Observation of the rare charm decay $D^0 \to K^-\pi^+e^+e^-$

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Introduction: $D^0 \to h'^- h^+ e^+ e^-$

- Rare charm decays $D^0 \to h'^- h^+ e^+ e^-$ and $D^0 \to h'^- h^+ \mu^+ \mu^-$ ($h/h' = K$ or π) are allowed in the Standard Model but are 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.
- With enough candidates, can start to do angular analyses and compare with theory predictions.
- Lepton Universality: Do electrons and muons couple with equal strength?
- LHCb: $\mathcal{B}(D^0 \to K^- \pi^+ \mu^+ \mu^-) = (4.17 \pm 0.12 \pm 0.40) \times 10^{-6}$ [PLB 757 (2016) 558].

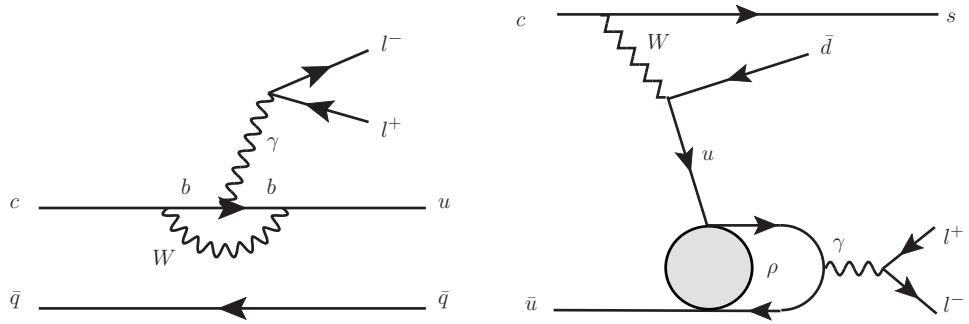
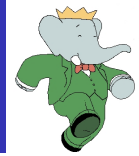


Figure: (left): Examples of Short (Penguin) and Long (VMD) distance decays.

Method



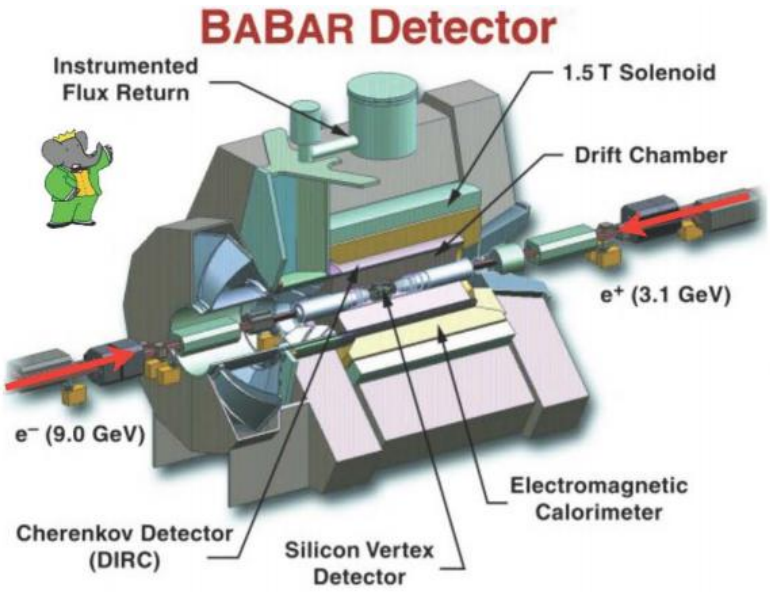
- Start with $D^{*+} \to D^0 \pi^+$ produced in $e^+e^- \to c\bar{c}$ continuum.
- Reconstruct signal $D^0 \to K^-\pi^+e^+e^-$ and normalization $D^0 \to K^-\pi^+\pi^+\pi^-$.
- Maximum Likelihood Fit to $m(D^0)$ and $\Delta m = m(D^{*+}) - m(D^0)$.
- Apply candidate-by-candidate reconstruction efficiencies and normalize to $D^0 \to K^-\pi^+\pi^+\pi^-$ to determine $D^0 \to K^-\pi^+e^+e^-$ branching fraction:

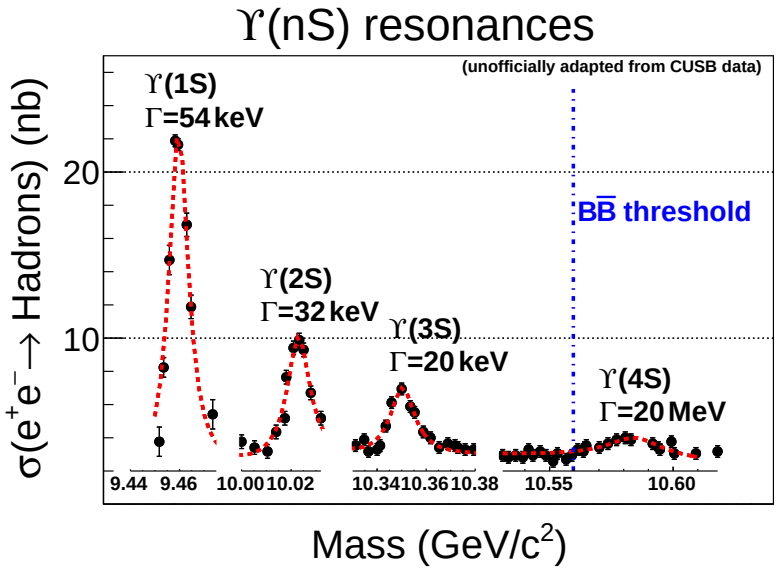
$$\frac{\mathcal{B}(D^0 \to K^-\pi^+e^+e^-)}{\mathcal{B}(D^0 \to K^-\pi^+\pi^+\pi^-)} = \frac{\hat{\epsilon}_{D^0 \to K^-\pi^+\pi^+\pi^-}}{N_{D^0 \to K^-\pi^+\pi^+\pi^-}} \frac{\mathcal{L}_{D^0 \to K^-\pi^+\pi^+\pi^-}}{\mathcal{L}_{D^0 \to K^-\pi^+e^+e^-}} \sum_i^{N_{D^0 \to K^-\pi^+e^+e^-}} \frac{1}{\epsilon^i_{D^0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

where $\mathcal{B}$ is the branching fraction, N is the yield, ϵ is the selection efficiency, and $\mathcal{L}$ is the integrated luminosity.

BABAR Detector at PEP-II

Asymmetric beam momenta ($E_{e^-} = 9.0\,\mathrm{GeV}, E_{e^+} = 3.1\,\mathrm{GeV}$), low multiplicity, low background, K/π particle identification, good μ and e identification with wide coverage.





Data Sample: 1999-2008

Charm production cross-section $\sim 1.6\,\mathrm{nb}$.

On-Peak data: $\sim 424\,\mathrm{fb}^{-1}$ at the $\Upsilon(4S)$.

Off-Peak data: $\sim 44\,\mathrm{fb}^{-1}$ at $40\,\mathrm{MeV}$ below the $\Upsilon(4S)$.

