D^0 Mixing and Charm Physics at BaBar

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HEP Seminar
Brookhaven National Laboratory
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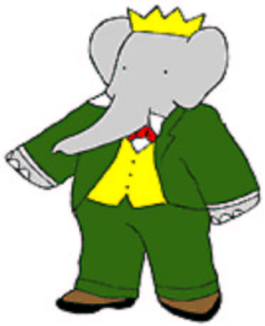
Outline:

- Introduction
- D^0 Mixing: Lifetime Ratio
- D^0 Mixing: Wrong-Sign Decay
- Three-Body D Decays
- Conclusion



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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.**
  - **Preliminary results on hadronic mixing $D^0 \to K^+\pi^-$.**
- **Dalitz amplitude analyses for many decay modes.**
  - **Preliminary fits to $D^0 \to K^0 h^+ h^-$.**
- **Charm baryon studies underway.**
- **Rare searches planned.**

Introduction

The PEP II Collider

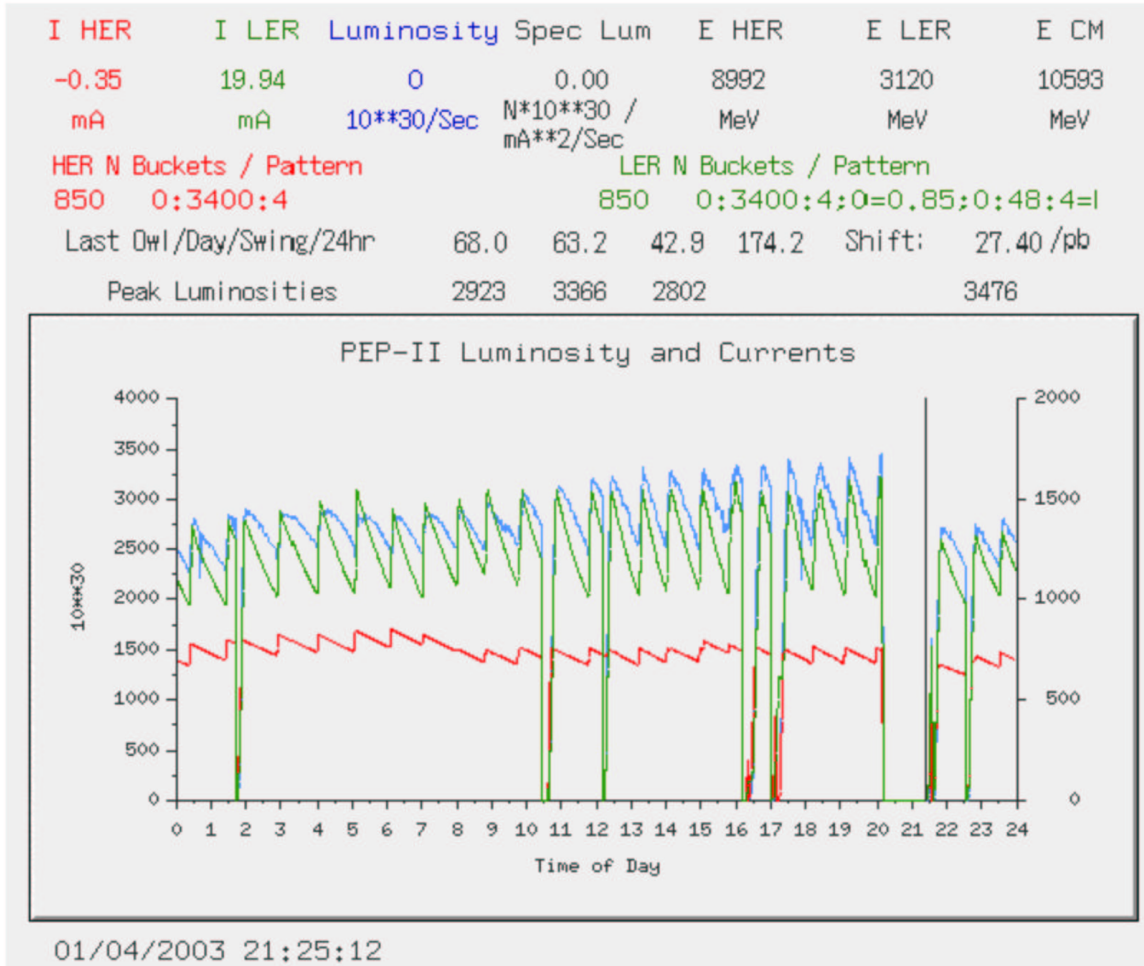
Record peak luminosity: 4.602×10^{33} cm^{-2} sec^{-1} (4 B pairs/second)

Other records:

- best shift: 108.3 pb^{-1}
- best 24 hours: 308.8 pb^{-1}
- best 7 days: 1865.0 pb^{-1}
- best month: 6.66 fb^{-1}

Design values:

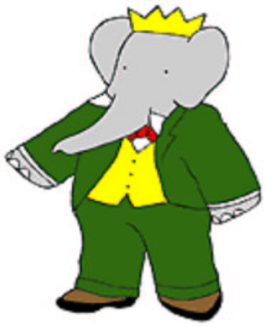
- luminosity: 3×10^{33}
- day: 135 pb–1
- month: 3.3 fb^{-1}



Introduction

The BaBar Collaboration

10 Countries
74 Institutes
~560 Physicists



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Imperial College, London
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U. Birmingham
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Russia
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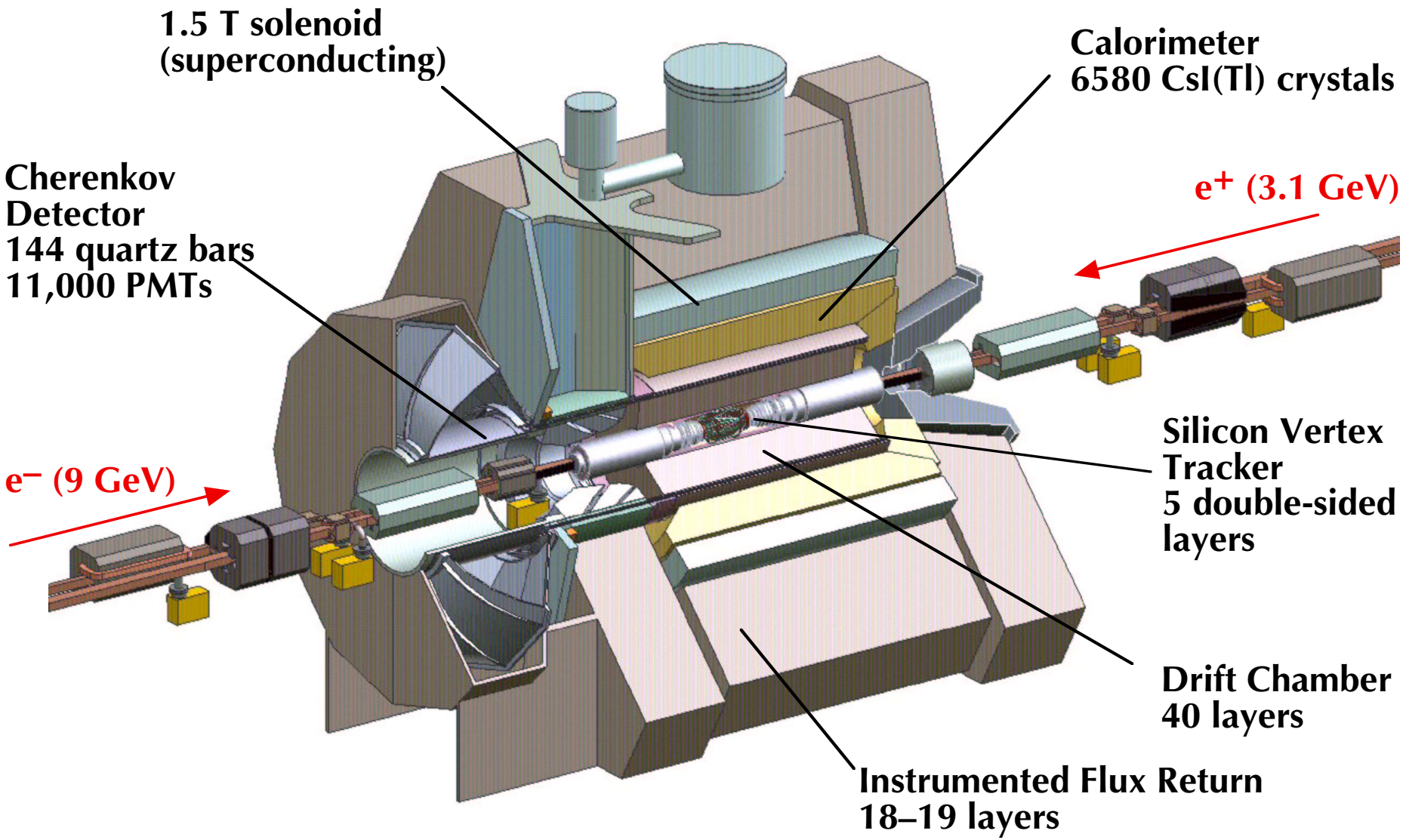
Introduction

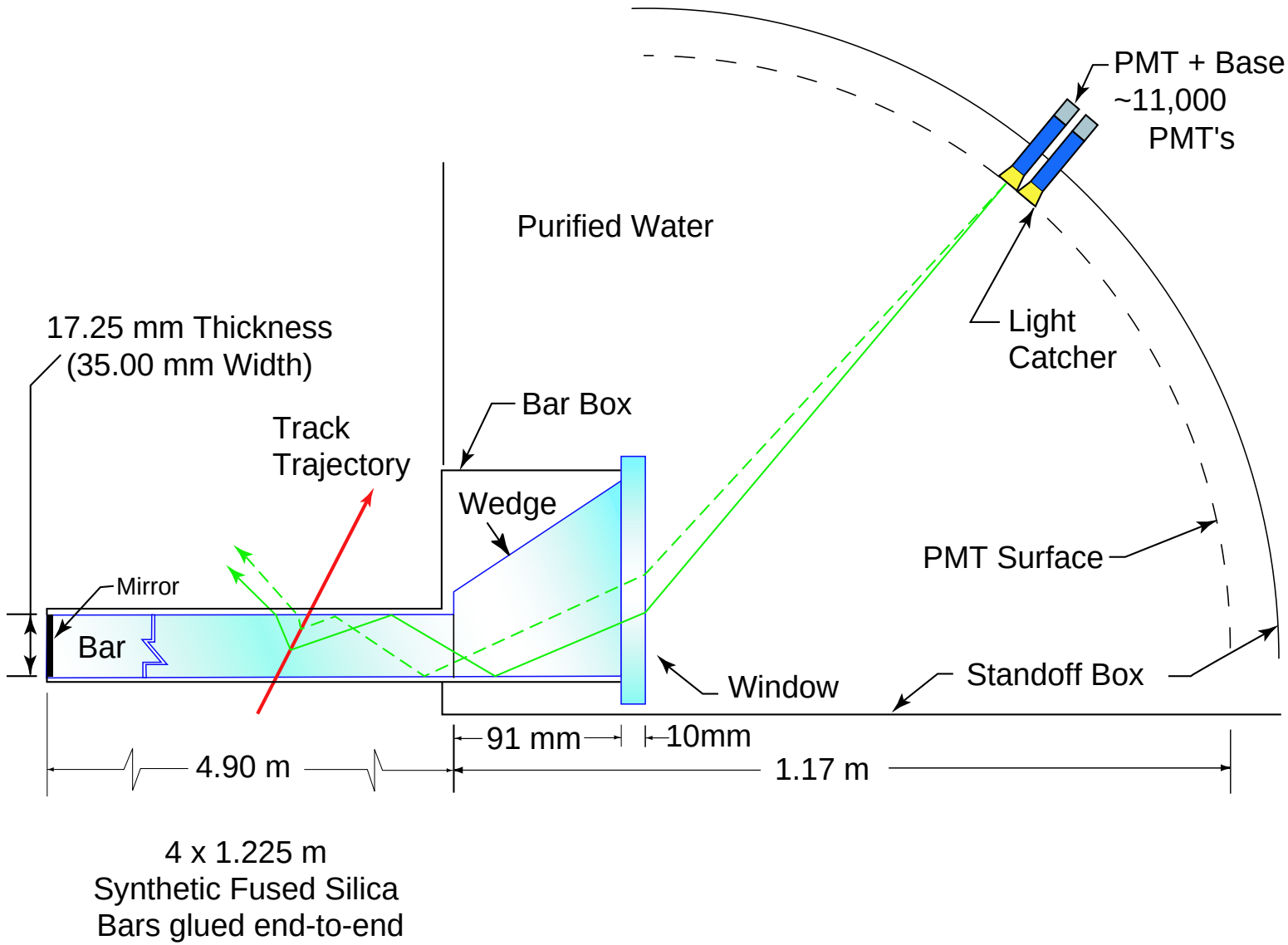
The BaBar Detector



Introduction

DIRC

Detection of Internally Reflected Cherenkov light

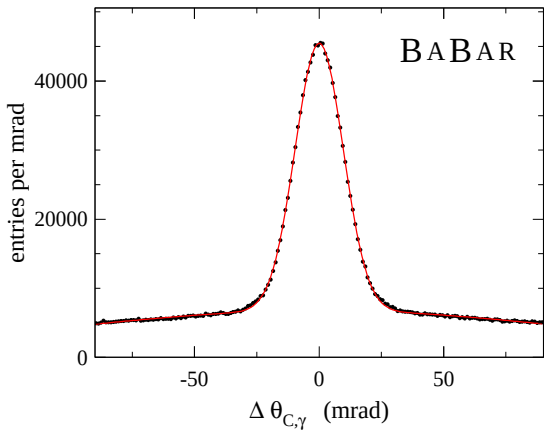


Introduction

DIRC

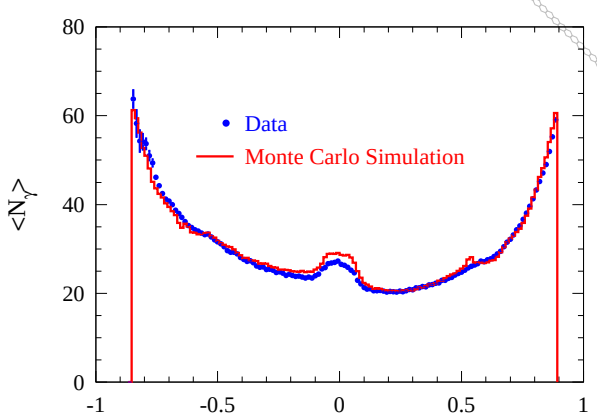
Works beautifully!

