



Search for the rare decay of the W boson into a pion and a photon in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration ^{*}

CERN, Geneva, Switzerland

ARTICLE INFO

Article history:

Received 11 November 2020

Received in revised form 18 February 2021

Accepted 25 May 2021

Available online 28 May 2021

Editor: M. Doser

Keywords:

CMS

Standard model

EWK

ABSTRACT

A search is performed for the rare decay $W^{\pm} \rightarrow \pi^{\pm} \gamma$ in proton-proton collisions at $\sqrt{s} = 13$ TeV. Data corresponding to an integrated luminosity of 137 fb^{-1} were collected during 2016 to 2018 with the CMS detector. This analysis exploits a novel search strategy based on W boson production in top quark pair events. An inclusive search for the $W^{\pm} \rightarrow \pi^{\pm} \gamma$ decay is not optimal at the LHC because of the high trigger thresholds. Instead, a trigger selection is exploited in which the W boson originating from one of the top quarks is used to tag the event in a leptonic decay. The W boson emerging from the other top quark is used to search for the $W^{\pm} \rightarrow \pi^{\pm} \gamma$ signature. Such decays are characterized by an isolated track pointing to a large energy deposit, and by an isolated photon of large transverse momentum. The presence of b quark jets reduces the background from the hadronization of light-flavor quarks and gluons. The $W^{\pm} \rightarrow \pi^{\pm} \gamma$ decay is not observed. An upper exclusion limit is set to this branching fraction, corresponding to 1.50×10^{-5} at 95% confidence level, whereas the expected upper exclusion limit is $0.85^{+0.52}_{-0.29} \times 10^{-5}$.

© 2021 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>). Funded by SCOAP³.

1. Introduction

Rare hadronic decays of W bosons represent probes of the strong interaction at the boundary between the perturbative and nonperturbative domains of quantum chromodynamics (QCD), offering insights into factorization and meson form factors at large energy scales [1–3]. In particular, exclusive decays of the W boson into final states containing a single meson can be used to test these theoretical frameworks in a context where the energy scales are sufficiently large. At such scales, corrections that depend on the momentum transferred to the hadron in the final state can be neglected. The observation of these decays would validate the QCD factorization formalism, and enhance the possibility to perform precise calculations using such an approach. Furthermore, at future colliders they could provide a new way to measure the mass of the W boson that is based solely on visible single-particle decay products. Theoretical calculations for such branching fractions ($\mathcal{B}$) have large uncertainties: the expected value of $\mathcal{B}(W^{\pm} \rightarrow \pi^{\pm} \gamma)$, for instance, is in the range of $10^{-9} - 10^{-7}$ [1,4]. Upper limits on $\mathcal{B}(W^{\pm} \rightarrow \pi^{\pm} \gamma)$ and on two other exclusive W boson decays were set previously at 95% confidence level (CL): $\mathcal{B}(W^{\pm} \rightarrow \pi^{\pm} \gamma) < 7.0 \times 10^{-6}$ [5], $\mathcal{B}(W^{\pm} \rightarrow D_s^{\pm} \gamma) < 1.3 \times 10^{-3}$ [6], and $\mathcal{B}(W^{\pm} \rightarrow \pi^{\pm} \pi^{\pm} \pi^{\mp}) < 1.01 \times 10^{-6}$ [7]. For the Z boson, there

are comparatively many more results on searches for such rare exclusive decay channels [8].

This Letter reports the results of the first search at the CERN LHC for the rare decay $W^{\pm} \rightarrow \pi^{\pm} \gamma$. The high energy thresholds for single photon triggers make an inclusive search, similar to the one performed by the CDF Collaboration [5], unsuitable at CMS. Therefore, this analysis uses a novel approach [4], focusing on W boson production from top quark-antiquark pair ($t\bar{t}$) events at the center-of-mass energy of 13 TeV. The muon or electron emerging from the leptonic decay of one of the two W bosons from the $t\bar{t}$ pair is used to select events at the trigger level. The other W boson in the event is employed to search for the rare decay $W^{\pm} \rightarrow \pi^{\pm} \gamma$. The decay is characterized by an isolated photon of large transverse momentum (p_T), and an isolated track corresponding to a particle with large p_T . The analysis exploits the reduced jet activity expected in the vicinity of the pion [4], which is produced via electroweak processes, to reject background pions. The b quark jets are used in the multivariate event selection to reduce the contribution from non $t\bar{t}$ backgrounds. The $W^{\pm} \rightarrow \pi^{\pm} \gamma$ branching fraction is determined by parametrizing the number of observed signal events (N_{sig}) as:

$$N_{\text{sig}} = \sigma_{t\bar{t}} \mathcal{L}_{\text{int}} \mathcal{B}(W^{\pm} \rightarrow \pi^{\pm} \gamma) \sum_{\ell} \mathcal{B}(W^{\mp} \rightarrow \ell^{\mp} \nu) \varepsilon_{\ell},$$

$$\ell = \mu, e, \tau, \quad (1)$$

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

where $\sigma_{t\bar{t}}$ is the $t\bar{t}$ production cross section, $\mathcal{B}(W^\mp \rightarrow \ell^\mp \nu)$ the branching fraction of the W boson into leptons, $\mathcal{L}_{\text{int}}$ the integrated luminosity, and ε_ℓ the efficiency for the whole selection procedure (including acceptance effects). The symbol τ_ℓ indicates that the leptonic decays of the τ lepton originating from $W \rightarrow \tau \nu$ are also considered in the computation.

2. The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid 6 m in 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 reside within the solenoid volume. Each of these systems is composed of a barrel and two endcap sections. Forward hadron calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid.

Events of interest are selected using a two-tiered trigger system [9]. 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 with a latency of about 4 μ s. 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. A more detailed description of the CMS detector, together with a definition of its coordinate system and relevant kinematic variables, can be found in Ref. [10].

3. Data samples and simulation

The analyzed collision data correspond to an integrated luminosity of 137 fb⁻¹ recorded by the CMS experiment in proton-proton (pp) collisions at $\sqrt{s} = 13$ TeV during 2016 (35.9 fb⁻¹), 2017 (41.5 fb⁻¹), and 2018 (59.7 fb⁻¹).

The signal process is simulated at leading order (LO) in perturbative QCD using the Monte Carlo (MC) event generator PYTHIA 8.226 (8.230) for 2016 (2017 and 2018) [11]. The transverse momentum of the W boson (p_T^W) decaying into a pion and a photon in the signal MC is weighted so that it matches that obtained in a next-to-LO (NLO) $W \rightarrow \ell \nu$ ($\ell = \mu, e$) simulation in POWHEG v2.0 [12–15], where the W boson originates from $t\bar{t}$ decay. This correction does not affect the total signal normalization.

The main background processes in this analysis are nonsignal $t\bar{t}$ production, Drell–Yan events, associated production of a vector boson and a photon or jets ($W\gamma \rightarrow \ell \nu \gamma$, $Z\gamma \rightarrow \ell \ell \gamma$ and $W + \text{jets} \rightarrow \ell \nu + \text{jets}$), along with standard model events comprised uniquely of jets produced through the strong interaction, referred to as QCD multijet events. The $t\bar{t}$ backgrounds are simulated at NLO using the POWHEG v2.0 framework [15], whereas the Drell–Yan, $W\gamma \rightarrow \ell \nu \gamma$, $Z\gamma \rightarrow \ell \ell \gamma$, $W + \text{jets} \rightarrow \ell \nu + \text{jets}$, and QCD multijet processes are simulated at NLO using the MADGRAPH5_aMC@NLO 2.2.2 (2.4.2) generator for 2016 (2017 and 2018) [16].

The NNPDF 3.0 NLO [17] (NNPDF 3.1 next-to-NLO [18]) parton distribution functions are used for generating all 2016 (2017 and 2018) MC samples. The generators are interfaced to PYTHIA for parton showering and parton fragmentation. The PYTHIA parameters affecting the description of the underlying event are set to the CUETP8M1 tune [19] (CP5 tune [20]) for the 2016 (2017 and 2018) simulation. For the 2016 $t\bar{t}$ backgrounds, the CP5 tune is used instead of CUETP8M1. The difference in generator version and configuration over the years of data taking reflects the improved knowledge of the production mechanisms in pp collisions at CMS.

All the simulated background samples are normalized to the cross sections obtained from the corresponding event generator.

For the signal, the $t\bar{t}$ cross section measured by CMS with the 2015 data [21] is used, together with the most up-to-date measurements of $\mathcal{B}(W \rightarrow \ell \nu)$ [8].

Generated events are processed through a simulation of the CMS detector based on GEANT4 [22] and reconstructed using the same algorithms used for collision data. Additional pp collisions in the same or nearby bunch crossings (pileup) are simulated and their distributions are weighted to reproduce the pileup multiplicity measured in data, which has an average of about 23 (32) interactions per bunch crossing in 2016 (2017 and 2018).

4. Event reconstruction

Events are reconstructed using the particle-flow (PF) algorithm [23], which combines information from the subdetectors to reconstruct and identify individual particles. The candidate pp interaction vertex with the largest value of summed physics-object p_T^2 is referred to as the primary vertex (PV). The physics objects are the jets, clustered using the jet finding algorithm [24,25] with the tracks assigned to candidate vertices as inputs, and the associated missing transverse momentum $\vec{p}_T^{\text{miss}}$, computed as the negative vector p_T sum of all the PF candidates in an event. This vector, whose magnitude is denoted as p_T^{miss} [26], is modified to account for corrections to the energy scale of the reconstructed jets in the event.

Muon candidates are reconstructed by identifying signals from the muon subsystems together with those from the inner tracker [27]. The inner detector track must be consistent with originating from the PV. The energy of muons is obtained from the curvature of the corresponding track. The p_T sum of the PF candidates within a cone of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$ around the muon direction is required to be <25% of the muon p_T after implementing a correction for neutral PF objects not associated with the PV. Here ϕ indicates the azimuthal angle in radians in the plane transverse to the beam axis.

Electron candidates are reconstructed from clusters in the ECAL that are matched to tracks reconstructed using a Gaussian-sum filter algorithm. The track is required to be consistent with originating from the PV. Electron identification proceeds through a multivariate classifier that involves observables sensitive to bremsstrahlung along the electron trajectory, the geometrical and energy-momentum compatibility between the electron track and the associated energy cluster in the ECAL, the energy distribution of the electromagnetic shower, and discrimination against electrons originating from photon conversion. The PF-based isolation variables are also used as input variables in the multivariate classifier, including the p_T of photons, charged and neutral hadrons in the event [28].

