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

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BELLE

Content

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

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

V_{ij} : quark flavour transition couplings

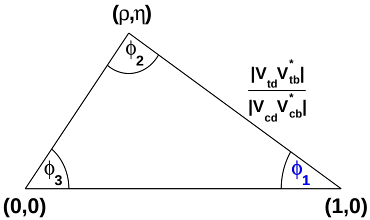
***CKM* mechanism not enough to explain the matter dominance**
$\Rightarrow$ New Physics beyond the Standard Model is needed

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



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

ϕ_1 most precisely measured from $b \to c\bar{c}s$ transitions ("Golden channel" $B^0 \to J/\psi K^0_S$)
Decays via charmless $b \to sq\bar{q}$ (like $B^0 \to \omega K^0_S$) transitions sensitive to ϕ_1

The Decay $B^0 \to \omega K^0_S$

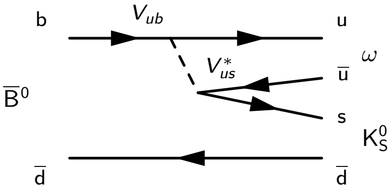
$B^0 \to \omega K^0_S$

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

$K^0_S \to \pi^+\pi^-$

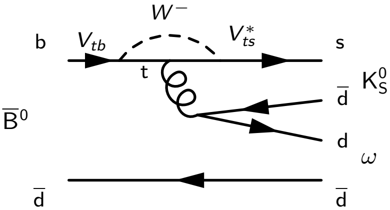
$B^0 \to \omega K^0_S$ sensitive to ϕ_1
$B^0 \to \omega K^0_S$ is a *CP* final state

Tree diagram



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

Penguin diagram



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

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

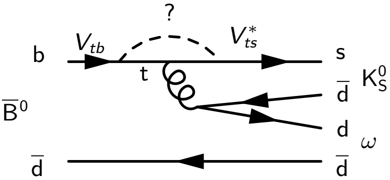
Measurement of

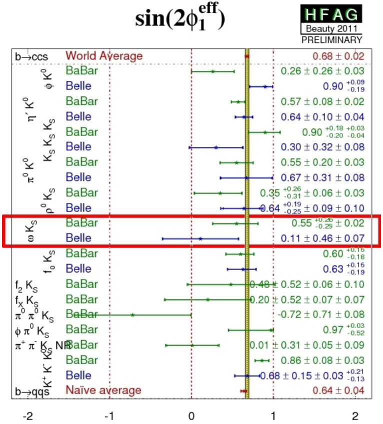
- The branching fraction $\mathcal{BR}(B^0 \to \omega K^0)$
- The *CP* parameters $\mathcal{A}_{CP}$ and $\mathcal{S}_{CP} \propto \sin 2\phi_1^{\rm eff}$ (tree diagram pollution)

Physical Motivation

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

- The Standard Model predicts that $\sin 2\phi_1^{\text{eff}}$ from $b \to sq\bar{q}$ should be larger than from $b \to c\bar{c}s$ ($B^0 \to J/\psi K^0_S$): $\sin 2\phi_1^{\text{eff}} - \sin 2\phi_1 \in (0.0; 0.2)$
- Measurements from penguin may be systematically lower (hint at New Physics?)
- Could be caused by unknown new particle in the loop carrying different weak phase
- Leads to a shift from $\sin 2\phi_1$



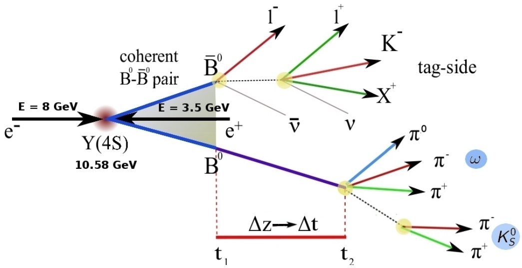


CP Violation in the *B* Meson System

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
$B^0 \to f_{CP} \neq \overline{B}^0 \to f_{CP}$
$\mathcal{S}_{CP}$: measure for the mixing induced *CP* violation
$B^0 \to \overline{B}^0 \to f_{CP} \neq \overline{B}^0 \to B^0 \to f_{CP}$



