Study of the decay of $B^0 \to \omega K^0_S$ at Belle

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Introduction to *CP* Violation

- Universe today is matter dominated
- Violation of $CP = C(\text{charge}) \times P(\text{parity})$ symmetry necessary to explain the matter-antimatter asymmetry after the Big Bang
- *CP violation* in the Standard Model: *Cabbibo-Kobayashi-Maskawa (CKM) mechanism*
- *CKM* mechanism desribes the relation between the weak and the mass eigenstates of quarks
- *CKM* mechanism expressed through a complex, unitary 3×3 matrix

CKM Matrix

$$\begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\text{weak}} = V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\text{mass}} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\text{mass}}$$

Vij : quark flavor transition couplings

CKM **mechanism not enough to explain all the missing antimatter**

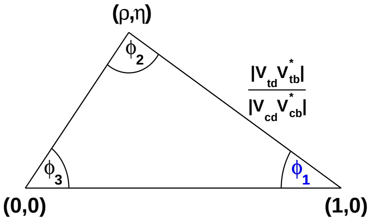
CP Violation in the Standard Model

Wolfenstein parametrisation

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$\lambda = \sin\theta_C \approx 0.22$, θ_C: Cabibbo angle

4 free parameters: 3 mixing angles and 1 complex phase



CKM matrix is unitary

$$\Rightarrow \underbrace{V_{ud}\cdot V^*_{ub}}_{\mathcal{O}(\lambda^3)} + \underbrace{V_{cd}\cdot V^*_{cb}}_{\mathcal{O}(\lambda^3)} + \underbrace{V_{td}\cdot V^*_{tb}}_{\mathcal{O}(\lambda^3)} = 0$$

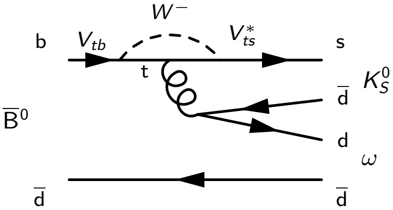
relevant for the B meson system

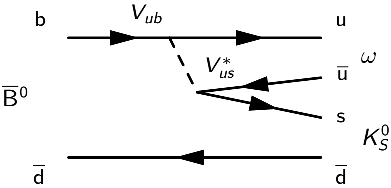
Sides with similar size $\Rightarrow$ large angles, precise determination of the observables (3 angles and 2 sides) possible

problem over-constrained $\Rightarrow$ leaves room for New Physics

Decays via charmless $b \to sq\bar{q}$ (like $B^0 \to \omega K^0_S$) transitions sensitive to ϕ_1

The Decay $B^0 \to \omega K_S^0$





Matrix elements for the two Feynman diagrams

- $M_{tree} \propto V_{ub} \cdot V_{us}^* \propto \lambda^3 \cdot \lambda \propto \lambda^4$
- $M_{peng} \propto V_{tb} \cdot V_{ts}^* \propto 1 \cdot \lambda^2 \propto \lambda^2$

$\Rightarrow$ Decay is dominated by the penguin contribution

Measurement of

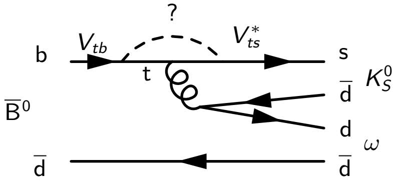
The branching fraction $\mathcal{BR}(B^0 \to \omega K_S^0)$

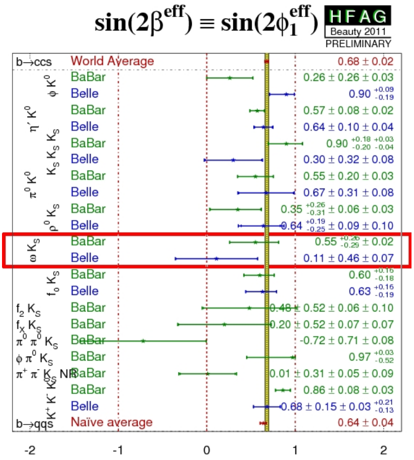
The CP parameters $\mathcal{A}_{\mathcal{CP}}$ and $\mathcal{S}_{\mathcal{CP}} = \sin \phi_1^{eff}$ (pollution from the tree diagram)

Physical Motivation

Why exactly the decay $B^0 \to \omega K_S^0$?

