Mixing in the D^0–$\overline{D^0}$ decay

Ulrik Egede
Imperial College London
13 November 2002

A search for *D*-mixing

- Motivation - why is *D*-mixing interesting.
- Formalism.
- Event selection.
- Method for extraction of statistical error.
- Inclusion of systematics.
- What systematics to include.
- Final result and comparisons.

Motivation

- *D*-mixing predicted at low level in Standard Model.
    - A measurable signal would be a strong hint of New Physics.
- As mixing level low the method for finding it is different from methods used for *B*-mixing.
    - We will always see much less than one oscillation.
    - Tagging required to have very high purity.
- As new physics is a likely source there is no reason to assume that *CP* violation will be small.

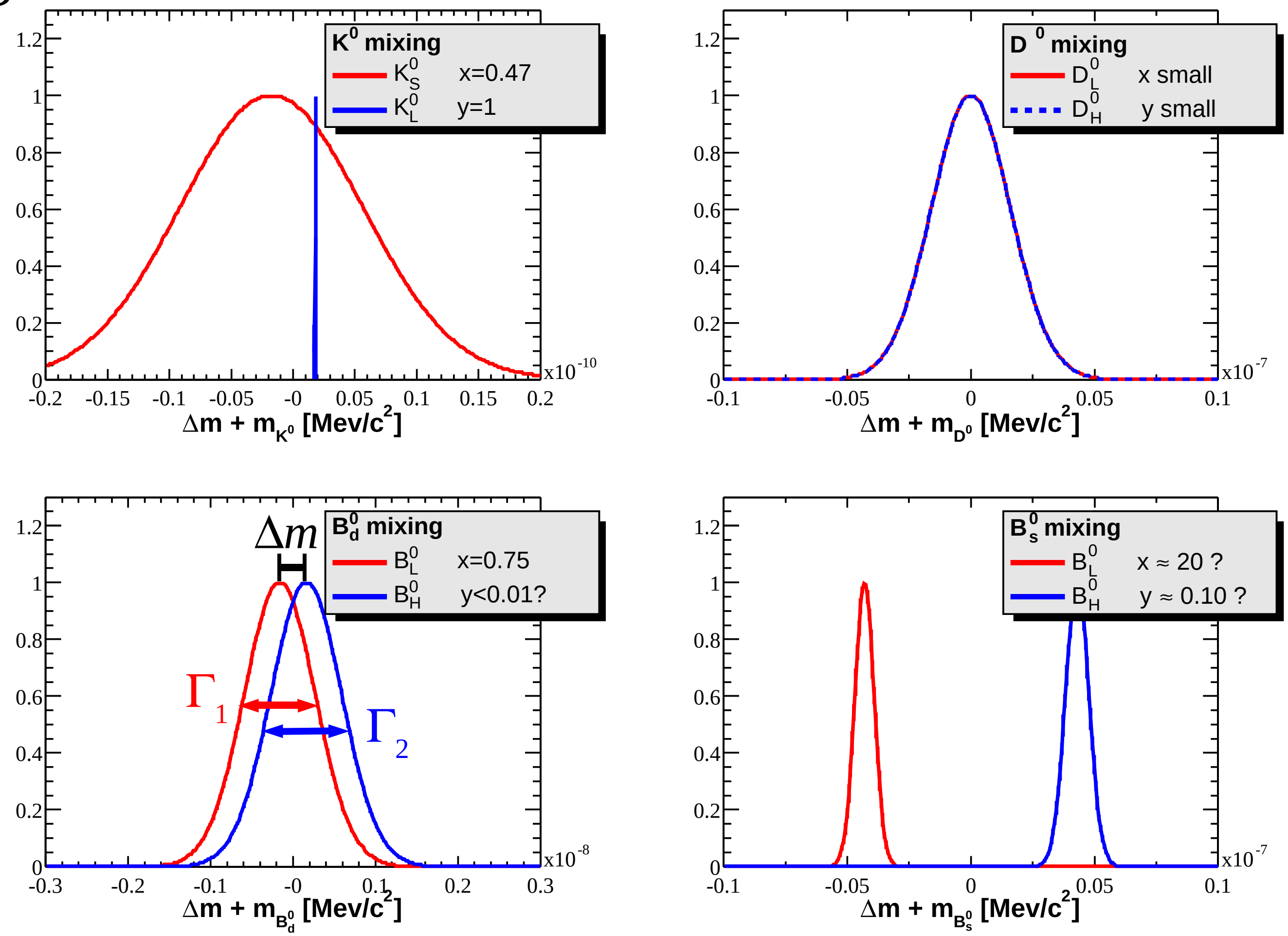
Motivation

- Only 4 types of mixing possible in meson sector.
- All but *D*-mixing discovered.
- Mixing defined in terms of parameters *x* and *y*:

$$x = \frac{\Delta m}{\Gamma}$$

$$y = \frac{\Delta \Gamma}{2\Gamma}$$

$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$



Formalism

- We look at the decay $D^0 \to K^+ \pi^-$ and $\overline{D}^0 \to K^- \pi^+$.
  - Production flavour of D^0 tagged by charge of slow pion in decay $D^{*\pm} \to D^0 \pi^\pm$.
  - The decay $D^0 \to K^+ \pi^-$ (+c.c) is called the wrong sign decay and is either a Doubly Cabibbo suppressed decay or mixing followed by the Cabibbo favoured decay.
- Only time evolution of wrong sign decay can identify mixing in hadronic decays.
- *CP* violation gives different apparent *x* and *y* for $D^0 \to K^+ \pi^-$ and $\overline{D}^0 \to K^- \pi^+$.

