Univerza v Ljubljani

THE UNIVERSITY OF TOKYO

Flavour Physics at B-factories and Hadron Colliders

Part 10: Mixing

Peter Križan

University of Ljubljana and J. Stefan Institute

Contents

B oscillations

$$P_{u,m} = \frac{1}{2}\Gamma_q e^{-\Gamma_q t}\left[1 \pm \cos(\Delta m_q t)\right]$$

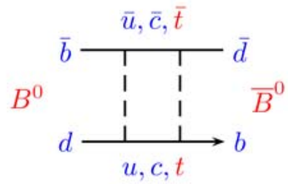
m=mixed, *u*=unmixed

(neglecting CP, CPT violation, $\Delta\Gamma/\Gamma=0$)

Motivation: proceeds through loop diagrams, could be a tool to discover new physical phenomena.

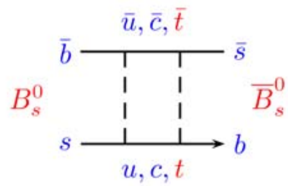
Mixing: estimates

$\Delta m \propto$



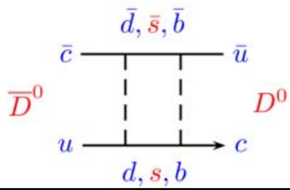
$|V_{tb}^* \, V_{td}|^2 m_t^2 \;\propto\; \lambda^6 m_t^2 \approx 3$

$|V_{cb}^* \, V_{cd}|^2 m_c^2 \;\propto\; \lambda^6 m_c^2 \approx 3 \cdot 10^{-4}$



$|V_{tb}^* \, V_{ts}|^2 m_t^2 \propto \lambda^4 \; m_t^2 \approx 70$

$|V_{cb}^* \, V_{cs}|^2 m_c^2 \propto \lambda^4 \; m_c^2 \approx 7 \cdot 10^{-3}$



$|V_{bu}^* \, V_{bc}|^2 m_b^2 \propto \lambda^{10} m_b^2 \approx 7 \cdot 10^{-6}$

$|V_{su}^* \, V_{sc}|^2 m_s^2 \propto \lambda^2 m_s^2 \approx 4 \cdot 10^{-3}$

$B_{d,s}$ oscillations: refined theoretical predictions

B decay constant
193±29 MeV
(LQCD)
208±27 MeV
(QCD sum rules)

ren. group
inv. param.
1.34±0.12
(LQCD)
1.10±0.15
(QCD sum rules)

NLO QCD corr.
0.55±0.01

$$\Delta m_d = 0.50\,ps^{-1}\left[\frac{F_{Bd}\sqrt{B_{Bd}}}{230MeV}\right]^2\left[\frac{m_t}{167GeV}\right]^{1.52}\left[\frac{|V_{td}|}{7.8\cdot 10^{-3}}\right]^2\left[\frac{\eta_B}{0.55}\right]$$

$$\Delta m_s = 17.2\,ps^{-1}\left[\frac{F_{Bs}\sqrt{B_{Bs}}}{260MeV}\right]^2\left[\frac{m_t}{167GeV}\right]^{1.52}\left[\frac{|V_{ts}|}{0.040}\right]^2\left[\frac{\eta_B}{0.55}\right]$$

B oscillations

Experimental methods:
time dependent

$$P_{u,m} = \frac{1}{2}\Gamma_q e^{-\Gamma_q t}\left[1 \pm \cos(\Delta m_q t)\right]$$

(neglecting CP, CPT violation, $\Delta\Gamma/\Gamma=0$), *m*=mixed, *u*=unmixed

need proper time measurement
$\sigma_t/\tau_B=\sigma_L/L \oplus (t/\tau_B)(\sigma_p/p)$

flavor tagging @decay and @production

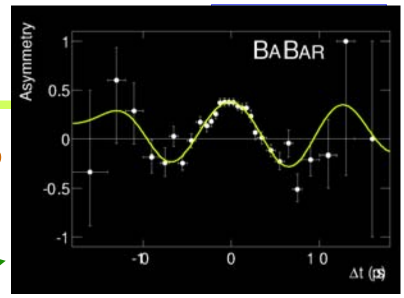
time integrated

$$\bar{\chi} = f_d\chi_d + f_s\chi_s$$

high energy Υ(4s)

lots of tagging and reconstruction methods

B_d oscillations

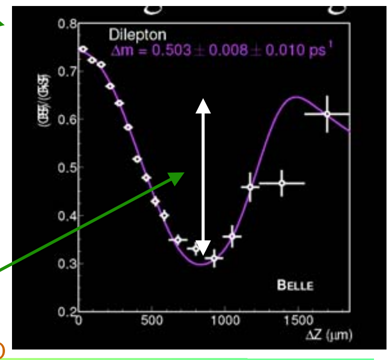


Examples of analyses:

(BaBar,hep-ex/0212017(02))

exclusive method, BaBar;
$B^0 \rightarrow D^* l \nu$, reconstruct D*;
flavor tagging other side NN;
asymmetry=$(P_u-P_m)/(P_u+P_m)$

Δm_d=0.492±0.018±0.013 ps^{-1}
(20fb^{-1})



semi inclusive, Belle;
two fast leptons;
flavor tagging – lepton charge;

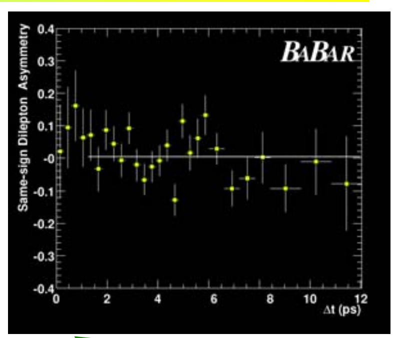
Δm_d=0.503±0.008±0.010 ps^{-1}
(29fb^{-1})

large amplitude ↔ good tagging ε
large statistics (Belle,PRD67,052004(03))

B_d oscillations

Oscillation probability including $\Delta\Gamma$

$$P_{u,m} = \frac{1}{2}\Gamma_q e^{-\Gamma_q t}\left[\cosh(\frac{\Delta\Gamma_q}{2}t) \pm \cos(\Delta M_q t)\right]$$



no assumption of CPT invariance:

$$|B_H> = p|B^0> + q|\overline{B}^0>$$

$$|B_L> = p'|B^0> - q'|\overline{B}^0>$$

$$\frac{q}{p} = \tan(\frac{\theta}{2})e^{i\phi}$$

$$\frac{q'}{p'} = \cot(\frac{\theta}{2})e^{i\phi}$$

CP violated if $Im(\phi)\neq 0$
dileptons: difference in
l^+l^+ and l^-l^- rates;

CPT violated if $\theta\neq\pi/2$;

expressions for $P_{u,m}$ changed
by dependence on θ,ϕ

Belle, dileptons:
$|m_{B0}-m_{\overline{B0}}|/m_{B0} < 1.16\times10^{-14}$
$|\Gamma_{B0}-\Gamma_{\overline{B0}}|/\Gamma_{B0} < 0.11$
@ 90% C.L.

How to measure B_s mixing?

Measure: probability that a B_s (at t=0) turns into an anti-B_s at time t.

Need:

- a well defined final state with precisely measured vertex, momentum
- a tag to determine the initial B_s flavour (B_s or anti-B_s at t=0)

Final states:

- μ Ds nu, Ds → ϕ π^+, K^+K_S, K^+K^*
- J/ψ K^* → $\mu\,\mu$ K π
- $D_s(*)$ π^+ ($\pi^+ \pi^+ \pi^-$)

Tagging:

- charge of kaon and lepton from the associated B decay (opposite side tagging)
- charge of kaon from the same side

B_s oscillations

Cannot be measured at a B factory: no B_s mesons!

First measurements were done at LEP (at E_{cms} of Z^0).

tagging
opposite side:
Neural net (NN) to separate tracks from primary and secondary vertex;
NN to compute charge estimators (jet charge, lepton charge, K charge, etc.) ;

same side:
wide b-jet (all B_s decay products + fragmentation products close in phase space) using large y_{cut} (JADE);
NN to compute charge estimator (from K, jet charge,…)

(Aleph,CERN-EP-2002-16)

B_s oscillations

$$P_{u,m} = \frac{1}{2}\Gamma_q e^{-\Gamma_q t}\left[1 \pm \cos(\Delta m_q t)\right]$$

