New CP Violation Results from Combined BABAR+Belle Measurements

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On behalf of the BABAR and Belle Collaborations

Les Rencontres de Physique de la Vallée d'Aoste

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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:

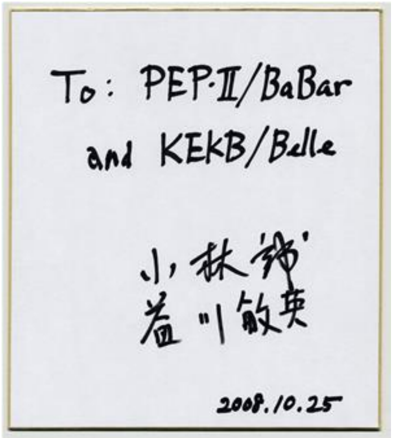
$$\mathcal{L}_Y = -Y^d_{ij}\bar{Q}_{Li}\phi d_{Rj} - Y^u_{ij}\bar{Q}_{Li}\epsilon\phi^* u_{Rj} + h.c.$$

- Kobayashi + Maskawa: cannot simultaneously align up- and down-type quarks,
  CKM matrix: 3 real parameters + 1 CP violating phase

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

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

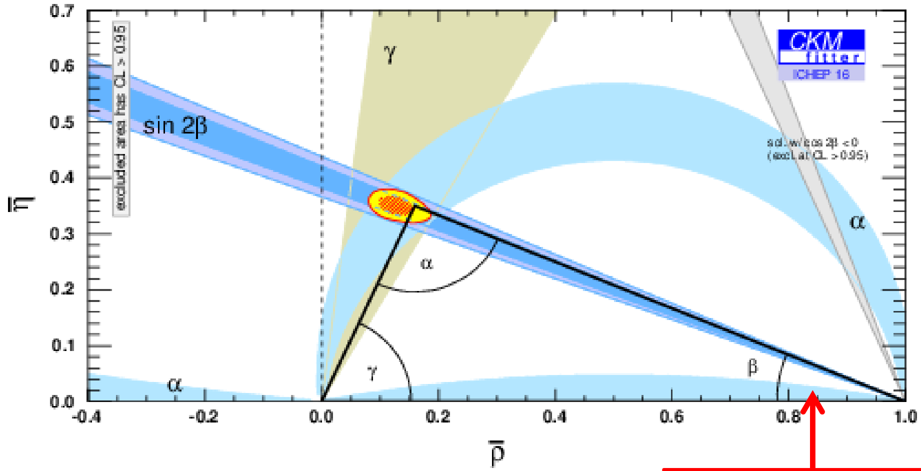
- Discovery CP violation in the B meson system
- Exploring and constraining the quark flavor structure of the Standard Model
- Experimental confirmation of the Kobayashi-Maskawa theory



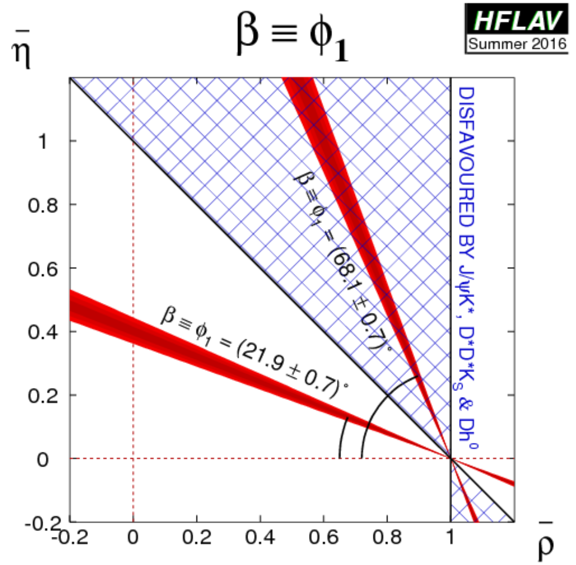
The Nobel Prize in Physics 2008

The Unitarity Triangle

- Unitarity requires $V_{td}V_{tb}^{*} + V_{cd}V_{cb}^{*} + V_{ud}V_{ub}^{*} = 0$ → Triangle in the complex plane



$B^0 \to J/\psi K_S^0$



- The determination of the angle β of the Unitarity Triangle from sin(2β) [= sin(2ϕ_1)] measurements, for example, using $B^0 \to J/\psi K_S^0$, leads to a trigonometric ambiguity:

β=21.9° or β=(π/2-21.9°)=68.1°

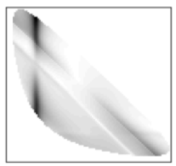
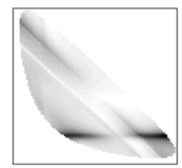
→ The ambiguity can be resolved by measuring also cos(2β) in addition to sin(2β).

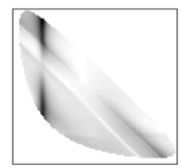
- cos(2β) is not well known. The current best single experimental uncertainty is ≈±0.36.

