Recent results on CP and CPT violation with the BaBar detector

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Physics of fundamental Symmetries and Interactions PSI 2016

Nature's simmetry (I)

- In the 1950's, it was discovered that the weak interaction **violates** each one of: time-reversal ("**T**"), charge ("**C**"), and parity ("**P**") fundamental symmetries of Nature.

- In 1964 it was discovered that the weak interaction also violated **CP** in the decay of neutral kaons.

- **CP** symmetry violation is one of the 3 necessary conditions (the "Sakharov conditions") for matter-antimatter asymmetry of the Universe to develop.

- These effects are incorporated in the Standard Model but nobody knows **why** these symmetry violations occur, nor why they **only** occur in the weak interaction…

- BaBar @ SLAC and Belle @ KEK were constructed to investigate these asymmetries primarly in B and D mesons system.

Nature's simmetry (II)

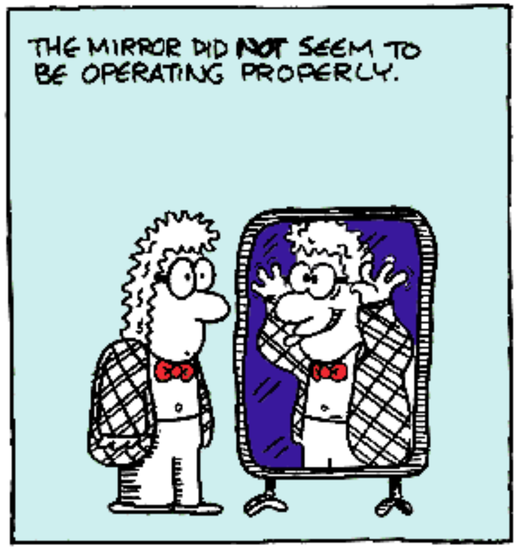
- Even if the weak interaction violated **C, P, T** and **CP is** believed that **CPT** in conserved

- **CPT** Invariance is required by every relativistic quantum field theory

- **CPT** Theorem states:

  all interactions are invariant under the successive operation of C (=charge conjugation), P (=parity operation), and T (=time reversal)

=> Masses, lifetimes, moments, etc. of particles and antiparticles must be identical



✓ A test of CPT symmetry in $\bar{B}^0$-B^0 mixing and in $B^0 \to \bar{c}cK^0$ decays

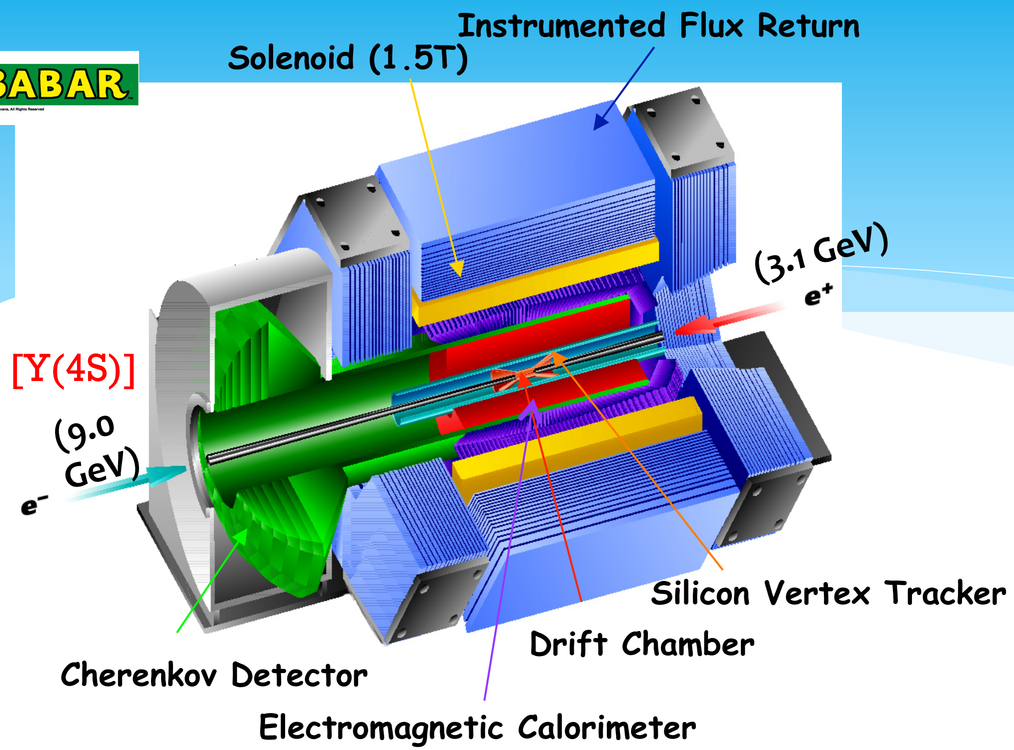
PRD 94, 011101 (R) (2016)

