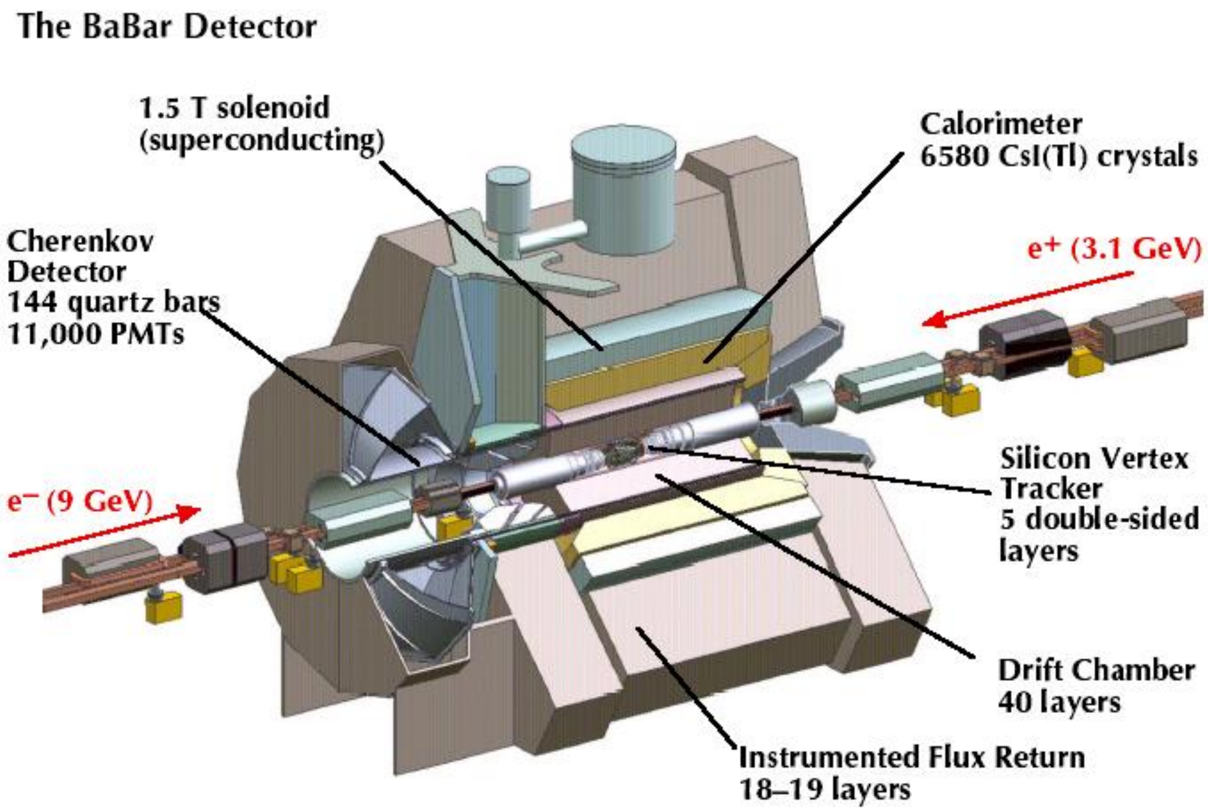
D^0 - $\bar{D}^0$ Mixing at BaBar

- Some formalism
- $D^0 \rightarrow K^+\pi^-$
- $D^0 \rightarrow K^+K^-$ or $\pi^+\pi^-$
- $D^0 \rightarrow K^+\pi^-\pi^0$
- $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$
- Summary



Rolf Andreassen

Formalism

- Produce charmed mesons as flavour eigenstates D^0 and $\overline{D}^0$.
- Decay according to

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$

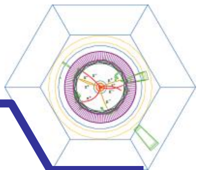
- making mass and lifetime eigenstates

$$\begin{aligned} |D_1\rangle &= p|D^0\rangle + q|\overline{D}^0\rangle \\ |D_2\rangle &= p|D^0\rangle - q|\overline{D}^0\rangle \end{aligned}$$

- which decay thus:

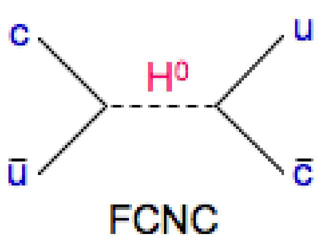
$$\begin{aligned} |D_1(t)\rangle &= e^{-i(m_1 - i\Gamma_1/2)t}|D_1\rangle \\ |D_2(t)\rangle &= e^{-i(m_2 - i\Gamma_2/2)t}|D_2\rangle \end{aligned}$$

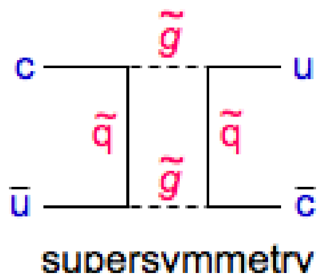
$$\begin{aligned} \Delta M &= m_1 - m_2 \\ \Delta\Gamma &= \Gamma_1 - \Gamma_2 \\ \Gamma &= (\Gamma_1 + \Gamma_2)/2 \\ x &= \Delta M/\Gamma \\ y &= \Delta\Gamma/2\Gamma \\ R_M &= (x^2 + y^2)/2 \end{aligned}$$

