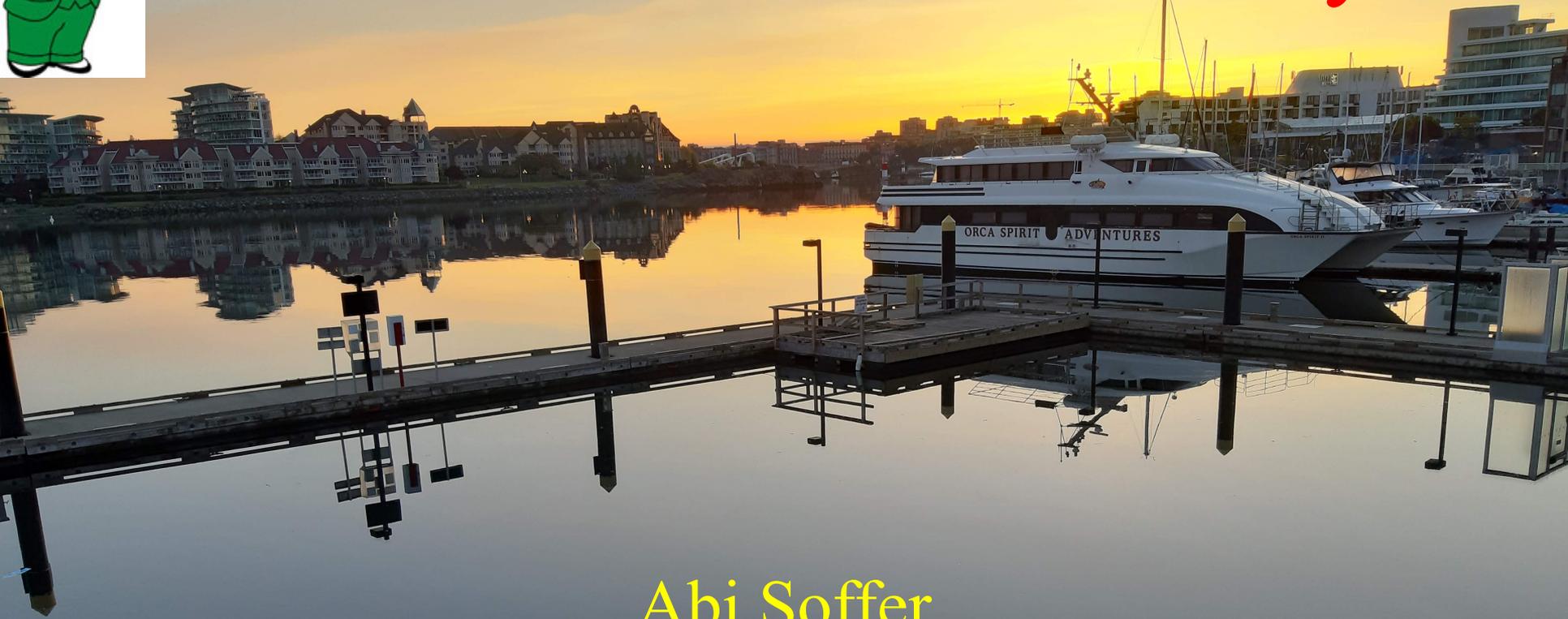


# Rare or forbidden $D^0$ decays

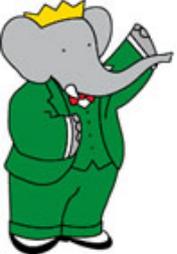


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On behalf of the BABAR Collaboration

FPCP 2019, Victoria



# Outline

- Motivation & overview
- The BABAR experiment and data set
- First observation of  $D^0 \rightarrow K^- \pi^+ e^+ e^-$
- Limits on 12 LFV and LNV  $D^0 \rightarrow hh' \ell \ell'$  modes
- Summary



