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Time-Dependent CP Violation Measurements in B Mesons at Belle

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For Belle collaboration

Quark Mixing and CP Violation

- The CP violation ($\not{CP}$) established within the SM in terms of "charged" weak currents:

$$\mathcal{L}_W^{(q)} = \frac{g}{\sqrt{2}}(W_\mu^+ \bar{u}_L \gamma^\mu V_{CKM} d_L + W_\mu^- \bar{d}_L \gamma^\mu V_{CKM}^\dagger u_L)$$

and 3-gen. quark mixing matrix: Cabibbo-Kobayashi-Maskawa matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Wolfenstein parametrization ($\lambda = \sin\theta_c$)

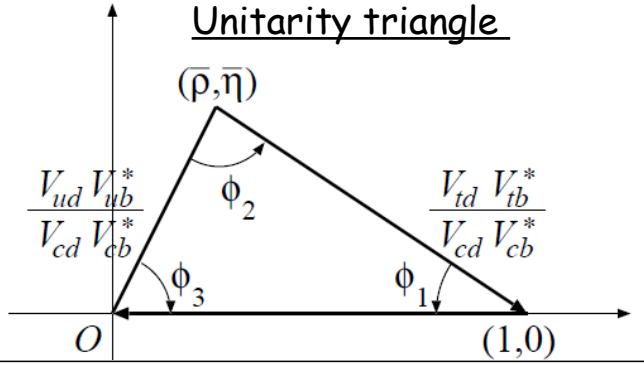
→ V_{CKM} induces $\not{CP}$ due to an existence of a complex phase ($CP(\mathcal{L}_W^{(q)}) \neq \mathcal{L}_W^{(q)}$)

→ unitarity conditions applied on V_{CKM} define a unitarity triangle (UT)

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

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \quad \mathcal{O}(\lambda^3)$$

Unitarity triangle



CP violation parameters:

$$\phi_1 = \beta = \arg\left(-\frac{V_{cb}^* V_{cd}}{V_{tb}^* V_{td}}\right)$$

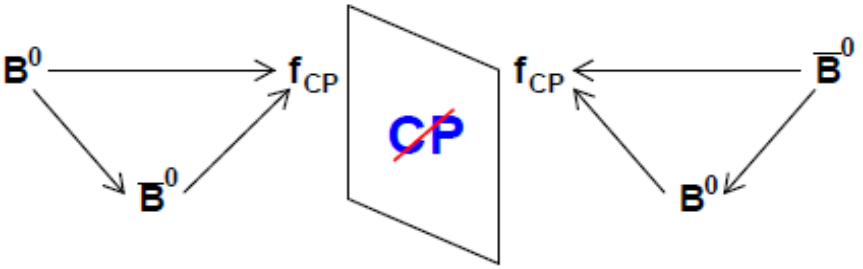
$$\phi_2 = \alpha = \arg\left(-\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}}\right)$$

$$\phi_3 = \gamma = \arg\left(-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right)$$

Time-Dependent $\not{CP}$ Measurements

- How can we measure the complex phases, i.e. UT angles?
- Make use of time-dependent analysis and measure the QM interference between B^0-$\bar{B}^0$ mixing and B^0 decay to a CP eigentstate in time:

$$\begin{aligned} A_{CP}(\Delta t) &= \frac{\Gamma(\bar{B}^0(\Delta t) \to f_{CP}) - \Gamma(B^0(\Delta t) \to f_{CP})}{\Gamma(\bar{B}^0(\Delta t) \to f_{CP}) + \Gamma(B^0(\Delta t) \to f_{CP})} \\ &= \mathcal{A}_{CP} \cos(\Delta m_d \Delta t) + \mathcal{S}_{CP} \sin(\Delta m_d \Delta t) \end{aligned}$$



$\mathcal{S}_{CP} = +\frac{2\mathcal{I}m\,\lambda_{CP}}{1+|\lambda_{CP}|^2}$ → mixing-induced CP violation (interference between tree & box diagram)

$\mathcal{A}_{CP} = -\frac{1-|\lambda_{CP}|^2}{1+|\lambda_{CP}|^2}$ → direct CP violation (in addition, penguin diagram plays a role in interference)

Δm_d → B^0-$\bar{B}^0$ mass difference Δt → B^0-$\bar{B}^0$ proper time difference $\lambda_{f_{CP}} = \xi_{f_{CP}} \frac{q}{p} \frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}$

- Measurements presented here:

$b \to s\bar{q}q \to \phi_1$ related measurements

$B^0 \to \omega K^0_S$
$B^0 \to \eta' K^0$

New

$b \to u\bar{u}d \to \phi_2$ related measurements

$B^0 \to \pi^+\pi^-$
$B^0 \to \rho^0\rho^0$

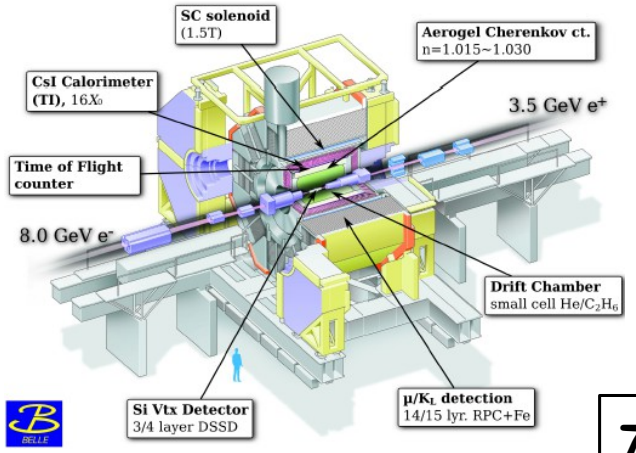
Recent

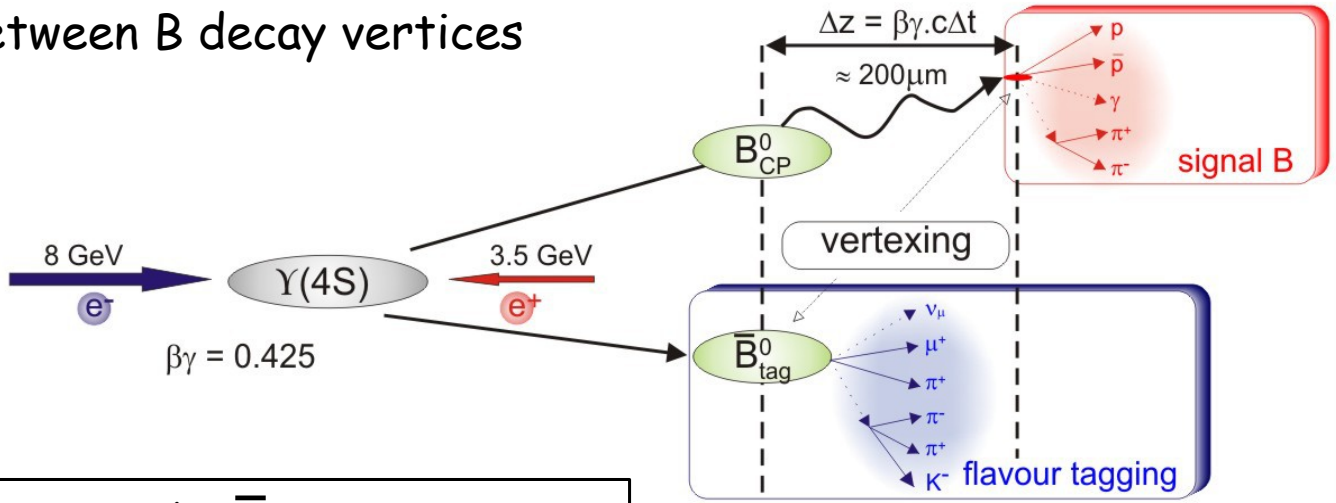
Experimental Principles of Time-Dependent CP Measurements at Belle

- How to determine time (Δt) and which $B^0/\bar{B}^0$ decayed to a CP-eigenstate?
  - Use asymmetric beam energy → "increase" B decay length → $\Delta z \approx 200\mu m$
  - Produce $\Upsilon(4S)$ → $B\bar{B}$ born in a coherent QM state (C=-1 & Bose statistics):

    B_{CP} → B^0 ($\bar{B}^0$) at time t

    B_{tag} → $\bar{B}^0$ (B^0) at time t
  - Reconstruct B_{CP} → to a final state f_{CP}
  - Determine the flavour tag of B_{tag} in 7 r-bins
  - Measure the distance between B decay vertices





772 x 10^6 $B\bar{B}$ pairs collected

CP Measurements in b → qq̄s Decays

- Motivation for $B^0 \to \omega K^0_S$ & $B^0 \to \eta' K^0$ measurements?
  - In contrast to b → cc̄s ($B^0 \to J/\Psi K^0_S$), the modes: b → uū̄s, b → dd̄s are **penguin diagram dominated** (tree is Cabbibo & color suppressed), b → ss̄s is **penguin only:**

$$\begin{aligned} A(c\bar{c}s) &= V_{cb}V^*_{cs}(T_{c\bar{c}s} + P^c_s - P^t_s) + V_{ub}V^*_{us}(P^u_s - P^t_s) \\ A(u\bar{u}s) &= V_{cb}V^*_{cs}(P^c_s - P^t_s) + V_{ub}V^*_{us}(T_{u\bar{u}s} + P^u_s - P^t_s) \\ A(s\bar{s}s) &= V_{cb}V^*_{cs}(P^c_s - P^t_s) + V_{ub}V^*_{us}(P^u_s - P^t_s) \end{aligned}$$

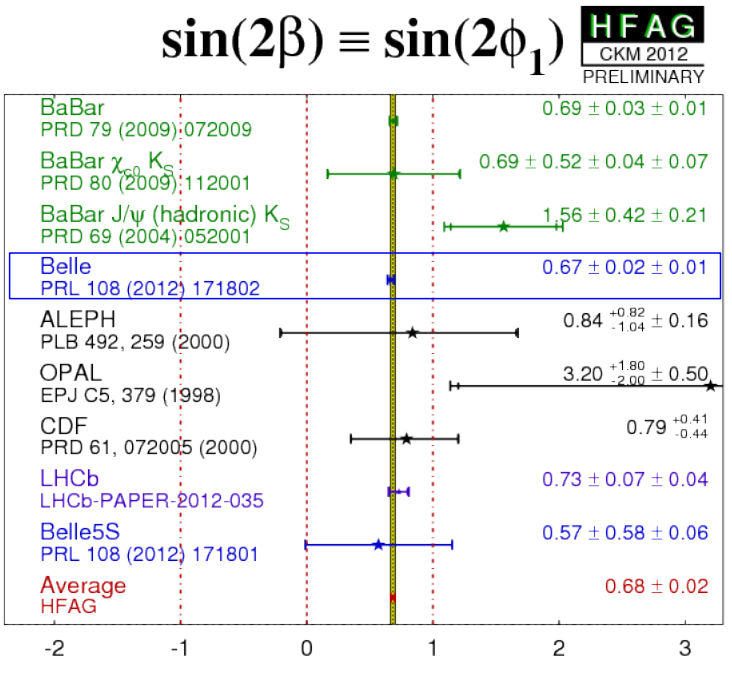
→ measurements sensitive to New Physics (NP)!

