D^0 Mixing, Lifetime Differences, and Hadronic Decays of Charmed Hadrons

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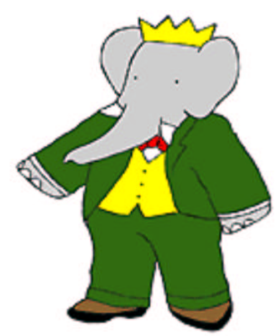
Outline:

- Introduction
- D^0 Lifetime Ratio
- D^0 Mixing: Status
- Three-Body D^0 Decays
- Conclusion



Introduction

Charm at B Factories

$\sigma(e^+e^- \to c\bar{c}) \approx 1.3$ **nb**

For 91 fb^{-1}, this corresponds to ~120 million charm pairs

or roughly 220,000 D*-tagged D^0 decays $D^{*+} \to D^0\pi^+,\ D^0 \to K^-\pi^+$ **+ c.c.**

Compare to these dedicated experiments:

E791: 35,400 D* tagged[1]

Focus: 120,000 D* tagged[2]

1. E791 Collaboration, Phys.Rev.Lett. 83 (1999) 32.
2. Focus Collaboration, Phys.Lett. B485 (2000) 62.

Introduction

Charm Physics at BaBar

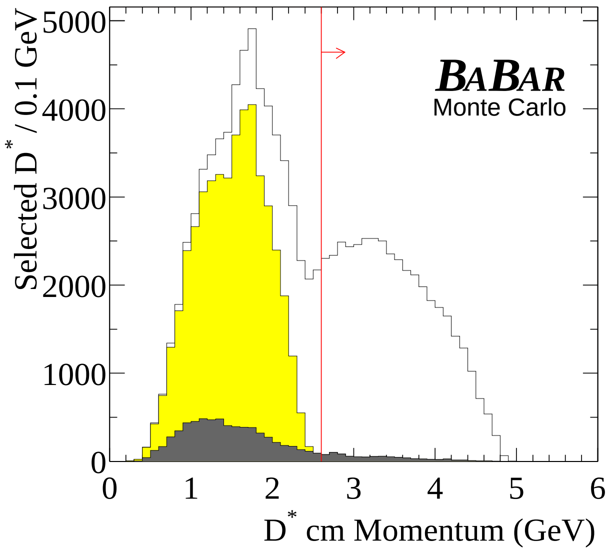
Overview:

- **Lifetime analyses are advanced but await final tracking studies.**
  - **Lifetime ratio results released.**
- **D^0 mixing analyses using various methods.**
  - **Hadronic mixing $D^0 \rightarrow K^+\pi^-$ nearly ready.**
- **Dalitz amplitude analyses for many decay modes.**
  - **First public results today.**
- **Charm baryon studies underway.**
- **Rare searches planned.**

Introduction

Selecting Charm Decays

Cut on momentum in center-of-mass (p^*):



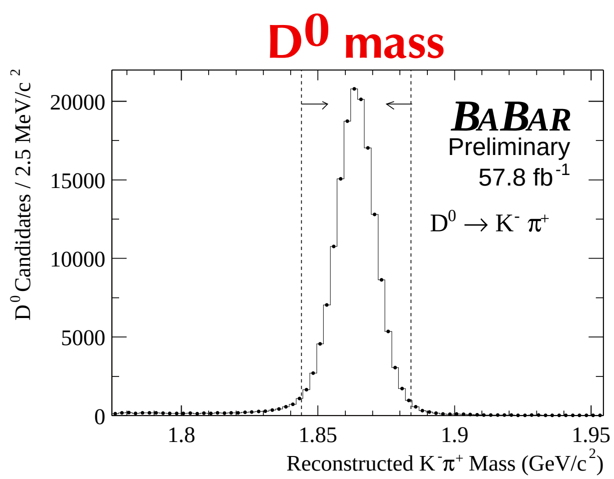
$$D^{*\pm} \to D^0 \pi_s^\pm$$
$$\quad \hookrightarrow K^- \pi^+$$

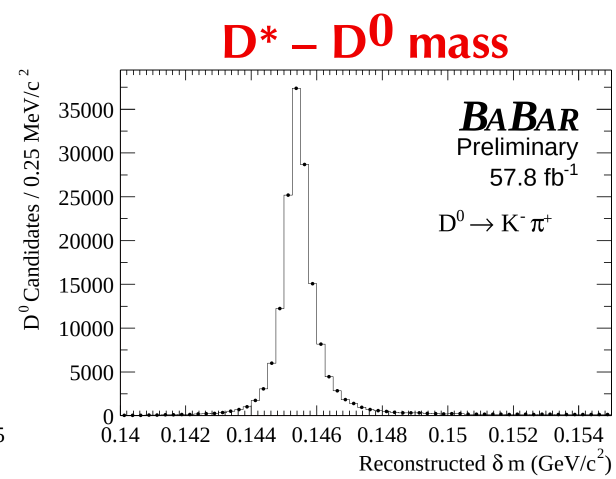
- Signal
- B Decay
- Background

Cut on excited decay:

$$D^{*+} \to D^0 \pi^+$$
$$D_S^{*+} \to D_S^+ \gamma$$

Use D0 mass sideband for background subtraction.





D^0 Lifetime Ratio

D^0 Mixing Nomenclature

Physical states $\{D_1, D_2\}$ **are a mixture of production states** $\{D^0, \overline{D^0}\}$

$$D_1 = \frac{pD_0 + q\overline{D^0}}{\sqrt{|p|^2 + |q|^2}} \qquad D_2 = \frac{pD_0 - q\overline{D^0}}{\sqrt{|p|^2 + |q|^2}} \quad ,$$

Each has its own lifetime $\{\Gamma_1, \Gamma_2\}$ **and mass** $\{M_1, M_2\}$**. If either of the quantities:**

$$x \equiv 2\frac{M_1 - M_2}{\Gamma_1 + \Gamma_2} \quad \textbf{or} \quad y \equiv \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2} \, ,$$

is nonzero, then D states will mix. The Standard Model predicts:

$$|x| \approx |y| < 10^{-3}$$

D^0 Lifetime Ratio

Measuring *y*

The decay modes $D^0 \to K^-K^+, \pi^-\pi^+$ are pure CP = +1 eigenstates and have exponential lifetime distributions with $\tau = 1/\Gamma_1$ (assuming CP conservation).

The decay mode $D^0 \to K^-\pi^+$ is a mixed CP state, with a decay distribution that is approximately exponential with $\tau = 1/\hat{\Gamma}$, where $\hat{\Gamma} = (\Gamma_1 + \Gamma_2)/2$.

The ratio of these lifetimes depends on *y*:

$$y \approx \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1 = \frac{\tau(K^-\pi^+)}{\tau(\pi^-\pi^+)} - 1$$

Advantage: many systematic uncertainties cancel in ratio.