[PRD 94 (2016) 052004]

Combined *BABAR*+Belle Analysis of $B^0 \to D^{(*)}h^0$ decays

- $B^0 \to D^{(*)}h^0$ with $D^0 \to K_S^0\pi^+\pi^-$decays enable to extract both sin(2β) and cos(2β).
- The approach is similar to the GGSZ method to extract γ from multi-body $B^\pm \to DK^\pm$.
- Interference between D^0 and $\bar{D}^0$, and variations over the Dalitz plot provide access to the CP-violating weak phase 2β.
- Illustration of the B meson decay rate as function of the $D^0 \to K_S^0\pi^+\pi^-$ Dalitz plot:

$|M_{B^0}(\Delta t)|^2 = \Big|$  $\times \cos(\Delta m \Delta t/2) - ie^{+2i\beta} \times$  $\times \sin(\Delta m \Delta t/2)\Big|^2$

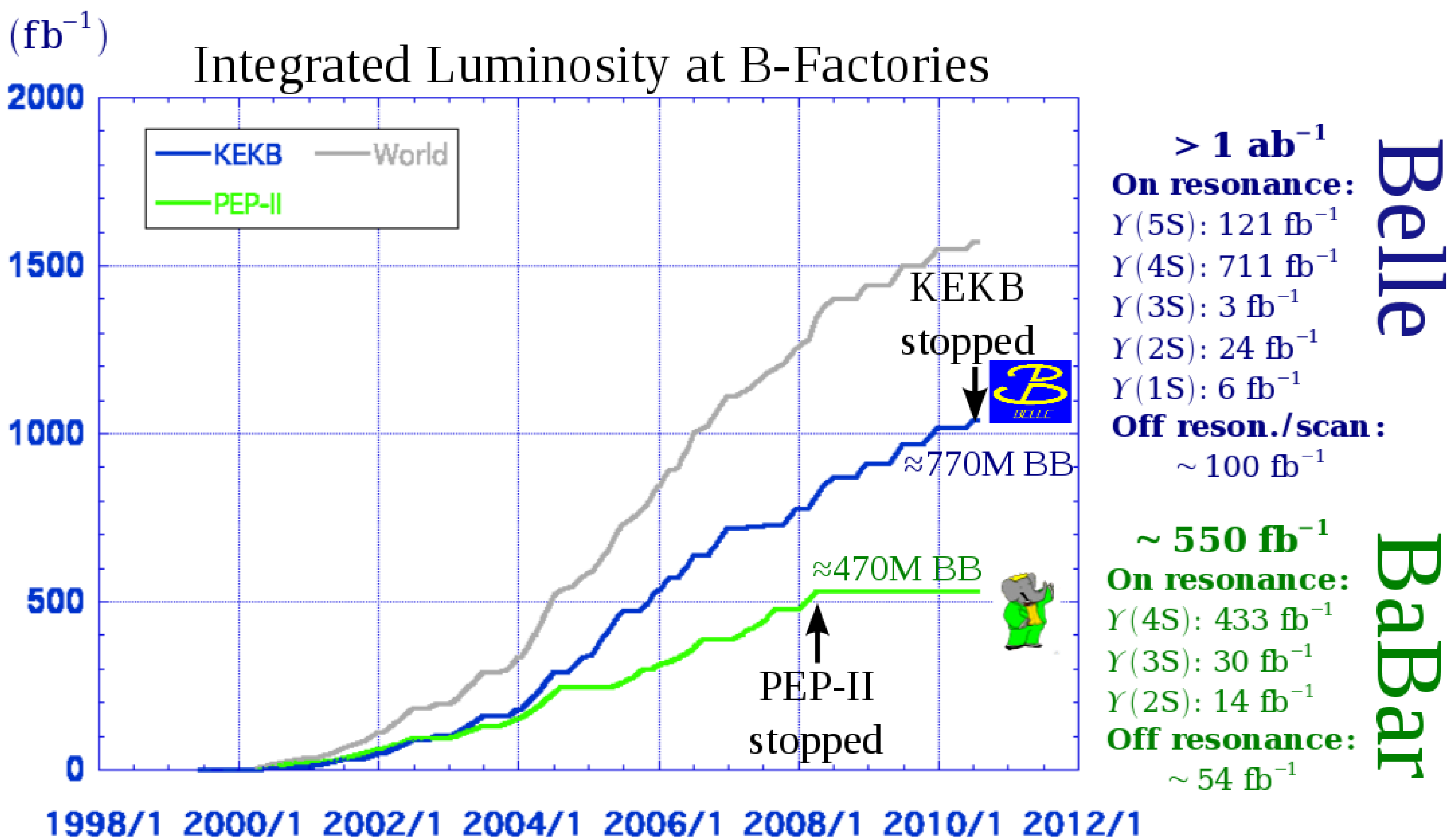
$|M_{\bar{B}^0}(\Delta t)|^2 = \Big|$  $\times \cos(\Delta m \Delta t/2) - ie^{-2i\beta} \times$  $\times \sin(\Delta m \Delta t/2)\Big|^2$

- If the $D^0 \to K_S^0\pi^+\pi^-$ Dalitz plot amplitude model is known, then both sin(2β) and cos(2β) can be extracted from the time evolution of the B decay.

[A. Bondar, P. Krokovny, T. Gershon PLB **624** 1 (2005)]

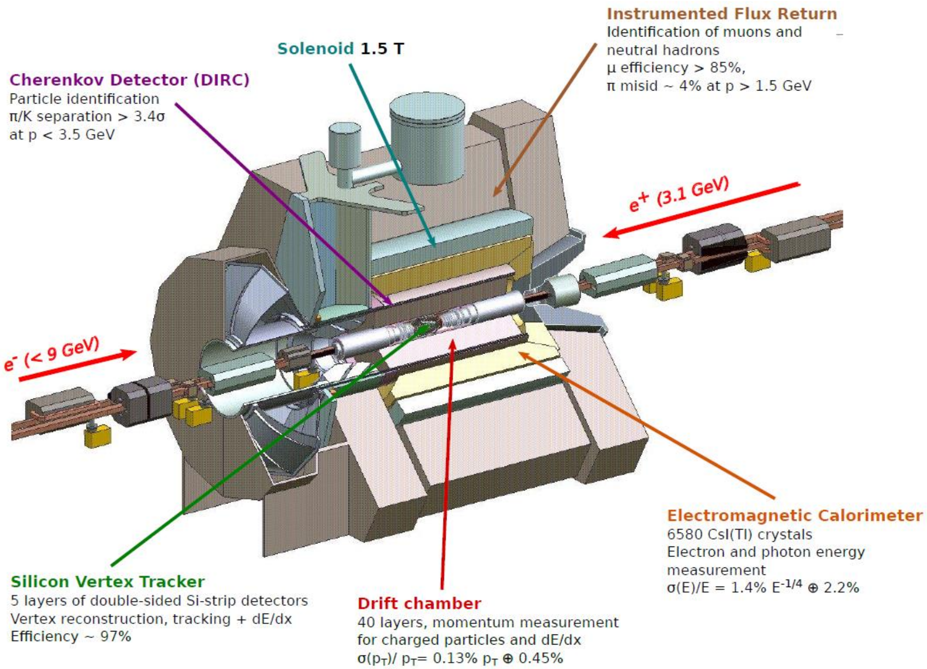
→ Perform time-dependent Dalitz analysis combining *BABAR*+Belle data to improve the sensitivity on cos(2β).