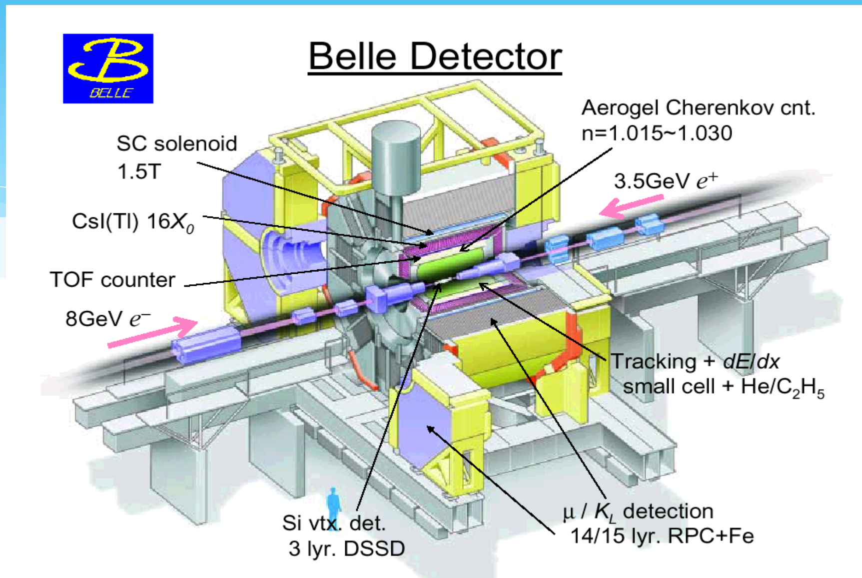
✓ Measurement of the Unitarity Triangle paramenter sin(2β) in $B^0 \to D^0h^0$ decays

PRD 115, 121604 (2016)

First combined BaBar+Belle analysis

The BaBar and Belle detectors





	BELLE	BaBar
Υ(5S)	121 fb^{-1}	
Υ(4S)	711 fb^{-1}	433 fb^{-1}
Υ(3S)	3.0 fb^{-1}	30 fb^{-1}
Υ(2S)	24 fb^{-1}	14 fb^{-1}
Υ(1S)	5.7 fb-1	
Off-resonance	87 fb^{-1}	54 fb^{-1}
Scan	68fb^{-1}	
Total	1020fb^{-1}	531fb^{-1}

A test of CPT symmetry in B^0-$\bar{B}^0$ mixing and in $B^0 \rightarrow c\bar{c}K^0$ decays

PRD 94, 011101 (R) (2016)

Analysis Motivation (I)

- ✓ The discovery of CP violation in 1964 motivated searches for T and CPT violation. Since CPT = CP×T .

- ✓ Violation of CP means that T or CPT or both are also violated.

- ✓ Large CP violation in the B^0 system was discovered in 2001 in the interplay of B^0 -$\bar{B}^0$ mixing and $B^0 \rightarrow c\bar{c}K^0$ decays.

- ✓ T violation was discovered only recently. **PRL 109, 211801 (2012)**

- ✓ In this present analysis, we test CPT symmetry quantitatively in B^0 -$\bar{B}^0$ mixing and in $B^0 \rightarrow c\bar{c}K^0$ decays.

Analysis Motivation (II)

Transitions in the B^0 - $\bar{B}^0$ system are well described by the quantum-mechanical evolution of a two-state wave function

$$\Psi = \psi_1|B^0\rangle + \psi_2|\bar{B}^0\rangle$$

using the Schrödinger equation $\dot{\Psi} = -i\mathcal{H}\Psi,$

where the Hamiltonian is given by two constant Hermitian matrices, $\mathcal{H}_{ij} = m_{ij} + i\Gamma_{ij}/2$

In this evolution, CP violation is described by three parameters, **|q/p| , Re (z)**, and **Im(z)**

$$|q/p| = 1 - \frac{2\mathrm{Im}(m_{12}^*\Gamma_{12})}{4|m_{12}|^2 + |\Gamma_{12}|^2},$$

$$z = \frac{(m_{11} - m_{22}) - i(\Gamma_{11} - \Gamma_{22})/2}{\Delta m - i\Delta\Gamma/2},$$

Δm and $\Delta\Gamma$ are the mass and the width differences of the two mass eigenstates

