Rare and Forbidden Decays of the D^0 Meson

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Outline of the Talk

- Motivation
- The *BABAR* Experiment
- Observation of $D^0 \to K^- \pi^+ e^+ e^-$ PRL **122** 081802 (2019)
- Search for forbidden $D^0 \to h^- h'^- l^+ l'^+$ and $D^0 \to h^- h'^+ l^+ l'^-$ PRL **124** 071802 (2020)
- Search for 7 Lepton Flavor Violating modes $D^0 \to X^0 e^\pm \mu^\mp$ PR**D 101** 112003 (2020)

Charge conjugation implied throughout

Motivation: Search for New Physics evidenced via rare decays

Most of us are familiar with the storied association of lepton number conservation with Beta decay:

$$\cancel{n \rightarrow p + e^-}$$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

Likewise, lepton flavor conservation is familiar from the most common form of muon decay:

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

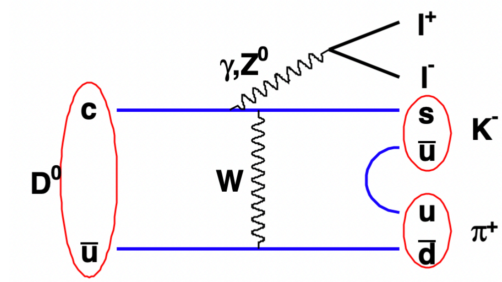
These conservation rules are well-supported by data.

The Standard Model only allows violation through complicated Feynman diagrams; at best, such processes should be extremely suppressed. Some NP theories, however, allow SM-suppressed processes that should be within experimental reach.

Motivation: Search for New Physics evidenced via rare decays

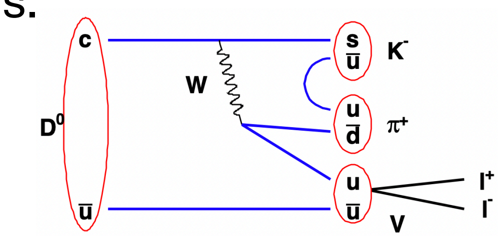
Neutrino oscillation demonstrates lepton flavor violation (LFV) readily…among neutrinos.

Observation of LFV among other particles or of lepton number violation (LNV) could provide insights into New Physics



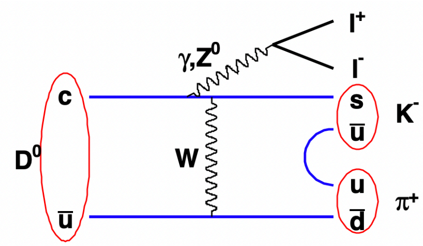
Even for modes that do not explicitly violate any conservation rules, there is a tension between dominant long-distance contributions, e.g. $D^0 \to XV \to Xl^+l^-$ and suppressed short-distance contributions such as loop and box diagrams.

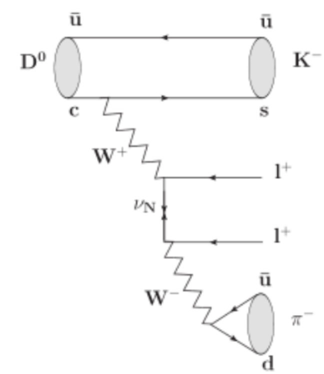
New virtual particles could substantially alter the relative importance of short-distance effects and with them, the overall decay rate.



New Physics in the charm sector

Multiple NP theories give rise to previously undiscovered particles that could contribute to bringing rates for many of these rare decay modes into reach of current experiments.