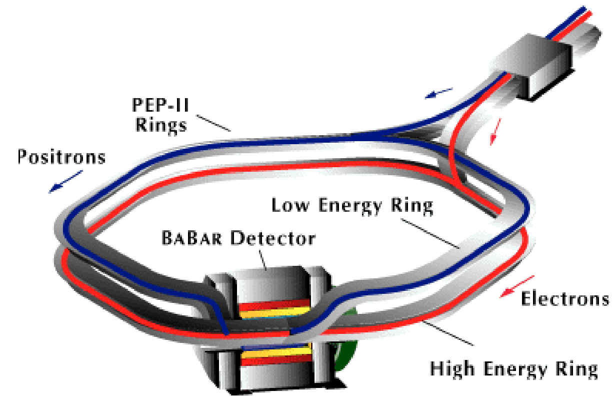
The BABAR and Belle Experiments

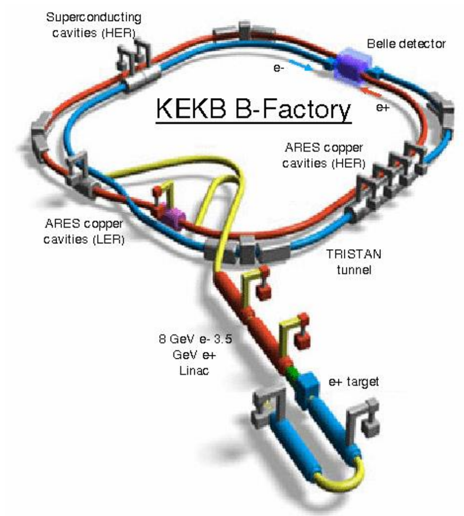


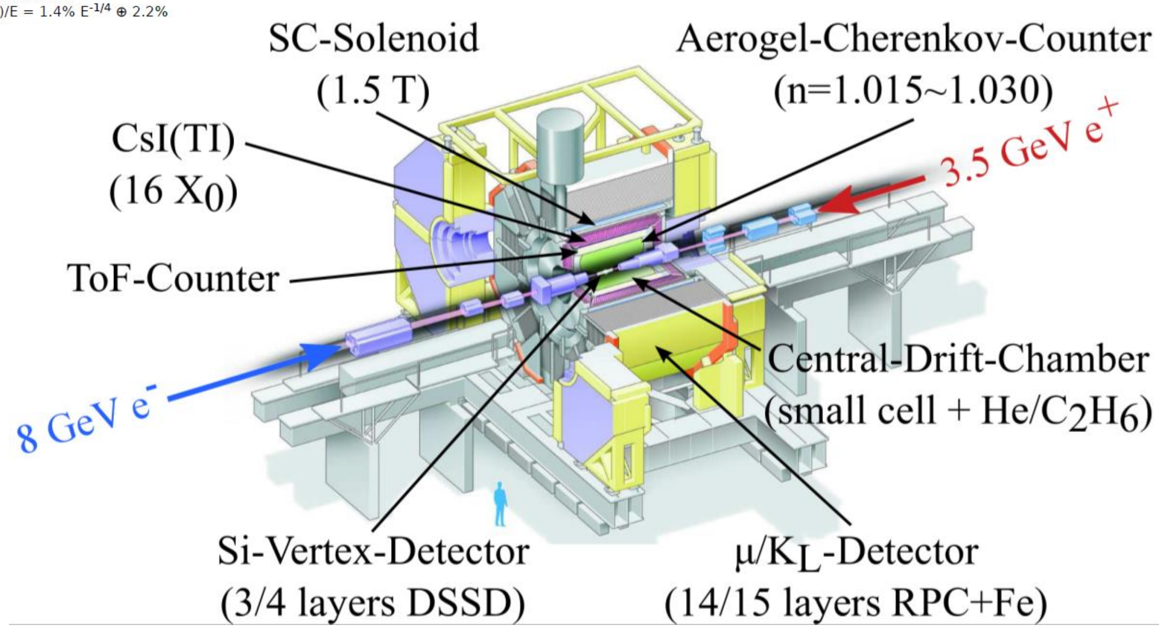
- Combined BABAR+Belle analyses to make full use of the about 1.1 ab^{-1} or ≈1240×10^{6} BB collected on the Υ(4S).
- In a first BABAR+Belle analysis, we previously demonstrated the feasibility and the advantage of the joint approach [PRL **115**, 121604 (2015), presented at La Thuile 2016].