  - Expected parameters within the SM:

$$\mathcal{A}_{CP} \simeq 0 \qquad \mathcal{S}_{CP} \simeq -\xi_{f_{CP}} \sin 2\phi_1$$

  - Observing a large difference $|\mathcal{S}_{CP} - \mathcal{S}_{J/\Psi K^0_S}|$ ($\mathcal{S}_{CP} = -\xi_{f_{CP}} \sin 2\phi_1^{\rm eff}$) → **a clear sign for NP**

HFAG: b → cc̄s results



$B^0 \to \omega K^0_S$ Analysis

- Simultaneous 7D unbinned ML fit ($B^0 \to \omega K^0_S$ & $B^\pm \to \omega K^\pm$(control sample)) to:

  → $M_{bc},\ \Delta E,\ \mathcal{F}_{B\bar{B}/q\bar{q}}(\mathcal{LR}_{B\bar{B}/q\bar{q}}),\ m_{3\pi}\,(\omega \to \pi^+\pi^-\pi^0),\ \cos\theta^{\rm Hel}_{3\pi},\ \Delta t,\ q$ (B flavour)

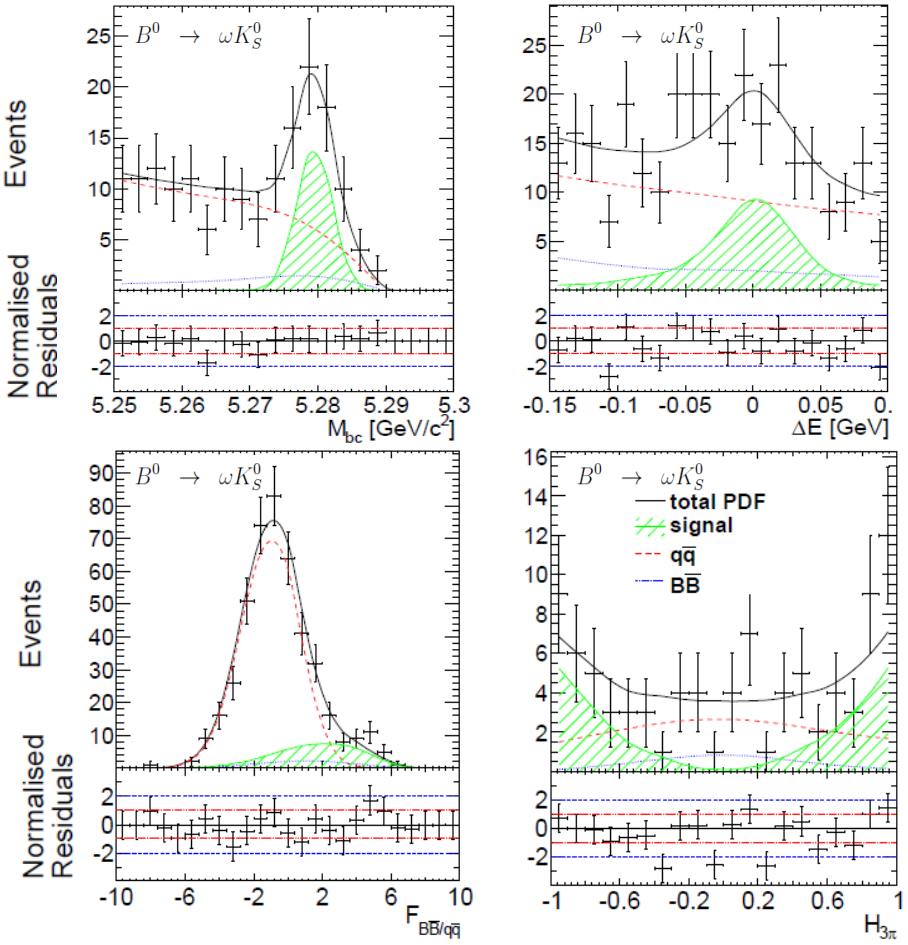
$$M_{\rm bc} \equiv \sqrt{(E^{\rm CMS}_{\rm beam})^2 - (p^{\rm CMS}_{\rm B})^2}$$

$$\Delta E \equiv E^{\rm CMS}_{\rm B} - E^{\rm CMS}_{\rm beam}$$

$$\mathcal{F}_{B\bar{B}/q\bar{q}} = \log\frac{\mathcal{LR} - 0.2}{1 - \mathcal{LR}}$$

Separate B events / continuum $e^+e^- \to q\bar{q}$
$q = u, d, s, c$

A simultaneous fit with a calibration (control) sample performed to significantly suppress systematic effects



$B^0 \to \omega K^0_S$ Analysis

- Fit results:
  - **Branching fraction measurements:**

Preliminary results

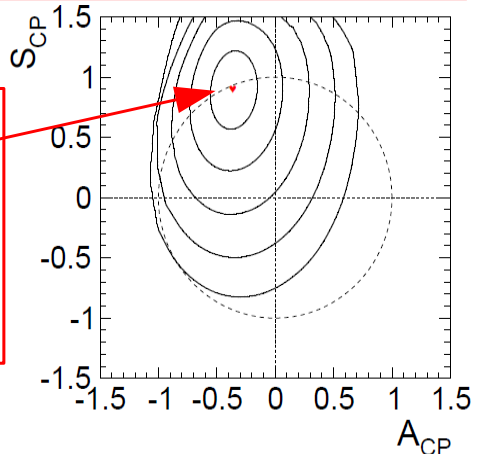
$$\mathcal{B}(B^0 \to \omega K^0_S) = (4.5 \pm 0.4\ (\text{stat}) \pm 0.3\ (\text{syst})) \times 10^{-6}$$
$$\mathcal{B}(B^\pm \to \omega K^\pm) = (6.8 \pm 0.4\ (\text{stat}) \pm 0.4\ (\text{syst})) \times 10^{-6}$$

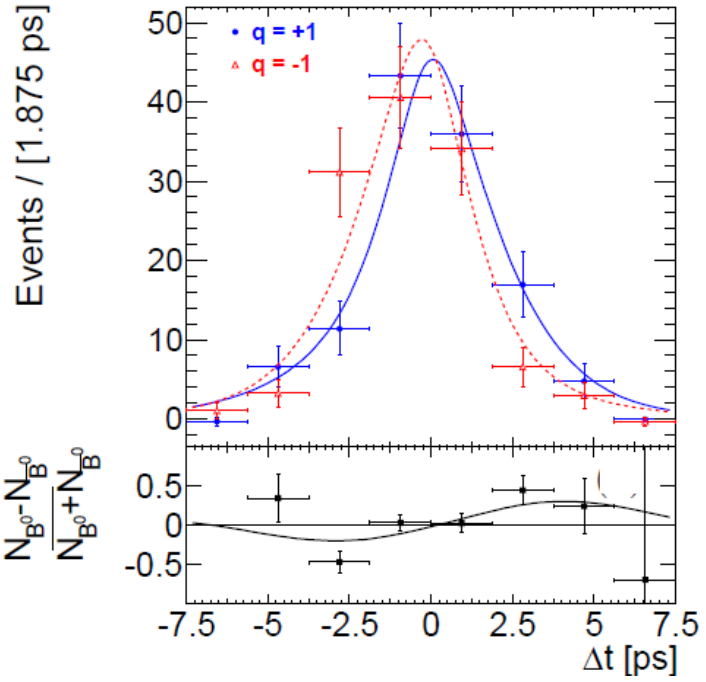
  - **~~CP~~ measurement:**

$$\mathcal{A}_{CP}(B^0 \to \omega K^0_S) = -0.36 \pm 0.19\ (\text{stat}) \pm 0.05\ (\text{syst})$$
$$\mathcal{S}_{CP}(B^0 \to \omega K^0_S) = +0.91 \pm 0.32\ (\text{stat}) \pm 0.05\ (\text{syst})$$