Cherenkov angle resolution width ~10 mrad



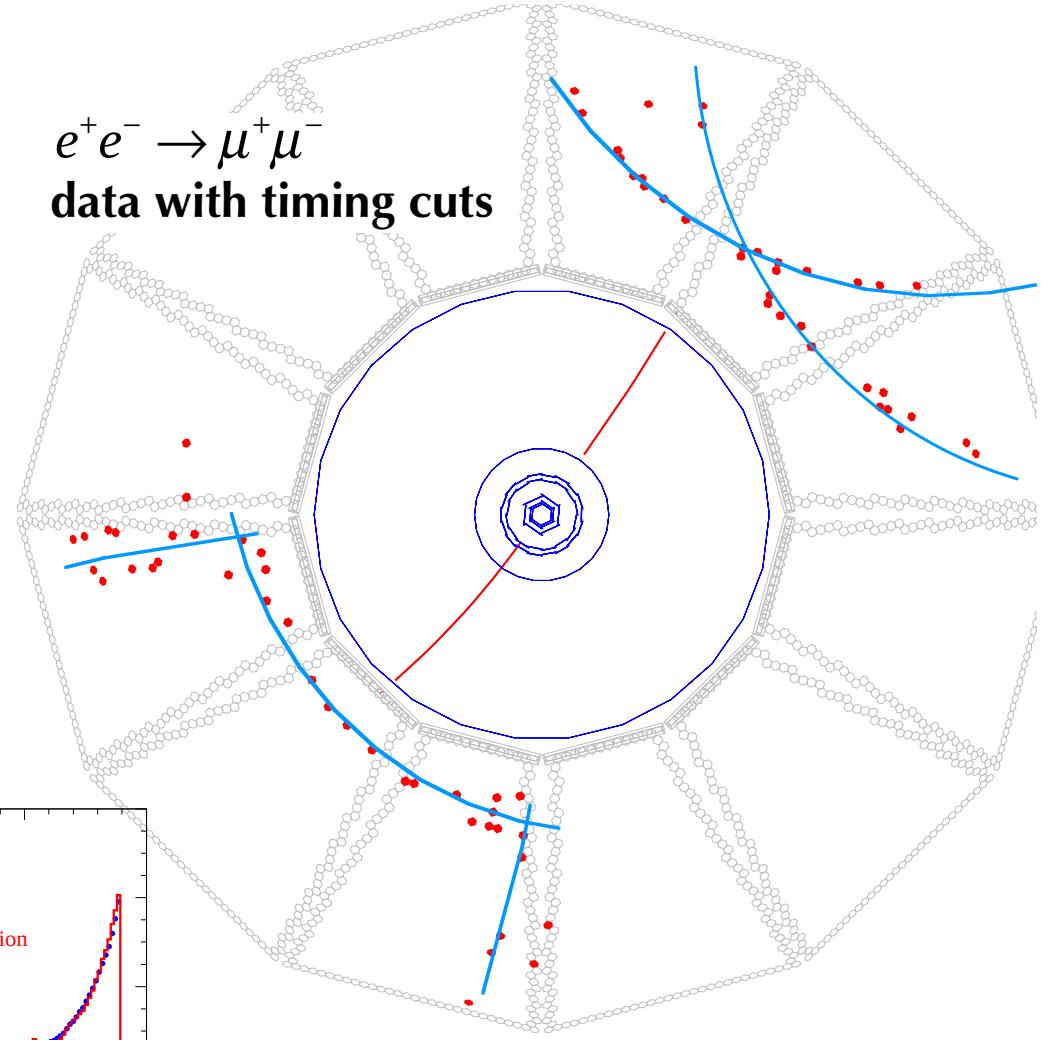
Photon yield > 20

$e^+e^- \rightarrow \mu^+\mu^-$



$e^+e^- \rightarrow \mu^+\mu^-$

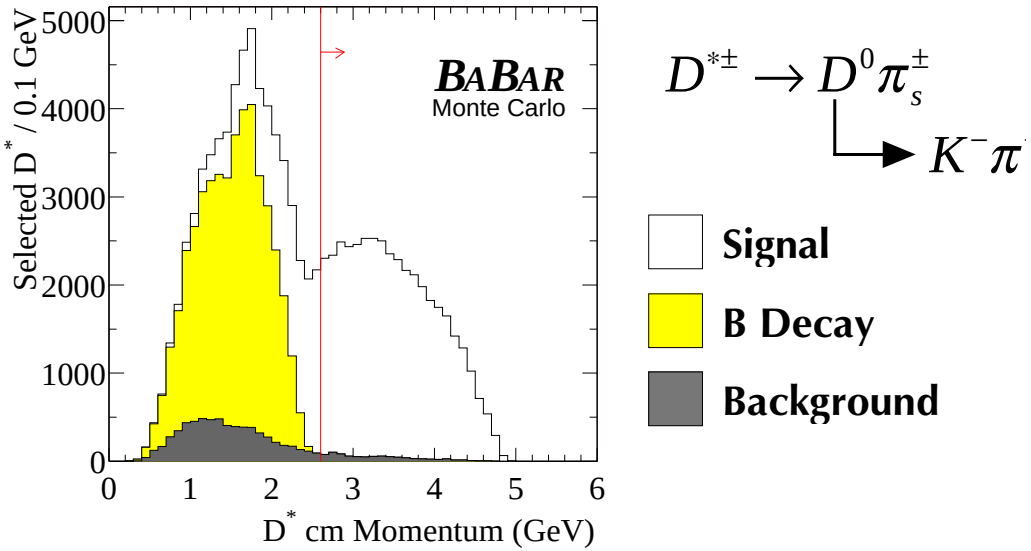
data with timing cuts



Introduction

Selecting Charm Decays

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

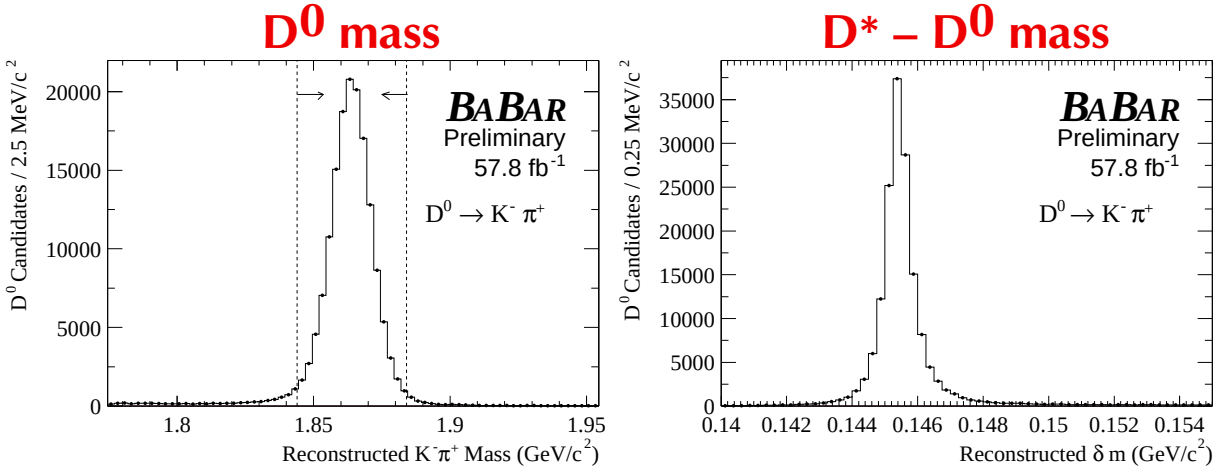


Cut on excited decay:

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

$$D_S^{*+} \to D_S^+ \gamma$$

Use D^0 mass sideband for background subtraction.



D^0 Mixing: 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:

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

is nonzero, then D states will mix.

Note the notational ambiguity:

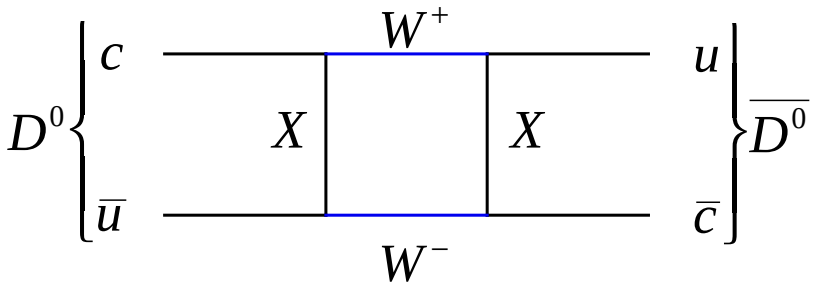
$$\begin{Bmatrix} D_1 \\ D_2 \\ q/p \\ x \\ y \end{Bmatrix} \Leftrightarrow \begin{Bmatrix} D_2 \\ D_1 \\ -q/p \\ -x \\ -y \end{Bmatrix}$$

D^0 Mixing: Lifetime Ratio

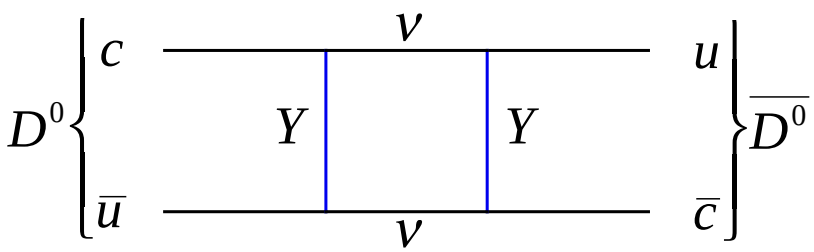
Physics Beyond the Standard Model

The Standard Model predicts: $|x| \approx |y| < 10^{-3}$

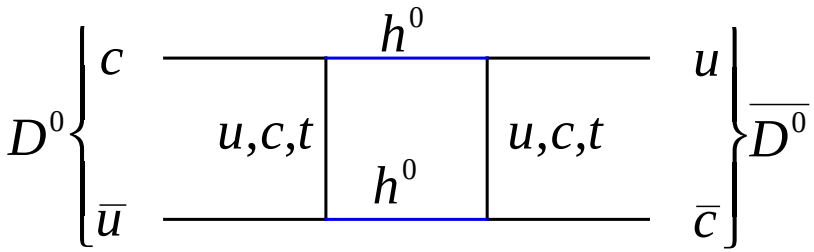
Possible source of new physics, generally $|x| > |y|$**:**



New quark X



Leptoquark Y



Non-standard Higgs h^0

D^0 Mixing: 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 and assigning** D_1 **to the CP+ state).**