D^0 Lifetime Ratio

The D^0 Sample

57.8 fb^{-1} of 2000–2001 data

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

158,000 events

99.5% purity

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

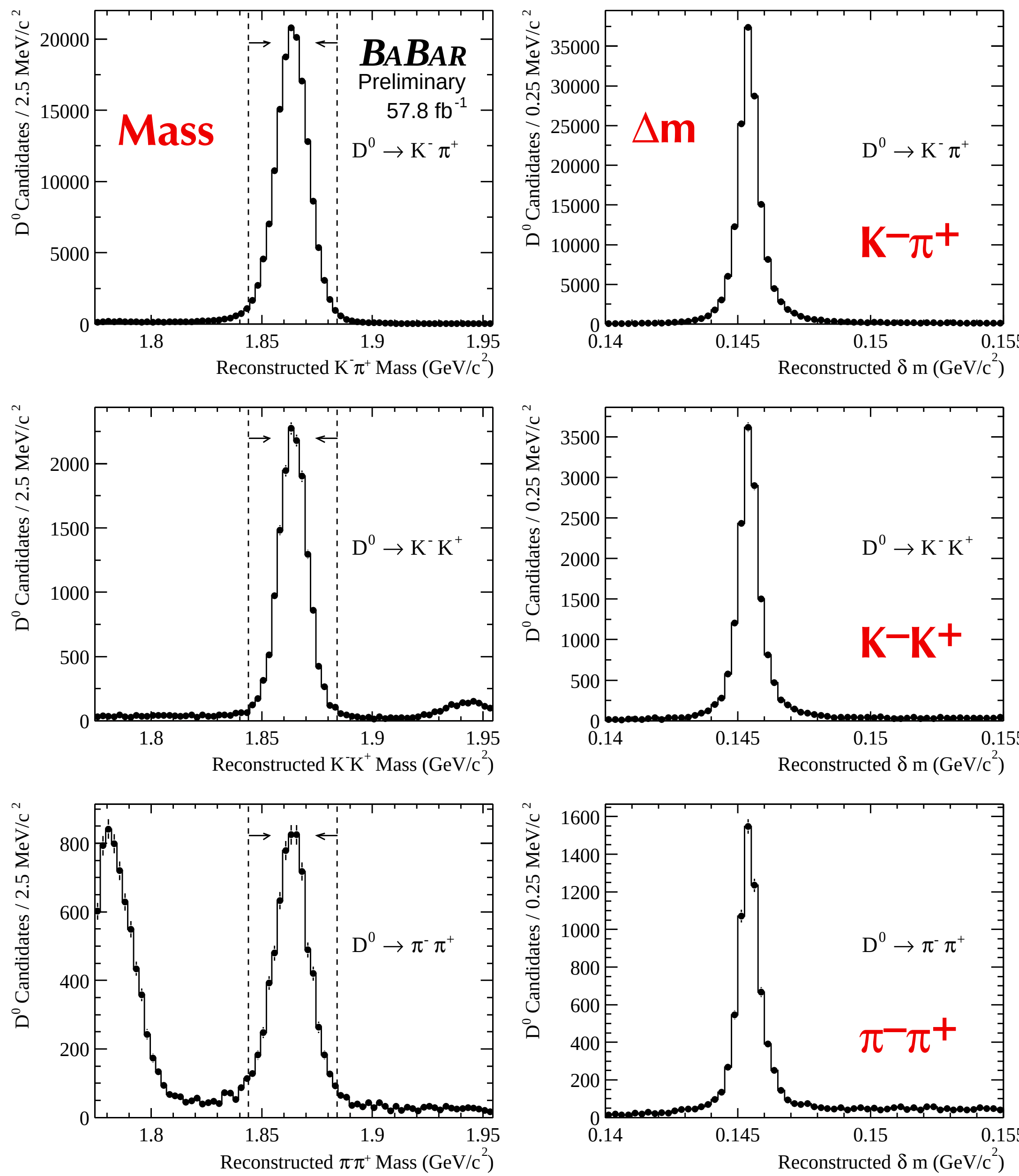
16,500 events

97.1% purity

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

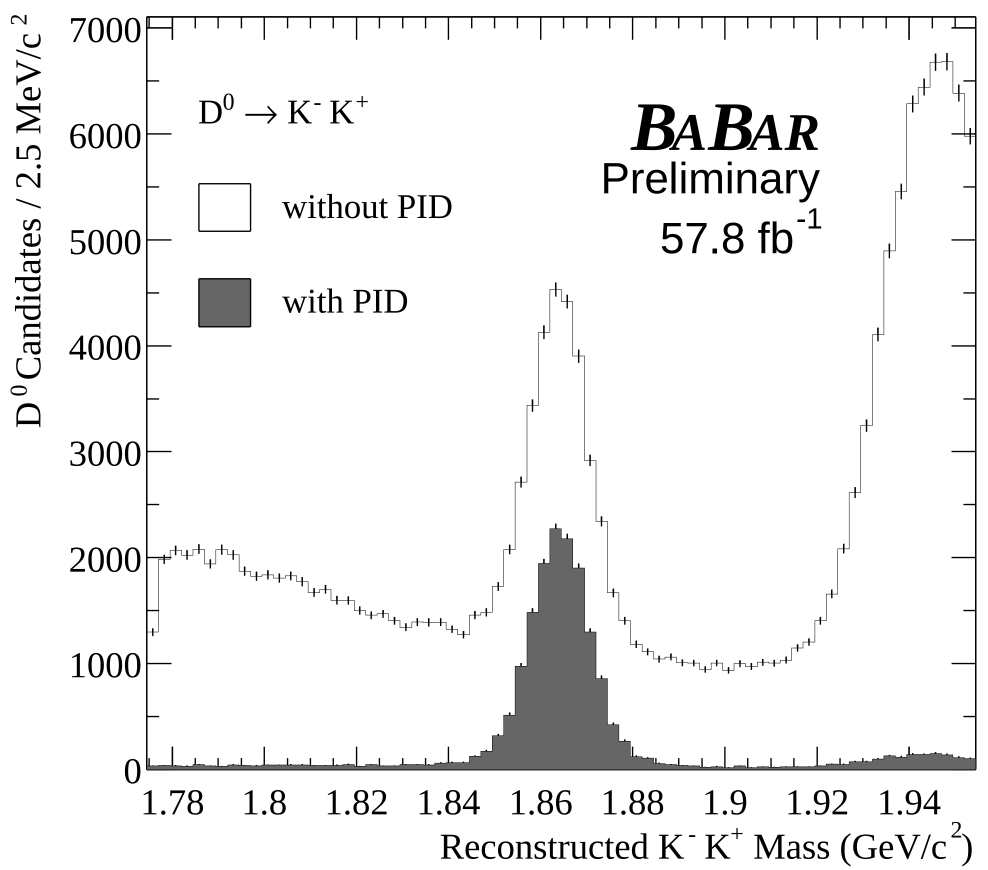
8,350 events

92.4% purity



D^0 Lifetime Ratio

Particle Identification Is Important

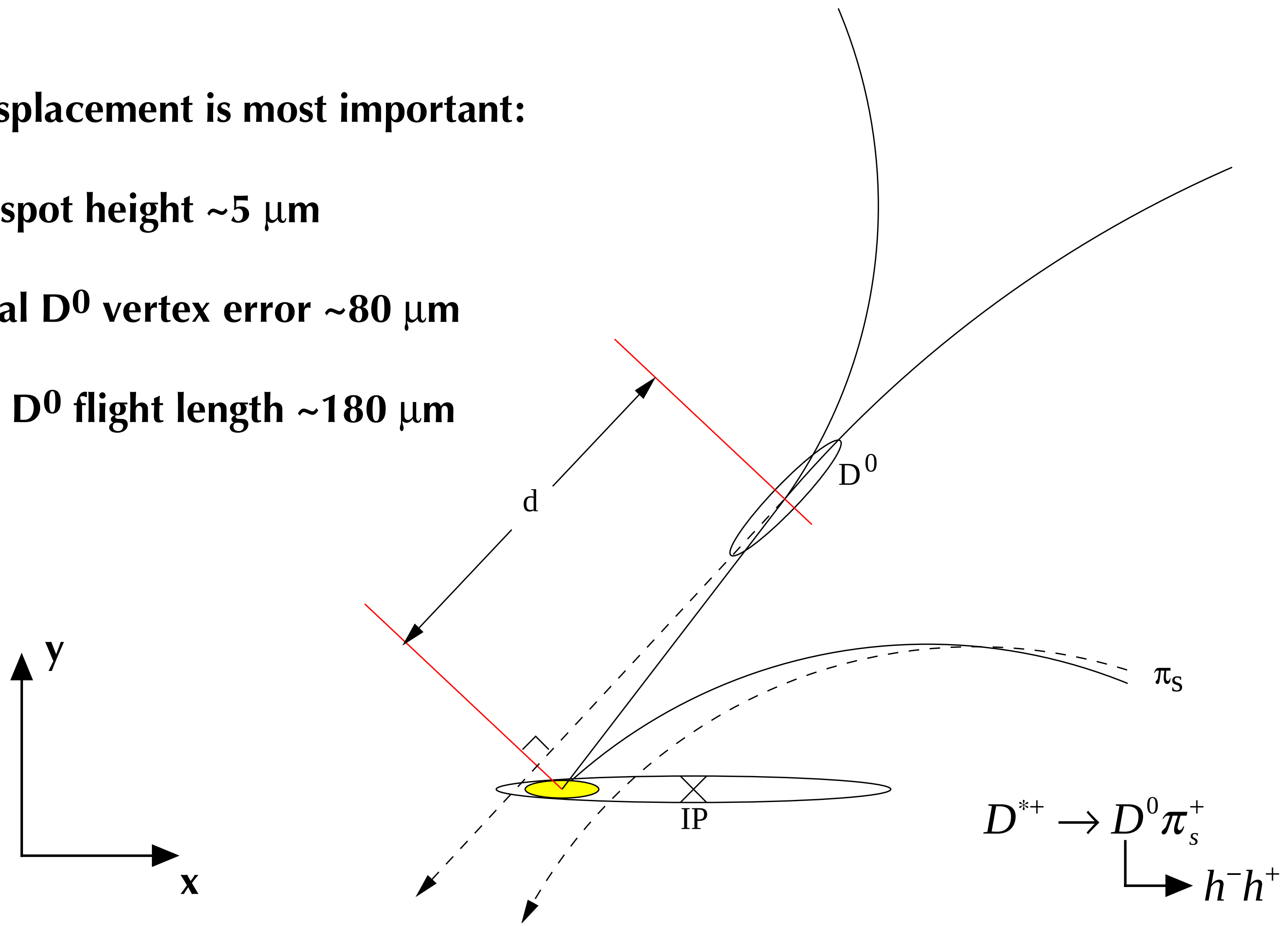


D^0 Lifetime Ratio

Measuring the Lifetime

Vertical displacement is most important:

- **Beamspot height ~5 μm**
- **Typical D^0 vertex error ~80 μm**
- **Mean D^0 flight length ~180 μm**



