Searches for *CP*/*T* and *CPT* violation in $B^0\overline{B^0}$ mixing

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on behalf of the *BaBar* collaboration

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Outline

- The $B^0\overline{B}^0$ oscillation formalism
- *CP/CPT* violation analysis methods in BaBar:
  - "Inclusive dilepton" method
  - $B \rightarrow D^* \, l \, \nu$ partial reconstruction method
  - Use of fully reconstructed B mesons
- Results
- Conclusions and future perspectives

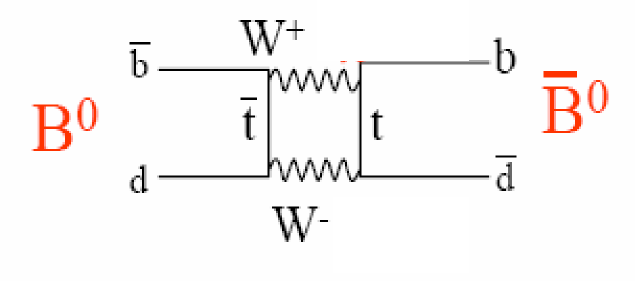
SM $B^0\overline{B}^0$ mixing formalism

CP eigenstates in neutral pseudoscalar meson systems:

$$|B^0_{CP=+1}\rangle = \frac{1}{\sqrt{2}}(|B^0\rangle + |\overline{B}^0\rangle)$$
$$|B^0_{CP=-1}\rangle = \frac{1}{\sqrt{2}}(|B^0\rangle - |\overline{B}^0\rangle)$$

Mass eigenstates:

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



- Time-dependent perturbation theory ($\mathbf{H}_{eff} = \mathbf{M} - i\Gamma/2$)

$$\left|\frac{q}{p}\right|^2 \cong 1 - \mathrm{Im}\,\frac{\Gamma_{12}}{M_{12}} \cong 1$$

CP conserved → (*CP* eigestates) = (mass eigenstates)

→ **$|q/p| = 1$**

CP violation in mixing depends on the size of $\mathrm{Im}(\Gamma_{12}/M_{12})$

SM prediction: $\mathrm{Im}(\Gamma_{12}/M_{12}) = o(10^{-4})$ (*)

(*) M. Ciuchini *et al.*, JHEP **0308**, 031 (2002);
M. Beneke *et al.*, Phys. Lett. **B576**, 173 (2003)

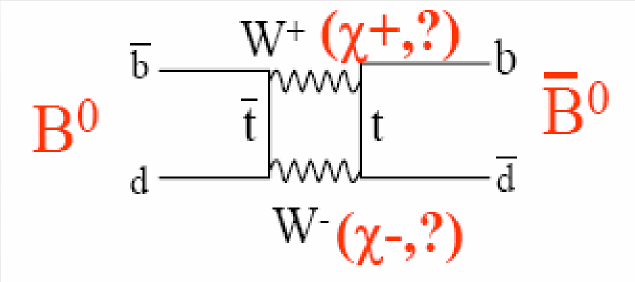
|q/p|: implications on New Physics

- *CP* asymmetry for inclusive semileptonic decays:

$$A_{SL} = \frac{\Gamma(\overline{B}^0 \to l^+ X) - \Gamma(B^0 \to l^- X)}{\Gamma(\overline{B}^0 \to l^+ X) + \Gamma(B^0 \to l^- X)} = \frac{1 - |q/p|^4}{1 + |q/p|^4} \cong 2(1 - |q/p|)$$

- General assumptions on NP models:
  - 3-generation unitarity
  - No NP in tree-level processes

  (see talk by H. Lacker in WG6-12-AM2)



$$\left\langle \overline{B}^0 \middle| M_{12} \middle| B^0 \right\rangle = C_d^2 e^{2i\phi_d} \left\langle \overline{B}^0 \middle| M_{12}^{\mathrm{SM}} \middle| B^0 \right\rangle$$

$$A_{SL} = -\mathrm{Re}\left(\frac{\Gamma_{12}}{M_{12}}\right)^{SM} \frac{\sin 2\phi_d}{C_d} + \mathrm{Im}\left(\frac{\Gamma_{12}}{M_{12}}\right)^{SM} \frac{\cos 2\phi_d}{C_d}$$

General $B^0\overline{B}^0$ mixing formalism

- Modified mass eigenstates if CPT violation is allowed:

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

$$\mathrm{Re}\, z \cong \left(m_{B^0} - m_{\overline{B}^0}\right)/\,\Delta m \cong 0$$
$$\mathrm{Im}\, z \cong \left(\Gamma_{B^0} - \Gamma_{\overline{B}^0}\right)/\,2\Delta m \cong 0$$

