

Measurement of $\cos(2\beta) = \cos(2\phi_1)$ in $\bar{B}^0 \rightarrow D^{(*)0} h^0$
with $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays by a combined
time-dependent Dalitz Plot analysis using data from
BABAR and Belle

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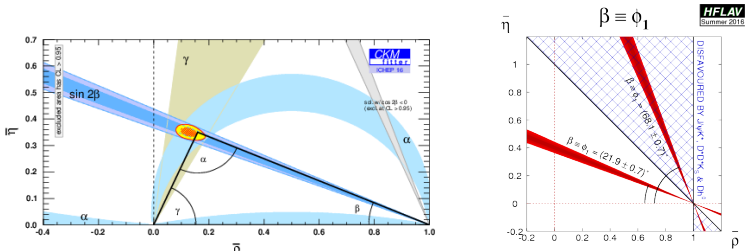
On behalf of the *BABAR* and Belle collaborations

Lake Louise Winter Institute 2018

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CKM Unitarity Triangle and $\cos 2\beta$

Measurement of $\sin 2\beta (= \sin 2\phi_1)$ [1] leads to $\beta = 21.9^\circ$ or $\beta = \pi/2 - 21.9^\circ = 68.1^\circ$ [2].



Time-dependent Dalitz Plot analysis of $\bar{B}^0 \rightarrow D^{(*)0} h^0$ with $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ determines both $\sin 2\beta$ and $\cos 2\beta$ [3].

$$|M_{\bar{B}^0}(\Delta t)|^2 = \left[\begin{array}{c} \text{DP} \\ \text{DP} \end{array} \right] \times \cos(\Delta m \Delta t / 2) - ie^{+2i\beta} \times \left[\text{DP} \right] \times \sin(\Delta m \Delta t / 2) \Bigg|_2$$

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Determination of $\cos 2\beta$

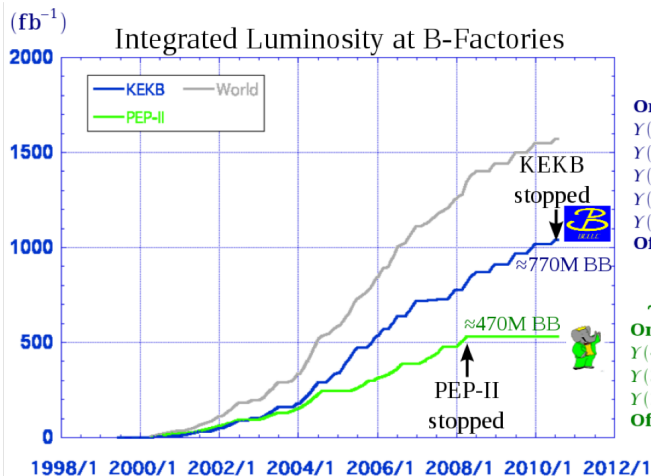
Previous *BABAR* + Belle analysis of $\bar{B}^0 \rightarrow D_{CP}^{(*)0} h^0$: $\sin(2\beta) = 0.66 \pm 0.11 \pm 0.06$ [4].
Both *BABAR* and Belle have independently measured $\cos(2\beta)$ using $\bar{B}^0 \rightarrow D^{(*)} h^0$:

- Neither sensitive enough to establish sign of $\cos(2\beta)$.
- Results outside physical region of parameter space:
e.g. $\cos(2\beta) = 1.06 \pm 0.33_{-0.15}^{+0.21}$ [5], $1.87_{-0.53-0.32}^{+0.40+0.22}$ [6].
- Used different set of resonances in Dalitz Plot amplitude models.

Steps in this analysis:

- 1 Dalitz Plot analysis of $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ from $D^{*+} \rightarrow D^0 \pi_s^+$ in $e^+ e^- \rightarrow c\bar{c}$.
- 2 Extract signal yield from $\bar{B}^0 \rightarrow D^{(*)0} h^0$ decays:
 - $(D^{*0} \rightarrow D^0 \pi^0)$, $D^0 \rightarrow K_S^0 \pi^+ \pi^-$.
 - $h^0 = \pi^0 \rightarrow \gamma\gamma$, $\eta \rightarrow \gamma\gamma$, $\eta \rightarrow \pi^+ \pi^- \pi^0$ and $\omega \rightarrow \pi^+ \pi^- \pi^0$.
- 3 Time-dependent *CP* analysis of the $\bar{B}^0 \rightarrow D^{(-)} h^0$ decay.