Example diagrams

Littlest Higgs with *T*-parity (LHT)
PR**D 83**, 114006 (2011)

Warped Extra Dimensions
PR**D 90**, 014035 (2014)

Minimal Supersymmetric Standard Model (MSSM)
PR**D 76**, 074010 (2007), PR**D 64** 114009 (2001)

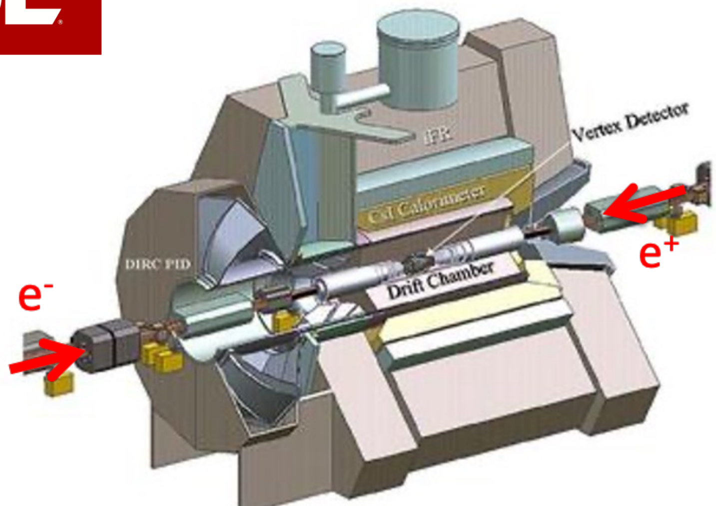
MSSM with R-parity Violation
PR**D 66**, 014009 (2002)

Leptoquarks
PR**D 93** 074001 (2016)

Majorana Neutrinos
Chin Phys **C 39** 013101 (2015)

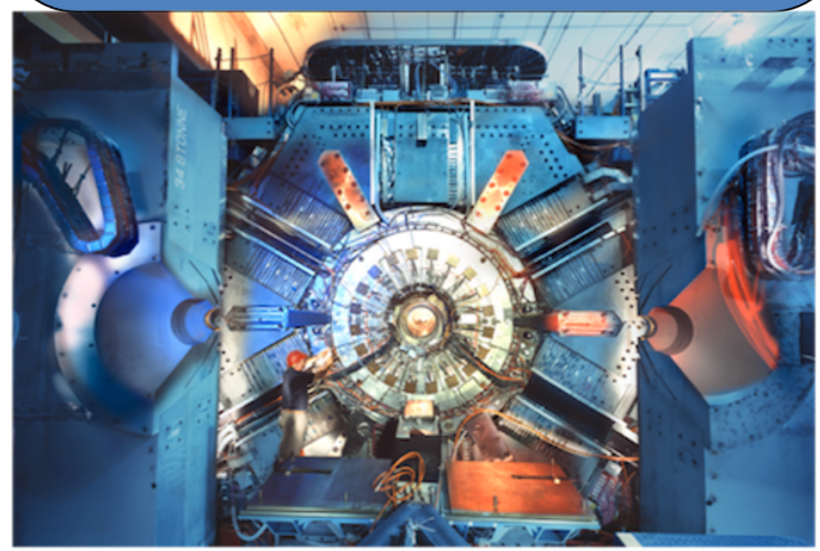
Not an exhaustive list!

