Physics Letters B 843 (2023) 137803

Contents lists available at ScienceDirect

Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

Search for a heavy composite Majorana neutrino in events with dilepton signatures from proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration *

CERN, Geneva, Switzerland

ARTICLE INFO

Article history:
Received 6 October 2022
Received in revised form 5 February 2023
Accepted 22 February 2023
Available online 14 June 2023
Editor: M. Doser

Keywords:
CMS
LHC
Composite fermions
Heavy leptons

ABSTRACT

Results are presented of a search for a heavy Majorana neutrino N_ℓ decaying into two same-flavor leptons ℓ (electrons or muons) and a quark-pair jet. A model is considered in which the N_ℓ is an excited neutrino in a compositeness scenario. The analysis is performed using a sample of proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ recorded by the CMS experiment at the CERN LHC, corresponding to an integrated luminosity of $138\,\mathrm{fb}^{-1}$. The data are found to be in agreement with the standard model prediction. For the process in which the N_ℓ is produced in association with a lepton, followed by the decay of the N_ℓ to a same-flavor lepton and a quark pair, an upper limit at 95% confidence level on the product of the cross section and branching fraction is obtained as a function of the N_ℓ mass m_{N_ℓ} and the compositeness scale Λ. For this model the data exclude the existence of N_e (N_μ) for m_{N_ℓ} below 6.0 (6.1) TeV, at the limit where m_{N_ℓ} is equal to Λ. For $m_{\mathrm{N}_\ell} \approx 1\,\mathrm{TeV}$, values of Λ less than 20 (23) TeV are excluded. These results represent a considerable improvement in sensitivity, covering a larger parameter space than previous searches in pp collisions at 13 TeV.

1. Introduction

The standard model (SM) of particle physics is an extremely successful theory that has been extensively verified against experimental results. Nevertheless, there are several fundamental aspects of particle phenomenology that are not explained within the SM. One of these is the appearance of three generations of leptons and quarks, regarded as fundamental fermions in the SM, and the related question of the mass hierarchy across the generations. A possible solution to these issues is offered by composite-fermion models [1–10], in which the quarks and leptons have substructure.

In the composite-fermion scenario, quarks and leptons are assumed to have an internal substructure that would manifest itself at some sufficiently high energy scale Λ, the compositeness scale. This scale plays the role of an expansion parameter with which a series of higher-dimensional operators are constructed in an effective field theory (EFT) framework. The fermions of the SM are considered as bound states of some not-yet-observed fundamental constituents, generically referred to as *preons* [2]. Two model-independent features [8,9,11,12] are experimentally relevant: excited states of quarks and leptons with masses lower than or equal to Λ, and gauge or contact effective interactions (GI or CI) between the ordinary fermions and these excited states. The gauge interaction involves both fermion and gauge boson fields, and, at the lowest order in the EFT expansion, is described by dimension-five operators. Conversely, the contact interaction involves only fermion fields, with corresponding operators of dimension six.

A particular case of such excited states is a heavy composite Majorana neutrino (N_ℓ, $\ell = \mathrm{e}, \mu, \tau$) [13–16], a neutral lepton having a mass above the electroweak energy scale. The introduction of an N_ℓ is well motivated as an explanation of the baryon asymmetry in the universe. Indeed, in the framework of baryogenesis via leptogenesis [17,18], heavy Majorana fermions are the source of the matter-antimatter asymmetry in CP violating decays in the early universe, and it has been proposed [19,20] that N_ℓ's could quantitatively account for the observed asymmetry. Such composite Majorana neutrinos would also lead to observable effects in neutrinoless double beta decay experiments [14,16].

As a general phenomenological framework we consider the composite neutrino model given in Ref. [21], in which the GI and CI enter into both the production and decay of N_ℓ's and are governed, respectively, by the effective Lagrangians

$$\mathcal{L}_{\mathrm{GI}} = \frac{g\,f}{\sqrt{2}\Lambda}\overline{N}\sigma^{\mu\nu}(\partial_\mu W_\nu)P_\mathrm{L}\ell + \mathrm{h.c.}, \tag{1}$$

$$\mathcal{L}_{\mathrm{CI}} = \frac{g_*^2\,\eta}{\Lambda^2}\bar{q}'\gamma^\mu P_\mathrm{L}q\,\overline{N}\gamma_\mu P_\mathrm{L}\ell + \mathrm{h.c.} \tag{2}$$

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

https://doi.org/10.1016/j.physletb.2023.137803
0370-2693/

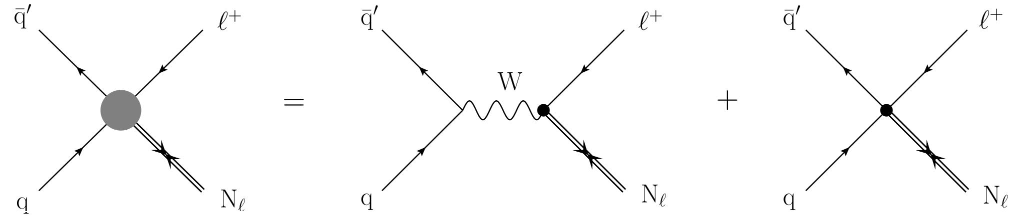

Fig. 1. The fermion interaction as a sum of gauge (center) and contact (right) contributions.

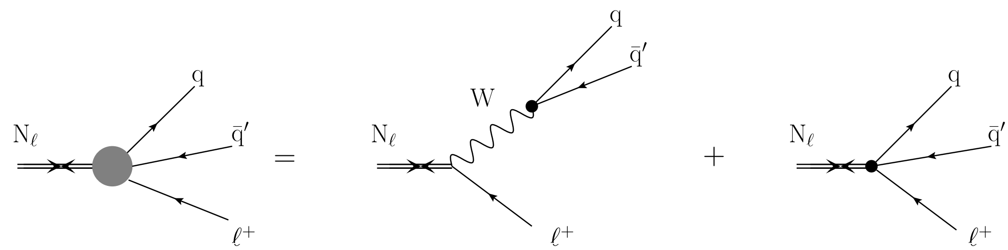

Fig. 2. Feynman diagrams for the decay of a heavy composite Majorana neutrino to $\ell q\bar{q}'$.

Here N, ℓ, W, and q are the N_ℓ, charged lepton, W boson, and quark fields, respectively, P_L is the left-handed chirality projection operator, and g is the $SU(2)_L$ gauge coupling. The effective coupling for contact interactions, g_*^2, takes the value 4π [21]. The factors f and η are additional couplings in the composite model; they are taken here to be unity, a choice that is commonly adopted in phenomenological studies and experimental analyses of composite-fermion models. The total amplitude for the production process is given by the coherent sum of the gauge and contact contributions, as shown in Fig. 1, as well as for the decay modes shown in Fig. 2. The production cross section via contact interaction is dominant for a wide range of Λ values, including the ones to which this search is sensitive.

In this work, we consider a composite neutrino, produced in association with a charged lepton, that subsequently decays to a charged lepton and a pair of quarks, leading to the experimental signature $\ell\ell q\bar{q}'$. Because the N_ℓ is a Majorana lepton at the TeV scale, the expected signal is characterized by two leptons ℓ with high transverse momentum (p_T) that may be of the same or opposite charge sign, but are of the same flavor. We focus on the cases in which these leptons are both electrons or both muons, and the quark pair is detected as a wide jet. A shape-based analysis is performed, searching for evidence of a signal in the distribution of the invariant mass of the system comprising the two leptons and the quark-pair jet.

The data sample of proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ was recorded in 2016–2018 with the CMS detector at the CERN LHC, and corresponds to an integrated luminosity of $138\,\text{fb}^{-1}$. A previous search for N_ℓ was performed by CMS with a data sample corresponding to $2.3\,\text{fb}^{-1}$ at $\sqrt{s} = 13\,\text{TeV}$ [22], and found agreement between the data and SM expectations. A 95% confidence level (CL) upper limit on the Majorana neutrino mass m_{N_ℓ} was placed at about 4.6 TeV for both the electron and muon channels. With the larger statistical power of the current data sample, the present search explores a wider range of the parameter space (m_{N_ℓ}, Λ). We further expand the composite model with recent considerations on the scope of validity of the effective operators in Eqs. (1) and (2) as derived in Ref. [23]. The unitarity bounds on these operators are used as guidance to optimize the search and extend the analysis sensitivity to lower m_{N_ℓ} and higher Λ compared with the previous search. Tabulated results are provided in the HEPData record for this analysis [24].

More generally, excited states interacting with the SM sector have been extensively searched for at high-energy collider facilities. The current most stringent bounds come from the recent LHC experiments. Excited charged leptons (e^*, μ^*) have been searched for in the channel $pp \to \ell\ell^* \to \ell\ell\gamma$ [25–30], where they would be produced via CI and then decay via GI, and in the channel $pp \to \ell\ell^* \to \ell\ell q\bar{q}'$ [30] where both production and decay proceed through CI.

2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. Within the field volume, there are the inner tracker, the crystal electromagnetic calorimeter (ECAL), and the brass and scintillator hadron calorimeter (HCAL). The inner tracker is composed of a pixel detector and a silicon strip tracker, and measures charged-particle trajectories in the pseudorapidity range $|\eta| < 2.5$. The finely segmented ECAL consists of nearly 76 000 lead-tungstate crystals that provide coverage up to $|\eta| = 3.0$. The HCAL consists of a sampling calorimeter, which utilizes alternating layers of brass as an absorber and plastic scintillator as an active material, covering the range $|\eta| < 3$, and is extended to $|\eta| < 5$ by the forward hadron calorimeters. The muon system covers the region $|\eta| < 2.4$ and consists of up to four planes of gas ionization muon detectors installed outside the solenoid and sandwiched between the layers of the steel flux-return yoke. Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of about 4 μs [31]. The second level, known as the high-level trigger, 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 around 1 kHz before data storage [32]. A detailed description of the CMS detector can be found in Ref. [33].

3. Monte Carlo simulation

The signal and the SM backgrounds are simulated using the Monte Carlo (MC) method. The simulated samples for the signal are generated at leading order (LO) with CalcHEP v3.6 [34], using the NNPDF 3.0 LO parton distribution functions (PDFs) with the four-flavor scheme [35]. Samples are generated for Λ values from 4 to 20 TeV, and with m_{N_ℓ} values from 0.5 TeV to Λ, the maximum value consistent with the model.

The background processes simulated are top quark pair production $\mathrm{t\bar{t}}$, single top quark production tW, the Drell–Yan (DY) process, W+jets, diboson production (WW, WZ, ZZ), $\mathrm{t\bar{t}}$ with vector boson production $\mathrm{t\bar{t}V}$, and SM production of jets through the strong interaction described by quantum chromodynamics (QCD). The $\mathrm{t\bar{t}}$ events are generated at next-to-leading order (NLO) with POWHEG v2.0 [36–40]. The POWHEG generator is also used to describe tW production at NLO. The DY, QCD, W+jets, and $\mathrm{t\bar{t}V}$ samples are generated at LO with MADGRAPH5_aMC@NLO v2.2.2 (v2.4.2) [41] for the 2016 (2017–2018) samples. The DY events are weighted by a p_{T}-dependent K factor, a function of the generator-level Z boson momentum $p_{\mathrm{T}}(\mathrm{Z})$. The K factor serves both to adjust a mismodeling of the $p_{\mathrm{T}}(\mathrm{Z})$ distribution [42,43] and to account for higher-order effects in the QCD and EW perturbative expansions. It is a product of two terms: one obtained as described in Ref. [44] from Drell–Yan NLO samples, produced with MADGRAPH5_aMC@NLO with the FXFX matching scheme [45], while the other is extracted from theoretical calculations [42]. The diboson processes are generated with PYTHIA [46] at LO.

For the simulation of all backgrounds we use the NNPDF 3.0 [35] PDFs for 2016, and NNPDF 3.1 next-to-NLO (NNLO) [47] for 2017–2018 samples. Parton showering and hadronization are described by PYTHIA 8.226 (8.230) with the CUETP8M1 [48] (CP5 [49]) tune for 2016 (2017–2018) samples. Additional collisions in the same or adjacent bunch crossings (pileup) are taken into account by superimposing simulated minimum bias interactions onto the hard scattering process, with a number distribution matching that observed in data. Simulated events are propagated through the GEANT4 [50] based simulation of the CMS detector, tuned for detector-related differences in each data-taking period. Normalization of the simulated background samples is performed using the most precise cross section calculations available [39–41,51–58], which are generally calculated to NLO or NNLO.

4. Event and object selection

Single-lepton triggers that require either an electron with $p_{\mathrm{T}} > 115$ GeV within $|\eta| < 2.5$ or a muon with $p_{\mathrm{T}} > 50$ GeV within $|\eta| < 2.4$ are used to select events in the $\mathrm{eeq\bar{q}'}$ and $\mu\mu\mathrm{q\bar{q}'}$ channels, respectively. The separate p_{T} requirements reflect different trigger thresholds; these do not affect the relative signal sensitivity, as the signal is characterized by high-momentum leptons in the final state. The primary vertex (PV) of the event is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in Section 9.4.1 of Ref. [59]. Electrons are reconstructed as superclusters in the ECAL associated with tracks in the tracking detector [60,61]. Requirements on energy deposits in the calorimeter and the number of track measurements are imposed to distinguish electrons from charged pions, and electrons associated with the PV from those produced by photon conversions. Muons are reconstructed using the tracker and muon detectors. Quality requirements, based on the minimum number of measurements in the silicon tracker, pixel detector, and muon detectors are applied to suppress backgrounds from hadron decays displaced from the PV and from hadron shower remnants that reach the muon system [62]. We require exactly two electrons, or two muons, that originate from the PV.