Previous Measurements

$$|q/p| = 1 - \frac{2\mathrm{Im}(m_{12}^{*}\Gamma_{12})}{4|m_{12}|^2 + |\Gamma_{12}|^2},$$

$$z = \frac{(m_{11} - m_{22}) - i(\Gamma_{11} - \Gamma_{22})/2}{\Delta m - i\Delta\Gamma/2},$$

- ✓ Testing T symmetry means measuring |q/p|.
- ✓ Testing CPT symmetry means measuring Im(z).
- ✓ Testing CP symmetry means measuring |q/p| and z.
- ✓ Present PDG average for |q/p|: $1 + (0.8 \pm 0.8) \times 10^{-3}$, no T violation seen.
- ✓ Present average for Im(z): $(-8 \pm 4) \times 10^{-3}$.
- ✓ Present average for Re(z): $(19 \pm 40) \times 10^{-3}$, no CPT violation seen.

A Test of CPT Symmetry in Mixing, and in B^0 Decay (I)

- Take advantage of the fact that B-mesons are produced as entangled pairs in Y(4S) decays.

- They can be expressed in terms of either flavor-eigenstantes B^0 and $\bar{B}^0$, or the states B_+ and B_- .

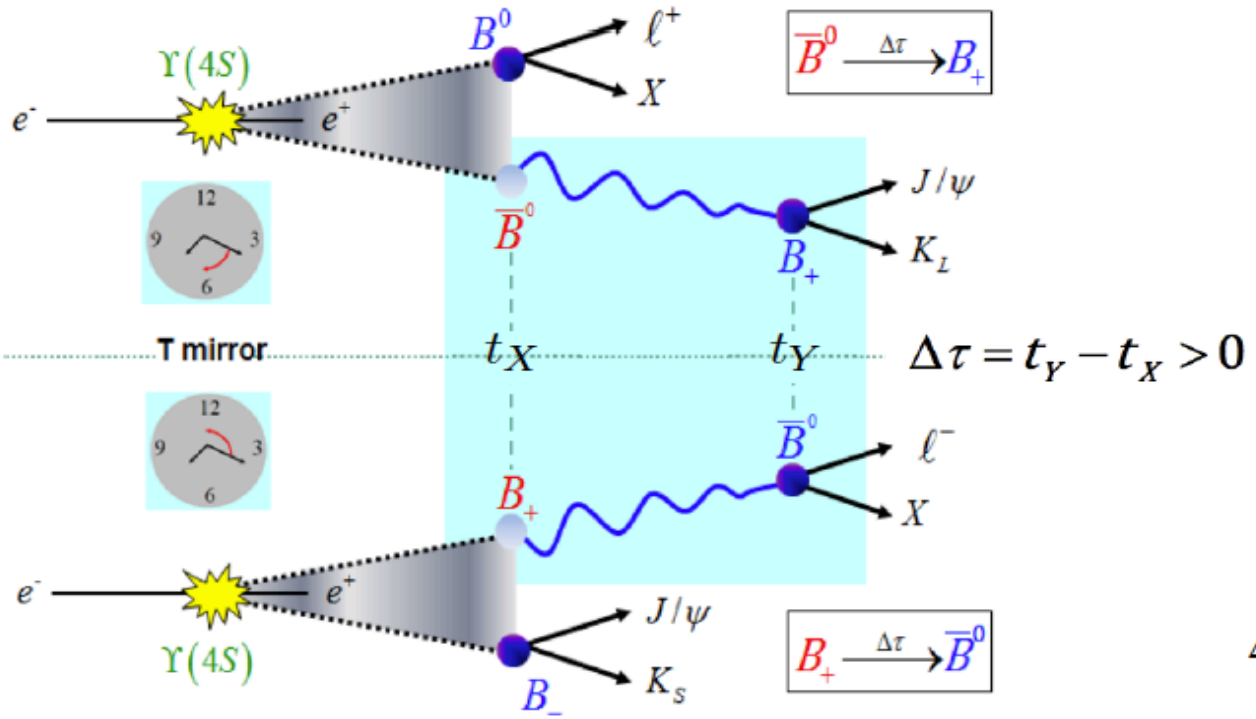
- The stated B_+ and B_- are tagged by decays to $J/\psi K_L$ (CP-even) and $J/\psi K_S$ (CP-odd) respectively.

- Flavor eigenstates can be tagged by semileptonic B decays to l^+X and l^-X.

