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

Fergus Wilson

Particle Physics Department
Rutherford Appleton Laboratory/STFC
United Kingdom

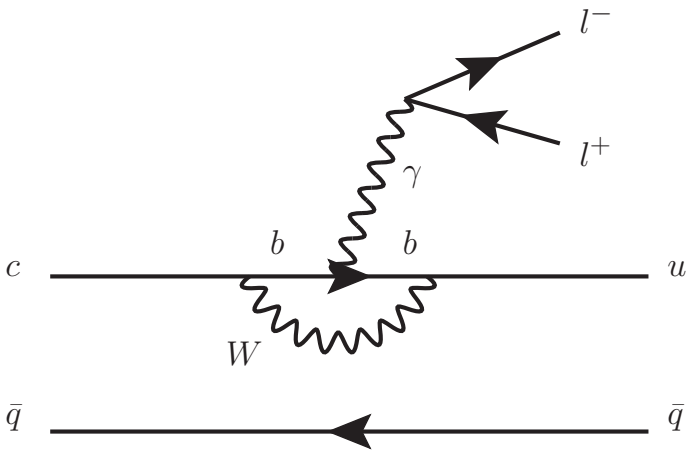
On behalf of the *BABAR* collaboration

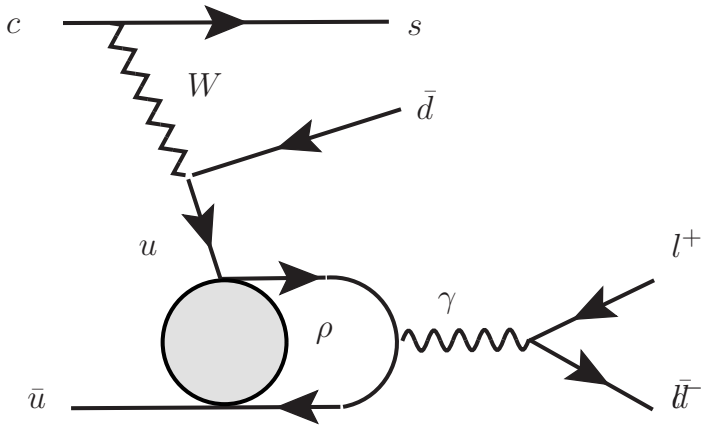
ICHEP 2018, Seoul

7^{th} July 2018

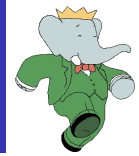
Introduction: $D^0 \to h'^- h^+ e^+ e^-$

- Flavor-changing neutral currents (FCNC) are expected to be very rare in charm decays.
- Short-distance contributions can occur at the one-loop level but are small:
  - Glashow-Iliopoulos-Maiani (GIM) cancellation almost exact.
  - Quark masses in the loop are small.
- Long-distance contributions can be several order of magnitude larger.
- 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].





