B_d Mixing Measurements with the BaBar Detector

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on behalf of the

BABAR Collaboration

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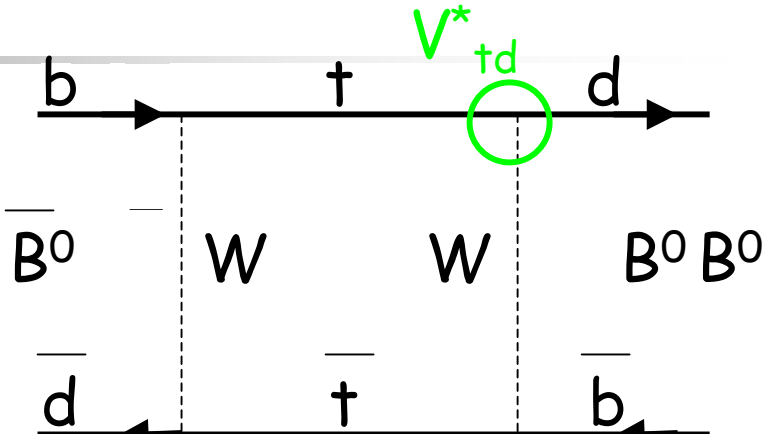
$B^0\overline{B}^0$ Mixing

-Proceeds through box diagram

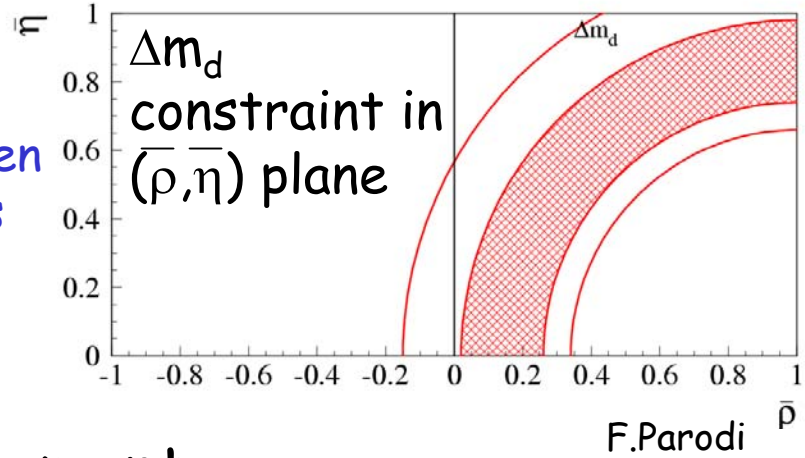


$$H = \begin{pmatrix} H_{11} H_{12} \\ H_{21} H_{11} \end{pmatrix} \qquad \frac{q}{p} = \left(\frac{H_{21}}{H_{12}} \right)^{\frac{1}{2}}$$

if $|q/p| \neq 1$ => CP violation in mixing (assuming CPT invariance

$$\Delta m_d = -2\,\mathrm{Re}\left(H_{12} H_{21}\right)^{\frac{1}{2}}$$ Mass difference between Hamiltonian eigenstates

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_w^2 e_B S_0(m_t^2 / m_W^2) m_{B_d} |V_{td}|^2 B_{B_d} f_{B_d}^2$$



- Δm_d sensitive to V_{td} CKM matrix element
- Extraction of V_{td} limited by theoretical hadronic uncertainties → $\sqrt{B_{B_d} f_{B_d}^2} = 235 \pm 33^{+00}_{-23}$ MeV

(D. Becirevic and L. Lellouch, at this conference)

$B^0\overline{B}^0$ Mixing at Asymmetric B Factories

Before B factories:

$$\Delta m_d = 0.472 \pm 0.017\ ps^{-1}$$

At BaBar, asymmetric B factory, we measure:

-can perform time dependent measurements

-high statistics sample of fully reconstructed B_d, no B_s

new result

-Mixing and lifetime with $B^0 \to D^{*-} l^+ \nu_l$ decays

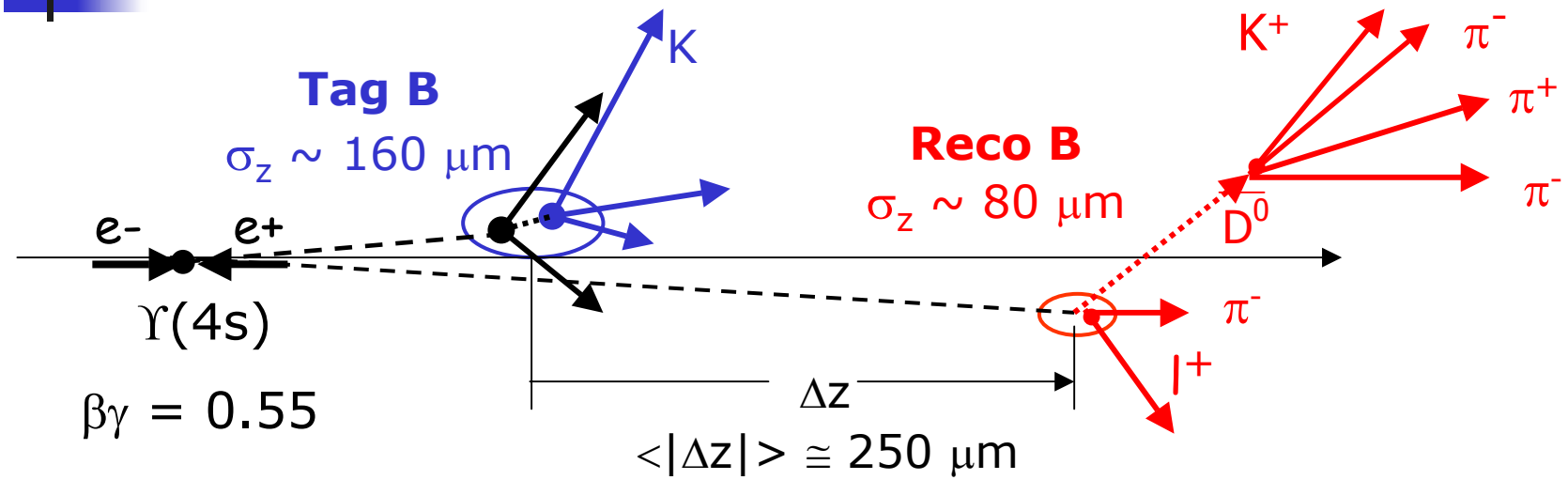
-Mixing with hadronic decays (PRL 88:221802[2002])