- **Search for T violation by comparing rates for transitions between flavor and CP states with the rates for the time-reversed processes**

A Test of CPT Symmetry in Mixing, and in B⁰ Decay (II)

- Example decay sequence:



$$\Delta t = t_{CP} - t_{\mathrm{flav}}$$

Reference (X, Y)	***T-Transformed (X, Y)***
$B^0 \to B_+$ $(l^-, J/\psi K_L)$	$B_+ \to B^0$ $(J/\psi K_S, l^+)$
$B^0 \to B_-$ $(l^-, J/\psi K_S)$	$B_- \to B^0$ $(J/\psi K_L, l^+)$
$\bar{B}^0 \to B_+$ $(l^+, J/\psi K_L)$	$B_+ \to \bar{B}^0$ $(J/\psi K_S, l^-)$
$\bar{B}^0 \to B_-$ $(l^+, J/\psi K_S)$	$B_- \to \bar{B}^0$ $(J/\psi K_L, l^-)$

Reference: Physical Process
(X,Y): Reconstructed Final States

B_+, B_- **tagged by** $J/\psi K_L$, $J/\psi K_S$

A Test of CPT Symmetry in Mixing, and in B^0 Decay (IIII)

Analysis performed using the four assumptions:

- ✓ $A=A(B^0 \rightarrow c\bar{c}K^0)$ and $\bar{A}(\bar{B}^0 \rightarrow c\bar{c}\bar{K}^0)$ have a single weak phase
- ✓ Assume and B does not decay to $c\bar{c}K^0$ and $\bar{B}^0$ does not decay $c\bar{c}K^0$
- ✓ CP violation in K -$\bar{K}^0$ Is negligible
- ✓ Assume that $\Delta\Gamma=0$

- ✓ We extract the parameter $|\bar{A}/A|$ which relates to CPT violation in decay amplitudes
- ✓ We also extract the real (Re) and Imaginary (Im) part of z which relate to CPT violation in mixing

A Test of CPT Symmetry in Mixing, and in B^0 Decay

Results :

$$Im(z)=0.010 \pm 0.030 \pm 0.013$$
$$Re(z)=-0.065 \pm 0.028 \pm 0.014$$

471×10^6 $B\bar{B}$ decays

The results for Im(Z) is not competitive with that from di-lepton decays

PRL 96, 211802 (2006)

The Re(z) result deviates from 0 by 2.1 σ.

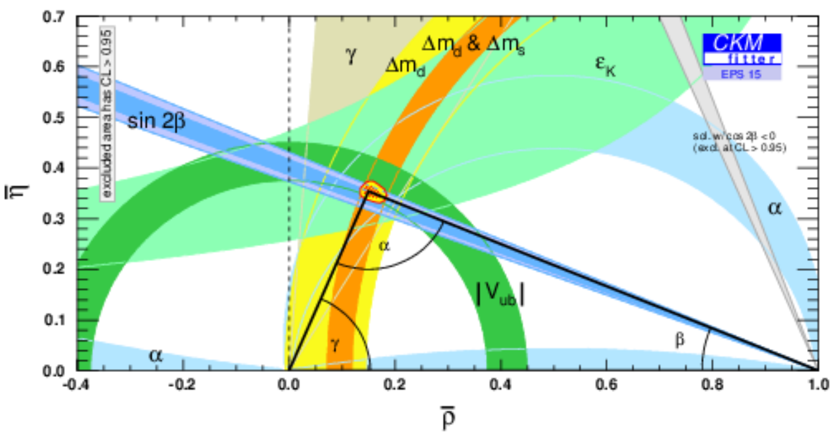
It replaces an older BABAR result from 88 M $B\bar{B}$ events, and it has uncertainties comparable with Belle from 535 M $B\bar{B}$ events

- 0.019 ± 0.037 ± 0.033. **PRD 85, 071105 (2012)**

$$|\bar{A}/A|=0.999 \pm 0.023 \pm 0.017$$

All the three results are in agreement with CPT symmetry in B^0 $\bar{B}^0$ mixing and in $B^0 \rightarrow c\,\bar{c}\,K^0$ decays.

Measurement of the Unitarity Triangle parameter sin(2β) in $B^0 \to D^0 h^0$ decays



PRD 115, 121604 (2016)

CP Violation in the SM: The CKM Matrix

- ✓ Mass eigenstates are not equal to the weak eigenstates: quark-mixing described by unitary CKM matrix.
- ✓ Complex matrix elements lead to different amplitudes for quarks and anti-quarks ->CP violation.
- ✓ The CKM matrix V_{ij} is unitary with 4 independent fundamental parameters