Not seeing a whale is excluded at  $2\sigma$

# Motivation

- Processes that are very rare or forbidden in the SM are probes of new physics, free of irreducible background.
- $D^0$  decays in this talk:
- **Radiative:**
  - $K^-\pi^+e^+e^-$
  - In SM: suppressed by  $O(\alpha^2)$
- **Lepton-flavor violating (LFV):**
  - $\pi^-\pi^+e^\pm\mu^\mp$ ,  $K^-\pi^+e^\pm\mu^\mp$ ,  $K^-K^+e^\pm\mu^\mp$
  - In SM: via neutrino oscillations,  $\text{Br} < 10^{-50}$
- **Lepton-number violating (LNV):**
  - $\pi^-\pi^-e^+e^+$ ,  $\pi^-\pi^-\mu^+\mu^+$ ,  $\pi^-\pi^-e^+\mu^+$
  - $K^-\pi^-e^+e^+$ ,  $K^-\pi^-\mu^+\mu^+$ ,  $K^-\pi^-e^+\mu^+$
  - $K^-K^-e^+e^+$ ,  $K^-K^-\mu^+\mu^+$ ,  $K^-Ke^+\mu^+$
  - In SM: Forbidden

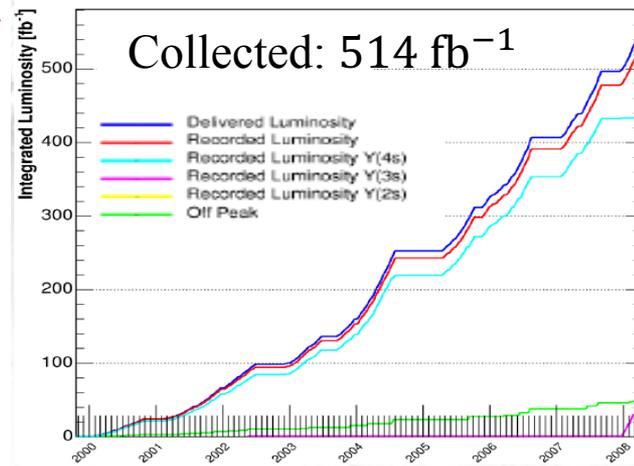
BABAR ref:

PRL 122 (2019) 081802

+charge conjugate

1905.00608  
submitted to PRL

# The BABAR experiment



**Data used for this talk:**

$424 \text{ fb}^{-1}$  on  $\Upsilon(4S)$

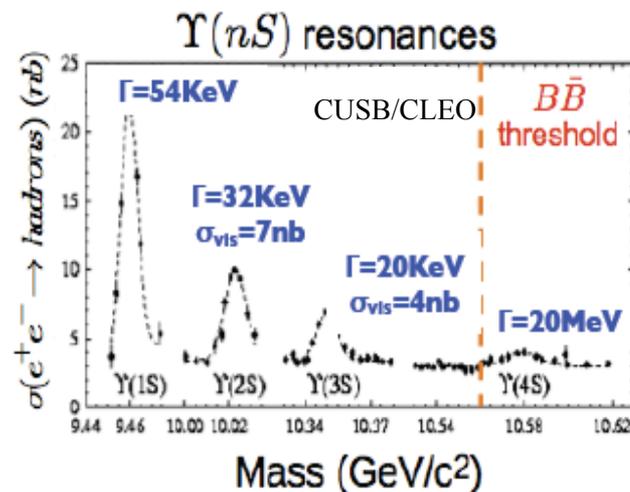
$40 \text{ fb}^{-1}$  off the  $\Upsilon(4S)$

$\sigma(e^+e^- \rightarrow c\bar{c}) = 1.3 \text{ fb}$

583 publications to date,  
10 submitted in 2018:

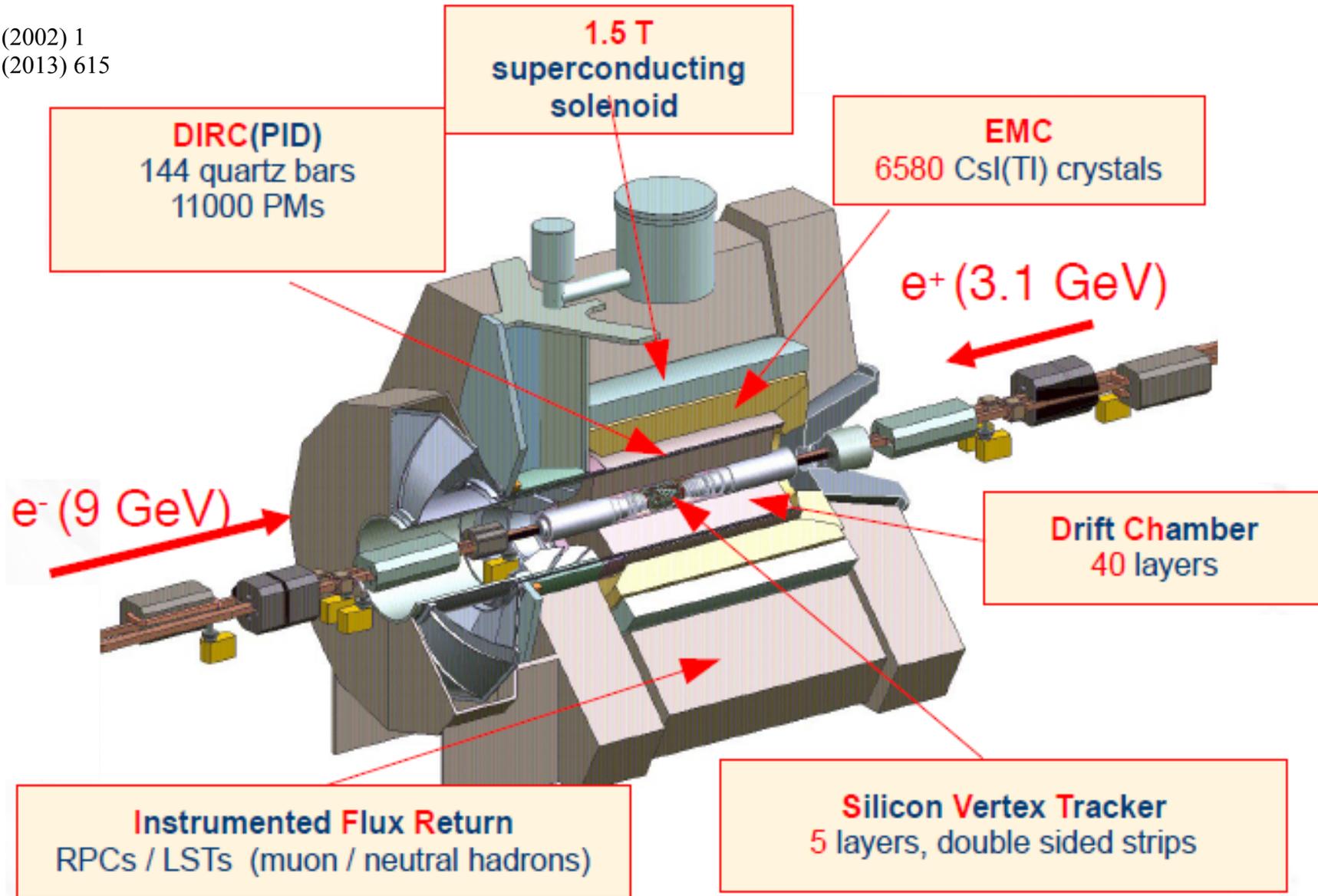
- 3: hadron physics
- 3: B physics & CPV
- 1: tau physics
- 1: rare-charm physics
- 1: bottomonium
- 1: direct NP search

