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Search for D^0 meson decays to $\pi^+\pi^-e^+e^-$ and $K^+K^-e^+e^-$ final states

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Abstract

A search for D^0 meson decays to the $\pi^+\pi^-e^+e^-$ and $K^+K^-e^+e^-$ final states is reported using a sample of proton-proton collisions collected by the LHCb experiment at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 6 fb^{-1}. The decay $D^0 \to \pi^+\pi^-e^+e^-$ is observed for the first time when requiring that the two electrons are consistent with coming from the decay of a ϕ or ρ^0/ω meson. The corresponding branching fractions are measured relative to the $D^0 \to K^-\pi^-[e^+e^-]_{\rho^0/\omega}$ decay, where the two electrons are consistent with coming from the decay of a ρ^0 or ω meson. No evidence is found for the $D^0 \to K^+K^-e^+e^-$ decay and world-best limits are set on its branching fraction. The results are compared to, and found to be consistent with, the branching fractions of the $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$ decays recently measured by LHCb and confirm lepton universality at the current precision.

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Within the standard model (SM), flavor-changing neutral-current (FCNC) processes are suppressed by the Glashow–Iliopoulos–Maiani mechanism [1]. Extensions of the SM can, however, significantly alter the probabilities at which these processes occur. Depending on the nature of potential beyond-SM (BSM) contributions, measurements of observables sensitive to FCNCs can probe energy scales of tens or even hundreds of TeV [2], providing a powerful tool in characterizing the allowed parameter space of BSM physics.

Rare charm decays may proceed via FCNC $c \to u\ell^+\ell^-$ transitions ($\ell = \mu$ or e). In the SM, these so-called *short-distance* contributions result in branching fractions of $\mathcal{O}(10^{-9})$ [3] for decays of the type $D \to X\ell^+\ell^-$, where X is one or more hadrons. The experimentally observable $D \to X\ell^+\ell^-$ decays are, however, dominated by *long-distance* processes involving intermediate hadronic resonances such as $D \to XY(\to \ell^+\ell^-)$ where Y is a hadronic resonance, *e.g.* a ρ^0, ω or ϕ meson. These resonances increase the SM branching fractions up to $\mathcal{O}(10^{-6})$ [3–6], with the broadest ones spanning the entire dilepton-mass spectrum. Accessing the short-distance contributions of interest therefore requires both large data sets and the use of complementary observables that are sensitive to short- and long-distance processes, such as angular distributions, charge-parity asymmetries or tests of lepton universality [5–19]. Despite the dominance of long-distance contributions, the effects of new physics may lead to deviations from the SM predictions. For example, the validity of lepton universality could be broken at the percent level [6].

The $D^0 \to h^+h^-\mu^+\mu^-$ decays ($h = \pi$ or K) were first observed by the LHCb collaboration [20], which subsequently studied their angular structure and charge-parity asymmetries [21, 22]. Charge-conjugate decays are implied throughout the Letter. The $D^0 \to h^+h^-e^+e^-$ decays offer the opportunity to probe the universality of the electroweak interaction couplings to leptons of different generations. However, electron final states are more challenging experimentally, in particular because the electrons lose a significant fraction of their energy as bremsstrahlung radiation while passing through the detector material. Until now, only upper limits on the branching fractions of $D^0 \to h^+h^-e^+e^-$ decays have been reported [23, 24].

This Letter reports the first search for the $D^0 \to \pi^+\pi^-e^+e^-$ and $D^0 \to K^+K^-e^+e^-$ decays at the LHCb experiment and opens the door for the first lepton universality tests with such decays. The analysis uses pp collision data collected between 2015 and 2018 at a center-of-mass energy $\sqrt{s} = 13\,\text{TeV}$, corresponding to an integrated luminosity of $6\,\text{fb}^{-1}$. The analysis method closely follows that of the LHCb analysis which observed the analogous decays with muons [20]. In particular, the analysis uses D^0 mesons originating from $D^{*+} \to D^0\pi^+$ decays with the D^{*+} mesons produced in the primary pp interaction. The branching fractions of the decays of interest are measured in regions of the dielectron mass relative to the $D^0 \to K^-\pi^+[e^+e^-]_{\rho^0/\omega}$ decay which has a branching fraction of $(4.0 \pm 0.5) \times 10^{-6}$ in the dielectron-mass range 565–950 MeV/c^2 [25], where the notation indicates that the contribution from the $\rho^0/\omega \to e^+e^-$ decay is dominant.