	CPT		$\not{CPT}$		
	CP, T	$\not{CP}, \not{T}$	$\not{CP}, T$	$CP, \not{T}$	$\not{CP}, \not{T}$
$\lvert q/p\rvert$	$=1$	$\neq 1$	$=1$	$=1$	$\neq 1$
z	$=0$	$=0$	$\neq 0$	$=0$	$\neq 0$

Different scenarios allowed, according to *CPT* conserved or not. In any case:
CP conserved → (*CP* eigestates) = (mass eigenstates) → **$|q/p| = 1$ <u>AND</u> $z = 0$**

Sidereal time-dependence of z

- Basic assumption: in a *CPT*-violating theory, Lorentz invariance is also violated [O. Greenberg, PRL **89**, 231602, (2002)]
  - z requires a more precise parameterization depending on the decaying meson 4-velocity [V. A. Kostelecký, PRL **80**, 1818 (2004)]:

$$z \approx \frac{\beta^\mu \Delta a_\mu}{\Delta m - i\Delta\Gamma/2}$$

- $\beta^\mu = \gamma_B(1, \vec{\beta}_B)$
- Δa contains Lorentz-violating coupling coefficients

  - $\beta \sim \beta_{\Upsilon(4S)}$ → constant in modulus but with direction varying in time according to the Earth rotation w.r.t. to the Universe:

$$z \equiv z(\hat{t}) = z_0 + z_1 \cos(\Omega\hat{t} + \phi)$$

    - $\Omega = 2\pi\ rad / sidereal\ day$ is the Earth's rotation frequency (1 sidereal day ~ 0.997 solar days)
    - $\hat{t}$ is the sidereal time calculated from the event time-stamp
    - z_0 and z_1 contain New Physics coefficients (Δa)

Rates for semileptonic B decays

- The calculation is straightforward (no DCS decay contribution):

$$\frac{dN}{d(\Delta t)} \propto \left|\frac{q}{p}\right|^{-2s_t} e^{-\frac{|\Delta t|}{\tau}}\left[\cosh\left(\frac{\Delta\Gamma\Delta t}{2}\right)-\cos(\Delta m\Delta t)\right]$$

Mixed events

$$\frac{dN}{d(\Delta t)} \propto e^{-\frac{|\Delta t|}{\tau}}\left[\cosh\left(\frac{\Delta\Gamma\Delta t}{2}\right)+\cos(\Delta m\Delta t)-s_t \operatorname{Re} z \sinh\left(\frac{\Delta\Gamma\Delta t}{2}\right)+s_t \operatorname{Im} z \sin(\Delta m\Delta t)\right]$$

Unmixed events

- In the perfect *B*-tagging limit (zero mistag):
  - Mixed events (χ_d ~ 18% of the total) → sensitivity to $|q/p|$
  - Unmixed events → sensitivity to z
  - $\Delta\Gamma$ measurements really challenging with inclusive events. Using the approximation: $\mathrm{Re}z \cdot \sinh(\Delta\Gamma\Delta t/2) \sim \mathrm{Re}z \cdot \Delta\Gamma \cdot \Delta t/2$, the quantity $\mathrm{Re}z \cdot \Delta\Gamma$ can be measured using the $\Delta\Gamma$ PDG value.