BABAR and Belle experiments



Belle

$> 1 \text{ ab}^{-1}$

On resonance:
 $Y(5S): 121 \text{ fb}^{-1}$
 $Y(4S): 711 \text{ fb}^{-1}$
 $Y(3S): 3 \text{ fb}^{-1}$
 $Y(2S): 24 \text{ fb}^{-1}$
 $Y(1S): 6 \text{ fb}^{-1}$

Off reson./scan:
 $\sim 100 \text{ fb}^{-1}$

BaBar

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

On resonance:
 $Y(4S): 433 \text{ fb}^{-1}$
 $Y(3S): 30 \text{ fb}^{-1}$
 $Y(2S): 14 \text{ fb}^{-1}$

Off resonance:
 $\sim 54 \text{ fb}^{-1}$

BaBar + Belle dataset: 1.1 ab^{-1} or $\approx 1.24 \times 10^9 B\bar{B}$ collected at $\Upsilon(4S)$ resonance.

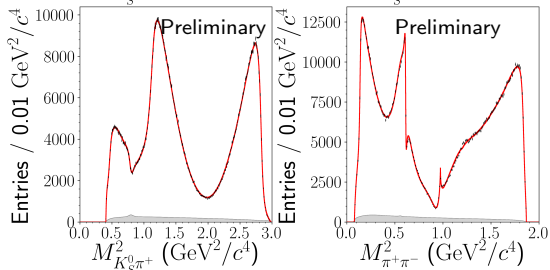
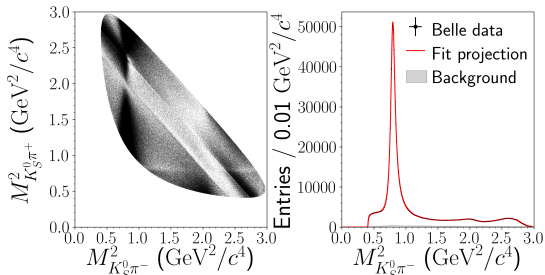
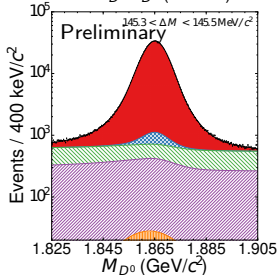
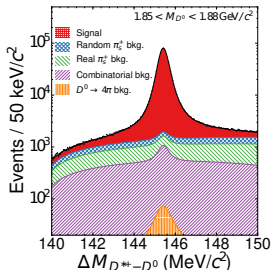
$D^0 \rightarrow K_S^0 \pi^+ \pi^-$ Dalitz Plot Amplitude Model

- Taken from flavor-tagged $D^{*+} \rightarrow D^0 \pi_S^+$ decays in $e^+ e^- \rightarrow c \bar{c}$ data.
- **Belle data only**: 924 fb^{-1} at $\Upsilon(4S)$, $\Upsilon(5S)$ and off-resonance.
- Fit to D^0 mass and $\Delta M = M_{D^{*+}} - M_{D^0}$ to define signal candidates.
- Then fit $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ Dalitz Plot

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

- Two-body intermediate resonances:
 - Cabibbo-favored: $K^*(892)^-$, $K_2^*(1430)^-$, $K^*(1680)^-$, $K^*(1410)^-$
 - Cabibbo-suppressed: $K^*(892)^+$, $K_2^*(1430)^+$, $K^*(1410)^+$
 - CP eigenstates: $\rho(770)^0$, $\omega(782)$, $f_2(1270)$, $\rho(1450)^0$
- LASS parameterisation used for $K_0^*(1430)^\mp$ and $K\pi_{L=0}$ S-wave [7].
- K-Matrix used for $\pi\pi_{L=0}$ S-wave [8].

$D^{*+} \rightarrow D^0 \pi_s$ yield and $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ Dalitz Plot



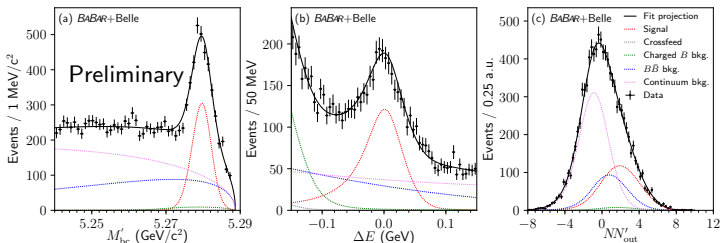
Yield = 1, 217, 329 ± 2, 015

$\bar{B}^0 \rightarrow D^{(*)0} h^0$ Signal Yield

- Five B^0 decay modes reconstructed: $D^0\pi^0$, $D^0\eta$, $D^0\omega$, $D^{*0}\pi^0$, $D^{*0}\eta$.
- Very similar selections applied to both *BABAR* and Belle data.
- Neural Net (*NN*) with 16 event-shape variables to reject $e^+e^- \rightarrow q\bar{q}$.
- Three-dimensional Maximum Likelihood fit to M'_{bc} , ΔE , and NN'_{out} .

