Measurement of the CKM phase φ_1 in $b \to c\bar{u}d$ transitions at Belle (and BaBar)

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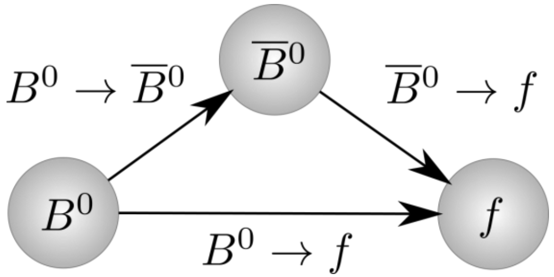
Outline

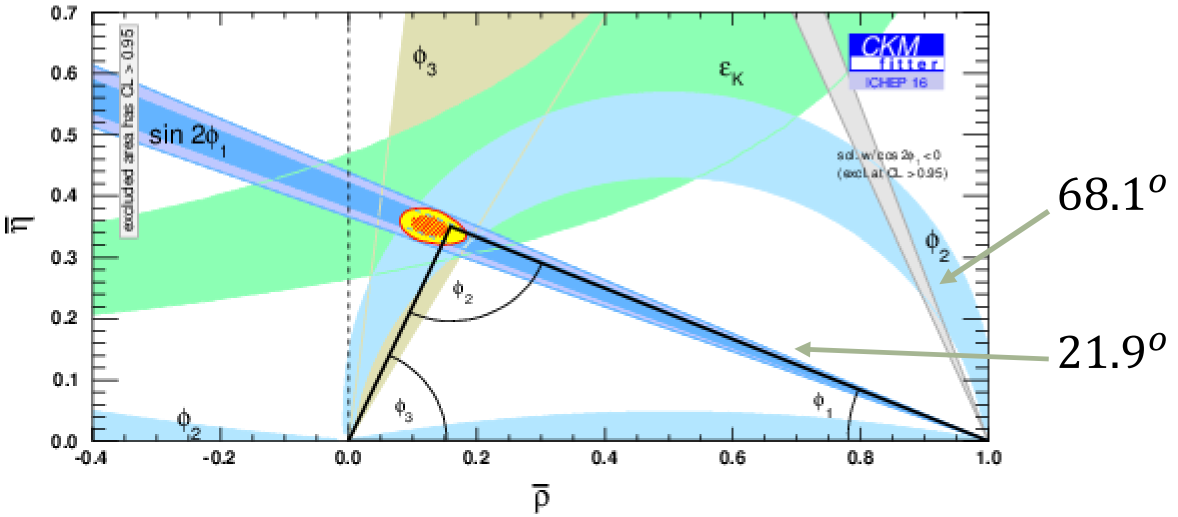
- CP violation study using the $b \to c\bar{u}d$ transition
- Recent results:
  - Combined BaBar + Belle analysis of $\bar{B}^0 \to D_{CP}^{(*)} h^0$ (2015)
  - Combined BaBar + Belle analysis of $\bar{B}^0 \to D^{(*)} h^0$, $D^0 \to K_S^0 \pi^+ \pi^-$ (2017 preliminary)
  - *Model-independent* analysis of $\bar{B}^0 \to D^{(*)} h^0$, $D^0 \to K_S^0 \pi^+ \pi^-$ with Belle data (2016)
- Prospects for measurement of the angle φ_1 in $b \to c\bar{u}d$ at LHCb and Belle II

Determination of the CKM angle φ_1

- Time-dependent interference between decays w/ and w/o oscillation



- A CP-specific final state f provides sensitivity to $\sin(2\varphi_1)$
- Tagging of the *initial B^0 flavor* is necessary
- Measurement of B^0 *decay vertex* is needed for time-dependent analysis



- The value of $\sin(2\varphi_1)$ is measured precisely in $b \to c\bar{c}s$ ($B^0 \to J/\psi K_S^0, \ldots$) transitions:

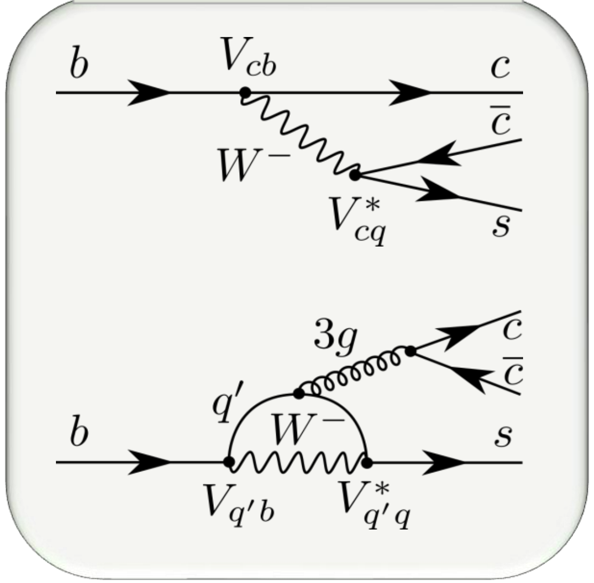
$$\sin(2\varphi_1)_{b\to c\bar{c}s} = 0.691 \pm 0.017$$