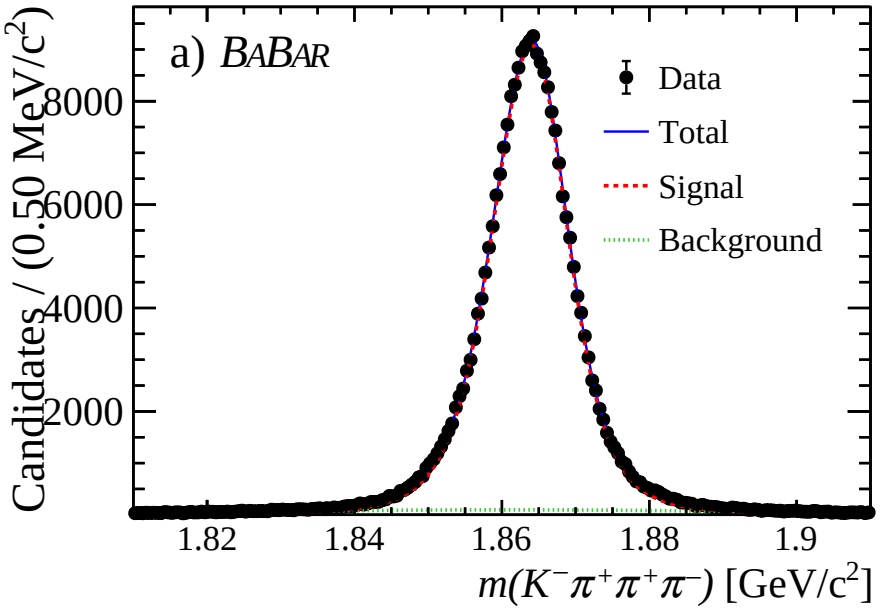
Selection

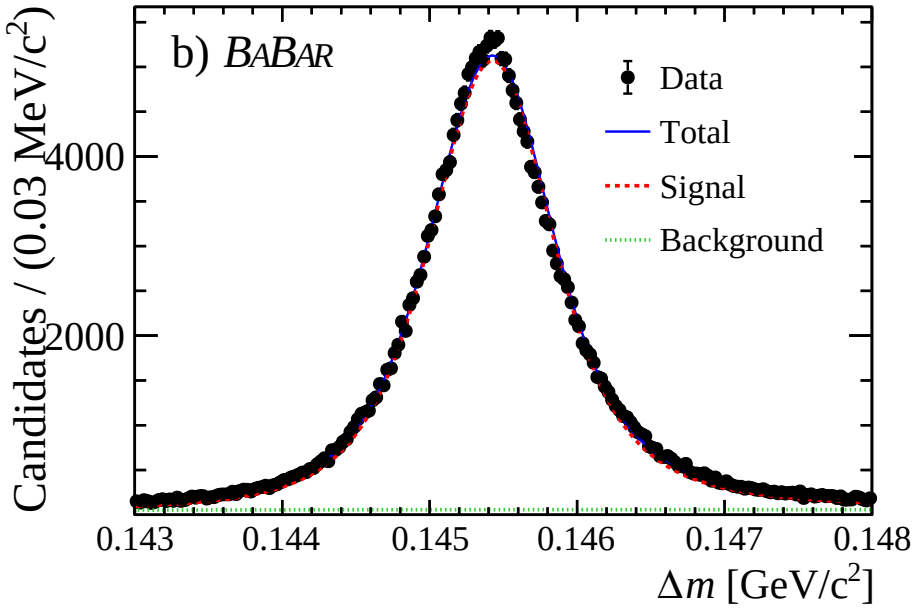
- Form a D^0 vertex from 4 tracks with appropriate mass hypothesis and particle identification.
- Combine D^0 and slow π^+ to form D^{*+}.
- Kaon charge opposite the slow π charge.
- Momentum of the slow pion in the laboratory frame, $p_{\pi_s} > 0.1\,\mathrm{GeV}/c$.
- Momentum of D^0 in the center-of-mass frame, $p^*_{D^0} > 2.4\,\mathrm{GeV}/c$.
  - This removes any charm decays from B-mesons $\Rightarrow$ we can use both on-peak and off-peak data.
- $m_{e^+e^-} > 0.1\,\mathrm{GeV}/c^2$.
- $0.143 < \Delta m < 0.148\,\mathrm{GeV}/c^2$
- $1.81 < m(D^0) < 1.91\,\mathrm{GeV}/c^2$.
- Replace e/μ mass hypothesis with K/π mass, reconstruct D^{*+} decay chain, and reject whole event if pass Δm and $m(D^0)$ criteria.

Maximum Likelihood Fit

- Maximum-Likelihood Fit to $m(D^0)$ and Δm. Fit range:
  - $1.81 < m(D^0) < 1.91\,\mathrm{GeV}/c^2$.
  - $0.143 < \Delta m < 0.148\,\mathrm{GeV}/c^2$.
- Probability Density Functions (PDFs):
  - Use asymmetric peaking functions for signal and normalization modes.
    - Signal mode: Bifurcated Gaussian for both $m(D^0)$ and Δm.
    - Normalization mode: Two Cruijff functions with shared mean for Δm and a single Cruijff for $m(D^0)$.
  - For backgrounds, use ARGUS functions for Δm and Chebychev polynomials for $m(D^0)$.
  - Other functions and ranges used as a cross-check.
- All parameters allowed to float except for ARGUS end-point.
- Apply candidate-by-candidate reconstruction efficiencies and normalise to $D^0 \to K^-\pi^+\pi^+\pi^-$ to determine $D^0 \to K^-\pi^+e^+e^-$ branching fraction.