A. Soffer, FPCP 2019



# The BABAR Detector

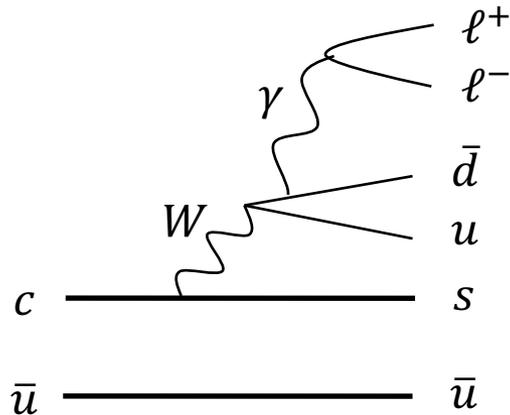
NIM A479 (2002) 1  
NIM A729 (2013) 615



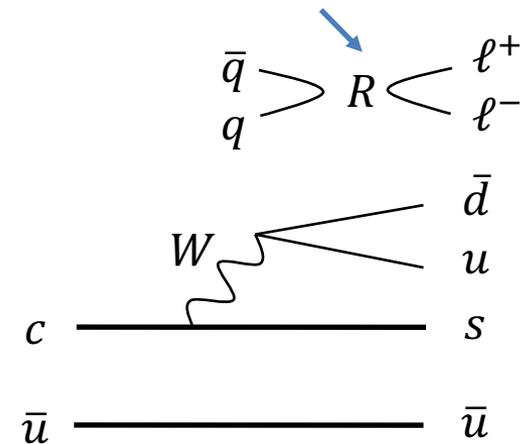
# Observation of $D^0 \rightarrow K^- \pi^+ e^+ e^-$

PRL 122 (2019) 081802

“Short-distance”



“Long-distance ( $R = \rho^0, \omega, \eta, \eta', \phi \dots$ )”



- In the SM: (Cappiello et al, JHEP 1304, 135) find that the LD diagram ( $D^0 \rightarrow \bar{K}^{*0} \rho^0$ ) dominates, expecting  $Br = 1.6 \times 10^{-5}$
- Due to the **4-body decay**, various **asymmetries** (forward-backward, triple-product) can be used to study new physics
- Previous limit (E791, PRL 86, 3969) is  $Br(D^0 \rightarrow K^- \pi^+ e^+ e^-) < 3.85 \times 10^{-4}$
- LHCb (PLB 757, 558) measured  $Br(D^0 \rightarrow K^- \pi^+ \mu^+ \mu^-) = (4.17 \pm 0.12 \pm 0.40) \times 10^{-6}$  in  $675 < m(\mu\mu) < 875$  MeV (i.e.,  $m(\ell\ell) \sim m_\rho$ )

# $D^0 \rightarrow K^- \pi^+ e^+ e^-$ analysis

- Reconstruct  $D^{*+} \rightarrow D^0 \pi^+$   
↳  $K^- \pi^+ e^+ e^-$
- Energy of photons radiated from the electrons is added to the  $D^0$  candidate
- $m(ee) > 200$  MeV to reject photon conversion and  $D^0 \rightarrow K^- \pi^+ \pi^0$   
↳  $e^+ e^- \gamma$
- Particle identification (PID) is applied to the tracks
- Discard  $D^0$  candidates if mass is consistent with 4-hadron decay
- $D^0$  momentum in center-of-mass frame  $> 2.4$  GeV