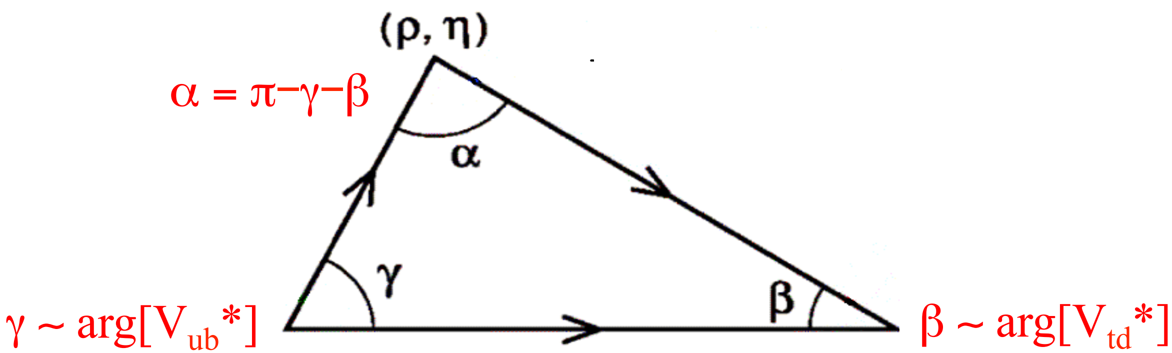
$$V^*_{ub}V_{ud} + V^*_{cb}V_{cd} + V^*_{tb}V_{td} = 0$$

- ✓ Unitarity constraint from 1st and 3rd columns: $\Sigma_i V^*_{i3}V_{i1}=0$

$$\begin{array}{c} \\ u \\ c \\ t \end{array}\begin{pmatrix} d & s & b \\ V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

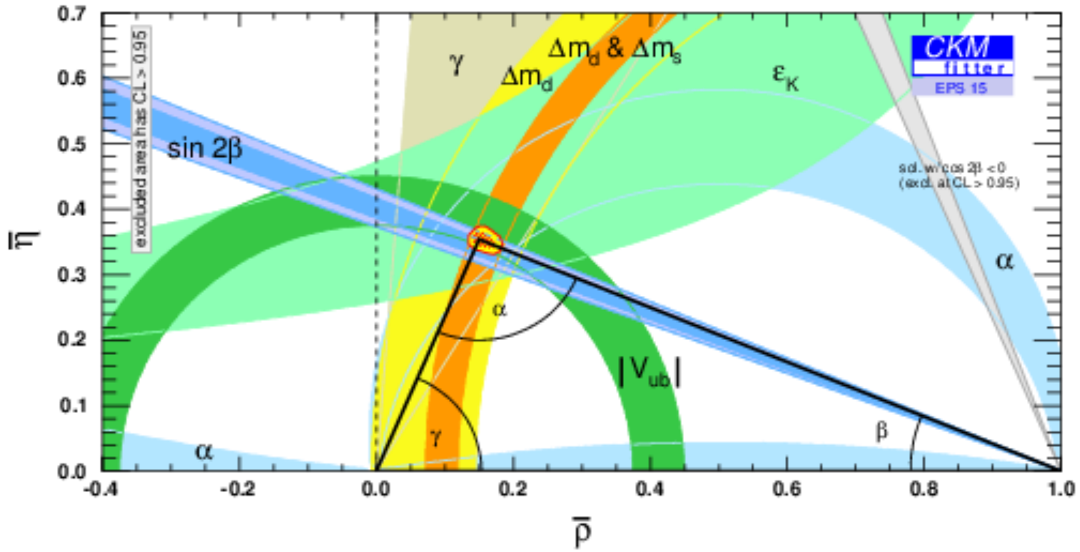
CKM phases
(in Wolfenstein convention)

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$



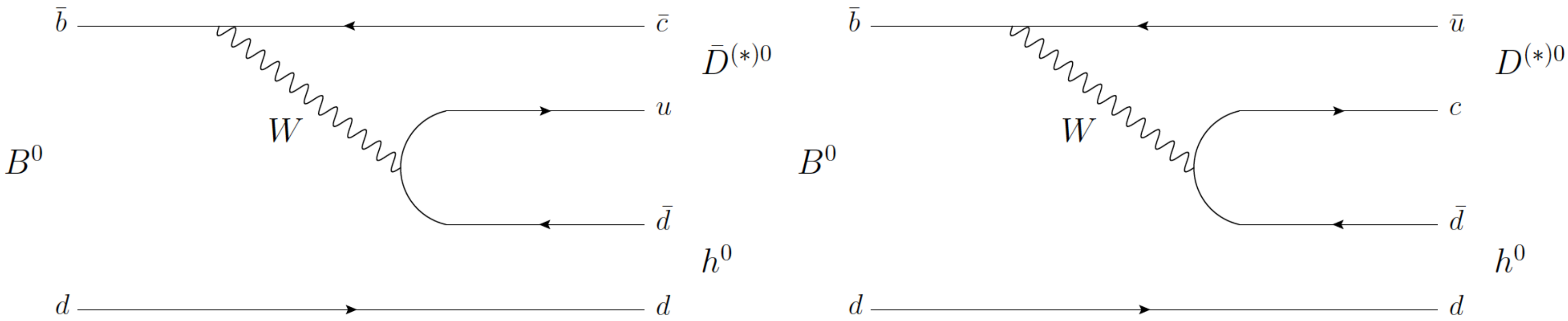
$$\alpha = \arg\left(-\frac{V_{td}V^*_{tb}}{V_{ud}V^*_{ub}}\right), \beta = \arg\left(-\frac{V_{cd}V^*_{cb}}{V_{td}V^*_{tb}}\right), \gamma = \arg\left(-\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}}\right)$$

