



Rare and Forbidden decays of the D^0 meson

Fabio Anulli

INFN Sezione di Roma

on behalf of the BABAR Collaboration

*European Physical Society conference on high-energy physics
EPS-HEP July 26-30, 2021*



Outline

- Introduction
- Observation of the rare decay $D^0 \rightarrow K^- \pi^+ e^+ e^-$
- Search for **forbidden charm decays**
 - Lepton Number Violation (LNV) in $D^0 \rightarrow h^- h'^- \ell^+ \ell'^+$ (9 decay modes)
 - Lepton Flavor Violation (LFV) in $D^0 \rightarrow h^- h'^+ e^\pm \mu^\mp$ (3 decay modes)
 - Lepton Flavor Violation in $D^0 \rightarrow X^0 e^\pm \mu^\mp$ (7 decay modes)
 - $h/h' = K$ or π ; $\ell/\ell' = e$ or μ ;
 - $X^0 = \pi^0, \eta, K_S^0, K^{*0}, \rho^0, \omega$ or ϕ
- Summary

Rare Charm decays



$$D^0 \rightarrow K^- \pi^+ e^+ e^- \quad (\text{and } D^0 \rightarrow K^- \pi^+ \mu^+ \mu^-)$$

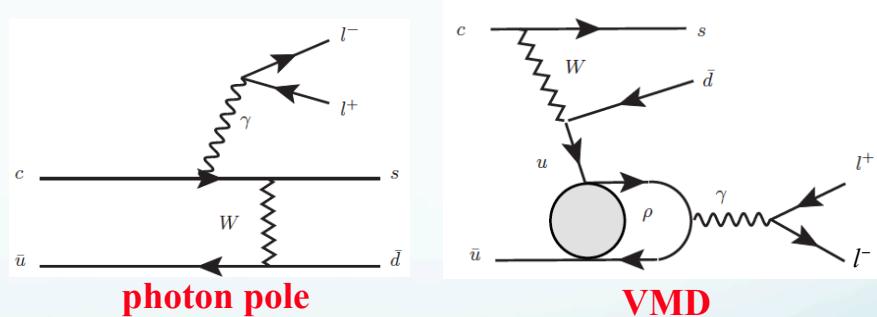
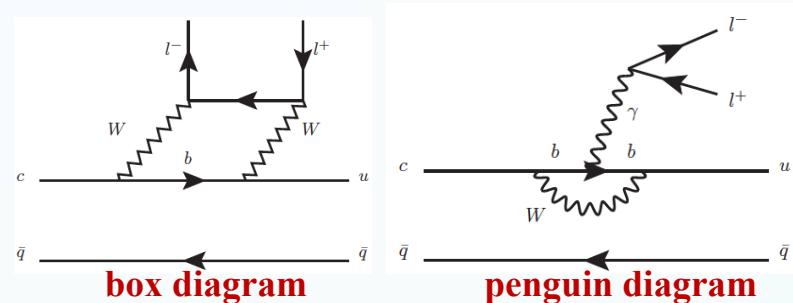
- Process forbidden at tree level in the SM, but allowed in loop and box diagrams
- The decays are characterized by:

- ***Short-distance contributions*** at one-loop level

- Glashow-Iliopoulos-Maiani (GIM) cancellation is almost exact
- Branching fraction $\mathcal{B} = \mathcal{O}(10^{-9})$

- ***Long-distance contributions***

- e.g. Vector Meson Dominance (VMD)
- Branching fraction up to $\mathcal{B} = \mathcal{O}(10^{-6})$



