PROCEEDINGS OF SCIENCE

Observation of the decay $D^0 \to K^-\pi^+e^+e^-$

Fergus WILSON[*†]
STFC Rutherford Appleton Laboratory, Harwell Campus, Didcot, Oxon, OX11 0QX, UK
E-mail: Fergus.Wilson@stfc.ac.uk

We report the observation of the rare charm decay $D^0 \to K^-\pi^+e^+e^-$, based on 468 fb^{-1} of e^+e^- annihilation data collected at or close to the center-of-mass energy of the $\Upsilon(4S)$ resonance with the BaBar detector at the SLAC National Accelerator Laboratory. We find the branching fraction in the invariant mass range $0.675 < m(e^+e^-) < 0.875$ GeV/c^2 of the electron-positron pair to be $\mathscr{B}(D^0 \to K^-\pi^+e^+e^-) = (4.0 \pm 0.5 \pm 0.2 \pm 0.1) \times 10^{-6}$, where the first uncertainty is statistical, the second systematic, and the third due to the uncertainty in the branching fraction of the decay $D^0 \to K^-\pi^+\pi^+\pi^-$ used as a normalization mode. The significance of the observation corresponds to 9.7 standard deviations including systematic uncertainties. This result is consistent with the recently reported $D^0 \to K^-\pi^+\mu^+\mu^-$ branching fraction, measured in the same invariant mass range, and with the value expected in the Standard Model. In a set of regions of $m(e^+e^-)$ where long-distance effects are potentially small, we determine a 90% confidence level (CL) upper limit on the branching fraction $\mathscr{B}(D^0 \to K^-\pi^+e^+e^-) < 3.1 \times 10^{-6}$.

European Physical Society Conference on High Energy Physics - EPS-HEP2019
10-17 July, 2019
Ghent, Belgium

[*] Speaker.
[†] on behalf of the *BABAR* Collaboration

PoS(EPS-HEP2019)234

The decay $D^0 \to K^-\pi^+e^+e^-$ is expected to be very rare in the standard model (SM) as it cannot occur at tree level. Short-distance contributions to the $D^0 \to K^-\pi^+e^+e^-$ branching fraction are expected to be $\mathscr{O}(10^{-9})$. However, decays with long-distance contributions, such as $D^0 \to XV$, where X is an accompanying particle or particles and V is a vector or pseudoscalar meson decaying to two leptons, could contribute at the level of $\mathscr{O}(10^{-6})$ through photon pole amplitudes or vector meson dominance. The LHCb Collaboration has measured $\mathscr{B}(D^0 \to K^-\pi^+\mu^+\mu^-) = (4.17 \pm 0.12 \pm 0.40) \times 10^{-6}$ in the mass range $0.675 < m(\mu^+\mu^-) < 0.875\,\mathrm{GeV}/c^2$, where the decay is dominated by the ρ^0 and ω resonances [1].

We report here the observation of the decay $D^0 \to K^-\pi^+e^+e^-$ with data recorded with the BABAR detector at the PEP-II asymmetric-energy e^+e^- collider operated at the SLAC National Accelerator Laboratory. The D^0 mesons are identified from the decay $D^{*+} \to D^0\pi^+$ produced in $e^+e^- \to c\bar{c}$ events. The data sample corresponds to $424\,\mathrm{fb}^{-1}$ of e^+e^- collisions collected at the center-of-mass energy of the $\Upsilon(4S)$ resonance (onpeak) and an additional $44\,\mathrm{fb}^{-1}$ of data collected 40 MeV below the $\Upsilon(4S)$ resonance (offpeak) [2]. The BABAR detector is described in detail in Ref. [3].

Events are required to contain at least five charged tracks. Candidate D^0 mesons are formed from four charged tracks reconstructed with the appropriate mass hypothesis for the $D^0 \to K^-\pi^+e^+e^-$ and $D^0 \to K^-\pi^+\pi^+\pi^-$ decays. Particle identification (PID) is applied to the charged tracks and the same criteria are applied to the signal and normalization modes. The four tracks must form a good-quality vertex with a χ^2 probability for the vertex fit greater than 0.005. In the case of $D^0 \to K^-\pi^+e^+e^-$, a bremsstrahlung energy recovery algorithm is applied to the electrons, in which the energy of photon showers that are within a small angle (typically 35 mrad) of the initial electron direction are added to the energy of the electron candidate. The electron-positron pair must have an invariant mass $m(e^+e^-) > 0.1\,\mathrm{GeV}/c^2$.

