B Mixing, Lifetimes, Lifetime Differences and CP/T/CPT Violation at the B factories

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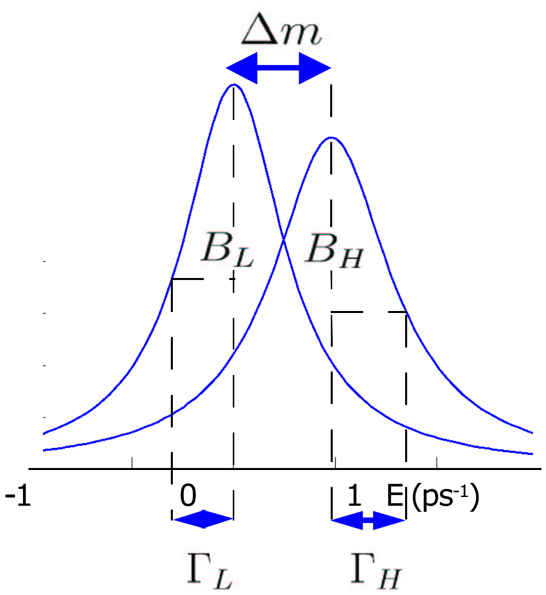
Flavor mixing in the B_d system

Mass states B_L, B_H superposition of B^0 and $\overline{B}^0$ flavor states:

$$\begin{aligned} |B_L\rangle &= p|B^0\rangle + q|\overline{B}^0\rangle \\ |B_H\rangle &= p|B^0\rangle - q|\overline{B}^0\rangle \end{aligned}$$

If CPT holds



Oscillation frequency $\Delta m = m_H - m_L \approx 0.5\ \text{ps}^{-1}$

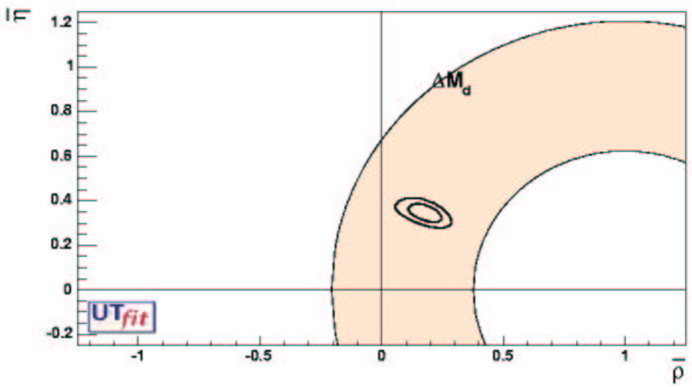
Average lifetime $1/\Gamma \approx 1.6$ ps

Lifetime difference $\Delta\Gamma = \Gamma_H - \Gamma_L \ll \Gamma$

Δm, Γ, ΔΓ

Oscillation Frequency Δm

Related to CKM matrix elements but



$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2 \eta_b S(x_t) m_{B_d} f_{B_d}^2 \hat{B}_{B_d} |V_{tb}|^2 |V_{td}|^2 =$$

$$= \frac{G_F^2}{6\pi^2} m_W^2 \eta_b S(x_t) m_{B_d} \underbrace{f_{B_d}^2 \hat{B}_{B_d}}_{\text{Not well known}} |V_{cb}|^2 \lambda^2 ((1-\bar{\rho})^2 + \bar{\eta}^2)$$

Not well known

Lifetime

Lifetime ratios of hadrons with beauty can be computed “from first principles”
Experiments provide important test of HQE

Lifetime difference ΔΓ

Standard Model: small $\frac{\Delta\Gamma}{\Gamma} \approx -0.3\%$

Usually assumed to be 0

CP,T,CPT violation in $B^0\overline{B}^0$ mixing

CPT violation

$$\mathrm{Prob}\,(B^0 \to B^0, t) \neq \mathrm{Prob}\,(\overline{B}^0 \to \overline{B}^0, t)$$ ➡ **CP** and **CPT** violation

Violated in mixing if $z \equiv 2\,\dfrac{\delta M - (i/2)\delta\Gamma}{\Delta m - (i/2)\Delta\Gamma} \neq 0$

$$2\,\delta M \equiv M_{11} - M_{22}$$
$$2\,\delta\Gamma \equiv \Gamma_{11} - \Gamma_{22}$$

Locality $\Rightarrow$ CPT invariance **Standard Model : 0**

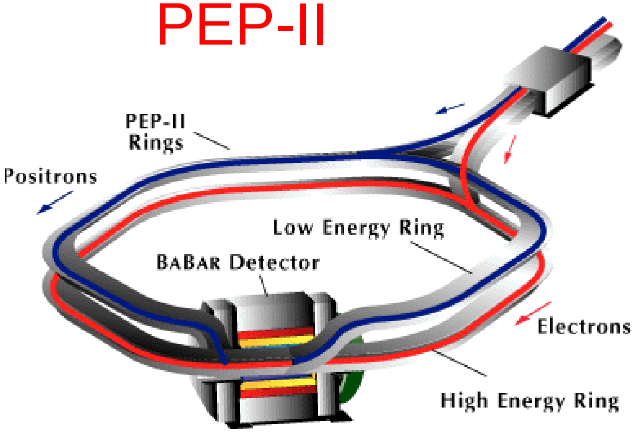
CP/T violation

$$\mathrm{Prob}\,(B^0 \to \overline{B}^0, t) \neq \mathrm{Prob}\,(\overline{B}^0 \to B^0, t)$$ ➡ **CP** and **T** violation