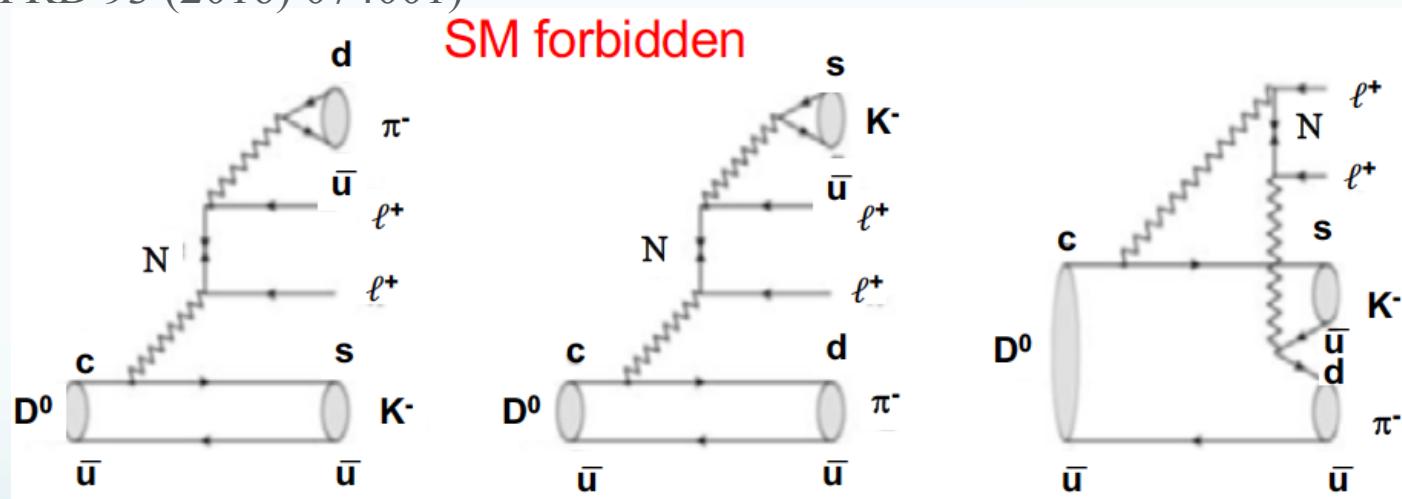
- Away from long-distance contributions, potential for New Physics to be visible
- Test of Lepton Universality, by comparing decays to electrons vs muons
- $D^0 \rightarrow K^- \pi^+ \mu^+ \mu^-$ observed at **LHCb** (PLB 757 (2016) 558)

Forbidden Charm decays



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

- LNV and LFV processes are essentially forbidden in the SM: $\mathcal{B} = \ll \mathcal{O}(10^{-40})$
- Predicted with measurable rates ($\mathcal{B} = \mathcal{O}(10^{-6})$) by several **New Physics** models (see *e.g.* PRD 93 (2016) 074001)



Examples of leading order $\Delta L = 2$ decays of the D^0 meson

- Previous results from **CLEO** (PRL 76 (1996) 3065), **E791** (PRL 86 (2001) 3969) and **BESIII** (PRD 99 (2019) 112002)
 - Upper limits in the range $(0.3 - 60) \times 10^{-5}$

Analysis strategy



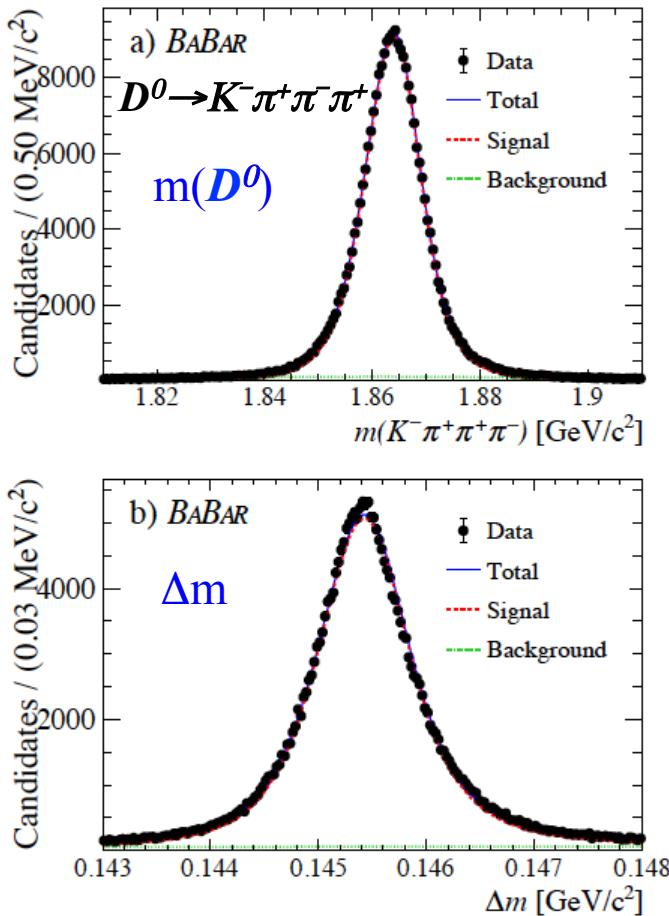
- A common analysis methodology is used for all the analyses presented
- Fully reconstruct the signal mode, e.g. $D^0 \rightarrow K^- \pi^+ e^+ e^-$
 - Identify D^0 candidates in the decay chain $e^+ e^- \rightarrow c\bar{c}$, $D^{*+} \rightarrow D^0 \pi^+$ with a slow π^+
- Use normalization modes: $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$, $D^0 \rightarrow K^- K^+ \pi^+ \pi^-$, $D^0 \rightarrow \pi^- \pi^+ \pi^+ \pi^-$, depending on the number of kaons in the signal mode
- Maximum-likelihood fit to $m(D^0)$ and $\Delta m = m(D^{*+}) - m(D^0)$ for $D^0 \rightarrow K^- \pi^+ e^+ e^-$, (fit only to Δm for LNV and LFV searches)
- Extract the branching fraction from the ratio
- Signal modes data sample:
 - 468 fb^{-1} collected at the $\Upsilon(4S)$ peak and “off peak” (*i.e.* $\sim 40 \text{ MeV}$ below $\Upsilon(4S)$ peak)
- Normalization modes data sample:
 - Only the 39 fb^{-1} “off peak” data are used
- $\sigma(e^+ e^- \rightarrow cc) = 1.3 \text{ nb}$ at the $\Upsilon(4S)$ peak