The candidate D^{*+} is formed by combining the D^0 candidate with a charged pion with a momentum in the laboratory frame greater than $0.1\,\mathrm{GeV}/c$. The pion is required to have a charge opposite to that of the kaon in the D^0 decay. A vertex fit is performed with the D^0 mass constrained to its known value and the requirement that the D^0 meson and the pion originate from the interaction region. The χ^2 probability of the fit is required to be greater than 0.005. The D^0 meson mass $m(D^0)$ must be in the range $1.81 < m(D^0) < 1.91\,\mathrm{GeV}/c^2$ and the mass difference, $\Delta m = m(D^{*+}) - m(D^0)$, between the reconstructed masses of the D^{*+} and D^0 candidates is required to satisfy $0.143 < \Delta m < 0.148\,\mathrm{GeV}/c^2$. After the application of the D^{*+} vertex fit, the D^0 candidate momentum in the PEP-II center-of-mass system, p^*, is required be greater than $2.4\,\mathrm{GeV}/c$.

To reject misreconstructed $D^0 \to K^-\pi^+e^+e^-$ candidates that originate from D^0 hadronic decays with large branching fractions, where one or more charged tracks are misidentified by the PID, the candidate is reconstructed assuming the kaon or pion mass hypothesis for the leptons. If the resulting candidate $m(D^0)$ is within $20\,\mathrm{MeV}/c^2$ of the known D^0 mass [4] and $|\Delta m| < 2\,\mathrm{MeV}/c^2$, the event is discarded. If two or more candidates are found in an event, the one with the highest vertex χ^2 probability is selected. The average reconstruction efficiency for the $D^0 \to K^-\pi^+\pi^+\pi^-$ decay is $\hat{\varepsilon}_{\mathrm{norm}} = (20.1 \pm 0.2)\%$. For the $D^0 \to K^-\pi^+e^+e^-$ decay, the average reconstruction efficiency $\hat{\varepsilon}_{\mathrm{sig}}$ varies between 5.0% and 8.9% depending on the $m(e^+e^-)$ mass range.

The $D^0 \to K^-\pi^+e^+e^-$ branching fraction is determined relative to that of the normalization

PoS(EPS-HEP2019)234

decay channel $D^0 \to K^-\pi^+\pi^+\pi^-$ using

$$\frac{\mathscr{B}(D^0 \to K^-\pi^+e^+e^-)}{\mathscr{B}(D^0 \to K^-\pi^+\pi^+\pi^-)} = \frac{\hat{\varepsilon}_{\rm norm}}{N_{\rm norm}} \frac{\mathscr{L}_{\rm norm}}{\mathscr{L}_{\rm sig}} \sum_i^{N_{\rm sig}} \frac{1}{\varepsilon^i_{\rm sig}}, \tag{1}$$

where $\mathscr{B}(D^0 \to K^-\pi^+\pi^+\pi^-)$ is the branching fraction of the normalization mode [4], and $N_{\rm norm}$ and $\hat{\varepsilon}_{\rm norm}$ are the $D^0 \to K^-\pi^+\pi^+\pi^-$ fitted yield and the reconstruction efficiency calculated from simulated $D^0 \to K^-\pi^+\pi^+\pi^-$ decays, respectively. The fitted $D^0 \to K^-\pi^+e^+e^-$ signal yield is represented by $N_{\rm sig}$, and $\varepsilon^i_{\rm sig}$ is the reconstruction efficiency for each signal candidate i, calculated from MC simulated $D^0 \to K^-\pi^+e^+e^-$ decays as a function of $m(e^+e^-)$ and $m(K^-\pi^+)$. The symbols $\mathscr{L}_{\rm sig}$ and $\mathscr{L}_{\rm norm}$ represent the integrated luminosities used for the signal $D^0 \to K^-\pi^+e^+e^-$ decay ($468.2 \pm 2.0\,{\rm fb}^{-1}$) and the normalization $D^0 \to K^-\pi^+\pi^+\pi^-$ decay ($39.3 \pm 0.2\,{\rm fb}^{-1}$), respectively [2].