B^0 or $\overline{B}^0$?
→ Look at the other *B* (tag-side):
If $l^- \Rightarrow \overline{B}^0$ on the tag-side and B^0 on the *CP*-side
If $l^+ \Rightarrow B^0$ on the tag-side and $\overline{B}^0$ on the *CP*-side

Δt measurement
Asymmetric beam energies at KEKB
⇒ Boost of the center of mass system
Measurement of $\Delta z \sim 100\,\mu$m instead of $\Delta t \sim$ ps
Obtain $\Delta t = \Delta z / c\langle\beta\gamma\rangle$

Approach

Goals

Study new methods to measure $\mathcal{BR}(B^0 \to \omega K^0)$, $\mathcal{A}_{CP}$ and $\mathcal{S}_{CP}$ and minimize the statistical and and systematic uncertainties

Approach

- Build an algorithm to reconstruct $B^0 \to \omega K^0_S$
- Study the backgrounds ($q\bar{q}$, other B decays)
- Build an improved model to discriminate signal and background (multidimensional fit)
- Test the model

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

- Apply model to the real data
- Determine $\mathcal{BR}(B^0 \to \omega K^0)$, $\mathcal{A}_{CP}$ and $\mathcal{S}_{CP}$ and the uncertainties from the full data set of Belle

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

	$\mathbf{B\overline{B}}$-pairs	$\mathcal{BR}(\mathbf{B^0 \to \omega K^0})$	$\mathcal{A}_{CP}$	$\mathcal{S}_{CP}$
Belle	388×10^6	$(4.4^{+0.8}_{-0.7} \pm 0.4) \times 10^{-6}$[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]

[1] PhysRevD.74.111101

[2] PhysRevD.76.091103

[3] PhysRevD.79.052003

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

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

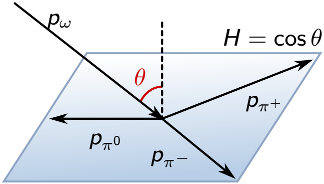
Measurement of $\mathcal{BR}(B^0 \to \omega K^0)$

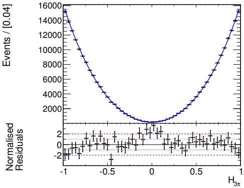
Extract $\mathcal{BR}(B^0 \to \omega K^0)$ by a 6D extended unbinned maximum likelihood fit

Fit observables

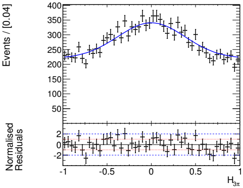
$\Delta E = E^{\mathrm{CMS}}_{B_{\mathrm{rec}}} - E^{\mathrm{CMS}}_{\mathrm{beam}}$
$\mathcal{F}_{\mathrm{B\bar{B}/q\bar{q}}}$: Fisher discriminant, event-shape dependent
$m_{3\pi}$: mass of the reconstructed 3π final state
Δt: time difference between the two B decays
$q = 1$ for B^0 and $q = -1$ for $\overline{B}^0$
New in this analysis: Helicity angles $\mathcal{H}_{3\pi}$, powerful observable for background discrimination

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





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



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

Toy MC studies

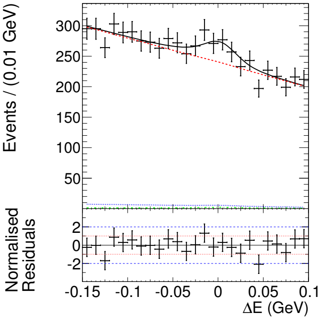
Test the model with Toy MC

Expected number of events

signal ~ 230

$q\bar{q} \sim 5300$

$B\bar{B} \sim 130$



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

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

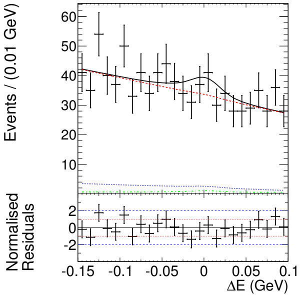
* Final result of BaBar

** Scaled to the full data set of Belle

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

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
  $\mathcal{BR}(B^0 \to \omega K^0) = [5.0 \pm 0.6] \times 10^{-6}$
  $\tau_{B^0} = [1.519 \pm 0.007]\,\mathrm{ps}$