- Fit for a signal peak over a polynomial background in the variables

$$m_D \equiv m(K^- \pi^+ e^+ e^-)$$

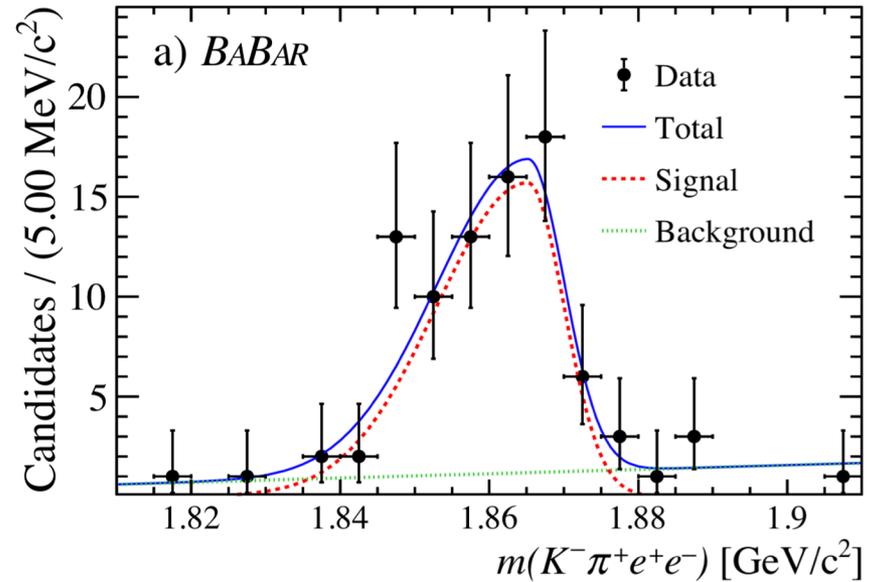
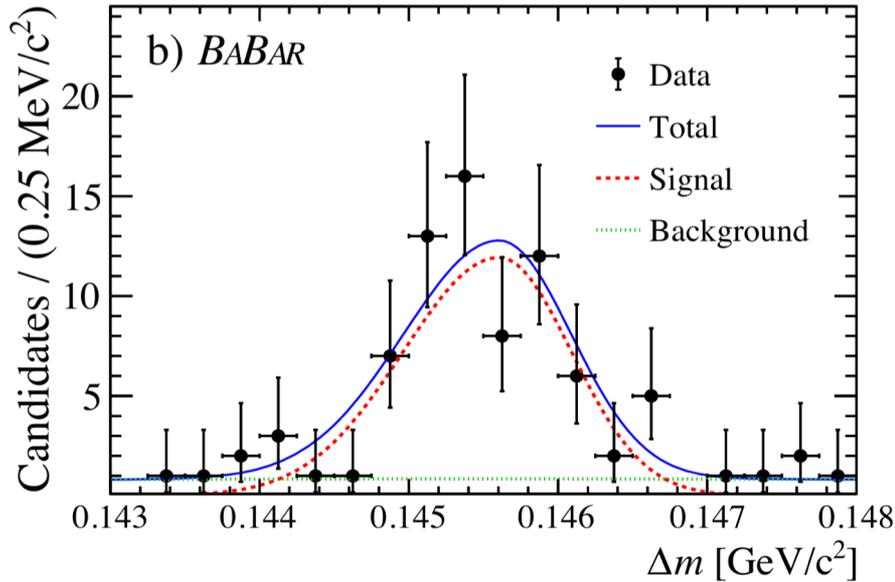
$$\Delta m = m_{D^*} - m_D$$

which are uncorrelated,

fit function = 2-sided normal dist. (“bifurcated gaussian”)  $e^{-(x-x_0)^2/2\sigma_{L,R}^2}$

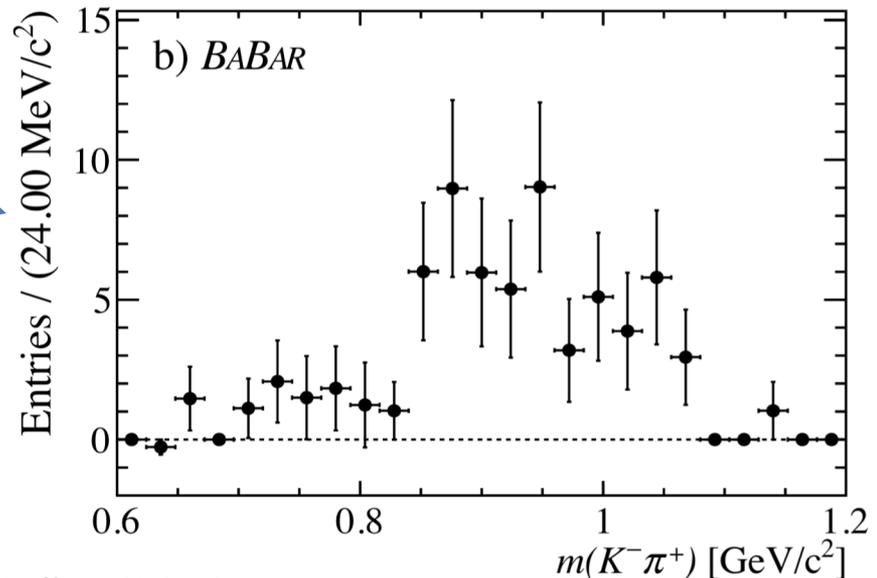
- Br measured wrt. the “normalization” mode  $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$ ,  
which is reconstructed in a similar way