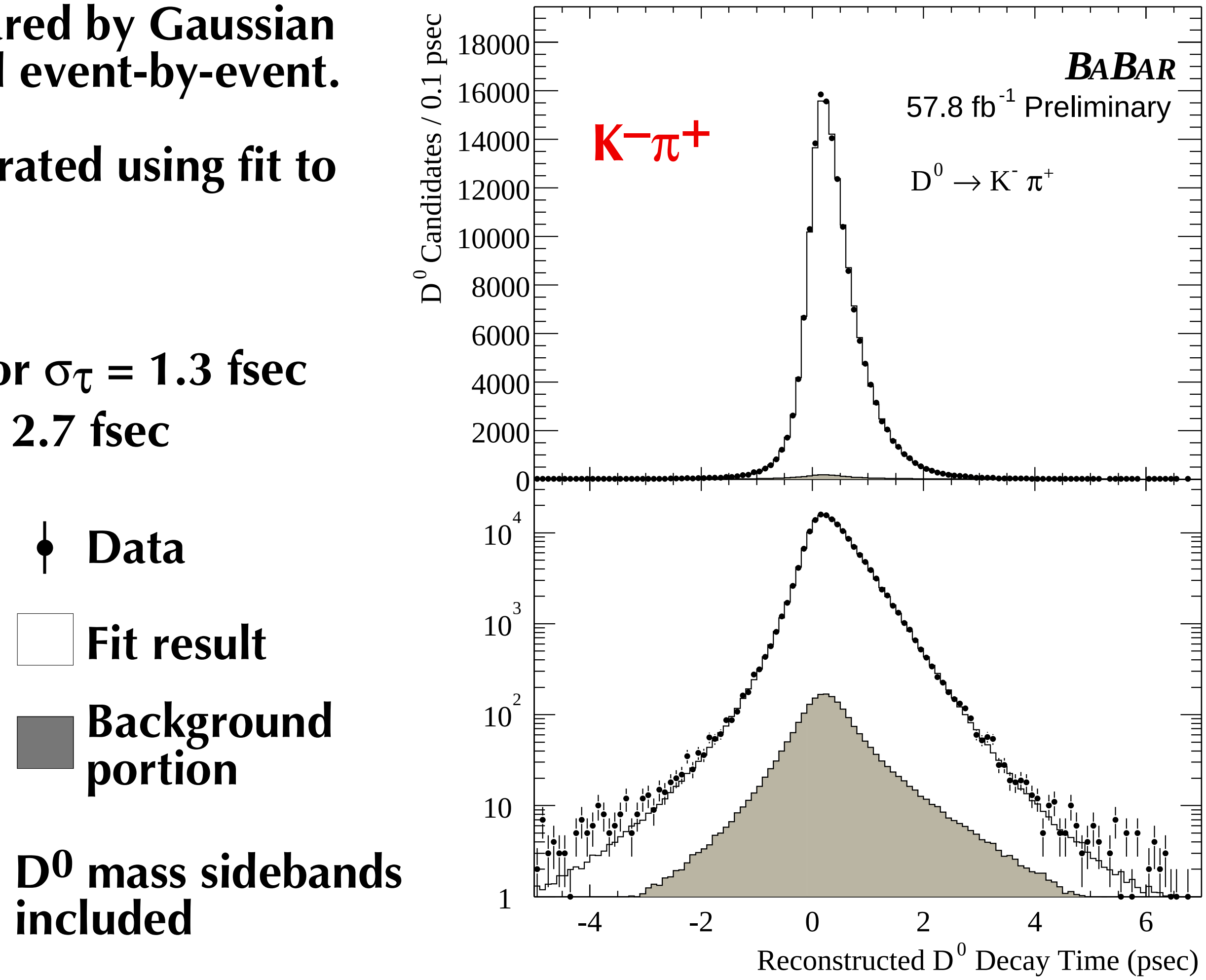
D^0 Lifetime Ratio

Lifetime Fits

Binless maximum likelihood

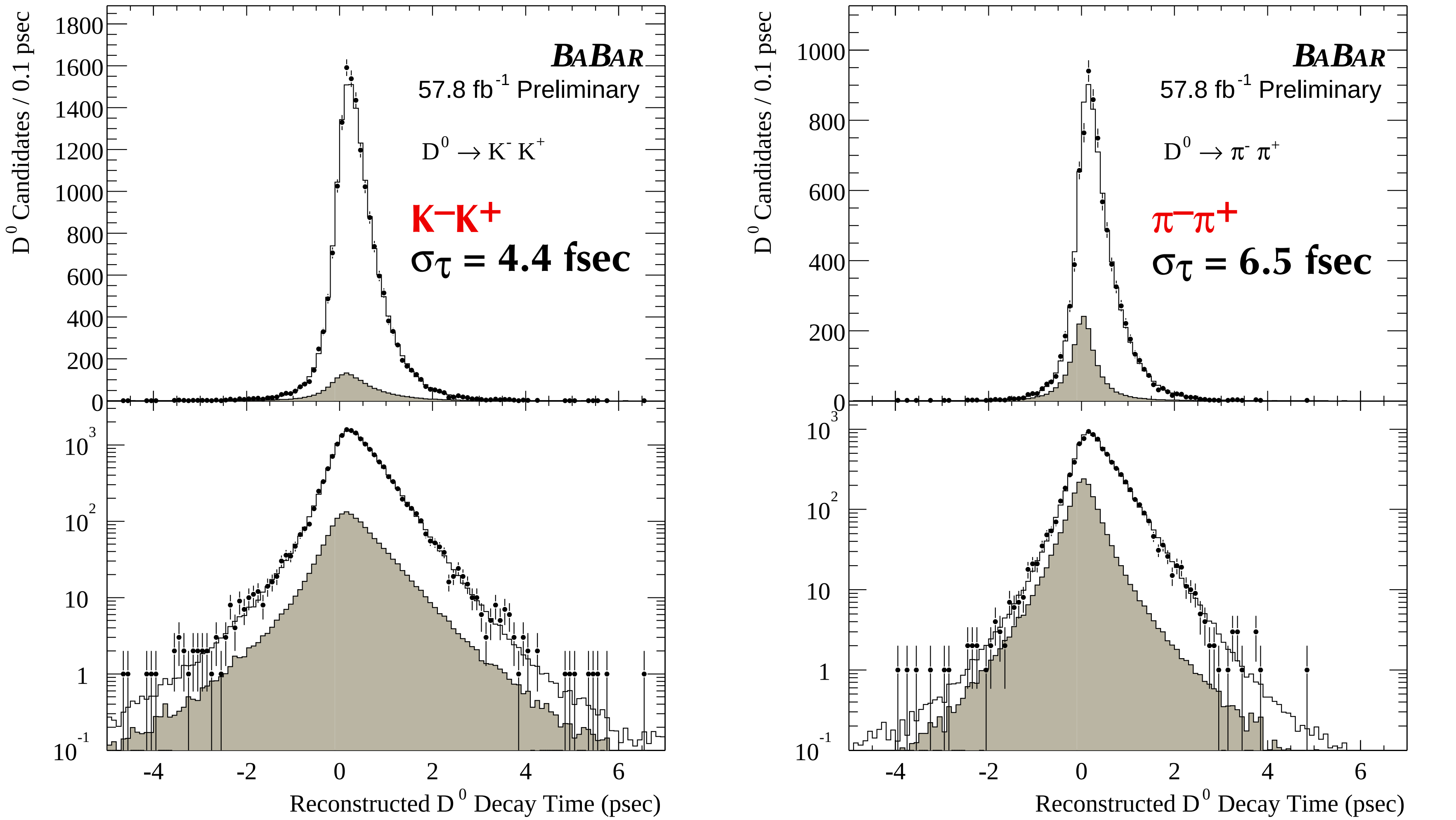
- **Exponential smeared by Gaussian errors, calculated event-by-event.**
- **Background separated using fit to D^0 mass.**

Lifetime statistical error σ_τ = 1.3 fsec
PDG average: 411.7 ± 2.7 fsec



D^0 Lifetime Ratio

Lifetime Fits

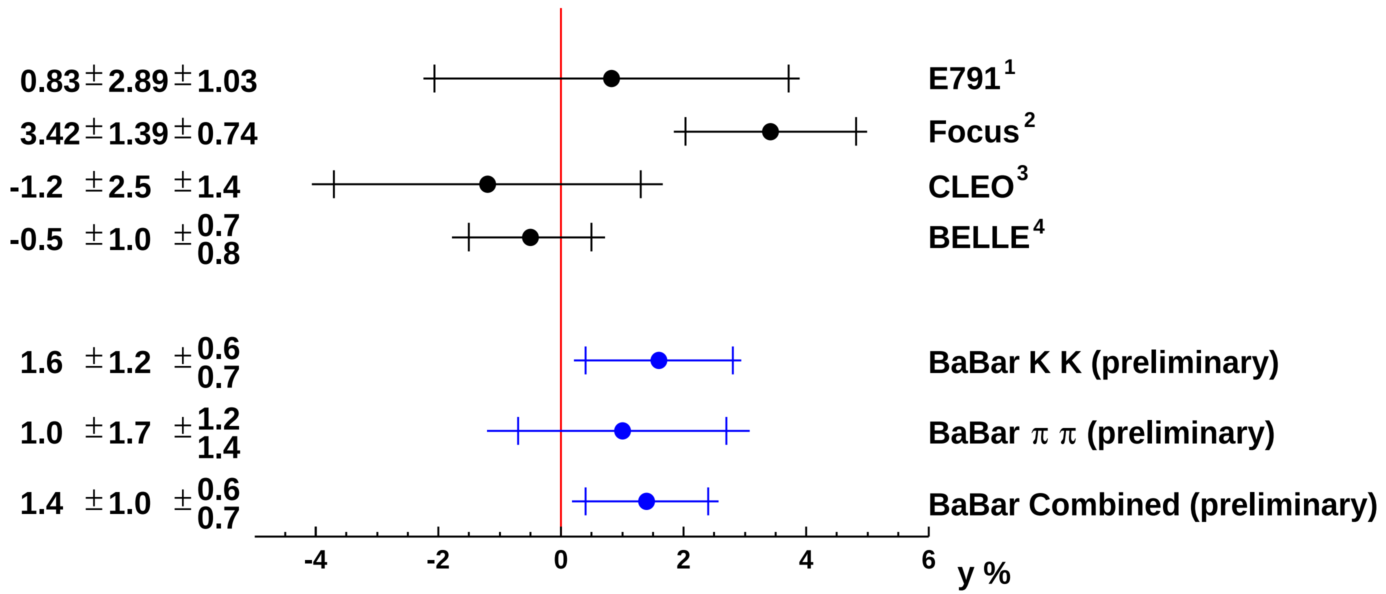


D^0 Lifetime Ratio

Results

$$y \approx \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1 = \frac{\tau(K^-\pi^+)}{\tau(\pi^-\pi^+)} - 1$$

	y Uncertainty (%)	
Systematic Uncertainty	K^-K^+	$\pi^-\pi^+$
Monte Carlo Statistics	$^{+0.4}_{-0.6}$	$^{+0.4}_{-0.9}$
Tracking	0.2	0.9
Particle Identification	0.2	0.4
Background and Fragmentation	0.2	0.6
Alignment and Vertexing	$^{+0.2}_{-0.1}$	$^{+0.3}_{-0.1}$
Quadrature Sum	$^{+0.6}_{-0.7}$	$^{+1.2}_{-1.4}$

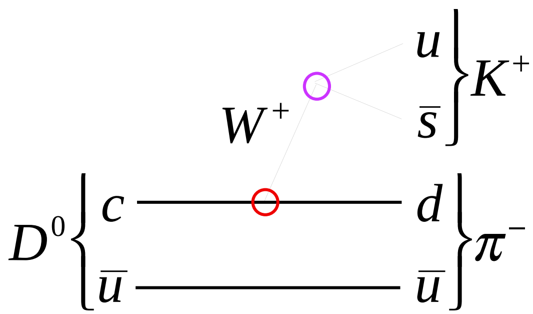


1. E791 Collaboration, Phys.Rev.Lett. 83 (1999) 32.
2. Focus Collaboration, Phys.Lett. B485 (2000) 62.
3. CLEO CONF-01.
4. BELLE Collaboration, Phys.Rev.Lett. 88 (2002) 05201.