Formalism

- Time evolution of wrong sign decays:

$$\Gamma(t) \simeq \exp\left(-\frac{t}{\tau_{D^0}}\right)\left[\quad R_D \quad + \quad \sqrt{R_D}\, y' \frac{t}{\tau_{D^0}} \quad + \quad \frac{x'^2 + y'^2}{4} \frac{t^2}{\tau_{D^0}^2} \quad\right]$$

Doubly Cabibbo suppressed decays — Interference — Mixing

  - Rotation in *(x,y)* plane due to unknown strong phase difference between the two ways of getting a WS decay.

$$x' = x\cos\delta + y\sin\delta, \;\; y' = y\cos\delta - x\sin\delta$$

  - Note that we are only sensitive to y' and x'^2. In fit we allow x'^2 to take unphysical negative values.
  - Overall rate to wrong sign decay

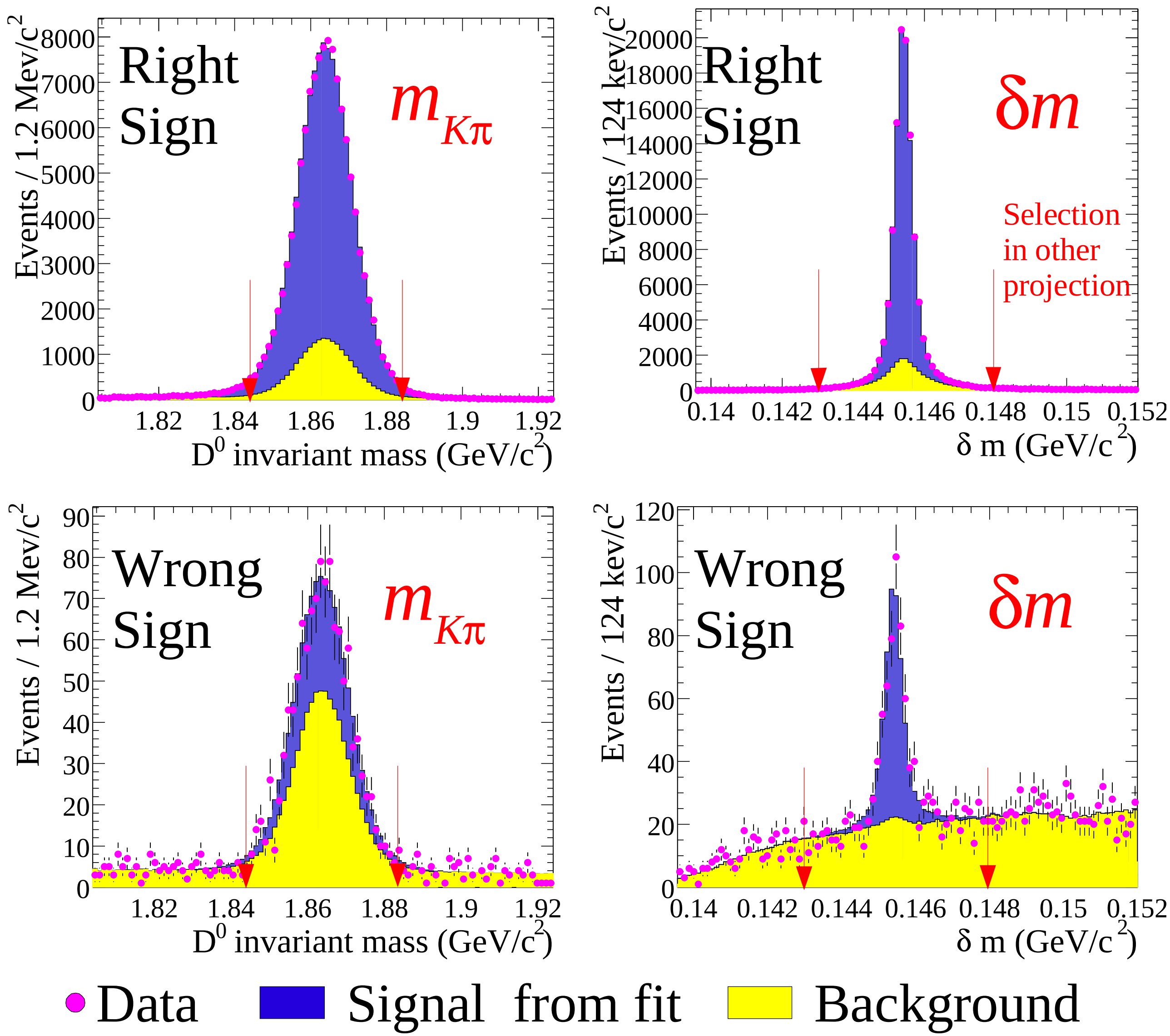
$$R_{WS} = \frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)} = R_D + y'\sqrt{R_D} + R_{mix} \qquad R_{mix} = \frac{x^2 + y^2}{2}$$

A look at the data

- Total luminosity 57.1 fb^{-1} corresponding to about 75 million $c\bar{c}$ events.
- Projections of data:

  $m_{K\pi}$: D^0 candidate mass.