# Fit in $675 < m(ee) < 685$ MeV



Signal  $m(K\pi)$  distribution  
using SPlot (NIM A555, 356)

- $K^* \rightarrow K^- \pi^+$  dominance seen
- Consistent with theory and with LHCb's  $D^0 \rightarrow K^- \pi^+ \mu^+ \mu^-$  results



# Results for $Br(D^0 \rightarrow K^- \pi^+ e^+ e^-)$

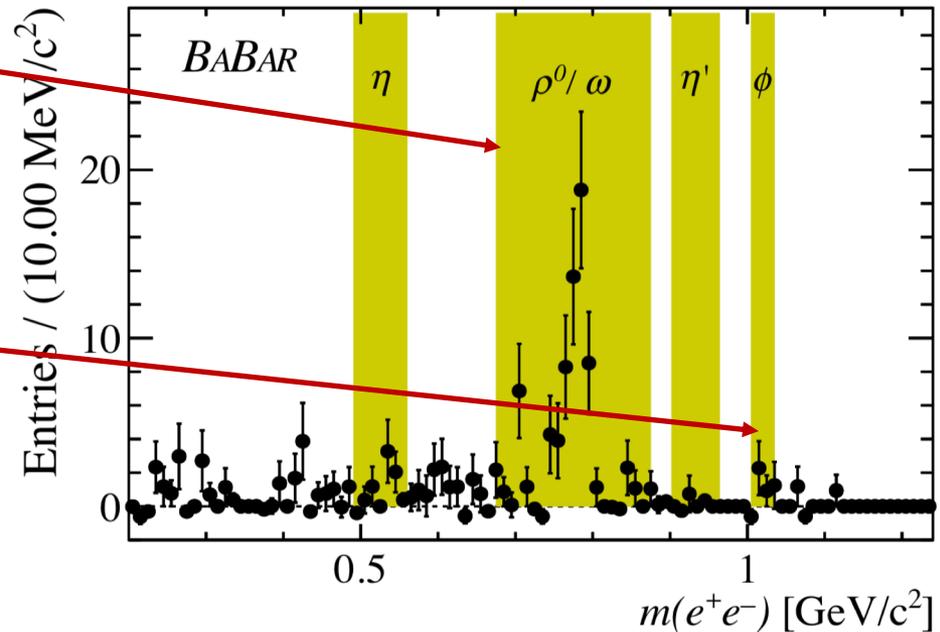
Signal  $m(ee)$  distribution (Splot)

- For  $m(ee) \in [675, 875]$  MeV:  
 $Br = (4.0 \pm 0.5 \pm 0.2 \pm 0.1) \times 10^{-6}$

PDG uncert. on  $Br(D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-)$

- For  $m(ee) \in [1005, 1035]$  MeV:  
 $Br = (0.11^{+0.15}_{-0.11} \pm 0.06) \times 10^{-6}$

- Significance =  $1.8\sigma$
- 90% CL UL:  $Br < 0.5 \times 10^{-6}$



- For  $m(ee)$  in the non-resonant range (unshaded):