D^0 Mixing: Status

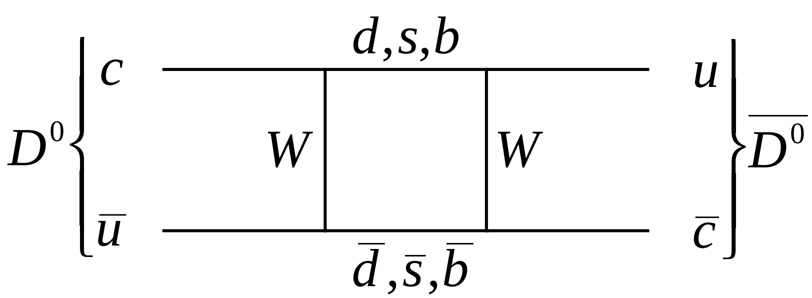
D^0 Mixing with $D^0 \to K^+\pi^-$

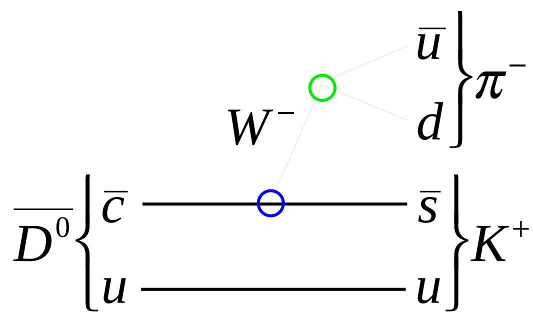
Wrong-sign D^0 decays can occur through a double-Cabibbo suppressed diagram:



$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Wrong-sign decays may also occur if a D^0 mixes to a $\overline{D^0}$ that then decays through a Cabibbo-favored diagram.





These two decay processes can be distinguished using the decay time distribution.

D^0 Mixing: Status

Decay Distribution

Mixing and double-Cabibbo suppressed decay modes interfere, producing the following (approximate) proper decay time distribution:

$$T_{WS}^{\pm}(t) = \left[R^{\pm} + y'^{\pm}\sqrt{R^{\pm}}\left(\frac{t}{\tau}\right) + \frac{1}{4}\{(x'^{\pm})^2 + (y'^{\pm})^2\}\left(\frac{t}{\tau}\right)^2 \right] T_{RS}(t)$$

where + (–) corresponds to D^0 ($\overline{D^0}$). If CP is conserved:

$$x'^{+} = x'^{-} = x' = x\cos\delta + y\sin\delta$$
$$y'^{+} = y'^{-} = y' = y\cos\delta - x\sin\delta$$

$$R^{+} = R^{-} = R \equiv \frac{\Gamma(D^0 \to K^{+}\pi^{-})}{\Gamma(D^0 \to K^{-}\pi^{+})}$$

in which the mixing parameters x and y are rotated by an unknown, relative strong phase δ.

D^0 Mixing: Status

Two-Fold Ambiguity

Standard parameterization is in terms of $\{R, x', y', A_D, A_M, \varphi\}$

$$R^\pm = \left[\frac{1+A_D}{1-A_D}\right]^{\pm 1/2} R$$

$$x'^\pm = \left[\frac{1+A_M}{1-A_M}\right]^{\pm 1/4} (x' \cos\varphi \pm y' \sin\varphi)$$

$$y'^\pm = \left[\frac{1+A_M}{1-A_M}\right]^{\pm 1/4} (y' \cos\varphi \pm x' \sin\varphi)$$

In terms of the observables $\{R^+, (x'^+)^2, y'^+\}$ **and** $\{R^-, (x'^-)^2, y'^-\}$**, however, there is an ambiguity:**

$$\begin{Bmatrix} x' \\ y' \\ \varphi \end{Bmatrix} \Leftrightarrow \begin{Bmatrix} -x' \\ -y' \\ \varphi + \pi \end{Bmatrix}$$

Thus it is not possible to determine the overall sign of x', y'**.**

D^0 Mixing: Status

Eight-Fold Ambiguity

Since we cannot measure the sign of $x'^{\pm}$

$$T_{WS}^{\pm}(t) = \left[R^{\pm} + y'^{\pm}\sqrt{R^{\pm}}\left(\frac{t}{\tau}\right) + \frac{1}{4}\{(x'^{\pm})^2 + (y'^{\pm})^2\}\left(\frac{t}{\tau}\right)^2 \right] T_{RS}(t),$$

this leads to four additional ambiguities (1–4):

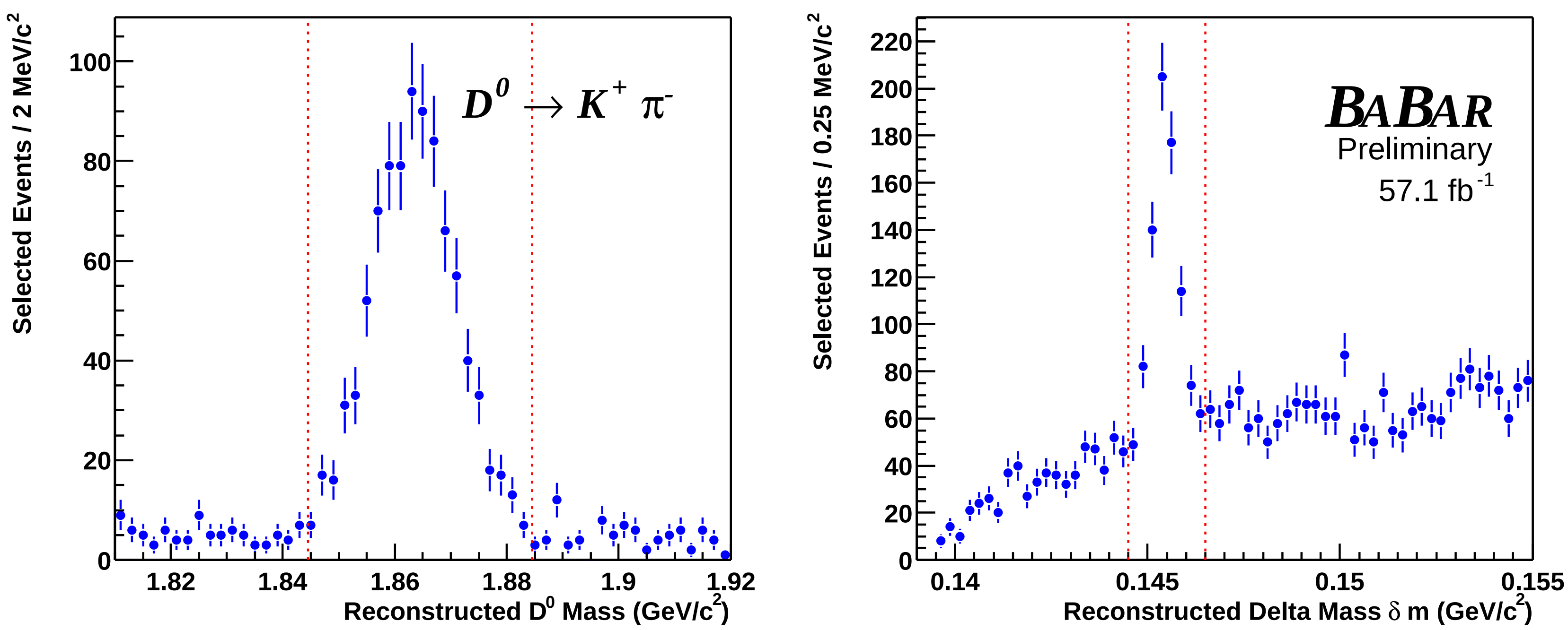
	x'^{+}	x'^{-}
1	> 0	> 0
2	< 0	> 0
3	> 0	< 0
4	< 0	< 0

Overall, there are eight possible solutions to $\{x', y', \varphi\}$ that cannot be distinguished by $D^0 \to K^+\pi^-$ decays alone.

D^0 Mixing: Status

Prospects

We have the data — the analyses will follow soon!



