein, D. Teyssier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

V. Cherepanov, G. Flügge, F. Hoehle, B. Kargoll, T. Kress, A. Künsken, J. Lingemann, T. Müller, A. Nehrkorn, A. Nowack, I.M. Nugent, C. Pistone, O. Pooth, A. Stahl [17]

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A.A. Bin Anuar, K. Borras [18], A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, C. Diez Pardos, G. Dolinska, G. Eckerlin, D. Eckstein, T. Eichhorn, E. Eren, E. Gallo [19], J. Garay Garcia, A. Geiser, A. Gizhko, J.M. Grados Luyando, P. Gunnellini, A. Harb, J. Hauk, M. Hempel [20], H. Jung, A. Kalogeropoulos, O. Karacheban [20], M. Kasemann, J. Keaveney, C. Kleinwort, I. Korol, D. Krücker, W. Lange, A. Lelek, J. Leonard, K. Lipka, A. Lobanov, W. Lohmann [20], R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, G. Mittag, J. Mnich, A. Mussgiller, E. Ntomari, D. Pitzl, R. Placakyte, A. Raspereza, B. Roland, M.Ö. Sahin, P. Saxena, T. Schoerner-Sadenius, C. Seitz, S. Spannagel, N. Stefaniuk, G.P. Van Onsem, R. Walsh, C. Wissing

Deutsches Elektronen-Synchrotron, Hamburg, Germany

V. Blobel, M. Centis Vignali, A.R. Draeger, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, M. Hoffmann, A. Junkes, R. Klanner, R. Kogler, N. Kovalchuk, V. Kutzner, T. Lapsien, T. Lenz, I. Marchesini, D. Marconi, M. Meyer, M. Niedziela, D. Nowatschin, F. Pantaleo [17], T. Peiffer, A. Perieanu, J. Poehlsen, C. Sander, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, H. Tholen, D. Troendle, E. Usai, L. Vanelderen, A. Vanhoefer, B. Vormwald

University of Hamburg, Hamburg, Germany

M. Akbiyik, C. Barth, S. Baur, C. Baus, J. Berger, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, S. Fink, B. Freund, R. Friese, M. Giffels, A. Gilbert, P. Goldenzweig, D. Haitz, F. Hartmann [17], S.M. Heindl, U. Husemann, I. Katkov [15], S. Kudella, P. Lobelle Pardo, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, S. Röcker, F. Roscher, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, J. Wagner-Kuhr, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

G. Anagnostou, G. Daskalakis, T. Geralis, V.A. Giakoumopoulou, A. Kyriakis, D. Loukas, I. Topsis-Giotis

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

S. Kesisoglou, A. Panagiotou, N. Saoulidou, E. Tziaferi

National and Kapodistrian University of Athens, Athens, Greece

I. Evangelou, G. Flouris, C. Foudas, P. Kokkas, N. Loukas, N. Manthos, I. Papadopoulos, E. Paradas

University of Ioánnina, Ioánnina, Greece

N. Filipovic

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

G. Bencze, C. Hajdu, P. Hidas, D. Horvath [21], F. Sikler, V. Veszpremi, G. Vesztergombi [22], A.J. Zsigmond

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi [23], A. Makovec, J. Molnar, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

M. Bartók [22], P. Raics, Z.L. Trocsanyi, B. Ujvari

Institute of Physics, University of Debrecen, Hungary

S. Bahinipati, S. Choudhury [24], P. Mal, K. Mandal, A. Nayak [25], D.K. Sahoo, N. Sahoo, S.K. Swain

National Institute of Science Education and Research, Bhubaneswar, India

S. Bansal, S.B. Beri, V. Bhatnagar, R. Chawla, U. Bhawandeep, A.K. Kalsi, A. Kaur, M. Kaur, R. Kumar, P. Kumari, A. Mehta, M. Mittal, J.B. Singh, G. Walia

Panjab University, Chandigarh, India

Ashok Kumar, A. Bhardwaj, B.C. Choudhary, R.B. Garg, S. Keshri, S. Malhotra, M. Naimuddin, N. Nishu, K. Ranjan, R. Sharma, V. Sharma

University of Delhi, Delhi, India

R. Bhattacharya, S. Bhattacharya, K. Chatterjee, S. Dey, S. Dutt, S. Dutta, S. Ghosh, N. Majumdar, A. Modak, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, A. Roy, D. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, S. Thakur

