Observation of CP Violation in $B^0 \to D_{CP}^{(*)} h^0$ Decays in a Combined Analysis using *BABAR* and Belle Data

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CKM Quark Mixing Matrix and the Unitarity Triangle

- Yukawa couplings of fermion fields to Higgs condensate ⇒ quark masses and mixing

$$\mathcal{L}_Y = -Y^d_{ij}\bar{Q}^I_{Li}\phi d^I_{Rj} - Y^u_{ij}\bar{Q}^I_{Li}\epsilon\phi^* u^I_{Rj} + h.c.$$

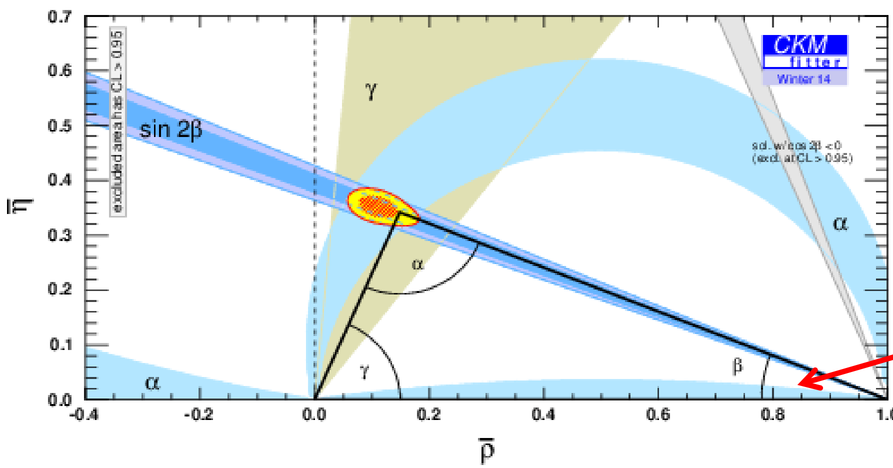
- In mass basis, quarks couple in charged-current W$^{\pm}$ interactions as

$$-\frac{g}{\sqrt{2}}\left(\bar{u}_L, \bar{c}_L, \bar{t}_L\right)\gamma^\mu W^\pm_\mu \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{V_{CKM}} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix} + h.c.$$

- Kobayashi-Maskawa theory: cannot align simultaneously up- and down-type quarks
  10 free parameters: 6 quark masses + 3 mixing angles + 1 complex CPV phase

- Unitarity Triangle:

$$\sum_i V_{ib}V^*_{id} = 0$$



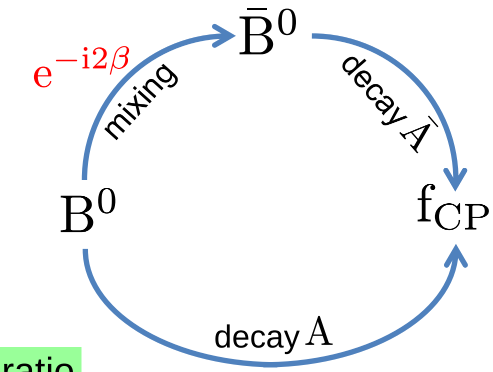
$\mathrm{B^0 \to J/\psi K^0_S}$

+ $\mathrm{B^0 \to D^{(*)}_{CP} h^0}$

new result

Determination of the angles $\Longleftrightarrow$ Measurements of CP asymmetries

Measurements of the Weak Phase β



- Interference between mixing and decay in neutral B meson decays to a CP eigenstate

- Interference characterized by: $\lambda = \frac{q}{p}\frac{\bar{A}}{A}$

phase factor due to mixing

decay amplitude ratio

- Time-dependent CP asymmetry:

$$A_{CP}(t) = \frac{\Gamma\left(\bar{B}^0(t) \to f_{CP}\right) - \Gamma\left(B^0(t) \to f_{CP}\right)}{\Gamma\left(\bar{B}^0(t) \to f_{CP}\right) + \Gamma\left(B^0(t) \to f_{CP}\right)} = \mathcal{S}\sin(\Delta mt) - \mathcal{C}\cos(\Delta mt)$$

