ϕ_1 Measurement at Belle

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February 14th, 2014
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MAX-PLANCK-GESELLSCHAFT

Outline

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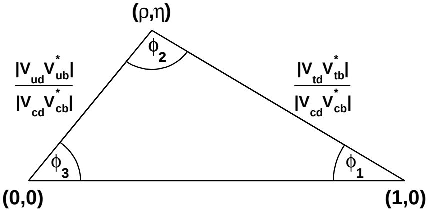


Imperfections of the Standard Model

The **Standard Model** (SM) is a successful theory. However, it is incomplete and has flows such as

- missing explanation of *gravity*
- missing explanation of *Dark Matter and Dark Energy* (over 95% of the content of the Universe)
- assumption that *neutrinos* are massless (cannot explain the observed mixing)
- insufficient explanation of the **matter-antimatter asymmetry** in the Universe today.

To explain the Universal matter dominance, violation of the *CP* symmetry is needed (Sakharov 1967)

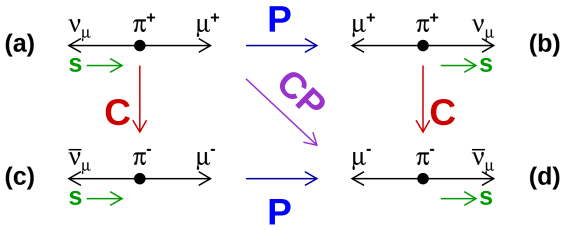
$CP = C$(charge conjugation) $\times P$(parity transformation)

C transforms a particle into its antiparticle

P transforms a right-handed particle into a left-handed particle

CP Symmetry

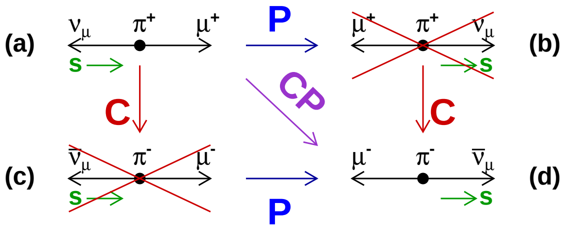
In the weak interaction...



(a) is the dominant process for π^+ decay. The neutrino ν_μ is always left-handed (Garwin et al. 1957; Friedman and Telegdi 1957)

CP Symmetry

In the weak interaction...



(a) is the dominant process for π^+ decay. The neutrino ν_μ is always left-handed (Garwin et al. 1957; Friedman and Telegdi 1957)

(b) *P* conjugate process never occurs because the neutrino would be right-handed

(c) *C* conjugate process also never occurs because $\overline{\nu}_\mu$ should be right-handed

(d) *CP* conjugate process has same decay rate as (a) $\Rightarrow$ combined *CP* symmetry is preserved.

CP Violation in the Standard Model

- Clear experimental observation of *CP* violation in K and B meson decays
- In SM, *CP* violation arises in charged weak current interactions

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

- Cabbibo-Kobayashi-Maskawa matrix V_{CKM} describes relative strengths of quark transitions

$$V_{\mathrm{CKM}} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- To conserve probability, $V_{\mathrm{CKM}} V_{\mathrm{CKM}}^\dagger = \mathbb{1}$ (unitarity)
- For 3 quark generations, unitarity reduces V_{CKM} to 3 real rotation angles and 1 complex phase

If V_{CKM} is complex, $CP\mathcal{L}_W^{(q)} \neq \mathcal{L}_W^{(q)}$ ie. *CP* is violated

- For only 2 quark generations, V_{CKM} real $\Rightarrow$ *CP* in SM conserved

CP Violation in the K system

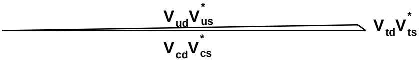
Represent $V_{\rm CKM}$ in terms of the Cabibbo angle, $\lambda = |V_{us}| = \sin\theta_{\rm C} \approx 0.23$

Gives a more intuitive picture of relative strengths between CKM elements

$$V_{\rm CKM} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \mathcal{O}\begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$$V_{\rm CKM} V_{\rm CKM}^{\dagger} = \mathbb{1} \Rightarrow \textstyle\sum_{j=1}^{3} V_{jk} V_{ij}^{*} = 0,\ i \neq k$$

