Search for rare and forbidden decays of the D^0 meson by *BaBar*

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Introduction

- observation of rare, LFV, LNV D decays may reveal Physics beyond Standard Model e.g., leptoquarks, R-parity violating Susy, Z' (Bause *et al.*, Eur.Phys.J.C 80 (2020) 1, 65)

$D^0 \to K^-\pi^+e^+e^-$ (rare)

- $\mathcal{B}(\text{SM}) \sim 10^{-6}$, VDM production, dominated by $D^0 \to K^{*0}\rho^0 (\to \gamma \to e^+e^-)$
- $\mathcal{B}(\text{NP})$ up to $\sim 10^{-5}$
- LHCb PLB 757 (2016) 558
  $\mathcal{B}(D^0 \to K^-\pi^+\mu^+\mu^-) = (4.17 \pm 0.12 \pm 0.40) \cdot 10^{-6}$
  for $0.675 < m(\mu^+\mu^-) < 0.875\,\text{GeV}/c^2$
- E791 PRL 86 (2001) 3969
  $\mathcal{B}(D^0 \to K^-\pi^+e^+e^-) < 38.5 \cdot 10^{-5}$

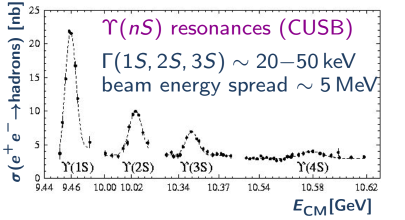
$D^0 \to h'^{\pm}h^{\mp}\ell'^{\pm}\ell^{\mp}$ (LFV), $D^0 \to h'^{\pm}h^{\pm}\ell'^{\mp}\ell^{\mp}$ (LFV, LNV), $D^0 \to X_h^0 e'^{\pm}\mu^{\mp}$ (LFV)

- $\mathcal{B}(\text{SM}) \sim 10^{-40}$ (neutrino mixing)
- $\mathcal{B}(\text{NP})$ up to $\sim 10^{-5}$
- BES III PRD 99 (2019) 112002, E791 PRL 86 (2001) 3969:
  $\mathcal{B}(D^0 \to h'^{\pm}h^{\mp}\ell'^{\pm}\ell^{\mp})$
  $\mathcal{B}(D^0 \to h'^{\pm}h^{\pm}\ell'^{\mp}\ell^{\mp}) < (0.3\text{–}55.3) \cdot 10^{-5}$
  $\mathcal{B}(D^0 \to X_h^0 \ell'^{\pm}\ell^{\mp})$

BaBar asymmetric *B*-factory, 1999-2008

- primary purpose: time-dependent CP violation of coherent B pairs
- secondarily: general purpose heavy flavour factory

center-of-mass energies

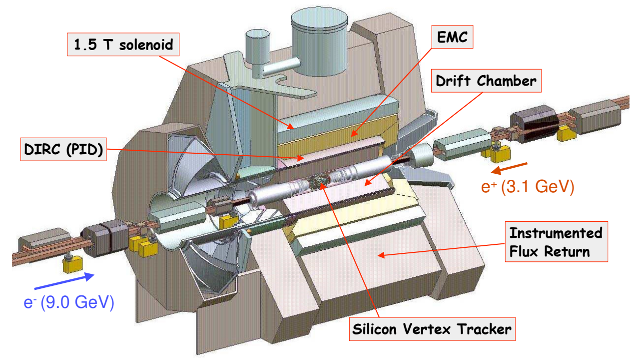


$\mathcal{L}$ vs. $\sqrt{s}$

energy	$\mathcal{L}(\text{fb}^{-1})$
$\Upsilon(4s)$	430
$\Upsilon(3s)$	30.2
$\Upsilon(2s)$	14.5
off-peak	54

yields

flavour	events
$B\bar{B}$	$470 \cdot 10^6$
$c\bar{c}$	$690 \cdot 10^6$
$\tau^+\tau^-$	$485 \cdot 10^6$



- *BaBar* competitive for D^0 meson rare and forbidden decays, better than LHCb for D^0 decays with electrons in final state