Normalization Mode: $D^0 \to K^-\pi^+\pi^+\pi^-$ (data)

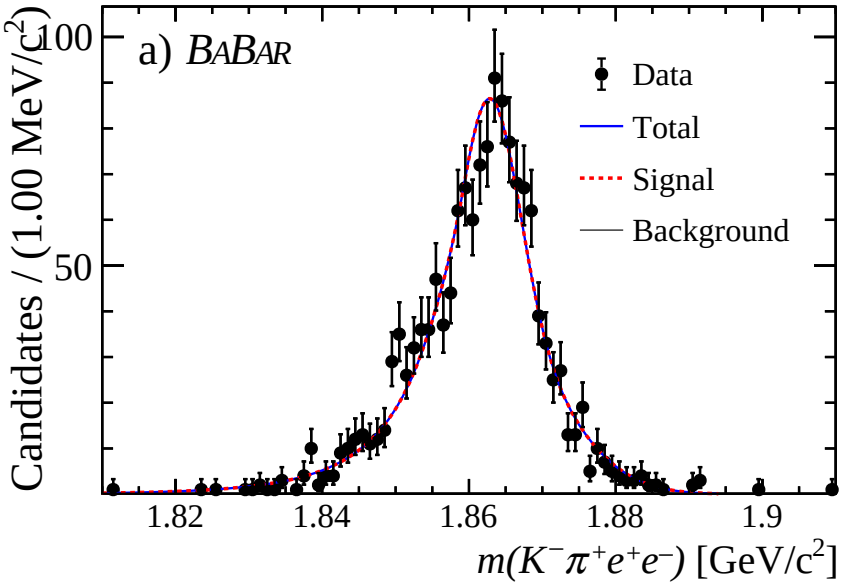


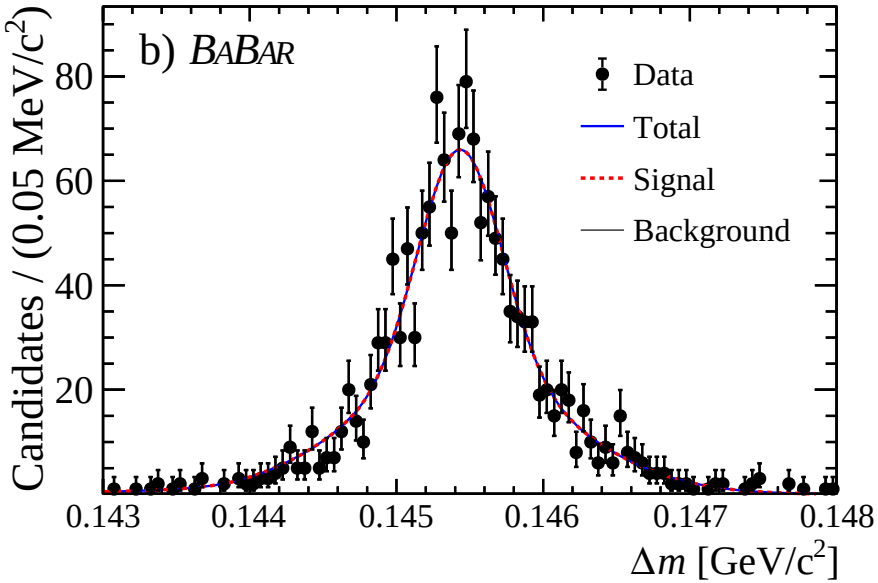


Fitted Yields on data:

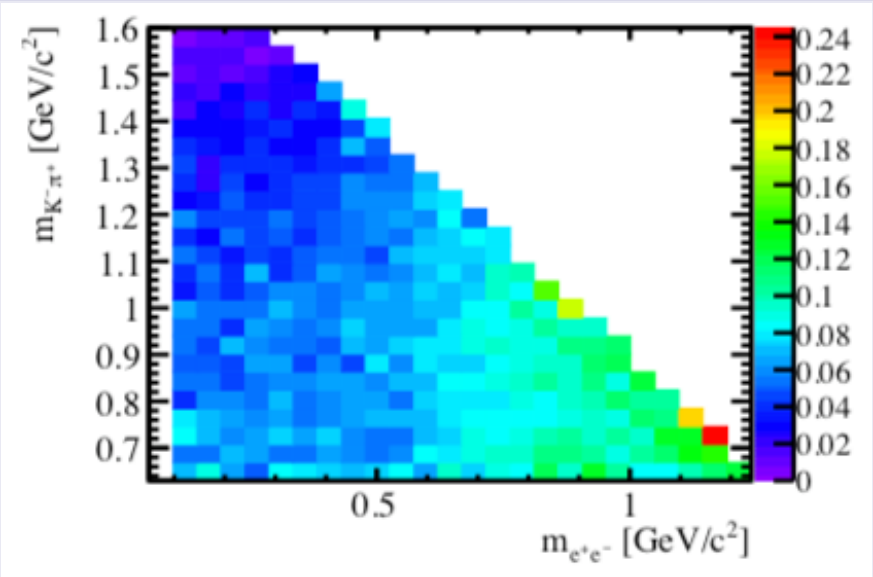
Decay mode $D^0 \to$	$N_{\rm norm}$ (candidates)	Syst. (%)	$\epsilon_{\rm norm}$ (%)
$K^-\pi^+\pi^-\pi^+$	$260\,870 \pm 520$	4.7	20.1 ± 0.2

Signal Mode: $D^0 \to K^-\pi^+e^+e^-$ (Simulation)



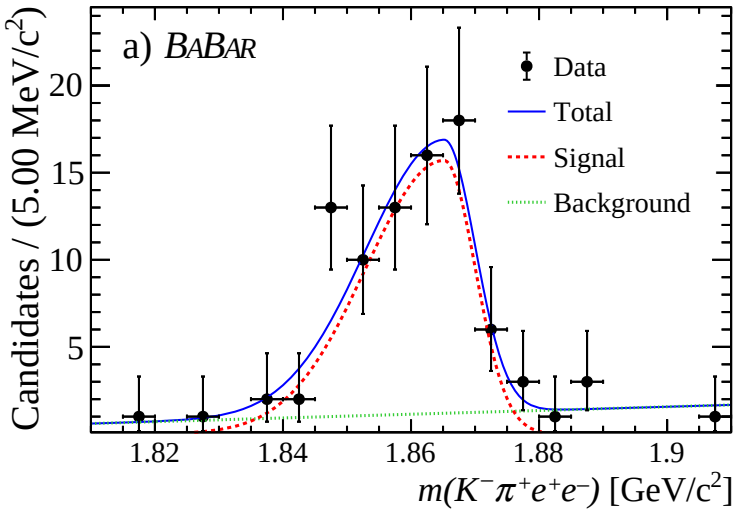


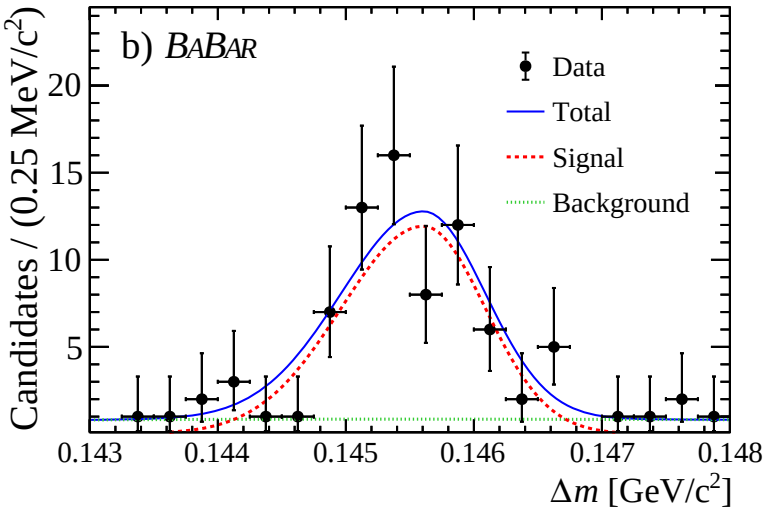
Reconstruction efficiency for $m(e^+e^-)$ and $m(K^-\pi^+)$