- Trigonometric ambiguity: $2\varphi_1 \to \pi - 2\varphi_1$

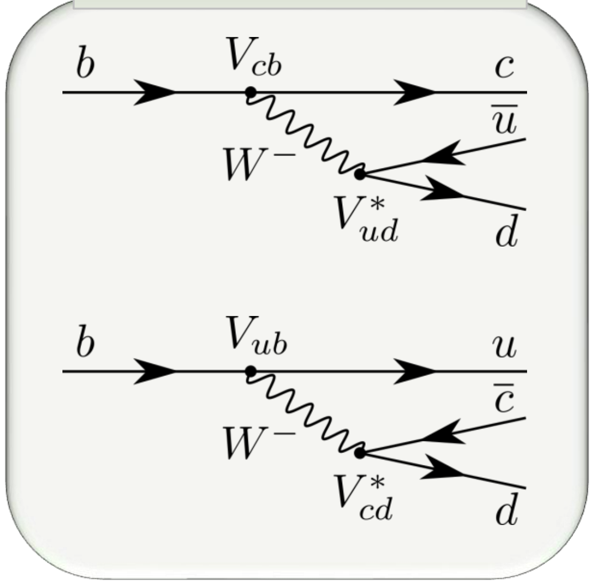
Features of the $b \to c\bar{u}d$ transition

- A complementary and theoretically clean approach to access φ_1
- The $\bar{B}^0 \to D^0_{CP} h^0$ ($h^0 = \pi^0, \eta^{(\prime)}, \omega$) decays are dominated by tree amplitudes and are not sensitive to most of physics beyond standard model (BSM)
- A sizable deviation in the CP asymmetry of $\bar{B}^0 \to D^0_{CP} h^0$ decays from $b \to c\bar{c}s$ would indicate BSM
- Time-dependent Dalitz analysis of the $\bar{B}^0 \to D^0 h^0$, $D^0 \to K^0_S \pi^+\pi^-$ decays can be employed to measure $\cos(2\varphi_1)$ and to resolve the trigonometric ambiguity.

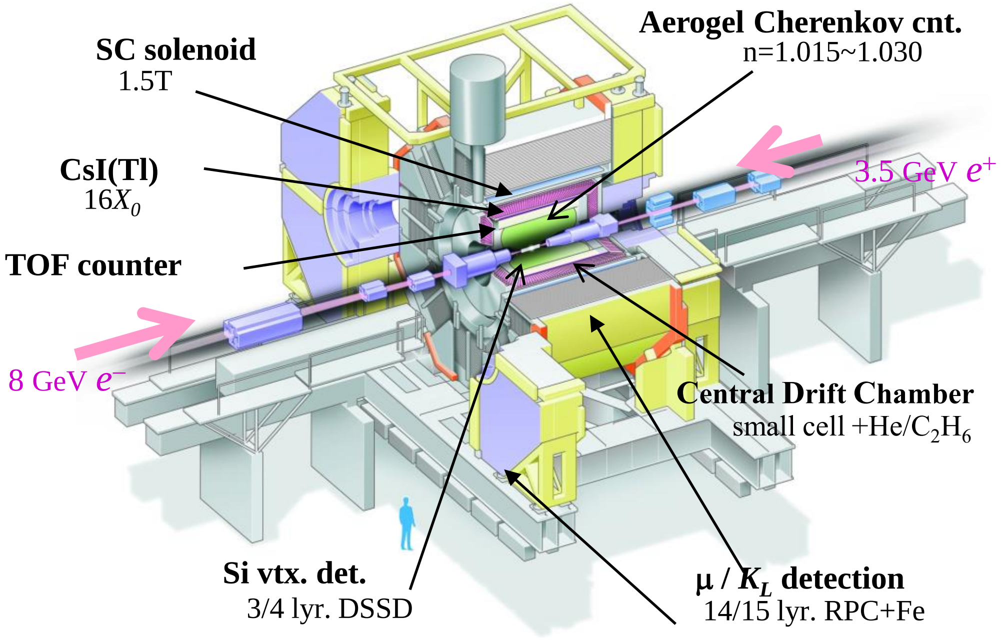
$b \to c\bar{c}s$
($B^0 \to J/\psi K^0_S$)

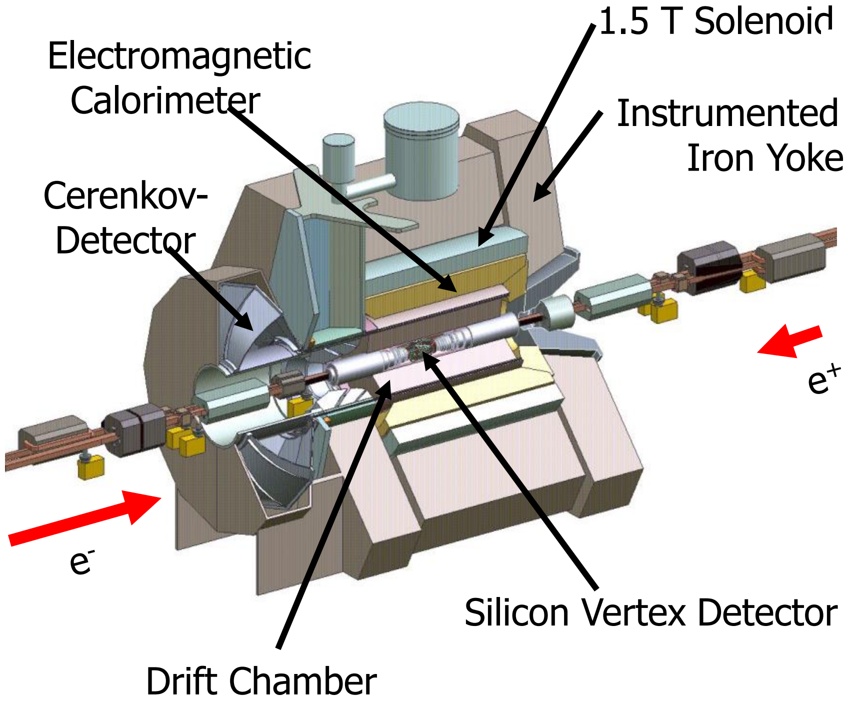


$b \to c\bar{u}d$
($\bar{B}^0 \to D^0 h^0$)



