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

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Young Scientist Workshop in Ringberg
July 24th, 2012

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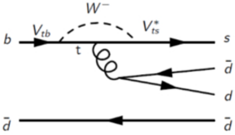
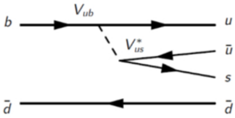
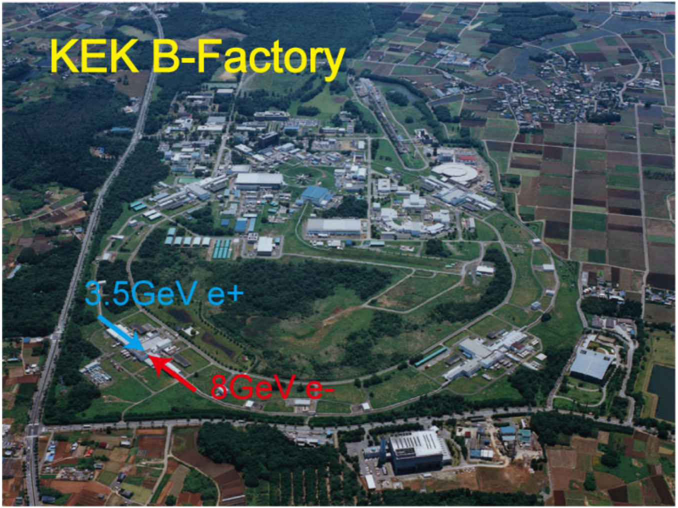
BELLE

Physics at Belle





Belle? Never heard of it...

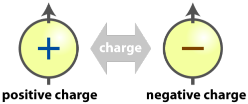


Standard Model is successful but incomplete

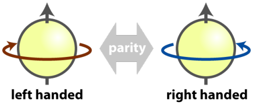
- Cannot explain Dark Matter
- Assumes that neutrinos are massless
- Insufficient explanation of the matter-antimatter asymmetry in the Universe today

To explain the matter-antimatter asymmetry **CP violation** is needed (Sakharov conditions)

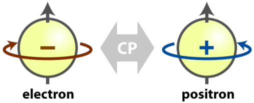
Charge conjugation



Parity transformation



CP transformation = Charge conjugation × Parity transformation



- CP violation in the Standard Model: Cabbibo-Kobayashi-Maskawa (CKM) mechanism
- CKM complex, unitary 3×3 matrix describes the relation between the weak and the mass eigenstates of quarks

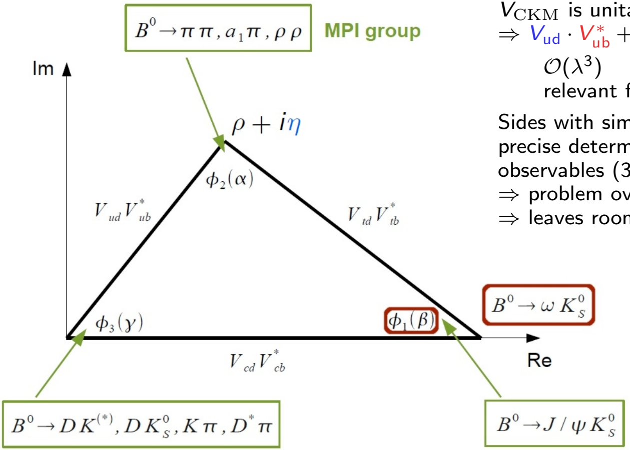
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_{\text{weak}} = V_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\text{mass}} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\text{mass}}$$

V_{ij} : quark flavour transition couplings

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

V_{CKM}: 4 free parameters (3 Euler angles and a complex phase)
$\lambda = \sin\theta_C \approx 0.22$, θ_C: Cabibbo angle
CP violation when $\eta \neq 0$

Unitarity triangle in the B meson system



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

V_{CKM} is unitary

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

$\mathcal{O}(\lambda^3)$ $\mathcal{O}(\lambda^3)$ $\mathcal{O}(\lambda^3)$

relevant for the B meson system

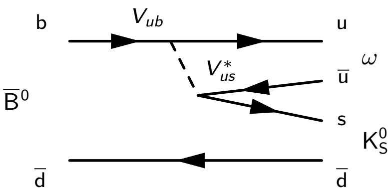
Sides with similar size $\Rightarrow$ large angles, precise determination of the observables (3 angles and 2 sides)
$\Rightarrow$ problem over-constrained
$\Rightarrow$ leaves room for New Physics

