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Search for forbidden decays of the D^0 meson and observation of $D^0 \to K^- \pi^+ e^+ e^-$

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On behalf of the BaBar collaboration

Motivation

- Processes that are very rare or forbidden in the Standard Model are powerful probes of new physics

- Radiative decays: suppressed by $O(\alpha^2)$
  - $D^0 \to K^-\pi^+e^+e^-$

PRL 122 (2019) 081802

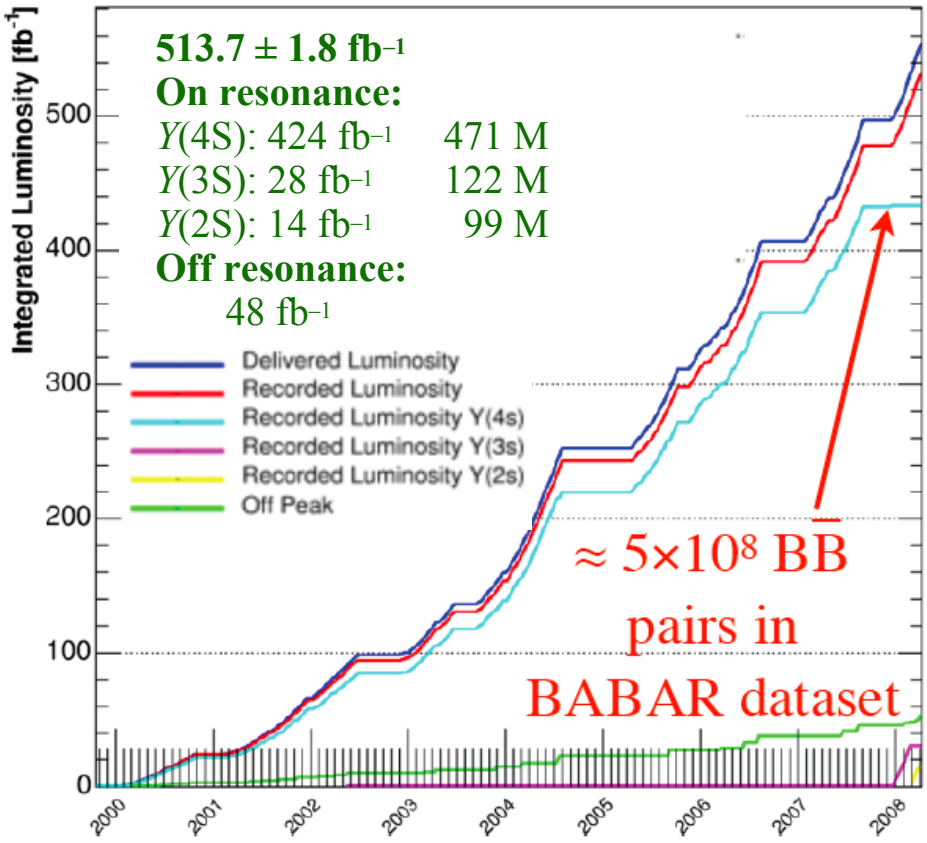
- Lepton-flavor violating (LFV): only allowed via neutrino oscillation, BF ~ 10^{-50}
  - $D^0 \to \pi^-\pi^+e^\pm\mu^\mp$
  - $D^0 \to K^-\pi^+e^\pm\mu^\mp$
  - $D^0 \to K^-K^+e^\pm\mu^\mp$

