Combined CP Violation Measurements by the BABAR and Belle Collaborations

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On behalf of the BABAR and Belle Collaborations

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CKM Quark Mixing Matrix

- The quark masses and mixing arise from Yukawa couplings of the fermion fields to the Higgs condensate:

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

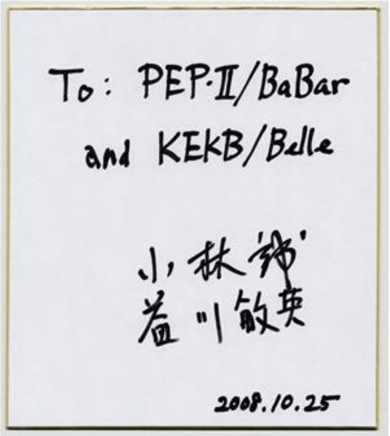
- Kobayashi + Maskawa: cannot simultaneously align up- and down-type quarks,

CKM matrix: 3 real parameters + 1 CP violating phase

$$\mathbf{V}_{\mathrm{CKM}} = \mathbf{V}_L^u \mathbf{V}_L^{d\dagger} = \begin{pmatrix} \mathrm{V_{ud}} & \mathrm{V_{us}} & \mathrm{V_{ub}} \\ \mathrm{V_{cd}} & \mathrm{V_{cs}} & \mathrm{V_{cb}} \\ \mathrm{V_{td}} & \mathrm{V_{ts}} & \mathrm{V_{tb}} \end{pmatrix} \approx$$

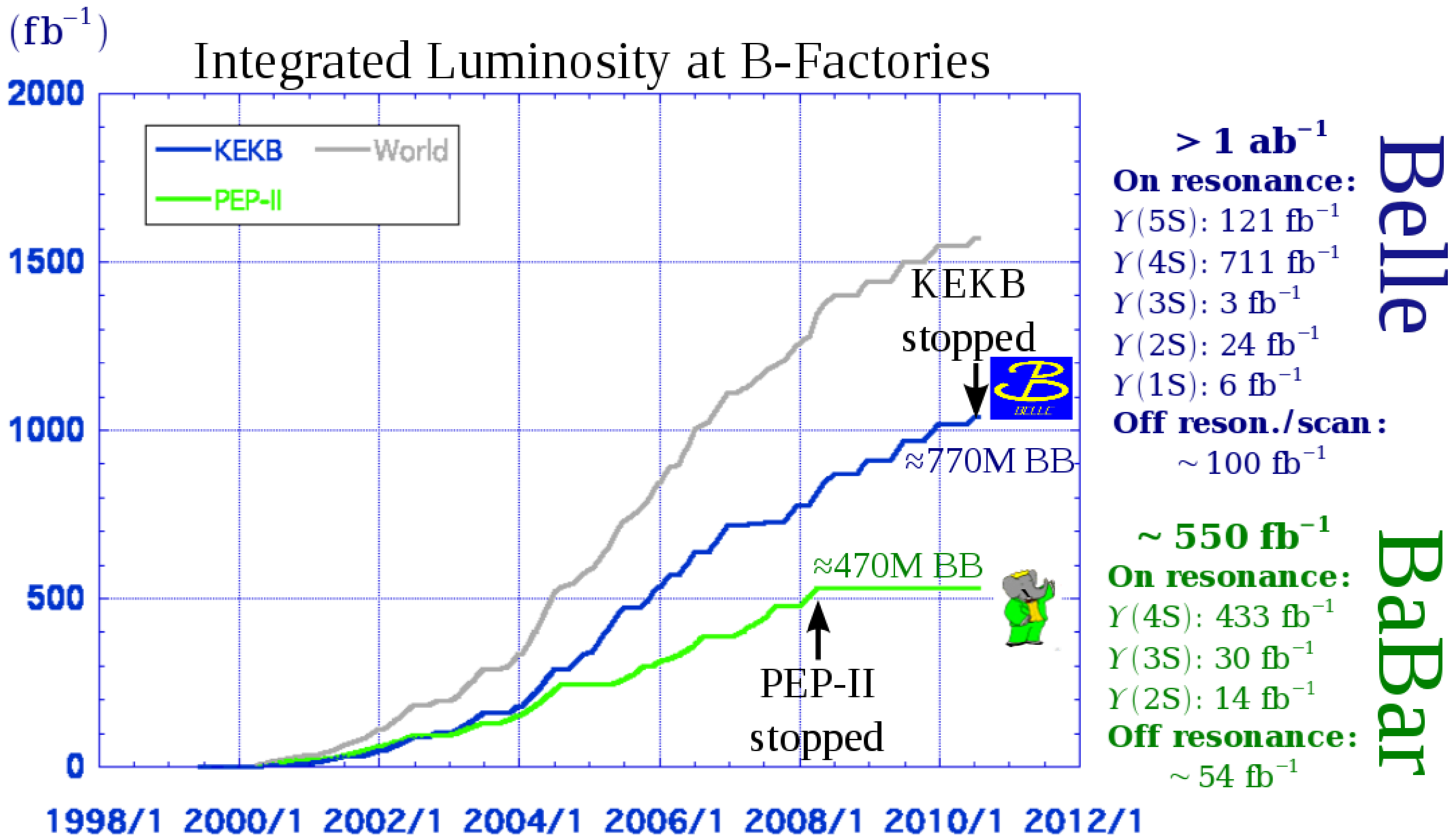
B factories *BABAR* (US) and Belle (Japan):