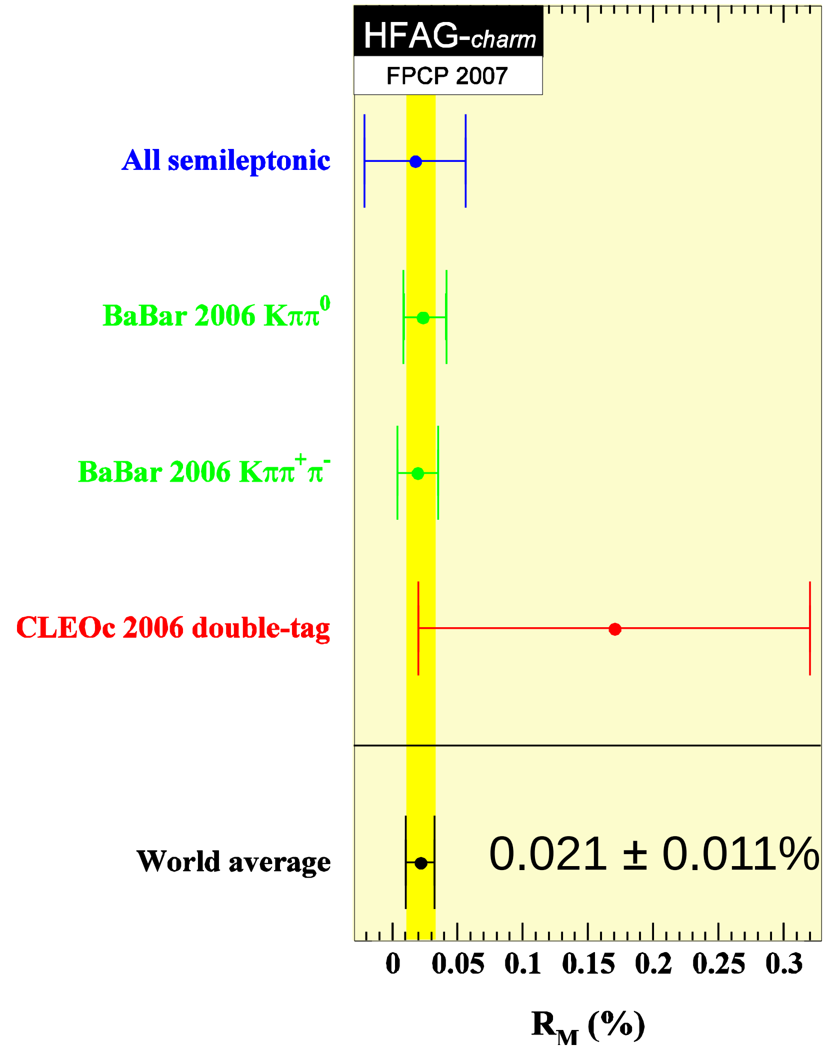


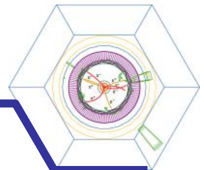
Motivation

- Knowledge of mixing needed to measure CP violation.
- Possible source of New Physics.
- Fill in gap between K and B_d, B_s mixing – charm mixing involves down-type quarks.
- Standard Model allows x, y up to ~1%.
- CP violation or |x| >> |y| would establish New Physics.



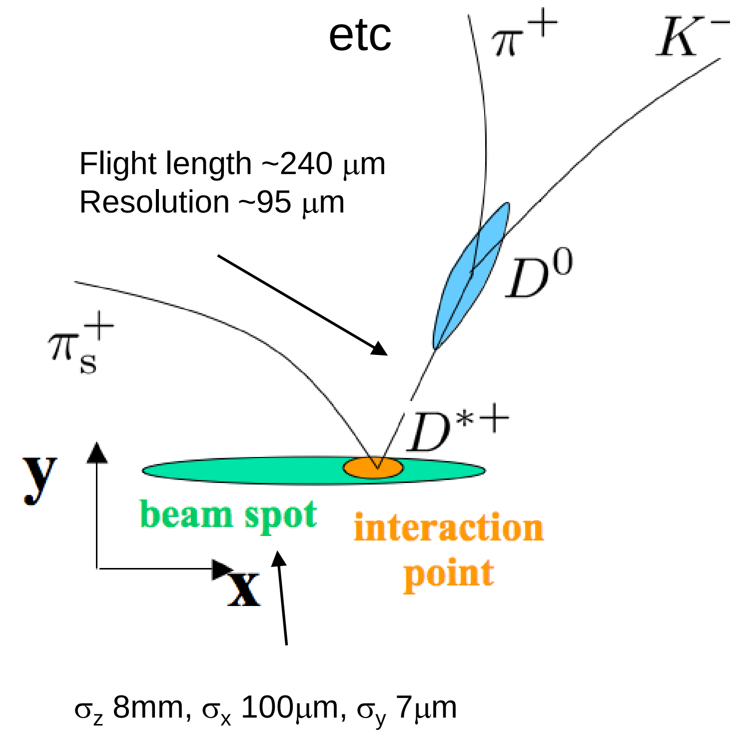






Experimental notation

- Almost always use D^0 from D^* decays for tagging and cleanliness.
- D^* decays to slow pion and neutral D; charge of pion tags production flavour of D.
- Classify backgrounds :
  - Correct D^0, random slow pion : 'mistag' if pion has wrong charge.
  - D^0 has correct tracks, but wrong particle assignments, or is missing a track : 'bad D^0' or 'mis-reconstructed charm'.
  - Ordinary combinatorics.
- For historical reasons, refer to Cabibbo-favoured decays as 'right-sign' (RS), doubly-Cabibbo-suppressed as 'wrong-sign' (WS).



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

- Decay-time distribution:

$$\frac{T_{WS}(t)}{e^{-\Gamma t}} \propto R_D + y'\sqrt{R_D}(\Gamma t) + \frac{1}{4}(x'^2 + y'^2)(\Gamma t)^2$$

Interference

|DCS|²

|Mix|²

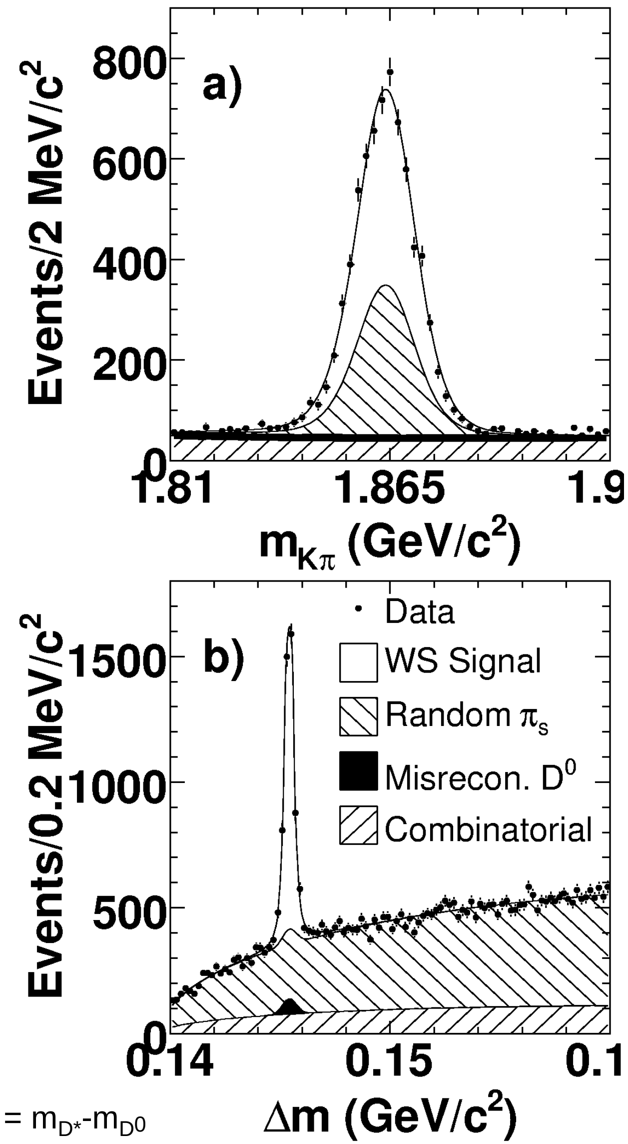
$$x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi}$$
$$y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$$