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 Mixing: Lifetime Ratio

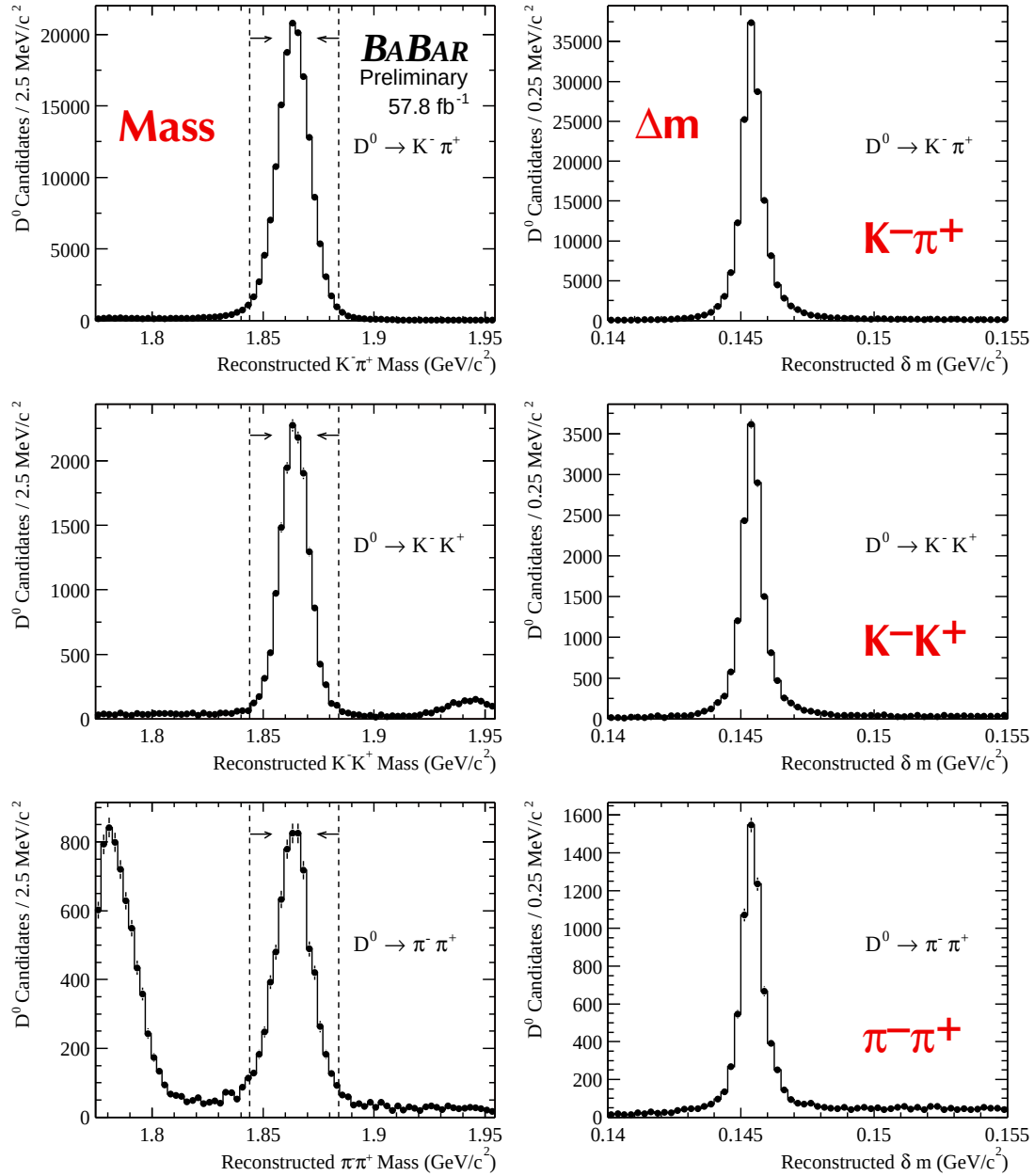
The D^0 Sample

57.8 fb^{-1} of 2000–2001 data

$D^0 \to K^-\pi^+$
158,000 events
99.5% purity

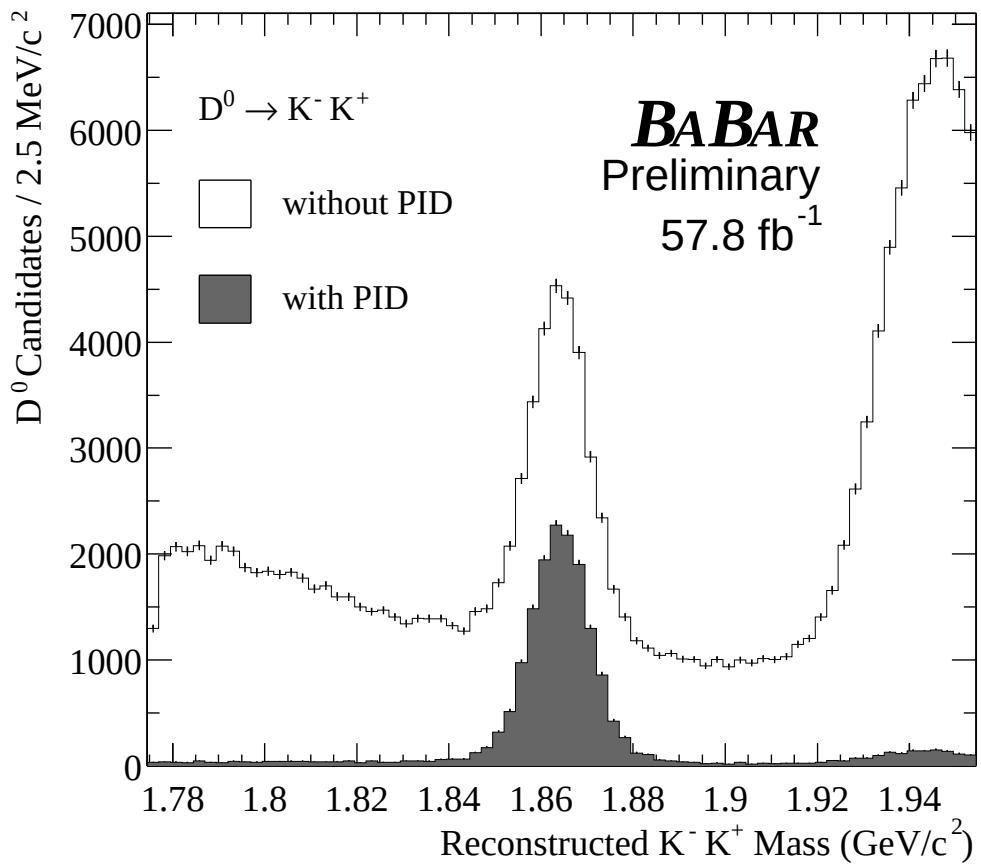
$D^0 \to K^-K^+$
16,500 events
97.1% purity

$D^0 \to \pi^-\pi^+$
8,350 events
92.4% purity



D^0 Mixing: Lifetime Ratio

Particle Identification Is Important

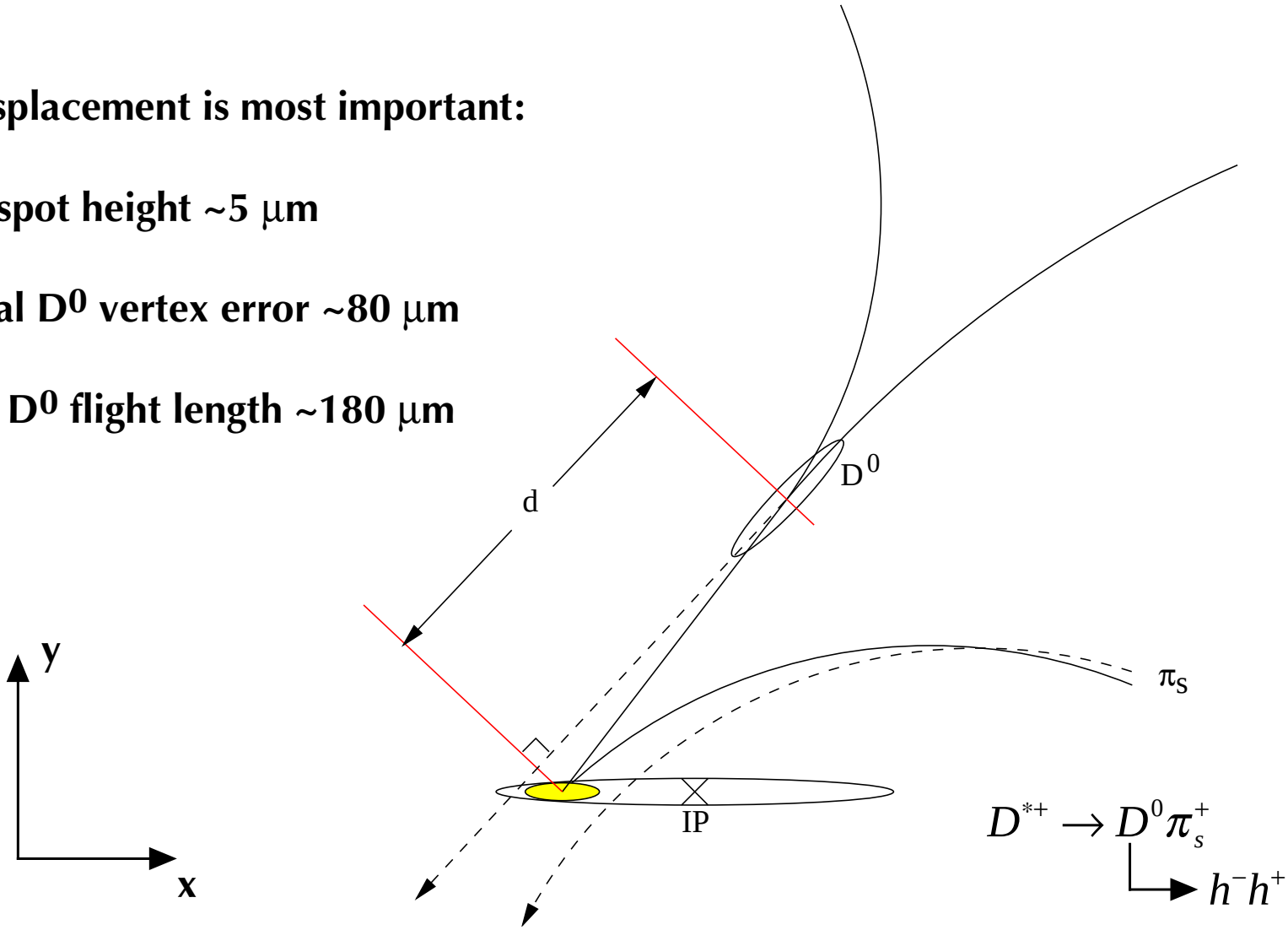


D^0 Mixing: Lifetime Ratio

Measuring the Lifetime

Vertical displacement is most important:

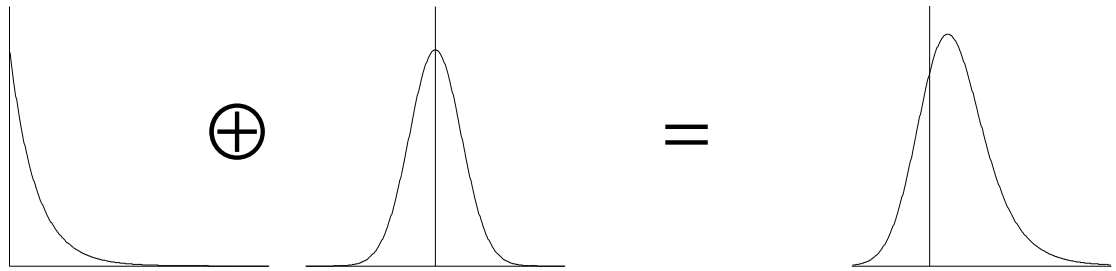
- **Beamspot height ~5 μm**
- **Typical D^0 vertex error ~80 μm**
- **Mean D^0 flight length ~180 μm**



D^0 Mixing: Lifetime Ratio

Fitting for the Mean Lifetime

Smeared lifetime distribution:



$$e^{-t/\tau} \qquad \frac{1}{\sqrt{2\pi}\delta} e^{-t^2/2\delta^2} \qquad \frac{1}{\sqrt{2\pi}\delta} \int_0^\infty e^{-t'/\tau} e^{-(t-t')^2/2\delta^2} dt'$$

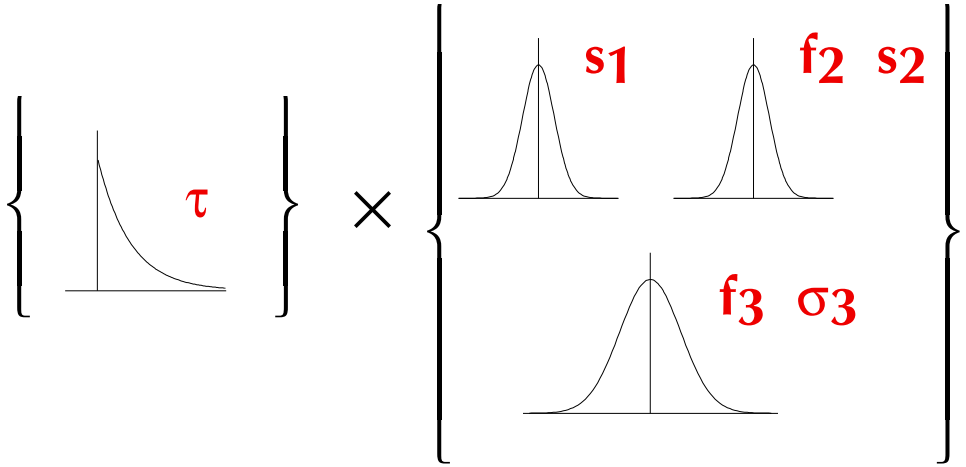
Binless maximum likelihood fit: minimize

$$-\ln P(\tau) = \sum \ln P_i(t_i, \delta t_i; \tau)$$

D^0 Mixing: Lifetime Ratio

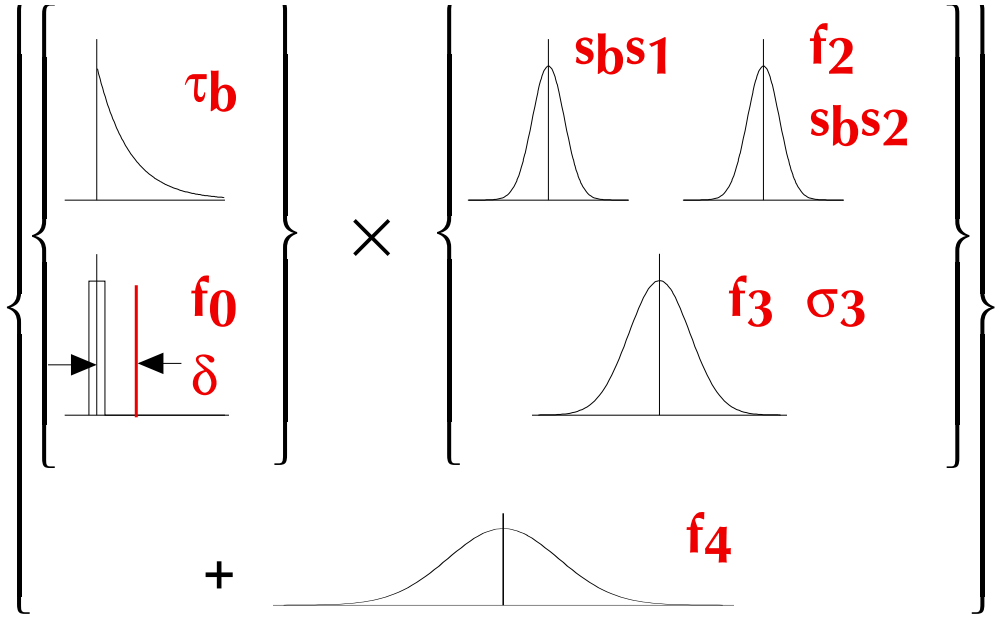
Likelihood Functions

Signal:



× (Purity)

Background:

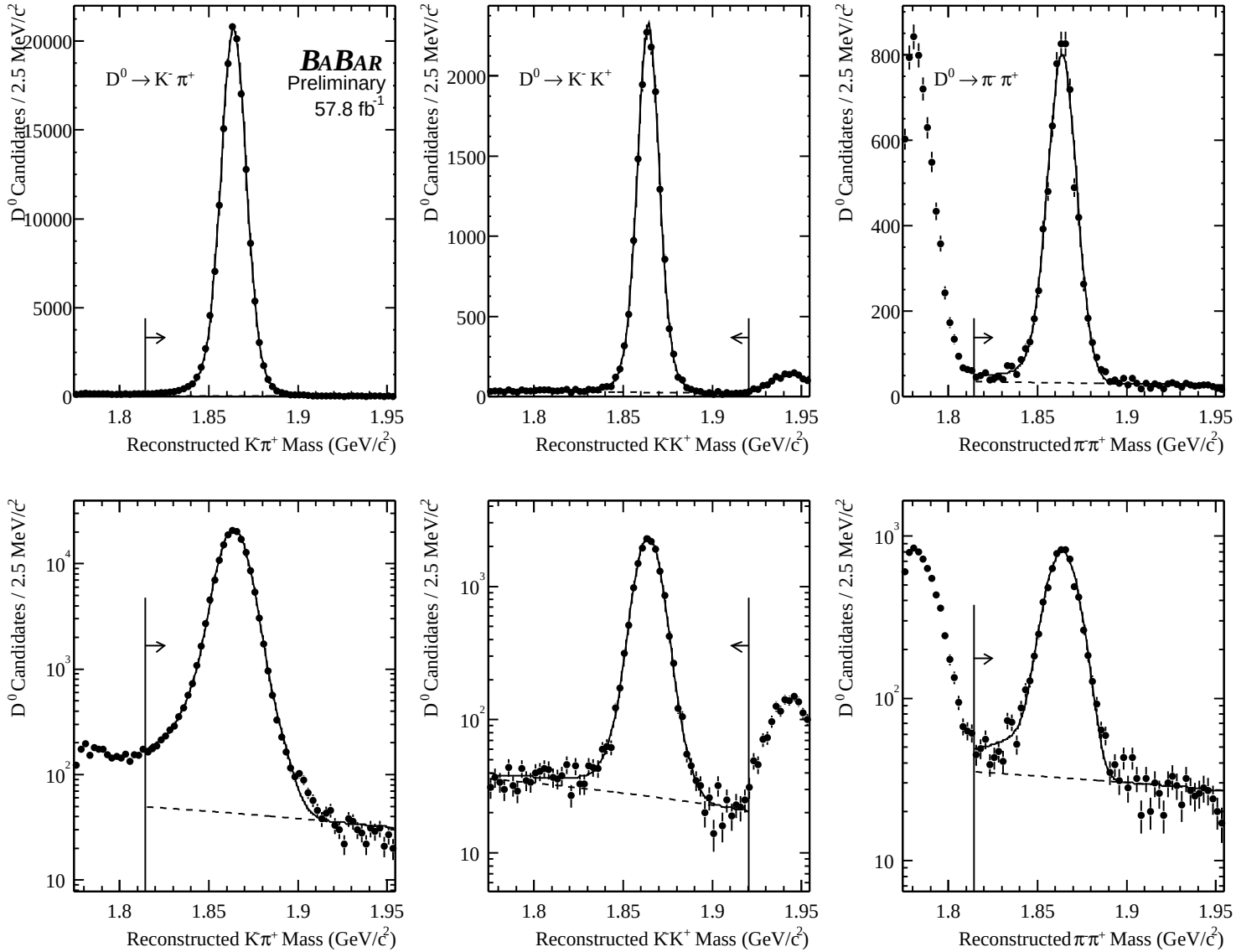


× (1 – Purity)

D^0 Mixing: Lifetime Ratio

Mass Fits

Determines event-by-event signal purities.