-Mixing with dilepton events (PRL 88:221803[2002])

$23 \times 10^6\ B\overline{B}$ ($B^0 \to D^{*-} l^+ \nu$ and dilepton)

$32 \times 10^6\ BB$ (hadronic)

$B^0\overline{B}^0$ Mixing with Fully Reconstructed B^0



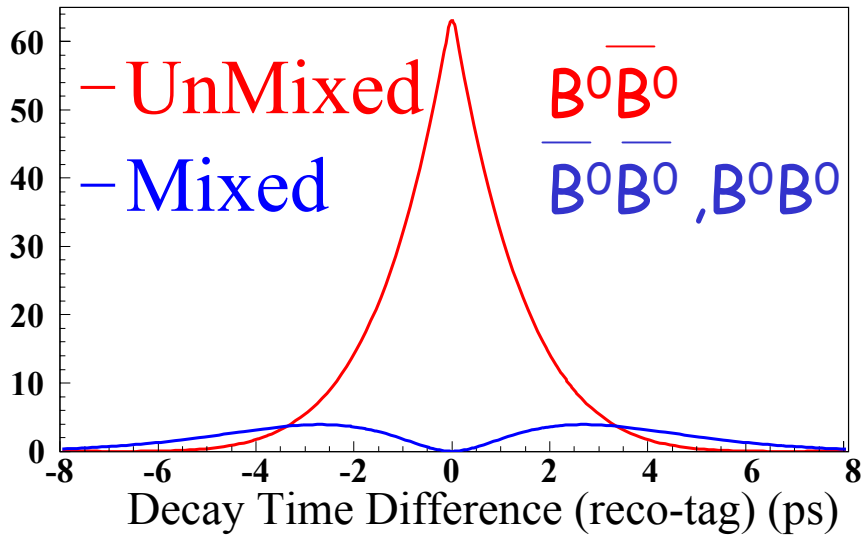
3. Reconstruct inclusively the vertex of the "other" B meson (B_{TAG})
4. Determine the flavor of B_{TAG}

1. Reconstruct one B meson in the flavor eigenstates $D^{*-}l^+\nu_l$ or hadronic (e.g. $D^{*-}\pi^+$)
2. Reconstruct the vertex position

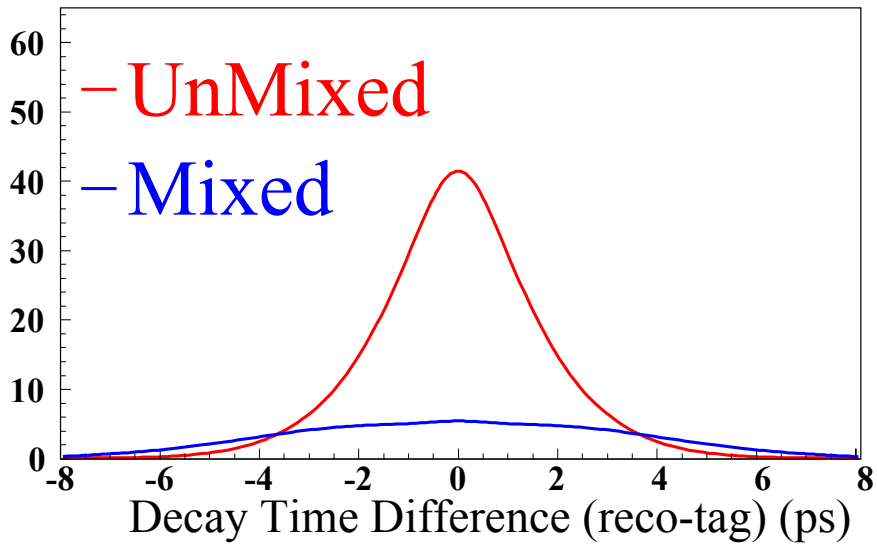
5. Compute the proper time difference $\Delta t \cong \Delta z/\gamma\beta c$
6. Fit the Δt spectra of mixed (B^0B^0 or $\overline{B}^0\overline{B}^0$) and unmixed ($B^0\overline{B}^0$) events

Δt Distribution of Mixed and Unmixed Events

perfect
flavor tagging & time resolution



realistic
mis-tagging & finite time resolution



Decay time distribution for signal events

$$f_{\substack{\text{Unmix}\\\text{Mix}}}(\Delta t) = \left\{ \frac{e^{-|\Delta t|/\tau_{B_d}}}{4\tau_{B_d}} \times \left(1 \pm (1-2w)\cos(\Delta m_d \Delta t) \right) \right\} \otimes \text{ResolutionFunction}$$