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

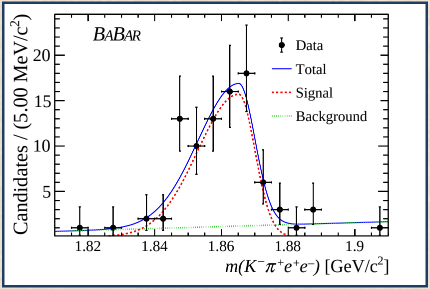
Phys. Rev. Lett. 122, 081802, 2019

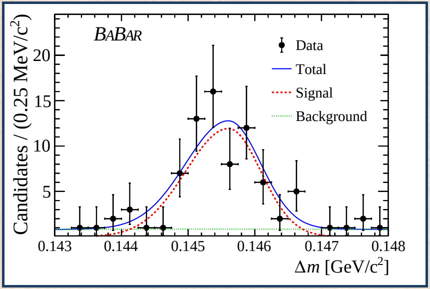
Selection

- measure $\dfrac{\mathcal{B}(D^0 \to K^-\pi^+e^+e^-)}{\mathcal{B}(D^0 \to K^-\pi^+\pi^+\pi^-)}$ where $D^{*+} \to D^0\pi^+$
- signal mode data sample: "on-peak" & "off-peak" CM energy collisions, $\mathcal{L} = 468.2 \pm 2.0\text{fb}^{-1}$
- normalization mode data sample: only "off-peak" CM energy collisions, $\mathcal{L} = 38.3 \pm 0.2\text{fb}^{-1}$
- select events with D^0 candidate decays into 4 tracks with appropriate PID and charge
- Bremsstrahlung energy recovery algorithm is applied to the electrons
- $p^*_{D^0} > 2.4\,\text{GeV}/c$
  - suppress combinatorial background, mainly from QED processes
  - (also removes D^0 from B decays)
- $\text{Prob}[\chi^2(\text{vertex fit})] > 0.005$ to ensure good-quality vertex
- veto background from hadronic D^0 decays with misidentification of hadrons to leptons
  - veto $|m(D^0)_{\text{reco}} - m(D^0)| < 20\,\text{MeV}/c^2$ and $|\Delta m_{\text{reco}} - \Delta m| < 2\,\text{MeV}/c^2$ $[\Delta m = m(D^{*0}) - m(D^0)]$ when assuming kaon or pion mass hypotheses for identified leptons

Signal yield, branching fraction fit $[m(D^0), \Delta m]$ and measurement

- simultaneous unbinned extended maximum-likelihood fit on $m(D^0)$ and Δm
- require $1.81 < m(D^0) < 1.91\,\mathrm{GeV}/c^2$, $0.143 < \Delta m < 0.148\,\mathrm{GeV}/c^2$, $0.675 < m(e^+e^-) < 0.875\,\mathrm{GeV}/c^2$
- signal: $m(D^0)$ and Δm modeled with asymmetric-sigma Gaussian
- background: $m(D^0)$ modeled with 1st order polynomial, Δm modeled with ARGUS function