D^0 Mixing: Lifetime Ratio

Lifetime Fits

Binless maximum likelihood:

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

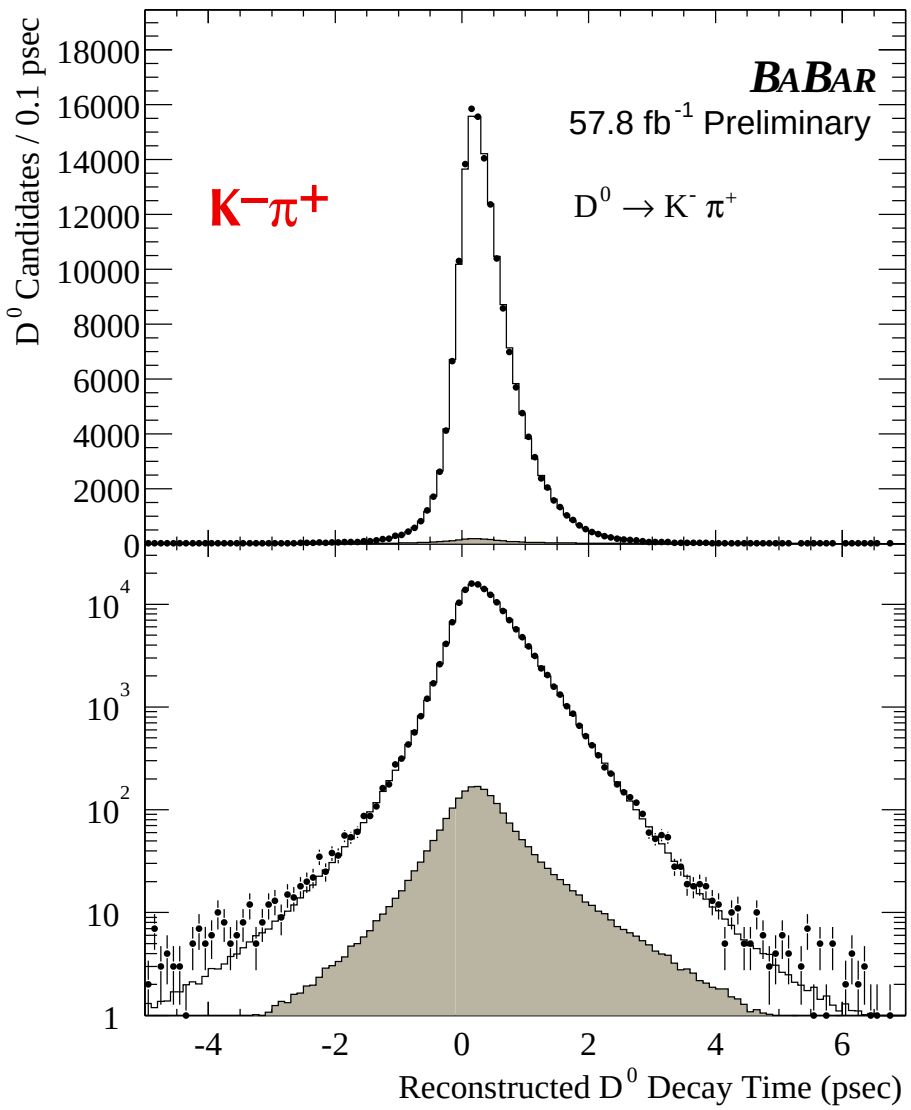
Lifetime statistical error σ_τ = 1.3 fsec.
PDG average: 411.7 ± 2.7 fsec.

Data

Fit result

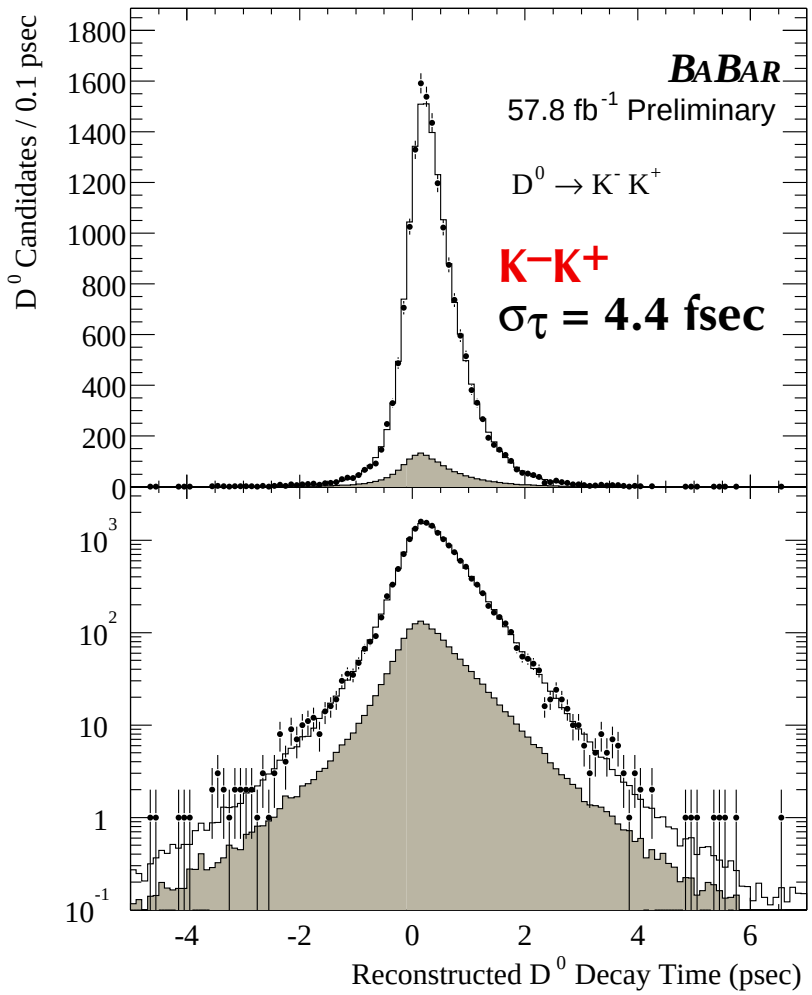
Background portion

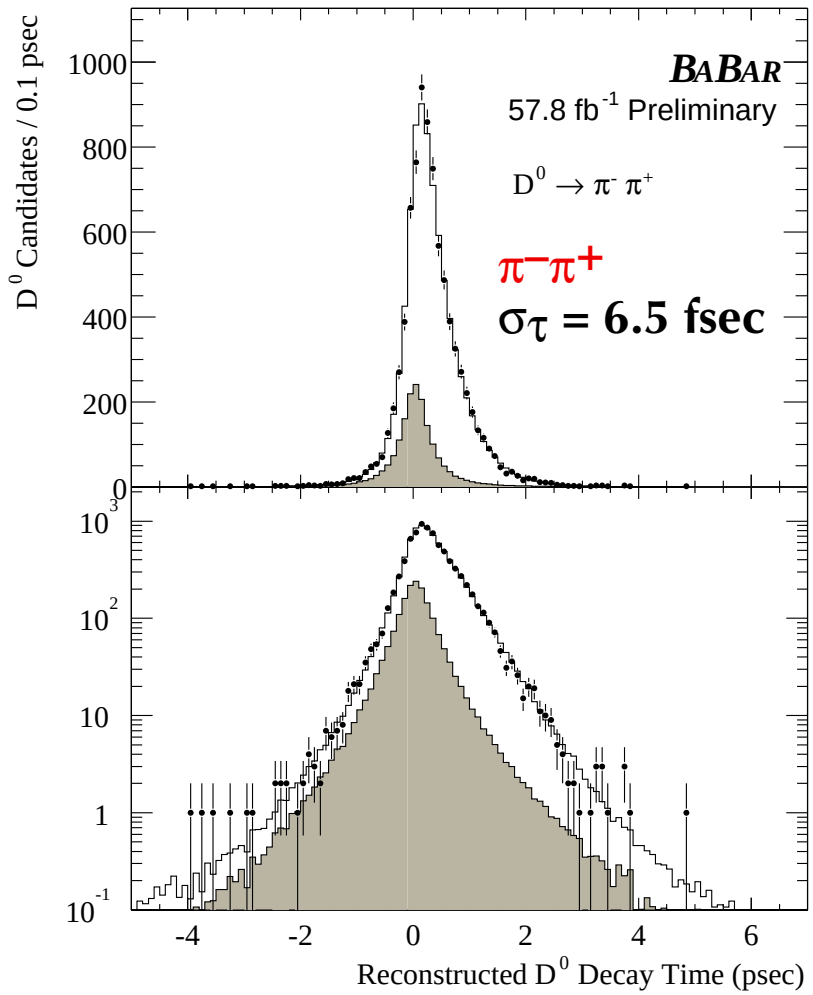
D^0 mass sidebands included



D^0 Mixing: Lifetime Ratio

Lifetime Fits



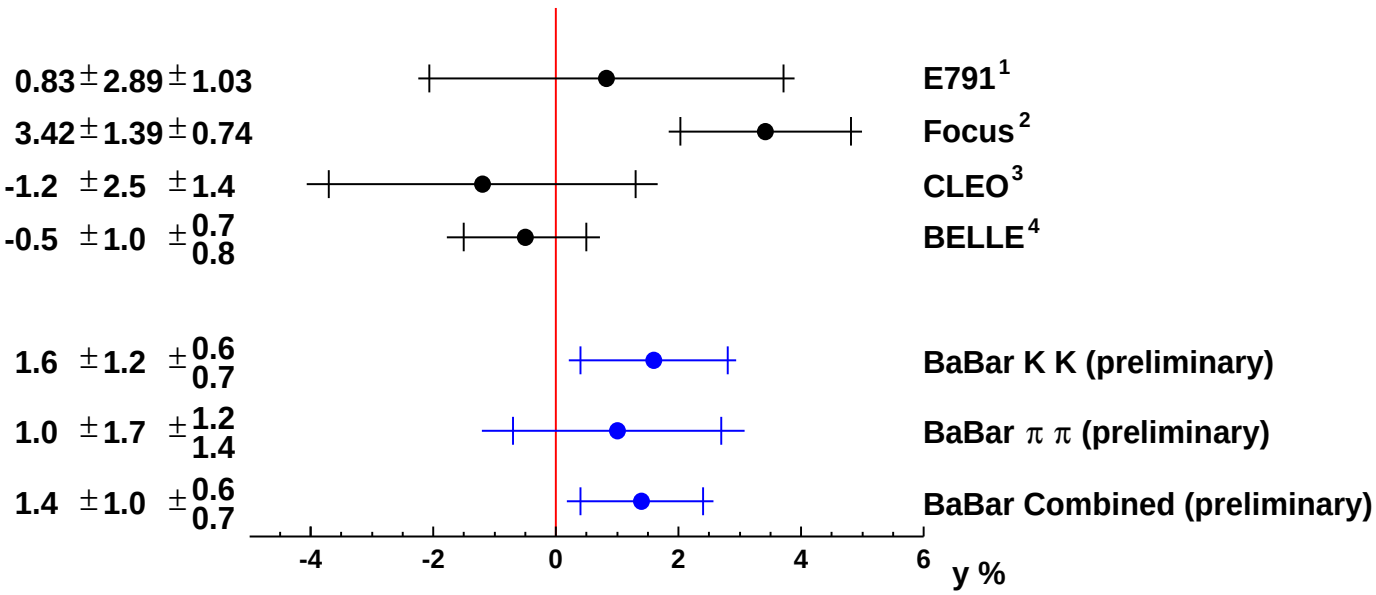


D^0 Mixing: Lifetime Ratio

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	$^{+0.6}_{-0.7}$	$^{+1.2}_{-1.4}$

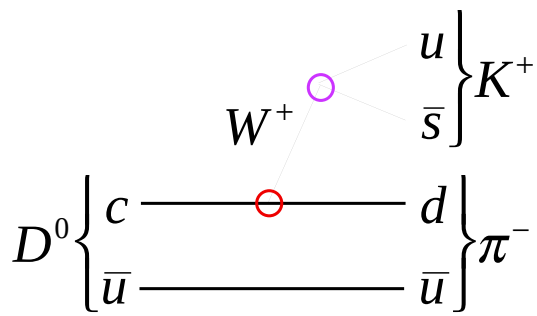


1. E791 Collaboration, Phys.Rev.Lett. 83 (1999) 32.
2. Focus Collaboration, Phys.Lett. B485 (2000) 62.
3. CLEO CONF-01.
4. BELLE Collaboration, Phys.Rev.Lett. 88 (2002) 05201.