Time-Dependent CP Violation in $B^0 \rightarrow D^{(*)0}h^0$



- ✓ sin(2β) is known at high precision from golden modes (mediated by $c\bar{c}s$); the uncertainty on β corresponds to less than 1°. **PRL 97 091801 (2001)**
- ✓ Motivation for measurement in $B^0 \rightarrow D^{(*)0}h^0$? : **PRD 79 072009 (2009)**
- ✓ Some tension exists between direct and indirect estimations of β.
  - ✓ Possibly related to penguin contributions to the $b \rightarrow c\bar{c}s$ process ??
  - ✓ Want first joint analysis to have a reasonably solid result expectation, to bootstrap confidence in sound results from the technique.

Analysis Motivation



- ✓ $B^0 \to D^{(*)0}h^0$ decays with $h^0 \in \{\pi^0, \eta^{(')}, \omega\}$ are mediated by tree-level amplitudes only.
- ✓ Interference between mixing and decay occurs when $D^{(*)0}$ and $\bar{D}^{(*)0}$ decay to a common final state.
- ✓ No penguin amplitudes, theoretically clean [NPB **659**, 321 (2003)] :
- ✓ These decays are not sensitive to most model of BSM
  - → Enables testing of, and comparison with, precision measurements from $b \to c\bar{c}s$.
  - → Can provide an alternative Standard Model reference for sin(2β).
  - → Belle2 and LHCb will be able to provide further precision in this set of channels.

Time-Dependent CP Violation in $B^0 \to D^{(*)0}h^0$

772 X 10^6 $B\overline{B}$ pairs @ Belle
471 x 10^6 $B\overline{B}$ pairs @ BABAR
collected at the Υ (4S).

Time-dependent rate of neutral B meson decaying to a CP eigenstates is:

$$g(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\{1 + q[\mathcal{S}\sin(\Delta m_d \Delta t) - \mathcal{C}\cos(\Delta m_d \Delta t)]\},$$

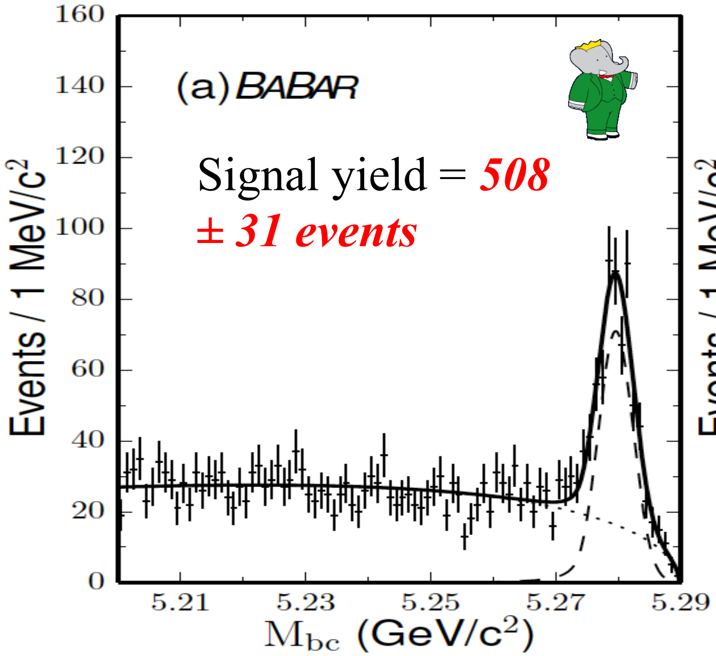
C=direct CP violation
Δm_d is the B^0 -$\overline{B^0}$ mixing frequency
Δt time interval between the decays of the two B mesons