Summary and outlook

Summary

- The decay $B^0 \to \omega K^0_S$ is sensitive to the angle ϕ_1. A possible deviation in the measurement of $\sin 2\phi_1$ could be a hint at New Physics
- We have built a model which improves the results than the previous Belle analysis
- Method was successfully applied to a subset of Belle's data

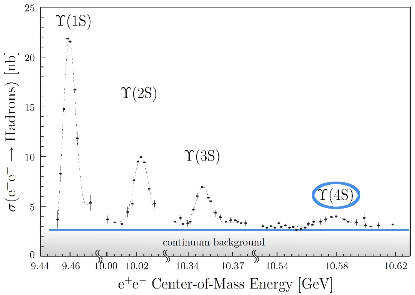
Outlook

- Add additional variables to the fit to improve the signal-background separation power
- Further reduce the systematic uncertainties by performing a simultaneous fit to the control sample $B^+ \to \omega K^+$ (same kinematics as $B^0 \to \omega K^0_S$)
- With this improvement the results from the full Belle statistics will dominate the world average for $\mathcal{A}_{CP}$ and $\mathcal{S}_{CP}$ and $\mathcal{BR}(B^0 \to \omega K^0)$
- But: Accuracy still too limited to challenge the Standard Model $\Rightarrow$ Belle II should provide more statistics for a precise measurement

Thank you
for your attention

Backup

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

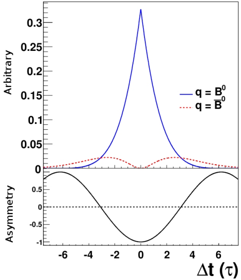
CP Violation in the B Meson System

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

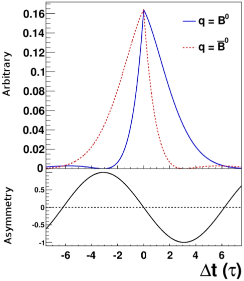
$B^0 \to f_{CP} \neq \overline{B}^0 \to f_{CP}$



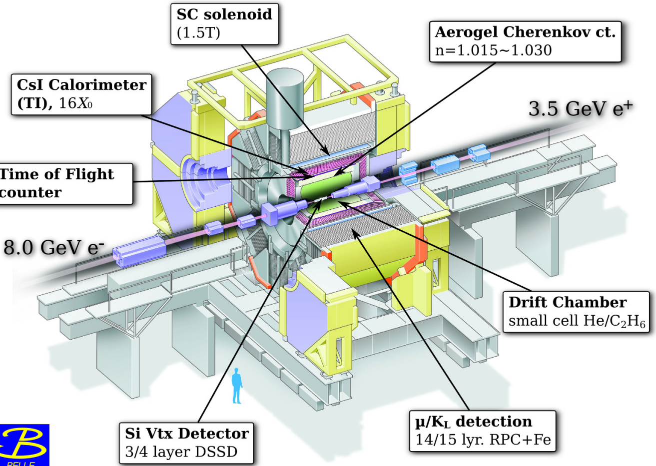
$\mathcal{A}_{CP} = 1$
$\mathcal{S}_{CP} = 0$