Violated in mixing if $\left|\dfrac{q}{p}\right| \neq 1$

Standard Model: small $\left|\dfrac{q}{p}\right| - 1 \approx 5 \times 10^{-4}$

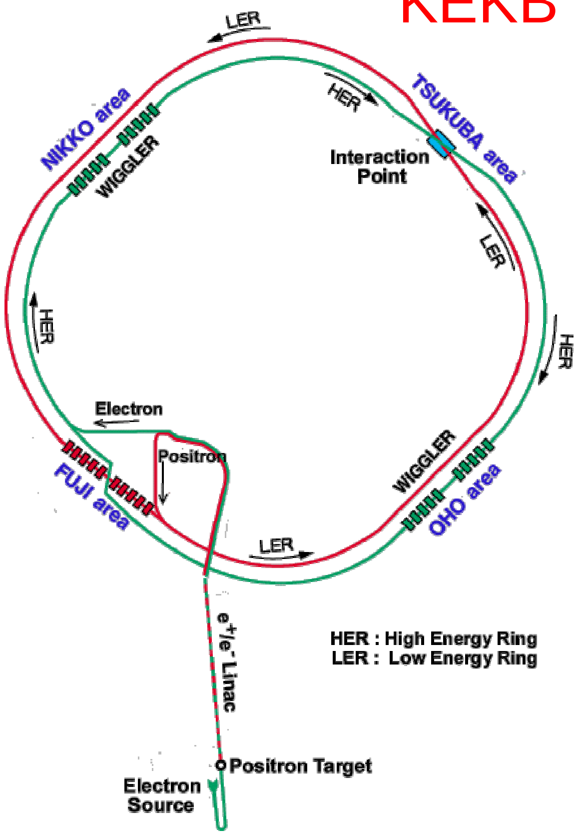
PEP-II



9 GeV $e^{-} \times$ 3.1 GeV e^{+}

Y(4S) boost $\beta\gamma = 0.55$

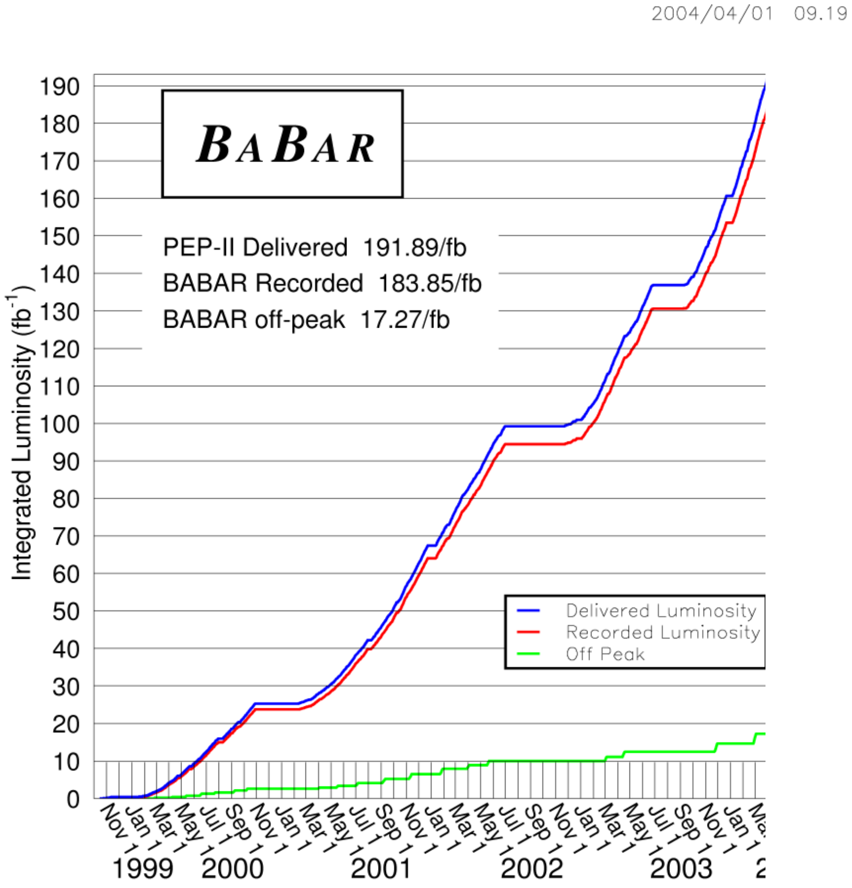
KEKB

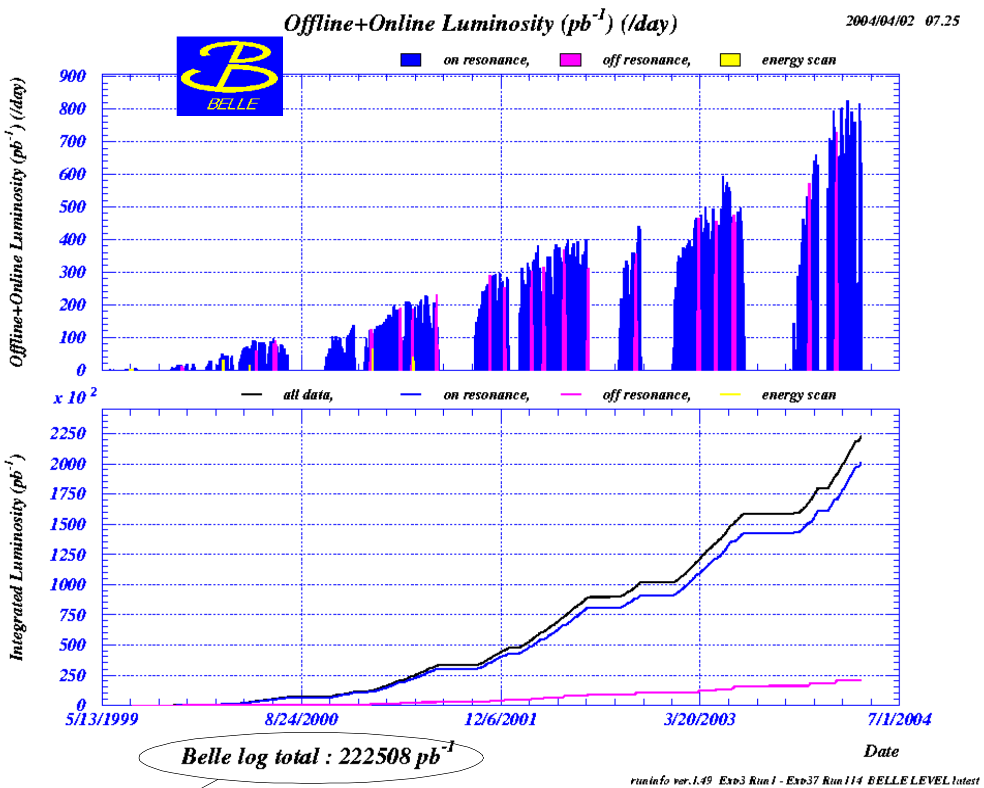


8 GeV $e^{-} \times$ 3.5 GeV e^{+}

Y(4S) boost $\beta\gamma = 0.43$

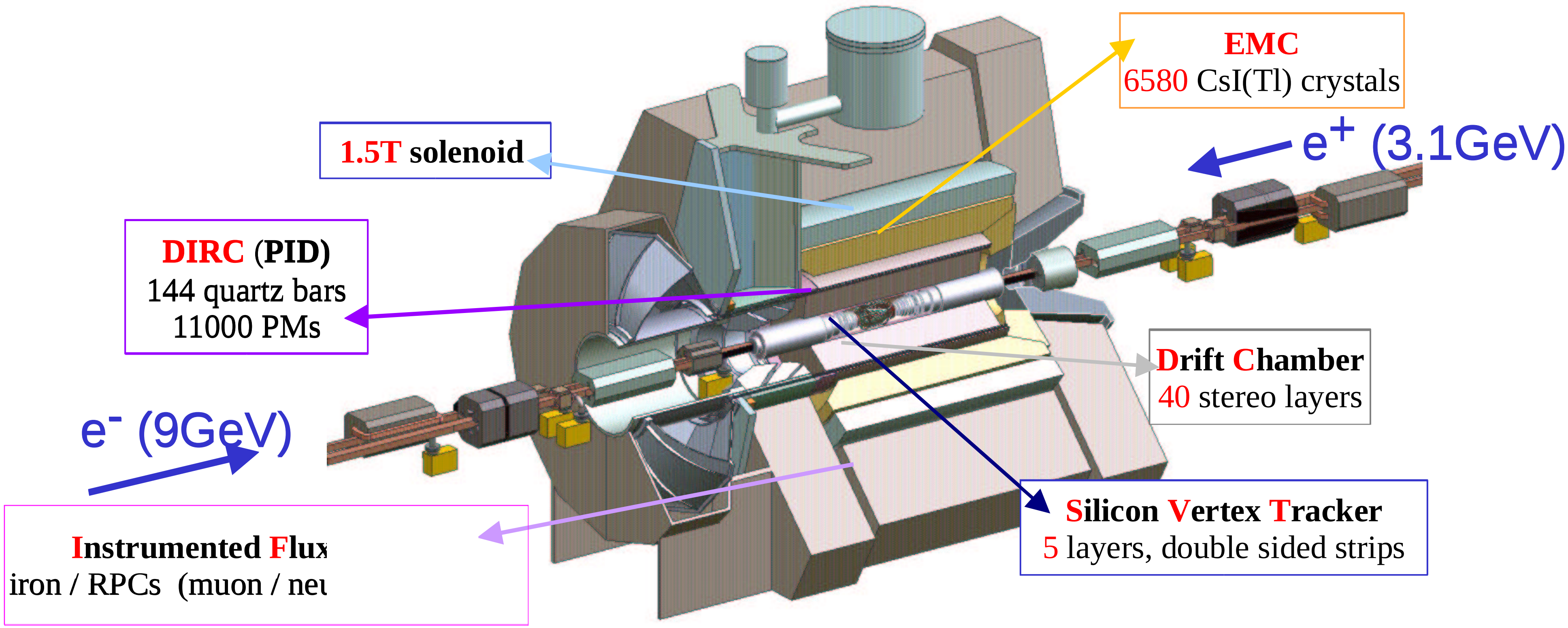
B factories, achieved luminosities



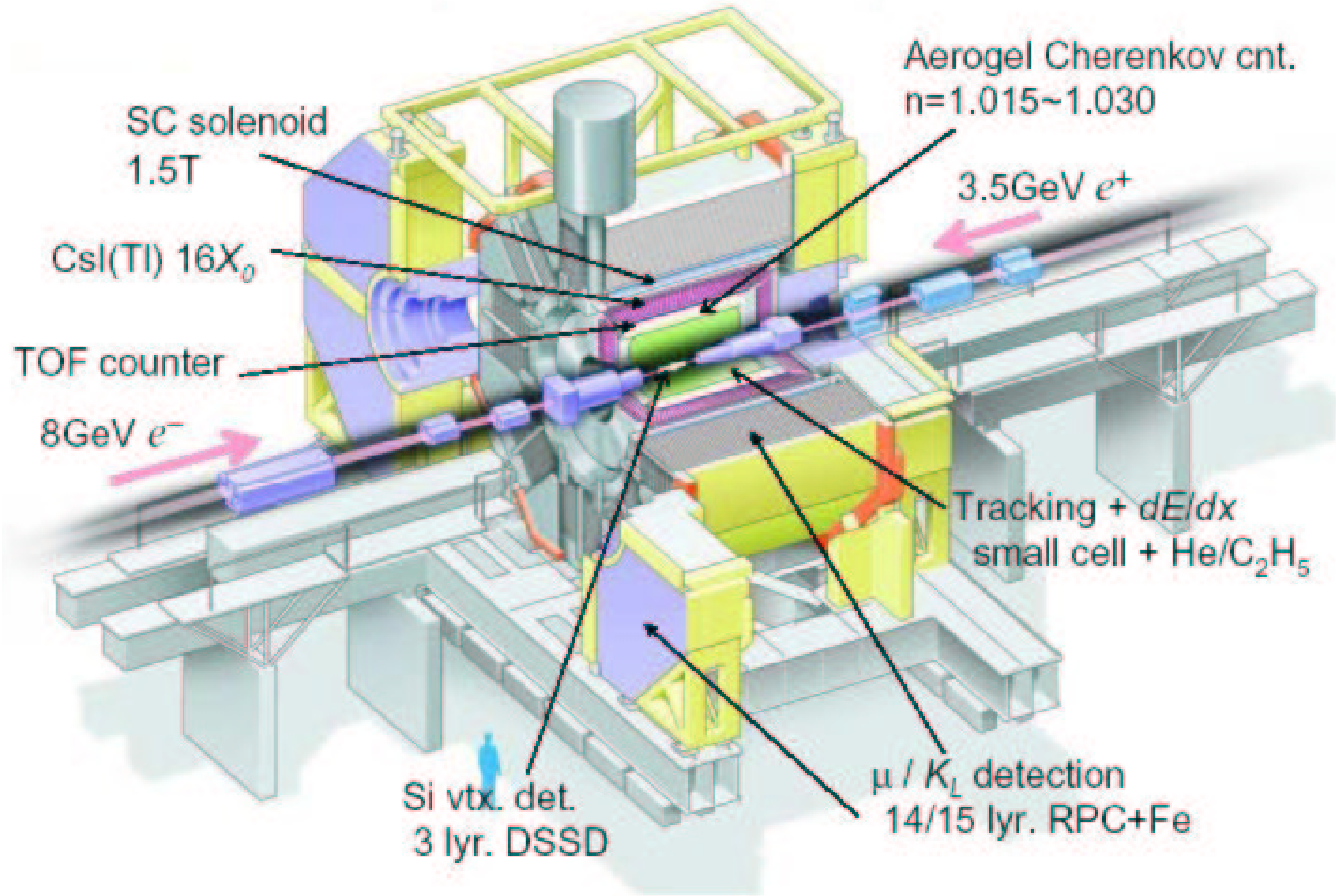


> 200 fb^{-1}

B factories, detectors: BaBar



B factories, detectors: Belle



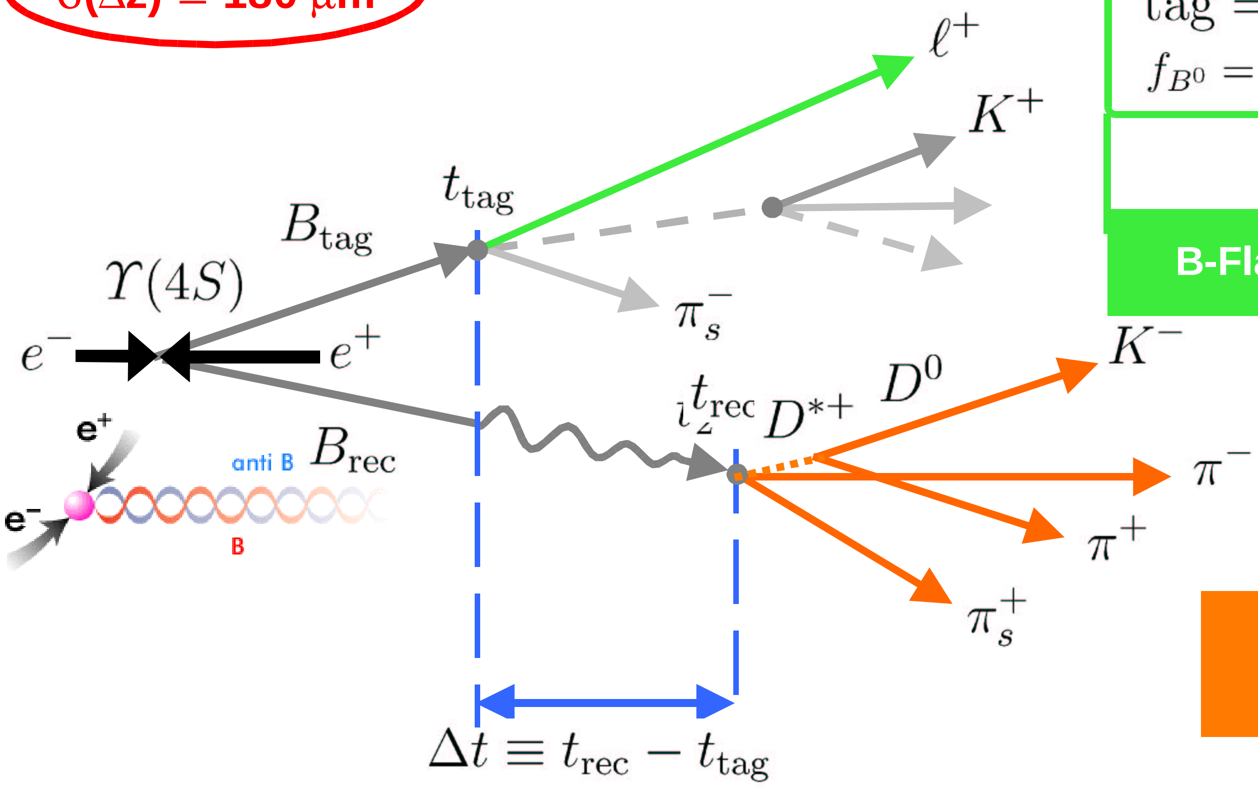
Coherent Time Evolution at the Υ(4S)

$\sigma(\Delta z) \cong 180\ \mu m$

$\mathrm{tag} = B^0,\ \overline{B}^0$

$f_{B^0} = X\ell^+\nu,\ XK^+,\ X\pi_s^-, \ldots$

B-Flavor Tagging



Exclusive B Meson Reconstruction

$\Delta t \approx \Delta z / c \langle \beta\gamma \rangle_{\Upsilon(4S)}$

$\langle|\Delta z|\rangle_{B\bar{B}} \approx 260\ \mu m$

$\langle|\Delta t|\rangle_{B\bar{B}} \approx 1.5\ \mathrm{ps}^-$

Vertexing & Time Difference Determination

$\mathrm{rec} = \mathrm{flav},\ \overline{\mathrm{flav}},\ CP$

$f_{\mathrm{flav}} = D^{*-}\pi^+, \ldots$

$f_{CP} = J/\psi\, K_S^0,\ J/\psi\, K_L^0, \ldots$