→ **First evidence of ~~CP~~ (3.1σ) in $B^0 \to \omega K^0_S$**

→ **No sign for NP**





$B^0 \to \eta' K^0$ Analysis

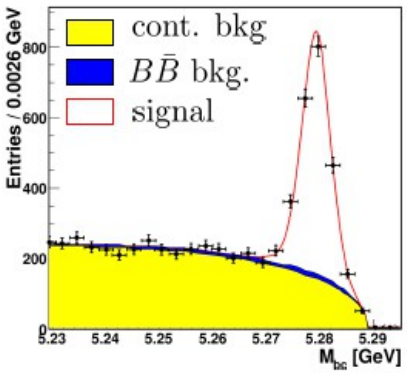
- S/B yield → 3D (2D) unbinned ML fit (where $\eta' \to \eta\pi^+\pi^-$ & $\eta' \to \rho^0\gamma$) to:

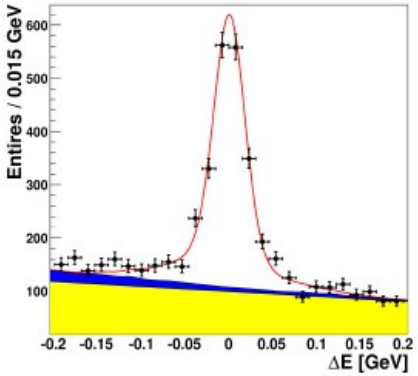
$$B^0 \to \eta' K_S^0 \quad \to \quad M_{bc},\ \Delta E,\ \mathcal{LR}_{B\bar{B}/q\bar{q}}$$

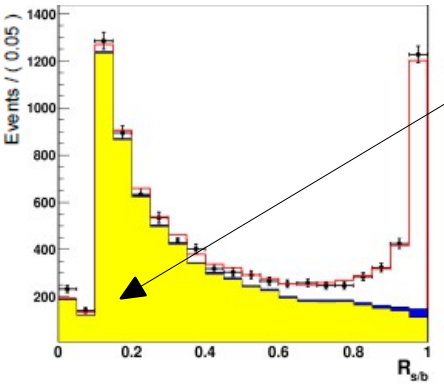
$\rho^0 \to \pi^+\pi^-$

$\eta \to \gamma\gamma,\ \eta \to \pi^+\pi^-\pi^0$

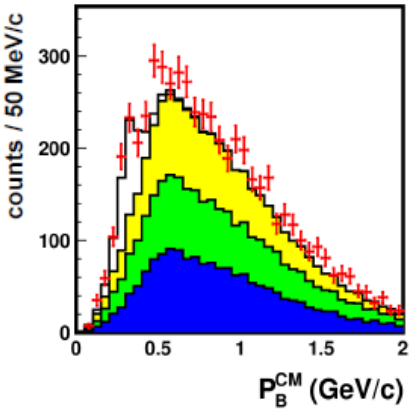
All η' decay modes combined

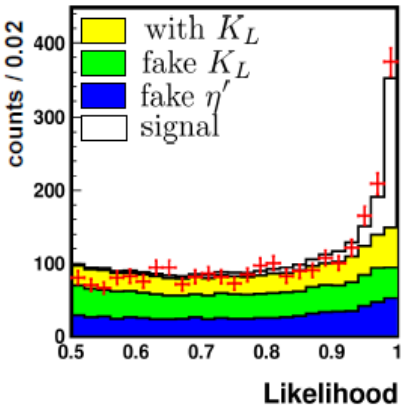






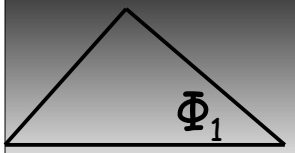
$$B^0 \to \eta' K_L^0 \quad \to \quad p_B^{\mathrm{CMS}},\ \mathcal{LR}_{B\bar{B}/q\bar{q}}$$





mode	This analysis 772 M $B\bar{B}$ N_{sig}	2007 analysis 534 M $B\bar{B}$ N_{sig}
$\eta' K_S$	2506.3 ± 63.1	1256.6 ± 42.1
$\eta' K_L$	1041.7 ± 41.1	478.8 ± 41.1

Data reprocessed with new tracking code
→ improved reconstruction efficiency



$B^0 \to \eta' K^0$ Analysis

- Δt x q CP fit with fixed S/B performed …
- Fit results:

$$\mathcal{A}_{CP}(B^0 \to \eta' K^0) = +0.03 \pm 0.05\ (\text{stat}) \pm 0.03\ (\text{syst})$$
$$\mathcal{S}_{CP}(B^0 \to \eta' K^0) = +0.68 \pm 0.07\ (\text{stat}) \pm 0.03\ (\text{syst})$$

