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Charm mixing, spectroscopy and decays

On behalf of the BaBar collaboration

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Introduction

- BaBar is not only a *B*-factory but also a charm factory.
  - Charm produced in fragmentation of $e^+e^- \to c\bar{c}$.
  - Cross section 1.3 nb compared to 1.1 nb for $e^+e^- \to B\bar{B}$
- Asymmetric design of no specific advantage
  - Produced *D* mesons have significant boost in centre of mass system.
  - Lifetime measurements come from transverse displacement in direction where beam spot is small.
- Analysis presented
  - A new search for *D*-mixing using semi-leptonic decays.
  - A search for flavour changing neutral currents and lepton flavour violating decays.
  - Excited *D*-meson states.

Mixing and *CP* violation in the charm sector

Mixing and CP violation still not discovered in the decay of *D* mesons.

- We define

$$x=\frac{\Delta m}{\Gamma} \qquad y=\frac{\Delta\Gamma}{2\Gamma} \qquad \Gamma=\frac{\Gamma_1+\Gamma_2}{2} \qquad R_{\text{mix}}=\frac{x^2+y^2}{2}$$

- Mixing above the % level or any discovery of *CP* violation would indicate new physics. SM prediction for *x* and *y* from 10^{-7} to 10^{-2}.

Three different methods used in BaBar:

- Lifetime analysis of mixing/doubly Cabibbo-suppressed decays $D^0 \to K^+\pi^-$
  - Published in Phys.Rev.Lett.91:171801,2003
- Lifetime difference analysis between Cabibbo-favoured $D^0 \to K^-\pi^+$ and Cabibbo-suppressed $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$
  - Published in Phys.Rev.Lett.91:121801,2003
- Search for mixing in semi-leptonic decays $D^0 \overset{\text{mixing}}{\to} \overline{D^0} \to K^+ e^- \overline{\nu_e}$
  - New analysis.

The semi-leptonic analysis

Analysis based on 87 fb^{-1} of data from BaBar.

Production flavour of the D^0 is identified from the π charge in the decay

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

Decay flavour is tagged from the electron charge in the decay

$$D^0 \rightarrow K^- \mathbf{e}^+ \nu_e$$

- Decay chains with equal pion and electron charge gives the *right sign* normalisation mode.
- Opposite pion and electron charge gives the *wrong sign* signal mode where mixing would show up.

$$D^0 \overset{\text{mixing}}{\rightarrow} \overline{D^0} \rightarrow K^+ \mathbf{e}^- \overline{\nu_e}$$

Any wrong sign decay will be from mixing

- The direct decay $D^0 \rightarrow K^+ \mathbf{e}^- \overline{\nu_e}$ not allowed.

Analysis method

Get as clean as possible *right sign* and *wrong sign* selection from kinematics and particle identification.

- Concentrate on electron sample – avoid less pure muon and tau sample.
- Mass difference $\Delta m = m_{Ke\pi} - m_{Ke}$ between reconstructed D^{*+} and partially reconstructed D^0 good discriminator.
  - Neural Network reconstruction of D^0 momentum vector to recover most of lost Δm resolution from missing neutrino. $\sigma_{\Delta m} \approx 2.2\,\mathrm{MeV}/c^2$
- Perform fit in Δm and the reconstructed proper time of the D^0 candidate.

$$\Gamma_{\mathrm{RS}}(t) = e^{-t} \otimes R \qquad \Gamma_{WS}(t) \simeq e^{-t} \frac{R_{\mathrm{mix}}}{2} t^2 \otimes R$$

  - Same Δm shape and resolution model *R* for right sign and wrong sign signal.
  - Use event mixing to constrain the shape of combinatoric background.