$\mathcal{S}_{CP}$ 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

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

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

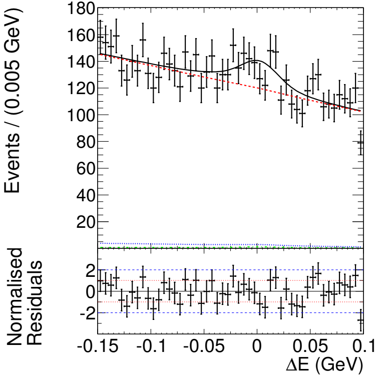
Test the model with Toy MC

Expected number of events

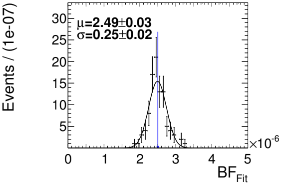
signal ~ 230

$q\bar{q} \sim 5300$

$B\bar{B} \sim 130$

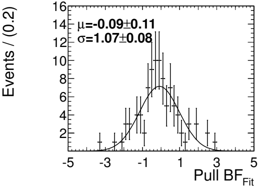


Expectations for $\mathcal{BR}(B^0 \to \omega K^0)$



Uncertainty 9.2%
Error scaled to final data sets
Belle (previous): 13% , BaBar: 13%
$\Rightarrow$ Our method is better

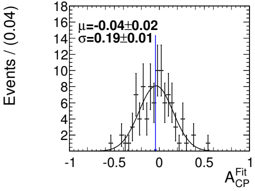
Pull distribution of $\mathcal{BR}(B^0 \to \omega K^0)$



No bias, correct error estimation

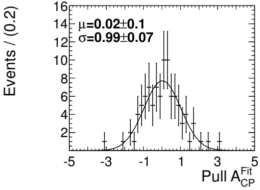
Toy MC studies for $\mathcal{A}_{CP}$ and $\mathcal{S}_{CP}$

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



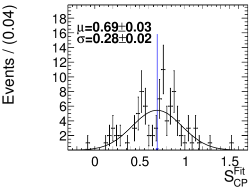
Uncertainty ± 0.19
Error scaled to final data set
Belle (previous): ± 0.24, BaBar: ± 0.20

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



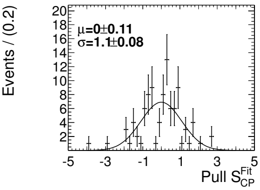
No bias, correct error estimation

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

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:

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

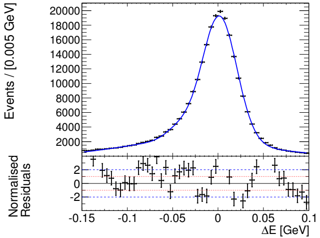
Signal Model

Signal Model

Signal model correlation matrix

	ΔE	$\mathcal{F}_{B\bar{B}/q\bar{q}}$	$m_{3\pi}$	$\mathcal{H}_{3\pi}$	Δt
ΔE	1	0.012	0.29	-0.003	0.007
$\mathcal{F}_{B\bar{B}/q\bar{q}}$		1	0.001	0.001	0.003
$m_{3\pi}$			1	-0.003	0.004
$\mathcal{H}_{3\pi}$				1	0.001
Δt					1

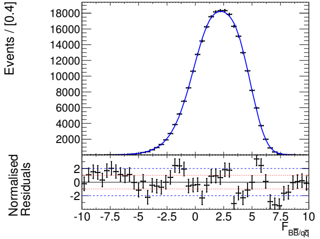
Signal MC ΔE and $\mathcal{F}_{B\bar{B}/q\bar{q}}$



ΔE signal MC

Triple Gaussian

$$\mathcal{P}_{\mathrm{Sig}}(\Delta E) = f_1 G(\Delta E;\, \mu_1,\, \sigma_1) + f_2 G(\Delta E;\, \mu_2,\, \sigma_2) + (1 - f_1 - f_2) G(\Delta E;\, \mu_3,\, \sigma_3)$$