- Discovery CP violation in the B meson system
- Exploring and constraining the quark flavor structure of the Standard Model
- Experimental confirmation of the Kobayashi-Maskawa theory



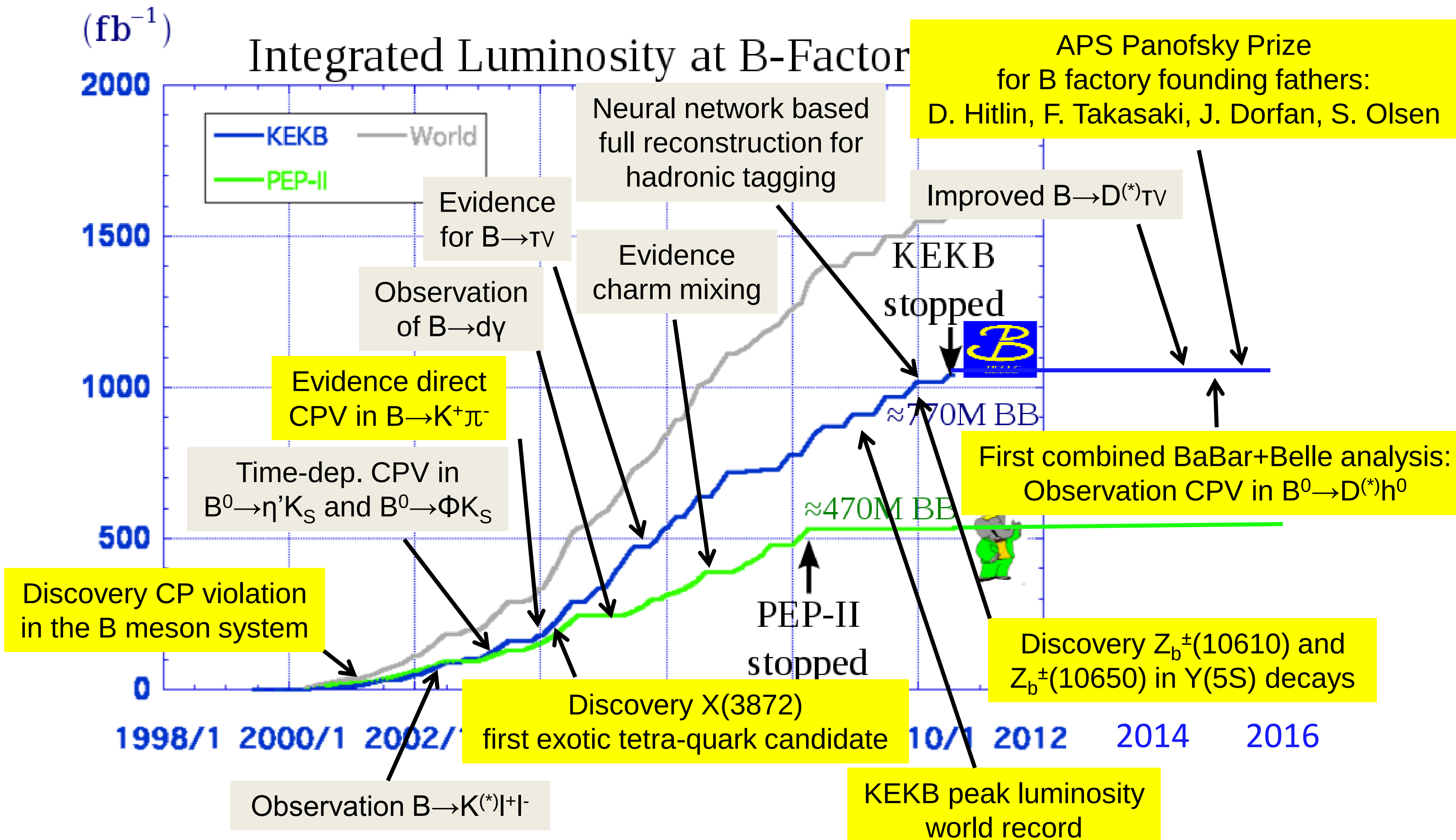