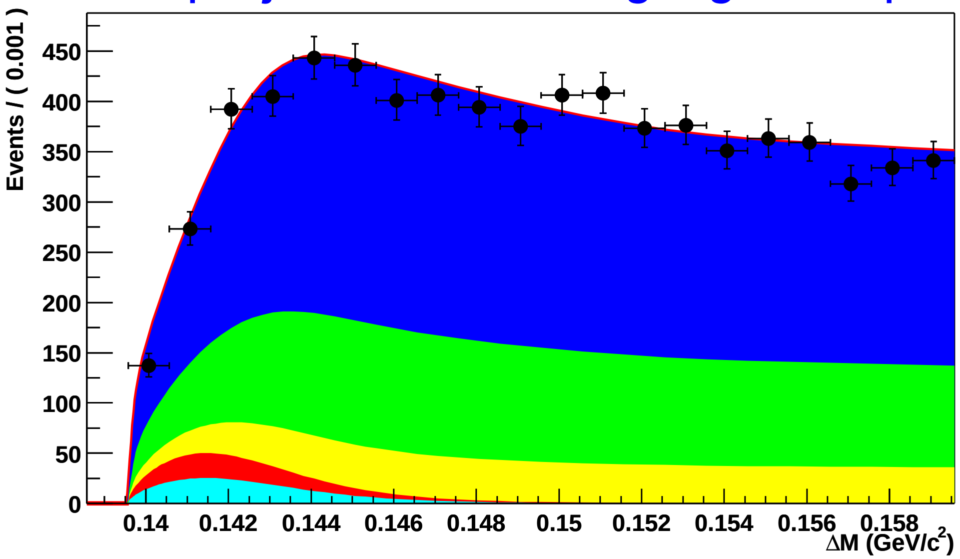
Extract result from $$\frac{n_{\mathrm{WS}}}{n_{\mathrm{RS}}} = \frac{\int \Gamma_{\mathrm{WS}}\,\mathrm{d}t}{\int \Gamma_{\mathrm{RS}}\,\mathrm{d}t} = R_{\mathrm{mix}}$$

Projections of fit to *wrong sign* data

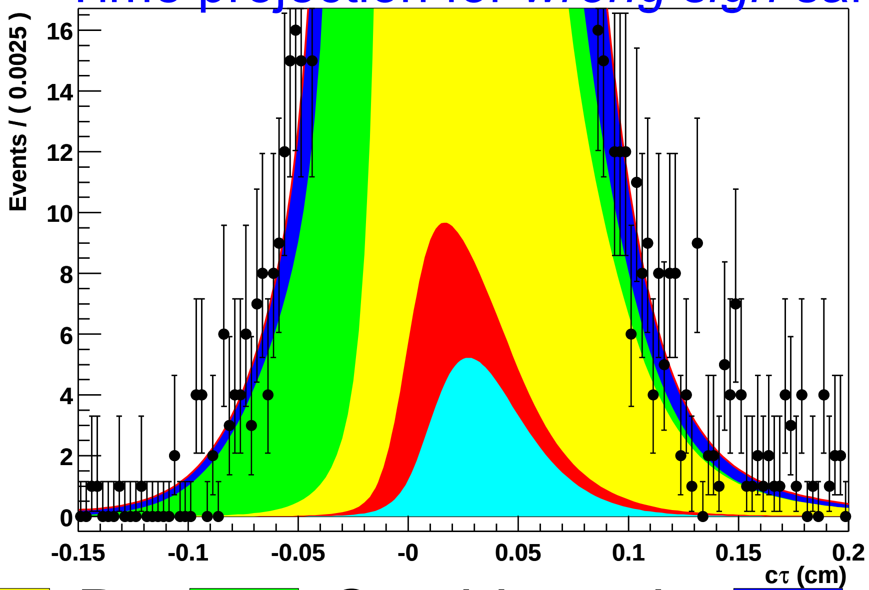
An unbinned maximum log likelihood fit performed on *right sign* and *wrong sign* samples separately.

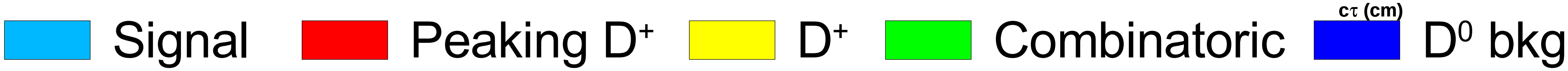
- A large sample of Toy Monte Carlo studies confirm that fit is of good quality.
- Embedded mixing events in fully simulated Monte Carlo demonstrate ability to see a signal.