The p_{T} of the leading (subleading) lepton is required to be higher than 150 (100) GeV. Isolation requirements are imposed to suppress backgrounds from jets that are misidentified as leptons or that contain leptons from heavy-flavor hadron decays. The isolation is defined as the p_{T} sum of tracks within a cone around the candidate direction of size $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$, where ϕ is the azimuthal angle in radians. The momentum of the candidate is excluded from the sum. The isolation is required to be less than 3 (10)% of candidate electron (muon) p_{T}.

Jets are reconstructed using the anti-k_{T} clustering scheme [63,64] applied to the objects reconstructed with a particle-flow algorithm [65]. The latter combines information from all CMS subdetectors and reconstructs individual particles in the event (electrons, muons, photons, and neutral and charged hadrons). Jets are reconstructed with a distance parameter $R = 0.8$ and are referred to here as "large-radius jets", labeled by the symbol "J". This value of R is chosen to capture both final-state quarks as a single jet. The large-radius jets are required to have $p_{\mathrm{T}} > 190$ GeV, $|\eta| < 2.4$, and to be separated from leptons by $\Delta R > 0.8$. The pileup per particle identification algorithm (PUPPI) [66,67] is used to mitigate the effect of pileup at the reconstructed particle level, making use of event pileup properties, tracking information, and a local shape variable that distinguishes between collinear and soft diffuse distributions of other particles surrounding the particle under consideration. The collinear component is attributed to particles originating from the hard scatter, and the soft diffuse one to particles originating from pileup interactions.

5. Analysis strategy and background estimation

To define the signal region (SR) for the search we require that the event contain two same-flavor leptons with invariant mass $m(\ell\ell) > 300$ GeV, together with at least one large-radius jet. The requirement on $m(\ell\ell)$ is introduced to reduce the DY background and part of the $\mathrm{t\bar{t}}$ background, with minimal effect on the signal acceptance. No requirement is placed on the charge of the leptons, to retain efficiency for both same and opposite sign signal events and to avoid the systematic uncertainty associated with the efficiency of the charge sign determination for such energetic particles. While a veto of opposite-sign lepton pairs would reduce the SM background, optimization studies have shown that it is better to impose kinematical requirements that retain the signal efficiency at high momenta.

For gauge-mediated decays of the N_ℓ, the fragmentation products of the two quarks from the W boson decay typically form at least one large-radius jet. In the case of contact-mediated decays, the two quarks are well separated, but at least one of them will be contained within a large-radius jet. The signal simulation shows that the efficiency for capturing one or both quarks in the jet is 98% for the CI-dominated case $m_{\mathrm{N}_\ell} = 5$ TeV, and 95% overall for the gauge or contact interaction with $m_{\mathrm{N}_\ell} > 1$ TeV.

The key variable for the analysis is the invariant mass $m(\ell\ell\mathrm{J})$ of the system comprising the two leptons and the leading large-radius jet. This variable provides good discrimination between the signal and SM background contributions and is also correlated with m_{N_ℓ}, which would become relevant for the signal characterization if an excess were observed. The statistical analysis is implemented with a maximum likelihood (ML) fit to extract the signal strength μ, the ratio of the signal yield observed to that predicted by the model. The inputs to the fit are the distributions in $m(\ell\ell\mathrm{J})$ of the estimated backgrounds, the expected signal, and the data.

The leading background to this search is DY production of a lepton pair accompanied by a jet from initial-state radiation. The second major background comes from processes that produce top quarks, $\mathrm{t\bar{t}}$ and tW.

The DY contribution is estimated from simulation, corrected by scale factors that serve to adjust the simulated $m(\ell\ell\mathrm{J})$ shape for differences with respect to the data. A scale factor for each $m(\ell\ell\mathrm{J})$

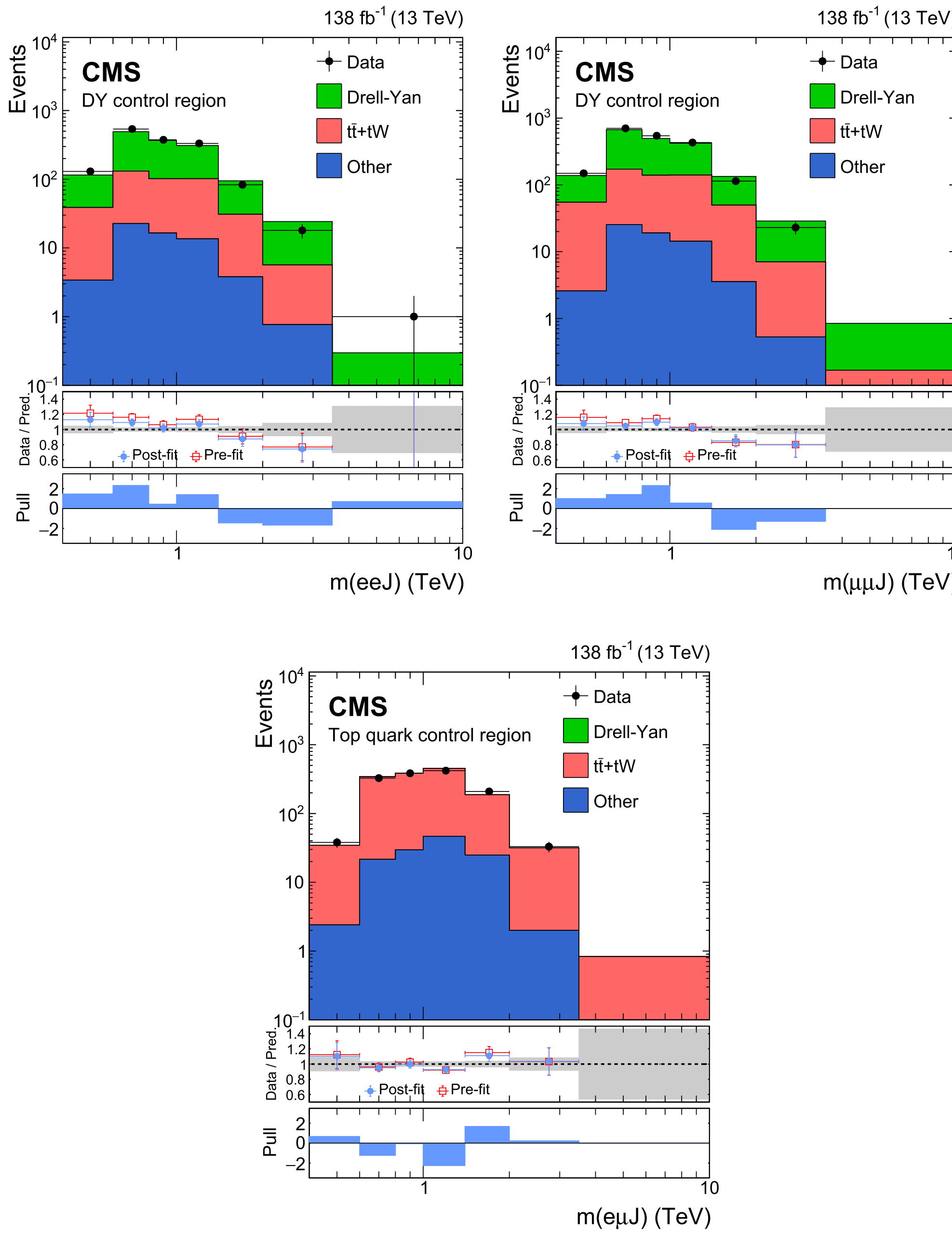

Fig. 3. Distribution of $m(\ell\ell\mathrm{J})$ in the DY-enriched CR for the electron (upper left) and muon (upper right) flavors, and of $m(\mathrm{e}\mu\mathrm{J})$ in the top-quark-enriched CR (lower). Data points are overlaid on the post-fit background (stacked histograms). The overflow is included in the last bin. The middle panels show ratios of the data to the pre-fit background prediction and post-fit background yield as red open squares and blue points, respectively. The gray band in the middle panels indicates the systematic component of the post-fit uncertainty. The lower panels show the distributions of the pulls, defined in the text.

bin and each data-taking year is taken from the DY-dominated $m(\ell\ell)$ region around the Z boson mass peak, $60 < m(\ell\ell) < 120\,\mathrm{GeV}$. The scale factors have values in the range 0.87–1.57. Their statistical uncertainties are combined with those of the simulation to estimate the total systematic uncertainty in the DY background prediction to be used in the fit.

In addition, we include in the fit an SM-dominated control region (CR) selected with the same criteria as the SR except in an $m(\ell\ell)$ band, $150 < m(\ell\ell) < 300\,\mathrm{GeV}$, that lies adjacent to the SR. This CR provides validation of the corrected simulation and improves the precision of the background prediction.

The $m(\ell\ell\mathrm{J})$ distributions of the electron and muon DY CRs are shown in Fig. 3, upper left and right, respectively. The distributions for both flavors are included in the ML fit to constrain the DY background contribution. In the figure the data are compared with the background estimated before (pre-fit) and after (post-fit) the simultaneous fit of the signal and control regions. The pulls shown in the lower panels are defined as the difference between data and the post-fit background prediction divided by the quadratic difference of the uncertainties in the data and the post-fit yields. The quadratic difference of the uncertainties is taken to account for the correlation between the data and the post-fit prediction.

The second most important background arises from the leptonic decays of top quarks from $\mathrm{t\bar{t}}$ and single top quark production. The $m(\ell\ell\mathrm{J})$ shape of this background is taken from the MC simulation, with a free normalization parameter in the ML fit for each data-taking year. To constrain these parameters, we include a top quark enriched CR in the fit. The definition of the CR exploits the fact that the decays of the top quarks from $\mathrm{t\bar{t}}$ production give rise to events with ee, $\mu\mu$, and eμ configurations, with the eμ final state

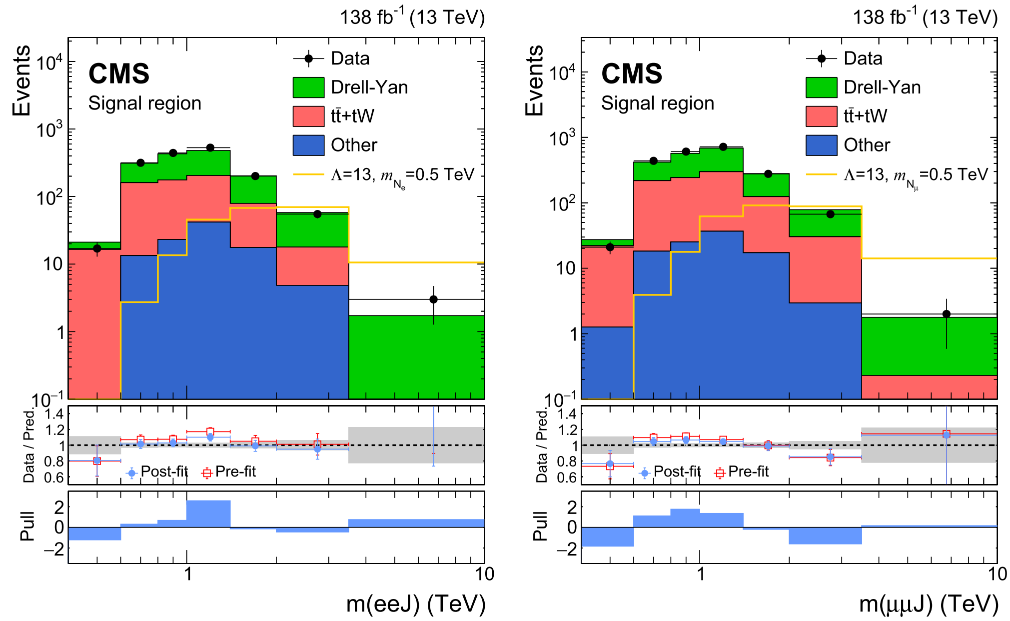

Fig. 4. Distributions of $m(\ell\ell J)$ for the data, and the post-fit backgrounds (stacked histograms), in the SRs of the $\mathrm{eeq\bar{q}'}$ (left) and the $\mu\mu\mathrm{q\bar{q}'}$ (right) channels. The template for one signal hypothesis is shown overlaid as a yellow solid line. The overflow is included in the last bin. The middle panels show ratios of the data to the pre-fit background prediction and post-fit background yield as red open squares and blue points, respectively. The gray band in the middle panels indicates the systematic component of the post-fit uncertainty. The lower panels show the distributions of the pulls, defined in the text.

having a branching fraction twice that of either of the same-flavor pairs. We thus select events having one muon and one electron, the leading (subleading) lepton having $p_T > 150\,(100)$ GeV. In addition, we reject events containing an electron and a muon, each with $p_T > 5$ GeV, that have angular separation $\Delta R < 0.1$. Fig. 3 (lower) shows the $m(\mathrm{e}\mu\mathrm{J})$ distribution of the CR data along with pre- and post-fit background estimates.

