



# Search for a heavy right-handed W boson and a heavy neutrino in events with two same-flavor leptons and two jets at $\sqrt{s} = 13$ TeV

The CMS Collaboration\*

## Abstract

A search for a heavy right-handed W boson ( $W_R$ ) decaying to a heavy right-handed neutrino and a charged lepton in events with two same-flavor leptons (e or  $\mu$ ) and two jets, is presented. The analysis is based on proton-proton collision data, collected by the CMS Collaboration at the LHC in 2016 and corresponding to an integrated luminosity of  $35.9 \text{ fb}^{-1}$ . No significant excess above the standard model expectation is seen in the invariant mass distribution of the dilepton plus dijet system. Assuming that couplings are identical to those of the standard model, and that only one heavy neutrino flavor  $N_R$  contributes significantly to the  $W_R$  decay width, the region in the two-dimensional ( $m_{W_R}, m_{N_R}$ ) mass plane excluded at 95% confidence level extends to approximately  $m_{W_R} = 4.4 \text{ TeV}$  and covers a large range of right-handed neutrino masses below the  $W_R$  boson mass. This analysis provides the most stringent limits on the  $W_R$  mass to date.

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## 1 Introduction

Heavy partners of the standard model (SM) gauge bosons, that are coupled to right-handed fermions, are predicted in left-right (LR) symmetric models [1–4]. These models explain the parity violation observed in weak interactions as the consequence of spontaneous symmetry breaking at a multi-TeV mass scale. This paper describes a search for such a heavy partner, a heavy right-handed gauge boson  $W_R$ , in events with two same-flavor leptons (e or  $\mu$ ) and two jets. The study was conducted by the CMS Collaboration at the CERN LHC, using proton-proton collision data corresponding to an integrated luminosity of  $35.9 \text{ fb}^{-1}$  recorded during the 2016 data taking period.

The right-handed bosons are assumed to interact with the SM particles with a coupling strength  $g_R$ . This is a free parameter in most LR models, but we assume a strict LR symmetry in our search so that the coupling constant  $g_R$  is the same as the SM coupling constant  $g_L$ . We also assume that the right-handed quark mixing matrix is the same as the Cabibbo–Kobayashi–Maskawa matrix. In addition to the gauge bosons, LR models usually include heavy right-handed neutrinos ( $N_R$ ) [5, 6]. The existence of these heavy neutrinos can explain the very small masses of the SM neutrinos as a consequence of the see-saw mechanism [7–9].

In this search, we consider the case in which the  $W_R$  boson decays to a first- or second-generation charged lepton and a heavy neutrino of the same lepton flavor. The heavy neutrino further decays to another charged lepton of the same flavor and a virtual  $W_R^*$ . The virtual  $W_R^*$  decays to two light quarks, producing the decay chain

$$W_R \rightarrow \ell N_R \rightarrow \ell \ell W_R^* \rightarrow \ell \ell q \bar{q}', \ell = e \text{ or } \mu.$$

The quarks hadronize into jets that can be observed by the CMS detector. The lepton flavor is conserved, and there is no charge requirement on the leptons, which can be opposite-sign or same-sign. The SM processes that have the same final state of two same-flavor leptons and two jets include Drell–Yan production of lepton pairs with additional jets (DY+jets),  $t\bar{t}$  production,  $tW$  from  $t$ -channel single top quark production, and diboson production ( $WZ$ ,  $ZZ$ ,  $WW$ ) with jets. Contributions due to events with jets misidentified as leptons are considered, but are found to be negligible. The discriminating variable in this search is the invariant mass  $m_{\ell\ell jj}$  constructed from the two leptons and two jets with the largest transverse momenta. We search for an excess of events above the SM prediction for different  $W_R$  mass hypotheses in windows of  $m_{\ell\ell jj}$ .

A search for  $W_R$  bosons that was performed by the CMS Collaboration at a center-of-mass energy of  $\sqrt{s} = 8 \text{ TeV}$  excluded  $W_R$  masses up to approximately 3 TeV at 95% confidence level (CL) [10]. An excess with a local significance of  $2.8\sigma$  was observed in that search in the electron channel at  $m_{eejj} \approx 2.1 \text{ TeV}$ . The excess did not appear to be consistent with signal events from the LR symmetric theory. The search presented in this paper extends this previous search using data collected at  $\sqrt{s} = 13 \text{ TeV}$  during 2016. It does not overlap with other heavy neutrino searches previously carried out by the CMS Collaboration [11–13]. The ATLAS Collaboration has also carried out similar searches [14–16].

## 2 The CMS detector

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 a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward

calorimeters extend the pseudorapidity ( $\eta$ ) coverage provided by the barrel and endcap detectors. Electrons are measured in the ECAL, while drift tubes, cathode strip chambers, and resistive-plate chambers embedded in the steel flux-return yoke outside the solenoid are used in the identification of muons. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [17].

### 3 Trigger, particle reconstruction, and event selection

Events of interest are selected online using a two-tiered trigger system [18]. The first level is composed of custom hardware processors and uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz. The second level consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to less than 1 kHz before data storage.

The leptons in the final state carry a large fraction of the rest energy of the  $W_R$ . Thus, a trigger with a high momentum requirement on the lepton is highly efficient for our signal. For events with electrons, we use an unprescaled double-electron trigger. This trigger requires a minimum transverse momentum ( $p_T$ ) of 33 GeV and an ECAL energy deposit with a pixel hit on an associated track. For the muon channel, and for an auxiliary measurement that is used to estimate the  $t\bar{t}$  background, we use unprescaled single-muon triggers that have no isolation requirement and a  $p_T > 50$  GeV requirement applied to the muon.

Global event reconstruction is performed using the particle-flow algorithm [19], which reconstructs and identifies each individual particle with an optimized combination of all subdetector information. At least one reconstructed vertex is required. For events with multiple collision vertices from additional collisions in the same or adjacent bunch crossings (pileup interactions), the reconstructed vertex with the largest value of summed  $p_T^2$  in the event, where the sum extends over all charged tracks associated with the vertex, is taken to be the primary pp interaction vertex (PV).

Electron candidates are identified by the association of a charged-particle track from the PV, with energy deposits clusters (superclusters) in the ECAL. The association takes into account energy deposits both from the electron and from bremsstrahlung photons produced during its passage through the inner detector. The electron momentum is estimated by combining the energy measurement in the ECAL with the momentum measurement in the tracker. The experimental mass resolution for barrel-barrel (barrel-endcap) dielectron pairs with a mass of 1 TeV is 1.0 (1.5)% [20]. To correct for observed discrepancies in energy scale and resolution between data and simulation, the measured electron energy is adjusted by a multiplicative factor that depends on  $\eta$  and  $R_9$ , where  $R_9$  is the ratio of the energy in a  $3 \times 3$  matrix of ECAL crystals, centered on the crystal with the largest energy, to the full energy collected by a supercluster. In addition, the electron energy in simulated events is smeared by 1–3% using a Gaussian expression that varies as a function of  $\eta$  and  $R_9$  [20]. Differences in electron identification (ID) efficiency between data and simulation were taken into account by applying a scale factor (SF) of  $0.972 \pm 0.006$  (stat+syst) in the barrel and  $0.983 \pm 0.007$  (stat+syst) in the endcaps.

Muons are reconstructed from tracker and muon chamber information. Each muon is required to have at least one hit in the pixel detector, at least six tracker layer hits, and segments in two or more muon detector stations. Muons are measured in the range  $|\eta| < 2.4$ . The  $p_T$  resolution in the barrel is better than 10% for muons with  $p_T$  up to 1 TeV [21]. The muon momentum resolution in data is well described in simulated events, with its uncertainty provided by a

smearing of 1% in the barrel and 2% in the endcaps. The muon curvature distributions in data and simulation are compared for different ranges of  $\eta$  and azimuthal angle ( $\phi$ , in radians), resulting in the assignment of a momentum scale uncertainty of 3% in the barrel and up to 9% in the endcaps. To account for differences in the reconstruction and identification efficiencies between data and simulation,  $\eta$ -dependent SFs in the range 0.95–0.99 are applied to simulated events [21]. Systematic uncertainties related to the dependence of the SFs on momentum are neglected, since they have an impact on the results of less than 1%.

Charged hadrons are identified by matching tracks to one or more calorimeter clusters, and by the absence of signal in the muon detectors. The energies of charged hadrons are determined from combinations of the track momenta and the corresponding ECAL and HCAL energies, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers.

Neutral hadrons are identified as ECAL and HCAL energy clusters that are not matched to charged particle trajectories. The energies of neutral hadrons are obtained from the corresponding corrected ECAL and HCAL energies.

For each event, hadronic jets are clustered from reconstructed particles with the anti- $k_T$  algorithm, operated with a size parameter  $R$  of 0.4, where  $R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$  [22, 23]. Charged hadrons that originate from pileup interactions are removed from the list of reconstructed particles using the charged-hadron pileup subtraction algorithm [19]. The contributions of neutral particles that originate from pileup interactions to the calorimeter energies are removed by applying a residual average area-based correction [24]. The jet momentum is defined as the vector sum of all particle momenta associated with the jet, and is found to be within 5 to 10% of the true momentum in simulated events over the whole  $p_T$  spectrum and detector acceptance. Jet energy corrections are derived from the simulation, and are confirmed with in-situ measurements of the energy balance in dijet, multijet, photon+jet, and leptonically decaying Z+jet events [25]. Jet identification algorithms [25] also remove contributions to jets from calorimeter noise and beam halo.

To reconstruct  $W_R$  candidates, we select the two leptons with the largest  $p_T$  and the two jets with the largest  $p_T$ . The leading (subleading) leptons are required to have  $p_T > 60$  (53) GeV and to be within the detector acceptance ( $|\eta| < 2.4$ ). Electrons are rejected if the supercluster lies in the range  $1.444 < |\eta| < 1.566$ , which corresponds to the transition region between the barrel and endcap sections of the ECAL, where the performance is degraded. To suppress muons originating from hadron decays or pion punch-through in jets, we remove muons for which the sum of the  $p_T$  of additional tracks that originate from the PV and that are inside a cone of  $R < 0.3$  around the muon is more than 10% of the muon  $p_T$ . We also require electrons to be isolated, i.e., the sum of the  $p_T$  of all tracks inside a cone of  $R < 0.3$  centered on the electron candidate, not associated with the electron and originating from the PV must be below 5 GeV. We use dedicated identification algorithms, optimized for the selection of high-momentum leptons [20, 21]. The two jet candidates must each have  $p_T > 40$  GeV and be within  $|\eta| < 2.4$ . To avoid having reconstructed leptons overlap jets, we impose a  $\Delta R > 0.4$  requirement between all jets and leptons.

## 4 Signal model

We use several auxiliary data samples to estimate signal and background contributions to our search as well as to validate our event selection. We use Monte Carlo (MC) simulation in the calculation of the signal efficiency and in the estimation of some of the SM backgrounds. In these

simulations, the response of the CMS detector is modeled using the GEANT4 package [26]. Pileup contributions are modeled by superimposing simulated inelastic proton-proton interactions onto the primary hard scattering. The simulated distribution of the number of pileup events is matched to that observed in the data.