The *BABAR* Detector



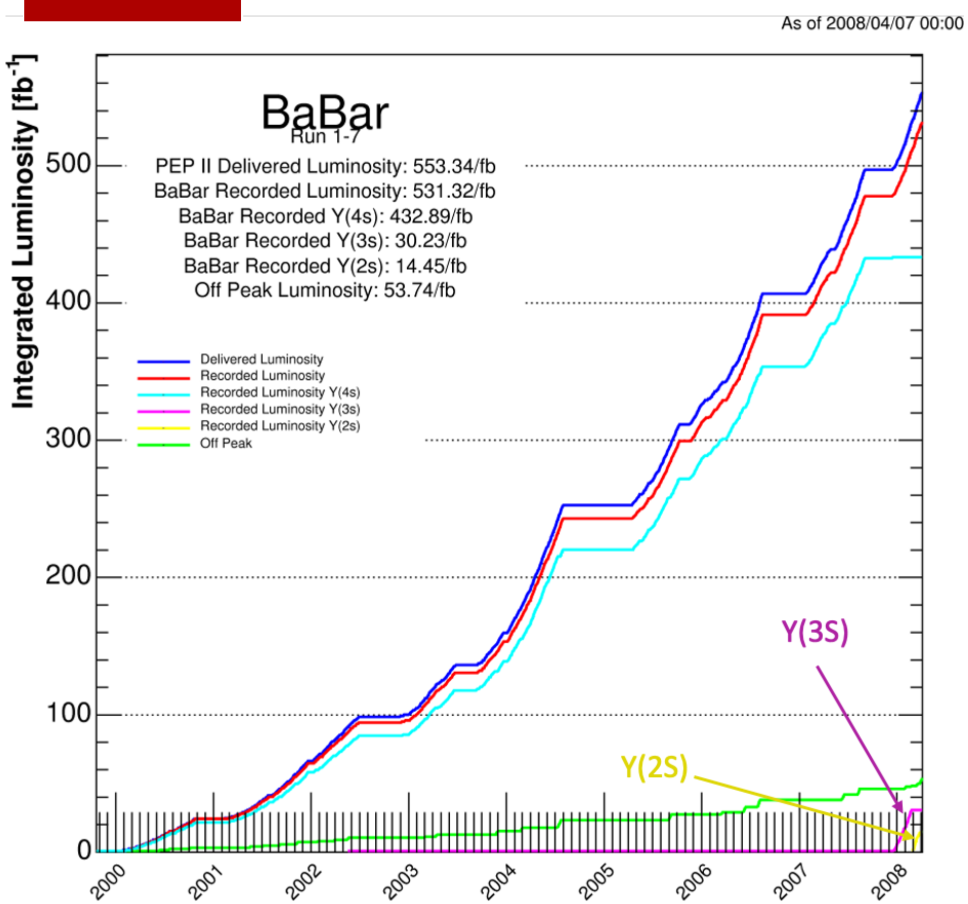
- Asymmetric-energy beams for boost
- Modern/state of the art detector
- 5 cylindrical subdetector systems with a 40-layer drift chamber + 5-layer vertex detector
- Excellent electromagnetic calorimetry
- Multiple measurements for particle identification
- Excellent momentum resolution

- Primarily designed for study of *CP*-violation in *B* meson decays
- Quality and general-purpose design make it suitable for a large variety of studies

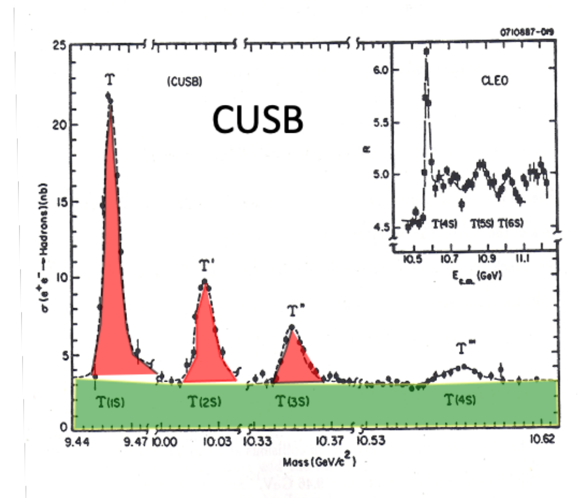


NIM A479,1 (2002),
update: NIM A729, 615 (2013)

The *BABAR* Running Era



7 Runs over the course of 9 years



This analysis uses 468 fb^{-1} of data

- First collisions with *BABAR* 1999
- Final data taken 12:43 p.m., April 7, 2008

NP and *B*-factories

B-factories are also charm factories

$$\sigma_{e^+e^- \to c\bar{c}} \approx 1.3 \text{ nb}$$

$$N_{c\bar{c}} \approx 1.3 \text{ nb} \times 468 \text{ fb}^{-1} \approx 6 \times 10^8 \text{ events}$$

Ensure pure sample of D^0 by requiring D^0 candidates from $D^{*\pm}$, i.e. $D^{*\pm} \to D^0\pi^\pm$

- Constrain D^0 mass to nominal value
- Require D^0 candidate and pion form vertex at interaction point
- Invariant mass of D^0 and pion consistent with D^* mass