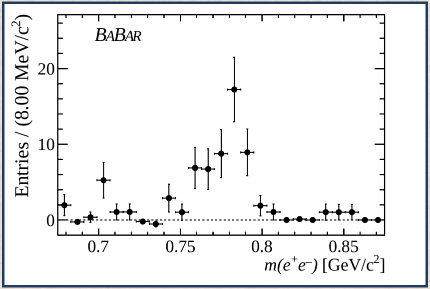


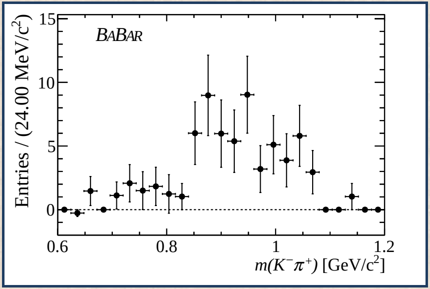
- $$\frac{\mathcal{B}(D^0 \to K^-\pi^+e^+e^-)}{\mathcal{B}(D^0 \to K^-\pi^+\pi^+\pi^-)} = \frac{\hat{\epsilon}_{\text{norm}}}{N_{\text{norm}}} \frac{\mathcal{L}_{\text{norm}}}{\mathcal{L}_{\text{sig}}} \sum_i^{N_{\text{sig}}} \frac{1}{\epsilon_{\text{sig,i}}[m(K^-\pi^+), m(e^+e^-)]}$$
- $\mathcal{B}(D^0 \to K^-\pi^+e^+e^-) = [4.0 \pm 0.5\,(\text{stat}) \pm 0.2\,(\text{syst}) \pm 0.1\,(\text{norm})] \cdot 10^{-6}$
  BABAR, Phys. Rev. Lett. 122 (2019) 8, 081802

$N_{\text{sig}} = 68 \pm 9$
$N_{\text{norm}} = 260870 \pm 520$
$9.7\,\sigma$ significance

world first observation!
compatible with LHCb result
assuming lepton universality

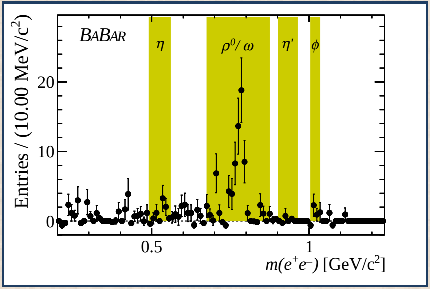
Distributions of $m(e^+e^-)$ and $m(K^-\pi^+)$





- background is subtracted with the sPlot technique

Distribution of $0.2 < m(e^+e^-) < 1.25\,\mathrm{GeV}/c^2$



- background is subtracted with the sPlot technique
- "continuum" yield corresponds to areas outside highlighted resonances

$m(e^+e^-)$ $[\mathrm{GeV}/c^2]$	N_{sig}	signif. $[\sigma]$	$\mathcal{B}$ $[\cdot 10^{-6}]$	$\mathcal{B}^{\mathrm{U.L.}}_{90\%}$ $[\cdot 10^{-6}]$
0.675 – 0.875	68 ± 9	9.7	$4.0 \pm 0.5 \pm 0.2 \pm 0.1$	-
ϕ region	$3.8^{+2.7}_{-1.9}$	1.8	$0.2^{+0.2}_{-0.1} \pm 0.1$	0.5
continuum	19 ± 7	2.6	$1.6 \pm 0.6 \pm 0.7$	3.1

(upper limits obtained with Feldman-Cousins method)

no evidence for short-distance NP production in continuum areas

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

Phys. Rev. Lett. 124 (2020) 7, 071802

$D^0 \to h'^- h^+ \ell'^{\pm} \ell^{\mp}$ & $D^0 \to h'^- h^- \ell'^+ \ell^+$ selection (1)

part of the analysis proceeds similarly to $D^0 \to K^- \pi^+ e^+ e^-$

- signal mode data sample: "on-peak" & "off-peak" CM energy collisions, $\mathcal{L} = 468.2 \pm 2.0 \mathrm{fb}^{-1}$
- normalization modes data sample: only "off-peak" CM energy collisions, $\mathcal{L} = 38.3 \pm 0.2 \mathrm{fb}^{-1}$
- Bremsstrahlung energy recovery algorithm is applied to the electrons
- $p^*_{D^0} > 2.4\,\mathrm{GeV}/c$
  - suppress combinatorial background, mainly from QED processes
  - (also removes D^0 from B decays)
- Prob[χ^2(vertex fit)] > 0.005 to ensure good-quality vertex
- veto background from hadronic D^0 decays with misidentification of hadrons to leptons
  - veto $|m(D^0)_{\mathrm{reco}} - m(D^0)| < 20\,\mathrm{MeV}/c^2$ and $|\Delta m_{\mathrm{reco}} - \Delta m| < 2\,\mathrm{MeV}/c^2$ $[\Delta m = m(D^{*0}) - m(D^0)]$ when assuming kaon or pion mass hypotheses for identified leptons