D^0 Mixing: Wrong-Sign Decay

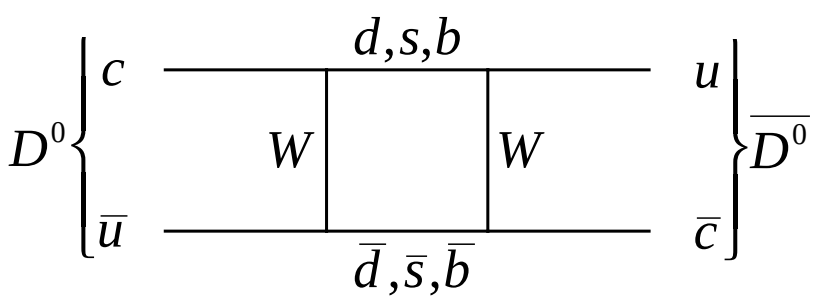
D^0 Mixing With $D^0 \to K^+\pi^-$

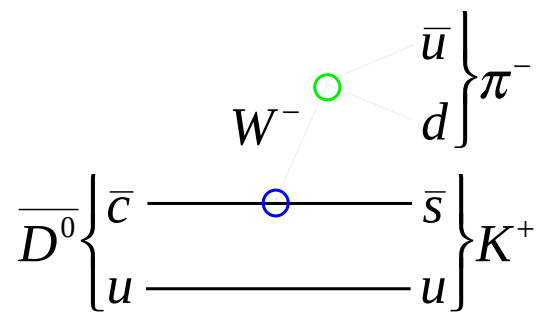
Wrong-sign D^0 decays can occur through a double-Cabibbo suppressed diagram:



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

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: Wrong-Sign Decay

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, then

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

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

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

D^0 Mixing: Wrong-Sign Decay

Four-Fold Ambiguity

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

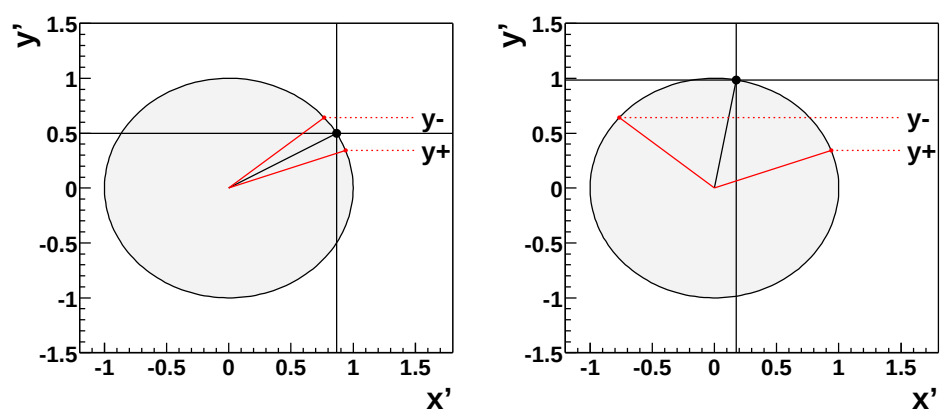
$$R^{\pm} = \left[\frac{1+A_D}{1-A_D}\right]^{\pm 1/2} R$$

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

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

Since we cannot measure the sign of $x'^{\pm}$, there is a four-fold ambiguity:

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



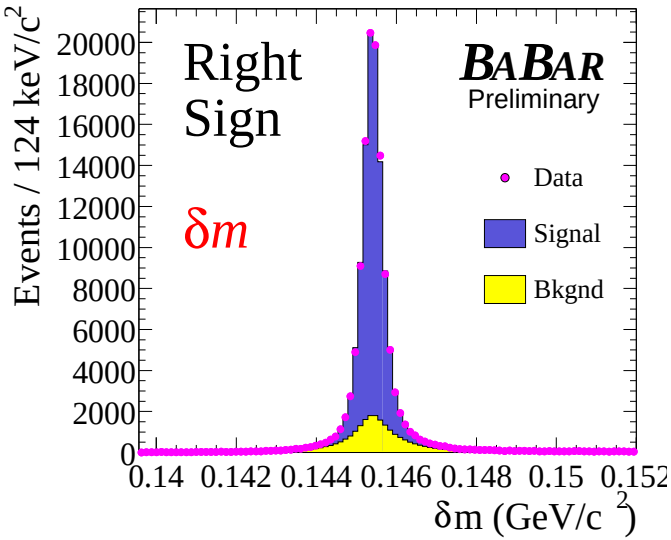
D^0 Mixing: Wrong-Sign Decay

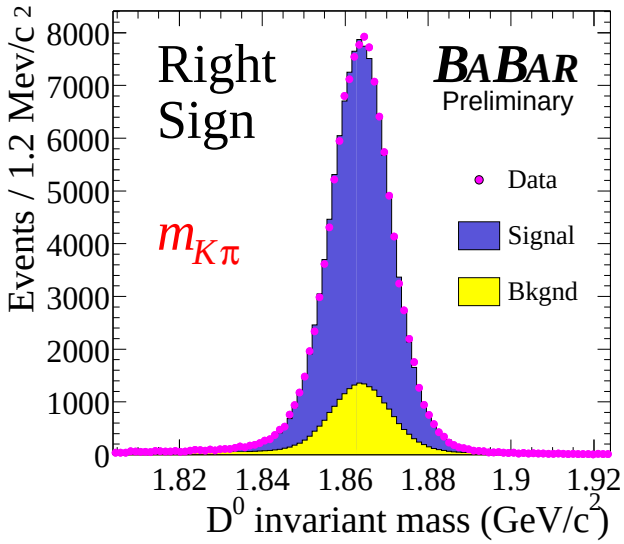
Data Samples

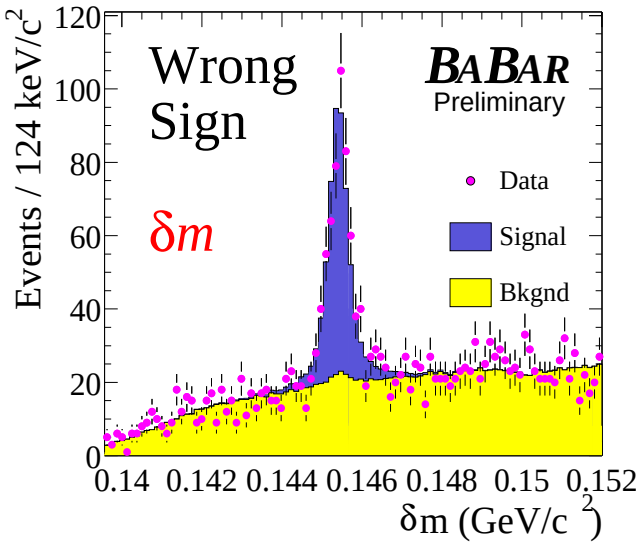
Projections, with fit.

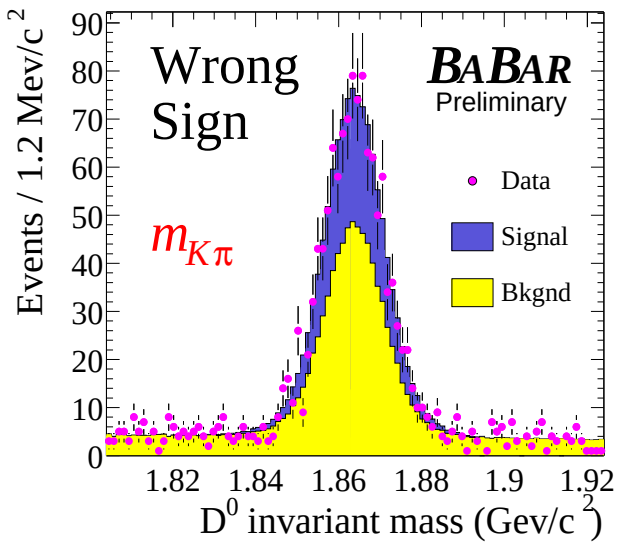
The larger right-sign sample is used to control the parameters of the wrong-sign sample.

57.1 fb^{-1}.
~440 wrong-sign events.





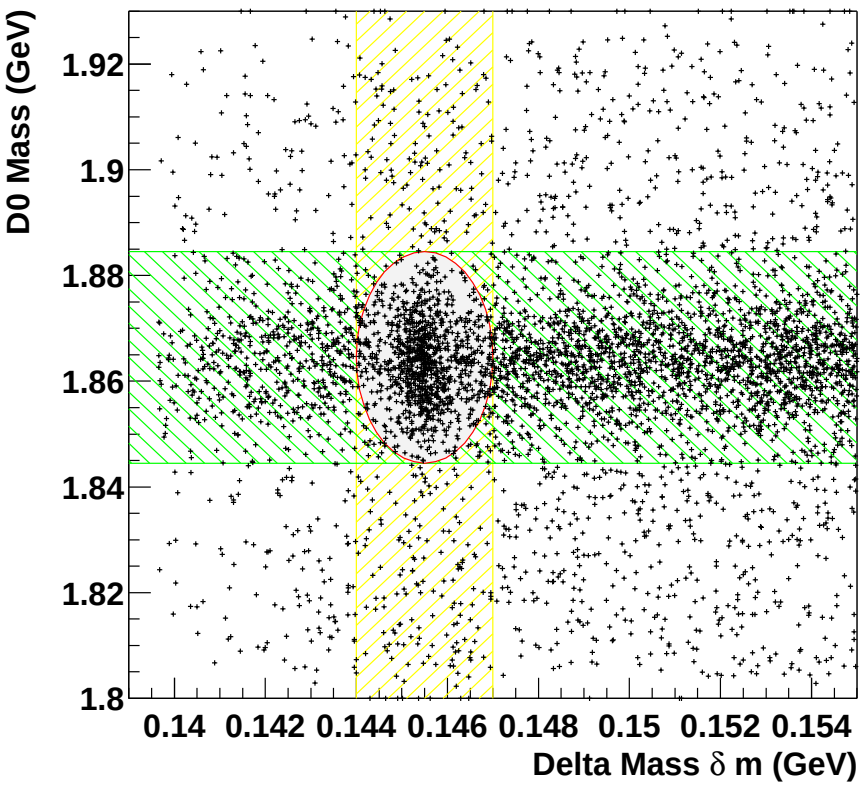


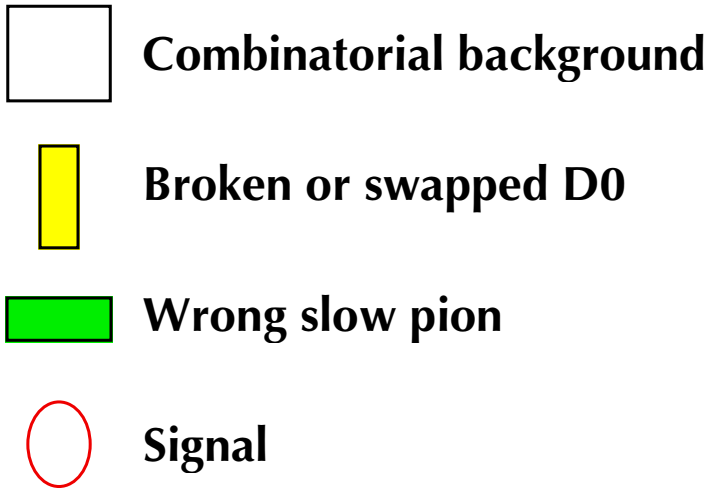


D^0 Mixing: Wrong-Sign Decay

Backgrounds

Double peaking background!





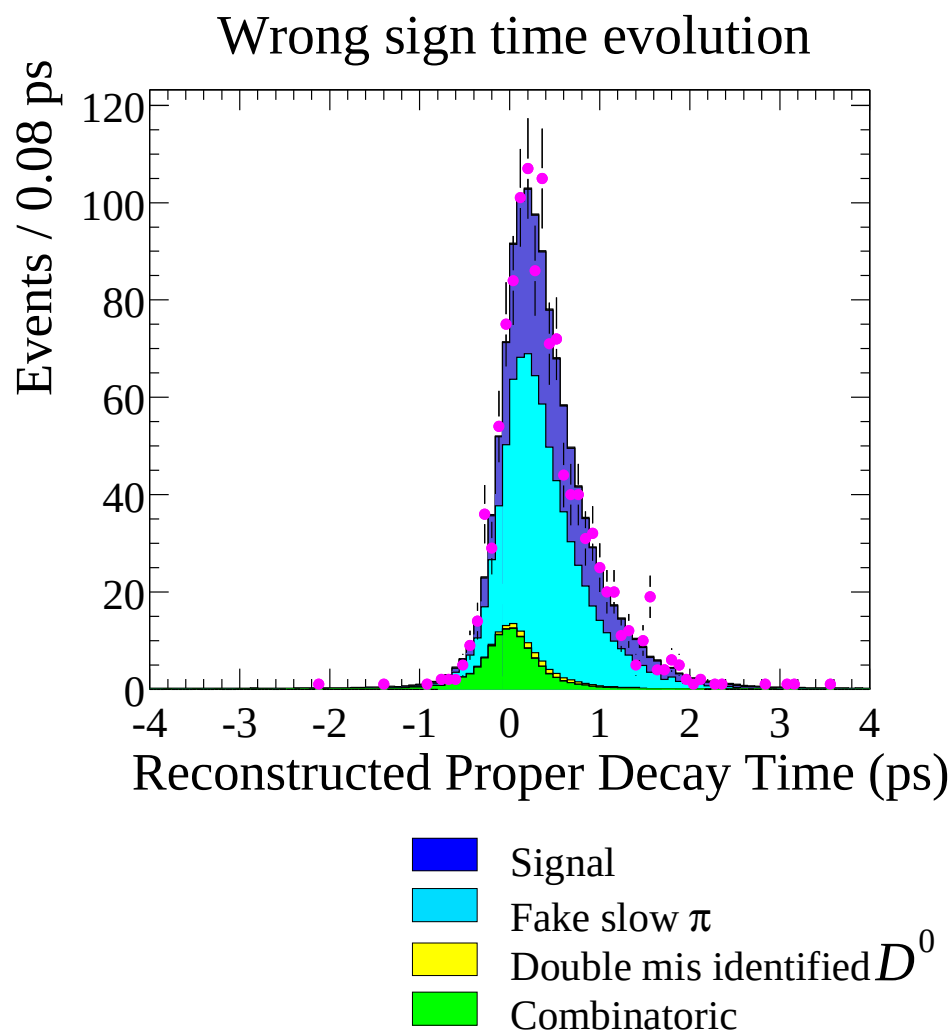
D^0 Mixing: Wrong-Sign Decay

Lifetime Fit

The right-sign sample fixes the lifetime and resolution for unmixed decays.

Deviations in the wrong-sign sample indicate mixing.

Background lifetime distributions determined from sidebands in data.