The remaining SM backgrounds, arising from QCD, W+jets, and diboson production, are small (∼5% of the total). Their contribution is taken directly from MC simulation, normalized to the theoretical cross sections cited in Section 3. These processes are designated "other" in the legends in Figs. 3 and 4. In the three highest $m(\ell\ell J)$ bins, which are the most sensitive to a signal, the fractions of backgrounds are approximately 60, 34, and 6% for DY, $\mathrm{t\bar{t}}$, and Other, respectively. The total event yield information for Fig. 4 is available in the HEPData record for this analysis [24].

6. Systematic uncertainties

Sources of systematic uncertainties affecting the $m(\ell\ell J)$ distribution include statistical uncertainties in the CR data and in the simulation, together with systematic uncertainties in quantities affecting the modeling in the simulation. The latter are accounted for with log-normal-distributed nuisance parameters in the fitting procedure described in Section 5. Uncertainties from a given source are treated as uncorrelated across the three data-taking years, with the exception of electron energy scale and resolution, small-background theoretical cross sections, and signal shape, which are fully correlated.

The integrated luminosities for the 2016, 2017, and 2018 data-taking years have individual uncertainties of 1.2–2.5% [68–70], while the overall uncertainty for the 2016–2018 period is 1.6%. These uncertainties affect the normalization of signal yields and those background yields that are taken from simulation. The imperfect modeling of pileup interactions is estimated by varying the total cross section for inelastic pp scattering used in the simulation by ±5% [71], and results in an uncertainty of 0.004 (0.006) in the fitted value of μ in the electron (muon) channel.

The lepton trigger, reconstruction, identification, and isolation efficiencies are measured in both data and simulation using $\mathrm{Z} \to \ell\ell$ events. Data-to-simulation scale factors are applied to all simulation samples to account for the differences observed between the two. The uncertainties in the lepton scale factors are propagated to the estimation of μ, and their effect is found to be 0.004 (0.006) for the electron (muon) signal.

Similarly, the momenta of leptons are varied in the simulation within their uncertainties from the nominal values to ascertain the effect of these uncertainties on the mass distributions. To evaluate the effect of the uncertainty in the momentum resolution of very high energy muons, a Gaussian smearing is applied to the muon momentum and propagated to the $m(\ell\ell J)$ distribution; the resulting effect on the signal yield is less than 0.3%, with a negligible impact on μ. The uncertainties in the jet energy scale and resolutions [72] affect the uncertainty in μ by 0.006–0.010.

For the DY background simulation we account for uncertainties in the higher-order QCD and EW corrections and in the data-to-simulation scale factors. The uncertainty in the $p_T(\mathrm{Z})$ reweighting described in Section 3 accounts for theoretical uncertainties, implemented as described in Ref. [44], and a component due to the MC samples, applied by varying the K factor by its upward and downward statistical uncertainty. Similarly, the scale factors are varied within their uncertainties to estimate their impact on the invariant mass distributions. The resulting uncertainties in the signal strength are up to 0.034–0.045 in the two leptonic final states considered.

Leaving the normalization of the top quark processes floating in the fit results in an uncertainty in the signal strength of up to 0.009 (0.008) in the electron (muon) channel. For the smaller SM backgrounds, the uncertainty in the cross section is used. The theoretical uncertainties in the signal simulation originating from the PDFs have been computed using the recommendations of Ref. [73], extracting weights from the MC replicas that vary from a few percent to about 8%, depending on m_{N_ℓ}. These weights affect the selection efficiency, but their uncertainties make a negligible contribution to the final systematic uncertainty. Finally, uncertainties related to the limited number of simulated events are taken into

Table 1
The impacts of each systematic uncertainty on the signal strength μ as extracted from the ML fit, for the N_ℓ signal point with $m_{\mathrm{N}_\ell} = 0.5\,\mathrm{TeV}$ and $\Lambda = 13\,\mathrm{TeV}$. Upper and lower uncertainties are given, for both electron and muon channels.

Source	$\mathrm{eeq\overline{q}'}$		$\mu\mu\mathrm{q\overline{q}'}$	
Luminosity	+0.004	−0.002	+0.002	−0.004
Lepton scale factors	+0.004	−0.002	+0.006	−0.006
Jet energy scale and resolution	+0.010	−0.006	+0.006	−0.003
Pileup	+0.004	−0.001	+0.006	−0.003
Lepton energy scale and resolution	+0.021	−0.017	+0.002	−0.002
$\mathrm{t\bar{t}}$, tW normalization	+0.009	−0.006	+0.008	−0.002
DY scale factors	+0.043	−0.045	+0.033	−0.034
DY K factor	+0.008	−0.007	+0.007	−0.003
Theory (PDF, cross section)	+0.005	−0.004	+0.002	−0.002
Limited MC sample size	+0.021	−0.019	+0.013	−0.005
Statistical	+0.083	−0.074	+0.061	−0.043
Total	+0.100	−0.091	+0.072	−0.055

account with the Barlow–Beeston lite approach [74]. They are considered for all bins of the distributions that are used to extract the results, and kept uncorrelated across the different samples and across the bins of an individual distribution [75]. The limited size of the simulated event and data samples are two major sources of uncertainty and account for up to 0.021 and 0.083 in μ for both lepton channels.

The impact of the systematic uncertainties on μ as extracted from the ML fit are summarized in Table 1. We have checked the sensitivity of the results to variations of the individual nuisance parameters; no significant overconstraining or underestimating of the systematic uncertainties was found.

7. Results

From the ML fit we extract values of μ for a range of the parameters m_{N_ℓ} and Λ of the signal model. The input data are the $m(\ell\ell\mathrm{J})$ distribution in the SR and in the DY CR with $150 < m(\ell\ell) < 300\,\mathrm{GeV}$, and the $m(\mathrm{e}\mu\mathrm{J})$ distribution for the top quark-enriched CR (Fig. 3). The result of the fit under the background-only hypothesis is shown in Fig. 4 for the $m(\ell\ell\mathrm{J})$ distribution of the $\mathrm{eeq\overline{q}'}$ and the $\mu\mu\mathrm{q\overline{q}'}$ channels.

The observed data and the estimated SM background contributions are in agreement, and no significant excess is observed. We derive upper limits at 95% CL on the product of cross section and branching fraction $\sigma(\mathrm{pp} \to \ell\mathrm{N}_\ell)\mathcal{B}(\mathrm{N}_\ell \to \ell\mathrm{q\overline{q}'})$, using a $\mathrm{CL_s}$ method [76,77], in the asymptotic approximation [78]. The adequacy of the asymptotic approximation has been verified with pseudo-experiments. The expected and observed upper limits for the $\mathrm{eeq\overline{q}'}$ and the $\mu\mu\mathrm{q\overline{q}'}$ channels are displayed in Fig. 5, for a benchmark value of $\Lambda = 13\,\mathrm{TeV}$. The limits are of order $10^{-4}\,\mathrm{pb}$ for a range of N_ℓ signal hypotheses.

The results are recast in terms of the EFT of Ref. [21] in Fig. 6, which shows the region in the $(m_{\mathrm{N}_\ell}, \Lambda)$ plane that is excluded by the data. The region of validity is constrained by the model's assumption that $m_{\mathrm{N}_\ell} < \Lambda$. A further consideration, discussed in Ref. [23], is that the unitarity of the scattering amplitude, as approximated in the perturbation expansion, can be violated for some values of the subenergies $\hat{s} \equiv s x_1 x_2$. These subenergies appear in the integral over $x_{1,2}$ weighted by the product of proton PDFs $\mathcal{P}(x_1)\mathcal{P}(x_2)$. Contours giving the fraction of this (x_1, x_2) phase space that is consistent with unitarity are shown as the solid magenta curves in Fig. 6. For the case of $\Lambda = m_{\mathrm{N}_\ell}$, the existence of $\mathrm{N_e}$ (N_μ) is excluded by the data for masses up to 6.0 (6.1) TeV at 95% CL, improving by more than 1 TeV the current most stringent limit on this class of resonances [22], results that are safe from potential violation of the underlying EFT. Moreover, the accessible range of Λ is almost twice that reached in the previous search, extending the sensitivity to $\approx$20 TeV at lower m_{N_ℓ} masses.

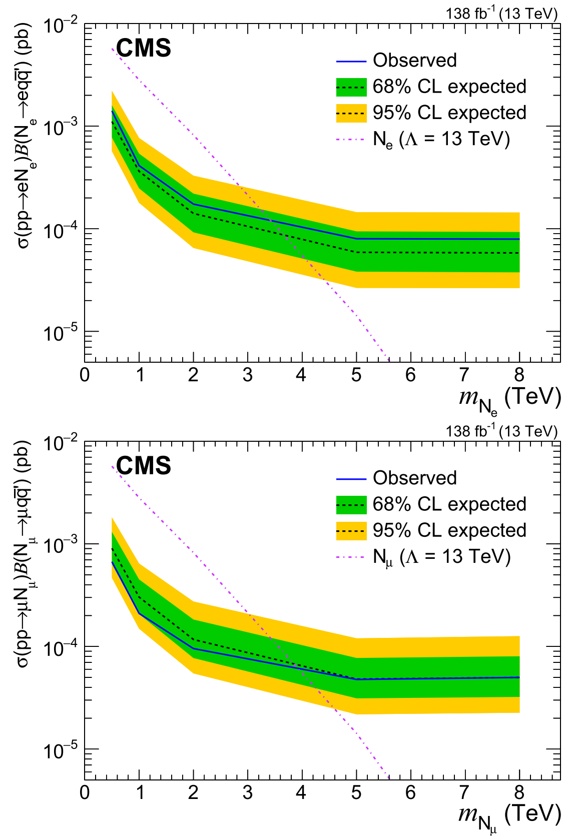

Fig. 5. Expected (black dashed lines with green dark and yellow light bands) and observed (solid blue lines) upper limits on the product of cross section and branching fraction for the $\mathrm{eeq\overline{q}'}$ (upper) and $\mu\mu\mathrm{q\overline{q}'}$ (lower) channels. The uncertainty bands account for the post-fit statistical and systematic uncertainty. The magenta dot-dashed lines denote the model cross sections for the benchmark scale parameter $\Lambda = 13\,\mathrm{TeV}$.

8. Summary

A search is reported for a heavy composite Majorana neutrino N_ℓ, where the flavor ℓ corresponds to an electron or muon, that appears in composite fermion models. In the specific model considered, the N_ℓ is produced in association with a lepton and subsequently decays into a same-flavor lepton plus two quarks, leading to a signature with two same-flavor leptons and at least one large-radius jet. The analysis is performed using a sample of proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ recorded by the CMS experiment at the CERN LHC, corresponding to an integrated luminosity of $138\,\mathrm{fb}^{-1}$. The data are found to be in agreement with the standard model expectations. In the context of an effective field theory with compositeness scale parameter Λ, an upper limit at 95% CL is established on $\sigma(\mathrm{pp} \to \ell\mathrm{N}_\ell)\mathcal{B}(\mathrm{N}_\ell \to \ell\mathrm{q\overline{q}'})$ as a function of Λ and the N_ℓ mass m_{N_ℓ}. Masses less than 6.0 (6.1) TeV are excluded for $\ell = \mathrm{e}\,(\mu)$, at the limit $m_{\mathrm{N}_\ell} = \Lambda$. For $m_{\mathrm{N}_\ell} \approx 1\,\mathrm{TeV}$, values of Λ less than 20 (23) TeV are excluded. The present search covers a parameter space larger by about 1.6 TeV in m_{N_ℓ} compared to previous searches in proton-proton collisions at 13 TeV.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

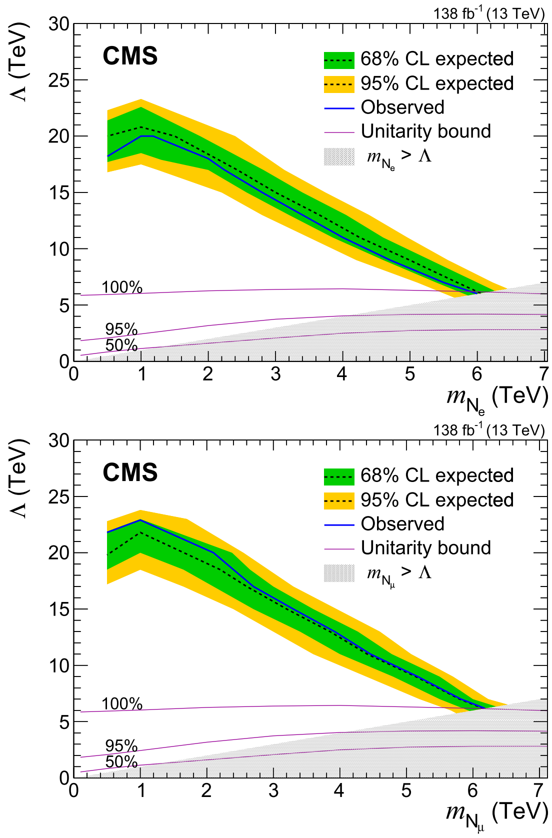

Fig. 6. Expected (black dashed lines with green dark and yellow light bands) and observed (solid blue lines) limits in the (m_{N_ℓ}, Λ) plane of the composite model for the $\mathrm{eeq\bar{q}'}$ (upper) and $\mu\mu\mathrm{q\bar{q}'}$ (lower) channels. The region below the curve is excluded. The gray shading indicates the region where m_{N_ℓ} would exceed Λ, the EFT scale parameter, and the three solid magenta lines in the lower part of the plots represent the fraction of the signal-model phase space that satisfies the unitarity condition in the EFT approximation.