Method

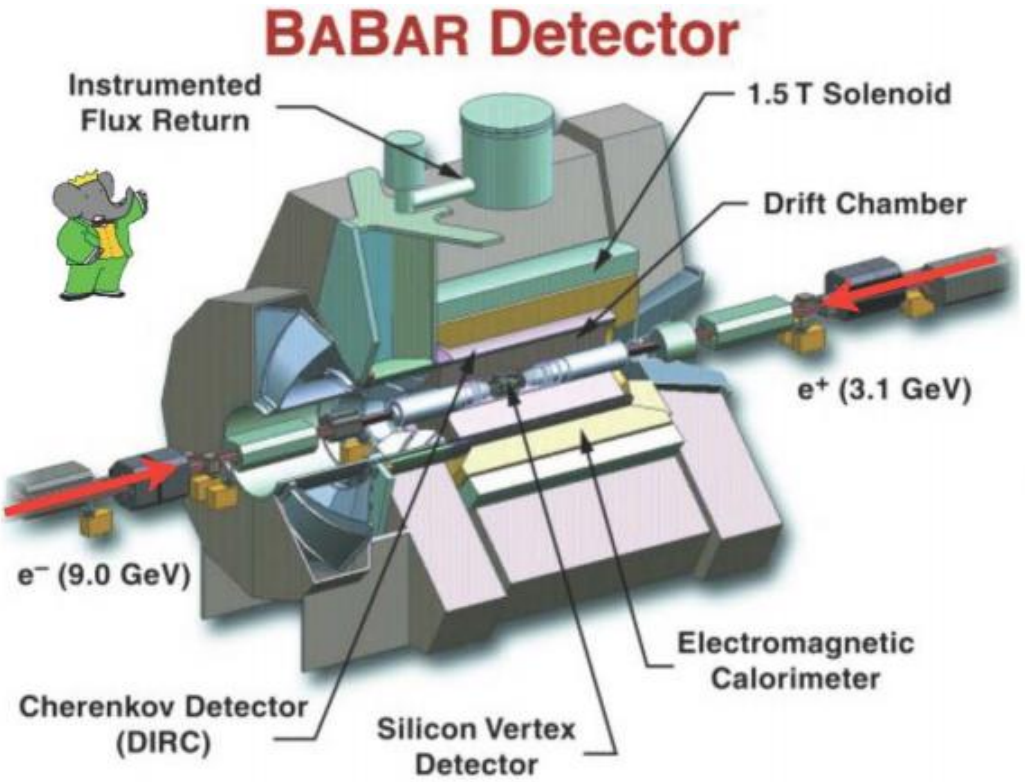


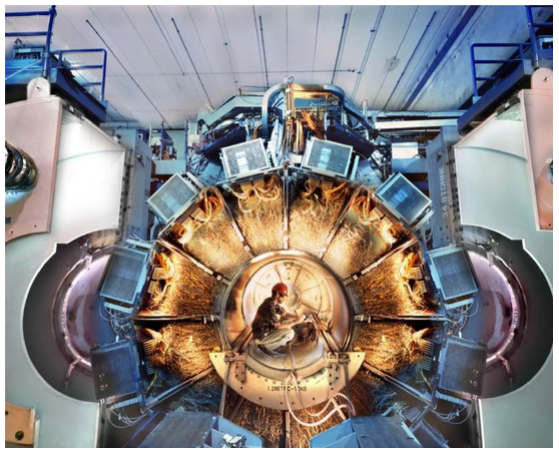
- Blinded analysis.
- Reconstruct $D^0 \to K^-\pi^+e^+e^-$ and $D^0 \to K^-\pi^+\pi^-\pi^+$ from $D^{*+} \to D^0\pi^+$ produced in $c\overline{c}$ continuum.
- Maximum-Likelihood Fit to m(D^0) and $\Delta m = m(D^{*+}) - m(D^0)$.
- Apply candidate-by-candidate reconstruction efficiencies and normalize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

$$\frac{\mathcal{B}(D^0 \to K^-\pi^+e^+e^-)}{\mathcal{B}(D^0 \to K^-\pi^+\pi^-\pi^+)} = \frac{N^{D^0\to K^-\pi^+e^+e^-}}{N^{D^0\to K^-\pi^+\pi^-\pi^+}} \frac{\epsilon^{D^0\to K^-\pi^+\pi^-\pi^+}}{\epsilon^{D^0\to K^-\pi^+e^+e^-}} \frac{\mathcal{L}^{D^0\to K^-\pi^+\pi^-\pi^+}}{\mathcal{L}^{D^0\to K^-\pi^+e^+e^-}}$$

BABAR Detector at PEP-II

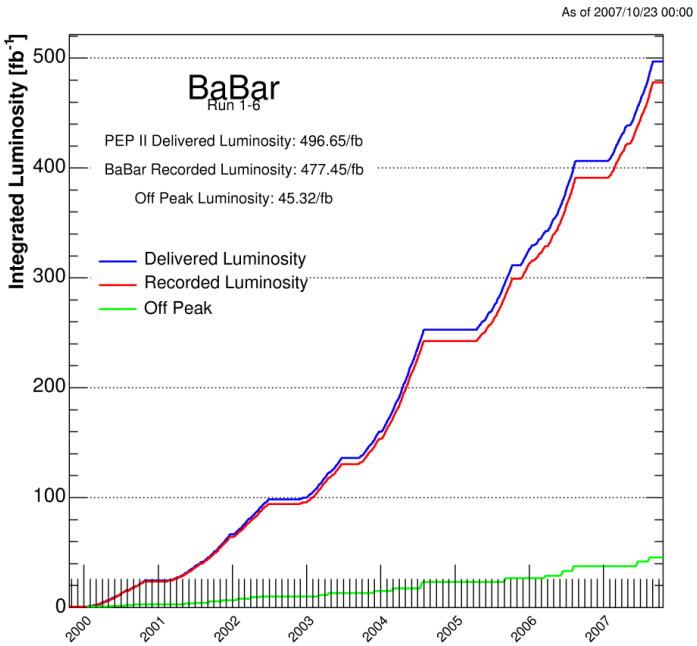
Asymmetric beam momenta, $\Upsilon(nS)$ production, low multiplicity, low background, K/π particle identification, good μ and e identification with wide coverage.

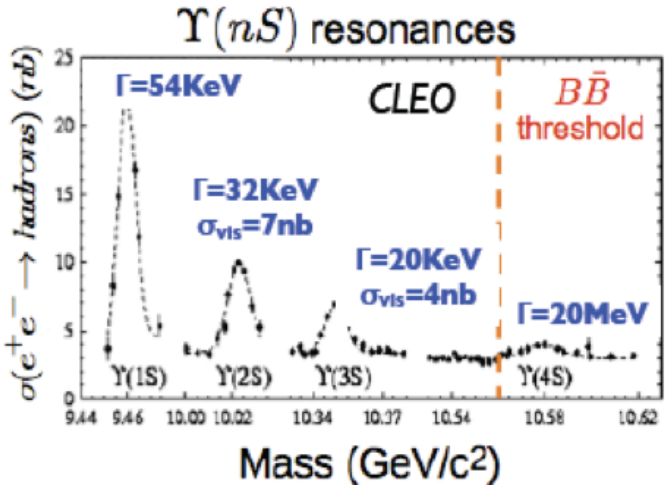




Data sample

Data-taking period: 1999-2008
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 $\Upsilon(4S)$.
Signal $D^0 \to K^-\pi^+e^+e^-$ data : On-Peak + Off-Peak.
Normalization $D^0 \to K^-\pi^+\pi^-\pi^+$ data: Off-Peak.