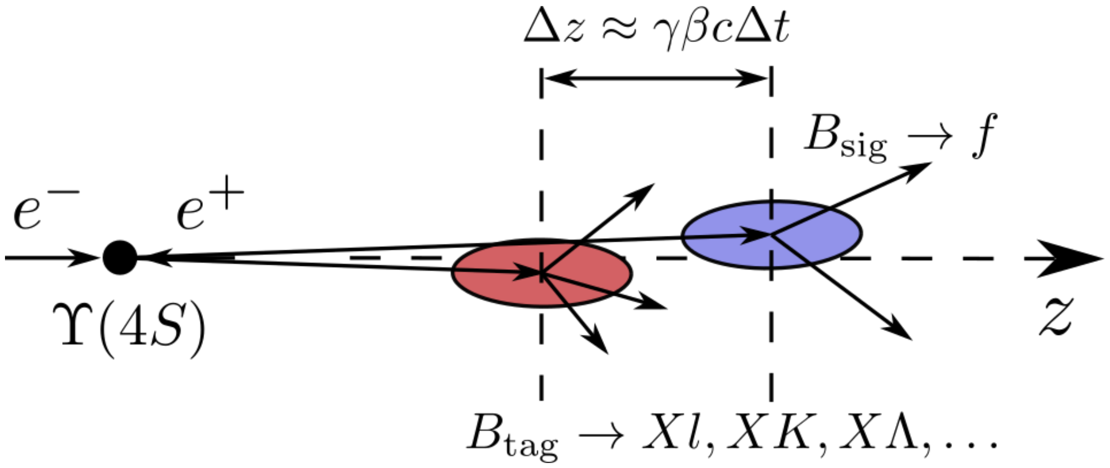
The Belle and BaBar experiments



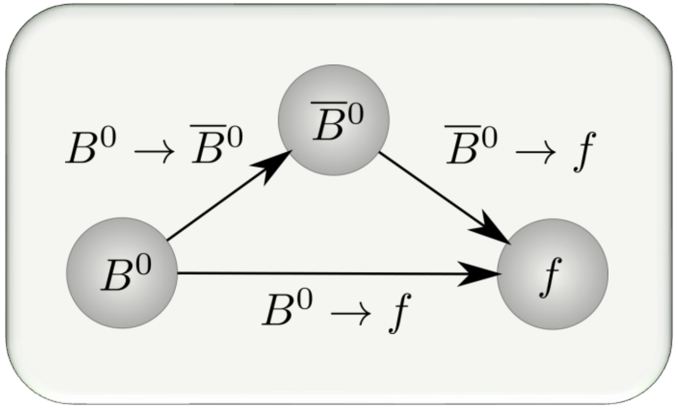


- The Belle experiment:
  - Operation period: 1999 – 2010
  - 1.04 ab^{-1} integrated luminosity
  - 772×10^6 $B\bar{B}$ pairs
- The BaBar experiment:
  - Operation period: 1999 – 2008
  - 541 fb^{-1} integrated luminosity
  - 471×10^6 $B\bar{B}$ pairs

Time-dependent measurements at an asymmetric B-factory



- Flight distance $\Delta z \approx 200\ \mu\text{m}$
- Vertex resolution $\sigma(\Delta z) \approx 130\ \mu\text{m}$
- Correct flavor tagging for $\approx 80\%$ events
- Boost factor:
  - Belle $\beta\gamma = 0.425$
  - BaBar $\beta\gamma = 0.56$



Time-dependent B decay rate

$$g(\Delta t) = \frac{1}{4\tau_B} e^{-\frac{|\Delta t|}{\tau_B}} (1 + q[A \sin(\Delta m \Delta t) - B \cos(\Delta m \Delta t)])$$

- $q = \pm 1$ denotes the initial flavor of signal B meson
- Standard model predicts $A = -\eta_f \sin(2\varphi_1)$ and $B = 0$ for a CP-specific final state with CP parity η_f

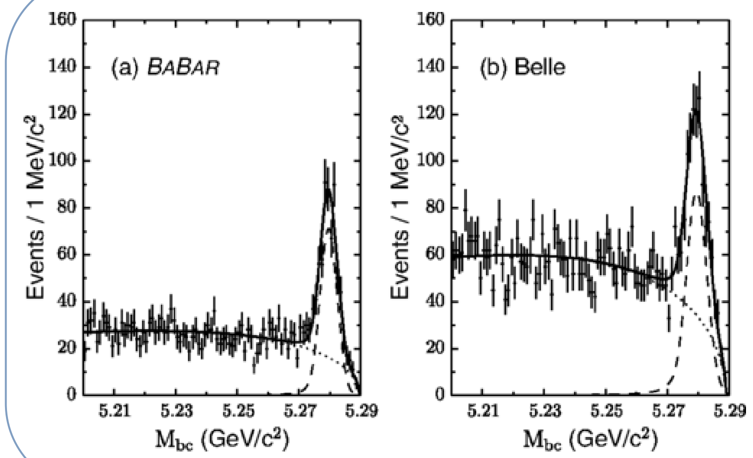
Combined BaBar + Belle analysis of $\bar{B}^0 \to D_{CP}^{(*)} h^0$

New approach: the first combined analysis of BaBar and Belle data

PRL 115, 121604 (2015)

Signal modes

- CP-even modes:
  - $D_{CP}\pi^0$ and $D_{CP}\eta$ with $D_{CP} \to K_S^0\pi^0, K_S^0\omega$
  - $D_{CP}\omega$ with $D_{CP} \to K_S^0\pi^0$
  - $D_{CP}^*\pi^0$ and $D_{CP}^*\eta$ with $D_{CP} \to K^+K^-$
- CP-odd modes:
  - $D_{CP}\pi^0$, $D_{CP}\eta$ and $D^0\omega$ with $D_{CP} \to K^+K^-$
  - $D_{CP}^*\pi^0$ and $D_{CP}^*\eta$ with $D_{CP} \to K_S^0\pi^0$



