D^0 Mixing at the BABAR Experiment: recent results

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Le detecteur de Matisse ou the Matisse detector — by G. Martinelli

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Outline

1. Mixing and CP Violation in the Charm Sector
2. Time-dependent analysis on the Dalitz Plot of the D^0 decays to $K_S^0\pi^+\pi^-$ and $K_S^0K^+K^-$
3. Conclusions

Mixing of neutral charmed mesons

Mixing occurs when flavour eigenstates differ from mass eigenstates

The time evolution of D^0 and $\bar{D}^0$ is obtained by solving:

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

diagonalized by $|\mathbf{D_{1,2}}\rangle = \mathbf{p}\,|\mathbf{D^0}\rangle \pm \mathbf{q}\,|\mathbf{\bar{D}^0}\rangle$

$\frac{q}{p} = \sqrt{\frac{M_{12}^* - i\Gamma_{12}^*/2}{M_{12} - i\Gamma_{12}/2}}$

$|q^2| + |p^2| = 1$

(assuming CPT invariance)

Mixing Parameters:

$x_{\mathrm{D}} = \frac{m_1 - m_2}{\Gamma}$ $\quad$ $y_{\mathrm{D}} = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$

$\Gamma = (\Gamma_1 + \Gamma_2)/2$

$A_f = \langle D^0 \mid \mathcal{H} \mid f \rangle$

$\bar{A}_f = \langle \bar{D}^0 \mid \mathcal{H} \mid f \rangle$

$\bar{A}_{\bar{f}} = \langle \bar{D}^0 \mid \mathcal{H} \mid \bar{f} \rangle$

CP Violation (CPV) can occur in 3 ways:

- in decay: $|A_f| \neq |\bar{A}_{\bar{f}}|$
- in mixing: $|q/p| \neq 1$
- in the interference between decay and mixing: $\phi_f \neq 0$

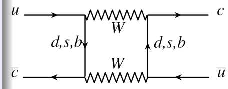
$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} = \left|\frac{q}{p}\right|\left|\frac{\bar{A}_f}{A_f}\right| e^{i(\Delta_f + \phi_f)}$$

strong phase (Δ_f) $\quad$ weak phase (ϕ_f)

Standard Model (SM) predictions & New Physics (NP)

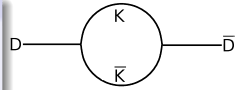
short-distance contributions

- virtual down type quarks involved in mixing loop (only in D system);
- b contribution is CKM suppressed and s and d contributions are GIM suppressed;
- possible NP contributions comparable to the SM ones;



long-distance contributions

- expected to be dominant;
- important uncertainties on their estimation;



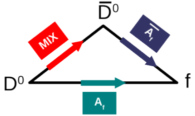
expectations and importance of the measurement of x_D and y_D

- the SM predictions for the mixing parameters vary in a range from $\mathbf{10^{-2}}$ to 10^{-7} [IJMP, A21:5686 (2006)];
- (SM) CP Violation is expected to be below the experimental sensitivity;
- combining all the measurements of D^0 mixing, the no-mixing hypothesis is excluded with a confidence level equivalent to $10.2\ \sigma$;
- this measurement completes the picture of mixing in the SM and it puts contraints in the space of parameters of NP models.

$D^0 \to K^0_S\pi^+\pi^-$, $K^0_S K^+K^-$ Time-Dependent Analysis on the Dalitz Plot

The presence of mixing reflects in the decay time distribution of $D^0 \to f$:

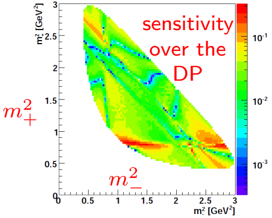
$$|\mathcal{A}|^2 \propto |A_f|^2 e^{-\Gamma t}\left[\frac{1+|\lambda_f|^2}{2}\cosh(y_D\Gamma t) + \frac{1-|\lambda_f|^2}{2}\cos(x_D\Gamma t) - Re\lambda_f \sinh(y_D\Gamma t) + Im\lambda_f \sin(x_D\Gamma t)\right]$$



- require the knowledge of the flavour of the D^0 at production; ($D^{*+} \to D^0\pi_s^+$ and C conjugate)
- the strong phase between A_f and $\bar{A}_f$ (Δ_f) is not measurable at B Factories $\Rightarrow$ x_D & y_D are redefined by a rotation of Δ_f.