Phase between RS and WS

- Allow for CP violation by fitting D^0 and $\overline{D^0}$ samples separately.

Yields from 384 fb^{-1}:

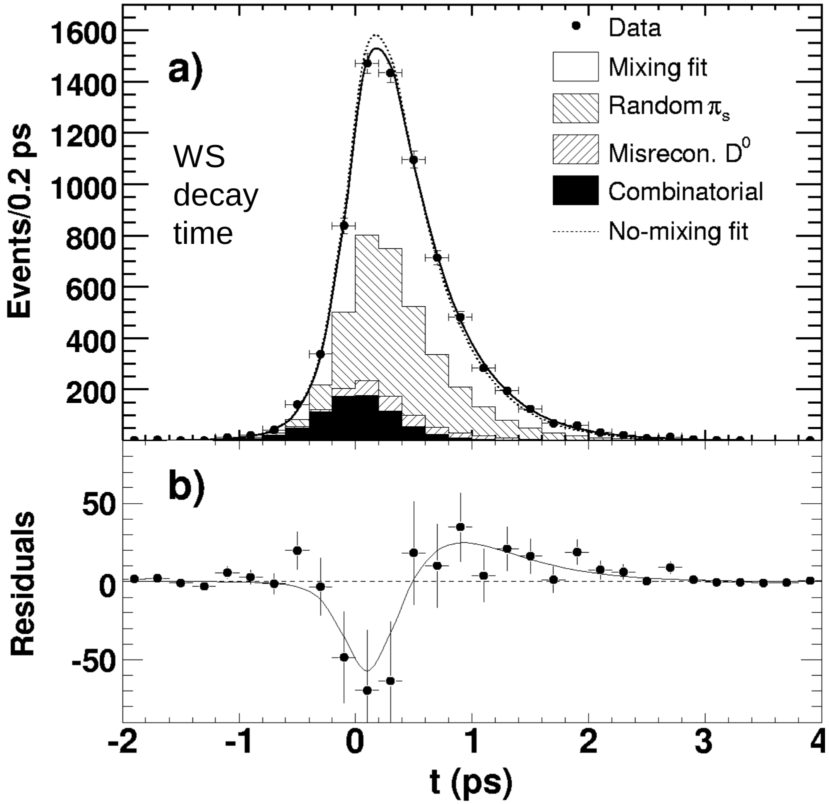
	Candidates
RS	1141500 ± 1200
WS	4030 ± 90



$\Delta m = m_{D^*} - m_{D^0}$

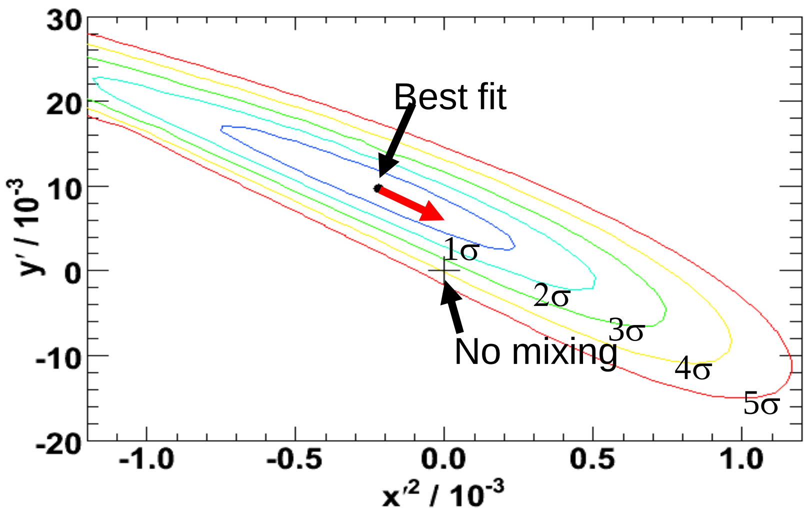
$D^0 \to K^+\pi^-$: Fit

- Fit in three stages:
  - Fit RS and WS to $m_{K\pi}$ and Δm.
  - Fit RS for D0 lifetime and resolution function.
  - Fit WS decay-time distribution.
- Three different models:
  - Impose no mixing and CP conservation.
  - Allow mixing, but keep CP conservation.
  - Allow both mixing and CP violation.
- Signal time resolution modelled as sum of three Gaussians.
- Combinatorial background sum of two Gaussians, with one power-law tail.
- Mis-reconstructed D^0 and mistag have signal time distribution.