  δm : Mass difference between D^{*+} and D^0 candidate.
- About 440 wrong sign signal events.



Event selection

- Momentum of D^{*+} in centre of mass frame above 2.6 GeV/c to select events from the $c\bar{c}$ continuum.
- Tight particle identification on both D^0 daughters.
- Good track and vertex quality required.
- Lifetime below 4 ps and estimated error below 0.4 ps.
- At least 6 hits on all tracks in Silicon Vertex Tracker (SVT).
- 2 ϕ and 2 z hits in first 3 layers of SVT.
- Helicity cut on $\cos\theta^*_{K\,D^0}$.
- Pion transverse momentum above 0.5 GeV/c for D^0 daughter.
- Multiple overlapping candidates are rejected.

Event categories

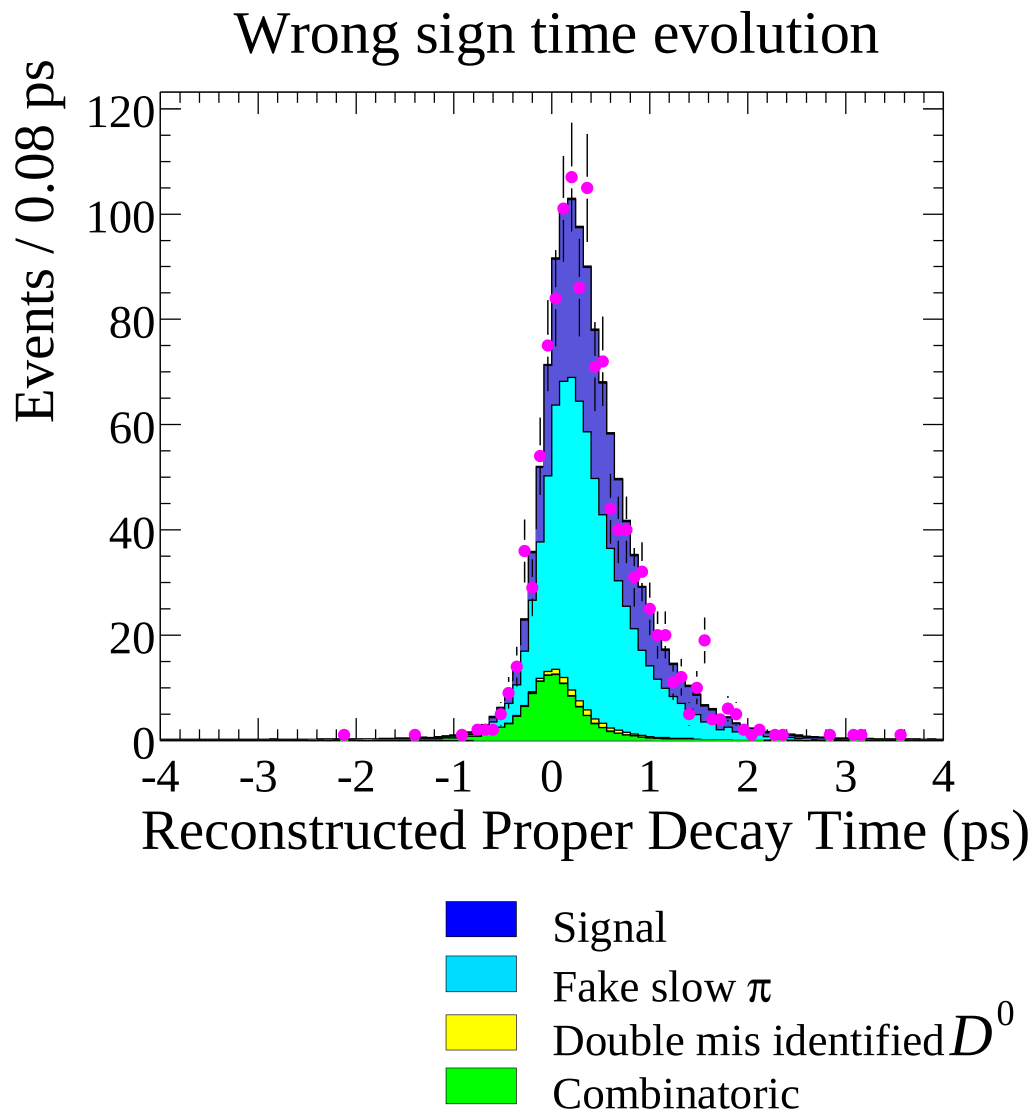
- Background for D^{*+} candidates are:
  - True D^0 with a fake slow π^+_s.
  - Combinatorial background.
  - Partially reconstructed D^0 with correct π^+_s.
  - Correctly reconstructed D^0 where K and π hypothesis are swapped.
- Different backgrounds have different lifetime evolution.
- Need to be measured individually to avoid bias of fit.