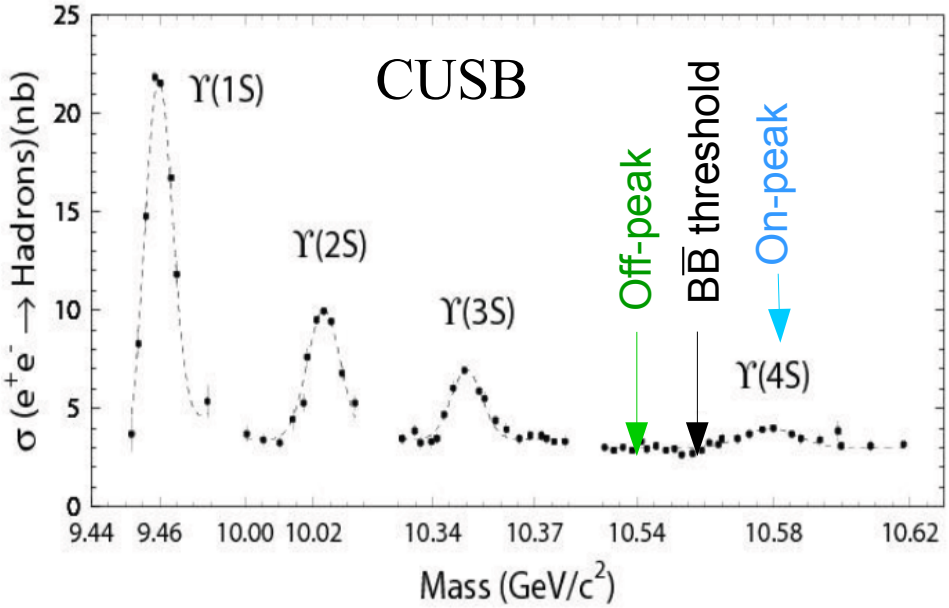
arXiv:1905.00608 [hep-ex]

- Lepton-number violating (LNV): forbidden
  - $D^0 \to \pi^-\pi^-e^+e^+$, $\pi^-\pi^-\mu^+\mu^+$, $\pi^-\pi^-e^+\mu^+$
  - $D^0 \to K^-\pi^-e^+e^+$, $K^-\pi^-\mu^+\mu^+$, $K^-\pi^-e^+\mu^+$
  - $D^0 \to K^-K^-e^+e^+$, $K^-K^-\mu^+\mu^+$, $K^-K^-e^+\mu^+$

The BaBar experiment

- Asymmetric B Factory experiment at SLAC-National Accelerator Laboratory
- Collected data from 1999 until 2008
  - Most of the time at Y(4S), “on peak”
  - About 1/10 non-resonant “off peak”
  - Smaller sample at Y(2S) and Y(3S)