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 and other centers 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, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MOST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MoSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 884104, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred 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 F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science – EOS" – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010; The Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Deutsche Forschungsgemeinschaft (DFG), under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and under project number 400140256 - GRK2497; the Hungarian Academy of Sciences, the New National Excellence Program - ÚNKP, the NKFIH research grants K 124845, K 124850, K 128713, K 128786, K 129058, K 131991, K 133046, K 138136, K 143460, K 143477, 2020-2.2.1-ED-2021-00181, and TKP2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369 and 2021/43/B/ST2/01552 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MCIN/AEI/10.13039/501100011033, ERDF "a way of making Europe", and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, and the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B05F650021 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

[1] J.C. Pati, A. Salam, J.A. Strathdee, Are quarks composite?, Phys. Lett. B 59 (1975) 265, https://doi.org/10.1016/0370-2693(75)90042-8.

[2] J.C. Pati, A. Salam, Supersymmetry at the preonic or prepreonic level and composite supergravity, Nucl. Phys. B 214 (1983) 109, https://doi.org/10.1016/0550-3213(83)90168-2.

[3] H. Harari, Composite models for quarks and leptons, Phys. Rep. 104 (1984) 159, https://doi.org/10.1016/0370-1573(84)90207-2.

[4] O.W. Greenberg, C.A. Nelson, Composite models of leptons, Phys. Rev. D 10 (1974) 2567, https://doi.org/10.1103/PhysRevD.10.2567.

[5] P.A.M. Dirac, The evolution of the physicist's picture of nature, Sci. Am. 208 (1963) 45, http://www.jstor.org/stable/24936146.

[6] H. Terazawa, K. Akama, Y. Chikashige, Unified model of the Nambu-Jona-Lasinio type for all elementary particle forces, Phys. Rev. D 15 (1977) 480, https://doi.org/10.1103/PhysRevD.15.480.

[7] E. Eichten, K.D. Lane, Dynamical breaking of weak interaction symmetries, Phys. Lett. B 90 (1980) 125, https://doi.org/10.1016/0370-2693(80)90065-9.

[8] E. Eichten, K.D. Lane, M.E. Peskin, New tests for quark and lepton substructure, Phys. Rev. Lett. 50 (1983) 811, https://doi.org/10.1103/PhysRevLett.50.811.

[9] U. Baur, M. Spira, P.M. Zerwas, Excited quark and lepton production at hadron colliders, Phys. Rev. D 42 (1990) 815, https://doi.org/10.1103/PhysRevD.42.815.

[10] U. Baur, I. Hinchliffe, D. Zeppenfeld, Excited quark production at hadron colliders, Int. J. Mod. Phys. A 2 (1987) 1285, https://doi.org/10.1142/S0217751X87000661.

[11] H. Terazawa, t quark mass predicted from a sum rule for lepton and quark masses, Phys. Rev. D 22 (1980) 2921, https://doi.org/10.1103/PhysRevD.22.2921; Erratum: https://doi.org/10.1103/PhysRevD.41.3541.

[12] N. Cabibbo, L. Maiani, Y. Srivastava, Anomalous Z decays: excited leptons?, Phys. Lett. B 139 (1984) 459, https://doi.org/10.1016/0370-2693(84)91850-1.

[13] O. Panella, Y.N. Srivastava, Bounds on compositeness from neutrinoless double beta decay, Phys. Rev. D 52 (1995) 5308, https://doi.org/10.1103/PhysRevD.52.5308, arXiv:hep-ph/9411224.
[14] O. Panella, C. Carimalo, Y.N. Srivastava, A. Widom, Neutrinoless double beta decay with composite neutrinos, Phys. Rev. D 56 (1997) 5766, https://doi.org/10.1103/PhysRevD.56.5766, arXiv:hep-ph/9701251.
[15] O. Panella, C. Carimalo, Y.N. Srivastava, Production of like sign dileptons in pp collisions through composite Majorana neutrinos, Phys. Rev. D 62 (2000) 015013, https://doi.org/10.1103/PhysRevD.62.015013, arXiv:hep-ph/9903253.
[16] S. Biondini, S. Dell'Oro, R. Leonardi, S. Marcocci, O. Panella, M. Presilla, F. Vissani, Complementarity between neutrinoless double beta decay and collider searches for heavy neutrinos in composite-fermion models, arXiv:2111.01053, 2021.
[17] M. Fukugita, T. Yanagida, Baryogenesis without grand unification, Phys. Lett. B 174 (1986) 45, https://doi.org/10.1016/0370-2693(86)91126-3.
[18] S. Davidson, E. Nardi, Y. Nir, Leptogenesis, Phys. Rep. 466 (2008) 105, https://doi.org/10.1016/j.physrep.2008.06.002, arXiv:0802.2962.
[19] D. Zhuridov, Baryogenesis from leptomesons, Phys. Rev. D 94 (2016) 035007, https://doi.org/10.1103/PhysRevD.94.035007, arXiv:1604.07740.
[20] S. Biondini, O. Panella, Leptogenesis and composite heavy neutrinos with gauge mediated interactions, Eur. Phys. J. C 77 (2017) 644, https://doi.org/10.1140/epjc/s10052-017-5206-x, arXiv:1707.00844.
[21] R. Leonardi, L. Alunni, F. Romeo, L. Fanò, O. Panella, Hunting for heavy composite Majorana neutrinos at the LHC, Eur. Phys. J. C 76 (2016) 593, https://doi.org/10.1140/epjc/s10052-016-4396-y, arXiv:1510.07988.
[22] CMS Collaboration, Search for a heavy composite Majorana neutrino in the final state with two leptons and two quarks at $\sqrt{s} = 13$ TeV, Phys. Lett. B 775 (2017) 315, https://doi.org/10.1016/j.physletb.2017.11.001, arXiv:1706.08578.
[23] S. Biondini, R. Leonardi, O. Panella, M. Presilla, Perturbative unitarity bounds for effective composite models, Phys. Lett. B 795 (2019) 644, https://doi.org/10.1016/j.physletb.2019.06.042, arXiv:1903.12285; Erratum: https://doi.org/10.1016/j.physletb.2019.134990.
[24] EXO-20-011, HEPData (collection), https://doi.org/10.17182/hepdata.133151, 2022.
[25] ATLAS Collaboration, Search for excited leptons in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector, Phys. Rev. D 85 (2012) 072003, https://doi.org/10.1103/PhysRevD.85.072003, arXiv:1201.3293.
[26] ATLAS Collaboration, Search for excited electrons and muons in $\sqrt{s} = 8$ TeV proton-proton collisions with the ATLAS detector, New J. Phys. 15 (2013) 093011, https://doi.org/10.1088/1367-2630/15/9/093011, arXiv:1308.1364.
[27] CMS Collaboration, Search for excited leptons in pp collisions at $\sqrt{s} = 7$ TeV, Phys. Lett. B 720 (2013) 309, https://doi.org/10.1016/j.physletb.2013.02.031, arXiv:1210.2422.
[28] CMS Collaboration, Search for excited leptons in proton-proton collisions at $\sqrt{s} = 8$ TeV, J. High Energy Phys. 03 (2016) 125, https://doi.org/10.1007/JHEP03(2016)125, arXiv:1511.01407.
[29] CMS Collaboration, Search for excited leptons in $\ell\ell\gamma$ final states in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 04 (2019) 015, https://doi.org/10.1007/JHEP04(2019)015, arXiv:1811.03052.
[30] CMS Collaboration, Search for an excited lepton that decays via a contact interaction to a lepton and two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 05 (2020) 052, https://doi.org/10.1007/JHEP05(2020)052, arXiv:2001.04521.
[31] CMS Collaboration, Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. Instrum. 15 (2020) P10017, https://doi.org/10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.
[32] CMS Collaboration, The CMS trigger system, J. Instrum. 12 (2017) P01020, https://doi.org/10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.
[33] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. 3 (2008) S08004, https://doi.org/10.1088/1748-0221/3/08/S08004.
[34] A. Belyaev, N.D. Christensen, A. Pukhov, CalcHEP 3.4 for collider physics within and beyond the Standard Model, Comput. Phys. Commun. 184 (2013) 1729, https://doi.org/10.1016/j.cpc.2013.01.014, arXiv:1207.6082.
[35] R.D. Ball, et al., NNPDF, Parton distributions for the LHC Run II, J. High Energy Phys. 04 (2015) 040, https://doi.org/10.1007/JHEP04(2015)040, arXiv:1410.8849.
[36] P. Nason, A new method for combining NLO QCD with shower Monte Carlo algorithms, J. High Energy Phys. 11 (2004) 040, https://doi.org/10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.
[37] S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method, J. High Energy Phys. 11 (2007) 070, https://doi.org/10.1088/1126-6708/2007/11/070, arXiv:0709.2092.
[38] S. Alioli, P. Nason, C. Oleari, E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX, J. High Energy Phys. 06 (2010) 043, https://doi.org/10.1007/JHEP06(2010)043, arXiv:1002.2581.
[39] S. Alioli, P. Nason, C. Oleari, E. Re, NLO single-top production matched with shower in POWHEG: s- and t-channel contributions, J. High Energy Phys. 09 (2009) 111, https://doi.org/10.1088/1126-6708/2009/09/111, arXiv:0907.4076; Erratum: https://doi.org/10.1007/JHEP02(2010)011.
[40] E. Re, Single-top Wt-channel production matched with parton showers using the POWHEG method, Eur. Phys. J. C 71 (2011) 1547, https://doi.org/10.1140/epjc/s10052-011-1547-z, arXiv:1009.2450.
[41] 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, J. High Energy Phys. 07 (2014) 079, https://doi.org/10.1007/JHEP07(2014)079, arXiv:1405.0301.
[42] J.M. Lindert, et al., Precise predictions for V+jets dark matter backgrounds, Eur. Phys. J. C 77 (2017) 829, https://doi.org/10.1140/epjc/s10052-017-5389-1, arXiv:1705.04664.
[43] CMS Collaboration, Measurements of differential Z boson production cross sections in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 12 (2019) 061, https://doi.org/10.1007/JHEP12(2019)061, arXiv:1909.04133.
[44] CMS Collaboration, Search for new physics in final states with an energetic jet or a hadronically decaying W or Z boson and transverse momentum imbalance at $\sqrt{s} = 13$ TeV, Phys. Rev. D 97 (2018) 092005, https://doi.org/10.1103/PhysRevD.97.092005, arXiv:1712.02345.
[45] R. Frederix, S. Frixione, Merging meets matching in MC@NLO, J. High Energy Phys. 12 (2012) 061, https://doi.org/10.1007/JHEP12(2012)061, arXiv:1209.6215.
[46] 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, https://doi.org/10.1016/j.cpc.2015.01.024, arXiv:1410.3012.
[47] R.D. Ball, et al., NNPDF, Parton distributions from high-precision collider data, Eur. Phys. J. C 77 (2017) 663, https://doi.org/10.1140/epjc/s10052-017-5199-5, arXiv:1706.00428.
[48] CMS Collaboration, Event generator tunes obtained from underlying event and multiparton scattering measurements, Eur. Phys. J. C 76 (2016) 155, https://doi.org/10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.
[49] CMS Collaboration, Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements, Eur. Phys. J. C 80 (2020) 4, https://doi.org/10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.
[50] S. Agostinelli, et al., GEANT4, GEANT4—a simulation toolkit, Nucl. Instrum. Methods A 506 (2003) 250, https://doi.org/10.1016/S0168-9002(03)01368-8.
[51] T. Melia, P. Nason, R. Rontsch, G. Zanderighi, W^+W^-, WZ and ZZ production in the POWHEG BOX, J. High Energy Phys. 11 (2011) 078, https://doi.org/10.1007/JHEP11(2011)078, arXiv:1107.5051.
[52] M. Beneke, P. Falgari, S. Klein, C. Schwinn, Hadronic top-quark pair production with NNLL threshold resummation, Nucl. Phys. B 855 (2012) 695, https://doi.org/10.1016/j.nuclphysb.2011.10.021, arXiv:1109.1536.
[53] M. Cacciari, M. Czakon, M. Mangano, A. Mitov, P. Nason, Top-pair production at hadron colliders with next-to-next-to-leading logarithmic soft-gluon resummation, Phys. Lett. B 710 (2012) 612, https://doi.org/10.1016/j.physletb.2012.03.013, arXiv:1111.5869.
[54] P. Bärnreuther, M. Czakon, A. Mitov, Percent level precision physics at the Tevatron: first genuine NNLO QCD corrections to $q\overline{q} \to t\bar{t} + X$, Phys. Rev. Lett. 109 (2012) 132001, https://doi.org/10.1103/PhysRevLett.109.132001, arXiv:1204.5201.
[55] M. Czakon, A. Mitov, NNLO corrections to top-pair production at hadron colliders: the all-fermionic scattering channels, J. High Energy Phys. 12 (2012) 054, https://doi.org/10.1007/JHEP12(2012)054, arXiv:1207.0236.
[56] M. Czakon, A. Mitov, NNLO corrections to top pair production at hadron colliders: the quark-gluon reaction, J. High Energy Phys. 01 (2013) 080, https://doi.org/10.1007/JHEP01(2013)080, arXiv:1210.6832.
[57] M. Czakon, P. Fiedler, A. Mitov, Total top-quark pair-production cross section at hadron colliders through $O(\alpha_S^4)$, Phys. Rev. Lett. 110 (2013) 252004, https://doi.org/10.1103/PhysRevLett.110.252004, arXiv:1303.6254.
[58] R. Gavin, Y. Li, F. Petriello, S. Quackenbush, FEWZ 2.0: a code for hadronic Z production at next-to-next-to-leading order, Comput. Phys. Commun. 182 (2011) 2388, https://doi.org/10.1016/j.cpc.2011.06.008, arXiv:1011.3540.
[59] CMS Collaboration, Technical proposal for the Phase-II upgrade of the Compact Muon Solenoid, CMS Technical Proposal CERN-LHCC-2015-010, CMS-TDR-15-02, http://cds.cern.ch/record/2020886, 2015.
[60] CMS Collaboration, Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC, J. Instrum. 16 (2021) P05014, https://doi.org/10.1088/1748-0221/16/05/P05014, arXiv:2012.06888.
[61] CMS Collaboration, ECAL 2016 refined calibration and Run2 summary plots, CMS Detector Performance Summary CMS-DP-2020-021, https://cds.cern.ch/record/2717925, 2020.
[62] CMS Collaboration, Performance of the reconstruction and identification of high-momentum muons in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. Instrum. 15 (2020) P02027, https://doi.org/10.1088/1748-0221/15/02/P02027, arXiv:1912.03516.
[63] M. Cacciari, G.P. Salam, G. Soyez, The anti-k_T jet clustering algorithm, J. High Energy Phys. 04 (2008) 063, https://doi.org/10.1088/1126-6708/2008/04/063, arXiv:0802.1189.
[64] M. Cacciari, G.P. Salam, G. Soyez, FastJet user manual, Eur. Phys. J. C 72 (2012) 1896, https://doi.org/10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.