For estimating the acceptance and efficiency for detecting  $W_R$  bosons, simulated signal samples of  $e\bar{e}j\bar{j}$  and  $\mu\bar{\mu}j\bar{j}$  final states are generated assuming  $m_{N_R} = 1/2m_{W_R}$ , using the PYTHIA 8.212 program [27] with the NNPDF2.3 [28] parton distribution functions (PDFs). Simulated signal samples with  $m_{N_R} \neq 1/2m_{W_R}$ , needed to estimate the 2D limits described in Section 6, are also generated using PYTHIA 8.212.

We focus our search on a region of phase-space where the signal is expected to appear. This signal region applies to events with two leptons with the same flavor and two jets. The invariant mass of the dilepton system must be above 200 GeV, to avoid contamination from resonant Z boson production. The  $m_{\ell\bar{\ell}j\bar{j}}$  must be greater than 600 GeV to ensure that all the kinematic requirements on the candidates are fully efficient. There is no charge requirement on the leptons, to ensure sensitivity to a wider class of models.

Using the selection requirements described above, the product of the acceptance and efficiency for  $W_R$  decays to the  $\ell\bar{\ell}j\bar{j}$  final state, increases from 30% at  $m_{W_R} = 1000$  GeV to 57% for  $m_{W_R} > 3000$  GeV in the electron channel, and similarly from 40 to 75% in the muon channel. For both channels, the signal efficiency reaches a plateau at  $m_{W_R} = 3000$  GeV. The efficiency for electron events is lower than the muon event efficiency because of differences between the selection requirements, and because of the omission of the transition regions between the ECAL barrel and endcaps in the case of electrons.

## 5 Background estimation

Standard model processes that produce events with the same final-state particles as the signal model include DY production of lepton pairs with additional jets in the final state, and  $t\bar{t}$  and diboson production. The DY+jets and  $t\bar{t}$  production are irreducible background processes that comprise most of the background events in the signal region. The contribution from diboson backgrounds is suppressed by the dilepton mass requirement ( $m_{\ell\bar{\ell}} > 200$  GeV). We also consider backgrounds for which candidate misidentification leads to events with two leptons and two jets in the final state. These backgrounds include W boson production with additional jets,  $t$ -channel single top quark events with additional jets, and QCD multijet events. These reducible backgrounds do not significantly contaminate our signal region. The diboson backgrounds constitute  $\sim 1.5\%$  of the total background in the signal region, the W+jets  $\sim 0.5\%$ , the single top quark events  $\sim 5\%$ , and the QCD events  $\sim 0.1\%$ .

The MC samples used to estimate the background processes are simulated with several MC event generators. The DY+jets and the  $t\bar{t}$  samples are generated with MADGRAPH5\_aMC@NLO 2.3.3 [29] at next-to-leading order (NLO) using the NLO NNPDF3.0 [30] PDF set. Diboson (WW, WZ, and ZZ) samples are generated at leading order (LO) using PYTHIA 8.212 along with the LO NNPDF2.3 [28] PDFs, while W+jets events are generated with MADGRAPH5\_aMC@NLO 2.3.3 [29] at leading order (LO) and single top quark events are produced in the  $tW$  channel with POWHEG v1.0 [31–34]. The more precise NLO calculations are used to normalize the SM simulated samples of diboson, W+jets and single top quark events to NLO accuracy. The NNPDF3.0 PDFs are used for samples generated at NLO. For all samples, PYTHIA 8.212 is used for parton showering, fragmentation and hadronization with the underlying event tune CUETP8M1 [35]. The DY+jets samples have one parton at the matrix element level, and additional par-

ton showering is modeled in PYTHIA. The potential double counting of partons generated using PYTHIA with those using MADGRAPH5\_aMC@NLO is minimized using the MLM [36] (FXFX [37]) matching scheme in the LO (NLO) samples.

We define different regions of phase-space (control regions) to estimate the contributions of the different SM backgrounds. To study the background contribution from DY+jets events we use a sample defined by the presence of two same-flavor, opposite-charge electrons or muons and two jets. The invariant mass of the dilepton system must satisfy  $m_{\ell\ell} < 200$  GeV. We call this the “low dilepton mass control region”. The “flavor control region”, used to study the  $t\bar{t}$  background contribution, corresponds to an event sample composed of one electron, one muon, and two jets. For this region the invariant mass of the dilepton system must satisfy  $m_{\ell\ell} > 200$  GeV, while the  $m_{\ell\ell jj}$  is required to be above 600 GeV.

## 5.1 Drell–Yan background

Monte Carlo simulation is used to estimate the background from high mass DY lepton pair production in association with additional jets, since no high purity control region has been identified having the same kinematic characteristics as the signal region. The normalization of DY+jets background in simulation is adjusted to match the event counts in data using a SF calculated as the ratio of data and simulation events under the Z resonance in the range  $80 < m_{\ell\ell} < 100$  GeV. This SF corrects for residual mismodeling between data and simulation, and includes the signal region requirements on the jets. The measured SF is  $1.07 \pm 0.01$  (stat) in both electron and muon channels.

We compare between data and MC all the kinematic distributions of the low dilepton mass control region for the ee and  $\mu\mu$  channels, respectively. The agreement in this control region is especially important since we derive the estimate for the shape of the DY+jets background directly from simulation. The distributions of some kinematic quantities in the low dilepton mass control region with the SF already applied are shown in Fig. 1 for both electron and muon channels. In these plots, all expected SM backgrounds, except for DY+jets and  $t\bar{t}$ , are labelled as *Other backgrounds*. Good agreement is observed in the shapes of the kinematic distributions in both cases.

To verify that the SF measured for DY+jets below the Z boson peak is valid also at higher dilepton masses, we use a dedicated control region, referred to as the “low  $m_{\ell\ell jj}$  control region”, which is defined by the signal region selections, except for an inverted  $m_{\ell\ell jj} < 600$  GeV requirement. In this control region, we check for agreement between data and simulation in events with high dilepton mass. The  $m_{\ell\ell jj}$  distributions with the DY SF applied are shown in Fig. 2.

## 5.2 $t\bar{t}$ background

The  $t\bar{t}$  background contribution is estimated directly from data in the flavor control region defined above, which has the same kinematic characteristics as the  $t\bar{t}$  events in the signal region. For this estimate, we use the events in the flavor control region, assuming that there is no contamination from signal events. This assumption, which corresponds to an imposition of the conservation of individual lepton flavor on our signal models, is valid since, at leading order, the decay of a  $W_R$  boson cannot yield events with an  $e\mu jj$  final state.

To calculate the number of events from  $t\bar{t}$  production in the  $eejj$  and the  $\mu\mu jj$  signal regions, we use simulated  $t\bar{t}$  events to determine transfer factors  $R_{\ell\ell/e\mu}$  ( $\ell\ell = ee$  or  $\mu\mu$ ) between the  $e\mu jj$  control region and the signal region. These factors are evaluated from the ratio of the number of simulated  $t\bar{t}$  events in the distributions of  $m_{eejj}$  or  $m_{\mu\mu jj}$  in the signal region to the number

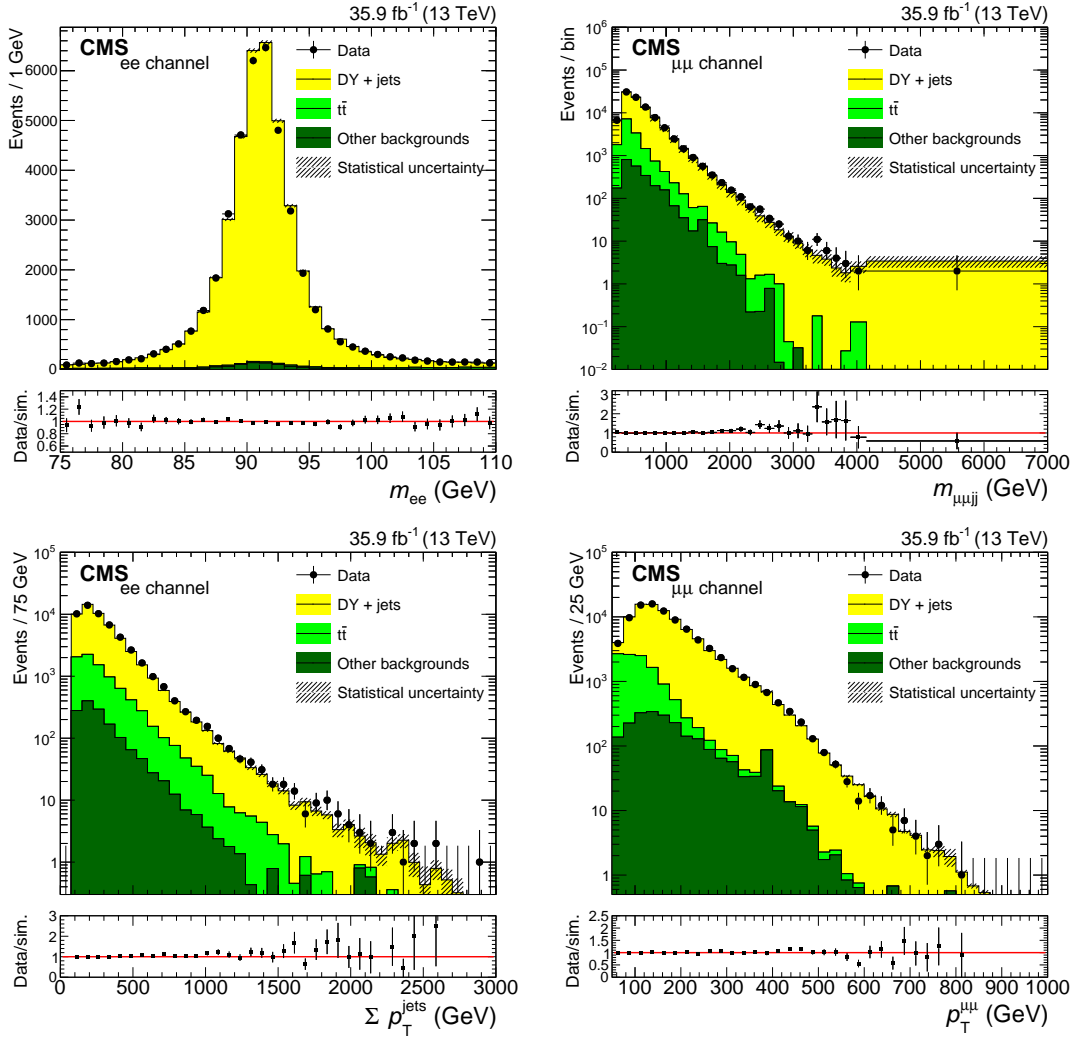


Figure 1: Kinematic distributions for events in the low dilepton mass control region with the DY SF applied. The dilepton mass (upper left) and the scalar sum of all jet transverse momenta (lower left) are shown for the  $ee$  DY plus two jets selection. The  $m_{\ell\ell ij}$  (upper right) and the dilepton transverse momentum (lower right) are shown for the  $\mu\mu$  DY plus two jets selection. The uncertainty bands on the simulated background histograms include only statistical uncertainties. The uncertainty bars in the ratio plots represent combined statistical uncertainties of data and simulation.



