BEACH 2014

CP Violation Measurements in B Mesons at Belle

Zbyněk Drásal
Charles University, Prague

For Belle collaboration

Quark Mixing and CP Violation

- In Standard Model the CP violation (~~CP~~) established in terms of "charged" currents:

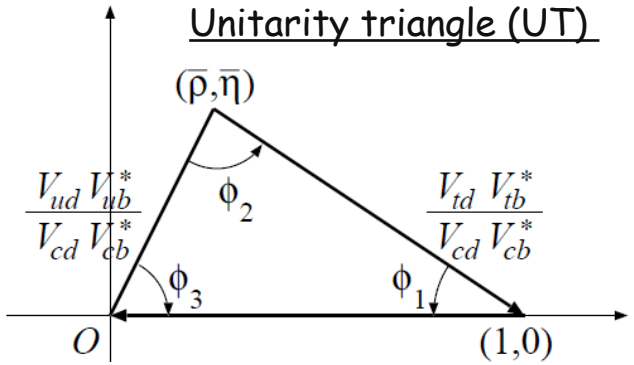
$$\mathcal{L}_W^{(q)} = \frac{g}{\sqrt{2}}(W_\mu^+ \bar{u}_L \gamma^\mu V_{CKM} d_L + W_\mu^- \bar{d}_L \gamma^\mu V_{CKM}^\dagger u_L)$$

and 3-gen. quark mixing matrix V_{CKM}, namely its complex phase ($CP(\mathcal{L}_W^{(q)}) \neq \mathcal{L}_W^{(q)}$):

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

Wolfenstein param. ($\lambda = \sin\theta_c$)

→ applying unitarity conditions $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$ → we obtain a unit. triangle



CP violation parameters:

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

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

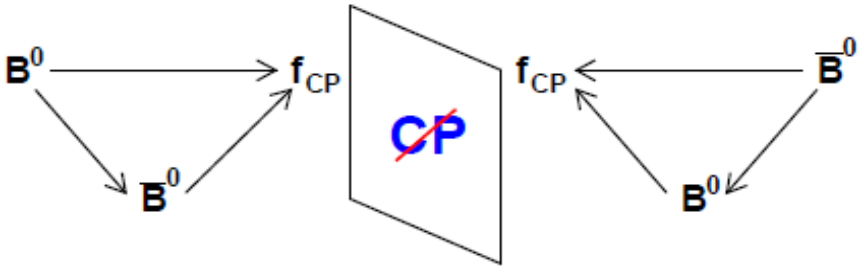
$$\phi_3 = \gamma = \arg\left(-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right)$$

- Question: **Is angle ϕ_1 determination from loop and tree decays consistent?**

Time-Dependent ~~CP~~ Measurements

- **How can we measure the complex phases, i.e. UT angles?**
  → apply 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 (tree & penguin diagram interfere)

Δm_d → B^0-$\bar{B}^0$ mass difference Δt → B^0-$\bar{B}^0$ proper time difference

$$\lambda_{fCP} = \xi_{fCP} \frac{q}{p} \frac{\bar{A}_{\bar{f}_{CP}}}{A_{f_{CP}}}$$

- **Measurements presented here:**

$b \to s\bar{q}q$ → ϕ_1 related measurements

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

Recent

$b \to u\bar{u}d$ → BR measurement (used in ϕ_2 isospin analysis)

$$B^0 \to \pi^0\pi^0$$

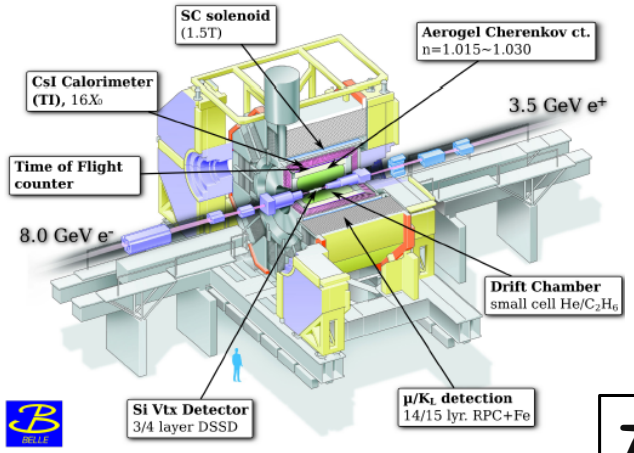
New

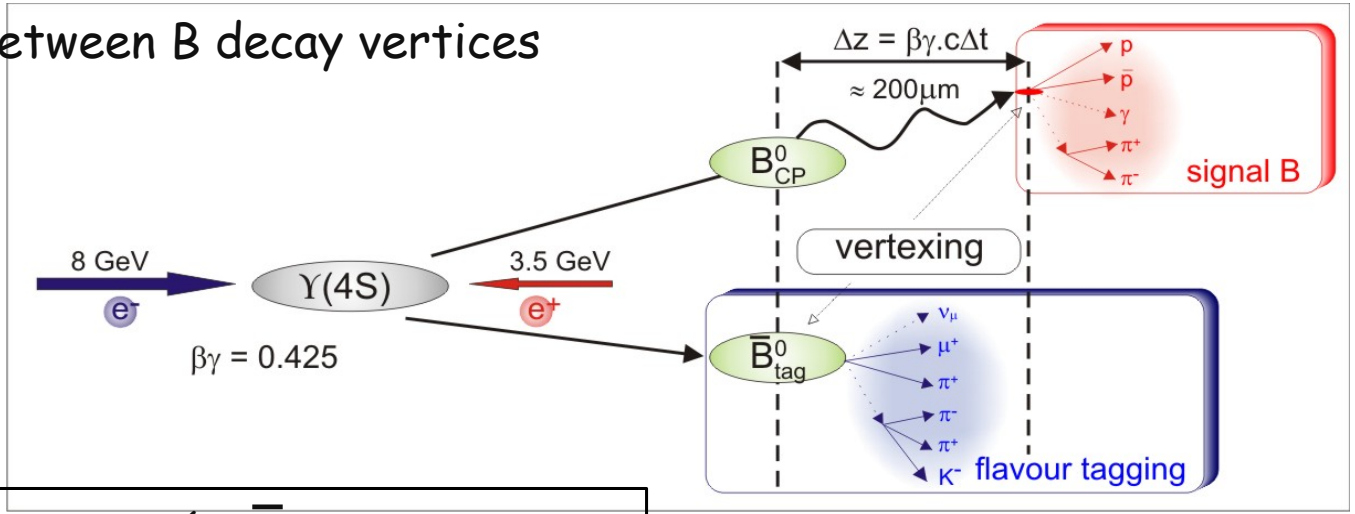
Experimental Principles of Time-Dependent $\not{CP}$ Measurements at Belle