The BaBar and Belle Experiments



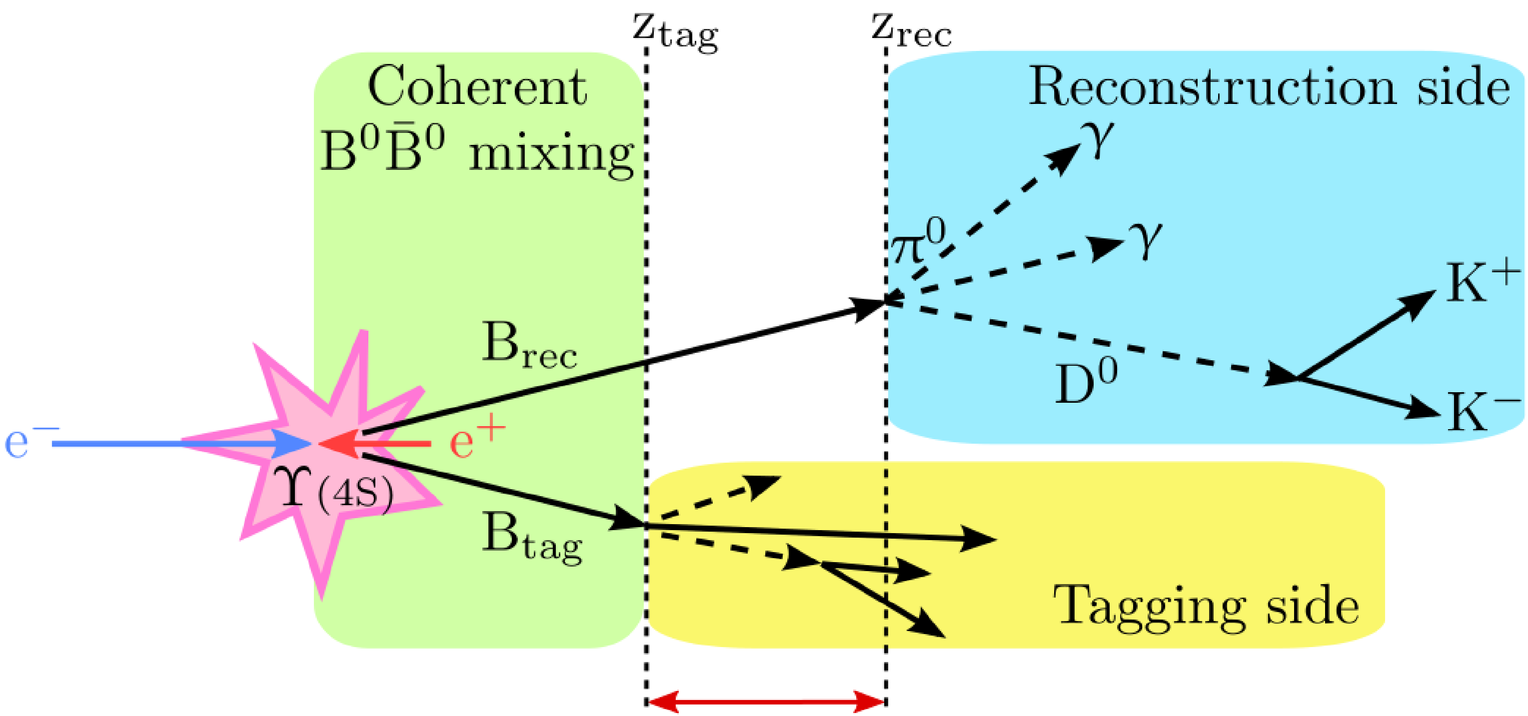






Principle of Time-dependent Measurements at BABAR and Belle

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

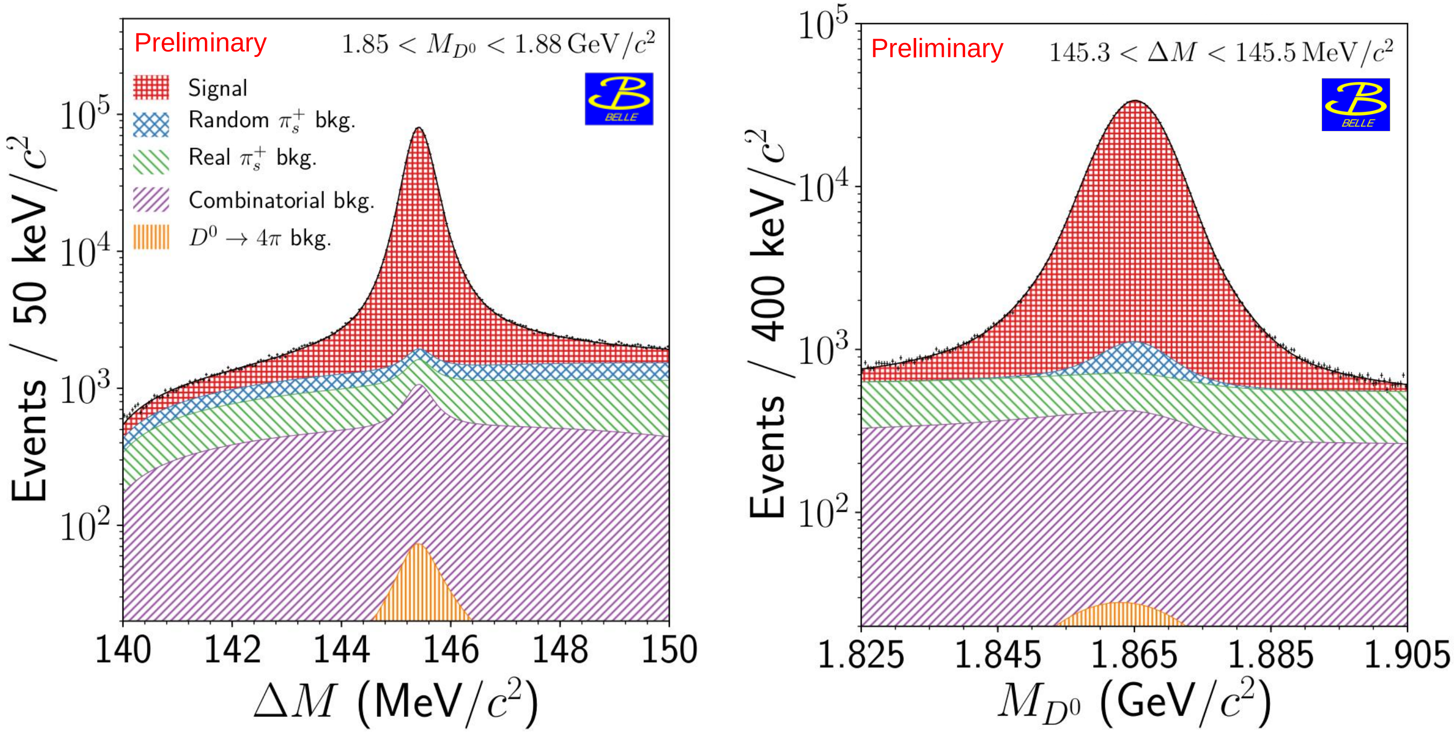


$\Delta z = \beta\gamma c\Delta t$, $\langle|\Delta z|\rangle \approx$ 200µm Belle
250 µm BABAR
effective tag efficiency >30%

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

Combined BABAR+Belle Analysis of $\mathrm{B^0 \to D^{(*)}h^0}$ decays

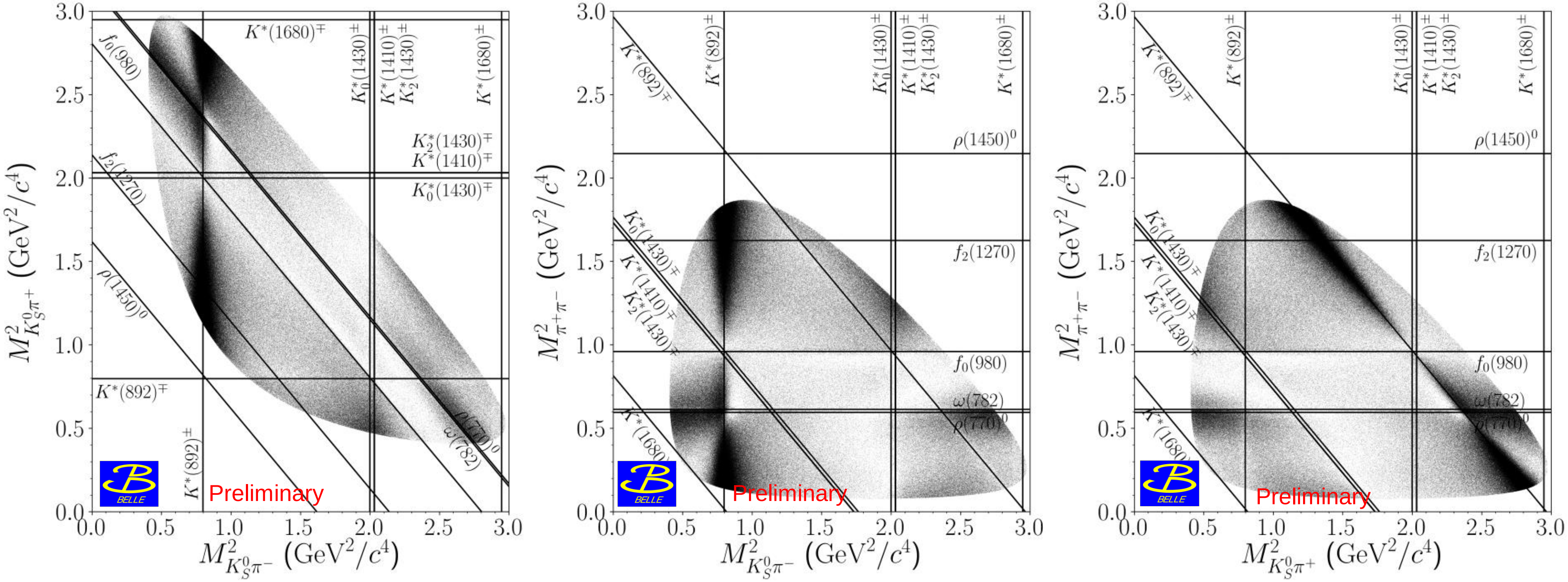
- The $\mathrm{D^0 \to K^0_S \pi^+ \pi^-}$ Dalitz model is directly obtained from flavor-tagged $\mathrm{e^+e^- \to c\bar{c}}$ data.
- Reconstruct $\mathrm{D^{*+} \to D^0 \pi^+_S}$ with $\mathrm{D^0 \to K^0_S \pi^+ \pi^-}$ decays.
- The charge of the low-momentum pion π^+_S tags the neutral D meson flavor.



- The yield is (1,217,300 ± 2,000) $\mathrm{D^0 \to K^0_S \pi^+ \pi^-}$ decays.
- The purity is 94% in the signal region.

Combined BABAR+Belle Analysis of $B^0 \to D^{(*)}h^0$ decays

- The $D^0 \to K_S^0\pi^+\pi^-$ Dalitz plot data distributions from the flavor-tagged $e^+e^- \to c\bar{c}$ data:



- The $D^0 \to K_S^0\pi^+\pi^-$ Dalitz plot is parameterized by the following model:

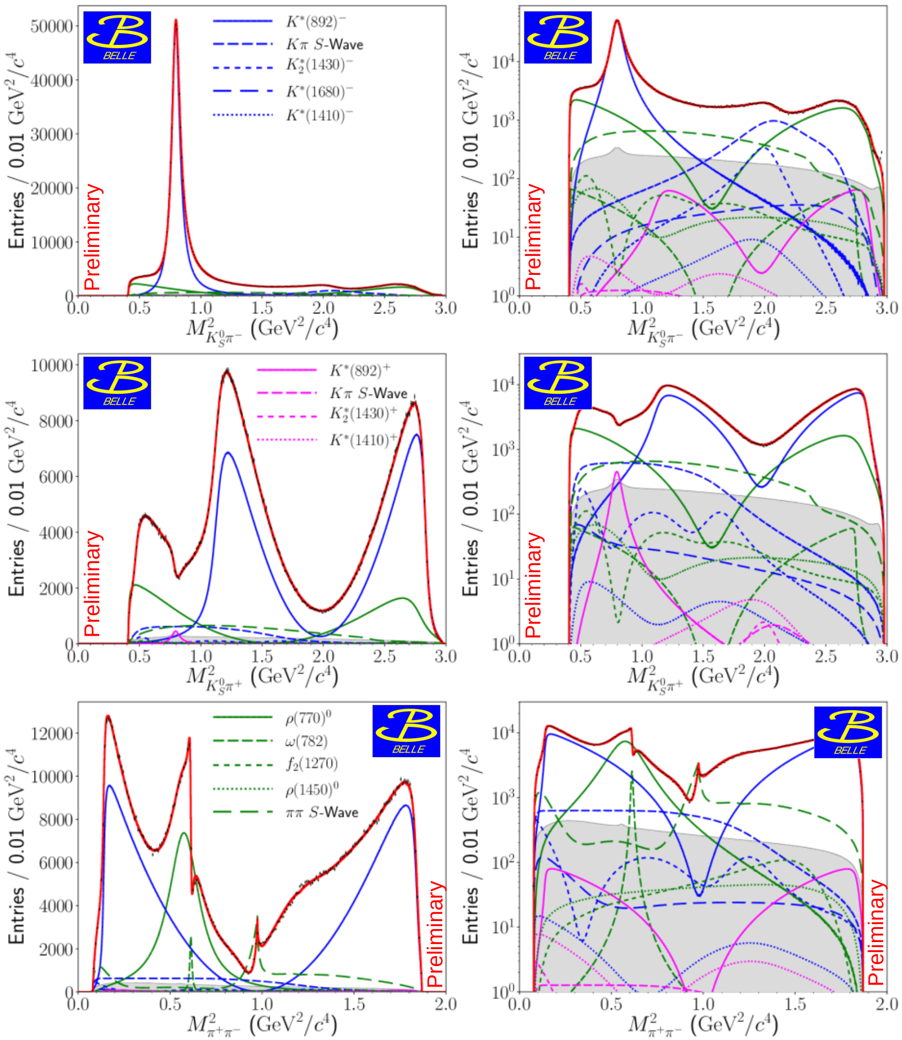
$$\mathcal{A}_{D^0}(m_+^2, m_-^2) = \sum_{r \neq (K\pi/\pi\pi)_{L=0}} a_r e^{i\phi_r} \mathcal{A}_r(m_+^2, m_-^2) + \mathcal{A}_{K\pi_{L=0}}(s) + F_1(s)$$

Isobar model for L≠0 LASS K-matrix

- The model parameters are estimated by a fit to the Dalitz plot distributions above.

Combined *BaBar*+Belle Analysis of $B^0 \to D^{(*)}h^0$ decays

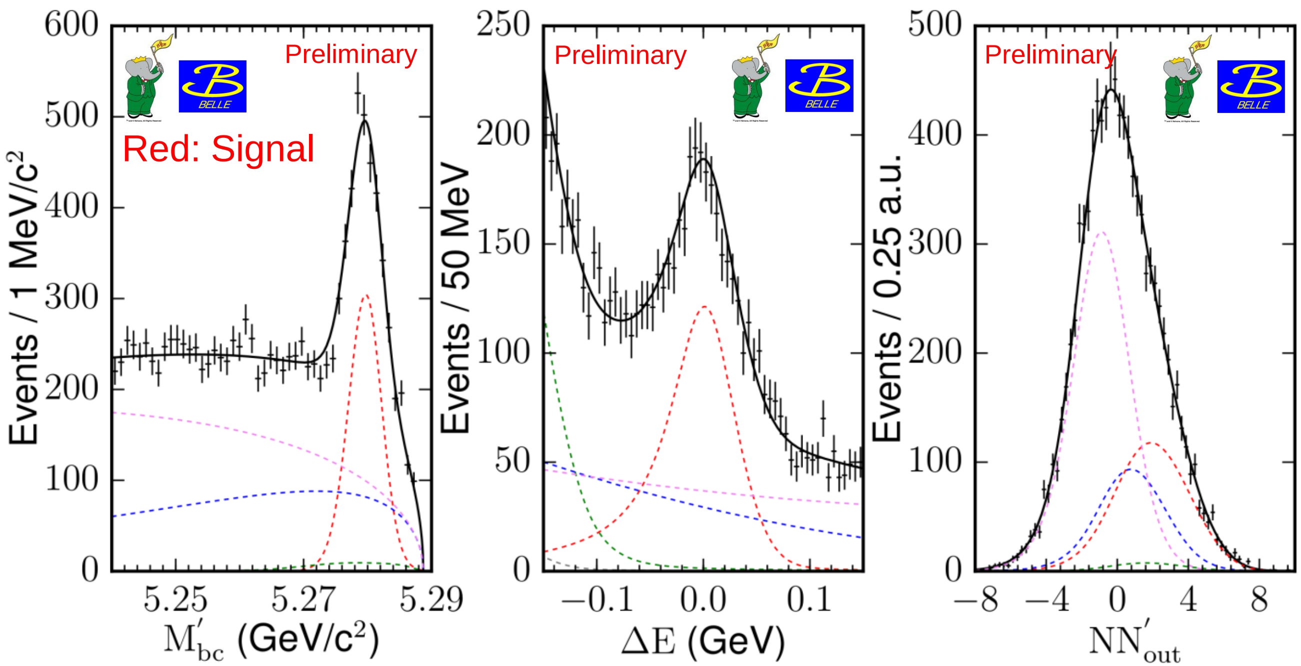
Projections of the $D^0 \to K^0_S\pi^+\pi^-$ Dalitz plot fit:



- The Dalitz plot model accounts for 14 intermediate two-body resonances.
- The K-matrix and LASS parameterizations are used to model the ππ and Kπ S-waves.
- The $D^0 \to K^0_S\pi^+\pi^-$ decay amplitude model extracted from $e^+e^- \to c\bar{c}$ data is used to extract sin(2β) and cos(2β) from the B^0 decay combining *BaBar*+Belle data.