Δm projection for *wrong sign* sample



Time projection for *wrong sign* sample



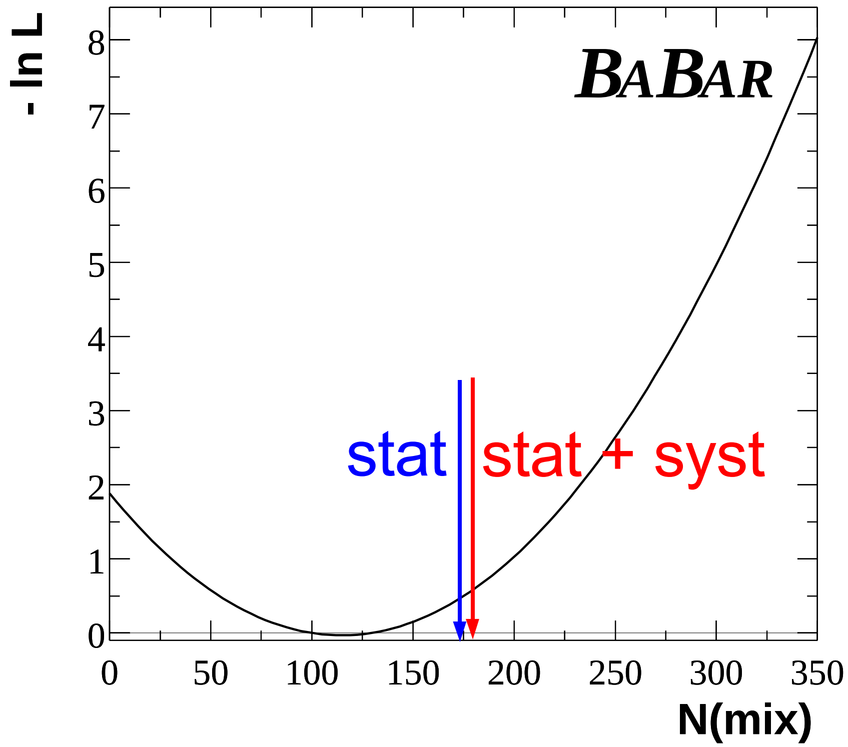


Final result

The fit gives a yield of N_{mix}=114±61 *wrong sign* signal events.

Systematics evaluated as fraction of statistical error.

Systematic	Error
Mixed Δm PDF	0.27
Mixed decay time PDF	0.06
Combinatoric Δm PDF	0.13
Bkg D^0 decay model	0.13
Bkg D^+ decay model	0.10
Total systematic	0.35
Total stat. + syst.	**1.06**



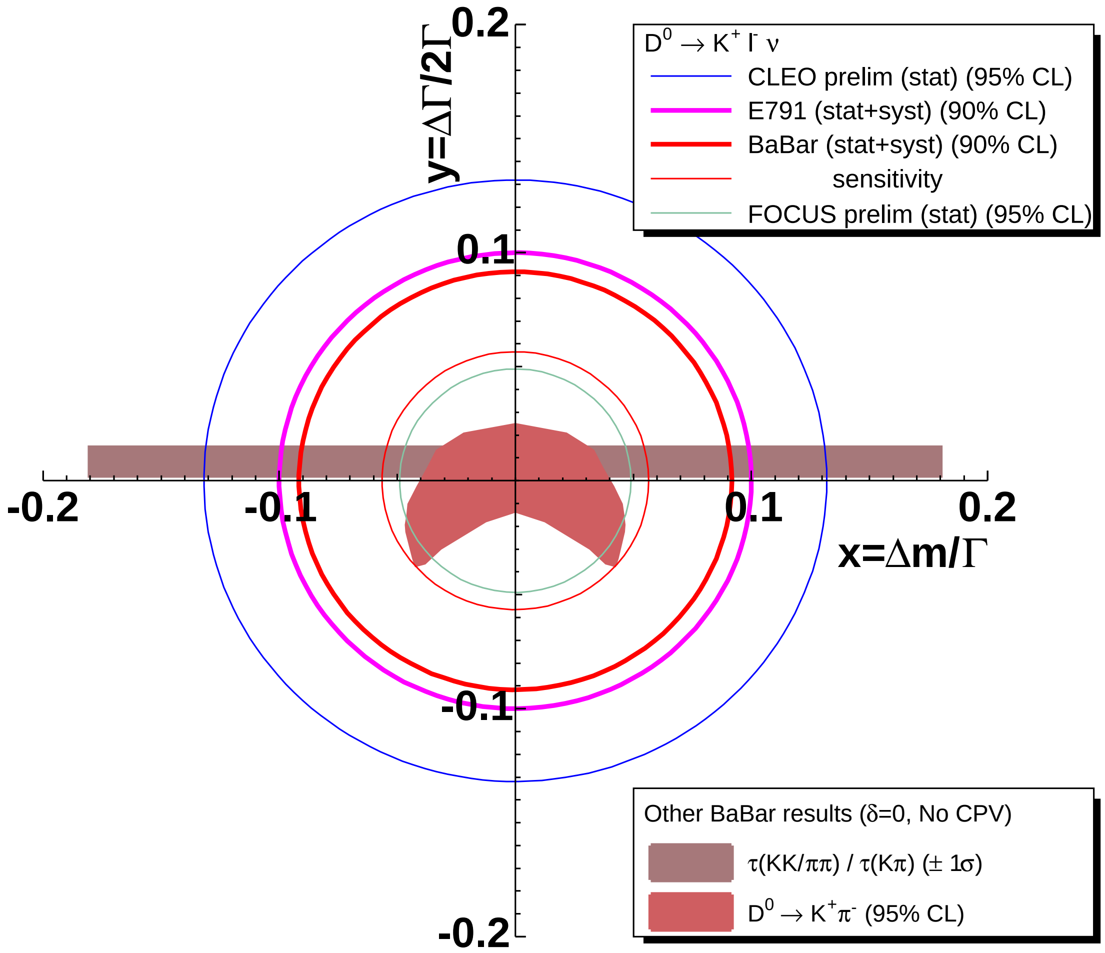
90% Confidence limit on number of mixing signal.

