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Search for lepton-flavor violating decays of heavy resonances and quantum black holes to $e\mu$ final states in proton-proton collisions at $\sqrt{s} = 13$ TeV

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Search for lepton-flavor violating decays of heavy resonances and quantum black holes to $e\mu$ final states in proton-proton collisions at $\sqrt{s} = 13$ TeV



The CMS collaboration

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

ABSTRACT: A search is reported for heavy resonances decaying into $e\mu$ final states in proton-proton collisions recorded by the CMS experiment at the CERN LHC at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 35.9fb^{-1} . The search focuses on resonance masses above 200 GeV. With no evidence found for physics beyond the standard model in the $e\mu$ mass spectrum, upper limits are set at 95% confidence level on the product of the cross section and branching fraction for this lepton-flavor violating signal. Based on these results, resonant τ sneutrino production in R-parity violating supersymmetric models is excluded for masses below 1.7 TeV, for couplings $\lambda_{132} = \lambda_{231} = \lambda'_{311} = 0.01$. Heavy Z' gauge bosons with lepton-flavor violating transitions are excluded for masses up to 4.4 TeV. The $e\mu$ mass spectrum is also interpreted in terms of non-resonant contributions from quantum black-hole production in models with one to six extra spatial dimensions, and lower mass limits are found between 3.6 and 5.6 TeV. In all interpretations used in this analysis, the results of this search improve previous limits by about 1 TeV. These limits correspond to the most sensitive values obtained at colliders.

KEYWORDS: Hadron-Hadron scattering (experiments), Supersymmetry

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1 Introduction

Several extensions of the standard model (SM) predict the existence of heavy particles that undergo lepton-flavor violating (LFV) decays, thereby motivating searches for deviations from the SM in $e\mu$ final states. This paper reports a search for such phenomena in the $e\mu$ invariant mass spectrum $m_{e\mu}$. The analysis is based on data corresponding to an integrated luminosity of 35.9 fb^{-1} collected in proton-proton (pp) collisions at $\sqrt{s} = 13 \text{ TeV}$ in the CMS detector at the CERN LHC. The search strategy is designed to be model independent as much as possible. The results are interpreted in terms of the characteristics of the following predicted states: a τ sneutrino ($\tilde{\nu}_\tau$), which can be the lightest supersymmetric particle (LSP) [1–3] in R-parity violating (RPV) supersymmetric (SUSY) models [4], a heavy Z' gauge boson in LFV models [5], and quantum black holes (QBHs) [6, 7]. The theoretical underpinnings in the context of this search are introduced below.

In RPV SUSY models, lepton flavor and lepton number are violated at the lowest Born level in interactions between fermions and their superpartners, where the $\tilde{\nu}_\tau$ can be the LSP. For resonant $\tilde{\nu}_\tau$ signals, the trilinear RPV part of the superpotential can be expressed as

$$W_{\text{RPV}} = \frac{1}{2} \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k,$$

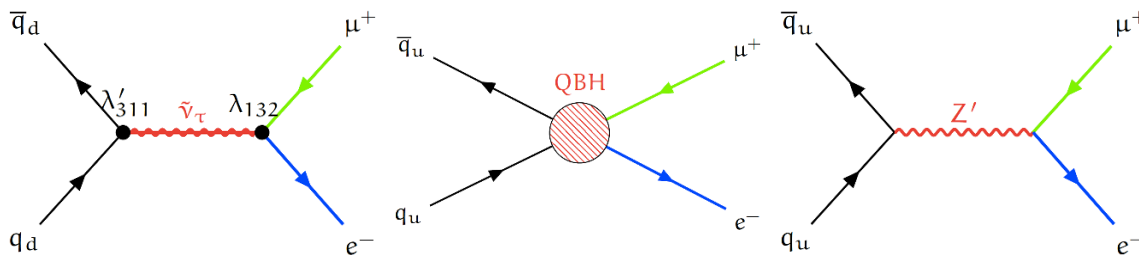


Figure 1. Leading order Feynman diagrams considered in our search. Left: resonant production of a τ sneutrino in an RPV SUSY model that includes the subsequent decay into an electron and a muon. The $\tilde{\nu}_\tau$ is produced from the annihilation of two down quarks via the λ'_{311} coupling, and then decays via the $\lambda_{132} = \lambda_{231}$ couplings into the electron muon final state. Middle: production of quantum black holes in a model with extra dimensions that involves subsequent decay into an electron and a muon. Right: resonant production of a Z' boson with subsequent decay into an electron and a muon.

where: i, j , and k are generation indices; L and Q are the $SU(2)_L$ doublet superfields of the leptons and quarks; and \bar{E} and \bar{D} are the respective $SU(2)_L$ singlet superfields of the charged leptons and down-like quarks.

For simplicity, we suppose that all RPV couplings vanish, except for λ_{132} , λ_{231} , and λ'_{311} , which are connected to the production and decay of the $\tilde{\nu}_\tau$, and we consider a SUSY mass hierarchy with $\tilde{\nu}_\tau$ as the LSP. In this model, the $\tilde{\nu}_\tau$ can be produced resonantly in pp collisions via the λ'_{311} coupling, and can decay either into $e\mu$ via the λ_{132} and λ_{231} couplings, or into $d\bar{d}$ via the λ'_{311} coupling. We consider only the $e\mu$ final state, and assume $\lambda_{132} = \lambda_{231}$. This analysis considers only $\tilde{\nu}_\tau$ that decay promptly and not long-lived $\tilde{\nu}_\tau$ [8], which could provide events with e and μ tracks from a displaced vertex.

An extension of the SM through the addition of an extra $U(1)$ gauge symmetry provides a massive Z' vector boson [5]. In our search, we assume that the Z' boson has couplings similar to the Z boson in the SM, but that the Z' boson can also decay to the LFV $e\mu$ final state with a branching fraction of 10%. The resulting Z' width is approximately 3% of its mass for masses above the $t\bar{t}$ threshold.

Theories that invoke extra spatial dimensions can offer effective fundamental Planck scales in the TeV region. Such theories also provide the possibility of producing microscopic black holes [6, 7] at the LHC. In contrast to semiclassical thermal black holes that can decay to high-multiplicity final states, QBHs are nonthermal objects, expected to decay predominantly to pairs of particles. We consider the production of spin-0, colorless, neutral QBHs in a model with LFV [9], in which the cross section for QBH production depends on the threshold mass m_{th} in n additional spatial dimensions. The $n = 1$ possibility corresponds to the Randall-Sundrum (RS) brane-world model [10], and $n > 1$ corresponds to the Arkani-Hamed-Dimopoulos-Dvali (ADD) model [11]. While the resonant $\tilde{\nu}_\tau$ and Z' signals generate narrow peaks in the invariant mass spectrum of the $e\mu$ pair, the distribution of the QBH signal is characterized by a sharp edge at the threshold of QBH production, followed by a monotonic decrease at larger masses. Feynman diagrams for all these three models are shown in figure 1.

Similar searches in the $e\mu$ mass spectrum have been carried out by the CDF [12] and D0 [13] experiments at the Fermilab Tevatron in $p\bar{p}$ collisions at a center-of-mass energy of 1.96 TeV and by the ATLAS and CMS experiments at the LHC in pp collisions at center-of-mass energies of 8 TeV [14, 15] and 13 TeV [16]. The search by CMS at 8 TeV has an integrated luminosity of 19.7 fb^{-1} , and excludes $\tilde{\nu}_\tau$ masses up to 1.28 TeV for $\lambda_{132} = \lambda_{231} = \lambda'_{311} = 0.01$. The search performed by ATLAS at 13 TeV with 3.2 fb^{-1} of luminosity excludes Z' bosons with mass up to $m_{Z'} = 3.01 \text{ TeV}$. The present search significantly extends these limits.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. A silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two end sections, reside within the solenoid volume. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and end calorimeters. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system and kinematic variables, can be found in ref. [17].

3 Event selection

The search is designed to be inclusive and model independent, requiring at least one prompt, isolated electron and at least one prompt, isolated muon in the event. This minimal selection also facilitates a reinterpretation of the results in terms of models with more complex signal topologies than the single $e\mu$ pair. Events that satisfy single-muon and single-photon triggers [18] with respective transverse momentum (p_T) thresholds of 50 and 175 GeV for muons and photons are selected for analysis. Electromagnetic energy deposited by an electron in the calorimeter activates the photon trigger used to record our events. The photon trigger is therefore as efficient as the corresponding electron trigger, while its weaker isolation requirements yield an event sample that can also be used in sideband analyses to estimate the background to the signal.

Electrons and muons are reconstructed and identified using standard CMS algorithms, described in refs. [19, 20].

To reconstruct an electron candidate, energy depositions in the ECAL are first combined into clusters, assuming that each cluster represents a single particle. The clusters are then combined in a way consistent with bremsstrahlung emission, to produce a single “supercluster”, which represents the electron or photon. These superclusters are used to seed tracking algorithms, and if a resulting track is found, it is associated to the supercluster to form an electron candidate. The electron candidate must pass the high-energy electron pairs (HEEP) selection [19], which requires the energy deposition in the ECAL to be consistent with that of an electron. The sum of the energy in the HCAL within a

cone of $\Delta R = 0.15$ centered around the electron candidate, must be less than 5% of its energy, after it is corrected for jet activity unrelated to the electron. The electron candidate must have a well-matched, prompt track in the η - ϕ plane that has no more than one hit missing in the inner portion of the tracker. The HEEP selection also requires electrons to be isolated, the requirement for which is that the scalar- p_T sum of tracks within a cone of radius $\Delta R = 0.3$ around the candidate direction, excluding the candidate's track, is less than 5 GeV, and the p_T sum of energy depositions in the calorimeters within this cone, taking account of small η -dependent offsets, is less than 3% of the p_T of the candidate.