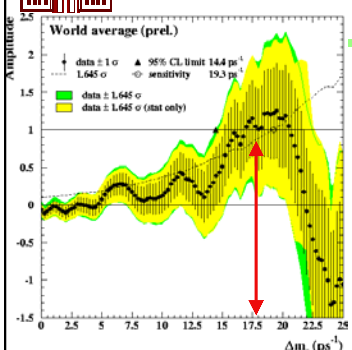
m=mixed, *u*=unmixed

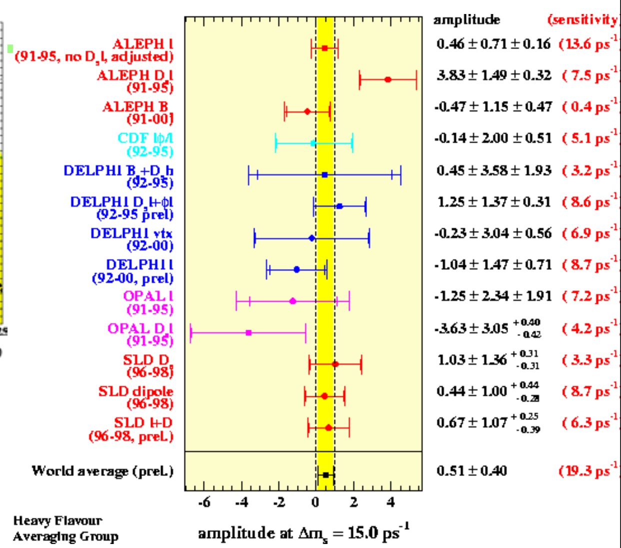
Fit the data in a different way: fix Δm_s and fit the oscillation amplitude A

$$P_m = \frac{1}{2}\Gamma_q e^{-\Gamma_q t}\left[1 - A\cos(\Delta m_q t)\right]$$

If A consistent with 0 -> no mixing.
Mixing established if A=1, and A=0 excluded with high significance.

B_s oscillations





data consistent with oscillations $\Delta m_s \sim 17.5 ps^{-1}$ @2.2σ

(HFAG,winter'03)

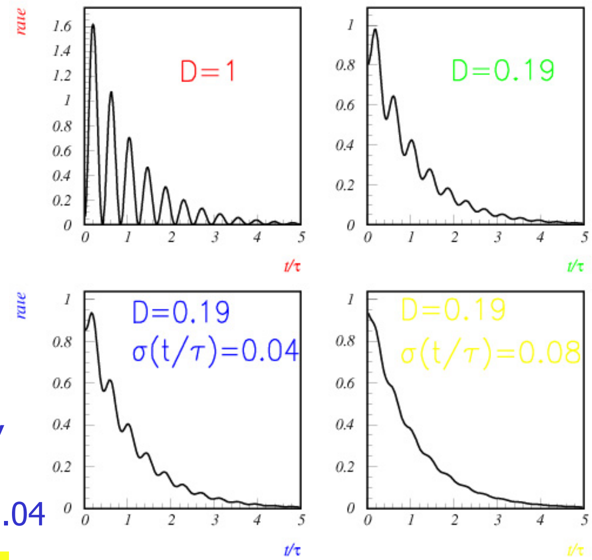
B_s mixing: dilution effects for x_s=15

Ideal

Dilution: Tagging

Dilution: Tagging, Vertex $\sigma(t/\tau)$=0.04

Dilution: Tagging, Vertex $\sigma(t/\tau)$=0.08



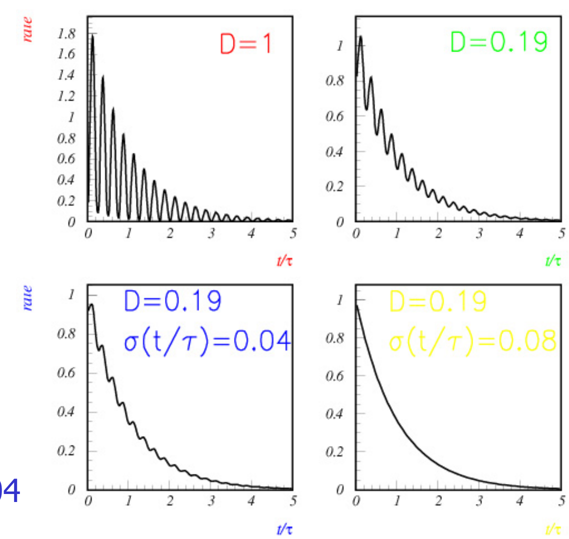
B_s mixing: dilution effects for x_s=25

Ideal

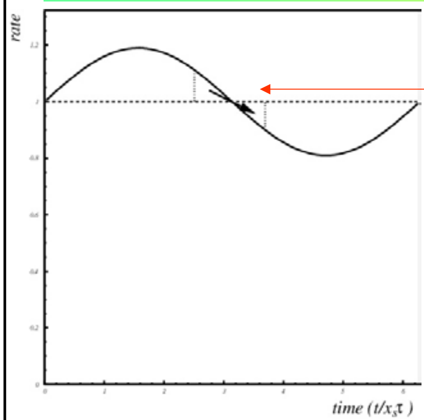
Dilution: Tagging

Dilution: Tagging, Vertex $\sigma(t/\tau)$=0.04

Dilution: Tagging, Vertex $\sigma(t/\tau)$=0.08



B_s mixing: dilution effects due to vertexing



Full curve: dilution tagging only

Dilution due to finite vertex resolution: events move in the region +- ~σ_t off the node