- **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

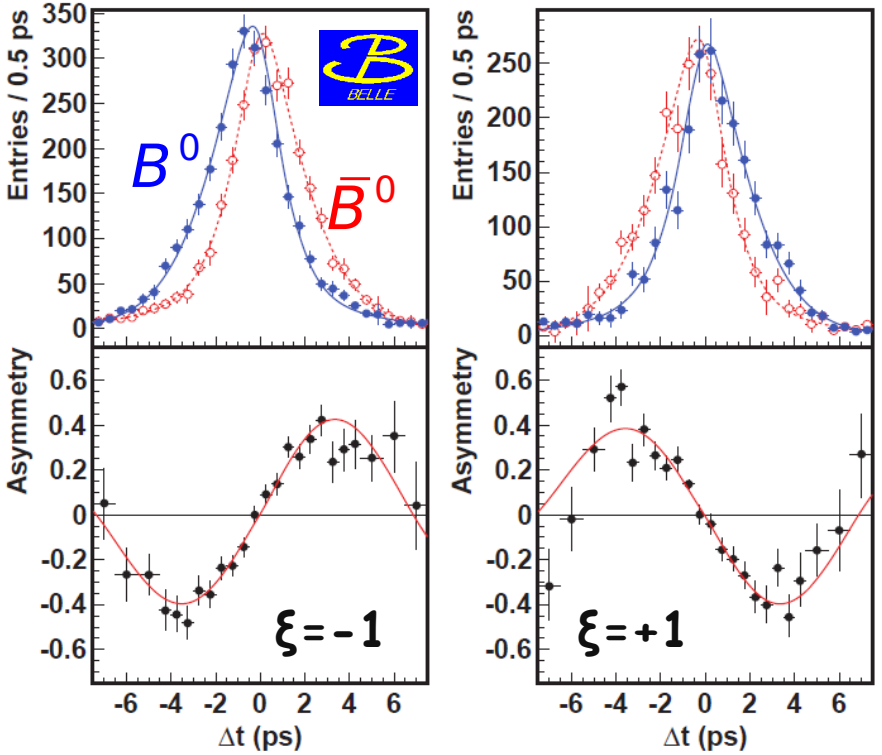




772 x 10^6 $B\bar{B}$ pairs collected

Φ_1 $\not{CP}$ Measurements in b → cc̄s Decays

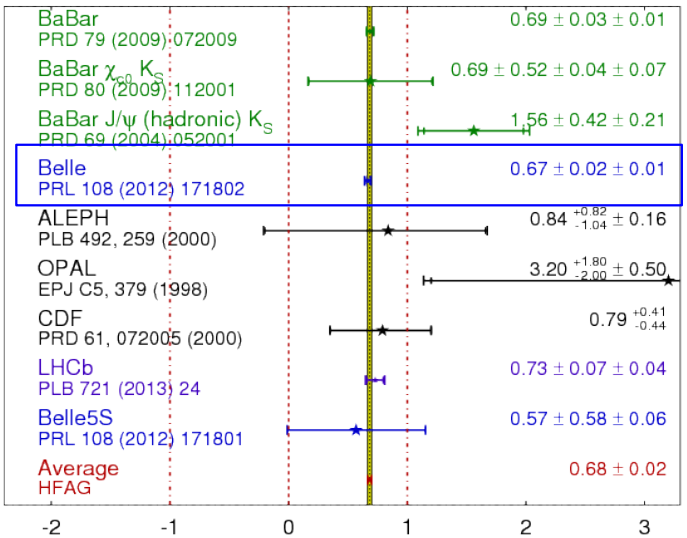
- **Overview of $\sin 2\phi_1$ Belle measurement in B → charmonium K^0 modes ...**
  - Decays b→cc̄s are **tree dominated** → $\mathcal{S}_{CP} = -\xi \sin 2\phi_1$



$$\sin 2\phi_1 = 0.667 \pm 0.023_{\text{stat}} \pm 0.012_{\text{syst}}$$
$$\mathcal{A}_{CP} = 0.006 \pm 0.016_{\text{stat}} \pm 0.012_{\text{syst}}$$

