B mesons: Lifetime and Mixing

a Review of results from Belle and BaBar

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Weak Interactions & Neutrinos, 2005

Outline

1. Neutral B mixing
   - The Standard Model picture
2. Δm_d & τ_{B^0} with partial reconstruction technique
   - Partial $B^0 \to D^{*-}\ell^+\nu$ reconstruction (*BABAR*)
   - Partial $B^0 \to D^{*-}\pi^+$ reconstruction (Belle)
   - CP violation in *B* mixing with dilepton events (Belle)
3. Fully reconstructed *B*
   - Determination of $\Delta\Gamma$, CP/T/CPT violation in mixing (*BABAR*)
   - Determination of $\Delta m_d, \tau_{B^0}, \tau_{B^+}$ (Belle)
4. Conclusions

Neutral B mixing

The Standard Model Picture

Flavour Eigenstates: B^0 & $\bar{B}^0$

$$|\psi\rangle = \alpha|B^0\rangle + \beta|\bar{B}^0\rangle$$
$$i\frac{d}{dt}|\psi\rangle = H|\psi\rangle$$

Hamiltonian (assuming CPT)

$$H = \begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}$$

Mass-width Eigenstates: B_H & B_L

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

Definition

$$\frac{q}{p} = -\sqrt{\frac{\langle \bar{B}^0|H|B^0\rangle}{\langle B^0|H|\bar{B}^0\rangle}}$$

SM predictions

$$\Gamma_{12} << M_{12}$$
$$1 - \left|\frac{q}{p}\right|^2 \sim \Im\frac{\Gamma_{12}}{M_{12}} < 10^{-3}$$

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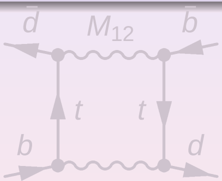

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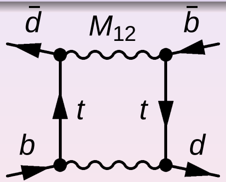

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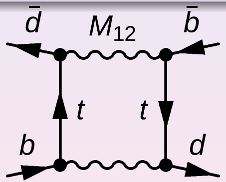

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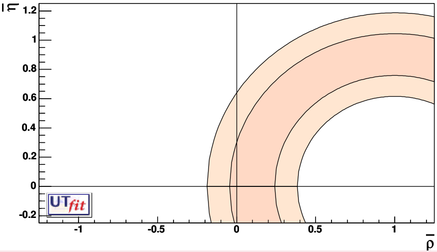
CKM constraint

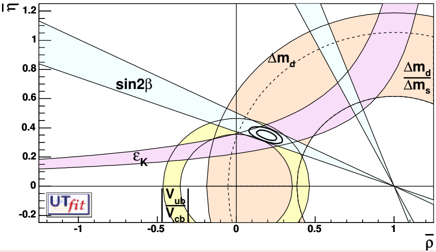
Δm_d is proportional to $|V_{tb}|^2\,|V_{td}|^2$

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2\, \eta_b\, S(m_t^2/m_W^2)\, f_B^2\, \hat{B}_B\, m_B\, |V_{tb}|^2\,|V_{td}|^2$$

Unfortunately the proportionality factor is known at $\sim 15\%$

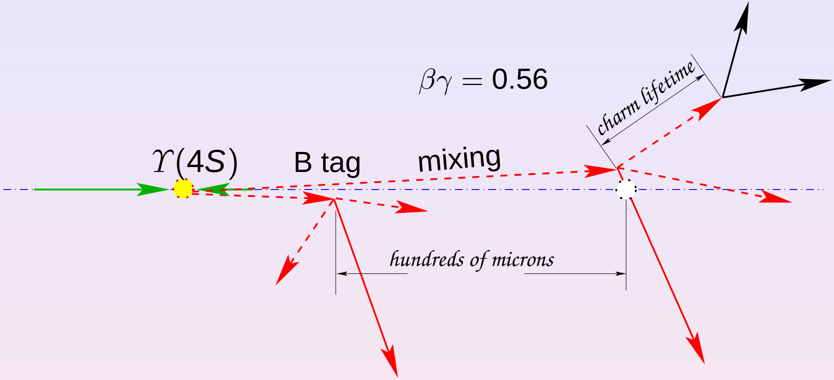


Δm_d constraint on $\bar{\rho}, \bar{\eta}$



... and the other constraints

Time dependent analyses:



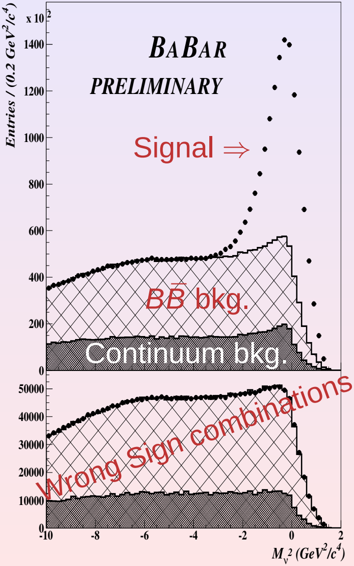
- B pair produced by $\Upsilon(4S)$ decay:

$$|B^0\rangle|\bar{B}^0\rangle - |\bar{B}^0\rangle|B^0\rangle = |B_H\rangle|B_L\rangle - |B_L\rangle|B_H\rangle$$

- Coherent state: time evolution is a pure phase
- The first B decay tag the state of the surviving one at the same moment

Partial $B^0 \to D^{*-}\ell^+\nu$ reconstruction

hep-ex/0408039



Key points

$B^0 \to D^{*-}\ell^+\nu \quad (D^{*-} \to \pi^-_{soft}\bar{D}^0)$

- $\pi^-_{soft} \sim$ at rest in D^{*-} frame
- $\vec{p}_{D^*} \sim \parallel \vec{p}^{\star}_{\pi^-_{soft}}$ and $E_{D^*} \sim f(E_{\pi_{soft}})$
- $B^0 \sim$ at rest in $\Upsilon(4S)$ frame
- $M_\nu^2 \sim (\sqrt{s}/2 - E_{D^*} - E_\ell)^2 - (\vec{p}_{D^*} + \vec{p}_\ell)^2$

Event selection

Lepton: $1.3 < p^\star < 2.4\,\mathrm{GeV}/c$

Soft pion: $60 < p^\star < 200\,\mathrm{MeV}/c$

Neutrino mass: $M_\nu^2 > -2.5\,\mathrm{GeV}/c^2$

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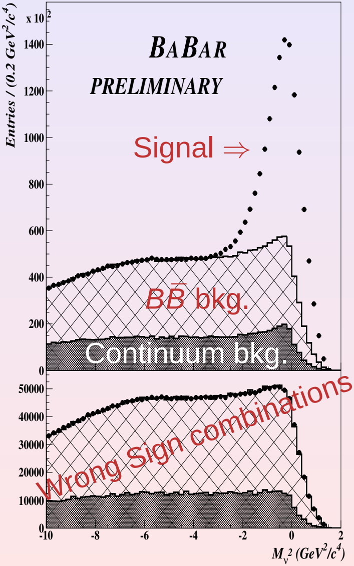

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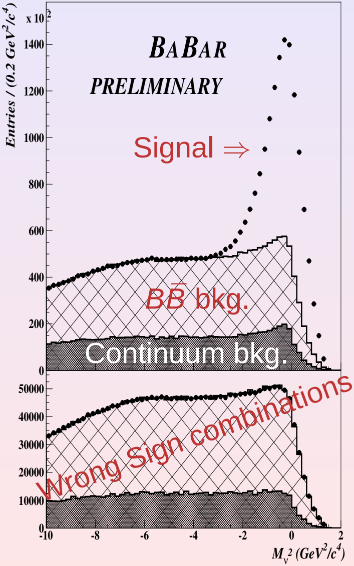