$$\mathcal{B}(\text{signal}) = \mathcal{B}(\text{norm}) \frac{N^{\text{signal}}}{N^{\text{norm}}} \frac{\epsilon^{\text{norm}}}{\epsilon^{\text{signal}}} \frac{\mathcal{L}^{\text{norm}}}{\mathcal{L}^{\text{signal}}}$$



D^0 normalization modes

$m(D^0)$ and Δm distributions of
 $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ normalization mode



Both $m(D^0)$ and Δm distributions
fitted with a Cruijff function

Fitted Yields in data $39.3 \pm 0.2 \text{ fb}^{-1}$

Decay mode	N_{norm} (candidates)	Syst. (%)	ϵ_{norm} (%)
$D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$	$260\,870 \pm 520$	4.7	20.1 ± 0.2
$K^- K^+ \pi^- \pi^+$	8480 ± 110	6.6	19.2 ± 0.2
$\pi^- \pi^+ \pi^- \pi^+$	$28\,470 \pm 220$	6.8	24.7 ± 0.2

Observation of $D^0 \rightarrow K^- \pi^+ e^+ e^-$

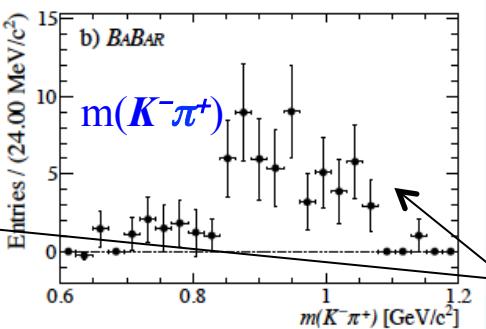
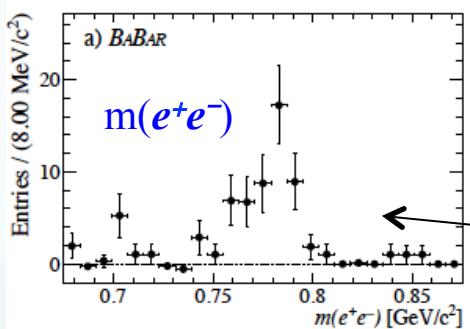
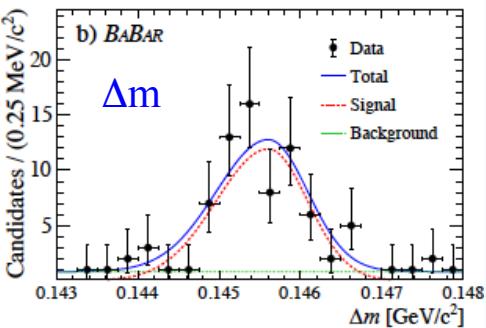
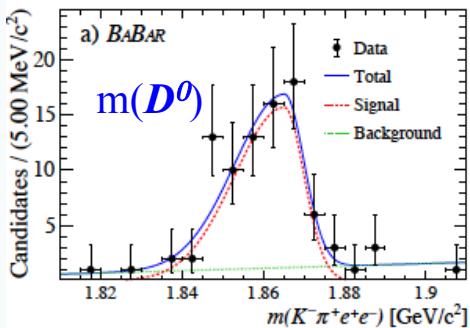


Phys. Rev. Lett. 122 (2019) 081802

Event selection



- Select events with D^0 candidate into four tracks with appropriate PID and charge
- Require good-quality common vertex for the four tracks
- Bremsstrahlung energy recovery algorithm applied to electrons
- Cut on center-of-mass D^0 momentum $p_{D^0}^* > 2.4 \text{ GeV}/c$
 - suppress combinatorial background (from QED processes) and remove B -meson decays
- Perform 2D unbinned maximum likelihood fit to Δm and $m(D^0)$
 - signal: asymmetric-sigma Gaussian function for both Δm and $m(D^0)$
 - normalization modes: Cruijff functions for both Δm and $m(D^0)$
 - background: Argus function for Δm and 2nd order Chebichev polynomial function for $m(D^0)$
- Fit range (for both signal and normalization modes):
 - $0.143 < \Delta m < 0.148 \text{ GeV}/c^2$
 - $1.81 < m(D^0) < 1.91 \text{ GeV}/c^2$



$N_{\text{sig}} = 68 \pm 9$
 $N_{\text{norm}} = 260870 \pm 520$
 Yield significance: 9.7σ

World first observation!