Modes Searched For

All BABAR searches presented here use $468\ \mathrm{fb}^{-1}\ e^+e^-$ data

$D^0 \to h^- h'^- l^+ l'^+$ (+ charge conjugates)

	e^+e^+	$\mu^+\mu^+$	$e^+\mu^+$
K^-K^-	LNV	LNV	LNV
$\pi^-\pi^-$	LNV	LNV	LNV
$K^-\pi^-$	LNV	LNV	LNV

Also necessarily LFV

$D^0 \to h^- h'^+ l^+ l'^-$ (+ charge conjugates)

	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$
K^-K^+	OK	OK	LFV
$\pi^-\pi^+$	OK	OK	LFV
$K^\mp\pi^\pm$	OK	OK	LFV

Discovery of $D^0 \to K^-\pi^+e^+e^-$ by *BABAR*
PRL **122** 081802 (2019)

LHCb first to discover
$D^0 \to K^-\pi^+\mu^+\mu^-$
PLB **757** 558 (2016);
$D^0 \to K^+K^-\mu^+\mu^-$
$D^0 \to \pi^+\pi^-\mu^+\mu^-$
PRL **119** 181805 (2017)

Search for LNV and LFV modes by *BABAR*
PRL **124** 071802 (2020)

Modes Searched For

$D^0 \to h^- h'^- l^+ l'^+$ (+ charge conjugates)

	e^+e^+	$\mu^+\mu^+$	$e^+\mu^+$
K^-K^-	LNV	LNV	LNV
$\pi^-\pi^-$	LNV	LNV	LNV
$K^-\pi^-$	LNV	LNV	LNV

Also necessarily LFV

$D^0 \to h^- h'^+ l^+ l'^-$ (+ charge conjugates)

	e^+e^-	$\mu^+\mu^-$	$e^\pm\mu^\mp$
K^-K^+	OK	OK	LFV
$\pi^-\pi^+$	OK	OK	LFV
$K^\mp\pi^\pm$	OK	OK	LFV

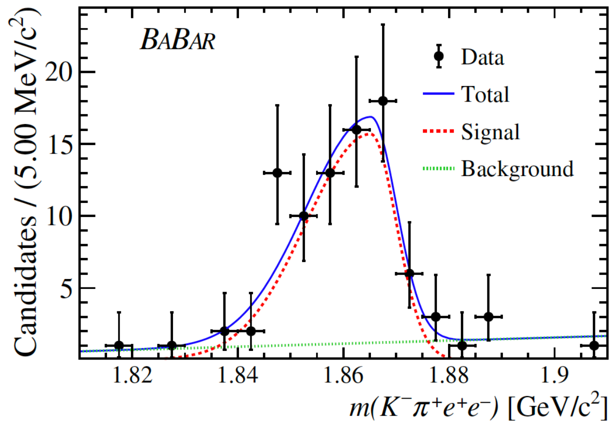
And the manifestly LFV: $D^0 \to X^0 e^\pm \mu^\mp$

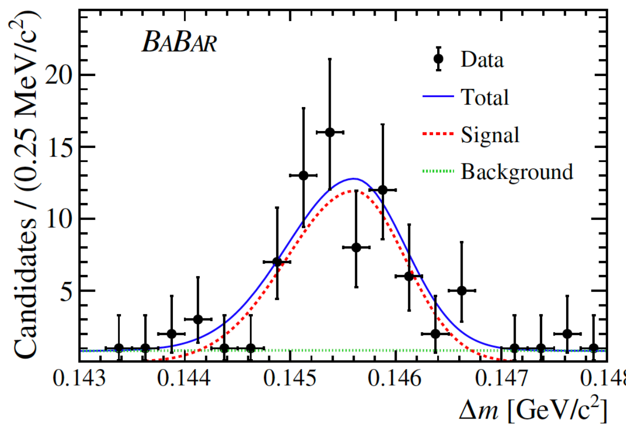
Where X^0 can be any of π^0, K_S^0, K^{*0}, ρ^0, ϕ, ω, or η