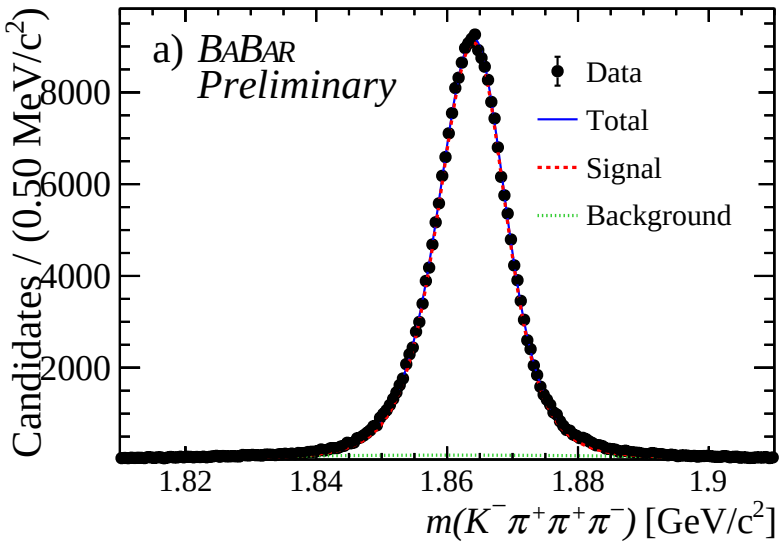
Selection

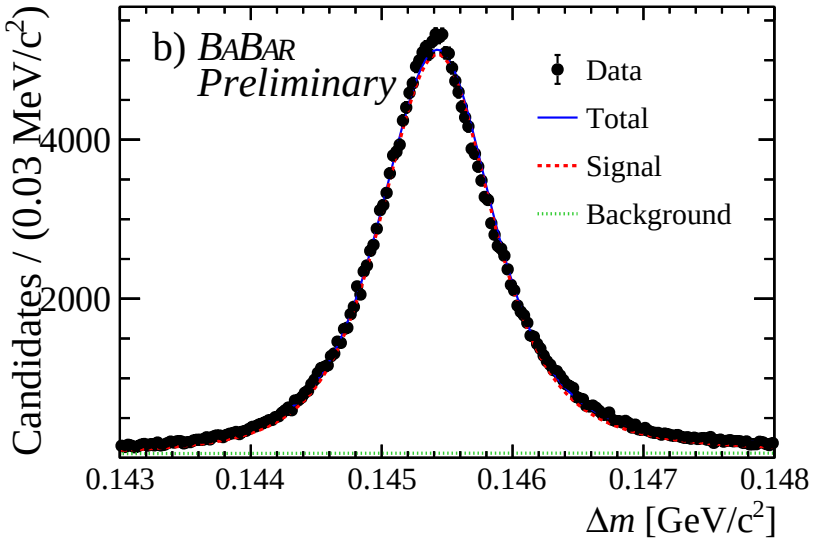
- Form a D^0 vertex from 4 tracks with appropriate mass hypothesis and particle identification.
- Combine D^0 and slow π^+ to form D^{*+}.
- Kaon charge opposite the slow π charge.
- Momentum of the slow pion in the laboratory frame, $p_{\pi_s} > 0.1\,\mathrm{GeV}/c$.
- Momentum of D^0 in the center-of-mass frame, $p^*_{D^0} > 2.4\,\mathrm{GeV}/c$.
- Per-event D^0 decay time error, $\sigma_t < 0.5\,\mathrm{ps}$.
- $m_{e^+e^-} > 0.1\,\mathrm{GeV}/c^2$.
- $0.143 < \Delta m < 0.148\,\mathrm{GeV}/c^2$, where $\Delta m = m_{D^{*+}} - m_{D^0}$.
- $1.81 < m_{D^0} < 1.91\,\mathrm{GeV}/c^2$.
- Reject events with cross-feed from $D^0 \to h^+h^-$ or $D^0 \to h^+h^-h^+h^-$

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):
  - 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 $m(D^0)$.
  - Backgrounds: ARGUS function 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.

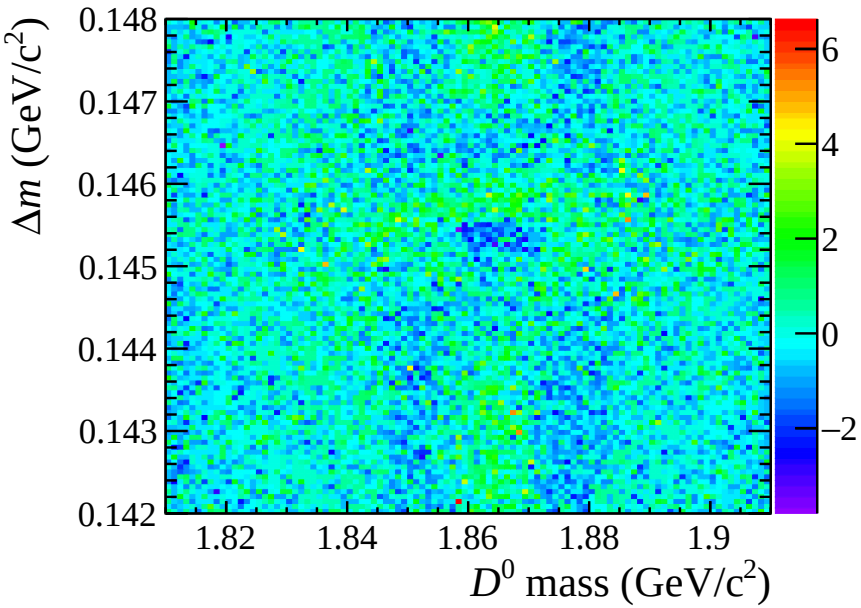
Normalization Mode: $D^0 \to K^-\pi^+\pi^-\pi^+$ (data)