To reconstruct a muon candidate, hits are first fitted separately to trajectories in the inner-tracker detector, and in the outer-muon system. The two trajectories are then combined in a global-muon track hypothesis. Muon candidates are required to have $p_T > 53$ GeV and to fall into the acceptance region of $|\eta| < 2.4$. The transverse and longitudinal impact parameters of muon candidates relative to the primary vertex must be less than 0.2 cm and < 0.5 cm, respectively. The reconstructed vertex with the largest value of summed physics-object p_T^2 is taken to be the primary pp interaction vertex. The physics objects chosen are those that have been defined using information from the various subdetectors, including jets, charged leptons, and the associated missing transverse momentum, which is defined as the negative vector sum of the p_T of those jets and charged leptons, measured in the silicon tracker. The track of the muon candidate must have at least one hit in the pixel detector and hits in at least six silicon-strip layers, and must contain matched segments in at least two muon detector planes. To suppress backgrounds arising from muons within jets, the scalar- p_T sum of all other tracks in the tracker within a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ around the muon candidate track, where η and ϕ are the pseudorapidity and azimuth angle of a track, is required to have less than 10% of the p_T of the muon candidate. The relative uncertainty in p_T of the muon track is required to be smaller than 30%.

To reduce loss in signal efficiency from misidentification of the sign of the electron's or muon's charge at large p_T , the electron and muon are not required to have opposite charges. Since highly energetic muons can produce bremsstrahlung in the ECAL along the direction of the inner-muon trajectory, such muons can be misidentified as electrons. An electron candidate is therefore rejected if there is a muon candidate with p_T greater than 5 GeV whose track has $\Delta R < 0.1$ relative to the electron candidate's track. Only one $e\mu$ pair is considered per event. When there is more than one $e\mu$ candidate, the pair with the highest invariant mass is selected for analysis.

The statistical interpretation is done based on the shape of the invariant $e\mu$ mass distribution of the signal as well as the background.

4 Signal simulation

The RPV SUSY $\tilde{\nu}_\tau$, Z' , and QBH signal events are generated at leading order (LO) precision, using the CALCHEP 3.6 [21], PYTHIA 8.203 [22], and QBH 2.0 [23] Monte Carlo (MC) generators, respectively. The relative width of the Z' signal is taken as 3% of its mass, and interference between the SM Z and Z' bosons is ignored. All simulated signal events

use PYTHIA for hadronization and CUETP8M1 provides the underlying-event tune [24]. The RPV and QBH signals are generated with the CTEQ6L [25] parton distribution functions (PDF) while the Z' boson signals are simulated using the NNPDF 3.0 PDF sets [26]. The LO RPV SUSY $\tilde{\nu}_\tau$ signal event yield is normalized to a next-to-leading order (NLO) calculation of the production cross section; in this calculation the factorization and renormalization scales are set to the mass of the $\tilde{\nu}_\tau$. The generated events are processed through a full simulation of the CMS detector, based on GEANT4 [27–29]. The simulated events incorporate additional pp interactions within the same or a nearby bunch crossings, termed pileup, that are weighted to match the measured distribution of the number of interactions per bunch crossing in data. The simulated event samples are normalized to the integrated luminosity of the data. The products of the total acceptance and efficiency for the three signal models in this analysis are determined through MC simulation. The trigger and object reconstruction efficiencies are corrected to the values measured in data. The selection efficiencies for the RPV $\tilde{\nu}_\tau$, Z' and QBH signals are $\approx 60\%$, 60% , and 55% when the resonance mass or mass threshold is 1 TeV and $\approx 66\%$, 64% , and 63% when the resonance mass or mass threshold is 4 TeV, respectively.

5 Background estimation

The SM backgrounds contributing to the $e\mu$ final state are divided into two categories. The first category comprises events with at least two real, isolated leptons; while the second category comprises events that include either jets or photons, misidentified as isolated leptons, or jets with leptons from heavy-flavor decays, both of which we refer to as fake background.

The expected SM background from processes with two real leptons is obtained from MC simulation. This background consists mostly of events from $t\bar{t}$ or WW production; the former process is dominant at lower masses and the latter becomes equally important above $m_{e\mu} \approx 1$ TeV. Other real lepton backgrounds estimated from MC simulation involve diboson contributions from WZ and ZZ events, single top quark production, and Drell-Yan (DY) production (i.e. $q\bar{q} \rightarrow \text{virtual } Z/\gamma \rightarrow \text{two leptons of opposite charge}$) in the $\tau\tau$ channel. The $DY \rightarrow \tau\tau$ background is generated at NLO using the MADGRAPH5_aMC@NLO 2.2.2 [30, 31] event generator. The cross sections used to normalize the contribution of these backgrounds are calculated at next-to-next-to-leading order for WW [32], ZZ [33], single top quark [34], and $t\bar{t}$ [35] processes, and also at NLO accuracy for WZ [36] and DY [37] events. All background processes are simulated using the NNPDF 3.0 PDF. For all background simulations, PYTHIA is used for hadronization and CUETP8M1 as the underlying event tune.

The main sources of fake background in the $e\mu$ selection are from W+jets, $W\gamma$ and DY+jets production, where a jet or a photon is misidentified as an electron or a muon. The $W\gamma$ process also contributes to the prompt background category through the internal conversion of γ to leptons. The QCD-multijet process provides subleading contributions to the fake lepton background. An estimate of the $W\gamma$ background is obtained at LO from MC simulation based on the MADGRAPH5_aMC@NLO event generator. DY+jets background in

ee and $\mu\mu$ channels are generated at NLO using the POWHEG 2.0 [38–40] event generator. A background estimate based on a control sample in data is made using jet-to-electron misidentification rates (F) to determine the $m_{e\mu}$ contributions from W+jets and multijet distributions. The jet-to-electron misidentification rate is measured in data, using a control sample collected with a single electromagnetic-cluster trigger. Data sidebands are used to evaluate the contributions to the control sample from genuine electrons and from photons misidentified as electrons. The jet-to-electron misidentification rate is then defined as the number of jets passing the full electron selection divided by the number of jet candidates in the sample. The rate is quantified in bins of p_T and η . The measured rate is used to estimate the W+jets and multijet contributions using data containing muons that pass the single-muon trigger and the full muon selection, and the number of electron candidates satisfying relaxed selection requirements, but failing the full electron selection. Each event is weighted by the factor $F/(1 - F)$ to determine the overall contribution from the jet backgrounds. Contributions from processes other than W+jets and multijet sources are subtracted from the sample, after correcting for the contribution from false events to avoid double counting, which is done using MC simulated background events. Background from jets mimicking muons is estimated to be only 1% of the total background, and is ignored in the analysis.

6 Systematic uncertainties

The uncertainty in the modeling of the $e\mu$ invariant mass distribution reflects the input of three types of systematic effects.

The first type includes those that affect the shape of the invariant mass distribution, with the dominant uncertainty arising from the leading $t\bar{t}$ and subleading WW backgrounds. The $t\bar{t}$ background provides an uncertainty of <30% in the total background yield at $m_{e\mu} \approx 1$ TeV, which reduces to <10% at $m_{e\mu} \approx 2$ TeV because of the reduced contribution of the $t\bar{t}$ process to the total background yield. The uncertainty in the WW background is estimated to be $\approx 2.5\%$ at $m_{e\mu} \approx 1$ TeV. This is estimated from the envelope of the resummed next-to-next-to-leading-logarithm calculation of the soft-gluon contributions to the cross section at NLO, as presented in ref. [41], using changes by factors of 2 and 0.5 implemented in the renormalization and factorization scales, respectively. Other uncertainties in the form of the invariant mass distribution are due to the uncertainty in the muon momentum scale, which depends on the η and ϕ of muons, and leads to an uncertainty in the total background yield of $\approx 1.1\%$, at $m_{e\mu} = 500$ GeV, and $\approx 25\%$ at $m_{e\mu} = 2$ TeV. Uncertainty in the muon-efficiency scale factor is 2–3% over the whole mass range. Apart from that, a momentum-dependent, one-sided downward systematic uncertainty is applied to the muon reconstruction and identification efficiency, to account for potential differences between simulated samples and data, in the response of the muon system to muons that interact radiatively with the detector material. This uncertainty is -1.6% in the region $|\eta| < 1.6$, and -14.4% in the region $1.6 < |\eta| < 2.4$, for muons with momentum of 4 TeV. Uncertainties in the electron p_T scale and resolution, the muon p_T resolution, and the pileup rate have negligible impact on the total background. Un-

certainty in the electron-efficiency scale factor is 2–3% over the whole mass range. The uncertainty associated with the choice of the PDF in the simulation is evaluated according to the PDF4LHC prescription [42, 43].

Uncertainties of the second type directly influence the normalization of the invariant mass distribution. A systematic uncertainty of 2.5% [44] in the integrated luminosity is taken for the backgrounds and signals. Among the uncertainties in the cross sections used for the normalization of various simulated backgrounds, the 5% uncertainty in the dominant $t\bar{t}$ background is most significant. A systematic uncertainty of 50% is applied to the estimate of jet background derived from data.

Uncertainties of the third type are associated with limited sizes of event samples in the MC simulation of background processes. In contrast to all other uncertainties, they are not correlated between bins of the invariant mass distribution.