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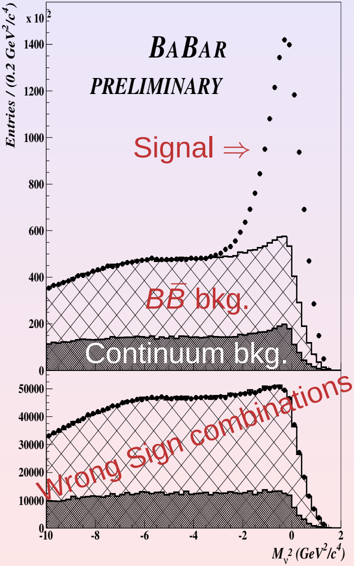

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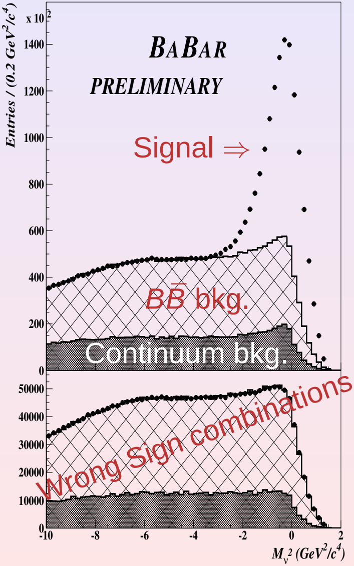

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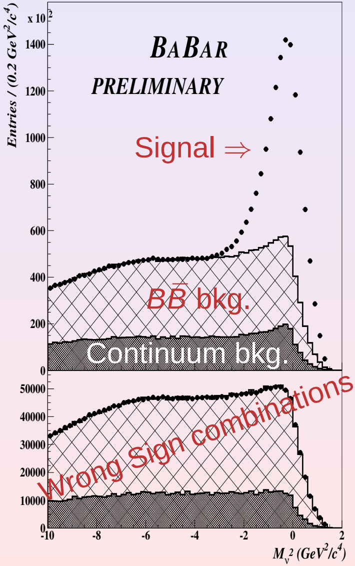

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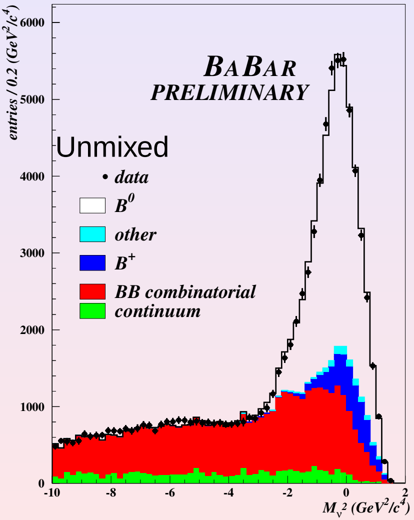
Companion B flavor tag



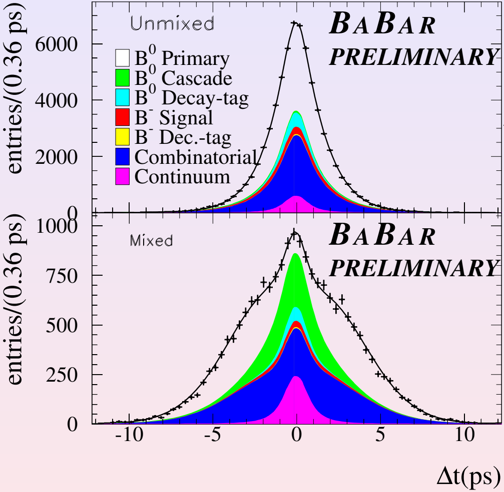
A second stiff lepton is required in the same event

- Its charge tags the flavor of the other B
- Reduces the continuum background
- Precise Δz reconstruction

Data sample

On 88×10^6 $B\bar{B}$ events:
$\sim 50 \times 10^3$ $B \rightarrow D^* \ell \nu$ candidates
$\sim 27 \times 10^3$ bkg. events