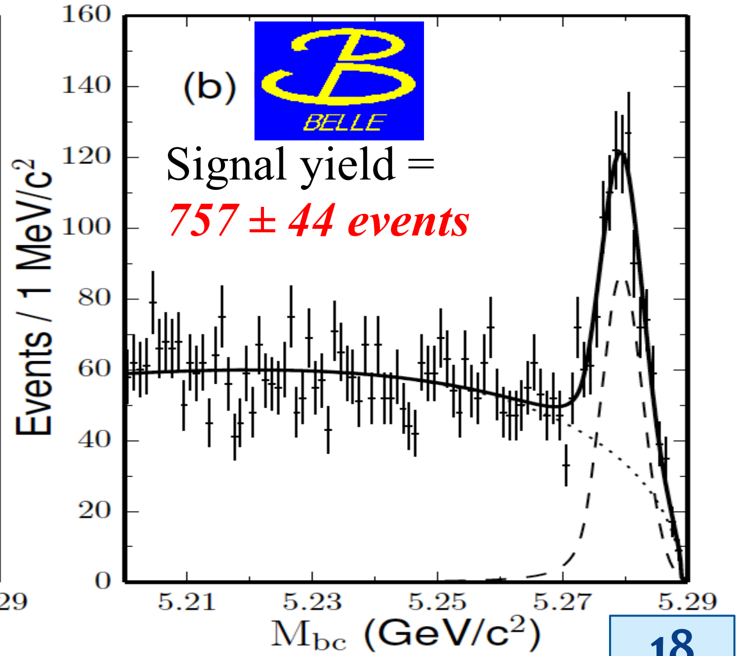
q = +1 (-1) ⇒ tagging *B* is a B^0 ($\overline{B^0}$)

$$\mathcal{S} = -\eta_f \sin(2\beta)$$

Signal yield determined by unbinned maximum likelihood to the M_{bc}

$$M_{bc} = \sqrt{(E^*_{beam}/c^2)^2 - (p^*_B/c)^2}$$



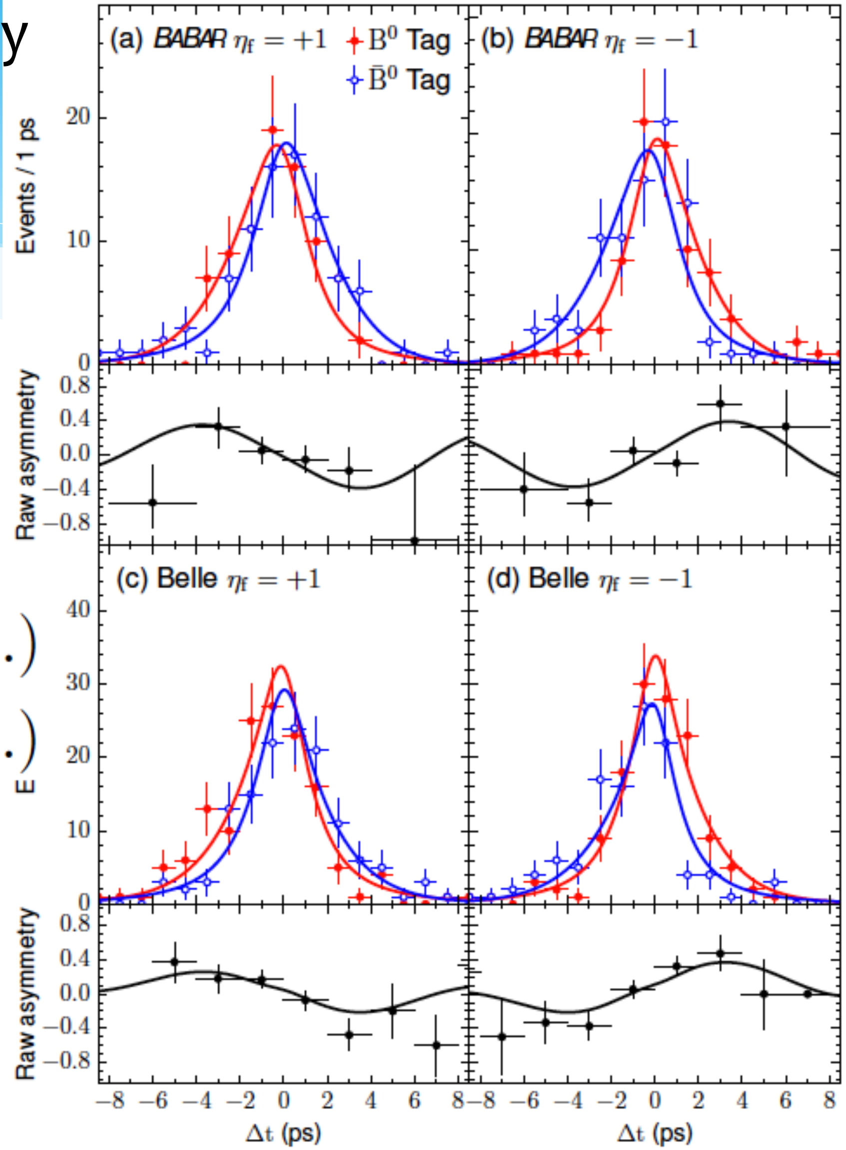


CP Violation in $B^0 \to D^{(*)0}h^0$

CP violation measurement performed by maximizing :

$$\ln \mathcal{L} = \sum_i \ln \mathcal{P}_i^{BABAR} + \sum_j \ln \mathcal{P}_j^{\text{Belle}},$$