- Measurement of the angles and the sides of the unitarity triangle → access to its area
- Amount of CP violation ∝ area of the unitary triangle
- CP violation predicted by the SM not enough to explain the matter-antimatter asymmetry

⇒ **New Physics required!**

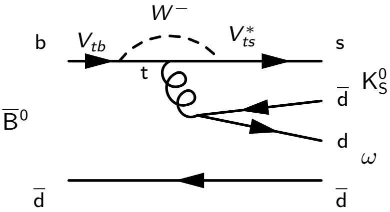
- New Physics could be found in B meson decays dominated by penguin Feynman diagrams
- New Physics enters the scene in the form of new particles in the loop
- Such are decays via $b \to s q \bar{q}$ transitions, such as $B^0 \to \omega K_S^0$

Tree diagram



$A_{\mathrm{tree}} \propto V_{\mathrm{ub}} \cdot V_{\mathrm{us}}^* \propto \lambda^3 \cdot \lambda \propto \lambda^4$

Penguin diagram

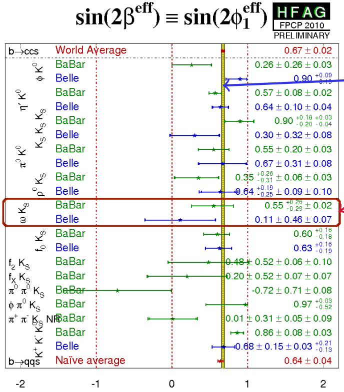


$A_{\mathrm{peng}} \propto V_{\mathrm{tb}} \cdot V_{\mathrm{ts}}^* \propto 1 \cdot \lambda^2 \propto \lambda^2$

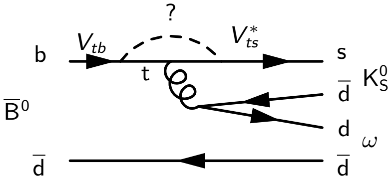
$\Rightarrow$ **Decay is dominated by the penguin contribution**

Physical Motivation

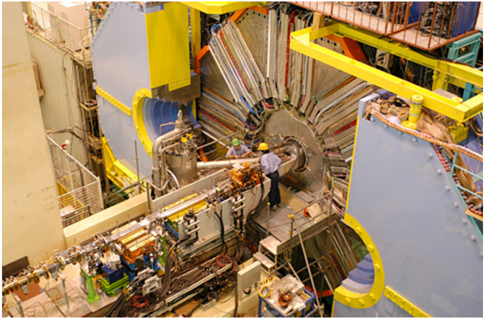
Why is the decay $B^0 \to \omega K^0_S$ so awesome?



- The SM predicts that $\sin 2\phi_1^{\mathrm{eff}}$ from $b \to s q\bar{q}$ should be larger than from $b \to c\bar{c}s$ ($B^0 \to J/\psi K^0_S$)
- Experiment: measurements for $B^0 \to \omega K^0_S$ tend to be lower!
- This discrepancy could be caused by unknown new particle in the loop



Capturing the Physics



NOT showing the ATLAS detector here

How to access the angle ϕ_1 from the decay $B^0 \to \omega K^0_S$?

- Decay $B^0 \to \omega K^0_S$ - a CP final state f_{CP}
- We measure number of events - N_{B^0} and $N_{\overline{B}0}$ decaying into f_{CP} in a certain period of time Δt
- $a_{CP}(\Delta t, f_{CP})$: Time-dependent CP asymmetry

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

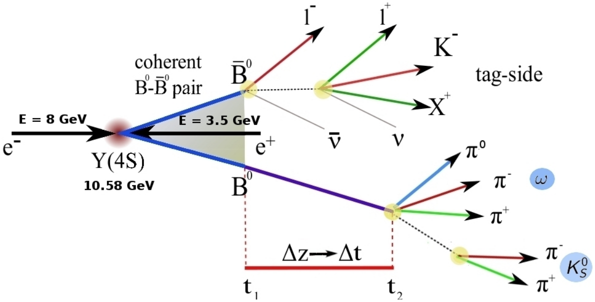
$\mathcal{A}_{CP}$: measure for the direct *CP* violation