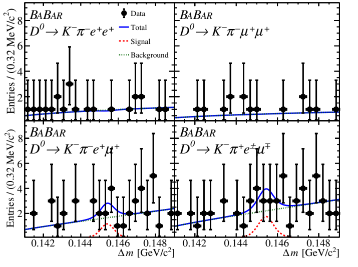
$D^0 \to h'^- h^+ \ell'^\pm \ell^\mp$ & $D^0 \to h'^- h^- \ell'^+ \ell^+$ selection (2)

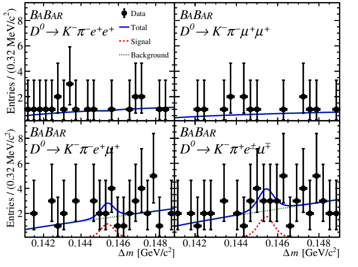
distinctive procedures

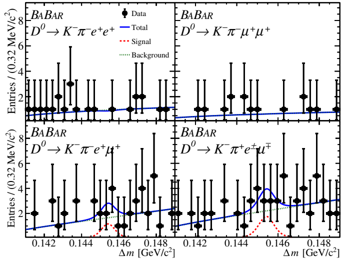
- select events with D^0 candidate decays into 4 tracks with appropriate PID and charge
- normalization modes: $D^0 \to \pi^- \pi^+ \pi^+ \pi^-$, $D^0 \to K^- \pi^+ \pi^+ \pi^-$, $D^0 \to K^- K^+ \pi^+ \pi^-$
- tighter PID
- multivariate discriminant (MVA) to reject $e^+ e^- \to c\bar{c}$ background, tuned for each signal mode
  - inputs: D^0 candidate tracks momenta, shape variables of event, D^{*+}, rest-of-event
- rather than doing simultaneous fits to $m(D^0)$ and Δm
  cut on $m(D^0)$ (within 3× reconstruction resolution) and do maximum-likelihood fit to Δm only

Signal + background fits on Δm distribution

- signal: modeled with Cruijff function
- background: modeled with ARGUS function







Results

Decay mode $D^0 \to$	N_{sig} [candidates]	ϵ_{sig} [%]	$\mathcal{B}$ [$\times 10^{-7}$]	$\mathcal{B}^{U.L.}_{90\%}$ [$\times 10^{-7}$] BABAR	previous
$\pi^-\pi^-e^+e^+$	$0.22 \pm 3.15 \pm 0.54$	4.38 ± 0.05	$0.27 \pm 3.90 \pm 0.67$	9.1	1120
$\pi^-\pi^-\mu^+\mu^+$	$6.69 \pm 4.88 \pm 0.80$	4.91 ± 0.05	$7.40 \pm 5.40 \pm 0.91$	15.2	290
$\pi^-\pi^-e^+\mu^+$	$12.42 \pm 5.30 \pm 1.45$	4.38 ± 0.05	$15.41 \pm 6.59 \pm 1.85$	30.6	790
$\pi^-\pi^+e^\pm\mu^\mp$	$1.37 \pm 6.15 \pm 1.28$	4.79 ± 0.06	$1.55 \pm 6.97 \pm 1.45$	17.1	150
$K^-\pi^-e^+e^+$	$-0.23 \pm 0.97 \pm 1.28$	3.19 ± 0.05	$-0.38 \pm 1.60 \pm 2.11$	5.0	28
$K^-\pi^-\mu^+\mu^+$	$-0.03 \pm 2.10 \pm 0.40$	3.30 ± 0.05	$-0.05 \pm 3.34 \pm 0.64$	5.3	3900
$K^-\pi^-e^+\mu^+$	$3.87 \pm 3.96 \pm 2.36$	3.48 ± 0.04	$5.84 \pm 5.97 \pm 3.56$	21.0	2180
$K^-\pi^+e^\pm\mu^\mp$	$2.52 \pm 4.60 \pm 1.35$	3.65 ± 0.05	$3.62 \pm 6.61 \pm 1.95$	19.0	5530
$K^-K^-e^+e^+$	$0.30 \pm 1.08 \pm 0.41$	3.25 ± 0.04	$0.43 \pm 1.54 \pm 0.58$	3.4	1520
$K^-K^-\mu^+\mu^+$	$-1.09 \pm 1.29 \pm 0.42$	6.21 ± 0.06	$-0.81 \pm 0.96 \pm 0.32$	1.0	940
$K^-K^-e^+\mu^+$	$1.93 \pm 1.92 \pm 0.83$	4.63 ± 0.05	$1.93 \pm 1.93 \pm 0.84$	5.8	570
$K^-K^+e^\pm\mu^\mp$	$4.09 \pm 3.00 \pm 1.59$	4.83 ± 0.05	$3.93 \pm 2.89 \pm 1.45$	10.0	1800