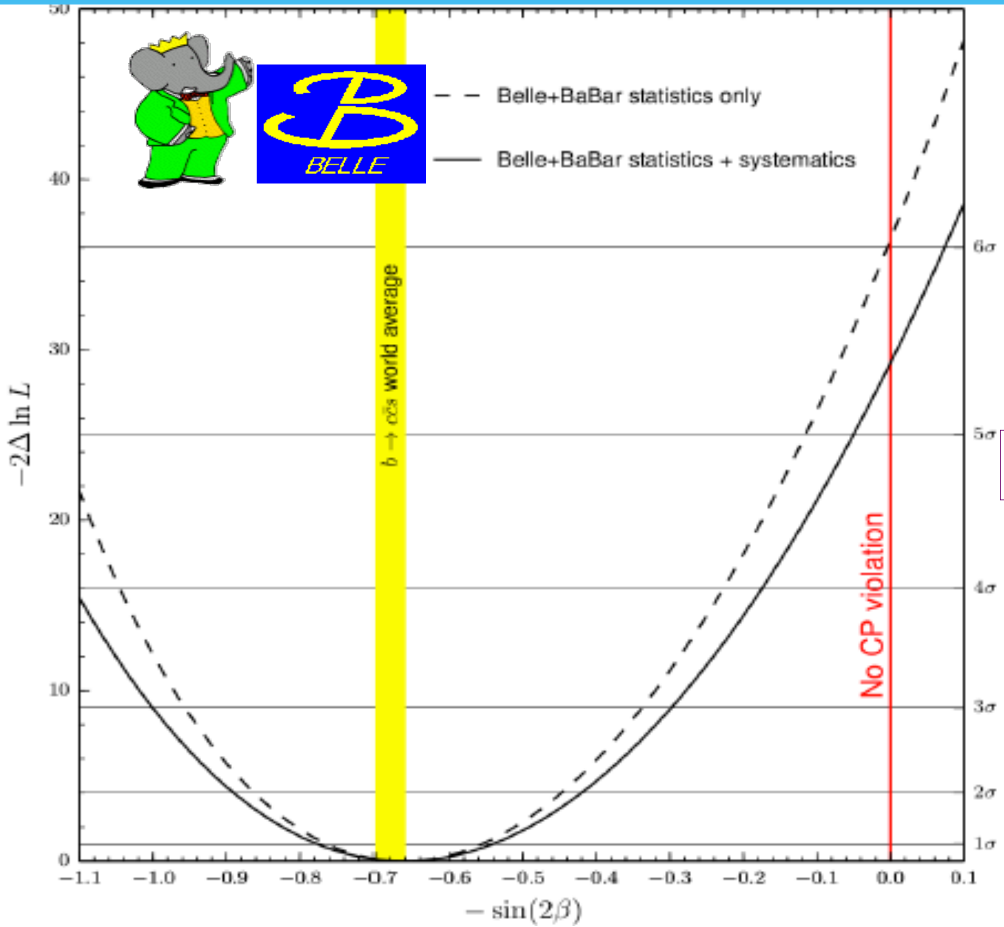
$$-\eta_f \mathcal{S} = +0.66 \pm 0.10\,(\text{stat.}) \pm 0.06\,(\text{syst.})$$
$$\mathcal{C} = -0.02 \pm 0.07\,(\text{stat.}) \pm 0.03\,(\text{syst.})$$



These results agrees with 0.2 σ with the world average

sin2β=0.68±0.02 from b->cc̄ s

Significance of the Results



1250 x 10^6 $B\bar{B}$ decays

Excludes the hypothesis of no mixing-induced CPV in $B^0 \longrightarrow D^{(*)0}h^0$ at a confidence level of $1 - (6.6 \times 10^{-8})$, corresponding to a significance of 5.4σ.

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Conclusions

- ✓We have presented a measurement of A test of **CPT** symmetry in **B^0-$\bar{B}^0$** mixing and in **$B^0 \rightarrow c\bar{c}K^0$** decays. **PRD 94, 011101 (R) (2016)**
- ✓Measurement of the Unitarity Triangle parameter **sin(2β)** in **$B^0 \rightarrow D^0h^0$** decays. **PRD 115, 121604 (2016)**
- ✓BaBar and Belle **<u>continues</u>** to produce leading results on several different test of fundamental simmetries

Thanks for your attention