HFAG: b → cc̄s results

$\sin(2\beta) \equiv \sin(2\phi_1)$ HFAG Moriond 2014 PRELIMINARY

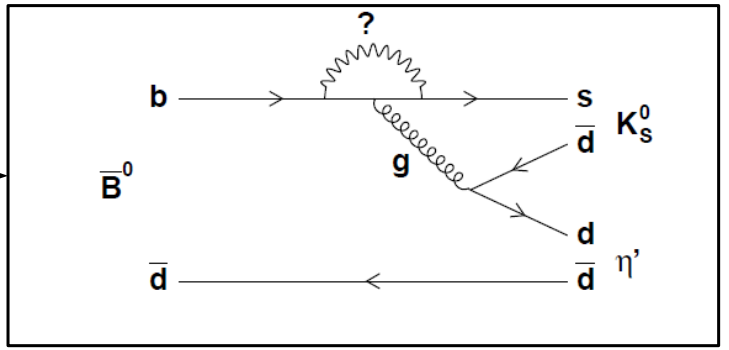


PRL **108**, 171802 (2012)

Φ_1 $\not{CP}$ 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 decays:
    b→uūs, b → dd̄s are **penguin dominated** (tree is CKM & color suppressed)
    b→ss̄s is **penguin only**

$$\begin{aligned} A(c\bar{c}s) &= V_{cb}V_{cs}^*(T_{c\bar{c}s} + P_s^c - P_s^t) + V_{ub}V_{us}^*(P_s^u - P_s^t) \\ A(u\bar{u}s) &= V_{cb}V_{cs}^*(P_s^c - P_s^t) + V_{ub}V_{us}^*(T_{u\bar{u}s} + P_s^u - P_s^t) \\ A(s\bar{s}s) &= V_{cb}V_{cs}^*(P_s^c - P_s^t) + V_{ub}V_{us}^*(P_s^u - P_s^t) \end{aligned}$$



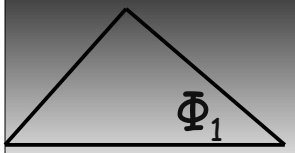
→ could be affected by new heavy particles

→ sensitive to **New Physics (NP)**

  - Expected parameters within the SM (Reminder: only small pollution from a tree process)

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

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



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

- $B^0 \to \eta' K^0$ consists of two CP final states:
  → $B^0 \to \eta' K_S^0$ (CP = -1)
  → $B^0 \to \eta' K_L^0$ (CP = +1)
- SM prediction: $|\mathcal{S}_{CP} - \mathcal{S}_{J/\Psi K_S^0}| \approx$ [-0.05; 0.09] ($SU(3)_F$), [-0,03; 0.03] (QCD factor.)
- Decay chain:

$$\eta' \to \eta\pi^+\pi^- \qquad \eta' \to \rho^0\gamma$$
$$\rho^0 \to \pi^+\pi^-$$
$$\eta \to \gamma\gamma,\ \eta \to \pi^+\pi^-\pi^0$$
$$K_S^0 \to \pi^+\pi^- \text{ or } \pi^0\pi^0$$

- S/B fraction determined from:

$$M_{\rm bc} \equiv \sqrt{(E_{\rm beam}^{\rm CMS})^2 - (p_{\rm B}^{\rm CMS})^2}$$
$$\Delta E \equiv E_{\rm B}^{\rm CMS} - E_{\rm beam}^{\rm CMS}$$
$$\mathcal{R}_{\rm S/B} = \frac{\mathcal{L}_{\rm sig}}{\mathcal{L}_{\rm sig}+\mathcal{L}_{\rm bkg}}\ (q\bar{q}\ \text{suppress.})$$
$\Big\}\ B^0 \to \eta' K_S^0$

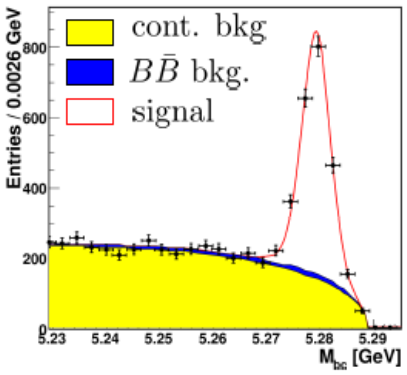
×

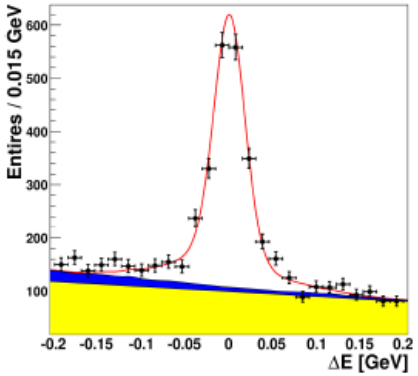
$$p_B^{\rm CMS}\ (\text{assuming}\ \Delta E = 0\,)$$
$$\mathcal{R}_{\rm S/B} = \frac{\mathcal{L}_{\rm sig}}{\mathcal{L}_{\rm sig}+\mathcal{L}_{\rm bkg}}\ (q\bar{q}\ \text{suppress.})$$
$\Big\}\ B^0 \to \eta' K_L^0$

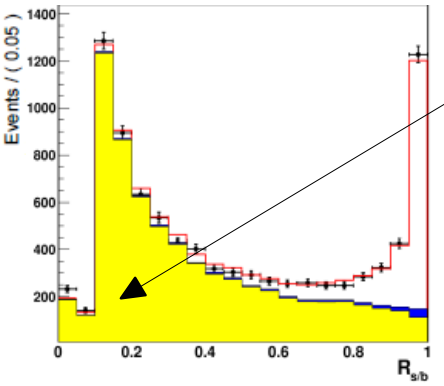
$B^0 \to \eta' K^0$ Analysis

- S/B → 3D (2D) unbinned ML fit + ~~CP~~ parameters → (Δt x q) fit with fixed S/B …

