CP violation and related issues

Part 10: Mixing

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Contents

B oscillations

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

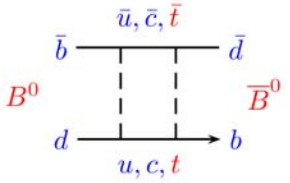
m=mixed, *u*=unmixed

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

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

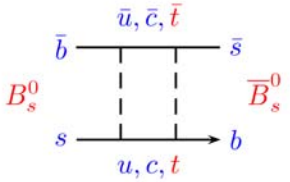
Mixing: estimates

$\Delta m \propto$



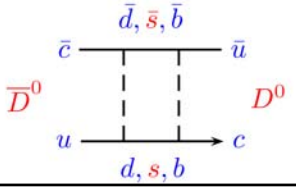
$|V_{tb}^* V_{td}|^2 m_t^2 \propto \lambda^6 m_t^2 \approx 3$

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



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

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



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

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

$B_{d,s}$ 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

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

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

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 Y(4s)

lots of tagging
and reconstruction
methods

B_d oscillations

Examples of analyses:

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

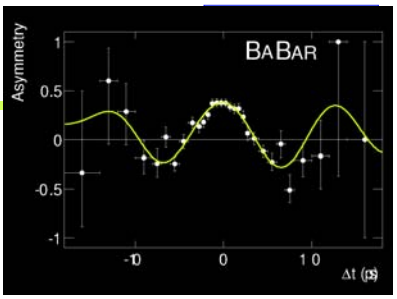
exclusive method, BaBar;
$B^0 \to D^* l \nu$, reconstruct D*;
flavor tagging other side NN;
asymmetry=$(P_u-P_m)/(P_u+P_m)$

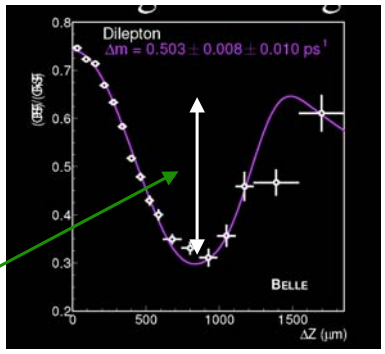
$\Delta m_d = 0.492 \pm 0.018 \pm 0.013$ ps^{-1}
(20fb^{-1})

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

$\Delta m_d = 0.503 \pm 0.008 \pm 0.010$ ps^{-1}
(29fb^{-1})

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





B_d oscillations

Oscillation probability including ΔΓ

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

no assumption of CPT invariance:

$$|B_H\rangle = p|B^0\rangle + q|\bar{B}^0\rangle$$

$$|B_L\rangle = p'|B^0\rangle - q'|\bar{B}^0\rangle$$

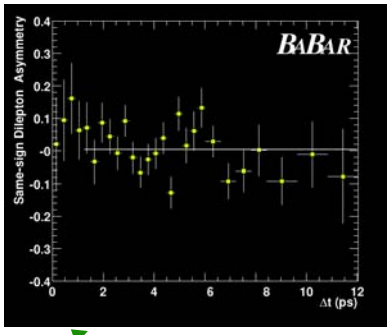
$$\frac{q}{p} = \tan(\frac{\theta}{2})e^{i\phi}$$

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

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:
$|m_{B0}-m_{\bar{B}0}|/m_{B0} < 1.16 \times 10^{-14}$
$|\Gamma_{B0}-\Gamma_{\bar{B}0}|/\Gamma_{B0} < 0.11$
@ 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^+ (π^+ π^+ π^-)