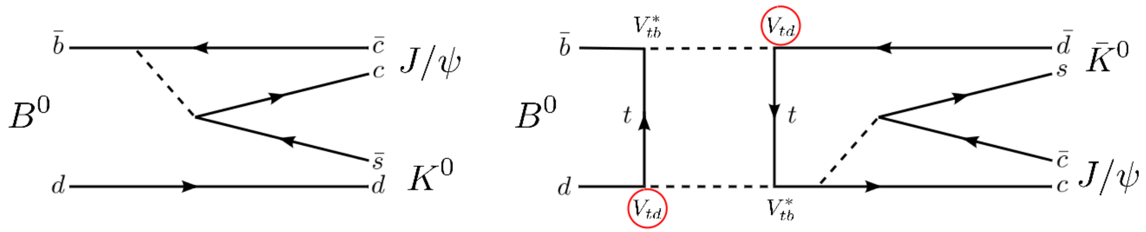
mixing-induced CPV

direct CPV

$$\mathcal{S} = \frac{2\,\mathrm{Im}(\lambda)}{|\lambda^2| + 1}$$

$$\mathcal{C} = \frac{1 - |\lambda^2|}{1 + |\lambda^2|}$$

- Example $B^0 \to J/\psi K^0_S$ (benchmark for $\sin(2\beta)$):

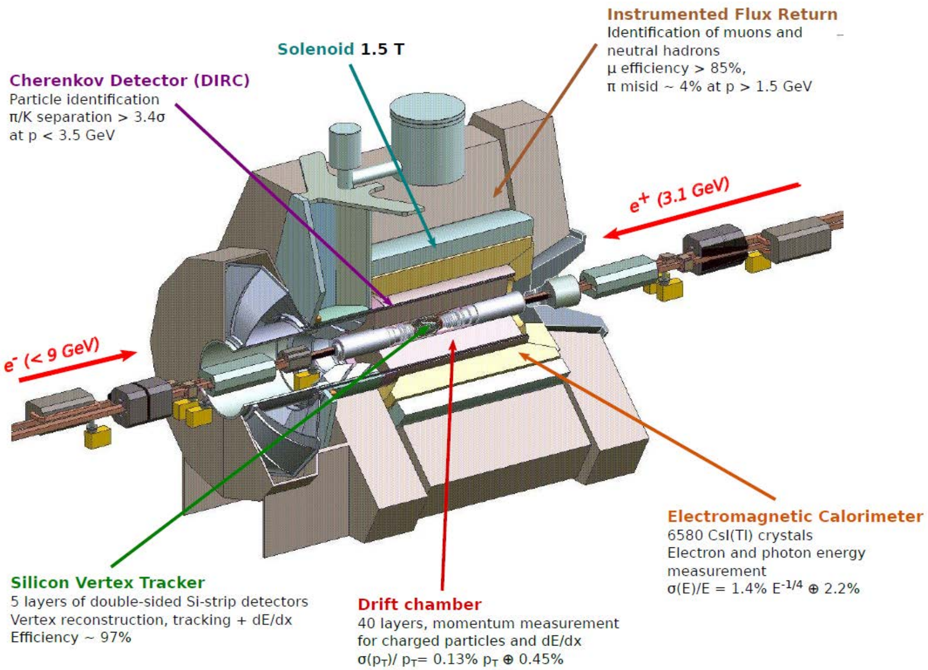


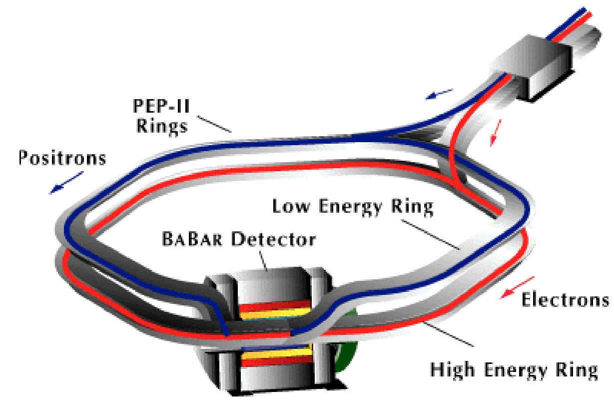
$\rightarrow$ mixing vertices V_{td} introduce phase $\rightarrow \mathcal{S} = -\eta_{f_{CP}}\sin(2\beta)$ and $\mathcal{C} = 0$