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$ and is described in detail in Refs. [26, 27]. Events are selected by a trigger that consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage which applies a full event reconstruction [28]. The hardware trigger requires the presence of an energy deposit in the electromagnetic calorimeter that may or may not be compatible with originating from the signal candidate, or a muon signature with large transverse momentum which is compatible with originating from any particle in the event. A first stage of the software trigger selects events with either a charged particle that has both a significant transverse momentum and large impact parameter, defined as the minimum distance of the particle trajectory from any primary pp-collision vertex (PV), or with a two-track vertex satisfying a multivariate classifier based on geometric and kinematic criteria which identify the vertex as likely to originate from the decay of a long-lived heavy particle. In a second stage of the software trigger, candidate $D^0 \to h^+ h^{(\prime)-} e^+ e^-$ decays are selected by combining four tracks that form a secondary vertex separated from any PV. All charged particles are required to have a significant impact parameter, as well as momentum $p > 3\,\mathrm{GeV}/c$ and transverse momentum $p_\mathrm{T} > 0.3\,\mathrm{GeV}/c$. The D^0 candidate must have large transverse momentum, a reconstructed mass, $m(D^0)$, in the range 1800–1950 MeV/c^2 (1700–2050 MeV/c^2) for data recorded in the years 2015–16 (2017–18), and its momentum vector must be aligned with the vector connecting the PV and the D^0 decay vertex. When more than one PV is reconstructed, the one with respect to which the D^0 candidate has the lowest impact-parameter χ^2 is chosen, defined as the difference in the vertex-fit χ^2 reconstructed with and without the candidate. Finally, $D^{*+} \to D^0 \pi^+$ candidates are selected by combining the D^0 meson with a charged particle from the same PV that has $p_\mathrm{T} > 120\,\mathrm{MeV}/c$.

Subsequently, signal candidates are further selected offline by tightening the kinematic and geometric criteria applied in the trigger. A dedicated algorithm associates reconstructed bremsstrahlung photons to tracks identified as electrons; when a given photon is associated with both electron tracks, it is attached to one chosen randomly. Throughout the analysis, signal candidates are split into two periods with different data-taking conditions (2015–16 and 2017–18) and further divided into two categories: candidates in which neither electron has an associated bremsstrahlung cluster, and all other candidates, referred to as the no-brem and with-brem categories, respectively. A multivariate classifier is used to remove D^0 candidates containing one or more fake tracks. Stringent particle-identification criteria are then applied to all charged particles to suppress both combinatorial background, from unrelated charged particles, and cross-feed backgrounds in which one type of $D^0 \to h^+ h^{(\prime)-} e^+ e^-$ decay is misidentified as another. The vertex formed by the D^0 and π^+ mesons is constrained to coincide with the PV and the momenta of the particles in the decay chain are updated accordingly. Only candidates with a difference between the reconstructed D^{*+} and D^0 masses, Δm, in the range 144–147 MeV/c^2 are considered. Further reduction of combinatorial background is achieved using a multivariate selection based on a boosted decision tree (BDT) [29, 30]. The following features are used to discriminate signal from background: the momentum, transverse momentum, and impact parameter of the pion from the D^{*+} decay; the fit quality of the D^0 vertex and its separation from the PV; the angle between the D^0 momentum vector and the vector connecting the PV and the D^0 decay vertex; and the fit quality of the D^{*+} vertex. The BDT classifier is trained separately for $D^0 \to \pi^+\pi^- e^+ e^-$ and $D^0 \to K^+ K^- e^+ e^-$ decays, using simulation samples [31, 32] as a proxy for the signal and data candidates with $m(D^0)$ greater than 1900 MeV/c^2 as a proxy for the background.