B^0 lifetime — Mistag probability — oscillation frequency

$B^0 \to D^{*-} l^+ \nu$ Selection

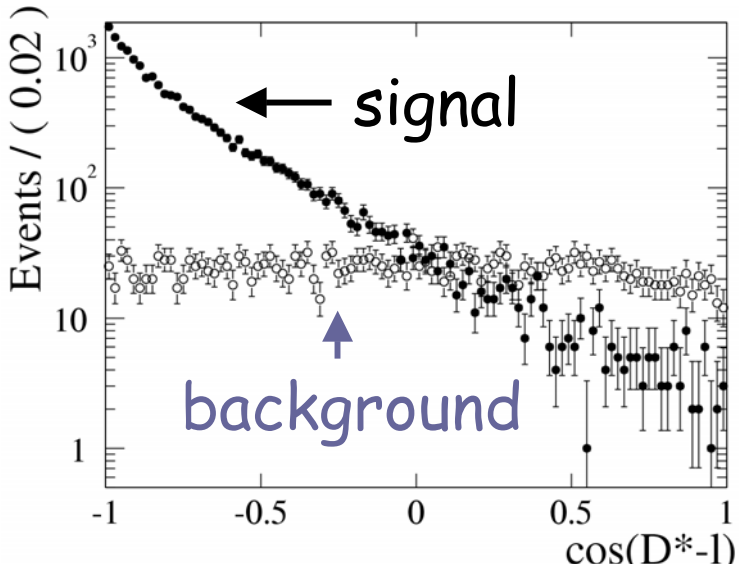
- Reconstruct candidate D* using full decay tree

$$D^{*+} \to D^0 \pi^+ \,,\; D^0 \to K^- \pi^+, K^- \pi^+ \pi^0, K^- \pi^+ \pi^- \pi^+, K_s \pi^+ \pi^-$$

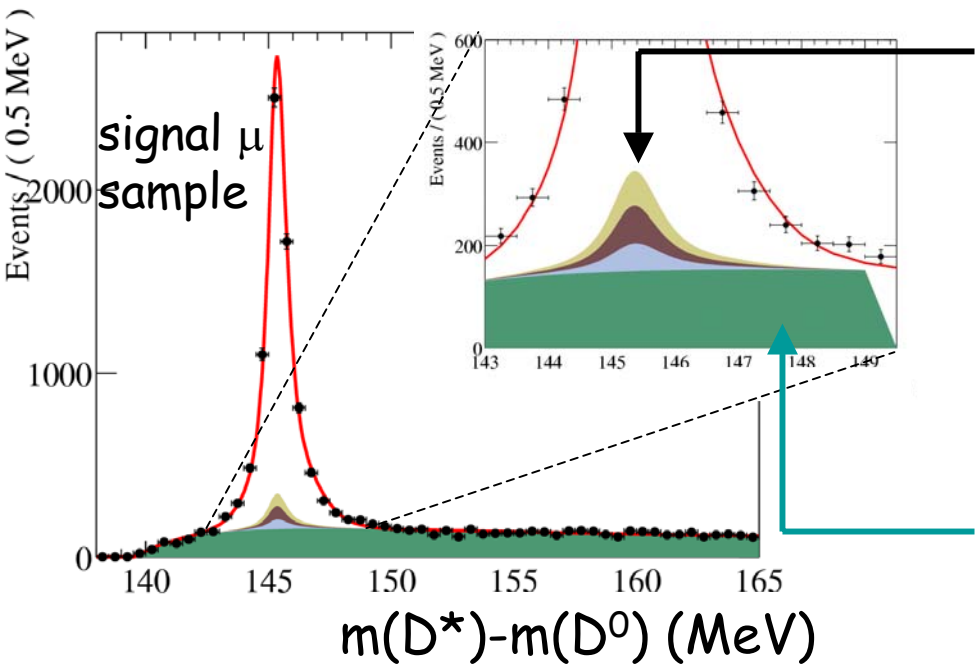
- Combine with lepton candidate ($p^* > 1.2$ GeV)

- Require consistency with D*-l kinematics (angles, missing ν)

- Cannot reconstruct B^0 mass and energy because of the missing ν => use $m(D^*)-m(D^0)$ distribution



Sample Composition



Peaking background:
real D*non from semileptonic decays

-uncorrelated lepton from other B
-fake lepton
-continuum events

Combinatoric:
fake D*

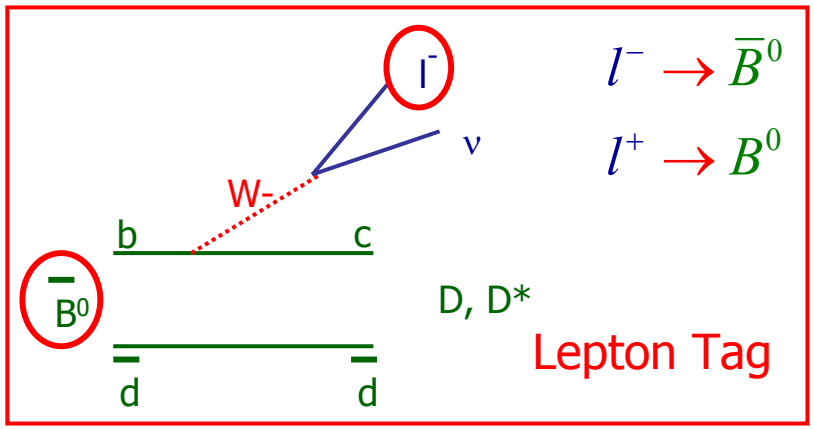
Category	Peak Yield	$f_{\rm cont.}$	$f_{\rm fake}$	$f_{\rm otherB.}$	$f_{\rm comb.}$
sig. sample e	7008 ± 91	1.5%	0.17%	3.1%	17.9%
sig. sample μ	6569 ± 88	2.3%	2.7%	2.9%	18.4%

- Select several control samples to characterize (fraction,Δt shape) the main sources of backgrounds