In the K system



$$\underset{\mathcal{O}(\lambda)}{V_{ud}V_{us}^*} + \underset{\mathcal{O}(\lambda)}{V_{cd}V_{cs}^*} + \underset{\mathcal{O}(\lambda^5)}{V_{td}V_{ts}^*} = 0$$

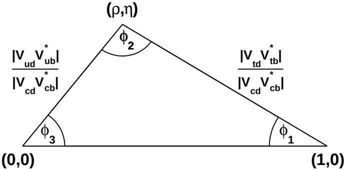
- Amount of *CP* violation (CKM complex phase) reflected in the area of the triangle
- All unitarity triangles have the same area, accessible through measurement of their angles and sides
- Small angles $\Rightarrow$ *CP* violation in the K sector is a small effect

CP Violation in the B system

$$\lambda = |V_{us}| = \sin\theta_\mathrm{C} \approx 0.23 \qquad V_\mathrm{CKM} V_\mathrm{CKM}^\dagger = \mathbb{1} \Rightarrow \sum_{j=1}^{3} V_{jk} V_{ij}^* = 0,\ i \neq k$$

$$V_\mathrm{CKM} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \mathcal{O}\begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

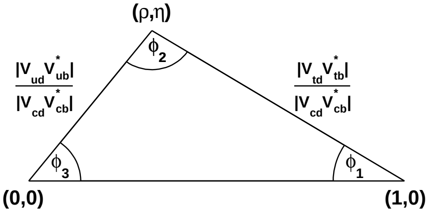
In the B system



$$\underset{\mathcal{O}(\lambda^3)}{V_{ud}V_{ub}^*} + \underset{\mathcal{O}(\lambda^3)}{V_{cd}V_{cb}^*} + \underset{\mathcal{O}(\lambda^3)}{V_{td}V_{tb}^*} = 0$$

- Larger angles $\Rightarrow$ *CP* violation in the B sector is a considerable effect
- *B* meson system is a perfect environment for *CP* violation measurements
- Only 2 parameters needed to constrain the triangle, but 2 sides and 3 angles are measurable $\rightarrow$ stringent test of the SM and search for New Physics possible

Outline



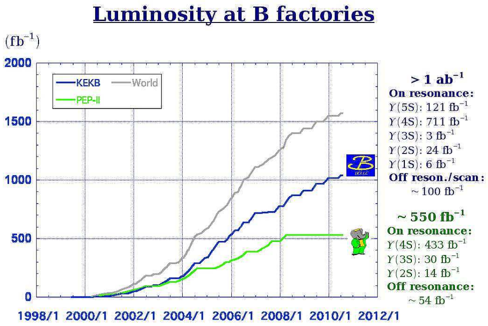
KEKB Accelerator

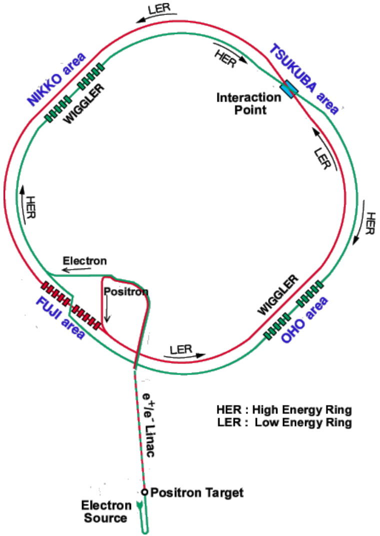
Asymmetric energy e^+e^- (3.5 on 8 GeV) collider