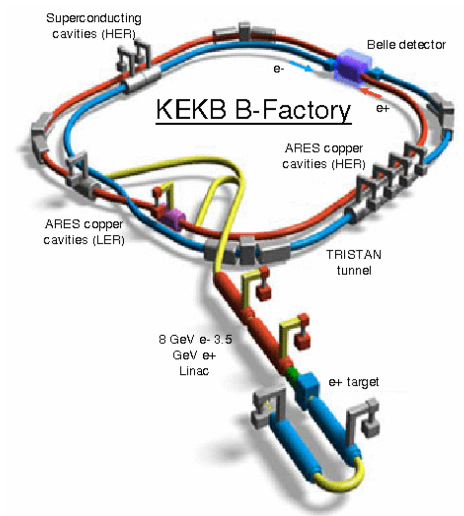
β can be precisely determined from the time-dependent CP asymmetry

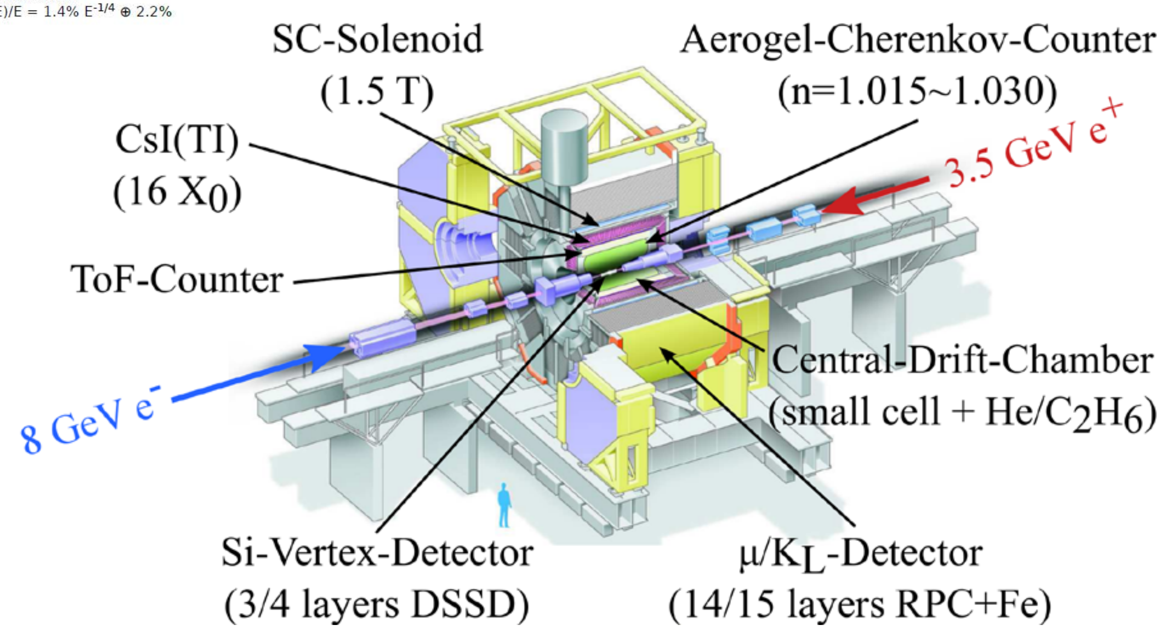
$$A_{CP}(t) = -\eta_{f_{CP}}\sin(2\beta)\sin(\Delta mt)$$