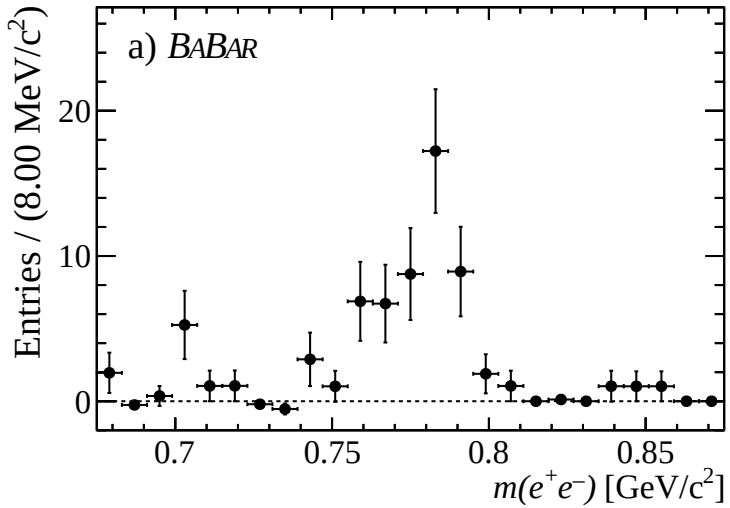


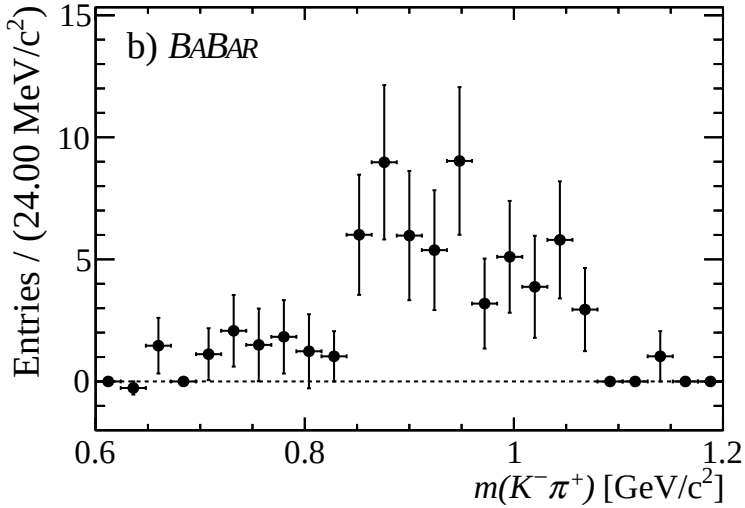
$D^0 \to K^-\pi^+e^+e^-$: $0.675 < m(e^+e^-) < 0.875\,\mathrm{GeV}/c^2$