- $B\overline{B}$ separation increased to $\sim 200\ \mu m$

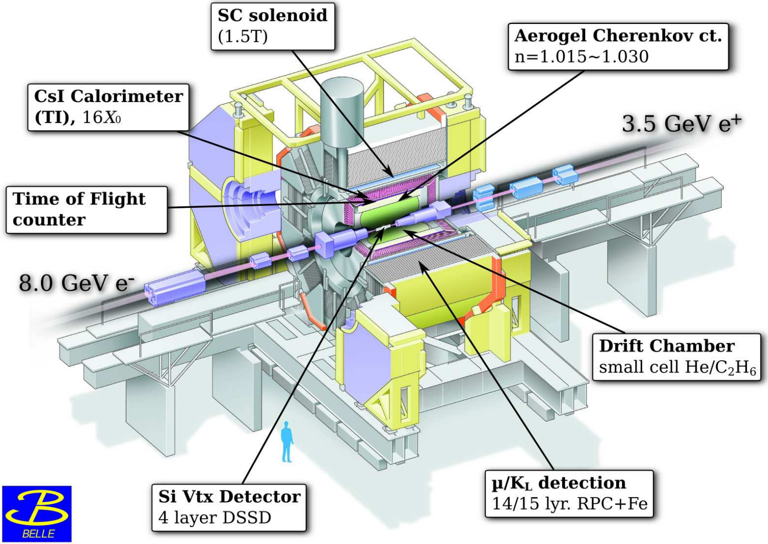
World record peak luminosity $2.1 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$

- Largest sample of 772×10^6 $B\overline{B}$ pairs

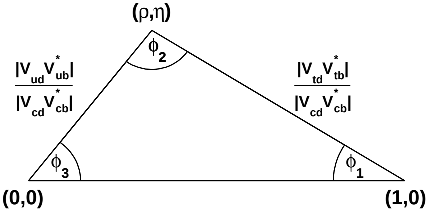




Belle Detector

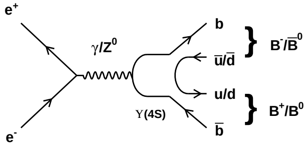


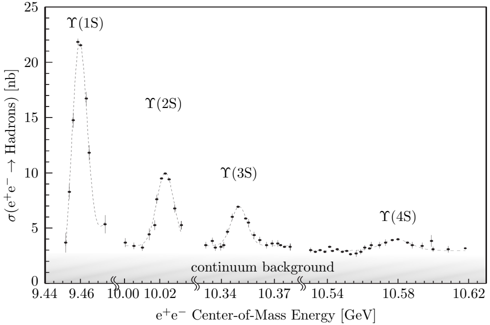
Outline



Measurement Principles at Belle

Production via $e^-e^+ \to \Upsilon(4S) \to B\overline{B}$





$$m_{\Upsilon(4S)} = 10.58\,\mathrm{GeV/c^2} \approx 2 \times m_B$$

$$m_B = 5.28\,\mathrm{GeV/c^2}$$

$\Upsilon(4S)$ resonance decays almost exclusively into a $B\overline{B}$ pair

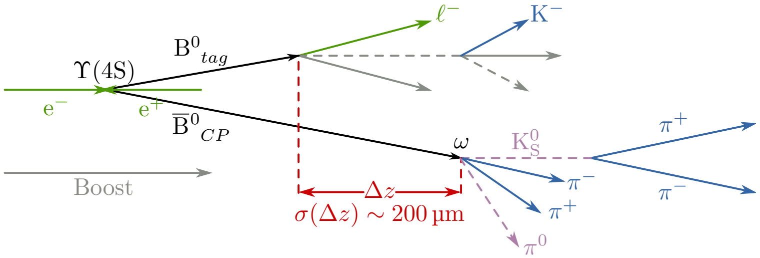
$\Upsilon(4S)$: $J^P = 1^-$

B: $J^P = 0^-$

$\Rightarrow$ B meson pair in a p-wave
$\Rightarrow$ asymmetric wave function
$\Rightarrow$ B mesons must have opposite flavour

$B\overline{B}$ pair coherent

Δt measurement at Belle

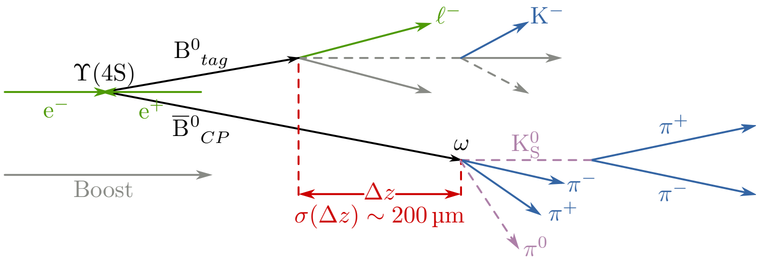


Δt measurement

- Asymmetric beam energies at KEKB
  $E(e^-) = 8\,\mathrm{GeV}$ and $E(e^+) = 3.5\,\mathrm{GeV}$
  $\Rightarrow \Upsilon(4S)$ produced with a boost $\beta\gamma c = 0.425$
- Measurement of $\sigma(\Delta z) \sim 100\,\mu m$ (measurable) instead of $\sigma(\Delta t) \sim \mathrm{ps}$ (unmeasurable)
- Obtain $\Delta t = \Delta z / \beta\gamma c$