The BABAR and Belle Experiments

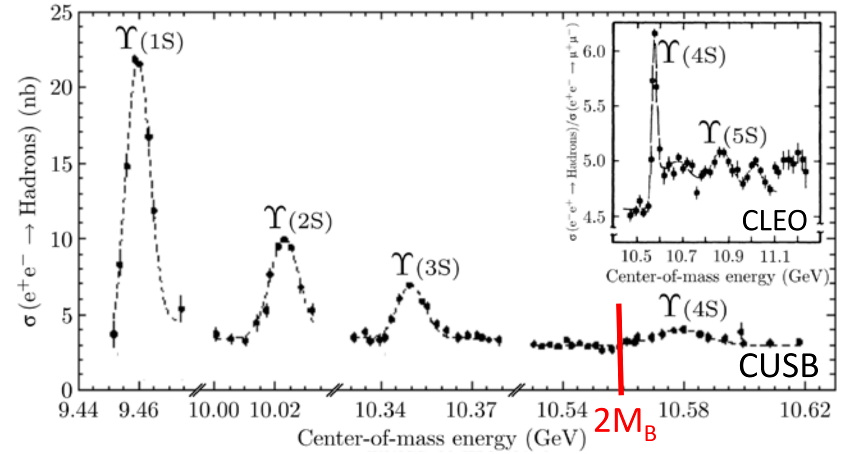


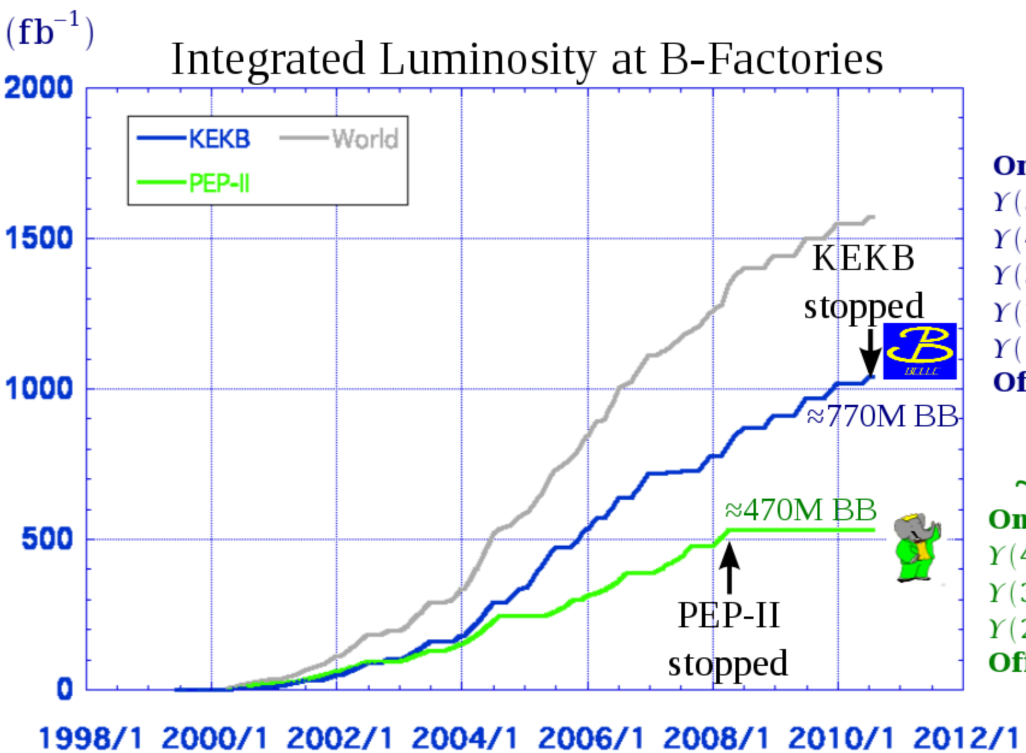






Data Recorded by the *BaBar* and Belle Experiments





Belle

$> 1\ ab^{-1}$

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 24 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

$\sim 100\ fb^{-1}$

BaBar

$\sim 550\ fb^{-1}$

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

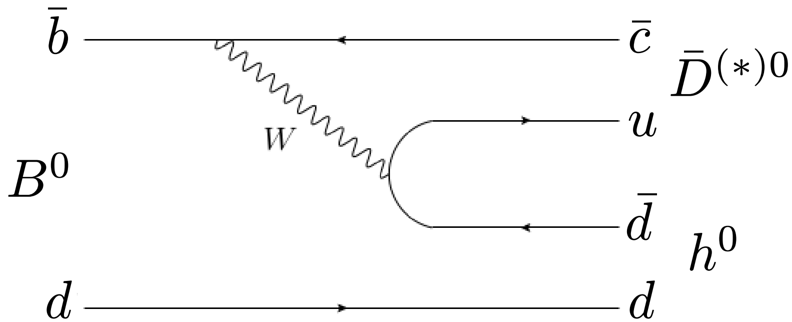
$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