Taking all systematic uncertainties into account, the resulting uncertainty in the background ranges from 15% at $m_{e\mu} = 200$ GeV to 40% at $m_{e\mu} = 2$ TeV. The increase in systematic uncertainty with increasing mass does not affect the sensitivity at large mass values, where the expected number of events from SM processes becomes negligible. All these uncertainties are also considered in the estimation of theoretical signals.

7 Results

The $e\mu$ mass distribution for the selected events is shown in figure 2, together with the corresponding cumulative distribution, integrated from the chosen $m_{e\mu}$ threshold to 10 TeV. The binning has been chosen to match the experimental resolution. A version of the invariant mass distribution with a coarser binning, which reduces statistical fluctuations and thus enhances the display of the simulated signals, is provided in the Appendix as figure 6. A simultaneous maximum likelihood fit to the data, including all systematic uncertainties, is performed. Its effect may be seen by comparing the ratio of data to expected background, before and after the fit. The fit represents a close estimate of the distribution used in setting the upper limits on cross sections, as described below.

After selection, 4 events are observed in data in the region $m_{e\mu} > 1.5$ TeV, where the expectation from SM backgrounds is 4.64 ± 0.42 (stat) ± 1.28 (syst). A detailed table showing the contribution from the different background processes as well as the observed data is given in table 1. The largest observed value of $m_{e\mu}$ is 1.89 TeV, and no significant excess is observed relative to the SM expectation. Below, we set limits on the product of the signal cross section (σ) and the branching fraction (\mathcal{B}) of signal to $e\mu$.

In the context of RPV SUSY model, the $\tilde{\nu}_\tau$ can be produced at the LHC through an s -channel $q\bar{q}$ interaction, which gives rise to a narrow resonance signal. For coupling values considered in this analysis, the intrinsic width of this signal is small compared to the detector resolution. To describe the response of the electromagnetic calorimeter, a Crystal Ball function [45] is used to model the signal. For each resonance mass, two parameters, the product of signal acceptance and efficiency ($A\epsilon$) and the mass resolution, define the line shape used for setting the limit. Both parameters are obtained from fits to MC signal events. The parametric forms of $A\epsilon$ and mass resolution as a function of signal mass are

| Mass range (GeV) | $m_{e\mu} < 500$ | $500 < m_{e\mu} < 1000$ | $1000 < m_{e\mu} < 1500$ | $m_{e\mu} > 1500$ |
|---------------------------------------|------------------|-------------------------|--------------------------|-------------------|
| Jet \rightarrow e misidentification | 3601 | 82.8 | 2.92 | 0.849 |
| $W\gamma$ | 2462 | 56.2 | 2.76 | 0.562 |
| Drell-Yan | 2638 | 5.31 | 0.343 | 0.0145 |
| Single t | 9930 | 141 | 2.81 | 0.178 |
| WW, WZ, ZZ | 11126 | 239 | 13.0 | 2.03 |
| $t\bar{t}$ | 96754 | 971 | 18.5 | 1.01 |
| Total background | 126513 | 1495 | 40.3 | 4.64 |
| Systematic uncertainty | 23495 | 420 | 13.5 | 1.28 |
| Data | 123150 | 1426 | 41 | 4 |

Table 1. Numbers of events for background processes, total background with its associated systematic uncertainties, and data, in four bins of $e\mu$ invariant mass.

| Parameter | Functional form |
|-----------------|---|
| $A\epsilon$ | $-0.838 + \frac{1.67 \times 10^{-2}}{(m_{\tilde{\nu}_\tau}^{-1.02} + 1.0 \times 10^{-2})} - 1.54 \times 10^{-5} m_{\tilde{\nu}_\tau}$ |
| Mass resolution | $1.79 \times 10^{-2} + 1.47 \times 10^{-5} m_{\tilde{\nu}_\tau} - 3.87 \times 10^{-9} m_{\tilde{\nu}_\tau}^2 + 4.34 \times 10^{-13} m_{\tilde{\nu}_\tau}^3$ |

Table 2. Parametrization functions for the product of the acceptance and efficiency, and for the invariant mass resolution for the RPV signal. The value of $m_{\tilde{\nu}_\tau}$ is given in units of GeV. The functions are shown in figures 7 and 8 in the appendix.

given in table 2, for the values discussed in section 4, and shown in the Appendix as figures 7 and 8, respectively. The invariant mass resolution ranges from 2.2%, at a resonance mass of 200 GeV to 3.1% at a mass of 3 TeV. The parametrization of the resonant line shape provides sensitivity for invariant masses between the simulated signal points. The QBH signal exhibits a broader distribution with a cliff at the threshold mass m_{th} that is smeared out by detector resolution, and a tail at larger masses that falls off because of the form of the proton PDF. The QBH signals are not parametrized but obtained from the simulated invariant mass distributions. The Z' signals give rise to resonance forms that are also taken directly from simulation.

An upper limit at 95% confidence level (CL) on $\sigma\mathcal{B}$ is determined using a Bayesian binned-likelihood approach [46], assuming a uniform prior for the signal cross section. The signal and background $m_{e\mu}$ distributions enter the likelihood binned to the nearest 1 GeV, which is well below the invariant mass resolution for masses >200 GeV. The nuisance parameters associated with the systematic uncertainties are modeled through log-normal distributions for uncertainties in the normalization. Uncertainties in the shape of the distributions are modeled through “template morphing” techniques [47]. A Markov Chain MC method [48] is used for integration. After integrating over all nuisance parameters for each mass hypothesis, the posterior probability density is calculated as a function of $\sigma\mathcal{B}$ for yields at 95% CL upper limit.

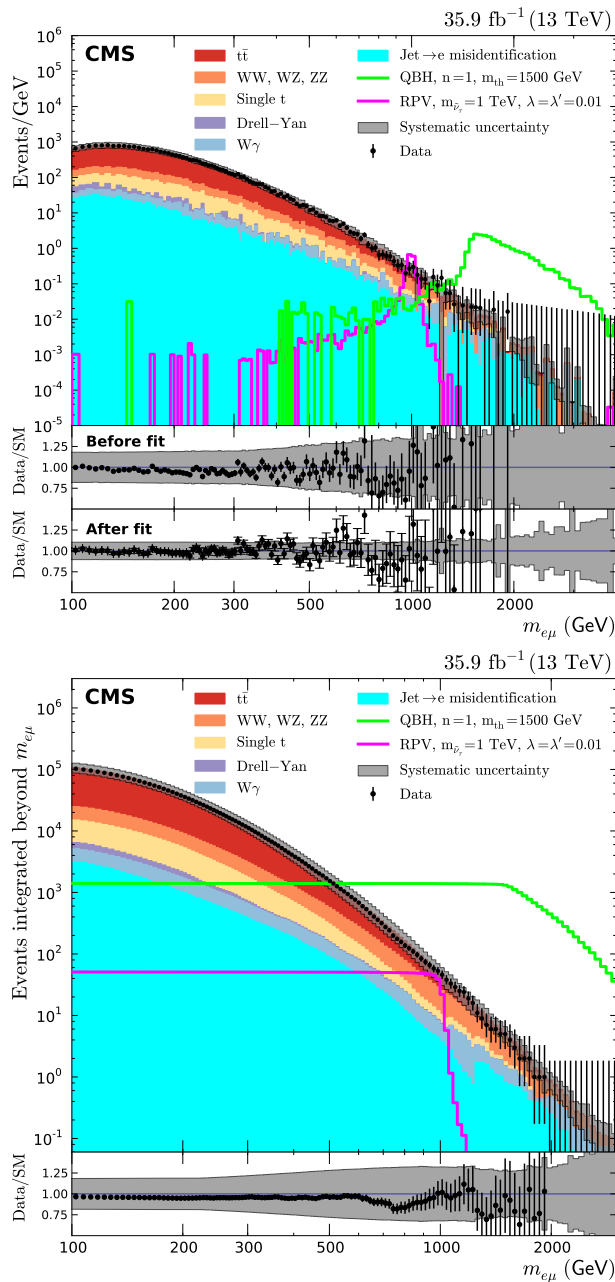


Figure 2. Upper: the invariant mass distribution for selected $e\mu$ pairs in data (black points with error bars), and stacked histograms representing expectations from SM processes before the fit. Also shown are the expectations for two possible signals. The two lower panels show the ratio of data to background expectations before and after the fit. The total systematic uncertainties are given by the gray bands. Lower: the cumulative (integral) distribution in events integrated beyond the chosen $m_{e\mu}$. The lower panel shows the ratio of data to background predictions before the fit. Some events in the invariant mass distribution can have a negative event weight and result in a rise of the cumulative mass distribution. In both figures the label λ refers to $\lambda_{132} = \lambda_{231}$, while λ' stands for λ'_{311} .