Belle; $\Delta z = 200\ \mu m$

Time dependent B decay rates: naïve mixing picture

Differential event rate, as a function of the difference between the proper decay times of the two B mesons in the final state

$\Delta\Gamma$ = 0, no CP/T/CPT violation

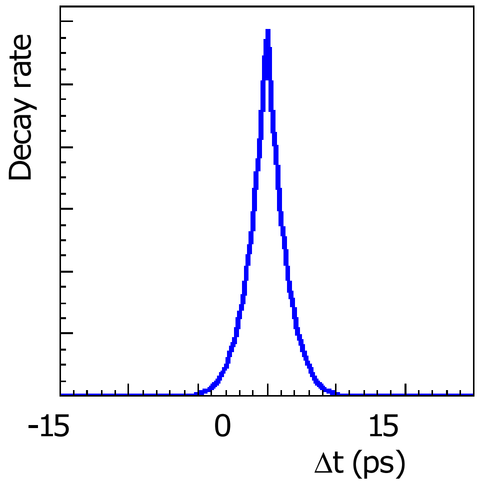
$$\frac{d}{d\Delta t}\mathcal{N}(\Upsilon(4S) \to B\overline{B} \to f_{\rm tag}, f_{\rm rec}) \propto \frac{1}{\Gamma}\, e^{-\Gamma|\Delta t|} \left\{ 1 \pm \cos(\Delta m\, \Delta t) \right\}$$

Exp. Decay

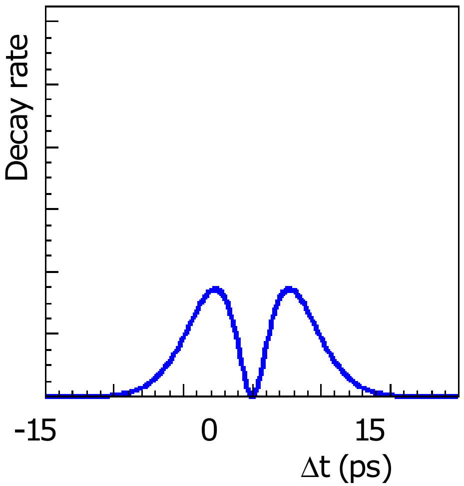
Oscillations with frequency Δm

Decay time distributions

$f_{tag} \neq f_{rec}$ (unmixed)

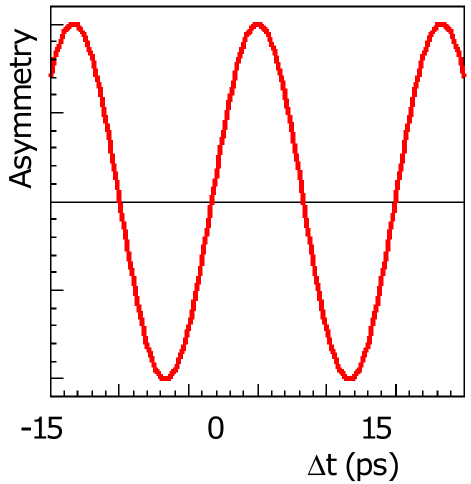


$f_{tag} = f_{rec}$ (mixed)



Mixed - Unmixed

Mixed +Unmixed



$B^0\bar{B}^0$ mixing with fully reconstructed hadronic events – BaBar

Fully reconstructed $B^0 \to D^{(*)-}\pi^+/\rho^+/a_1^+, J/\psi K^{*0}$

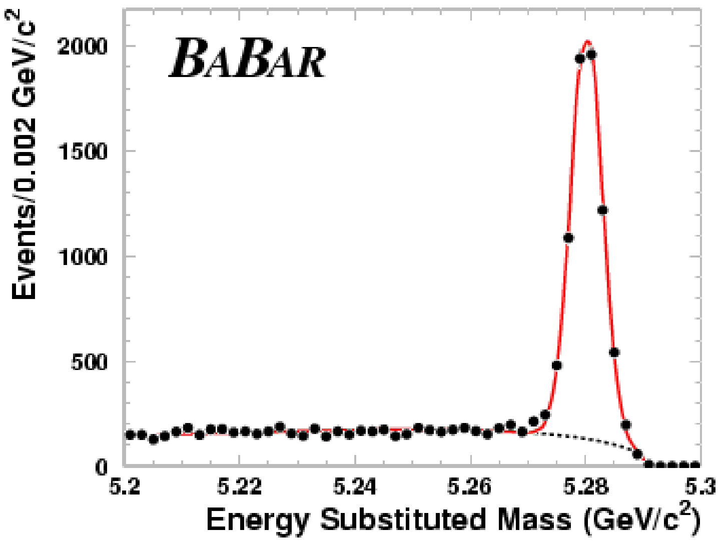
$\Delta E = E^*_B - \sqrt{s}/2$

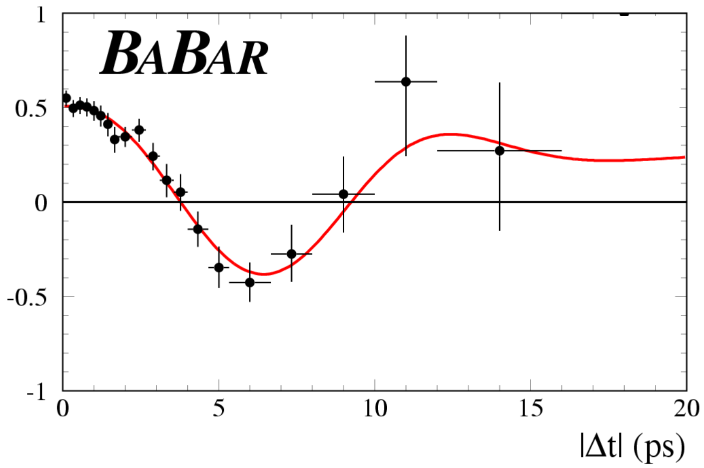
$m_{ES} = \sqrt{(s/4 - p^{*2}_B)}$

Other side tagged using
flavor tagging algorithm (neural network)

Larger systematics associated with:

- Δt resolution function
- τ^0 lifetime





30 fb^{-1}

$\Delta m_d = 0.516 \pm 0.016 \pm 0.010$ ps^{-1}

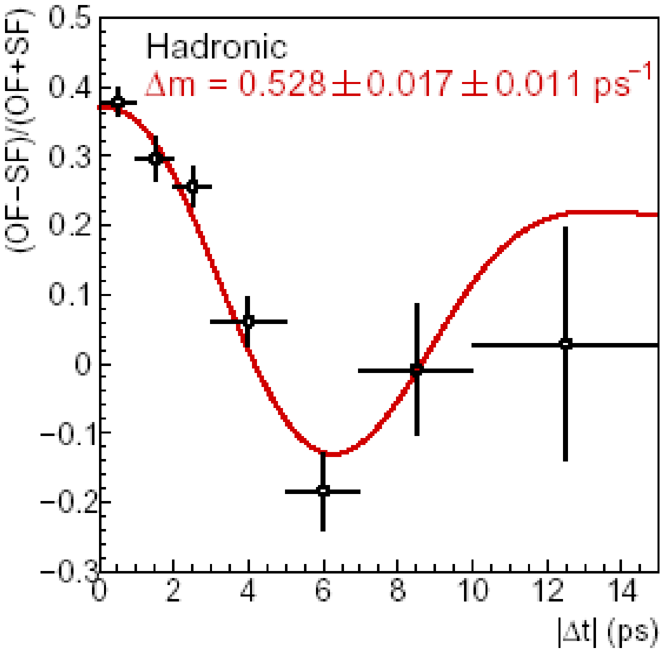
PRL 88[2002]