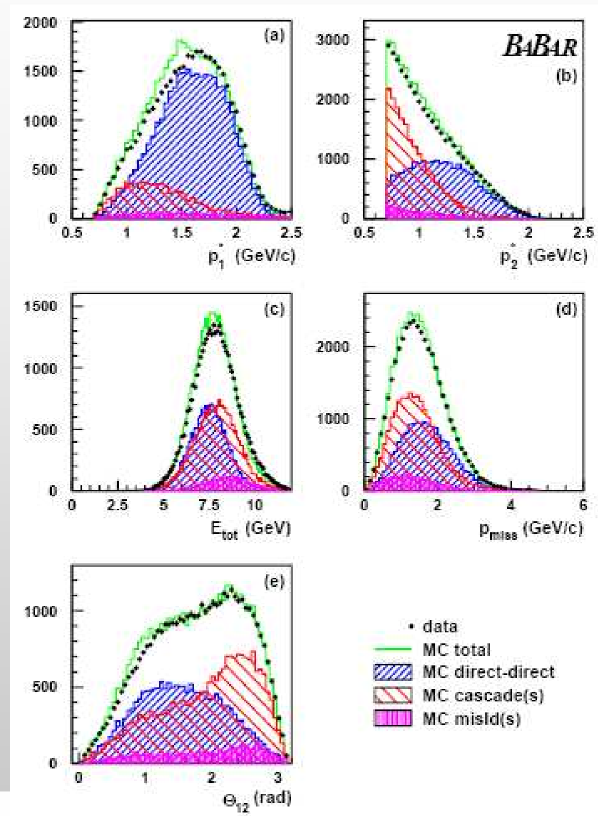
Comparison of two methods

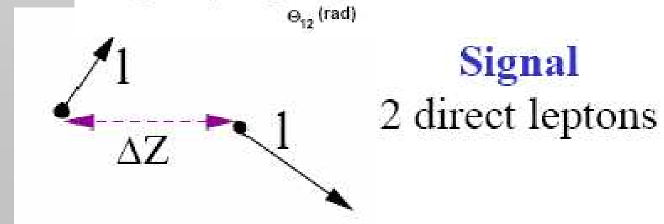
- Inclusive dileptons ($B^0_1 \rightarrow l^\pm X$, $B^0_2 \rightarrow l^\pm X$) :
  - Use of all events with two semileptonic decays (BR ~ 4%)
  - High number of selected events
  - Significant charged-B background
  - Use of control samples (e.g. Bhabhas for electrons) is necessary
- Partial reconstruction of the $B^0_{rec} \rightarrow D^* \, l \, \nu$ ($D^* \rightarrow D^0\pi$) decay (the other B is lepton-tagged, i.e. $B^0_{tag} \rightarrow l^\pm X$) :
  - Lower statistics ($D^* \, l \, \nu$ + soft pion efficiency)
  - Lower charged-B background
  - Charge detection asymmetries fitted from the data
  - Possible use of kaon-tagged events ($B^0_{tag} \rightarrow K^\pm X$)

Dileptons: event selection

- $\Delta t = t^+ - t^-$ (random choice for same sign)
- Selection:
  - Electron and muon ID selectors
  - Continuum rejection:
    - R_2, aplanarity, number of tracks
    - Invariant mass cuts for J/ψ, ψ', converted γ
    - ~ 3% non $B\bar{B}$ events surviving
  - Neural network for direct lepton selection
- Number of events after selection:
  - 1.183K opposite-sign
  - 221K same-sign

S/B ~ 0.7





Dileptons: detection asymmetries

- a^{dir} = charge detection asymmetry for direct leptons

a^{dir} and $|q/p|$ completely degenerate

- a^{dir}_e from control samples (Bhabhas and radiative Bhabhas) integrated on the direct e phase space:

From particle ID → $a_e = (0.4 \pm 0.2) \times 10^{-3}$

From tracking → $a_{trk} = (0.8 \pm 0.3) \times 10^{-3}$

→ $\mathbf{a_{e1}^{dir} = 1.2 \times 10^{-3}}$

- a_μ free in the Δt fit → significant reduction in the associated systematics

Systematic Effects	$\sigma(\|q/p\|)$ $(\times 10^{-3})$	$\sigma(\mathrm{Im}\,z)$ $(\times 10^{-3})$	$\sigma(\Delta\Gamma \times \mathrm{Re}\,z)$ $(\times 10^{-3}\,\mathrm{ps}^{-1})$
Ch. asym. of non-$B\overline{B}$ bkg	0.6	0.0	0.0
Ch. asym. in tracking	1.0	0.0	0.0
Ch. asym. of electrons	1.4	0.0	0.0
PDF modeling	0.3	2.5	1.2
Fraction of bkg components	0.2	0.4	0.1
Δm, τ_{B^0}, $\tau_{B^\pm}$ and $\Delta\Gamma$	0.2	1.9	1.1
SVT alignment	0.5	0.6	1.2
Total	1.9	3.2	2.0

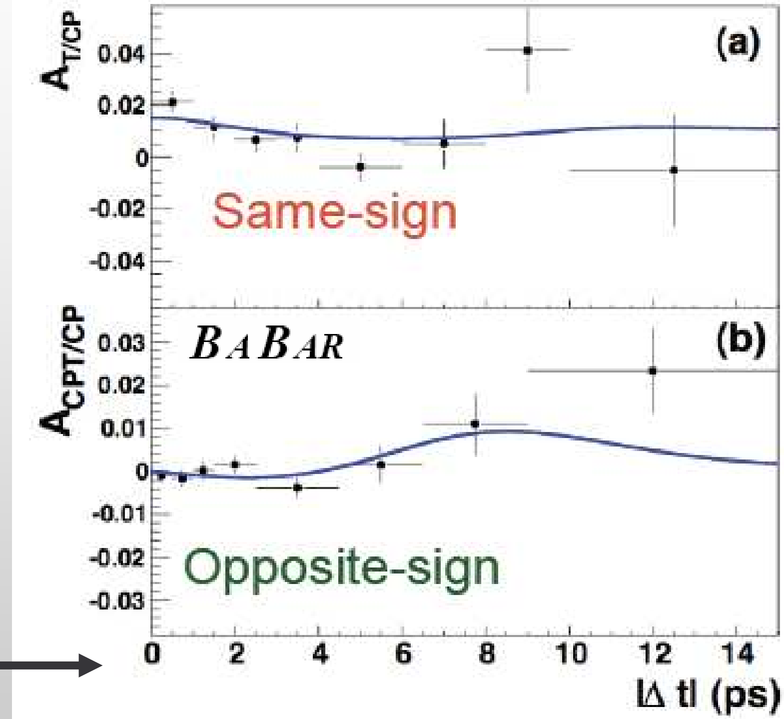
Still main systematic contribution for $|q/p|$