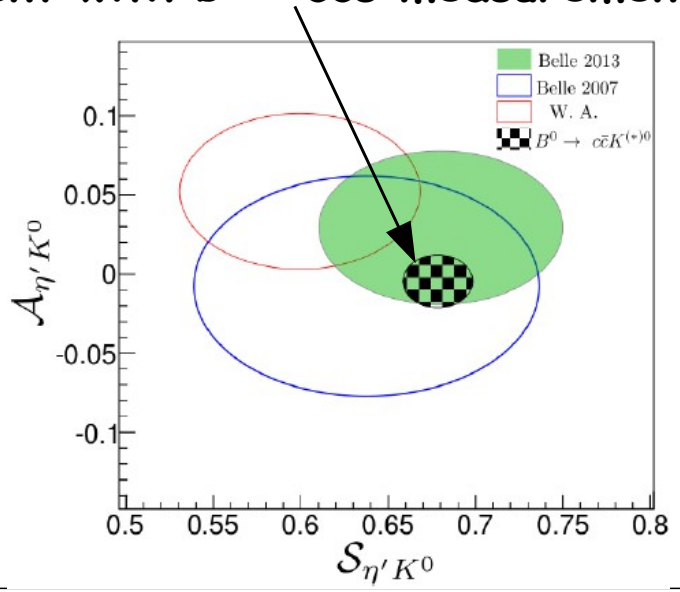
Preliminary results

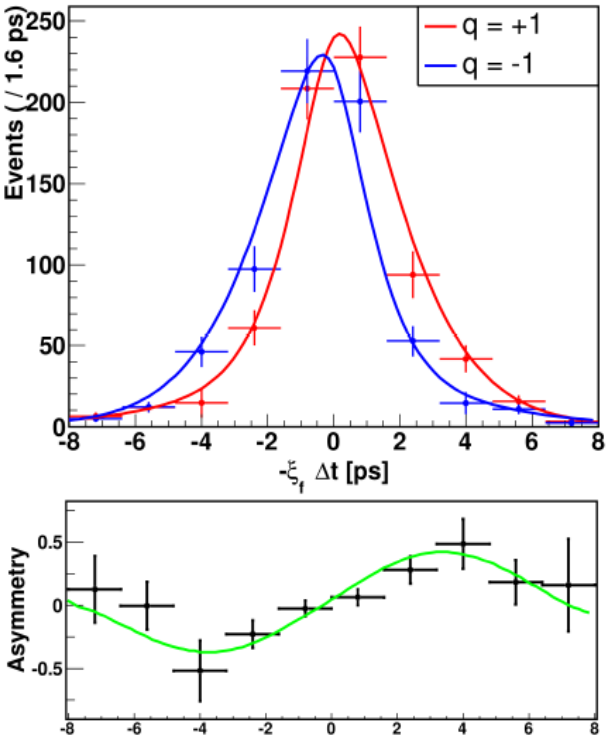
→ **the world's most precise $\not{CP}$ measurement in**

$$B^0 \to \eta' K^0$$

→ **results well consistent with b → $c\bar{c}s$ measurements**

→ **no sign for NP**





Φ_2 $\not{CP}$ Measurements in b → uūd Decays

- **Recent measurements at Belle in b → uūd decays:**

  $B^0 \to \pi^+\pi^-$ → tree (T) + penguin (P) diagram dominated

  $B^0 \to \rho^0\rho^0$ → colour suppressed tree (C) (+ penguin (P) diagram dominated)

  - penguin contribution can't be ignored ...
  - both weak and strong phases play a role ...

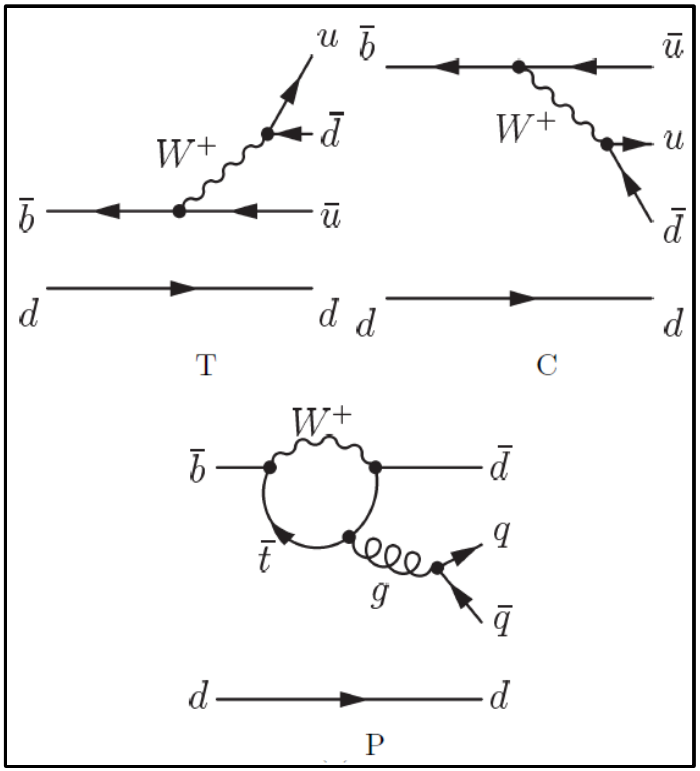
  → expected **non-zero effect of direct $\not{CP}$ in SM**

  → **no clean extraction** of single CKM phase possible:

$$\mathcal{S}_{CP} \sim \sin(2\phi_2 + 2\Delta\phi_2)$$

How to extract ϕ_2 → **combine ππ (ρρ) results using isospin analysis** ...

(For $B \to \pi\pi$, see Gronau & London PRL 65, 3381, 1990)

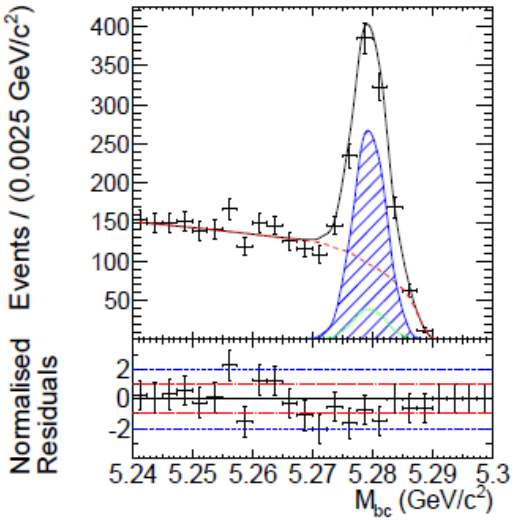


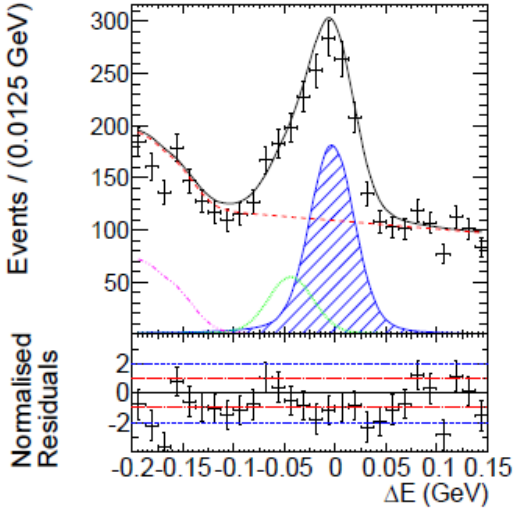
$B^0 \to \pi^+\pi^-$ Analysis

Φ_2

- 7D unbinned ML fit to:

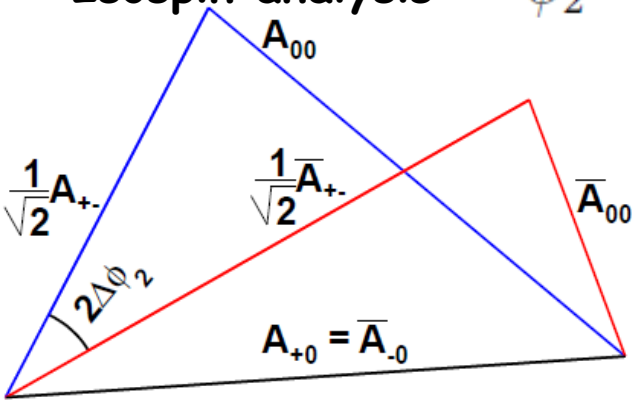
$$M_{bc},\ \Delta E,\ \mathcal{F}_{B\bar{B}/q\bar{q}},\ \mathcal{LR}^{+}_{K/\pi},\ \mathcal{LR}^{-}_{K/\pi},\ \Delta t,\ q$$





This analysis 772 M $B\bar{B}$		Previous 534 M $B\bar{B}$	
	N_{sig}		N_{sig}
$\pi^+\pi^-$	$\simeq 2360$	$\pi^+\pi^-$	1464

Isospin analysis → ϕ_2



$$A_{+0} = \frac{1}{\sqrt{2}}A_{+-} + A_{00}, \quad \bar{A}_{-0} = \frac{1}{\sqrt{2}}\bar{A}_{+-} + \bar{A}_{00}$$

→ combined Belle results:

$\mathcal{B}(B^0 \to \pi^+\pi^-)$
$\mathcal{B}(B^0 \to \pi^0\pi^0)$
$\mathcal{B}(B^+ \to \pi^+\pi^0)$
$\mathcal{A}_{CP}(B^0 \to \pi^+\pi^-)$
$\mathcal{S}_{CP}(B^0 \to \pi^+\pi^-)$
$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0)$

8-fold ambiguity

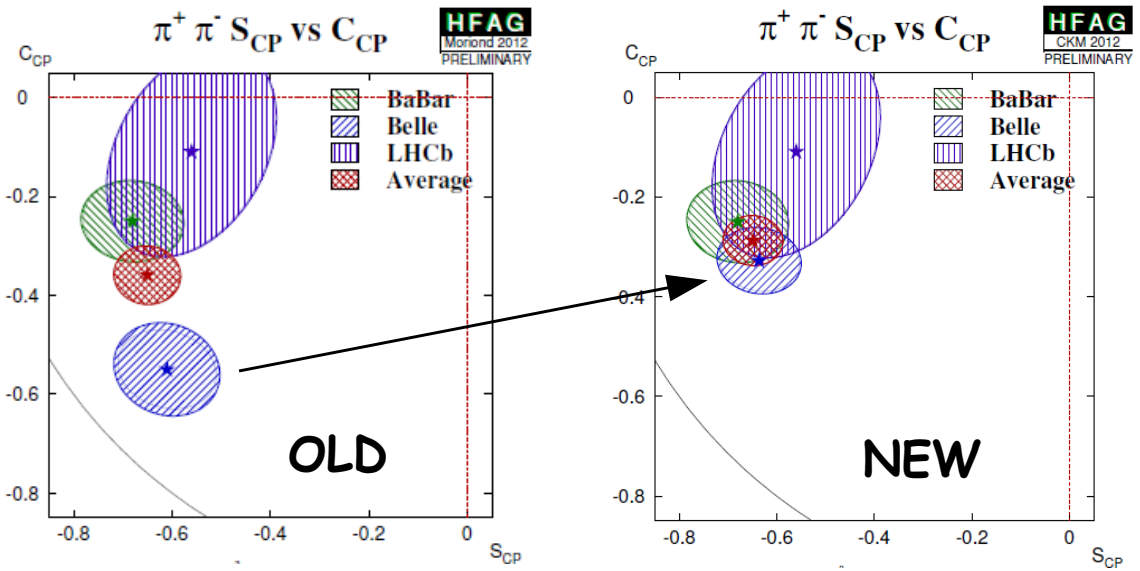
$B^0 \to \pi^+\pi^-$ Analysis

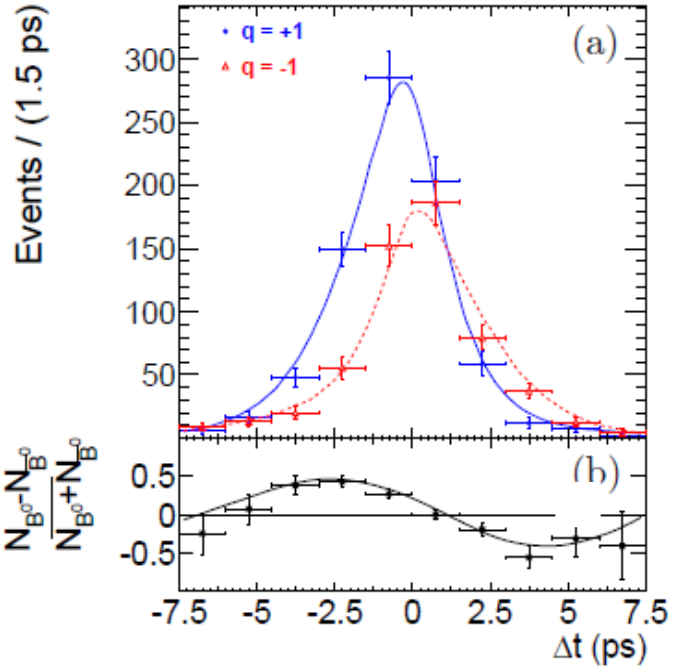
- Fit results:

http://arxiv.org/abs/1302.0551v2

$$\mathcal{A}_{CP}(B^0 \to \pi^+\pi^-) = +0.33 \pm 0.06\ (\text{stat}) \pm 0.03\ (\text{syst})$$
$$\mathcal{S}_{CP}(B^0 \to \pi^+\pi^-) = -0.64 \pm 0.08\ (\text{stat}) \pm 0.03\ (\text{syst})$$