Photon reconstruction is performed in the region $|\eta| < 2.5$, excluding the ECAL barrel-endcap transition region $1.44 < |\eta| < 1.57$. The energies of photons are obtained from the ECAL measurement. An electron veto is implemented to minimize photon misidentification, combining information from the ECAL and the pixel tracker. As in the electron case, photon identification proceeds through a multivariate classifier that makes use of PF-based isolation variables [29,30].

Jets are reconstructed from the PF candidates using the anti- k_T clustering algorithm [24] with a distance parameter of 0.4, as implemented in the FASTJET library [25]. Jets originating from b quarks are tagged with the DEEPCSV algorithm [31], which uses secondary vertices, together with other lifetime information, and exploits a deep neural-network architecture. For the chosen working point, the efficiency to select b quark jets is around 90%, and the rate for incorrectly tagging jets originating from the hadronization of gluons or u, d, s quarks is about 10%. Jet momentum is determined as the vectorial sum of all particle momenta in the jet

and, based on simulation, is typically within 5 to 10% of the true momentum over the whole p_T spectrum and detector acceptance. Additional pp interactions within the same or nearby bunch crossings can contribute additional tracks and calorimetric energy depositions, increasing the apparent jet momentum. To mitigate this effect, tracks identified as originating from pileup vertices are discarded and an offset correction is applied to correct for remaining contributions. Jet energy corrections are derived from simulation studies so the average measured energy of jets becomes identical to that of particle-level jets. In situ measurements of the momentum balance in dijet, photon+jet, Z+jet, and multijet events are used to determine any residual differences between the jet energy scale in data and in simulation, and appropriate corrections are made [32]. Additional selection criteria are applied to remove jets potentially originating from instrumental effects or reconstruction failures.

5. Event selection

The analysis strategy and selection criteria were designed before inspecting the signal region (SR) in the collision data. Events are chosen at trigger level with either a muon or an electron with p_T above 24 (27) GeV for muons in the 2016 and 2018 (2017) samples, and 27 (32) GeV for electrons in the 2016 (2017 and 2018) samples, following changes in the trigger reconstruction algorithms for these particles throughout the data-taking periods. The reconstructed isolated muon and electron candidates that match the trigger conditions must satisfy specific offline identification criteria, and are required to be in the region $|\eta| < 2.4$, with $p_T > 25$ GeV (or > 28 GeV for 2017) for muons, and > 33 GeV (or > 30 GeV for 2016) for electrons. The muon and electron tracks should be within $|d_z| < 0.5$ cm of the PV along the beam axis, and $|d_{xy}| < 0.2$ cm in the transverse plane.

Events where multiple leptons satisfy the selection criteria are discarded to reduce the Drell-Yan background contribution. Pions are selected by searching for particle tracks with $p_T > 20$ GeV and charge opposite to that of the lepton. To reduce contamination from pion candidates misidentified as leptons, the requirements $\Delta\phi(\mu, \pi) > 0.09$ and $\Delta\phi(e, \pi) > 0.05$ are imposed on the angle between the lepton and the candidate pion. These requirements remove the region where the lepton and the candidate pion overlap. Their effect on the signal efficiency is negligible. To ensure the compatibility of the pion track with the PV, we also require $|d_z| < 0.5$ cm and $|d_{xy}| < 0.2$ cm. The pion with largest p_T that satisfies all these requirements is chosen for further analysis. Isolated photons with $p_T > 20$ GeV and $|\eta| < 2.5$ are selected. The condition $\Delta\phi(\ell, \gamma) > 0.04$ reduces the misidentification of the trigger lepton as the selected photon. The photon with the largest p_T that satisfies all these requirements is chosen for further analysis, and the event is retained if the pion-photon invariant mass is in the range $50 < m_{\pi\gamma} < 100$ GeV.

5.1. Pion isolation

Since the pion from the $W^\pm \rightarrow \pi^\pm \gamma$ decay originates from an electroweak process, minimal jet activity related to this decay is expected in its vicinity. For this reason, the analysis implements a pion-isolation variable based on the p_T sum of all the PF candidates (excluding the pion itself) contained in a cone with radius ΔR around the pion, divided by the pion p_T^π ($\Sigma p_T/p_T^\pi$). The cone is defined to be $0.02 < \Delta R < 0.5$, with the lower bound helping to exclude from the sum the single charged particles generating two nearby reconstructed tracks. To reduce the contribution from pileup, charged particles entering the sum are required to originate from the PV, with the same d_{xy} and d_z criteria as used for

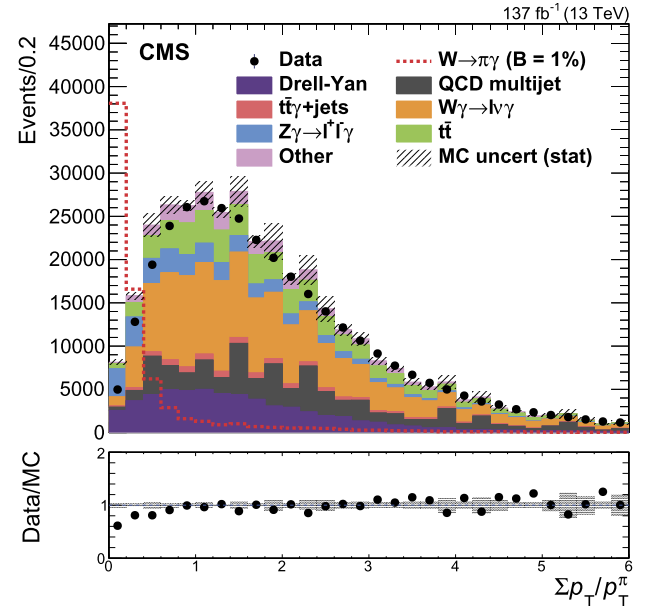


Fig. 1. Event distribution as a function of the pion-isolation variable $\Sigma p_T/p_T^\pi$. The simulated MC distribution for the signal is given by the dashed red line and corresponds to a 1% branching fraction for the $W^\pm \rightarrow \pi^\pm \gamma$ decay. The statistical uncertainties in the data are small and thus not visible. In the lower plot, the ratio between data and the background component of the MC is shown. The gray bands represent the statistical uncertainty in the MC background.

the pion. Fig. 1 shows the distribution of the pion-isolation variable for signal events, which appear to be highly isolated, whereas background events indicate a clear presence of jet activity. A discrepancy between data and MC is observed for background events at low values of the pion-isolation variable. This discrepancy, independent of the data-taking period, does not affect the background characterization extracted from data, but somewhat reduces the effectiveness of the multivariate selection technique described in Section 5.2, which is trained on simulated events. As far as the signal is concerned, this discrepancy is included in the systematic uncertainty as discussed in Section 7.

5.2. Multivariate selection

The final event selection is performed using a multivariate analysis technique. A boosted decision tree (BDT) classifier is trained using half of the signal and background MC events, and is validated through the other half. The requirement of a muon or an electron generates differences in the background distributions and the two cases are therefore handled as separate channels. The steps in the training and validation are carried out on the merged sample corresponding to the three years of data taking. The BDT input variables with good discriminating power and whose distributions are well described by the simulation are the transverse momenta of the lepton (p_T^ℓ), pion (p_T^π), and photon (p_T^γ), the p_T^{miss} in the event, the pion-isolation variable, and the number of the b -tagged jets in the event with $p_T > 25$ GeV (n_b), which provides particularly good suppression of the background topologies characterized by no b -tagged jets. Distributions of the BDT discriminant for collision data with simulated signal and background are shown in Fig. 2. The shape of the data is in agreement with the MC background.

Finally, thresholds for the BDT discriminant are defined for the two channels to identify a unique SR and a unique control region (CR) from the merging of the two lepton channels. These thresholds aim at obtaining the highest possible significance, while fulfilling the requirements discussed in the following. The CR, which includes a negligible signal contribution with respect to the SR, is

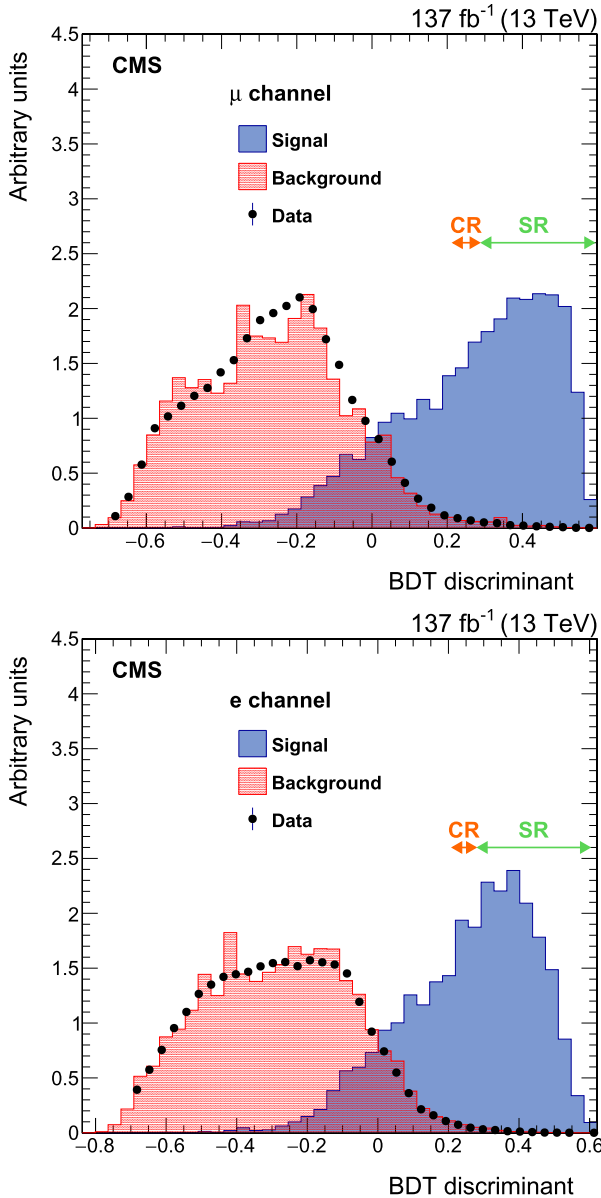


Fig. 2. Event distributions as a function of the BDT discriminant for the muon (upper) and electron (lower) channels. The green and orange arrows indicate the intervals of the BDT discriminant used to define a signal (SR) and a control region (CR). The signal histogram is enhanced so that the signal and background histograms are normalized to the same area. The statistical uncertainties in the data are small and thus not visible.

chosen so that the $m_{\pi\gamma}$ distribution contains enough events to be well fitted and to limit the impact of the systematic uncertainty in the background description. This is obtained for $0.206 < \text{BDT discriminant} < 0.281$ in the muon channel and $0.209 < \text{BDT discriminant} < 0.269$ in the electron channel. The SR should contain a number of events comparable to that in the CR, which is the case for values of the BDT discriminant > 0.281 in the muon channel and > 0.269 in the electron channel.

