Rare and forbidden decays of the D^0 meson

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Introduction: rare charm decays

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

- $D^0 \to h'^-h^+e^+e^-$ and $D^0 \to h'^-h^+\mu^+\mu^-$ ($h/h' = K$ or π) allowed but very suppressed. Decay characterized by:
  - Short-distance contributions at the one-loop level, $\mathcal{O}(10^{-8})$:
    - Glashow-Iliopoulos-Maiani (GIM) cancellation almost exact.
    - Quark masses in the loop are small.
  - Long-distance contributions e.g. Vector Meson Dominance (VMD), $\mathcal{O}(10^{-6})$.
- Away from long-distance contributions, potential for New Physics to be visible.
- Lepton Universality: Do electrons and muons couple with equal strength?
- $\mathcal{B}(D^0 \to K^-\pi^+\mu^+\mu^-) = (4.17 \pm 0.12 \pm 0.40) \times 10^{-6}$ in mass region $0.675 < m(\mu^+\mu^-) < 0.875\,\mathrm{GeV}/c^2$ [1].

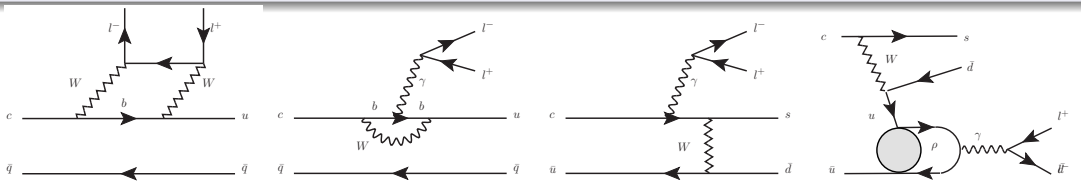


Figure: Left to Right: Short-distance: box, penguin diagrams; Long-distance: photon pole, VMD.

Introduction: forbidden charm decays

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

- $\ell/\ell' = e$ or μ; $X^0 = \pi^0$, K^0_S, K^{*0}, ρ^0, ϕ, ω, or η.
- Lepton Number Violation (LNV) and Lepton Flavor Violation (LFV) essentially forbidden in the Standard Model $<< \mathcal{O}(10^{-40})$.
- Predicted by many New Physics models (see e.g. Ref. [2]).

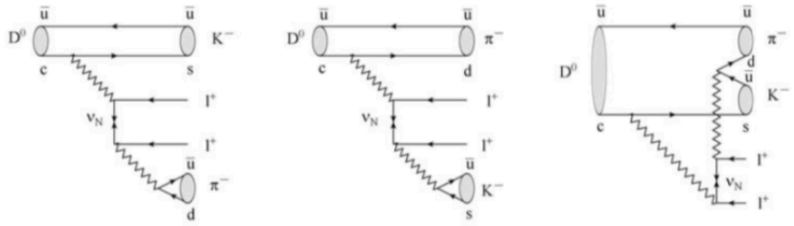


Figure: Examples of leading order $\Delta L = 2$ D^0 meson decays.

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

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

- Reconstruct $D^0 \to K^-\pi^+e^+e^-$ and $D^0 \to K^-\pi^+\pi^+\pi^-$ (normalization mode) from $D^{*+} \to D^0\pi^+$ produced in $e^+e^- \to c\bar{c}$.
- Maximum-Likelihood fit to $m(D^0)$ and $\Delta m = m(D^{*+}) - m(D^0)$.
- Apply candidate-by-candidate reconstruction efficiencies ϵ.

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

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

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

- Normalization mode $D^0 \to K^- K^+ \pi^+ \pi^-$, $D^0 \to K^- \pi^+ \pi^+ \pi^-$, or $D^0 \to \pi^- \pi^+ \pi^+ \pi^-$ depending on number of kaons in signal final state.
- Multivariate discriminant (MVA) to reject $e^+ e^- \to c\bar{c}$ background.
- For signal: cut on $m(D^0)$, Maximum Likelihood fit to Δm only.
- Use average reconstruction efficiencies ϵ for signal.