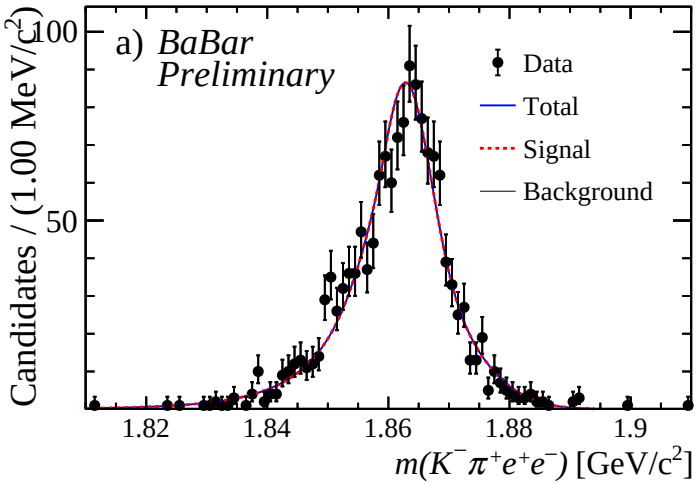


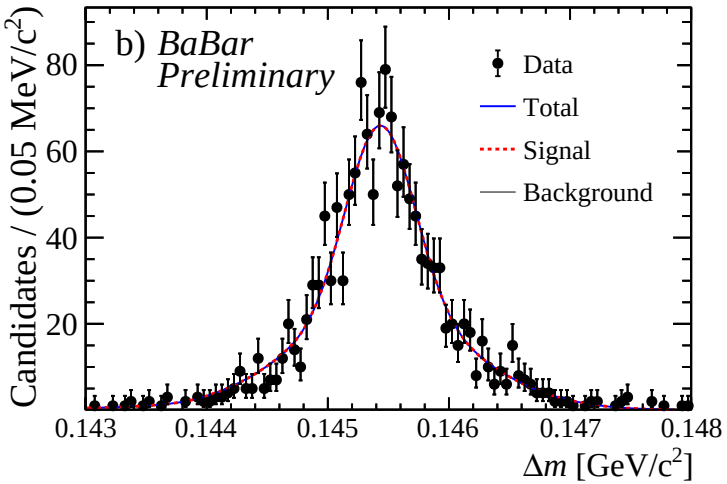
Fitted Yield $= 260\,870 \pm 520$

Pulls $= (n_{\text{fit}} - n_{\text{data}})/\sigma$

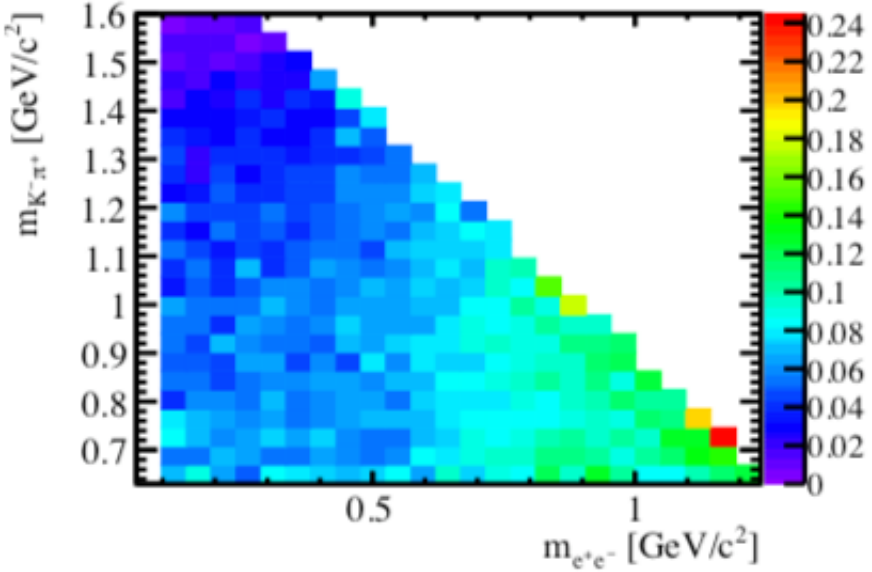


Signal Mode: $D^0 \to K^-\pi^+e^+e^-$ (Monte Carlo)