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

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

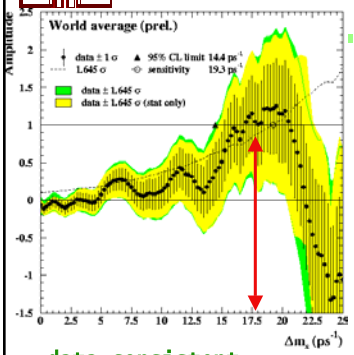
m=mixed, *u*=unmixed

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

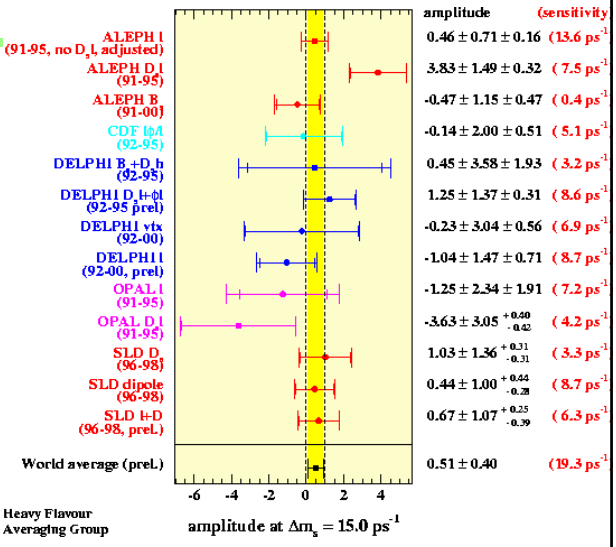
$$P_m = \frac{1}{2}\Gamma_q e^{-\Gamma_q t}\left[1 - A\cos(\Delta m_q t)\right]$$

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

B_s oscillations



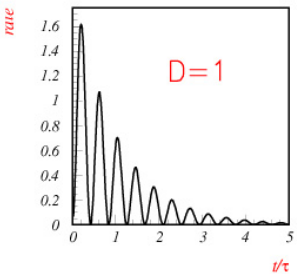
data consistent with oscillations
Δm_s~17.5ps^{-1}
@2.2σ

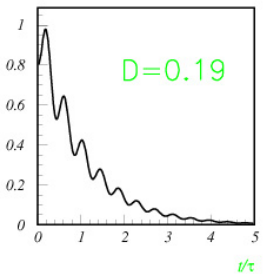


(HFAG,winter'03)