The Nobel Prize in Physics 2008

The BaBar and Belle Experiments

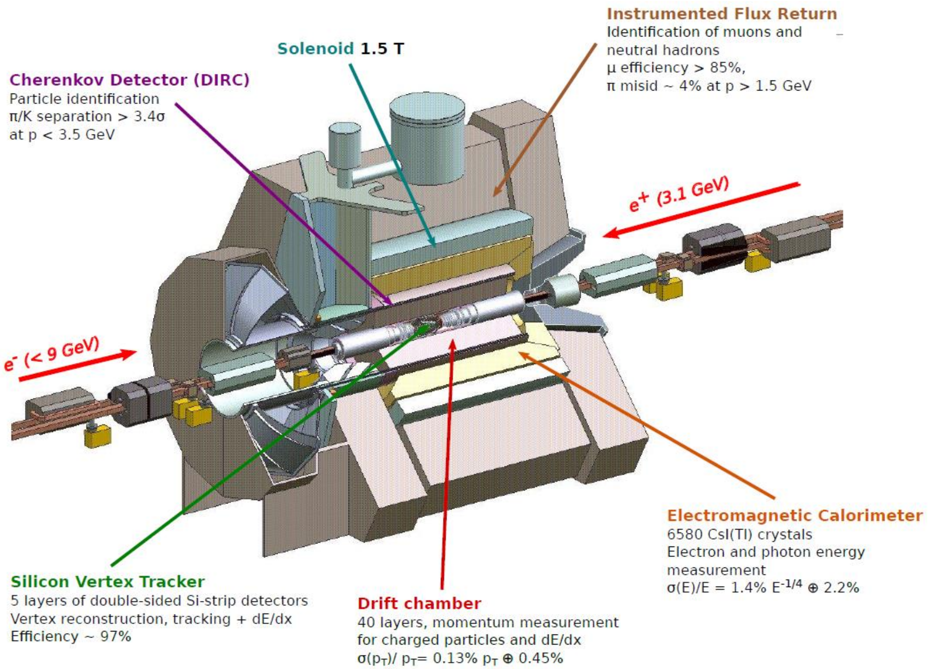


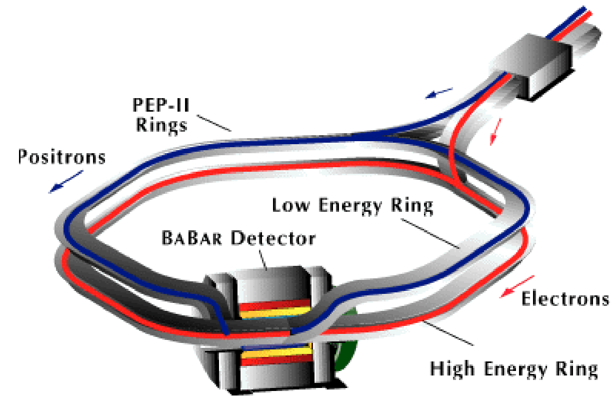
BaBar and Belle performed a very successful flavor physics program leading to many major discoveries