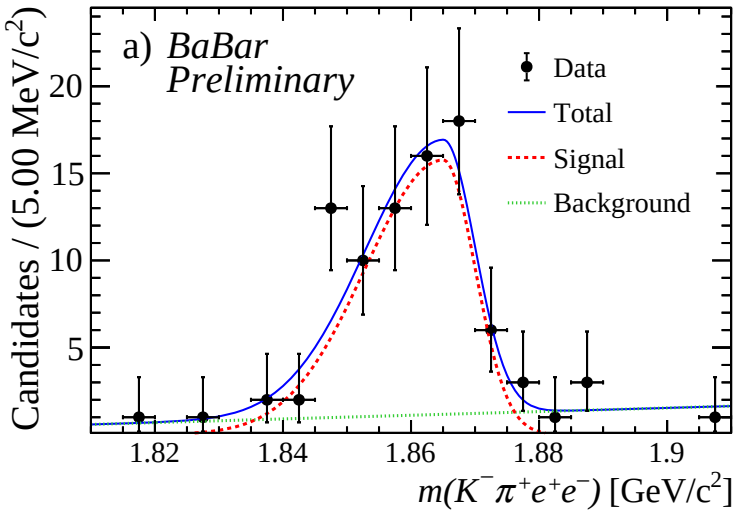


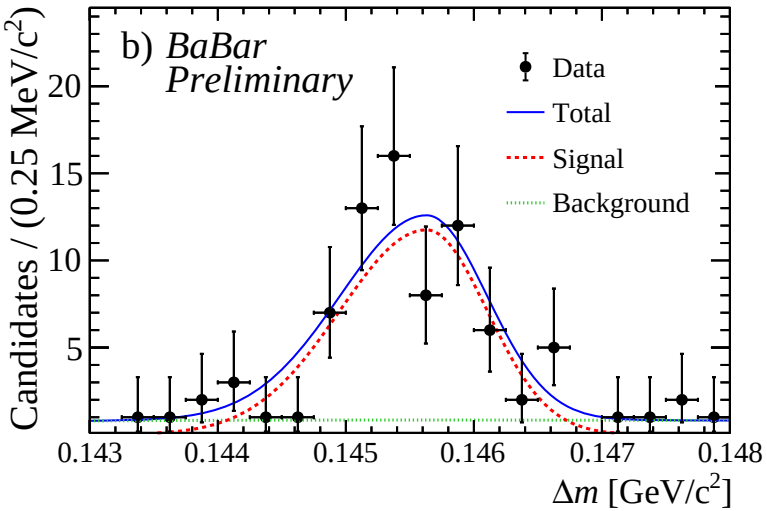
Reconstruction efficiency for $m(e^+e^-)$ and $m(K^-\pi^+)$

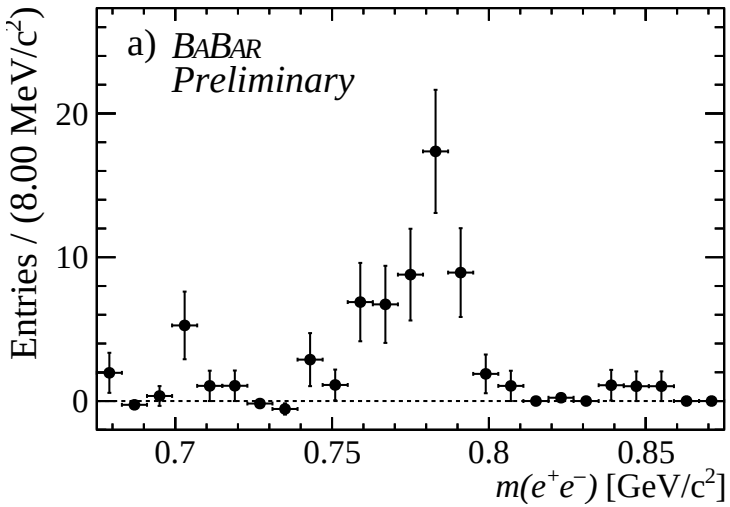


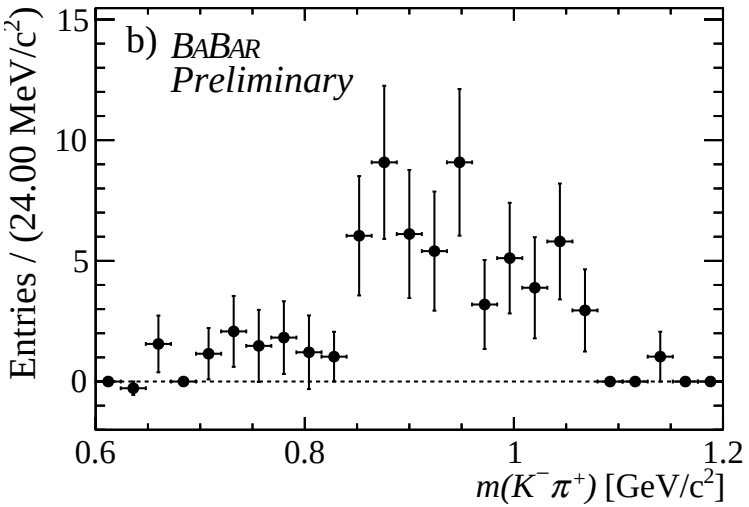
$D^0 \to K^-\pi^+e^+e^-$: $0.675 < m(e^+e^-) < 0.875\,\mathrm{GeV}/c^2$