Δm_d & τ_{B^0} determination

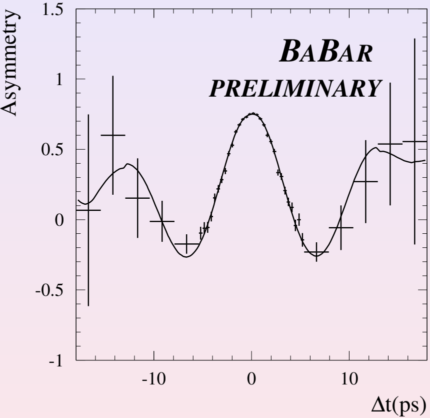


Binned maximm-likelihood fit to $\Delta t, \sigma(\Delta t)$

- τ_{B^0} & Δm_d free parameters
  $$\mathcal{S} = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}(1 \pm \cos \Delta m_d\ \Delta t)$$
- Backgrounds fraction from M_ν^2
- Free parameters for detector response
  - Resolution on Δt
  - Dilution and bias on Δt from cascade leptons tag

Fit results and systematic errors

hep-ex/0408039



Preliminary results ($88 \times 10^6 B\bar{B}$):

$$\tau_{B^0} = (1.501 \pm 0.008 \pm 0.030)\,\mathrm{ps}$$
$$\Delta m_d = (0.523 \pm 0.004 \pm 0.007)\,\mathrm{ps}^{-1}$$

Main systematic error

- Analysis bias
- SVT misalignment

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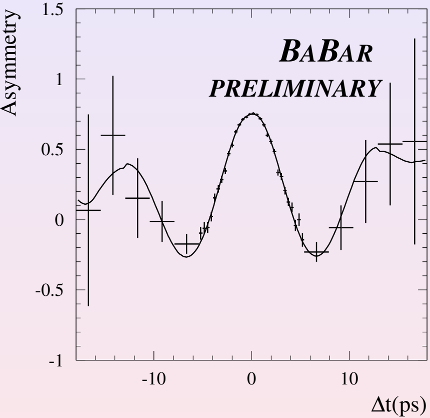

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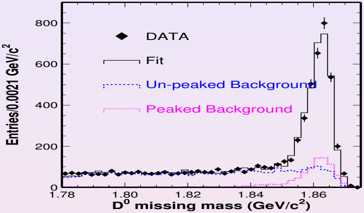
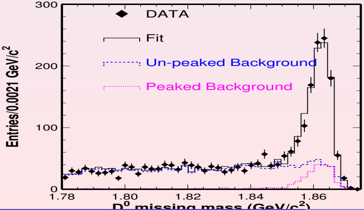
PRD *67*, 092004 (2003)



$\Uparrow$ unmixed / mixed $\Downarrow$



Kinematical constraints

$B^0 \to D^{*-}\pi^+_{prompt} \quad (D^{*-} \to \pi^-_{soft}\bar{D}^0)$

Identify only π^+_{prompt} and π^-_{soft}.

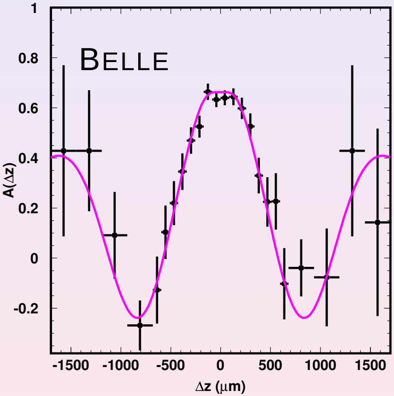
Kinematical constraints:

- B mass and energy in $\Upsilon(4S)$ frame
- D^* mass
- $M^2_{D_{miss}} > 1.85\,\mathrm{GeV}/c^2$
- D^* helicity defined

Selection:

- $2.05 < p_{\pi^+_p} < 2.45\,\mathrm{GeV}/c$
- $p_{\pi^+_s} < 450\,\mathrm{MeV}/c$

Final result:
PRD *67*, 092004 (2003)



- Lepton tag for the companion B
- Resolution function from "*tuned*" MC
- Δm_d is the only free parameter in the Δt fit