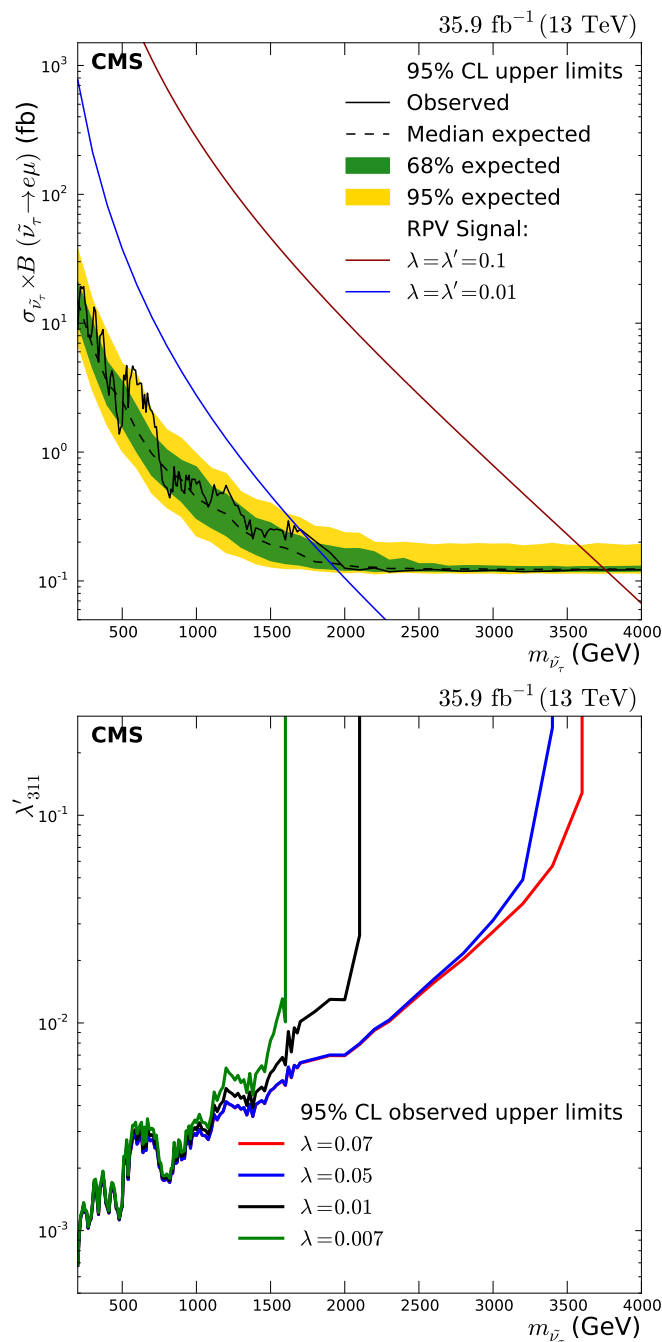


Figure 3. Upper: upper limits at 95% CL on the product of the signal cross section and branching fraction for the $\tilde{\nu}_\tau$ signal, as a function of the mass of the RPV resonance. The 68 and 95% CL intervals on the median expected limits are indicated, respectively, by the inner green and outer yellow shadings. Predictions for an RPV SUSY model are shown for two values of the coupling parameter. Lower: upper limits at 95% CL on the RPV $\tilde{\nu}_\tau$ signal in the $(m_{\tilde{\nu}_\tau}, \lambda'_{311})$ parameter plane, for four values of λ , where the regions to the left of and above the limits are excluded. In both figures λ refers to $\lambda_{132} = \lambda_{231}$, while λ' stands for λ'_{311} .

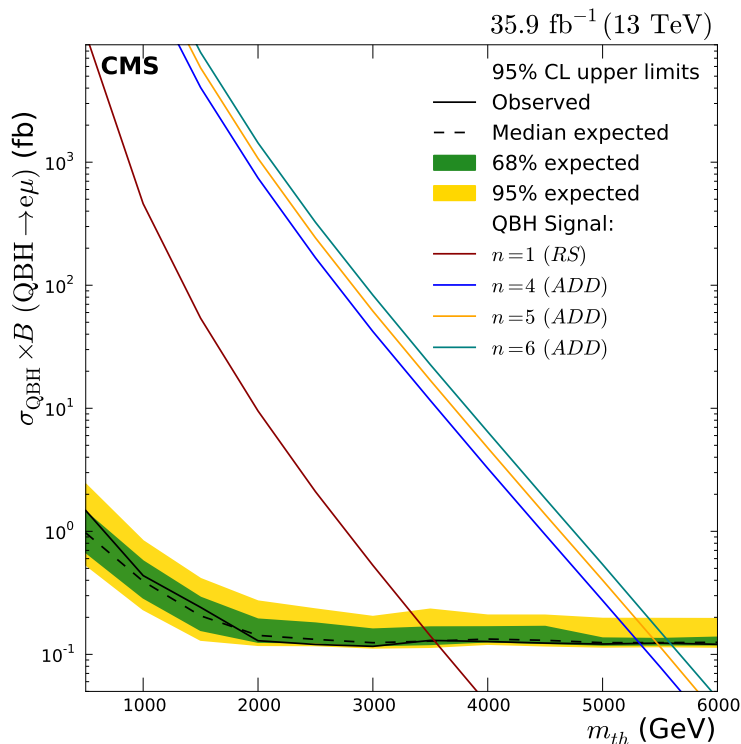


Figure 4. Upper limits at 95% CL on the median product of the signal cross section and the branching fraction for the QBH decay to $e\mu$ as a function of threshold mass m_{th} . The 68 and 95% CL intervals on the median are indicated, respectively, by the inner green and outer yellow shadings. Predictions are also shown for several models with large extra spatial dimensions, specifically for 1 extra dimension (RS) and for 4, 5, and 6 extra dimensions (ADD).

The limits at 95% CL on $\sigma\mathcal{B}$ for the RPV $\tilde{\nu}_\tau$ signal are shown in figure 3 (left). The signal cross section is calculated at NLO for the RPV couplings $\lambda_{132} = \lambda_{231} = \lambda'_{311} = 0.01$ and 0.1. The factorization and renormalization scales that enter the calculation are set to the mass of the $\tilde{\nu}_\tau$. For RPV coupling $\lambda_{132} = \lambda_{231} = \lambda'_{311} = 0.01$, we obtain a lower mass limit of 1.7 TeV, while a limit of 1.9 TeV is expected. For RPV coupling 0.1, we both observe and expect a 3.8 TeV mass limit. In the narrow-width approximation, $\sigma\mathcal{B}$ scales with the RPV couplings as [15]:

$$\sigma\mathcal{B} \propto (\lambda'_{311})^2 [(\lambda_{132})^2 + (\lambda_{231})^2] / [3(\lambda'_{311})^2 + (\lambda_{132})^2 + (\lambda_{231})^2].$$

Using this relation and the observed upper bounds, we obtain limit contours in the $(m_{\tilde{\nu}_\tau}, \lambda'_{311})$ parameter plane for several fixed values of λ . The result is shown in figure 3 (right).

In the QBH search, we set mass limits on the production threshold in models with $n = 1$ (RS) and $n > 1$ (ADD) extra dimensions. The limits at 95% CL on $\sigma\mathcal{B}$ for the QBH signal are shown in figure 4. The observed and expected lower mass limits on m_{th} are numerically the same and correspond to 3.6, 5.3, 5.5, and 5.6 TeV for $n = 1, 4, 5,$ and 6, respectively. In the ADD model, the results are given for $n = 4, 5,$ and 6. The

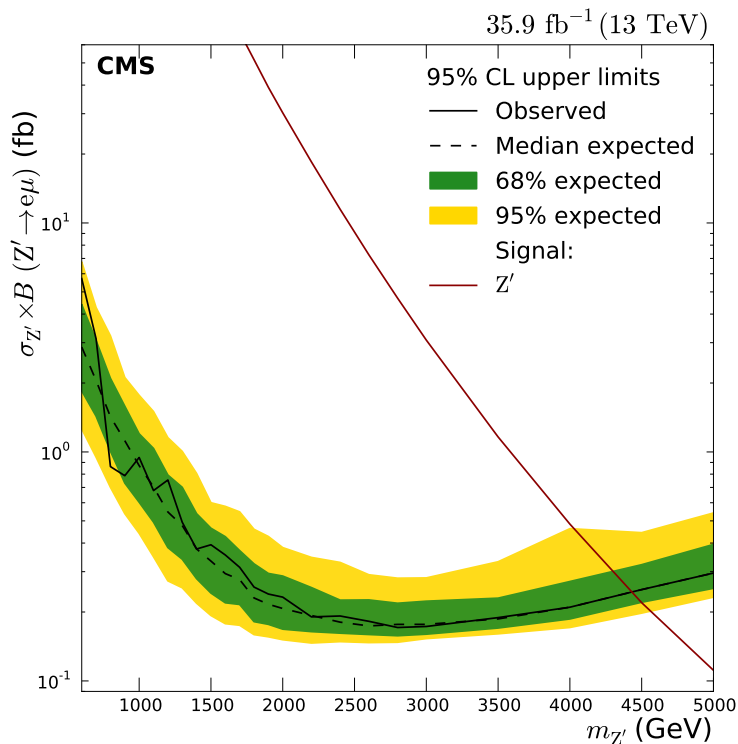


Figure 5. The upper limits at 95% CL on the product of the signal cross section and the branching fraction, assuming $\mathcal{B} = 10\%$ for the decay $Z' \rightarrow e\mu$, as a function of $m_{Z'}$. The 68 and 95% CL intervals on the median are indicated, respectively, by the inner green and outer yellow shadings.

expected and observed limits at 95% CL on the Z' mass are also the same and equal to 4.4 TeV, as shown in figure 5. With increasing Z' boson mass, the phase space for the on-shell Z' production in pp collisions at 13 TeV decreases because of decreasing parton-parton luminosity, leading to the production of an increasing fraction of off-shell objects at lower masses. This effect leads to weaker Z' boson mass limits at higher mass values. The observed limit looks smoother than for the RPV signal (figure 5), because there are fewer signal mass hypotheses probed. The results presented in this paper also put constraints on specific models involving LFV Z' such as proposed in refs. [49].