Flavor Tagging

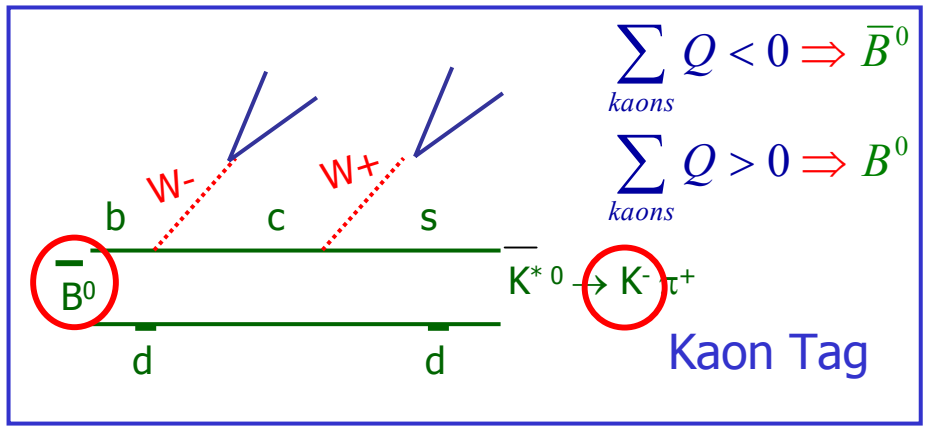
Hierarchical, Mutually Exclusive, Tagging Categories

For electrons, muons and Kaons use the charge correlation



$l^- \rightarrow \bar{B}^0$

$l^+ \rightarrow B^0$



$\sum_{kaons} Q < 0 \Rightarrow \bar{B}^0$

$\sum_{kaons} Q > 0 \Rightarrow B^0$

Neural network exploits information carried by non-identified leptons and kaons, soft pions from D^* decays

Tagging Category	Efficiency ε(%)	Mistag Fraction w(%)	$Q=\varepsilon(1-2w)^2$ (%)
Lepton	11.1	8.6	7.6
Kaon	34.7	18.1	14.1
Neural Net	54.2	37.7	3.3

$B^0 \to D^{*-} l^+ \nu$ Mixing Likelihood Fit Results

- Simultaneous fit to all signal and background samples

float Δm, τ_{B0} , mistag probabilities, signal and background Δt resolution parameters, fraction of charged B

Preliminary

$\Delta m_d = 0.492 \pm 0.018 \pm 0.013 ps^{-1}$

$\tau_{B0} = 1.523^{+0.024}_{-0.023} \pm 0.022 ps$

correlation coefficient $\rho(\Delta m, \tau_{B0}) = -0.22$

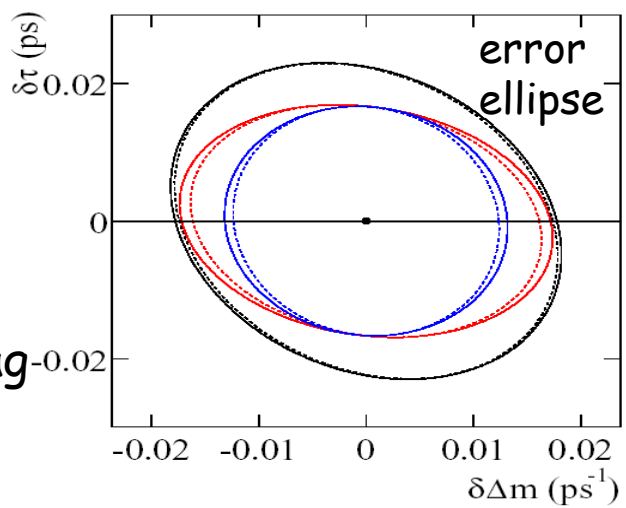
$$A_{mix}(\Delta t) = \frac{N_{unmixed}(\Delta t) - N_{mixed}(\Delta t)}{N_{unmixed}(\Delta t) + N_{mixed}(\Delta t)} \approx (1 - 2\langle w \rangle)\cos(\Delta m \Delta t)$$

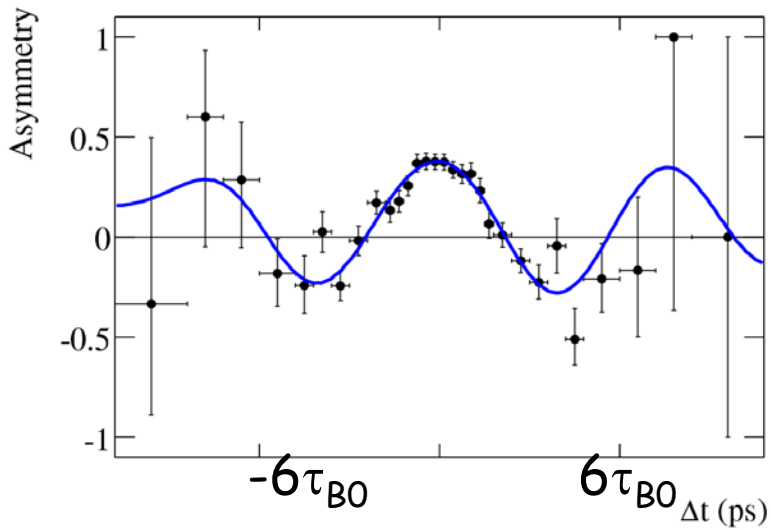
Floating parameters:

Innermost

- Δm, τ_{B0}
- Δm, τ_{B0}, mistag
- Δm, τ_{B0}, f_{B+}
- Δm, τ_{B0}, f_{B+}, mistag
- All signal Δt par