Dileptons: Δt fit and results

- Binned maximum likelihood fit to Δt distribution for different categories:
  - Signal: 2 direct leptons
  - "Cascades": one of the 2 leptons is actually coming from a secondary D-meson decay
  - Other (e.g. leptons from τ decays, from charmonium resonances …)
  - Non-$B\bar{B}$ background

Both B^0 and B^+ (applies to Signal, "Cascades" and Other)

Resulting fitted asymmetries →



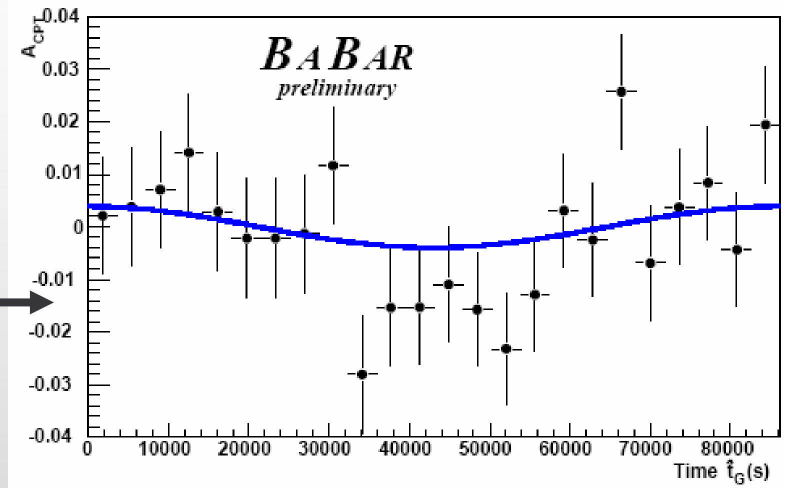
$$
\begin{aligned}
|q/p| - 1 &= (-0.8 \pm 2.7(\mathrm{stat.}) \pm 1.9(\mathrm{syst.})) \times 10^{-3}, \\
\mathrm{Im}\, z &= (-13.9 \pm 7.3(\mathrm{stat.}) \pm 3.2(\mathrm{syst.})) \times 10^{-3}, \\
\Delta\Gamma \times \mathrm{Re}\, z &= (-7.1 \pm 3.9(\mathrm{stat.}) \pm 2.0(\mathrm{syst.})) \times 10^{-3}\,\mathrm{ps}^{-1}.
\end{aligned}
$$

232M $B\bar{B}$ pairs
PRL **96**, 251802 (2006)

Dileptons: adding sidereal time-dependence

$$z \equiv z(\hat{t}) = z_0 + z_1 \cos(\Omega \hat{t} + \phi)$$

Opposite-sign asymmetry projected on the GMST (Greenwich Mean Sidereal Time) axis, modulo 1 day



$$\begin{aligned}
\mathrm{Im}\, z_0 &= (-14.1 \pm 7.3(\mathrm{stat.}) \pm 2.4(\mathrm{syst.})) \times 10^{-3}, \\
\Delta\Gamma \times \mathrm{Re}\, z_0 &= (-7.2 \pm 4.1(\mathrm{stat.}) \pm 2.1(\mathrm{syst.})) \times 10^{-3}\ \mathrm{ps}^{-1}, \\
\mathrm{Im}\, z_1 &= (-24.0 \pm 10.7(\mathrm{stat.}) \pm 5.9(\mathrm{syst.})) \times 10^{-3}, \\
\Delta\Gamma \times \mathrm{Re}\, z_1 &= (-18.8 \pm 5.5(\mathrm{stat.}) \pm 4.0(\mathrm{syst.})) \times 10^{-3}\ \mathrm{ps}^{-1}.
\end{aligned}$$