8 Summary

A search for heavy resonances decaying into $e\mu$ pairs has been carried out in proton-proton collisions, recorded with the CMS detector at the LHC at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 35.9 fb^{-1} . Good agreement is observed between the data and the standard model expectation. Limits are set on the resonant production of τ sneutrinos ($\tilde{\nu}_\tau$) in R-parity violating supersymmetric models. For couplings $\lambda_{132} = \lambda_{231} = \lambda'_{311} = 0.01$ and 0.1, a $\tilde{\nu}_\tau$ is excluded for masses below 1.7 and 3.8 TeV respectively, assuming it is the lightest supersymmetric particle. Lower limits of 5.3, 5.5, and 5.6 TeV are set on the threshold mass of quantum black holes in a model with 4, 5, and 6 large extra spatial dimensions, respectively. For the model with a single, warped

extra spatial dimension, the lower limit on the threshold mass is 3.6 TeV. Also, a Z' boson with a 10% branching fraction to the $e\mu$ channel is excluded for masses below 4.4 TeV. In all cases, the results of this search improve the previous lower limits by about 1 TeV.

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A Additional analysis plots

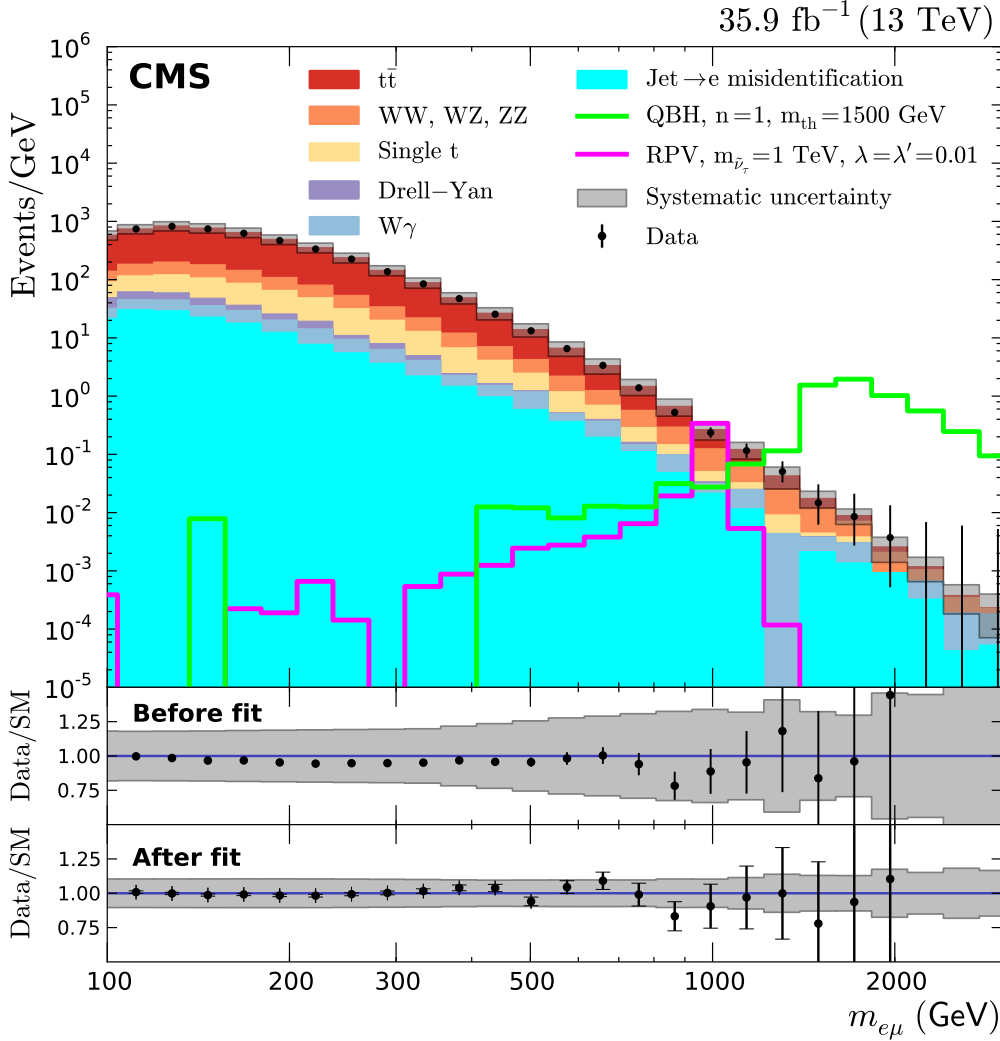


Figure 6. Invariant mass of the $e\mu$ pair for all events that pass the event selection criteria. In the lower panels, we show the ratio of the data to the before-fit and after-fit background predictions, including uncertainties. The label λ stands for $\lambda_{132} = \lambda_{231}$, while λ' stands for λ'_{311} . The content is the same as in figure 2, but with a coarser binning.

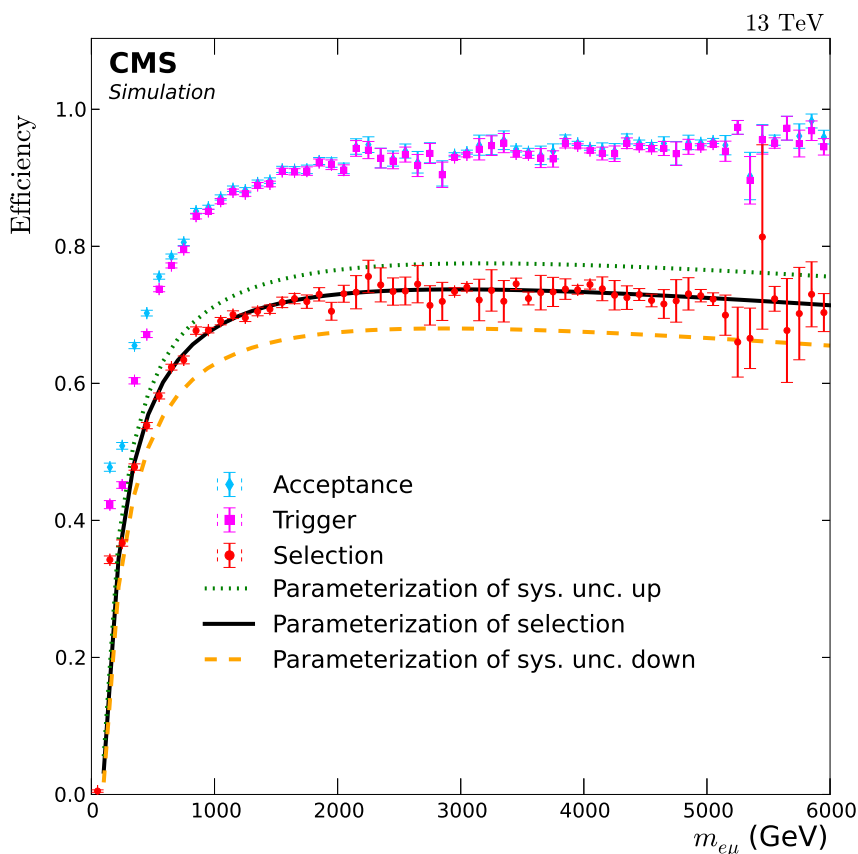


Figure 7. Efficiency of the RPV signal for all events after the acceptance requirements (light blue triangular points), after acceptance and trigger requirements (magenta square points), and after the full selection, which includes acceptance and trigger criteria (red round points). The reconstruction efficiency is also included, with the product of the final acceptance and efficiency parametrized for the statistical interpretation by a function illustrated by the black line. The systematic uncertainties are obtained by propagating the effect of the systematic uncertainties to the efficiency. The systematically shifted upper and lower efficiency points are not shown in the figure, but just the parametrization of both dependencies, with upward shifts in dotted green and downward shifts in dashed orange.

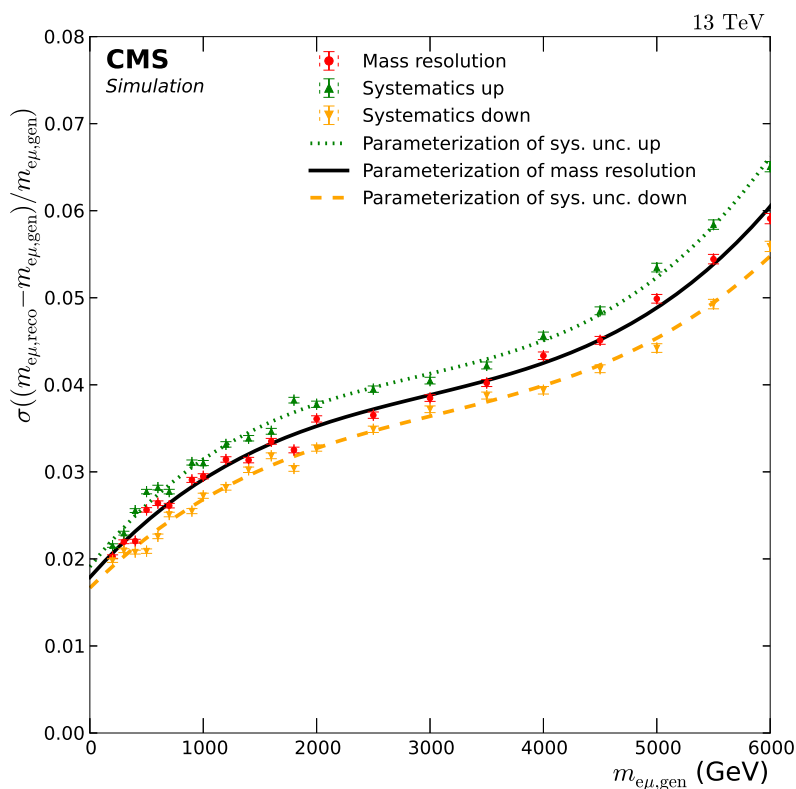


Figure 8. Relative mass resolution for all $e\mu$ pairs, obtained through simulation of the RPV signal, from the reconstructed mass $m_{e\mu, reco}$ and the generated mass $m_{e\mu, gen}$, as a function of the generated mass. The effect of the systematic uncertainties on the mass resolution is shown. The systematically shifted upper and lower mass resolutions are shown in the figure with the corresponding parameterization for the upward shifts in dotted green and the downward shifts in dashed orange.