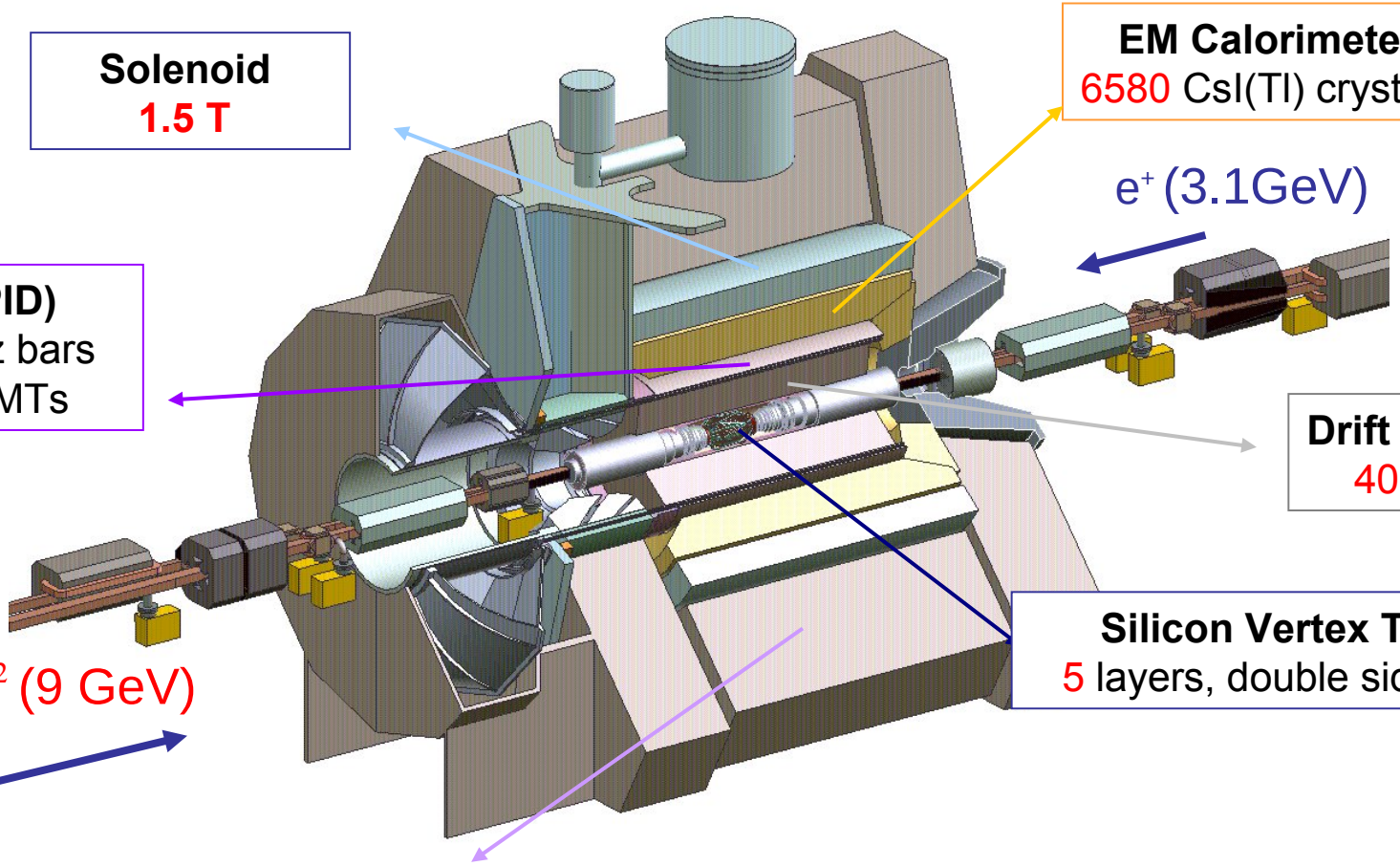


- 470 x 10^6 $B\bar{B}$ pairs
- 600 x 10^6 $e^+e^- \rightarrow c\bar{c}$

Process	Cross section (nb)
bb	1.1
cc	1.3
light quark qq	~2.1
ττ	0.9
ee	~40

The BaBar Detector

Detector optimized for B vertex separation and momentum measurement, K-π particle identification and precision calorimetry



Solenoid
1.5 T

EM Calorimeter
6580 CsI(Tl) crystals

e^+ (3.1GeV)

DIRC (PID)
144 quartz bars
11000 PMTs

Drift Chamber
40 layers

Silicon Vertex Tracker
5 layers, double sided strips

e^2 (9 GeV)

Instrumented Flux Return
iron / RPCs (muon / neutral hadrons)

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

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

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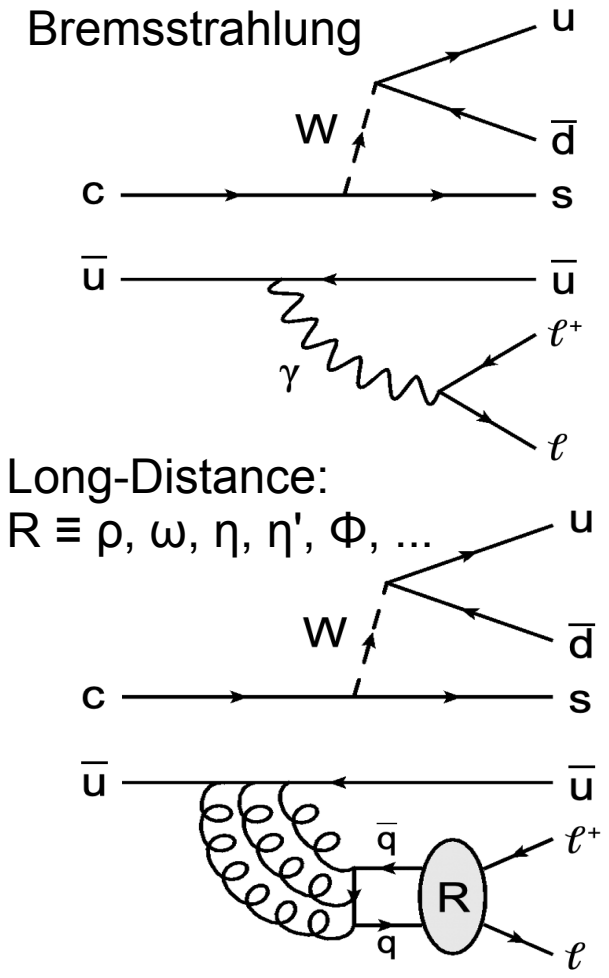
- Radiative D decay, suppressed by $O(\alpha^2)$
- In Standard Model, BF($D^0 \to K^-\pi^+\ell^+\ell^-$) ~ 1.6×10^{-5}
  - Dominated by LD contributions $D \to K^{*0}\rho^0$