- Cleaner probe of short-distance contributions (and hence new physics)
- $19 \pm 7$  events after subtraction of  $9.9 \pm 0.9$  events expected from the  $\rho^0$  tail
- $Br = (1.6 \pm 0.6 \pm 0.7) \times 10^{-6}$ , Significance =  $2.6\sigma$
- 90% CL UL:  $Br < 3.1 \times 10^{-6}$
- First study of  $D^0 \rightarrow K^- \pi^+ \ell^+ \ell^-$  in non-resonant region

# $D^0 \rightarrow hh' \ell \ell'$ : LFV & LNV



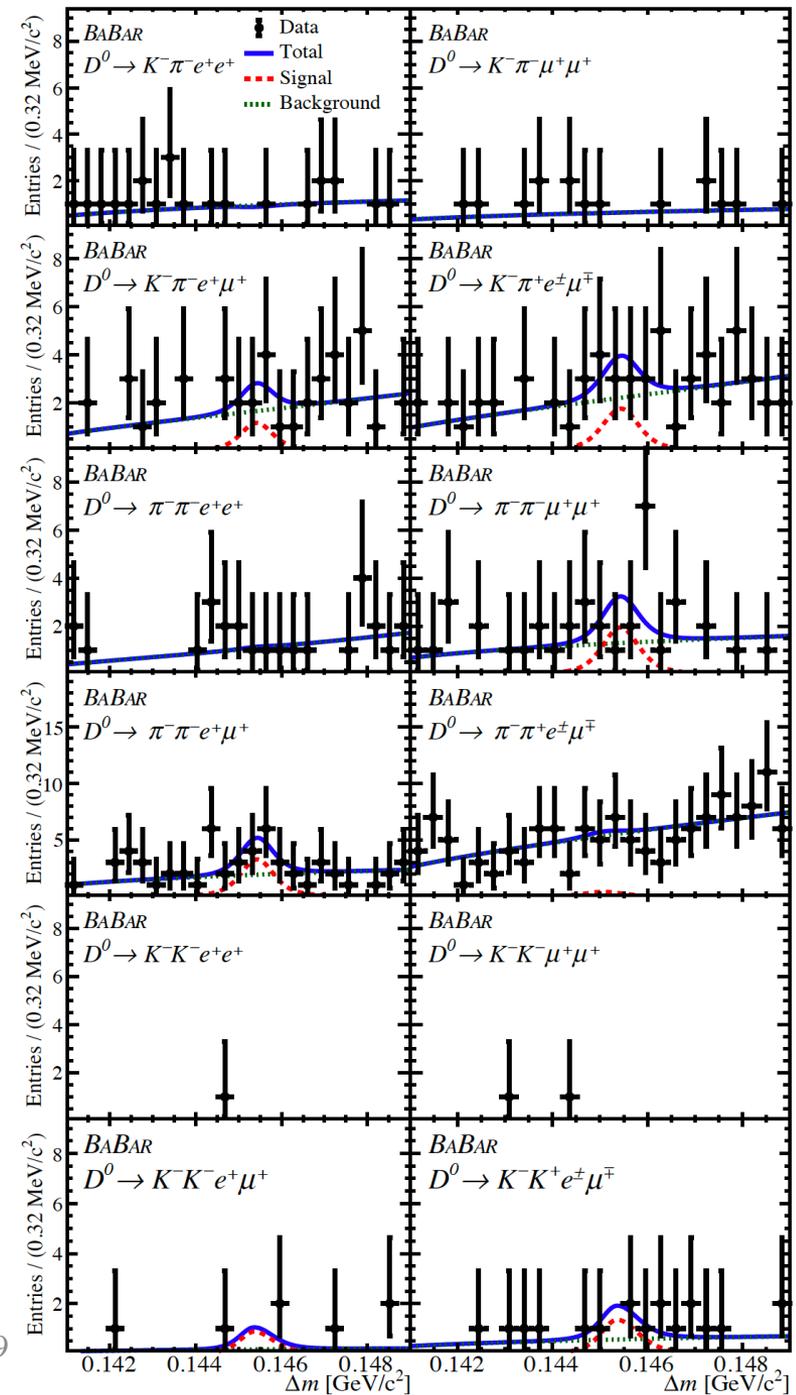
$\underbrace{hh'}_{K/\pi} \quad \underbrace{\ell\ell'}_{e/\mu}$