Saha Institute of Nuclear Physics, Kolkata, India

P.K. Behera

Indian Institute of Technology Madras, Madras, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty [17], P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, S. Dugad, G. Kole, B. Mahakud, S. Mitra, G.B. Mohanty, B. Parida, N. Sur, B. Sutar

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, S. Bhowmik [26], R.K. Dewanjee, S. Ganguly, M. Guchait, Sa. Jain, S. Kumar, M. Maity [26], G. Majumder, K. Mazumdar, T. Sarkar [26], N. Wickramage [27]

Tata Institute of Fundamental Research-B, Mumbai, India

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

Indian Institute of Science Education and Research (IISER), Pune, India

H. Behnamian, S. Chenarani [28], E. Eskandari Tadavani, S.M. Etesami [28], A. Fahim [29], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi [30], F. Rezaei Hosseinabadi, B. Safarzadeh [31], M. Zeinali

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia [a,b], C. Calabria [a,b], C. Caputo [a,b], A. Colaleo [a], D. Creanza [a,c], L. Cristella [a,b], N. De Filippis [a,c], M. De Palma [a,b], L. Fiore [a], G. Iaselli [a,c], G. Maggi [a,c], M. Maggi [a], G. Miniello [a,b], S. My [a,b], S. Nuzzo [a,b], A. Pompili [a,b], G. Pugliese [a,c], R. Radogna [a,b], A. Ranieri [a], G. Selvaggi [a,b], L. Silvestris [a,17], R. Venditti [a,b], P. Verwilligen [a]

[a] *INFN Sezione di Bari, Bari, Italy*
[b] *Università di Bari, Bari, Italy*
[c] *Politecnico di Bari, Bari, Italy*

G. Abbiendi [a], C. Battilana, D. Bonacorsi [a,b], S. Braibant-Giacomelli [a,b], L. Brigliadori [a,b], R. Campanini [a,b], P. Capiluppi [a,b], A. Castro [a,b], F.R. Cavallo [a], S.S. Chhibra [a,b], G. Codispoti [a,b], M. Cuffiani [a,b], G.M. Dallavalle [a], F. Fabbri [a], A. Fanfani [a,b], D. Fasanella [a,b], P. Giacomelli [a], C. Grandi [a], L. Guiducci [a,b], S. Marcellini [a], G. Masetti [a], A. Montanari [a], F.L. Navarria [a,b], A. Perrotta [a], A.M. Rossi [a,b], T. Rovelli [a,b], G.P. Siroli [a,b], N. Tosi [a,b,17]

[a] *INFN Sezione di Bologna, Bologna, Italy*
[b] *Università di Bologna, Bologna, Italy*

S. Albergo [a,b], M. Chiorboli [a,b], S. Costa [a,b], A. Di Mattia [a], F. Giordano [a,b], R. Potenza [a,b], A. Tricomi [a,b], C. Tuve [a,b]

[a] *INFN Sezione di Catania, Catania, Italy*
[b] *Università di Catania, Catania, Italy*

G. Barbagli [a], V. Ciulli [a,b], C. Civinini [a], R. D'Alessandro [a,b], E. Focardi [a,b], V. Gori [a,b], P. Lenzi [a,b], M. Meschini [a], S. Paoletti [a], G. Sguazzoni [a], L. Viliani [a,b,17]

[a] *INFN Sezione di Firenze, Firenze, Italy*
[b] *Università di Firenze, Firenze, Italy*

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera [17]

INFN Laboratori Nazionali di Frascati, Frascati, Italy

V. Calvelli [a,b], F. Ferro [a], M. Lo Vetere [a,b], M.R. Monge [a,b], E. Robutti [a], S. Tosi [a,b]

[a] *INFN Sezione di Genova, Genova, Italy*
[b] *Università di Genova, Genova, Italy*

L. Brianza [17], M.E. Dinardo [a,b], S. Fiorendi [a,b,17], S. Gennai [a], A. Ghezzi [a,b], P. Govoni [a,b], M. Malberti, S. Malvezzi [a], R.A. Manzoni [a,b,17], D. Menasce [a], L. Moroni [a], M. Paganoni [a,b], D. Pedrini [a], S. Pigazzini, S. Ragazzi [a,b], T. Tabarelli de Fatis [a,b]

[a] INFN Sezione di Milano-Bicocca, Milano, Italy
[b] Università di Milano-Bicocca, Milano, Italy