Simple estimate: linear approx around the node, fraction of events that move from the up part of the wave to the down part: ~$(\Delta m_s \sigma_t)^2/2$

Amplitude reduced by a factor $(1-(\Delta m_s \sigma_t)^2/2)$

Full calculation: convolution, **$\exp(-(\Delta m_s \sigma_t)^2/2)$**

Simple estimate: the first term in expansion.

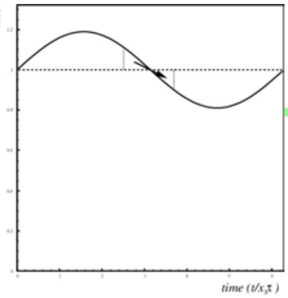
H. G. Moser, A. Roussarie, NIM **A384** (1997)

B_s mixing: dilution effects due to vertexing

$1-\cos(\Delta m_s t)$ ← No dilution

$1-D\cos(\Delta m_s t)$ ← Dilution, tagging only

$1-D'\cos(\Delta m_s t), D' = De^{-\frac{(\Delta m_s \sigma_t)^2}{2}}$ ← Dilution due to finite proper time resolution σ_t (vertex and momentum resolution



B_s mixing: sensitivity in Δm_s

Simple estimate of the statistics required for a significant measurement: fix Δm_s, and divide the events in two classes, those from the 'up' part of the wave, and those from the 'down' part.

The measured oscillation amplitude for a given Δm_s differs from zero if the two classes are found to be differently populated (and the difference is statistically significant).

The distribution over the two classes is binomial, with probability for the 'up' part equal to $p=1/2+cD'$, where c is a constant of order 1.

B_s mixing: sensitivity in Δm_s

Error on p for a measurement with N reconstructed and tagged events: $\sigma(p) = \sqrt{(p(1-p)/N)}$.

For p ~1/2: $\sigma(p) \sim ½ \, 1/\sqrt{N}$

Error on the amplitude D': $\sigma(D') \sim 1/(2c\sqrt{(N)})$

and the significance of the measurement equals to

$D'/\sigma(D') \sim 2c\sqrt{N}\, D \exp(-(\Delta m_s \sigma_t)^2/2)$

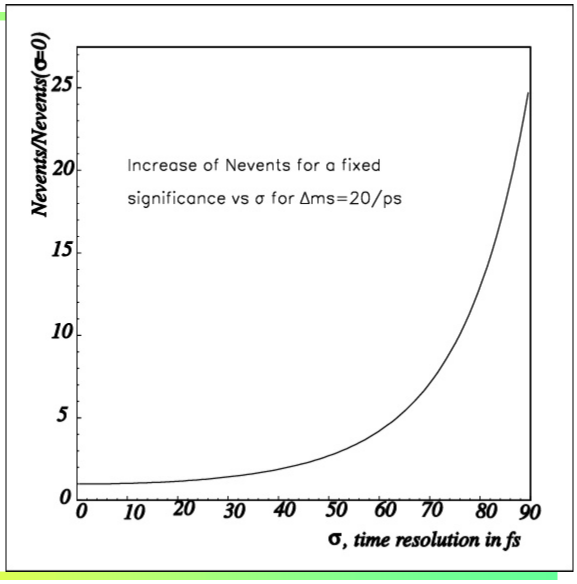
For a given required significance, the number of events needed is proportional to $\exp(+(\Delta m_s \sigma_t)^2)$.

-> a very steep function of the proper time resolution and the mixing parameter above $\Delta m_s \sigma_t=1$

-> If $\Delta ms=20/ps$, need $\sigma_t < 50$ fs to stay below this limit.

B_s mixing: sensitivity in Δm_s

Increase in the number of events needed for a given significance vs resolution.