Hadronic $D^0 \to \pi^+\pi^-\pi^+\pi^-$ and $D^0 \to K^+K^-\pi^+\pi^-$ decays, where two pions are misidentified as electrons, constitute a major source of background, which is reduced by a multivariate electron-identification discriminant that combines information from the Cherenkov detectors, the calorimeters and the muon chambers. Finally, selection criteria based on the BDT response and on the electron identification discriminant are optimized by maximizing the figure-of-merit $\epsilon_{h^+h^-e^+e^-}/(5/2 + \sqrt{N_\mathrm{bkg}})$ [33], where $\epsilon_{h^+h^-e^+e^-}$ is the signal efficiency, and N_bkg is the total background yield in the $m(D^0)$ range 1700–1900 MeV/c^2

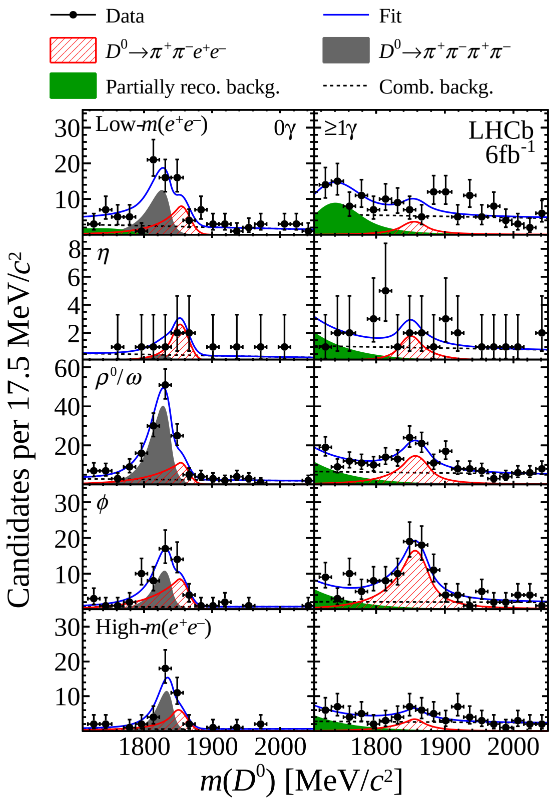

Figure 1: Mass distributions of selected $D^0 \to \pi^+\pi^-e^+e^-$ candidates in the low-$m(e^+e^-)$, η, ρ^0/ω, ϕ and high-$m(e^+e^-)$ regions in the (left, 0γ) no-brem and (right, $\geq 1\gamma$) with-brem categories. Fit projections are also shown.

(1700–2050 MeV/c^2) for the no-brem (with-brem) category. The no-brem category has a significantly larger contamination from backgrounds in which hadrons are wrongly identified as electrons and therefore significantly worse sensitivity to the signals of interest. To facilitate an extrapolation of the yields of misidentified background from the no-brem to the with-brem category, the optimal selection thresholds obtained for the with-brem category are used for the no-brem category. Candidate $D^0 \to K^-\pi^+[e^+e^-]_{\rho^0/\omega}$ decays are selected using the response of the BDT classifier trained on the $D^0 \to \pi^+\pi^-e^+e^-$ ($D^0 \to K^+K^-e^+e^-$) signal when being used to normalize the branching fraction of $D^0 \to \pi^+\pi^-e^+e^-$ ($D^0 \to K^+K^-e^+e^-$). Only one candidate is kept at random if an event contains several signal or normalization candidate decays after the final selection, which happens in less than 0.5% of selected events. To avoid potential biases on the measured signal candidate yields, candidate decays in the $m(D^0)$ signal region were examined only after the analysis procedure was finalized.