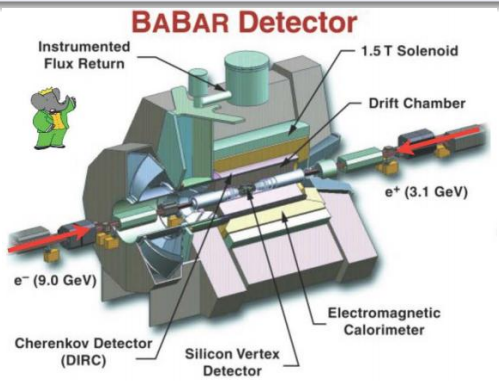
$D^0 \to X^0 e^\pm \mu^\mp$

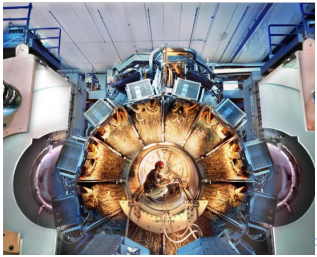
- As for $D^0 \to h'^- h^- \ell'^+ \ell^+$ and $D^0 \to h'^- h^+ e^\pm \mu^\mp$
- Reconstruct 8 intermediate X^0 meson decays:
  - $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$, $K^0_S \to \pi^+ \pi^-$, $\rho^0 \to \pi^+ \pi^-$, $\bar{K}^{*0} \to K^- \pi^+$, $\phi \to K^+ K^-$
  - $\omega \to \pi^+ \pi^- \pi^0$, $\eta \to \pi^+ \pi^- \pi^0$
- Retune MVA for each X^0 with new observables.
- For signal: cut on $m(D^0), m(X^0)$, Maximum Likelihood fit to Δm only.

BABAR Detector at PEP-II

Asymmetric beam momenta, $E_{CMS} = 10.58\,\mathrm{GeV}$, low multiplicity, low background, K/π particle identification, good μ and e identification with wide coverage.

Signal data sample: $\sim 468\,\mathrm{fb}^{-1}$
Charm production cross-section $\sim 1.3\,\mathrm{nb}$





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

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

- Form a D^0 vertex from 4 tracks with appropriate mass hypothesis and particle identification (PID).
- Combine D^0 and a "slow" π^+ to form D^{*+}.
- Momentum of the slow pion in the laboratory frame, $\pi^+ > 0.1\,\mathrm{GeV}/c$.
- Kaon charge opposite the "slow" π^+ charge.
- Momentum of D^0 in the center-of-mass frame, $p^*_{D^0} > 2.4\,\mathrm{GeV}/c$; removes charm decays from B-mesons.
- $0.143 < \Delta m < 0.148\,\mathrm{GeV}/c^2$, where $\Delta m = m(D^{*+}) - m(D^0)$.
- $1.81 < m(D^0) < 1.91\,\mathrm{GeV}/c^2$.

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

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

Criteria for normalization modes remains the same. Changes for the signal modes:

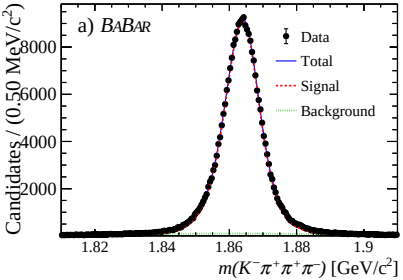
- Apply tighter PID selection than $D^0 \to K^- \pi^+ e^+ e^-$.
- Tune MVA for each signal mode to reject background. MVA inputs: momenta of charged tracks, D^{*+}; event shape variables.
- Restrict $m(D^0)$ to $\sim 3 \times$ reconstructed width around D^0 Particle Data Group (PDG) mass.
- $0.141 < \Delta m < 0.149\ (0.201)\,\mathrm{GeV}/c^2$ if $< 2 (= 2)$ kaons in final state.

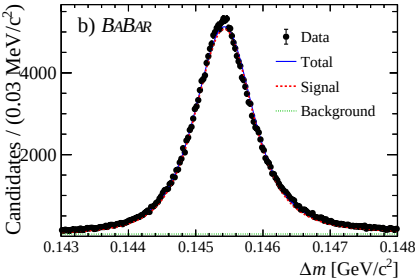
$D^0 \to X^0 e^\pm \mu^\mp$

Criteria for normalization modes remains the same. Changes for the signal modes with respect to $D^0 \to h'^- h^- \ell'^+ \ell^+$ and $D^0 \to h'^- h^+ e^\pm \mu^\mp$:

- Retune PID for each signal mode.
- Retune MVA for each signal mode. MVA inputs: momenta of charged tracks, neutrals, X^0, and D^{*+}; event shape variables.
- Restrict $m(D^0)$ to $\sim 3 \times$ reconstructed width around D^0 PDG mass.
- Restrict $m(X^0)$ to $\sim 3 \times$ reconstructed width around X^0 PDG mass.
- $0.1395 < \Delta m < 0.1610\,\mathrm{GeV}/c^2$.