$B^0\bar{B}^0$ mixing with fully reconstructed hadronic events – Belle

Fully reconstructed $B^0 \to D^{(*)-}\pi^+/\rho^+$

use of same variables ΔE and m_{ES}

Other side tagged using flavor tagging algorithm (multidimensional likelihood)



Larger systematics associated with:

- Δt resolution function
- Fit bias

29 fb^{-1}

$\Delta m_d = 0.528 \pm 0.017 \pm 0.011 ps^{-1}$

PL B 542 [2002]

$B^0\bar{B}^0$ mixing with partially reconstructed $D^*\pi$ - Belle

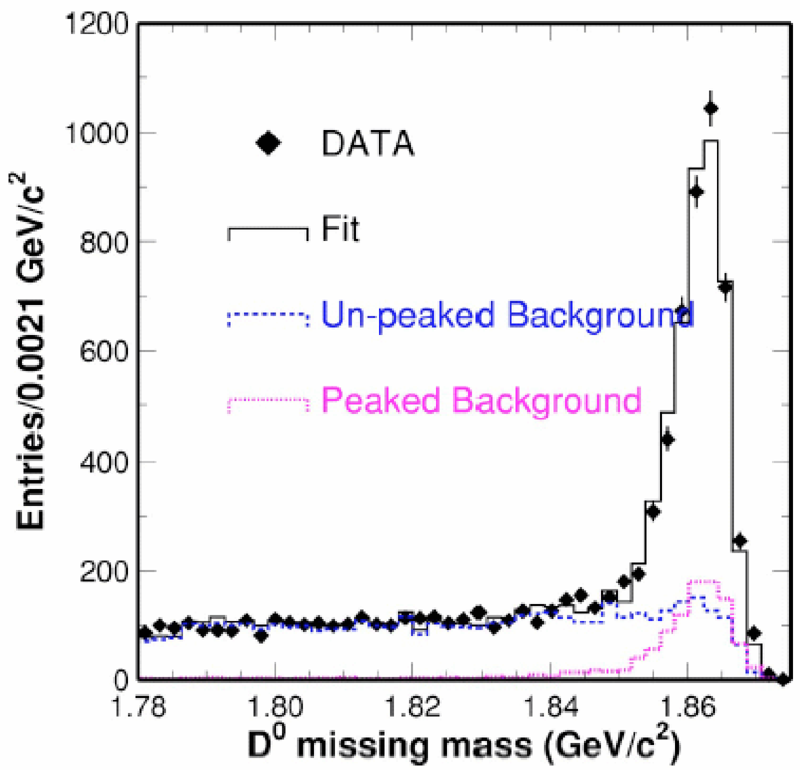
Partial reconstruction method:

D^{*-} information from the soft π of $D^{*-} \rightarrow \bar{D}^0\pi^-$

D^{*-} combined with fast π from $B \rightarrow D^*\pi$ and beam information

high momentum lepton on the tag side

contribution of various backgrounds from the D^0 missing mass



Larger systematics associated with:

- Δt resolution function
- Background fraction

29 fb^{-1}

$\Delta m_d = 0.509 \pm 0.017 \pm 0.020\ ps^{-1}$

PRD 67[2003]

$B^0\bar{B}^0$ mixing with D*lν - BaBar

Reconstruction of $B^0 \to D^*l\nu$

with $D^{*-} \to \bar{D}^0\pi^-$ and $\bar{D}^0 \to K^+\pi^-, K^+\pi^-\pi^0, K^+\pi^-\pi^+\pi^-, K_s\pi^+\pi^-$

Simultaneus measurement of Δm_d and lifetime !

Combine with lepton candidate (p* > 1.2 GeV)

Require consistency of kinematics (angles, missing ν)

Other side tagged using flavor tagging algorithm (neural network)

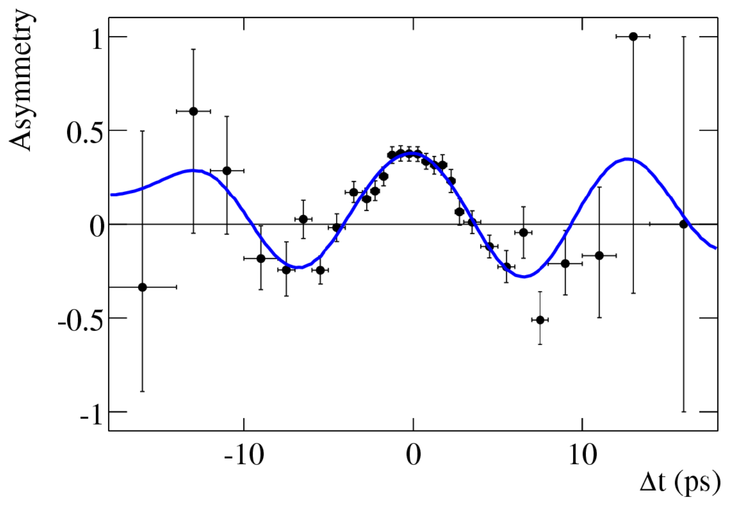
Larger systematics associated with:

- Background modeling and fit bias

20 fb^{-1}

Δm_d=0.492±0.018±0.013 ps^{-1}

PRD 67[2003]



Reconstruction of $B^0 \to D^*l\nu$
with $D^{*-} \to \bar{D}^0\pi^-$
and $\bar{D}^0 \to K^+\pi^-, K^+\pi^-\pi^0, K^+\pi^-\pi^+\pi^-$

similar analysis, but no lifetime fit

Other side tagged using flavor tagging algorithm (multidimensional likelihood)

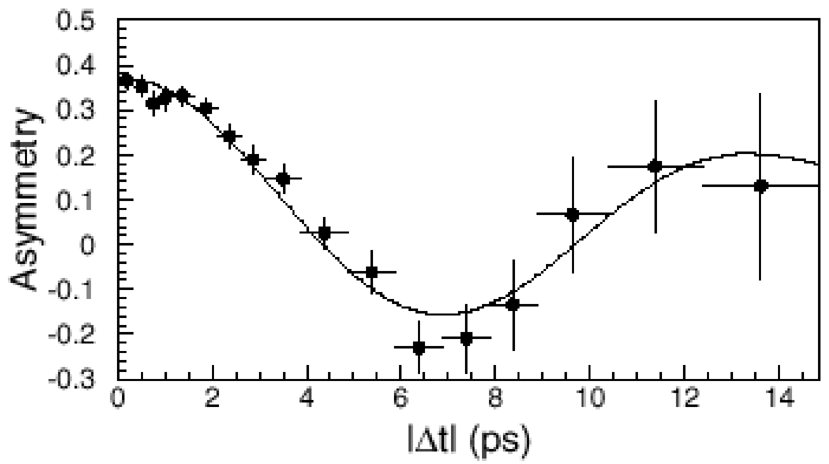
Larger systematics associated with:

- Δt resolution and range
- Background

29 fb^{-1}

$\Delta m_d = 0.494 \pm 0.012 \pm 0.015\ ps^{-1}$

PRL 89[2002]



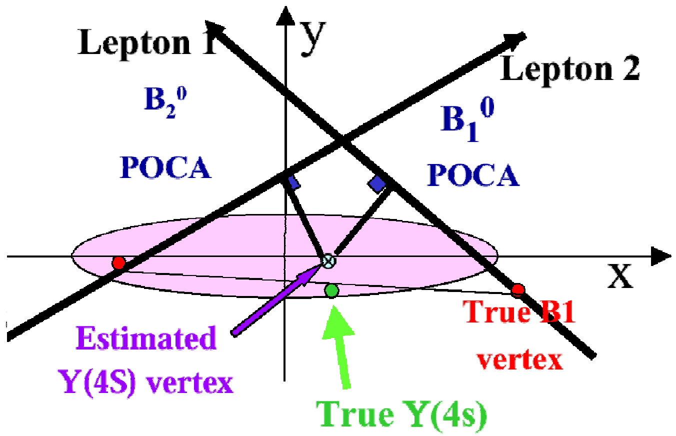
$B^0\bar{B}^0$ mixing with inclusive dilepton events - BaBar

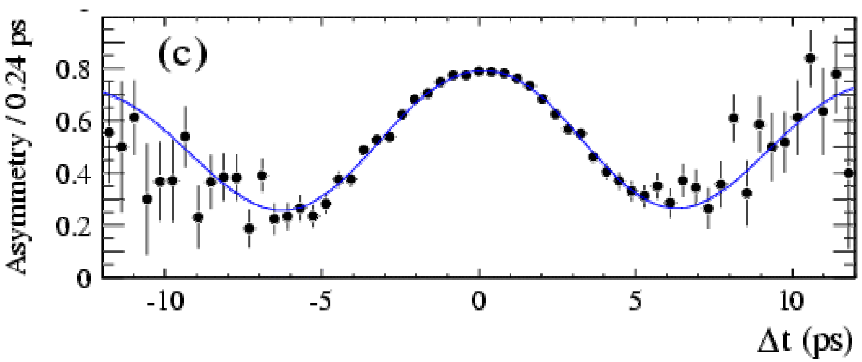
Events with 2 high momentum leptons
high statistics but charged B background

B flavor tagged by the lepton sign
Charm decay background

Decay vertex from lepton tacks – IP

Larger systematics associated with:
- B lifetimes
- Δt resolution





20 fb^{-1}

$\Delta m_d = 0.493 \pm 0.012 \pm 0.009$ ps^{-1}

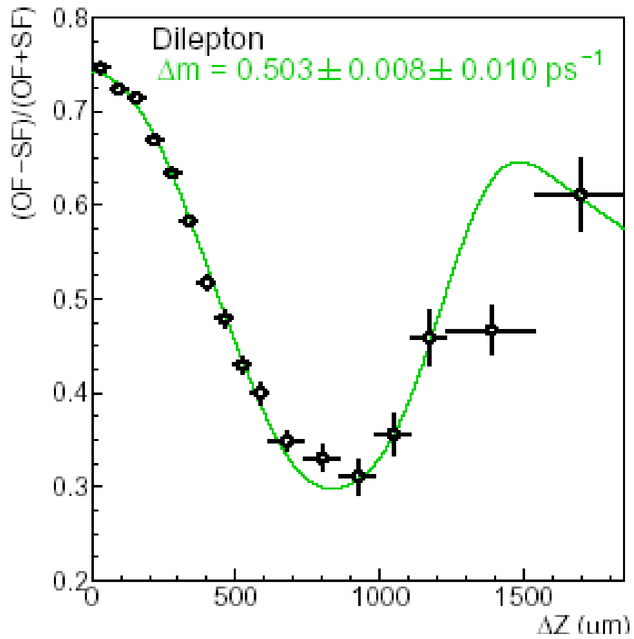
PRL 88[2002]

$B^0\bar{B}^0$ mixing with inclusive dilepton events - Belle

Events with 2 high momentum leptons

Similar analysis + limits on CPT violation parameters in mixing

Larger systematics associated with:
- B lifetimes
- Detector response



Most precise single measurement !