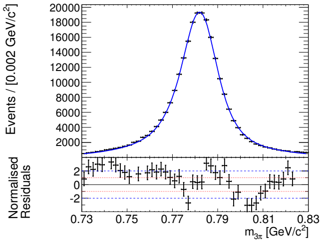


$\mathcal{F}_{\mathrm{B\bar{B}/q\bar{q}}}$ signal MC

Triple Gaussian in each r-bin l

$$\mathcal{P}_{\mathrm{Sig,l}}(\mathcal{F}_{\mathrm{B\bar{B}/q\bar{q}}}) = f_1 G(\mathcal{F}_{\mathrm{B\bar{B}/q\bar{q}}};\, \mu_{1,\mathrm{l}},\, \sigma_{1,\mathrm{l}}) + f_2 G(\Delta E;\, \mu_{2,\mathrm{l}},\, \sigma_{2,\mathrm{l}}) + (1 - f_1 - f_2) G(\Delta E;\, \mu_{3,\mathrm{l}},\, \sigma_{3,\mathrm{l}})$$

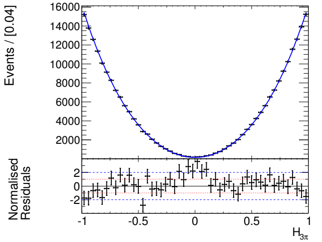
Signal MC $m_{3\pi}$ and $\mathcal{H}_{3\pi}$



$m_{3\pi}$ signal MC

Triple Gaussian

$$\mathcal{P}_{\rm Sig}(m_{3\pi}) = f_1 G(m_{3\pi};\, \mu_1,\, \sigma_1) + f_2 G(m_{3\pi};\, \mu_2,\, \sigma_2) + (1 - f_1 - f_2) G(m_{3\pi};\, \mu_3,\, \sigma_3)$$

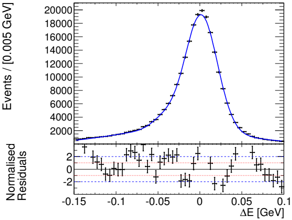


$\mathcal{H}_{3\pi}$ signal MC

4th order Chebyshev

$$\mathcal{P}_{\rm Sig}(\mathcal{H}_{3\pi}) = \sum_{i=0}^{4} c_i C_i(\mathcal{H}_{3\pi})$$

ΔE signal MC



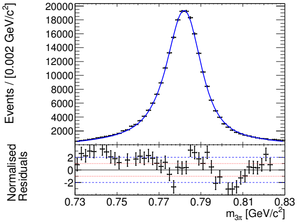
ΔE signal MC

$$\mathcal{P}_{\rm Sig}(\Delta E) = f_1 G(\Delta E;\, \mu_1,\, \sigma_1) + f_2 G(\Delta E;\, \mu_2,\, \sigma_2) + (1 - f_1 - f_2) G(\Delta E;\, \mu_3,\, \sigma_3)$$

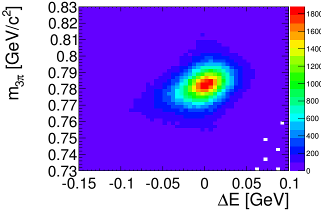
$$\mathcal{P}_{\rm Sig}(m_{3\pi}) = f_1 G(m_{3\pi};\, \mu_1,\, \sigma_1) + f_2 G(m_{3\pi};\, \mu_2,\, \sigma_2) + (1 - f_1 - f_2) G(m_{3\pi};\, \mu_3,\, \sigma_3)$$

Correlations modeled by

$\mu_1(m_{3\pi}) = \mu_0 + A \cdot \Delta E$ and
$\sigma_1(m_{3\pi}) = \sigma_0 + B \cdot \Delta E^2$