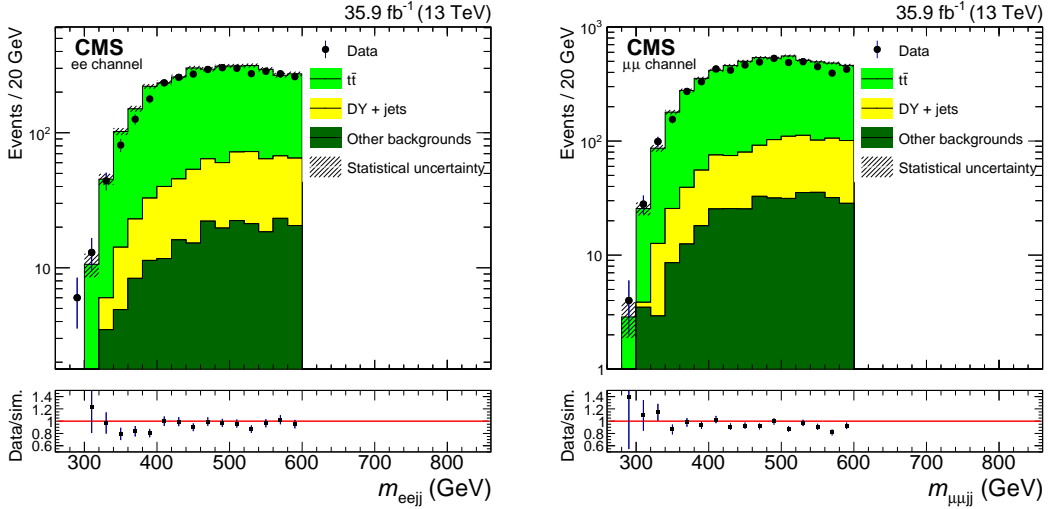


Figure 2: The  $m_{\ell\ell jj}$  distribution in the low  $m_{\ell\ell jj}$  control region with the DY SF applied for the electron (left) and muon (right) channel. The uncertainty bands on the simulated background histograms include only statistical uncertainties. The uncertainty bars in the ratio plots represent combined statistical uncertainties of data and simulation.

Table 1: Transfer factors applied to the number of events in the flavor control region to estimate the number of  $t\bar{t}$  events in the  $e\ell jj$  and  $\mu\mu jj$  signal regions.

Channel	Transfer factor	Stat. uncertainty	Syst. uncertainty
$e\mu jj \rightarrow ee jj$	0.42	0.01	0.07
$e\mu jj \rightarrow \mu\mu jj$	0.72	0.02	0.14

of events in the distribution of  $m_{e\mu jj}$  in the flavor control region. The number of events in the signal region is then given by:

$$N_{t\bar{t}}(\text{signal region}) = N_{t\bar{t}}(\text{flavor control region}) R_{\ell\ell/e\mu}. \quad (1)$$

Using the transfer factor, we can account for the difference in the efficiency and acceptance between electrons and muons in these final states. The values of the transfer factors obtained are given in Table 1. The  $R_{\ell\ell/e\mu}$  as a function of the  $m_{\ell\ell jj}$  distribution is fit to a constant. A systematic uncertainty is assigned by fitting the transfer factor to a linear function and taking the difference between the values of this function at the high and low  $m_{\ell\ell jj}$ . Figure 3 shows a comparison between simulated events and data for several kinematic variables in the flavor control region.

The  $t\bar{t}$  background contribution in the signal region is estimated without the direct use of simulated events. However, the agreement between simulation and data in the flavor control region suggests that other modeling using simulation, such as the signal acceptance, is reliable.

## 6 Results

The strategy followed in this analysis is to search for deviations from the shape of the  $m_{\ell\ell jj}$  distribution expected in the standard model. This distribution extends over a range of several TeV. While the LR symmetric models motivate the choice of the  $\ell\ell jj$  final state, we do not impose requirements on the signal shape specific to these models, in order to maintain sensitivity to other models. The strategy to search for an excess of events in a wide mass range is effective in analyzing the data without exploiting other characteristics of the benchmark signal model and

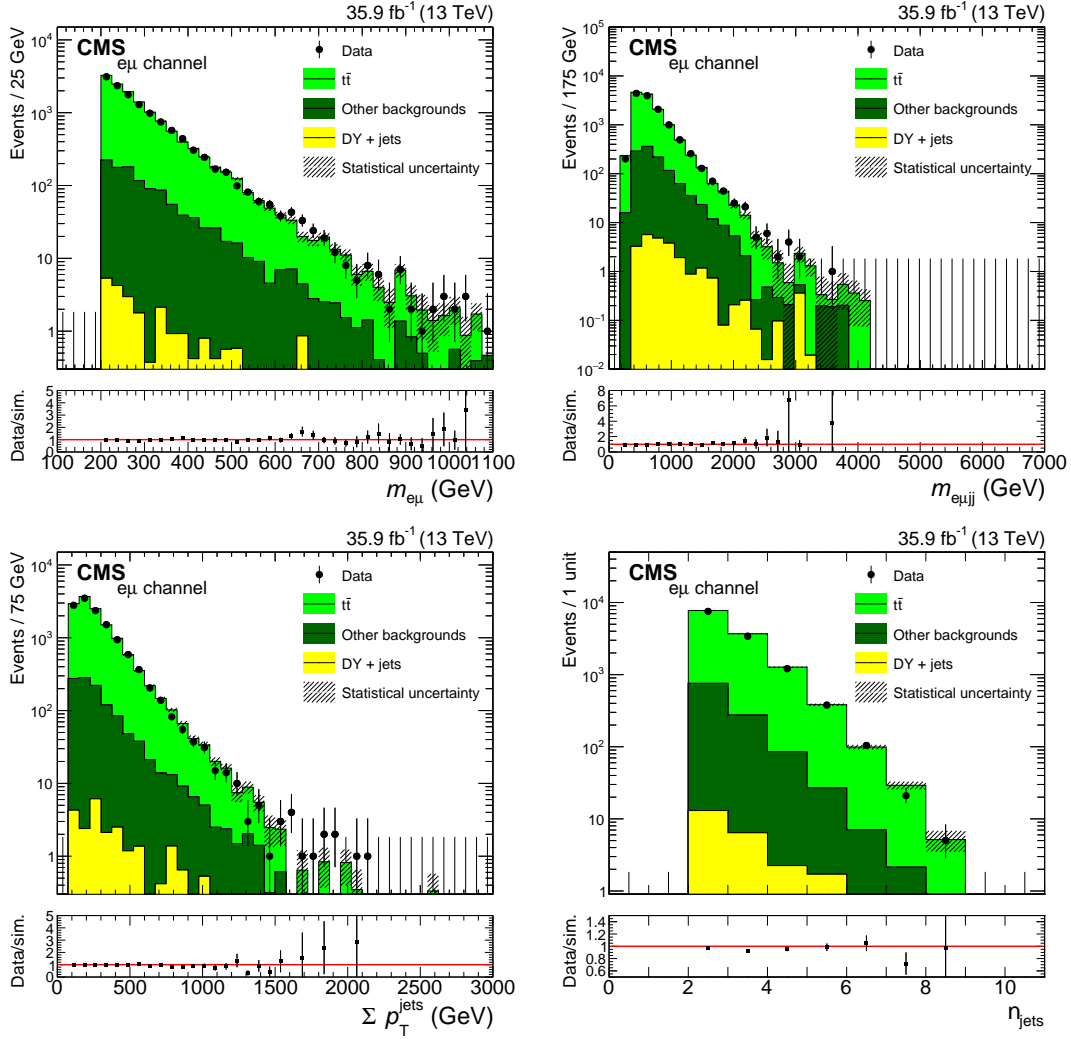


Figure 3: Kinematic distributions for events in the flavor control region with the DY SF applied. The dilepton mass (upper left), the  $m_{\ell\ell jj}$  (upper right), the scalar sum of all jet transverse momenta (lower left), and the number of jets (lower right) are shown. The uncertainty bands on the simulated background histograms include only statistical uncertainties. The uncertainty bars in the ratio plots represent combined statistical uncertainties of data and simulation.

reduces the effect of the uncertainties in the shapes of the backgrounds, especially in the high- $m_{\ell\ell j}$  region. The expected number of signal and background events is estimated by counting the events falling in a particular  $m_{\ell\ell j}$  window. The upper and lower limits of the mass window are chosen as a function of  $m_{W_R}$  to obtain the most stringent expected cross section upper limits. Optimizing with respect to signal significance instead results in comparable mass windows. The width of the mass window for the electron final state varies from 130 GeV at low masses ( $m_{W_R} \simeq 800$  GeV) to 3100 GeV at high masses ( $m_{W_R} \simeq 6000$  GeV). For muons, the mass window varies more, and becomes as large as 3800 GeV. The upper and lower bounds are fitted as functions of  $m_{W_R}$  to third degree polynomials to reduce the effect of statistical fluctuations in the optimization procedure.

The probability of the observed number of events being produced by a combination of background and signal with a cross section  $\sigma$  is calculated using a Bayesian approach with flat signal prior and a fit model with nuisance parameters introduced to address the uncertainties, with log-normal priors. The exclusion limit on the cross section  $\sigma$  is defined as the upper bound of the one-sided 95% credibility interval determined from the posterior likelihood distribution for the signal cross section. This procedure is repeated for each mass hypothesis.

In order to take into account the statistical and systematic uncertainties, pseudo-experiments are performed, varying the expected number of events from signal and background according to the uncertainties as described below. The median of the distribution of the excluded cross section produced by pseudo-experiments and the intervals containing 68 and 95% of the pseudo-experiments are then quoted in the expected limits and their uncertainties.

The sources of systematic uncertainty considered in this analysis are the uncertainty in the integrated luminosity determination [38], the normalization uncertainty in the  $t\bar{t}$  background, the uncertainties due to proton PDFs, and factorization and renormalization scales for the DY+jets background and the signal, and the systematic effects related to candidate reconstruction. This last set of uncertainties, affecting the shape of the  $m_{\ell\ell j}$  distribution, include uncertainties in the jet and lepton energy scales and resolutions, and in the lepton reconstruction, trigger, isolation, and identification SFs.

In order to propagate the uncertainties in candidate reconstruction, a large number of pseudo-experiments are performed, varying all the uncertainty sources at the same time in an uncorrelated fashion, each according to a Gaussian distribution with mean equal to the nominal value and width equal to the uncertainty of the single source. The variations are performed before the event selection, so each pseudo-experiment is processed using the full analysis chain. The expected number of events for signal and background in a mass window is evaluated for each pseudo-experiment. The values used to extract the limit are given by the mean of the pseudo-experiment distribution, and their standard deviation is the propagated uncertainty. The uncertainties in the candidate reconstruction are then implemented as nuisance parameters with log-normal priors in the limit evaluation. The effects of these uncertainties on the signal and background yields are listed in Table 2.

The uncertainty in the integrated luminosity affects only the normalization of the  $m_{\ell\ell j}$  distributions, as does the uncertainty in the  $t\bar{t}$  extrapolation SF given by the sum in quadrature of its statistical and systematic uncertainties, evaluated as described in Section 5.

The uncertainties in the estimation of the DY+jets background are implemented as a function of  $m_{\ell\ell j}$  following the PDF4LHC prescription [39], and affect both shape and normalization of the  $m_{\ell\ell j}$  distributions. Table 3 lists the range of values of these uncertainties, which are included in the evaluation of the limits as nuisance parameters with log-normal priors.