    Cappiello et al. JHEP 1304,135 (2013)



- Because it is a 4-body decay, various asymmetry can be measured to study new physics: angular analysis, forward-backward, triple-product
- Previous measurements by E791:
  - BF($D^0 \to K^-\pi^+e^+e^-$)<38.5 x 10^{-5} PRL86,3969 (2001)
- Recent LHCb measurement of muonic mode PLB 757, 558 (2016):
  - BF($D^0 \to K^-\pi^+\mu^+\mu^-$)=(4.16 ± 0.12 ± 0.40) x 10^{-6}
  - In 675 < m($\mu^+\mu^-$) < 875 MeV (around the mass region of the ρ meson)

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

- Reconstruct D^0 from $D^{*+} \to D^0\pi^+$
- 5 charged track in the final state
  - Particle identification criteria to all tracks
  - Veto events consistent with $D^0 \to$ 4-hadrons decays
    - using $m_D = m(K^-\pi^+\pi^+\pi^-)$ (i.e. assigning π mass to electrons)
  - $m(e^+e^-)>200$ MeV to reject conversions and Dalitz decays in $D \to K\pi\pi^0$ (with $\pi^0 \to e^+e^-\gamma$)
  - $P(D^0) > 2.4$ GeV (center-of-mass frame) to reject D mesons from B decays
  - Bremsshtrahlung recovery algorithm applied to electron candidates adding energy of nearby calorimeter clusters to the D^0 candidate

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

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- Measure branching fraction relative to $D^0 \to K^-\pi^+\pi^+\pi^-$ which is reconstructed in a similar way: cancellation of tracking and (some) particle identification systematics

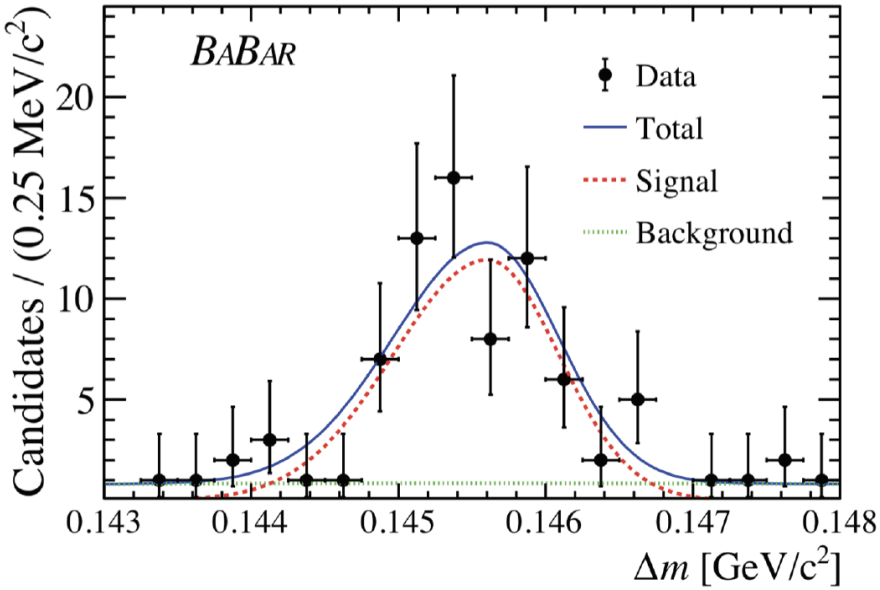
$$\frac{\mathcal{B}(D^0 \to K^-\pi^+e^+e^-)}{\mathcal{B}(D^0 \to K^-\pi^+\pi^+\pi^-)} = \frac{\hat{\epsilon}_{\rm norm}}{N_{\rm norm}} \frac{\mathcal{L}_{\rm norm}}{\mathcal{L}_{\rm sig}} \sum_i^{N_{\rm sig}} \frac{1}{\epsilon^i_{\rm sig}}$$