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The CMS collaboration

Yerevan Physics Institute, Yerevan, Armenia

A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik, Wien, Austria

W. Adam, F. Ambrogio, E. Asilar, T. Bergauer, J. Brandstetter, E. Brondolin, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, M. Friedl, R. Frühwirth¹, V.M. Ghete, J. Grossmann, J. Hrubec, M. Jeitler¹, A. König, N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, E. Pree, N. Rad, H. Rohringer, J. Schieck¹, R. Schöffbeck, M. Spanring, D. Spitzbart, A. Taurok, W. Waltenberger, J. Wittmann, C.-E. Wulz¹, M. Zarucki

Institute for Nuclear Problems, Minsk, Belarus

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

Universiteit Antwerpen, Antwerpen, Belgium

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

Vrije Universiteit Brussel, Brussel, Belgium

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

Université Libre de Bruxelles, Bruxelles, Belgium

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

Ghent University, Ghent, Belgium

T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov², D. Poyraz, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

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

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

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

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

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

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato³, E. Coelho, E.M. Da Costa, G.G. Da Silveira⁴, D. De Jesus Damiao, S. Fonseca De Souza, L.M. Huertas Guativa, H. Malbouisson, M. Medina Jaime⁵, M. Melo De Almeida, C. Mora Herrera,

L. Mundim, H. Nogima, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote³, F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade Estadual Paulista ^a, Universidade Federal do ABC ^b, São Paulo, Brazil

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

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

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

University of Sofia, Sofia, Bulgaria

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

Beihang University, Beijing, China

W. Fang⁶, X. Gao⁶, L. Yuan

Institute of High Energy Physics, Beijing, China

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

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

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

Tsinghua University, Beijing, China

Y. Wang

Universidad de Los Andes, Bogota, Colombia

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

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

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

University of Split, Faculty of Science, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov⁷, T. Susa

University of Cyprus, Nicosia, Cyprus

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

Charles University, Prague, Czech Republic

M. Finger⁸, M. Finger Jr.⁸

Universidad San Francisco de Quito, Quito, Ecuador

E. Carrera Jarrin

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

H. Abdalla⁹, Y. Assran^{10,11}, S. Elgammal¹¹

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

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

Department of Physics, University of Helsinki, Helsinki, Finland

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

Helsinki Institute of Physics, Helsinki, Finland

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

Lappeenranta University of Technology, Lappeenranta, Finland

T. Tuuva

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

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

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

A. Abdulsalam¹², C. Amendola, I. Antropov, S. Baffioni, F. Beaudette, P. Busson,
L. Cadamuro, C. Charlot, R. Granier de Cassagnac, M. Jo, I. Kucher, S. Lisniak,
A. Lobanov, J. Martin Blanco, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard,
R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, Y. Yilmaz, A. Zabi, A. Zghiche

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

J.-L. Agram¹³, J. Andrea, D. Bloch, J.-M. Brom, M. Buttignol, E.C. Chabert, C. Collard,
E. Conte¹³, X. Coubez, F. Drouhin¹³, J.-C. Fontaine¹³, D. Gelé, U. Goerlach, M. Jansová,
P. Juillot, A.-C. Le Bihan, N. Tonon, P. Van Hove

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

S. Gadrat

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

S. Beauceron, C. Bernet, G. Boudoul, N. Chanon, R. Chierici, D. Contardo, P. Depasse,
H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde,
I.B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, A.L. Pequegnot, S. Perries,
A. Popov¹⁴, V. Sordini, M. Vander Donckt, S. Viret, S. Zhang

Georgian Technical University, Tbilisi, GeorgiaT. Toriashvili¹⁵**Tbilisi State University, Tbilisi, Georgia**Z. Tsamalaidze⁸**RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany**C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer, V. Zhukov¹⁴**RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany**

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

RWTH Aachen University, III. Physikalisches Institut B, Aachen, GermanyG. Flügge, B. Kargoll, T. Kress, A. Künsken, T. Müller, A. Nehr Korn, A. Nowack, C. Pistone, O. Pooth, A. Stahl¹⁶**Deutsches Elektronen-Synchrotron, Hamburg, Germany**M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras¹⁷, V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, F. Costanza, V. Danilov, A. De Wit, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, E. Eren, E. Gallo¹⁸, J. Garay Garcia, A. Geiser, J.M. Grados Luyando, A. Grohsjean, P. Gunnellini, M. Guthoff, A. Harb, J. Hauk, M. Hempel¹⁹, H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, J. Knolle, I. Korol, D. Krücker, W. Lange, A. Lelek, T. Lenz, K. Lipka, W. Lohmann¹⁹, R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, A. Mussgiller, D. Pitzl, A. Raspereza, M. Savitskyi, P. Saxena, R. Shevchenko, N. Stefaniuk, H. Tholen, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev**University of Hamburg, Hamburg, Germany**

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

Institut für Experimentelle Teilchenphysik, Karlsruhe, GermanyM. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, N. Faltermann, B. Freund, R. Friese, M. Giffels, M.A. Harrendorf, F. Hartmann¹⁶, S.M. Heindl, U. Husemann, F. Kassel¹⁶, S. Kudella, H. Mildner, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov,

G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

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

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

National and Kapodistrian University of Athens, Athens, Greece

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

National Technical University of Athens, Athens, Greece

K. Kousouris, I. Papakrivopoulos

University of Ioánnina, Ioánnina, Greece

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

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

M. Csanad, N. Filipovic, G. Pasztor, O. Surányi, G.I. Veres²⁰

Wigner Research Centre for Physics, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath²¹, Á. Hunyadi, F. Sikler, V. Veszpremi, G. Vesztergombi²⁰, T.Á. Vámi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Karancsi²², A. Makovec, J. Molnar, Z. Szillasi

Institute of Physics, University of Debrecen, Debrecen, Hungary

M. Bartók²⁰, P. Raics, Z.L. Trocsanyi, B. Ujvari

Indian Institute of Science (IISc), Bangalore, India

S. Choudhury, J.R. Komaragiri

National Institute of Science Education and Research, Bhubaneswar, India

S. Bahinipati²³, P. Mal, K. Mandal, A. Nayak²⁴, D.K. Sahoo²³, N. Sahoo, S.K. Swain

Panjab University, Chandigarh, India

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

University of Delhi, Delhi, India

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

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

R. Bhardwaj²⁵, R. Bhattacharya, S. Bhattacharya, U. Bhawandeep²⁵, D. Bhowmik, S. Dey, S. Dutt²⁵, S. Dutta, S. Ghosh, N. Majumdar, K. Mondal, S. Mukhopadhyay, S. Nandan, A. Purohit, P.K. Rout, A. Roy, S. Roy Chowdhury, S. Sarkar, M. Sharan, B. Singh, S. Thakur²⁵

Indian Institute of Technology Madras, Madras, India

P.K. Behera

Bhabha Atomic Research Centre, Mumbai, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, A.K. Mohanty¹⁶, P.K. Netrakanti, L.M. Pant, P. Shukla, A. Topkar

Tata Institute of Fundamental Research-A, Mumbai, India

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

Tata Institute of Fundamental Research-B, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Kumar, M. Maity²⁶, G. Majumder, K. Mazumdar, T. Sarkar²⁶, N. Wickramage²⁷

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

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

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

S. Chenarani²⁸, E. Eskandari Tadavani, S.M. Etesami²⁸, M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, S. Paktinat Mehdiabadi²⁹, F. Rezaei Hosseinabadi, B. Safarzadeh³⁰, M. Zeinali

University College Dublin, Dublin, Ireland

M. Felcini, M. Grunewald

INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy

M. Abbrescia^{a,b}, C. Calabria^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, L. Cristella^{a,b}, N. De Filippis^{a,c}, M. De Palma^{a,b}, A. Di Florio^{a,b}, F. Errico^{a,b}, L. Fiore^a, A. Gelmi^{a,b}, G. Iaselli^{a,c}, S. Lezki^{a,b}, G. Maggi^{a,c}, M. Maggi^a, B. Marangelli^{a,b}, G. Miniello^{a,b}, S. My^{a,b}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, R. Radogna^a, A. Ranieri^a, G. Selvaggi^{a,b}, A. Sharma^a, L. Silvestris^{a,16}, R. Venditti^a, P. Verwilligen^a, G. Zito^a

INFN Sezione di Bologna ^a, Università di Bologna ^b, Bologna, Italy

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

INFN Sezione di Catania ^a, Università di Catania ^b, Catania, Italy

S. Albergo^{a,b}, S. Costa^{a,b}, A. Di Mattia^a, F. Giordano^{a,b}, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