$$M'_{bc} = \sqrt{E_{\text{beam}}^{*2} - \left(\vec{p}_{D^{(*)}0}^* + \frac{\vec{p}_{h^0}^*}{|\vec{p}_{h^0}^*|} \sqrt{(E_{\text{beam}}^* - E_{D^{(*)}0}^*)^2 - m_{h^0}^2} \right)^2}; \quad \Delta E = E_B^* - E_{\text{beam}}^*$$

- Yields: *BABAR* = 1129 ± 48 ; Belle = 1567 ± 56 .



Time-dependent CP analysis

- Fit proper-time interval Δt independently to $BABAR$ and Belle data

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

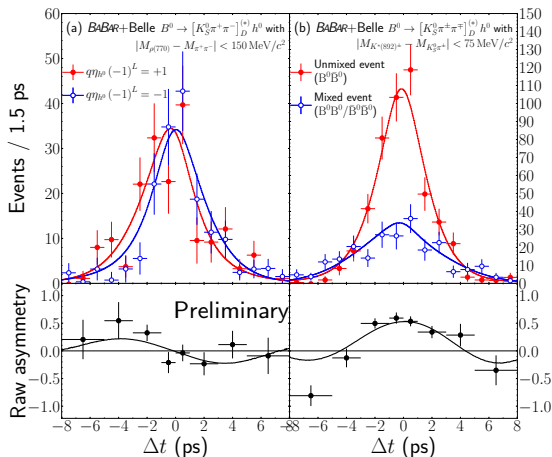
- PDFs \mathcal{P} convoluted with time-dependent resolution functions \mathcal{R}

$$\mathcal{P}_{\text{exp}} = \sum_k f_k \int [\mathcal{P}_k(\Delta t) \mathcal{R}_k(\Delta t - \Delta t')] d\Delta t'$$

- Apply experiment-specific **resolution** models and **flavor-tagging** algorithms.
- Apply common signal Dalitz plot signal model:

$$\begin{aligned} \mathcal{P}_{\text{sig}} \propto & [|\mathcal{A}_{\bar{D}^0}|^2 + |\mathcal{A}_{D^0}|^2] - q[|\mathcal{A}_{\bar{D}^0}|^2 - |\mathcal{A}_{D^0}|^2] \cos(\Delta m \Delta t) \\ & \pm 2q\eta_h^0 (-1)^L [\Im(\mathcal{A}_{D^0} \mathcal{A}_{\bar{D}^0}^*) \cos 2\beta - \Re(\mathcal{A}_{D^0} \mathcal{A}_{\bar{D}^0}^*) \sin 2\beta] \sin(\Delta m \Delta t) \end{aligned}$$

Time-dependent CP analysis

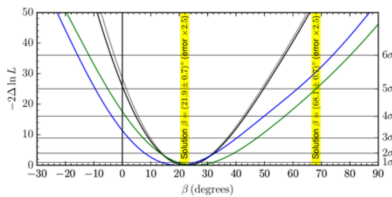
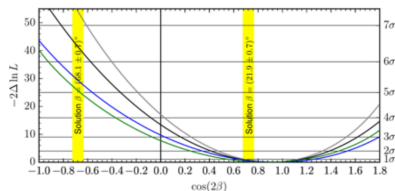


$$\sin 2\beta = 0.80 \pm 0.14(\text{stat.}) \pm 0.06(\text{syst.}) \pm 0.03(\text{model})$$

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

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

Summary and Conclusion



- $\sin 2\beta$ in good agreement with World Average, $\sin 2\beta = 0.69 \pm 0.02$.
- **Most precise measurement of $\cos 2\beta$.**
- **First evidence for $\cos 2\beta > 0$ (3.7σ).**
- **Exclusion of second solution $\pi/2 - \beta = (68.1 \pm 0.7)^\circ$ (7.3σ).**
- **Exclusion of $\beta = 0$ (5.1σ).**
- **Observation of CP violation in $B^0 \rightarrow D^{(*)0} h^0$.**
- In preparation for Phys. Rev. Lett. and Phys. Rev. D.

Bibliography

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