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Rare and forbidden decays of the D^0 meson

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Rare or forbidden decays of the D^0 meson are an excellent probe for physics beyond the Standard Model. In this talk, we report the observation of the rare charm decay $D^0 \to K^-\pi^+e^+e^-$ with a 9.7σ significance. In addition, we present a search for nine lepton-number-violating and three lepton-flavor-violating neutral charm decays of the type $D^0 \to h'^-h^-\ell'^+\ell^+$ and $D^0 \to h'^-h^+\ell^\pm\ell^\mp$, where h and h′ represent a K or π meson. Furthermore, a search for seven lepton-number-violating decays of the type $D^0 \to X^0e^\pm\mu^\mp$, with X^0 a π^0, K^0_S, K^{*0}, ρ^0, ϕ, ω, or η meson, is also presented. The results are based on 468 fb^{-1} of e^+e^- collision data collected at or close to the $\Upsilon(4S)$ resonance with the BABAR detector at the SLAC National Accelerator Laboratory.

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1. The *BABAR* experiment

The *BABAR* experiment is located at the SLAC national accelerator Laboratory, where electrons and positrons are collided at a center-of-mass (CM) energy equivalent to that of $\Upsilon(4S)$ resonance. The $\Upsilon(4S)$ almost instantly decays into a $B\bar{B}$ pair, thus resulting in a B meson factory with millions of events recorded by the *BABAR* detector. Data collection took place from 1999 till 2008 and a total of 424 fb^{-1} was collected at the $\Upsilon(4S)$ resonance (on-peak). In addition, 39.3 fb^{-1} was collected at a CM energy below the $\Upsilon(4S)$ resonance (off-peak). In this talk, the *BABAR* dataset is used to search for rare and forbidden decays of the D^0, which can hint to what lies beyond the Standard Model (SM).

2. $D^0 \to K^-\pi^+e^+e^-$

The rare decay $D^0 \to K^-\pi^+e^+e^-$ does not occur at tree level in the SM. It proceeds via loop or box diagrams, where the non-resonant short distance contributions are of $O(10^{-9})$ and the long distance contributions are dominated by $D^0 \to K^{*0}\rho^0$. New Physics models predict potential contributions that can enhance the branching fraction of the four body decay from $O(10^{-9})$ up to $O(10^{-5})$ [1] .

To measure $\mathcal{B}(D^0 \to K^-\pi^+e^+e^-)$, a sample of D^0 mesons is obtained using $e^+e^- \to c\bar{c}$ events where $D^{*+} \to D^0\pi^+$. The signal branching fraction is measured using the full *BABAR* dataset (on and off-resonance) relative to the normalization decay $D^0 \to K^-\pi^+\pi^+\pi^-$, where the latter is measured using off-peak data only. Signal selections starts with the requirement that each event has at least five charged tracks. Particle identication (PID) criteria, determined using information from the different detector subsystems, is applied to four of these tracks, and used to reconstruct the D^0 meson in both the signal and normalization modes. The D^0 meson is required to have a center-of-mass momentum greater than 2.4 GeV/c and a vertex fit is applied to remove poorly reconstructed candidates. Furthermore, the mass of the D^0 is required to be in the range $1.81 < m_{D^0} < 1.91$ GeV/c^2 and the corresponding D^{*+}mass difference must satisfy $0.143 < \Delta M < 0.148$ GeV/c^2. Mis-reconstructed $D^0 \to K^-\pi^+e^+e^-$ candidates, where the D^0 decay is indeed hadronic, are vetoed by assigning a kaon or pion hypothesis for the leptons. If the resulting D^0 candidate has a mass within 20 MeV/c^2 of the D^0 nominal mass and $|\Delta m| < 2$ MeV/c^2, the candidate is rejected. The branching fraction is then calculated as:

$$\frac{\mathcal{B}(D^0 \to K^-\pi^+e^+e^-)}{\mathcal{B}((D^0 \to K^-\pi^+\pi^+\pi^-)} = \frac{\hat{\epsilon}}{N_{\text{norm}}}\frac{\mathcal{L}_{\text{norm}}}{\mathcal{L}_{\text{sig}}}\sum_i^{N_{\text{sig}}}\frac{1}{\epsilon^i_{\text{sig}}}. \quad (1)$$