D^0 mixing

Completely different: Δm very small, $(\Delta m\ t) << 1$ ->

Time evolution, mixed decays:

$$P_m = \frac{1}{2}\Gamma_q e^{-\Gamma_q t}\left[1-\cos(\Delta m_q t)\right] \rightarrow \frac{1}{2}\Gamma_q e^{-\Gamma_q t}\frac{(\Delta m_q t)^2}{2}$$

Almost nothing happens before the D meson decays.

The method: search for D mixing in the decay sequence:
$D^{*+} \rightarrow D^0\pi^+$, $D^0 \rightarrow$ flavour specific final state.

$D^{*+} \rightarrow D^0\ \pi^+$ → $\bar{D}^0$ or D^0 at production time

$D^0 \rightarrow K^-\ e^+\ \nu$

K^- → $\bar{D}^0$ or D^0 at decay time

D^0 mixing in $D^0 \to K\pi$ and $Kl\nu$ decays

The method: search for D mixing in the decay sequence: $D^{*+} \to D^0\pi^+$, $D^0 \to$ flavour specific final state.

Semileptonic decay:

- $K^- e^+ \nu$: no mixing (RS, Right Sign)
- $K^+ e^- \nu$: mixing (WS, Wrong Sign)

→ measure WS rate

Hadronic decay:

- $K^- \pi^+$: no mixing
- $K^+ \pi^-$: mixing or doubly Cabbibo suppressed (DCSD)

→ measure WS time evolution

D^0 mixing in $D^0 \to K\pi$ decays

$D^0 \to K\pi$ time evolution

$$dN/dt \ \alpha \ \{R_D + R_D^{1/2} y' t + (x'^2 + y'^2) \ t^2/4\} \ e^{-t}$$

interference mixing

$x' = x \cos\delta + y \sin\delta$

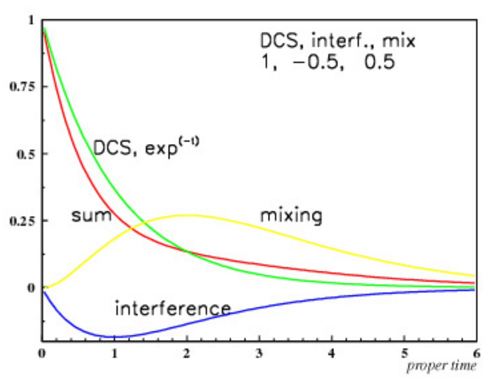
$y' = y \cos\delta - x \sin\delta$

$x = \Delta M/\Gamma \quad y = \Delta\Gamma/2\Gamma$

δ = strong phase difference

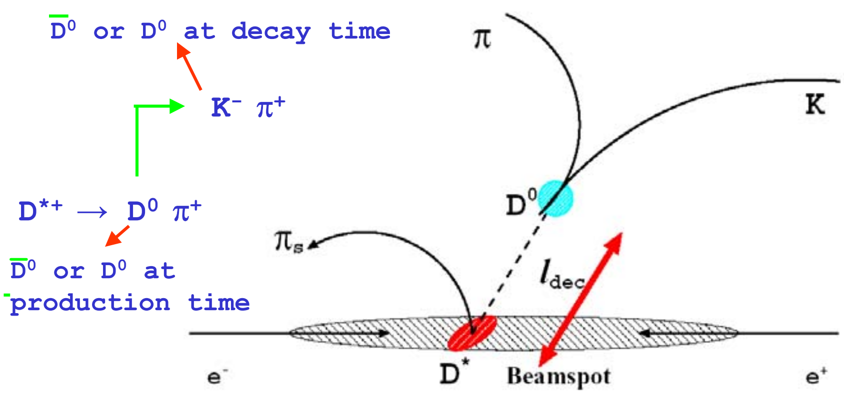
SM: $x < 10^{-3}$, $y < 10^{-3}$ (long dist. effects);

new physics: $x >> y$, CPV



D^0 mixing in $D^0 \to K\pi$ decays

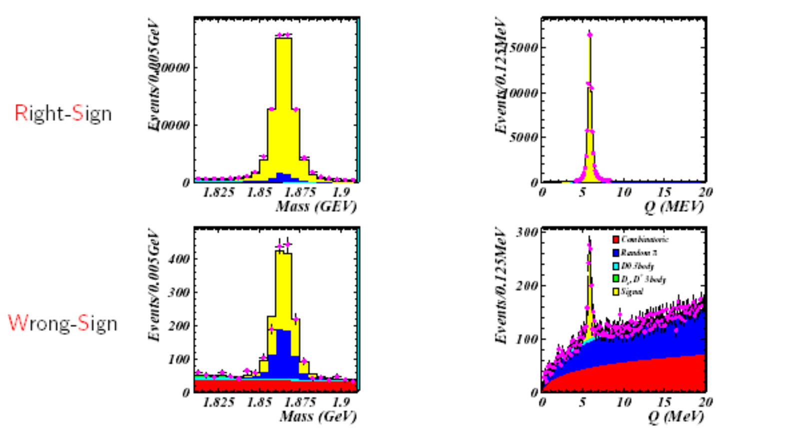
$D^0 \to K\pi$ time evolution measurement