Fit projections.
Background subtracted



$\mathcal{B}(D^0 \rightarrow K^- \pi^+ e^+ e^-) = [4.0 \pm 0.5 \text{ (stat)} \pm 0.2 \text{ (syst)} \pm 0.1 \text{ (norm)}] \times 10^{-6}$

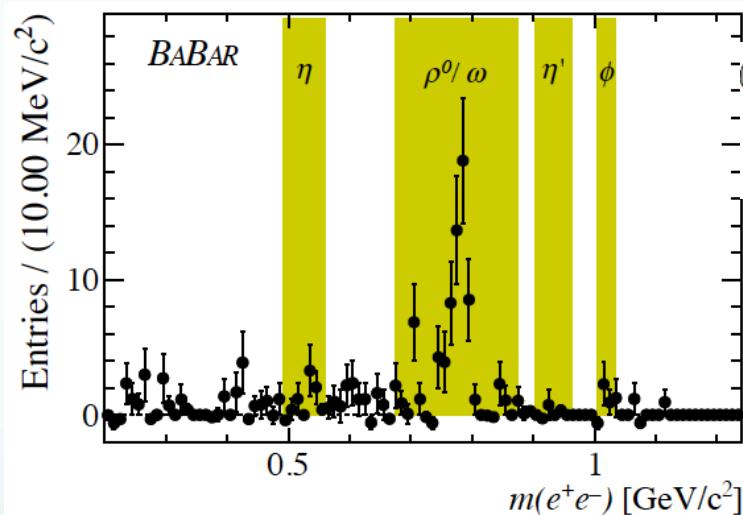
BABAR, PRL 122 (2019) 081802

LHCb: $\mathcal{B}(D^0 \rightarrow K^- \pi^+ \mu^+ \mu^-) = [4.17 \pm 0.12 \pm 0.40] \times 10^{-6}$ (PLB 757 (2016) 558)
 Compatible results assuming Lepton Universality

$D^0 \rightarrow K^- \pi^+ e^+ e^-$: $m(e^+ e^-) > 0.2 \text{ GeV}/c^2$



The decay is studied from $0.2 \text{ GeV}/c^2$ up, separating the resonant from the non-resonant (*continuum*) production of the $e^+ e^-$ pair



$m(e^+ e^-)$ (GeV/c ²)	N_{sig} (cands.)	Signif. (σ)	\mathcal{B} ($\times 10^{-6}$)	$\mathcal{B}_{90\%}^{\text{U.L.}}$ ($\times 10^{-6}$)
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

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

- Background-subtracted fit projection onto $m(e^+ e^-)$
- Highlighted bands correspond to mass intervals excluded from “continuum” region

No significant $D^0 \rightarrow K^- \pi^+ e^+ e^-$ production seen for continuum production of the $e^+ e^-$ pair, nor for resonant production besides the ρ/ω region

Search for LNV and LFV decays

$$D^0 \rightarrow \begin{pmatrix} K^- \pi^- \\ \pi^- \pi^- \\ K^- K^- \end{pmatrix} \begin{pmatrix} e^+ e^+ \\ \mu^+ \mu^+ \\ e^+ \mu^+ \end{pmatrix}$$

$$D^0 \rightarrow \begin{pmatrix} K^- \pi^+ \\ \pi^- \pi^+ \\ K^- K^+ \end{pmatrix} e^\pm \mu^\mp$$

$$D^0 \rightarrow \begin{pmatrix} \pi^0 \\ K_S^0 \\ K^{*0} \\ \rho^0 \\ \omega \\ \phi \\ \eta \end{pmatrix} e^\pm \mu^\mp$$



Phys. Rev. Lett. 124 (2020) 071802



Phys. Rev. D 110
(2020) 112003

Event selection



$D^0 \rightarrow h^- h'^- \ell^+ \ell'^+$ and $D^0 \rightarrow h^- h'^+ e^\pm \mu^\mp$

- Criteria for normalization modes remains the same. Changes for the signal modes:
 - Tighten PID selection than $D^0 \rightarrow K^- \pi^+ e^+ e^-$
 - MVA based on Fisher discriminant for each signal mode to reject $c\bar{c}$ background. MVA inputs: momenta of charged tracks, D^{*+} and event shape variables.
 - Require $m(D^0)$ to be within 3 x reconstructed width around nominal D^0 mass (PDG)
 - Extract signal yield from 1D unbinned ML fit to Δm
 - **Fit range $0.141 < \Delta m < 0.149$ (0.201) GeV/c^2** for $\pi\pi$, $K\pi$ (KK) modes