Here, $\mathcal{L}_{\text{sig}}$ and $\mathcal{L}_{\text{norm}}$ are the luminosity of the data sample for the signal and normalization modes. $\hat{\epsilon_{\text{norm}}}$, $\epsilon^i_{\text{sig}}$and N_{norm}, N_{sig} are the reconstruction efficiencies and yields of the normalization and signal modes, respectively. The latter are determined for each signal candidate i, which is calculated from simulation as a function of the $m(e^+e^-)$ and $m(K^-\pi^+)$. The signal and normalization yields are determined using an extended unbinned maximum likelihood fit to the Δm and the four body mass distributions, as shown in Fig. 1. A bifurcated Gaussian is used to model the signal, while an Argus and Chebychev functions are used to model the backgrounds for the signal and normalization modes respectively [2]. A signal is observed, where $N_{sig} = 68 \pm 9$, with 9.7

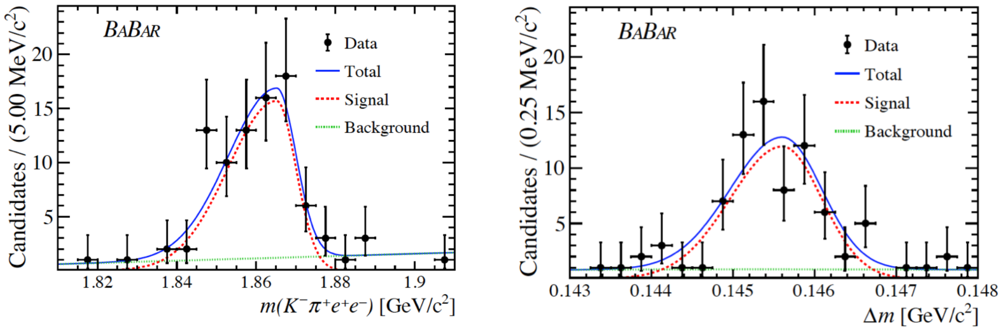

Figure 1: Fits to to the four body mass $m(K^-\pi^+\pi^+\pi^-)$ (left) and the mass difference Δm (right) in the region $0.675 < m_{e^+e^-} < 0.875$ GeV/c^2.

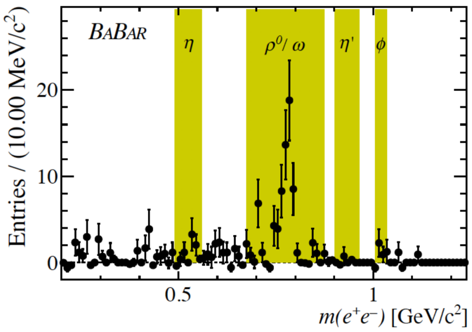

Figure 2: Projections of the fit to $m_{e^+e^-}$ (left) for $D^0 \to K^-\pi^+e^+e^-$ candidates with $m_{e^+e^-} > 0.200$ GeV/c^2. The shaded bands denote the resonances which are excluded from the "continuum" region.

σ significance. The resulting branching fraction is determined to be $\mathcal{B}(D^0 \to K^-\pi^+e^+e^-) = (4.0 \pm 0.5 \pm 0.2 \pm 0.1) \times 10^{-6}$, where the first uncertainty is statistical, the second systematic and the last uncertainty is related to the branching fraction of the normalization mode [3]. The result is the world's first measurement of $D^0 \to K^-\pi^+e^+e^-$ and is consistent with the measurement of $\mathcal{B}(D^0 \to K^-\pi^+\mu^+\mu^-)$ by LHCb [4].