Fit result ($31 \times 10^6 B\bar{B}$ pairs):

$$\Delta m_d = (0.509 \pm 0.017 \pm 0.020)\,\mathrm{ps}^{-1}$$

CP violation in B mixing

In the previous analyses it was assumed CP in B mixing i.e. $\left|\frac{p}{q}\right| = 1$

Time dependent decay rate for same sign dileptons if CP is violates:

$$\Gamma\left(\Upsilon(4S) \to \ell^+\ell^+, \Delta t\right) = \frac{|A_\ell|^4}{8\tau_{B^0}} E^{-|\Delta t|/\tau_{B^0}} \left|\frac{p}{q}\right|^2 \left[\cosh\left(\frac{\Delta\Gamma}{2}\Delta t\right) - \cos(\Delta m_d \Delta t\right]$$

$$\Gamma\left(\Upsilon(4S) \to \ell^-\ell^-, \Delta t\right) = \Gamma\left(\Upsilon(4S) \to \ell^+\ell^+, \Delta t\right) \left|\frac{q}{p}\right|^4$$

Time independent CP asymmetry:

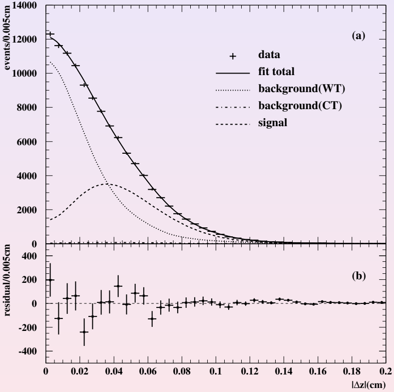
$$A_{sl} = \frac{\Gamma\left(\Upsilon(4S) \to \ell^+\ell^+, \Delta t\right) - \Gamma\left(\Upsilon(4S) \to \ell^-\ell^-, \Delta t\right)}{\Gamma\left(\Upsilon(4S) \to \ell^+\ell^+, \Delta t\right) + \Gamma\left(\Upsilon(4S) \to \ell^-\ell^-, \Delta t\right)} = \frac{1 - |q/p|^4}{1 + |q/p|^4}$$

Robust SM prediction: $A_{sl} \sim< 10^{-3}$

R. Cahn et al. PRD *60,* 76006 (1999)

Belle new measurement of A_{sl}

hep-ex/0505017



Events with:

- Two leptons with same charge $1.2 < p^{\star} < 2.3\,\mathrm{GeV}/c$
- Veto on Conversions and J/Ψ
- On 78 fb^{-1}:

$46533 + +\mathrm{Events}$

$45477 - -\mathrm{Events}$

Charge dependent Corrections for

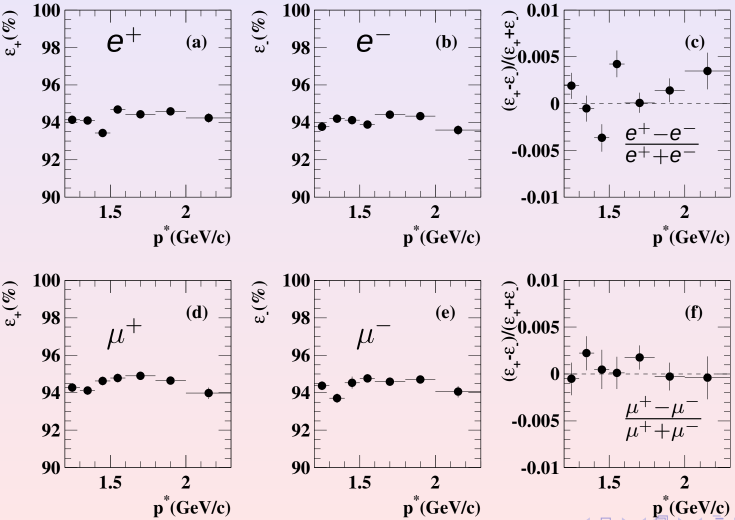
- Tracking & PID efficiency
- PID misidentification rate