$D^0 \rightarrow X^0 e^\pm \mu^\mp$

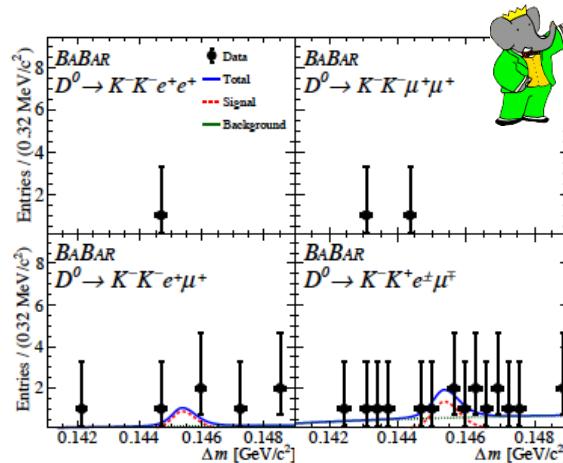
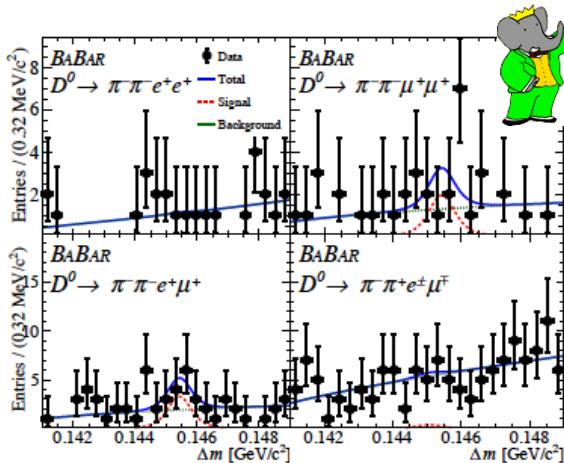
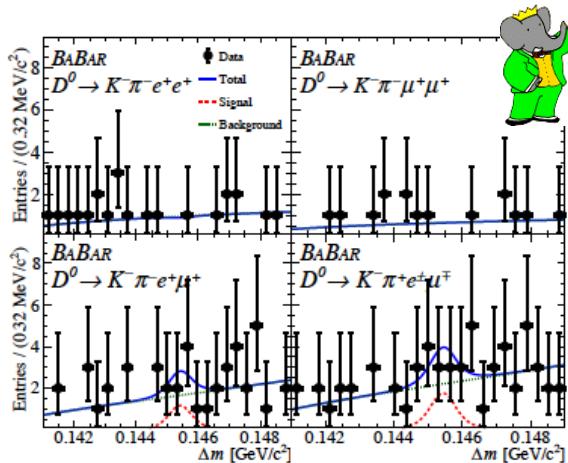
- Criteria for normalization modes remains the same. Changes for the signal modes with respect to $D^0 \rightarrow h^- h'^+ e^\pm \mu^\mp$:
 - Retune PID selection for each signal mode.
 - MVA based on BDT discriminant for each signal mode. MVA inputs: momenta of charged tracks, neutrals, X^0 ; D^{*+} event shape variables.
 - Require $m(D^0)$ and $m(X^0)$ to be within 3 x reconstructed width around nominal PDG mass
 - Extract signal yield from 1D unbinned ML fit to Δm
 - **Fit range $0.1395 < \Delta m < 0.1610$ GeV/c^2**

$D^0 \rightarrow h^- h'^- \ell^+ \ell'^+$ and $D^0 \rightarrow h^- h'^+ e^\pm \mu^\mp$ fit results



- Δm fit functions

- **Signal:** modeled with Cruijff function
- **Background:** modeled with Argus function



- No significant signal in any mode
 - data consistent with background
- Efficiencies between 3.2 to 6.2% depending on mode
- Systematic uncertainties between 5 to 19% depending on mode
- For Upper Limit extraction use the normalization mode with same number of kaons

$D^0 \rightarrow h^- h'^- \ell^+ \ell'^+$ and $D^0 \rightarrow h^- h'^+ e^\pm \mu^\mp$ results



Decay mode $D^0 \rightarrow$	N_{sig} [candidates]	ϵ_{sig} [%]	\mathcal{B} [$\times 10^{-7}$]	$\mathcal{B}_{90\%}^{\text{U.L.}}$ [$\times 10^{-7}$]	$BABAR$	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

BABAR UL in the range (1- 30) $\times 10^{-7}$: 1-3 orders of magnitude more stringent constraints