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

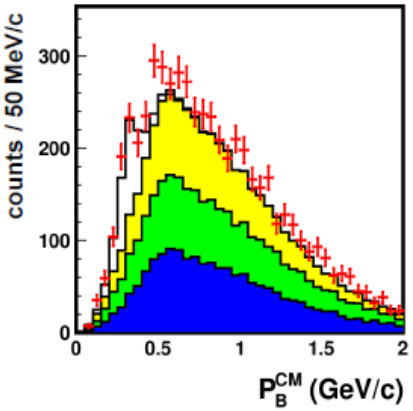


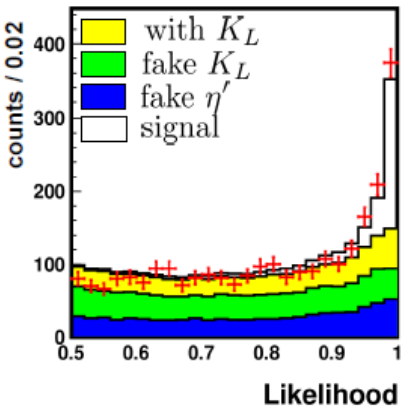




All η' decay modes combined

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



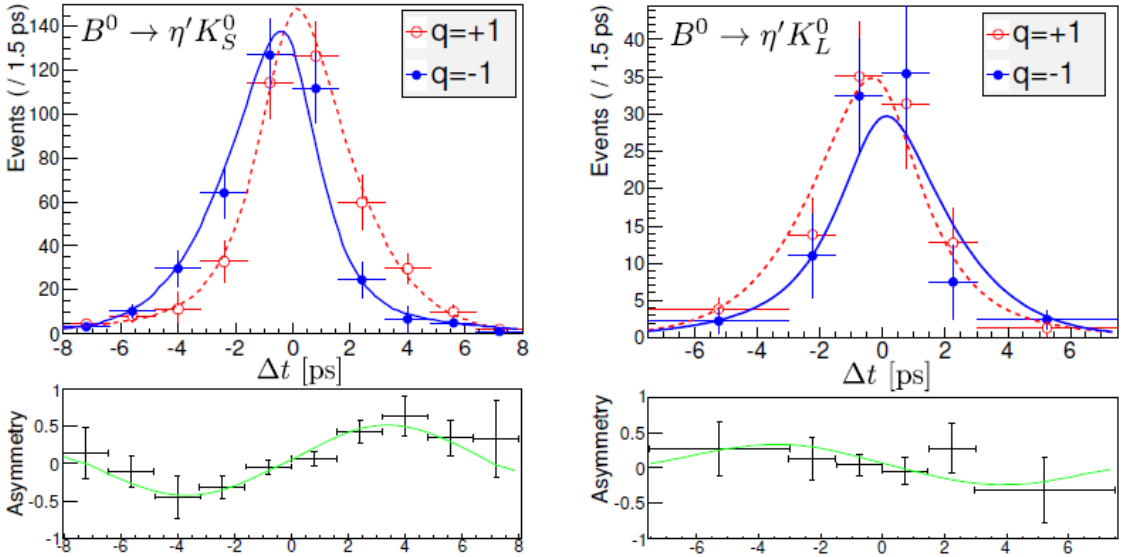


mode	This analysis 772 M $B\bar{B}$ N_{sig}	2007 analysis 534 M $B\bar{B}$ N_{sig}
$\eta' K_S$	2506.3 ± 63.1	1256.6 ± 42.1
$\eta' K_L$	1041.7 ± 41.1	478.8 ± 41.1

Data reprocessed with new tracking code
→ improved reconstruction efficiency

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

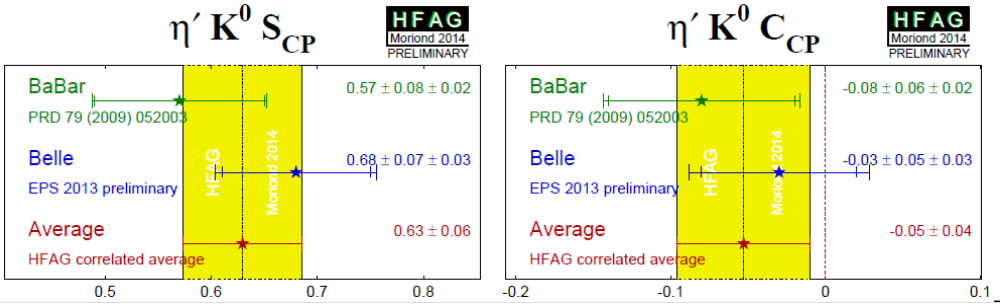
- **Fit results:**

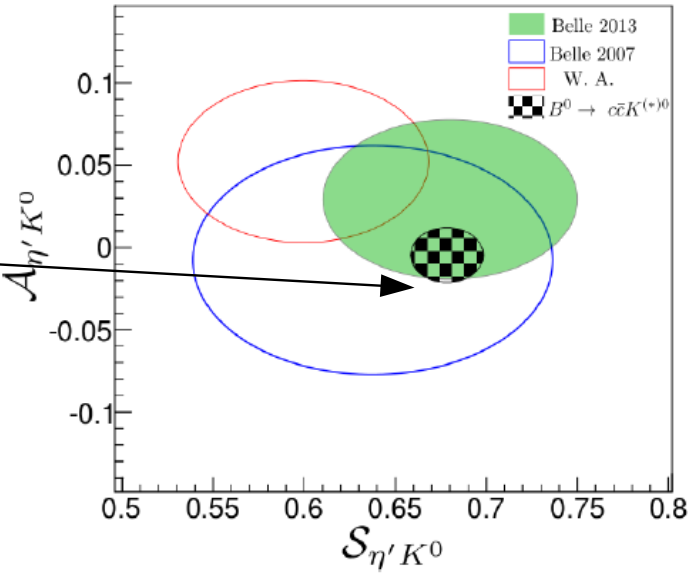


$$\mathcal{S}_{CP} = +0.68 \pm 0.07_{\text{stat}} \pm 0.03_{\text{syst}}$$
$$\mathcal{A}_{CP} = +0.03 \pm 0.05_{\text{stat}} \pm 0.04_{\text{syst}}$$