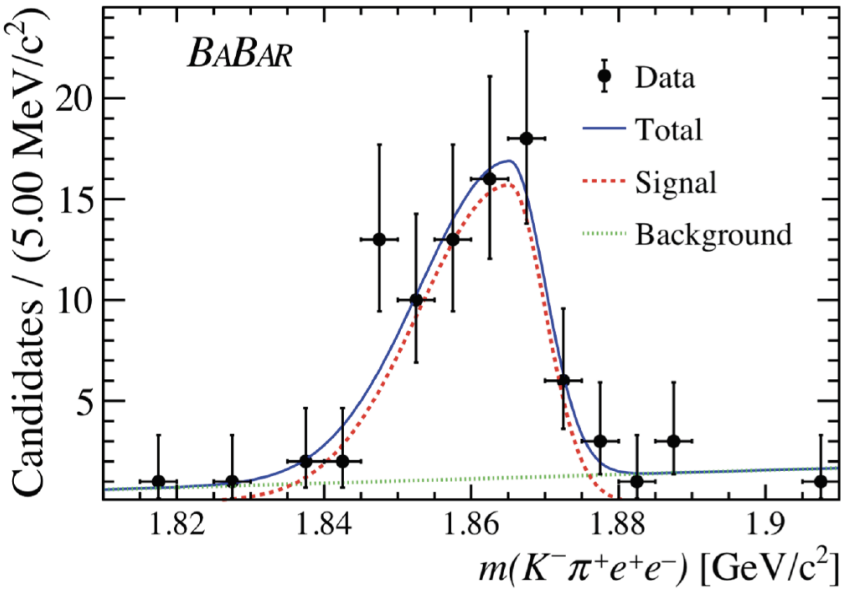
- Signal extracted by a 2-D fit in the variables

$m_D = m(K^-\pi^+e^+e^-)$ and $\Delta m = m_{D^*} - m_D$

Signal: double-sided Gaussian
Background: polynomial function

- In the fit range $675 < m(e^+e^-) < 875$ MeV





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

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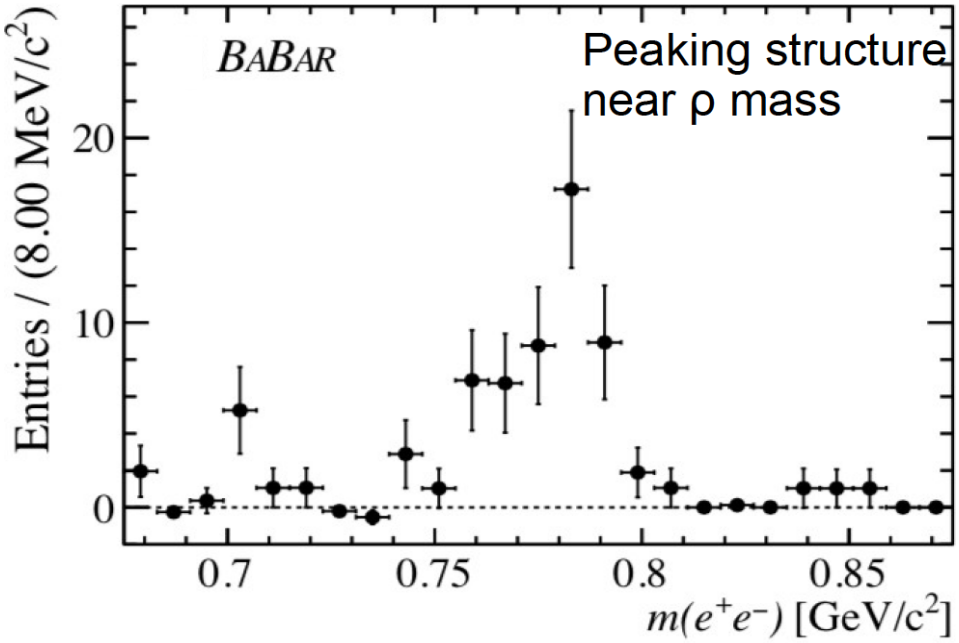
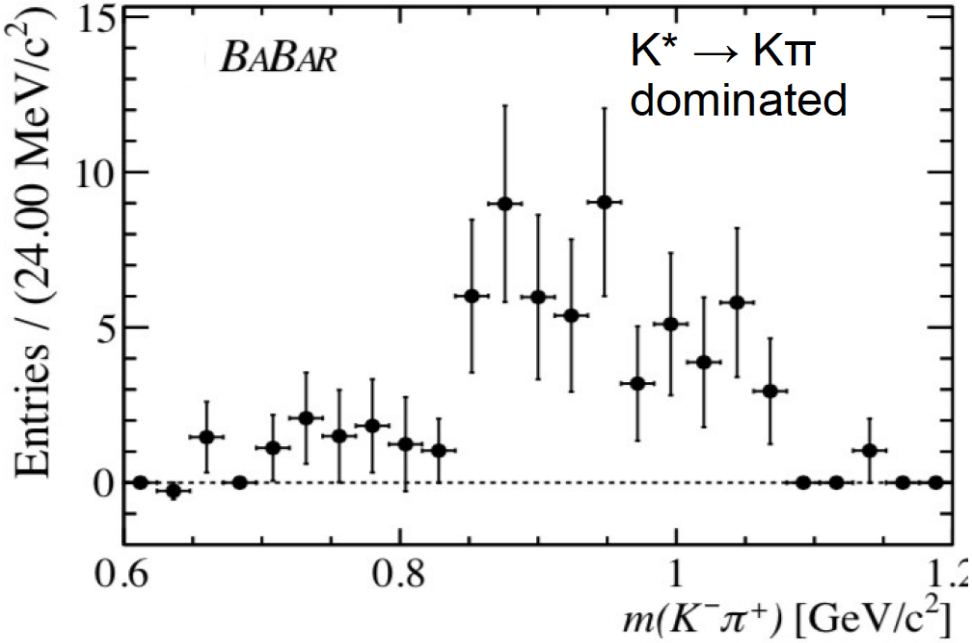
- Projection of signal fit to $m(e^+e^-)$ and $m(K^-\pi^+)$
  - Background subtracted using sPlot technique