D^0 mixing in $D^0 \to K\pi$ decays

Signal extraction

$M = M(K, \pi)$ $\quad Q = M(K^+, \pi^-, \pi_{\rm slow}) - M(K^+, \pi^-) - M_\pi$



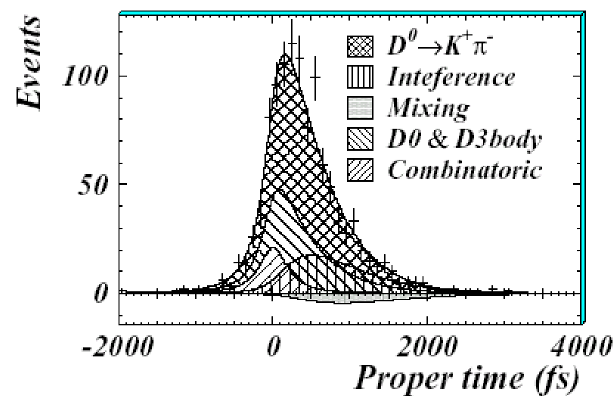
D^0 mixing in $D^0 \to K\pi$ decays

Free fit

$R_D=(0.287 \pm 0.037)\%$,
$y'=(2.54^{+1.11}_{-1.02})\%$,
$x'^2=-(0.153^{+0.08}_{-0.10})\%$

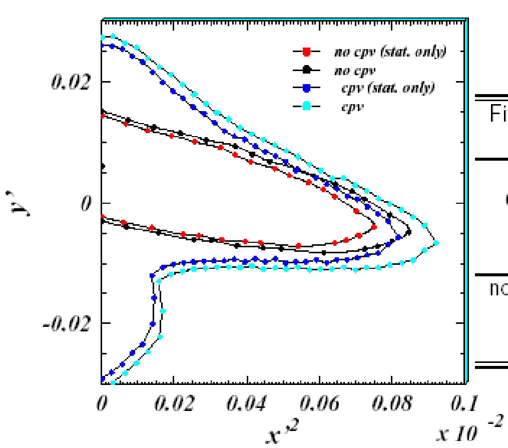
Physical region

$R=(0.343^{+0.027}_{-0.026})\%$,
$y'=(0.60 \pm 0.33)\%$,
$x'^2=0\%$



D^0 mixing in $D^0 \to K\pi$ decays

Results: 95% contour in x'^2 and y' plane (with 90 fb^{-1})

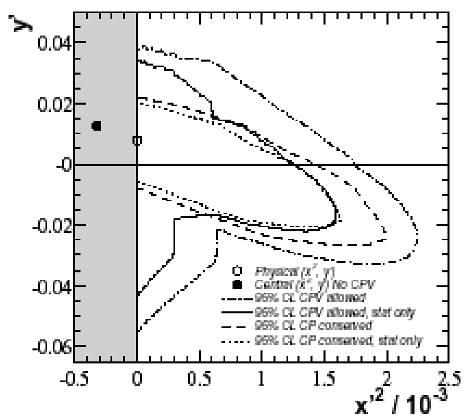


Fit case	Parameter	95% C.L. interval ($\times 10^{-3}$)
CPV	A_D	$-250 < A_D < 110$
	A_M	$-991 < A_M < 1000$
	x'^2	$x'^2 < 0.89$
	y'	$-30 < y' < 27$
no CPV	x'^2	$x'^2 < 0.81$
	y'	$-8.2 < y' < 16$
	R_D	$2.7 < R_D < 4.0$