Normalization Mode Example: $D^0 \to K^-\pi^+\pi^+\pi^-$





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

Decay mode $D^0 \to$	N_{norm} (candidates)	Syst. (%)	ϵ_{norm} (%)
$K^-\pi^+\pi^-\pi^+$	$260\,870 \pm 520$	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

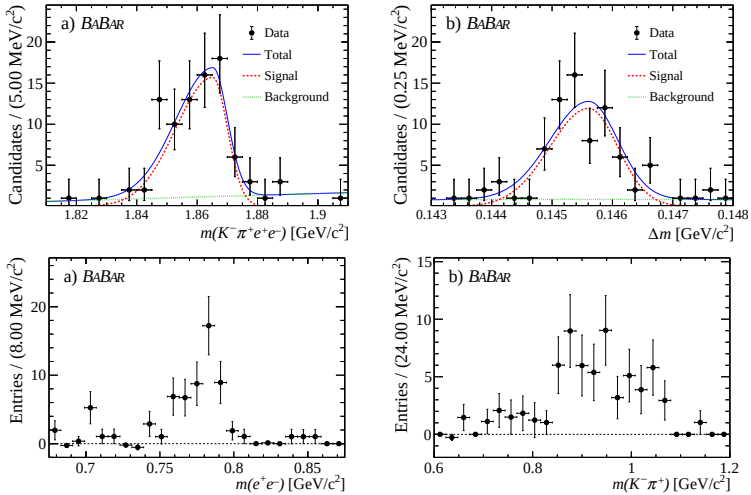
Normalization modes use off-peak data ($40\,\text{MeV}$ below $\Upsilon(4S)$).

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

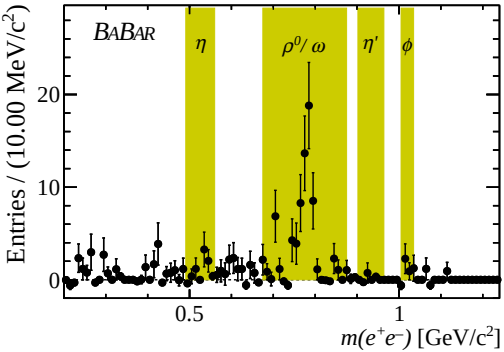
Phys. Rev. Lett. 122 (2019) 081802

$D^0 \to K^-\pi^+e^+e^-$: $0.675 < m(e^+e^-) < 0.875\,\mathrm{GeV}/c^2$

$N_{sig} = 68 \pm 9$ candidates. Yield significance 9.7σ



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



Background-subtracted fit projection onto $m(e^+e^-)$.

Green = resonances excluded from "continuum" region.

$m(e^+e^-)$ (GeV/c^2)	N_{sig} (cands.)	Signif. (σ)	$\mathcal{B}$ ($\times 10^{-6}$)	$\mathcal{B}^{\mathrm{U.L.}}_{90\%}$ ($\times 10^{-6}$)
$0.675 - 0.875$	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

$\pm$ Statistical $\pm$ Systematic ($\pm$ Normal. $\mathcal{B}$).

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

$\mathcal{B}$ in mass region $0.675 < m(e^+e^-) < 0.875\,\mathrm{GeV}/c^2$ agrees with LHCb result [1] $\mathcal{B}(D^0 \to K^-\pi^+\mu^+\mu^-) = (4.17 \pm 0.12 \pm 0.40) \times 10^{-6}$.