PRD **101** 112003 (2020)

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

- Require at least 5 charged tracks in event
- Correct electron energy using Bremsstrahlung algorithm
- Require $p^*_{D^0} > 2.4\ \mathrm{GeV/c}$
- Require D^0 from $D^{*\pm}$
- Normalize against $D^0 \to K^-\pi^+\pi^+\pi^-$ mode
- Fit invariant mass and $\Delta m = m_{D*} - m_D$ independently
- Fit in different $m(e^+e^-)$ ranges to test long- vs short-distance





Fits for $0.675 < m(e^+e^-) < 0.875\ \mathrm{GeV/c^2}$

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

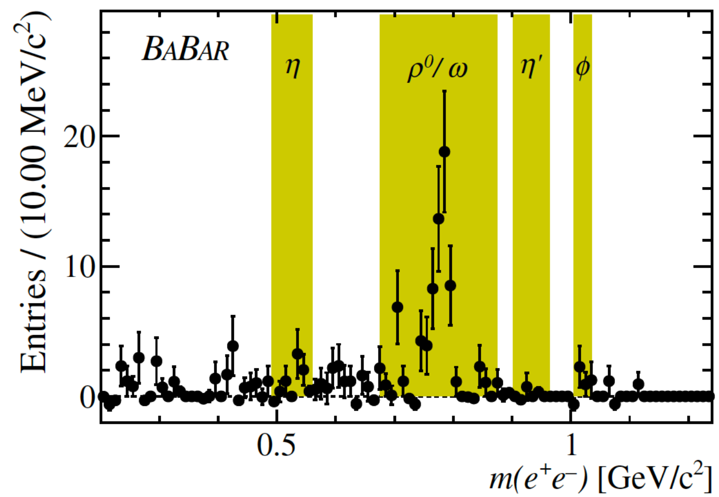
For $0.675 < m(e^+e^-) < 0.875\ \mathrm{GeV/c^2}$, dominated by long-distance effects, we find:

$$\mathscr{B}(D^0 \to K^-\pi^+e^+e^-) = (4.0 \pm 0.5 \pm 0.2 \pm 0.1) \times 10^{-6}$$

For the continuum region, dominated by short-distance effects, we find no significant signal and set an upper limit:

$$\mathscr{B}(D^0 \to K^-\pi^+e^+e^-) < 3.1 \times 10^{-6}$$

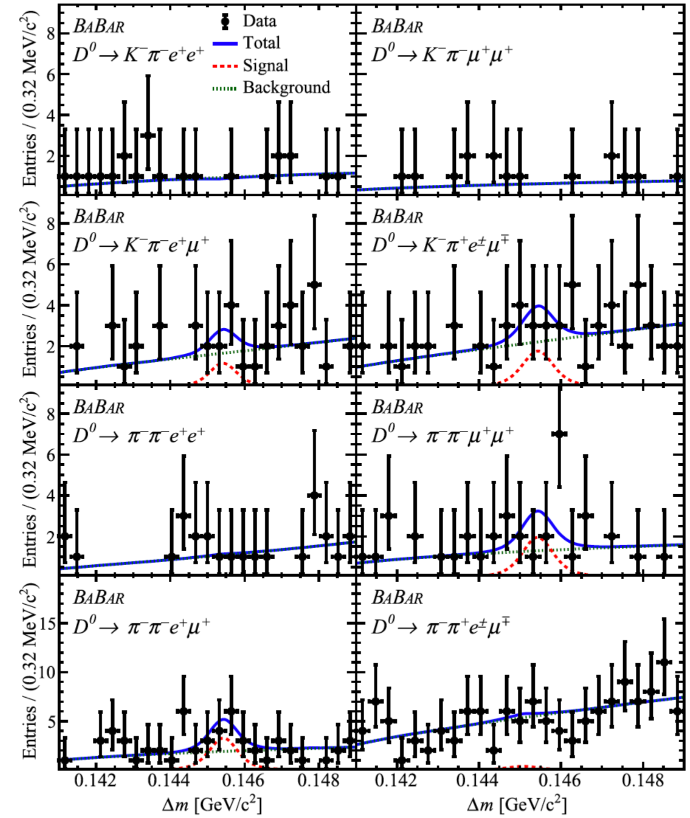
90% CL Upper Limit



The continuum region is defined as the ranges in $m(e^+e^-)$ shown on the graph, excluding the color bands.