Precise vertex measurement is the key to acccessing *CP* violation in B decays

Δt measurement at Belle



B flavour determination

- Suppose you can find a B decay to a *CP* eigenstate, B_{CP}, eg. $B^0(\overline{B}^0) \to \omega K^0_S$
- Suppose also, that the other B is flavour-specific final state, $B_{\rm Tag}$, eg. $B^0 \to D^{*-}\ell^+\nu_\ell$ $(q=+1)$, $\overline{B}^0 \to D^{*+}\ell^-\overline{\nu}_\ell$ $(q=-1)$
- Probability of finding B_{CP} at time Δt after $B_{\rm Tag}$ decayed with flavour, q

$$\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 + q\left(\mathcal{A}_{CP}\cos\Delta m_d\Delta t + \mathcal{S}_{CP}\sin\Delta m_d\Delta t\right)\right]$$

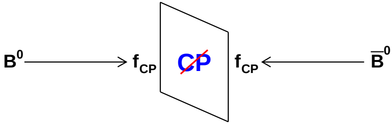
Types of CP Violation

Two types of CP violation can be measured from a CP final state of the B

$$\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\left[1 + q\left(\mathcal{A}_{CP}\cos\Delta m_d \Delta t + \mathcal{S}_{CP}\sin\Delta m_d \Delta t\right)\right]$$

Direct CP violation $\mathcal{A}_{CP}$

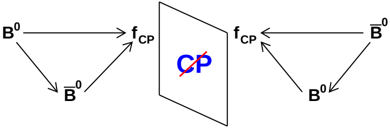
Different decay rates



acpscp.mp4

Mixing-induced CP violation $\mathcal{S}_{CP}$

Arises from an interference between $B^0 - \overline{B}^0$ mixing and the final state



Outline

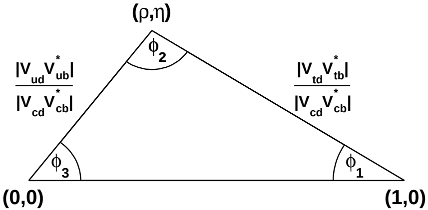
Introduction to *CP* Violation

Belle Detector

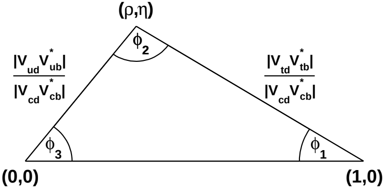
Measurement Principles

Measurement of ϕ_1

- Measurement in $b \to c\bar{c}s$ Transitions
- Measurement in $b \to sq\bar{q}$ Transitions
- Measurement in $B \to \omega K$ Decays

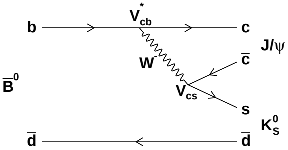


Measurement of ϕ_1: $b \to c\bar{c}s$

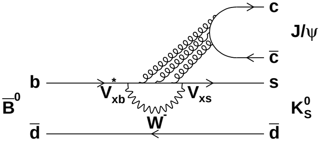


- ϕ_1 the most precisely measured parameter of the unitarity triangle
- Most accurate measurement of $\sin 2\phi_1$ in $b \to c\bar{c}s$ transitions

Tree diagram



Penguin diagram

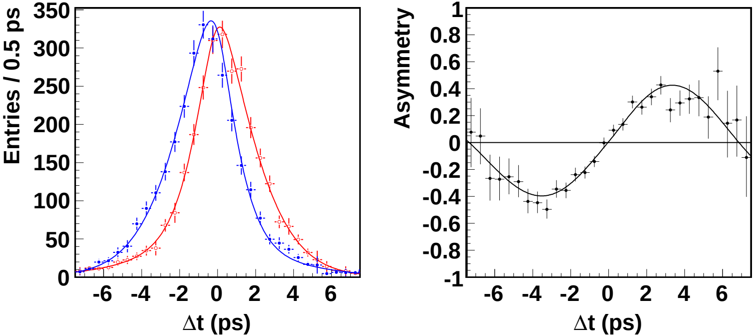


- Theoretically clean, dominant tree process, loop diagrams ("penguins") strongly suppressed
- Experimentally clean, rather free from background

$$\mathcal{A}_{CP} \approx 0, \; \mathcal{S}_{CP} = \sin 2\phi_1$$

Measurement of ϕ_1: $b \to c\bar{c}s$

CP violation in the B sector first observed in the "golden channel" $B \to J/\psi K^0_S$
Belle, PRL **108**, 171802 (2012)