$\sigma_{syst} > \sigma_{stat}$

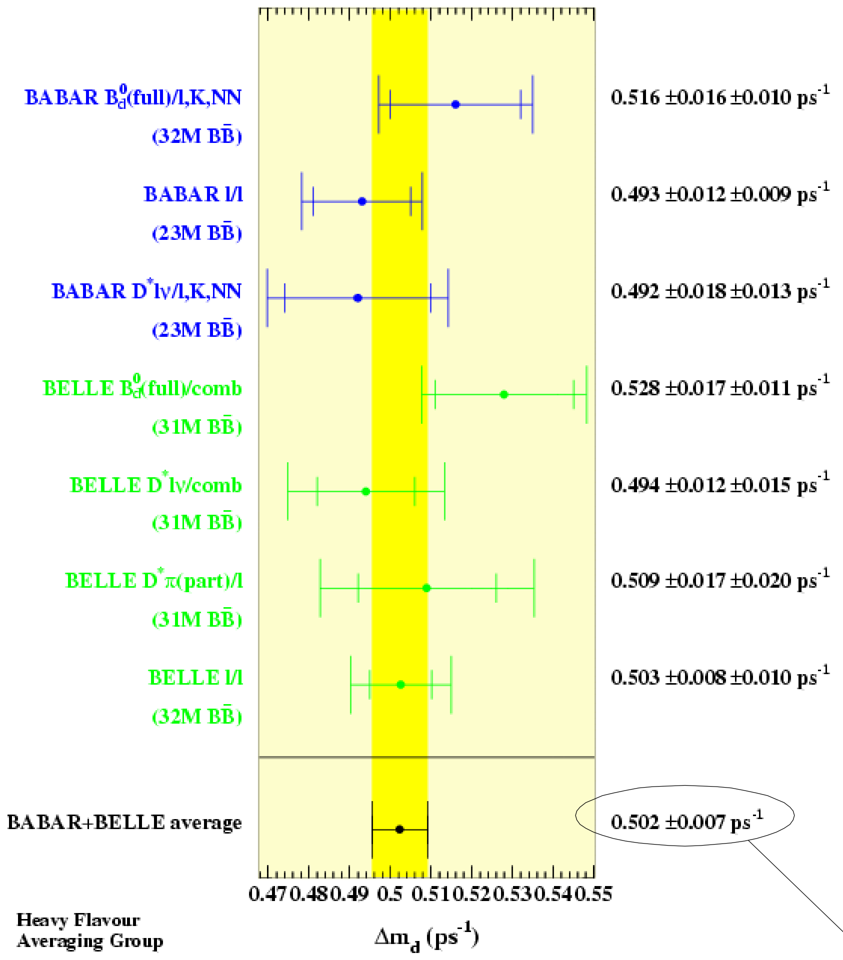
29 fb^{-1}

$\Delta m_d = 0.503 \pm 0.008 \pm 0.010\ ps^{-1}$

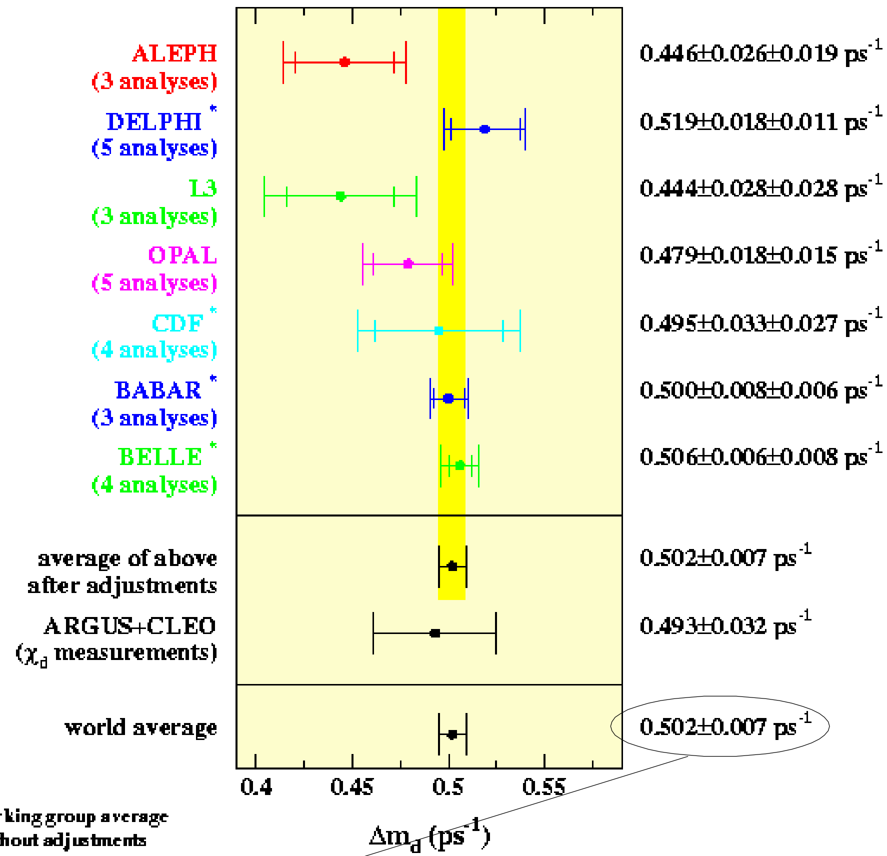
PR D 67[2003]

$B^0\bar{B}^0$ mixing

Δm_d at the B factories



Δm_d , all experiments

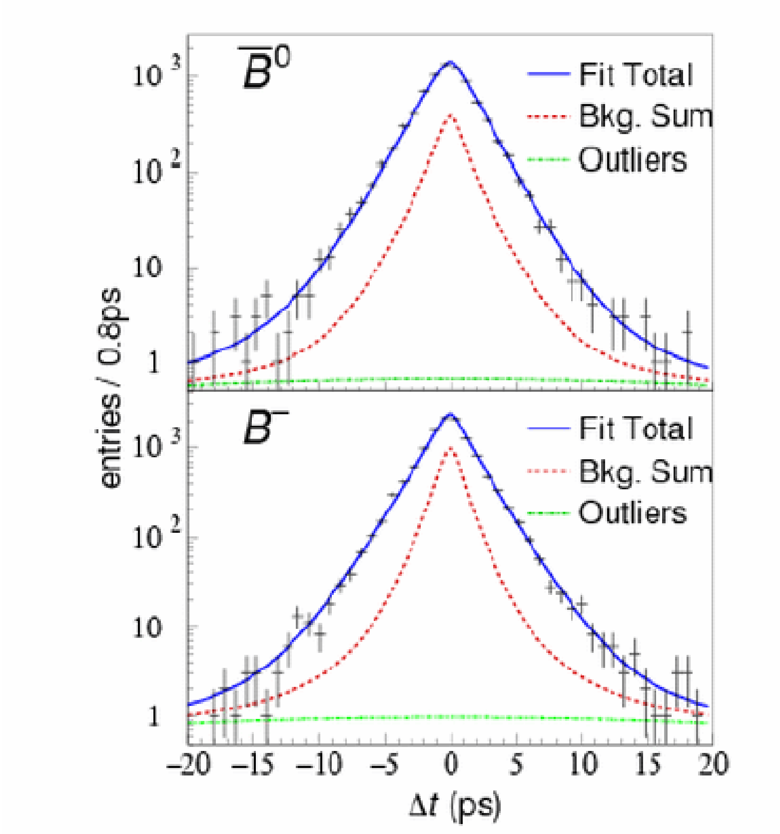


B factories average **0.502±0.007** world average

B^0 and B^+ lifetimes with fully reconstructed hadronic events – Belle

Fully reconstructed $B^0 \to D^{(*)-}\pi^+/\rho^+/a_1^+, J/\psi K_s, J/\psi K^{*0}$

$B^+ \to \overline{D}^0\pi^+, J/\psi K^+$



Larger systematics associated with:

- Background shape
- MC statistics
- Δt resolution (cancels in ratio)

29 fb^{-1}

PRL 88[2002]

τ^0 =1.554±0.030±0.019 ps

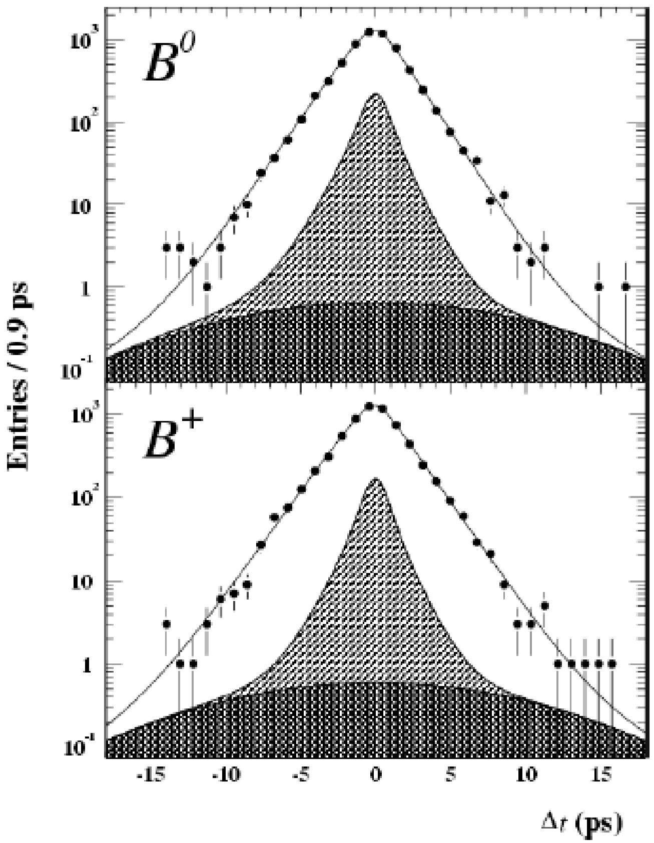
τ^+ =1.695±0.026±0.015 ps

τ^+/τ^0 =1.091±0.023±0.014

B^0 and B^+ lifetimes with fully reconstructed hadronic events – BaBar

Fully reconstructed $B^0 \to D^{(*)-}\pi^+/\rho^+/a_1^+$, $J/\psi K_s$, $J/\psi K^{*0}$