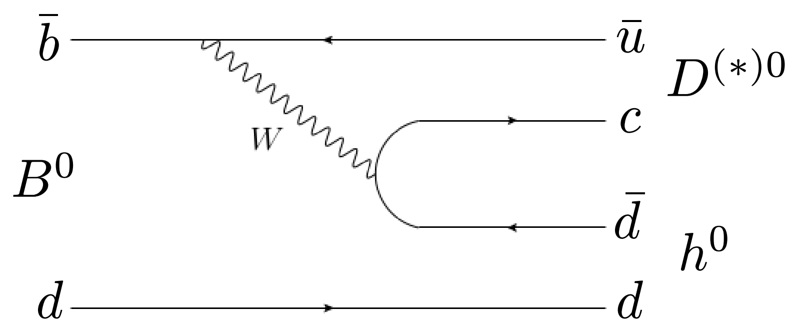
$\sim 54\ fb^{-1}$

Combined Belle+*BaBar* analysis to make full use of the ≈1240×10^6 BB collected on the $\Upsilon(4S)$

Combined Belle and *BaBar* Analysis of $\mathbf{B^0 \rightarrow D^{(*)}_{CP} h^0}$



CKM-favored



CKM-disfavored

- $\mathrm{B^0 \rightarrow D^{(*)}_{CP} h^0}$ decays with $\mathrm{h^0} \in \{\pi^0, \eta, \omega\}$ mediated only by tree-level amplitudes
- Theoretically clean [NPB **659**, 321 (2003)]:

  → Enables to test the precision measurements of $\mathrm{b \rightarrow c\bar{c}s}$

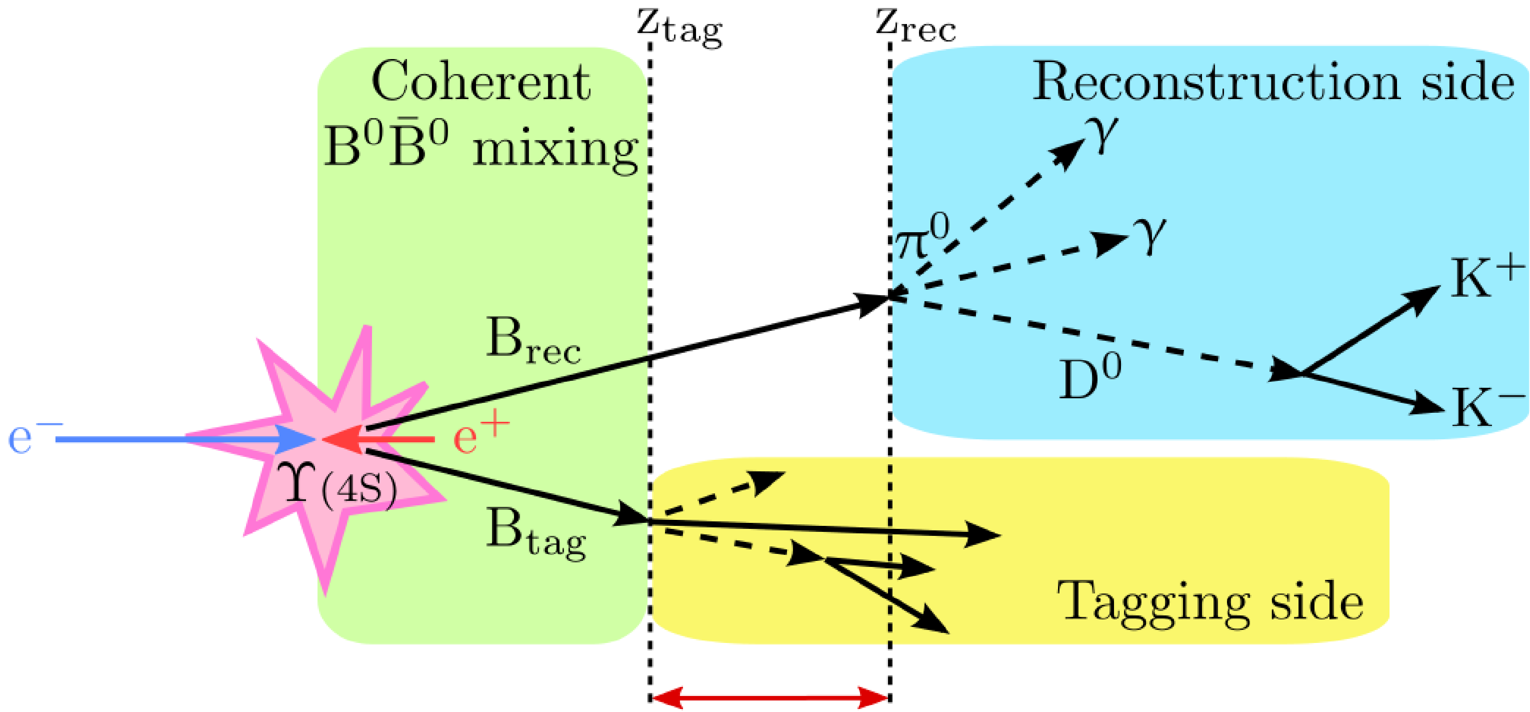
  → Can provide a SM reference of $\sin(2\beta)$, e.g. for BSM searches in $\mathrm{b \rightarrow s}$ penguins