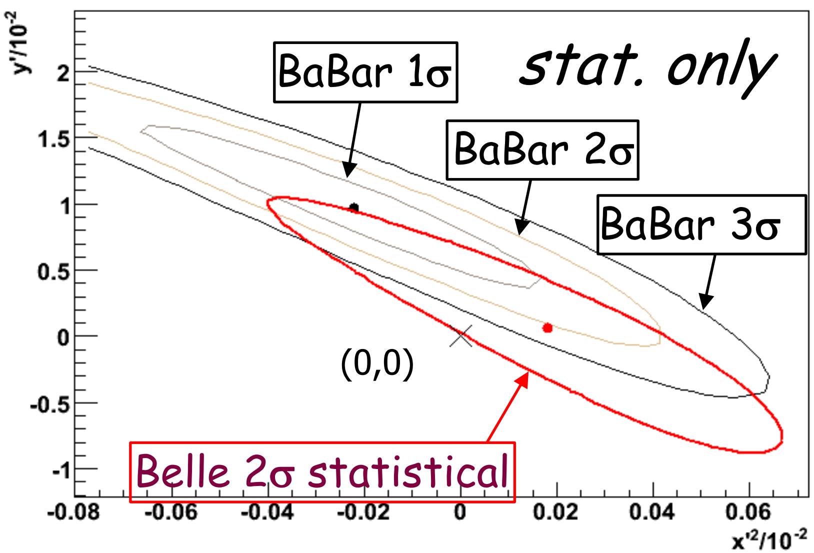


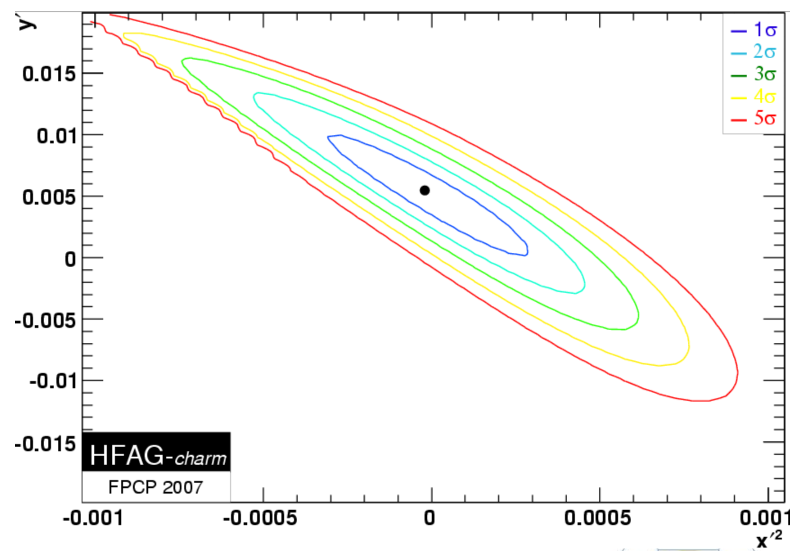
Points show difference between data and no-mixing fit; curve shows difference between fit with and without mixing.

$D^0 \rightarrow K^+\pi^-$: Results



Fit	Parameter	Result $[\times 10^3]$
No *CPV*, no mix	R_D	$3.53 \pm 0.08 \pm 0.04$
No *CPV*, mix	R_D	$3.03 \pm 0.16 \pm 0.10$
	x'^2	$-0.22 \pm 0.30 \pm 0.21$
	y'	$9.7 \pm 4.4 \pm 3.1$
CPV and mix	R_D	$3.03 \pm 0.16 \pm 0.10$
	x'^{2+}	$-0.24 \pm 0.43 \pm 0.30$
	y'^+	$9.8 \pm 6.4 \pm 4.5$
	x'^{2-}	$-0.20 \pm 0.41 \pm 0.29$
	y'^-	$9.6 \pm 6.1 \pm 4.3$





$D^0 \rightarrow h^+h^-$

D mixing changes the decay width of final states with definite CP.

Lifetime for $D^0 \rightarrow$ CP state

$$\tau^+_{CP} = \tau_{K\pi}\left[1+\left|\frac{q}{p}\right|(y\cos\phi_f - x\sin\phi_f)\right]^{-1}$$

$$\tau^-_{CP} = \tau_{K\pi}\left[1+\left|\frac{p}{q}\right|(y\cos\phi_f + x\sin\phi_f)\right]^{-1}$$

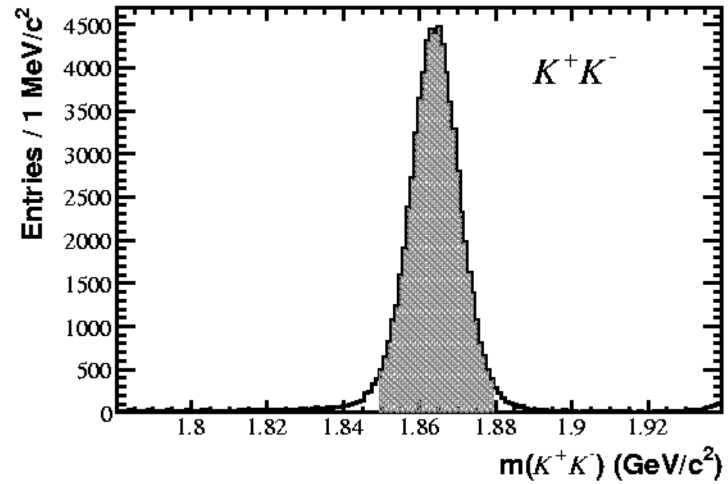
Lifetime for $\bar{D}^0 \rightarrow$ CP state

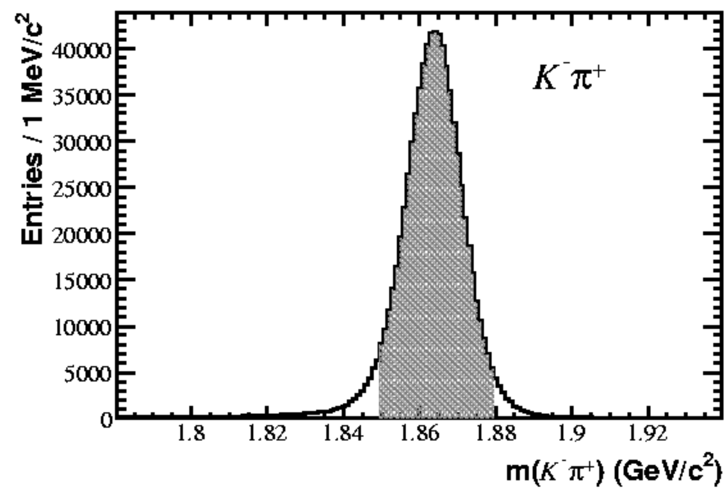
Lifetime for $D^0 \rightarrow K\pi$

Extract two quantities:

$$y_{CP} = \frac{2\tau_{K\pi}}{\tau^+_{CP}+\tau^-_{CP}}$$

$$\Delta Y = \frac{2\tau_{K\pi}}{\tau^+_{CP}+\tau^-_{CP}}\frac{\tau^+_{CP}-\tau^-_{CP}}{\tau^+_{CP}+\tau^-_{CP}}$$