Default fit

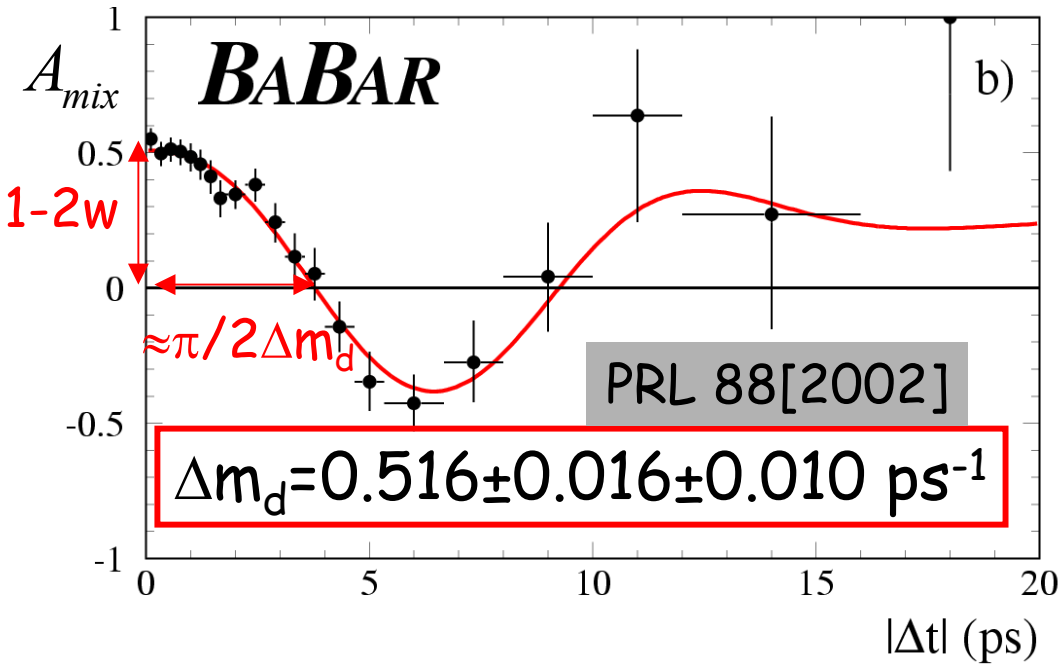




Mixing with Hadronic Events

- Fully reconstructed $B^0 \to D^{(*)-}\pi^+/\rho^+/a_1^+, J/\psi K^{*0}$
- All Δt and mistag parameters simultaneously extracted from data
  - → used for sin2β measurement
- Largest syst. is B^0 lifetime

6347 B^0
(purity ~86%)



- lifetime measurements with hadronic events

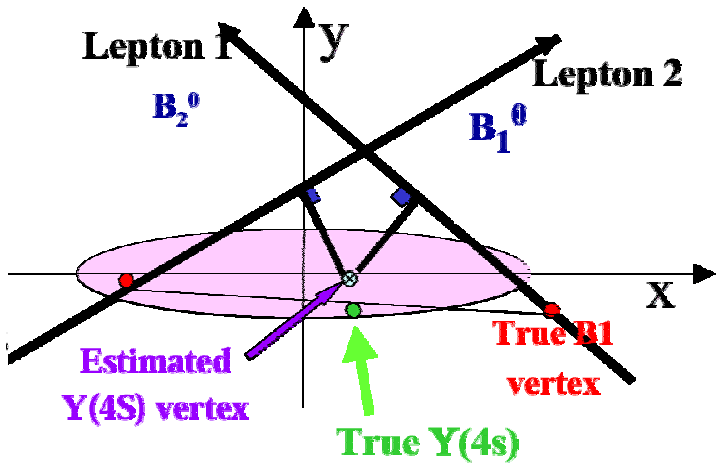
PRL 87 [2001]

$\tau_0 = 1.546 \pm 0.032 \pm 0.022$ ps
$\tau_\pm = 1.673 \pm 0.032 \pm 0.023$ ps
$\tau_\pm/\tau_0 = 1.082 \pm 0.026 \pm 0.012$

Mixing with Inclusive Dilepton Events

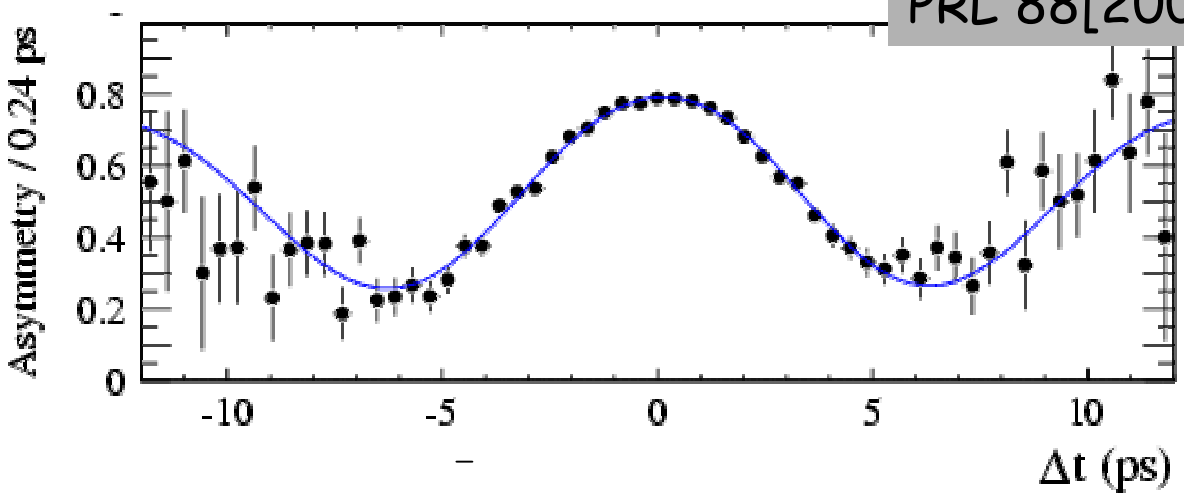
Very precise mixing measurement

- Select events with 2 high momentum leptons (sample contains ~50% B^+)
- Largest syst. is B^0 lifetime and resolution function parameterization