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

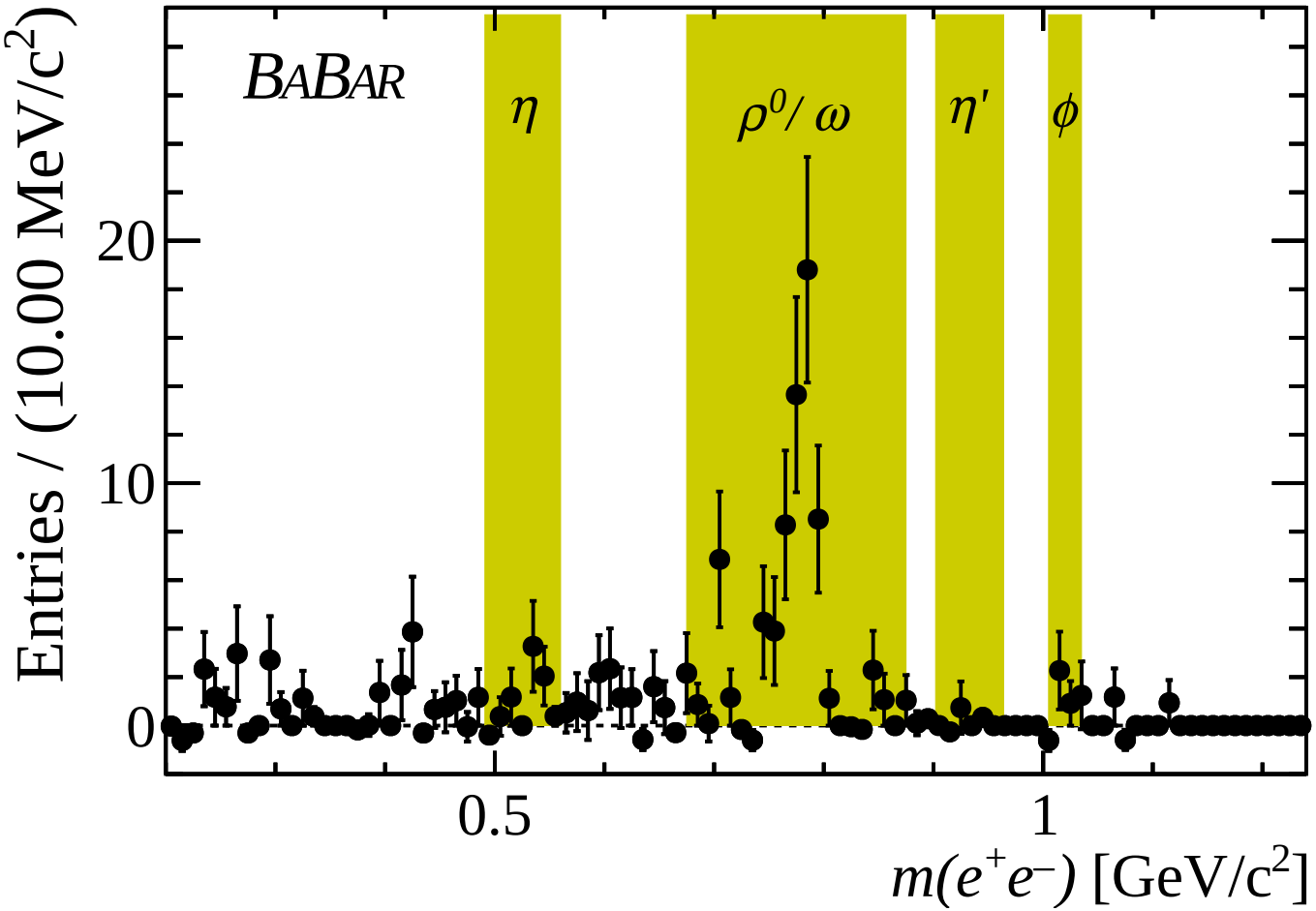








$D^0 \to K^-\pi^+e^+e^-$: $m(e^+e^-) > 0.2\,\mathrm{GeV}/c^2$



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

Yellow = resonance regions excluded from continuum.

$N_{sig} = 19 \pm 7$ candidates (continuum region)

$N_{sig} = 3.8^{+2.7}_{-1.9}$ candidates (ϕ region)

$D^0 \to K^-\pi^+e^+e^-$ Branching Fractions and Limits

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

Uncertainties: Statistical $\pm$ Systematic $\pm$ Normalization $\mathcal{B}$.

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

Conclusion

- The decay $D^0 \to K^-\pi^+e^+e^-$ has been observed for the first time.
- In the mass range $0.675 < m(e^+e^-) < 0.875\,\mathrm{GeV}/c^2$:
  - 68 ± 9 candidates with a significance 9.7σ.
  - $m(e^+e^-)$ and $m(K^-\pi^+)$ distributions similar to results seen in $D^0 \to K^-\pi^+\mu^+\mu^-$.
  - $\mathcal{B}(D^0 \to K^-\pi^+e^+e^-) = (4.0 \pm 0.5 \pm 0.2 \pm 0.1) \times 10^{-6}$.
  - 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.
- Upper limits placed on branching fraction in ϕ region.
- No evidence for short-distance or new physics effects in the continuum range.
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