→ world's most precise ~~CP~~ measurement in $B^0 \to \eta' K$

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



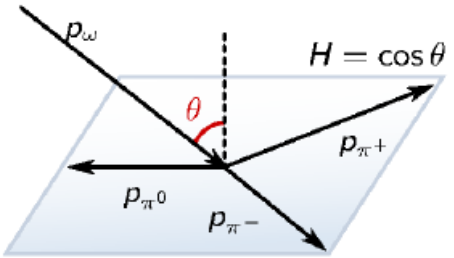


$B^0 \to \omega K^0_S$ Analysis

- $B^0 \to \omega K^0_S$ represents a CP final state (CP = -1), $B^\pm \to \omega K^\pm$ (control sample)
- SM prediction: $|\mathcal{S}_{CP} - \mathcal{S}_{J/\Psi K^0_S}| \approx$ [0.1; 0.2] (pQCD, QCDf,...)
- Applied extended ML fit to 7 variables:

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

$\cos\theta^{\rm Hel}_{3\pi},\ \Delta t,\ q$ (flavour)

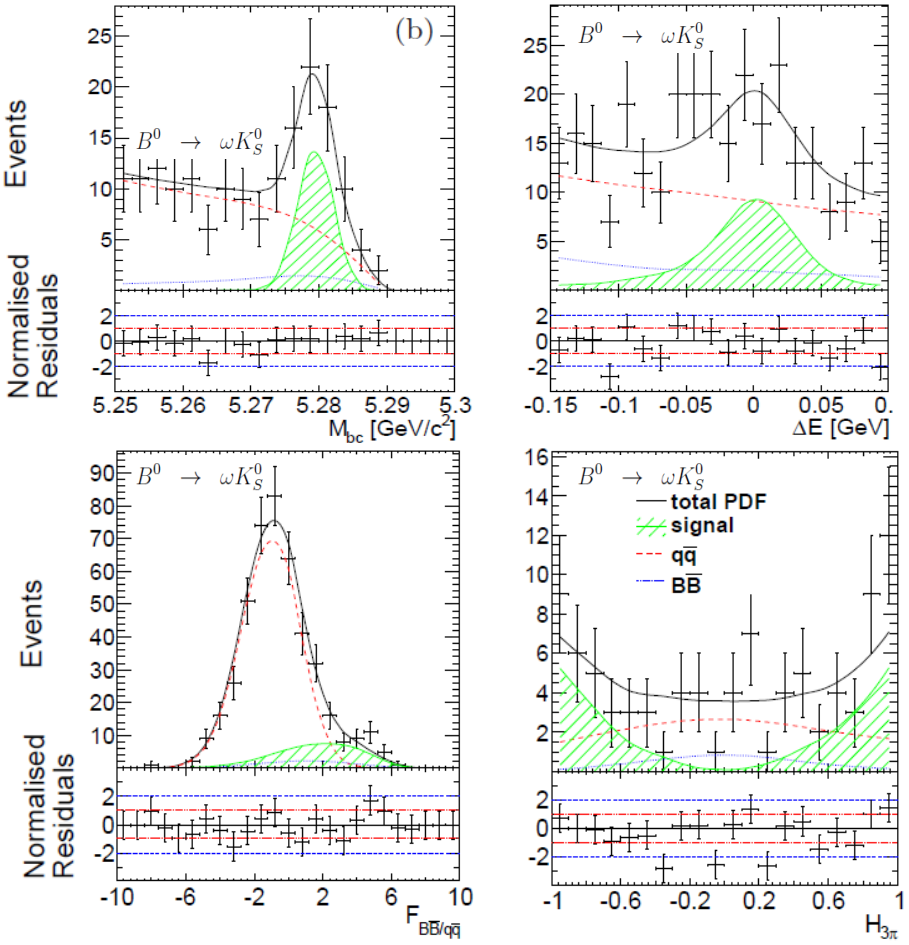


$$M_{\rm bc} \equiv \sqrt{(E^{\rm CMS}_{\rm beam})^2 - (p^{\rm CMS}_{\rm B})^2}$$