Normalising to number of right-sign events gives result on mixing.

$$R_{mix} = 0.0023 \pm 0.0012(\mathrm{stat}) \pm 0.0004(\mathrm{syst})$$

$$R_{mix} < 0.0042 (90\% \ \mathrm{C.L.})$$

Comparison to other results



BaBar measurements:

Wrong sign hadronic analysis

$$R_{mix} < 1.3 \times 10^{-3} \quad (95\% \text{ CL})$$

Semileptonic analysis

$$R_{mix} < 4.6 \times 10^{-3} \quad (90\% \text{ CL})$$

Lifetime difference for $D^0 \to K^+ K^-$ and $D^0 \to \pi^+ \pi^-$

$$y_{CP} = 0.8 \pm 0.4 ^{+0.5}_{-0.4} \%$$

Search for rare D^0 decays

New results on a search for the decays

- Flavour Changing Neutral Current decays: $D^0 \to e^+ e^-$ $D^0 \to \mu^+ \mu^-$
- Lepton Flavour Violation decays: $D^0 \to \mu^\pm e^\mp$

In the Standard Model the FCNC decays are highly suppressed by the GIM mechanism. The LFV decays are strictly forbidden.

Opposed to rare decay searches in the *K* and *B* sector, rare *D* decays are sensitive to new physics involving the up-quark sector.

- R-parity violating supersymmetry could increase Branching fractions to experimentally accessible level.
- MSSM predicts suppression of factor 10^6 compared to $B^0 \to l^+ l^-$

Main challenge of analysis is to reject background from hadronic *D* decays and pure combinatorics.