Signal yield

BaBar: 508 ± 31

Belle: 757 ± 44

Background

- Dominant source of background originates from $e^+e^- \to q\bar{q}$, $q \in \{u, d, s, c\}$
- Flavor-specific decays like $B^- \to D^{(*)0}\rho^-$. Less than 8% of the signal

Main kinematic variables

$$M_{bc} = \sqrt{\left(E_{\text{beam}}^*\right)^2 - (p_{\text{B}}^*)^2}$$

* denotes the e^+e^- center-of-mass frame

$$\Delta E = E_B^* - E_{\text{beam}}^*$$

Combined BaBar + Belle analysis of $\bar{B}^0 \to D_{CP}^{(*)} h^0$

PRL 115, 121604 (2015)

Time-dependent B decay rate

$$g(\Delta t) \propto 1 + q[A \sin(\Delta m \Delta t) + B \cos(\Delta m \Delta t)]$$

$A = -\eta_f \sin(2\varphi_1)$ and $B = 0$ for a CP-specific final state

Maximum likelihood fit of the Δt distributions

$$\sin(2\varphi_1) = 0.66 \pm 0.10\ (\text{stat.}) \pm 0.06\ (\text{syst.})$$

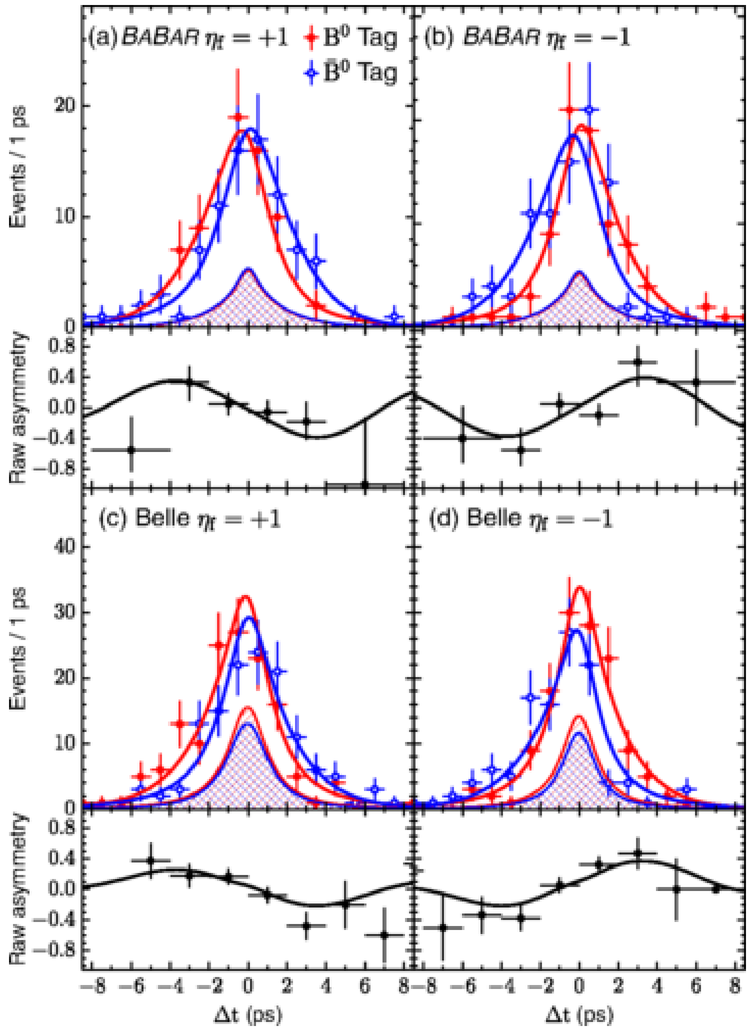
- No significant direct CP violation found:

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

Main systematics sources

- Peaking background (0.049)
- Δt resolution functions (0.020)
- Vertex resolution (0.015)

Observation of CP violation at 5.4σ confidence level



Combined BaBar + Belle analysis of $\bar{B}^0 \to D^{(*)} h^0$ with $D^0 \to K_S^0 \pi^+ \pi^-$ Moriond 2017

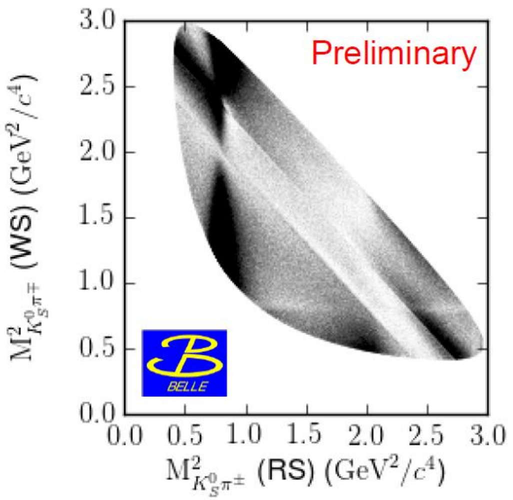
The method

- Time-dependent Dalitz analysis enables to extract both $\sin(2\varphi_1)$ and $\cos(2\varphi_1)$ [Bondar, Krokovny, Gershon PLB 624, 1 (2005)]
- Variation of the (unknown) D^0 decay amplitude phase over the Dalitz plot provides the sensitivity
- A (phenomenological) D^0 decay amplitude model is required to predict the phase

The $D^0 \to K_S^0 \pi^+ \pi^-$ decay model

- The model is obtained from flavor-tagged $e^+e^- \to c\bar{c}$ $(D^{*\pm} \to D^0 \pi^\pm)$ data
- The model includes 14 intermediate two-body resonances
- The K-matrix and LASS parametrizations are used to model the $\pi\pi$ and $K\pi$ S-waves