Signal and normalization yields are measured with unbinned extended maximum-likelihood fits to the $m(D^0)$ distributions, in regions of the dielectron mass, $m(e^+e^-)$, which is computed constraining the mass of the D^0 meson to its known value [34]. The fit results are shown for $D^0 \to \pi^+\pi^-e^+e^-$ and $D^0 \to K^+K^-e^+e^-$ candidates in Figs. 1 and 2, respectively. The fit results for $D^0 \to K^-\pi^+[e^+e^-]_{\rho^0/\omega}$ can be found in the supplemental material of this letter [35]. For the signal modes, the $m(e^+e^-)$ regions are defined in Table 1 according to the presence of known intermediate resonances and aligned with

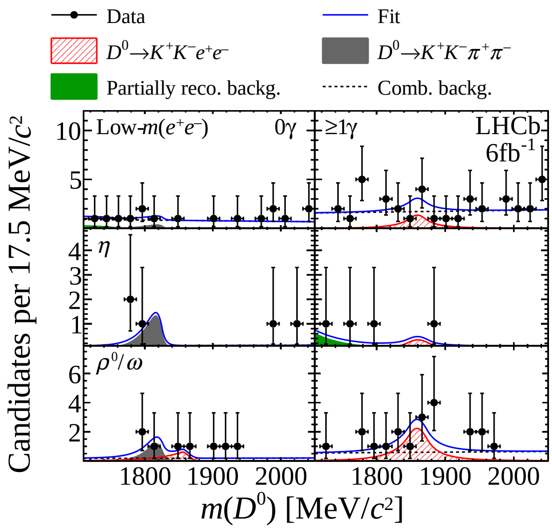

Figure 2: Mass distributions of selected $D^0 \to K^+K^-e^+e^-$ candidates in the low-$m(e^+e^-)$, η and ρ^0/ω regions in the (left) no-brem (0γ) and (right) with-brem ($\geq 1\gamma$) categories. Fit projections are also shown.

Ref. [21]. Thus, the lowest $m(e^+e^-)$ region starts at two times the muon mass, m_μ. All fits include four main components: signal, combinatorial background, peaking background from misidentified hadronic decays and background from partially reconstructed D^0-meson decays, where at least one charged or neutral particle has not been reconstructed. The fit also accounts for the small fraction of $D^0 \to h^+h^-e^+e^-$ decays in which the dielectron pair is produced in one $m(e^+e^-)$ region and reconstructed in another. All fits are validated to return unbiased results using large numbers of pseudoexperiments. The signal is described with a Crystal Ball [36] distribution for the no-brem category and with a double-sided Crystal Ball distribution for the with-brem category. In both cases, the distribution parameters are determined from simulation. The mass shape of the peaking background is determined using a Bukin distribution [37] fitted to simulated samples of $D^0 \to h^+h^{(\prime)-}\pi^+\pi^-$ decays, where the D^0 mass is calculated by assigning both pion candidates the electron mass. The peaking background in the with-brem category has a small, but not negligible, yield and a shape which is very similar to the signal. Its yield in the with-brem category is extrapolated from the no-brem category using the relevant efficiencies from simulation. The combinatorial background is described by a first-order polynomial function with its slope determined from data candidates with $\Delta m > 150\,\text{MeV}/c^2$ and $m(D^0) > 1900\,\text{MeV}/c^2$. All shape parameters of the signal, peaking background and combinatorial background are fixed. Partially reconstructed backgrounds are modeled using a Bukin distribution fitted to simulated events in the low $m(e^+e^-)$ region ($< 525\,\text{MeV}/c^2$), and an exponential function with its shape parameter determined in the fit to the selected candidates in other $m(e^+e^-)$ ranges. Alternative parametrizations are studied as a source of systematic uncertainty. The yields of each component are allowed to vary in the fits, which are performed simultaneously between the bremsstrahlung categories, periods of data-taking, and dielectron-mass regions. The yield of the combinatorial background is constrained to the yield determined in the Δm sideband 155–165 MeV/c^2 extrapolated to the signal region.