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

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

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



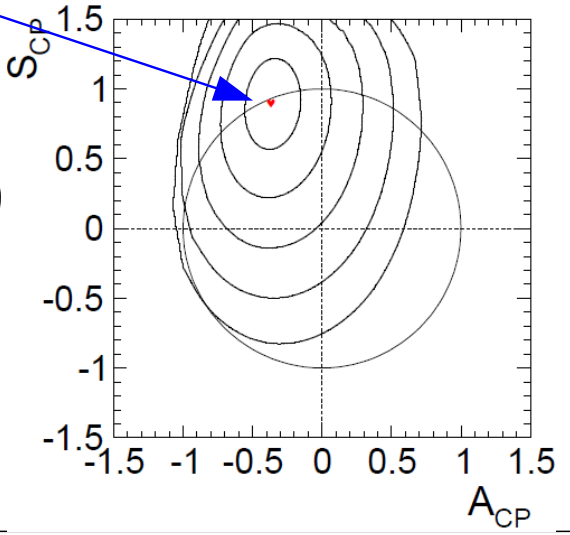
$B^0 \to \omega K^0_S$ Analysis

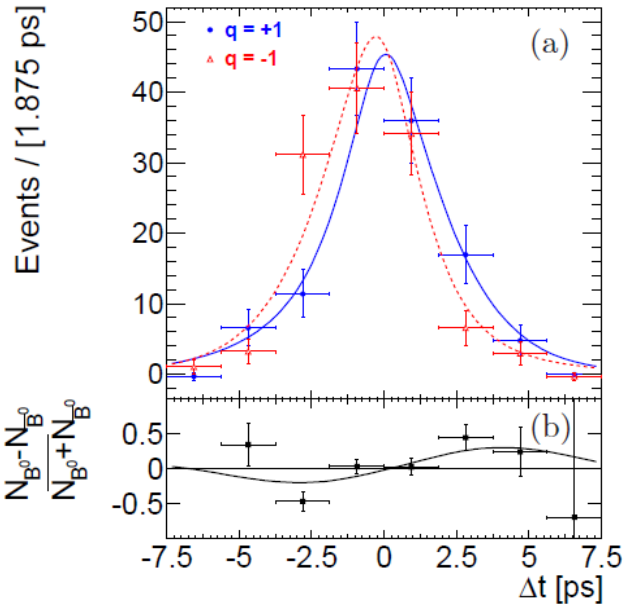
- **Fit results** compared to **older measurements:**

	$B\bar{B}$-pairs	$\mathcal{BR}(B^0 \to \omega K^0)$	$\mathcal{A}_{CP}$	$\mathcal{S}_{CP}$
Belle	388×10^6	$(4.4^{+0.8}_{-0.7} \pm 0.4) \times 10^{-6}$	-	-
Belle	535×10^6	-	$-0.09 \pm 0.29 \pm 0.06$	$+0.11 \pm 0.46 \pm 0.07$
BaBar	467×10^6	$(5.4 \pm 0.8 \pm 0.3) \times 10^{-6}$	$+0.52^{+0.22}_{-0.20} \pm 0.03$	$+0.55^{+0.26}_{-0.29} \pm 0.02$
Belle	772×10^6	$(4.5 \pm 0.4 \pm 0.3) \times 10^{-6}$	$-0.36 \pm 0.19 \pm 0.05$	$+0.91 \pm 0.32 \pm 0.05$

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

→ no clear sign for NP observed



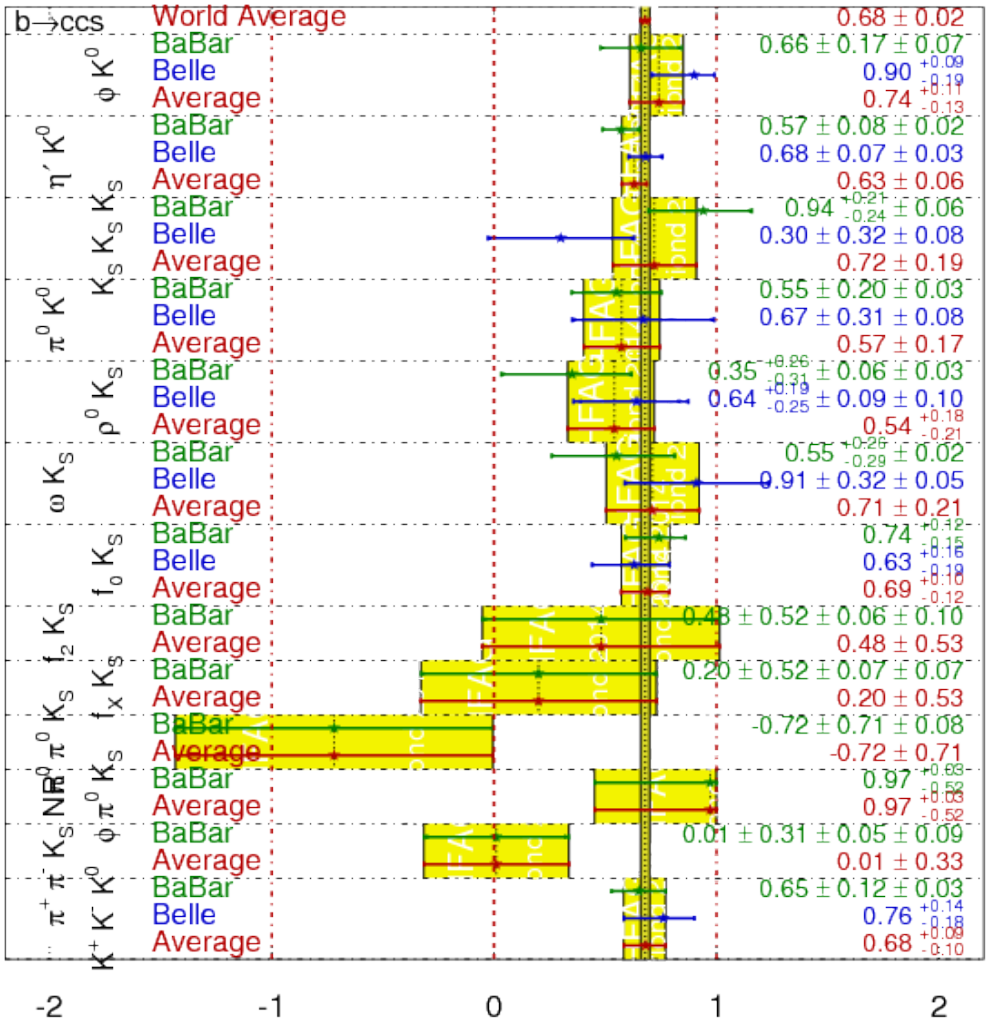


- Paper published in PRD (July 14)
  „Phys. Rev. D **90**, 012002"