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

$\mathcal{S}_{CP}$: measure for the mixing induced *CP* violation

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

$$\mathcal{S}_{CP} = \sin 2\phi_1$$



We need N_{B^0} and $N_{\overline{\mathrm{B}}^0}$ decaying into $\mathrm{B}^0 \rightarrow \omega \mathrm{K}_S^0$ in a certain period of time Δt

N_{B^0} and $N_{\overline{\mathrm{B}}^0}$: 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 KEKB
$\Rightarrow$ Boost of the center of mass system
Measurement of $\Delta z \sim 100\,\mu\mathrm{m}$ instead of $\Delta t \sim \mathrm{ps}$
Obtain $\Delta t = \Delta z / c\langle\beta\gamma\rangle$

We have the data, now what?

→ Start of the analysis

Belle's analysis recipy

Ingredients:

240 signal events

360 background events from other B decays

17000 background events from u, d, s, c quark decays

7 fit variables

Preparation (blind):

- Develop an algorithm to reconstruct $B^0 \to \omega K^0_S$
- Study the shape of the signal and the backgrounds
- Build a 7D multidimensional fit to discriminate signal and background
- Test the performance of the fit (bias?)

Preparation (with real data):

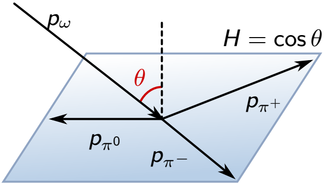
- Apply your 7D fit to the data
- Fit result: $\mathcal{A}_{CP}$ $\mathcal{S}_{CP}$ $N(B^0 \to \omega K^0_S)$
- Perform systematic studies

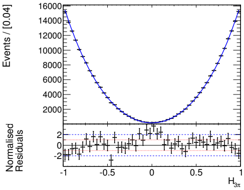
Extract $N(\mathrm{B}^0 \to \omega K_\mathrm{S})$, $\mathcal{A}_\mathrm{CP}$ and $\mathcal{S}_\mathrm{CP}$ from a 7D extended unbinned maximum likelihood fit

Fit observables

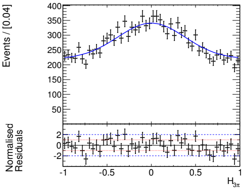
- $\Delta E = E_{B_\mathrm{rec}}^\mathrm{CMS} - E_\mathrm{beam}^\mathrm{CMS}$
- M_bc: beam-constrained mass of the B meson, $M_\mathrm{bc} = \sqrt{(E_\mathrm{beam}^\mathrm{cms})^2 - (p_\mathrm{B}^\mathrm{cms})^2}$
- $\mathcal{F}_{\mathrm{B\bar{B}/q\bar{q}}}$: Fisher discriminant, event-shape dependent
- $m_{3\pi}$: mass of the reconstructed ω candidates
- $\mathcal{H}_{3\pi}$: helicity of the reconstructed ω candidates
- Δt: time difference between the two B decays
- $q = 1$ for B^0 and $q = -1$ for $\overline{\mathrm{B}}^0$

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





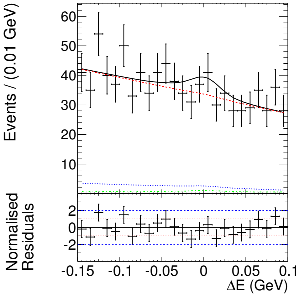
$\mathcal{H}_{3\pi}$ Signal



$\mathcal{H}_{3\pi}$ $\mathrm{q\bar{q}}$ bkg

Results from the Fit to the Data

Projection of
$\Delta E = E^{\mathrm{CMS}}_{B_{\mathrm{rec}}} - E^{\mathrm{CMS}}_{\mathrm{beam}}$



Black: Full PDF
Total background
$B\overline{B}$ background

Partial box opening with 152×10^6 $B\overline{B}$ pairs
(Full statistics: 772×10^6 $B\overline{B}$ pairs)
Unbinned maximum likelihood fit to 6 observables

Preliminary Result from 152×10^6 $B\overline{B}$ pairs

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

$\tau_{B^0} = [1.522 \pm 0.35(\mathrm{stat})]\,\mathrm{ps}$ (cross-check)