The resulting signal yields and significances with respect to zero, including statistical

Table 1: Yields of (top) $D^0 \to \pi^+\pi^-e^+e^-$ and (bottom) $D^0 \to K^+K^-e^+e^-$ signal decays and their significance, $\mathcal{S}$, in units of Gaussian standard deviations, with respect to zero.

$m(e^+e^-)$ region	[MeV/c^2]	Yield	$\mathcal{S}$
	$D^0 \to \pi^+\pi^-e^+e^-$		
Low mass	$2m_\mu$–525	37 ± 13	2.8σ
η	525–565	10 ± 7	1.6σ
ρ^0/ω	565–950	97 ± 21	5.5σ
ϕ	950–1100	100 ± 18	8.1σ
High mass	> 1100	30 ± 11	2.9σ
	$D^0 \to K^+K^-e^+e^-$		
Low mass	$2m_\mu$–525	4 ± 8	1.2σ
η	525–565	1 ± 2	1.1σ
ρ^0/ω	> 565	12 ± 7	2.2σ

and systematic uncertainties, are reported in Table 1. Significances exceeding five standard deviations are reported for $D^0 \to \pi^+\pi^-e^+e^-$ decays, where the two electrons are consistent with coming from an intermediate ϕ or ρ^0/ω meson.

The signal yields, $N^i_{h^+h^-e^+e^-}$, in the $m(e^+e^-)$ region i are used to compute the branching fractions as

$$\mathcal{B}^i(D^0 \to h^+h^-e^+e^-) = \frac{N^i_{h^+h^-e^+e^-}\, \mathcal{B}(D^0 \to K^-\pi^+[e^+e^-]_{\rho^0/\omega})}{R^i_\epsilon\, N_{K^-\pi^+e^+e^-}},$$

where $N_{K^-\pi^+e^+e^-}$ is the yield of the normalization mode, which is determined to be 820 ± 39 (875 ± 40) after applying the selection optimized for $D^0 \to \pi^+\pi^-e^+e^-$ ($D^0 \to K^+K^-e^+e^-$) decays, while $R^i_\epsilon = \epsilon^i_{h^+h^-e^+e^-}/\epsilon_{K^-\pi^+e^+e^-}$ corresponds to the ratio of geometrical acceptances, reconstruction and selection efficiencies of the signal relative to the normalization decays.

The efficiencies are determined using simulated events that are corrected to account for known differences between data and simulation. A particular challenge is the unknown amplitude composition of the decays under study. Samples of background-subtracted and efficiency-corrected $D^0 \to h^+h^{(\prime)-}\mu^+\mu^-$ decays are used to correct the five-dimensional decay model of the corresponding dielectron mode. In addition, particle-identification, hardware-trigger, and tracking efficiencies as well as the dielectron-mass resolution are corrected using dedicated control channels in data.

Systematic uncertainties related to the determination of the yields arise due to limited knowledge of the various fit components and are evaluated using pseudoexperiments, where alternative fit models are tested. These include variations of the signal and background shape parameters within the uncertainties determined from the fits to simulation, and a signal shape obtained with a modified electron momentum resolution. In addition, a Bukin distribution is tested as an alternative distribution to represent the signal. Since not all selection criteria can be applied to background simulation because of limited simulated sample sizes, the misidentified background shapes are recomputed using an alternative set of selection criteria. The combinatorial background shape is determined in alternative Δm ranges. The fraction of signal decays migrating into other regions of dielectron mass is varied within its uncertainty. Furthermore, fit components are re-evaluated using simulated samples corresponding to different data-taking years. The dominant systematic

Table 2: Branching fractions of (top) $D^0 \to \pi^+\pi^-e^+e^-$ and (bottom) $D^0 \to K^+K^-e^+e^-$ decays in different ranges of dielectron mass, where the uncertainties are statistical, systematic and due to the limited knowledge of the normalization branching fraction. The reported upper limits correspond to 90% (95%) confidence level. The correlations between the various dielectron-mass ranges are reported in the supplemental material [35].