A direct measurement of the mixing parameters x_D & y_D is possible
(assuming CP is conserved in decay)

In the time-dependent analysis on the Dalitz Plot of the decays $D^0 \to K^0_S\pi^+\pi^-$, $K^0_S K^+K^-$: f and the CP-conjugate $\bar{f}$ belong to the same DP $\Rightarrow$ this allows the parameterization of $|\mathcal{A}|^2$ using only one amplitude among A_f and $\bar{A}_f$ and get rid of Δ_f.



The sensitivity over the Dalitz Plot (DP)

the DP amplify the sensitivity to mixing since λ_f varies on the DP: $\lambda_f = \lambda_f(m^2_-, m^2_+)$ $\Rightarrow$ there can be large interferences and relative phases.

Fit in the $(\Delta m, m_{D^0})$ plane to data $L_{\text{int}} = 468\,\text{fb}^{-1}$

Cat2 $=$ true D^0 & misrec π_s
Cat3 $=$ misrec D^0 & true π_s
Cat4 $=$ misrec D^0 & misrec π_s

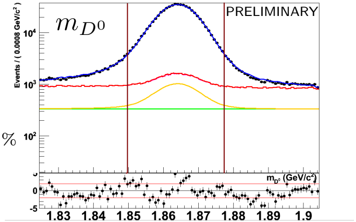
$\Delta m = m_{D^*} - m_{D^0}$

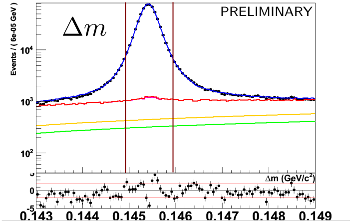
$K_S^0 \pi^+ \pi^-$

in the signal box:

$\varepsilon_{sig} = 14.4\%$

$\frac{N_{sig}}{N_{sig}+N_{bkg}} = 98.5\%$



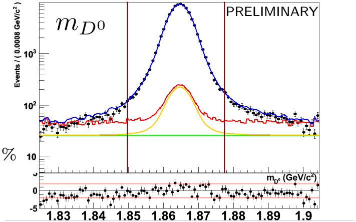


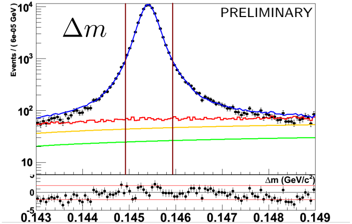
$K_S^0 K^+ K^-$

in the signal box:

$\varepsilon_{sig} = 14.6\%$

$\frac{N_{sig}}{N_{sig}+N_{bkg}} = 99.2\%$

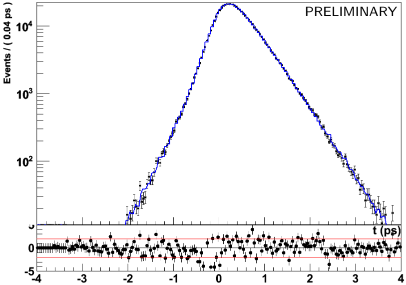




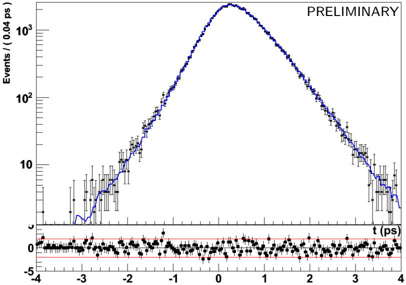
Fit to data (1)

fit projections: D^0 proper time

$K_S^0\pi^+\pi^-$



$K_S^0K^+K^-$



The fitted average lifetime is found to be consistent with the world average lifetime

$$\tau_D = (410.1 \pm 1.5)\ \text{fs}$$

Fit to data (2)