[M. Röhrken, Moriond 2017]



Combined BaBar + Belle analysis of $\bar{B}^0 \to D^{(*)} h^0$ with $D^0 \to K_S^0 \pi^+ \pi^-$

Signal modes

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

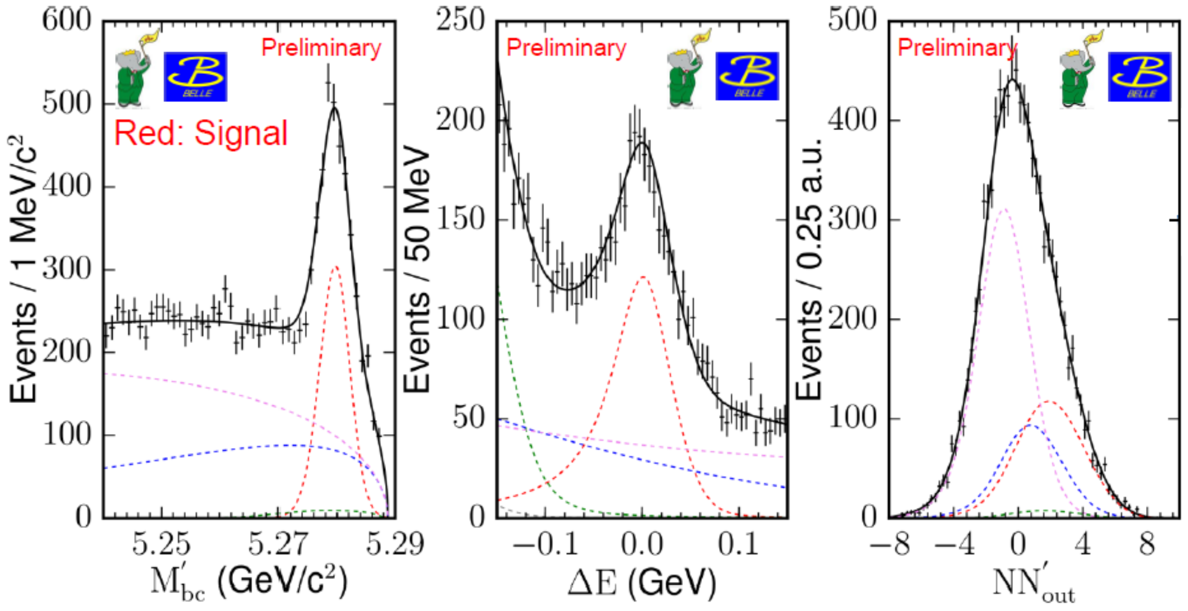
Background

- Similar to the $\bar{B}^0 \to D_{CP}^{(*)} h^0$ case

Main variables

- M'_{bc} – modified M_{bc}
- ΔE – energy difference
- NN'_{out} – neural net response

[M. Röhrken, Moriond 2017]



Signal yield from 3D fit: BaBar: 1129 ± 48; Belle: 1567 ± 56

Combined BaBar + Belle analysis of $\bar{B}^0 \to D^{(*)} h^0$ with $D^0 \to K_S^0 \pi^+ \pi^-$

Maximum likelihood fit of the Δt distributions

$$\sin(2\varphi_1) = 0.80 \pm 0.14\,(\text{stat.}) \pm 0.06\,(\text{syst.}) \pm 0.03\,(\text{model})$$

$$\cos(2\varphi_1) = 0.91 \pm 0.24\,(\text{stat.}) \pm 0.09\,(\text{syst.}) \pm 0.07\,(\text{model})$$

$$\varphi_1 = \left(22.5 \pm 4.4\,(\text{stat.}) \pm 1.2\,(\text{syst.}) \pm 0.6\,(\text{model})\right)^0$$

Main systematics sources

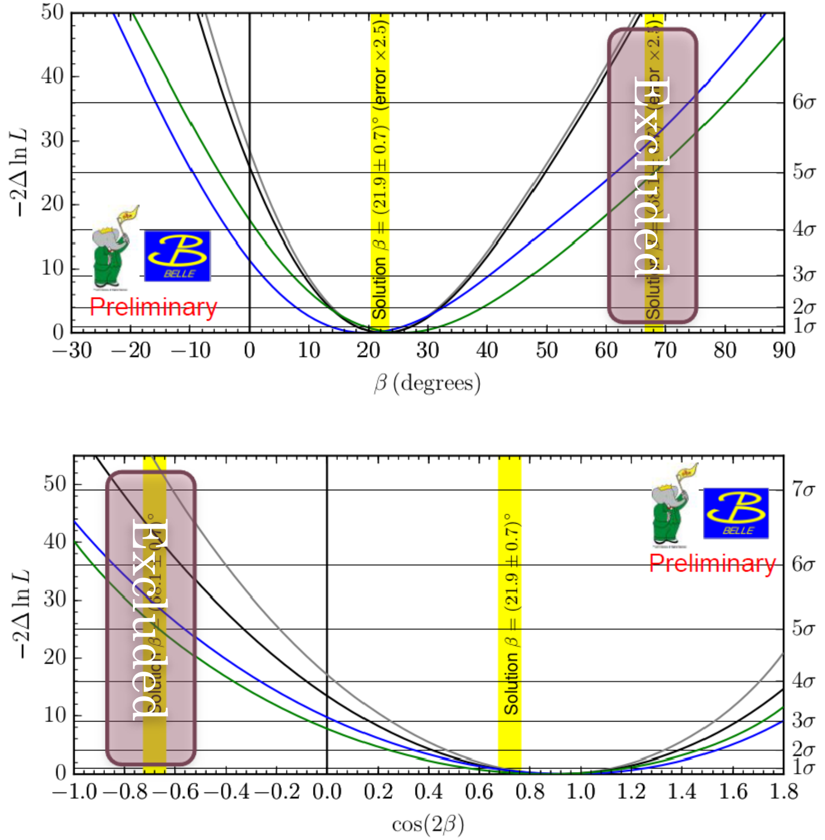
- Possible fit bias
- Vertex reconstruction
- Δt resolution function
- Signal purity
- Background Δt p.d.f.s