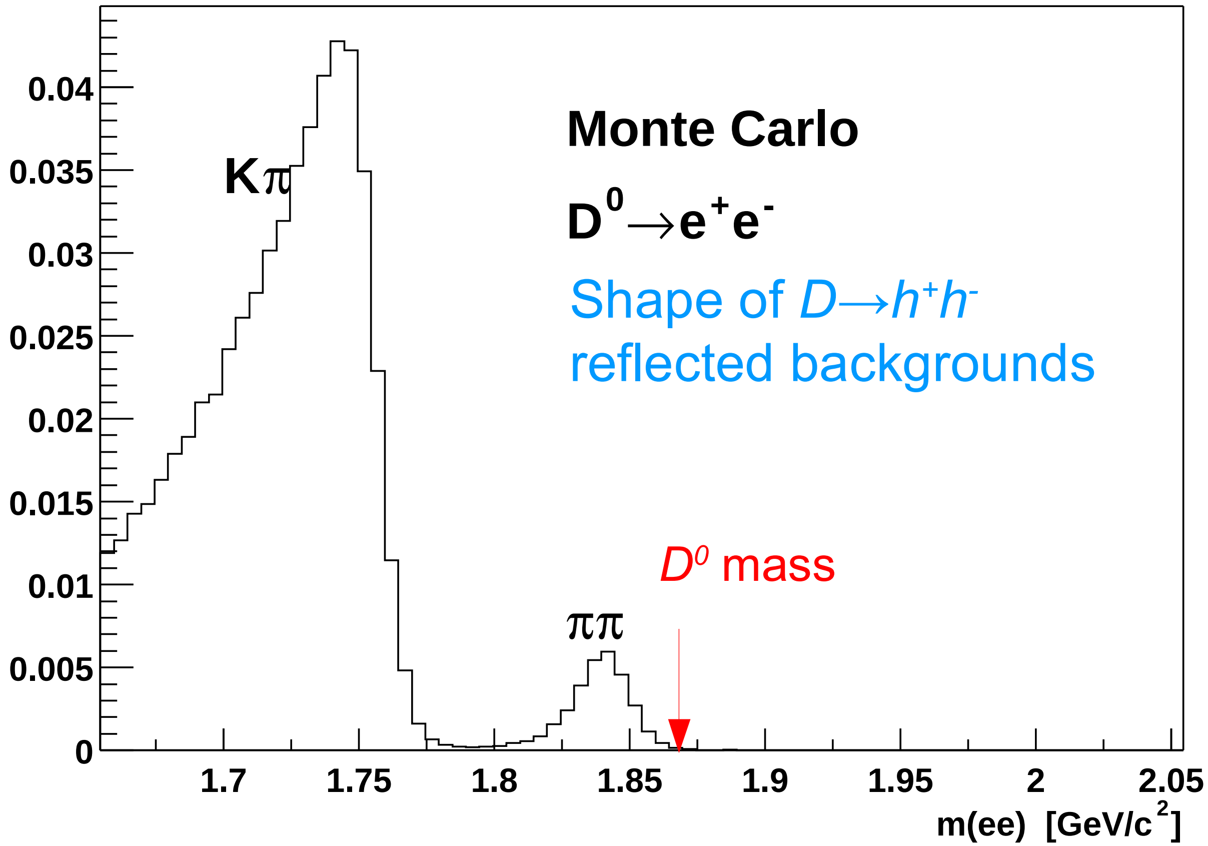
Method

Data

Use 121 fb^{-1} $D^{*+} \to D^0 \pi^+$ tagged sample with $p^*_{D^0} > 2.4\,\mathrm{GeV}/c$ to avoid combinatorics from B decays.

Branching fractions normalised to $D^0 \to \pi^+ \pi^-$ due to similar kinematics.

- Decays treated equally apart from particle identification
- 95% efficiency per electron with 0.2% pion contamination.
- 60% efficiency per muon with 2.0% pion contamination.



Method

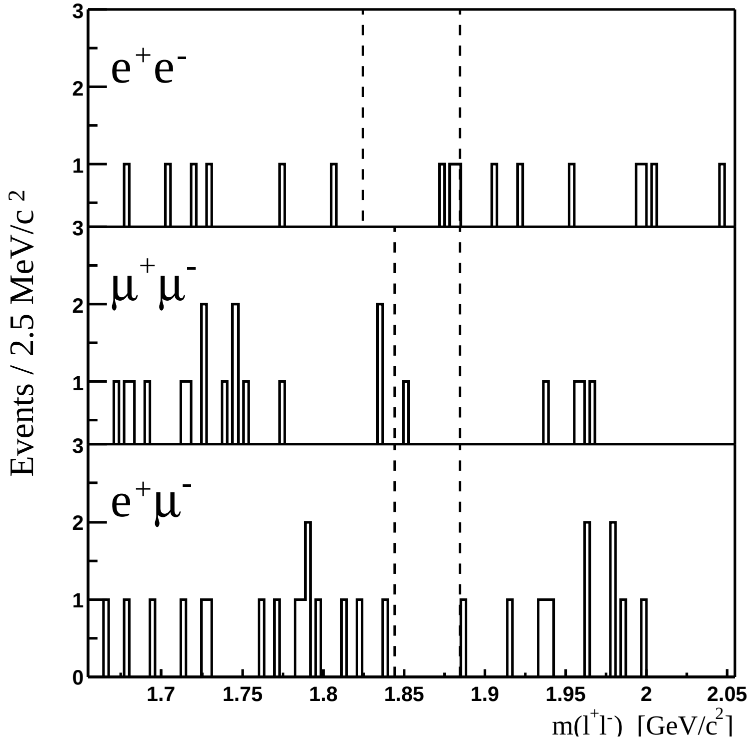
Selection

Optimised separately for each decay mode using vertex quality, lifetime of D^0 and width of mass windows.