(90% Confidence Level (CL) Upper Limits (UL) calculated using Feldman-Cousins method)

BABAR, Phys. Rev. Lett. 124 (2020) 7, 071802

previous upper limits improved by order 100×

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

Phys. Rev. D 101 (2020) 11, 112003

$D^0 \to X^0 e^\pm \mu^\mp$ selection (1)

part of the analysis proceeds similarly to $D^0 \to K^- \pi^+ e^+ e^-$

- signal mode data sample: "on-peak" & "off-peak" CM energy collisions, $\mathcal{L} = 468.2 \pm 2.0\text{fb}^{-1}$
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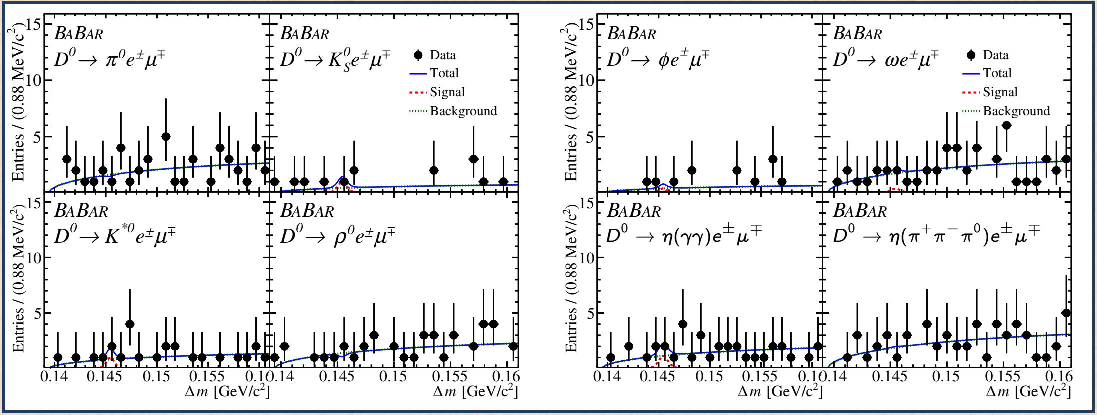
$D^0 \to X^0 e^\pm \mu^\mp$ selection (2)

distinctive procedures

- select events with oppositely charged electron and muon and
  - $X^0 = \pi^0 \to \gamma\gamma$
  - $X^0 = \eta \to \gamma\gamma$, $X^0 = \eta \to \pi^+\pi^-\pi^0$
  - $X^0 = \rho \to \pi^+\pi^-$
  - $X^0 = \omega \to \pi^+\pi^-\pi^0$
  - $X^0 = K^0_S \to \pi^+\pi^-$
  - $X^0 = \phi \to K^+K^-$
  - $X^0 = \bar{K}^{*0} \to K^-\pi^+$
- require $m(X^0)$ match within $3\times$ reconstruction resolution, $E_\gamma > 25\,\text{MeV}$
- normalization modes: $D^0 \to \pi^-\pi^+\pi^+\pi^-$, $D^0 \to K^-\pi^+\pi^+\pi^-$, $D^0 \to K^-K^+\pi^+\pi^-$
- tighter PID
- multivariate discriminant (MVA) to reject $e^+e^- \to c\bar{c}$ background, tuned for each signal mode
  - inputs: D^0 candidate tracks momenta, shape variables of event, D^{*+}, rest-of-event, including photons
- rather than doing simultaneous fits to $m(D^0)$ and Δm
  cut on $m(D^0)$ (within $3\times$ reconstruction resolution) and do maximum-likelihood fit to Δm only