The products of the signal efficiency and the acceptance for the two channels, ε_ℓ , are computed separately for the 2016, 2017, and 2018 samples. They are evaluated as the ratio between the number of signal events in the MC sample in the SR, and the initial number of events generated in each channel. The efficiencies are given in Table 1 with their total uncertainties.

Table 1

The product of signal efficiency and acceptance per year and per lepton channel.

Year	ε_μ	ε_e
2016	0.12 ± 0.01	0.07 ± 0.01
2017	0.11 ± 0.01	0.07 ± 0.01
2018	0.12 ± 0.01	0.07 ± 0.01

6. Signal and background yield extraction

The signal and background yields are extracted using an unbinned maximum likelihood fit to the $m_{\pi\gamma}$ distribution in the SR. The probability density function (pdf) used to perform the fit is defined as follows:

$$f = \left(\frac{N_{\text{sig}}}{N_{\text{sig}} + N_{\text{bkg}}(\text{SR})} f_{\text{sig}} + \frac{N_{\text{bkg}}(\text{SR})}{N_{\text{sig}} + N_{\text{bkg}}(\text{SR})} f_{\text{bkg}} \right) \mathcal{G}, \quad (2)$$

where $N_{\text{bkg}}(\text{SR})$ is a floating parameter representing the number of background events in the SR, and $\mathcal{G}$ is a Gaussian pdf used to account for the nuisance parameters that model the systematic uncertainties. The functional form of the signal is determined fitting the $m_{\pi\gamma}$ distribution obtained from simulation. The sum of a double crystal ball (DCB) function [33] and a Gaussian pdf is chosen to characterize the signal lineshape f_{sig} , whose parameters, excluding the normalization, are then fixed in the fit to the $m_{\pi\gamma}$ distribution of the data.

The CR is used to estimate the functional form of the background directly from data. A linear polynomial (f_{bkg}) is chosen to describe the background. The values of the slope and the intercept (normalization) of this straight line can then vary in the fit to the $m_{\pi\gamma}$ distribution of the data in the SR.

The number of signal events N_{sig} is not sensitive to the contribution of W bosons that are not produced via $t\bar{t}$ decay. It was verified in simulation that such processes are rejected by the requirement of $t\bar{t}$ production with a large p_T lepton and jets originating from the hadronization of b quarks. Another contribution to the number of signal events that is not considered arises from the associated production of a top quark and a W boson, which is expected to be two orders of magnitude smaller than that from $t\bar{t}$ events.

7. Systematic uncertainties

Systematic uncertainties are treated as nuisance parameters in the fit to the $m_{\pi\gamma}$ distribution. These uncertainties are included as log-normal pdfs in the likelihood and will be discussed in the following in descending order of impact on the final result.

The $t\bar{t}$ production cross section in pp collisions at $\sqrt{s} = 13$ TeV, which is included in Eq. (1), was measured by CMS using the 2015 data [21] to be 815 ± 43 pb, where the total uncertainty is the quadratic sum of the statistical, systematic, and luminosity-related components. The integrated luminosities of the 2016, 2017, and 2018 data taking periods are individually known with uncertainties in the 2.3–2.5% range [34–36], whereas the total 2016–2018 integrated luminosity has an uncertainty of 1.8%; the improvement in precision reflects the uncorrelated time evolution of some systematic effects.

The choice of pdfs used to describe the background has an influence on the measured $W^\pm \rightarrow \pi^\pm \gamma$ branching fraction. To estimate this effect, a fit is performed to the data in the SR with the nominal background pdf, i.e., a linear function. The same distribution is then fitted again using an alternative pdf, namely an exponential. The following pull is calculated for the branching fraction:

$$\frac{|\mathcal{B}_{\text{lin}} - \mathcal{B}_{\text{exp}}|}{\sigma_{\mathcal{B}_{\text{lin}}}}, \quad (3)$$

where $\mathcal{B}_{\text{lin}}$ represents the value of the $W^\pm \rightarrow \pi^\pm \gamma$ branching fraction as extracted from the fit with a linear function, $\sigma_{\mathcal{B}_{\text{lin}}}$ is its uncertainty, and $\mathcal{B}_{\text{exp}}$ indicates the value of the branching fraction extracted from the fit using the exponential function. The pull amounts to 14.6% and is taken as an estimate of the systematic uncertainty associated with the background parametrization.

The parameters representing the peak and width of the Gaussian component of the DCB pdf for the signal are extracted with their uncertainties through a fit to the simulated events. To include the limited event count in the MC sample, we take the width of the DCB function and its uncertainty as extracted from the fit to the MC events. Moreover, we include a 1% uncertainty in the position of peak of the DCB function to account for the photon energy scale, which dominates the uncertainty in the pion-photon invariant mass. First, we fit the data in the SR fixing the values of the peak and the width of the DCB function to their central values (nominal case). We then repeat the fit after increasing and decreasing these parameters by their uncertainties (shifted parameters). We compare the results by calculating a set of pulls in the parameter of interest:

$$\frac{|\mathcal{B}_{\text{nominal}} - \mathcal{B}_{\text{shifted}}|}{\sigma_{\mathcal{B}_{\text{nominal}}}}, \quad (4)$$

where $\sigma_{\mathcal{B}_{\text{nominal}}}$ represents the uncertainty associated to $\mathcal{B}_{\text{nominal}}$. The largest pull of 10.6% is an estimate of the systematic uncertainty associated with the parametrization of the signal. Since the other parameters of the signal lineshape are highly correlated with each other, as well as with the peak and the width of the Gaussian component of the DCB function, it is not necessary to float them within their uncertainties.

The contributions to the uncertainties in ε_ℓ include the statistical uncertainties, the BDT modeling, the modeling of kinematic variables for the signal in PYTHIA, the scale factors that correct for differences between detector conditions in collision data and simulation, and the charge-misidentification in the tracking algorithm. To assess the uncertainty in modeling of the BDT, the performance of a BDT trained and validated with the nominal input variables is compared with that of a BDT trained with the same variables, and validated with variables to which a Gaussian spreading or a shift is applied. The width of the spreading corresponds to 5% of the value of p_T^ℓ , p_T^π , p_T^γ , and p_T^{miss} . The pion isolation is shifted upwards by 10%, based on the agreement between collision data and simulation observed in Fig. 1. The number of b jets, n_b , is increased or decreased by 1 for 5% of the events in the training samples of 2016 and 2017, and for 10% of the events in the training sample of 2018, thus accounting for the larger uncertainties in the jet energy calibration during part of the 2018 data taking. For energy and momentum, this spreading corresponds to the largest expected resolution. For charged particle tracks, it includes the uncertainties in the tracking efficiency. The largest change in ε_ℓ is 1% for a given background rejection efficiency in the muon channel, and 2% in the electron channel.

The procedure for modeling a process in PYTHIA represents another source of systematic uncertainty, since inaccuracies of the model have an impact on the signal acceptance. As a first step in the evaluation of this uncertainty, we consider the p_T distribution of the generated signal W bosons, which is corrected to match that obtained from NLO $t\bar{t}$ MC generated events in POWHEG v2 (as discussed in Section 3). To assess the effect of a systematic change in the p_T^W reweighting, the p_T^W spectrum is shifted upwards and downwards by 5%, which corresponds to the maximum uncertainty in the weights used. The performance of the BDT

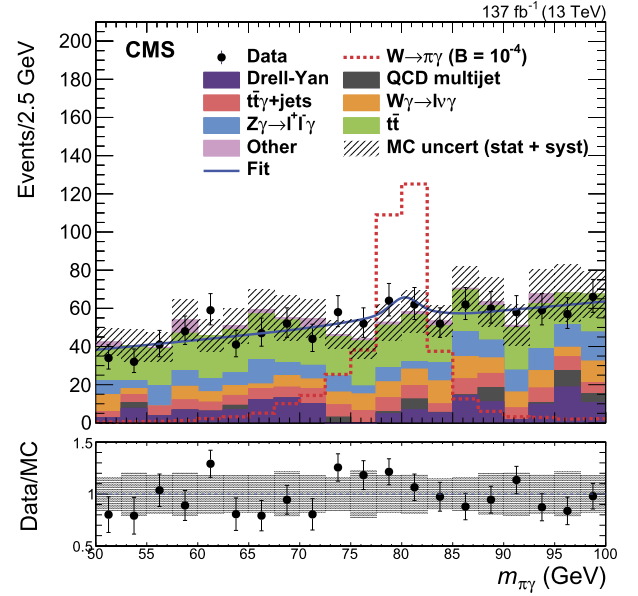


Fig. 3. Event distribution as a function of $m_{\pi\gamma}$ for the combination of the lepton channels. The simulated MC distribution for the signal is given by the dashed red line and corresponds to a 10^{-4} branching fraction for the $W^\pm \rightarrow \pi^\pm \gamma$ decay. The uncertainties in the data are statistical only. The blue line represents the best fit to the data using the model described in Eq. (2). In the lower plot, the ratio between data and the background component of the MC is shown. The gray bands represent the uncertainty (statistical + systematic) in the MC background.

trained and validated through the nominal variables is compared to that of a BDT trained on the nominal variables, and tested using MC events where the p_T^W -based reweighting is shifted by 5%. The most significant changes in signal efficiency for a given background rejection efficiency are about 2% and 3% in the muon and the electron channels, respectively.

The signal acceptance also depends on the angular spectrum of the particles involved in the $W^\pm \rightarrow \pi^\pm \gamma$ decay. To evaluate the uncertainty on ε_ℓ related to the PYTHIA modeling of the W polarization, we modify this angular spectrum. Specifically, we consider the generated distribution in θ^* , the angle between the pion direction in the W boson rest frame and the direction of the W boson momentum in the laboratory. We use $\sin^2 \theta^*$ and $\cos \theta^*$ distributions, corresponding to longitudinal and transverse polarizations of the W boson, respectively. By taking the ratio of each of these to the observed θ^* distributions, we obtain two sets of weights that are used to reweight the signal. In similarity with p_T^W , a BDT is trained on a set of nominal events, and validated on a set that has the signal renormalization implemented. The most significant changes in terms of ε_ℓ for a given background rejection efficiency are about 3% and 5% for the muon and the electron channels, respectively.

An additional uncertainty of 1.4% arises from the use of scale factors in the simulation, and an uncertainty of 1% covers the effects of charge misidentification in the tracking algorithm. These uncertainties, derived from detector performance studies [27–29, 37], are summed in quadrature to the statistical and to the other systematic uncertainties, described above, in the signal efficiency, as presented in Table 1.