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

PRL 88[2002]



99010 dileptons
($B^0\bar{B}^0$ purity ~40%)

with the same sample:
T and CP violation in mixing

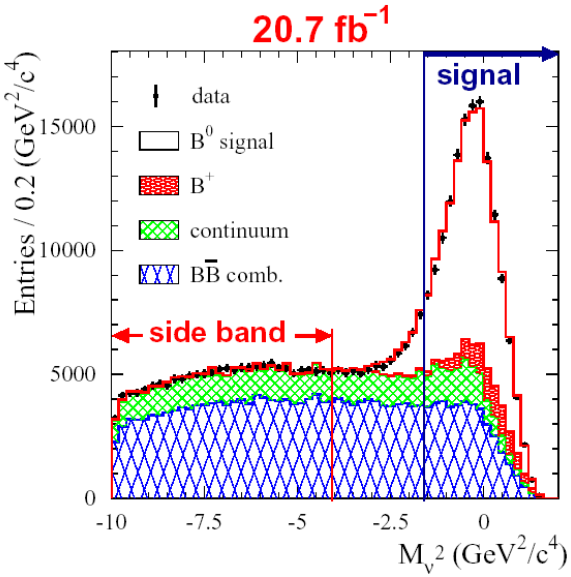
$|q/p| = 0.998 \pm 0.006 \pm 0.007$

PRL 88[2002]

B^0 Lifetime with Partially Reconstructed $B^0 \to D^{*-} l^+ \nu$

$$B^0 \longrightarrow D^{*-} \ell^+ \nu_\ell$$
$$D^{*-} \longrightarrow D^0 \pi_s^-$$

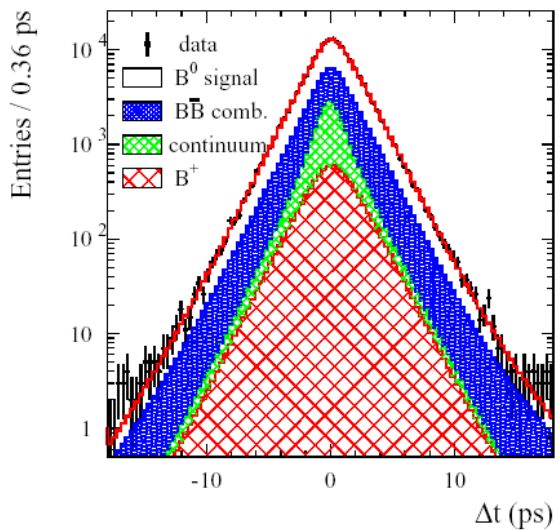
reconstruct lepton and π only



Kinematic constraints at the $\Upsilon(4S)$:

$-p_{D^*} = \alpha p_\pi + \beta$ π in a small cone around D* direction, α and β from simulation

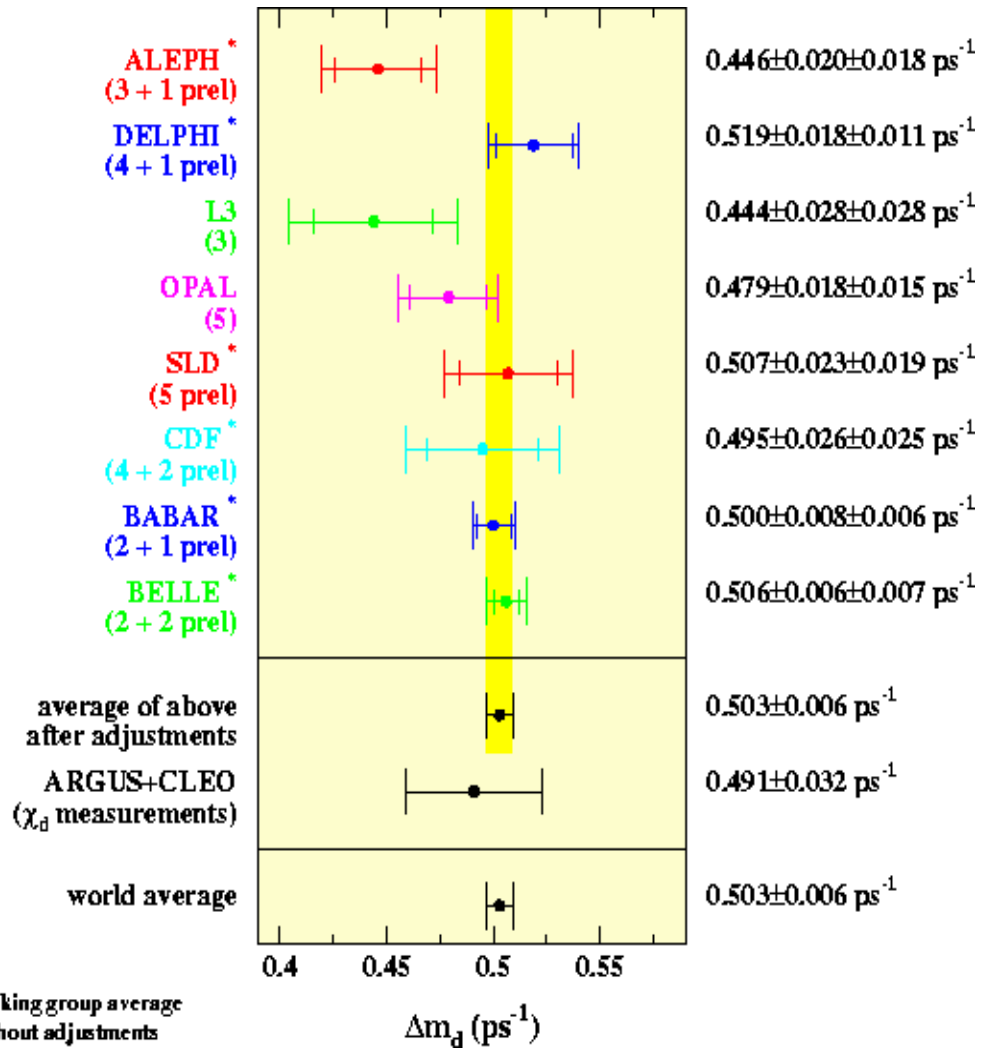
$-M^2_\nu = (p_{B0} - p_{D^*} - p_l)^2 \approx 0$ missing neutrino