$N_{sig} = 68 \pm 9$ candidates. Yield significance $> 10\sigma$



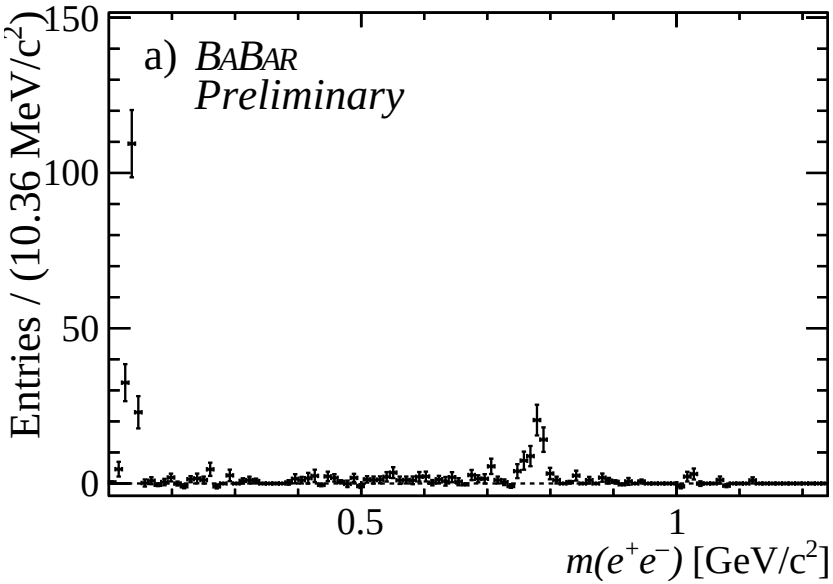


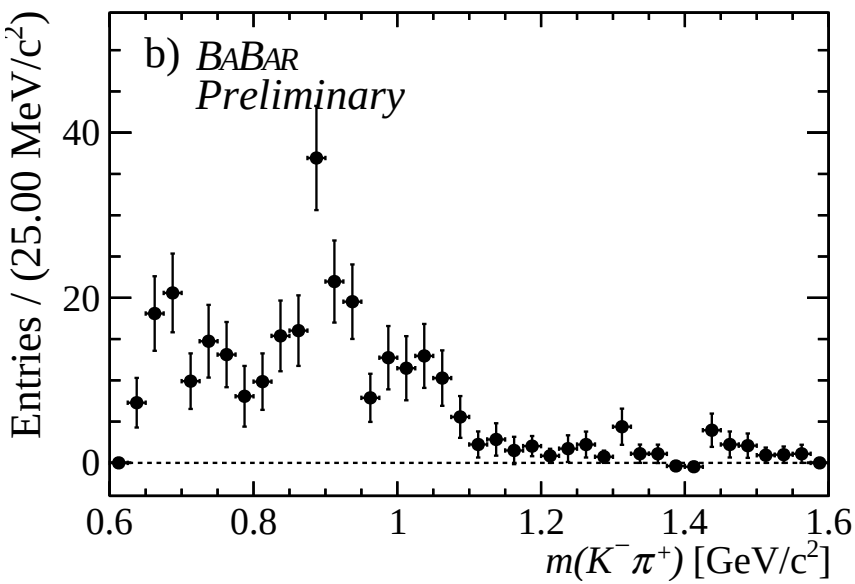




$D^0 \to K^-\pi^+e^+e^-$: $m(e^+e^-) > 0.1\,\mathrm{GeV}/c^2$

$N_{sig} = 308 \pm 18$ candidates

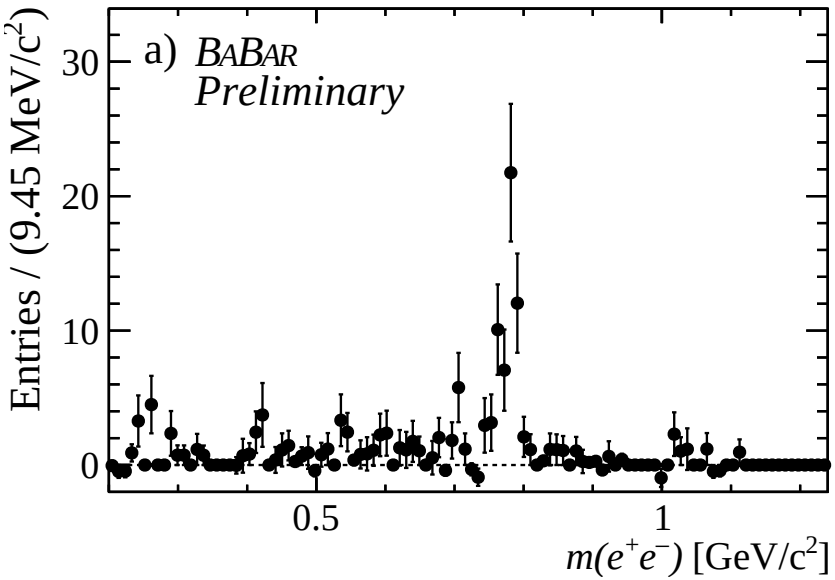


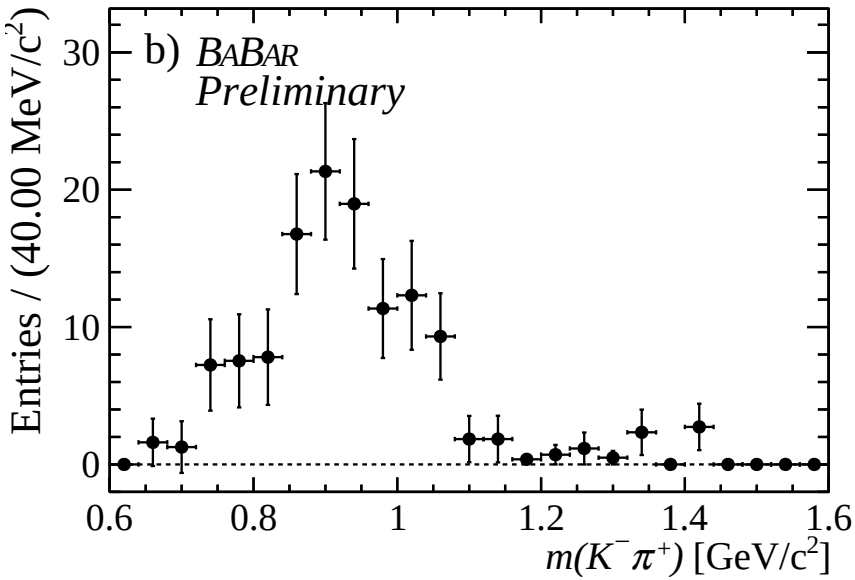