Background

From correlations in $D^0 \to \pi^+ \pi^-$ sample background efficiency is factorised.

This allows measurement of background in sidebands before all selection criteria are applied.



Systematics

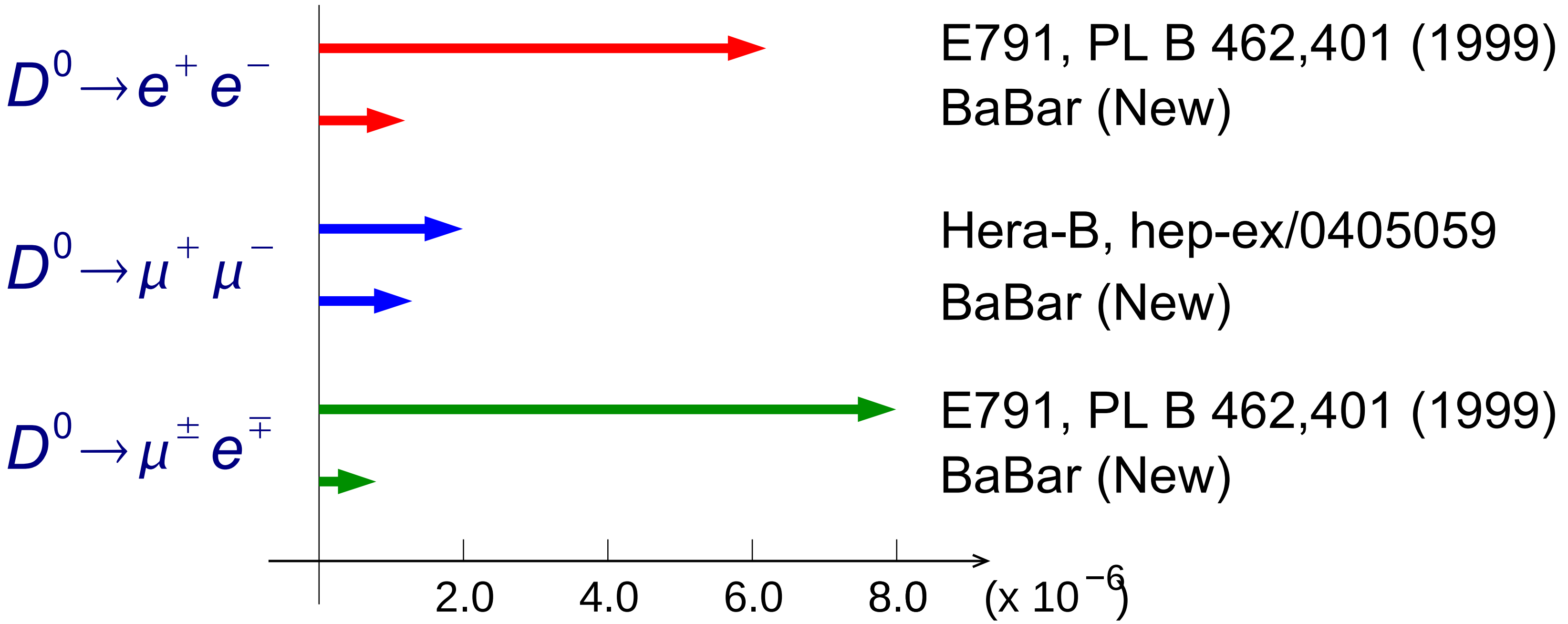
Main systematics are from sideband statistics and PID uncertainty in relative efficiency between pion and lepton mode.

Included in limits following method of Conrad, Botner, Hallgren and Perez, PRD 67, 012002 (2003)

Limits and comparison

	$D^0 \to e^+e^-$	$D^0 \to \mu^+\mu^-$	$D^0 \to e^\pm\mu^\mp$
N_{bg}^{hh}	0.02	3.34 ± 0.31	0.21
$N_{\text{bg}}^{\text{comb}}$	2.21 ± 0.38	1.28 ± 0.32	1.93 ± 0.36
N_{bg}	2.23 ± 0.38	4.63 ± 0.45	2.14 ± 0.36
S $[10^{-7}]$	2.25 ± 0.12	4.53 ± 0.30	3.27 ± 0.20
N_{obs}	3	1	0
UL obtained	1.2×10^{-6}	1.3×10^{-6}	8.1×10^{-7}

@ 90% CL



Spectroscopy – New charm states

Until recently there was a good agreement between potential models and predicted charm states.