8. Results

The $m_{\pi\gamma}$ distribution is shown in Fig. 3 for the combination of the two lepton channels and the three data-taking periods.

No significant excess is observed above the expected background. An observed upper limit at 95% CL is set on the branching

fraction of the W boson to a pion and a photon using the asymptotic CL_s method [38,39]:

$$\mathcal{B}(W^{\pm} \rightarrow \pi^{\pm} \gamma) < 1.50 \times 10^{-5}, \quad (5)$$

and the expected upper limit is $0.85^{+0.52}_{-0.29} \times 10^{-5}$.

The total uncertainty is dominated by the statistical contributions, which account for $\approx 80\%$. The largest systematic uncertainties arise from the measurements of the $t\bar{t}$ cross section ($\approx 5\%$) and the integrated luminosity ($\approx 2\%$).

9. Summary

A first search is reported for the rare decay $W^{\pm} \rightarrow \pi^{\pm} \gamma$ at the LHC. The search is based on the proton-proton collision data collected at a center-of-mass energy of 13 TeV at the CMS experiment in 2016–2018, corresponding to an integrated luminosity of 137 fb^{-1} . Because of the high trigger thresholds for single photons, which make an inclusive search unsuitable at CMS, the measurement is performed using top quark-antiquark pair events, where one of the produced W bosons decays into leptons. This is the first search for $W^{\pm} \rightarrow \pi^{\pm} \gamma$ that adopts such a strategy. The rare decay is characterized by an isolated track, for which a specific pion-isolation variable is defined, and an isolated photon with large transverse momentum. The data are compatible with the background-only hypothesis. The upper limit on the branching fraction of the W boson to a pion and a photon is 1.50×10^{-5} at the confidence level of 95%.

Since this result is statistically limited, it can be significantly improved with larger integrated luminosities. Our study demonstrates the feasibility of a search for such rare decays of the W bosons at the LHC and defines a search strategy that can be adopted at future hadron colliders. This paves the way to increasingly precise measurements that could, on the one hand, provide effective validation of the QCD factorization formalism and, on the other, offer an alternative way to measure the mass of the W boson.

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.

Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MOST, and NSFC (China); COLCIENCIAS (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); GSRT (Greece); NKFI (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); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, ROSATOM, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MoSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (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, and 765710 (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the 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 Deutsche Forschungsgemeinschaft (DFG) under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306; the Lendület ("Momentum") Program and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NK-FIA research grants 123842, 123959, 124845, 124850, 125105, 128713, 128786, and 129058 (Hungary); the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Ministry of Science and Higher Education, project no. 02.a03.21.0005 (Russia); the Tomsk Polytechnic University Competitiveness Enhancement Program; the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Thalís and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

- [1] Y. Grossman, M. König, M. Neubert, Exclusive radiative decays of W and Z bosons in QCD factorization, *J. High Energy Phys.* 04 (2015) 101, [https://doi.org/10.1007/JHEP04\(2015\)101](https://doi.org/10.1007/JHEP04(2015)101), arXiv:1501.06569.
- [2] T. Melia, Exclusive hadronic W decay: $W \rightarrow \pi \gamma$ and $W \rightarrow \pi \pi \pi$, *Nucl. Part. Phys. Proc.* 273 (2016) 2012, <https://doi.org/10.1016/j.nuclphysbps.2015.09.341>.
- [3] G. Perez, Y. Soreq, E. Stamou, K. Tobioka, Prospects for measuring the Higgs boson coupling to light quarks, *Phys. Rev. D* 93 (2016) 013001, <https://doi.org/10.1103/PhysRevD.93.013001>, arXiv:1505.06689.
- [4] M. Mangano, T. Melia, Rare exclusive hadronic W decays in a $t\bar{t}$ environment, *Eur. Phys. J. C* 75 (2015) 258, <https://doi.org/10.1140/epjc/s10052-015-3482-x>, arXiv:1410.7475.
- [5] T. Aaltonen, et al., CDF, Search for the rare radiative decay: $W \rightarrow \pi \gamma$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, *Phys. Rev. D* 85 (2012) 032001, <https://doi.org/10.1103/PhysRevD.85.032001>, arXiv:1104.1585.
- [6] T. Aaltonen, et al., CDF, Search for the rare decay $W^{\pm} \rightarrow D_{s}^{\pm} \gamma$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, *Phys. Rev. D* 122 (1998) 091101, <https://doi.org/10.1103/PhysRevD.58.091101>.
- [7] CMS Collaboration, Search for W boson decays to three charged pions, *Phys. Rev. Lett.* 122 (2019) 151802, <https://doi.org/10.1103/PhysRevLett.122.151802>, arXiv:1901.11201.
- [8] Particle Data Group, P.A. Zyla, et al., Review of particle physics, *Prog. Theor. Exp. Phys.* 2020 (2020) 083C01, <https://doi.org/10.1093/ptep/ptaa104>.

- [9] CMS Collaboration, The CMS trigger system, *J. Instrum.* 12 (2017) P01020, <https://doi.org/10.1088/1748-0221/12/01/P01020>, arXiv:1609.02366.
- [10] CMS Collaboration, The CMS experiment at the CERN LHC, *J. Instrum.* 3 (2008) S08004, <https://doi.org/10.1088/1748-0221/3/08/S08004>.
- [11] 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.
- [12] P. Nason, A new method for combining NLO QCD with shower Monte Carlo algorithms, *J. High Energy Phys.* 11 (2014) 040, <https://doi.org/10.1088/1126-6708/2004/11/040>, arXiv:hep-ph/0409146.
- [13] S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method, *J. High Energy Phys.* 11 (2017) 070, <https://doi.org/10.1088/1126-6708/2007/11/070>, arXiv:0709.2092.
- [14] 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](https://doi.org/10.1007/JHEP06(2010)043), arXiv:1002.2581.
- [15] J.M. Campbell, R.K. Ellis, P. Nason, E. Re, Top-pair production and decay at NLO matched with parton showers, *J. High Energy Phys.* 04 (2015) 114, [https://doi.org/10.1007/JHEP04\(2015\)114](https://doi.org/10.1007/JHEP04(2015)114), arXiv:1412.1828.
- [16] 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](https://doi.org/10.1007/JHEP07(2014)079), arXiv:1405.0301.
- [17] 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](https://doi.org/10.1007/JHEP04(2015)040), arXiv:1410.8849.
- [18] 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.
- [19] 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.
- [20] 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.
- [21] V. Khachatryan, et al., CMS, Measurement of the $t\bar{t}$ production cross section using events in the $e\mu$ final state in pp collisions at $\sqrt{s} = 13$ TeV, *Eur. Phys. J. C* 77 (2017) 172, <https://doi.org/10.1140/epjc/s10052-017-4718-8>, arXiv:1611.04040.
- [22] 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](https://doi.org/10.1016/S0168-9002(03)01368-8).
- [23] 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.
- [24] 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.
- [25] 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.
- [26] CMS Collaboration, Performance of missing transverse momentum reconstruction in proton-proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector, *J. Instrum.* 14 (2019) P07004, <https://doi.org/10.1088/1748-0221/14/07/P07004>, arXiv:1903.06078.
- [27] CMS Collaboration, Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV, *J. Instrum.* 13 (2018) P06015, <https://doi.org/10.1088/1748-0221/13/06/P06015>, arXiv:1804.04528.
- [28] CMS Collaboration, Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV, *J. Instrum.* 10 (2015) P06005, <https://doi.org/10.1088/1748-0221/10/06/P06005>, arXiv:1502.02701.
- [29] CMS Collaboration, Performance of photon reconstruction and identification with the CMS detector in proton-proton collisions at $\sqrt{s} = 8$ TeV, *J. Instrum.* 10 (2015) P08010, <https://doi.org/10.1088/1748-0221/10/08/P08010>, arXiv:1502.02702.
- [30] 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.
- [31] CMS Collaboration, Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV, *J. Instrum.* 13 (2018) P05011, <https://doi.org/10.1088/1748-0221/13/05/p05011>, arXiv:1712.07158.
- [32] 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.
- [33] M.J. Oreglia, A study of the reactions $\psi' \rightarrow \gamma \gamma \psi$, Ph.D. thesis, Stanford University, 1980, <http://www.slac.stanford.edu/cgi-wrap/getdoc/slac-r-236.pdf>, SLAC Report SLAC-R-236.
- [34] CMS Collaboration, CMS luminosity measurements for the 2016 data-taking period, CMS Physics Analysis Summary CMS-PAS-LUM-17-001, <https://cds.cern.ch/record/2257069>, 2017.
- [35] 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>, 2017.
- [36] 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>, 2018.
- [37] CMS Collaboration, Description and performance of track and primary-vertex reconstruction with the CMS tracker, *J. Instrum.* 9 (2014) P10009, <https://doi.org/10.1088/1748-0221/9/10/P10009>, arXiv:1405.6569.
- [38] 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](https://doi.org/10.1016/S0168-9002(99)00498-2), arXiv:hep-ex/9902006.
- [39] 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>.

The CMS Collaboration

A.M. Sirunyan[†], A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, A. Escalante Del Valle, R. Frühwirth¹, M. Jeitler¹, N. Krammer, L. Lechner, D. Liko, I. Mikulec, F.M. Pitters, N. Rad, J. Schieck¹, R. Schöffbeck, M. Spanring, S. Templ, W. Waltenberger, C.-E. Wulz¹, M. Zarucki

Institut für Hochenergiephysik, Wien, Austria

V. Chekhovsky, A. Litomin, V. Makarenko, J. Suarez Gonzalez

Institute for Nuclear Problems, Minsk, Belarus

M.R. Darwish², E.A. De Wolf, D. Di Croce, X. Janssen, T. Kello³, A. Lelek, M. Pieters, H. Rejeb Sfar, H. Van Haevermaet, P. Van Mechelen, S. Van Putte, N. Van Remortel

Universiteit Antwerpen, Antwerpen, Belgium

F. Blekman, E.S. Bols, S.S. Chhibra, J. D'Hondt, J. De Clercq, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, A. Morton, Q. Python, S. Tavernier, W. Van Doninck, P. Van Mulders

Vrije Universiteit Brussel, Brussel, Belgium

D. Beghin, B. Bilin, B. Clerbaux, G. De Lentdecker, B. Dorney, L. Favart, A. Grebenyuk, A.K. Kalsi, I. Makarenko, L. Moureaux, L. Pétré, A. Popov, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, L. Wezenbeek

Université Libre de Bruxelles, Bruxelles, Belgium

T. Cornelis, D. Dobur, M. Gruchala, I. Khvastunov⁴, M. Niedziela, C. Roskas, K. Skovpen, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit

Ghent University, Ghent, Belgium

G. Bruno, F. Bury, C. Caputo, P. David, C. Delaere, M. Delcourt, I.S. Donertas, A. Giammanco, V. Lemaitre, K. Mondal, J. Prisciandaro, A. Taliencio, M. Teklishyn, P. Vischia, S. Wertz, S. Wuyckens

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

G.A. Alves, C. Hensel, A. Moraes

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, E. Belchior Batista Das Chagas, H. Brandao Malbouisson, W. Carvalho, J. Chinellato⁵, E. Coelho, E.M. Da Costa, G.G. Da Silveira⁶, D. De Jesus Damiao, S. Fonseca De Souza, J. Martins⁷, D. Matos Figueiredo, M. Medina Jaime⁸, C. Mora Herrera, L. Mundim, H. Nogima, P. Rebello Teles, L.J. Sanchez Rosas, A. Santoro, S.M. Silva Do Amaral, A. Sznajder, M. Thiel, F. Torres Da Silva De Araujo, A. Vilela Pereira

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

C.A. Bernardes^{a,b}, L. Calligaris^a, T.R. Fernandez Perez Tomei^a, E.M. Gregores^{a,b}, D.S. Lemos^a, P.G. Mercadante^{a,b}, S.F. Novaes^a, Sandra S. Padula^a

^a Universidade Estadual Paulista, São Paulo, Brazil

^b Universidade Federal do ABC, São Paulo, Brazil

A. Aleksandrov, G. Antchev, I. Atanasov, 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

University of Sofia, Sofia, Bulgaria

T. Cheng, W. Fang³, Q. Guo, H. Wang, L. Yuan

Beihang University, Beijing, China

M. Ahmad, G. Bauer, Z. Hu, Y. Wang, K. Yi^{9,10}

Department of Physics, Tsinghua University, Beijing, China

E. Chapon, G.M. Chen¹¹, H.S. Chen¹¹, M. Chen, T. Javaid¹¹, A. Kapoor, D. Leggat, H. Liao, Z.-A. Liu¹¹, R. Sharma, A. Spiezia, J. Tao, J. Thomas-wilsker, J. Wang, H. Zhang, S. Zhang¹¹, J. Zhao

Institute of High Energy Physics, Beijing, China

A. Agapitos, Y. Ban, C. Chen, Q. Huang, A. Levin, Q. Li, M. Lu, X. Lyu, Y. Mao, S.J. Qian, D. Wang, Q. Wang, J. Xiao

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

Z. You

Sun Yat-Sen University, Guangzhou, China

X. Gao³

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

M. Xiao

Zhejiang University, Hangzhou, China

C. Avila, A. Cabrera, C. Florez, J. Fraga, A. Sarkar, M.A. Segura Delgado

Universidad de Los Andes, Bogota, Colombia

J. Jaramillo, J. Mejia Guisao, F. Ramirez, J.D. Ruiz Alvarez, C.A. Salazar González, N. Vanegas Arbelaez

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, D. Ferencek, D. Majumder, M. Roguljic, A. Starodumov¹², T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

M.W. Ather, A. Attikis, E. Erodotou, A. Ioannou, G. Kole, M. Kolosova, S. Konstantinou, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, D. Tsiakkouri

University of Cyprus, Nicosia, Cyprus

M. Finger¹³, M. Finger Jr.¹³, A. Kveton, J. Tomsa

Charles University, Prague, Czech Republic

E. Ayala

Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

H. Abdalla¹⁴, A.A. Abdelalim^{15,16}, S. Elgammal¹⁷

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

A. Lotfy, M.A. Mahmoud

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

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

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

Department of Physics, University of Helsinki, Helsinki, Finland

E. Brücken, F. Garcia, J. Havukainen, V. Karimäki, M.S. Kim, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, H. Siikonen, E. Tuominen, J. Tuominiemi

Helsinki Institute of Physics, Helsinki, Finland

P. Luukka, T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

C. Amendola, M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, B. Lenzi, E. Locci, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro¹⁸, M. Titov, G.B. Yu

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

S. Ahuja, F. Beaudette, M. Bonanomi, A. Buchot Perraguin, P. Busson, C. Charlot, O. Davignon, B. Diab, G. Falmagne, R. Granier de Cassagnac, A. Hakimi, I. Kucher, A. Lobanov, C. Martin Perez, M. Nguyen, C. Ochando, P. Paganini, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A. Zabi, A. Zghiche

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

J.-L. Agram¹⁹, J. Andrea, D. Bloch, G. Bourgatte, J.-M. Brom, E.C. Chabert, C. Collard, J.-C. Fontaine¹⁹, D. Gelé, U. Goerlach, C. Grimault, A.-C. Le Bihan, P. Van Hove

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

E. Asilar, S. Beauceron, C. Bernet, G. Boudoul, C. Camen, A. Carle, N. Chanon, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, Sa. Jain, I.B. Laktineh, H. Lattaud, A. Lesauvage, M. Lethuillier, L. Mirabito, L. Torterotot, G. Touquet, M. Vander Donckt, S. Viret

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

A. Khvedelidze¹³, Z. Tsamalaidze¹³

Georgian Technical University, Tbilisi, Georgia

L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, M. Preuten, M.P. Rauch, J. Schulz, M. Teroerde

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

D. Eliseev, M. Erdmann, P. Fackeldey, B. Fischer, S. Ghosh, T. Hebbeker, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, G. Mocellin, S. Mondal, S. Mukherjee, D. Noll, A. Novak, T. Pook, A. Pozdnyakov, Y. Rath, H. Reithler, J. Roemer, A. Schmidt, S.C. Schuler, A. Sharma, S. Wiedenbeck, S. Zaleski

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

C. Dziwok, G. Flügge, W. Haj Ahmad²⁰, O. Hlushchenko, T. Kress, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl²¹, T. Ziemons

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

H. Aarup Petersen, M. Aldaya Martin, P. Asmuss, I. Babounikau, S. Baxter, O. Behnke, A. Bermúdez Martínez, A.A. Bin Anuar, K. Borras²², V. Botta, D. Brunner, A. Campbell, A. Cardini, P. Connor, S. Consuegra Rodríguez, V. Danilov, A. De Wit, M.M. Defranchis, L. Didukh, D. Domínguez Damiani, G. Eckerlin, D. Eckstein, T. Eichhorn, L.I. Estevez Banos, E. Gallo²³, A. Geiser, A. Giraldi, A. Grohsjean, M. Guthoff, A. Harb, A. Jafari²⁴, N.Z. Jomhari, H. Jung, A. Kasem²², M. Kasemann, H. Kaveh, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, T. Lenz, J. Lidrych, K. Lipka, W. Lohmann²⁵, T. Madlener, R. Mankel, I.-A. Melzer-Pellmann, J. Metwally, A.B. Meyer, M. Meyer, M. Missiroli, J. Mnich, A. Mussgiller, V. Myronenko, Y. Otari, D. Pérez Adán, S.K. Pflitsch, D. Pitzl, A. Raspereza, A. Saggio, A. Saibel, M. Savitskyi, V. Scheurer, C. Schwanenberger, A. Singh, R.E. Sosa Ricardo, N. Tonon, O. Turkot, A. Vagnerini, M. Van De Klundert, R. Walsh, D. Walter, Y. Wen, K. Wichmann, C. Wissing, S. Wuchterl, O. Zenaiev, R. Zlebcik

Deutsches Elektronen-Synchrotron, Hamburg, Germany

R. Aggleton, S. Bein, L. Benato, A. Benecke, K. De Leo, T. Dreyer, A. Ebrahimi, M. Eich, F. Feindt, A. Fröhlich, C. Garbers, E. Garutti, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, V. Kutzner, J. Lange, T. Lange, A. Malara, C.E.N. Niemeyer, A. Nigamova,

K.J. Pena Rodriguez, O. Rieger, P. Schleper, S. Schumann, J. Schwandt, D. Schwarz, J. Sonneveld, H. Stadie, G. Steinbrück, B. Vormwald, I. Zoi

University of Hamburg, Hamburg, Germany

J. Bechtel, T. Berger, E. Butz, R. Caspart, T. Chwalek, W. De Boer, A. Dierlamm, A. Droll, K. El Morabit, N. Faltermann, K. Flöh, M. Giffels, A. Gottmann, F. Hartmann²¹, C. Heidecker, U. Husemann, I. Katkov²⁶, P. Keicher, R. Koppenhöfer, S. Maier, M. Metzler, S. Mitra, D. Müller, Th. Müller, M. Musich, G. Quast, K. Rabbertz, J. Rauser, D. Savoie, D. Schäfer, M. Schnepf, M. Schröder, D. Seith, I. Shvetsov, H.J. Simonis, R. Ulrich, M. Wassmer, M. Weber, R. Wolf, S. Wozniewski

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

G. Anagnostou, P. Asenov, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki, A. Stakia

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

M. Diamantopoulou, D. Karasavvas, G. Karathanasis, P. Kontaxakis, C.K. Koraka, A. Manousakis-katsikakis, A. Panagiotou, I. Papavergou, N. Saoulidou, K. Theofilatos, K. Vellidis, E. Vourliotis

National and Kapodistrian University of Athens, Athens, Greece

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

National Technical University of Athens, Athens, Greece

I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, K. Manitaras, N. Manthos, I. Papadopoulos, J. Strologas

University of Ioánnina, Ioánnina, Greece

M. Bartók²⁷, M. Csanad, M.M.A. Gadallah²⁸, S. Lökös²⁹, P. Major, K. Mandal, A. Mehta, G. Pasztor, O. Surányi, G.I. Veres

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

G. Bencze, C. Hajdu, D. Horvath³⁰, F. Sikler, V. Veszpremi, G. Vesztergombi[†]

Wigner Research Centre for Physics, Budapest, Hungary

S. Czellar, J. Karacsi²⁷, J. Molnar, Z. Szillasi, D. Teyssier

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

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

Institute of Physics, University of Debrecen, Debrecen, Hungary

T. Csorgo³¹, F. Nemes³¹, T. Novak

Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary

S. Choudhury, J.R. Komaragiri, D. Kumar, L. Panwar, P.C. Tiwari

Indian Institute of Science (IISc), Bangalore, India

S. Bahinipati³², D. Dash, C. Kar, P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu, A. Nayak³³, D.K. Sahoo³², N. Sur, S.K. Swain

National Institute of Science Education and Research, HBNI, Bhubaneswar, India

S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra³⁴, R. Gupta, A. Kaur, S. Kaur, P. Kumari, M. Meena, K. Sandeep, S. Sharma, J.B. Singh, A.K. Virdi

Panjab University, Chandigarh, India

A. Ahmed, A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, A. Kumar, M. Naimuddin, P. Priyanka, K. Ranjan, A. Shah