B_s mixing: dilution effects for x_s=15

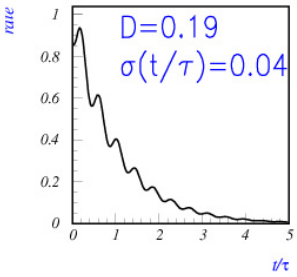
Ideal

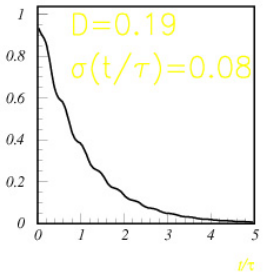




Dilution: Tagging

Dilution: Tagging, Vertex

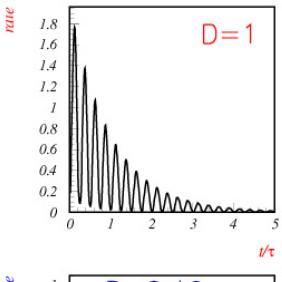


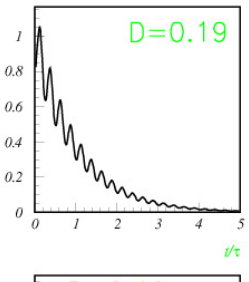


Dilution: Tagging, Vertex

B_s mixing: dilution effects for x_s=25

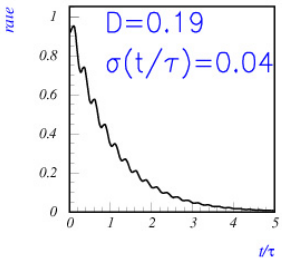
Ideal

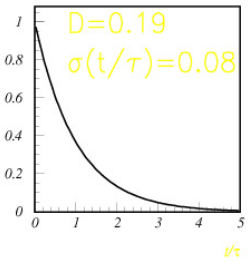




Dilution: Tagging

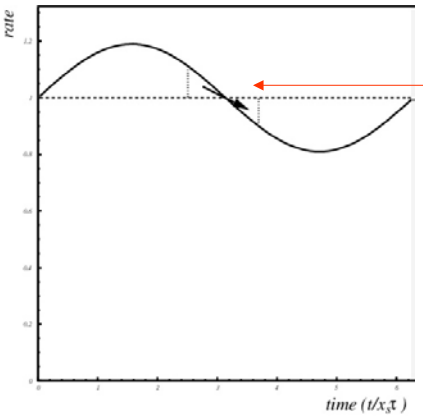
Dilution: Tagging, Vertex





Dilution: Tagging, Vertex

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.

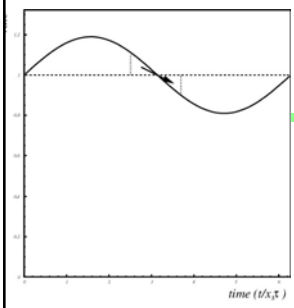
H. G. Moser, A. Roussarie, NIM **A384** (1997)

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.

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

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

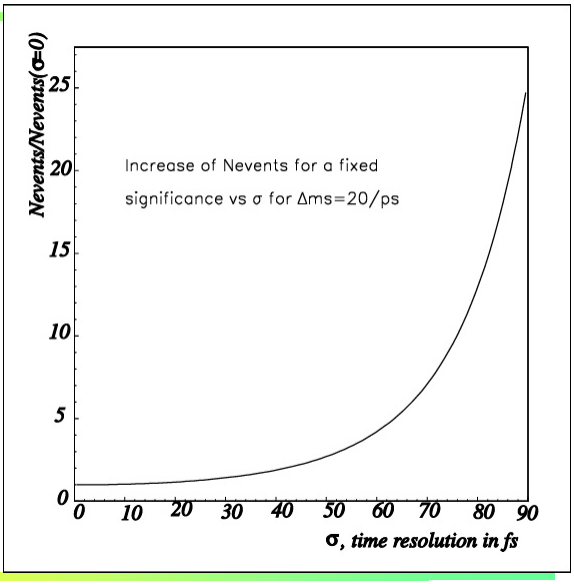
For a given required significance, the number of events needed is proportional to $\exp(+(\Delta m_s\ \sigma_t)^2)$.

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

-> If Δms=20/ps, need σ_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

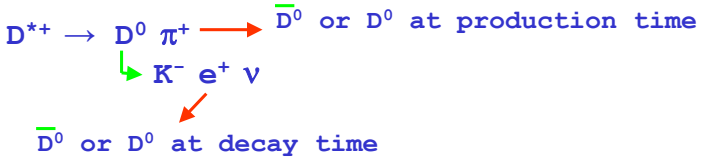
Δm very small, $(\Delta m\ t)<<1$ ->

Time evolution:

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

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^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

$D^0 \to Kp$ time evolution

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

interference mixing

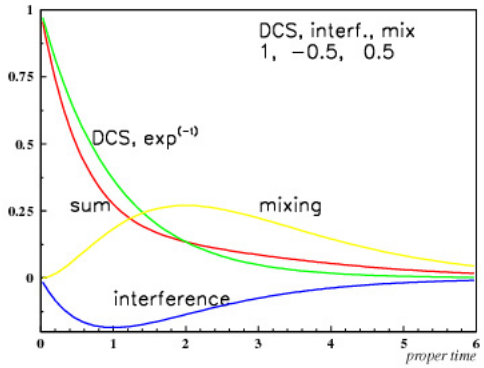
$x' = x \cos\delta + y \sin\delta$

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

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

δ= strong phase difference

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

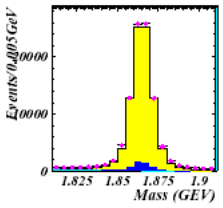


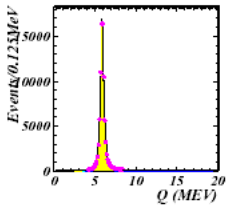
D^0 mixing in $D^0 \to K\pi$ decays

Signal extraction

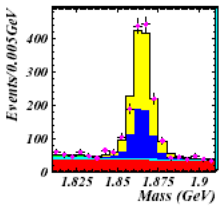
$M = M(K,\pi)$ $\quad$ $Q = M(K^+,\pi^-,\pi_{slow}) - M(K^+,\pi^-) - M_\pi$