Table 2: Effect of systematic uncertainties in candidate reconstruction efficiencies, energy scale and resolutions on the signal and background yields. The Signal column shows the range of uncertainties computed at each of the  $W_R$  mass points. The Background column indicates the range of the uncertainties for the backgrounds.

Uncertainty	Signal (%)	Background (%)
Jet energy resolution	3.2–26	0.90–25
Jet energy scale	0.20–29	4.8–27
Electron energy resolution	3.7–4.8	2.7–4.5
Electron energy scale	3.7–6.4	4.9–5.9
Electron reco/trigger/ID	8.7–11	6.1–10
Muon energy resolution	4.7–10	6.9–12
Muon energy scale	4.7–10	6.2–12
Muon trigger/ID/iso	2.3–4.7	1.9–5.2

Table 3: Uncertainties affecting the  $m_{\ell\ell jj}$  distribution shape and normalization. The uncertainties in the  $t\bar{t}$  SFs affect the  $t\bar{t}$  background, the uncertainties in the DY PDF and the DY factorization and renormalization scales affect the DY+jets background, and the uncertainty in the integrated luminosity affects both signal and backgrounds.

Uncertainty	Magnitude (%)
$t\bar{t}$ extrapolation $ee/e\mu$ SF	17 (stat+syst)
$t\bar{t}$ extrapolation $\mu\mu/e\mu$ SF	20 (stat+syst)
DY $ee$ PDF	15–70 (syst)
DY $ee$ renormalization/factorization	5.0–40 (syst)
DY $\mu\mu$ PDF	10–70 (syst)
DY $\mu\mu$ renormalization/factorization	10–50 (syst)
Integrated luminosity	2.5 (stat+syst)

Concerning uncertainties in the signal arising from the PDF and scale uncertainties, only the effect on the  $W_R$  signal acceptance is considered in the expected limit calculation. The effect is implemented as a function of  $m_{\ell\ell jj}$  as for the DY+jets background.

All of the uncertainties that affect the shape of the  $m_{\ell\ell jj}$  distribution also affect the number of events in specific mass ranges and effectively become normalization uncertainties.

To include the statistical uncertainties for each process in the evaluation of the limits, Gamma distributions are used [40]. In the limit estimation, pseudo-experiments are generated based on the expected number of events, sampled according to a Gamma distribution and multiplied by the log-normal distributions of the systematics uncertainties.

In Table 4, the expected number of events, including the statistical and systematic uncertainties, for the  $W_R$  signal, the DY+jets and  $t\bar{t}$  background events, and the total of additional smaller background sources are reported, together with the observed number of events, for several representative  $W_R$  mass points. The signal normalization is obtained for the assumptions  $m_{N_R} = 1/2m_{W_R}$  and  $g_R = g_L$ . In Fig. 4, we present the observed  $m_{\ell\ell jj}$  distribution in the signal region and compare it to the expected backgrounds and the signal shape for  $m_{W_R} = 4$  TeV. No significant deviations are seen in the data with respect to expectation.

Table 4: Number of expected events for signal, DY+jets,  $t\bar{t}$ , Other, and All backgrounds, as well as the observed number of events in different  $W_R$  mass windows. All uncertainties are included in the expected number of events. In each table cell, the entry is of the form (mean  $\pm$  stat  $\pm$  syst).

$m_{W_R}$ [mass window] (GeV)	Signal	DY+jets	$t\bar{t}$	Other	All backgrounds	Data
Electron channel						
2200 [1960–2810]	$474.0 \pm 3.7 \pm 44.7$	$15.7^{+5.1}_{-3.9} \pm 3.0$	$23.6^{+5.9}_{-4.8} \pm 2.8$	$9.1^{+4.1}_{-2.9} \pm 2.3$	$48.3^{+8.8}_{-6.9} \pm 4.8$	56
2800 [2530–3840]	$114.1 \pm 0.9 \pm 10.6$	$4.1^{+3.2}_{-1.9} \pm 0.8$	$5.8^{+3.6}_{-2.3} \pm 0.8$	$4.0^{+3.2}_{-1.9} \pm 0.8$	$14.0^{+5.7}_{-3.6} \pm 1.4$	15
3600 [3250–5170]	$19.2 \pm 0.2 \pm 1.8$	$1.0^{+2.3}_{-0.8} \pm 0.2$	$0.4^{+2.1}_{-0.4} \pm 0.1$	$0.2^{+1.9}_{-0.2} \pm 0.1$	$1.6^{+3.7}_{-0.9} \pm 0.2$	3.0
Muon channel						
2200 [1860–2800]	$744.0 \pm 4.7 \pm 47.5$	$35.0^{+7.0}_{-5.9} \pm 4.8$	$40.1^{+7.4}_{-6.3} \pm 7.0$	$12.0^{+4.6}_{-3.4} \pm 1.3$	$87.1^{+11.1}_{-9.3} \pm 8.6$	74
2800 [2430–3930]	$177.0 \pm 1.1 \pm 13.1$	$8.4^{+4.0}_{-2.8} \pm 1.3$	$9.9^{+4.3}_{-3.1} \pm 1.8$	$2.7^{+2.8}_{-1.5} \pm 0.3$	$20.9^{+6.5}_{-4.5} \pm 2.2$	18
3600 [3190–5500]	$29.2 \pm 0.2 \pm 2.6$	$1.6^{+2.5}_{-1.1} \pm 0.5$	$0.7^{+2.2}_{-0.7} \pm 0.1$	$0.2^{+1.9}_{-0.2} \pm 0.1$	$2.6^{+3.9}_{-1.3} \pm 0.5$	4.0

Expected and observed exclusion limits on the signal cross section at 95% CL are shown in Fig. 5, taking into account all the systematic and statistical uncertainties described in this section. For the  $W_R$  model, with  $m_{N_R} = 1/2m_{W_R}$ , the observed lower limit at 95% CL on the mass of the right-handed  $W$  boson is 4.4 TeV for both channels, while the expected exclusion limit is 4.4 TeV for the electron channel and 4.5 TeV for the muon channel, giving an improvement of  $\sim 1.4$  TeV from the previous analysis at 8 TeV. The most significant excess, of  $\sim 1.5\sigma$ , is observed at  $m_{\ell\ell jj} \simeq 3.4$  TeV in the electron channel. A  $2.8\sigma$  excess seen at  $m_{eejj} \approx 2.1$  TeV with the 8 TeV analysis is thus not confirmed by the present data. The lower edge of the 95% CL band disappears at high masses because of the small number of events in that region. Assuming that only one heavy neutrino flavor  $N_R$  contributes significantly to the  $W_R$  decay width, the region in the two-dimensional  $(m_{W_R}, m_{N_R})$  mass plane is analyzed, covering a large range of neutrino masses below the  $W_R$  boson mass. The  $W_R$  cross section limits obtained for  $m_{N_R} = 1/2m_{W_R}$  are scaled to this 2D plane by applying an  $m_{W_R}$ - and  $m_{N_R}$ -dependent SF to the cross section limit. This SF is calculated using  $W_R$  signal events at the generator level that pass the signal selection, and accounts for the change in the  $W_R$  acceptance and efficiency as  $m_{N_R}$  changes for fixed  $m_{W_R}$ . The expected and observed upper limits on the cross section for different  $W_R$  and  $N_R$  mass hypotheses are shown in Fig. 6. The 2D exclusion limits are less stringent in the region

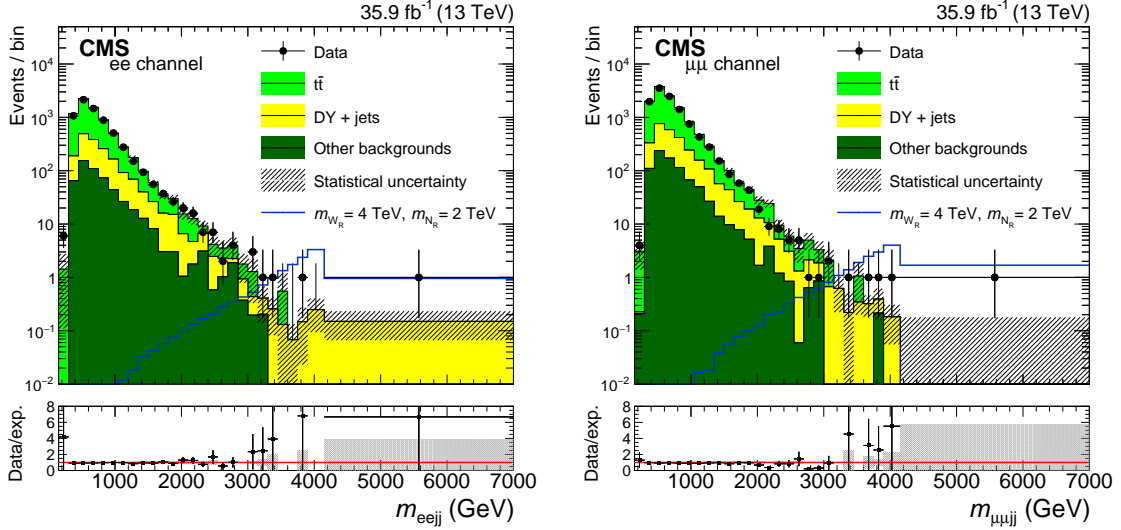


Figure 4: The  $m_{\ell\ell jj}$  distribution in the signal region for the electron (left) and muon (right) channel. The uncertainty bands on the simulated background histograms include only statistical uncertainties. The uncertainty bars in the ratio plots represent combined statistical uncertainties of data and simulation. The gray error band around unity represents the systematic uncertainty on the simulation.

$m_{N_R} \lesssim 1/8 m_{W_R}$ , where the selection efficiency in generator level events is lower than in fully reconstructed events.

## 7 Summary

A search for a right-handed analogue of the standard model W boson in the decay channel of two leptons and two jets has been presented. The analysis is based on proton-proton collision data collected at  $\sqrt{s} = 13$  TeV by the CMS experiment at the LHC in 2016, corresponding to an integrated luminosity of  $35.9 \text{ fb}^{-1}$ . No significant excess over the standard model background expectations is observed in the invariant mass distribution of the dilepton plus dijet system. Thus the  $2.8\sigma$  excess previously observed in data recorded by CMS at 8 TeV is not confirmed. Assuming that couplings are identical to those of the standard model, a region in the two-dimensional plane ( $m_{W_R}, m_{N_R}$ ) covering a large range of right-handed neutrino masses is excluded at 95% confidence level. A  $W_R$  boson decaying into a right-handed heavy neutrino with a mass  $m_{N_R} = 1/2 m_{W_R}$  is excluded at 95% confidence level up to a mass of 4.4 TeV, providing the most stringent limit to date.