The time evolution

- The right sign data gives D^0 lifetime and resolution model for signal.
- Mixing is any deviation from this in wrong sign sample.
- Unbinned log likelihood fit using:

  $$m_{K\pi},\ \delta m,\ t \text{ and } \sigma_t$$

- Minimal use of Monte Carlo events for estimate of signal and background shapes.



Fit quality

- Profile plots like this are used to judge fit quality.
- Top plots are fit to data on linear and log scale.
  - Inset shows selected region in $m_{K\pi}$ and δm.
- Binned χ^2 distribution is in bottom plot.

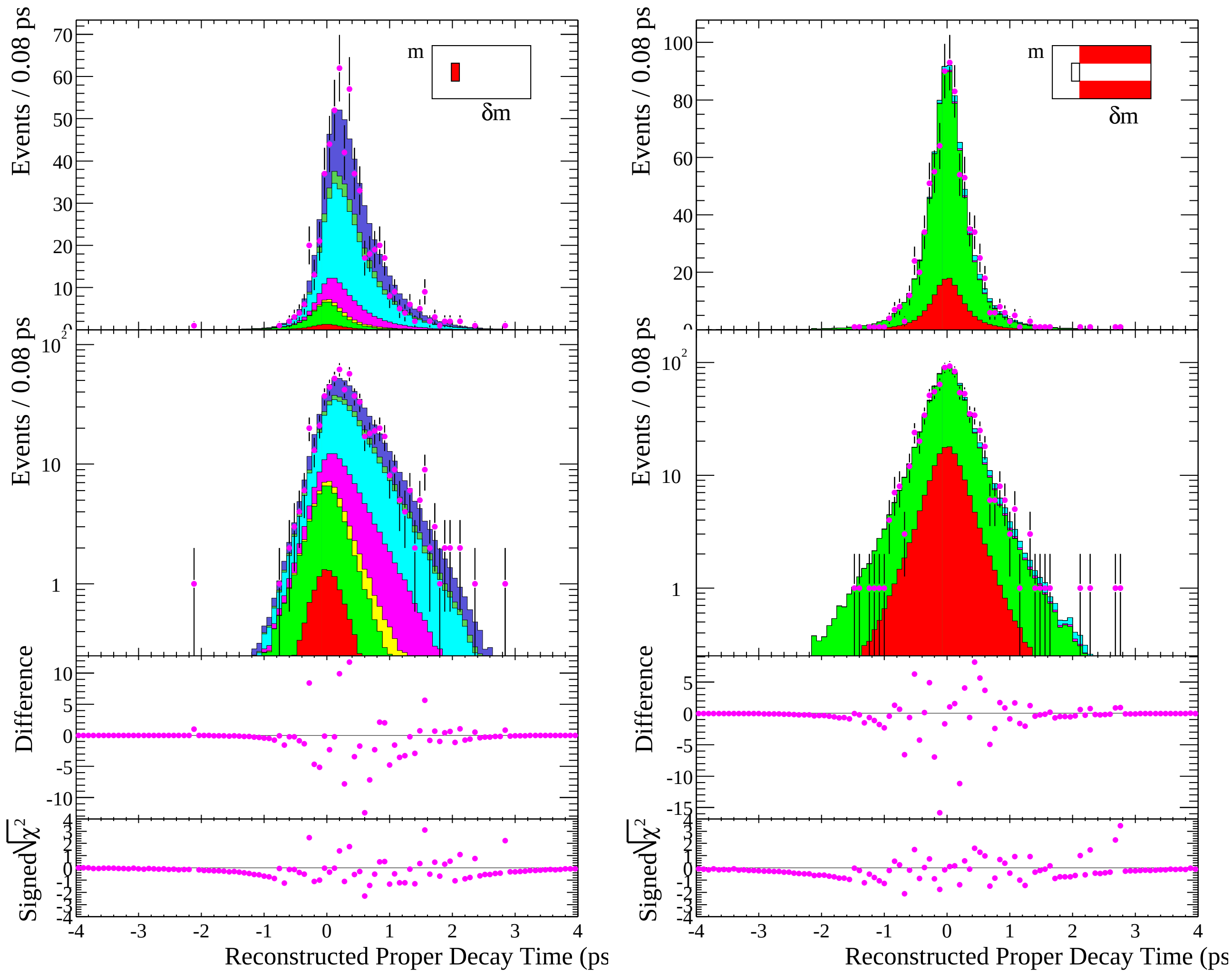
Combinatoric

Double misID D^0

Fake slow π

Signal D^0

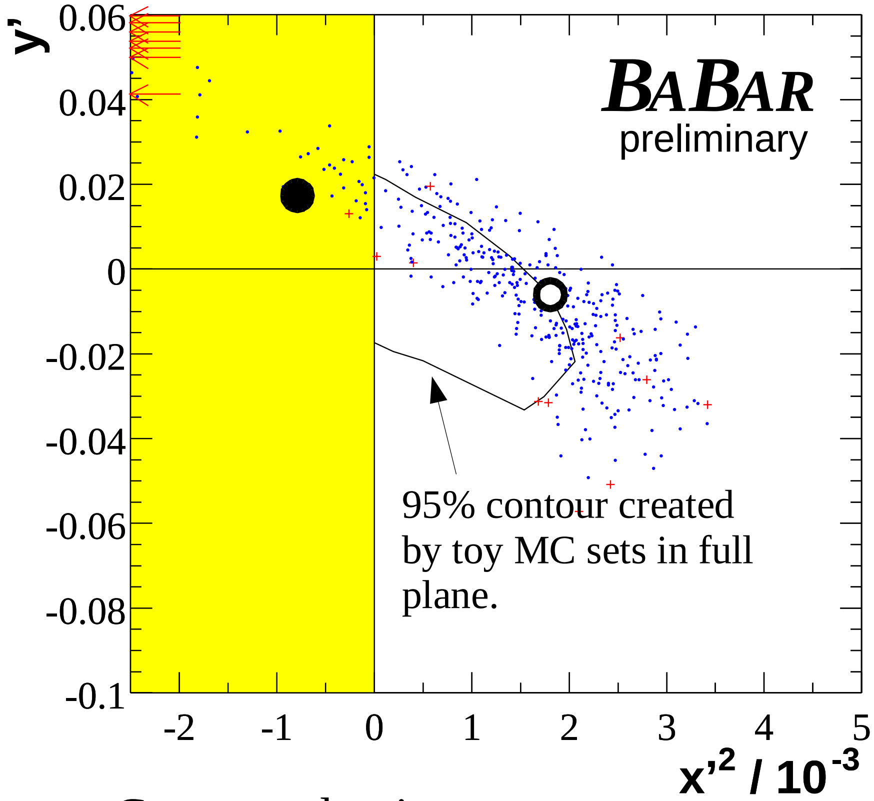
No DCH　DCH



Signal region D^0　　Sideband

The statistical error

- We do not trust the likelihood surface to give a good estimate of the statistical error due to the unphysical region (x'^2<0).
  - We use a frequentist method where we map out the contour in the physical region of (x'^2, y') by toy Monte Carlo samples.
  - Test point is inside 95% contour if above 95% of toy MC's, based on a likelihood value difference estimate, are *better* than data.