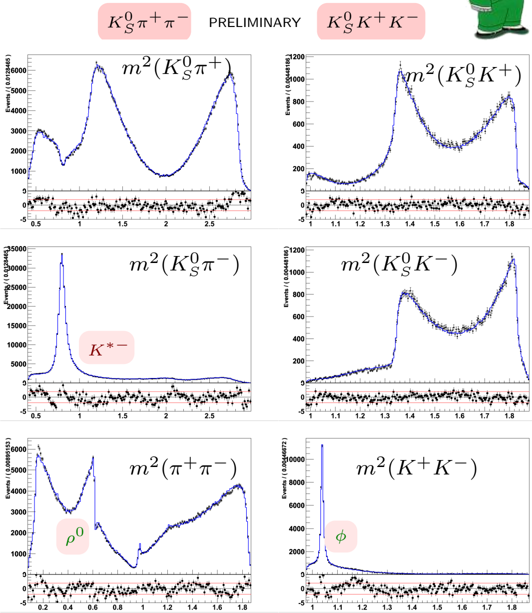
fit projections: Dalitz variables

Many resonances contribute to the total amplitude.
In a single DP we have:

- D decays through Cabibbo Favoured and Doubly Cabibbo Suppressed processes;
- D decays through CP eigenstates;

To model the resonances we use the following model:

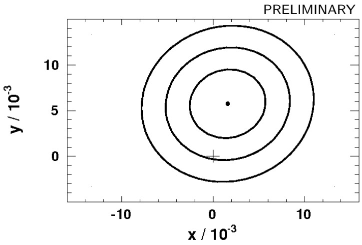
- Breit-Wigner parameterization for P-waves and D-waves
- K-matrix formalism for the $\pi\pi$ S-wave
- LASS-like parameterization for the $K\pi$ S-wave



Results

Systematic Error

A systematic error (model) is associated to the Dalitz Plot model. Other systematic errors come from the appoximations in the modeling of experimental and selection criteria effects.



Mixing Parameters:

$x_{\mathrm{D}} = [1.6 \pm 2.3(\mathrm{stat}) \pm 1.2(\mathrm{syst}) \pm 0.8(\mathrm{model})] \times 10^{-3}$

$y_{\mathrm{D}} = [5.7 \pm 2.0(\mathrm{stat}) \pm 1.3(\mathrm{syst}) \pm 0.7(\mathrm{model})] \times 10^{-3}$

$(L_{\mathrm{int}} = 468\,\mathrm{fb}^{-1})$

Mixing Significance

The no-mixing hypothesis is disfavoured with a confidence level equivalent to 1.9 σ standard deviations. This is the best direct measurement of the mixing parameters.

Belle measurement on 540 fb^{-1}: $(D^0 \to K_S^0 \pi^+ \pi^-)$

[PRL 99, 131803 (2007)]

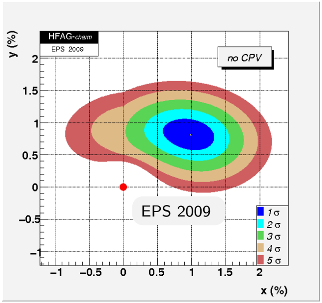
$x_{\mathrm{D}} = [8.0 \pm 2.9(\mathrm{stat})^{+0.9}_{-0.7}(\mathrm{syst})^{+1.0}_{-1.4}(\mathrm{model})] \times 10^{-3}$

$y_{\mathrm{D}} = [3.3 \pm 2.4(\mathrm{stat})^{+0.8}_{-1.2}(\mathrm{syst})^{+0.6}_{-0.8}(\mathrm{model})] \times 10^{-3}$