Signal + background fits on Δm distribution

- $D^0 \to \phi e^{\pm}\mu^{\mp}$ modeled with sum of two asymmetric-sigma Gaussian functions
- $D^0 \to \rho e^{\pm}\mu^{\mp}$ modeled with sum of two Cruijff functions
- all other signal modes modeled with single Cruijff function
- background modeled with ARGUS function



Results

Decay mode $D^0 \to$	N_{sig} [candidates]	ϵ_{sig} [%]	$\mathcal{B}$ [$\times 10^{-7}$]	$\mathcal{B}^{U.L.}_{90\%}$ [$\times 10^{-7}$] BABAR	previous
$D^0 \to \pi^0 e^\pm \mu^\mp$	$-0.3 \pm 2.0 \pm 0.9$	2.15 ± 0.03	$-0.6 \pm 4.8 \pm 2.3$	8.0	860
$D^0 \to K^0_S e^\pm \mu^\mp$	$0.7 \pm 1.7 \pm 0.7$	3.01 ± 0.04	$1.9 \pm 4.6 \pm 1.9$	8.6	500
$D^0 \to \overline{K}^{*0} e^\pm \mu^\mp$	$0.8 \pm 1.8 \pm 0.8$	2.31 ± 0.03	$2.8 \pm 6.1 \pm 2.6$	12.4	830
$D^0 \to \rho^0 e^\pm \mu^\mp$	$-0.7 \pm 1.7 \pm 0.4$	2.10 ± 0.03	$-1.8 \pm 4.4 \pm 1.0$	5.0	490
$D^0 \to \phi e^\pm \mu^\mp$	$0.0 \pm 1.4 \pm 0.3$	3.43 ± 0.04	$0.1 \pm 3.8 \pm 0.9$	5.1	340
$D^0 \to \omega e^\pm \mu^\mp$	$0.4 \pm 2.3 \pm 0.5$	1.46 ± 0.03	$1.8 \pm 9.5 \pm 1.9$	17.1	1200
$D^0 \to \eta e^\pm \mu^\mp$			$6.1 \pm 9.7 \pm 2.3$	22.5	1000
with $\eta \to \gamma\gamma$	$1.6 \pm 2.3 \pm 0.5$	2.96 ± 0.04	$7.0 \pm 10.5 \pm 2.4$	24.0	
with $\eta \to \pi^+\pi^-\pi^0$	$0.0 \pm 2.8 \pm 0.7$	2.46 ± 0.04	$0.4 \pm 25.8 \pm 6.0$	42.8	

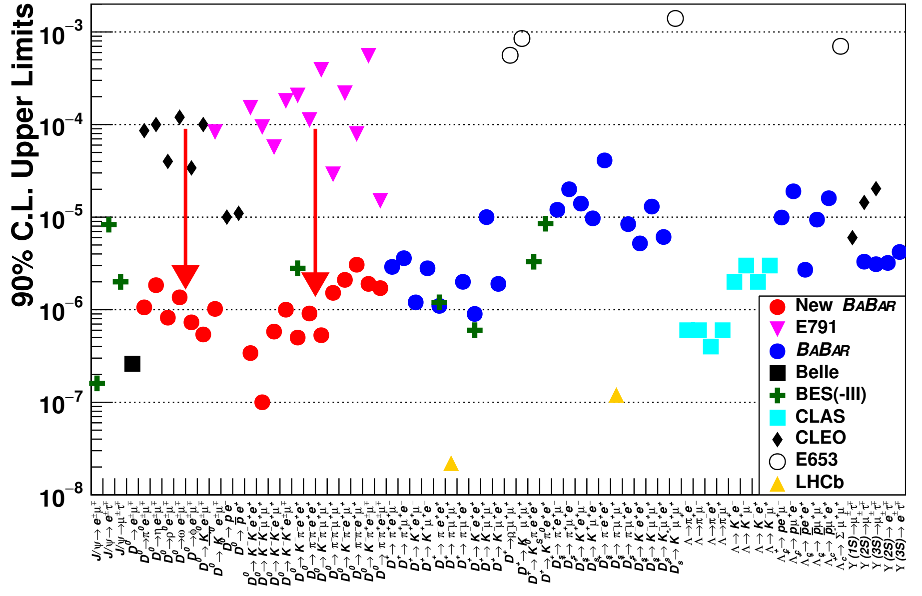
(90% Confidence Level (CL) Upper Limits (UL) calculated using Feldman-Cousins method)