232M $B\bar{B}$ pairs Preliminary
hep-ex/0607103

can be directly related to *CPT*-violating coefficients Δa_μ

$$\begin{aligned}
\Delta a_0 - 0.30 \Delta a_Z &\approx -(5.2 \pm 4.0)(\Delta m/\Delta\Gamma) \times 10^{-15}\ \mathrm{GeV}, \\
\sqrt{(\Delta a_X)^2 + (\Delta a_Y)^2} &\approx (37 \pm 16)|\Delta m/\Delta\Gamma| \times 10^{-15}\ \mathrm{GeV}.
\end{aligned}$$

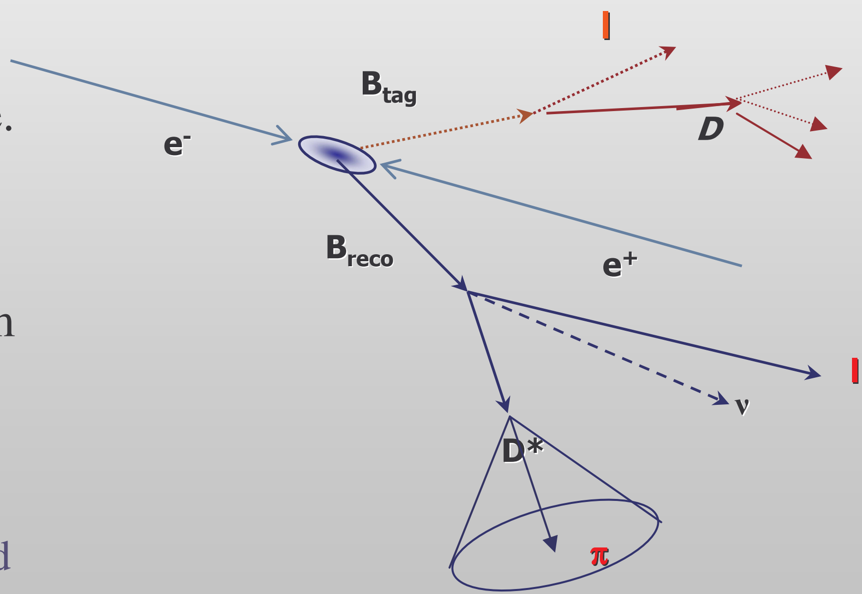
D* l ν: reconstruction technique

- On the reconstructed side ($B^0 \rightarrow D^* l \nu$) just the lepton and the π from $D^* \rightarrow D^0\pi$ are detected. Due to the reduced amount of phase space in the decay, the D* 4-momentum can be approximately inferred from the pion corresponding quantities.
- With this approximation the "missing" (neutrino) mass is computed:

$$M_\nu^2 = \left(P_B - P_{D^*} - P_l\right)^2$$

assuming the B at rest in the CM frame.

- 471K events selected (S/B ~ 2 in signal region)
- Detection asymmetries determined from data by:
  - Including untagged B^0 and $\bar{B}^0$ events in the sample
  - Using an extended maximum likelihood method