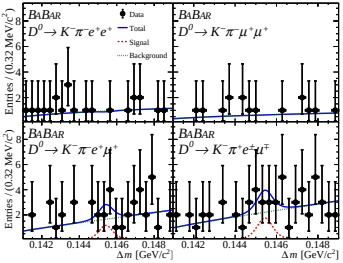
$$D^0 \to h'^- h^- \ell'^+ \ell^+$$

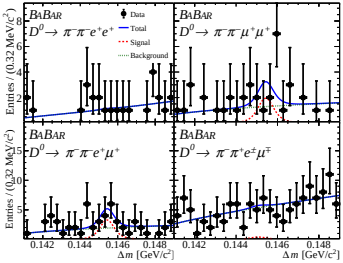
and

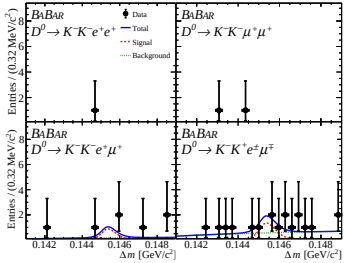
$$D^0 \to h'^- h^+ e^\pm \mu^\mp$$

arXiv:1905.00608, accepted by PRL

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







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

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

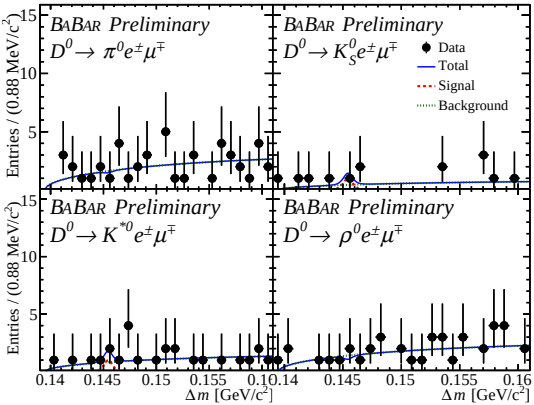
Uncertainties: $\pm$ Statistical $\pm$ Systematic

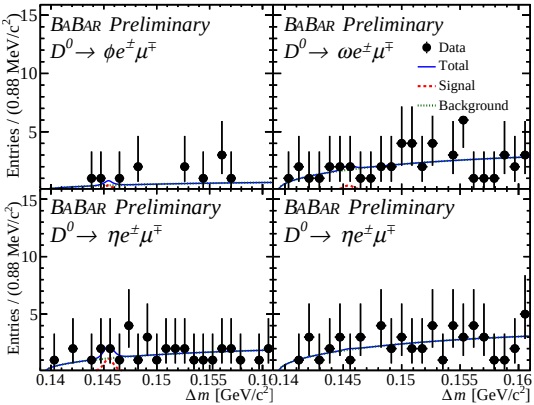
90% Confidence Level (CL) Upper Limits (UL) calculated using Feldman-Cousins method.

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

To be submitted to PRD

$D^0 \to X^0 e^\pm \mu^\mp$ fits



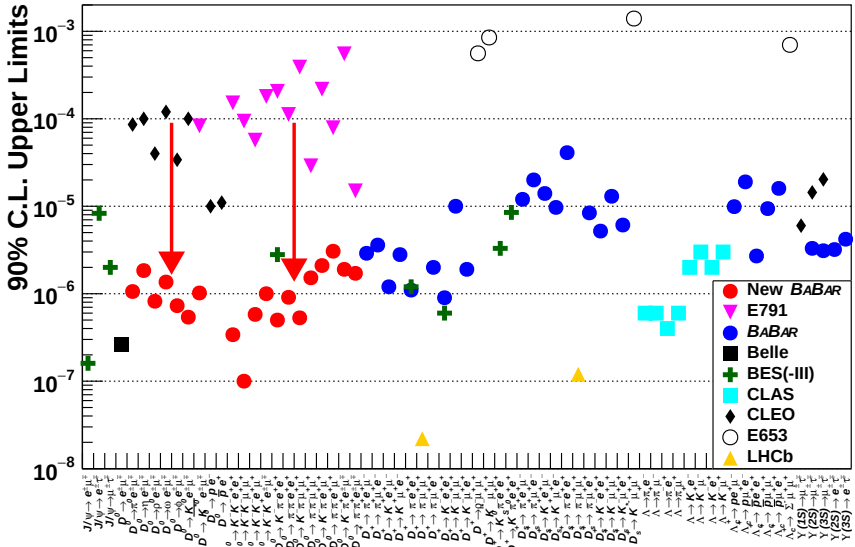


$D^0 \to X^0 e^\pm \mu^\mp$ results (preliminary)