$\tau_{B0} = 1.529 \pm 0.012 \pm 0.029$ ps

PRL 89[2002]

Summary



- New simultaneous measurement of Δm_d and τ_{B0} with the exclusive $B^0 \to D^{*-} l^+ \nu_l$ sample

Preliminary

$\Delta m_d = 0.492 \pm 0.018 \pm 0.013$ ps^{-1}

$\tau_{B0} = 1.523^{+0.024}_{-0.023} \pm 0.022$ ps

- Combined BaBar result for B_d mixing frequency:

$\Delta m_d = 0.500 \pm 0.008 \pm 0.006$ ps^{-1}

2% error

Backup slide

Signal Δt Model

- Signal Model (including a $B^{\pm}$ component):

$$\mathcal{G}^{\pm}_{\rm sig} = [(1 - f_{B^+}) \cdot \mathcal{G}^{\pm}_{B^0} + f_{B^+} \cdot \mathcal{G}^{\pm}_{B^+}] \otimes \mathcal{R} \, ,$$

  - neutral and charged B physics models:

$$\mathcal{G}^{\pm}_{B^0}(\Delta t; \tau_{B^0}, \Delta m_{B^0}, \omega_{B^0}) = \frac{1}{4\tau_{B^0}} e^{-|\Delta t|/\tau_{B^0}} \left[1 \pm (1 - 2\omega_{B^0}) \cos(\Delta m_{B^0} \Delta t)\right]$$

$$\mathcal{G}^{\pm}_{B^+}(\Delta t; \tau_{B^0}, \Delta m_{B^0}, \omega_{B^0}) = \frac{1}{4\tau_{B^+}} e^{-|\Delta t|/\tau_{B^+}} \left[1 \pm (1 - 2\omega_{B^+})\right] \, ,$$

    The ratios τ_{B^+}/τ_{B^0} and $\omega_{B^+}/\omega_{B^0}$ are kept constant.

  - Resolution function

$$\mathcal{R}(\delta\Delta t, \sigma_{\Delta t}; \vec{p}) = f \cdot G + (1 - f - f_{\rm out}) \cdot G \otimes E + f_{\rm out} \cdot G_{\rm out} \, .$$

    G = Gaussian, $E = e^{(x/a)}$ for $x < 0$.
    Width of G and decay constant of E scale with $\sigma_{\Delta t}$. Width and bias of $G_{\rm out}$ do not scale with $\sigma_{\Delta t}$. Outler shape is fixed.

Backup slide

Background Δt Model

$$
\begin{aligned}
\mathcal{G}_{\rm BG} &= f_{\rm osc}\cdot\mathcal{G}_{\rm osc} + (1-f_{\rm osc})\cdot\mathcal{G}_{\rm pmt}\ , \\
\mathcal{G}^{\pm}_{\rm pmt}(\Delta t) &= (1/2)\cdot\delta(\Delta t)\cdot\left(1\pm\cdot(1-\omega_{\rm pmt})\right), \\
\mathcal{G}^{\pm}_{\rm osc}(\Delta t) &= (1/4)\cdot\exp(-|\Delta t|/\tau_{\rm bg})\cdot\left(1\pm\cdot(1-\omega_{\rm osc})\cos\Delta m_{\rm bg}\Delta t\right).
\end{aligned}
$$

- continuum — all prompt ($f_{\rm osc}=0$).
- uncorrelated — no oscillating behavior ($\Delta m_{\rm bg}=0$).
- Each Δt model convoluted with a double-gaussian resolution function. Widths scaled with $\sigma_{\Delta t}$. Wide gaussian scale factors and biases are shared among four background models.

Backup slide

Systematic error

Source	$\delta\Delta m_{B^0}$ $[10^{-3}\mathrm{ps}^{-1}]$	$\delta\tau_{B^0}$ [fs]	Note
Selection and fit bias	± 12.3	± 17.8	Stat error on generic MC fit
z scale	± 2.0	± 6.0	0.4% recipe
PEP-II boost	± 0.5	± 1.5	0.1% recipe
SVT alignment	± 3.0	± 5.6	diffDL, diffEL recipes with sig MC
Beamspot position	± 1.0	± 5.0	Move/smear BS in sig MC
Bkg / signal prob.	± 2.9	± 3.2	Vary $m(D^*) - m(D^0)$ fits
Fixed B^+/B^0 lifetime ratio	∓ 0.3	± 1.9	Vary lifetime ratio by $\pm 1\sigma$ (PDG2002)
Fixed B^+/B^0 mistag ratio	∓ 0.1	∓ 0.3	Vary mistag ratios by $\pm 1\sigma$ (BAD119)
more...			