$D^0 \rightarrow X^0 e^\pm \mu^\mp$ fit results

- Δm fit functions

- **Signal:** Cruijff functions for all modes, with exception of $D^0 \rightarrow \phi e^\pm \mu^\mp$ modeled with sum of two asymmetric-sigma Gaussian functions
- **Background:** modeled with Argus function

$$X^0 = \pi^0 \rightarrow \gamma\gamma$$

$$X^0 = \eta \rightarrow \gamma\gamma$$

$$X^0 = \eta \rightarrow \pi^+ \pi^- \pi^0$$

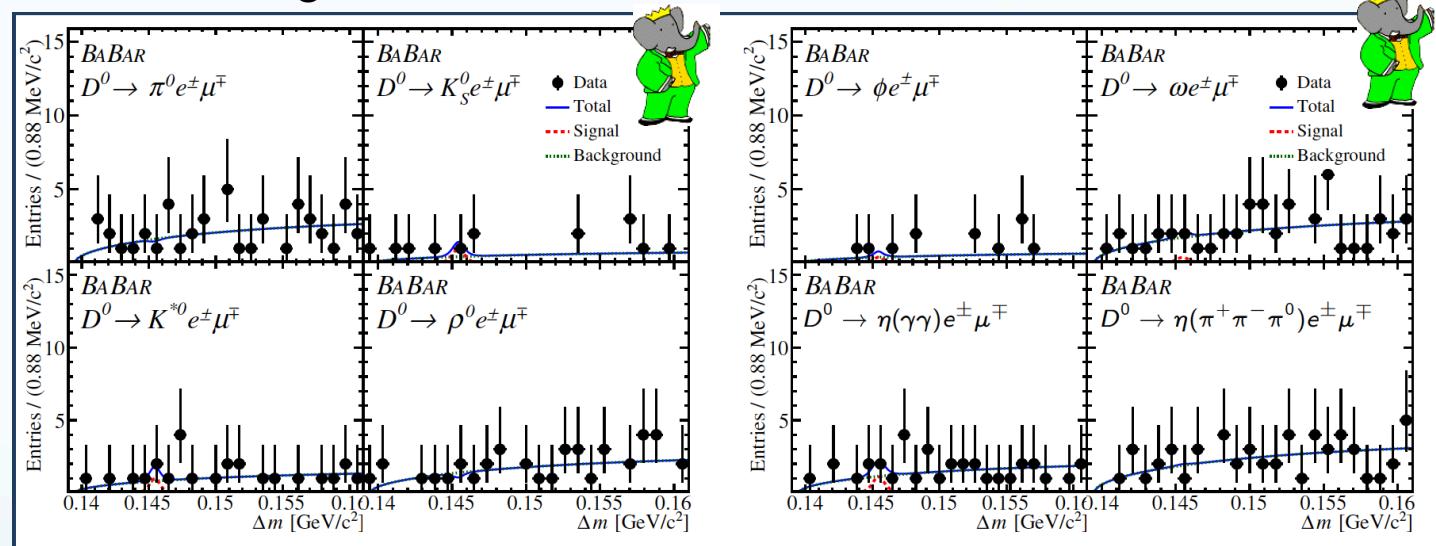
$$X^0 = K_S^0 \rightarrow \pi^+ \pi^-$$

$$X^0 = \rho \rightarrow \pi^+ \pi^-$$

$$X^0 = \omega \rightarrow \pi^+ \pi^- \pi^0$$

$$X^0 = \phi \rightarrow K^+ K^-$$

$$X^0 = \bar{K}^{*0} \rightarrow K^- \pi^+$$



- **No significant signal in any mode**
- Efficiencies between 1.6 to 3.6% depending on mode
- Systematic uncertainties: additive 0.4 – 0.9 events, multiplicative 4.2 – 7.8% depending on mode