$m(e^+e^-)$ region	[MeV/c^2]	$\mathcal{B}$ [10^{-7}]
	$D^0 \to \pi^+\pi^-e^+e^-$	
Low mass	$2m_\mu$–525	$< 4.8\,(5.4)$
η	525–565	$< 2.3\,(2.7)$
ρ^0/ω	565–950	$4.5 \pm 1.0 \pm 0.7 \pm 0.6$
ϕ	950–1100	$3.8 \pm 0.7 \pm 0.4 \pm 0.5$
High mass	> 1100	$< 2.0\,(2.2)$
	$D^0 \to K^+K^-e^+e^-$	
Low mass	$2m_\mu$–525	$< 1.0\,(1.1)$
η	525–565	$< 0.4\,(0.5)$
ρ^0/ω	> 565	$< 2.2\,(2.5)$

uncertainty arising from assumptions in the fit is determined by fully neglecting all partially reconstructed backgrounds. The impact of neglecting further misidentified backgrounds is found to be negligible everywhere except in the signal ρ^0/ω dielectron-mass region, where a contribution from $D^0 \to K^-\pi^+e^+e^-$ decays misreconstructed as the signal are found, and the appropriate systematic uncertainty is computed. The statistical uncertainty on the normalization yield leads to a relative systematic uncertainty of 4.8% (4.5%) for $D^0 \to \pi^+\pi^-e^+e^-$ ($D^0 \to K^+K^-e^+e^-$).

Systematic uncertainties affecting the efficiency ratio include residual data-simulation differences and limitations in the data-driven methods used to determine the particle-identification, tracking and trigger efficiencies. Uncertainties are evaluated directly on the efficiency ratio to take into account cancellations caused by similarities between the signal and normalization modes. The uncertainty due to finite simulated sample sizes is evaluated using a bootstrapping technique [38]. The impact of different detector occupancies in data and simulation is evaluated by recomputing the efficiencies using an additional correction accounting for the deviations. The efficiency ratios are recomputed varying the parameters used to smear the dielectron mass within their statistical uncertainties, and varying the resonant models of the signal decays within their uncertainties. In addition, the efficiency ratios are recomputed after artificially injecting an additional nonresonant component, representing unknown short-distance physics, into the simulated signal distributions at 10% of the total number of events. The impact of charm hadrons produced in beauty hadron decays is evaluated and found to be negligible.

To summarize, the biggest systematic uncertainties arise from finite simulated sample sizes, the limited knowledge of the signal-decay resonant structure, and the models used in the fit. The total systematic uncertainty depends on the decay mode and dielectron-mass region and ranges between approximately 10% and 70% of the corresponding statistical precision [35].

Measured branching fractions for $D^0 \to \pi^+\pi^-e^+e^-$ and $D^0 \to K^+K^-e^+e^-$ decays in regions of $m(e^+e^-)$ are reported in Table 2 if the statistical significance exceeds three standard deviations, where the first uncertainty accounts for the statistical component, the second for the systematic, and the third corresponds to a 13.7% relative uncertainty on $\mathcal{B}(D^0 \to K^-\pi^+[e^+e^-]_{\rho^0/\omega})$ [25]. The Feldman–Cousins approach [39] is used to report the statistical uncertainties on the branching fractions. Upper limits are derived in all other $m(e^+e^-)$ regions using the CL_s method including the effects due to the systematic uncertainties [40, 41]. Integrating over the dielectron-mass regions defined in Table 2, and accounting for correlations [35], the total branching fraction for $D^0 \to \pi^+\pi^-e^+e^-$ decays with $m(e^+e^-)$ greater than two times the muon mass is measured to be