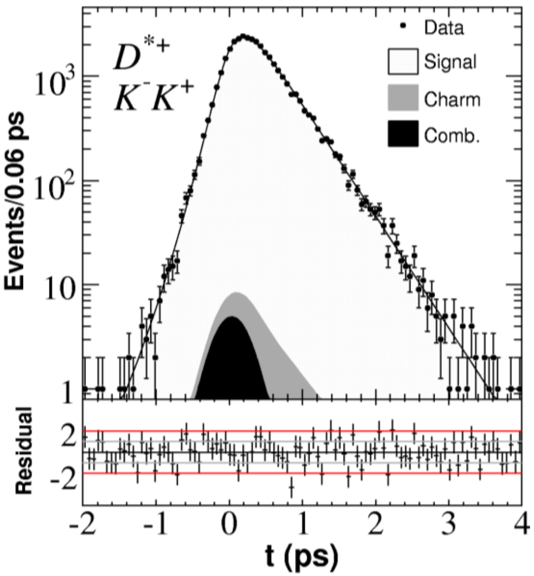


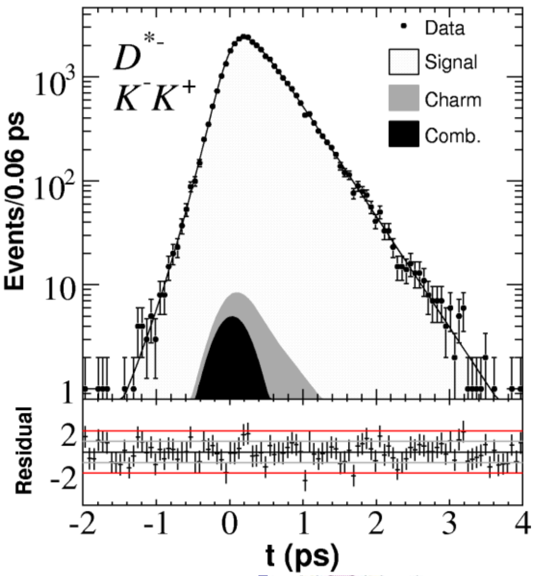


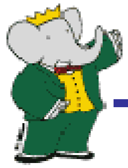
$D^0 \to h^+h^-$ (ctd)

- Reconstruct three modes:
  - $D^{*+} \to D^0 \pi^+$, $D^0 \to K\pi$
  - $D^{*+} \to D^0 \pi^+$, $D^0 \to KK$
  - $D^{*+} \to D^0 \pi^+$, $D^0 \to \pi\pi$
- High purity allows small systematic uncertainty.
- Fit for lifetime of all modes simultaneously.
- Three contributions to fit function:
  - Signal : Exponential convolved with sum of three Gaussians.
  - Combinatorial background : Two Gaussians, power-law tail.
  - Mis-reconstructed charm: Exponential convolved with single Gaussian. Lifetime extracted from fit to Monte Carlo events.

Sample	Size	Purity [%]
$K^-\pi^+$	730880	99.9
K^+K^-	69696	99.6
$\pi^+\pi^-$	30679	98.0

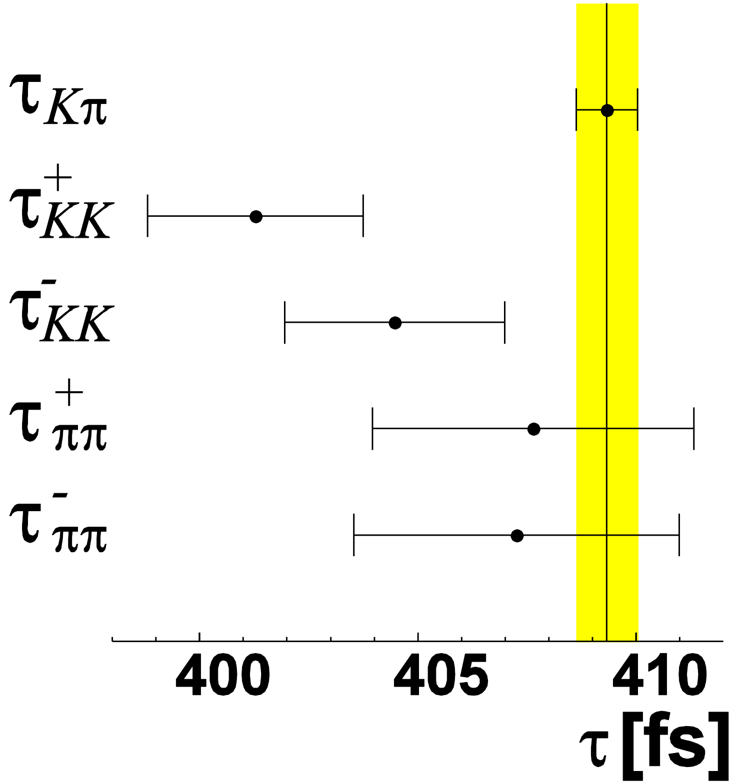






D0 → h+h- : Results

	y_{CP} [%]	ΔY [%]
K^+K^-	$1.60 \pm 0.46 \pm 0.17$	$-0.40 \pm 0.44 \pm 0.12$
$\pi^+\pi^-$	$0.46 \pm 0.65 \pm 0.25$	$0.05 \pm 0.64 \pm 0.32$



- Combining KK and pp results gives 3-sigma evidence of mixing :

  y_{CP} = (1.24 ± 0.39 ± 0.08)%

- CP violation consistent with zero.