- Belle 388×10^6 $B\overline{B}$ pairs
  $\mathcal{BR}(B^0 \to \omega K^0) = [4.4^{+0.8}_{-0.7} \pm 0.4] \times 10^{-6}$
- World average
  $\mathcal{BR}(B^0 \to \omega K^0) = [5.0 \pm 0.6] \times 10^{-6}$
  $\tau_{B^0} = [1.519 \pm 0.007]\,\mathrm{ps}$

Conclusion

- The decay $B^0 \to \omega K^0_S$ is sensitive to the angle ϕ_1
- Deviations in the measured value of ϕ_1 could be a hint at New Physics
- So far, the analysis method is providing us with better results than the previous Belle analysis
- The analysis method is being improved in order to reduce the uncertainties of the measurement

Thank you
for your attention

Backup

Previous Measurements of $B^0 \to \omega K^0_S$

	$B\overline{B}$-pairs	$\mathcal{BR}(\mathbf{B^0} \to \boldsymbol{\omega} \mathbf{K^0})$	$\mathcal{A}_{CP}$	$\mathcal{S}_{CP}$
Belle	388×10^6	$(4.4^{+0.8}_{-0.7} \pm 0.4) \times 10^{-6}$[1]	-	-
Belle	535×10^6	-	$-0.09 \pm 0.29 \pm 0.06$	$0.11 \pm 0.46 \pm 0.07$[2]
BaBar	467×10^6	$(5.4 \pm 0.8 \pm 0.3) \times 10^{-6}$	$0.52^{+0.22}_{-0.20} \pm 0.03$	$0.55^{+0.26}_{-0.29} \pm 0.02$ [3]

Full data set of Belle 772×10^6 $\mathbf{B\overline{B}}$ **pairs**

[1] PhysRevD.74.111101

[2] PhysRevD.76.091103

[3] PhysRevD.79.052003

Challenging analysis

- $\mathcal{BR}(B^0 \to \omega K^0) \sim 10^{-6}$ (small)
- Large background contribution from $q\overline{q}$ (u, d, s, c) background

Our method

- Use loose cuts on the observables for maximum signal sensitivity
- Multidimensional fit to the modelled probability density functions to extract $\mathcal{BR}(B^0 \to \omega K^0)$, $\mathcal{A}_{CP}$, $\mathcal{S}_{CP}$ and their uncertainties

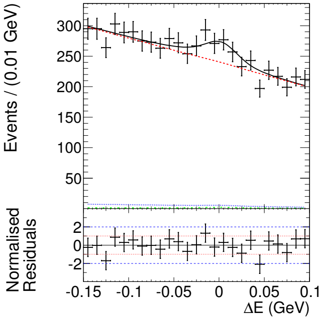
Toy MC studies

Test the model with Toy MC
Expected number of events

signal $\sim$ 230

$q\bar{q}$ $\sim$ 5300

$B\overline{B}$ $\sim$ 130



Projection of
$\Delta E = E^{\mathrm{CMS}}_{B_{\mathrm{rec}}} - E^{\mathrm{CMS}}_{\mathrm{beam}}$

Full data set of Belle: 772×10^6 $B\overline{B}$ pairs

Expectations for the statistical uncertainty of:

- $\mathcal{BR}(B^0 \to \omega K^0)$

BaBar (final)	Belle (previous)	Belle (current)
13% *	13% **	9.2% **

- $\mathcal{A}_{CP}$

BaBar (final)	Belle (previous)	Belle (current)
0.20 *	0.24 **	0.19 **

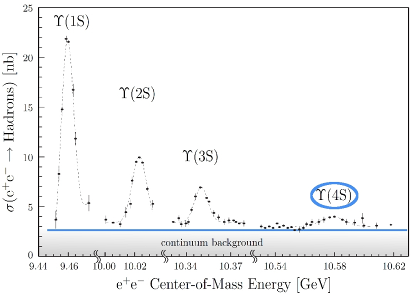
- $\mathcal{S}_{CP}$

BaBar (final)	Belle (previous)	Belle (current)
0.26 *	0.38 **	0.28 **

* Final result of BaBar
** Scaled to the full data set of Belle

$\Rightarrow$ **Our method is better than the previous Belle analysis**

CP Violation Measurement



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

B Meson production

- $\Upsilon(4S)$ resonance decays almost exclusively into a $B\bar{B}$ 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 have opposite flavour
$\mathrm{B\overline{B}}$ pair coherent