INFN Sezione di Firenze ^a, Università di Firenze ^b, Firenze, Italy

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

INFN Laboratori Nazionali di Frascati, Frascati, ItalyL. Benussi, S. Bianco, F. Fabbri, D. Piccolo, F. Primavera¹⁶**INFN Sezione di Genova ^a, Università di Genova ^b, Genova, Italy**V. Calvelli^{a,b}, F. Ferro^a, F. Ravera^{a,b}, E. Robutti^a, S. Tosi^{a,b}**INFN Sezione di Milano-Bicocca ^a, Università di Milano-Bicocca ^b, Milano, Italy**A. Benaglia^a, A. Beschi^b, L. Brianza^{a,b}, F. Brivio^{a,b}, V. Ciriolo^{a,b,16}, M.E. Dinardo^{a,b}, S. Fiorendi^{a,b}, S. Gennai^a, A. Ghezzi^{a,b}, P. Govoni^{a,b}, M. Malberti^{a,b}, S. Malvezzi^a, R.A. Manzoni^{a,b}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, K. Pauwels^{a,b}, D. Pedrini^a, S. Pigazzini^{a,b,32}, S. Ragazzi^{a,b}, T. Tabarelli de Fatis^{a,b}**INFN Sezione di Napoli ^a, Università di Napoli 'Federico II' ^b, Napoli, Italy, Università della Basilicata ^c, Potenza, Italy, Università G. Marconi ^d, Roma, Italy**S. Buontempo^a, N. Cavallo^{a,c}, S. Di Guida^{a,d,16}, F. Fabozzi^{a,c}, F. Fienga^{a,b}, G. Galati^{a,b}, A.O.M. Iorio^{a,b}, W.A. Khan^a, L. Lista^a, S. Meola^{a,d,16}, P. Paolucci^{a,16}, C. Sciacca^{a,b}, F. Thyssen^a, E. Voevodina^{a,b}**INFN Sezione di Padova ^a, Università di Padova ^b, Padova, Italy, Università di Trento ^c, Trento, Italy**P. Azzi^a, N. Bacchetta^a, L. Benato^{a,b}, D. Bisello^{a,b}, A. Boletti^{a,b}, R. Carlin^{a,b}, A. Carvalho Antunes De Oliveira^{a,b}, P. Checchia^a, M. Dall'Osso^{a,b}, P. De Castro Manzano^a, T. Dorigo^a, U. Dosselli^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, S. Lacaprara^a, P. Lujan, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, R. Rossin^{a,b}, F. Simonetto^{a,b}, A. Tiko, E. Torassa^a, M. Zanetti^{a,b}, P. Zotto^{a,b}**INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy**A. Braghieri^a, A. Magnani^a, P. Montagna^{a,b}, S.P. Ratti^{a,b}, V. Re^a, M. Ressegotti^{a,b}, C. Riccardi^{a,b}, P. Salvini^a, I. Vai^{a,b}, P. Vitulo^{a,b}**INFN Sezione di Perugia ^a, Università di Perugia ^b, Perugia, Italy**L. Alunni Solestizi^{a,b}, M. Biasini^{a,b}, G.M. Bilei^a, C. Cecchi^{a,b}, D. Ciangottini^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b}, R. Leonardi^{a,b}, E. Manoni^a, G. Mantovani^{a,b}, V. Mariani^{a,b}, M. Menichelli^a, A. Rossi^{a,b}, A. Santocchia^{a,b}, D. Spiga^a**INFN Sezione di Pisa ^a, Università di Pisa ^b, Scuola Normale Superiore di Pisa ^c, Pisa, Italy**K. Androsov^a, P. Azzurri^{a,16}, G. Bagliesi^a, L. Bianchini^a, T. Boccali^a, L. Borrello, R. Castaldi^a, M.A. Ciocci^{a,b}, R. Dell'Orso^a, G. Fedi^a, L. Giannini^{a,c}, A. Giassi^a, M.T. Grippo^{a,31}, F. Ligabue^{a,c}, T. Lomtadze^a, E. Manca^{a,c}, G. Mandorli^{a,c}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verdini^a**INFN Sezione di Roma ^a, Sapienza Università di Roma ^b, Rome, Italy**L. Barone^{a,b}, F. Cavallari^a, M. Cipriani^{a,b}, N. Daci^a, D. Del Re^{a,b}, E. Di Marco^{a,b}, M. Diemoz^a, S. Gelli^{a,b}, E. Longo^{a,b}, F. Margaroli^{a,b}, B. Marzocchi^{a,b}, P. Meridiani^a,

G. Organtini^{a,b}, F. Pandolfi^a, R. Paramatti^{a,b}, F. Preiato^{a,b}, S. Rahatlou^{a,b}, C. Rovelli^a, F. Santanastasio^{a,b}

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

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

INFN Sezione di Trieste ^a, Università di Trieste ^b, Trieste, Italy

S. Belforte^a, M. Casarsa^a, F. Cossutti^a, G. Della Ricca^{a,b}, A. Zanetti^a

Kyungpook National University

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

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

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

Hanyang University, Seoul, Korea

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

Korea University, Seoul, Korea

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

Seoul National University, Seoul, Korea

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

University of Seoul, Seoul, Korea

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

Sungkyunkwan University, Suwon, Korea

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

Vilnius University, Vilnius, Lithuania

V. Dudenas, A. Juodagalvis, J. Vaitkus

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

I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali³³, F. Mohamad Idris³⁴, W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

Reyes-Almanza, R, Ramirez-Sanchez, G., Duran-Osuna, M. C., H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz³⁵, Rabadan-Trejo, R. I., R. Lopez-Fernandez, J. Mejia Guisao, A. Sanchez-Hernandez

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

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

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

A. Morelos Pineda

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

P.H. Butler

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

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

National Centre for Nuclear Research, Swierk, Poland

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

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

K. Bunkowski, A. Byszuk³⁶, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

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

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

Joint Institute for Nuclear Research, Dubna, Russia

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavin, A. Lanev, A. Malakhov, V. Matveev^{37,38}, P. Moisev, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

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

Y. Ivanov, V. Kim³⁹, E. Kuznetsova⁴⁰, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Institute for Nuclear Research, Moscow, Russia

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

Institute for Theoretical and Experimental Physics, Moscow, Russia

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

Moscow Institute of Physics and Technology, Moscow, Russia

T. Aushev, A. Bylinkin³⁸

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

M. Chadeeva⁴¹, R. Chistov⁴¹, P. Parygin, D. Philippov, S. Polikarpov, E. Tarkovskii, E. Zhemchugov

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin³⁸, I. Dremin³⁸, M. Kirakosyan³⁸, S.V. Rusakov, A. Terkulov

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

A. Baskakov, A. Belyaev, E. Boos, V. Bunichev, M. Dubinin⁴², L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin

Novosibirsk State University (NSU), Novosibirsk, Russia

V. Blinov⁴³, D. Shtol⁴³, Y. Skovpen⁴³

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

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

National Research Tomsk Polytechnic University, Tomsk, Russia

A. Babaev

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

P. Adzic⁴⁴, P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

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

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

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain

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

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

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

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, B. Akgun, E. Auffray, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Botta, T. Camporesi, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, D. d'Enterria, A. Dabrowski, V. Daponte, A. David, M. De Gruttola, A. De Roeck, N. Deelen, M. Dobson, T. du Pree, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita⁴⁵, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, D. Gulhan, J. Hegeman, V. Innocente, A. Jafari, P. Janot, O. Karacheban¹⁹, J. Kieseler, V. Knünz, A. Kornmayer, M. Krammer¹, C. Lange, P. Lecoq, C. Lourenço, M.T. Lucchini, L. Malgeri, M. Mannelli, A. Martelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic⁴⁶, F. Moortgat, M. Mulders, H. Neugebauer, J. Ngadiuba, S. Orfanelli, L. Orsini, F. Pantaleo¹⁶, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabaday, A. Racz, T. Reis, G. Rolandi⁴⁷, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas⁴⁸, A. Stakia, J. Steggemann, M. Stoye, M. Tosi, D. Treille, A. Tsiros, V. Veckalns⁴⁹, M. Verweij, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl[†], L. Caminada⁵⁰, K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

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

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

Universität Zürich, Zurich, Switzerland

T.K. Aarrestad, C. Amsler⁵¹, D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, I. Neutelings, D. Pinna, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, A. Zucchetta

National Central University, Chung-Li, Taiwan

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

National Taiwan University (NTU), Taipei, Taiwan

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

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

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

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

M.N. Bakirci⁵², A. Bat, F. Boran, S. Cerci⁵³, S. Damarseckin, Z.S. Demiroglu, C. Dozen, I. Dumanoglu, S. Girgis, G. Gokbulut, Y. Guler, I. Hos⁵⁴, E.E. Kangal⁵⁵, O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir⁵⁶, B. Tali⁵³, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Middle East Technical University, Physics Department, Ankara, Turkey

G. Karapinar⁵⁷, K. Ocalan⁵⁸, M. Yalvac, M. Zeyrek

Bogazici University, Istanbul, Turkey

E. Gülmez, M. Kaya⁵⁹, O. Kaya⁶⁰, S. Tekten, E.A. Yetkin⁶¹

Istanbul Technical University, Istanbul, Turkey

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

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

B. Grynyov

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

L. Levchuk

University of Bristol, Bristol, U.K.

F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, D.M. Newbold⁶², S. Paramesvaran, T. Sakuma, S. Seif El Nasr-storey, D. Smith, V.J. Smith

Rutherford Appleton Laboratory, Didcot, U.K.