BABAR, Phys. Rev. D 101 (2020) 11, 112003

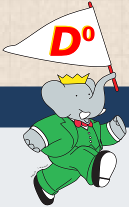
previous upper limits improved by order $100\times$

Rare and forbidden D^0 decays summary

from F. Wilson, Lake Louise, 2020

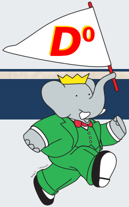


Conclusions



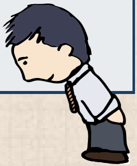
$D^0 \to K^-\pi^+e^+e^-$

- decay $D^0 \to K^-\pi^+e^+e^-$ observed for the first time
- in the mass range $0.675 < m(e^+e^-) < 0.875\,\text{GeV}/c^2$
  - $\mathcal{B}(D^0 \to K^-\pi^+e^+e^-) = [4.0 \pm 0.5\,(\text{stat}) \pm 0.2\,(\text{syst}) \pm 0.1\,(\text{norm})] \cdot 10^{-6}$
  - agrees with LHCb PLB 757 (2016) 558, $\mathcal{B}(D^0 \to K^-\pi^+\mu^+\mu^-) = (4.17 \pm 0.12 \pm 0.40) \cdot 10^{-6}$
- no evidence for violation of lepton universality
- no evidence for short-distance or New Physics contributions in the continuum range
- Phys. Rev. Lett. 122 (2019) 081802



$D^0 \to h'^-h^+\ell'^\pm\ell^\mp$, $D^0 \to h'^-h^-\ell'^+\ell^+$, $D^0 \to X^0e^\pm\mu^\mp$

- $D^0 \to h'^-h^+\ell'^\pm\ell^\mp$, $D^0 \to h'^-h^-\ell'^+\ell^+$: 12 new $\mathcal{B}^{\text{U.L.}}_{90\%}$ in range $(1.0 - 30.6) \cdot 10^{-7}$
  - Phys. Rev. Lett. 124 (2020) 7, 071802
- $D^0 \to X^0e^\pm\mu^\mp$: 7 new $\mathcal{B}^{\text{U.L.}}_{90\%}$ in range $(5.0 - 23.0) \cdot 10^{-7}$
  - Phys. Rev. D 101 (2020) 11, 112003
- order $100\times$ more stringent upper limits than previous results



Thanks for your attention!

Backup Slides

Distribution functions

- two-piece Gaussian: Gaussian with different left-right resolutions, also known as
  - bifurcated Gaussian
  - asymmetric-sigma Gaussian
- Cruijff function: centered Gaussian with different left-right resolutions and non-Gaussian tails

  $$\exp\left[\frac{-(x-\mu)^2}{\sigma^2_{L,R} + a_{L,R}(x-m)^2}\right]$$
- ARGUS function, H. Albrecht et al. (ARGUS Collaboration), Phys. Lett. B 241 (1990) 278
- Crystal Ball function, T. Skwarnicki, A study of the radiative cascade transitions between the Υ' and Υ resonances, Ph.D. thesis, Institute of Nuclear Physics, Krakow, 1986, Report No. DESY-F31-86-02.

Major systematics

- signal model used in simulations to estimate selection efficiency
  - $\mathcal{B}(D^0 \to K^-\pi^+e^+e^-)$: 1.8% from comparison signal model with just ρ pole vs. phase-space
- normalization branching fractions uncertainty
- PID