Summary of $\not{CP}$ in $b \to q\bar{q}s$

$$\sin(2\beta^{eff}) \equiv \sin(2\phi_1^{eff})$$

HFAG Moriond 2014 PRELIMINARY



Belle results:

$$S_{\eta' K^0} = +0.68 \pm 0.07 \pm 0.03$$

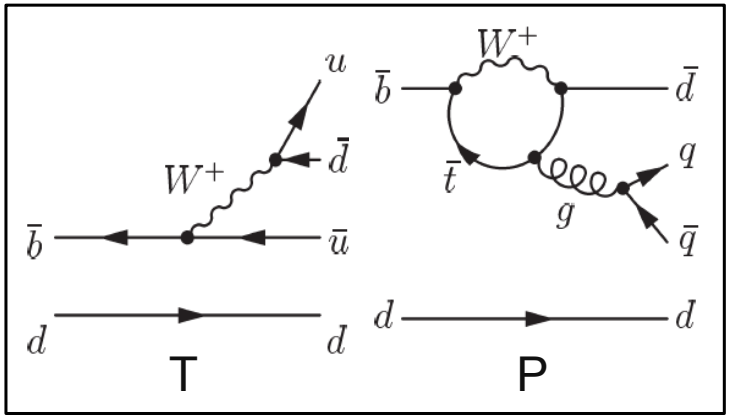
$$S_{\omega K^0_S} = +0.91 \pm 0.32 \pm 0.05$$

No evidence of NP at current level of sensitivity...

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

- **Recent Belle result in b → uūd decays:** $B^0 \to \pi^+\pi^-$
  - both tree (T) & penguin (P) contribute …
  - → expected **non-zero effect of direct $\not{CP}$ in SM**
  - → **no clean extraction** of single CKM phase:

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



- **How to extract ϕ_2 ?** Combine Belle ππ results by isospin analysis (Gronau & London PRL **65**, 3381, 1990)

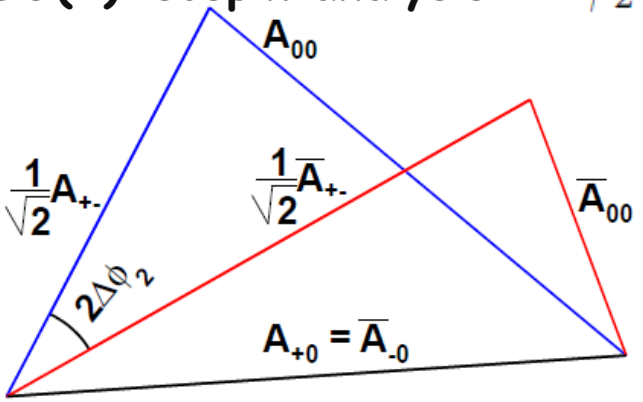
$$\mathcal{B}(B^0 \to \pi^+\pi^-) = (5.04 \pm 0.21_{\rm stat} \pm 0.18_{\rm syst}) \times 10^{-6}$$
$$\mathcal{B}(B^\pm \to \pi^\pm\pi^0) = (5.86 \pm 0.26_{\rm stat} \pm 0.38_{\rm syst}) \times 10^{-6}$$ } PRD **87**, 031103(R)

$\mathcal{B}(B^0 \to \pi^0\pi^0)$ ⟶ **New**

$$\mathcal{A}_{\rm CP}(B^0 \to \pi^+\pi^-) = +0.33 \pm 0.06_{\rm stat} \pm 0.03_{\rm syst}$$
$$\mathcal{S}_{\rm CP}(B^0 \to \pi^+\pi^-) = -0.64 \pm 0.08_{\rm stat} \pm 0.03_{\rm syst}$$ } PRD **88**, 092003

$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0)$ ⟶ Coming soon

SU(2) isospin analysis → ϕ_2

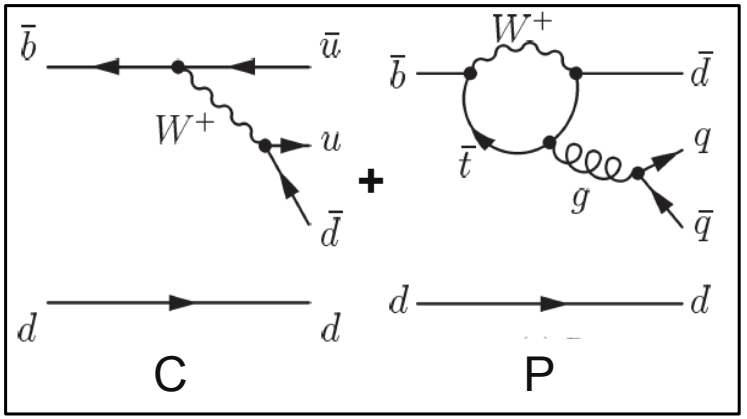


$$A_{+0} = \frac{1}{\sqrt{2}}A_{+-} + A_{00}, \quad \bar{A}_{-0} = \frac{1}{\sqrt{2}}\bar{A}_{+-} + \bar{A}_{00}$$