- Experimental difficulties: - Low B and $\mathrm{D_{CP}}$ branching fractions [$\mathcal{O}(10^{-4})$ and $\mathcal{O}(\leq 10^{-2})$]
  - Low reconstruction efficiencies
  - Significant background
- Previous measurements by Belle and *BaBar* could not establish CPV in $\mathrm{B^0 \rightarrow D^{(*)} h^0}$

Perform time-dependent CP violation measurement combining Belle+*BaBar* data

Combined Belle and *BaBar* Analysis of $B^0 \to D_{CP}^{(*)} h^0$

Threshold $B\bar{B}$ production on the $\Upsilon(4S)$:



eff. tagging efficiency >30%

Proper time interval distribution follows:

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

Experimental effects due to finite vertex resolution and imperfect tagging are important

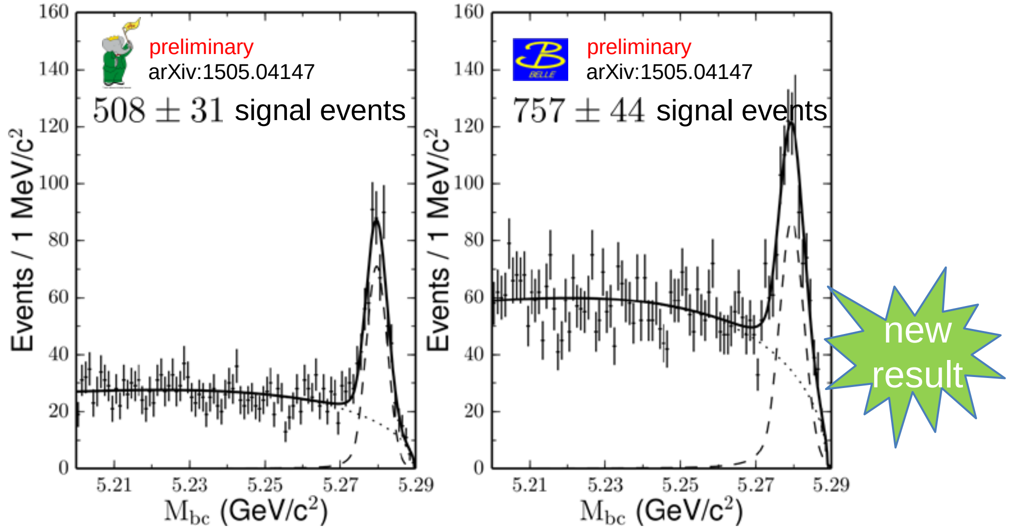
Combined Belle and BABAR Analysis of $\mathbf{B^0 \to D^{(*)}_{CP} h^0}$

- Reconstruct $\mathrm{B^0 \to D^{(*)}_{CP} h^0}$ with $\mathrm{h^0}$ in $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma, \pi^+\pi^-\pi^0$ and $\omega \to \pi^+\pi^-\pi^0$

$$\mathrm{D_{CP} \to K^+K^-, K^0_S\pi^0, K^0_S\omega}$$

$$\mathrm{D^{*0} \to D_{CP}\pi^0}$$

- In total 12 final states are reconstructed (7 CP-even and 5 CP-odd states)
- Suppression of $\mathrm{e^+e^- \to q\bar{q}\ (q \in \{u, d, s, c\})}$ continuum background by neural networks
- Coherent analysis strategy, apply almost same selection on Belle and BABAR data
- Extract signal from beam-constrained mass $\mathrm{M_{bc} \equiv m_{ES}} = \sqrt{(\mathrm{E^*_{beam}}/c^2)^2 - (\mathrm{p^*_B}/c)^2}$