[65] CMS Collaboration, Particle-flow reconstruction and global event description with the CMS detector, J. Instrum. 12 (2017) P10003, https://doi.org/10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.
[66] CMS Collaboration, Pileup mitigation at CMS in 13 TeV data, J. Instrum. 15 (2020) P09018, https://doi.org/10.1088/1748-0221/15/09/p09018, arXiv:2003.00503.
[67] D. Bertolini, P. Harris, M. Low, N. Tran, Pileup per particle identification, J. High Energy Phys. 10 (2014) 059, https://doi.org/10.1007/JHEP10(2014)059, arXiv:1407.6013.
[68] CMS Collaboration, Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS, Eur. Phys. J. C 81 (2021) 800, https://doi.org/10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.
[69] CMS Collaboration, CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV, CMS Physics Analysis Summary CMS-PAS-LUM-17-004, https://cds.cern.ch/record/2621960/, 2018.
[70] CMS Collaboration, CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV, CMS Physics Analysis Summary CMS-PAS-LUM-18-002, https://cds.cern.ch/record/2676164/, 2019.
[71] CMS Collaboration, Measurement of the inelastic proton-proton cross section at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 07 (2018) 161, https://doi.org/10.1007/JHEP07(2018)161, arXiv:1802.02613.
[72] CMS Collaboration, Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV, J. Instrum. 12 (2017) P02014, https://doi.org/10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.
[73] J. Butterworth, et al., PDF4LHC recommendations for LHC Run II, J. Phys. G 43 (2016) 023001, https://doi.org/10.1088/0954-3899/43/2/023001, arXiv:1510.03865.
[74] R.J. Barlow, C. Beeston, Fitting using finite Monte Carlo samples, Comput. Phys. Commun. 77 (1993) 219, https://doi.org/10.1016/0010-4655(93)90005-W.
[75] J.S. Conway, Incorporating nuisance parameters in likelihoods for multisource spectra, in: PHYSTAT 2011, 2011, p. 115, arXiv:1103.0354.
[76] T. Junk, Confidence level computation for combining searches with small statistics, Nucl. Instrum. Methods A 434 (1999) 435, https://doi.org/10.1016/S0168-9002(99)00498-2, arXiv:hep-ex/9902006.
[77] A.L. Read, Presentation of search results: the CL_s technique, J. Phys. G 28 (2002) 2693, https://doi.org/10.1088/0954-3899/28/10/313.
[78] G. Cowan, K. Cranmer, E. Gross, O. Vitells, Asymptotic formulae for likelihood-based tests of new physics, Eur. Phys. J. C 71 (2011) 1554, https://doi.org/10.1140/epjc/s10052-011-1554-0, arXiv:1007.1727; Erratum: https://doi.org/10.1140/epjc/s10052-013-2501-z.

The CMS Collaboration

A. Tumasyan [1]

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, J.W. Andrejkovic, T. Bergauer, S. Chatterjee, K. Damanakis, M. Dragicevic, A. Escalante Del Valle, P.S. Hussain, M. Jeitler [2], N. Krammer, L. Lechner, D. Liko, I. Mikulec, P. Paulitsch, F.M. Pitters, J. Schieck [2], R. Schöfbeck, D. Schwarz, S. Templ, W. Waltenberger, C.-E. Wulz [2]

Institut für Hochenergiephysik, Vienna, Austria

M.R. Darwish [3], T. Janssen, T. Kello [4], H. Rejeb Sfar, P. Van Mechelen

Universiteit Antwerpen, Antwerpen, Belgium

E.S. Bols, J. D'Hondt, A. De Moor, M. Delcourt, H. El Faham, S. Lowette, S. Moortgat, A. Morton, D. Müller, A.R. Sahasransu, S. Tavernier, W. Van Doninck, D. Vannerom

Vrije Universiteit Brussel, Brussel, Belgium

B. Clerbaux, G. De Lentdecker, L. Favart, D. Hohov, J. Jaramillo, K. Lee, M. Mahdavikhorrami, I. Makarenko, A. Malara, S. Paredes, L. Pétré, N. Postiau, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer

Université Libre de Bruxelles, Bruxelles, Belgium

D. Dobur, J. Knolle, L. Lambrecht, G. Mestdach, M. Niedziela, C. Rendón, C. Roskas, A. Samalan, K. Skovpen, M. Tytgat, N. Van Den Bossche, B. Vermassen, L. Wezenbeek

Ghent University, Ghent, Belgium

A. Benecke, G. Bruno, F. Bury, C. Caputo, P. David, C. Delaere, I.S. Donertas, A. Giammanco, K. Jaffel, Sa. Jain, V. Lemaitre, K. Mondal, A. Taliercio, T.T. Tran, P. Vischia, S. Wertz

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

G.A. Alves, E. Coelho, C. Hensel, A. Moraes, P. Rebello Teles

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, M. Alves Gallo Pereira, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato [5], E.M. Da Costa, G.G. Da Silveira [6], D. De Jesus Damiao, V. Dos Santos Sousa,

S. Fonseca De Souza, J. Martins [7], C. Mora Herrera, K. Mota Amarilo, L. Mundim, H. Nogima, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, F. Torres Da Silva De Araujo [8], A. Vilela Pereira

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

C.A. Bernardes [6], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, P.G. Mercadante, S.F. Novaes, Sandra S. Padula

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil

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

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

A. Dimitrov, T. Ivanov, L. Litov, B. Pavlov, P. Petkov, A. Petrov, E. Shumka

University of Sofia, Sofia, Bulgaria

S. Thakur

Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile

T. Cheng, T. Javaid [9], M. Mittal, L. Yuan

Beihang University, Beijing, China

M. Ahmad, G. Bauer [10], Z. Hu, S. Lezki, K. Yi [10,11]

Department of Physics, Tsinghua University, Beijing, China

G.M. Chen [9], H.S. Chen [9], M. Chen [9], F. Iemmi, C.H. Jiang, A. Kapoor, H. Kou, H. Liao, Z.-A. Liu [12], V. Milosevic, F. Monti, R. Sharma, J. Tao, J. Thomas-Wilsker, J. Wang, H. Zhang, J. Zhao

Institute of High Energy Physics, Beijing, China

A. Agapitos, Y. An, Y. Ban, C. Chen, A. Levin, C. Li, Q. Li, X. Lyu, Y. Mao, S.J. Qian, X. Sun, D. Wang, J. Xiao, H. Yang

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

M. Lu, Z. You

Sun Yat-Sen University, Guangzhou, China

X. Gao [4], D. Leggat, H. Okawa, Y. Zhang

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) – Fudan University, Shanghai, China

Z. Lin, C. Lu, M. Xiao

Zhejiang University, Hangzhou, Zhejiang, China

C. Avila, D.A. Barbosa Trujillo, A. Cabrera, C. Florez, J. Fraga

Universidad de Los Andes, Bogota, Colombia

J. Mejia Guisao, F. Ramirez, M. Rodriguez, J.D. Ruiz Alvarez

Universidad de Antioquia, Medellin, Colombia

D. Giljanovic, N. Godinovic, D. Lelas, I. Puljak

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

Z. Antunovic, M. Kovac, T. Sculac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, B.K. Chitroda, D. Ferencek, S. Mishra, M. Roguljic, A. Starodumov [13], T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

A. Attikis, K. Christoforou, M. Kolosova, S. Konstantinou, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, A. Stepennov

University of Cyprus, Nicosia, Cyprus

M. Finger [13], M. Finger Jr. [13], A. Kveton

Charles University, Prague, Czech Republic

E. Ayala

Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

H. Abdalla [14], Y. Assran [15,16]

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

M. Abdullah Al-Mashad, M.A. Mahmoud

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt

S. Bhowmik, R.K. Dewanjee, K. Ehataht, M. Kadastik, T. Lange, S. Nandan, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, H. Kirschenmann, K. Osterberg, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

S. Bharthuar, E. Brücken, F. Garcia, J. Havukainen, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, M. Lotti, L. Martikainen, M. Myllymäki, J. Ott, M.m. Rantanen, H. Siikonen, E. Tuominen, J. Tuominiemi

Helsinki Institute of Physics, Helsinki, Finland

P. Luukka, H. Petrow, T. Tuuva

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland

C. Amendola, M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, P. Jarry, V. Lohezic, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro [17], P. Simkina, M. Titov

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

C. Baldenegro Barrera, F. Beaudette, A. Buchot Perraguin, P. Busson, A. Cappati, C. Charlot, F. Damas, O. Davignon, B. Diab, G. Falmagne, B.A. Fontana Santos Alves, S. Ghosh, R. Granier de Cassagnac, A. Hakimi, B. Harikrishnan, G. Liu, J. Motta, M. Nguyen, C. Ochando, L. Portales, R. Salerno, U. Sarkar, J.B. Sauvan, Y. Sirois, A. Tarabini, E. Vernazza, A. Zabi, A. Zghiche

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France

J.-L. Agram [18], J. Andrea, D. Apparu, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, D. Darej, U. Goerlach, C. Grimault, A.-C. Le Bihan, P. Van Hove

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France

S. Beauceron, B. Blancon, G. Boudoul, A. Carle, N. Chanon, J. Choi, D. Contardo, P. Depasse, C. Dozen [19], H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, I.B. Laktineh, M. Lethuillier, L. Mirabito, S. Perries, L. Torterotot, M. Vander Donckt, P. Verdier, S. Viret

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France

A. Khvedelidze [13], I. Lomidze, Z. Tsamalaidze [13]

Georgian Technical University, Tbilisi, Georgia

V. Botta, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, N. Röwert, M. Teroerde

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

S. Diekmann, A. Dodonova, N. Eich, D. Eliseev, M. Erdmann, P. Fackeldey, D. Fasanella, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, M.y. Lee, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, S. Mondal, S. Mukherjee, D. Noll, A. Novak, F. Nowotny, A. Pozdnyakov, Y. Rath, W. Redjeb, H. Reithler, A. Schmidt, S.C. Schuler, A. Sharma, L. Vigilante, S. Wiedenbeck, S. Zaleski

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

C. Dziwok, G. Flügge, W. Haj Ahmad [20], O. Hlushchenko, T. Kress, A. Nowack, O. Pooth, A. Stahl, T. Ziemons, A. Zotz

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

H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, S. Baxter, M. Bayatmakou, O. Behnke, A. Bermúdez Martínez, S. Bhattacharya, A.A. Bin Anuar, F. Blekman [21], K. Borras [22], D. Brunner, A. Campbell, A. Cardini, C. Cheng, F. Colombina, S. Consuegra Rodríguez, G. Correia Silva, M. De Silva, L. Didukh, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, O. Filatov, E. Gallo [21], A. Geiser, A. Giraldi, G. Greau, A. Grohsjean, V. Guglielmi, M. Guthoff, A. Jafari [23], N.Z. Jomhari, B. Kaech, A. Kasem [22], M. Kasemann, H. Kaveh, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Pernia, K. Lipka [24], W. Lohmann [25], R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, J. Metwally, A.B. Meyer, G. Milella, M. Mormile, A. Mussgiller, A. Nürnberg, Y. Otarid, D. Pérez Adán, A. Raspereza, B. Ribeiro Lopes, J. Rübenach, A. Saggio, A. Saibel, M. Savitskyi, M. Scham [26,22], V. Scheurer, S. Schnake [22], P. Schütze, C. Schwanenberger [21], M. Shchedrolosiev, R.E. Sosa Ricardo, D. Stafford, N. Tonon [†], M. Van De Klundert, F. Vazzoler, A. Ventura Barroso, R. Walsh, D. Walter, Q. Wang, Y. Wen, K. Wichmann, L. Wiens [22], C. Wissing, S. Wuchterl, Y. Yang, A. Zimermmane Castro Santos