First evidence for $\cos(2\varphi_1) > 0$ @ 3.7σ

Direct exclusion of the 2nd solution @ 7.3σ

Observation of CP violation @ 5.1σ

[M. Röhrken, Moriond 2017]



Model-independent analysis of $\bar{B}^0 \to D^{(*)}h^0$ with $D^0 \to K_S^0\pi^+\pi^-$

PRD 94, 052004 (2016)

The binned Dalitz plot approach

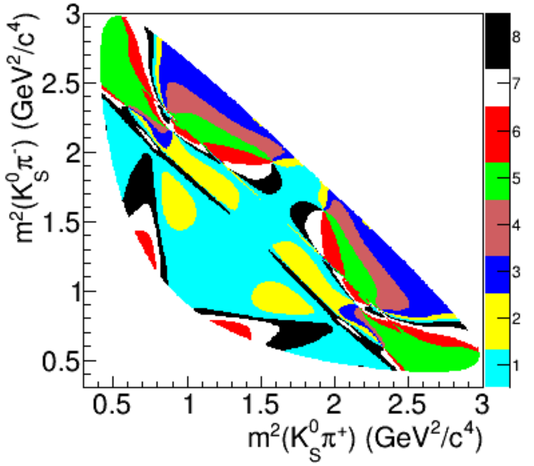
- Dalitz plot is divided into 16 regions [Giri et al. PRD 68, 054018 (2003)]
- Three parameters K_i, C_i and S_i are defined for the i^{th} region:
  - K_i – probability of D^0 meson decay into the i^{th} region
  - C_i and S_i – cos and sin of the decay amplitude phase difference between $\bar{D}^0$ and D^0 *averaged* over the i^{th} region

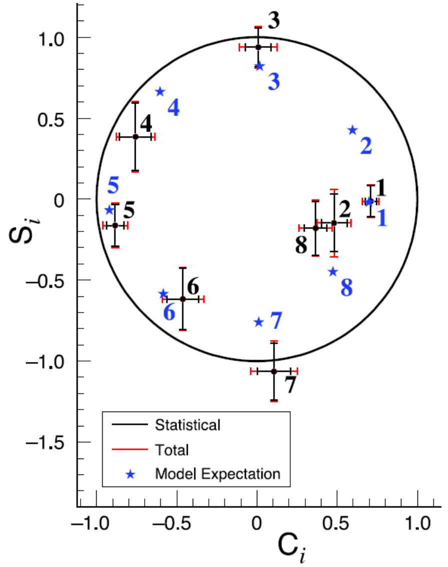
$$g_i(\Delta t) \propto U_i + q[A_i \sin(\Delta m \Delta t) - B_i \cos(\Delta m \Delta t)]$$

$$U_i = K_i + K_{-i}, \qquad A_i = K_i - K_{-i},$$

$$B_i = 2\sqrt{K_i K_{-i}}(S_i \cos(2\varphi_1) + C_i \sin(2\varphi_1))$$

- The parameters C_i and S_i have been measured in coherent decays of $D^0\bar{D}^0$ pairs in CLEO experiment [PRD 82, 112006 (2010)]
- The equal-phase Dalitz plot partitioning increases sensitivity to φ_1 [Bondar, Poluektov Eur. Phys. J. C47, 347 (2006); C55, 51 (2008)]



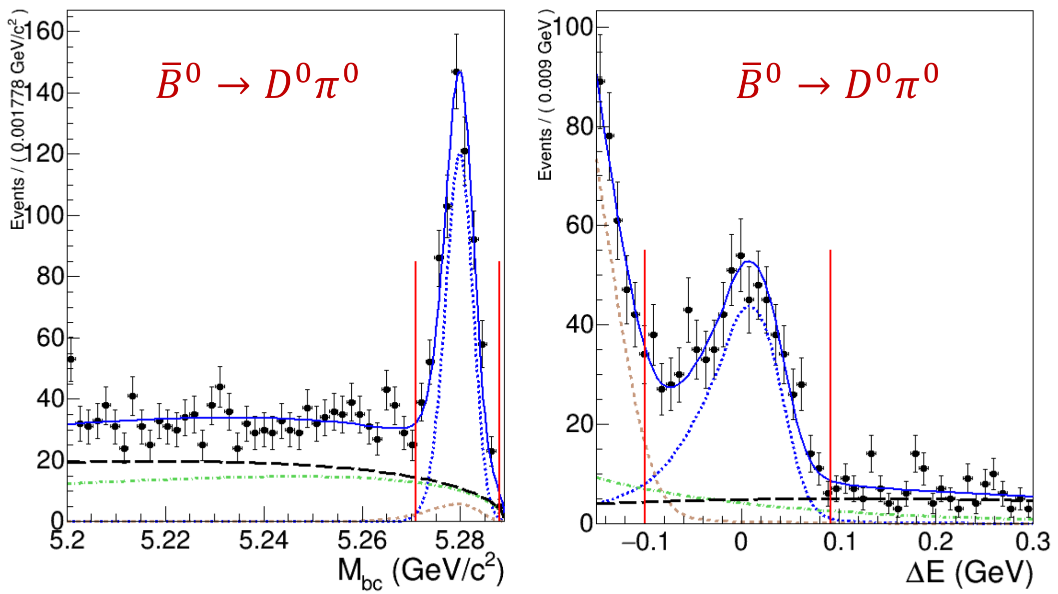


Model-independent analysis of $\bar{B}^0 \to D^{(*)}h^0$ with $D^0 \to K_S^0\pi^+\pi^-$