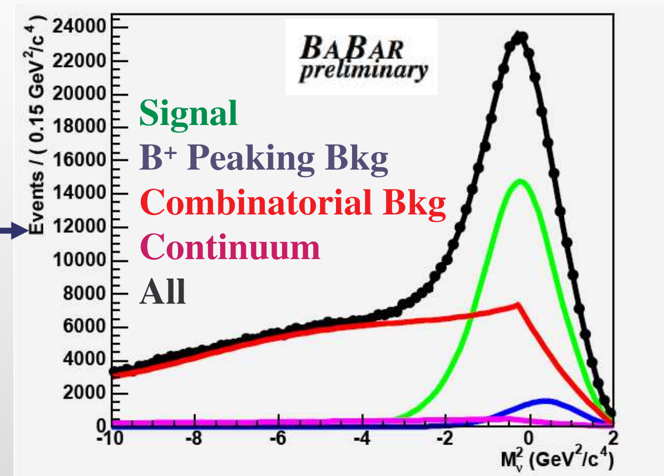


D* l ν: neutrino mass and Δt fits

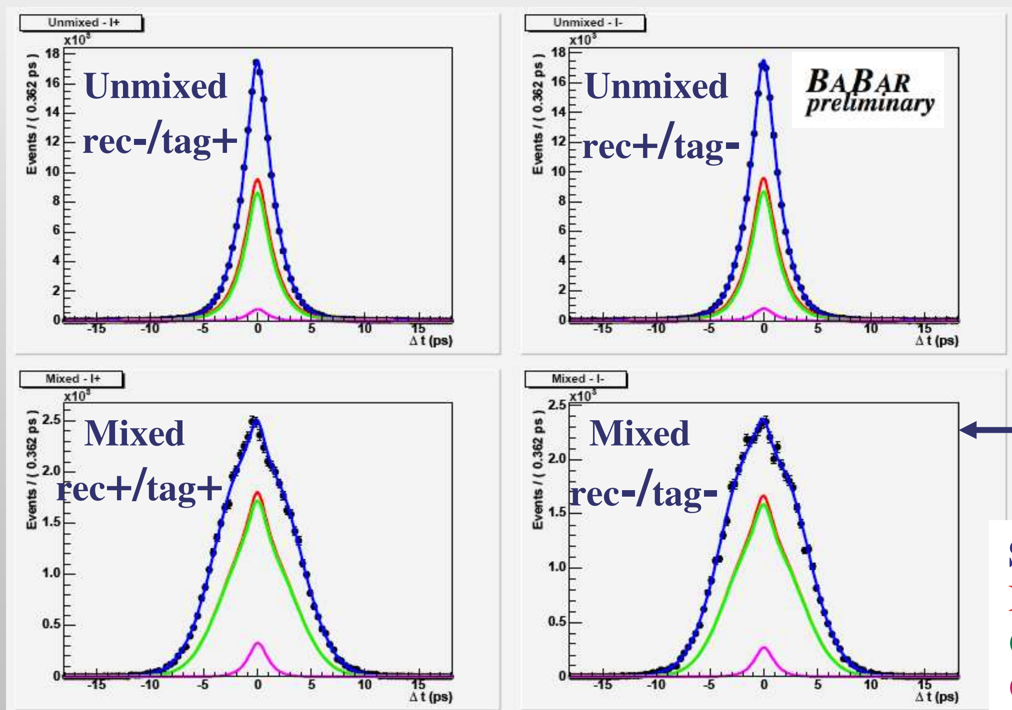
- Total PDF = $\Sigma_i f_i P_i(\Delta t)$

  i = {signal, B^+ peaking bkg, combinatorial bkg, continuum}

- f_i determined from M_ν^2 fits



- $\Delta t = t_{rec} - t_{tag}$
- PDF projections on Δt for the 4 different tagged categories



Signal
B+ Peaking Bkg
Combinatorial Bkg
Continuum

$D^* \ell \nu$: systematics and results

- Main sources of systematics:
  - Background asymmetries (fixed from sidebands or off-resonance data)

Source	Syst. error ($\cdot 10^{-3}$)
Reconstruction asymmetry for combinatorial background	1.1
Asymmetries for continuum	1.0
Tagging asymmetry for decay-side tagged events	0.2
M_ν^2 fractions	1.0
Likelihood fit bias	0.6
Physical parameter fixing	0.5
Mistag parameters	0.0
Resolution function	0.3
Sideband-fixed parameters	0.5
Total	2.0

  - Determination of f_i from M_ν^2 fits (especially for untagged events)

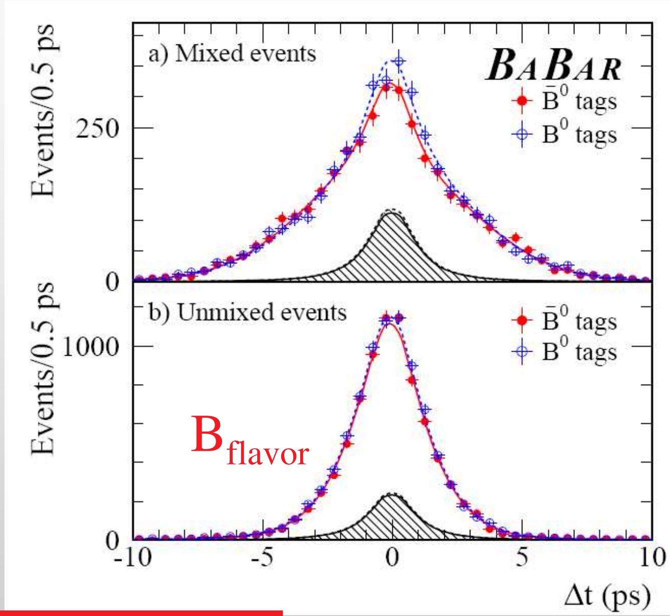
$$|q/p| - 1 = (6.5 \pm 3.4(\text{stat.}) \pm 2.0(\text{syst.})) \cdot 10^{-3}$$

1.7σ significance, compatible with the hypothesis of no *CP/T* violation in mixing