Combined BaBar+Belle Analysis of $B^0 \to D^{(*)}h^0$ decays

- Reconstruct $B^0 \to D^{(*)}h^0$ with h^0 in $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma, \pi^+\pi^-\pi^0$ and $\omega \to \pi^+\pi^-\pi^0$
  $D \to K^0_S\pi^+\pi^-$ and $D^{*0} \to D\pi^0$.
- In total, 5 B^0 decay modes are reconstructed.
- $e^+e^- \to q\bar{q}$ $(q \in \{u, d, s, c\})$ continuum background is identified by neural networks.
- Coherent analysis strategy, apply almost same selection on BaBar and Belle data.
- Extract signal by 3D fit of beam-constr. mass M'_{bc}, energy-difference ΔE and NN'_{out}.



BaBar:
1129 ± 48 signal events

Belle:
1567 ± 56 signal events

Combined $\textit{B\scriptsize{A}\normalsize{B}\scriptsize{AR}}$+Belle Analysis of $\mathbf{B^0 \to D^{(*)} h^0}$ decays

- 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:

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

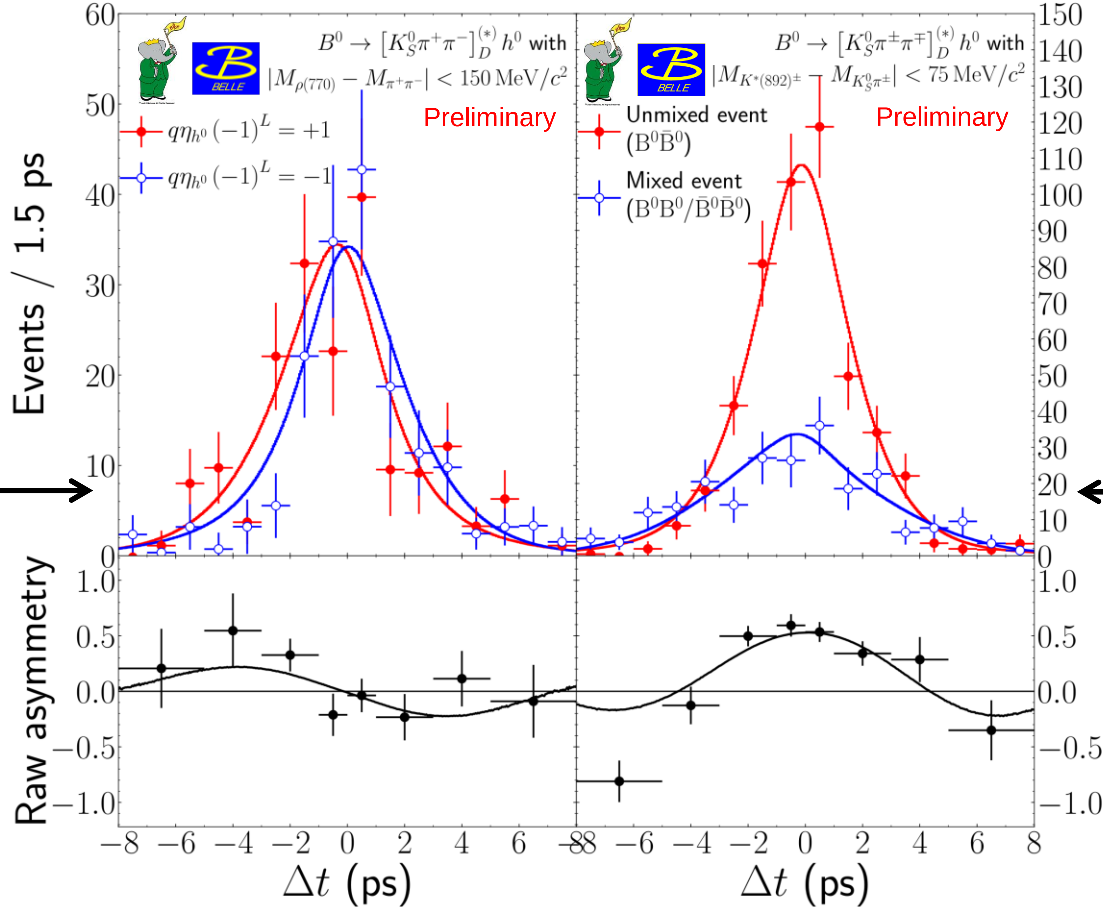
- Apply BABAR and Belle specific resolution models and flavor tagging algorithms.