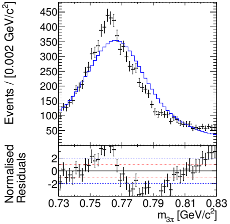


$m_{3\pi}$ signal MC

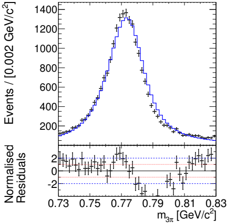


29% corr. between ΔE and $m_{3\pi}$

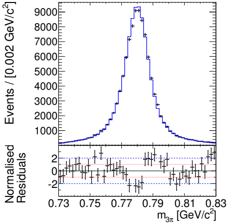
ω mass projection in bins of ΔE



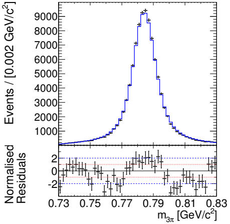
$-0.15\ GeV < \Delta E < -0.1\ GeV$



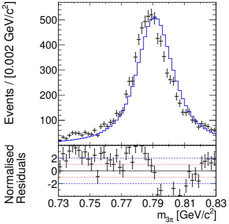
$-0.1\ GeV < \Delta E < -0.05\ GeV$



$-0.05\ GeV < \Delta E < 0.\ GeV$



$0.\ GeV < \Delta E < 0.05\ GeV$

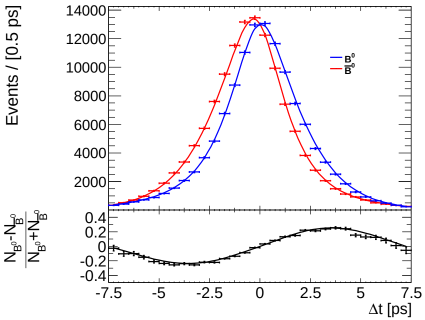


$0.05\ GeV < \Delta E < 0.1\ GeV$

$m_{3\pi}$ peak shifts to the right as ΔE increases

Width of $m_{3\pi}$ peak shrinks for small values of $|\Delta E|$

Model in the first and last bin may be good enough because very few (~ 10) events expected there



Δt signal MC

Input $\tau_{B^0} = 1.534\,\mathrm{ps}$
SVD1 $\tau_{B^0} = 1.522 \pm 0.006\,\mathrm{ps}$ (2σ from input)
SVD2 $\tau_{B^0} = 1.517 \pm 0.005\,\mathrm{ps}$ (3.4σ)

Input $\mathcal{A}_{CP} = 0$
SVD1 $\mathcal{A}_{CP} = -0.053 \pm 0.007$ (7.6σ)
SVD2 $\mathcal{A}_{CP} = -0.037 \pm 0.006$ (6.2σ)

Input $\mathcal{S}_{CP} = 0.689$
SVD1 $\mathcal{S}_{CP} = +0.697 \pm 0.010$ (0.8σ)
SVD2 $\mathcal{S}_{CP} = +0.690 \pm 0.008$ (0.1σ)

$$\mathcal{P}_{\mathrm{Sig}}(\Delta t, q) = (1 - f_{ol})\frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \cdot \left[1 - q\Delta w + q(1-2w)\Big(\mathcal{A}_{CP}\cos(\Delta m \Delta t) + \mathcal{S}_{CP}\sin(\Delta m \Delta t)\Big)\right] \otimes R_{B^0\bar{B}^0} + f_{ol}\mathcal{P}_{ol}$$

Continuum Model

Sideband

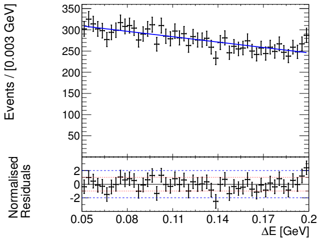
$$5.2\,\mathrm{GeV/c^2} < \mathrm{M_{bc}} < 5.25\,\mathrm{GeV/c^2}$$
$$0.05\,\mathrm{GeV} < \Delta\mathrm{E} < 0.2\,\mathrm{GeV}$$

Continuum Model

Continuum model correlation matrix

	ΔE	$\mathcal{F}_{B\bar{B}/q\bar{q}}$	$m_{3\pi}$	$\mathcal{H}_{3\pi}$	Δt
ΔE	1	0.007	0.005	0.001	0.012
$\mathcal{F}_{B\bar{B}/q\bar{q}}$		1	0.002	0.005	0.007
$m_{3\pi}$			1	-0.015	0.005
$\mathcal{H}_{3\pi}$				1	-0.001
Δt					1