Three-Body D^0 Decays

Some Interesting Three-Body Decays

Analysis of 22 fb^{-1} of 1999–2000 data

- **K particle identification**
- **K_S vertex fit, flight length**
- $D^{\pm *} \to D^0 \pi^{\pm}$
- $p^* > 2.2$ **GeV/c**

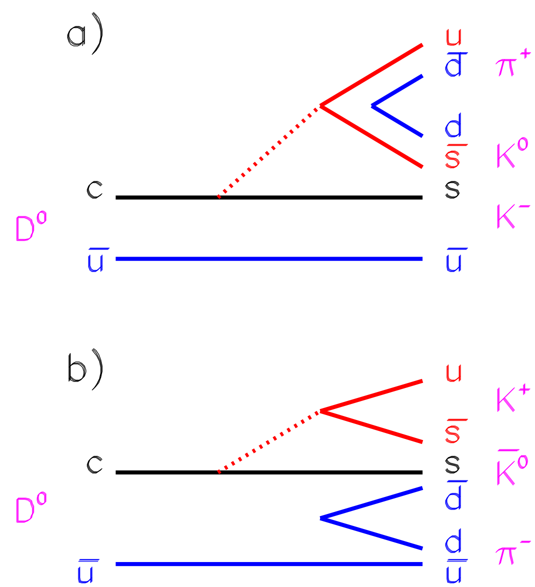
$$D^0 \to \overline{K^0} \pi^+ \pi^-$$

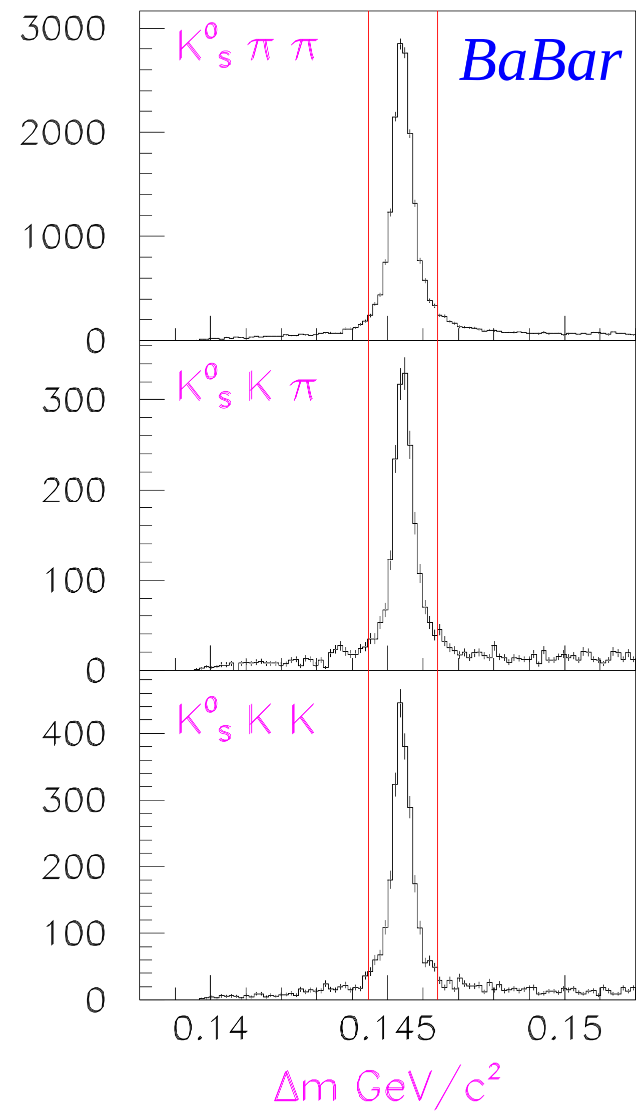
$$D^0 \to K^0 K^- \pi^+ \quad (a)$$

$$D^0 \to \overline{K^0} K^+ \pi^- \quad (b)$$

$$D^0 \to \overline{K^0} K^+ K^-$$

(+ c.c.)

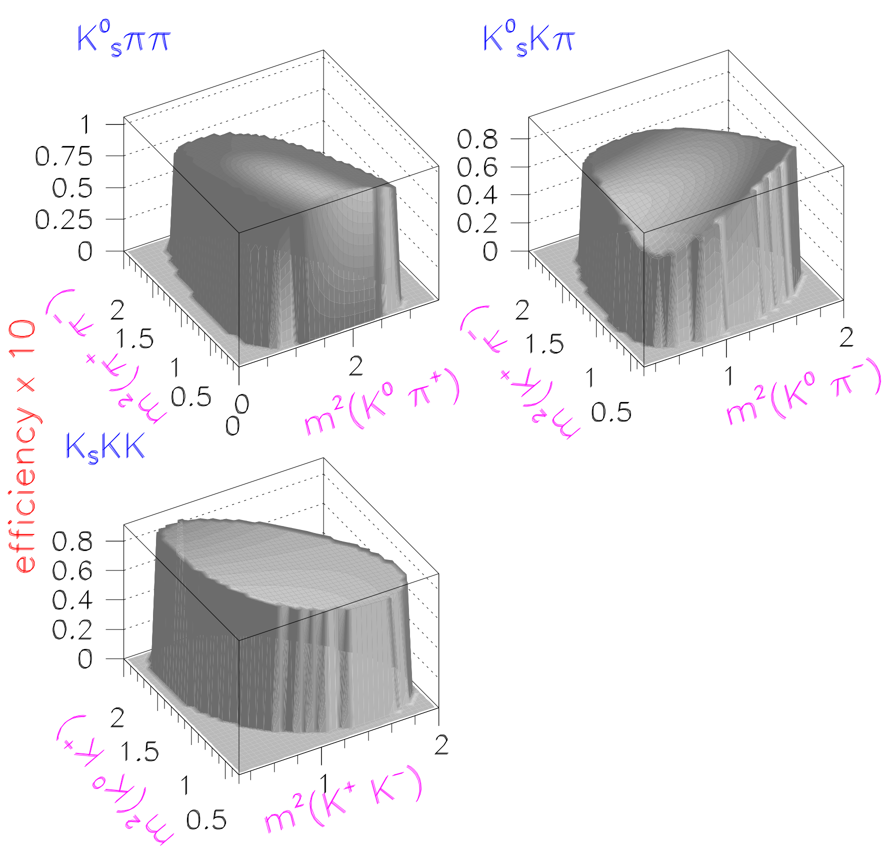


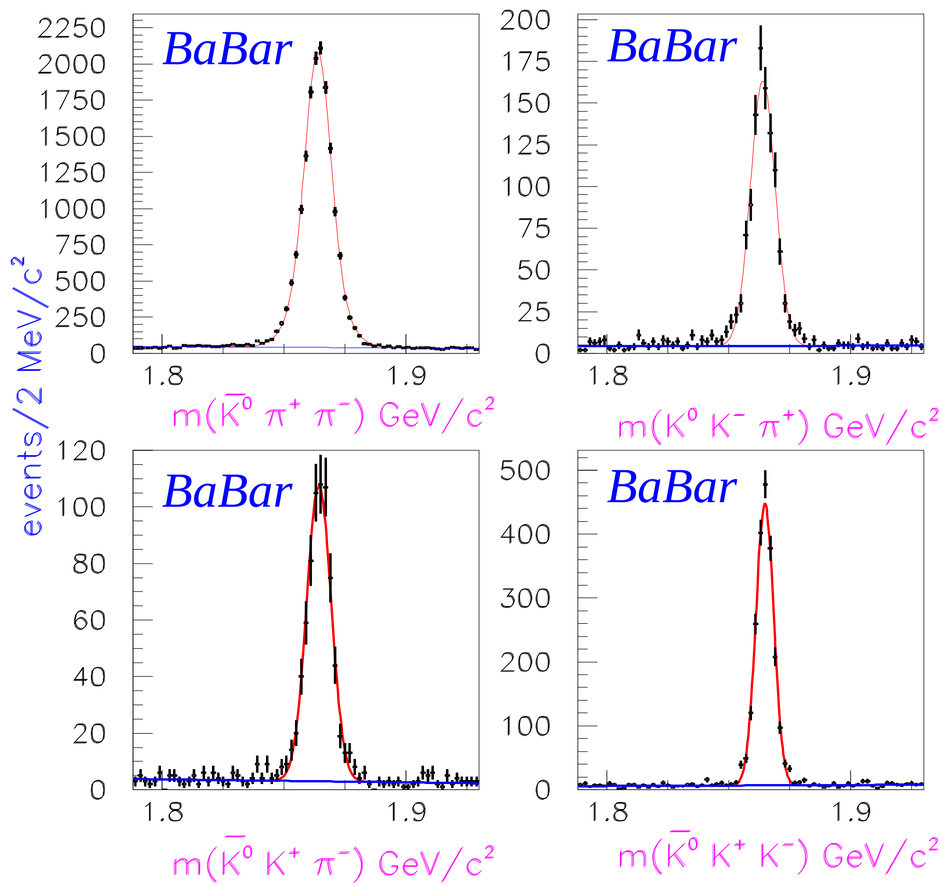


Three-Body D^0 Decays

Reconstruction Efficiencies and Yields

Efficiency determined from uniform phase space Monte Carlo.
Yields determined from fits to D^0 mass distribution.