Conclusions

Summary

- Measuring x_D and y_D is important for SM Physics and for New Physics models which must be able to account for the result of this measurement;
- The time-dependent analysis on the Dalitz Plot $D^0 \to K^0_S \pi^+\pi^-$, $K^0_S K^+K^-$ allowed a *direct* measurement of the mixing parameters disfavouring the no-mixing hypothesis with a confidence level equivalent to $1.9\ \sigma$
- This result was presented at the Rencontres de Moriond EW 2010 by Jordi Garra Tic ("$D^0 - \bar{D}^0$ mixing and charm CP violation").



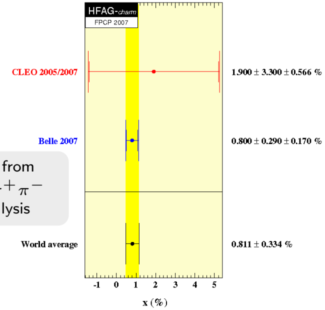
Future Developments in *BABAR* ($L^{tot}_{int} = 530\ \text{fb}^{-1}$)

- CPV measurement in the Dalitz $K^0_S\pi^+\pi^-, K^0_S K^+K^-$ analysis;
- update of the $D^0 \to K^+\pi^-$ wrong-sign analysis;
  $L_{int} = 384\,\text{fb}^{-1}$, mixing significance of $3.9\ \sigma$
  [PRL 2111802 (2007)];
- update of the $D^0 \to K^-\pi^+, K^+K^-, \pi^+\pi^-$ lifetime ratio analysis;
  $L_{int} = 384\,\text{fb}^{-1}$, mixing significance of $4.1\ \sigma$
  [PRD 80, 071103 (2009)].

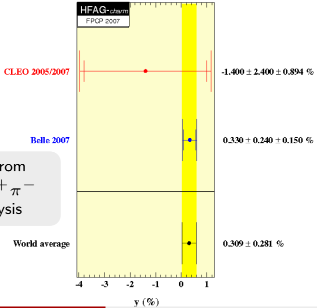
Part I

Back-up Slides

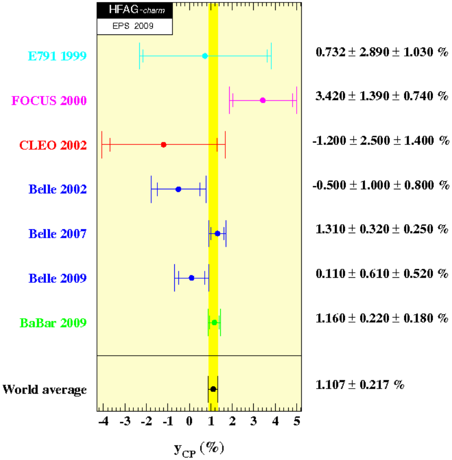
D^0 mixing: the experimental situation (not complete)



x_{D} from $K_S^0\pi^+\pi^-$ analysis



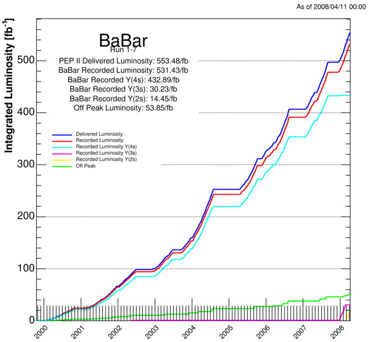
y_{D} from $K_S^0\pi^+\pi^-$ analysis



$$y_{\mathrm{CP}} \equiv \Gamma(\mathrm{CP}+)/<\Gamma> -1$$

$$y_{\mathrm{CP}} = \frac{1}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) y_{\mathrm{D}} \cos\phi - \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) x_{\mathrm{D}} \sin\phi$$