Combined Belle and BABAR Analysis of $\mathbf{B^0 \to D^{(*)}_{CP} h^0}$

- Perform measurement by maximizing the combined log-likelihood function:

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

- Physics PDFs are convoluted with specific resolution functions

$$\mathcal{P}^{\text{Exp.}} = \sum_{\mathrm{k}} \mathrm{f_k} \int \left[\mathrm{P_k}\left(\Delta t'\right) \mathrm{R_k}\left(\Delta t - \Delta t'\right)\right] \mathrm{d}\left(\Delta t'\right)$$

- Apply Belle and BABAR specific resolution models, and flavor tagging algorithms

- Apply common signal model:

$$\mathrm{P_{sig}}(\Delta t, \mathrm{q}) = \frac{1}{4\tau_{\mathrm{B^0}}} \mathrm{e}^{-\frac{|\Delta t|}{\tau_{\mathrm{B^0}}}} \left[1 + \mathrm{q}\left(\mathcal{S}\sin(\Delta m \Delta t) - \mathcal{C}\cos(\Delta m \Delta t)\right)\right]$$

- SM prediction $-\eta_f \mathcal{S} = \sin(2\beta)$ and $\mathcal{C} = 0$

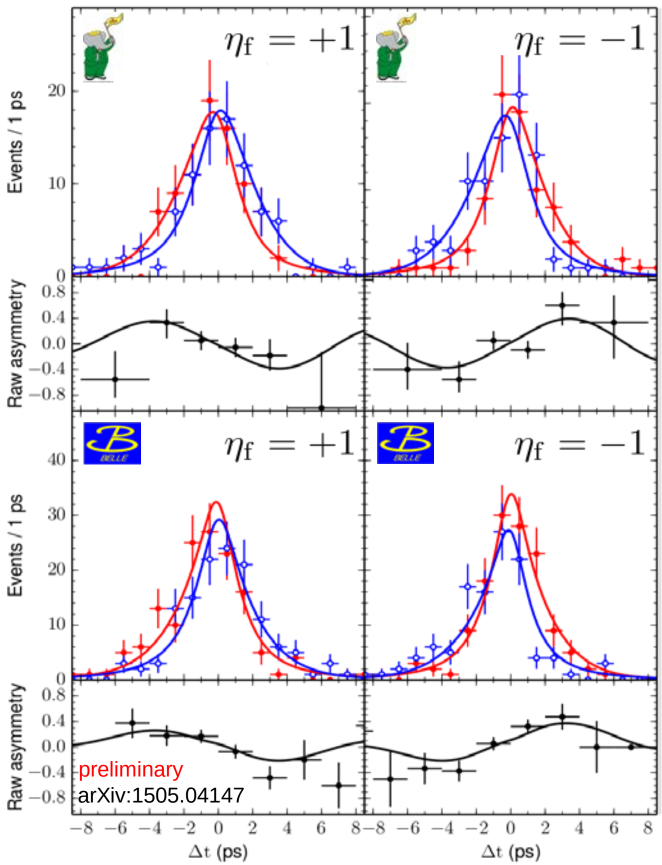
new result

Belle+BABAR with 1.1 ab^{-1}: arXiv:1505.04147

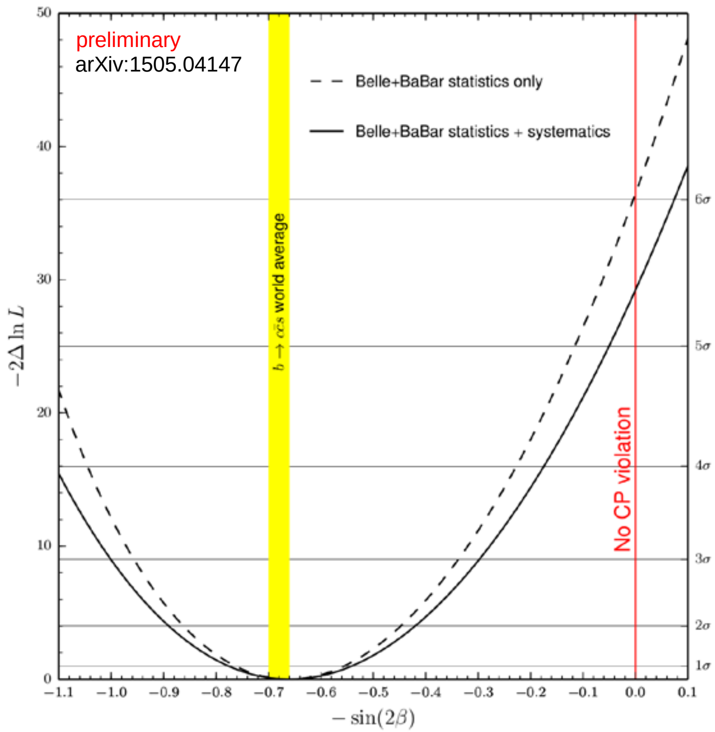
$$-\eta_f \mathcal{S} = +0.66 \pm 0.10\,(\text{stat.}) \pm 0.06\,(\text{syst.})$$