The $D^0 \to K^-\pi^+e^+e^-$ and $D^0 \to K^-\pi^+\pi^+\pi^-$ yields are determined from extended unbinned maximum likelihood fits to the uncorrelated Δm and four-body mass distributions. For the $D^0 \to K^-\pi^+e^+e^-$ signal, a Gaussian-like function with different lower and upper widths is used for both Δm and $m(K^-\pi^+e^+e^-)$. The background in the $D^0 \to K^-\pi^+e^+e^-$ channel is modeled with an ARGUS threshold function [5] for Δm and a first-order Chebyshev polynomial for $m(K^-\pi^+e^+e^-)$. For the $D^0 \to K^-\pi^+\pi^+\pi^-$ normalization mode, the Δm and $m(K^-\pi^+\pi^-\pi^+)$ distributions are each represented by two Cruijff functions with shared means [6]. The background is represented by an ARGUS threshold function for Δm and a second-order Chebyshev polynomial for $m(K^-\pi^+\pi^-\pi^+)$. All yields and shape parameters are allowed to vary in the fits except for the ARGUS function threshold end point, which is set to the kinematic threshold for the $D^{*+} \to D^0\pi^+$ decay.

Decays of intermediate mesons to the final state $e^+e^-\gamma$ can potentially appear in the $m(e^+e^-)$ spectrum as the photon is not reconstructed. However, the constraint $m(D^0) > 1.81\,{\rm GeV}/c^2$ is effective in reducing the background from these decays despite their relatively high branching fractions. We investigate the backgrounds by generating simulation samples $D^0 \to K^-\pi^+V$, with intermediate decays $\rho^0/\omega/\phi \to e^+e^-$ and $\eta/\eta' \to e^+e^-\gamma$. We expect to find 0.3 ± 0.2 $e^+e^-\gamma$ background decays in the $0.675 < m(e^+e^-) < 0.875\,{\rm GeV}/c^2$ range.

The fitted yield for the $D^0 \to K^-\pi^+\pi^+\pi^-$ normalization data sample is $260\,870 \pm 520$. For the $D^0 \to K^-\pi^+e^+e^-$ signal mode, the fitted yield, after the subtraction of the $e^+e^-\gamma$ background, is 68 ± 9 in the range $0.675 < m(e^+e^-) < 0.875\,{\rm GeV}/c^2$. The significance $S = \sqrt{-2\Delta\ln\mathscr{L}}$ of the signal yield in this mass range, including statistical and systematic uncertainties, is 9.7 standard deviations (σ), where $\Delta\ln\mathscr{L}$ is the change in the log-likelihood from the maximum value to the value when the number of $D^0 \to K^-\pi^+e^+e^-$ signal decays is set to $N_{\rm sig} = 0$.

Figure 1 shows the results of the fit to the $m(K^-\pi^+e^+e^-)$ and Δm distributions of the $D^0 \to K^-\pi^+e^+e^-$ signal mode in the mass range $0.675 < m(e^+e^-) < 0.875\,{\rm GeV}/c^2$. Also shown are the projection of the fit to the $D^0 \to K^-\pi^+e^+e^-$ signal mode as a function of $m(e^+e^-)$ and $m(K^-\pi^+)$, where the background has been subtracted using the *sPlot* technique [7]. A peaking structure is visible in $m(e^+e^-)$ centered near the ρ^0 mass. A broader structure is seen in $m(K^-\pi^+)$ near the known mass of the $\bar{K}^*(892)^0$ meson. Both distributions are similar to the distributions shown in Ref. [1] for the decay $D^0 \to K^-\pi^+\mu^+\mu^-$.