→ **the world's most precise $\mathcal{CP}$ measurement in** $B^0 \to \pi^+\pi^-$

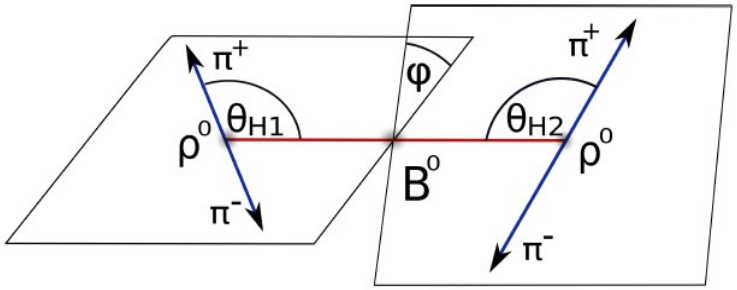


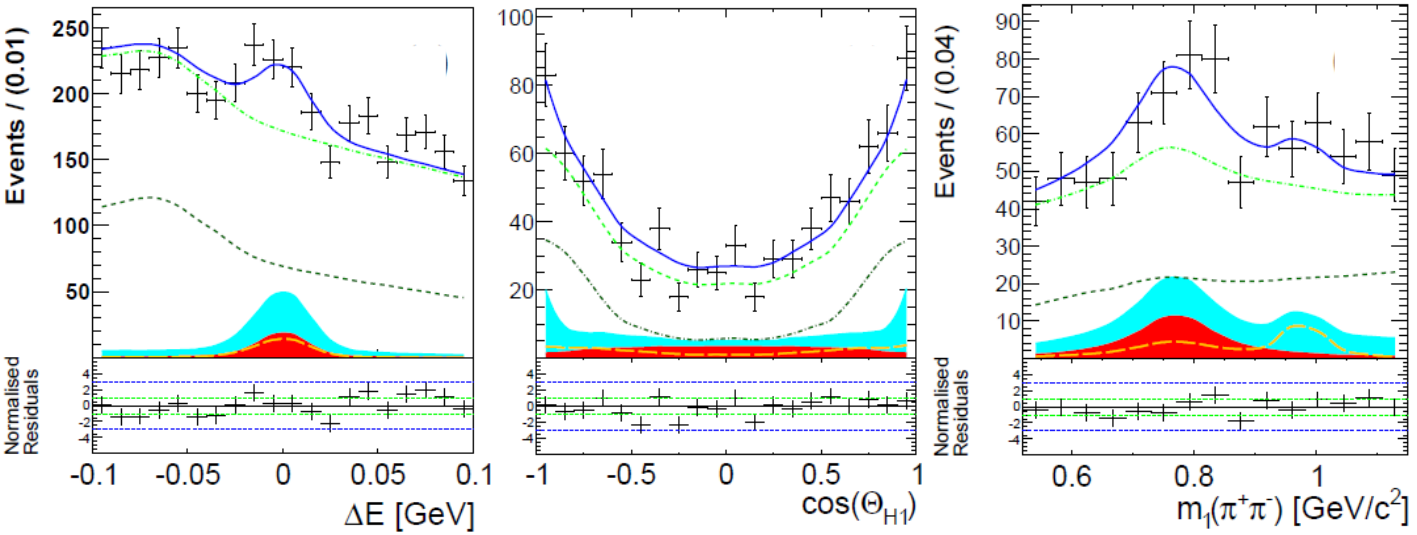


$B^0 \to \rho^0\rho^0$ Analysis

- 6D unbinned ML fit to:

$$\Delta E,\ M^1_{\pi^+\pi^-},\ M^2_{\pi^+\pi^-},\ \cos\theta^1_{\rm Hel},\ \cos\theta^2_{\rm Hel},\ \mathcal{F}_{B\bar{B}/q\bar{q}}$$





- $B^0 \to \rho^0\rho^0, B^0 \to f_0\rho^0$, all $B^0 \to 4\pi$, non-peaking $B\bar{B}$ all non-peaking
- Dominant background → continuum

$\not{CP}$ & angular analysis:

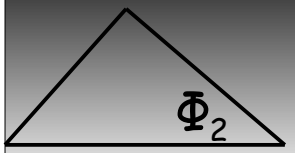
$\rho^0\rho^0$ → not a pure CP state

- longitudinal → CP even
- transversal → mixed

→ use **angular analysis** to find long. component f_L

Isospin analysis → ϕ_2

The same procedure as for $B^0 \to \pi^+\pi^-$ but with long. component f_L only



$B^0 \to \rho^0\rho^0$ Analysis

- Fit results:

http://arxiv.org/abs/1212.4015v2

$$\mathcal{B}(B^0 \to \rho^0\rho^0) = (1.02 \pm 0.30\ (\text{stat}) \pm 0.15\ (\text{syst})) \times 10^{-6}$$

→ 3.4σ significance

$$f_L = 0.21^{+0.18}_{-0.22}\ (\text{stat}) \pm 0.13\ (\text{syst})$$

Compared to BaBar (387M $B\bar{B}$) & previous Belle (535M $B\bar{B}$) results:

→ **BR consistent with previous results**

→ **f_L differs by 2.1σ from BaBar!**

Belle: $f_L = 0.21^{+0.18}_{-0.22}\ (\text{stat}) \pm 0.13\ (\text{syst})$

BaBar: $f_L = 0.75^{+0.11}_{-0.14}\ (\text{stat}) \pm 0.04\ (\text{syst})$

$$\mathcal{B}(B^0 \to f_0\rho^0) \times \mathcal{B}(f_0 \to \pi^+\pi^-) = (0.86 \pm 0.27\ (\text{stat}) \pm 0.14\ (\text{syst})) \times 10^{-6}$$

→ 3.0σ significance

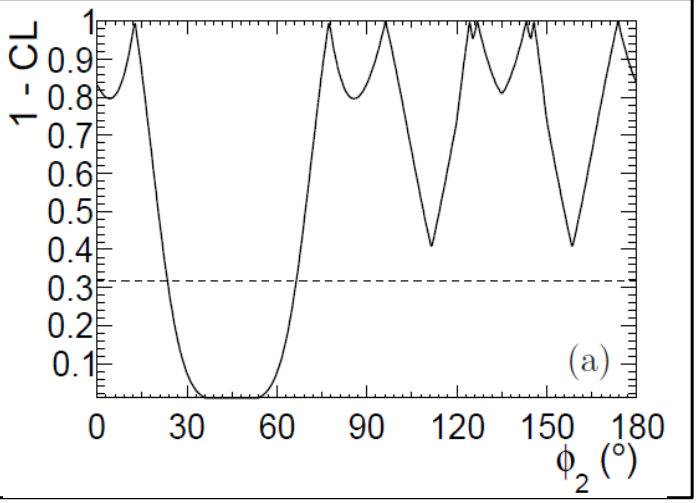
$B^0 \to \pi^+\pi^-$, $B^0 \to \rho^0\rho^0$ Isospin Analyses

- Isospin analyses → ϕ_2 constraints:

$B \to \pi\pi$

$23.8^\circ < \phi_2 < 66.8^\circ$

→ **excluded @ 1σ CL**



Combined:

$B^0 \to \pi^+\pi^-$, $B^+ \to \pi^+\pi^0$ } 772M $B\bar{B}$ pairs used ...

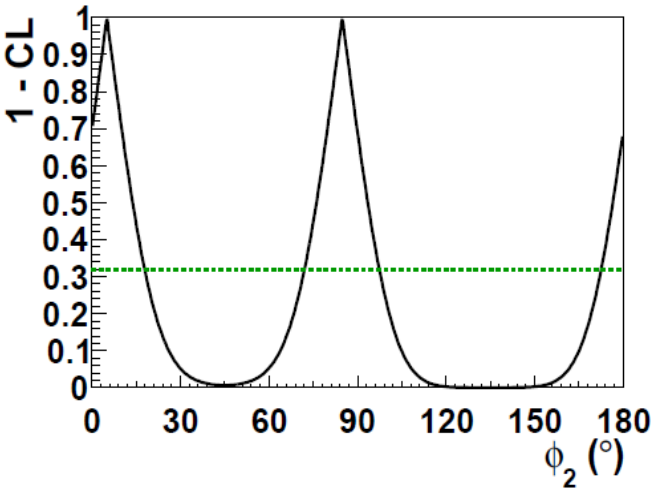
$B^0 \to \pi^0\pi^0$ 275M $B\bar{B}$ pairs

$B \to \rho\rho$

$\phi_2 = (84.9 \pm 12.9)^\circ \quad \Delta\phi_2 = (0.0 \pm 9.6)^\circ$

→ **negligible penguin contribution → small BR($B^0 \to \rho^0\rho^0$)**

→ 8-fold ambiguity degenerated to 2-fold only



Combined:

$B^0 \to \rho^0\rho^0$ 772M $B\bar{B}$ pairs used ...

$B^\pm \to \rho^\pm\rho^0$ 85M $B\bar{B}$ pairs

$B^0 \to \rho^+\rho^-$ 535M (275M) $B\bar{B}$ pairs

Summary

- 2 new measurements of time-dependent $\not{CP}$ in b → qq̄s transitions:
  - First evidence of $\not{CP}$ in $B^0 \to \omega K_S^0$:

    $$\mathcal{S}_{CP}(B^0 \to \omega K_S^0) = +0.91 \pm 0.32\ (\text{stat}) \pm 0.05\ (\text{syst})$$

  - The world's most precise measurement of $\mathcal{B}(B^0 \to \omega K_S^0)$ and $\mathcal{B}(B^\pm \to \omega K^\pm)$
  - The world's most precise measurement of $\not{CP}$ in $B^0 \to \eta' K^0$:

    $$\mathcal{S}_{CP}(B^0 \to \eta' K^0) = +0.68 \pm 0.07\ (\text{stat}) \pm 0.03\ (\text{syst})$$

- 2 recent measurements providing new constraints on ϕ_2
  - The world's most precise measurement of $\not{CP}$ in $B^0 \to \pi^+\pi^-$

    $$\mathcal{A}_{CP}(B^0 \to \pi^+\pi^-) = +0.33 \pm 0.06\ (\text{stat}) \pm 0.03\ (\text{syst})$$
    $$\mathcal{S}_{CP}(B^0 \to \pi^+\pi^-) = -0.64 \pm 0.08\ (\text{stat}) \pm 0.03\ (\text{syst})$$

    → excluded $23.8^\circ < \phi_2 < 66.8^\circ$ @ 1σ CL using isospin analysis
  - Measurement of $\mathcal{B}(B^0 \to \rho^0\rho^0) = (1.02 \pm 0.30\ (\text{stat}) \pm 0.15\ (\text{syst})) \times 10^{-6}$, extracted ϕ_2 using isospin analysis: $\phi_2 = (84.9 \pm 12.9)^\circ$ & $\Delta\phi_2 = (0.0 \pm 9.6)^\circ$ → penguin negligible
  - First evidence of $B^0 \to f_0\rho^0$

Back-up Slides

Belle Experiment (Tsukuba, Japan)

- Operated at KEKB collider (1999-2010)
- KEKB - asymmetric e^+e^- collider
  - 3.5 on 8.0 GeV ($\beta\gamma = 0.425$)
  - **772 x 10^6 $B\bar{B}$** pairs data sample accumulated
  - Peak luminosity (world record) 2.1 x 10^{34} $cm^{-2}s^{-1}$