Deutsches Elektronen-Synchrotron, Hamburg, Germany

A. Albrecht, S. Albrecht, M. Antonello, S. Bein, L. Benato, M. Bonanomi, P. Connor, K. De Leo, M. Eich, K. El Morabit, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, M. Hajheidari, J. Haller, A. Hinzmann, H.R. Jabusch, G. Kasieczka, P. Keicher, R. Klanner, W. Korcari, T. Kramer, V. Kutzner, F. Labe, J. Lange, A. Lobanov, C. Matthies, A. Mehta, L. Moureaux, M. Mrowietz, A. Nigamova, Y. Nissan, A. Paasch, K.J. Pena Rodriguez, T. Quadfasel, M. Rieger, O. Rieger, D. Savoiu, P. Schleper, M. Schröder, J. Schwandt, M. Sommerhalder, H. Stadie, G. Steinbrück, A. Tews, M. Wolf

University of Hamburg, Hamburg, Germany

S. Brommer, M. Burkart, E. Butz, R. Caspart, T. Chwalek, A. Dierlamm, A. Droll, N. Faltermann, M. Giffels, J.O. Gosewisch, A. Gottmann, F. Hartmann [27], M. Horzela, U. Husemann, M. Klute, R. Koppenhöfer, S. Maier, S. Mitra, Th. Müller, M. Neukum, M. Oh, G. Quast, K. Rabbertz, J. Rauser, M. Schnepf, D. Seith, I. Shvetsov, H.J. Simonis, N. Trevisani, R. Ulrich, J. van der Linden, R.F. Von Cube, M. Wassmer, S. Wieland, R. Wolf, S. Wozniewski, S. Wunsch, X. Zuo

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

G. Anagnostou, P. Assiouras, G. Daskalakis, A. Kyriakis, A. Stakia

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

M. Diamantopoulou, D. Karasavvas, P. Kontaxakis, A. Manousakis-Katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, I. Zisopoulos

National and Kapodistrian University of Athens, Athens, Greece

G. Bakas, T. Chatzistavrou, K. Kousouris, I. Papakrivopoulos, G. Tsipolitis, A. Zacharopoulou

National Technical University of Athens, Athens, Greece

K. Adamidis, I. Bestintzanos, I. Evangelou, C. Foudas, P. Gianneios, C. Kamtsikis, P. Katsoulis, P. Kokkas, P.G. Kosmoglou Kioseoglou, N. Manthos, I. Papadopoulos, J. Strologas

University of Ioánnina, Ioánnina, Greece

M. Csanád, K. Farkas, M.M.A. Gadallah [28], S. Lökös [29], P. Major, K. Mandal, G. Pásztor, A.J. Rádl [30], O. Surányi, G.I. Veres

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

M. Bartók [31], G. Bencze, C. Hajdu, D. Horvath [32,33], F. Sikler, V. Veszpremi

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi [31], J. Molnar, Z. Szillasi, D. Teyssier

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

P. Raics, B. Ujvari [34]

Institute of Physics, University of Debrecen, Debrecen, Hungary

T. Csorgo [30], F. Nemes [30], T. Novak

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary

J. Babbar, S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra [35], R. Gupta, A. Kaur, A. Kaur, H. Kaur, M. Kaur, S. Kumar, P. Kumari, M. Meena, K. Sandeep, T. Sheokand, J.B. Singh [36], A. Singla, A.K. Virdi

Panjab University, Chandigarh, India

A. Ahmed, A. Bhardwaj, B.C. Choudhary, A. Kumar, M. Naimuddin, K. Ranjan, S. Saumya

University of Delhi, Delhi, India

S. Baradia, S. Barman [37], S. Bhattacharya, D. Bhowmik, S. Dutta, S. Dutta, B. Gomber [38], M. Maity [37], P. Palit, G. Saha, B. Sahu, S. Sarkar

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

P.K. Behera, S.C. Behera, P. Kalbhor, J.R. Komaragiri [39], D. Kumar [39], A. Muhammad, L. Panwar [39], R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar, P.C. Tiwari [39], S. Verma

Indian Institute of Technology Madras, Madras, India

K. Naskar [40]

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, I. Das, S. Dugad, M. Kumar, G.B. Mohanty, P. Suryadevara

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, R. Chudasama, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee, A. Thachayath

Tata Institute of Fundamental Research-B, Mumbai, India

S. Bahinipati [41], C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu [42], A. Nayak [42], P. Saha, S.K. Swain, D. Vats [42]

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India

A. Alpana, S. Dube, B. Kansal, A. Laha, S. Pandey, A. Rastogi, S. Sharma

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

H. Bakhshiansohi [43], E. Khazaie, M. Zeinali [44]

Isfahan University of Technology, Isfahan, Iran

S. Chenarani [45], S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

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

M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia [a,b], R. Aly [a,c,46], C. Aruta [a,b], A. Colaleo [a], D. Creanza [a,c], N. De Filippis [a,c], M. De Palma [a,b], A. Di Florio [a,b], W. Elmetenawee [a,b], F. Errico [a,b], L. Fiore [a], G. Iaselli [a,c], M. Ince [a,b], G. Maggi [a,c], M. Maggi [a], I. Margjeka [a,b], V. Mastrapasqua [a,b], S. My [a,b], S. Nuzzo [a,b], A. Pellecchia [a,b], A. Pompili [a,b], G. Pugliese [a,c], R. Radogna [a], D. Ramos [a], A. Ranieri [a], G. Selvaggi [a,b], L. Silvestris [a], F.M. Simone [a,b], Ü. Sözbilir [a], A. Stamerra [a], R. Venditti [a], 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 [a,b], D. Bonacorsi [a,b], L. Borgonovi [a], L. Brigliadori [a], R. Campanini [a,b], P. Capiluppi [a,b], A. Castro [a,b], F.R. Cavallo [a], M. Cuffiani [a,b], G.M. Dallavalle [a], T. Diotalevi [a,b], F. Fabbri [a], A. Fanfani [a,b], P. Giacomelli [a], L. Giommi [a,b], C. Grandi [a], L. Guiducci [a,b], S. Lo Meo [a,47], L. Lunerti [a,b], S. Marcellini [a], G. Masetti [a], F.L. Navarria [a,b], A. Perrotta [a], F. Primavera [a,b], A.M. Rossi [a,b], T. Rovelli [a,b], G.P. Siroli [a,b]

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

S. Costa [a,b,48], A. Di Mattia [a], R. Potenza [a,b], A. Tricomi [a,b,48], C. Tuve [a,b]

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

G. Barbagli [a], G. Bardelli [a,b], B. Camaiani [a,b], A. Cassese [a], R. Ceccarelli [a,b], V. Ciulli [a,b], C. Civinini [a], R. D'Alessandro [a,b], E. Focardi [a,b], G. Latino [a,b], P. Lenzi [a,b], M. Lizzo [a,b], M. Meschini [a], S. Paoletti [a], R. Seidita [a,b], G. Sguazzoni [a], L. Viliani [a]

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

L. Benussi, S. Bianco, S. Meola [27], D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

M. Bozzo [a,b], P. Chatagnon [a], F. Ferro [a], R. Mulargia [a], E. Robutti [a], S. Tosi [a,b]

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

[b] Università di Genova, Genova, Italy

A. Benaglia [a], G. Boldrini [a], F. Brivio [a,b], F. Cetorelli [a,b], F. De Guio [a,b], M.E. Dinardo [a,b], P. Dini [a], S. Gennai [a], A. Ghezzi [a,b], P. Govoni [a,b], L. Guzzi [a,b], M.T. Lucchini [a,b], M. Malberti [a], S. Malvezzi [a], A. Massironi [a], D. Menasce [a], L. Moroni [a], M. Paganoni [a,b], D. Pedrini [a], B.S. Pinolini [a], S. Ragazzi [a,b], N. Redaelli [a], T. Tabarelli de Fatis [a,b], D. Zuolo [a,b]

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

S. Buontempo [a], F. Carnevali [a,b], N. Cavallo [a,c], A. De Iorio [a,b], F. Fabozzi [a,c], A.O.M. Iorio [a,b], L. Lista [a,b,49], P. Paolucci [a,27], B. Rossi [a], C. Sciacca [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], N. Bacchetta [a,50], D. Bisello [a,b], P. Bortignon [a], A. Bragagnolo [a,b], R. Carlin [a,b], P. Checchia [a], T. Dorigo [a], F. Fanzago [a], F. Gasparini [a,b], U. Gasparini [a,b], G. Grosso [a], L. Layer [a,51], E. Lusiani [a], M. Margoni [a,b], A.T. Meneguzzo [a,b], J. Pazzini [a,b], P. Ronchese [a,b], R. Rossin [a,b], F. Simonetto [a,b], G. Strong [a], M. Tosi [a,b], H. Yarar [a,b], M. Zanetti [a,b], A. Zucchetta [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

S. Abu Zeid [a,52], C. Aimè [a,b], A. Braghieri [a], S. Calzaferri [a,b], D. Fiorina [a,b], P. Montagna [a,b], V. Re [a], C. Riccardi [a,b], P. Salvini [a], I. Vai [a], P. Vitulo [a,b]

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

P. Asenov [a,53], G.M. Bilei [a], S. Biondini [b,103], D. Ciangottini [a,b], L. Fanò [a,b], M. Magherini [a,b], E. Manoni [a], G. Mantovani [a,b], V. Mariani [a,b], M. Menichelli [a], F. Moscatelli [a,53], O. Panella [a], A. Piccinelli [a,b], M. Presilla [a,b], A. Rossi [a,b], A. Santocchia [a,b], D. Spiga [a], T. Tedeschi [a,b]

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

P. Azzurri [a], G. Bagliesi [a], V. Bertacchi [a,c], R. Bhattacharya [a], L. Bianchini [a,b], T. Boccali [a], E. Bossini [a,b], D. Bruschini [a,c], R. Castaldi [a], M.A. Ciocci [a,b], V. D'Amante [a,d], R. Dell'Orso [a], M.R. Di Domenico [a,d], S. Donato [a], A. Giassi [a], F. Ligabue [a,c], G. Mandorli [a,c], D. Matos Figueiredo [a], A. Messineo [a,b], M. Musich [a,b], F. Palla [a], S. Parolia [a,b], G. Ramirez-Sanchez [a,c], A. Rizzi [a,b], G. Rolandi [a,c], S. Roy Chowdhury [a], T. Sarkar [a], A. Scribano [a], N. Shafiei [a,b], P. Spagnolo [a], R. Tenchini [a], G. Tonelli [a,b], N. Turini [a,d], 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
[d] Università di Siena, Siena, Italy

P. Barria [a], M. Campana [a,b], F. Cavallari [a], D. Del Re [a,b], E. Di Marco [a], M. Diemoz [a], E. Longo [a,b], P. Meridiani [a], G. Organtini [a,b], F. Pandolfi [a], R. Paramatti [a,b], C. Quaranta [a,b], S. Rahatlou [a,b], C. Rovelli [a], F. Santanastasio [a,b], L. Soffi [a], R. Tramontano [a,b]

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

N. Amapane [a,b], R. Arcidiacono [a,c], S. Argiro [a,b], M. Arneodo [a,c], N. Bartosik [a], R. Bellan [a,b], A. Bellora [a,b], C. Biino [a], N. Cartiglia [a], M. Costa [a,b], R. Covarelli [a,b], N. Demaria [a], M. Grippo [a,b], B. Kiani [a,b], F. Legger [a],

C. Mariotti [a], S. Maselli [a], A. Mecca [a,b], E. Migliore [a,b], E. Monteil [a,b], M. Monteno [a], M.M. Obertino [a,b], G. Ortona [a], L. Pacher [a,b], N. Pastrone [a], M. Pelliccioni [a], M. Ruspa [a,c], K. Shchelina [a], F. Siviero [a,b], V. Sola [a], A. Solano [a,b], D. Soldi [a,b], A. Staiano [a], M. Tornago [a,b], D. Trocino [a], G. Umoret [a,b], A. Vagnerini [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], V. Candelise [a,b], M. Casarsa [a], F. Cossutti [a], A. Da Rold [a,b], G. Della Ricca [a,b], G. Sorrentino [a,b]

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

S. Dogra, C. Huh, B. Kim, D.H. Kim, G.N. Kim, J. Kim, J. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, M.S. Ryu, S. Sekmen, Y.C. Yang

Kyungpook National University, Daegu, Korea

H. Kim, D.H. Moon

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

E. Asilar, T.J. Kim, J. Park

Hanyang University, Seoul, Korea

S. Choi, S. Han, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, J. Yoo

Korea University, Seoul, Korea

J. Goh

Kyung Hee University, Department of Physics, Seoul, Korea

H.S. Kim, Y. Kim, S. Lee

Sejong University, Seoul, Korea

J. Almond, J.H. Bhyun, J. Choi, S. Jeon, J. Kim, J.S. Kim, S. Ko, H. Kwon, H. Lee, S. Lee, B.H. Oh, S.B. Oh, H. Seo, U.K. Yang, I. Yoon

Seoul National University, Seoul, Korea

W. Jang, D.Y. Kang, Y. Kang, D. Kim, S. Kim, B. Ko, J.S.H. Lee, Y. Lee, J.A. Merlin, I.C. Park, Y. Roh, D. Song, I.J. Watson, S. Yang