S. Buontempo [a], N. Cavallo [a,c], G. De Nardo, S. Di Guida [a,d,17], M. Esposito [a,b], F. Fabozzi [a,c], F. Fienga [a,b], A.O.M. Iorio [a,b], G. Lanza [a], L. Lista [a], S. Meola [a,d,17], P. Paolucci [a,17], C. Sciacca [a,b], F. Thyssen [a,b]

[a] INFN Sezione di Napoli, Napoli, Italy
[b] Università di Napoli 'Federico II', Napoli, Italy
[c] Università della Basilicata, Potenza, Italy
[d] Università G. Marconi, Roma, Italy

P. Azzi [a,17], N. Bacchetta [a], L. Benato [a,b], D. Bisello [a,b], A. Boletti [a,b], R. Carlin [a,b], A. Carvalho Antunes De Oliveira [a,b], P. Checchia [a], M. Dall'Osso [a,b], P. De Castro Manzano [a], T. Dorigo [a], U. Dosselli [a], F. Gasparini [a,b], U. Gasparini [a,b], A. Gozzelino [a], S. Lacaprara [a], M. Margoni [a,b], A.T. Meneguzzo [a,b], J. Pazzini [a,b], N. Pozzobon [a,b], P. Ronchese [a,b], F. Simonetto [a,b], E. Torassa [a], M. Zanetti [a,b], P. Zotto [a,b], G. Zumerle [a,b]

[a] INFN Sezione di Padova, Padova, Italy
[b] Università di Padova, Padova, Italy
[c] Università di Trento, Trento, Italy

A. Braghieri [a], A. Magnani [a,b], P. Montagna [a,b], S.P. Ratti [a,b], V. Re [a], C. Riccardi [a,b], P. Salvini [a], I. Vai [a,b], P. Vitulo [a,b]

[a] INFN Sezione di Pavia, Pavia, Italy
[b] Università di Pavia, Pavia, Italy

L. Alunni Solestizi [a,b], G.M. Bilei [a], D. Ciangottini [a,b], L. Fanò [a,b], P. Lariccia [a,b], R. Leonardi [a,b], G. Mantovani [a,b], M. Menichelli [a], A. Saha [a], A. Santocchia [a,b]

[a] INFN Sezione di Perugia, Perugia, Italy
[b] Università di Perugia, Perugia, Italy

K. Androsov [a,32], P. Azzurri [a,17], G. Bagliesi [a], J. Bernardini [a], T. Boccali [a], R. Castaldi [a], M.A. Ciocci [a,32], R. Dell'Orso [a], S. Donato [a,c], G. Fedi, A. Giassi [a], M.T. Grippo [a,32], F. Ligabue [a,c], T. Lomtadze [a], L. Martini [a,b], A. Messineo [a,b], F. Palla [a], A. Rizzi [a,b], A. Savoy-Navarro [a,33], P. Spagnolo [a], R. Tenchini [a], G. Tonelli [a,b], A. Venturi [a], P.G. Verdini [a]

[a] INFN Sezione di Pisa, Pisa, Italy
[b] Università di Pisa, Pisa, Italy
[c] Scuola Normale Superiore di Pisa, Pisa, Italy

L. Barone [a,b], F. Cavallari [a], M. Cipriani [a,b], D. Del Re [a,b,17], M. Diemoz [a], S. Gelli [a,b], E. Longo [a,b], F. Margaroli [a,b], B. Marzocchi [a,b], P. Meridiani [a], G. Organtini [a,b], R. Paramatti [a], F. Preiato [a,b], S. Rahatlou [a,b], C. Rovelli [a], F. Santanastasio [a,b]

[a] INFN Sezione di Roma, Roma, Italy
[b] Università di Roma, Roma, Italy

N. Amapane [a,b], R. Arcidiacono [a,c,17], S. Argiro [a,b], M. Arneodo [a,c], N. Bartosik [a], R. Bellan [a,b], C. Biino [a], N. Cartiglia [a], M. Costa [a,b], R. Covarelli [a,b], A. Degano [a,b], N. Demaria [a], L. Finco [a,b], B. Kiani [a,b], C. Mariotti [a], S. Maselli [a], E. Migliore [a,b], V. Monaco [a,b], E. Monteil [a,b], M. Monteno [a], M.M. Obertino [a,b], L. Pacher [a,b], N. Pastrone [a], M. Pelliccioni [a], G.L. Pinna Angioni [a,b], F. Ravera [a,b], A. Romero [a,b], M. Ruspa [a,c], R. Sacchi [a,b], V. Sola [a], A. Solano [a,b], A. Staiano [a], P. Traczyk [a,b], P.P. Trapani [a,b]