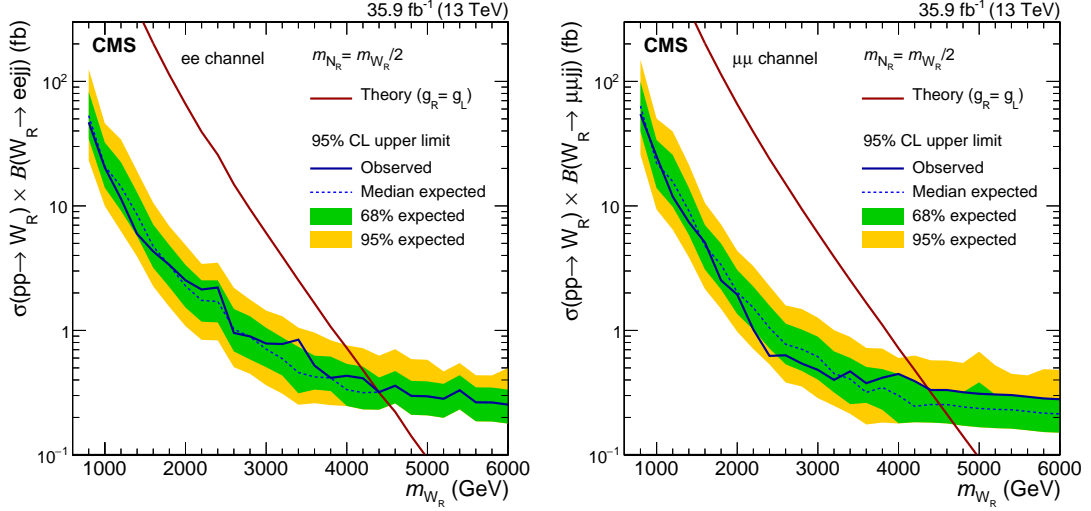


Figure 5: Expected and observed 95% CL upper limits on the product of  $\sigma(pp \rightarrow W_R)$  and branching fraction  $B(W_R \rightarrow \ell\ell jj)$  for the electron channel on the left and for the muon channel on the right. The inner (green) band and the outer (yellow) band indicate the expected 68% and 95% CL exclusion regions.

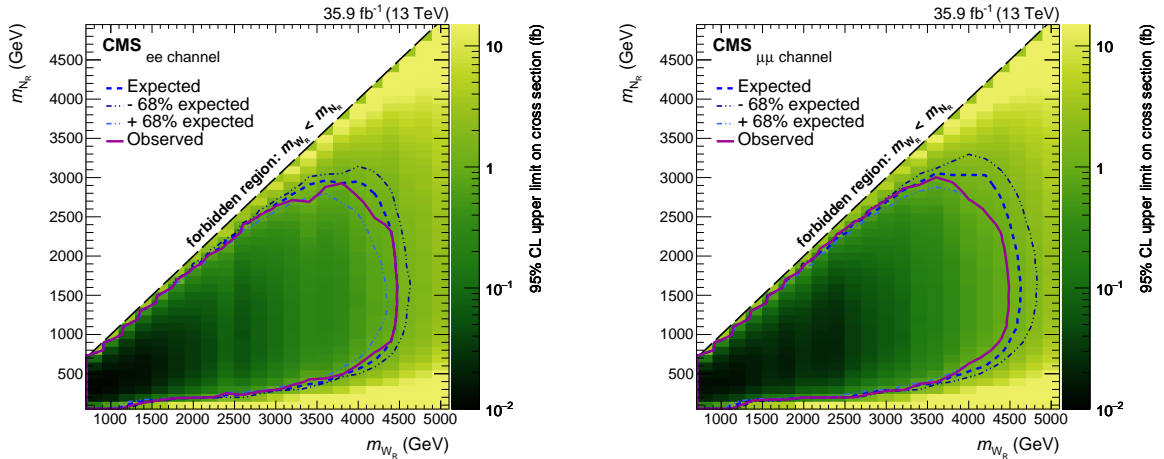


Figure 6: Upper limit on the cross section for different  $W_R$  and  $N_R$  mass hypotheses, for the electron channel on the left and for the muon channel on the right. The expected and observed exclusions are shown as the dotted (blue) curve and the solid (red) curve, respectively. The thin-dotted (blue) curves indicate the region in  $(m_{W_R}, m_{N_R})$  parameter space that is expected to be excluded at 68% CL in the case that no signal is present in the data.

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## A The CMS Collaboration

### Yerevan Physics Institute, Yerevan, Armenia

A.M. Sirunyan, A. Tumasyan

### Institut für Hochenergiephysik, Wien, Austria

W. Adam, F. Ambrogio, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, M. Friedl, R. Frühwirth<sup>1</sup>, V.M. Ghete, J. Grossmann, J. Hrubec, M. Jeitler<sup>1</sup>, A. König, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, E. Pree, N. Rad, H. Rohringer, J. Schieck<sup>1</sup>, R. Schöfbeck, M. Spanring, D. Spitzbart, A. Taurok, W. Waltenberger, J. Wittmann, C.-E. Wulz<sup>1</sup>, M. Zarucki

### Institute for Nuclear Problems, Minsk, Belarus

V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

### Universiteit Antwerpen, Antwerpen, Belgium

E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, M. Pieters, M. Van De Klundert, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

### Vrije Universiteit Brussel, Brussel, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

### Université Libre de Bruxelles, Bruxelles, Belgium

D. Beghin, B. Bilin, H. Brun, B. Clerboux, G. De Lentdecker, H. Delannoy, B. Dorney, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, A.K. Kalsi, T. Lenzi, J. Luetic, T. Seva, E. Starling, C. Vander Velde, P. Vanlaer, D. Vannerom, R. Yonamine

### Ghent University, Ghent, Belgium

T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov<sup>2</sup>, D. Poyraz, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

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

H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, C. Caputo, A. Caudron, P. David, S. De Visscher, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrkowski, L. Quertenmont, A. Saggio, M. Vidal Marono, S. Wertz, J. Zobec

### Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

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

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

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato<sup>3</sup>, E. Coelho, E.M. Da Costa, G.G. Da Silveira<sup>4</sup>, D. De Jesus Damiao, S. Fonseca De Souza, H. Malbouisson, M. Medina Jaime<sup>5</sup>, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote<sup>3</sup>, F. Torres Da Silva De Araujo, A. Vilela Pereira

### Universidade Estadual Paulista <sup>a</sup>, Universidade Federal do ABC <sup>b</sup>, São Paulo, Brazil

S. Ahuja<sup>a</sup>, C.A. Bernardes<sup>a</sup>, L. Calligaris<sup>a</sup>, T.R. Fernandez Perez Tomei<sup>a</sup>, E.M. Gregores<sup>b</sup>, P.G. Mercadante<sup>b</sup>, S.F. Novaes<sup>a</sup>, Sandra S. Padula<sup>a</sup>, D. Romero Abad<sup>b</sup>, J.C. Ruiz Vargas<sup>a</sup>

**Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria**

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, A. Marinov, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

**University of Sofia, Sofia, Bulgaria**

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

**Beihang University, Beijing, China**

W. Fang<sup>6</sup>, X. Gao<sup>6</sup>, L. Yuan

**Institute of High Energy Physics, Beijing, China**

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, F. Romeo, S.M. Shaheen, A. Spiezia, J. Tao, C. Wang, Z. Wang, E. Yazgan, H. Zhang, J. Zhao

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

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

**Tsinghua University, Beijing, China**

Y. Wang

**Universidad de Los Andes, Bogota, Colombia**

C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado

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

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

**University of Split, Faculty of Science, Split, Croatia**

Z. Antunovic, M. Kovac

**Institute Rudjer Boskovic, Zagreb, Croatia**

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov<sup>7</sup>, T. Susa

**University of Cyprus, Nicosia, Cyprus**

M.W. Ather, A. Attikis, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

**Charles University, Prague, Czech Republic**

M. Finger<sup>8</sup>, M. Finger Jr.<sup>8</sup>

**Universidad San Francisco de Quito, Quito, Ecuador**

E. Carrera Jarrin

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

Y. Assran<sup>9,10</sup>, S. Elgammal<sup>10</sup>, S. Khalil<sup>11</sup>

**National Institute of Chemical Physics and Biophysics, Tallinn, Estonia**

S. Bhowmik, R.K. Dewanjee, M. Kadastik, L. Perrini, M. Raidal, C. Veelken

**Department of Physics, University of Helsinki, Helsinki, Finland**

P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen

**Helsinki Institute of Physics, Helsinki, Finland**

J. Havukainen, J.K. Heikkilä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen, E. Tuominen, J. Tuominiemi

**Lappeenranta University of Technology, Lappeenranta, Finland**

T. Tuuva

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

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, S. Ghosh, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, M. Machet, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

**Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France**

A. Abdulsalam<sup>12</sup>, C. Amendola, I. Antropov, S. Baffioni, F. Beaudette, P. Busson, L. Cadamuro, C. Charlot, R. Granier de Cassagnac, M. Jo, I. Kucher, S. Lisniak, A. Lobanov, J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, Y. Yilmaz, A. Zabi, A. Zghiche

**Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France**

J.-L. Agram<sup>13</sup>, J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, E. Conte<sup>13</sup>, X. Coubez, F. Drouhin<sup>13</sup>, J.-C. Fontaine<sup>13</sup>, D. Gelé, U. Goerlach, M. Jansová, P. Juillot, A.-C. Le Bihan, N. Tonon, P. Van Hove

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

S. Gadrat

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

S. Beauceron, C. Bernet, G. Boudoul, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries, A. Popov<sup>14</sup>, V. Sordini, M. Vander Donckt, S. Viret, S. Zhang

**Georgian Technical University, Tbilisi, Georgia**

T. Toriashvili<sup>15</sup>

**Tbilisi State University, Tbilisi, Georgia**

Z. Tsamalaidze<sup>8</sup>

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

C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, M.P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer, V. Zhukov<sup>14</sup>

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

A. Albert, D. Duchardt, M. Endres, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, S. Knutzen, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, M. Radziej, H. Reithler, M. Rieger, F. Scheuch, D. Teyssier, S. Thüer

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

G. Flügge, B. Kargoll, T. Kress, A. Künsken, T. Müller, A. Nehr Korn, A. Nowack, C. Pistone, O. Pooth, A. Stahl<sup>16</sup>

**Deutsches Elektronen-Synchrotron, Hamburg, Germany**

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras<sup>17</sup>, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, V. Danilov, A. De Wit, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, A. Elwood, E. Eren, E. Gallo<sup>18</sup>, J. Garay Garcia, A. Geiser, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, M. Guthoff, A. Harb, J. Hauk, M. Hempel<sup>19</sup>, H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, J. Knolle, I. Korol, D. Krücker, W. Lange, A. Lelek, T. Lenz, K. Lipka, W. Lohmann<sup>19</sup>, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, A. Mussgiller, D. Pitzl, A. Raspereza, M. Savitskyi, P. Saxena, R. Shevchenko, N. Stefaniuk, H. Tholen, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

**University of Hamburg, Hamburg, Germany**

R. Aggleton, S. Bein, V. Blobel, M. Centis Vignali, T. Dreyer, E. Garutti, D. Gonzalez, J. Haller, A. Hinzmann, M. Hoffmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, D. Marconi, J. Multhaupt, M. Niedziela, D. Nowatschin, T. Peiffer, A. Perieanu, A. Reimers, C. Scharf, P. Schleper, A. Schmidt, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, D. Troendle, E. Usai, A. Vanhoefer, B. Vormwald