- Combining with earlier measurement using untagged sample:

  y_{CP} = (1.03 ± 0.33 ± 0.19)%

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

- Wrong-sign decay rate varies across Dalitz plot:

DCS term

Resonance phase

$$\mathcal{A}(m_{K^-\pi^+}, m_{K^-\pi^0}, t) = e^{-\Gamma t}[|\bar{A}_D|^2 + |\bar{A}_D||A_D|\,(y''\cos\delta_D - x''\sin\delta_D)\,\Gamma t\; |A_D|^2(x''^2 + y''^2)(\Gamma t)^2]$$

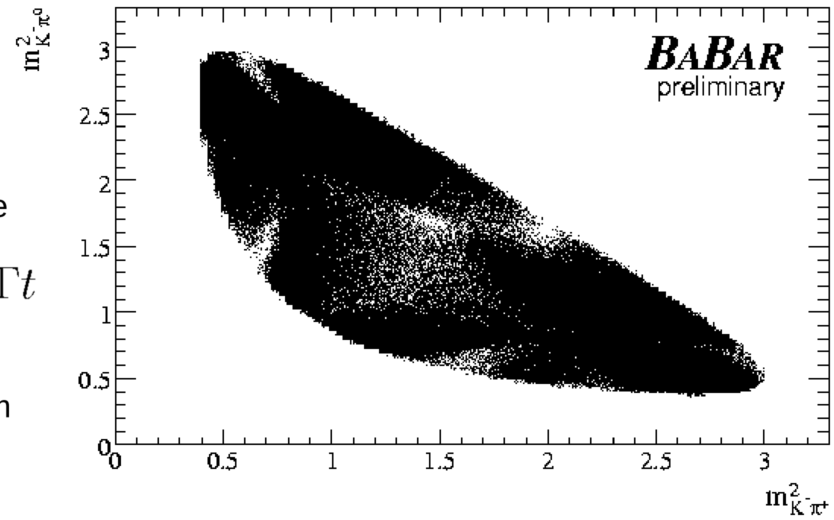
Interference term

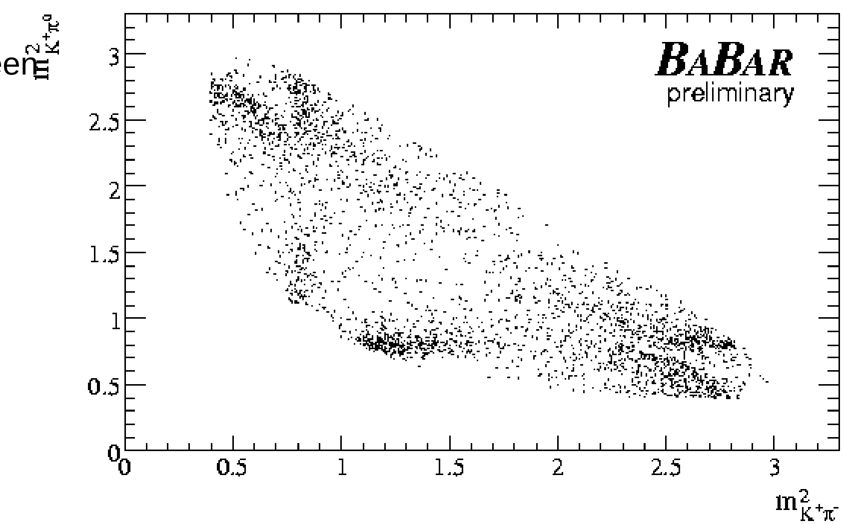
CF (mixed) term

$$x'' = x\cos\delta_{K\pi\pi^0} + y\sin\delta_{K\pi\pi^0}$$
$$y'' = y\cos\delta_{K\pi\pi^0} - x\sin\delta_{K\pi\pi^0}$$

Phase between RS and WS

- Subscript D indicates dependence on position in Dalitz plot.
- Determine A_D from time-independent fit to right-sign Dalitz plot.
- Fit for A_D simultaneously with x, y.