221M $B\bar{B}$ pairs
Preliminary
hep-ex/0607091

CP/T and *CPT* using fully reconstructed B meson decays

- Complementary to inclusive semileptonic methods
- B_{rec} = B_{flavor} ($B^0 \rightarrow D^{(*)}\pi/\rho/a_1$, $J/\psi\ K^{*0}$)
  B_{CP} ($B^0 \rightarrow (c\bar{c})K_S$, $J/\psi\ K_L$)
- "Standard" B reconstruction using ΔE / m_{ES}
  - 22.6K tagged events selected, <S/B> ~ 5
- Δt PDFs much more complicated, involving large values of $\mathrm{Re}\lambda_{CP}$, $\mathrm{Im}\lambda_{CP}$



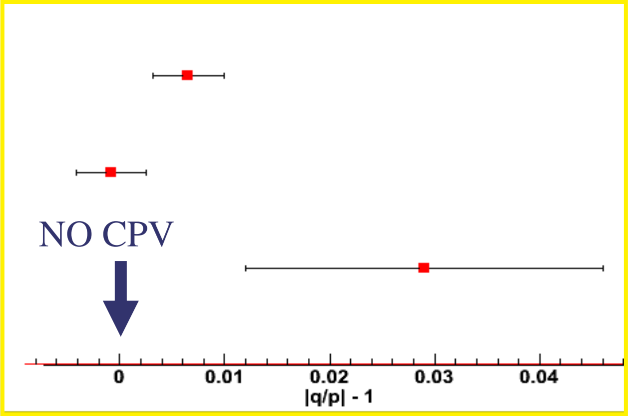
$$\mathrm{sgn}(\mathrm{Re}\,\lambda_{CP})\Delta\Gamma/\Gamma = -0.008 \pm 0.037(\mathrm{stat.}) \pm 0.018(\mathrm{syst.})$$
$$|q/p| = 1.029 \pm 0.013(\mathrm{stat.}) \pm 0.011(\mathrm{syst.})$$
$$(\mathrm{Re}\,\lambda_{CP}/|\lambda_{CP}|)\,\mathrm{Re}\,\mathsf{z} = 0.014 \pm 0.035(\mathrm{stat.}) \pm 0.034(\mathrm{syst.})$$
$$\mathrm{Im}\,\mathsf{z} = 0.038 \pm 0.029(\mathrm{stat.}) \pm 0.025(\mathrm{syst.})$$

88M $B\bar{B}$ pairs
PRD **70**, 012007 (2004)

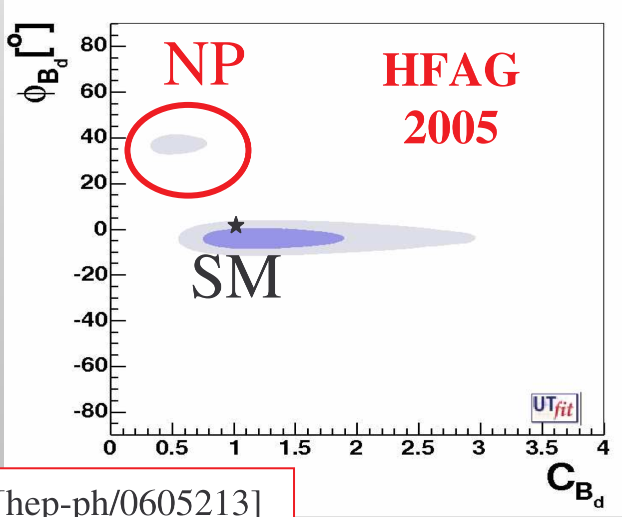
$|\Delta\Gamma/\Gamma|$ effectively measured with this method

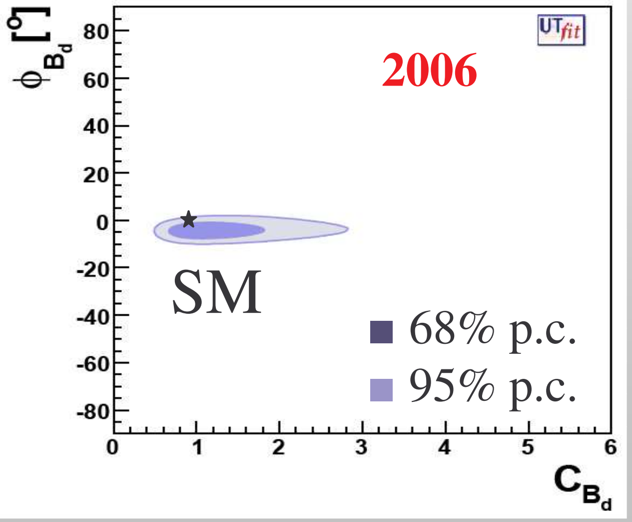
Results: *CP/T* violation

- Two new |q/p| determinations in 2006 with different methods
- Both compatible with the hypothesis of no *CP/T* violation in mixing (D* *l* ν @ 9.8% C.L.)