[arXiv:1905.00608](https://arxiv.org/abs/1905.00608)

- **Lepton-flavor violating (LFV):**
  - $\pi^- \pi^+ e^\pm \mu^\mp$ ,  $K^- \pi^+ e^\pm \mu^\mp$ ,  $K^- K^+ e^\pm \mu^\mp$
- **Lepton-number violating (LNV):**
  - $\pi^- \pi^- e^+ e^+$ ,  $\pi^- \pi^- \mu^+ \mu^+$ ,  $\pi^- \pi^- e^+ \mu^+$
  - $K^- \pi^- e^+ e^+$ ,  $K^- \pi^- \mu^+ \mu^+$ ,  $K^- \pi^- e^+ \mu^+$
  - $K^- K^- e^+ e^+$ ,  $K^- K^- \mu^+ \mu^+$ ,  $K^- K e^+ \mu^+$
- Similar selections to those shown earlier, and:
- Background from  $e^+ e^- \rightarrow$  multi-leptons: suppressed with PID cuts on the  $hh'$
- Background from semileptonic charm decays in which a hadron is misidentified as a lepton: suppressed with a Fisher discriminant of 9 kinematic & event-shape variables.

# $D^0 \rightarrow hh'\ell\ell'$ yields

- Signal yield determined for each mode from fit to  $\Delta m$  distribution
- Fit function =  $e^{-(x-x_0)^2}/[2\sigma_{L,R}^2 + \alpha_{L,R}(x-x_0)^2]$  (“Cruiff” function)
- No significant signal seen
- Signal Br and upper limits determined wrt. normalization mode  $D^0 \rightarrow hh'\pi\pi$





# $D^0 \rightarrow hh' \ell \ell'$ Br limits

- BABAR results:

E791, PRL 86 3969 (2001)

Decay mode $D^0 \rightarrow$	$N_{\text{sig}}$ (candidates)	$\epsilon_{\text{sig}}$ (%)	$\mathcal{B}$ ( $\times 10^{-7}$ )	$\mathcal{B}$ 90% U.L. ( $\times 10^{-7}$ )	Previous best limit ( $\times 10^{-7}$ )
$\pi^- \pi^- e^+ e^+$	$0.22 \pm 3.15 \pm 0.54$	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	$15.4 \pm 6.59 \pm 1.85$	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	2060
$K^- \pi^- \mu^+ \mu^+$	$-0.03 \pm 2.10 \pm 0.40$	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	950
$K^- K^- e^+ \mu^+$	$1.93 \pm 1.92 \pm 0.83$	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

# Summary

- First observation of  $D^0 \rightarrow K^- \pi^+ e^+ e^-$ 
  - Dominated by the “long-distance” decay  $D^0 \rightarrow K^{*0} \rho^0$ , as expected
  - In  $m(\ell\ell) \sim m_\rho$  region:  $\text{Br} = (4.0 \pm 0.5 \pm 0.2 \pm 0.1) \times 10^{-6}$
  - Consistent with lepton universality wrt. LHCb’s result  
 $\text{Br}(D^0 \rightarrow K^- \pi^+ \mu^+ \mu^-) = (4.17 \pm 0.12 \pm 0.40) \times 10^{-6}$
  - SM expectation  $\sim 1.6 \times 10^{-5}$
  - In the non-resonant region (more sensitive to “short-distance” interactions) we find  $\text{Br} < 3.1 \times 10^{-6}$
- New limits on 3 LFV and 9 LNV  $D^0 \rightarrow hh' \ell\ell'$  decays
  - Between 8 and 735 times tighter than previous limits set by E791