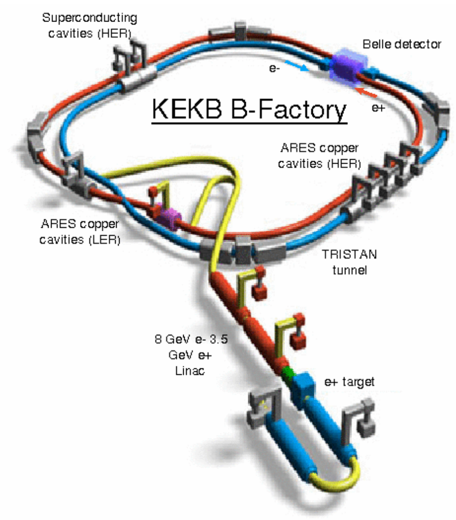
The BABAR and Belle Experiments

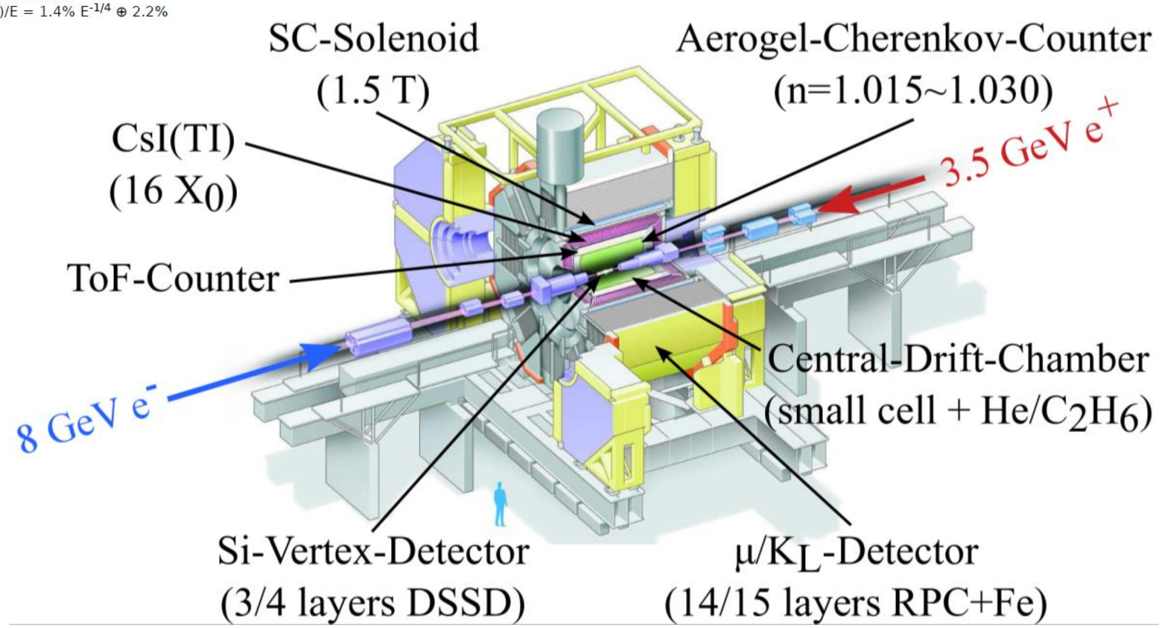


The BaBar and Belle Experiments







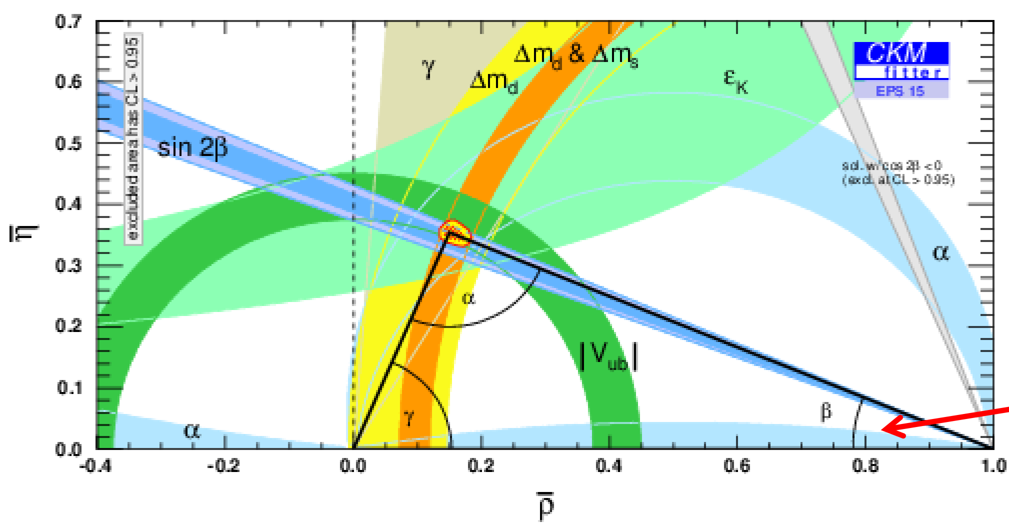


Unitarity Triangle

$$\mathbf{V}_{\mathrm{CKM}} = \mathbf{V}_L^u \mathbf{V}_L^{d\dagger} = \begin{pmatrix} \mathrm{V_{ud}} & \mathrm{V_{us}} & \mathrm{V_{ub}} \\ \mathrm{V_{cd}} & \mathrm{V_{cs}} & \mathrm{V_{cb}} \\ \mathrm{V_{td}} & \mathrm{V_{ts}} & \mathrm{V_{tb}} \end{pmatrix} \approx$$

- Unitarity of the CKM matrix imposes vanishing relations, which can be interpreted as triangles in the complex plane