**Institut für Experimentelle Teilchenphysik, Karlsruhe, Germany**

M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, N. Faltermann, B. Freund, R. Friese, M. Giffels, M.A. Harrendorf, F. Hartmann<sup>16</sup>, S.M. Heindl, U. Husemann, F. Kassel<sup>16</sup>, S. Kudella, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

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

G. Anagnostou, G. Daskalakis, T. Gerasis, A. Kyriakis, D. Loukas, I. Topsis-Giotis

**National and Kapodistrian University of Athens, Athens, Greece**

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

**National Technical University of Athens, Athens, Greece**

K. Kousouris, I. Papakrivopoulos

**University of Ioánnina, Ioánnina, Greece**

I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F.A. Triantis, D. Tsitsonis

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

M. Csanad, N. Filipovic, G. Pasztor, O. Surányi, G.I. Veres

**Wigner Research Centre for Physics, Budapest, Hungary**

G. Bencze, C. Hajdu, D. Horvath<sup>20</sup>, Á. Hunyadi, F. Sikler, V. Veszpremi, G. Vesztergombi<sup>†</sup>, T.Á. Vámi

**Institute of Nuclear Research ATOMKI, Debrecen, Hungary**

N. Beni, S. Czellar, J. Karancsi<sup>21</sup>, A. Makovec, J. Molnar, Z. Szillasi

**Institute of Physics, University of Debrecen, Debrecen, Hungary**

M. Bartók<sup>22</sup>, P. Raics, Z.L. Trocsanyi, B. Ujvari



**Indian Institute of Science (IISc), Bangalore, India**

S. Choudhury, J.R. Komaragiri

**National Institute of Science Education and Research, Bhubaneswar, India**S. Bahinipati<sup>23</sup>, P. Mal, K. Mandal, A. Nayak<sup>24</sup>, D.K. Sahoo<sup>23</sup>, S.K. Swain**Panjab University, Chandigarh, India**

S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, M. Kaur, S. Kaur, R. Kumar, P. Kumari, M. Lohan, A. Mehta, S. Sharma, J.B. Singh, G. Walia

**University of Delhi, Delhi, India**

Ashok Kumar, Aashaq Shah, A. Bhardwaj, B.C. Choudhary, R.B. Garg, S. Keshri, A. Kumar, S. Malhotra, M. Naimuddin, K. Ranjan, R. Sharma

**Saha Institute of Nuclear Physics, HBNI, Kolkata, India**R. Bhardwaj<sup>25</sup>, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep<sup>25</sup>, D. Bhowmik, S. Dey, S. Dutt<sup>25</sup>, S. Dutta, S. Ghosh, N. Majumdar, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, P.K. Rout, A. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, B. Singh, S. Thakur<sup>25</sup>**Indian Institute of Technology Madras, Madras, India**

P.K. Behera

**Bhabha Atomic Research Centre, Mumbai, India**R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty<sup>16</sup>, P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar**Tata Institute of Fundamental Research-A, Mumbai, India**

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

**Tata Institute of Fundamental Research-B, Mumbai, India**S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Kumar, M. Maity<sup>26</sup>, G. Majumder, K. Mazumdar, N. Sahoo, T. Sarkar<sup>26</sup>, N. Wickramage<sup>27</sup>**Indian Institute of Science Education and Research (IISER), Pune, India**

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

**Institute for Research in Fundamental Sciences (IPM), Tehran, Iran**S. Chenarani<sup>28</sup>, E. Eskandari Tadavani, S.M. Etesami<sup>28</sup>, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi<sup>29</sup>, F. Rezaei Hosseinabadi, B. Safarzadeh<sup>30</sup>, M. Zeinali**University College Dublin, Dublin, Ireland**

M. Felcini, M. Grunewald

**INFN Sezione di Bari <sup>a</sup>, Università di Bari <sup>b</sup>, Politecnico di Bari <sup>c</sup>, Bari, Italy**M. Abbrescia<sup>a,b</sup>, C. Calabria<sup>a,b</sup>, A. Colaleo<sup>a</sup>, D. Creanza<sup>a,c</sup>, L. Cristella<sup>a,b</sup>, N. De Filippis<sup>a,c</sup>, M. De Palma<sup>a,b</sup>, A. Di Florio<sup>a,b</sup>, F. Errico<sup>a,b</sup>, L. Fiore<sup>a</sup>, A. Gelmi<sup>a,b</sup>, G. Iaselli<sup>a,c</sup>, S. Lezki<sup>a,b</sup>, G. Maggi<sup>a,c</sup>, M. Maggi<sup>a</sup>, B. Marangelli<sup>a,b</sup>, G. Miniello<sup>a,b</sup>, S. My<sup>a,b</sup>, S. Nuzzo<sup>a,b</sup>, A. Pompili<sup>a,b</sup>, G. Pugliese<sup>a,c</sup>, R. Radogna<sup>a</sup>, A. Ranieri<sup>a</sup>, G. Selvaggi<sup>a,b</sup>, A. Sharma<sup>a</sup>, L. Silvestris<sup>a,16</sup>, R. Venditti<sup>a</sup>, P. Verwilligen<sup>a</sup>, G. Zito<sup>a</sup>**INFN Sezione di Bologna <sup>a</sup>, Università di Bologna <sup>b</sup>, Bologna, Italy**G. Abbiendi<sup>a</sup>, C. Battilana<sup>a,b</sup>, D. Bonacorsi<sup>a,b</sup>, L. Borgonovi<sup>a,b</sup>, S. Braibant-Giacomelli<sup>a,b</sup>, L. Brigliadori<sup>a,b</sup>, R. Campanini<sup>a,b</sup>, P. Capiluppi<sup>a,b</sup>, A. Castro<sup>a,b</sup>, F.R. Cavallo<sup>a</sup>, S.S. Chhibra<sup>a,b</sup>, G. Codispoti<sup>a,b</sup>, M. Cuffiani<sup>a,b</sup>, G.M. Dallavalle<sup>a</sup>, F. Fabbri<sup>a</sup>, A. Fanfani<sup>a,b</sup>, D. Fasanella<sup>a,b</sup>,

P. Giacomelli<sup>a</sup>, C. Grandi<sup>a</sup>, L. Guiducci<sup>a,b</sup>, S. Marcellini<sup>a</sup>, G. Masetti<sup>a</sup>, A. Montanari<sup>a</sup>, F.L. Navarria<sup>a,b</sup>, A. Perrotta<sup>a</sup>, A.M. Rossi<sup>a,b</sup>, T. Rovelli<sup>a,b</sup>, G.P. Siroli<sup>a,b</sup>, N. Tosi<sup>a</sup>

**INFN Sezione di Catania<sup>a</sup>, Università di Catania<sup>b</sup>, Catania, Italy**

S. Albergo<sup>a,b</sup>, S. Costa<sup>a,b</sup>, A. Di Mattia<sup>a</sup>, F. Giordano<sup>a,b</sup>, R. Potenza<sup>a,b</sup>, A. Tricomi<sup>a,b</sup>, C. Tuve<sup>a,b</sup>

**INFN Sezione di Firenze<sup>a</sup>, Università di Firenze<sup>b</sup>, Firenze, Italy**

G. Barbagli<sup>a</sup>, K. Chatterjee<sup>a,b</sup>, V. Ciulli<sup>a,b</sup>, C. Civinini<sup>a</sup>, R. D'Alessandro<sup>a,b</sup>, E. Focardi<sup>a,b</sup>, G. Latino, P. Lenzi<sup>a,b</sup>, M. Meschini<sup>a</sup>, S. Paoletti<sup>a</sup>, L. Russo<sup>a,31</sup>, G. Sguazzoni<sup>a</sup>, D. Strom<sup>a</sup>, L. Viliani<sup>a</sup>

**INFN Laboratori Nazionali di Frascati, Frascati, Italy**

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera<sup>16</sup>

**INFN Sezione di Genova<sup>a</sup>, Università di Genova<sup>b</sup>, Genova, Italy**

V. Calvelli<sup>a,b</sup>, F. Ferro<sup>a</sup>, F. Ravera<sup>a,b</sup>, E. Robutti<sup>a</sup>, S. Tosi<sup>a,b</sup>

**INFN Sezione di Milano-Bicocca<sup>a</sup>, Università di Milano-Bicocca<sup>b</sup>, Milano, Italy**

A. Benaglia<sup>a</sup>, A. Beschi<sup>b</sup>, L. Brianza<sup>a,b</sup>, F. Brivio<sup>a,b</sup>, V. Ciriolo<sup>a,b,16</sup>, M.E. Dinardo<sup>a,b</sup>, S. Fiorendi<sup>a,b</sup>, S. Gennai<sup>a</sup>, A. Ghezzi<sup>a,b</sup>, P. Govoni<sup>a,b</sup>, M. Malberti<sup>a,b</sup>, S. Malvezzi<sup>a</sup>, R.A. Manzoni<sup>a,b</sup>, D. Menasce<sup>a</sup>, L. Moroni<sup>a</sup>, M. Paganoni<sup>a,b</sup>, K. Pauwels<sup>a,b</sup>, D. Pedrini<sup>a</sup>, S. Pigazzini<sup>a,b,32</sup>, S. Ragazzi<sup>a,b</sup>, T. Tabarelli de Fatis<sup>a,b</sup>

**INFN Sezione di Napoli<sup>a</sup>, Università di Napoli 'Federico II'<sup>b</sup>, Napoli, Italy, Università della Basilicata<sup>c</sup>, Potenza, Italy, Università G. Marconi<sup>d</sup>, Roma, Italy**

S. Buontempo<sup>a</sup>, N. Cavallo<sup>a,c</sup>, S. Di Guida<sup>a,d,16</sup>, F. Fabozzi<sup>a,c</sup>, F. Fienga<sup>a,b</sup>, G. Galati<sup>a,b</sup>, A.O.M. Iorio<sup>a,b</sup>, W.A. Khan<sup>a</sup>, L. Lista<sup>a</sup>, S. Meola<sup>a,d,16</sup>, P. Paolucci<sup>a,16</sup>, C. Sciacca<sup>a,b</sup>, F. Thyssen<sup>a</sup>, E. Voevodina<sup>a,b</sup>

**INFN Sezione di Padova<sup>a</sup>, Università di Padova<sup>b</sup>, Padova, Italy, Università di Trento<sup>c</sup>, Trento, Italy**

P. Azzi<sup>a</sup>, N. Bacchetta<sup>a</sup>, L. Benato<sup>a,b</sup>, D. Bisello<sup>a,b</sup>, A. Boletti<sup>a,b</sup>, R. Carlin<sup>a,b</sup>, A. Carvalho Antunes De Oliveira<sup>a,b</sup>, P. Checchia<sup>a</sup>, P. De Castro Manzano<sup>a</sup>, T. Dorigo<sup>a</sup>, U. Dosselli<sup>a</sup>, F. Gasparini<sup>a,b</sup>, U. Gasparini<sup>a,b</sup>, A. Gozzelino<sup>a</sup>, S. Lacaprara<sup>a</sup>, M. Margoni<sup>a,b</sup>, A.T. Meneguzzo<sup>a,b</sup>, N. Pozzobon<sup>a,b</sup>, P. Ronchese<sup>a,b</sup>, R. Rossin<sup>a,b</sup>, F. Simonetto<sup>a,b</sup>, A. Tiko, E. Torassa<sup>a</sup>, M. Zanetti<sup>a,b</sup>, P. Zotto<sup>a,b</sup>, G. Zumerle<sup>a,b</sup>