- Apply common signal model:

$$\begin{aligned} \mathrm{P_{sig}}(\Delta \mathrm{t}) \propto & \left[|\mathcal{A}_{\bar{D}^0}|^2 + |\mathcal{A}_{D^0}|^2 \right] \\ & \mp \left(|\mathcal{A}_{\bar{D}^0}|^2 - |\mathcal{A}_{D^0}|^2 \right) \cos(\Delta m \Delta t) \\ & \pm 2 \eta_{h^0} \left(-1 \right)^L \left[\mathrm{Im} \left(\mathcal{A}_{D^0} \mathcal{A}^*_{\bar{D}^0} \right) \cos(2\beta) - \mathrm{Re} \left(\mathcal{A}_{D^0} \mathcal{A}^*_{\bar{D}^0} \right) \sin(2\beta) \right] \sin(\Delta m \Delta t) \end{aligned}$$

Combined BABAR+Belle Analysis of $B^0 \to D^{(*)}h^0$ decays

CP eigenstate final states



Flavor-specific final states

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

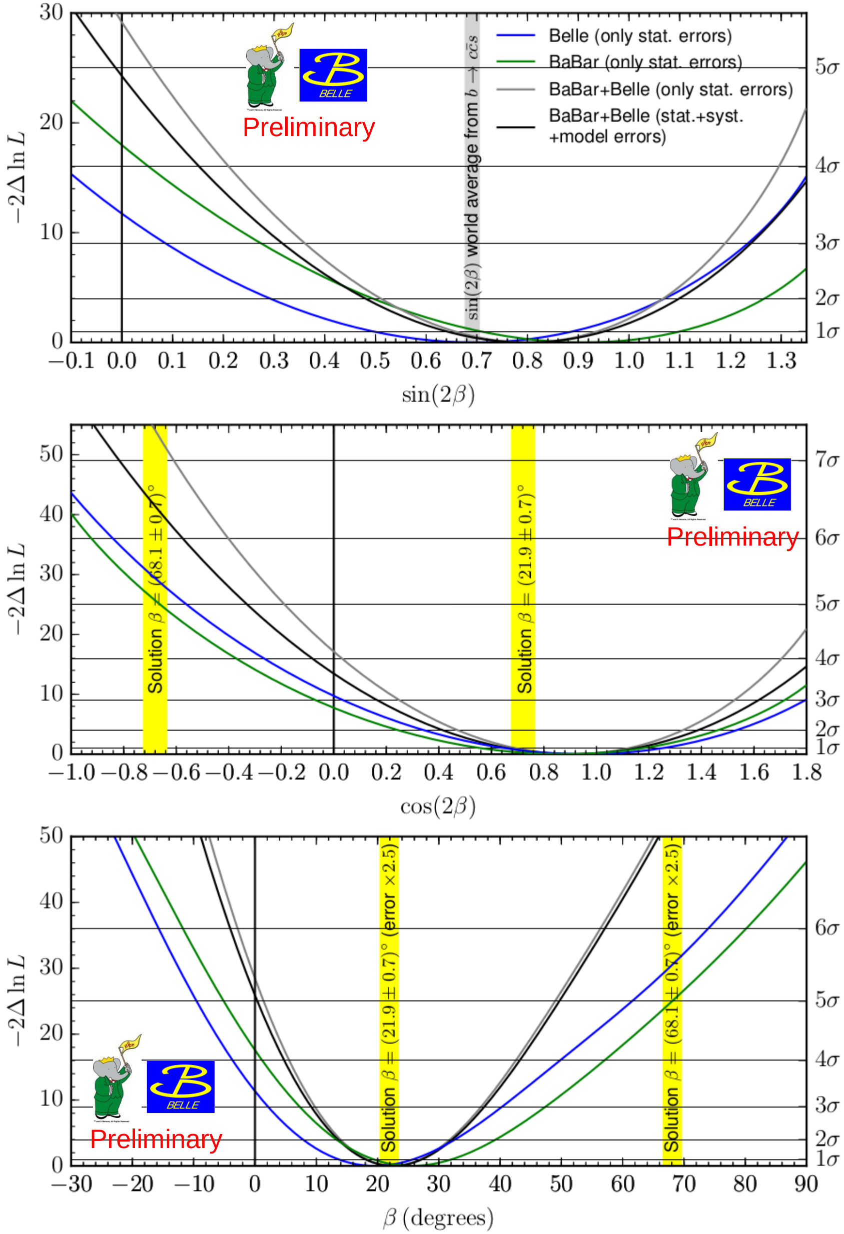
Preliminary

$$\sin(2\beta) = 0.80 \pm 0.14\,(\mathrm{stat.}) \pm 0.06\,(\mathrm{syst.}) \pm 0.03\,(\mathrm{model})$$

$$\cos(2\beta) = 0.91 \pm 0.22\,(\mathrm{stat.}) \pm 0.09\,(\mathrm{syst.}) \pm 0.07\,(\mathrm{model})$$

$$\beta = (22.5 \pm 4.4\,(\mathrm{stat.}) \pm 1.2\,(\mathrm{syst.}) \pm 0.6\,(\mathrm{model}))^\circ$$

Combined BaBar+Belle Analysis of $B^0 \to D^{(*)}h^0$ decays



- First evidence for $\cos(2\beta) > 0$ (3.7σ)

- Direct exclusion of the 2nd solution

$$\pi/2 - \beta = (68.1 \pm 0.7)°$$

  of the CKM Unitarity Triangle (7.3σ)

  → Reduction of the trigonometric ambiguity of the CKM Unitarity Triangle

- Exclusion of $\beta = 0°$ (5.1σ)

  → Observation of CP violation in $B^0 \to D^{(*)}h^0$ decays

Summary

- The BABAR and Belle experiments recently started performing measurements combining the about 1.1 ab^{-1} collected on the Υ(4S), which allows for an unprecedented sensitivity in time-dependent CP violation measurements.

- Results of the new analysis presented:
  - First evidence for $\cos(2\beta) > 0$ at h the level of 3.7σ
  - Exclusion of the 2nd solution of the CKM Unitarity Triangle

    $\pi/2 - \beta = (68.1 \pm 0.7)^\circ$ at 7.3σ
  - Good agreement with $\sin(2\beta)$from $\mathrm{b} \to \mathrm{c\bar{c}s}$ and an observation of CP violation at 5.1σ