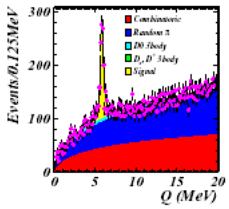
Right-Sign





Wrong-Sign





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

Free fit

$R_D = (0.287 \pm 0.037)\%$,

$y' = (2.54^{+1.11}_{-1.02})\%$,

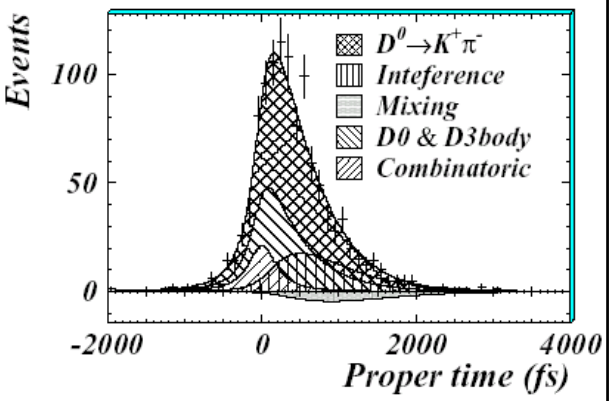
$x'^2 = -(0.153^{+0.08}_{-0.10})\%$

Physical region

$R = (0.343^{+0.027}_{-0.026})\%$,

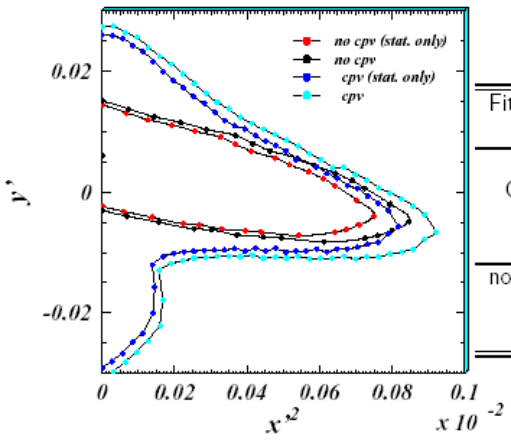
$y' = (0.60 \pm 0.33)\%$,

$x'^2 = 0\%$



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

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

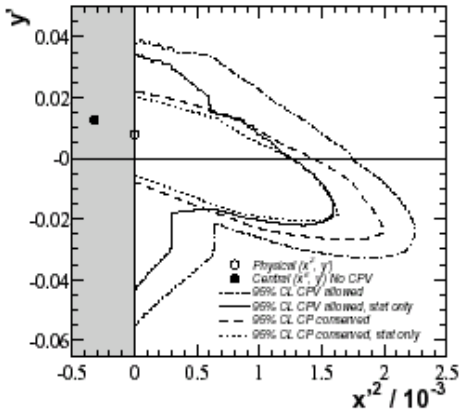


Fit case	Parameter	95% C.L. interval ($\times 10^{-3}$)
CPV	A_D	$-250 < A_D < 110$
	A_M	$-991 < A_M < 1000$
	x'^2	$x'^2 < 0.89$
	y'	$-30 < y' < 27$
no CPV	x'^2	$x'^2 < 0.81$
	y'	$-8.2 < y' < 16$
	R_D	$2.7 < R_D < 4.0$