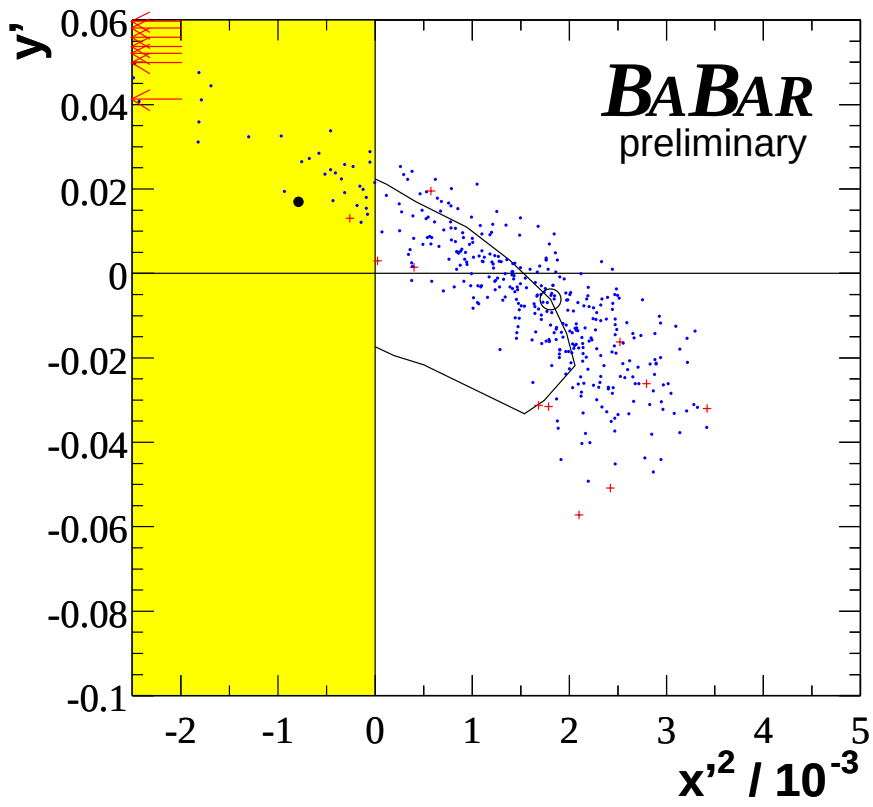


D^0 Mixing: Wrong-Sign Decay

95% Confidence Limits

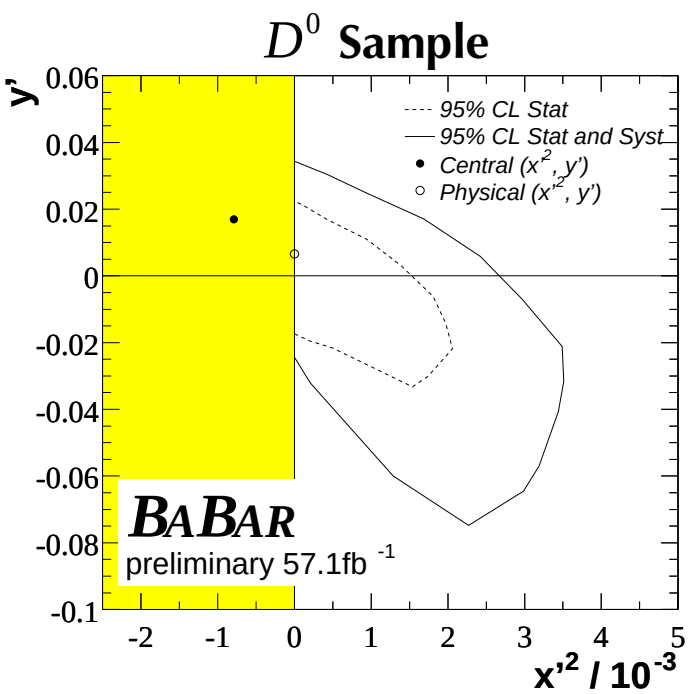
Use frequentist definition, implemented with toy Monte Carlo.

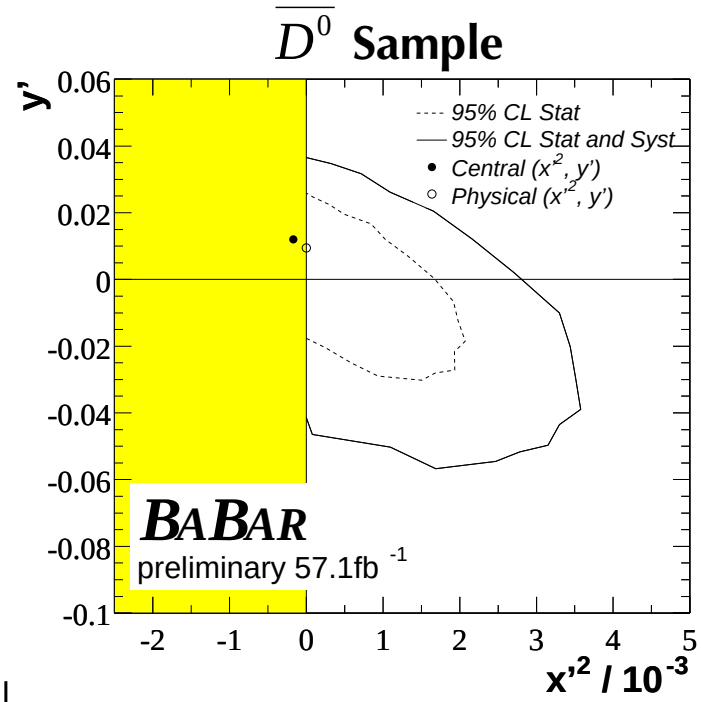
All fits allow $x'^2 < 0$.



D^0 Mixing: Wrong-Sign Decay

Results





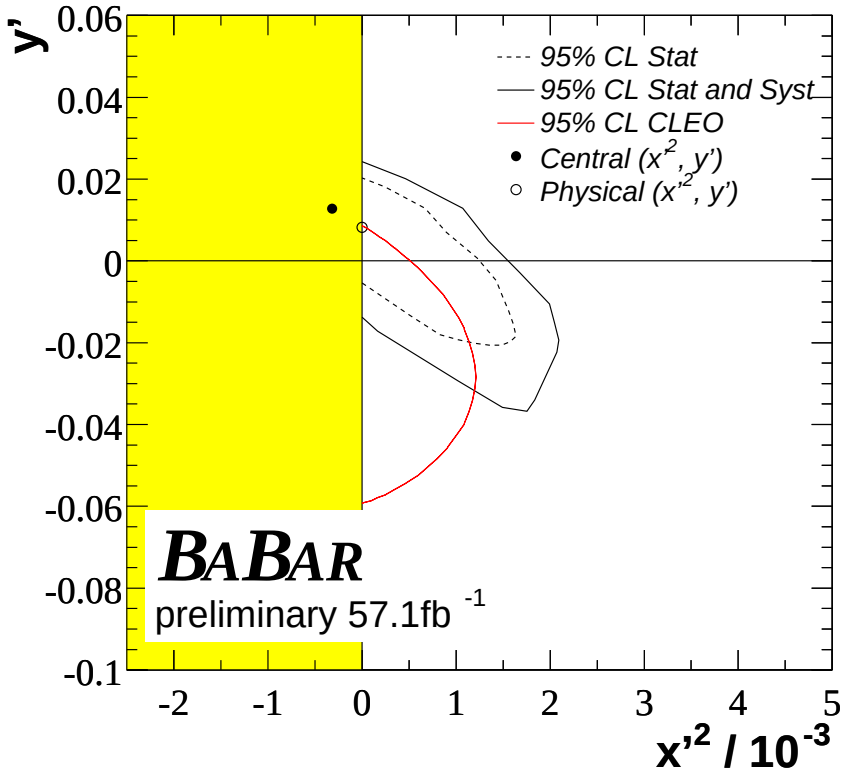
	D^0 Events Only			$\overline{D^0}$ Events Only		
	Fit Value		95% CL	Fit Value		95% CL
Parameter	x'^2 free	$x'^2 \geq 0$		x'^2 free	$x'^2 \geq 0$	
R_D (%)	0.32	0.35	$0.16 < R_D < 0.62$	0.26	0.27	$0.12 < R_D < 0.56$
$x'^2 \cdot 10^3$	– 0.8	0	$x'^2 < 3.5$	– 0.2	0	$x'^2 < 3.6$
$y' \cdot 10^2$	1.7	0.7	$-7.5 < y' < 3.4$	1.2	0.9	$-5.7 < y' < 3.6$
R_{WS} (%)	0.39 ± 0.03 (stat) ± 0.03 (syst)			0.32 ± 0.03 (stat) ± 0.04 (syst)		

D^0 Mixing: Wrong-Sign Decay

Results, CP Conserved

Fit D^0 and $\overline{D^0}$ together (ignore CP violation).

Comparison to CLEO limits (which use delta log likelihood).



Parameter	Fit Value x'^2 free	Fit Value $x'^2 \geq 0$	95% CL
R_D (%)	0.3	0.31	$0.22 < R_D < 0.46$
$x'^2 \cdot 10^3$	– 0.3	0	$x'^2 < 2.1$
$y' \cdot 10^2$	1.3	0.8	$-3.7 < y' < 2.4$
R_{WS} (%)	0.36 ± 0.03 (stat) ± 0.03 (syst)		

D^0 Mixing: Wrong-Sign Decay

Mixing Plans

Several items in the works:

- **Update lifetime ratio with full 91 fb^{-1} data set.**
- **Final hadronic D^0 mixing numbers with improved systematic analysis.**
- **Mixing with semi-leptonic decays.**
- **Experiments with wrong-sign $D^0 \to K^+\pi^-\pi^0$, perhaps with Dalitz analysis.**

Three-Body D 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**

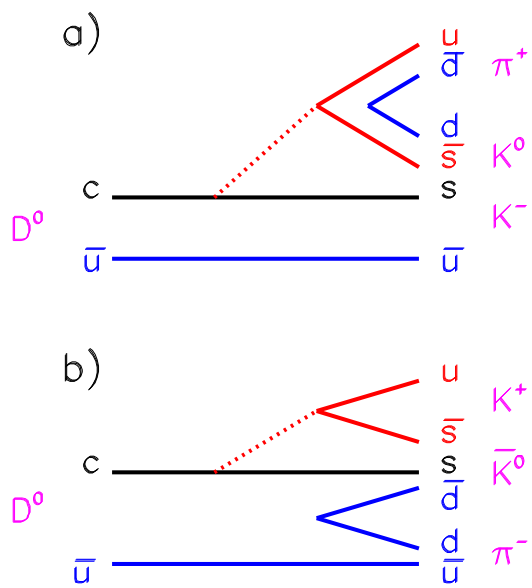
$$D^0 \to \overline{K^0} \pi^+ \pi^-$$

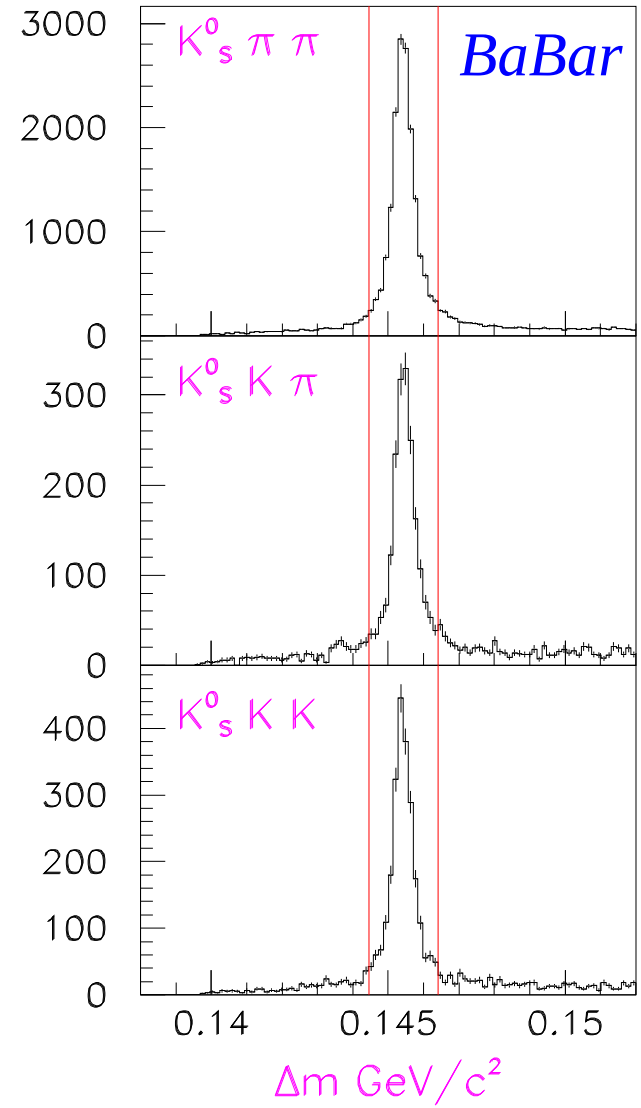
$$D^0 \to K^0 K^- \pi^+ \quad (a)$$

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

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

(+ c.c.)