University of Seoul, Seoul, Korea

S. Ha, H.D. Yoo

Yonsei University, Department of Physics, Seoul, Korea

M. Choi, M.R. Kim, H. Lee, Y. Lee, Y. Lee, I. Yu

Sungkyunkwan University, Suwon, Korea

T. Beyrouthy, Y. Maghrbi

College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait

K. Dreimanis, G. Pikurs, M. Seidel, V. Veckalns

Riga Technical University, Riga, Latvia

M. Ambrozas, A. Carvalho Antunes De Oliveira, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

Vilnius University, Vilnius, Lithuania

N. Bin Norjoharuddeen, S.Y. Hoh [54], I. Yusuff [54], Z. Zolkapli

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

J.F. Benitez, A. Castaneda Hernandez, H.A. Encinas Acosta, L.G. Gallegos Maríñez, M. León Coello, J.A. Murillo Quijada, A. Sehrawat, L. Valencia Palomo

Universidad de Sonora (UNISON), Hermosillo, Mexico

G. Ayala, H. Castilla-Valdez, I. Heredia-De La Cruz [55], R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, A. Sánchez Hernández

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

C. Oropeza Barrera, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

I. Bubanja, J. Mijuskovic [56], N. Raicevic

University of Montenegro, Podgorica, Montenegro

A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, M. Gul, H.R. Hoorani, W.A. Khan, M. Shoaib, M. Waqas

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

V. Avati, L. Grzanka, M. Malawski

AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland

H. Bialkowska, M. Bluj, B. Boimska, M. Górski, M. Kazana, M. Szleper, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

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

M. Araujo, P. Bargassa, D. Bastos, A. Boletti, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, T. Niknejad, M. Pisano, J. Seixas, J. Varela

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

P. Adzic [57], M. Dordevic, P. Milenovic, J. Milosevic

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, M. Barrio Luna, Cristina F. Bedoya, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, D. Fernández Del Val, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. León Holgado, D. Moran, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, D.D. Redondo Ferrero, L. Romero, S. Sánchez Navas, J. Sastre, L. Urda Gómez, J. Vazquez Escobar, C. Willmott

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

J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, Spain

B. Alvarez Gonzalez, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, C. Ramón Álvarez, V. Rodríguez Bouza, A. Soto Rodríguez, A. Trapote, C. Vico Villalba

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, C. Fernandez Madrazo, A. García Alonso, G. Gomez, C. Lasaosa García, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, J. Piedra Gomez, C. Prieels, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, J.M. Vizan Garcia

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

M.K. Jayananda, B. Kailasapathy [58], D.U.J. Sonnadara, D.D.C. Wickramarathna

University of Colombo, Colombo, Sri Lanka

W.G.D. Dharmaratna, K. Liyanage, N. Perera, N. Wickramage

University of Ruhuna, Department of Physics, Matara, Sri Lanka

D. Abbaneo, J. Alimena, E. Auffray, G. Auzinger, J. Baechler, P. Baillon [†], D. Barney, J. Bendavid, M. Bianco, B. Bilin, A. Bocci, E. Brondolin, C. Caillol, T. Camporesi, G. Cerminara, N. Chernyavskaya, S.S. Chhibra, S. Choudhury, M. Cipriani, L. Cristella, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, M. Dünser, N. Dupont, F. Fallavollita [59], A. Florent, L. Forthomme, G. Franzoni, W. Funk, S. Ghosh, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, E. Govorkova, M. Haranko, J. Hegeman, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, N. Kratochwil, S. Laurila, P. Lecoq, E. Leutgeb, A. Lintuluoto, C. Lourenço, B. Maier, L. Malgeri, M. Mannelli, A.C. Marini, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, S. Orfanelli, L. Orsini, F. Pantaleo, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Piparo, M. Pitt, H. Qu, T. Quast, D. Rabady, A. Racz, G. Reales Gutiérrez, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas [60], A.G. Stahl Leiton, S. Summers, K. Tatar, V.R. Tavolaro, D. Treille, P. Tropea, A. Tsirou, J. Wanczyk [61], K.A. Wozniak, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

L. Caminada [62], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli [62], L. Noehte [62], T. Rohe

Paul Scherrer Institut, Villigen, Switzerland

T.K. Aarrestad, K. Androsov [61], M. Backhaus, P. Berger, A. Calandri, K. Datta, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, M. Galli, K. Gedia, F. Glessgen, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, L. Marchese, C. Martin Perez, A. Mascellani [61], F. Nessi-Tedaldi, J. Niedziela, F. Pauss, V. Perovic, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, F. Riti, D. Ruini, D.A. Sanz Becerra, J. Steggemann [61], D. Valsecchi [27], R. Wallny

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

C. Amsler [63], P. Bärtschi, C. Botta, D. Brzhechko, M.F. Canelli, K. Cormier, A. De Wit, R. Del Burgo, J.K. Heikkilä, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, I. Neutelings, A. Reimers, P. Robmann, S. Sanchez Cruz, K. Schweiger, M. Senger, Y. Takahashi

Universität Zürich, Zurich, Switzerland

C. Adloff [64], C.M. Kuo, W. Lin, P.K. Rout, S.S. Yu

National Central University, Chung-Li, Taiwan

L. Ceard, Y. Chao, K.F. Chen, P.s. Chen, H. Cheng, W.-S. Hou, R. Khurana, G. Kole, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, H.y. Wu, E. Yazgan, P.r. Yu

National Taiwan University (NTU), Taipei, Taiwan

C. Asawatangtrakuldee, N. Srimanobhas

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

D. Agyel, F. Boran, Z.S. Demiroglu, F. Dolek, I. Dumanoglu [65], E. Eskut, Y. Guler [66], E. Gurpinar Guler [66], C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir [67], A. Polatoz, A.E. Simsek, B. Tali [68], U.G. Tok, S. Turkcapar, E. Uslan, I.S. Zorbakir

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

G. Karapinar [69], K. Ocalan [70], M. Yalvac [71]

Middle East Technical University, Physics Department, Ankara, Turkey

B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya [72], O. Kaya [73], S. Tekten [74]

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak [65], Y. Komurcu, S. Sen [65]

Istanbul Technical University, Istanbul, Turkey

O. Aydilek, S. Cerci [68], B. Hacisahinoglu, I. Hos [75], B. Isildak [76], B. Kaynak, S. Ozkorucuklu, C. Simsek, D. Sunar Cerci [68]

Istanbul University, Istanbul, Turkey

B. Grynyov

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

L. Levchuk

National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine

D. Anthony, E. Bhal, J.J. Brooke, A. Bundock, E. Clement, D. Cussans, H. Flacher, M. Glowacki, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou [77], K. Walkingshaw Pass, R. White

University of Bristol, Bristol, United Kingdom

A.H. Ball, K.W. Bell, A. Belyaev [78], C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, K.V. Ellis, K. Harder, S. Harper, M.-L. Holmberg [79], J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, G. Salvi, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, C.E. Brown, O. Buchmuller, V. Cacchio, V. Cepaitis, G.S. Chahal [80], D. Colling, J.S. Dancu, P. Dauncey, G. Davies, J. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, A. Howard, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, M. Mieskolainen, D.G. Monk, J. Nash [81], M. Pesaresi, B.C. Radburn-Smith, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, L.H. Vage, T. Virdee [27], M. Vojinovic, N. Wardle, S.N. Webb, D. Winterbottom

Imperial College, London, United Kingdom

K. Coldham, J.E. Cole, A. Khan, P. Kyberd, I.D. Reid

Brunel University, Uxbridge, United Kingdom

S. Abdullin, A. Brinkerhoff, B. Caraway, J. Dittmann, K. Hatakeyama, A.R. Kanuganti, B. McMaster, M. Saunders, S. Sawant, C. Sutantawibul, J. Wilson

Baylor University, Waco, TX, USA

R. Bartek, A. Dominguez, R. Uniyal, A.M. Vargas Hernandez

Catholic University of America, Washington, DC, USA

S.I. Cooper, D. Di Croce, S.V. Gleyzer, C. Henderson, C.U. Perez, P. Rumerio [82], C. West

The University of Alabama, Tuscaloosa, AL, USA

A. Akpinar, A. Albert, D. Arcaro, C. Cosby, Z. Demiragli, C. Erice, E. Fontanesi, D. Gastler, S. May, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, S. Yuan

Boston University, Boston, MA, USA

G. Benelli, B. Burkle, X. Coubez [22], D. Cutts, M. Hadley, U. Heintz, J.M. Hogan [83], T. Kwon, G. Landsberg, K.T. Lau, D. Li, J. Luo, M. Narain, N. Pervan, S. Sagir [84], F. Simpson, E. Usai, W.Y. Wong, X. Yan, D. Yu, W. Zhang

Brown University, Providence, RI, USA

J. Bonilla, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, P.T. Cox, R. Erbacher, G. Haza, F. Jensen, O. Kukral, G. Mocellin, M. Mulhearn, D. Pellett, B. Regnery, Y. Yao, F. Zhang

University of California, Davis, Davis, CA, USA

M. Bachtis, R. Cousins, A. Datta, D. Hamilton, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, E. Manca, W.A. Nash, S. Regnard, D. Saltzberg, B. Stone, V. Valuev

University of California, Los Angeles, CA, USA

R. Clare, J.W. Gary, M. Gordon, G. Hanson, G. Karapostoli, O.R. Long, N. Manganelli, W. Si, S. Wimpenny

University of California, Riverside, Riverside, CA, USA

J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, D. Diaz, J. Duarte, R. Gerosa, L. Giannini, J. Guiang, R. Kansal, V. Krutelyov, R. Lee, J. Letts, M. Masciovecchio, F. Mokhtar, M. Pieri, B.V. Sathia Narayanan, V. Sharma, M. Tadel, E. Vourliotis, F. Würthwein, Y. Xiang, A. Yagil

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

N. Amin, C. Campagnari, M. Citron, G. Collura, A. Dorsett, V. Dutta, J. Incandela, M. Kilpatrick, J. Kim, A.J. Li, P. Masterson, H. Mei, M. Oshiro, M. Quinnan, J. Richman, U. Sarica, R. Schmitz, F. Setti, J. Sheplock, P. Siddireddy, D. Stuart, S. Wang

University of California, Santa Barbara – Department of Physics, Santa Barbara, CA, USA

A. Bornheim, O. Cerri, I. Dutta, A. Latorre, J.M. Lawhorn, N. Lu, J. Mao, H.B. Newman, T.Q. Nguyen, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, R.Y. Zhu

California Institute of Technology, Pasadena, CA, USA

J. Alison, S. An, M.B. Andrews, P. Bryant, T. Ferguson, A. Harilal, C. Liu, T. Mudholkar, S. Murthy, M. Paulini, A. Roberts, A. Sanchez, W. Terrill

Carnegie Mellon University, Pittsburgh, PA, USA

J.P. Cumalat, W.T. Ford, A. Hassani, G. Karathanasis, E. MacDonald, F. Marini, R. Patel, A. Perloff, C. Savard, N. Schonbeck, K. Stenson, K.A. Ulmer, S.R. Wagner, N. Zipper

University of Colorado Boulder, Boulder, CO, USA

J. Alexander, S. Bright-Thonney, X. Chen, D.J. Cranshaw, J. Fan, X. Fan, D. Gadkari, S. Hogan, J. Monroy, J.R. Patterson, D. Quach, J. Reichert, M. Reid, A. Ryd, J. Thom, P. Wittich, R. Zou

Cornell University, Ithaca, NY, USA

M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, L.A.T. Bauerdick, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, K.F. Di Petrillo, J. Dickinson, V.D. Elvira, Y. Feng, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, S. Grünendahl, O. Gutsche, R.M. Harris, R. Heller, T.C. Herwig, J. Hirschauer, L. Horyn, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, D. Lincoln, R. Lipton, T. Liu, C. Madrid, K. Maeshima, C. Mantilla, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena [85], F. Ravera, A. Reinsvold Hall [86], L. Ristori, E. Sexton-Kennedy, N. Smith, A. Soha, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, H.A. Weber, I. Zoi

Fermi National Accelerator Laboratory, Batavia, IL, USA

P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, R.D. Field, D. Guerrero, M. Kim, E. Koenig, J. Konigsberg, A. Korytov, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, A. Muthirakalayil Madhu, N. Rawal, D. Rosenzweig, S. Rosenzweig, K. Shi, J. Wang, Z. Wu

University of Florida, Gainesville, FL, USA

T. Adams, A. Askew, R. Habibullah, V. Hagopian, T. Kolberg, G. Martinez, H. Prosper, C. Schiber, O. Viazlo, R. Yohay, J. Zhang

Florida State University, Tallahassee, FL, USA

M.M. Baarmand, S. Butalla, T. Elkafrawy [52], M. Hohlmann, R. Kumar Verma, M. Rahmani, F. Yumiceva

Florida Institute of Technology, Melbourne, FL, USA

M.R. Adams, H. Becerril Gonzalez, R. Cavanaugh, S. Dittmer, O. Evdokimov, C.E. Gerber, D.J. Hofman, D.S. Lemos, A.H. Merrit, C. Mills, G. Oh, T. Roy, S. Rudrabhatla, M.B. Tonjes, N. Varelas, X. Wang, Z. Ye, J. Yoo

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

M. Alhusseini, K. Dilsiz [87], L. Emediato, R.P. Gandrajula, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili [88], J. Nachtman, O. Neogi, H. Ogul [89], Y. Onel, A. Penzo, C. Snyder, E. Tiras [90]