[a] INFN Sezione di Torino, Torino, Italy
[b] Università di Torino, Torino, Italy
[c] Università del Piemonte Orientale, Novara, Italy

S. Belforte [a], M. Casarsa [a], F. Cossutti [a], G. Della Ricca [a,b], A. Zanetti [a]

[a] INFN Sezione di Trieste, Trieste, Italy
[b] Università di Trieste, Trieste, Italy

D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S. Lee, S.W. Lee, Y.D. Oh, S. Sekmen, D.C. Son, Y.C. Yang

Kyungpook National University, Daegu, Republic of Korea

A. Lee

Chonbuk National University, Jeonju, Republic of Korea

H. Kim

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Republic of Korea

J.A. Brochero Cifuentes, T.J. Kim

Hanyang University, Seoul, Republic of Korea

S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, Y. Kim, B. Lee, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

Korea University, Seoul, Republic of Korea

J. Almond, J. Kim, H. Lee, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

Seoul National University, Seoul, Republic of Korea

M. Choi, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park, G. Ryu, M.S. Ryu

University of Seoul, Seoul, Republic of Korea

Y. Choi, J. Goh, C. Hwang, J. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

V. Dudenas, A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

I. Ahmed, Z.A. Ibrahim, J.R. Komaragiri, M.A.B. Md Ali [34], F. Mohamad Idris [35], W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz [36], A. Hernandez-Almada, R. Lopez-Fernandez, R. Magaña Villalba, J. Mejia Guisao, A. Sanchez-Hernandez

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

S. Carpinteyro, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

D. Krofcheck

University of Auckland, Auckland, New Zealand

P.H. Butler

University of Canterbury, Christchurch, New Zealand

A. Ahmad, M. Ahmad, Q. Hassan, H.R. Hoorani, W.A. Khan, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

K. Bunkowski, A. Byszuk [37], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, M. Walczak

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Rodrigues Antunes, J. Seixas, O. Toldaiev, D. Vadruccio, J. Varela, P. Vischia

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, G. Kozlov, A. Lanev, A. Malakhov, V. Matveev [38,39], V. Palichik, V. Perelygin, M. Savina, S. Shmatov, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

L. Chtchipounov, V. Golovtsov, Y. Ivanov, V. Kim [40], E. Kuznetsova [41], V. Murzin, V. Oreshkin, V. Sulimov, A. Vorobyev

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, M. Toms, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia

A. Bylinkin [39]

Moscow Institute of Physics and Technology, Moscow, Russia

M. Chadeeva [42], E. Popova, E. Tarkovskii

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

V. Andreev, M. Azarkin [39], I. Dremin [39], M. Kirakosyan, A. Leonidov [39], S.V. Rusakov, A. Terkulov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, M. Dubinin [43], L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

V. Blinov [44], Y. Skovpen [44], D. Shtol [44]

Novosibirsk State University (NSU), Novosibirsk, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, V. Kachanov, A. Kalinin, D. Konstantinov, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

P. Adzic [45], P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic, V. Rekovic

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

J. Alcaraz Maestre, M. Barrio Luna, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, E. Navarro De Martino, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, M.S. Soares

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

J.F. de Trocóniz, M. Missiroli, D. Moran

Universidad Autónoma de Madrid, Madrid, Spain

J. Cuevas, J. Fernandez Menendez, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, S. Sanchez Cruz, I. Suárez Andrés, J.M. Vizan Garcia

Universidad de Oviedo, Oviedo, Spain

I.J. Cabrillo, A. Calderon, J.R. Castiñeiras De Saa, E. Curras, M. Fernandez, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, F. Matorras, J. Piedra Gomez, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, P. Bloch, A. Bocci, A. Bonato, C. Botta, T. Camporesi, R. Castello, M. Cepeda, G. Cerminara, M. D'Alfonso, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, E. Di Marco [46], M. Dobson, B. Dorney, T. du Pree, D. Duggan, M. Dünser, N. Dupont, A. Elliott-Peisert, S. Fartoukh, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, K. Gill, M. Girone, F. Glege, D. Gulhan, S. Gundacker, M. Guthoff, J. Hammer, P. Harris, J. Hegeman, V. Innocente, P. Janot, J. Kieseler, H. Kirschenmann, V. Knünz, A. Kornmayer [17], M.J. Kortelainen, K. Kousouris, M. Krammer [1], C. Lange, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic [47], F. Moortgat, S. Morovic, M. Mulders, H. Neugebauer, S. Orfanelli, L. Orsini, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, A. Racz, T. Reis, G. Rolandi [48], M. Rovere, M. Ruan, H. Sakulin, J.B. Sauvan, C. Schäfer, C. Schwick, M. Seidel, A. Sharma, P. Silva, P. Sphicas [49], J. Steggemann, M. Stoye, Y. Takahashi, M. Tosi, D. Treille, A. Triossi, A. Tsirou, V. Veckalns [50], G.I. Veres [22], N. Wardle, H.K. Wöhri, A. Zagozdzinska [37], W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