Backup slide

Systematic error

Source	$\delta\Delta m_{B^0}$ $[10^{-3}\mathrm{ps}^{-1}]$	$\delta\tau_{B^0}$ [fs]	Note
Signal resolution model	± 0.9	± 3.4	G+G+G vs GExp+G
Fixed signal outlier shape	± 1.0	± 5.4	Vary outlier width & bias
Bkg Δt models	± 1.2	± 6.3	Vary comb. bkg model
Total syst. error	**13**	**22**	

Backup slide

Mistag fraction determined from simultaneous fit to B_{flav} sample

Tagging Category	Efficiency ε(%)	Mistag Fraction w(%)	$B^0/\overline{B}^0$ diff. Δw(%)	$Q=\varepsilon(1-2w)^2$ (%)
Lepton	11.1 ± 0.2	8.6 ± 0.9	0.6 ± 1.5	7.6 ± 0.4
Kaon	34.7 ± 0.4	18.1 ± 0.7	-0.9 ± 1.1	14.1 ± 0.6
NT1	7.7 ± 0.2	22.0 ± 1.5	1.4 ± 2.3	2.4 ± 0.3
NT2	14.0 ± 0.3	37.3 ± 1.3	-4.7 ± 1.9	0.9 ± 0.2
All	67.5 ± 0.5			25.1 ± 0.8

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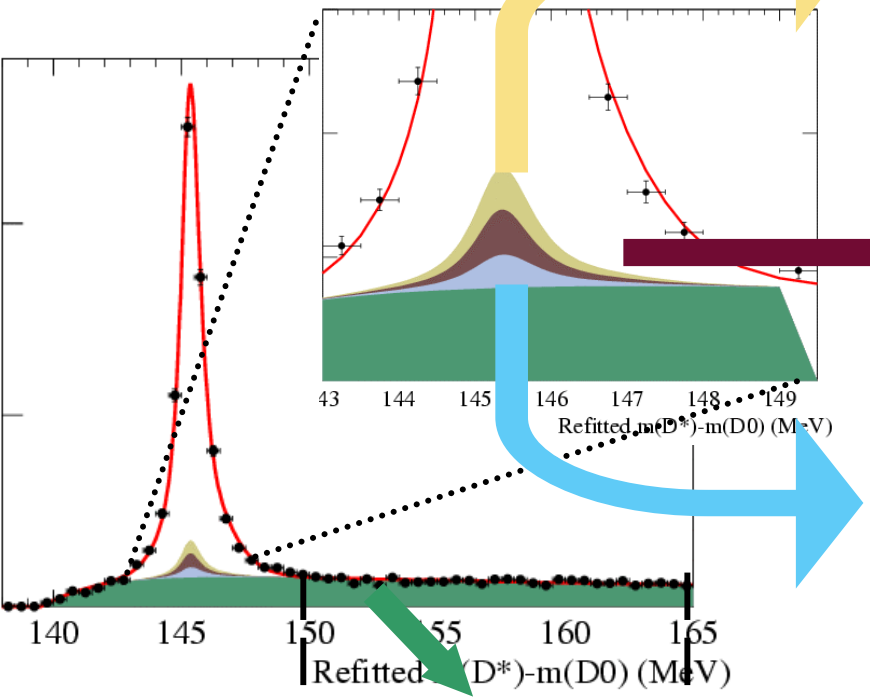
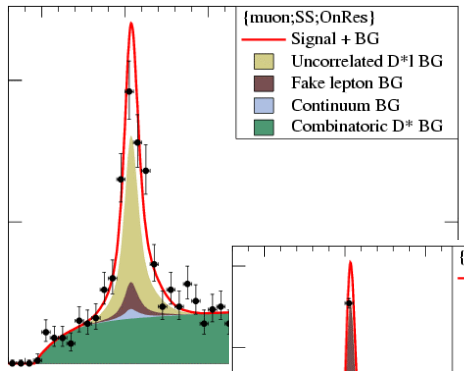
Signal μ Sample

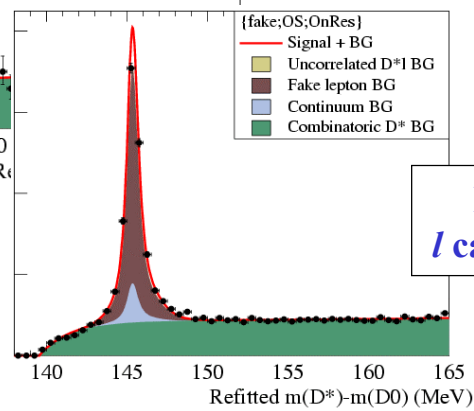
Peaking Bkgs



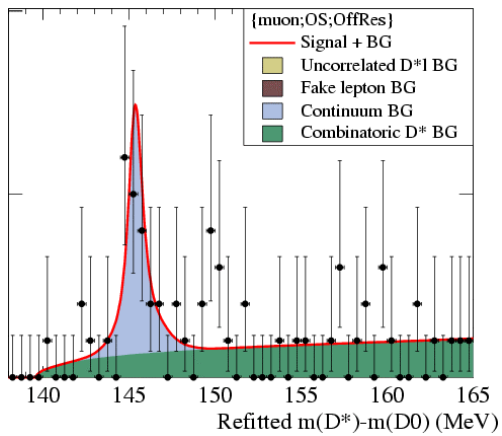
Combinatoric Enriched : Sideband



"*l* not from B_{rec}" Enriched : D^* with flipped *l*



Fake *l* Enriched : *l* candidate fails *e*,μ ID



Continuum D^* Enriched : Off-resonance Data

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