$|\Delta z|$ binned maximum likelihood fit

- Detector response
- Background contributions

Belle Tracking : Charge Asymmetry

hep-ex/0505017



Belle Tracking : Particle ID Asymmetry

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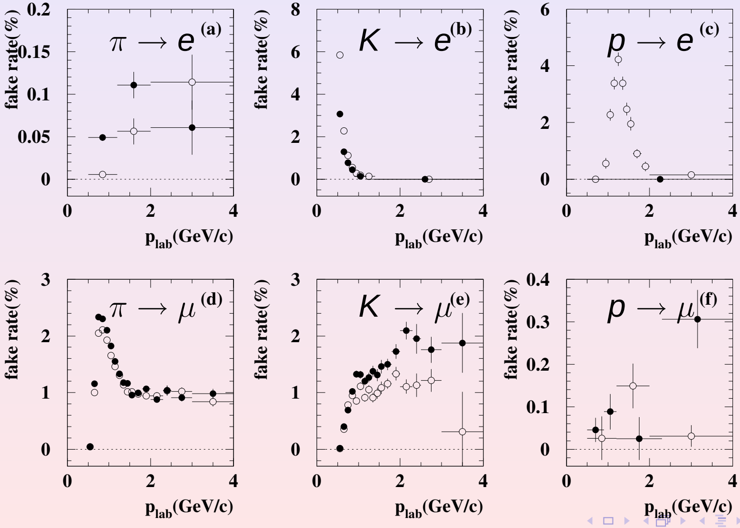
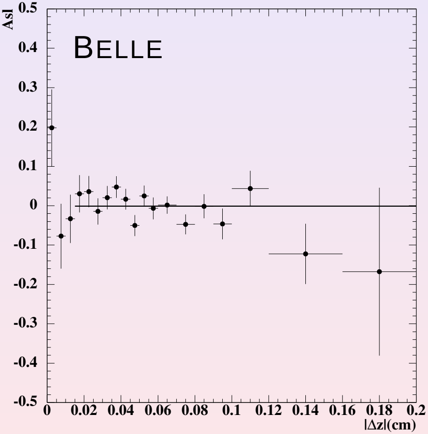


- ● positive
- ○ negative

Belle result for A_{sl}

hep-ex/0505017



$|\Delta z|$ fit of A_{sl} gives

Fit range:150 μm − 2mm

$$A_{sl} = (-1.1 \pm 7.9 \pm 7.0) \times 10^{-3}$$
$$|q/p| = 1.0005 \pm 0.0040 \pm 0.0035$$

Main systematic from continuum subtraction (4.9×10^{-3})

$\Re(\epsilon_B) \times 10^3$: BaBar [a] vs. Belle

[a] PRL 88,231801(2002)

$1.2 \pm 2.9 \pm 3.6$	BaBar
$-0.3 \pm 2.0 \pm 1.7$	Belle

CPT and $\Delta\Gamma = 0$ assumed so far

Releasing the CPT requirement on the $B\,\bar{B}$ mixing matrix the mass-width eigenstates are:

$$|B_H\rangle = p\sqrt{1-z}|B^0\rangle + q\sqrt{1+z}|\bar{B}^0\rangle$$
$$|B_L\rangle = p\sqrt{1+z}|B^0\rangle - q\sqrt{1-z}|\bar{B}^0\rangle$$

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Discrete Symmetries

$$CPT \Rightarrow \quad z = 0$$

$$CP \Rightarrow \quad z = 0 \quad \& \quad \left|\frac{q}{p}\right| = 1$$

$$T \Rightarrow \quad \left|\frac{q}{p}\right| = 1$$

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How to measure $z, \frac{q}{p}, \Delta\Gamma$ in a single shot