$D^0 \rightarrow X^0 e^\pm \mu^\mp$ results

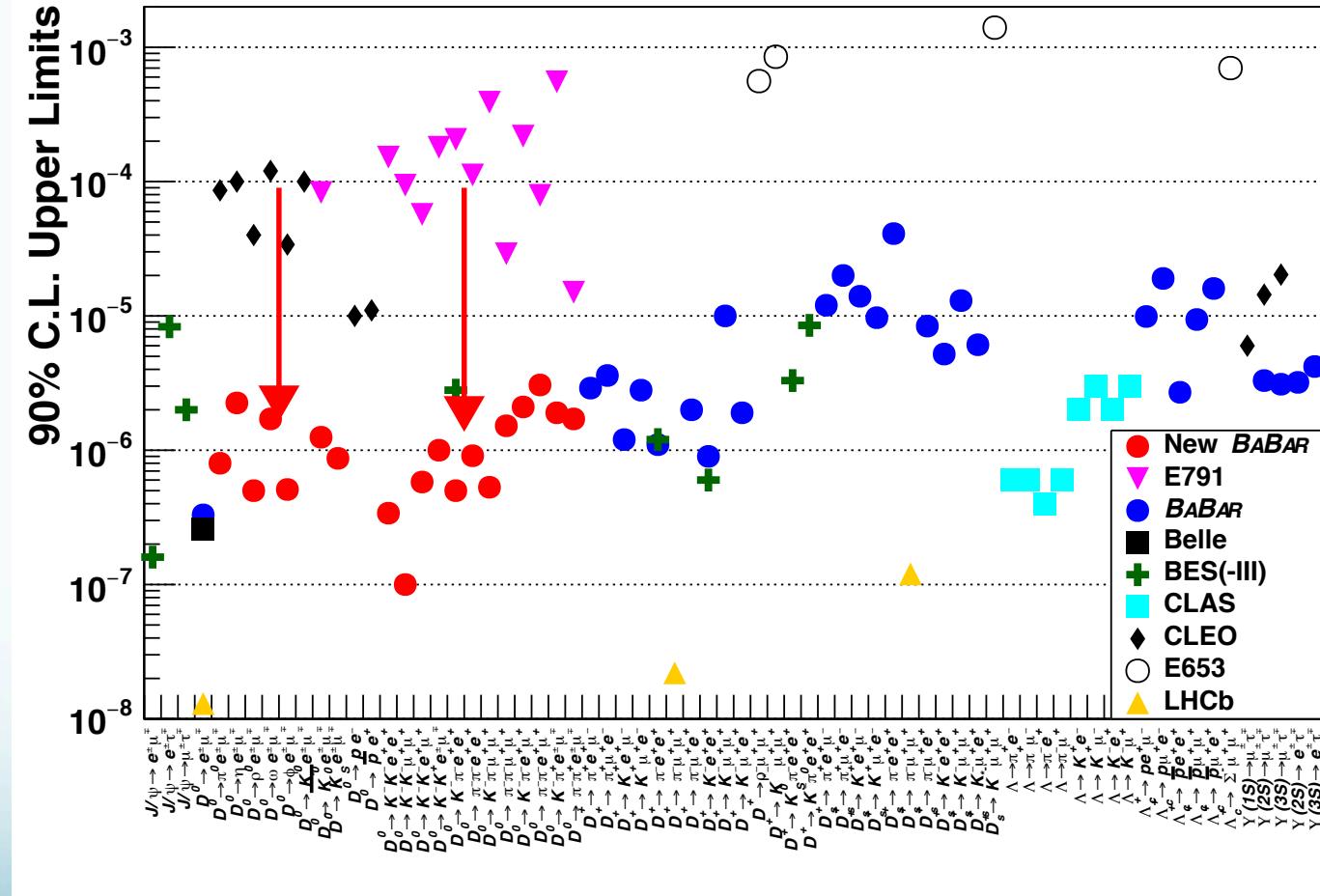
Decay mode $D^0 \rightarrow$	N_{sig} [candidates]	ϵ_{sig} [%]	\mathcal{B} [$\times 10^{-7}$]	$\mathcal{B}_{90\%}^{\text{U.L.}}$ [$\times 10^{-7}$]	<i>BABAR</i>	previous
$D^0 \rightarrow \pi^0 e^\pm \mu^\mp$	$-0.3 \pm 2.0 \pm 0.9$	2.15 ± 0.03	$-0.6 \pm 4.8 \pm 2.3$	8.0	860	
$D^0 \rightarrow K_s^0 e^\pm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

BABAR UL in the range $(5-22.5) \times 10^{-7}$: 1-2 orders of magnitude more stringent constraints

Summary plot for LFV and LNV decays



BABAR has lower limits on most D^0 and D^+ modes,



Summary

$D^0 \rightarrow K^- \pi^+ e^+ e^-$ Phys. Rev. Lett. 122 (2019) 081802

- First observation of the $D^0 \rightarrow K^- \pi^+ e^+ e^-$ decay
- In the mass range $0.675 < m(e^+ e^-) < 0.875 \text{ GeV}/c^2$:
 - $\mathcal{B}(D^0 \rightarrow K^- \pi^+ e^+ e^-) = (4.0 \pm 0.5 \pm 0.2 \pm 0.1) \times 10^{-6}$
 - Agrees with LHCb $\mathcal{B}(D^0 \rightarrow K^- \pi^+ \mu^+ \mu^-) = (4.17 \pm 0.12 \pm 0.40) \times 10^{-6}$
- No evidence for violation of lepton universality
- No evidence for short-distance or NP effects in the continuum $m(e^+ e^-)$ range

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

- $D^0 \rightarrow h^- h'^- \ell^+ \ell'^+$, $D^0 \rightarrow h^- h'^+ e^\pm \mu^\mp$: 12 U.L. (90% C.L.) in range $(1.0 - 30.6) \times 10^{-7}$
 - Phys. Rev. Lett. 124 (2020) 071802
- $D^0 \rightarrow X^0 e^\pm \mu^\mp$: 7 U.L. (90% C.L.) in range $(5.0 - 23.0) \times 10^{-7}$
 - Phys. Rev. D 101 (2020) 112003
- One to three orders of magnitude more stringent constraints than previous results