The newly discovered states do not fit in well.

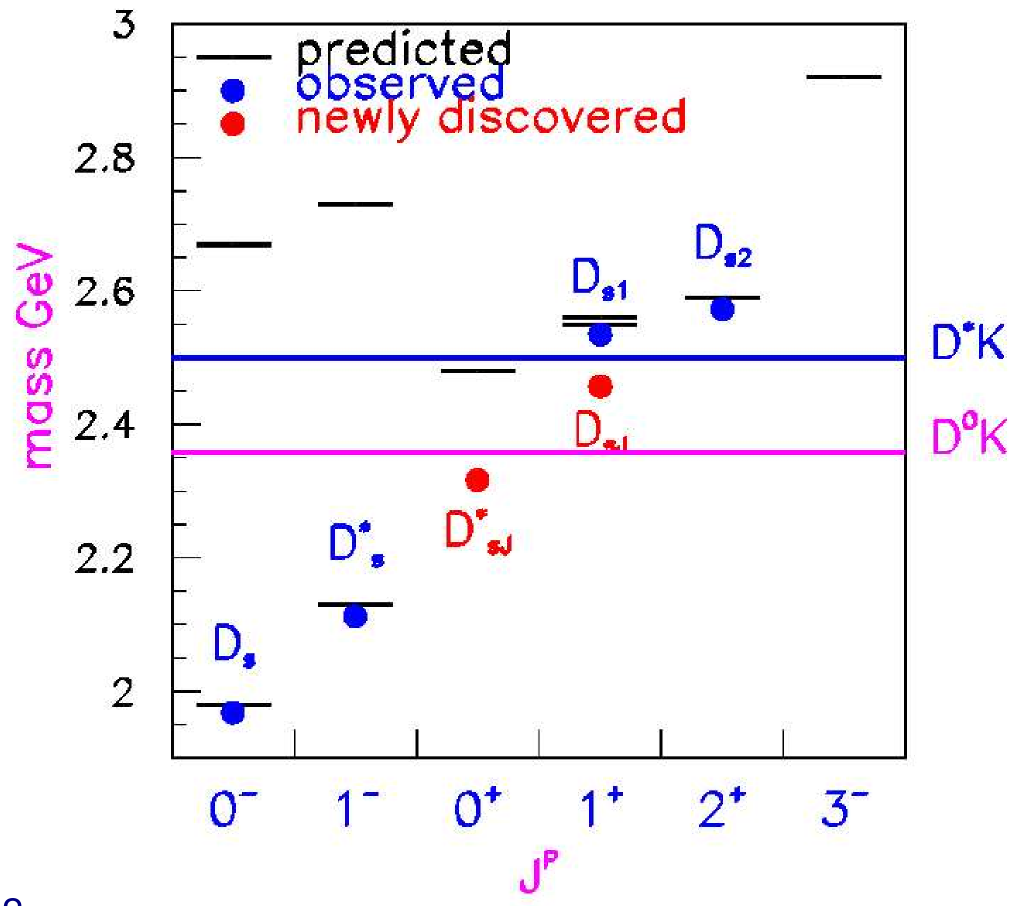
- Reaction is some 40 published theory papers on the subject.