- Fully reconstruct one *Bboth in CP and flavor* eigenstate decay modes
- tag the companion B
- fit the proper time distribution with:

$$\frac{dN(\Upsilon(4S) \to B_{tag}, B_{rec} \text{ after } t)}{dt} \propto$$

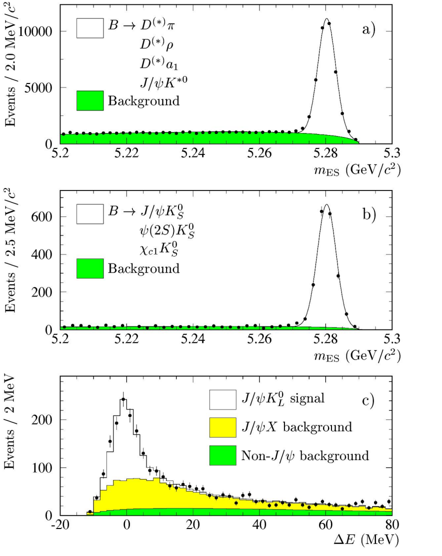
$$e^{-\Gamma|t|}\left\{\frac{1}{2}c_{+}\cosh\Delta\Gamma t/2 + \frac{1}{2}c_{-}\cos\Delta m t - \Re s\,\sinh\Delta\Gamma t/2 + \Im s\,\sin\Delta m t\right\}$$

- $\Delta\Gamma$ explicitely appears in the hyperbolic terms
- z and $\frac{q}{p}$ appear in the $c_{\pm}$ and s coefficients

Data Sample

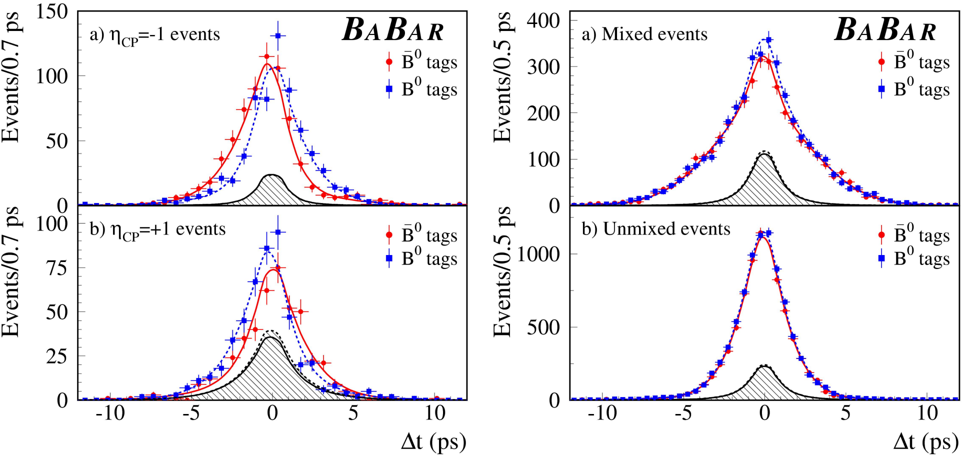
$$\mathcal{L} = 82\,\text{fb}^{-1}\,,\ \sim 88 \times 10^6\ B\bar{B}\ \text{pairs}$$

$B_{flav.}$	$B^0 \rightarrow D^{*-}\pi^+(\rho^+, a_1^+)$
$31027 ev.$	$B^0 \rightarrow D^{-}\pi^+(\rho^+, a_1^+)$
	$B^0 \rightarrow J/\psi K^{*0}$
B_{CP}	$B^0 \rightarrow J/\psi K^0_S$
	$B^0 \rightarrow \psi(2S) K^0_S$
$2603 ev.$	$B^0 \rightarrow \chi_{c1} K^0_S$
	$B^0 \rightarrow J/\psi K^0_L$
$B_{ch.}$	$B^+ \rightarrow \bar{D}^{(*)0}\pi^+$
Control	$B^+ \rightarrow \psi(2S) K^+$
sample	$B^+ \rightarrow \chi_{c1} K^+$
	$B^+ \rightarrow J/\psi K^{*+}$



Fit results

PRD 70, 012007(2004)