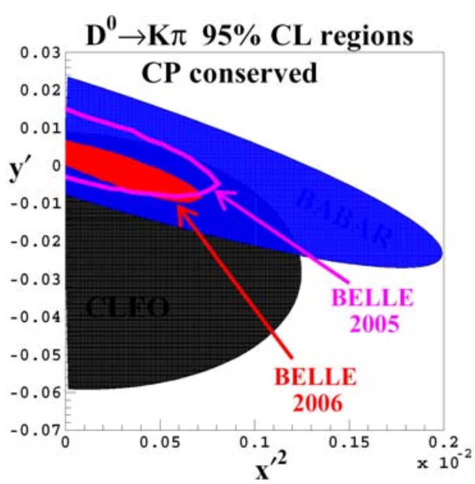
D^0 mixing in $D^0 \to K\pi$ decays

Results: 95% contour in x'^2 and y' plane (with 57.1 fb^{-1})

BaBar



D^0 mixing in $D^0 \to K\pi$ decays



CLEO,
PRL 84, 5038 (2000),
9.0 fb^{-1}

BABAR,
PRL 91, 171801 (2003),
57.1 fb^{-1}

BELLE,
PRL 94, 071801 (2005)
90 fb^{-1}

BELLE,
PRL 96, 151801 (2006)
400 fb^{-1}

D^0 mixing in $D^0 \to Ke\nu$ decays

Again tag with D^{*+} charge: $D^{*+} \to D^0\pi^+$, $D^0 \to K^-e^+\nu$

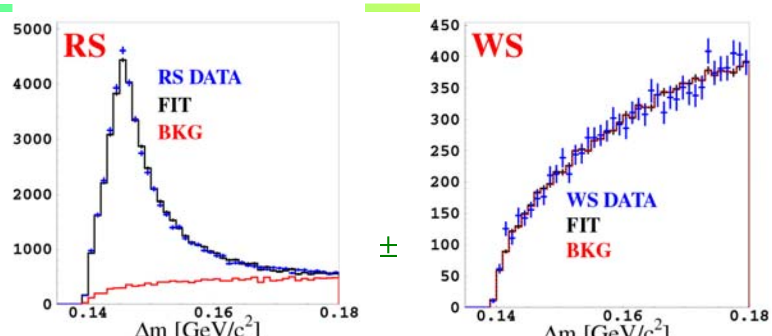
Selection criteria:

- c.m.s. momentum of the Ke system > 2 GeV (bb, combinatorial background)
- Invariant mass of e^-e^+ ($e^+ \to \pi^+$) > 0.15GeV (γ conversions)
- Cut on decay time (backgrounds $\delta(t) + e^{-t}$, signal $t^2 e^{-t}$)

Neutrino reconstruction: hermiticity of the spectrometer, kinematic constraints.

Main observable: $\Delta m = m(\pi_s Ke\nu) - m(Ke\nu)$

D^0 mixing in $D^0 \to Ke\nu$ decays



$m(\pi_s Ke\nu) - m(Ke\nu)$

$N_{RS} = 40198 \pm 329$ $N_{WS} = 19 \pm 67$

$r_D = (N_{WS}/N_{RS})(\varepsilon_{RS}/\varepsilon_{WS}) = (0.20 \pm 0.70)\ 10^{-3}$

$r_D < 1.4\ 10^{-3}$ (90% conf. level)

$r_D = (x^2 + y^2)/2$

D^0 mixing in $D^0 \to Ke\nu$ decays

BaBar: employs neural net techniques to reconstruct the D^0 momentum vector (including again the neutrino), and to reject background events.

Yield: fit to Δm, t distributions.

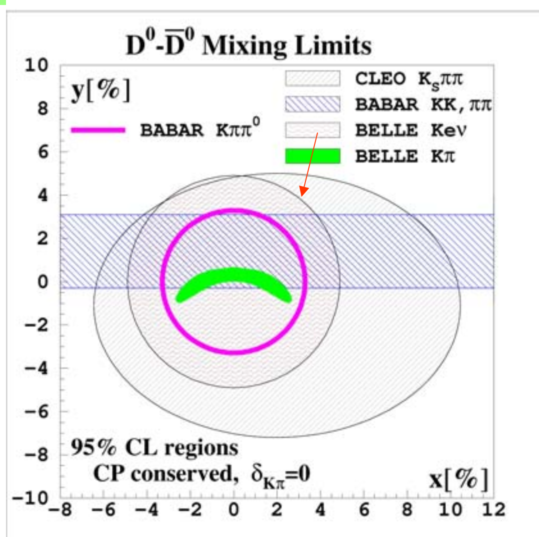
$N_{RS} = 49620 \pm 265$ $N_{WS} = 114 \pm 61$