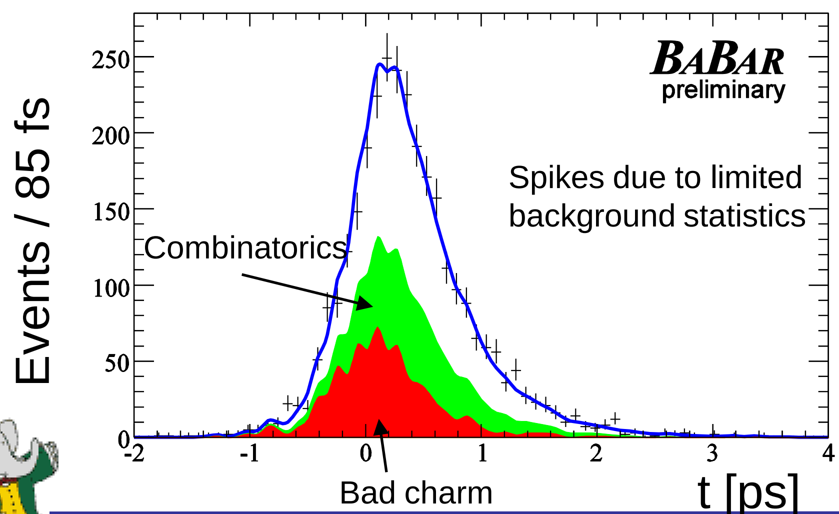


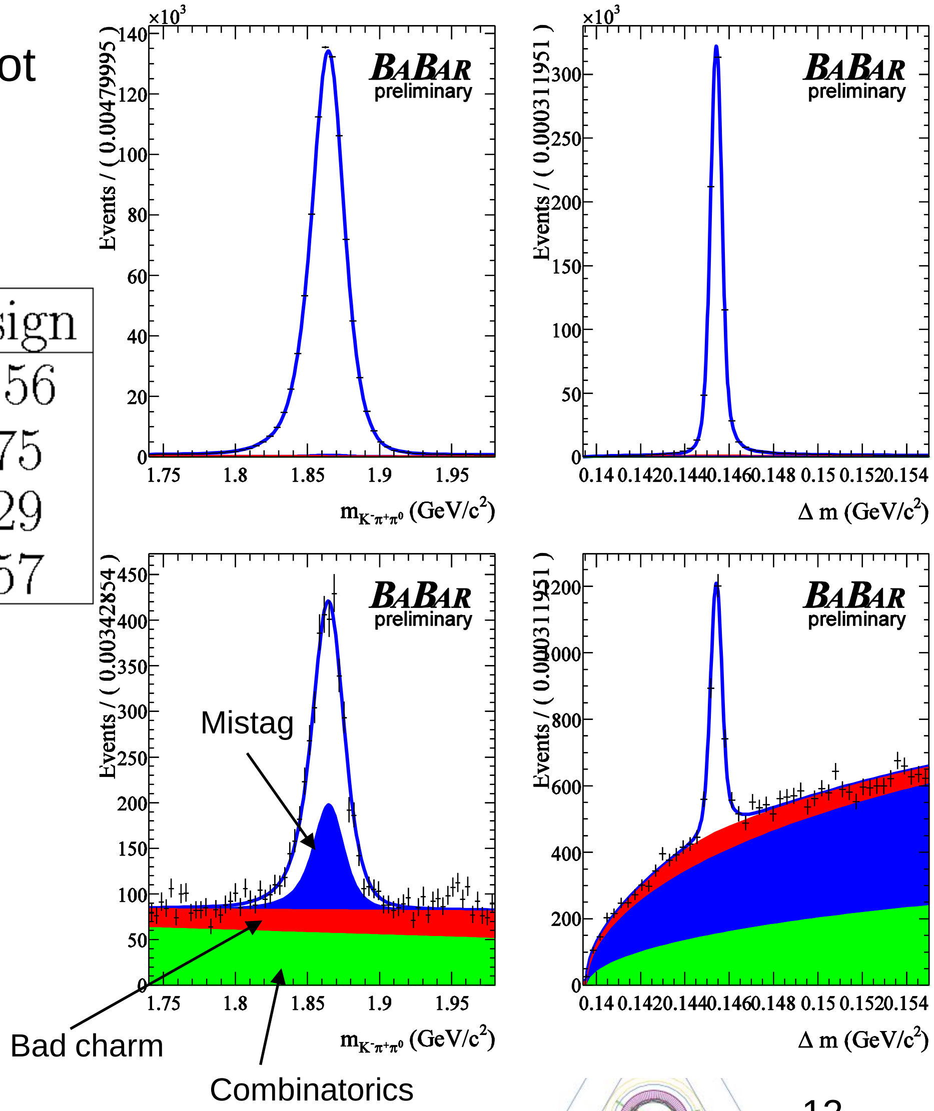


$D^0 \to K^+\pi^-\pi^0$ (ctd)

- Extract background time and Dalitz-plot distributions from D^0 mass sidebands.
- Yields from 384 fb^{-1}:

Category	Right-sign	Wrong-sign
Signal	639802 ± 1538	1483 ± 56
Bad D^0	3317 ± 93	227 ± 75
Mistag	2384 ± 57	765 ± 29
Combinatoric	1537 ± 57	499 ± 57

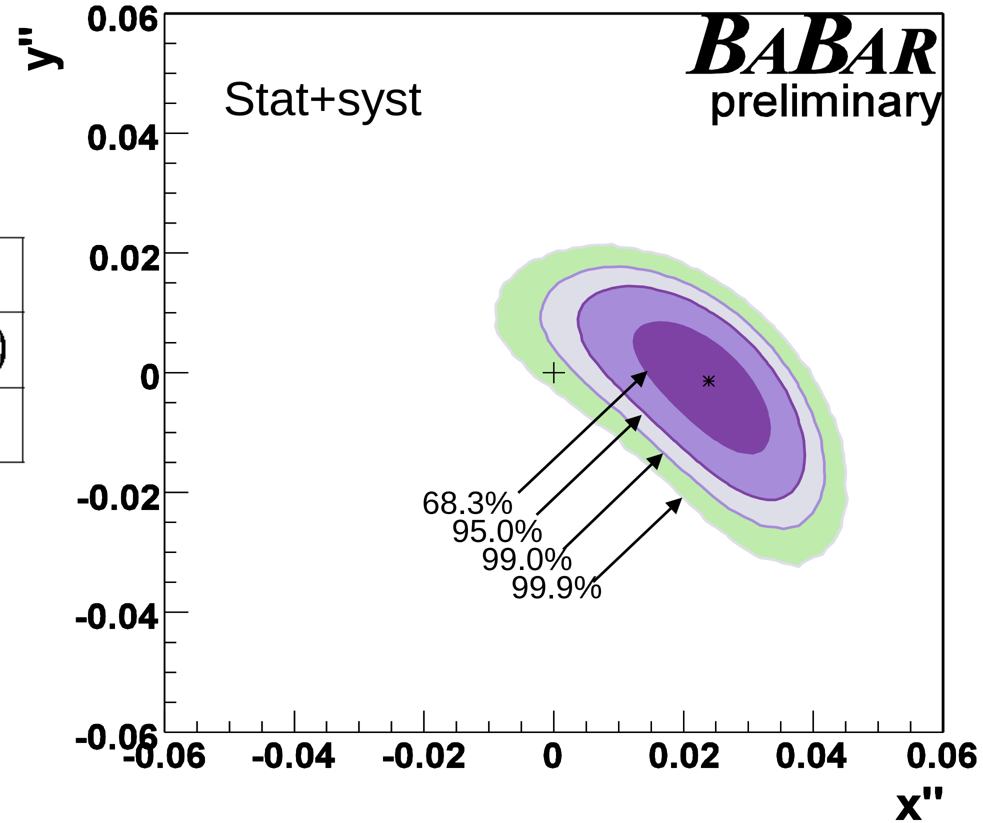




$D^0 \to K^+\pi^-\pi^0$: Results

No mixing is excluded at the 99% confidence level.

x'' [%]	$2.39 \pm 0.61 \pm 0.32$
y'' [%]	$-0.14 \pm 0.60 \pm 0.40$
R_M [%]	0.029 ± 0.016



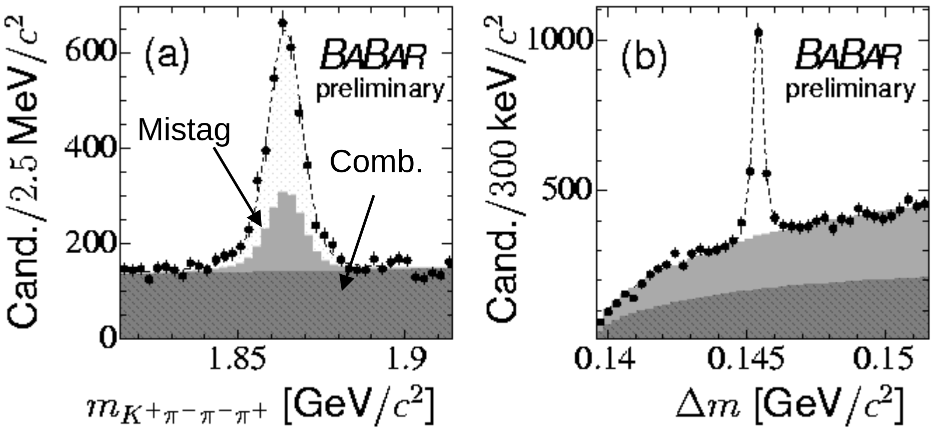
$D^0 \to K^+\pi^-\pi^+\pi^-$

- Decay time difference integrated over phase space (indicated by tilde):

$$\frac{\Gamma_{WS}(t)}{\Gamma_{RS}(t)} = \tilde{R}_D + \alpha\tilde{y}'\sqrt{\tilde{R}_D}(\Gamma t) + \frac{1}{4}(\tilde{x}'^2 + \tilde{y}'^2)(\Gamma t)^2$$