$BF(D^0 \to K^-\pi^+e^+e^-) = (4.0 \pm 0.5 \pm 0.2 \pm 0.1) \times 10^{-6}$ $\quad 675 < m(e^+e^-) < 875$ MeV

Consistent with theory and with LHCb results
on $D^0 \to K^-\pi^+\mu^+\mu^-$ in the same $m(\ell^+\ell^-)$ range

$D^0 \to K^-\pi^+e^+e^-$: other $m(e^+e^-)$ regions

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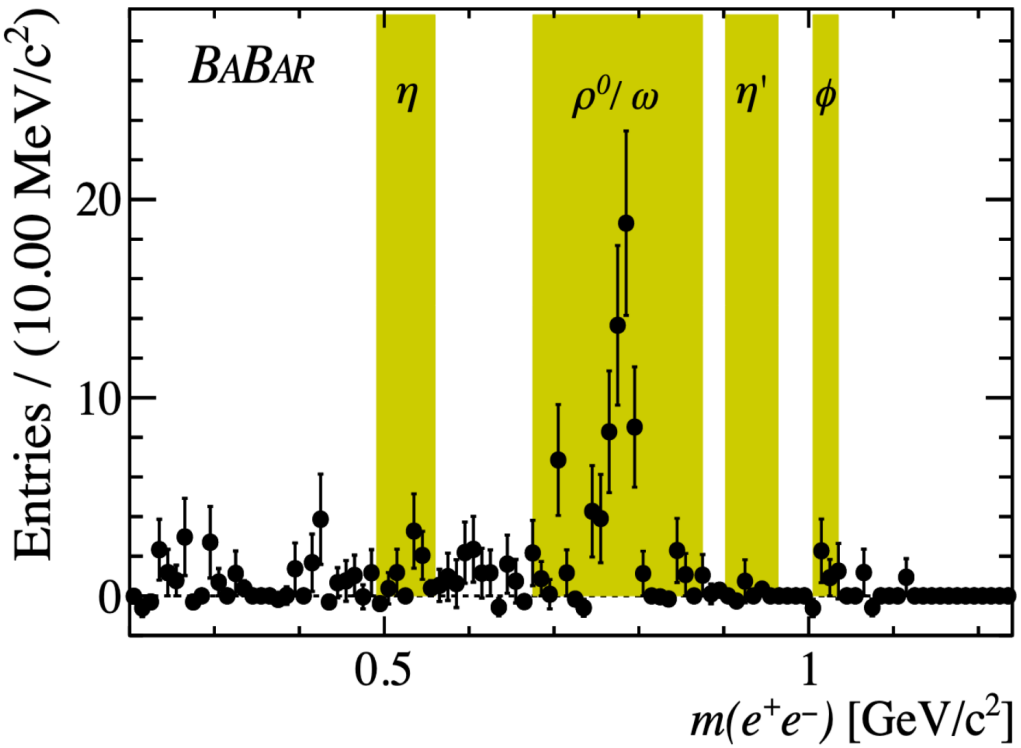
- For $m(e^+e^-)$ in Φ mass region
  - $1005 < m(e^+e^-) < 1035$ MeV