Furthermore, Fig. 2 shows the projection of the signal yield as a function of $m(e^+e^-)$ in the region $m(e^+e^-) > 0.2$ GeV/c^2. Below 200 MeV/c^2, the distribution is dominated by the decay $D^0 \to K^-\pi^+\pi^0, \pi^0 \to e^+e^-\gamma$. The fit to the $D^0 \to K^-\pi^+e^+e^-$ candidates is then repeated in the region about the ϕ meson mass and the resulting yield is measured to be $3.8^{+3.7}_{-1.8}$ with a significance of 1.8σ. A frequentist approach, namely Feldman and Cousins (FC) [5], is then used to determine the 90% confidence level (CL) limit. The upper limit on the branching fraction at the 90% confidence level is determined to be 0.5×10^{-6}. The same procedure is also repeated in the continuum $m(e^+e^-)$ range, where all the resonances shown in Fig. 2 are excluded, and the resulting upper limit is determined to be $\mathcal{B}(D^0 \to K^-\pi^+e^+e^-) < 3.1 \times 10^{-6}$.

3. $D^0 \to h'^- h^- \ell'^+ \ell^+$ and $D^0 \to h'^- h^+ \ell^\pm \ell^\mp$

Lepton-flavour violating (LFV) and lepton number violating (LNV) decays are prohibited in the Standard Model. New Physics models allow for LFV and LNV four body decays of charm mesons with a branching fraction up to $O(10^{-6})$ to $O(10^{-5})$ [6]. Using the same dataset as described in Section 2, the search for 9 LFV decays and 3 LNV decays of the type $D^0 \to h'^- h^- \ell'^+ \ell^+$ and $D^0 \to h'^- h^+ \ell^\pm \ell^\mp$, where $h = K$ or π and ℓ is an electron or muon.

The branching fractions are measured relative to the normalization modes, $D^0 \to K^- K^+ \pi^- \pi^+$, $K^- \pi^+ \pi^- \pi^+$, or $\pi^+ \pi^- \pi^+ \pi^-$ based on whether the signal mode has two, one, or zero kaons respectively in the final state. The D^0 mesons are accessed via $e^+ e^- \to c\bar{c}$, where $D^{*+} \to D^0 \pi^+$, and a similar selection criteria, as described in Section 2, is applied to reconstruct the D^0 mesons and suppress backgrounds from hadronic decays. An additional source of background from semi-leptonic charm backgrounds or charm decays with additional charged or neutral particles in the final state is further suppressed using a multivariate selection based on a Fisher discriminant. Nine variables are used in the Fisher discriminant, which include the thrust and sphericity of the D^{*+}, the ratio of the second-to-zeroth Fox Wolfram moment [7], the momentum of the D^0 daughter tracks, and the angles between the D^{*+} thrust and sphericity axes and those of the rest of the event. A requirement on the output of the Fisher discriminant retains 90% of the simulated signal while removing 30 to 50% of the background from data.

The signal yield is extracted from a two-dimensional extended maximum likelihood fit in m_{D^0} and Δm, where $1.874 > m_{D^0} > 1.848, 1.852$, and 1.856 GeV/c^2 for modes with two, one or zero electrons. The signal region in Δm is defined as $0.1401 < \Delta m < 0.201$ GeV/c^2 for modes with 2 kaon candidates and $0.1401 < \Delta m < 0.149$ GeV/c^2 for modes with 0 or 1 kaon candidates. The sum of multiple Cruijff and Crystal ball functions is used to model the signal, while the background is fit with an ARGUS threshold function for Δm and a Chebychev polynomial for $m(D^0)$ [2]. Figure 3 shows the projection of the unbinned maximum-likelihood fits for signal modes with less than 2 kaons. The signal yield is found to be consistent with zero for all LFV and LNV decays. The corresponding upper limits are determined, using the FC method, to be in the range between $(1.0 - 30.6) \times 10^{-7}$ [8]. Here, the main sources of systematic uncertainty are attributed to the parametrization of the fit model, the branching fraction of the normalization mode, as well as tracking and PID. The calculated upper limits are between 1 and 3 orders of magnitude more stringent than previous searches [9].