- Background, mistagging, resolution
- Doubly Cabibbo suppressed interference

Fit results

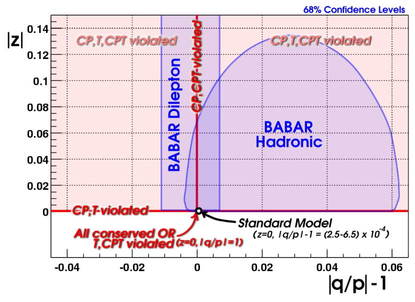
PRD 70, 012007(2004)

Results

$$\begin{aligned} \mathrm{sgn}[\Re(\lambda_{CP})]\Delta\Gamma/\Gamma &= -0.008 \pm 0.037 \pm 0.018 \\ |q/p| &= 1.029 \quad \pm 0.013 \pm 0.011 \\ [\Re(\lambda_{CP})/|\lambda_{CP}|]\Re z &= 0.014 \quad \pm 0.035 \pm 0.034 \\ \Im(z) &= 0.038 \quad \pm 0.029 \pm 0.025 \end{aligned}$$

The 90% confidence-level interval for $\Delta\Gamma/\Gamma$

$$\mathrm{sgn}[\Re(\lambda_{CP})]\Delta\Gamma/\Gamma \in [-8.4\%, 6.8\%]$$



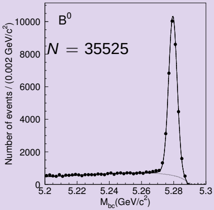
Belle Semileptonic & Hadronic selection

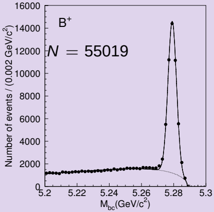
PRD **71,** 072003 (2005)

$\mathcal{L} = 140\,\text{fb}^{-1}$

Hadronic

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



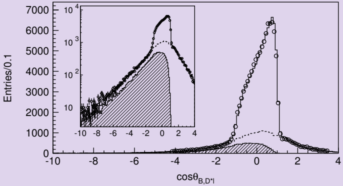


$$m_{bc} = \sqrt{s/4 - |\vec{p_B}|^2}$$

$$\Delta E = \sqrt{s}/2 - E_B$$

Semileptonic

- $B^0 \to D^{*-}\ell^+\nu_\ell$
- $D^{*-} \to \bar{D}^0\pi^- D^0 \to K\pi(\pi\ldots)$

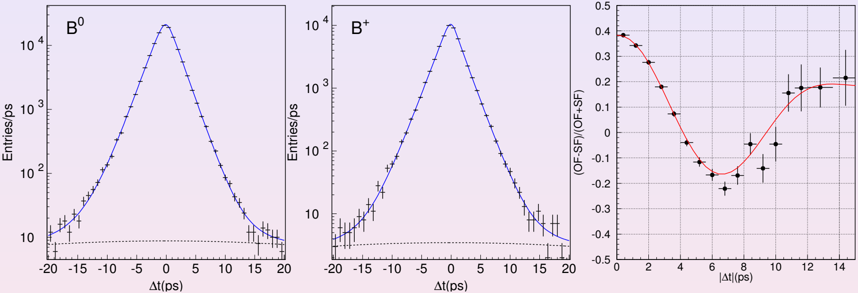


$N = 84823$

Belle Analysis Results

PRD **71,** 072003 (2005)

Unbinned simultaneous fit to all distributions (32 parameters)



Fit results:

$$\Delta m_d = (0.511 \pm 0.005 \pm 0.006)\,\mathrm{ps}^{-1}$$

$$\tau_{B^0} = (1.534 \pm 0.008 \pm 0.010)\,\mathrm{ps}$$

$$\tau_{B^+}/\tau_{B^0} = 1.066 \pm 0.008 \pm 0.008$$

Conclusions:

- Δm_d measurements at B-Factories are reaching the $\mathcal{O}(1\%)$ precision level.
- The measurements are quite sound. Different methods with completely different systematic effects are in good agreement.
- New ideas: search for CP/CPT violation in mixing, but...
- The Standard Model framework correctly describes the observed data.
- Progress on the theoretical side ($f_B, \hat{B}$) and more data on the experimental side may still bring some surprises.