- Theory predicts in the Standard Model that $\sin 2\phi_1^{\mathrm{eff}}$ from $b \to sq\bar{q}$ should be larger than for $b \to c\bar{c}s$ $(\sin 2\phi_1^{\mathrm{eff}} - \sin 2\phi_1 \ \epsilon \ (0.0; 0.2))$
- But the measurement may be systematically lower, giving a hint of New Physics
- Could be caused by unknown new particle in the loop carrying different weak phase
- Leads to a measured shift from $\sin 2\phi_1$





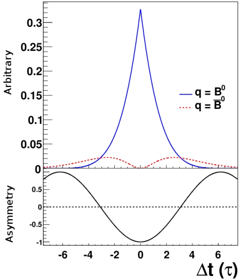
CP Violation in the B Meson System

Time-dependent CP asymmetry

$$a_{CP}(\Delta t, f_{CP}) = \frac{N_{\overline{B}^0}(\Delta t, f_{CP}) - N_{B^0}(\Delta t, f_{CP})}{N_{\overline{B}^0}(\Delta t, f_{CP}) + N_{B^0}(\Delta t, f_{CP})} = \mathcal{A}_{CP}\cos(\Delta m \Delta t) + \mathcal{S}_{CP}\sin(\Delta m \Delta t)$$

$\mathcal{A}_{CP}$ measure for the direct CP violation

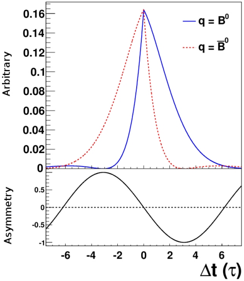
$B^0 \to f_{CP} \neq \overline{B}^0 \to f_{CP}$



$\mathcal{A}_{CP} = 1$
$\mathcal{S}_{CP} = 0$

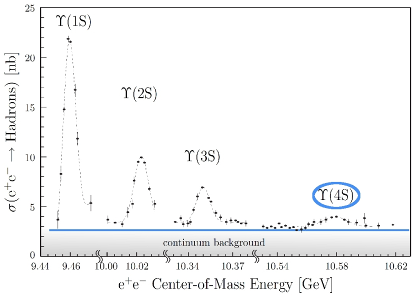
$\mathcal{S}_{CP}$ measure for the indirect CP violation

$B^0 \to \overline{B}^0 \to f_{CP} \neq \overline{B}^0 \to B^0 \to f_{CP}$



$\mathcal{A}_{CP} = 0$
$\mathcal{S}_{CP} = 1$

CP Violation Measurement



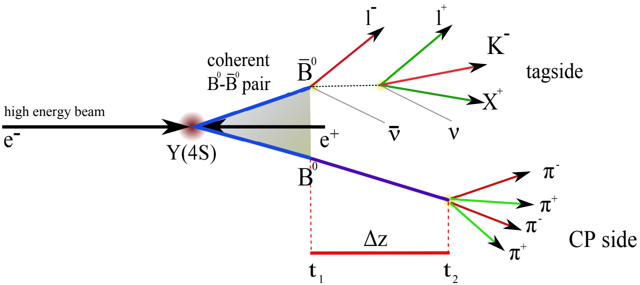
$$
\begin{aligned}
m_{\Upsilon(4S)} &= 10.58\,\mathrm{GeV/c^2} \approx 2 \times m_B \\
m_B &= 5.28\,\mathrm{GeV/c^2}
\end{aligned}
$$

B Meson production

- $\Upsilon(4S)$ resonance decays almost exclusively into a $B^0\overline{B}^0$ pair
- $\Upsilon(4S)$: $J^{PC} = 1^{--}$
  B: $J^{PC} = 0^{--}$

$\Rightarrow$ B meson pair in a p-wave
$\Rightarrow$ asymmetric wave function
$\Rightarrow$ B mesons have opposite flavour
$B^0\overline{B}^0$ pair coherent

CP Violation Measurement



B^0 or $\overline{\mathrm{B}}^0$?