W. Bertl, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

Paul Scherrer Institut, Villigen, Switzerland

F. Bachmair, L. Bäni, L. Bianchini, B. Casal, G. Dissertori, M. Dittmar, M. Donegà, C. Grab, C. Heidegger, D. Hits, J. Hoss, G. Kasieczka, P. Lecomte [†], W. Lustermann, B. Mangano, M. Marionneau, P. Martinez Ruiz del Arbol, M. Masciovecchio, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, F. Pandolfi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Rossini, M. Schönenberger, A. Starodumov [51], V.R. Tavolaro, K. Theofilatos, R. Wallny

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler [52], L. Caminada, M.F. Canelli, A. De Cosa, C. Galloni, A. Hinzmann, T. Hreus, B. Kilminster, J. Ngadiuba, D. Pinna, G. Rauco, P. Robmann, D. Salerno, Y. Yang, A. Zucchetta

Universität Zürich, Zurich, Switzerland

V. Candelise, T.H. Doan, Sh. Jain, R. Khurana, M. Konyushikhin, C.M. Kuo, W. Lin, Y.J. Lu, A. Pozdnyakov, S.S. Yu

National Central University, Chung-Li, Taiwan

Arun Kumar, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, P.H. Chen, C. Dietz, F. Fiori, W.-S. Hou, Y. Hsiung, Y.F. Liu, R.-S. Lu, M. Miñano Moya, E. Paganis, A. Psallidas, J.f. Tsai, Y.M. Tzeng

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, G. Singh, N. Srimanobhas, N. Suwonjandee

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

A. Adiguzel, S. Damarseckin, Z.S. Demiroglu, C. Dozen, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, I. Hos, E.E. Kangal [53], O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut [54], K. Ozdemir [55], S. Ozturk [56], A. Polatoz, B. Tali [57], S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Cukurova University - Physics Department, Science and Art Faculty, Adana, Turkey

B. Bilin, S. Bilmis, B. Isildak [58], G. Karapinar [59], M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

E. Gülmez, M. Kaya [60], O. Kaya [61], E.A. Yetkin [62], T. Yetkin [63]

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak, S. Sen [64]

Istanbul Technical University, Istanbul, Turkey

B. Grynyov

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine

L. Levchuk, P. Sorokin

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

R. Aggleton, F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, H. Flacher, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, J. Jacob, L. Kreczko, C. Lucas, D.M. Newbold [65], S. Paramesvaran, A. Poll, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev [66], C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

M. Baber, R. Bainbridge, O. Buchmuller, A. Bundock, D. Burton, S. Casasso, M. Citron, D. Colling, L. Corpe, P. Dauncey, G. Davies, A. De Wit, M. Della Negra, R. Di Maria, P. Dunne, A. Elwood, D. Futyan, Y. Haddad, G. Hall, G. Iles, T. James, R. Lane, C. Laner, R. Lucas [65], L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, J. Nash, A. Nikitenko [51], J. Pela, B. Penning, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, C. Seez, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta [67], T. Virdee [17], J. Wright, S.C. Zenz

Imperial College, London, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leslie, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Brunel University, Uxbridge, United Kingdom

A. Borzou, K. Call, J. Dittmann, K. Hatakeyama, H. Liu, N. Pastika

Baylor University, Waco, USA

O. Charaf, S.I. Cooper, C. Henderson, P. Rumerio, C. West

The University of Alabama, Tuscaloosa, USA

D. Arcaro, A. Avetisyan, T. Bose, D. Gastler, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Boston University, Boston, USA

G. Benelli, E. Berry, D. Cutts, A. Garabedian, J. Hakala, U. Heintz, J.M. Hogan, O. Jesus, K.H.M. Kwok, E. Laird, G. Landsberg, Z. Mao, M. Narain, S. Piperov, S. Sagir, E. Spencer, R. Syarif