K.W. Bell, A. Belyaev⁶³, C. Brew, R.M. Brown, L. Calligaris, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

Imperial College, London, U.K.

G. Auzinger, R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, S. Casasso, D. Colling, L. Corpe, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, A. Elwood, Y. Haddad, G. Hall, G. Iles, T. James, M. Komm, R. Lane, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, L. Mastrolorenzo, T. Matsushita, J. Nash⁶⁴, A. Nikitenko⁷, V. Palladino, M. Pesaresi, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, T. Strebler, S. Summers, A. Tapper, K. Uchida, M. Vazquez Acosta⁶⁵, T. Virdee¹⁶, N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

Brunel University, Uxbridge, U.K.

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

Baylor University, Waco, U.S.A.

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

Catholic University of America, Washington DC, U.S.A.

R. Bartek, A. Dominguez

The University of Alabama, Tuscaloosa, U.S.A.

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

Boston University, Boston, U.S.A.

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

Brown University, Providence, U.S.A.

G. Benelli, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan⁶⁶, K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, J. Pazzini, S. Piperov, S. Sagir, R. Syarif, D. Yu

University of California, Davis, Davis, U.S.A.

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

University of California, Los Angeles, Los Angeles, U.S.A.

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

University of California, Riverside, Riverside, U.S.A.

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

University of California, San Diego, La Jolla, U.S.A.

J.G. Branson, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech⁶⁷, J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, Santa Barbara - Department of Physics, Santa Barbara, U.S.A.

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

California Institute of Technology, Pasadena, U.S.A.

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

Carnegie Mellon University, Pittsburgh, U.S.A.

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

University of Colorado Boulder, Boulder, U.S.A.

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

Cornell University, Ithaca, U.S.A.

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

Fermi National Accelerator Laboratory, Batavia, U.S.A.

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, G. Bolla[†], K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, R. Lopes De Sá, J. Lykken, K. Maeshima, N. Magini, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, O. Prokofyev, G. Rakness, L. Ristori, A. Savoy-Navarro⁶⁸, B. Schneider, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck, W. Wu

University of Florida, Gainesville, U.S.A.

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, A. Carnes, M. Carver, D. Curry, R.D. Field, I.K. Furic, S.V. Gleyzer, B.M. Joshi, J. Konigsberg, A. Korytov,

K. Kotov, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, K. Shi, D. Sperka, N. Terentyev, L. Thomas, J. Wang, S. Wang, J. Yelton

Florida International University, Miami, U.S.A.

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

Florida State University, Tallahassee, U.S.A.

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

Florida Institute of Technology, Melbourne, U.S.A.

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

University of Illinois at Chicago (UIC), Chicago, U.S.A.

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, I.D. Sandoval Gonzalez, M.B. Tonjes, N. Varelas, H. Wang, Z. Wu, J. Zhang

The University of Iowa, Iowa City, U.S.A.

B. Bilki⁶⁹, W. Clarida, K. Dilsiz⁷⁰, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, H. Mermerkaya⁷¹, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul⁷², Y. Onel, F. Ozok⁷³, A. Penzo, C. Snyder, E. Tiras, J. Wetzel, K. Yi

Johns Hopkins University, Baltimore, U.S.A.

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

The University of Kansas, Lawrence, U.S.A.

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

Kansas State University, Manhattan, U.S.A.

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

Lawrence Livermore National Laboratory, Livermore, U.S.A.

F. Rebassoo, D. Wright

University of Maryland, College Park, U.S.A.

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

Massachusetts Institute of Technology, Cambridge, U.S.A.

D. Abercrombie, B. Allen, V. Azzolini, R. Barbieri, A. Baty, G. Bauer, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.-J. Lee, A. Levin, P.D. Luckey, B. Maier, A.C. Marini, C. McGinn, C. Mironov, S. Narayanan,

X. Niu, C. Paus, C. Roland, G. Roland, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch, S. Zhaozhong

University of Minnesota, Minneapolis, U.S.A.

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

University of Mississippi, Oxford, U.S.A.

J.G. Acosta, S. Oliveros

University of Nebraska-Lincoln, Lincoln, U.S.A.

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

State University of New York at Buffalo, Buffalo, U.S.A.

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

Northeastern University, Boston, U.S.A.

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

Northwestern University, Evanston, U.S.A.

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

University of Notre Dame, Notre Dame, U.S.A.

R. Bucci, N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko³⁷, M. Planer, A. Reinsvold, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

The Ohio State University, Columbus, U.S.A.

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

Princeton University, Princeton, U.S.A.

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

University of Puerto Rico, Mayaguez, U.S.A.

S. Malik, S. Norberg

Purdue University, West Lafayette, U.S.A.

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

Purdue University Northwest, Hammond, U.S.A.

T. Cheng, N. Parashar

Rice University, Houston, U.S.A.

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

University of Rochester, Rochester, U.S.A.

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

The Rockefeller University, New York, U.S.A.

R. Ciesielski, K. Goulios, C. Mesropian

Rutgers, The State University of New Jersey, Piscataway, U.S.A.

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

University of Tennessee, Knoxville, U.S.A.

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

Texas A&M University, College Station, U.S.A.

O. Bouhali⁷⁴, A. Castaneda Hernandez⁷⁴, A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁷⁵, R. Mueller, Y. Pakhotin, R. Patel, A. Perloff, L. Perniè, D. Rathjens, A. Safonov, A. Tatarinov

Texas Tech University, Lubbock, U.S.A.

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

Vanderbilt University, Nashville, U.S.A.

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

University of Virginia, Charlottesville, U.S.A.

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

Wayne State University, Detroit, U.S.A.

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

University of Wisconsin - Madison, Madison, WI, U.S.A.

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

- †: Deceased
- 1: Also at Vienna University of Technology, Vienna, Austria
 - 2: Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
 - 3: Also at Universidade Estadual de Campinas, Campinas, Brazil
 - 4: Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
 - 5: Also at Universidade Federal de Pelotas, Pelotas, Brazil
 - 6: Also at Université Libre de Bruxelles, Bruxelles, Belgium
 - 7: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
 - 8: Also at Joint Institute for Nuclear Research, Dubna, Russia
 - 9: Also at Cairo University, Cairo, Egypt
 - 10: Also at Suez University, Suez, Egypt
 - 11: Now at British University in Egypt, Cairo, Egypt
 - 12: Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia
 - 13: Also at Université de Haute Alsace, Mulhouse, France
 - 14: Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
 - 15: Also at Tbilisi State University, Tbilisi, Georgia
 - 16: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
 - 17: Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
 - 18: Also at University of Hamburg, Hamburg, Germany
 - 19: Also at Brandenburg University of Technology, Cottbus, Germany
 - 20: Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
 - 21: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
 - 22: Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
 - 23: Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India
 - 24: Also at Institute of Physics, Bhubaneswar, India
 - 25: Also at Shoolini University, Solan, India
 - 26: Also at University of Visva-Bharati, Santiniketan, India
 - 27: Also at University of Ruhuna, Matara, Sri Lanka
 - 28: Also at Isfahan University of Technology, Isfahan, Iran
 - 29: Also at Yazd University, Yazd, Iran
 - 30: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
 - 31: Also at Università degli Studi di Siena, Siena, Italy
 - 32: Also at INFN Sezione di Milano-Bicocca; Università di Milano-Bicocca, Milano, Italy
 - 33: Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia
 - 34: Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia
 - 35: Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico
 - 36: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
 - 37: Also at Institute for Nuclear Research, Moscow, Russia
 - 38: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
 - 39: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
 - 40: Also at University of Florida, Gainesville, U.S.A.
 - 41: Also at P.N. Lebedev Physical Institute, Moscow, Russia
 - 42: Also at California Institute of Technology, Pasadena, U.S.A.
 - 43: Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia

- 44: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
- 45: Also at INFN Sezione di Pavia; Università di Pavia, Pavia, Italy
- 46: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 47: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 48: Also at National and Kapodistrian University of Athens, Athens, Greece
- 49: Also at Riga Technical University, Riga, Latvia
- 50: Also at Universität Zürich, Zurich, Switzerland
- 51: Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria
- 52: Also at Gaziosmanpasa University, Tokat, Turkey
- 53: Also at Adiyaman University, Adiyaman, Turkey
- 54: Also at Istanbul Aydin University, Istanbul, Turkey
- 55: Also at Mersin University, Mersin, Turkey
- 56: Also at Piri Reis University, Istanbul, Turkey
- 57: Also at Izmir Institute of Technology, Izmir, Turkey
- 58: Also at Necmettin Erbakan University, Konya, Turkey
- 59: Also at Marmara University, Istanbul, Turkey
- 60: Also at Kafkas University, Kars, Turkey
- 61: Also at Istanbul Bilgi University, Istanbul, Turkey
- 62: Also at Rutherford Appleton Laboratory, Didcot, U.K.
- 63: Also at School of Physics and Astronomy, University of Southampton, Southampton, U.K.
- 64: Also at Monash University, Faculty of Science, Clayton, Australia
- 65: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
- 66: Also at Bethel University, ST. PAUL, U.S.A.
- 67: Also at Utah Valley University, Orem, U.S.A.
- 68: Also at Purdue University, West Lafayette, U.S.A.
- 69: Also at Beykent University, Istanbul, Turkey
- 70: Also at Bingol University, Bingol, Turkey
- 71: Also at Erzincan University, Erzincan, Turkey
- 72: Also at Sinop University, Sinop, Turkey
- 73: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 74: Also at Texas A&M University at Qatar, Doha, Qatar
- 75: Also at Kyungpook National University, Daegu, Korea