$$\mathcal{B}(D^0 \to \pi^+\pi^-[e^+e^-]_{m(e^+e^-)>2m_\mu}) = (13.3 \pm 1.1 \pm 1.7 \pm 1.8) \times 10^{-7},$$

where the uncertainties are statistical, systematic and due to the limited knowledge of the normalization-mode branching fraction, respectively. The result is consistent with the SM expectations [5, 6] and with the branching fraction of $D^0 \to \pi^+\pi^-\mu^+\mu^-$ of $(9.6 \pm 1.2) \times 10^{-7}$ [20]. No total branching fraction is quoted for $D^0 \to K^+K^-e^+e^-$ decays as no significant signal is observed in any of the dielectron-mass regions.

In summary, a study of the $D^0 \to \pi^+\pi^-e^+e^-$ and $D^0 \to K^+K^-e^+e^-$ decays is performed in regions of the dielectron mass using pp collisions collected by the LHCb experiment at $\sqrt{s} = 13\,\text{TeV}$. The decay $D^0 \to \pi^+\pi^-e^+e^-$ is observed for the first time when requiring that the two electrons are consistent with coming from the decay of a ϕ or ρ^0/ω mesons. No evidence is found for the $D^0 \to K^+K^-e^+e^-$ decay and world-best limits are set on its branching fraction which improves previous best limits by two orders of magnitude. The results are compared to, and found to be consistent with, the branching fractions of the $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$ decays recently measured by LHCb, and confirm lepton universality at the current precision.

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Supplemental material for the Letter "Search for D^0 meson decays to $\pi^+\pi^-e^+e^-$ and $K^+K^-e^+e^-$ final states"

The fit results for $D^0 \to K^-\pi^+[e^+e^-]_{\rho^0/\omega}$ decays are shown in Fig. 3 for candidates selected as normalization sample for measurement of the branching fraction of both $D^0 \to \pi^+\pi^-e^+e^-$ and $D^0 \to K^+K^-e^+e^-$ decays. The measured branching fractions in dielectron-mass regions for $D^0 \to \pi^+\pi^-e^+e^-$ and $D^0 \to K^+K^-e^+e^-$ decays are reported in Table 3 and Table 4, respectively. A summary of the systematic uncertainties is listed in Table 5. The correlation matrices for the measurements, including statistical and systematic uncertainties, are given in Tables 6 and 7.

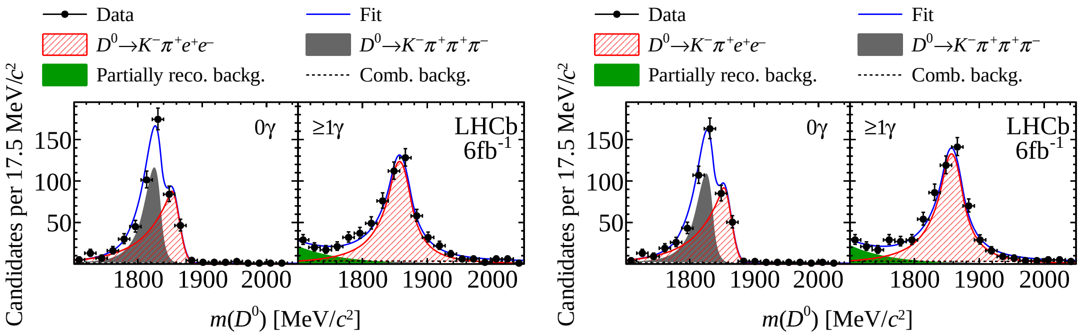

Figure 3: Distributions of $m(D^0)$ for selected $D^0 \to K^-\pi^-[e^+e^-]_{\rho^0/\omega}$ candidates in the dielectron-mass region between 675–875 MeV/c^2 split within no-brem and with-brem categories, with the selection optimized for (left) $D^0 \to \pi^+\pi^-e^+e^-$ and (right) $D^0 \to K^+K^-e^+e^-$ decays. Fit projections are also shown.