University of Delhi, Delhi, India

M. Bharti³⁵, R. Bhattacharya, S. Bhattacharya, D. Bhowmik, S. Dutta, S. Ghosh, B. Gomber³⁶, M. Maity³⁷, S. Nandan, P. Palit, P.K. Rout, G. Saha, B. Sahu, S. Sarkar, M. Sharan, B. Singh³⁵, S. Thakur³⁵

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

P.K. Behera, S.C. Behera, P. Kalbhor, A. Muhammad, R. Pradhan, P.R. Pujahari, A. Sharma, A.K. Sikdar

Indian Institute of Technology Madras, Madras, India

D. Dutta, V. Kumar, K. Naskar³⁸, P.K. Netrakanti, L.M. Pant, P. Shukla

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, M.A. Bhat, S. Dugad, R. Kumar Verma, G.B. Mohanty, U. Sarkar

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, R. Chudasama, M. Guchait, S. Karmakar, S. Kumar, G. Majumder, K. Mazumdar, S. Mukherjee, D. Roy

Tata Institute of Fundamental Research-B, Mumbai, India

S. Dube, B. Kansal, S. Pandey, A. Rane, A. Rastogi, S. Sharma

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

H. Bakhshiansohi³⁹, M. Zeinali⁴⁰

Department of Physics, Isfahan University of Technology, Isfahan, Iran

S. Chenarani⁴¹, S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

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

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia^{a,b}, R. Aly^{a,b,42}, 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}, A. Di Pilato^{a,b}, W. Elmetenawee^{a,b}, L. Fiore^a, A. Gelmi^{a,b}, M. Gul^a, G. Iaselli^{a,c}, M. Ince^{a,b}, S. Lezki^{a,b}, G. Maggi^{a,c}, M. Maggi^a, I. Margjeka^{a,b}, V. Mastrapasqua^{a,b}, J.A. Merlin^a, S. My^{a,b}, S. Nuzzo^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, A. Ranieri^a, G. Selvaggi^{a,b}, L. Silvestris^a, F.M. Simone^{a,b}, 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. Borghonovi^a, S. Braibant-Giacomelli^{a,b}, R. Campanini^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, C. Ciocca^a, M. Cuffiani^{a,b}, G.M. Dallavalle^a, T. Diotallevi^{a,b}, F. Fabbri^a, A. Fanfani^{a,b}, E. Fontanesi^{a,b}, P. Giacomelli^a, L. Giommi^{a,b}, C. Grandi^a, L. Guiducci^{a,b}, F. Iemmi^{a,b}, S. Lo Meo^{a,43}, 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}, N. Tosi^a

^a INFN Sezione di Bologna, Bologna, Italy

^b Università di Bologna, Bologna, Italy

S. Albergo^{a,b,44}, S. Costa^{a,b}, A. Di Mattia^a, R. Potenza^{a,b}, A. Tricomi^{a,b,44}, C. Tuve^{a,b}

^a INFN Sezione di Catania, Catania, Italy

^b Università di Catania, Catania, Italy

G. Barbagli^a, A. Cassese^a, R. Ceccarelli^{a,b}, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, F. Fiori^a, 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, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

M. Bozzo^{a,b}, F. Ferro^a, R. Mulargia^{a,b}, E. Robutti^a, S. Tosi^{a,b}

^a INFN Sezione di Genova, Genova, Italy

^b Università di Genova, Genova, Italy

A. Benaglia^a, A. Beschi^{a,b}, F. Brivio^{a,b}, F. Cetorelli^{a,b}, V. Ciriolo^{a,b,21}, 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. Malberti^a, S. Malvezzi^a, A. Massironi^a, D. Menasce^a, F. Monti^{a,b}, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, T. Tabarelli de Fatis^{a,b}, D. Valsecchi^{a,b,21}, D. Zuolo^{a,b}

^a INFN Sezione di Milano-Bicocca, Milano, Italy

^b Università di Milano-Bicocca, Milano, Italy

S. Buontempo^a, N. Cavallo^{a,c}, A. De Iorio^{a,b}, F. Fabozzi^{a,c}, F. Fienga^a, A.O.M. Iorio^{a,b}, L. Lista^{a,b}, S. Meola^{a,d,21}, P. Paolucci^{a,21}, B. Rossi^a, C. Sciacca^{a,b}, E. Voevodina^{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, D. Bisello^{a,b}, P. Bortignon^a, A. Bragagnolo^{a,b}, R. Carlin^{a,b}, P. Checchia^a, P. De Castro Manzano^a, T. Dorigo^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, S.Y. Hoh^{a,b}, L. Layer^{a,45}, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, M. Presilla^{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}, P. Zotto^{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

C. Aime^{a,b}, A. Braghieri^a, S. Calzaferri^{a,b}, D. Fiorina^{a,b}, 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, P. Vitulo^{a,b}

^a INFN Sezione di Pavia, Pavia, Italy

^b Università di Pavia, Pavia, Italy

M. Biasini^{a,b}, G.M. Bilei^a, D. Ciangottini^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b}, G. Mantovani^{a,b}, V. Mariani^{a,b}, M. Menichelli^a, F. Moscatelli^a, A. Piccinelli^{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

K. Androsov^a, P. Azzurri^a, G. Bagliesi^a, V. Bertacchi^{a,c}, L. Bianchini^a, T. Boccali^a, R. Castaldi^a, M.A. Ciocci^{a,b}, R. Dell'Orso^a, M.R. Di Domenico^{a,b}, S. Donato^a, L. Giannini^{a,c}, A. Giassi^a, M.T. Grippo^a, F. Ligabue^{a,c}, E. Manca^{a,c}, G. Mandorli^{a,c}, A. Messineo^{a,b}, F. Palla^a, G. Ramirez-Sanchez^{a,c}, A. Rizzi^{a,b}, G. Rolandi^{a,c}, S. Roy Chowdhury^{a,c}, A. Scribano^a, N. Shafiei^{a,b}, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b}, N. Turini^a, 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

F. Cavallari^a, M. Cipriani^{a,b}, 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,b}, R. Tramontano^{a,b}

^a INFN Sezione di Roma, Rome, Italy

^b Sapienza Università di Roma, Rome, 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},
J. Berenguer Antequera^{a,b}, C. Biino^a, A. Cappati^{a,b}, N. Cartiglia^a, S. Cometti^a, M. Costa^{a,b},
R. Covarelli^{a,b}, N. Demaria^a, B. Kiani^{a,b}, F. Legger^a, 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}, G. Ortona^a, L. Pacher^{a,b}, N. Pastrone^a,
M. Pelliccioni^a, G.L. Pinna Angioni^{a,b}, M. Ruspa^{a,c}, R. Salvatico^{a,b}, 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,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}, F. Vazzoler^{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. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak,
B.C. Radburn-Smith, S. Sekmen, Y.C. Yang

Kyungpook National University, Daegu, Republic of Korea

H. Kim, D.H. Moon

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

B. Francois, T.J. Kim, J. Park

Hanyang University, Seoul, Republic of Korea

S. Cho, S. Choi, Y. Go, S. Ha, B. Hong, K. Lee, K.S. Lee, J. Lim, J. Park, S.K. Park, J. Yoo

Korea University, Seoul, Republic of Korea

J. Goh, A. Gurtu

Kyung Hee University, Department of Physics, Seoul, Republic of Korea

H.S. Kim, Y. Kim

Sejong University, Seoul, Republic of Korea

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

Seoul National University, Seoul, Republic of Korea

D. Jeon, J.H. Kim, B. Ko, J.S.H. Lee, I.C. Park, Y. Roh, D. Song, I.J. Watson

University of Seoul, Seoul, Republic of Korea

H.D. Yoo

Yonsei University, Department of Physics, Seoul, Republic of Korea

Y. Choi, C. Hwang, Y. Jeong, H. Lee, Y. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

Y. Maghrbi

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

V. Veckalns⁴⁶

Riga Technical University, Riga, Latvia

A. Juodagalvis, A. Rinkevicius, G. Tamulaitis, A. Vaitkevicius

Vilnius University, Vilnius, Lithuania

W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

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

J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada, L. Valencia Palomo

Universidad de Sonora (UNISON), Hermosillo, Mexico

G. Ayala, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz⁴⁷, R. Lopez-Fernandez, C.A. Mondragon Herrera, D.A. Perez Navarro, A. Sanchez-Hernandez

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

S. Carrillo Moreno, C. Oropeza Barrera, M. Ramirez-Garcia, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

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

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

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

J. Mijuskovic⁴, N. Raicevic

University of Montenegro, Podgorica, Montenegro

D. Krofcheck

University of Auckland, Auckland, New Zealand

S. Bheesette, P.H. Butler

University of Canterbury, Christchurch, New Zealand

A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, H.R. Hoorani, W.A. Khan, M.A. Shah, 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, T. Frueboes, M. Górski, M. Kazana, M. Szleper, P. Traczyk, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

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

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, J. Seixas, K. Shchelina, O. Toldaiev, J. Varela

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

S. Afanasiev, V. Alexakhin, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev^{48,49}, V.V. Mitsyn, V. Palichik, V. Perelygin, M. Savina, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, V. Trofimov, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

G. Gavrilo, V. Golovtsov, Y. Ivanov, V. Kim⁵⁰, E. Kuznetsova⁵¹, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Volkov, A. Vorobyev

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

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, G. Pivovarov, D. Tlisov[†], A. Toropin

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, V. Gavrilo, N. Lychkovskaya, A. Nikitenko⁵², V. Popov, G. Safronov, A. Spiridonov, A. Steppenov, M. Toms, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia

T. Aushev

Moscow Institute of Physics and Technology, Moscow, Russia

O. Bychkova, M. Chadeeva⁵³, D. Philippov, E. Popova, E. Zhemchugov

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

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Terkulov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Belyaev, E. Boos, M. Dubinin⁵⁴, L. Dudko, A. Ershov, V. Klyukhin, O. Kodolova, I. Lokhtin, S. Obraztsov, M. Perfilov, S. Petrushanko, V. Savrin, A. Snigirev

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

V. Blinov⁵⁵, T. Dimova⁵⁵, L. Kardapoltsev⁵⁵, I. Ovtin⁵⁵, Y. Skovpen⁵⁵

Novosibirsk State University (NSU), Novosibirsk, Russia

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

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia

A. Babaev, A. Iuzhakov, V. Okhotnikov, L. Sukhikh

National Research Tomsk Polytechnic University, Tomsk, Russia

V. Borchsh, V. Ivanchenko, E. Tcherniaev

Tomsk State University, Tomsk, Russia

P. Adzic⁵⁶, P. Cirkovic, M. Dordevic, P. Milenovic, J. Milosevic

University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Belgrade, Serbia

M. Aguilar-Benitez, J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, Cristina F. Bedoya, C.A. Carrillo Montoya, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, J.P. Fernández Ramos, J. Flix, M.C. Fouz, A. García Alonso, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. León Holgado, D. Moran, Á. Navarro Tobar, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, S. Sánchez Navas, M.S. Soares, A. Triossi, L. Urda Gómez, C. Willmott