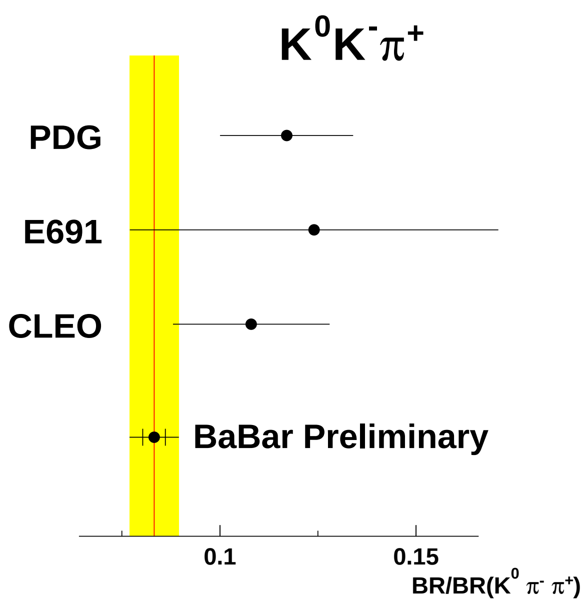
Three-Body D^0 Decays

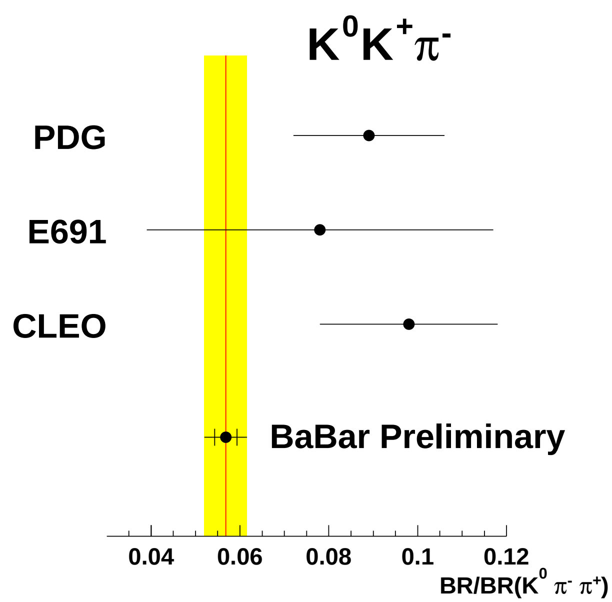
Branching Ratios

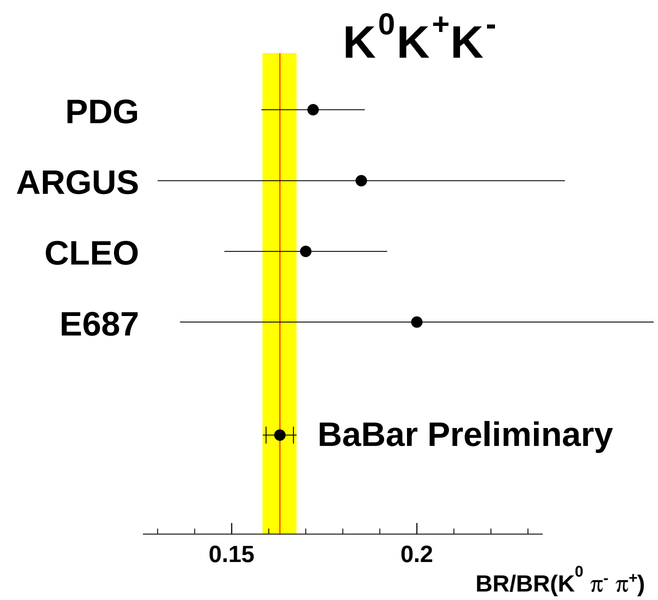
$$\frac{\Gamma(D^0 \to K^0 K^- \pi^+)}{\Gamma(D^0 \to K^0 \pi^+ \pi^-)} = 8.32 \pm 0.29\,(\text{stat}) \pm 0.56\,(\text{syst}) \times 10^{-2}$$

$$\frac{\Gamma(D^0 \to K^0 K^+ \pi^-)}{\Gamma(D^0 \to K^0 \pi^+ \pi^-)} = 5.68 \pm 0.25\,(\text{stat}) \pm 0.41\,(\text{syst}) \times 10^{-2}$$

$$\frac{\Gamma(D^0 \to K^0 K^+ K^-)}{\Gamma(D^0 \to K^0 \pi^+ \pi^-)} = 16.30 \pm 0.37\,(\text{stat}) \pm 0.27\,(\text{syst}) \times 10^{-2}$$







Three-Body D^0 Decays

Dalitz Amplitude Analysis

Unbinned maximum likelihood fit:

$$L(\vec{c}) = x \cdot G(m) \frac{\sum c_i c_j^* A_i A_j^*}{\int dm_x^2 dm_y^2 A(m_x^2, m_y^2) \sum c_i c_j^* A_i A_j^*} + \frac{1-x}{\int dm_x^2 dm_y^2 A(m_x^2, m_y^2)}$$

where x is the fraction signal, $A(m_x^2, m_y^2)$ is the acceptance, $G(m)$ is the reconstructed D^0 mass distribution, A_i are the amplitudes under consideration, and $\vec{c} = \{c_i\}$ are the complex coefficients that are being fitted.

Integrals are calculated using a Monte Carlo method.

Each amplitude is a product of a line shape (Breit-Wigner) and an angular distribution:

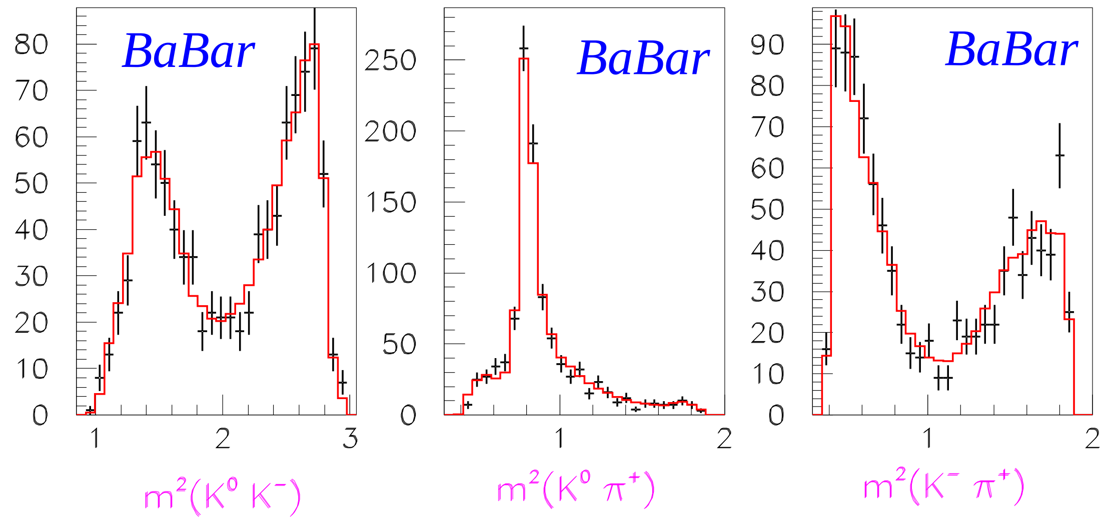
$$A_i = BW_i(m) \times T_i(\Omega)$$

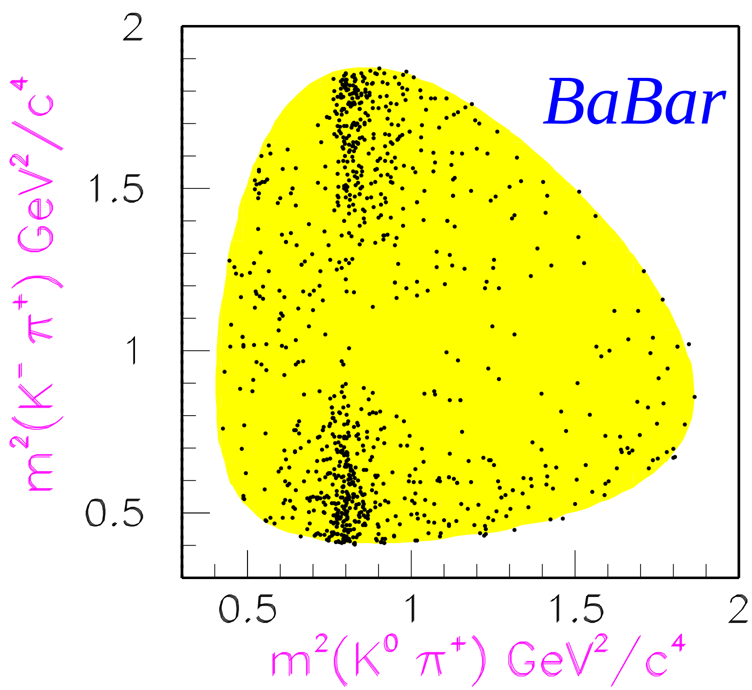
Three-Body D^0 Decays

Amplitude Analysis
for $D^0 \to K^0 K^- \pi^+$

Preliminary

$\chi^2 / \mathrm{NDF} = 46/44$





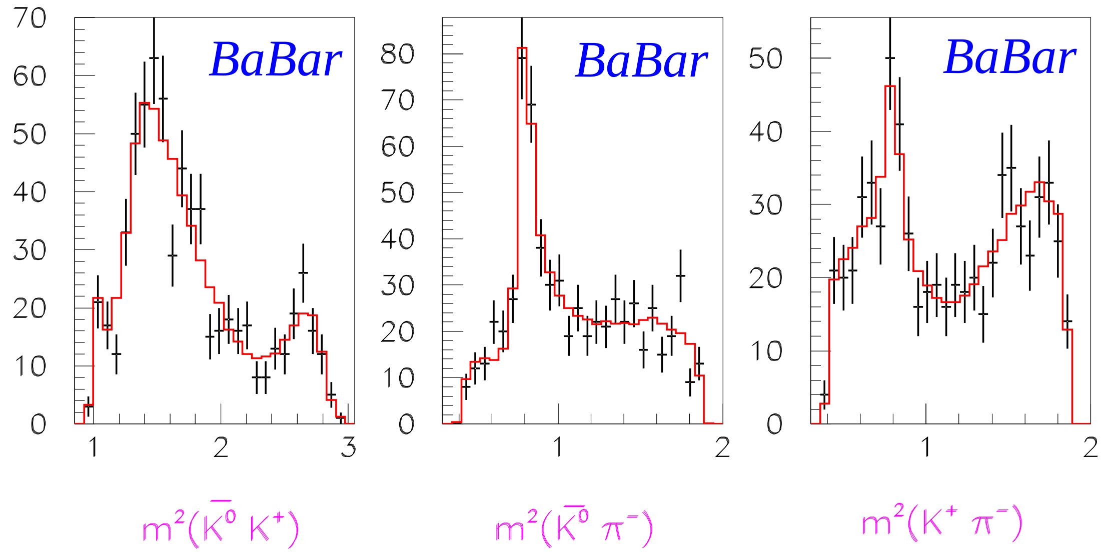
Final state	Fraction %	Phase (degrees)
$\bar{K}_0^{*0}(1430)K^0$	$4.8 \pm 1.4 \pm 1.6$	52 ± 27
$\bar{K}_1^{*0}(892)K^0$	$0.8 \pm 0.5 \pm 0.1$	175 ± 22
$\bar{K}_1^{*0}(1680)K^0$	$6.9 \pm 1.2 \pm 1.0$	-169 ± 16
$\bar{K}_2^{*0}(1430)K^0$	$2.0 \pm 0.6 \pm 0.1$	51 ± 18
$K_0^{*+}(1430)K^-$	$13.3 \pm 3.5 \pm 3.9$	-41 ± 25
$K_1^{*+}(892)K^-$	$63.6 \pm 5.1 \pm 2.6$	0.
$K_1^{*+}(1680)K^-$	$15.6 \pm 3.0 \pm 1.4$	-178 ± 10
$K_2^{*+}(1430)K^-$	$13.8 \pm 2.6 \pm 7.9$	-52 ± 7
$a_0^-(980)\pi^+$	$2.9 \pm 2.3 \pm 0.7$	-100 ± 13
$a_0^-(1450)\pi^+$	$3.1 \pm 1.9 \pm 0.9$	31 ± 16
$a_2^-(1310)\pi^+$	$0.7 \pm 0.4 \pm 0.1$	-149 ± 27
Non-Reson.	$2.3 \pm 0.5 \pm 5.6$	-136 ± 23
Sum	129.8 ± 8.2	

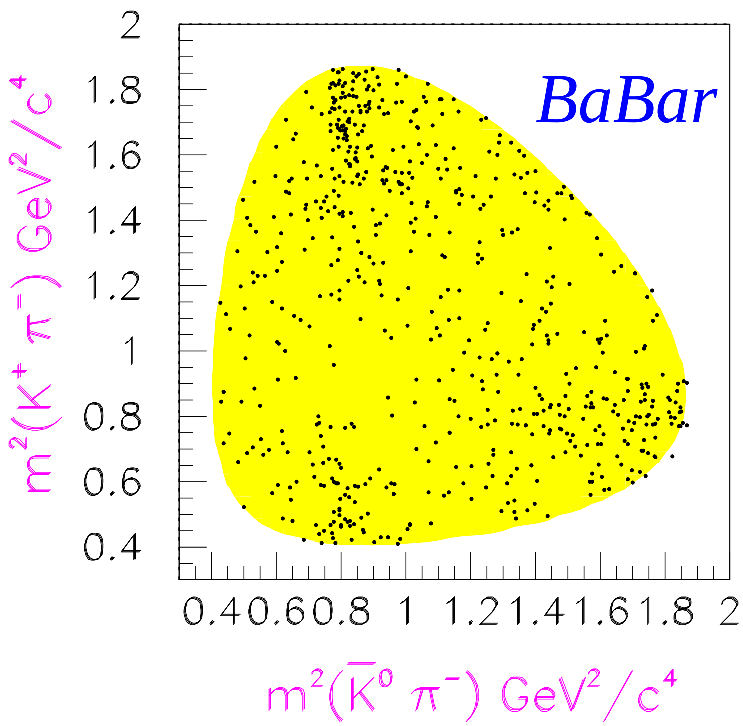
Three-Body D^0 Decays

Amplitude Analysis for $D^0 \to K^0 K^+ \pi^-$

Preliminary

$\chi^2 / \text{NDF} = 25/29$





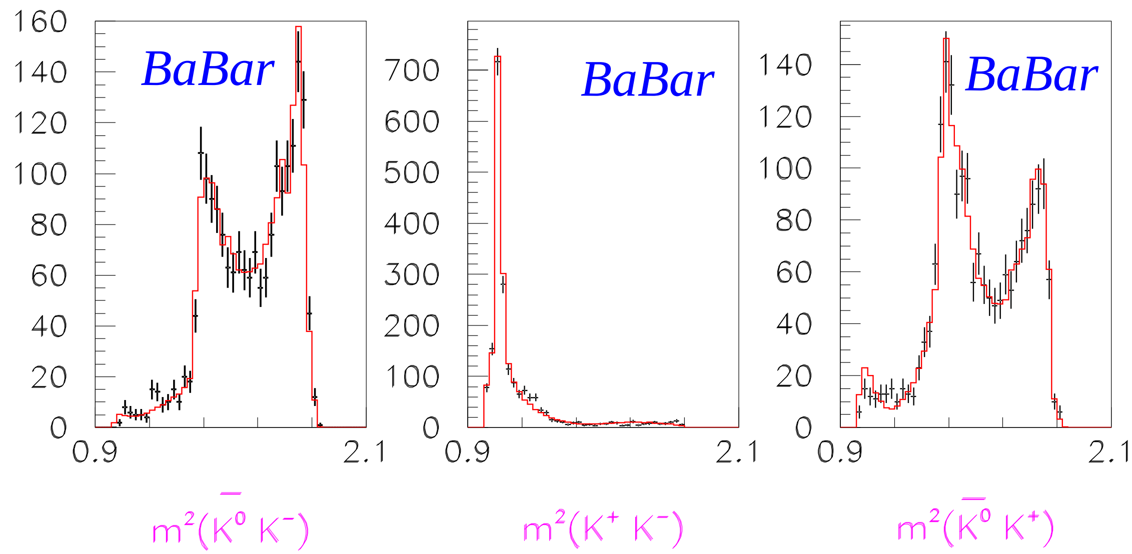
Final state	Fraction %	Phase (degrees)
$K_0^{*0}(1430)\overline{K^0}$	26.0 ± 16.1 ± 3.3	–38 ± 22
$K_1^{*0}(892)\overline{K^0}$	2.8 ± 1.4 ± 0.5	–126 ± 19
$K_1^{*0}(1680)\overline{K^0}$	15.2 ± 11.9 ± 0.5	161 ± 9
$K_2^{*0}(1430)\overline{K^0}$	1.7 ± 2.5 ± 0.2	53 ± 38
$K_0^{*-}(1430)K^+$	2.4 ± 8.2 ± 1.0	–142 ± 115
$K_1^{*-}(892)K^+$	35.6 ± 7.7 ± 2.3	0.
$K_1^{*-}(1680)K^+$	5.1 ± 5.7 ± 1.1	124 ± 27
$K_2^{*-}(1430)K^+$	1.0 ± 1.0 ± 0.2	–26 ± 38
$a_0^+(980)\pi^-$	15.1 ± 12.5 ± 0.6	-160 ± 42
$a_0^+(1450)\pi^-$	2.2 ± 2.7 ± 1.2	148 ± 25
Non-Reson.	36.6 ± 25.8 ± 2.7	-172 ± 13
Sum	143.7 ± 37.4	

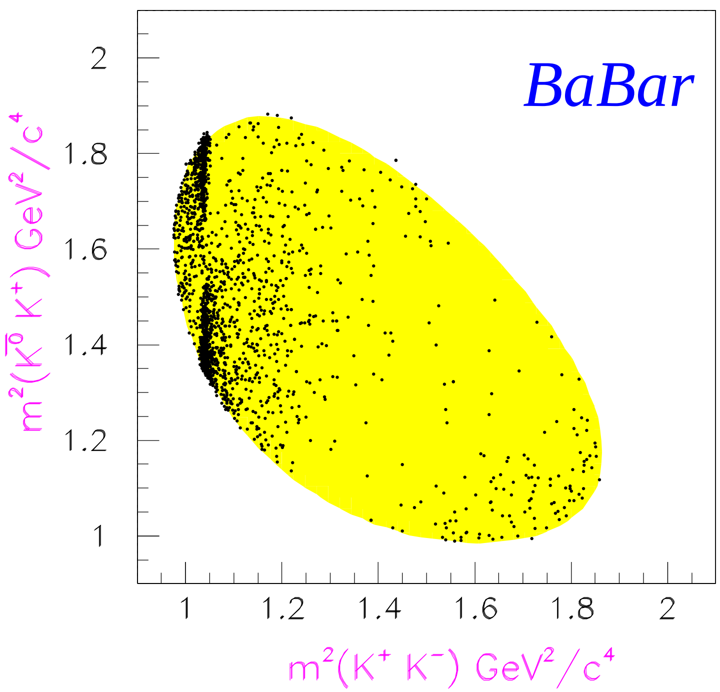
Three-Body D^0 Decays

Amplitude Analysis
for $D^0 \to K^0 K^+ K^-$

Preliminary

$\chi^2/\text{NDF} = 98/59$





Final state	Fraction %	Phase (degrees)
$\overline{K^0}\phi$	45.4 ± 1.6 ± 1.0	0.
$\overline{K^0}a_0(980)^0$	60.9 ± 7.5 ± 13.3	109 ± 5
$\overline{K^0}f_0(980)$	12.2 ± 3.1 ± 8.6	–161 ± 14
$a_0(980)^+K^-$	34.3 ± 3.2 ± 6.8	–53 ± 4
$a_0(980)^-K^+$	3.2 ± 1.9 ± 0.5	-13 ± 15
Non-Reson.	0.4 ± 0.3 ± 0.8	40 ± 44
Sum	156.4 ± 9.1	