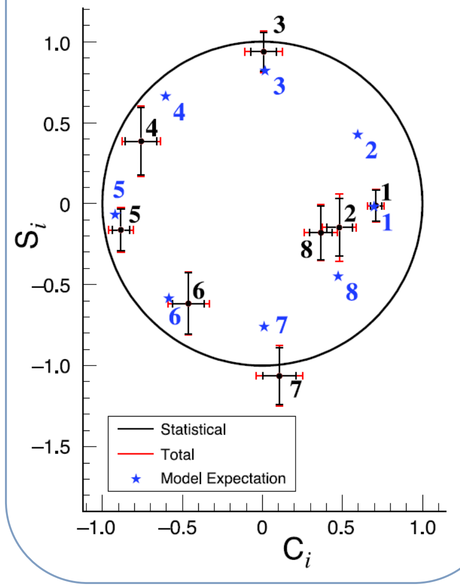
PRD 94, 052004 (2016)

Signal modes

- D^0h^0, with h^0 in
  - $\pi^0 \to \gamma\gamma$,
  - $\eta \to \gamma\gamma, \pi^+\pi^-\pi^0$,
  - $\eta' \to [\gamma\gamma]_\eta\pi^+\pi^-$
  - $\omega \to \pi^+\pi^-\pi^0$
- $D^{*0}h^0 \to D^0\pi^0$ with
  - $D^{*0} \to D^0\pi^0$
  - h^0 in $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$



CLEO Collaboration
PRD 82, 112006 (2010)



Main variables

- M_{bc} – beam-energy constrained mass
- ΔE – energy difference

The parameters of Dalitz plot

- C_i and S_i from CLEO-c (external input)
- K_i from $B^- \to D^0\pi^-$ decays

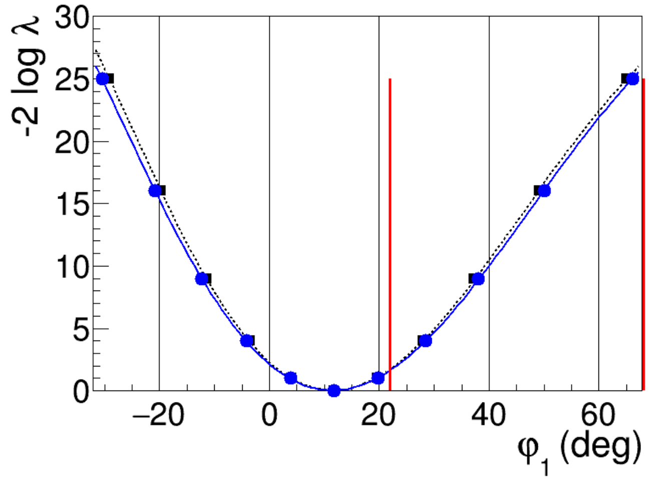
Signal yield

962 ± 41

Model-independent analysis of $\bar{B}^0 \to D^{(*)}h^0$ with $D^0 \to K_S^0\pi^+\pi^-$

Maximum likelihood fit of the Δt distributions

$$\sin(2\varphi_1) = 0.43 \pm 0.27\,(\text{stat.}) \pm 0.08\,(\text{syst.})$$
$$\cos(2\varphi_1) = 1.06 \pm 0.33\,(\text{stat.})\,^{+0.21}_{-0.15}\,(\text{syst.})$$
$$\varphi_1 = \left(11.7 \pm 7.8\,(\text{stat.}) \pm 2.1\,(\text{syst.})\right)^0$$

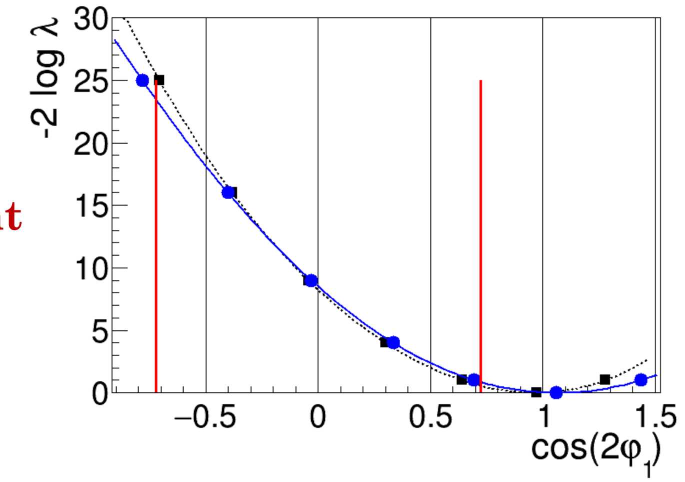


Main systematics sources

- Uncertainties of C_i and S_i (dominant)
- Δt resolution function
- Signal purity
- Background Δt p.d.f.s
- Uncertainties of K_i