Brown University, Providence, USA

R. Breedon, G. Breto, D. Burns, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, M. Gardner, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, J. Smith, M. Squires, D. Stolp, M. Tripathi, S. Wilbur, R. Yohay

University of California, Davis, Davis, USA

C. Bravo, R. Cousins, A. Dasgupta, P. Everaerts, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, D. Saltzberg, C. Schnaible, E. Takasugi, V. Valuev, M. Weber

University of California, Los Angeles, USA

K. Burt, R. Clare, J. Ellison, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, J. Heilman, P. Jandir, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, A. Shrinivas, W. Si, H. Wei, S. Wimpenny, B.R. Yates

University of California, Riverside, Riverside, USA

J.G. Branson, G.B. Cerati, S. Cittolin, M. Derdzinski, R. Gerosa, A. Holzner, D. Klein, V. Krutelyov, J. Letts, I. Macneill, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech [68], C. Welke, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, San Diego, La Jolla, USA

N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, A. Dishaw, V. Dutta, K. Flowers, M. Franco Sevilla, P. Geffert, C. George, F. Golf, L. Gouskos, J. Gran, R. Heller, J. Incandela, S.D. Mullin, A. Ovcharova, J. Richman, D. Stuart, I. Suarez, J. Yoo

University of California, Santa Barbara - Department of Physics, Santa Barbara, USA

D. Anderson, A. Apresyan, J. Bendavid, A. Bornheim, J. Bunn, Y. Chen, J. Duarte, J.M. Lawhorn, A. Mott, H.B. Newman, C. Pena, M. Spiropulu, J.R. Vlimant, S. Xie, R.Y. Zhu

California Institute of Technology, Pasadena, USA

M.B. Andrews, V. Azzolini, T. Ferguson, M. Paulini, J. Russ, M. Sun, H. Vogel, I. Vorobiev, M. Weinberg

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, T. Mulholland, K. Stenson, S.R. Wagner

University of Colorado Boulder, Boulder, USA

J. Alexander, J. Chaves, J. Chu, S. Dittmer, K. Mcdermott, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Cornell University, Ithaca, USA

D. Winn

Fairfield University, Fairfield, USA

S. Abdullin, M. Albrow, G. Apollinari, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla, K. Burkett, J.N. Butler, H.W.K. Cheung, F. Chlebana, S. Cihangir[†], M. Cremonesi, V.D. Elvira, I. Fisk, J. Freeman, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, D. Hare, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, B. Kreis, S. Lammel, J. Linacre, D. Lincoln, R. Lipton, M. Liu, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, C. Newman-Holmes[†], V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck, Y. Wu

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, S. Das, R.D. Field, I.K. Furic, J. Konigsberg, A. Korytov, J.F. Low, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, D. Rank, L. Shchutska, D. Sperka, L. Thomas, J. Wang, S. Wang, J. Yelton

University of Florida, Gainesville, USA

S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida International University, Miami, USA

A. Ackert, J.R. Adams, T. Adams, A. Askew, S. Bein, B. Diamond, S. Hagopian, V. Hagopian, K.F. Johnson, A. Khatiwada, H. Prosper, A. Santra

Florida State University, Tallahassee, USA

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, T. Roy, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, I. Bucinskaite, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, K. Jung, P. Kurt, C. O'Brien, I.D. Sandoval Gonzalez, P. Turner, N. Varelas, H. Wang, Z. Wu, M. Zakaria, J. Zhang

University of Illinois at Chicago (UIC), Chicago, USA

B. Bilki[69], W. Clarida, K. Dilsiz, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya[70], A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul, Y. Onel, F. Ozok[71], A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

The University of Iowa, Iowa City, USA

I. Anderson, B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, P. Maksimovic, C. Martin, M. Osherson, J. Roskes, U. Sarica, M. Swartz, M. Xiao, Y. Xin, C. You

Johns Hopkins University, Baltimore, USA

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, C. Bruner, J. Castle, L. Forthomme, R.P. Kenny III, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, S. Sanders, R. Stringer, J.D. Tapia Takaki, Q. Wang

The University of Kansas, Lawrence, USA

A. Ivanov, K. Kaadze, Y. Maravin, A. Mohammadi, L.K. Saini, N. Skhirtladze, S. Toda

Kansas State University, Manhattan, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