Background-subtracted projection of fit onto left: $m(e^+e^-)$ and right: $m(K^-\pi^+)$.

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

$$N_{sig} = 134 \pm 13 \text{ candidates}$$

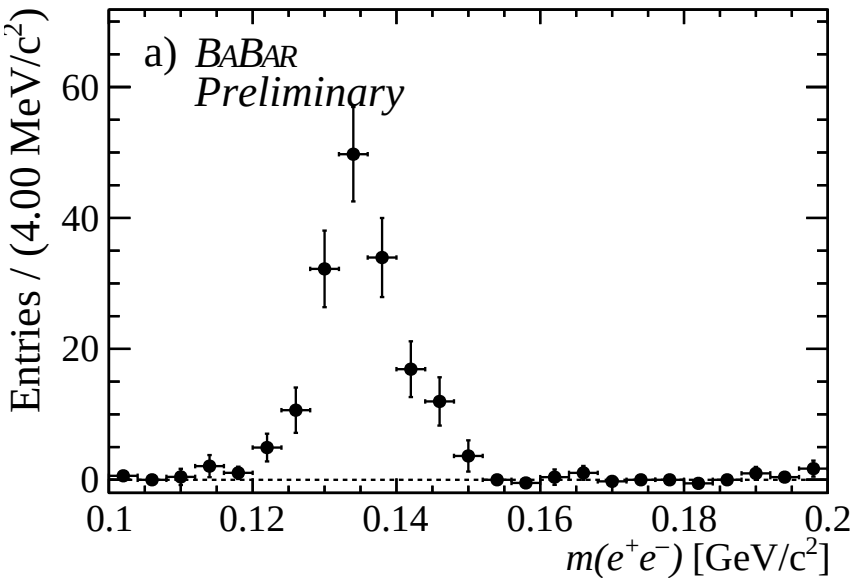


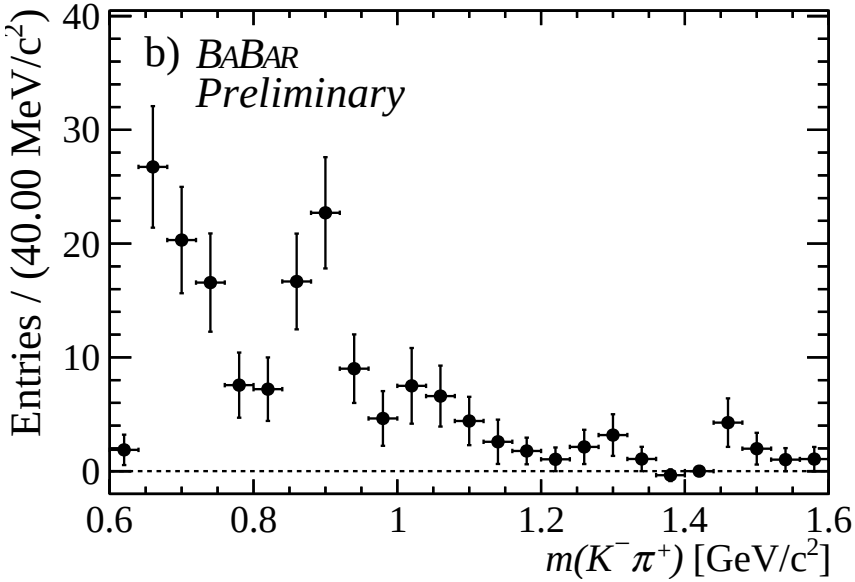


Background-subtracted projection of fit onto left: $m(e^+e^-)$ and right: $m(K^-\pi^+)$.