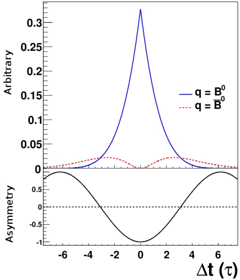
CP Violation in the *B* Meson System

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

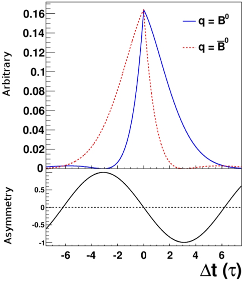
$B^0 \to f_{CP} \neq \overline{B}^0 \to f_{CP}$



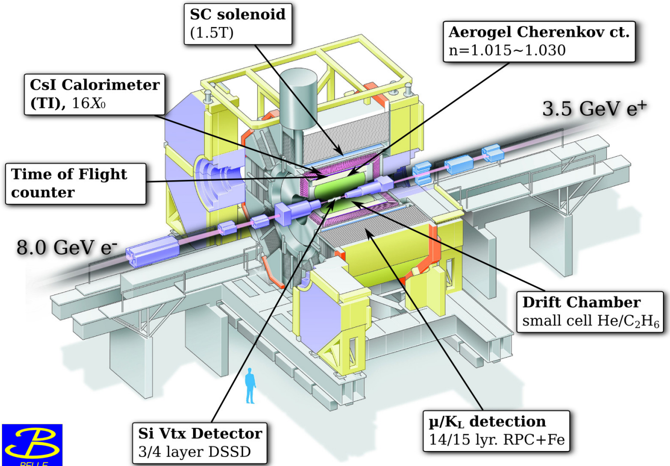
$\mathcal{A}_{CP} = 1$
$\mathcal{S}_{CP} = 0$

$\mathcal{S}_{CP}$ measure for the mixing induced *CP* violation

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



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


SC solenoid
(1.5T)
Aerogel Cherenkov ct.
n=1.015~1.030
CsI Calorimeter
(TI), $16X_0$
3.5 GeV e+
Time of Flight
counter
8.0 GeV e-
Drift Chamber
small cell He/C_2H_6
μ/K_L detection
14/15 lyr. RPC+Fe
Si Vtx Detector
3/4 layer DSSD

Toy MC Study

Toy MC Study

100 pseudo-experiments generated:
907 events for SVD1 and 5554 events for SVD2

	N_{Sig}	$N_{\mathrm{q\bar{q}}}$	$N^{\mathrm{Charm}}_{\mathrm{B^0\overline{B}0}}$	$N^{\mathrm{Charm}}_{\mathrm{B^+B^-}}$	$N^{\mathrm{Charmless}}_{\mathrm{B^0\overline{B}0}}$	$N^{\mathrm{Charmless}}_{\mathrm{B^+B^-}}$	$N^{\mathrm{PB,\,Charm}}_{\mathrm{B^0\overline{B}0}}$	N_{Mis}
# SVD1	37	849	4	4	4	3	6	0
# SVD2	196	5241	12	28	25	19	31	2

$N_{\mathrm{Sig}} = \mathcal{B}(B^0 \to \omega K^0_S) \sum_i (N^i_{\mathrm{B\bar{B}}} \epsilon^i_{\mathrm{Rec}} \eta^i)$, $i =$ [SVD1, SVD2],
$\mathcal{B}(B^0 \to \omega K^S_0) = 2.5 \cdot 10^{-6}$

Free parameters in the fit

- $\mathcal{BR}(B^0 \to \omega K^0_S)$, $\mathcal{A}_{CP}$ and $\mathcal{S}_{CP}$
- $N^{1,2}_{\mathrm{q\bar{q}}}$
- $N^{\mathrm{Charm;1,2}}_{\mathrm{B^0\overline{B}0}}$
- ΔE slope for $q\bar{q}$, $C^{1,2}_{q\bar{q}}(\Delta E)$