$B^+ \to \overline{D}^0\pi^+$, $J/\psi K^+$, $\psi(2S)K^+$



Larger systematics associated with:

- Background shape
- MC statistics
- Δt resolution

20 fb^{-1}

PRL 87[2001]

$\tau^0 = 1.546 \pm 0.032 \pm 0.022$ ps

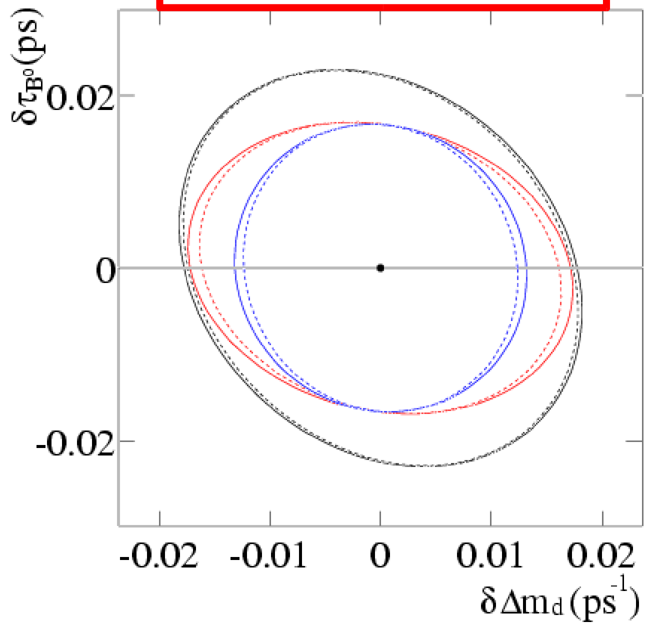
$\tau^+ = 1.673 \pm 0.032 \pm 0.023$ ps

$\tau^+/\tau^0 = 1.082 \pm 0.026 \pm 0.012$

Reconstruction of $B^0 \to D^* l \nu$
with $D^{*-} \to \overline{D}^0 \pi^-$ and
$\overline{D}^0 \to K^+\pi^-, K^+\pi^-\pi^0, K^+\pi^-\pi^+\pi^-, K_s\pi^+\pi^-$

Larger systematics associated with:
- Background modeling and fit bias

Simultaneus measurement of Δm_d and lifetime !



20 fb^{-1}

$\tau^0 = 1.523 \pm 0.024 \pm 0.022$ ps

PR D 67[2003]

B^0 lifetime with partially reconstructed $B^0 \to D^{*-} l^+ \nu$ - BaBar

$B^0 \to D^{*-} l^+ \nu$ with $D^{*-} \to D^0 \pi^-$
Reconstruct lepton and soft π only

$p_{D^*} = \alpha p_\pi + \beta$

π in a small cone around D* direction,

α and β from simulation

$M^2_\nu = (p_{B^0} - p_{D^*} - p_l)^2 \approx 0$

Missing neutrino

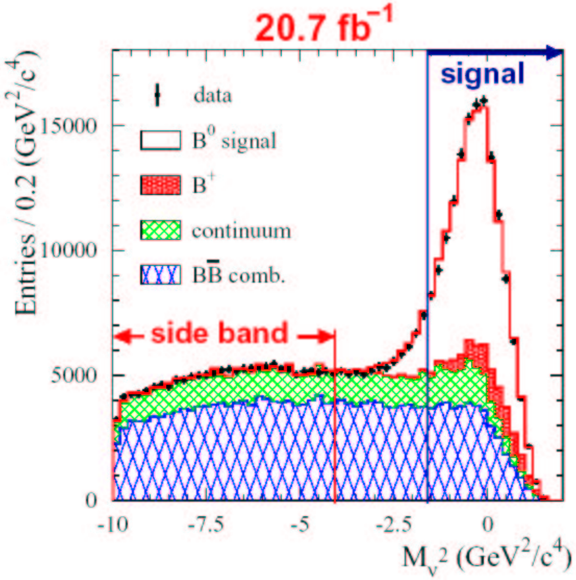
Larger systematics associated with:

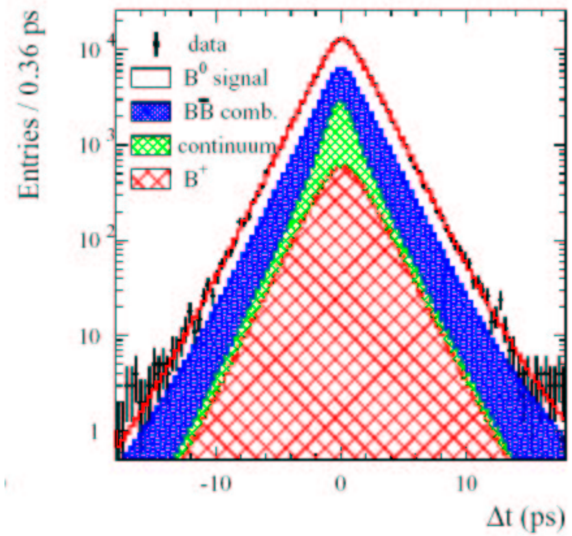
- Δt resolution
- D^0 track bias

21 fb^{-1}

$\tau^0 = 1.529 \pm 0.012 \pm 0.029$ ps

PRL 89[2002]





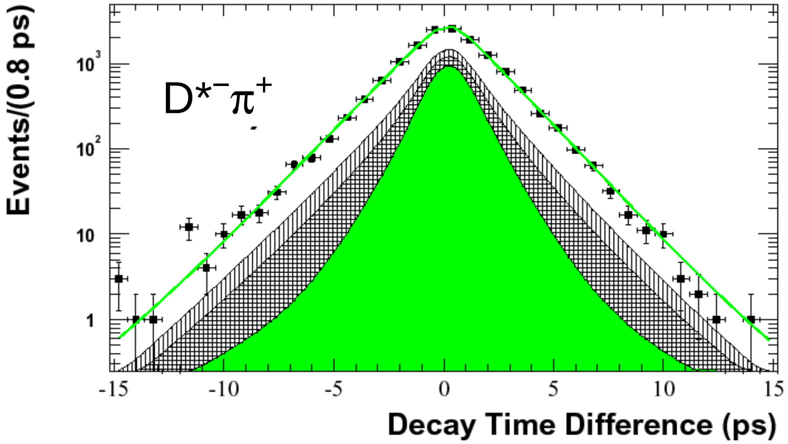
Other lifetime measurements in BaBar

Partially reconstructed $B^0 \to D^{*-}\pi^+$ and $B^0 \to D^{*-}\rho^+$

21 fb^{-1}

τ^0 = 1.533 ±0.034 ±0.038 ps

PRD 67[2003]



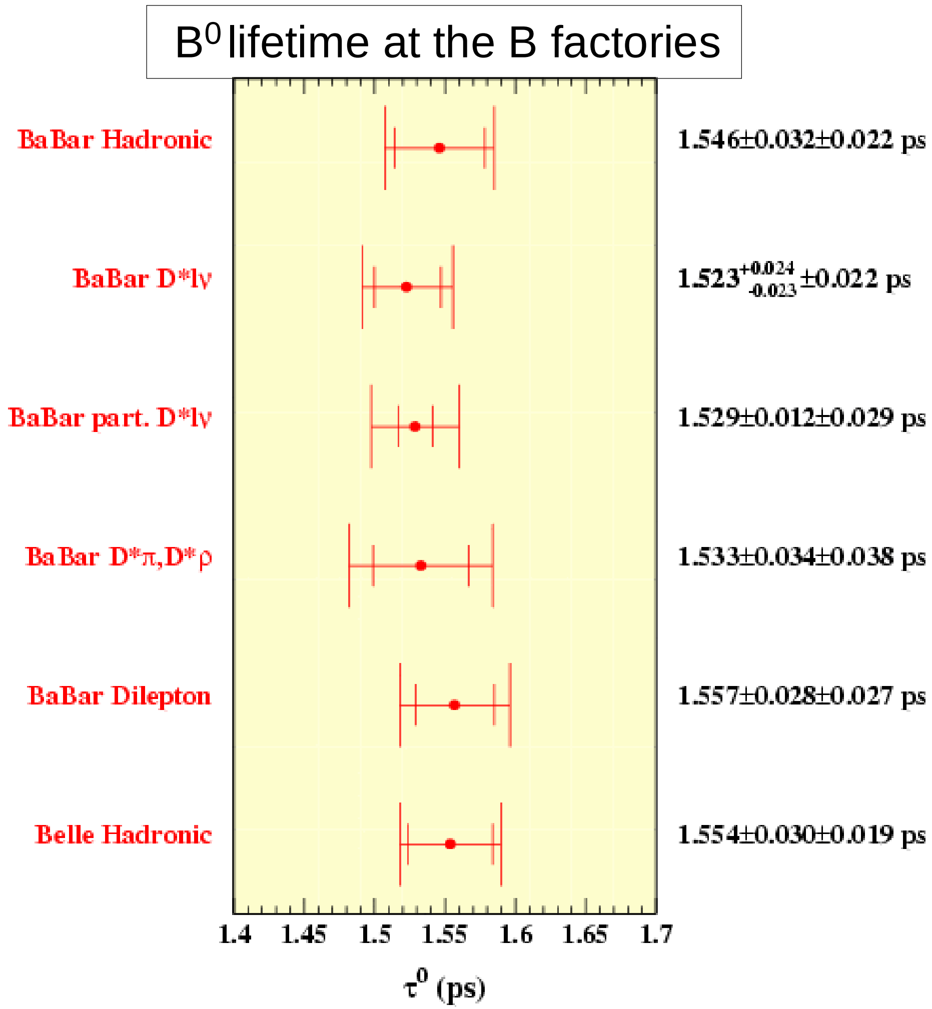
Inclusive dilepton events (*preliminary*)

21 fb^{-1}

τ^0 =1.557±0.028 ±0.027 ps
τ^+ =1.655±0.026 ±0.027 ps

τ^+/τ^0 =1.064±0.031±0.026

B^0 and B^+ lifetimes



Experimental averages

$\tau^0 = 1.536 \pm 0.014$ ps

$\tau^+ = 1.671 \pm 0.018$ ps

$\tau^+/\tau^0 = 1.086 \pm 0.017$

Theoretical prediction

$\tau^+/\tau^0 = 1.06 \pm 0.02$

Time dependent B decay rates: beyond the naïve mixing picture

Again, the differential event rate as a function of the difference between the proper decay times of the two B mesons in the final state