$D^*_{sJ}(2317)^+$

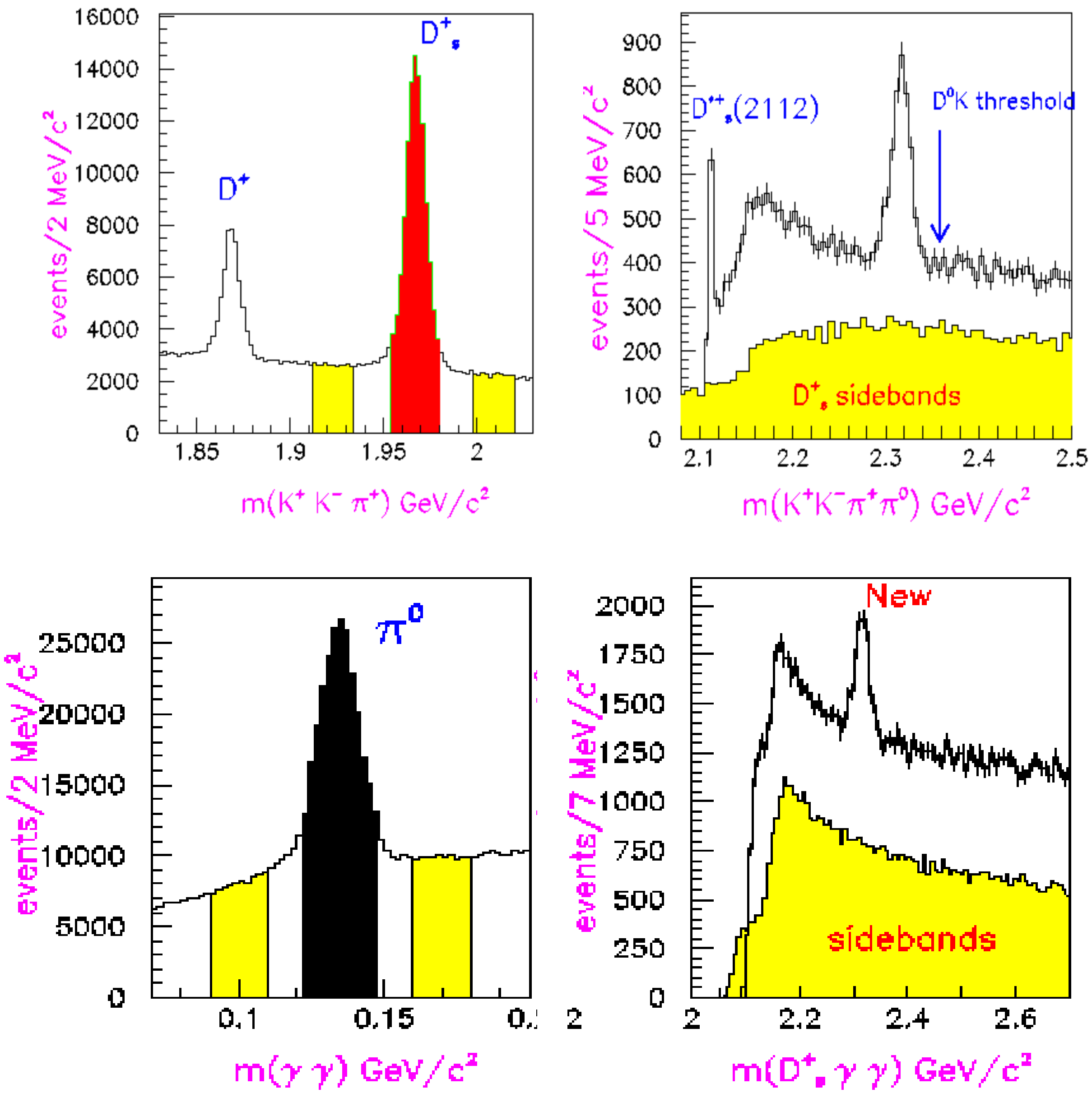
$$m = 2317 \pm 0.4 \quad \text{MeV}/c^2$$
$$\sigma = 7.3 \pm 0.2 \quad \text{MeV}/c^2$$

$D_{sJ}(2458)^+$

$$m = 2458.0 \pm 1.0 \pm 1.0 \quad \text{MeV}/c^2$$



Projections showing $D^*_{sJ}(2317)^+ \rightarrow D_s\,\pi^0$ signal



Conclusion

Search for mixing in the charm sector

- Semi-leptonic analysis from BaBar presented for the first time.

  $$R_{\text{mix}} < 0.0042\,(90\,\%\ \text{C.L.})$$

- Now 3 very different analysis available all sensitive to *x* and *y* at the percent level.
- All have prospects for update to larger dataset.

Rare decays

- A search for the FCNC and LFV decays $D^0 \to e^+ e^-$, $D^0 \to \mu^+ \mu^-$ and $D^0 \to \mu^\pm e^\mp$ presented.
- Limits a factor 2 to 10 better than previous limits.

Spectroscopy

- Discovery of the state $D^*_{sJ}(2317)^+$ and confirmation of $D_{sJ}(2458)^+$.
- Ongoing studies of these and other proposed charm states.