The *BABAR* detector and the data sample

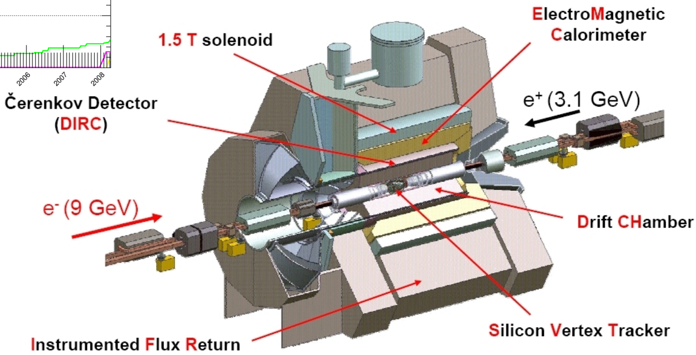


RUN1 → RUN6: $e^+e^- \rightarrow \Upsilon(4S)$ + off-peak

$$L_{\Upsilon(4S)} = 432.9 \text{ fb}^{-1}$$

RUN7 : $e^+e^- \rightarrow \Upsilon(3S), \Upsilon(2S)$ + off-peak

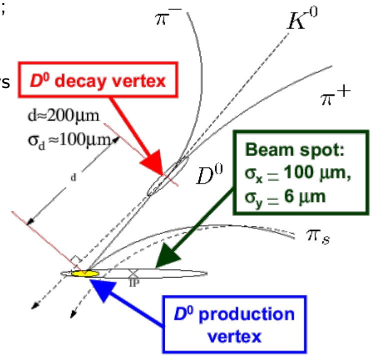
$$L_{\Upsilon(3S)} = 30.2 \text{ fb}^{-1},\ L_{\Upsilon(2S)} = 14.5 \text{ fb}^{-1}$$



D^0 mesons selection at a B Factory

tagged sample of D

1. select D^0 from: $D^{*+} \to \pi_s^+ D^0$, $D^{*-} \to \pi_s^- \overline{D}^0$:
   - identify D^0 flavour at production using π_s charge;
   - select events around the peak of Δm ($\Delta m = m_{D^*} - m_{D^0}$, $\sigma \sim 350$ keV);
   - $|p_{\rm cm}(D^0)| > 2.5\,\mathrm{GeV}/c$ to reject D from B decays and improve signal significance;
2. require that the D^* and D^0 production vertices fall inside the luminous region (beam spot):
   - the D^* decays immediately after being created;
   - allows the determination of the D^0 flight time t and its error σ_t;
3. reconstruct the D^0 in the final state f:
   - select events around the peak of m_{D^0}, the reconstructed D^0 mass;
   - use selection criteria in order to reject bkg events (transverse momentum of the tracks, number of hits in SVT/DCH, ...), depending on f;
4. fit the distribution of the events in the (Δm, m_{D^0}) plane in order to discriminate signal from bkg events.



untagged sample of D:
- no D^* requirement
- x4 statistics
- more bkg

Time-dependent analysis on the Dalitz Plot

Once the events are selected we perform a fit in 3 steps:

1) Selection Variables Fit and yields extraction

- evaluate signal and bkg PDF shapes for m_{D^0} and Δm, extraction of the yields in the large (Δm,m_{D^0}) region and rescale to the signal box

2) Proper Time and Dalitz Fit in the signal box (m_{D^0},Δm)

- Step2a: Time Dependent and Dalitz Integrated Fit
- Step2b: Time Integrated and Dalitz Dependent Fit

3) Time Dependent Dalitz Fit in signal box range

- float signal Dalitz model parameter and mixing parameters
- float resolution function parameters

Time-dependent analysis on the Dalitz Plot

The most important systematic errors:

Uncertainty Source	$\sigma_x(\%)$	$\sigma_y(\%)$
fit bias	0.07	0.06
final mixing fit cuts	0.04	0.05
charge-flavour correlation	0.05	0.04
SVT misalignments	0.03	0.08
Dalitz Plot model	0.08	0.07