BACKUP SLIDES

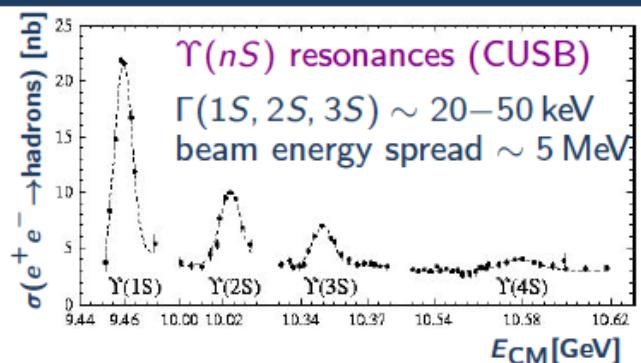
References

- J. P. Lees *et al.* [BABAR Collaboration], *Observation of the decay $D^0 \rightarrow K^- \pi^+ e^+ e^-$* , Phys. Rev. Lett. 122 (2019) 081802, [arXiv:1808.09680].
- J. P. Lees *et al.* [BABAR Collaboration], *Search for rare or forbidden decays of the D0 meson*, Phys. Rev. Lett. 124 (2020) 071802, [arXiv:1905.00608].
- J. P. Lees *et al.* [BABAR Collaboration], *Search for lepton-flavor-violating decays $D^0 \rightarrow X^0 e^\pm \mu^\mp$* , Phys. Rev. D 101 (2020) 112003, [arXiv:2004.09457].
- R. Aaij *et al.* [LHCb Collaboration], *First observation of the decay $D^0 \rightarrow K^- \pi^+ \mu^+ \mu^-$ in the ρ^0 - ω region of the dimuon mass spectrum*, Phys. Lett. B 757 (2016) 558 [arXiv: 1510.08367].
- S. de Boer and G. Hiller, *Flavor and new physics opportunities with rare charm decays into leptons*, Phys. Rev. D 93 (2016) 074001, [arXiv:1510.00311].
- Bause et al, *The new physics reach of null tests with $D \rightarrow \pi l\bar{l}$ and $D_s \rightarrow K l\bar{l}$ decays*, Eur. Phys. J. C80 (2020) 65.

BABAR at PEP-II asymmetric B factory

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

center-of-mass energies

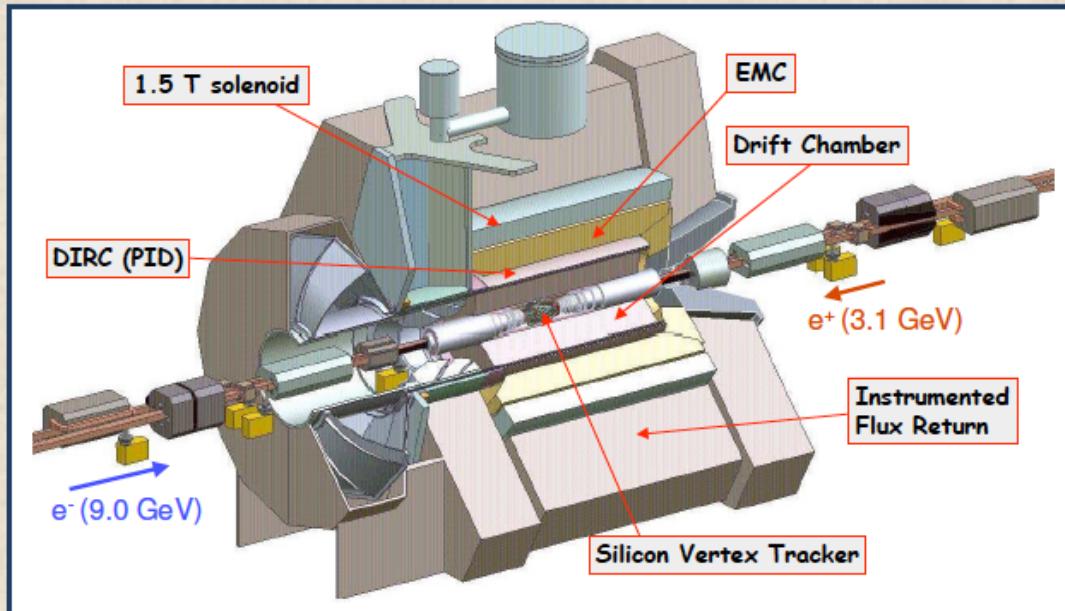


\mathcal{L} vs. \sqrt{s}

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