- Unitarity Triangle arises from $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$

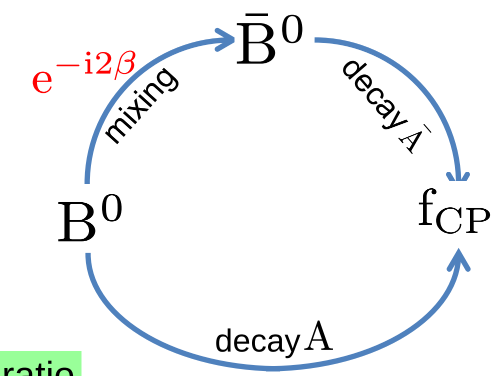


$b \to c\bar{c}s$ (e.g. $B^0 \to J/\psi K_S^0$)

$+\ B^0 \to D_{CP}^{(*)}h^0$

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:

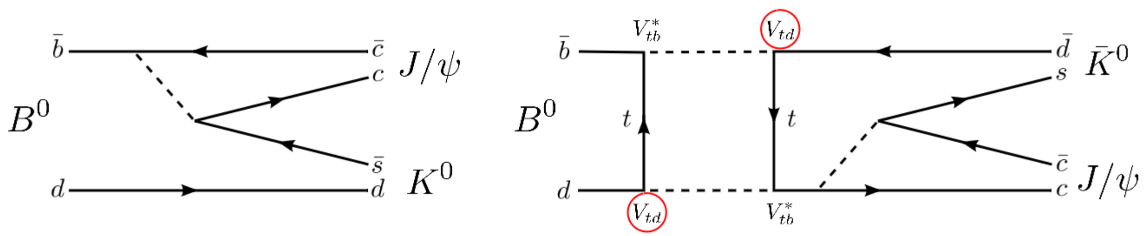
$$A_{CP}(t) = \frac{\Gamma\left(\bar{B}^0(t) \to f_{CP}\right) - \Gamma\left(B^0(t) \to f_{CP}\right)}{\Gamma\left(\bar{B}^0(t) \to f_{CP}\right) + \Gamma\left(B^0(t) \to f_{CP}\right)} = \mathcal{S}\sin(\Delta m t) - \mathcal{C}\cos(\Delta m t)$$

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

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

mixing-induced CPV | direct CPV

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



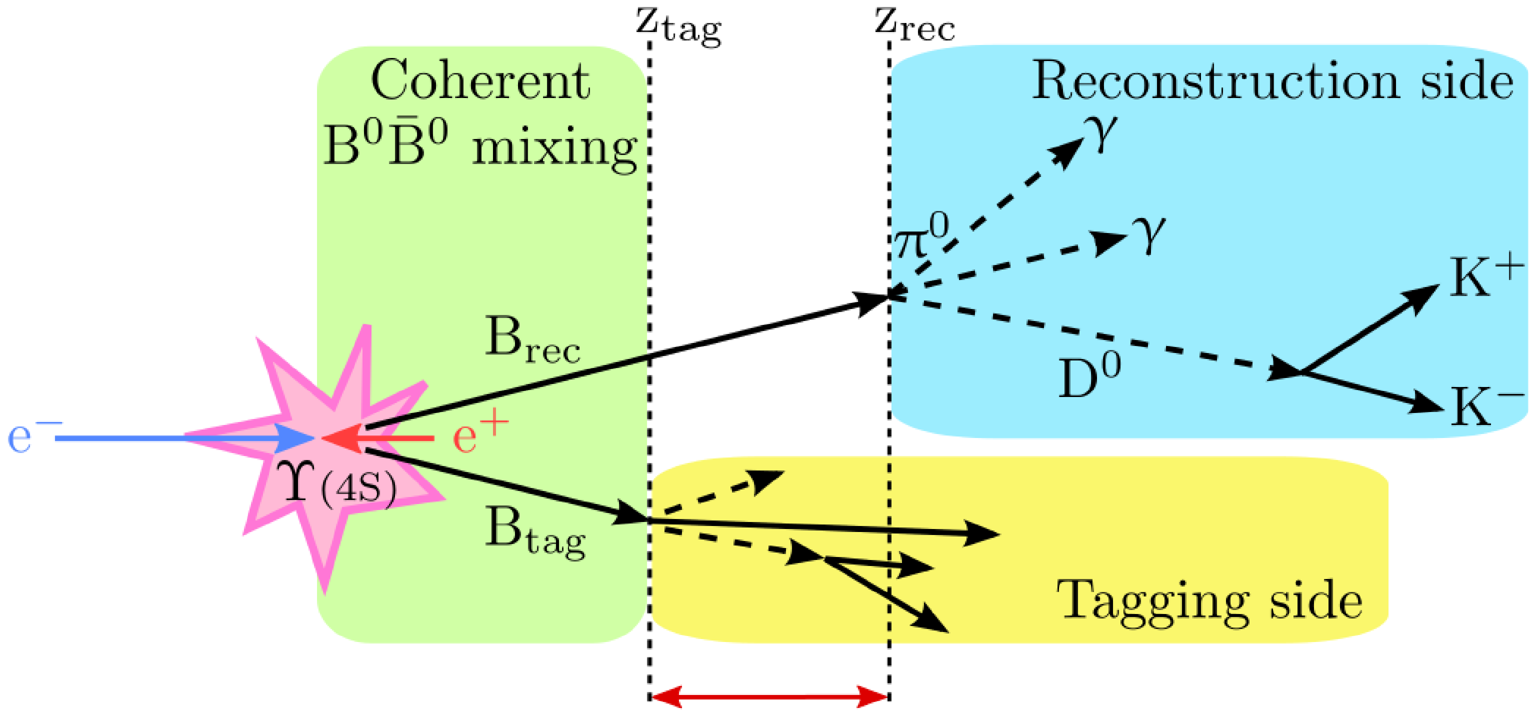
→ mixing vertices V_{td} introduce phase → $\mathcal{S} = -\eta_{f_{CP}}\sin(2\beta)$ and $\mathcal{C} = 0$