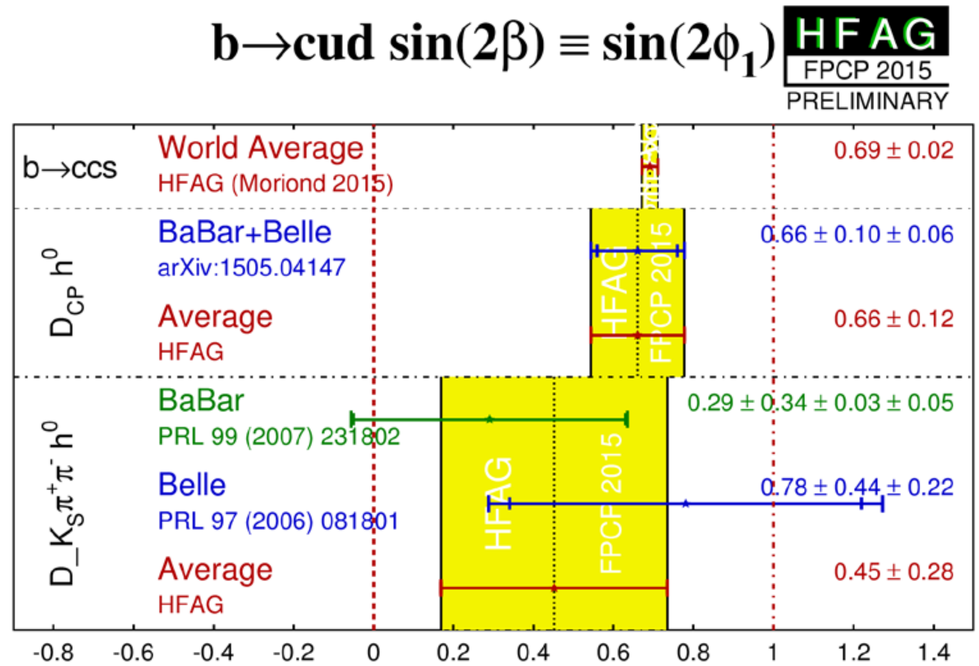
$$\mathcal{C} = -0.02 \pm 0.07\,(\text{stat.}) \pm 0.03\,(\text{syst.})$$

preliminary



Combined Belle and *BaBar* Analysis of $\mathrm{B^0 \to D^{(*)}_{CP} h^0}$





- Very good agreement with the $\sin(2\beta)$ world average from $\mathrm{b \to c\bar{c}s}$
- Exclude the no-mixing induced CP violation hypothesis at 5.4σ
  → First observation of CP violation in $\mathrm{B^0 \to D^{(*)}_{CP} h^0}$ decays
- First measurement performed on more than 1 ab^{-1} collected on the $\Upsilon(4S)$

Summary

Performed CP violation analysis of $\mathrm{B}^0 \to \mathrm{D}^{(*)}_{\mathrm{CP}}\mathrm{h}^0$ combining final *BABAR* and Belle data sets:

- First analysis using more than 1 ab^{-1} collected on the $\Upsilon(4\mathrm{S})$
- No sign of direct CP violation
- Exclude the no-mixing induced CP violation hypothesis at 5.4σ

  → First observation of CP violation in $\mathrm{B}^0 \to \mathrm{D}^{(*)}_{\mathrm{CP}}\mathrm{h}^0$ decays
- Very good agreement with $\sin(2\beta)$ from $\mathrm{b} \to \mathrm{c}\bar{\mathrm{c}}\mathrm{s}$
- Paper has been submitted to Physical Review Letters (arXiv:1505.04147)