$BF(D^0 \to K^-\pi^+e^+e^-) = (0.22\ ^{+0.15}_{-0.11} \pm 0.06) \times 10^{-6}$

$BF(D^0 \to K^-\pi^+e^+e^-) < 0.5 \times 10^{-6}$ at 90% CL

Background subtracted (sPlot)



- For $m(e^+e^-)$ in the non-resonant mass windows (non-shaded regions in plot)
  - Cleaner probe of short-distance contributions (and hence new physics)
  - 19 ± 7 events after subtraction of 9.9 ± 0.9 events expected from the ρ^0 tail

$BF(D^0 \to K^-\pi^+e^+e^-) = (1.6 \pm 0.6 \pm 0.7) \times 10^{-6}$
$BF(D^0 \to K^-\pi^+e^+e^-) < 3.1 \times 10^{-6}$ at 90% CL

First study in the non-resonant region

$D^0 \to hh'\ell\ell'$

$D^0 \to hh'\ell\ell'$

arXiv:1905.00608 [hep-ex]

- Similar selection used for the forbidden LFV and LNV decay search
  - $D^{*+} \to D^0\pi^+$
  - $D^0 \to h\, h'\, \ell\ell'$ where h= K, π and ℓ = e, μ

- Lepton-flavor violating (LFV)
  - $D^0 \to \pi^-\pi^+e^\pm\mu^\mp$
  - $D^0 \to K^-\pi^+e^\pm\mu^\mp$
  - $D^0 \to K^-K^+e^\pm\mu^\mp$
- Lepton-number violating (LNV)
  - $D^0 \to \pi^-\pi^-e^+e^+$, $\pi^-\pi^-\mu^+\mu^+$, $\pi^-\pi^-e^+\mu^+$
  - $D^0 \to K^-\pi^-e^+e^+$, $K^-\pi^-\mu^+\mu^+$, $K^-\pi^-e^+\mu^+$
  - $D^0 \to K^-K^-e^+e^+$, $K^-K^-\mu^+\mu^+$, $K^-K^-e^+\mu^+$

Measured relative to corresponding normalization modes

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

$D^0 \to hh'\ell\ell'$: selection

arXiv:1905.00608 [hep-ex]

- Veto events consistent with $D^0 \to$ 4-hadrons decays
  - using $m_D = m(K^-\pi^+\pi^+\pi^-)$ (i.e. assigning π mass to electrons)
- Background from $e^+e^- \to$ multi-leptons suppressed by PID on hh'
- Significant background from semileptonic charm decays in which a hadron is misidentified as a lepton
- Fisher discriminant using kinematic and event shape variables
  - 90% signal efficiency