To cross-check the normalization procedure, the signal mode $D^0 \to K^-\pi^+e^+e^-$ in Eq. (1) is replaced with the decay $D^0 \to K^-\pi^+$, which has a well-known branching fraction [4]. The

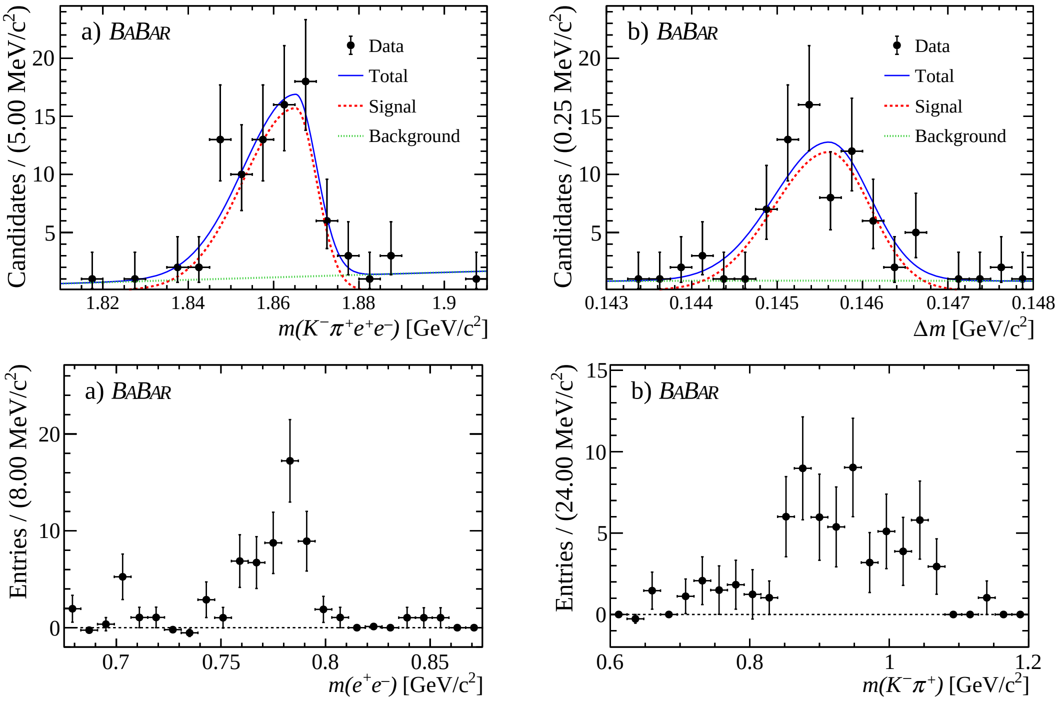

Figure 1: Top plots: Fits to $D^0 \to K^-\pi^+e^+e^-$ data distributions for (a) $m(K^-\pi^+e^+e^-)$ and (b) Δm mass for candidates with $0.675 < m(e^+e^-) < 0.875\,\mathrm{GeV}/c^2$. Bottom plots: Projections of the fits to the $D^0 \to K^-\pi^+e^+e^-$ data distributions onto (a) $m(e^+e^-)$ and (b) $m(K^-\pi^+)$ for candidates with $0.675 < m(e^+e^-) < 0.875\,\mathrm{GeV}/c^2$. The background has been subtracted using the *sPlot* technique [7].

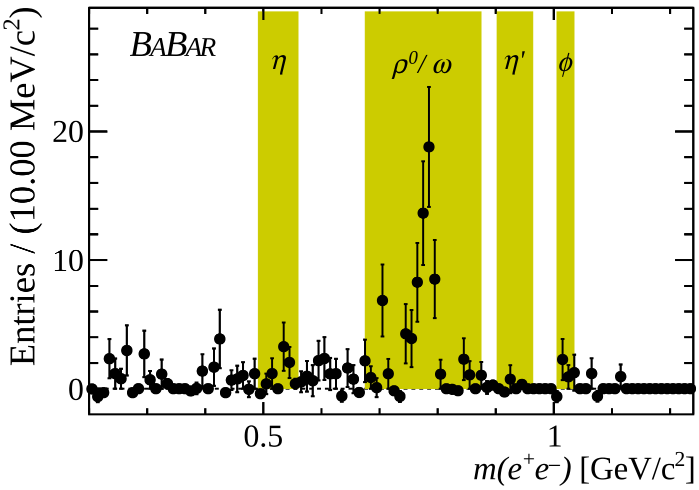

Figure 2: Projection of the fits to the $D^0 \to K^-\pi^+e^+e^-$ data distributions onto $m(e^+e^-)$ for candidates with $m(e^+e^-) > 0.2\,\mathrm{GeV}/c^2$. The background has been subtracted using the *sPlot* technique [7]. The shaded bands indicate the $m(e^+e^-)$ regions excluded from the "continuum" region.