World's most precise measurement of $\sin 2\phi_1$

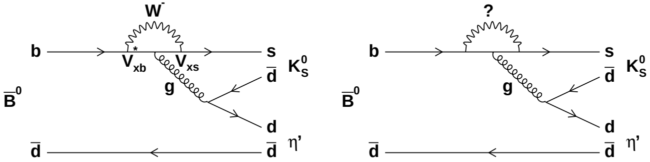
by Belle: $\mathcal{S}_{CP}(J/\psi K^0_S) = \sin 2\phi_1 = 0.67 \pm 0.02 \pm 0.01$

BaBar: $\mathcal{S}_{CP}(J/\psi K^0_S) = \sin 2\phi_1 = 0.69 \pm 0.03 \pm 0.01$

The next generation of B factories will push the uncertainty down to 1%

Measurement of ϕ_1: $b \to sq\bar{q}$

FCNC forbidden at tree level or tree CKM suppressed
$\Rightarrow$ penguin diagram dominates



- $\mathcal{S}_{CP} = \sin 2\phi_1$, same as $b \to c\bar{c}s$
- Penguin amplitudes highly sensitive to New Physics
- Could be affected by a heavy unknown particle in the loop
- Measure branching fraction and *CP* violation parameters
- A deviation of these measurements from SM expectations will be an indication of New Physics

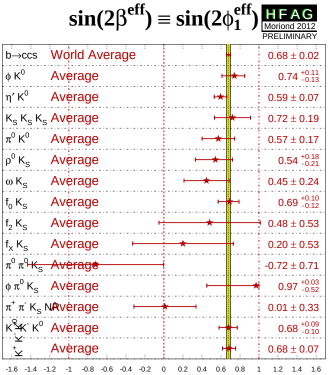
Measurement of ϕ_1: $b \to sq\bar{q}$

Theory

hep-ph/0707.1323, hep-ph/0702252

Mode	$\mathcal{S}_{CP} - \sin 2\phi_1$
$B^0 \to \phi K^0_S$	0.02 ± 0.01
$B^0 \to \eta' K^0_S$	0.01 ± 0.01
$B^0 \to K^0_S K^0_S K^0_S$	$0.02^{+0.02}_{-0.03}$
$B^0 \to K^0_S \pi^0$	$0.07^{+0.05}_{-0.04}$
$B^0 \to \rho^0 K^0_S$	$-0.08^{+0.08}_{-0.12}$
$B^0 \to \omega K^0_S$	0.13 ± 0.08
$B^0 \to K^0_S \pi^0 \pi^0$	$0.03^{+0.02}_{-0.03}$
$B^0 \to K^+ K^- K^0_S$	$0.03^{+0.02}_{-0.03}$

Experiment

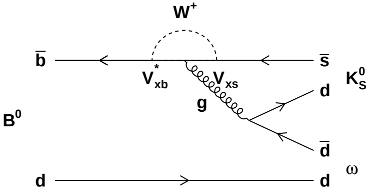


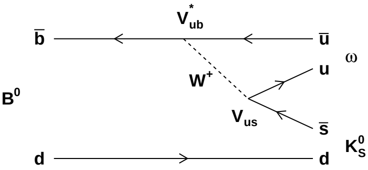
- Predicted in SM to have higher *CP* asymmetries than $b \to sq\bar{q}$
- But most $b \to sq\bar{q}$ measurements at or below $b \to c\bar{c}s$ measurements
- More experimental precision required

Measurement of ϕ_1: $B \to \omega K$

My PhD thesis

The final measurement of $B \to \omega K$ with the full data set of Belle 772×10^6 $B\bar{B}$ pairs