**INFN Sezione di Pavia<sup>a</sup>, Università di Pavia<sup>b</sup>, Pavia, Italy**

A. Braghieri<sup>a</sup>, A. Magnani<sup>a</sup>, P. Montagna<sup>a,b</sup>, S.P. Ratti<sup>a,b</sup>, V. Re<sup>a</sup>, M. Ressegotti<sup>a,b</sup>, C. Riccardi<sup>a,b</sup>, P. Salvini<sup>a</sup>, I. Vai<sup>a,b</sup>, P. Vitulo<sup>a,b</sup>

**INFN Sezione di Perugia<sup>a</sup>, Università di Perugia<sup>b</sup>, Perugia, Italy**

L. Alunni Solestizi<sup>a,b</sup>, M. Biasini<sup>a,b</sup>, G.M. Bilei<sup>a</sup>, C. Cecchi<sup>a,b</sup>, D. Ciangottini<sup>a,b</sup>, L. Fanò<sup>a,b</sup>, P. Lariccia<sup>a,b</sup>, R. Leonardi<sup>a,b</sup>, E. Manoni<sup>a</sup>, G. Mantovani<sup>a,b</sup>, V. Mariani<sup>a,b</sup>, M. Menichelli<sup>a</sup>, A. Rossi<sup>a,b</sup>, A. Santocchia<sup>a,b</sup>, D. Spiga<sup>a</sup>

**INFN Sezione di Pisa<sup>a</sup>, Università di Pisa<sup>b</sup>, Scuola Normale Superiore di Pisa<sup>c</sup>, Pisa, Italy**

K. Androsov<sup>a</sup>, P. Azzurri<sup>a,16</sup>, G. Bagliesi<sup>a</sup>, L. Bianchini<sup>a</sup>, T. Boccali<sup>a</sup>, L. Borrello, R. Castaldi<sup>a</sup>, M.A. Ciocci<sup>a,b</sup>, R. Dell'Orso<sup>a</sup>, G. Fedia<sup>a</sup>, L. Giannini<sup>a,c</sup>, A. Giassi<sup>a</sup>, M.T. Grippo<sup>a,31</sup>, F. Ligabue<sup>a,c</sup>, T. Lomtadze<sup>a</sup>, E. Manca<sup>a,c</sup>, G. Mandorli<sup>a,c</sup>, A. Messineo<sup>a,b</sup>, F. Palla<sup>a</sup>, A. Rizzi<sup>a,b</sup>, P. Spagnolo<sup>a</sup>, R. Tenchini<sup>a</sup>, G. Tonelli<sup>a,b</sup>, A. Venturi<sup>a</sup>, P.G. Verdini<sup>a</sup>

**INFN Sezione di Roma<sup>a</sup>, Sapienza Università di Roma<sup>b</sup>, Rome, Italy**

L. Barone<sup>a,b</sup>, F. Cavallari<sup>a</sup>, M. Cipriani<sup>a,b</sup>, N. Daci<sup>a</sup>, D. Del Re<sup>a,b</sup>, E. Di Marco<sup>a,b</sup>, M. Diemoz<sup>a</sup>,

S. Gelli<sup>a,b</sup>, E. Longo<sup>a,b</sup>, B. Marzocchi<sup>a,b</sup>, P. Meridiani<sup>a</sup>, G. Organtini<sup>a,b</sup>, F. Pandolfi<sup>a</sup>, R. Paramatti<sup>a,b</sup>, F. Preiato<sup>a,b</sup>, S. Rahatlou<sup>a,b</sup>, C. Rovelli<sup>a</sup>, F. Santanastasio<sup>a,b</sup>

**INFN Sezione di Torino <sup>a</sup>, Università di Torino <sup>b</sup>, Torino, Italy, Università del Piemonte Orientale <sup>c</sup>, Novara, Italy**

N. Amapane<sup>a,b</sup>, R. Arcidiacono<sup>a,c</sup>, S. Argiro<sup>a,b</sup>, M. Arneodo<sup>a,c</sup>, N. Bartosik<sup>a</sup>, R. Bellan<sup>a,b</sup>, C. Biino<sup>a</sup>, N. Cartiglia<sup>a</sup>, R. Castello<sup>a,b</sup>, F. Cenna<sup>a,b</sup>, M. Costa<sup>a,b</sup>, R. Covarelli<sup>a,b</sup>, A. Degano<sup>a,b</sup>, N. Demaria<sup>a</sup>, B. Kiani<sup>a,b</sup>, C. Mariotti<sup>a</sup>, S. Maselli<sup>a</sup>, E. Migliore<sup>a,b</sup>, V. Monaco<sup>a,b</sup>, E. Monteil<sup>a,b</sup>, M. Monteno<sup>a</sup>, M.M. Obertino<sup>a,b</sup>, L. Pacher<sup>a,b</sup>, N. Pastrone<sup>a</sup>, M. Pelliccioni<sup>a</sup>, G.L. Pinna Angioni<sup>a,b</sup>, A. Romero<sup>a,b</sup>, M. Ruspa<sup>a,c</sup>, R. Sacchi<sup>a,b</sup>, K. Shchelina<sup>a,b</sup>, V. Sola<sup>a</sup>, A. Solano<sup>a,b</sup>, A. Staiano<sup>a</sup>

**INFN Sezione di Trieste <sup>a</sup>, Università di Trieste <sup>b</sup>, Trieste, Italy**

S. Belforte<sup>a</sup>, M. Casarsa<sup>a</sup>, F. Cossutti<sup>a</sup>, G. Della Ricca<sup>a,b</sup>, A. Zanetti<sup>a</sup>

**Kyungpook National University**

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

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

H. Kim, D.H. Moon, G. Oh

**Hanyang University, Seoul, Korea**

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

**Korea University, Seoul, Korea**

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

**Seoul National University, Seoul, Korea**

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

**University of Seoul, Seoul, Korea**

H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park

**Sungkyunkwan University, Suwon, Korea**

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

**Vilnius University, Vilnius, Lithuania**

V. Dudenias, A. Juodagalvis, J. Vaitkus

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

I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali<sup>33</sup>, F. Mohamad Idris<sup>34</sup>, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

Reyes-Almanza, R, Ramirez-Sanchez, G., Duran-Osuna, M. C., H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz<sup>35</sup>, Rabadan-Trejo, R. I., R. Lopez-Fernandez, J. Mejia Guisao, A. Sanchez-Hernandez

**Universidad Iberoamericana, Mexico City, Mexico**

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

**Benemerita Universidad Autonoma de Puebla, Puebla, Mexico**

J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

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

A. Morelos Pineda

**University of Auckland, Auckland, New Zealand**

D. Krofcheck

**University of Canterbury, Christchurch, New Zealand**

S. Bheesette, P.H. Butler

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

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

**National Centre for Nuclear Research, Swierk, Poland**

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

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

K. Bunkowski, A. Byszuk<sup>36</sup>, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

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

P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, L. Lloret Iglesias, M.V. Nemallapudi, J. Seixas, G. Strong, O. Toldaiev, D. Vadrucio, J. Varela

**Joint Institute for Nuclear Research, Dubna, Russia**

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev<sup>37,38</sup>, P. Moisezenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

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

Y. Ivanov, V. Kim<sup>39</sup>, E. Kuznetsova<sup>40</sup>, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

**Institute for Nuclear Research, Moscow, Russia**

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

**Institute for Theoretical and Experimental Physics, Moscow, Russia**

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

**Moscow Institute of Physics and Technology, Moscow, Russia**

T. Aushev, A. Bylinkin<sup>38</sup>

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

M. Chadeeva<sup>41</sup>, P. Parygin, D. Philippov, S. Polikarpov, E. Popova, V. Rusinov

**P.N. Lebedev Physical Institute, Moscow, Russia**

V. Andreev, M. Azarkin<sup>38</sup>, I. Dremin<sup>38</sup>, M. Kirakosyan<sup>38</sup>, S.V. Rusakov, A. Terkulov

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

A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin<sup>42</sup>, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, M. Perfilov, V. Savrin

**Novosibirsk State University (NSU), Novosibirsk, Russia**

V. Blinov<sup>43</sup>, D. Shtol<sup>43</sup>, Y. Skovpen<sup>43</sup>

**State Research Center of Russian Federation, Institute for High Energy Physics of NRC "Kurchatov Institute", Protvino, Russia**

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

**National Research Tomsk Polytechnic University, Tomsk, Russia**

A. Babaev

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

P. Adzic<sup>44</sup>, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

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

J. Alcaraz Maestre, I. Bachiller, M. Barrio Luna, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, M.S. Soares, A. Triossi, A. Álvarez Fernández

**Universidad Autónoma de Madrid, Madrid, Spain**

C. Albajar, J.F. de Trocóniz

**Universidad de Oviedo, Oviedo, Spain**

J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, S. Sanchez Cruz, P. Vischia, J.M. Vizán García

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

I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, J. Garcia-Ferrero, A. García Alonso, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

**CERN, European Organization for Nuclear Research, Geneva, Switzerland**

D. Abbaneo, B. Akgun, E. Auffray, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Botta, T. Camporesi, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, N. Deelen, M. Dobson, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita<sup>45</sup>, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, D. Gulhan, J. Hegeman, V. Innocente, A. Jafari, P. Janot, O. Karacheban<sup>19</sup>, J. Kieseler, V. Knünz, A. Kornmayer, M. Kramer<sup>1</sup>, 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<sup>46</sup>, F. Moortgat, M. Mulders, H. Neugebauer, J. Ngadiuba, S. Orfanelli, L. Orsini, F. Pantaleo<sup>16</sup>, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabadý, A. Racz, T. Reis, G. Rolandi<sup>47</sup>, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva,

P. Sphicas<sup>48</sup>, A. Stakia, J. Steggemann, M. Stoye, M. Tosi, D. Treille, A. Tsirou, V. Veckalns<sup>49</sup>, M. Verweij, W.D. Zeuner

**Paul Scherrer Institut, Villigen, Switzerland**

W. Bertl<sup>†</sup>, L. Caminada<sup>50</sup>, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

**ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland**

M. Backhaus, L. Bäni, P. Berger, B. Casal, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, C. Grab, C. Heidegger, D. Hits, J. Hoss, T. Klijnsma, W. Luster, M. Marionneau, M.T. Meinhard, D. Meister, F. Micheli, P. Musella, F. Nessi-Tedaldi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, M. Quittnat, M. Reichmann, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

**Universität Zürich, Zurich, Switzerland**

T.K. Aarrestad, C. Amsler<sup>51</sup>, D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, I. Neutelings, D. Pinna, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, A. Zucchetta

**National Central University, Chung-Li, Taiwan**

V. Candelise, Y.H. Chang, K.y. Cheng, T.H. Doan, Sh. Jain, R. Khurana, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

**National Taiwan University (NTU), Taipei, Taiwan**

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

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

B. Asavapibhop, K. Kovitanggoon, G. Singh, N. Srimanobhas

**Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey**

M.N. Bakirci<sup>52</sup>, A. Bat, F. Boran, S. Damarseckin, Z.S. Demiroglu, C. Dozen, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, I. Hos<sup>53</sup>, E.E. Kangal<sup>54</sup>, O. Kara, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir<sup>55</sup>, S. Ozturk<sup>52</sup>, A. Polatoz, D. Sunar Cerci<sup>56</sup>, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