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

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

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

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



$\Delta z = \beta\gamma c\Delta t, \langle|\Delta z|\rangle \approx$ 200µm Belle
250 µm *BABAR*

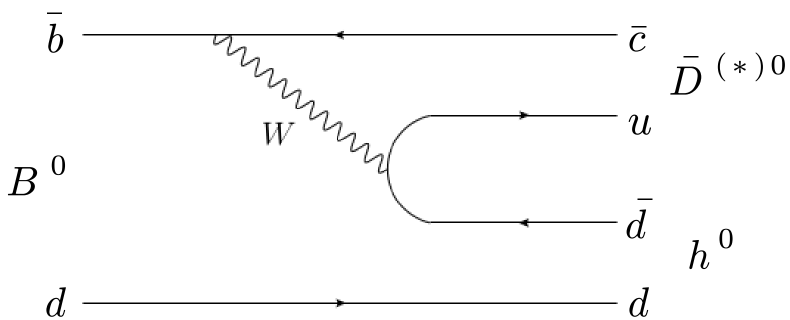
effective tag efficiency >30%

Proper time interval distribution follows:

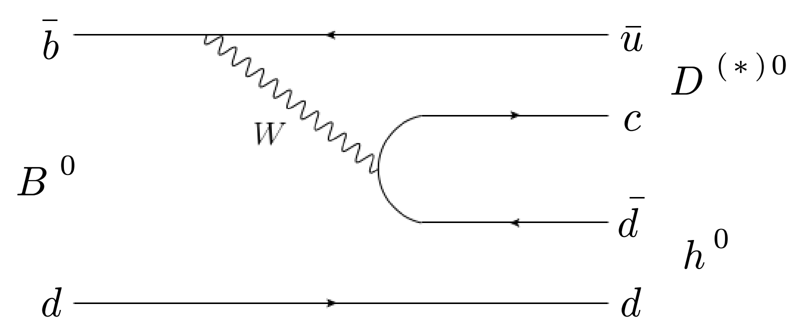
$$\boxed{\mathcal{P}(\Delta t, q) = \frac{1}{4\tau_{B^0}} e^{-\frac{|\Delta t|}{\tau_{B^0}}} \left[1 + q\left(\mathcal{S}\sin(\Delta m \Delta t) - \mathcal{C}\cos(\Delta m \Delta t)\right)\right]}$$ with $q = +1(-1)$ for $B^0(\bar{B}^0)$

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

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



CKM-favored



CKM-disfavored

- $\mathrm{B^0 \to D^{(*)}_{CP} h^0}$ 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 $\mathrm{b \to c\bar{c}s}$

  → Can provide a SM reference of $\sin(2\beta)$, e.g. for BSM searches in $\mathrm{b \to s}$ 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 $\mathrm{B^0 \to D^{(*)} h^0}$