DCS branching ratio

$$\begin{aligned} \tilde{x}' &= x\cos\tilde{\delta} + y\sin\tilde{\delta} \\ \tilde{y}' &= y\cos\tilde{\delta} - x\sin\tilde{\delta} \end{aligned}$$



	D^0 candidates	$\overline{D}^0$ candidates
RS	351100 ± 600	349200 ± 600
WS	1162 ± 53	1040 ± 51

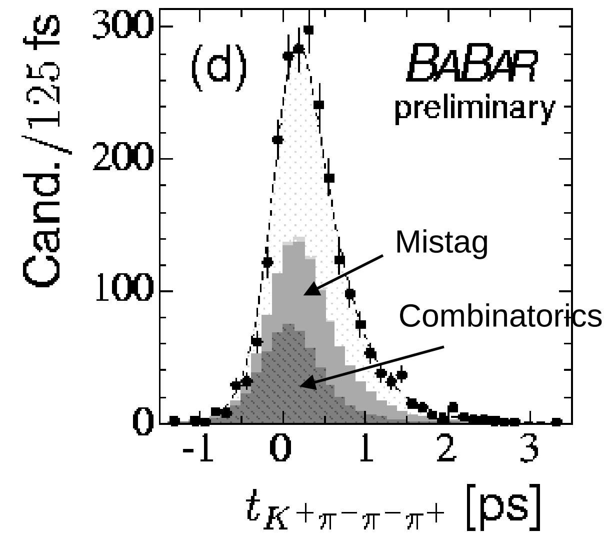
Yields from 230 fb^{-1}

- With CP violation:

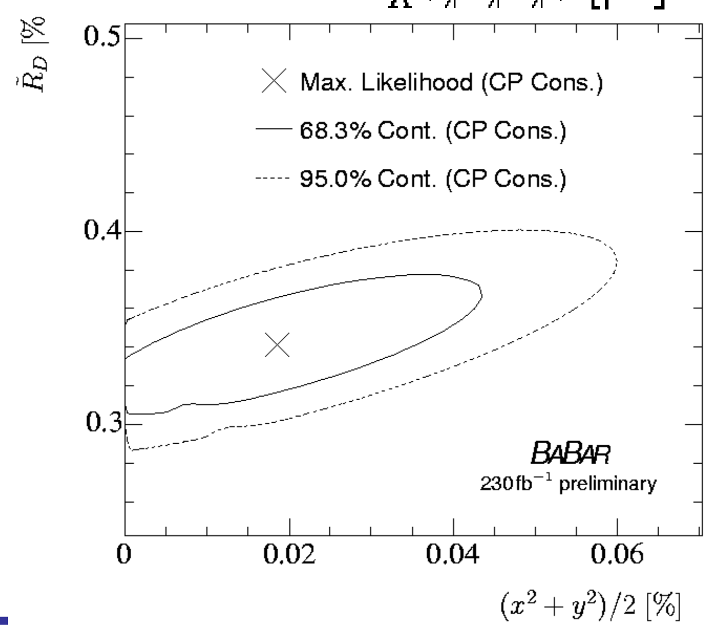
$$\begin{aligned} \left(\tilde{x}'^2 + \tilde{y}'^2\right) &\to |p/q|^{\pm 2}\left(\tilde{x}'^2 + \tilde{y}'^2\right) \\ \alpha\tilde{y}' &\to |p/q|^{\pm 1}\left(\alpha\tilde{y}'\cos\tilde{\phi} \pm \beta\tilde{x}'\sin\tilde{\phi}\right) \end{aligned}$$

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

CP conserved		CP violation allowed	
R_M [%]	$0.019^{+0.016}_{-0.015} \pm 0.002$	R_M [%]	$0.017^{-0.017}_{-0.016} \pm 0.003$
$\alpha\tilde{y}'$	$-0.006^{+0.005}_{-0.005} \pm 0.001$	$\alpha\tilde{y}' \cos\tilde{\phi}$	$-0.006^{+0.008}_{-0.006} \pm 0.006$
		$\beta\tilde{x}' \sin\tilde{\phi}$	$0.002^{-0.005}_{-0.003} \pm 0.006$
		$\|p/q\|$	$1.1^{+4.0}_{-0.6} \pm 0.1$



- Fit in two stages:
  - Extract D^0 mass and Δm parameters.
  - Fix shape parameters, fit to (m_{D0}, Δm, t).
- Signal shape is exponential convolved with double Gaussian.
- Combinatorial background modelled by Gaussian with power-law tail.
- Fit RS and WS distributions simultaneously.
- Time-resolution parameters and D^0 lifetime for WS fixed to RS values.
- Data consistent with no-mixing at 4.3% confidence level.



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Summary

- BaBar has observed mixing in the neutral D system :
- $D^0 \to K^+\pi^-$
    - 384 fb^{-1}, 3.9 σ away from no mixing, $(x'^2, y') = (-0.22\pm0.30\pm0.21, 9.7\pm4.4\pm3.1) \times 10^{-3}$
- $D^0 \to h^+h^-$
    - 384 fb^{-1}, 3.0 σ away from no mixing, $y_{CP} = 1.24\pm0.39\pm0.13$
- $D^0 \to K^+\pi^-\pi^0$
    - 384 fb^{-1}, no mixing excluded at 99% CL, $(x'', y'') = (2.39\pm0.61\pm0.32, -0.14\pm0.60\pm0.40)\%$
- $D^0 \to K^+\pi^-\pi^+\pi^-$
    - 230 fb^{-1}, compatible with no mixing at 4.3% CL, $R_M = 0.019\pm0.016\pm0.020$
- With the final BaBar dataset of roughly 750 fb^{-1}, still more accurate determination of mixing will be possible with these and other modes.