- Use of $A_{CP/T}$ in *UTfit* with other Unitary Triangle constraints to estimate NP parameters

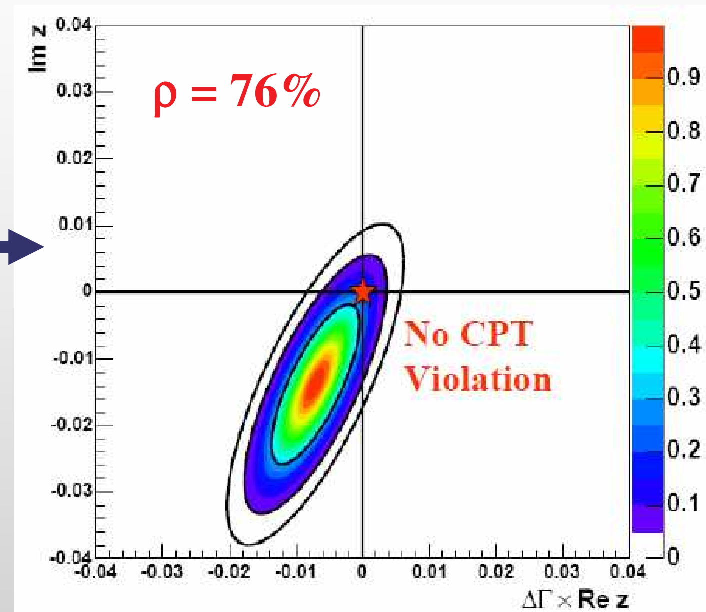


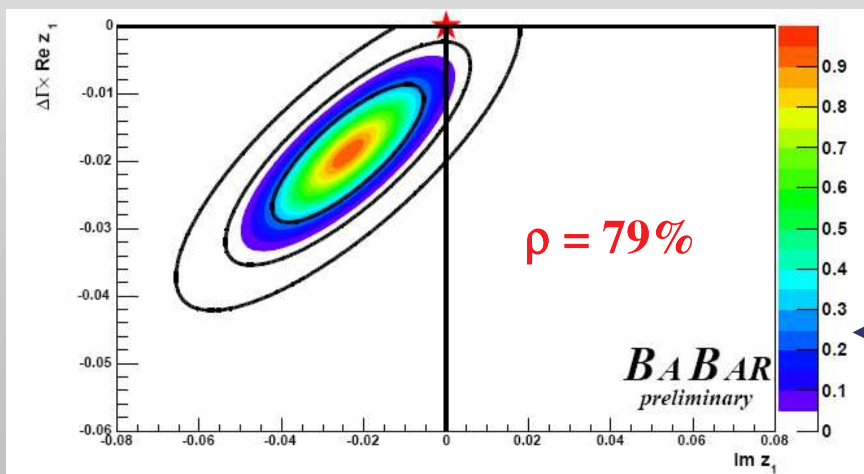


[hep-ph/0605213]

Results: *CPT* violation

- *CPT* violation with constant z: in the (Rez·ΔΓ, Imz) plane the result is compatible with SM (0,0) at:
  - ~1.5σ (assuming $\Delta\Gamma = 0.006\ ps^{-1}$)
  - < 1σ (assuming ΔΓ = 0)





- Sidereal-time dependent *CPT* violation: in the ($Rez_1 \cdot \Delta\Gamma$, Imz_1) plane result compatible with (0,0) at 2.2σ

Conclusions and future perspectives

- No evidence of *CP/T* or *CPT* violation in $B^0\bar{B}^0$ mixing up to now

Parameter	Current stat. error (10^{-3})	Current syst. error (10^{-3})	Exp. stat. error with 1 ab^{-1} (10^{-3})
|q/p| (dileptons)	2.7	1.9	**1.3**
|q/p| (D* l ν)	3.4	2.0	**1.6**
|q/p| (full reco)	13.0	11.0	**3.7**
$\Delta\Gamma$ x Rez	7.3	3.2	**3.5**
Imz	3.9	2.0	**1.9**
$\Delta\Gamma$ x Rez_1	10.7	5.9	**5.2**
Imz_1	5.5	4.0	**2.6**

← Better sensitivity if kaon-tagged events will be added

- All measurements are statistically dominated: with 1 ab^{-1} statistical errors will be of the same size as systematics
- Some (NOT most) of the systematic errors are statistics-dependent ← sizeable expected reduction (full reco)

⇒

- SM |q/p| probably not observable at "regular" *b*-factories
- More stringent constraints on general NP models on the way