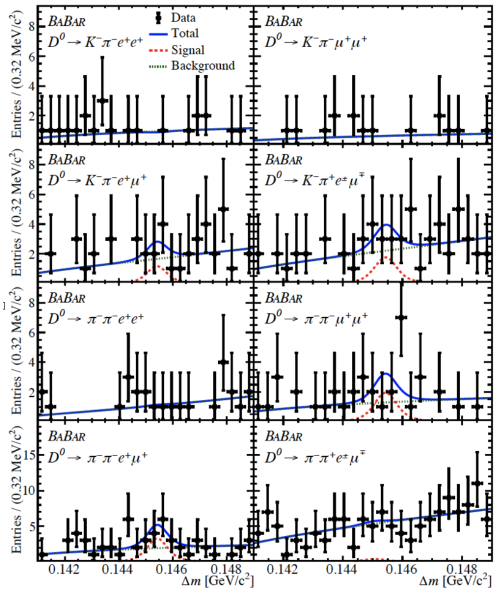

Figure 3: Projections of the unbinned maximum-likelihood fits as a function of Δm for signal modes with less than 2 kaons. The total fit is shown in blue while the signal D^0 component is shown in red.

4. $D^0 \to X^0 e^{\pm}\mu^{\mp}$

The decay $D^0 \to X^0 e^{\pm}\mu^{\mp}$ is also forbidden in the Standard Model and suppressed up to the order of $O(10^{-50})$. However, new physics models which require LFV predict branching fractions for this decay up to $O(10^{-6})$. Using the same dataset and signal reconstruction as described in Section 2, a search for $D^0 \to X^0 e^{\pm}\mu^{\mp}$,where $X = \pi^0, K^0_s, K^{(*0)}, \rho^0, \phi, \omega, \eta$ meson is performed. PID criteria is applied to each of the X^0 daughter tracks, and m_{X^0} is required to be within 3 times the root-mean-square width (RMS). A multivariate selection, based on a Boosted Decision tree, is used to suppress backgrounds where the D^0 is mis-reconstructed or charged tracks and neutral particles are lost in the event. Eight input variables, including the lepton momenta and theX^0mass, are used for each of the modes. The signal region is defined in the $m_{(D^0)}$-Δm plane where $0.1447 < \Delta m < 0.1462$ GeV/c^2 and the signal RMS of $m_{(D^0)}$ ranges between 5 and 21 MeV/c^2. An extended maximum likelihood fit to the Δm distribution is applied to extract the signal yield, as shown in Fig. 4. The observed signal is consistent with zero for all 7 modes and the resulting 90% confidence limits are determined using the FC approach [10]. The measured limits are 1-2 orders of magnitude more stringent than previous results.

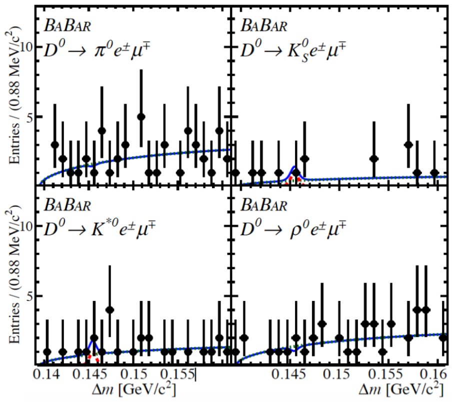

Figure 4: Projections of the unbinned maximum-likelihood fits as a function of Δm for 4 signal modes in the mass range $0.1395 < \Delta m < 0.1610$ GeV/c^2. The total fit is shown in blue while the signal D^0 component is shown in red.

5. Conclusion

Rare and forbidden decays of D^0 mesons are an interesting probe of what may lie beyond the Standard Model. With the BaBar dataset, the world's first observation of $D^0 \to K^-\pi^+e^+e^-$ is reported. Searches for LFV and LNV decays of the D^0 meson are also performed and the upper limits determined are 1-3 orders of magnitude more stringent than existing constraints.

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