Challenging analysis

- $\mathcal{BR}(B \to \omega K) \sim 10^{-6}$ (small)
- Large background contribution from $q\bar{q}$ (u, d, s, c) background

	$B^0 \to \omega K^0_S$	$B^+ \to \omega K^+$
signal	≈ 240	≈ 1150
$q\bar{q}(q = u, d, s, c)$ BG	≈ 17000	≈ 85000
$B\bar{B}$ BG	≈ 360	≈ 1700

Measurement of ϕ_1: $B^0 \to \omega K^0_S$

Black font: previous measurements
Blue font: Full Belle data set of 772×10^6 $B\overline{B}$ pairs

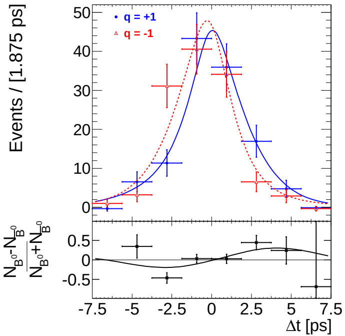
	$\mathbf{B\overline{B}}$-pairs	$\mathcal{BR}(\mathbf{B^0 \to \omega K^0})$	$\mathcal{A}_{CP}$	$\mathcal{S}_{CP}$
Belle	388×10^6	$(4.4^{+0.8}_{-0.7} \pm 0.4) \times 10^{-6}$	-	-
Belle	535×10^6	-	$-0.09 \pm 0.29 \pm 0.06$	$0.11 \pm 0.46 \pm 0.07$
BaBar	467×10^6	$(5.4 \pm 0.8 \pm 0.3) \times 10^{-6}$	$0.52^{+0.22}_{-0.20}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

	$\mathbf{B\overline{B}}$-pairs	$\mathcal{BR}(\mathbf{B^+ \to \omega K^+})$	$\mathcal{A}_{CP}$
Belle	388×10^6	$(8.1 \pm 0.6 \pm 0.6) \times 10^{-6}$	$0.05^{+0.08}_{-0.07} \pm 0.01$
BaBar	383×10^6	$(6.3 \pm 0.5 \pm 0.3) \times 10^{-6}$	$-0.01 \pm 0.07 \pm 0.01$
Belle	772×10^6	$(6.8 \pm 0.4 \pm 0.4) \times 10^{-6}$	$-0.03 \pm 0.04 \pm 0.01$

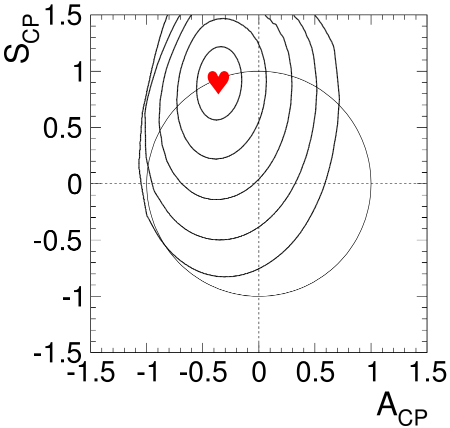
Paper submitted to PRD, in review; arXiv 1311.6666

Measurement of ϕ_1: $B^0 \to \omega K^0_S$

First evidence of *CP* violation in $B^0 \to \omega K^0_S$



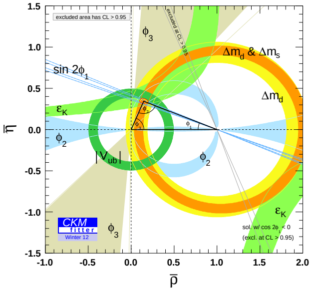
Clear asymmetry can be seen in the difference between the B^0 and $\overline{B}^0$ distributions



CP conservation $(\mathcal{A}_{CP}, \mathcal{S}_{CP}) = (0, 0)$ ruled out by 3.1 standard deviations

Conclusion

- *CP* violation is a fascinating effect with a great impact in cosmology
- Predicted in the Standard Model; it has been observed in K and B decays
- ϕ_1 is the most precisely measured parameter of the unitarity triangle
- ϕ_1 accessible in penguin-dominated decays, sensitive to New Physics
- So far, measurements of the unitarity triangle consistent with the Standard Model prediction but with huge uncertainties
- More precise theoretical calculations and measurements needed to challenge the Standard Model



Thank you for your attention