$\rightarrow$ Look at the other B (tag-side):

If $l^- \Rightarrow \overline{\mathrm{B}}^0$ on the tag-side and B^0 on the CP-side

If $l^+ \Rightarrow \mathrm{B}^0$ on the tag-side and $\overline{\mathrm{B}}^0$ on the CP-side

Δt measurement

Asymmetric beam energies at the Belle experiment:

$E_{e^-} = 8\,\mathrm{GeV}$, $E_{e^+} = 3.5\,\mathrm{GeV}$

$\Rightarrow$ Boost in the center of mass system

Measurement of $\Delta z \sim 100\,\mu\mathrm{m}$ instead of $\Delta t \sim \mathrm{ps}$

Obtain $\Delta t = \Delta z / c\langle\beta\gamma\rangle$

Approach

Goal 1: Determination of $\mathcal{BR}(B^0 \to \omega K_S^0)$, $\mathcal{A}_{CP}$ and $\mathcal{S}_{CP}$
Goal 2: Minimize the statistical and and systematic uncertainties

Approach to Goal 1

- Build an algorithm to reconstruct $\mathcal{BR}(B^0 \to \omega K_S^0)$
- Study the different backgrounds
- Build a model to separate the signal from the background (multidimensional fit)
- Test the model

So far: “Blind Analysis“. Study only from Monte Carlo (MC) samples

- Apply model to the real data
- Determine $\mathcal{BR}(B^0 \to \omega K_S^0)$, $\mathcal{A}_{CP}$ and $\mathcal{S}_{CP}$ and the uncertainties

Approach to Goal 2

- Improve the models of the previous analysis
- Use the full available data of Belle (accelerator shut down in June 2010)

Prevoius Measurements of $B^0 \to \omega K_S^0$

	$B^0\overline{B}^0$-pairs	$\mathcal{BR}(B^0 \to \omega K_S^0)$	$\mathcal{A}_{CP}$	$\mathcal{S}_{CP}$
Belle	388×10^6	$(4.4^{+0.8}_{-0.7} \pm 0.4) \times 10^{-6}$	-	-
Belle	657×10^6	-	$-0.09 \pm 0.29 \pm 0.06$	$0.11 \pm 0.46 \pm 0.07$
BaBar	535×10^6	$(5.4 \pm 0.8 \pm 0.3) \times 10^{-6}$	$-0.52^{+0.22}_{-0.20} \pm 0.03$	$0.55^{+0.26}_{-0.29} \pm 0.02$

Challenging analysis

- $\mathcal{BR}(B^0 \to \omega K_S^0) \sim 10^{-6}$ small
- Large background contribution from $q\bar{q}$ background

Our method

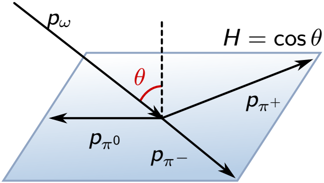
- Use loose cuts on the observables to collect maximum signal
- Multidimensional fit to the observables including the event shape to separate signal and background

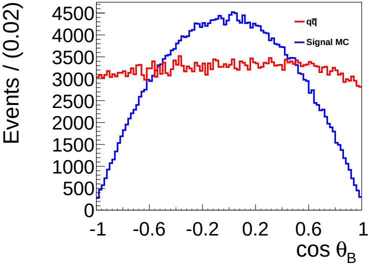
Measurement of $\mathcal{BR}(B^0 \to \omega K^0_S)$

Extract $\mathcal{BR}(B^0 \to \omega K^0_S)$ by a 6D extended unbinned maximum likelihood fit
Fit variables: ΔE, $\mathcal{F}_{\mathrm{B\bar{B}/q\bar{q}}}$, $m_{3\pi}$, $\mathcal{H}_{3\pi}$, q, Δt

$\Delta E = E_{B_{\mathrm{rec}}} - E_{\mathrm{beam}}$
$\mathcal{F}_{\mathrm{B\bar{B}/q\bar{q}}}$ Fisher discriminant, event-shape dependent
$q = 1$ for B^0 and $q = -1$ for $\overline{\mathrm{B}}^0$
New in this analysis: $\mathcal{H}_{3\pi}$, powerful observable for background discrimination

Multidimensional analysis $\Rightarrow$ model for signal and background necessary