✔ **Direct exclusion of the 2nd solution @ 5.1σ**

✔ **The first model-independent measurement of $\cos(2\varphi_1)$**



4.10.2017

ICPPA-2017

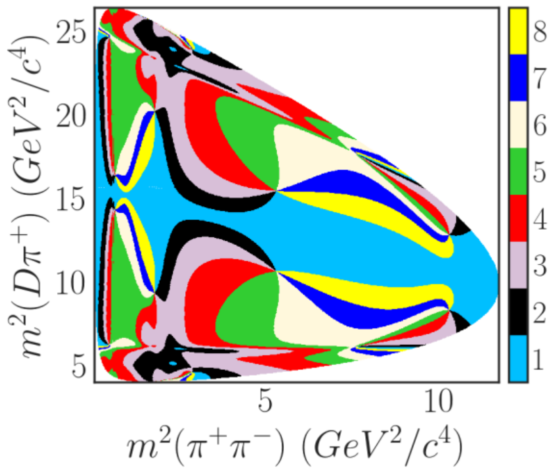
Prospects for LHCb and Belle II

Appropriate $b \to c\bar{u}d$ processes

- $\bar{B}^0 \to D_{CP}^{(*)0} h^0$
- $\bar{B}^0 \to D^{(*)0} h^0$ with $D^0 \to K_S^0 \pi^+ \pi^-$
- $\bar{B}^0 \to D_{CP}^{(*)0} \pi^+ \pi^-$
- $\bar{B}^0 \to D^{(*)0} \pi^+ \pi^-$ with $D^0 \to K_S^0 \pi^+ \pi^-$

- Model uncertainty can limit future precise measurements.
- A model-independent approach should be employed

$\bar{B}^0 \to D^0 \pi^+ \pi^-$ Dalitz plane



The $\bar{B}^0 \to D^0_{(CP)} \pi^+ \pi^-$ decay

- May have only charged final-state particles
- Accessible for LHCb
- Can be analyzed with the binned Dalitz plot approach

Estimates for the model-independent approach

- Belle II with $50 \times$ (*Belle data set*) will be able to measure the angle φ_1 in $b \to c\bar{u}d$ transitions with precision below one degree
- LHCb with $70 \times$ (*run I data set*) will be able to measure the angle φ_1 in $\bar{B}^0 \to D^0_{(CP)} \pi^+ \pi^-$ decays with precision about 1.5^0

Conclusions

- The $b \to c\bar{u}d$ transition provides theoretically clean and the most precise approach to measure the $\cos(2\varphi_1)$

$$\cos(2\varphi_1) = 0.91 \pm 0.24\,(\text{stat.}) \pm 0.09\,(\text{syst.}) \pm 0.07\,(\text{model})$$

BaBar + Belle

$$\cos(2\varphi_1) = 1.06 \pm 0.33\,(\text{stat.})^{+0.21}_{-0.15}\,(\text{syst.})$$

Belle model ind.

- Study of the $\bar{B}^0 \to D^{(*)0} h^0$ decays with the full BaBar and Belle data sets resolved the angle φ_1 ambiguity

- In the future, the angle φ_1 can be measured in $b \to c\bar{u}d$ transitions with precision below one degree in a model-independent way

Backup

The CKM CP violation mechanism

$$\mathcal{L} \propto -\frac{g}{\sqrt{2}}(\bar{u}_L, \bar{c}_L, \bar{t}_L)\gamma^\mu W_\mu^+ V_{CKM}(d_L, s_L, b_L)^T + h.c.$$

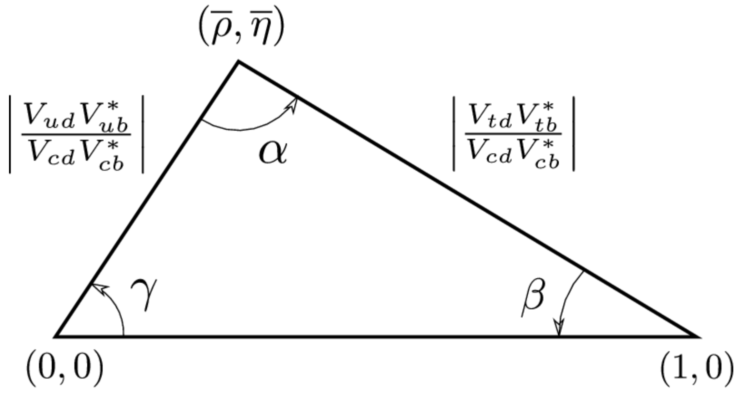
The CKM matrix

- The unitary matrix of quark mixing for weak charged currents (Cabibbo, Kobayashi and Maskawa, CKM)

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Four independent parameters
- Can be parametrized with three Euler angles and single phase.

The Unitarity Triangle



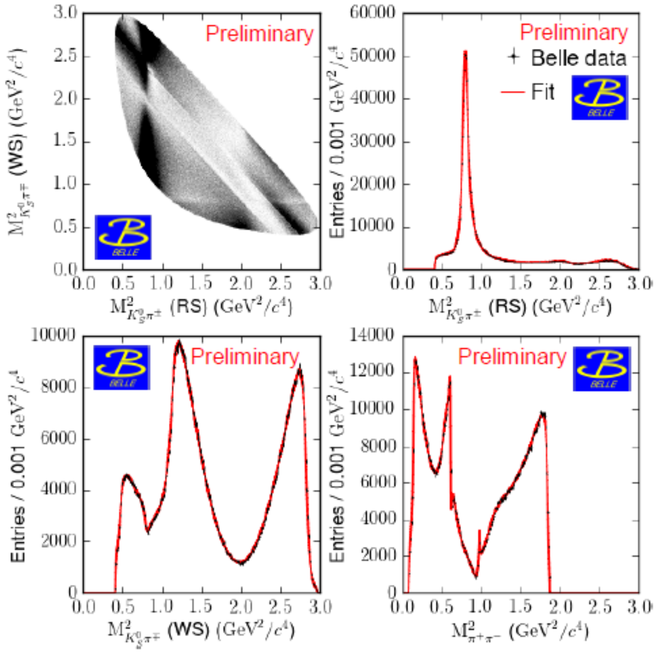
$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} + 1 = 0$$

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

- The $D \to K^0_S\pi^+\pi^-$ Dalitz model is directly obtained from flavor-tagged $e^+e^- \to c\bar{c}$ data.

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

Isobar model for L≠0 — LASS — K-matrix



- The Dalitz 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 $D \to K^0_S\pi^+\pi^-$ Dalitz 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.