Table 3: Measured branching fractions of $D^0 \to \pi^+\pi^-e^+e^-$ decays in regions of the dielectron mass, which are used to compute the total branching fraction. The total uncertainty is reported, including the statistical, systematic and due to the limited knowledge of the normalization mode branching fraction uncertainties.

$m(e^+e^-)$ region	[MeV/c^2]	$\mathcal{B}$ [10^{-7}]
	$D^0 \to \pi^+\pi^-e^+e^-$	
Low mass	$2m_\mu$–525	$2.8^{+1.2}_{-1.1}$
η	525–565	$1.0^{+0.7}_{-0.6}$
ρ^0/ω	565–950	4.5 ± 1.4
ϕ	950–1100	3.8 ± 0.9
High mass	> 1100	$1.1^{+0.5}_{-0.4}$

Table 4: Measured branching fractions of $D^0 \to K^+K^-e^+e^-$ decays in regions of dielectron mass. The total uncertainty is reported, including the statistical, systematic and due to the limited knowledge of the normalization mode branching fraction uncertainties.

$m(e^+e^-)$ region	[MeV/c^2]	$\mathcal{B}$ [10^{-8}]
	$D^0 \to K^+K^-e^+e^-$	
Low mass	$2m_\mu$–525	$0.9^{+4.3}_{-1.1}$
η	525–565	$0.1^{+1.7}_{-0.2}$
ρ^0/ω	> 565	$9.9^{+6.4}_{-5.1}$

Table 5: Summary of relative systematic uncertainties on ratio of yields ($\frac{\Delta R_\epsilon}{R_\epsilon}$) and ratio of efficiencies ($\frac{\Delta R_\epsilon}{R_\epsilon}$) for (top) $D^0 \to \pi^+\pi^-e^+e^-$ and (bottom) $D^0 \to K^+K^-e^+e^-$ decays in different ranges of dielectron mass. The last column shows the sum in quadrature of the contributions. The uncertainty due to the limited knowledge of the normalization mode branching fraction (13.7%) is not shown in this table.

$m(e^+e^-)$ region	[MeV/c^2]	$\frac{\Delta R_N}{R_N}$[%]	$\frac{\Delta R_\epsilon}{R_\epsilon}$[%]	$\frac{\Delta\mathcal{B}}{\mathcal{B}}$[%]
	$D^0 \to \pi^+\pi^-e^+e^-$			
Low mass	$2m_\mu$–525	8.1	10.1	12.9
η	525–565	11.7	16.9	20.6
ρ^0/ω	565–950	15.1	4.8	15.8
ϕ	950–1100	8.2	5.9	10.1
High mass	> 1100	11.9	13.0	17.6
	$D^0 \to K^+K^-e^+e^-$			
Low mass	$2m_\mu$–525	9.2	8.8	12.7
η	525–565	9.8	15.4	18.3
ρ^0/ω	> 565	10.3	5.5	11.7

Table 6: Correlation coefficients related to the statistical and systematic uncertainties of the branching fractions of $D^0 \to \pi^+\pi^-e^+e^-$ decays in different dilepton mass regions.

$m(e^+e^-)$ region [MeV/c^2]	$2m_\mu$–525	525–565	565–950	950–1100	>1100
$2m_\mu$–525	1.00	0.14	0.33	0.34	0.22
525–565		1.00	0.25	0.25	0.17
565–950			1.00	0.54	0.37
950–1100				1.00	0.37
>1100					1.00

Table 7: Correlation coefficients related to the statistical and systematic uncertainties of the branching fractions of $D^0 \to K^+K^-e^+e^-$ decays in different dielectron mass regions.

$m(e^+e^-)$ region [MeV/c^2]	$2m_\mu$–525	525–565	> 565
$2m_\mu$–525	1.00	0.05	0.02
525–565		1.00	0.17
> 565			1.00

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