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

C. Albajar, J.F. de Trocóniz, R. Reyes-Almanza

Universidad Autónoma de Madrid, Madrid, Spain

B. Alvarez Gonzalez, J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, E. Palencia Cortezon, C. Ramón Álvarez, J. Ripoll Sau, V. Rodríguez Bouza, S. Sanchez Cruz, A. Trapote

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

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, G. Gomez, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, F. Ricci-Tam, T. Rodrigo, 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. Kailasapathy⁵⁷, 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

T.K. Aarrestad, D. Abbaneo, E. Auffray, G. Auzinger, J. Baechler, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, N. Beni, M. Bianco, A. Bocci, E. Bossini, E. Brondolin, T. Camporesi, M. Capeans Garrido, G. Cerminara, L. Cristella, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, A. De Roeck, M. Deile, R. Di Maria, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, N. Emriskova, F. Fallavollita⁵⁸, D. Fasanella, S. Fiorendi, A. Florent, G. Franzoni, J. Fulcher, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Guilbaud, D. Gulhan, M. Haranko, J. Hegeman, Y. Iiyama, V. Innocente, T. James, P. Janot, J. Kaspar, J. Kieseler, M. Komm, N. Kratochwil, C. Lange, S. Laurila, P. Lecoq, K. Long, C. Lourenço, L. Malgeri, S. Mallios, M. Mannelli, F. Meijers, S. Mersi, E. Meschi, F. Moortgat, M. Mulders, S. Orfanelli, L. Orsini, F. Pantaleo²¹, L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, T. Quast, D. Rabad, A. Racz, M. Rieger, M. Rovere, H. Sakulin, J. Salfeld-Nebgen, S. Scarfi, C. Schäfer, C. Schwick, M. Selvaggi, A. Sharma, P. Silva, W. Snoeys, P. Sphicas⁵⁹, S. Summers, V.R. Tavolaro, D. Treille, A. Tsiros, G.P. Van Onsem, A. Vartak, M. Verzetti, K.A. Wozniak, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

L. Caminada⁶⁰, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe

Paul Scherrer Institut, Villigen, Switzerland

M. Backhaus, P. Berger, A. Calandri, N. Chernyavskaya, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T. Gadek, T.A. Gómez Espinosa, C. Grab, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, M.T. Meinhard, F. Micheli, F. Nessi-Tedaldi, J. Niedziela, F. Pauss, V. Perovic, G. Perrin, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, V. Stampf, J. Steggemann⁶¹, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

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

C. Amsler⁶², C. Botta, D. Brzhechko, M.F. Canelli, R. Del Burgo, J.K. Heikkilä, M. Huwiler, A. Jofrehei, B. Kilminster, S. Leontsinis, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, I. Neutelings, G. Rauco, A. Reimers, P. Robmann, K. Schweiger, Y. Takahashi

Universität Zürich, Zurich, Switzerland

C. Adloff⁶³, C.M. Kuo, W. Lin, A. Roy, T. Sarkar³⁷, S.S. Yu

National Central University, Chung-Li, Taiwan

L. Ceard, P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Y.y. Li, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen, E. Yazgan

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, C. Asawatangtrakuldee, N. Srimanobhas

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

F. Boran, S. Damarseckin⁶⁴, Z.S. Demiroglu, F. Dolek, C. Dozen⁶⁵, I. Dumanoglu⁶⁶, E. Eskut, G. Gokbulut, Y. Guler, E. Gurpinar Guler⁶⁷, I. Hos⁶⁸, C. Isik, E.E. Kangal⁶⁹, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir⁷⁰, A. Polatoz, A.E. Simsek, B. Tali⁷¹, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

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

B. Isildak⁷², G. Karapinar⁷³, K. Ocalan⁷⁴, M. Yalvac⁷⁵

Middle East Technical University, Physics Department, Ankara, Turkey

B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya⁷⁶, O. Kaya⁷⁷, Ö. Özçelik, S. Tekten⁷⁸, E.A. Yetkin⁷⁹

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak⁶⁶, Y. Komurcu, S. Sen⁸⁰

Istanbul Technical University, Istanbul, Turkey

F. Aydogmus Sen, S. Cerci⁷¹, B. Kaynak, S. Ozkorucuklu, D. Sunar Cerci⁷¹

Istanbul University, Istanbul, Turkey

B. Grynyov

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

L. Levchuk

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

E. Bhal, S. Bologna, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, T. Sakuma, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou⁸¹, J. Taylor, A. Titterton

University of Bristol, Bristol, United Kingdom

K.W. Bell, A. Belyaev⁸², C. Brew, R.M. Brown, D.J.A. Cockerill, K.V. Ellis, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, T. Schuh, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, P. Bloch, S. Bonomally, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, V. Cepaitis, G.S. Chahal⁸³, D. Colling, P. Dauncey, G. Davies, M. Della Negra, G. Fedi, G. Hall, G. Iles, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, V. Milosevic, J. Nash⁸⁴, V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, M. Stoye, A. Tapper, K. Uchida, T. Virdee²¹, N. Wardle, S.N. Webb, D. Winterbottom, A.G. Zecchinelli

Imperial College, London, United Kingdom

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

Brunel University, Uxbridge, United Kingdom

S. Abdullin, A. Brinkerhoff, K. Call, B. Caraway, J. Dittmann, K. Hatakeyama, A.R. Kanuganti, C. Madrid, B. McMaster, N. Pastika, S. Sawant, C. Smith, J. Wilson

Baylor University, Waco, USA

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

Catholic University of America, Washington, DC, USA

A. Buccilli, O. Charaf, S.I. Cooper, S.V. Gleyzer, C. Henderson, C.U. Perez, P. Rumerio, C. West

The University of Alabama, Tuscaloosa, USA

A. Akpinar, A. Albert, D. Arcaro, C. Cosby, Z. Demiragli, D. Gastler, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, S. Yuan, D. Zou

Boston University, Boston, USA

G. Benelli, B. Burklee, X. Coubez²², D. Cutts, Y.t. Duh, M. Hadley, U. Heintz, J.M. Hogan⁸⁵, K.H.M. Kwok, E. Laird, G. Landsberg, K.T. Lau, J. Lee, M. Narain, S. Sagir⁸⁶, R. Syarif, E. Usai, W.Y. Wong, D. Yu, W. Zhang

Brown University, Providence, USA

R. Band, C. Brainerd, R. Breedon, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, F. Jensen, W. Ko[†], O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, M. Shi, D. Taylor, K. Tos, M. Tripathi, Y. Yao, F. Zhang

University of California, Davis, Davis, USA

M. Bachtis, R. Cousins, A. Dasgupta, D. Hamilton, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, N. Mccoll, W.A. Nash, S. Regnard, D. Saltzberg, C. Schnaible, B. Stone, V. Valuev

University of California, Los Angeles, USA

K. Burt, Y. Chen, R. Clare, J.W. Gary, G. Hanson, G. Karapostoli, O.R. Long, N. Manganelli, M. Olmedo Negrete, M.I. Paneva, W. Si, S. Wimpenny, Y. Zhang

University of California, Riverside, Riverside, USA

J.G. Branson, P. Chang, S. Cittolin, S. Cooperstein, N. Deelen, J. Duarte, R. Gerosa, D. Gilbert, V. Krutelyov, J. Letts, M. Masciovecchio, S. May, S. Padhi, M. Pieri, V. Sharma, M. Tadel, F. Würthwein, A. Yagil

University of California, San Diego, La Jolla, USA

N. Amin, C. Campagnari, M. Citron, A. Dorsett, V. Dutta, J. Incandela, B. Marsh, H. Mei, A. Ovcharova, H. Qu, M. Quinnan, J. Richman, U. Sarica, D. Stuart, S. Wang

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

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

California Institute of Technology, Pasadena, USA

J. Alison, M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, W.T. Ford, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

University of Colorado Boulder, Boulder, USA

J. Alexander, Y. Cheng, J. Chu, D.J. Cranshaw, A. Datta, A. Frankenthal, K. Mcdermott, J. Monroy, J.R. Patterson, D. Quach, A. Ryd, W. Sun, S.M. Tan, Z. Tao, J. Thom, P. Wittich, M. Zientek

Cornell University, Ithaca, USA

M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl,

O. Gutsche, R.M. Harris, S. Hasegawa, R. Heller, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, P. Klabbers, T. Klijnsma, B. Klima, M.J. Kortelainen, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, V. Papadimitriou, K. Pedro, C. Pena⁵⁴, O. Prokofyev, F. Ravera, A. Reinsvold Hall, L. Ristori, B. Schneider, E. Sexton-Kennedy, N. Smith, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, H.A. Weber, A. Woodard

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, D. Bourilkov, L. Cadamuro, V. Cherepanov, F. Errico, R.D. Field, D. Guerrero, B.M. Joshi, M. Kim, J. Konigsberg, A. Korytov, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, D. Rosenzweig, K. Shi, J. Sturdy, J. Wang, S. Wang, X. Zuo

University of Florida, Gainesville, USA

T. Adams, A. Askew, D. Diaz, R. Habibullah, S. Hagopian, V. Hagopian, K.F. Johnson, R. Khurana, T. Kolberg, G. Martinez, H. Prosper, C. Schiber, R. Yohay, J. Zhang

Florida State University, Tallahassee, USA

M.M. Baarmand, S. Butalla, T. Elkafrawy⁸⁷, M. Hohlmann, D. Noonan, M. Rahmani, M. Saunders, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

M.R. Adams, L. Apanasevich, H. Becerril Gonzalez, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, C. Mills, G. Oh, T. Roy, M.B. Tonjes, N. Varelas, J. Viinikainen, X. Wang, Z. Wu, Z. Ye

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

M. Alhusseini, K. Dilsiz⁸⁸, S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili⁸⁹, A. Moeller, J. Nachtman, H. Ogul⁹⁰, Y. Onel, F. Ozok⁹¹, A. Penzo, C. Snyder, E. Tiras, J. Wetzel

The University of Iowa, Iowa City, USA

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

Johns Hopkins University, Baltimore, USA

C. Baldenegro Barrera, P. Baringer, A. Bean, A. Bylinkin, T. Isidori, S. Khalil, J. King, G. Krintiras, A. Kropivnitskaya, C. Lindsey, N. Minafra, M. Murray, C. Rogan, C. Royon, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang, J. Williams, G. Wilson