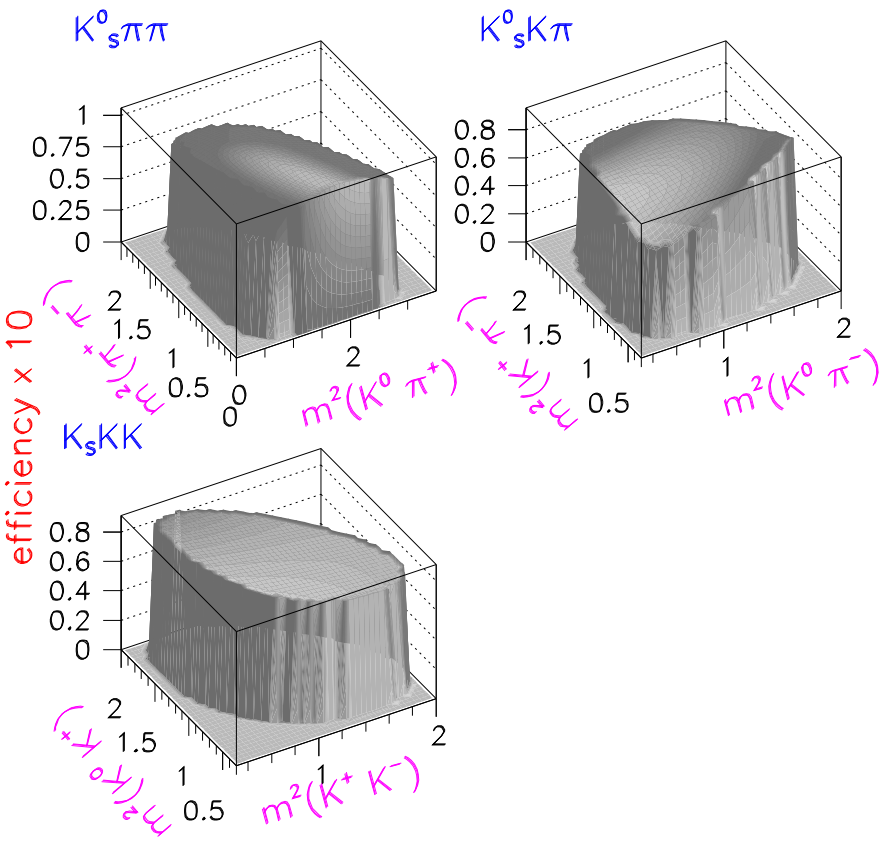


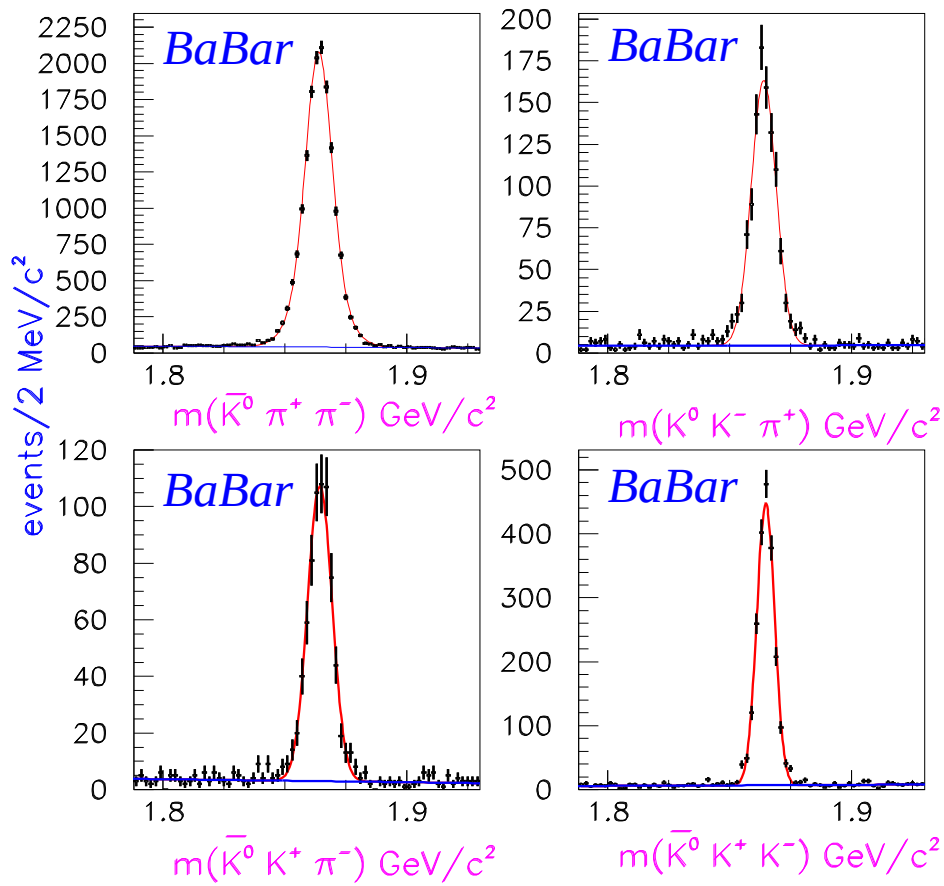


Three-Body D Decays

Reconstruction Efficiencies and Yields

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





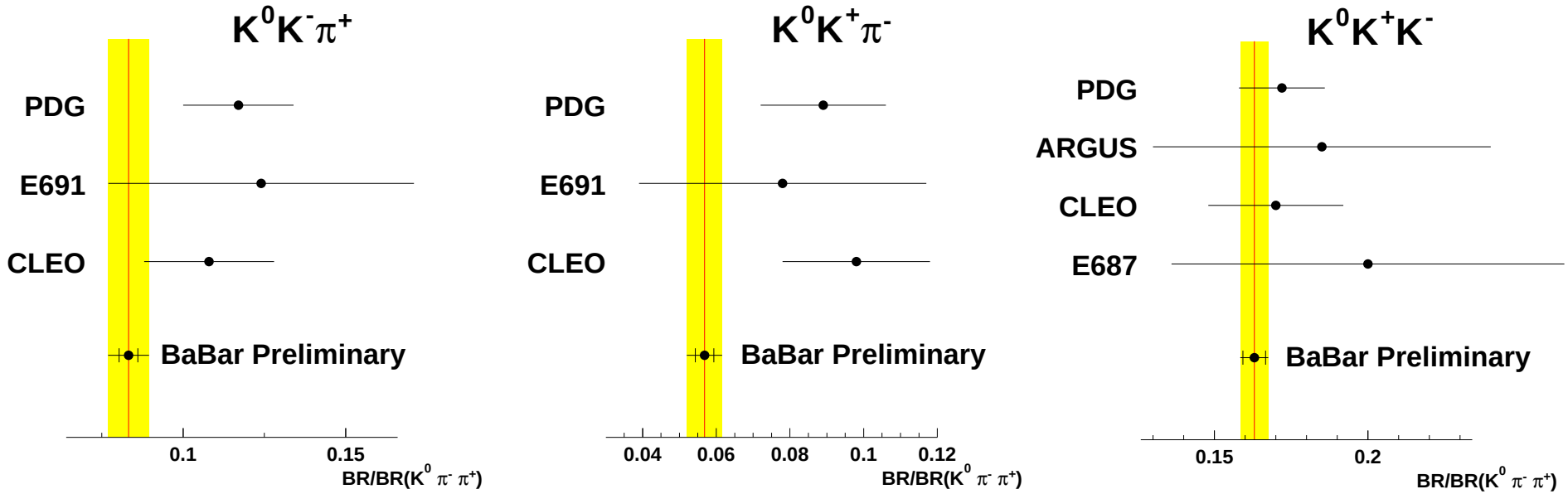
Three-Body D Decays

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 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:

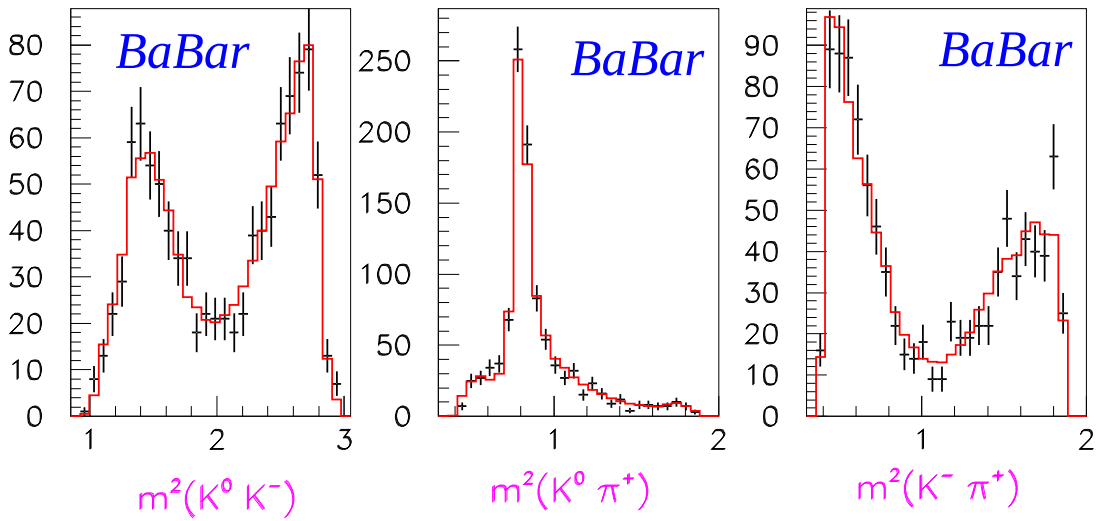
$$A_i = BW_i(m) \times T_i(\Omega)$$

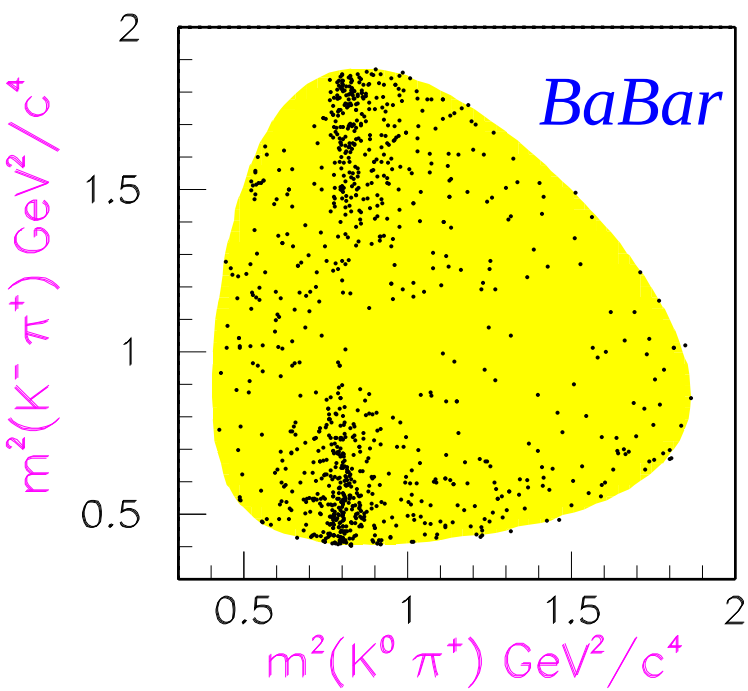
Three-Body D Decays

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

Preliminary

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





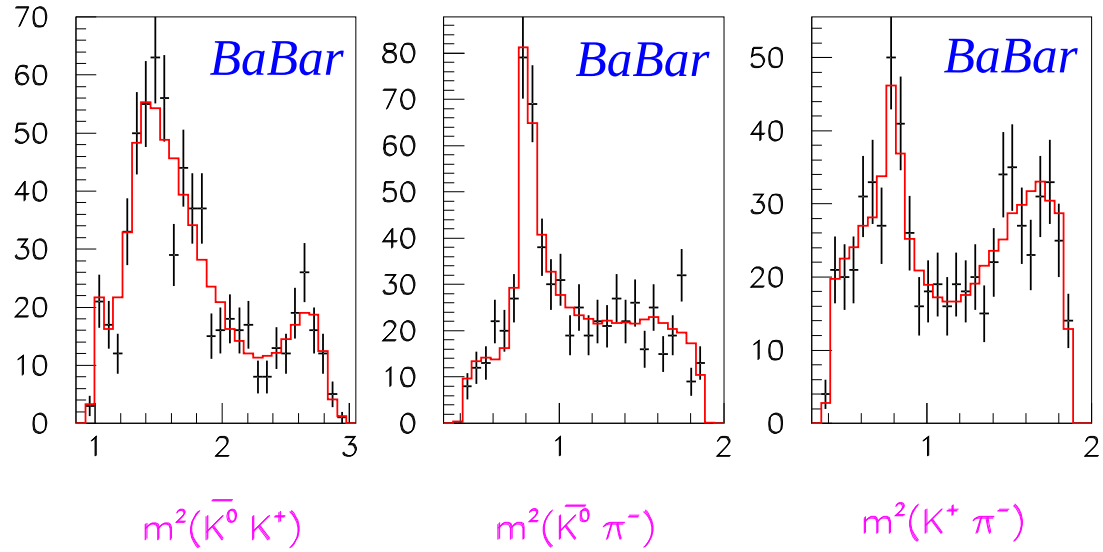
Final state	Fraction %	Phase (degrees)
$\bar{K}_0^{*0}(1430)K^0$	$4.8 \pm 1.4 \pm 1.6$	52 ± 27
$\bar{K}_1^{*0}(892)K^0$	$0.8 \pm 0.5 \pm 0.1$	175 ± 22
$\bar{K}_1^{*0}(1680)K^0$	$6.9 \pm 1.2 \pm 1.0$	-169 ± 16
$\bar{K}_2^{*0}(1430)K^0$	$2.0 \pm 0.6 \pm 0.1$	51 ± 18
$K_0^{*+}(1430)K^-$	$13.3 \pm 3.5 \pm 3.9$	-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	

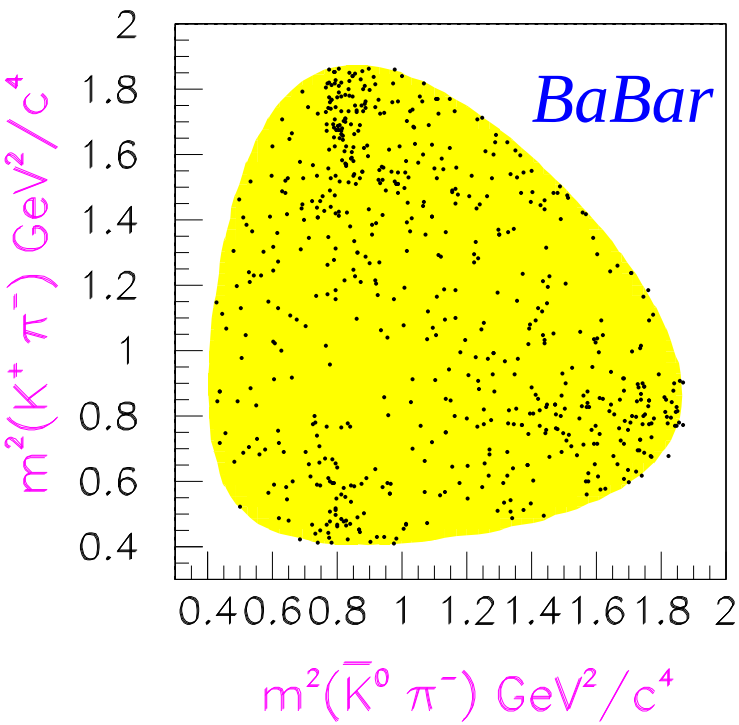
Three-Body D Decays

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

Preliminary

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





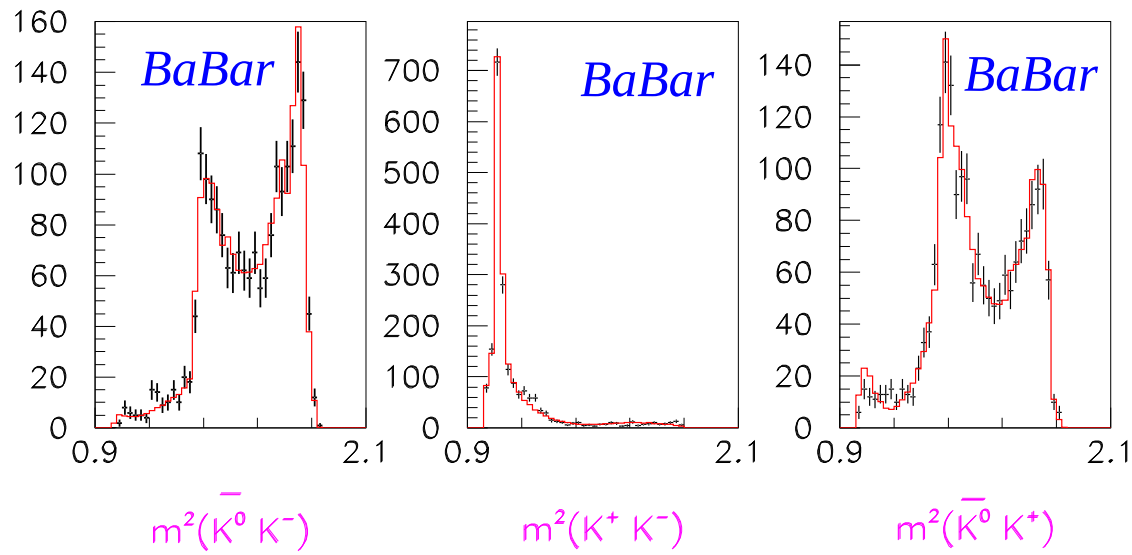
Final state	Fraction %	Phase (degrees)
$K_0^{*0}(1430)\overline{K^0}$	$26.0 \pm 16.1 \pm 3.3$	-38 ± 22
$K_1^{*0}(892)\overline{K^0}$	$2.8 \pm 1.4 \pm 0.5$	-126 ± 19
$K_1^{*0}(1680)\overline{K^0}$	$15.2 \pm 11.9 \pm 0.5$	161 ± 9
$K_2^{*0}(1430)\overline{K^0}$	$1.7 \pm 2.5 \pm 0.2$	53 ± 38
$K_0^{*-}(1430)K^+$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