Search for forbidden $D^0 \rightarrow hh'll'$ decays

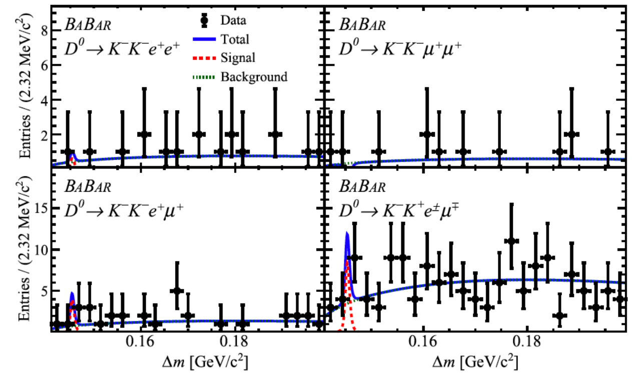
- Require at least 5 charged tracks with particle ID
- Bremsstrahlung energy recovery algorithm for electrons
- Require $p^*_{D^0} > 2.4\ \mathrm{GeV/c}$
- Require D^0 from $D^{*\pm}$
- Fisher discriminant in 9 variables to reduce backgrounds
- Normalize against $D^0 \rightarrow \pi^-\pi^+\pi^+\pi^-$, $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$, and $D^0 \rightarrow K^-K^+\pi^+\pi^-$modes
- Two-dimensional fit to invariant mass and $\Delta m = m_{D*} - m_D$



Projections of 2D fit onto Δm axis

Search for forbidden $D^0 \to hh'll'$ decays

No significant signals found.



Much tighter upper limits than previously determined

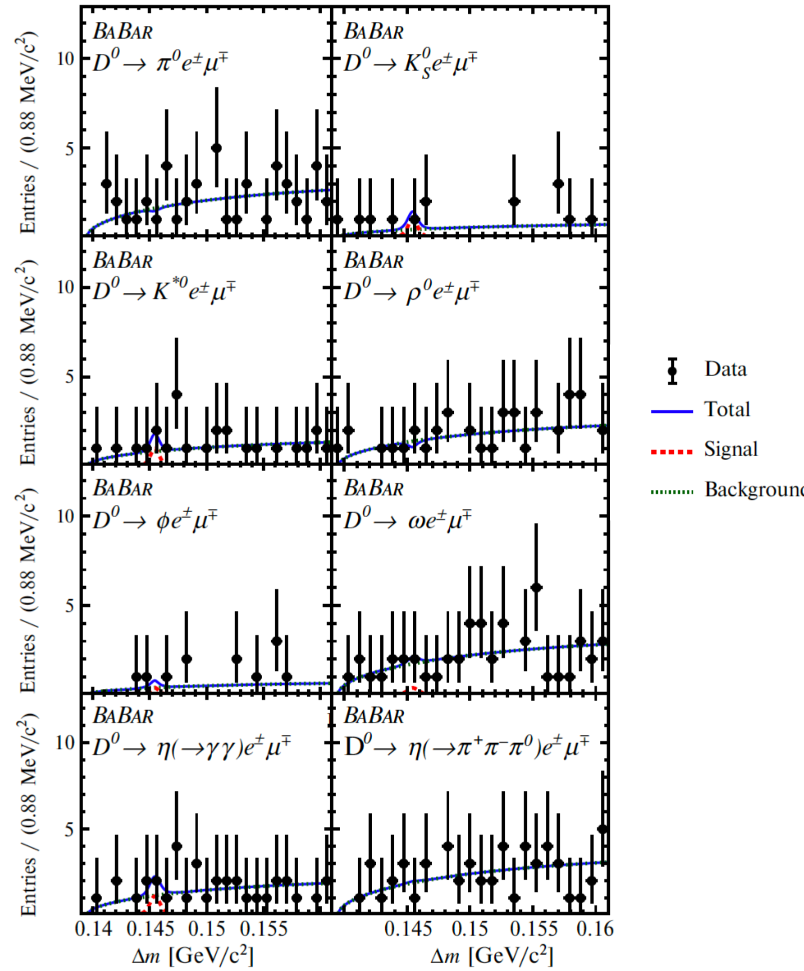
Decay mode $D^0 \to$	$N_{\rm sig}$ (candidates)	$\epsilon_{\rm sig}$ (%)	$\mathcal{B}$ ($\times 10^{-7}$)	$\mathcal{B}$ 90% U.L. ($\times 10^{-7}$) BABAR	Previous
$\pi^-\pi^-e^+e^+$	$0.22 \pm 3.15 \pm 0.54$	4.38 ± 0.05	$0.27 \pm 3.90 \pm 0.67$	9.1	1120
$\pi^-\pi^-\mu^+\mu^+$	$6.69 \pm 4.88 \pm 0.80$	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 [21]
$K^-\pi^-\mu^+\mu^+$	$-0.03 \pm 2.10 \pm 0.40$	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