$D^0 \to K^-\pi^+$ decay is selected using the same criteria as used for the $D^0 \to K^-\pi^+\pi^+\pi^-$ mode, which is again used as the normalization mode. The $D^0 \to K^-\pi^+$ yield is determined using an unbinned maximum likelihood fit to Δm and the two-body invariant mass $m(K^-\pi^+)$, using similar functions as for $D^0 \to K^-\pi^+e^+e^-$. The $D^0 \to K^-\pi^+$ signal yield is $1\,881\,950 \pm 1380$ with an average reconstruction efficiency of $\hat{\varepsilon}_{\rm sig} = (27.4 \pm 0.2)\%$. We determine $\mathscr{B}(D^0 \to K^-\pi^+) = (3.98 \pm 0.08 \pm 0.10)\%$ using Eq. (1), where the uncertainties are statistical and systematic, respectively; the current world-average is $(3.89 \pm 0.04)\%$ [4].

The main sources of systematic uncertainty are associated with the model parameterizations used in the fits and the normalization procedure, signal MC model, fit bias, tracking and PID efficiencies, luminosity, backgrounds from intermediate decays to $e^+e^-\gamma$, and the normalization mode branching fraction. Some of the tracking and PID systematic effects cancel in the branching fraction determination since they affect both the signal and normalization modes.

Systematic uncertainties associated with the model parameterization are estimated by repeating the fit with the $D^0 \to K^-\pi^+e^+e^-$ signal parameters for the Δm and four-body distributions fixed to values taken from simulation. Alternative fits are also performed with the default peaking and background functions for the signal and normalization modes replaced with alternative functions. The resulting uncertainties are 1.9% and 1.0% for the signal and normalization yields, respectively.

In the mass range $0.675 < m(e^+e^-) < 0.875\,{\rm GeV}/c^2$, we replace the signal phase-space simulation model with a model assuming $D^0 \to \bar{K}^*(892)^0\rho^0$ with $\bar{K}^*(892)^0 \to K^-\pi^+$ and $\rho^0 \to e^+e^-$ and assign half the difference with the default reconstruction efficiency as a systematic uncertainty, equivalent to a relative change of 1.8%. We also use this number as an estimate of the relative change in other regions of $m(e^+e^-)$ and $m(K^-\pi^+)$ where no suitable alternative simulation model exists.

The fit bias and fit bias systematic uncertainty for the signal yield are taken from an ensemble of fits to MC pseudodata samples. The largest fit bias found is 0.4 ± 0.1 candidates and we attribute a value of half this, ± 0.2, as a systematic uncertainty. To account for imperfect knowledge of the tracking efficiency, we assign an uncertainty of 0.8% per track for the leptons and 0.7% for the kaon and pion. For the PID, we estimate an uncertainty of 0.7% per electron, 0.2% per pion, and 1.1% per kaon [3]. A systematic uncertainty of 0.8% is associated with the knowledge of the luminosity ratio, $\mathscr{L}_{\rm norm}/\mathscr{L}_{\rm sig}$ [2].

The overall systematic uncertainty in the yields is 5.3% for the signal and 3.6% for the normalization mode. As the PID and tracking systematic uncertainties of the kaons and pions are correlated and cancel, the combined systematic uncertainty in the $D^0 \to K^-\pi^+e^+e^-$ branching fraction is 3.8%, where the uncertainty in the $D^0 \to K^-\pi^+\pi^+\pi^-$ branching fraction is excluded [4]. The branching fraction $\mathscr{B}(D^0 \to K^-\pi^+e^+e^-)$ in the mass range $0.675 < m(e^+e^-) < 0.875\,{\rm GeV}/c^2$ is determined to be $(4.0 \pm 0.5 \pm 0.2 \pm 0.1) \times 10^{-6}$, where the first uncertainty is statistical, the second systematic, and the third comes from the uncertainty in $\mathscr{B}$ $(D^0 \to K^-\pi^+\pi^+\pi^-)$ [4]. This result is compatible within the uncertainties with $\mathscr{B}(D^0 \to K^-\pi^+\mu^+\mu^-)$ reported in Ref. [1].