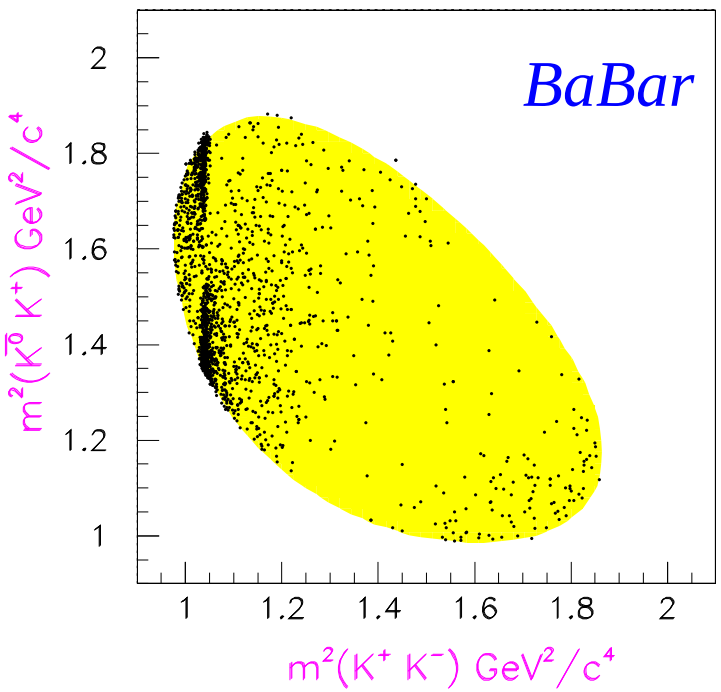
Three-Body D Decays

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

Preliminary

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





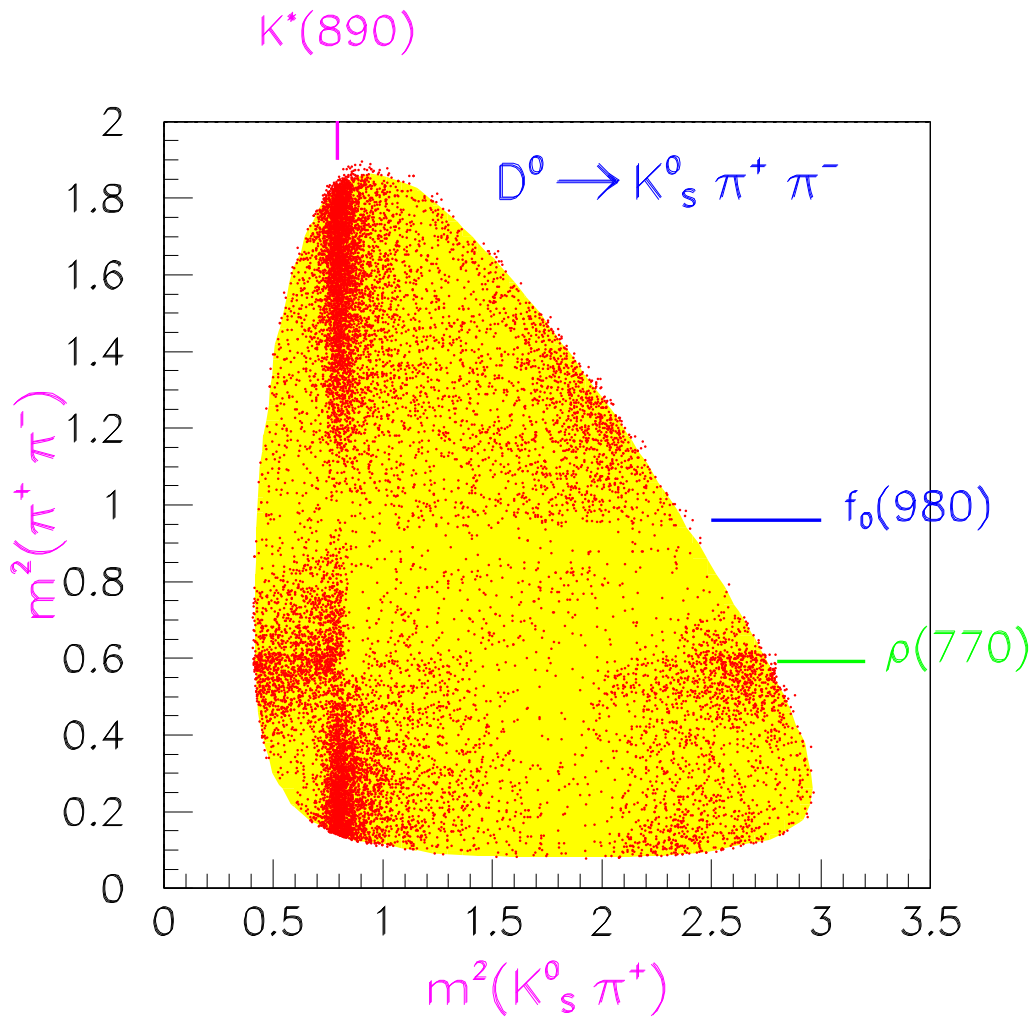
Final state	Fraction %	Phase (degrees)
$\overline{K^0}\phi$	$45.4 \pm 1.6 \pm 1.0$	0.
$\overline{K^0}a_0(980)^0$	$60.9 \pm 7.5 \pm 13.3$	109 ± 5
$\overline{K^0}f_0(980)$	$12.2 \pm 3.1 \pm 8.6$	-161 ± 14
$a_0(980)^+K^-$	$34.3 \pm 3.2 \pm 6.8$	-53 ± 4
$a_0(980)^-K^+$	$3.2 \pm 1.9 \pm 0.5$	-13 ± 15
Non-Reson.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

Three-Body D Decays

$D_0 \rightarrow K^0 \pi^+ \pi^-$

A real challenge to fit.

One interesting question:
Is there a "κ" ?



Three-Body D Decays

Dalitz Analyses Still Relevant

Still many open questions in meson spectroscopy.

$N^{2S+1}L_J$	J^{PC}	ud, uu, dd I = 1	uu, dd, ss I = 0	su, sd I = 1/2
1^1S_0	0^{-+}	π	η, η'	K
1^3S_1	1^{--}	ρ	ω, ϕ	K_0^*
1^1P_1	1^{+-}	$b_1(1235)$	$h_1(1170), h_1(1380)$	K_{1B}
1^3P_0	0^{++}	?	?	$K_0^*(1430)$

$a_0(980), a_0(1450)$?

$f_0(400–1200), f_0(980), f_0(1370), f_j(1710)$?

Exotic states?

- gg?
- $q\bar{q}g$?
- $q\bar{q}q\bar{q}$?
- extra poles?
- $c\bar{c}$ mixture?

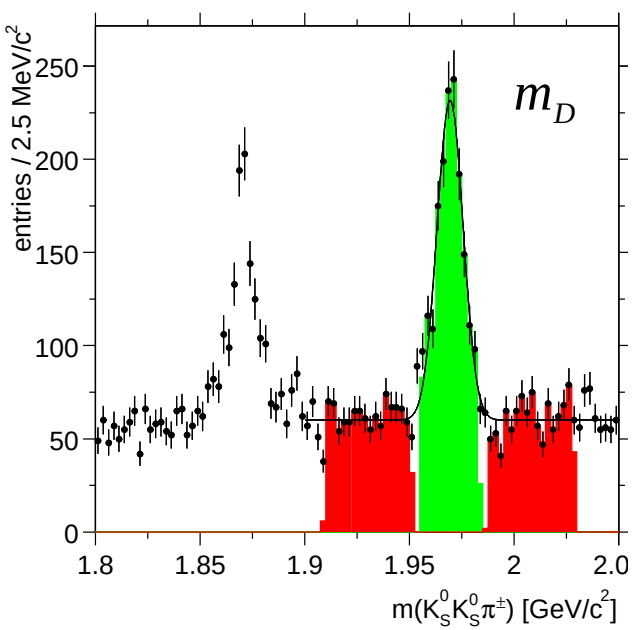
Three-Body D Decays

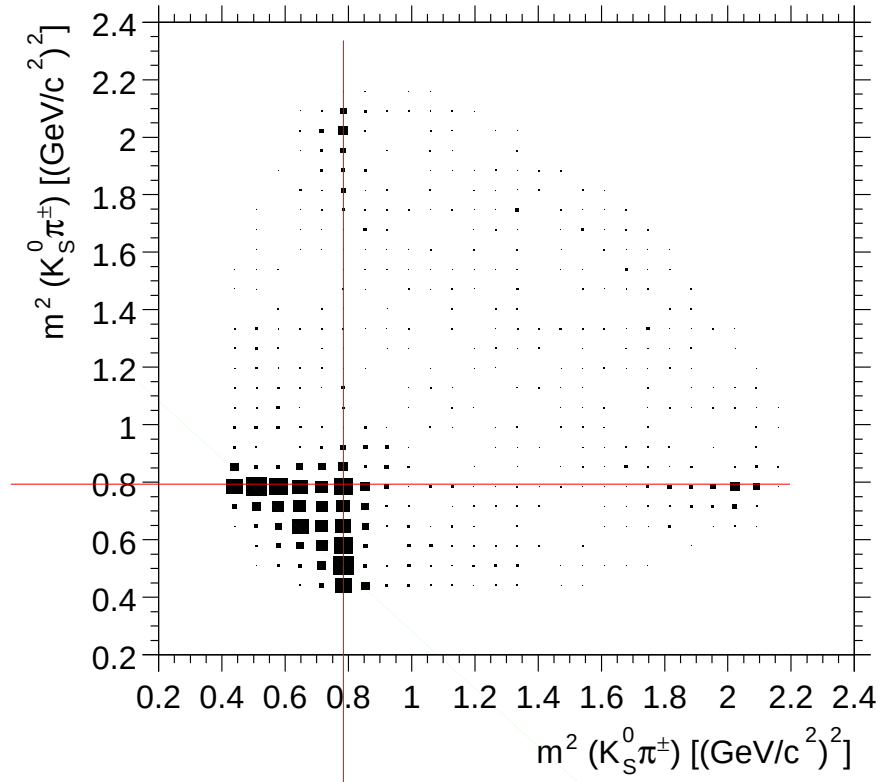
$D_S^{\pm} \to K_S^0 K_S^0 \pi^{\pm}$

18.4 fb^{-1} of data (preliminary):

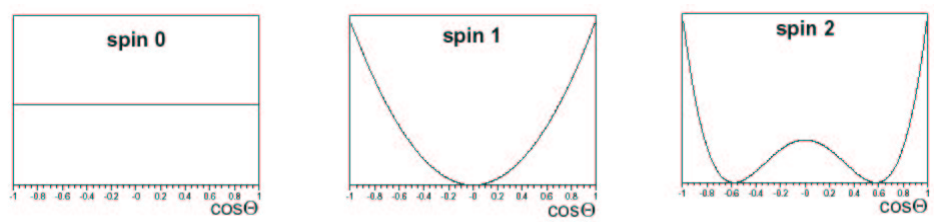
- K_S^0 **quality and lifetime**
- $p^* > 2.5$ **GeV**
- $D_S^{*\pm} \to D_S^{\pm}\gamma$ **tag**

Challenge: high background





$K^*(892)$ $f_j(1710)$



Three-Body D Decays

Plans

Analyses we hope to release before too long:

$D^0 \to K^0 h^+ h^-$ **updated to full data set**
$D_S^+ \to K_S^0 K_S^0 \pi^+,\ 3\pi^\pm$

Other decay modes that have been discussed:

$D^0 \to h^+ h^- \pi^0,\ K^- \pi^+ \eta,\ K^- \pi^+ \eta'$
$D^+ \to K^- \pi^+ \pi^+$
$D_S^+ \to \pi^+ \Omega,\ \pi^+ \rho$

Dalitz analyses have become very important for some *b* physics analyses. We expect new tools and analysis methods to be developed to deal with *b* samples and our high-statistics charm samples.

Conclusion

Summary

- **BaBar is also a charm factory!**
- **Measurement of the D^0 mixing parameter y, based on 57.8 fb^{-1} of data:**

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

- **Competitive wrong-sign D^0 analysis, based on 57.1 fb^{-1} of data. For example, assuming CP conservation, 95% CL limits:**

$$x'^2 < 0.0021, \quad -0.037 < y' < 0.024$$

- **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× PDG2002 precision), based on 22 fb^{-1} of data.**
- **We have 91 fb^{-1} of data available — our work has just begun.**