Decay mode	$N_{\rm sig}$ (candidates)	$\epsilon_{\rm sig}$ (%)	$\prod \mathcal{B}_i$ (%)	$\mathcal{B}$ ($\times 10^{-7}$)	$\mathcal{B}^{\rm U.L.}_{90\%}$ ($\times 10^{-7}$) *BABAR*	Previous
$D^0 \to \pi^0 e^\pm \mu^\mp$	$-0.3 \pm 2.0 \pm 0.9$	2.15	98.8	$-0.6 \pm 4.9 \pm 2.3$	8.1	860
$D^0 \to K^0_S e^\pm \mu^\mp$	$0.7 \pm 1.7 \pm 0.7$	3.01	69.2	$1.9 \pm 4.6 \pm 1.9$	8.6	500
$D^0 \to \overline{K}^{*0} e^\pm \mu^\mp$	$0.8 \pm 1.8 \pm 0.8$	2.31	66.6	$2.8 \pm 6.1 \pm 2.6$	12.4	830
$D^0 \to \rho^0 e^\pm \mu^\mp$	$-0.7 \pm 1.7 \pm 0.4$	2.10	100.0	$-1.8 \pm 4.4 \pm 1.0$	5.0	490
$D^0 \to \phi\, e^\pm \mu^\mp$	$0.0 \pm 1.4 \pm 0.3$	3.43	49.2	$0.1 \pm 3.8 \pm 0.9$	5.1	340
$D^0 \to \omega e^\pm \mu^\mp$	$0.4 \pm 2.3 \pm 0.5$	1.46	88.2	$1.8 \pm 9.7 \pm 1.9$	17.3	1200
$D^0 \to \eta e^\pm \mu^\mp$				$6.1 \pm 9.7 \pm 2.3$	23.0	1000
with $\eta \to \gamma\gamma$	$1.6 \pm 2.3 \pm 0.5$	2.96	39.4	$7.0 \pm 10.5 \pm 2.4$	24.0	-
with $\eta \to \pi^+\pi^-\pi^0$	$0.0 \pm 2.8 \pm 0.7$	2.46	22.6	$0.4 \pm 26.1 \pm 6.1$	43.3	-

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

Summary plot of charm LFV and LNV results



Conclusion

$D^0 \to K^-\pi^+e^+e^-$ Phys. Rev. Lett. 122 (2019) 081802 [3]

- The decay $D^0 \to K^-\pi^+e^+e^-$ is observed for the first time.
- In the mass range $0.675 < m(e^+e^-) < 0.875\,\mathrm{GeV}/c^2$:
  - $\mathcal{B}(D^0 \to K^-\pi^+e^+e^-) = (4.0 \pm 0.5 \pm 0.2 \pm 0.1) \times 10^{-6}$.
  - Agrees with $\mathcal{B}(D^0 \to K^-\pi^+\mu^+\mu^-) = (4.17 \pm 0.12 \pm 0.40) \times 10^{-6}$.
- No evidence for deviation from equal lepton-coupling strengths.
- No evidence for short-distance or New Physics effects in the continuum range.

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

- $D^0 \to h'^-h^-\ell'^+\ell^+$, $D^0 \to h'^-h^+e^\pm\mu^\mp$: 12 new $\mathcal{B}^{\mathrm{U.L.}}_{90\%}$ in range $(1.0 - 30.6) \times 10^{-7}$.
- $D^0 \to X^0e^\pm\mu^\mp$: 7 new $\mathcal{B}^{\mathrm{U.L.}}_{90\%}$ in range $(5.0 - 23.0) \times 10^{-7}$.
- One to three orders of magnitude more stringent than previous results.
- arXiv:1905.00608, submitted to PRL [4] and $D^0 \to X^0e^\pm\mu^\mp$ to be submitted to PRD.

References

[1] LHCb Collaboration, R. Aaij *et al.*, *First observation of the decay $D^0 \to K^-\pi^+\mu^+\mu^-$ in the $\rho^0 - \omega$ region of the dimuon mass spectrum*, Phys. Lett. B **757** (2016) 558, arXiv:1510.08367.

[2] 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.

[3] *BABAR* Collaboration, J. P. Lees *et al.*, *Observation of the decay $D^0 \to K^-\pi^+e^+e^-$*, Phys. Rev. Lett. **122** (2019) 081802, arXiv:1808.09680.

[4] *BABAR* Collaboration, J. P. Lees *et al.*, *Search for rare or forbidden decays of the D^0 meson*, arXiv:1905.00608 BABAR-PUB-19-002, SLAC-PUB-17424, arXiv:1905.00608.