Figure 2 shows the projection of the signal yield as a function of $m(e^+e^-)$ for the fit to Δm and $m(K^-\pi^+e^+e^-)$ in the mass range $m(e^+e^-) > 0.2\,{\rm GeV}/c^2$ above the $\pi^0 \to e^+e^-\gamma$ decay region, where the background has been subtracted using the *sPlot* technique. We determine the signal yield in the region of the ϕ meson by repeating the fit to Δm and $m(K^-\pi^+e^+e^-)$ with the $m(e^+e^-)$ distribution restricted to the mass range $1.005 < m(e^+e^-) < 1.035\,{\rm GeV}/c^2$. This range corresponds to ±3 times the ϕ mass width, based on simulation and taking into account the detector resolution. The fitted yield is $3.8^{+2.7}_{-1.9}$, where the uncertainty is statistical only; the statistical significance S is 1.8σ. The branching fraction is determined to be $(2.2^{+1.5}_{-1.1} \pm 0.6) \times 10^{-7}$, where the second uncertainty is systematic and is dominated by the uncertainty on the model parameterization. We use the frequentist approach of Feldman and Cousins [8] to determine a 90% CL branching fraction upper limit of 0.5×10^{-6}.

We repeat the fit to Δm and $m(K^-\pi^+e^+e^-)$ in the "continuum" $m(e^+e^-)$ region that is predicted to be relatively unaffected by intermediates states, and is defined by excluding the following $m(e^+e^-)$ mass ranges: $m(e^+e^-) < 0.2\,\mathrm{GeV}/c^2$, $0.675 < m(e^+e^-) < 0.875\,\mathrm{GeV}/c^2$, $0.491 < m(e^+e^-) < 0.560\,\mathrm{GeV}/c^2$, $0.902 < m(e^+e^-) < 0.964\,\mathrm{GeV}/c^2$, and $1.005 < m(e^+e^-) < 1.035\,\mathrm{GeV}/c^2$. These correspond to ranges dominated by the decays of the π^0 and ρ^0/ω mesons or potentially affected by the decays of η, η', and ϕ mesons, respectively. Simulation samples of $D^0 \to K^-\pi^+\eta$ and $D^0 \to K^-\pi^+\eta'$, with $\eta/\eta' \to e^+e^-\gamma$, are used to determine the asymmetric $m(e^+e^-)$ mass ranges centered on the known η and η' masses. These $m(e^+e^-)$ mass ranges exclude 90% of any remaining simulated η and η' candidates that pass the selection criteria. The number of background decays from intermediate states in the continuum region is predicted to be 9.9 ± 0.9, dominated by the decay $\rho^0/\omega \to e^+e^-$ with $m(e^+e^-)$ less than $0.675\,\mathrm{GeV}/c^2$. The fitted yield in the continuum region, after the subtraction of this background, is 19 ± 7, with a statistical significance $S = 2.6\sigma$. This corresponds to a branching fraction $(1.6 \pm 0.6 \pm 0.7) \times 10^{-6}$, where the second uncertainty is systematic and is dominated by our knowledge of the model parameterization. The result is not significant and we determine a 90% CL branching fraction upper limit of 3.1×10^{-6}.

In summary, we have presented the first observation of the decay $D^0 \to K^-\pi^+e^+e^-$ [9]. The branching fraction in the mass range $0.675 < m(e^+e^-) < 0.875\,\mathrm{GeV}/c^2$ is $(4.0 \pm 0.5 \pm 0.2 \pm 0.1) \times 10^{-6}$, compatible with the result for $\mathscr{B}(D^0 \to K^-\pi^+\mu^+\mu^-)$ [1], and with theoretical predictions for the SM contribution [10] for this mass region. We have placed 90% CL branching fraction upper limits on the decay $D^0 \to K^-\pi^+e^+e^-$ in the $m(e^+e^-)$ mass region of the ϕ meson and in $m(e^+e^-)$ mass regions where long-distance effects are potentially small.

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PoS(EPS-HEP2019)234