PDG 2018 listings

PR**D 99**, 112002 (2019)

Search for forbidden $D^0 \to X^0 \mu^\pm e^\mp$ decays

- Require at least 3 or 5 charged tracks with particle ID
- Bremsstrahlung energy recovery algorithm for electrons
- Require $p^*_{D^0} > 2.4\ \mathrm{GeV/c}$
- Require D^0 from $D^{*\pm}$
- Boosted Decision Tree (BDT) discriminant in 8 variables to reduce backgrounds
- Normalize against $D^0 \to \pi^-\pi^+\pi^+\pi^-$, $D^0 \to K^-\pi^+\pi^+\pi^-$, and $D^0 \to K^-K^+\pi^+\pi^-$modes
- Perform maximum likelihood fit to $\Delta m = m_{D*} - m_D$



Search for forbidden $D^0 \to X^0\mu^{\pm}e^{\mp}$ decays

No significant signals found

Improve 90% CL upper limits by 1 to 2 orders of magnitude

Decay mode	N_{sig} (candidates)	ϵ_{sig} (%)	$\mathcal{B}$ ($\times 10^{-7}$)	$\mathcal{B}$ 90% U.L. ($\times 10^{-7}$)	
				BABAR	Previous
$D^0 \to \pi^0 e^{\pm}\mu^{\mp}$	$-0.3 \pm 2.0 \pm 0.9$	2.15 ± 0.03	$-0.6 \pm 4.8 \pm 2.2$	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	$1.9 \pm 4.6 \pm 1.9$	8.7	500
$D^0 \to \bar{K}^{*0} e^{\pm}\mu^{\mp}$	$0.8 \pm 1.8 \pm 0.8$	2.31 ± 0.03	$2.8 \pm 6.1 \pm 2.6$	12.5	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	$0.4 \pm 25.8 \pm 6.0$	43.0	

Conclusions

- Study of rare and forbidden D^0 decay modes with *BABAR*
- First observation of $D^0 \to K^+\pi^-e^+e^-$
  - $\mathscr{B}(D^0 \to K^-\pi^+e^+e^-) = (4.0 \pm 0.5 \pm 0.2 \pm 0.1) \times 10^{-6}$ "long-distance"
  - $\mathscr{B}(D^0 \to K^-\pi^+e^+e^-) < 3.1 \times 10^{-6}$ 90% CL upper limit "short-distance"
- Search for $D^0 \to hh'll'$ - upper limits tightened by 1-3 orders of magnitude
- Search for $D^0 \to X^0e^\pm\mu^\mp$ - upper limits tightened by 1-2 orders of magnitude
- All consistent with the Standard Model
- 13 years after end of data taking, *BABAR* continues to produce important results

Thank you!