- Example of toy MC's created in single test point:



Converged point for fit to data.
Test point of toy Monte Carlo set.
+ Fit worse than data.
Fit better than data.

Statistical method

- Simply using likelihood surface not good as:
  - Shape of LL surface depends strongly on true value of mixing.
  - Unphysical region requires some Bayesian approach. Which prior to use?
- In our method we avoid both problems:
  - Pick a test point α_c.
  - Calculate for data

$$\Delta \ln \mathscr{L}^{data}(\alpha_c) = \ln \mathscr{L}^{data}(\alpha_c) - \ln \mathscr{L}^{data}_{max}$$

- Generate multiple toy MC sets *i* with parameters $\alpha_{c.}$
- Fit each of them and calculate

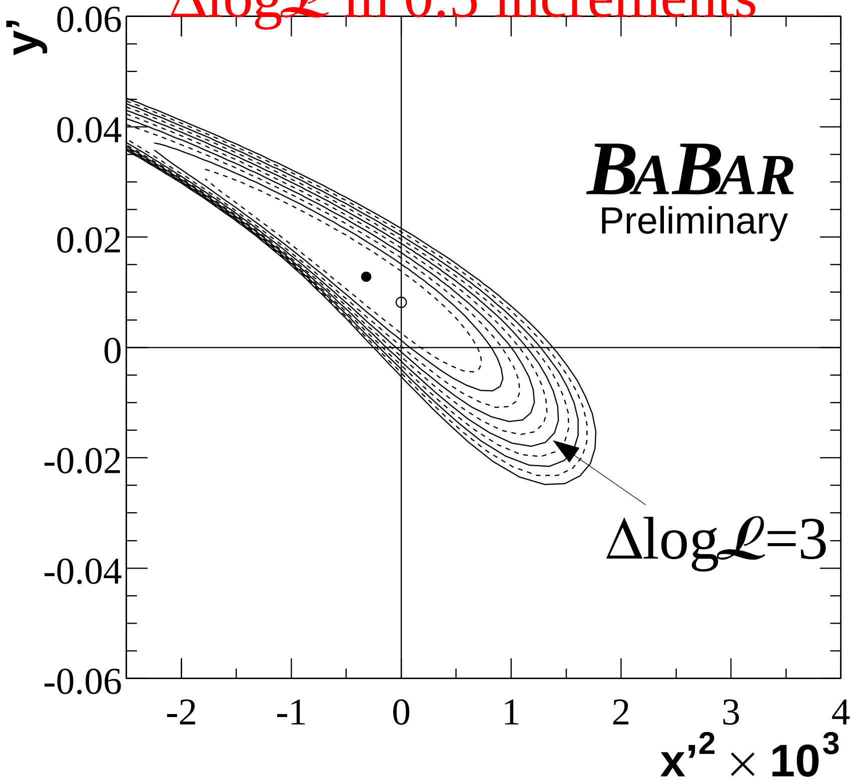
$$\Delta \ln \mathscr{L}^{i}(\alpha_c) = \ln \mathscr{L}^{i}(\alpha_c) - \ln \mathscr{L}^{i}_{max}$$

- If $\Delta \ln \mathscr{L}^{i}(\alpha_c) > \Delta \ln \mathscr{L}^{data}(\alpha_c)$ the toy MC *i* is *better* than the data.
- If above 95% of toy MC's at α_c are better than the data the point is inside the 95% contour.