The University of Iowa, Iowa City, IA, USA

O. Amram, B. Blumenfeld, L. Corcodilos, J. Davis, A.V. Gritsan, S. Kyriacou, P. Maksimovic, J. Roskes, S. Sekhar, M. Swartz, T.Á. Vámi

Johns Hopkins University, Baltimore, MD, USA

A. Abreu, L.F. Alcerro Alcerro, J. Anguiano, P. Baringer, A. Bean, Z. Flowers, T. Isidori, J. King, G. Krintiras, M. Lazarovits, C. Le Mahieu, C. Lindsey, J. Marquez, N. Minafra, M. Murray, M. Nickel, C. Rogan, C. Royon, R. Salvatico, S. Sanders, C. Smith, Q. Wang, J. Williams, G. Wilson

The University of Kansas, Lawrence, KS, USA

B. Allmond, S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, T. Mitchell, A. Modak, K. Nam, D. Roy

Kansas State University, Manhattan, KS, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, CA, USA

E. Adams, A. Baden, O. Baron, A. Belloni, A. Bethani, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, Y. Lai, S. Lascio, A.C. Mignerey, S. Nabili, C. Palmer, C. Papageorgakis, L. Wang, K. Wong

University of Maryland, College Park, MD, USA

D. Abercrombie, W. Busza, I.A. Cali, Y. Chen, M. D'Alfonso, J. Eysermans, C. Freer, G. Gomez-Ceballos, M. Goncharov, P. Harris, M. Hu, D. Kovalskyi, J. Krupa, Y.-J. Lee, K. Long, C. Mironov, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, J. Wang, Z. Wang, B. Wyslouch, T.J. Yang

Massachusetts Institute of Technology, Cambridge, MA, USA

R.M. Chatterjee, B. Crossman, A. Evans, J. Hiltbrand, Sh. Jain, B.M. Joshi, C. Kapsiak, M. Krohn, Y. Kubota, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

University of Minnesota, Minneapolis, MN, USA

L.M. Cremaldi

University of Mississippi, Oxford, MS, USA

K. Bloom, M. Bryson, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, C. Joo, R. Kamalieddin, I. Kravchenko, I. Reed, J.E. Siado, G.R. Snow [†], W. Tabb, A. Wightman, F. Yan, A.G. Zecchinelli

University of Nebraska-Lincoln, Lincoln, NE, USA

G. Agarwal, H. Bandyopadhyay, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, M. Morris, D. Nguyen, J. Pekkanen, S. Rappoccio, A. Williams

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

G. Alverson, E. Barberis, Y. Haddad, Y. Han, A. Krishna, J. Li, J. Lidrych, G. Madigan, B. Marzocchi, D.M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, A. Tishelman-Charny, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northeastern University, Boston, MA, USA

S. Bhattacharya, J. Bueghly, Z. Chen, A. Gilbert, K.A. Hahn, Y. Liu, N. Odell, M.H. Schmitt, M. Velasco

Northwestern University, Evanston, IL, USA

R. Band, R. Bucci, M. Cremonesi, A. Das, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, K. Mohrman, C. Moore, Y. Musienko [13], R. Ruchti, A. Townsend, M. Wayne, H. Yockey, M. Zarucki, L. Zygala

University of Notre Dame, Notre Dame, IN, USA

B. Bylsma, M. Carrigan, L.S. Durkin, B. Francis, C. Hill, M. Joyce, A. Lesauvage, M. Nunez Ornelas, K. Wei, B.L. Winer, B.R. Yates

The Ohio State University, Columbus, OH, USA

F.M. Addesa, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, B. Greenberg, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, G. Kopp, S. Kwan, D. Lange, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, D. Stickland, C. Tully

Princeton University, Princeton, NJ, USA

S. Malik, S. Norberg

University of Puerto Rico, Mayaguez, PR, USA

A.S. Bakshi, V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, D. Kondratyev, A.M. Koshy, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, A. Purohit, J.F. Schulte, M. Stojanovic, J. Thieman, F. Wang, R. Xiao, W. Xie

Purdue University, West Lafayette, IN, USA

J. Dolen, N. Parashar

Purdue University Northwest, Hammond, IN, USA

D. Acosta, A. Baty, T. Carnahan, M. Decaro, S. Dildick, K.M. Ecklund, P.J. Fernández Manteca, S. Freed, P. Gardner, F.J.M. Geurts, A. Kumar, W. Li, B.P. Padley, R. Redjimi, J. Rotter, W. Shi, S. Yang, E. Yigitbasi, L. Zhang [91], Y. Zhang

Rice University, Houston, TX, USA

A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, E. Ranken, R. Taus, G.P. Van Onsem

University of Rochester, Rochester, NY, USA

K. Goulianos

The Rockefeller University, New York, NY, USA

B. Chiarito, J.P. Chou, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, D. Jaroslawski, O. Karacheban [25], I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Routray, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, H. Wang

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

H. Acharya, A.G. Delannoy, S. Fiorendi, T. Holmes, E. Nibigira, S. Spanier

University of Tennessee, Knoxville, TN, USA

O. Bouhali [92], M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon [93], H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, D. Rathjens, A. Safonov

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

N. Akchurin, J. Damgov, V. Hegde, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, I. Volobouev, A. Whitbeck

Texas Tech University, Lubbock, TX, USA

E. Appelt, S. Greene, A. Gurrola, W. Johns, A. Melo, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, J. Viinikainen

Vanderbilt University, Nashville, TN, USA

B. Cardwell, B. Cox, G. Cummings, J. Hakala, R. Hirosky, A. Ledovskoy, A. Li, C. Neu, C.E. Perez Lara, B. Tannenwald

University of Virginia, Charlottesville, VA, USA

P.E. Karchin, N. Poudyal

Wayne State University, Detroit, MI, USA

S. Banerjee, K. Black, T. Bose, S. Dasu, I. De Bruyn, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Herve, C.K. Koraka, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, A. Mohammadi, S. Mondal, G. Parida, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, H.F. Tsoi, W. Vetens

University of Wisconsin – Madison, Madison, WI, USA

S. Afanasiev, V. Andreev, Yu. Andreev, T. Aushev, M. Azarkin, A. Babaev, A. Belyaev, V. Blinov [94], E. Boos, V. Borshch, D. Budkouski, V. Bunichev, V. Chekhovsky, R. Chistov [94], A. Dermenev, T. Dimova [94], I. Dremin, M. Dubinin [85], L. Dudko, V. Epshteyn [95], A. Ershov, G. Gavrilov, V. Gavrilov, S. Gninenko, V. Golovtcov, N. Golubev, I. Golutvin, I. Gorbunov, A. Gribushin, V. Ivanchenko, Y. Ivanov, V. Kachanov, L. Kardapoltsev [94], V. Karjavine, A. Karneyeu, V. Kim [94], M. Kirakosyan, D. Kirpichnikov, M. Kirsanov, V. Klyukhin, O. Kodolova [96], D. Konstantinov, V. Korenkov, A. Kozyrev [94], N. Krasnikov, E. Kuznetsova [97], A. Lanev, P. Levchenko, A. Litomin, N. Lychkovskaya, V. Makarenko, A. Malakhov, V. Matveev [94], V. Murzin, A. Nikitenko [98], S. Obraztsov, A. Oskin, I. Ovtin [94], V. Palichik, P. Parygin [99], V. Perelygin, S. Petrushanko, S. Polikarpov [94], V. Popov, E. Popova [99], O. Radchenko [94], M. Savina, V. Savrin, D. Selivanova, V. Shalaev, S. Shmatov, S. Shulha, Y. Skovpen [94], S. Slabospitskii, V. Smirnov, D. Sosnov, V. Sulimov, E. Tcherniaev, A. Terkulov, O. Teryaev, I. Tlisova, M. Toms [100], A. Toropin, L. Uvarov, A. Uzunian, E. Vlasov [101], A. Vorobyev, N. Voytishin, B.S. Yuldashev [102], A. Zarubin, I. Zhizhin, A. Zhokin

Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN

[†] Deceased.
[1] Also at Yerevan State University, Yerevan, Armenia.
[2] Also at TU Wien, Vienna, Austria.
[3] Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt.
[4] Also at Université Libre de Bruxelles, Bruxelles, Belgium.
[5] Also at Universidade Estadual de Campinas, Campinas, Brazil.
[6] Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.
[7] Also at UFMS, Nova Andradina, Brazil.
[8] Also at The University of the State of Amazonas, Manaus, Brazil.
[9] Also at University of Chinese Academy of Sciences, Beijing, China.
[10] Also at Nanjing Normal University Department of Physics, Nanjing, China.
[11] Now at The University of Iowa, Iowa City, Iowa, USA.
[12] Also at University of Chinese Academy of Sciences, Beijing, China.
[13] Also at an institute or an international laboratory covered by a cooperation agreement with CERN.
[14] Also at Cairo University, Cairo, Egypt.
[15] Also at Suez University, Suez, Egypt.
[16] Now at British University in Egypt, Cairo, Egypt.
[17] Also at Purdue University, West Lafayette, Indiana, USA.
[18] Also at Université de Haute Alsace, Mulhouse, France.
[19] Also at Department of Physics, Tsinghua University, Beijing, China.
[20] Also at Erzincan Binali Yildirim University, Erzincan, Turkey.
[21] Also at University of Hamburg, Hamburg, Germany.
[22] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[23] Also at Isfahan University of Technology, Isfahan, Iran.
[24] Also at Bergische University Wuppertal (BUW), Wuppertal, Germany.
[25] Also at Brandenburg University of Technology, Cottbus, Germany.
[26] Also at Forschungszentrum Jülich, Juelich, Germany.
[27] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[28] Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.
[29] Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary.
[30] Also at Wigner Research Centre for Physics, Budapest, Hungary.
[31] Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
[32] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[33] Now at Universitatea Babes-Bolyai – Facultatea de Fizica, Cluj-Napoca, Romania.
[34] Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary.
[35] Also at Punjab Agricultural University, Ludhiana, India.
[36] Also at UPES – University of Petroleum and Energy Studies, Dehradun, India.
[37] Also at University of Visva-Bharati, Santiniketan, India.
[38] Also at University of Hyderabad, Hyderabad, India.
[39] Also at Indian Institute of Science (IISc), Bangalore, India.
[40] Also at Indian Institute of Technology (IIT), Mumbai, India.
[41] Also at IIT Bhubaneswar, Bhubaneswar, India.
[42] Also at Institute of Physics, Bhubaneswar, India.
[43] Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.

[44] Also at Sharif University of Technology, Tehran, Iran.
[45] Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.
[46] Also at Helwan University, Cairo, Egypt.
[47] Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.
[48] Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.
[49] Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy.
[50] Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA.
[51] Also at Università di Napoli 'Federico II', Napoli, Italy.
[52] Also at Ain Shams University, Cairo, Egypt.
[53] Also at Consiglio Nazionale delle Ricerche – Istituto Officina dei Materiali, Perugia, Italy.
[54] Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia.
[55] Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
[56] Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.
[57] Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
[58] Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
[59] Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy.
[60] Also at National and Kapodistrian University of Athens, Athens, Greece.
[61] Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.
[62] Also at Universität Zürich, Zurich, Switzerland.
[63] Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
[64] Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.
[65] Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey.
[66] Also at Konya Technical University, Konya, Turkey.
[67] Also at Izmir Bakircay University, Izmir, Turkey.
[68] Also at Adiyaman University, Adiyaman, Turkey.
[69] Also at Istanbul Gedik University, Istanbul, Turkey.
[70] Also at Necmettin Erbakan University, Konya, Turkey.
[71] Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey.
[72] Also at Marmara University, Istanbul, Turkey.
[73] Also at Milli Savunma University, Istanbul, Turkey.
[74] Also at Kafkas University, Kars, Turkey.
[75] Also at Istanbul University – Cerrahpasa, Faculty of Engineering, Istanbul, Turkey.
[76] Also at Ozyegin University, Istanbul, Turkey.
[77] Also at Vrije Universiteit Brussel, Brussel, Belgium.
[78] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[79] Also at University of Bristol, Bristol, United Kingdom.
[80] Also at IPPP Durham University, Durham, United Kingdom.
[81] Also at Monash University, Faculty of Science, Clayton, Australia.
[82] Also at Università di Torino, Torino, Italy.
[83] Also at Bethel University, St. Paul, Minnesota, USA.
[84] Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
[85] Also at California Institute of Technology, Pasadena, California, USA.
[86] Also at United States Naval Academy, Annapolis, Maryland, USA.
[87] Also at Bingol University, Bingol, Turkey.
[88] Also at Georgian Technical University, Tbilisi, Georgia.
[89] Also at Sinop University, Sinop, Turkey.
[90] Also at Erciyes University, Kayseri, Turkey.
[91] Also at Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) – Fudan University, Shanghai, China.
[92] Also at Texas A&M University at Qatar, Doha, Qatar.
[93] Also at Kyungpook National University, Daegu, Republic of Korea.
[94] Also at another institute or international laboratory covered by a cooperation agreement with CERN.
[95] Now at Istanbul University, Istanbul, Turkey.
[96] Also at Yerevan Physics Institute, Yerevan, Armenia.
[97] Now at University of Florida, Gainesville, Florida, USA.
[98] Also at Imperial College, London, United Kingdom.
[99] Now at University of Rochester, Rochester, New York, USA.
[100] Now at Baylor University, Waco, Texas, USA.
[101] Now at INFN Sezione di Torino, Università di Torino, Torino, Italy; Università del Piemonte Orientale, Novara, Italy.
[102] Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.
[103] Also at University of Basel, Basel, Switzerland.