8-fold ambiguity

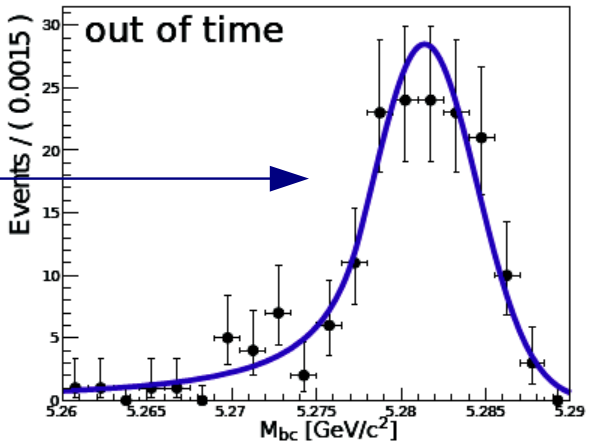
$B^0 \to \pi^0\pi^0$ Analysis

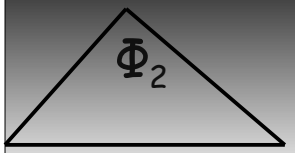
- Proceeds via **b→u** transition:
  colour suppressed tree (C) & penguin (P) contribute



- Previous BR measurements [x 10^{-6}]:
  - Belle: $\mathcal{B} = 2.3^{+0.4+0.2}_{-0.5-0.3}$ PRL **84**, 181803 (05)
  - Belle: $\mathcal{B} = 1.1 \pm 0.3 \pm 0.1$ ICHEP 06 (535 M $B\bar{B}$)
  - BaBar: $\mathcal{B} = 1.83 \pm 0.21 \pm 0.13$ PRD **87**, 052009 (13)
  - Theory: $\mathcal{B} \leq 1.0$ Nuclear Phys. **B**, 675 p.333 (03)

- Strategy → fit $M_{\rm bc}, \Delta E, T_{\rm cont}$ (TMVA based continuum suppression var.)
  - But... substantial $B\bar{B}$ bkg observed in data! Why?
  - Out-of-time electromag. interactions in ECL show up as correlated with $B\bar{B}$ bkg & peak under signal!
    → efficiently removed using ECL timing information
    → analysis with 751.5 M $B\bar{B}$ pairs (Belle reprocessed data with timing information)

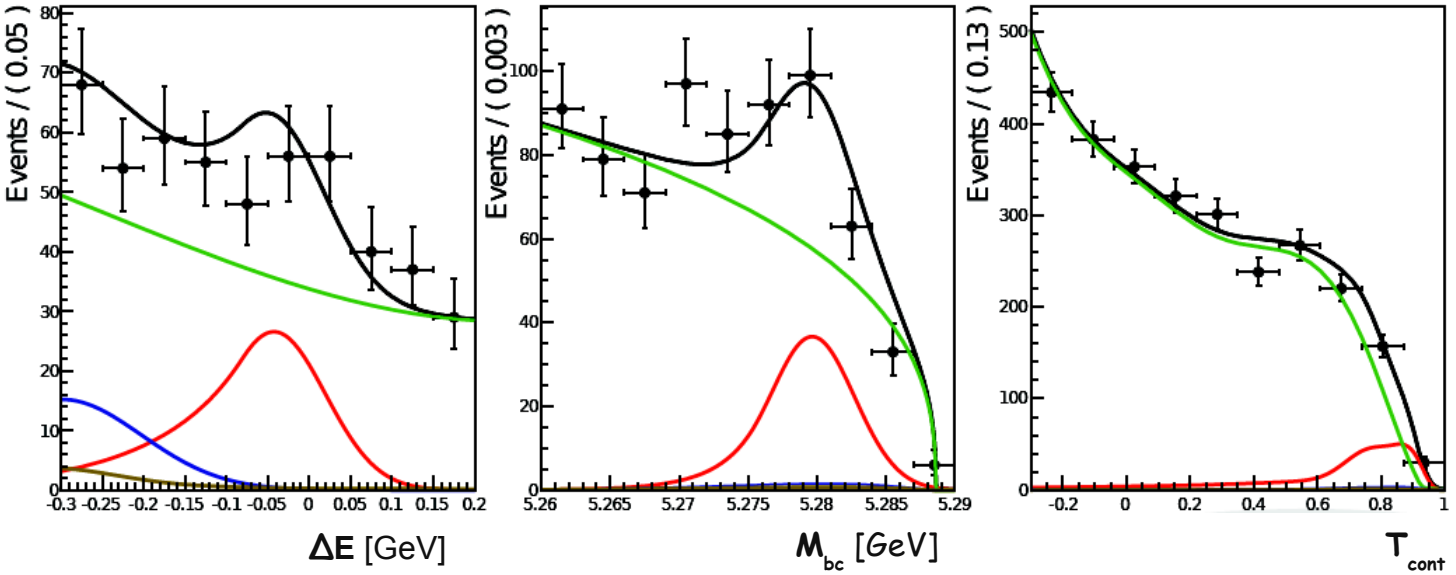




$B^0 \to \pi^0\pi^0$ Analysis

- Fit results:

Total PDF
Signal
Continuum
Rare B
$B \to \rho\pi$



→ fit projections to signal region displayed

→ applying ECL TDC cut removes out-of-time background ($B\bar{B}$ bkg is then negligible)!

- **Preliminary result:**

$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (0.90 \pm 0.12_{\rm stat} \pm 0.10_{\rm syst}) \times 10^{-6} \quad (6.7\sigma)$$

→ new Belle result consistent with theoretical predictions

Summary

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

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

  - The world's most precise measurement of $\not{CP}$ in $B^0 \to \eta' K^0$:

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

  → no evidence of NP at current level of experimental sensitivity

- 1 new measurement important for isospin analysis & constraints on ϕ_2
  - Precise measurement of $\mathcal{B}(B^0 \to \pi^0\pi^0)$

$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (0.90 \pm 0.12_{\text{stat}} \pm 0.10_{\text{syst}}) \times 10^{-6} \quad (6.7\sigma)$$

  → preliminary result consistent with theoretical prediction

Thank you for your attention!