C. Anelli, A. Baden, O. Baron, A. Belloni, B. Calvert, S.C. Eno, C. Ferraioli, J.A. Gomez, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Kolberg, J. Kunkle, Y. Lu, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, M.B. Tonjes, S.C. Tonwar

University of Maryland, College Park, USA

D. Abercrombie, B. Allen, A. Apyan, R. Barbieri, A. Baty, R. Bi, K. Bierwagen, S. Brandt, W. Busza, I.A. Cali, Z. Demiragli, L. Di Matteo, G. Gomez Ceballos, M. Goncharov, D. Hsu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, K. Krajczar, Y.S. Lai, Y.-J. Lee, A. Levin, P.D. Luckey, B. Maier, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, J. Salfeld-Nebgen, G.S.F. Stephans, K. Sumorok, K. Tatar, M. Varma, D. Velicanu, J. Veverka, J. Wang, T.W. Wang, B. Wyslouch, M. Yang, V. Zhukova

Massachusetts Institute of Technology, Cambridge, USA

A.C. Benvenuti, R.M. Chatterjee, A. Evans, A. Finkel, A. Gude, P. Hansen, S. Kalafut, S.C. Kao, Y. Kubota, Z. Lesko, J. Mans, S. Nourbakhsh, N. Ruckstuhl, R. Rusack, N. Tambe, J. Turkewitz

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

E. Avdeeva, R. Bartek, K. Bloom, D.R. Claes, A. Dominguez [72], C. Fangmeier, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, A. Malta Rodrigues, F. Meier, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

University of Nebraska-Lincoln, Lincoln, USA

M. Alyari, J. Dolen, J. George, A. Godshalk, C. Harrington, I. Iashvili, J. Kaisen, A. Kharchilava, A. Kumar, A. Parker, S. Rappoccio, B. Roozbahani

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, A. Hortiangtham, A. Massironi, D.M. Morse, D. Nash, T. Orimoto, R. Teixeira De Lima, D. Trocino, R.-J. Wang, D. Wood

Northeastern University, Boston, USA

S. Bhattacharya, K.A. Hahn, A. Kubik, A. Kumar, N. Mucia, N. Odell, B. Pollack, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

Northwestern University, Evanston, USA

N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, N. Marinelli, F. Meng, C. Mueller, Y. Musienko [38], M. Planer, A. Reinsvold, R. Ruchti, G. Smith, S. Taroni, M. Wayne, M. Wolf, A. Woodard

University of Notre Dame, Notre Dame, USA

J. Alimena, L. Antonelli, J. Brinson, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, R. Hughes, W. Ji, B. Liu, W. Luo, D. Puigh, B.L. Winer, H.W. Wulsin

The Ohio State University, Columbus, USA

S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, D. Lange, J. Luo, D. Marlow, J. Mc Donald, T. Medvedeva, K. Mei, M. Mooney, J. Olsen, C. Palmer, P. Piroué, D. Stickland, A. Svyatkovskiy, C. Tully, A. Zuranski

Princeton University, Princeton, USA

S. Malik

University of Puerto Rico, Mayaguez, USA

A. Barker, V.E. Barnes, S. Folgueras, L. Gutay, M.K. Jha, M. Jones, A.W. Jung, D.H. Miller, N. Neumeister, J.F. Schulte, X. Shi, J. Sun, F. Wang, W. Xie, L. Xu

Purdue University, West Lafayette, USA

N. Parashar, J. Stupak

Purdue University Calumet, Hammond, USA

A. Adair, B. Akgun, Z. Chen, K.M. Ecklund, F.J.M. Geurts, M. Guilbaud, W. Li, B. Michlin, M. Northup, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, Z. Tu, J. Zabel

Rice University, Houston, USA

B. Betchart, A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, K.H. Lo, P. Tan, M. Verzetti

University of Rochester, Rochester, USA

A. Agapitos, J.P. Chou, E. Contreras-Campana, Y. Gershtein, T.A. Gómez Espinosa, E. Halkiadakis, M. Heindl, D. Hidas, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, K. Nash, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

Rutgers, The State University of New Jersey, Piscataway, USA

A.G. Delannoy, M. Foerster, J. Heideman, G. Riley, K. Rose, S. Spanier, K. Thapa

University of Tennessee, Knoxville, USA

O. Bouhali [73], A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, E. Juska, T. Kamon [74], R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Rose, A. Safonov, A. Tatarinov, K.A. Ulmer