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 $D^0 \to Ke\nu$ decays

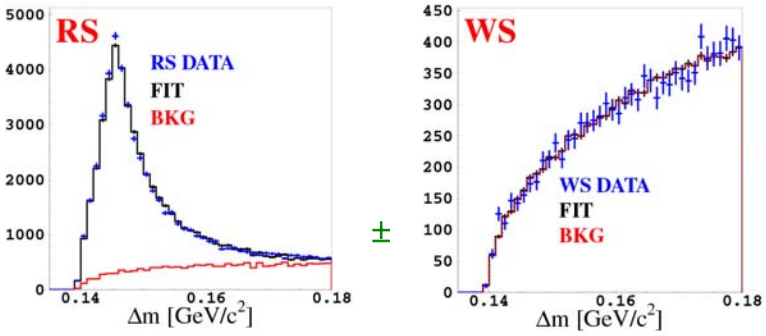
Selection criteria:

- c.m.s. momentum of the Ke system > 2 GeV (bb, combinatorial background)
- Invariant mass of e^-e^+ ($e^+ \to p^+$) > 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



$\pm$

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

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

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

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

D^0 mixing in $D^0 \to K e \nu$ decays

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

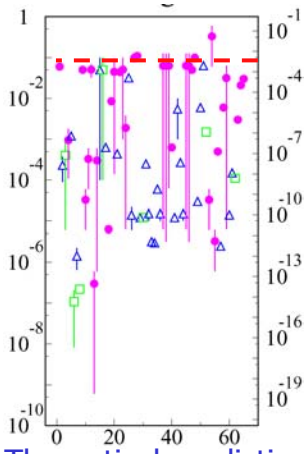
Yield: fit to Δm, t distributions.

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

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

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

D^0 mixing in $D^0 \to K e \nu$ 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

B_d oscillations

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

Belle, dilepton analysis:

$$|B_H> = p|B^0> + q|\bar{B}^0> \qquad \frac{q}{p} = \tan(\frac{\theta}{2})e^{i\phi}$$

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

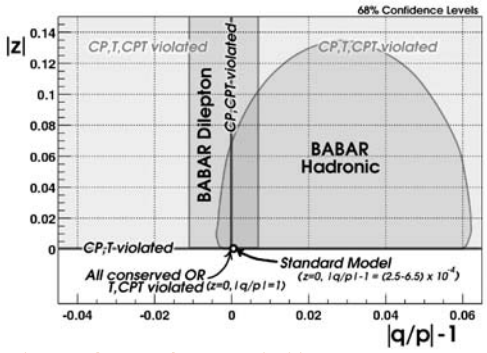
CP violated if $Im(\phi)\neq 0$

CPT violated if $\theta \neq \pi/2$;
CP violation and $\Delta\Gamma/\Gamma$ small:
$Re(\cos\theta)=0.00\pm0.12$
$Im(\cos\theta)=0.03\pm0.03$

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

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

$z\neq 0 \leftrightarrow$ CPT



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

B_d oscillations

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

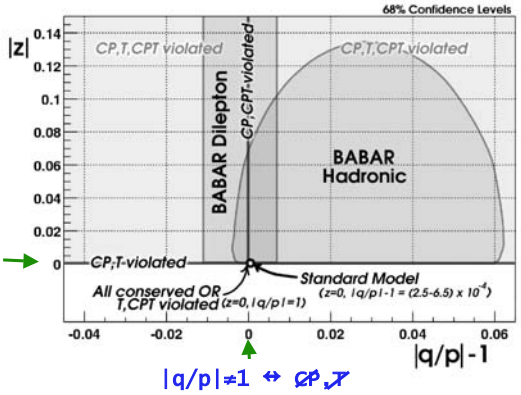
$$z = \frac{\delta M - \frac{i}{2}\delta\Gamma}{\frac{1}{2}(\Delta m - \frac{i}{2}\Delta\Gamma)} \qquad \delta M = \frac{M_{11} - M_{22}}{2} \qquad \delta\Gamma = \frac{\Gamma_{11} - \Gamma_{22}}{2}$$

$z \neq 0 \leftrightarrow$ 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))

$|z| \neq 0 \leftrightarrow$ CP,CPT



$|q/p| \neq 1 \leftrightarrow$ CP,T