$r_D = (2.3 \pm 1.2(stat))\, 10^{-3}$

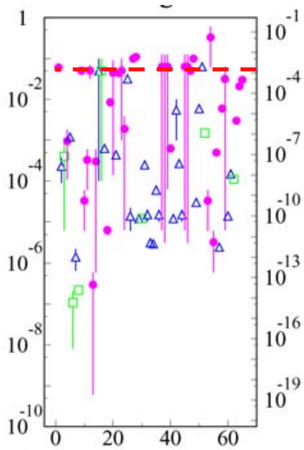
$r_D < 4.2\, 10^{-3}$ (90% conf. level)

D^0 mixing in $D^0 \to Ke\nu$ decays

Comparison to other methods



D^0 mixing in $D^0 \to Ke\nu$ decays



BaBar: $r_D < 4.2\ 10^{-3}$ (90% conf. level)

Belle: $r_D < 1.4\ 10^{-3}$ (90% conf. level)

Theoretical predictions for r_D (right scale)

Backup slides

How about assumptions on CP, CPT violation, $\Delta\Gamma/\Gamma=0$?

B_d oscillations

Belle, dilepton analysis:

$$|B_H\rangle = p|B^0\rangle + q|\overline{B}^0\rangle \qquad \frac{q}{p} = \tan\left(\frac{\theta}{2}\right)e^{i\phi}$$

$$|B_L\rangle = p'|B^0\rangle - q'|\overline{B}^0\rangle \qquad \frac{q'}{p'} = \cot\left(\frac{\theta}{2}\right)e^{i\phi}$$

CP violated if $Im(\phi)\neq 0$

CPT violated if $\theta \neq \pi/2$;

CP violation and $\Delta\Gamma/\Gamma$ small:

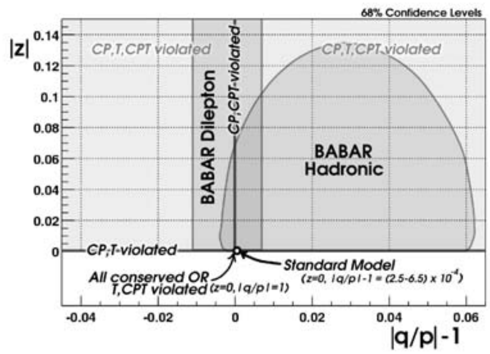
$\mathcal{Re}(\cos\theta)=0.00\pm0.12$

$Im(\cos\theta)=0.03\pm0.03$

BaBar:
fully reconstructed B in flavor or CP eigenstate;
different tagging categories;
multiparameter fit including $|q/p|$, $\Delta\Gamma/\Gamma$, λ_{CP},

$$z = \frac{\delta M - \frac{i}{2}\delta\Gamma}{\frac{1}{2}(\Delta m - \frac{i}{2}\Delta\Gamma)}$$

$z\neq 0$ ↔ ~~CPT~~



(BaBar,hep-ex/0303043(03))

B_d oscillations

BaBar:
general time dependent decay rates of B^0B^0;
CPT violation in mixing:

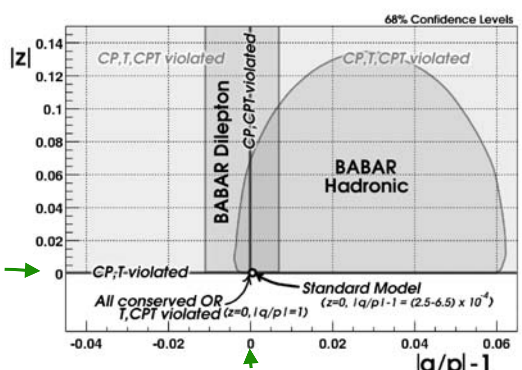
$$z = \frac{\delta M - \frac{i}{2}\delta\Gamma}{\frac{1}{2}(\Delta m - \frac{i}{2}\Delta\Gamma)} \qquad \delta M = \frac{M_{11}-M_{22}}{2} \qquad \delta\Gamma = \frac{\Gamma_{11}-\Gamma_{22}}{2}$$

$z\neq 0$ ↔ ~~CPT~~

fully reconstructed B in flavor or CP eigenstate;
different tagging categories;
multiparameter fit including $|q/p|$, $\Delta\Gamma/\Gamma$, λ_{CP}, z…

(BaBar,hep-ex/0303043(03))

$|z|\neq 0$ ↔ ~~CP~~, ~~CPT~~ →



$|q/p|\neq 1$ ↔ ~~CP~~, ~~T~~