$D^0 \to K^-\pi^+e^+e^-$: $0.10 < m(e^+e^-) < 0.20\,\mathrm{GeV}/c^2$

$$N_{sig} = 175 \pm 14 \text{ candidates}$$

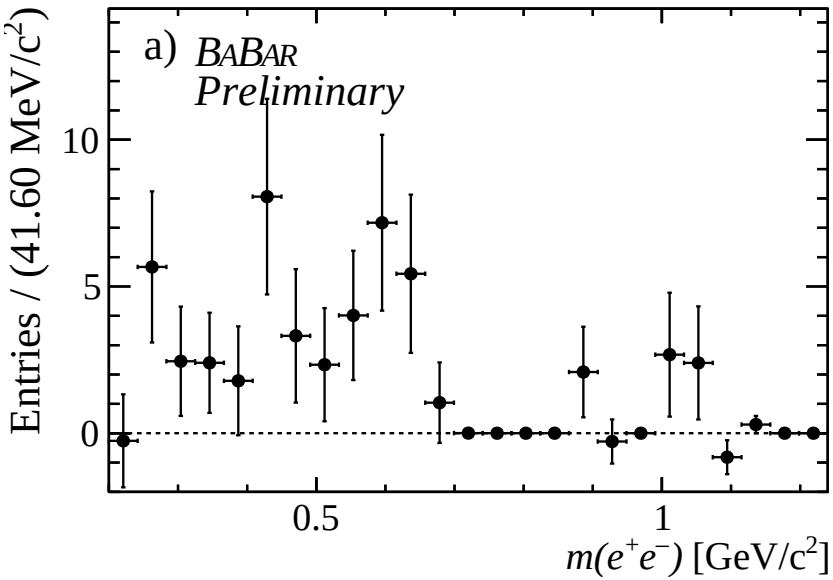


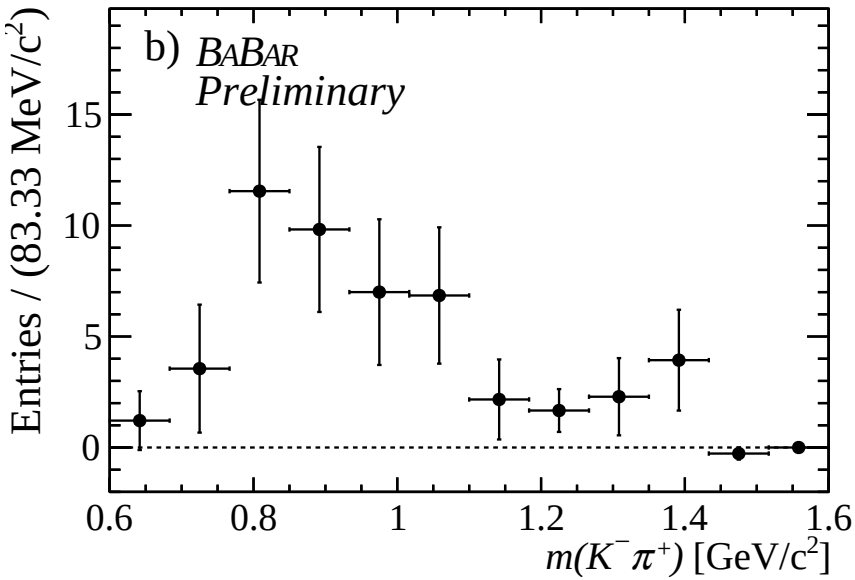


Background-subtracted projection of fit onto left: $m(e^+e^-)$ and right: $m(K^-\pi^+)$.

$0.20 < m(e^+e^-) < 0.675\,\mathrm{GeV}/c^2$ or $m(e^+e^-) > 0.875$

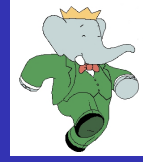
$N_{sig} = 59 \pm 9$ candidates





Background-subtracted projection of fit onto left: $m(e^+e^-)$ and right: $m(K^-\pi^+)$.

Systematic Uncertainties on Yields and $\mathcal{B}(D^0 \to K^-\pi^+e^+e^-)$



Criteria	$K^-\pi^+e^+e^-$	$K^-\pi^+\pi^-\pi^+$	$\mathcal{B}(D^0 \to K^-\pi^+e^+e^-)$
Additive (cands.)			
Fit Bias	0.20	-	
MC Parameters	0.70	-	
PDF Variation	1.25	2570	
Total Additive (cands.)	1.45	2570	
Multiplicative (%)			
Tracking Corrections [C]	3.0%	2.8%	
PID Corrections [C]	2.7%	1.2%	
Phase-space MC	1.8%	–	
K^0_S Correction	–	1.0%	
Luminosity [C]	0.6%	0.6%	
Total Multiplicative (%)	4.2%	3.3%	
Total (%)	4.7%	3.6%	3.9%

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

$m(e^+e^-)$ (GeV/c^2)	N_{sig} (cands.)	$\hat{\epsilon}_{\mathrm{sig}}$ (%)	$\mathcal{B}$ $(\times 10^{-6})$
$0.100 - 0.200$	175 ± 14	5.0 ± 0.2	-
> 0.100	308 ± 18	5.9 ± 0.2	-
> 0.200	134 ± 13	8.0 ± 0.2	$8.8 \pm 0.8 \pm 0.5 \pm 0.2$
$0.200 - 0.675$ or > 0.875	59 ± 9	6.4 ± 0.2	$4.8 \pm 0.7 \pm 0.3 \pm 0.1$
$0.675 - 0.875$	68 ± 9	8.9 ± 0.2	$3.95 \pm 0.53 \pm 0.16 \pm 0.08$

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

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 $> 10\sigma$.
  - $\mathcal{B}(D^0 \to K^-\pi^+e^+e^-) = (3.95 \pm 0.53 \pm 0.16 \pm 0.08) \times 10^{-6}$.
  - 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.
  - $m(e^+e^-)$ and $m(K^-\pi^+)$ distributions similar to results seen in $D^0 \to K^-\pi^+\mu^+\mu^-$.
- To be submitted to Phys. Rev. Lett.