The University of Kansas, Lawrence, USA

S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, T. Mitchell, A. Modak, A. Mohammadi

Kansas State University, Manhattan, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

E. Adams, A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, T. Koeth, A.C. Mignerey, S. Nabili, M. Seidel, A. Skuja, S.C. Tonwar, L. Wang, K. Wong

University of Maryland, College Park, USA

D. Abercrombie, B. Allen, R. Bi, S. Brandt, W. Busza, I.A. Cali, Y. Chen, M. D'Alfonso, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, M. Klute, D. Kovalskyi, J. Krupa, Y.-J. Lee, P.D. Luckey, B. Maier,

A.C. Marini, C. McGinn, C. Mironov, S. Narayanan, X. Niu, C. Paus, D. Rankin, C. Roland, G. Roland, Z. Shi, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, Z. Wang, B. Wyslouch

Massachusetts Institute of Technology, Cambridge, USA

R.M. Chatterjee, A. Evans, P. Hansen, J. Hiltbrand, Sh. Jain, M. Krohn, Y. Kubota, Z. Lesko, J. Mans, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

K. Bloom, S. Chauhan, D.R. Claes, C. Fangmeier, L. Finco, F. Golf, J.R. González Fernández, C. Joo, I. Kravchenko, J.E. Siado, G.R. Snow[†], W. Tabb, F. Yan

University of Nebraska-Lincoln, Lincoln, USA

G. Agarwal, H. Bandyopadhyay, C. Harrington, L. Hay, I. Iashvili, A. Kharchilava, C. McLean, D. Nguyen, J. Pekkanen, S. Rappoccio, B. Roozbahani

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, C. Freer, Y. Haddad, A. Hortiangtham, J. Li, 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, USA

S. Bhattacharya, J. Bueghly, Z. Chen, A. Gilbert, T. Gunter, K.A. Hahn, N. Odell, M.H. Schmitt, K. Sung, M. Velasco

Northwestern University, Evanston, USA

R. Bucci, N. Dev, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, K. Lannon, N. Loukas, N. Marinelli, I. Mcalister, F. Meng, K. Mohrman, Y. Musienko⁴⁸, R. Ruchti, P. Siddireddy, S. Taroni, M. Wayne, A. Wightman, M. Wolf, L. Zygala

University of Notre Dame, Notre Dame, USA

J. Alimena, B. Bylsma, B. Cardwell, L.S. Durkin, B. Francis, C. Hill, A. Lefeld, B.L. Winer, B.R. Yates

The Ohio State University, Columbus, USA

B. Bonham, P. Das, G. Dezoort, P. Elmer, B. Greenberg, N. Haubrich, S. Higginbotham, A. Kalogeropoulos, G. Kopp, S. Kwan, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, D. Stickland, C. Tully

Princeton University, Princeton, USA

S. Malik, S. Norberg

University of Puerto Rico, Mayaguez, USA

V.E. Barnes, R. Chawla, S. Das, L. Gutay, M. Jones, A.W. Jung, G. Negro, N. Neumeister, C.C. Peng, S. Piperov, A. Purohit, H. Qiu, J.F. Schulte, M. Stojanovic¹⁸, N. Trevisani, F. Wang, A. Wildridge, R. Xiao, W. Xie

Purdue University, West Lafayette, USA

J. Dolen, N. Parashar

Purdue University Northwest, Hammond, USA

A. Baty, S. Dildick, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, A. Kumar, W. Li, B.P. Padley, R. Redjimi, J. Roberts[†], J. Rorie, W. Shi, A.G. Stahl Leiton

Rice University, Houston, 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

University of Rochester, Rochester, USA

B. Chiarito, J.P. Chou, A. Gandrakota, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, E. Hughes, S. Kaplan, O. Karacheban²⁵, I. Laflotte, A. Lath, R. Montalvo, K. Nash, M. Osherson, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, H. Wang

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

H. Acharya, A.G. Delannoy, S. Spanier

University of Tennessee, Knoxville, USA

O. Bouhali⁹², M. Dalchenko, A. Delgado, R. Eusebi, J. Gilmore, T. Huang, T. Kamon⁹³, H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, L. Perniè, D. Rathjens, A. Safonov

Texas A&M University, College Station, USA

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

Texas Tech University, Lubbock, USA

E. Appelt, S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska

Vanderbilt University, Nashville, USA

M.W. Arenton, B. Cox, G. Cummings, J. Hakala, R. Hirosky, M. Joyce, A. Ledovskoy, A. Li, C. Neu, B. Tannenwald, Y. Wang, E. Wolfe, F. Xia

University of Virginia, Charlottesville, USA

P.E. Karchin, N. Poudyal, P. Thapa

Wayne State University, Detroit, USA

K. Black, T. Bose, J. Buchanan, C. Caillol, S. Dasu, I. De Bruyn, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Hervé, U. Hussain, A. Lanaro, A. Loeliger, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, S. Trembath-reichert, W. Vetens

University of Wisconsin – Madison, Madison, WI, USA

[†] Deceased.

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

² Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt.

³ Also at Université Libre de Bruxelles, Bruxelles, Belgium.

⁴ Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.

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 Universidade Federal de Pelotas, Pelotas, Brazil.

⁹ Also at Nanjing Normal University Department of Physics, Nanjing, China.

¹⁰ Now at The University of Iowa, Iowa City, USA.

¹¹ Also at University of Chinese Academy of Sciences, Beijing, China.

¹² Also at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC 'Kurchatov Institute', Moscow, Russia.

¹³ Also at Joint Institute for Nuclear Research, Dubna, Russia.

¹⁴ Also at Cairo University, Cairo, Egypt.

¹⁵ Also at Helwan University, Cairo, Egypt.

- ¹⁶ Now at Zewail City of Science and Technology, Zewail, Egypt.
- ¹⁷ Now at British University in Egypt, Cairo, Egypt.
- ¹⁸ Also at Purdue University, West Lafayette, USA.
- ¹⁹ Also at Université de Haute Alsace, Mulhouse, France.
- ²⁰ Also at Erzincan Binali Yildirim University, Erzincan, Turkey.
- ²¹ Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
- ²² Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
- ²³ Also at University of Hamburg, Hamburg, Germany.
- ²⁴ Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran.
- ²⁵ Also at Brandenburg University of Technology, Cottbus, Germany.
- ²⁶ Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
- ²⁷ Also at Institute of Physics, University of Debrecen, Debrecen, Hungary, Debrecen, Hungary.
- ²⁸ Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.
- ²⁹ Also at Eszterhazy Karoly University, Karoly Robert Campus, Gyongyos, Hungary.
- ³⁰ Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
- ³¹ Also at Wigner Research Centre for Physics, Budapest, Hungary.
- ³² Also at IIT Bhubaneswar, Bhubaneswar, India, Bhubaneswar, India.
- ³³ Also at Institute of Physics, Bhubaneswar, India.
- ³⁴ Also at G.H.G. Khalsa College, Punjab, India.
- ³⁵ Also at Shoolini University, Solan, India.
- ³⁶ Also at University of Hyderabad, Hyderabad, India.
- ³⁷ Also at University of Visva-Bharati, Santiniketan, India.
- ³⁸ Also at Indian Institute of Technology (IIT), Mumbai, India.
- ³⁹ Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
- ⁴⁰ Also at Sharif University of Technology, Tehran, Iran.
- ⁴¹ Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.
- ⁴² Now at INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy.
- ⁴³ Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.
- ⁴⁴ Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.
- ⁴⁵ Also at Università di Napoli 'Federico II', NAPOLI, Italy.
- ⁴⁶ Also at Riga Technical University, Riga, Latvia, Riga, Latvia.
- ⁴⁷ Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
- ⁴⁸ Also at Institute for Nuclear Research, Moscow, Russia.
- ⁴⁹ Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
- ⁵⁰ Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- ⁵¹ Also at University of Florida, Gainesville, USA.
- ⁵² Also at Imperial College, London, United Kingdom.
- ⁵³ Also at P.N. Lebedev Physical Institute, Moscow, Russia.
- ⁵⁴ Also at California Institute of Technology, Pasadena, USA.
- ⁵⁵ Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
- ⁵⁶ Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- ⁵⁷ Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
- ⁵⁸ Also at INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy.
- ⁵⁹ Also at National and Kapodistrian University of Athens, Athens, Greece.
- ⁶⁰ Also at Universität Zürich, Zurich, Switzerland.
- ⁶¹ Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.
- ⁶² Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
- ⁶³ Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.
- ⁶⁴ Also at Şırnak University, Şırnak, Turkey.
- ⁶⁵ Also at Department of Physics, Tsinghua University, Beijing, China.
- ⁶⁶ Also at Near East University, Research Center of Experimental Health Science, Nicosia, Turkey.
- ⁶⁷ Also at Beykent University, Istanbul, Turkey.
- ⁶⁸ Also at Istanbul Aydin University, Application and Research Center for Advanced Studies (App. & Res. Cent. for Advanced Studies), Istanbul, Turkey.
- ⁶⁹ Also at Mersin University, Mersin, Turkey.
- ⁷⁰ Also at Piri Reis University, Istanbul, Turkey.
- ⁷¹ Also at Adiyaman University, Adiyaman, Turkey.
- ⁷² Also at Ozyegin University, Istanbul, Turkey.
- ⁷³ Also at Izmir Institute of Technology, Izmir, Turkey.
- ⁷⁴ Also at Necmettin Erbakan University, Konya, Turkey.
- ⁷⁵ Also at Bozok Universitesi Rektörlüğü, Yozgat, Turkey.
- ⁷⁶ Also at Marmara University, Istanbul, Turkey.
- ⁷⁷ Also at Milli Savunma University, Istanbul, Turkey.
- ⁷⁸ Also at Kafkas University, Kars, Turkey.
- ⁷⁹ Also at Istanbul Bilgi University, Istanbul, Turkey.
- ⁸⁰ Also at Hacettepe University, Ankara, Turkey.
- ⁸¹ Also at Vrije Universiteit Brussel, Brussel, Belgium.
- ⁸² Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- ⁸³ Also at IPPP Durham University, Durham, United Kingdom.
- ⁸⁴ Also at Monash University, Faculty of Science, Clayton, Australia.
- ⁸⁵ Also at Bethel University, St. Paul, Minneapolis, USA, St. Paul, USA.
- ⁸⁶ Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.

⁸⁷ Also at Ain Shams University, Cairo, Egypt.

⁸⁸ Also at Bingol University, Bingol, Turkey.

⁸⁹ Also at Georgian Technical University, Tbilisi, Georgia.

⁹⁰ Also at Sinop University, Sinop, Turkey.

⁹¹ Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.

⁹² Also at Texas A&M University at Qatar, Doha, Qatar.

⁹³ Also at Kyungpook National University, Daegu, Republic of Korea.