**Middle East Technical University, Physics Department, Ankara, Turkey**

G. Karapinar<sup>57</sup>, K. Ocalan<sup>58</sup>, M. Yalvac, M. Zeyrek

**Bogazici University, Istanbul, Turkey**

I.O. Atakisi, E. Gülmez, M. Kaya<sup>59</sup>, O. Kaya<sup>60</sup>, S. Tekten, E.A. Yetkin<sup>61</sup>

**Istanbul Technical University, Istanbul, Turkey**

M.N. Agaras, S. Atay, A. Cakir, K. Cankocak, Y. Komurcu

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

B. Grynyov

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

L. Levchuk

**University of Bristol, Bristol, United Kingdom**

F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher,

---

J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, D.M. Newbold<sup>62</sup>, S. Paramesvaran, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

**Rutherford Appleton Laboratory, Didcot, United Kingdom**

K.W. Bell, A. Belyaev<sup>63</sup>, C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

**Imperial College, London, United Kingdom**

G. Auzinger, R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, D. Colling, L. Corpe, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, Y. Haddad, G. Hall, G. Iles, T. James, M. Komm, R. Lane, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, T. Matsushita, J. Nash<sup>64</sup>, A. Nikitenko<sup>7</sup>, V. Palladino, M. Pesaresi, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, T. Strebler, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta<sup>65</sup>, T. Virdee<sup>16</sup>, N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

**Brunel University, Uxbridge, United Kingdom**

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, A. Morton, I.D. Reid, L. Teodorescu, S. Zahid

**Baylor University, Waco, USA**

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

**Catholic University of America, Washington DC, USA**

R. Bartek, A. Dominguez

**The University of Alabama, Tuscaloosa, USA**

A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

**Boston University, Boston, USA**

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

**Brown University, Providence, USA**

G. Benelli, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan<sup>66</sup>, K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, J. Pazzini, S. Piperov, S. Sagir, R. Syarif, D. Yu

**University of California, Davis, Davis, USA**

R. Band, C. Brainerd, R. Breedon, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, W. Ko, R. Lander, C. Mclean, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, J. Smith, D. Stolp, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang

**University of California, Los Angeles, USA**

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, S. Regnard, D. Saltzberg, C. Schnaible, V. Valuev

**University of California, Riverside, Riverside, USA**

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

**University of California, San Diego, La Jolla, USA**

J.G. Branson, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech<sup>67</sup>, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

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

N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, M. Citron, A. Dishaw, V. Dutta, M. Franco Sevilla, L. Gouskos, R. Heller, J. Incandela, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, J. Yoo

**California Institute of Technology, Pasadena, USA**

D. Anderson, A. Bornheim, J. Bunn, J.M. Lawhorn, H.B. Newman, T. Q. Nguyen, C. Pena, M. Spiropulu, J.R. Vlimant, R. Wilkinson, S. Xie, Z. Zhang, R.Y. Zhu

**Carnegie Mellon University, Pittsburgh, USA**

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

**University of Colorado Boulder, Boulder, USA**

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

**Cornell University, Ithaca, USA**

J. Alexander, J. Chaves, Y. Cheng, J. Chu, A. Datta, K. Mcdermott, N. Mirman, J.R. Patterson, D. Quach, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

**Fermi National Accelerator Laboratory, Batavia, USA**

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla<sup>†</sup>, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, A. Savoy-Navarro<sup>68</sup>, B. Schneider, 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, W. Wu

**University of Florida, Gainesville, USA**

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, R.D. Field, I.K. Furic, S.V. Gleyzer, B.M. Joshi, J. Konigsberg, A. Korytov, K. Kotov, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, K. Shi, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. Wang, J. Yelton

**Florida International University, Miami, USA**

Y.R. Joshi, S. Linn, P. Markowitz, J.L. Rodriguez

**Florida State University, Tallahassee, USA**

A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, A. Santra, V. Sharma, R. Yohay

**Florida Institute of Technology, Melbourne, USA**

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

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

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer,



O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, I.D. Sandoval Gonzalez, M.B. Tonjes, N. Varelas, H. Wang, Z. Wu, J. Zhang

**The University of Iowa, Iowa City, USA**

B. Bilki<sup>69</sup>, W. Clarida, K. Dilsiz<sup>70</sup>, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya<sup>71</sup>, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul<sup>72</sup>, Y. Onel, F. Ozok<sup>73</sup>, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

**Johns Hopkins University, Baltimore, USA**

B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, W.T. Hung, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

**The University of Kansas, Lawrence, USA**

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, J. Castle, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang

**Kansas State University, Manhattan, USA**

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

**Lawrence Livermore National Laboratory, Livermore, USA**

F. Rebassoo, D. Wright

**University of Maryland, College Park, USA**

A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar

**Massachusetts Institute of Technology, Cambridge, USA**

D. Abercrombie, B. Allen, V. Azzolini, R. Barbieri, A. Baty, G. Bauer, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, 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, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch, S. Zhaozhong

**University of Minnesota, Minneapolis, USA**

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

**University of Mississippi, Oxford, USA**

J.G. Acosta, S. Oliveros

**University of Nebraska-Lincoln, Lincoln, USA**

E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

**State University of New York at Buffalo, Buffalo, USA**

A. Godshalk, C. Harrington, I. Iashvili, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

**Northeastern University, Boston, USA**

G. Alverson, E. Barberis, C. Freer, A. Hortiangtham, A. Massironi, D.M. Morse, T. Orimoto, R. Teixeira De Lima, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

**Northwestern University, Evanston, USA**

S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

**University of Notre Dame, Notre Dame, USA**

R. Bucci, N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko<sup>37</sup>, M. Planer, A. Reinsvold, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

**The Ohio State University, Columbus, USA**

J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, T.Y. Ling, W. Luo, B.L. Winer, H.W. Wulsin

**Princeton University, Princeton, USA**

S. Cooperstein, O. Driga, P. Elmer, J. Hardenbrook, P. Hebda, S. Higginbotham, A. Kalogeropoulos, D. Lange, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, J. Salfeld-Nebgen, D. Stickland, C. Tully

**University of Puerto Rico, Mayaguez, USA**

S. Malik, S. Norberg

**Purdue University, West Lafayette, USA**

A. Barker, V.E. Barnes, S. Das, L. Gutay, M. Jones, A.W. Jung, A. Khatiwada, D.H. Miller, N. Neumeister, C.C. Peng, H. Qiu, J.F. Schulte, J. Sun, F. Wang, R. Xiao, W. Xie

**Purdue University Northwest, Hammond, USA**

T. Cheng, J. Dolen, N. Parashar

**Rice University, Houston, USA**

Z. Chen, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Guilbaud, M. Kilpatrick, W. Li, B. Michlin, B.P. Padley, J. Roberts, J. Rorie, W. Shi, Z. Tu, J. Zabel, A. Zhang

**University of Rochester, Rochester, USA**

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

**The Rockefeller University, New York, USA**

R. Ciesielski, K. Goulianos, C. Mesropian

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

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

**University of Tennessee, Knoxville, USA**

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

**Texas A&M University, College Station, USA**

O. Bouhali<sup>74</sup>, A. Castaneda Hernandez<sup>74</sup>, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon<sup>75</sup>, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov

**Texas Tech University, Lubbock, USA**

N. Akchurin, J. Damgov, F. De Guio, P.R. Duderov, J. Faulkner, E. Gurpinar, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

**Vanderbilt University, Nashville, USA**

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

**University of Virginia, Charlottesville, USA**

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

**Wayne State University, Detroit, USA**

R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

**University of Wisconsin - Madison, Madison, WI, USA**

M. Brodski, J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, L. Dodd, S. Duric, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, A. Levine, K. Long, R. Loveless, V. Rekovic, T. Ruggles, A. Savin, N. Smith, W.H. Smith, N. Woods

†: Deceased

1: Also at Vienna University of Technology, Vienna, Austria

2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

3: Also at Universidade Estadual de Campinas, Campinas, Brazil

4: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil

5: Also at Universidade Federal de Pelotas, Pelotas, Brazil

6: Also at Université Libre de Bruxelles, Bruxelles, Belgium

7: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia

8: Also at Joint Institute for Nuclear Research, Dubna, Russia

9: Also at Suez University, Suez, Egypt

10: Now at British University in Egypt, Cairo, Egypt

11: Also at Zewail City of Science and Technology, Zewail, Egypt

12: Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia

13: Also at Université de Haute Alsace, Mulhouse, France

14: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

15: Also at Tbilisi State University, Tbilisi, Georgia

16: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

17: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

18: Also at University of Hamburg, Hamburg, Germany

19: Also at Brandenburg University of Technology, Cottbus, Germany

20: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary

21: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary

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

23: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India

24: Also at Institute of Physics, Bhubaneswar, India

25: Also at Shoolini University, Solan, 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 Yazd University, Yazd, Iran

30: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran

31: Also at Università degli Studi di Siena, Siena, Italy

- 32: Also at INFN Sezione di Milano-Bicocca; Università di Milano-Bicocca, Milano, Italy
- 33: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
- 34: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
- 35: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
- 36: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
- 37: Also at Institute for Nuclear Research, Moscow, Russia
- 38: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
- 39: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
- 40: Also at University of Florida, Gainesville, USA
- 41: Also at P.N. Lebedev Physical Institute, Moscow, Russia
- 42: Also at California Institute of Technology, Pasadena, USA
- 43: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia
- 44: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 45: Also at INFN Sezione di Pavia; Università di Pavia, Pavia, Italy
- 46: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 47: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 48: Also at National and Kapodistrian University of Athens, Athens, Greece
- 49: Also at Riga Technical University, Riga, Latvia
- 50: Also at Universität Zürich, Zurich, Switzerland
- 51: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
- 52: Also at Gaziosmanpasa University, Tokat, Turkey
- 53: Also at Istanbul Aydin University, Istanbul, Turkey
- 54: Also at Mersin University, Mersin, Turkey
- 55: Also at Piri Reis University, Istanbul, Turkey
- 56: Also at Adiyaman University, Adiyaman, Turkey
- 57: Also at Izmir Institute of Technology, Izmir, Turkey
- 58: Also at Necmettin Erbakan University, Konya, Turkey
- 59: Also at Marmara University, Istanbul, Turkey
- 60: Also at Kafkas University, Kars, Turkey
- 61: Also at Istanbul Bilgi University, Istanbul, Turkey
- 62: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 63: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 64: Also at Monash University, Faculty of Science, Clayton, Australia
- 65: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
- 66: Also at Bethel University, ST. PAUL, USA
- 67: Also at Utah Valley University, Orem, USA
- 68: Also at Purdue University, West Lafayette, USA
- 69: Also at Beykent University, Istanbul, Turkey
- 70: Also at Bingol University, Bingol, Turkey
- 71: Also at Erzincan University, Erzincan, Turkey
- 72: Also at Sinop University, Sinop, Turkey
- 73: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 74: Also at Texas A&M University at Qatar, Doha, Qatar
- 75: Also at Kyungpook National University, Daegu, Korea