Toy MC studies for $B^0 \to \omega K^0_S$

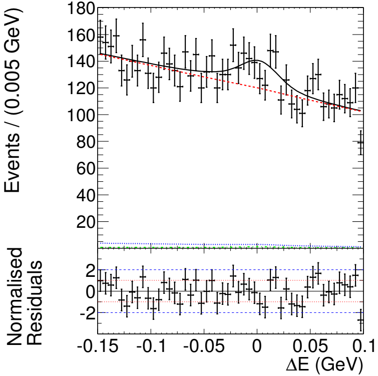
Test the model with Toy MC

Expected number of events

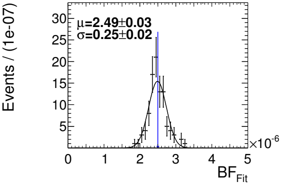
signal $\sim$ 230

$q\bar{q} \sim$ 5300

$B\bar{B} \sim$ 130



Expectations for $\mathcal{B}(B^0 \to \omega K_S)$



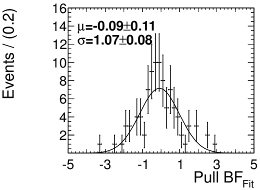
Uncertainty 9.2%

Error scaled to final data sets

Belle (previous): 13% , BaBar: 13%

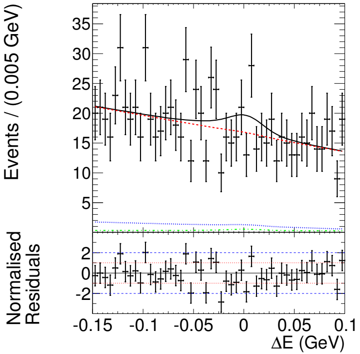
$\Rightarrow$ Our method is better

Pull distribution of $\mathcal{B}(B^0 \to \omega K_S)$



No bias, correct error estimation

Results from the Fit to the Data



Black: Full PDF

Total background

$B\bar{B}$ background

Preliminary Result from $135 \times 10^6 B\bar{B}$ Pairs

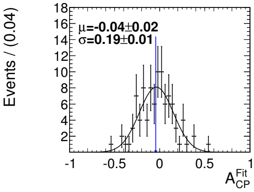
$\mathcal{B}(B^0 \to \omega K^0) = [4.94^{+1.28}_{-1.14}] \times 10^{-6}$

World average

$\mathcal{B}(B^0 \to \omega K^0) = [5.0 \pm 0.6] \times 10^{-6}$

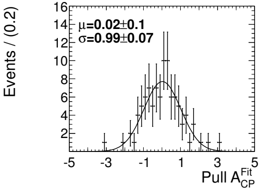
Toy MC studies for $\mathcal{A}_{CP}$ and $\mathcal{S}_{CP}$

Expectations for $\mathcal{A}_{CP}$



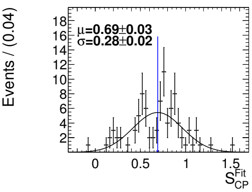
Uncertainty ± 0.19
Error scaled to final data set
Belle (previous): ± 0.24, BaBar: ± 0.20

Pull distribution of $\mathcal{A}_{CP}$



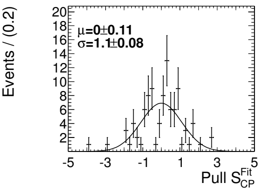
No bias, correct error estimation

Expectations for $\mathcal{S}_{CP}$



Uncertainty ± 0.28
Error scaled to final data set
Belle (previous): ± 0.38, BaBar: ± 0.26

Pull distribution of $\mathcal{S}_{CP}$



No bias, correct error estimation

Summary and outlook

Outlook:

Find a way to add $M_{\rm bc}$ to the fit $\Rightarrow$ 7D fit

Further reduce the uncertainties by performing a simultaneous 7D fit to the charged decay with the same kinematics $B^+ \to \omega K^+$

- The decay $B^0 \to \omega K_S^0$ can provide us with knowledge of New Physics
- We have built a model which will provide better results than the previous Belle analysis
- The method is about be improved even to further reduce the statistical and systematic uncertainties for $\mathcal{A}_{CP}$ and $\mathcal{S}_{CP}$
- With this improvement the results from this analysis will dominate the world average for $\mathcal{A}_{CP}$ and $\mathcal{S}_{CP}$ and $\mathcal{BR}(B^0 \to \omega K_S^0)$

Thank you
for your attention