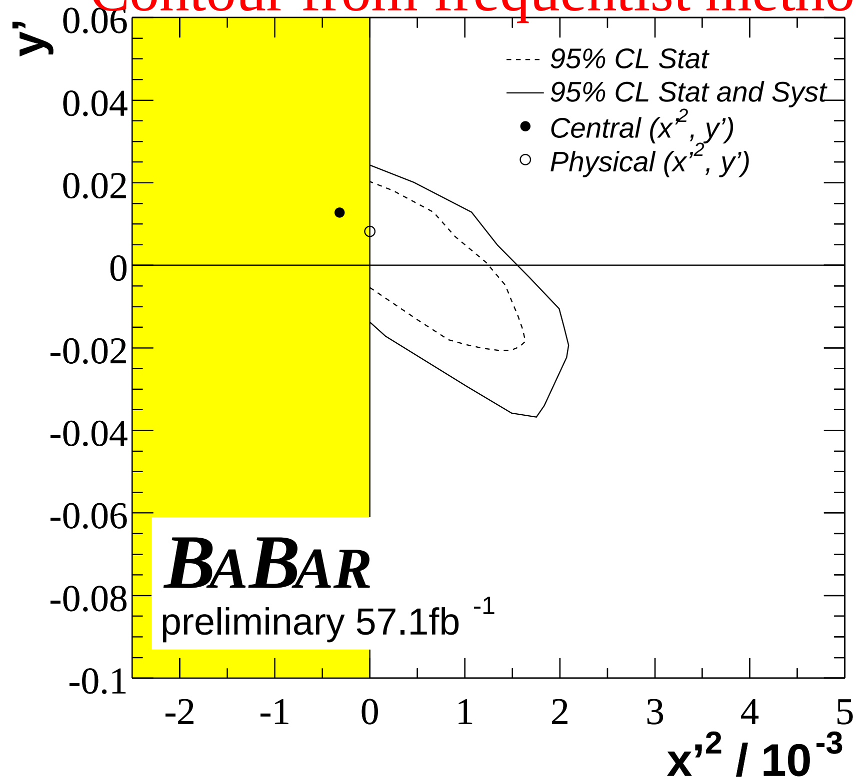
Likelihood contour

- The 95% statistical contour obtained from the frequentist method can be compared to the contour of the log likelihood with $\Delta\log\mathcal{L}=3$.