$\Delta\Gamma$ = 0, no CP/T/CPT violation

$$\frac{d}{d\Delta t}\mathcal{N}(\Upsilon(4S) \to B\overline{B} \to f_{\rm tag}, f_{\rm rec}) \propto \frac{1}{\Gamma} e^{-\Gamma|\Delta t|} \left\{ 1 \pm \cos(\Delta m \, \Delta t) \right\}$$

B factories precision measurements $\Rightarrow$ *correction to naïve mixing picture*

CP,T,CPT violation, $\Delta\Gamma \neq 0$:

effect and magnitude on B decay rate measurement similar

combined analysis to disentangle effects

B decay into CP eigenstates

Allow $\Delta\Gamma \neq 0$

$$\frac{d}{d\Delta t}\mathcal{N}(\Upsilon(4S) \to B\overline{B} \to f_{\rm tag}, f_{\rm rec}) \propto$$

$$\frac{1}{\Gamma}\, e^{-\Gamma|\Delta t|} \left\{ \cosh\left(\frac{\Delta\Gamma\,\Delta t}{2}\right) \pm \sqrt{1 - T_{f_{\rm tag}, f_{\rm rec}}{}^2}\, \sinh\left(\frac{\Delta\Gamma\,\Delta t}{2}\right) - \boxed{C_{f_{\rm tag}, f_{\rm rec}}} \times \cos(\Delta m\, \Delta t) + \boxed{S_{f_{\rm tag}, f_{\rm rec}}} \times \sin(\Delta m\, \Delta t) \right\}$$

Different expression for coefficients C and S

$$C_{\pm, f_{CP}} = \pm C_{f_{CP}} = \pm \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2} \qquad S_{\pm, f_{CP}} = \pm S_{f_{CP}} = \pm \frac{2\,\mathrm{Im}\,\lambda_{f_{CP}}}{1 + |\lambda_{f_{CP}}|^2}$$

$$\boxed{\lambda_{f_{CP}} \equiv \frac{q}{p}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}}}$$

complex CP-parameter characterizes interference between mixing & decay

Time dependent B decay rates allowing $\Delta\Gamma \neq 0$, CP/T/CPT violation

Allow $\Delta\Gamma \neq 0$

$$\frac{d}{d\Delta t}\mathcal{N}(\Upsilon(4S) \to B\overline{B} \to f_{\rm tag}, f_{\rm rec}) \propto$$
$$\frac{1}{\Gamma} e^{-\Gamma|\Delta t|} \left\{ \cosh\left(\frac{\Delta\Gamma\,\Delta t}{2}\right) \pm \sqrt{1 - T_{f{\rm tag},\,f{\rm rec}}{}^2}\, \sinh\left(\frac{\Delta\Gamma\,\Delta t}{2}\right) - C_{f{\rm tag},\,f{\rm rec}} \times \cos(\Delta m\,\Delta t) + S_{f{\rm tag},\,f{\rm rec}} \times \sin(\Delta m\,\Delta t) \right\}$$

=1 if $\Delta\Gamma$=0

with

$$C_{f{\rm tag},\,f{\rm rec}} = \frac{|a_m|^2 - |a_u|^2}{|a_m|^2 + |a_u|^2} \qquad S_{f{\rm tag},\,f{\rm rec}} = \frac{2\,{\rm Im}(a_u^* a_m)}{|a_m|^2 + |a_u|^2}$$

and

$$T_{f{\rm tag},\,f{\rm rec}}{}^2 \equiv C_{f{\rm tag},\,f{\rm rec}}{}^2 + S_{f{\rm tag},\,f{\rm rec}}{}^2 \leq 1$$

Different expression for coefficients C and S

Allow CP/CPT violation

$$a_u \equiv \overline{A}_{f{\rm tag}} A_{f{\rm rec}} - A_{f{\rm tag}} \overline{A}_{f{\rm rec}}$$
$$a_m \equiv \sqrt{1 - z^2}\left(\frac{q}{p}\overline{A}_{f{\rm tag}}\overline{A}_{f{\rm rec}} - \frac{p}{q}A_{f{\rm tag}}A_{f{\rm rec}}\right) + z\,\left(\overline{A}_{f{\rm tag}}A_{f{\rm rec}} + A_{f{\rm tag}}\overline{A}_{f{\rm rec}}\right)$$

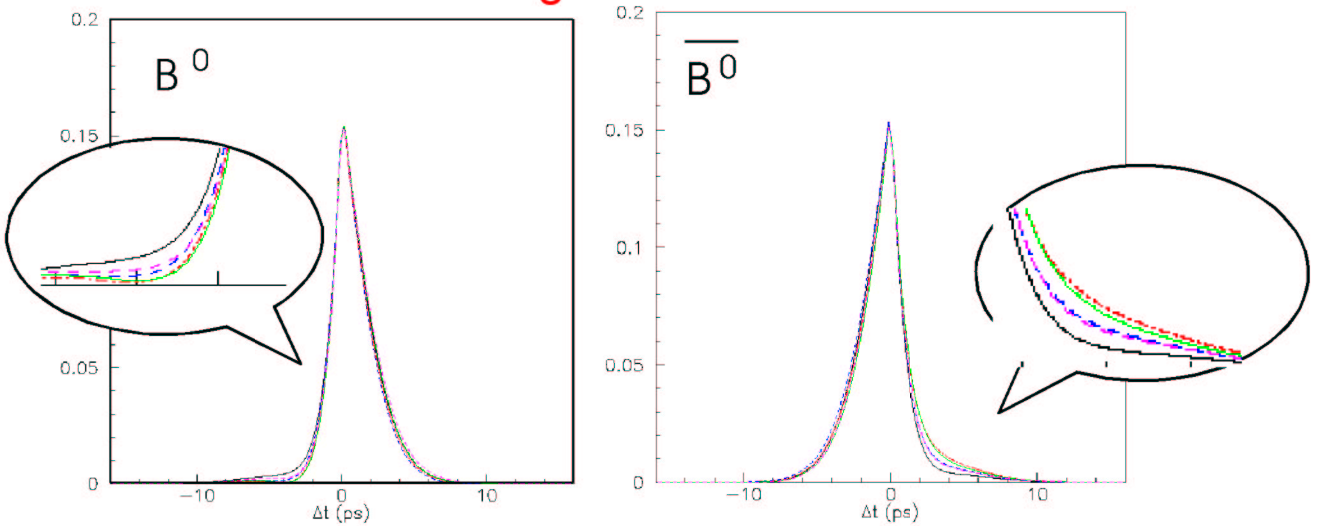
=1 w/o CP/CPT violation *Absent w/o CP/CPT violation*

If $z \neq 0$ Prob($B^0 \to B^0$,t) $\neq$ Prob($\overline{B}^0 \to \overline{B}^0$,t)

Effect of $\Delta\Gamma\neq0$, CP/T/CPT violation on B decay rate

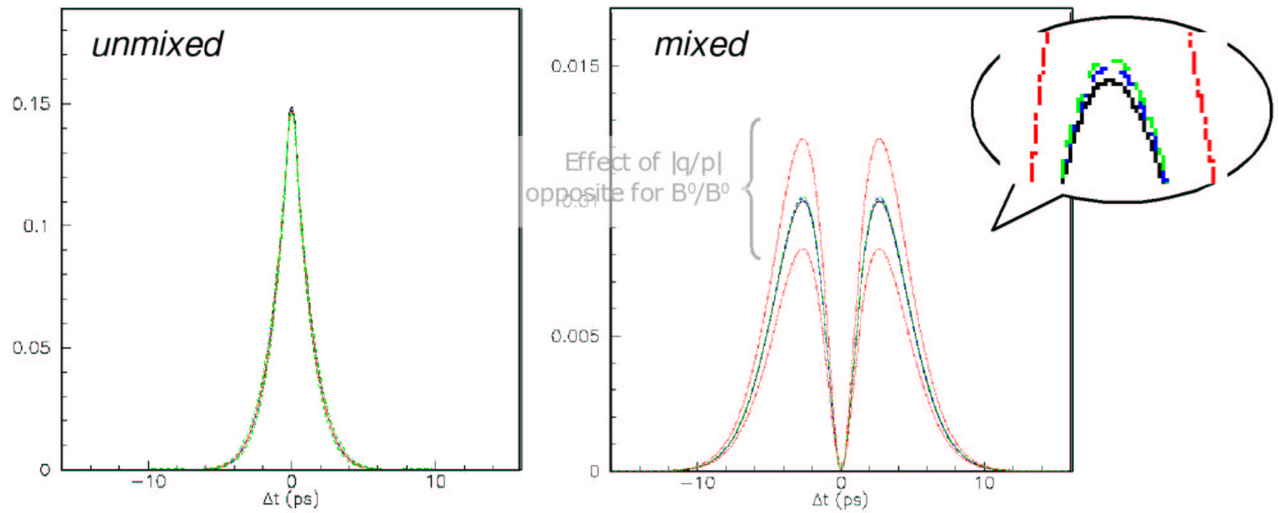
CP eigenstates

Naïve model
& $Re(z) = 0.2$
& $\Delta\Gamma/\Gamma = 20\%$
& $|q/p| = 0.9$



Flavor eigenstates

Naïve model
& $\Delta\Gamma/\Gamma = 20\%$
& $|q/p| = 0.9$
& $Im(z) = 0.1$



Detector effects not included

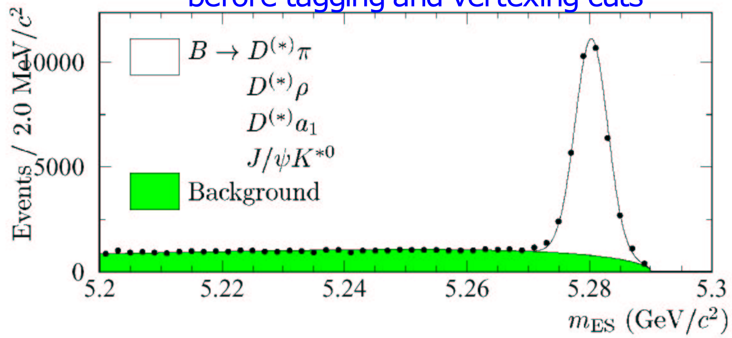
82 fb^{-1} – 88 million BB pairs

before tagging and vertexing cuts

B decays to flavor-specific final states

31000 events

$$B^0 \to D^{(*)-}\pi^+/\rho^+/a_1^+$$
$$B^0 \to J/\psi\ K^{*0}(\to K^+\pi^-)$$

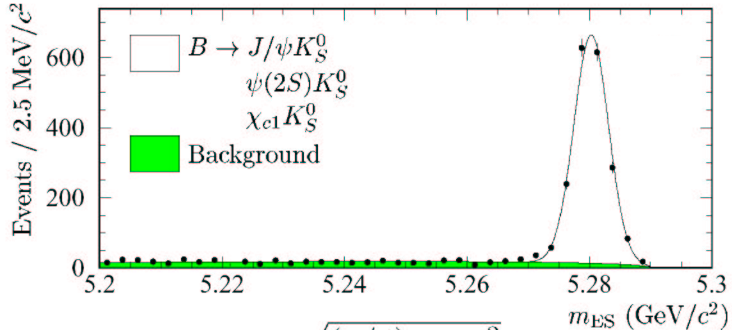


B decays to CP-eigenstates with charmonium .