Texas A&M University, College Station, USA

N. Akchurin, C. Cowden, J. Damgov, F. De Guio, C. Dragoiu, P.R. Dudero, J. Faulkner, E. Gurpinar, S. Kunori, K. Lamichhane, S.W. Lee, T. Libeiro, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Texas Tech University, Lubbock, USA

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, P. Sheldon, S. Tuo, J. Velkovska, Q. Xu

Vanderbilt University, Nashville, USA

M.W. Arenton, P. Barria, B. Cox, J. Goodell, R. Hirosky, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, X. Sun, Y. Wang, E. Wolfe, F. Xia

University of Virginia, Charlottesville, USA

C. Clarke, R. Harr, P.E. Karchin, J. Sturdy

Wayne State University, Detroit, USA

D.A. Belknap, C. Caillol, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, I. Ojalvo, T. Perry, G.A. Pierro, G. Polese, T. Ruggles, A. Savin, N. Smith, W.H. Smith, D. Taylor, N. Woods

University of Wisconsin–Madison, Madison, WI, USA

† Deceased.
[1] Also at Vienna University of Technology, Vienna, Austria.
[2] Also at State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China.
[3] Also at Institut Pluridisciplinaire Hubert Curien (IPHC), Université de Strasbourg, CNRS/IN2P3, Strasbourg, France.
[4] Also at Universidade Estadual de Campinas, Campinas, Brazil.
[5] Also at Universidade Federal de Pelotas, Pelotas, Brazil.
[6] Also at Université Libre de Bruxelles, Bruxelles, Belgium.
[7] Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
[8] Also at Joint Institute for Nuclear Research, Dubna, Russia.
[9] Also at Helwan University, Cairo, Egypt.
[10] Now at Zewail City of Science and Technology, Zewail, Egypt.
[11] Now at Fayoum University, El-Fayoum, Egypt.
[12] Also at British University in Egypt, Cairo, Egypt.
[13] Now at Ain Shams University, Cairo, Egypt.
[14] Also at Université de Haute Alsace, Mulhouse, France.
[15] Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
[16] Also at Tbilisi State University, Tbilisi, Georgia.
[17] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[18] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[19] Also at University of Hamburg, Hamburg, Germany.
[20] Also at Brandenburg University of Technology, Cottbus, Germany.
[21] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[22] Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
[23] Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
[24] Also at Indian Institute of Science Education and Research, Bhopal, India.
[25] Also at Institute of Physics, Bhubaneswar, India.
[26] Also at University of Visva-Bharati, Santiniketan, India.
[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.
[30] Also at Yazd University, Yazd, Iran.
[31] Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
[32] Also at Università degli Studi di Siena, Siena, Italy.
[33] Also at Purdue University, West Lafayette, USA.
[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 University of Florida, Gainesville, USA.
[42] Also at P.N. Lebedev Physical Institute, Moscow, Russia.
[43] Also at California Institute of Technology, Pasadena, USA.
[44] Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
[45] Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
[46] Also at INFN Sezione di Roma; Università di Roma, Roma, Italy.
[47] Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
[48] Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
[49] Also at National and Kapodistrian University of Athens, Athens, Greece.
[50] Also at Riga Technical University, Riga, Latvia.
[51] Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
[52] Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland.
[53] Also at Mersin University, Mersin, Turkey.
[54] Also at Cag University, Mersin, Turkey.
[55] Also at Piri Reis University, Istanbul, Turkey.
[56] Also at Gaziosmanpasa University, Tokat, Turkey.
[57] Also at Adiyaman University, Adiyaman, Turkey.
[58] Also at Ozyegin University, Istanbul, Turkey.
[59] Also at Izmir Institute of Technology, Izmir, Turkey.
[60] Also at Marmara University, Istanbul, Turkey.
[61] Also at Kafkas University, Kars, Turkey.

[62] Also at Istanbul Bilgi University, Istanbul, Turkey.
[63] Also at Yildiz Technical University, Istanbul, Turkey.
[64] Also at Hacettepe University, Ankara, Turkey.
[65] Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
[66] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[67] Also at Instituto de Astrofísica de Canarias, La Laguna, Spain.
[68] Also at Utah Valley University, Orem, USA.
[69] Also at Argonne National Laboratory, Argonne, USA.
[70] Also at Erzincan University, Erzincan, Turkey.
[71] Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
[72] Now at The Catholic University of America, Washington, USA.
[73] Also at Texas A&M University at Qatar, Doha, Qatar.
[74] Also at Kyungpook National University, Daegu, Republic of Korea.