- Signal extracted from a fit to Δm after cutting on m_D around nominal D mass

$m_D = m(h\ h'\ \ell\ell')$

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

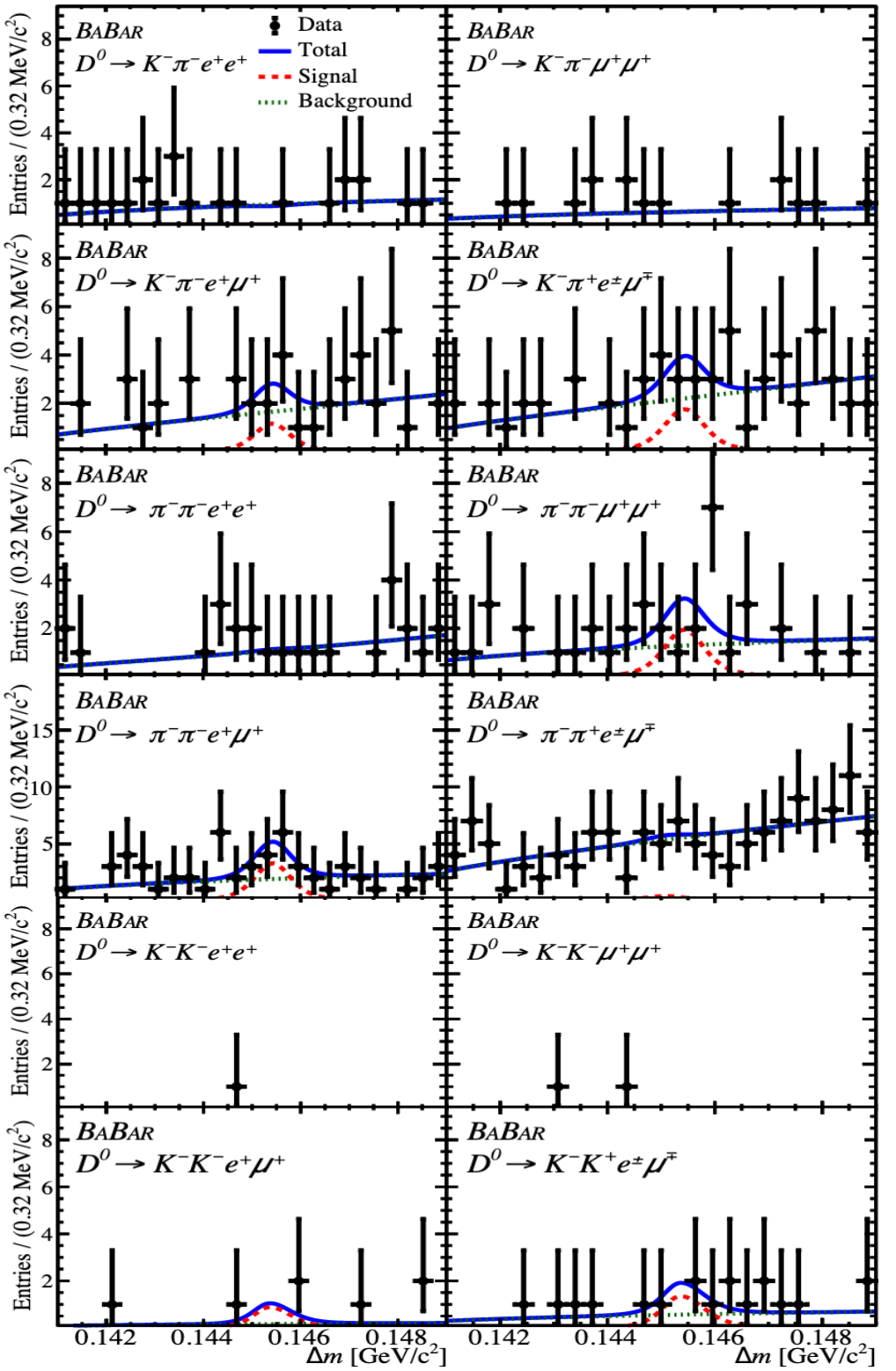
(2 e) 1.848
(1 e) 1.852
(0 e) 1.856
} < m(D) < 1.874 GeV

0.141 < Δm < 0.201 GeV (2 K)
0.141 < Δm < 0.149 GeV (<2 K)

$D^0 \to hh'\ell\ell'$: fit results

- After all selection criteria: < 100 events per signal mode
- Signal yield determined for each mode from unbinned ML fit to Δm
  - Signal: Cruijff function
    - F(x)= $e^{-(x-x_0)^2/[2\sigma_{L,R}^2+\alpha_{L,R}(x-x_0)^2]}$
  - Background: Argus function
- No significant signal seen
- Signal Upper limits determined compared with normalization modes

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



$D^0 \to hh'\ell\ell'$: BF limits

arXiv:1905.00608 [hep-ex]

From E791
PRL 86 3969 (2001)

Decay mode $D^0 \to$	N_{sig} (candidates)	ϵ_{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

Improvements of 1-3 order of magnitude on BF limits

Summary

- New BaBar results from searches for rare and forbidden charm decays
- First observation of $D^0 \to K^-\pi^+e^+e^-$
  - BF($D^0 \to K^-\pi^+e^+e^-$) = (4.0 ± 0.5 ± 0.2 ± 0.1) x 10^{-6} in the rho mass range
    - Consistent with LHCb for BF($D^0 \to K^-\pi^+\mu^+\mu^-$)
  - Non-resonant BF($D^0 \to K^-\pi^+e^+e^-$) < 3.1 x 10^{-6} at 90% CL
- Limits on 12 LFV and LNV decays $D^0 \to h\, h'\, \ell\ell'$
  - BF limits ranging from (1 – 30) x 10^{-7}
  - Improvements over previous limits of 1-3 order of magnitudes