2600 events

CP = -1

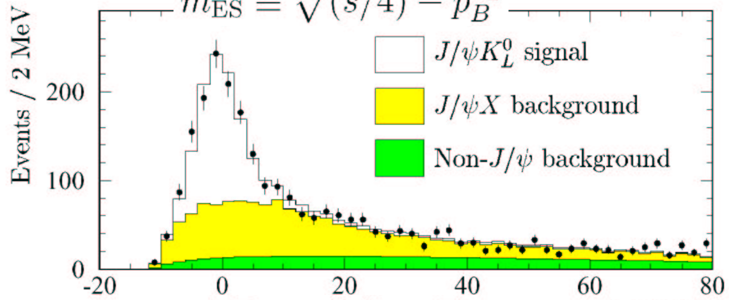
$$B^0_{CP} \to J/\psi\,(\to \ell^+\ell^-)\,K^0_S$$
$$B^0_{CP} \to J/\psi\,K^0_S(\to \pi^0\pi^0)$$
$$B^0_{CP} \to \psi(2S)(\to \ell^+\ell^-,\ J/\psi\,\pi\pi)\,K^0_S$$
$$B^0_{CP} \to \chi_{c1}(\to J/\psi\,\gamma)\,K^0_S$$



$$m_{ES} \equiv \sqrt{(s/4) - p_B^{*2}}$$

CP = +1

$$B^0_{CP} \to J/\psi\ K^0_L$$



$$\Delta E \equiv \sqrt{s}/2 - E_B^*$$

Limits on $\Delta\Gamma$ and search for CP,T,CPT violation in mixing – BaBar – fit strategy

$$\underbrace{\frac{d}{d\Delta t}\mathcal{N}(\Upsilon(4S)\to B\overline{B}\to f_{\rm tag}, f_{\rm rec})}\otimes\underbrace{\textbf{Detector response}(\Delta t, f_{tag}, f_{rec})}$$

Must take into account %-level physics effects:

- Possible direct CP violation in the CP eigenstate sample (λ_{CP})
- Correlation between reco B and tag B via interference between CKM allowed and doubly-CKM suppressed decays

Must model:

- Incorrect assignments of the flavour tagging algorithm
- Δt resolution that is comparable to the B lifetime and asymmetric for positive and negative Δt
- possible asymmetries in detector response for positive and negative particles

Limits on ΔΓ and search for CP,T,CPT violation in mixing – BaBar – results

Preliminary result

Simultaneous fit

Mixing

$$\mathrm{sign}(\mathrm{Re}\,\lambda_{CP}) \times \Delta\Gamma/\Gamma = -0.008 \pm 0.037 \pm 0.018 \quad [-0.084, +0.068]$$

SM: -0.003

CP & T violation

$$|\,q/p\,| = 1.029 \pm 0.013 \pm 0.011 \quad [+1.001, +1.057]$$

SM: 1 + ~ 5×10^{-4}

CPT & CP violation

$$(\mathrm{Re}\,\lambda_{CP}/\,|\,\lambda_{CP}\,|\,) \times \mathrm{Re}\,z = 0.014 \pm 0.035 \pm 0.034 \quad [-0.072, +0.101]$$

SM: 0

$$\mathrm{Im}\,z = 0.038 \pm 0.029 \pm 0.025 \quad [-0.028, +0.104]$$

SM: 0

90% CL intervals

Parameter correlations O(5%), largest correlation 17%

Assuming CPT invariance – Consistent with above results

Mixing

$$\mathrm{sgn}(\mathrm{Re}\lambda_{CP})\Delta\Gamma/\Gamma = -0.009 \pm 0.037 \pm 0.018 \quad [-0.097, +0.069]$$

CP & T violation

$$|\,q/p\,| = 1.029 \pm 0.013 \pm 0.011 \quad [+1.001, +1.057]$$

Search for CP,T,CPT violation in mixing using inclusive dileptons

Indirect CP Violation using dilepton sample

$$a_T(\Delta t) \equiv \frac{\mathcal{N}(\ell^+\ell^+) - \mathcal{N}(\ell^-\ell^-)}{\mathcal{N}(\ell^+\ell^+) + \mathcal{N}(\ell^-\ell^-)} \approx \frac{1 - |q/p|^4}{1 + |q/p|^4}$$

PRL 88[2002]

$$a_T = (0.5 \pm 1.2 \pm 1.4)\%$$ → |q/p| = 0.998 ± 0.006 ± 0.007

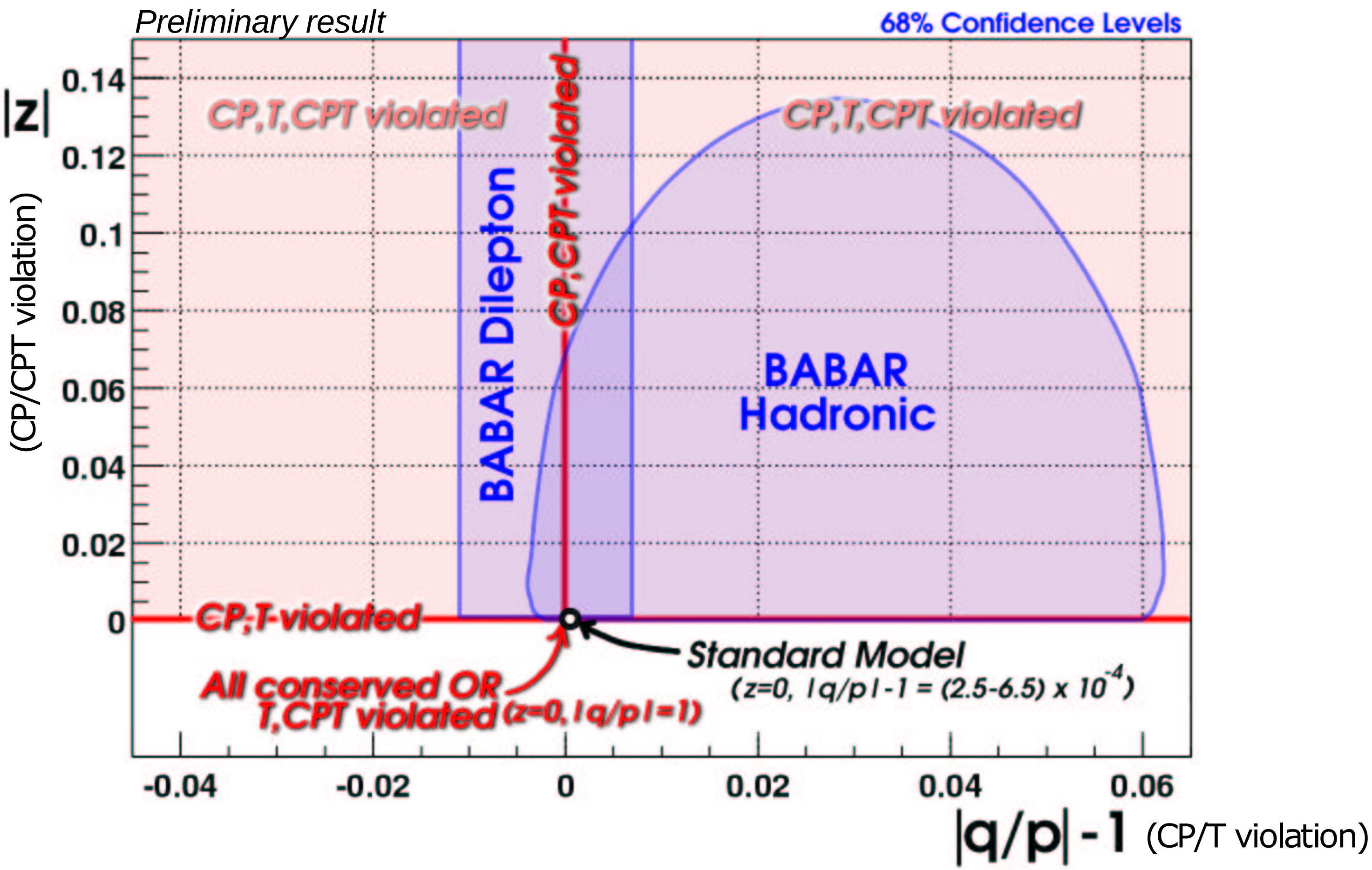
systematics associated with charge asymmetry in lepton detection, background charge asymmetry ...

CPT violation parameters in mixing – measured with oscillation frequency - nalysis assumes ΔΓ and CP violating effects are negligibly small

Im(z) = -0.03 ± 0.01 ± 0.03
Re(z) = 0.00 ± 0.12 ± 0.02

PRD 67[2003]

Search for CP,T,CPT violation in mixing – BaBar



Summary

- Δm_d - very well measured - theoretically limited

- B^0 and B^+ lifetimes - well measured - ratio in good agreement with predictions

- Improved limit on $\Delta\Gamma/\Gamma$

  - $\Delta\Gamma/\Gamma < 8\%$ (90% C.L.)
  - $\Delta\Gamma/\Gamma < 20\ \%$ (90% C.L., PDG 2003 (DELPHI))

- Measurement of CP and T violation (|q/p|) consistent with Standard Model expectation

- Test of CPT invariance outside K^0 system

– BaBar (2003):	Im(z) = $0.038 \pm 0.029 \pm 0.025$ Re(z) = $0.014 \pm 0.035 \pm 0.034$
– Belle dilepton (2002)	Im(z) = $-0.03 \pm 0.01 \pm 0.03$ Re(z) = $0.00 \pm 0.12 \pm 0.02$
– OPAL (1997)	Im(z) = $0.040 \pm 0.032 \pm 0.012$