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

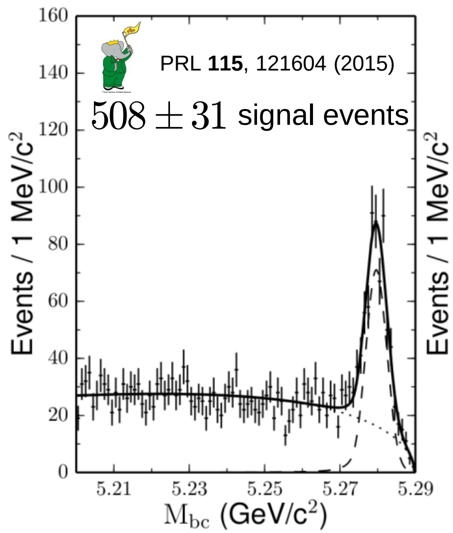
Combined Belle and *BABAR* Analysis of $\mathbf{B^0 \to D^{(*)}_{CP} h^0}$

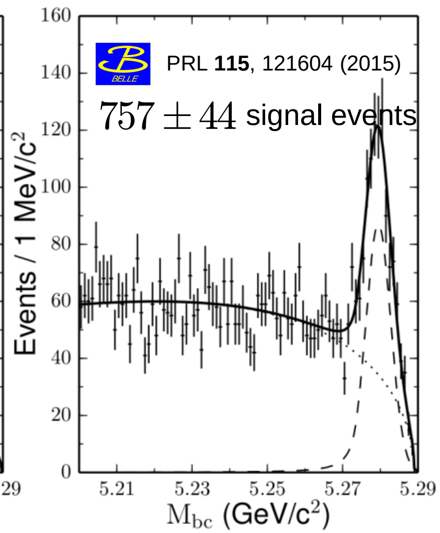
- Reconstruct $\mathrm{B^0 \to D^{(*)}_{CP} h^0}$ with $\mathrm{h^0}$ in $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma, \pi^+\pi^-\pi^0$ and $\omega \to \pi^+\pi^-\pi^0$

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

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

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





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

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

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

- Physics PDFs are convoluted with specific resolution functions

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

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

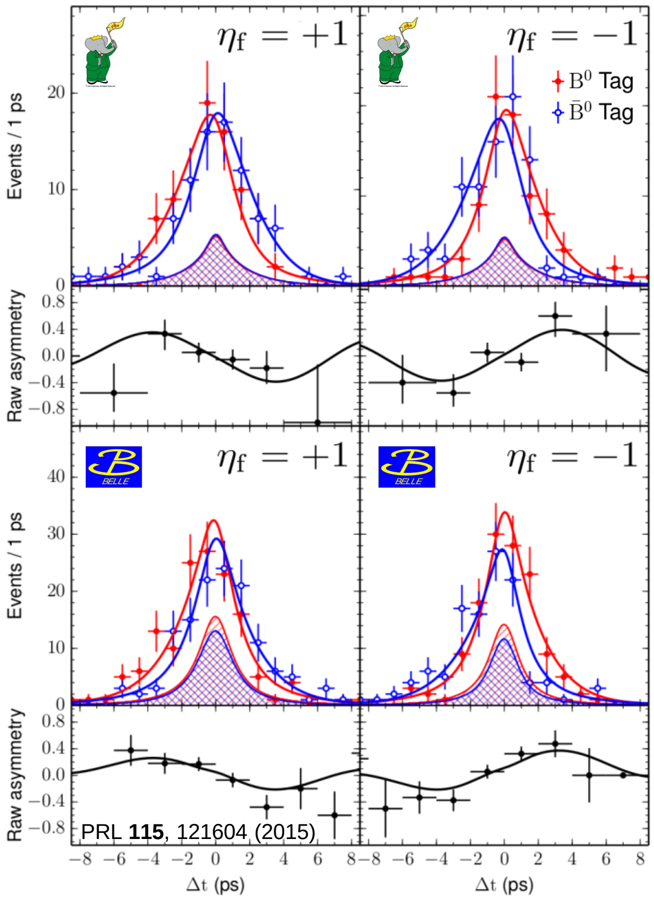
- Apply common signal model:

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

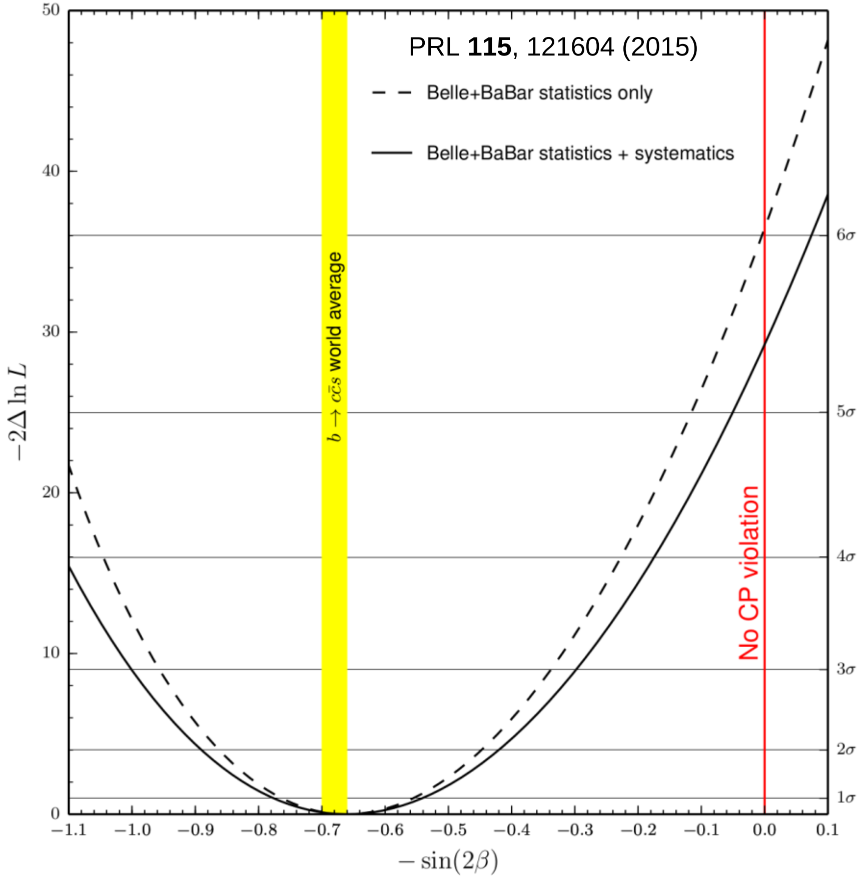
- SM prediction $-\eta_{\mathrm{f}}\mathcal{S} = \sin(2\beta)$ and $\mathcal{C} = 0$

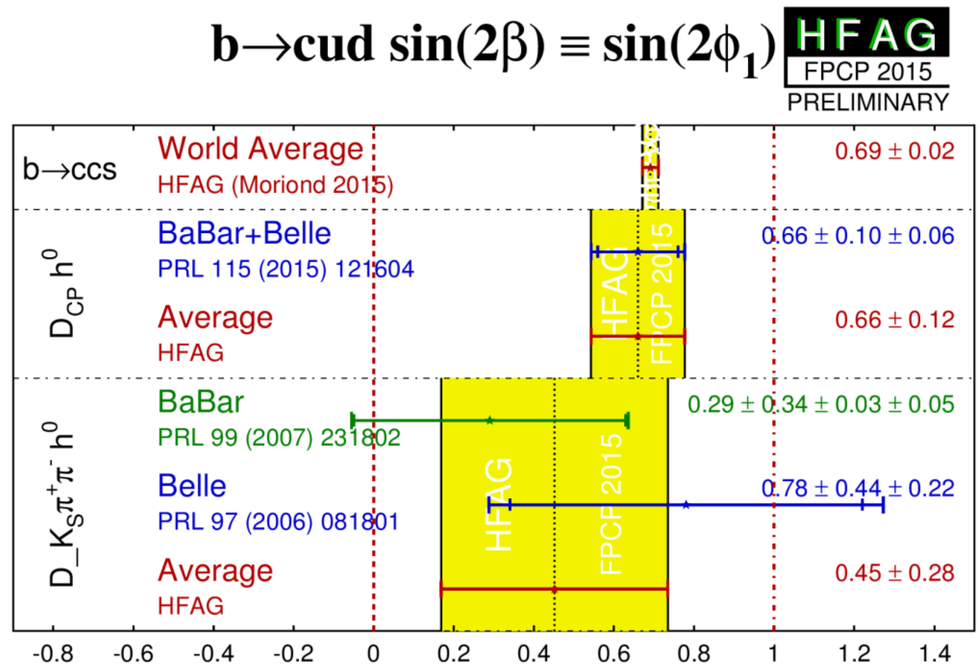
Belle+BABAR with 1.1 ab^{-1}: PRL **115**, 121604 (2015)

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



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 using an integrated luminosity of more than 1 ab^{-1}

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 an integrated luminosity of more than 1 ab^{-1}
- No sign of direct CP violation
- Exclude the no-mixing induced CP violation hypothesis at 5.4σ

  $\to$ 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 $\mathrm{b} \to \mathrm{c\bar{c}s}$:

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

- Results have been published in Physical Review Letters [PRL **115**, 121604 (2015)]