Conclusion

Summary

- BaBar is also a Charm factory!
- There are still surprises in D^0 mixing formalism.
- Measurement of the D^0 mixing parameter y, based on 57.8 fb^{-1} of data:

$$y = 1.4 \pm 1.0\,(\text{stat})\,^{+0.6}_{-0.7}\,(\text{syst})\,\%$$

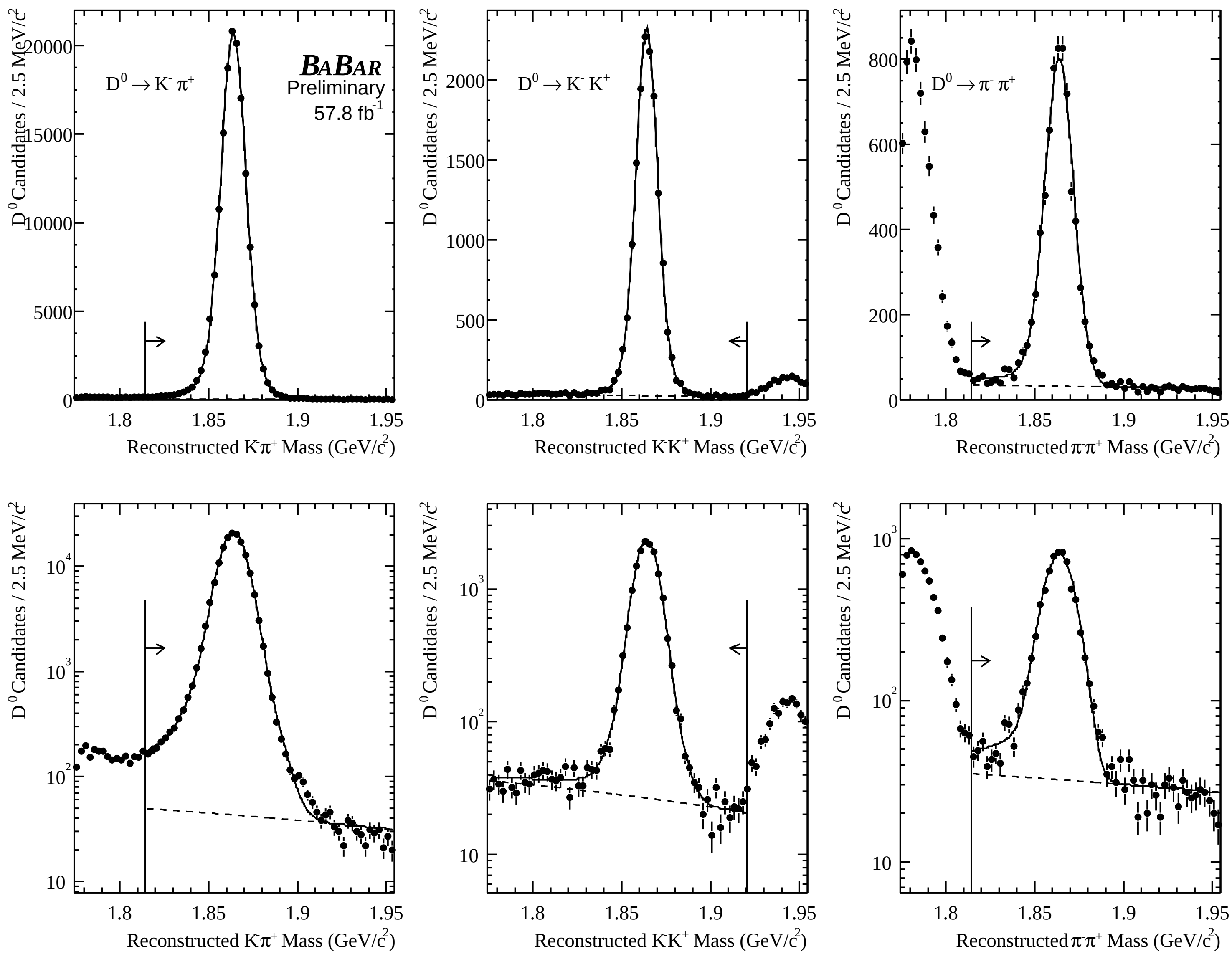
- First Dalitz amplitude analyses of $D^0 \to K_S K^- \pi^+, \overline{K_S} K^+ \pi^-, \overline{K_S} K^+ K^-$ plus updated branching ratios (10$\times$ current precision), based on 22 fb^{-1} of data.

- We have 91 fb^{-1} of data available — our work has just begun.

Additional Material

Mass Fits

Determines event-by-event signal purities.

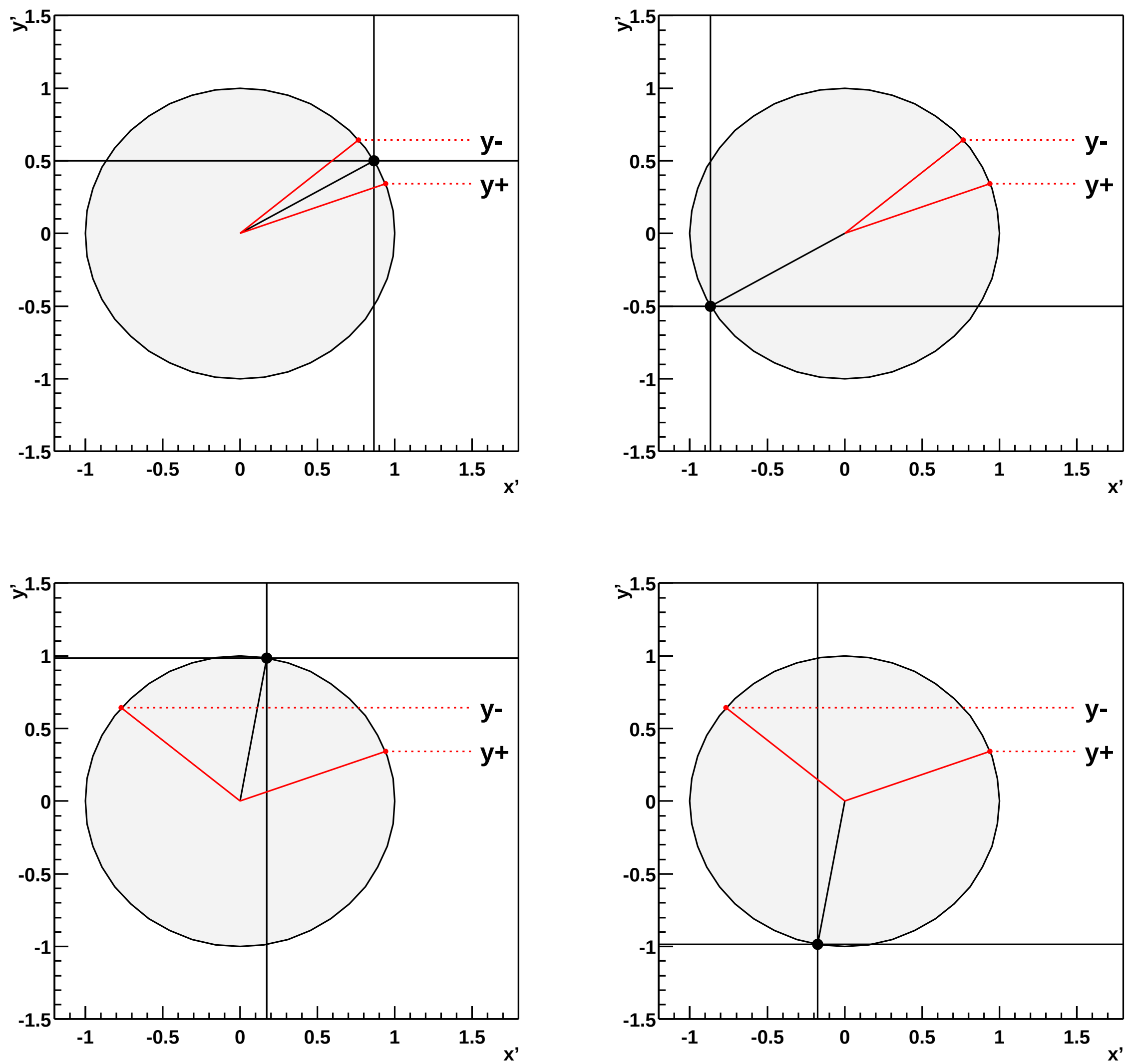


Additional Material

Geometric Interpretation of Eight-Fold Ambiguity

$$x'^{\pm} = \left[\frac{1+A_M}{1-A_M}\right]^{\pm 1/4} \left(x'\cos\varphi \pm y'\sin\varphi\right)$$

$$y'^{\pm} = \left[\frac{1+A_M}{1-A_M}\right]^{\pm 1/4} \left(y'\cos\varphi \pm x'\sin\varphi\right)$$



Additional Material

Calculating Mixing Limits

At current statistics, the likelihood space in x'^2 and y' is non-Gaussian and not translationally invariant.

- Traditional confidence limit methods are not adequate.
- Performing a blind analysis is more complex.