$\Delta\log\mathcal{L}$ in 0.5 increments

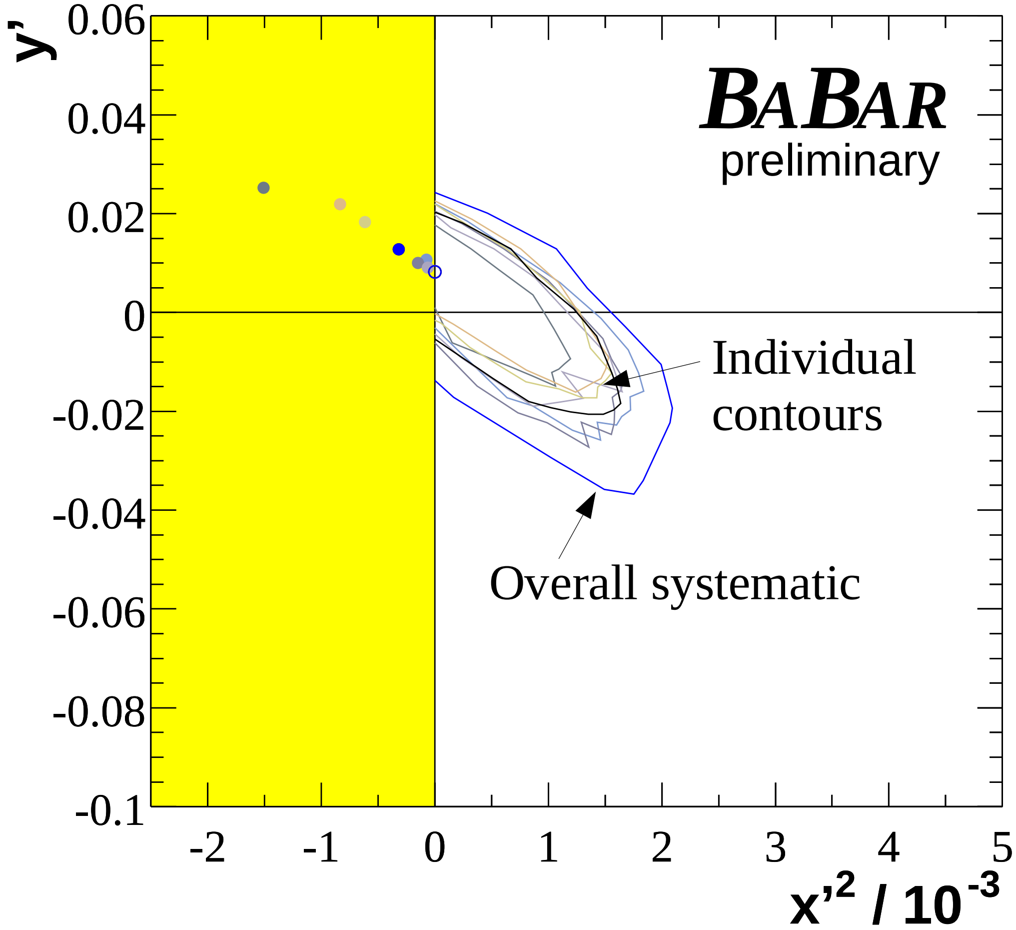


Contour from frequentist method



Systematics + Statistics: How?

- The problem is non-linear so no simple solution.
- For each systematic check we can make a contour.
- Difference between contours added in quadrature to statistical contour.
- This is a conservative approach.

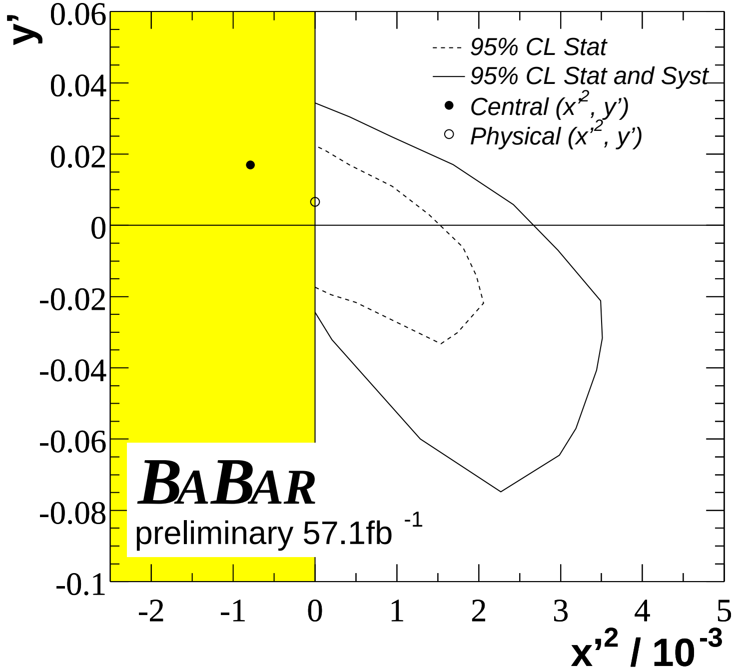


Systematic effects

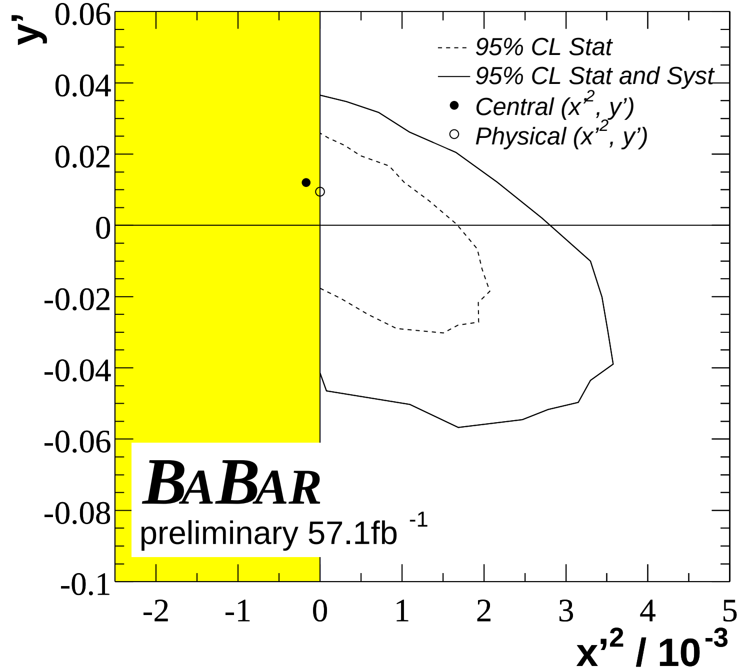
- Fit:
  - Variations in Probability Density Functions of signal and background.
  - Assignment of events to signal and background.
  - Effect of locked parameters in final fit.
- Event selection:
  - Vary the event selection cuts. Hard to distinguish from statistical fluctuations. This is the dominant systematic.
- Detector effects:
  - Fit for an apparent mixing signal in the right sign sample to check alignment effects.