Toy MC studies for $B^0 \to \omega K_S^0$

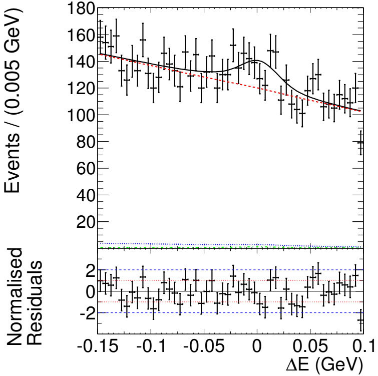
Test the model with Toy MC

Expected number of events

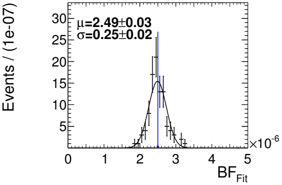
signal ~ 230

$q\bar{q} \sim 5300$

$B\overline{B} \sim 130$



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



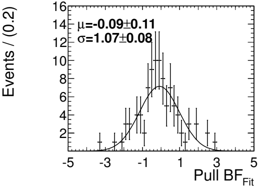
Uncertainty 9.2%

Error scaled to final data sets

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

$\Rightarrow$ Our method is better

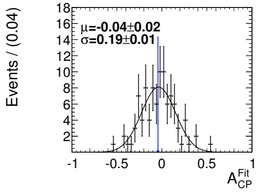
Pull distribution of $\mathcal{BR}(B^0 \to \omega K^0)$



No bias, correct error estimation

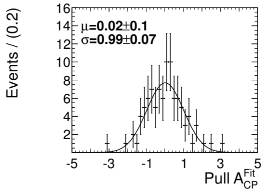
Toy MC studies for $\mathcal{A}_{\mathcal{CP}}$ and $\mathcal{S}_{\mathcal{CP}}$

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



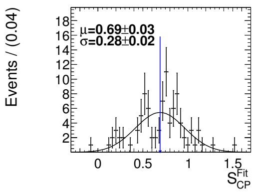
Uncertainty ± 0.19
Error scaled to final data set
Belle (previous): ± 0.24, BaBar: ± 0.20

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



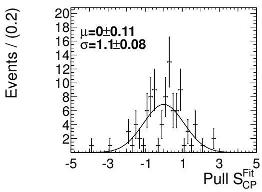
No bias, correct error estimation

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

B Reconstruction

$B^0 \to \omega K_S$, $\omega \to \pi^+\pi^-\pi^0$

General selection criteria for the reconstruction

π^+ **candidates**

- $L_{K/\pi} < 0.9$ in order to remove tracks consistent with kaon hypothesis

π^0 **candidates**

- $118\ MeV/c^2 < m(\gamma\gamma) < 150\ MeV/c^2$, mass fit $\chi^2 < 50$
- $E_\gamma > 50\ MeV$ in ECL barrel, $E_\gamma > 100\ MeV$ in ECL endcap

K_S **candidates**

- "Good K_S" cut
- $0.482\ GeV/c^2 < m(\pi^+\pi^-) < 0.514\ GeV/c^2$ $(m(K_S) \pm 16\ MeV))$

ω **candidates**

- $0.73\ GeV/c^2 < m(\pi^+\pi^-\pi^0) < 0.83\ GeV/c^2$ $(m(\omega) \pm 50\ MeV))$

B Reconstruction

B^0 candidates

- $M_{\rm bc} > 5.27\ GeV/c^2$ and -0.15 $GeV < \Delta E < 0.1\ GeV$
- Best B selection: best $M_{\rm bc} = \sqrt{(E_{beam}^{cms})^2 - (p_B^{cms})^2}$

Reconstruction efficiency: 13.2% for SVD1 and 16.8% for SVD2
Misreconstruction fraction: 2.3% for SVD1 and 2.4% for SVD2
$\sim$ 230 events expected (118 for previous analysis)

Fit to ΔE, $\mathcal{F}_{\rm B\bar{B}/q\bar{q}}$, $m_{3\pi}$, $\mathcal{H}_{3\pi}$, Δt, q

Fit region:

- $-0.15\,\rm GeV < \Delta E < 0.1\,GeV$
- $-2 < \mathcal{F}_{\rm B\bar{B}/q\bar{q}} < 2$
- $0.73\,\rm GeV/c^2 < m_{3\pi} < 0.83\,GeV/c^2$
- $-1 < \mathcal{H}_{3\pi} < 1$
- $-70\,\rm ps < \Delta t < 70\,ps$