Results allowing for *CP* violation

95% confidence contour for D^0



95% confidence contour for $\overline{D}^0$



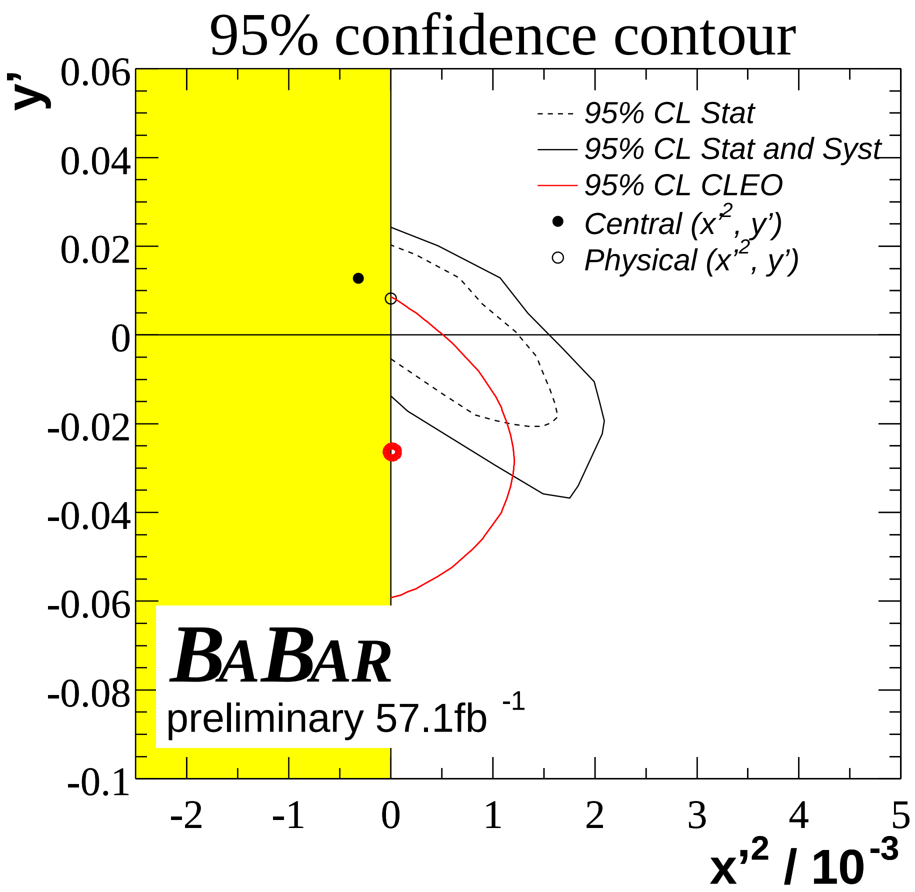
	Fit to D^0 events only			Fit to anti-D^0 events only		
Parameter	Fitted central value		95% C.L	Fitted central value		95% C.L
	x'^2 free	x'^2 physical		x'^2 free	x'^2 physical	
R_D [%]	0.32	0.35	$0.18 < R_D < 0.62$	0.26	0.27	$0.12 < R_D < 0.56$
x'^2 [$\cdot 10^3$]	-0.8	0	$x'^2 < 3.5$	-0.2	0	$x'^2 < 3.6$
y' [%]	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)		

Special case results

- Several assumptions can be made.
- Allows comparison with earlier results.
- Fit with no mixing:
  - Wrong sign decay assumed to be exponential.
  - Only Doubly Cabibbo suppressed decays.
  - Direct *CP* violation: $A_D = \frac{R_D(D^0) - R_D(\overline{D}^0)}{R_D(D^0) + R_D(\overline{D}^0)}$

Parameter	
R_D [%]	0.36 ± 0.02 (stat) ± 0.03 (sys)
A_D [%]	9.5 ± 6.1 (stat) ± 8.3 (sys)

Mixing but no *CP* violation



- BaBar result in special case of no *CP* violation.
- Comparison not straight forward between this result and CLEO result (Phys. Rev. Lett. 84:5038-5042, 2000).
- Statistical methods very different.

Parameter	Fitted central value		95% C.L.
	x'^2 free	x'^2 physical	
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' [%]	1.3	0.8	$-3.7 < y' < 2.4$
R_{WS} [%]	0.36 ± 0.03 (stat) ± 0.03 (syst)		

Towards a PRL

- This preliminary result was presented in mid October.
- A few changes required for result to go to PRL.
  - Need to combine contours.
  - Finalise addition of systematics.
- Seriously limited by manpower.
- We have thoughts about writing a NIM article on the statistical method used.

Summary

- Preliminary results on *D*-mixing from 57 fb^{-1} of data from BaBar presented.
- Results are compatible with no mixing and no *CP* violation.

D^0	$\overline{D}^0$	No *CP* violation
$R_{WS} = (0.39 \pm 0.03 \pm 0.03)\%$	$R_{WS} = (0.32 \pm 0.03 \pm 0.04)\%$	$R_{WS} = (0.36 \pm 0.02 \pm 0.03)\%$