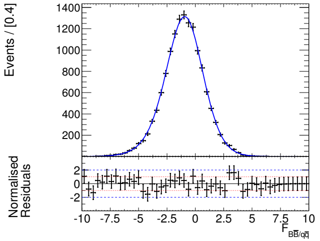
Continuum ΔE and $\mathcal{F}_{B\bar{B}/q\bar{q}}$



ΔE continuum

First order Chebyshev

$$\mathcal{P}_{q\bar{q}}(\Delta E) = \sum_{i=0}^{1} c_i C_i(\Delta E)$$

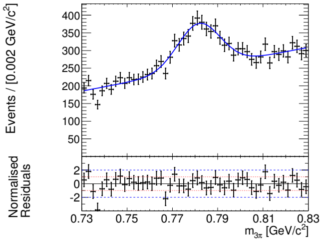


$\mathcal{F}_{B\bar{B}/q\bar{q}}$ continuum

Double Gaussian in each r-bin l for SVD2, single Gaussian for SVD1

$$\begin{aligned}\mathcal{P}_{q\bar{q},l}(\mathcal{F}_{B\bar{B}/q\bar{q}}) = {} & fG(\mathcal{F}_{B\bar{B}/q\bar{q}};\, \mu_{1,l},\, \sigma_{1,l}) \\ & +(1-f)G(\Delta E;\, \mu_{2,l},\, \sigma_{2,l})\end{aligned}$$

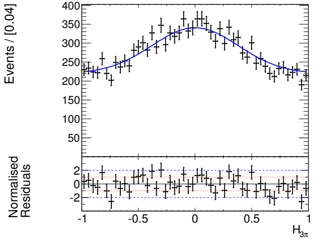
Continuum $m_{3\pi}$ and $\mathcal{H}_{3\pi}$



$m_{3\pi}$ continuum

Gaussian + 1st order Chebyshev

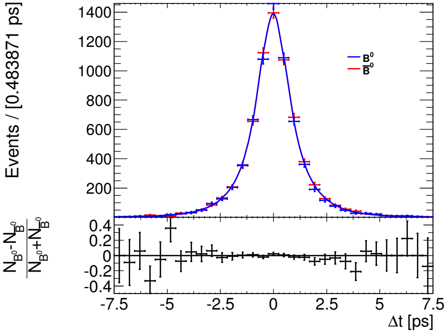
$$\mathcal{P}_{q\bar{q}}(m_{3\pi}) = fG(m_{3\pi}, \mu, \sigma) + (1-f)\sum_{i=0}^{1} c_i C_i(m_{3\pi})$$



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

Gaussian + 1st order Chebyshev

$$\mathcal{P}_{q\bar{q}}(\mathcal{H}_{3\pi}) = fG(\mathcal{H}_{3\pi}, \mu, \sigma) + (1-f)\sum_{i=0}^{1} c_i C_i(\mathcal{H}_{3\pi})$$



Δt continuum

Lifetime+prompt

$$\mathcal{P}_{\mathrm{q\bar{q}}}(\Delta t) = (1-f_{ol})\left[(1-f_\delta)\frac{e^{-|\Delta t|/\tau_{q\bar{q}}}}{2\tau_{q\bar{q}}} + f_\delta\delta(\Delta t - \mu_\delta)\right] \otimes R_{q\bar{q}}$$
$$+f_{ol}\mathcal{P}_{ol}$$

Neutral Charm Model (peaking background)

Peaking background (three pions and a K_S^0 final states)

$B^0 \to D^{*-}\pi^+$, with $D^{*-} \to \bar{D}^0\pi^-$ and $\bar{D}^0 \to K_S^0\pi^0$

$B^0 \to D^-\pi^+$, with $D^- \to K_S^0\pi^-\pi^0$

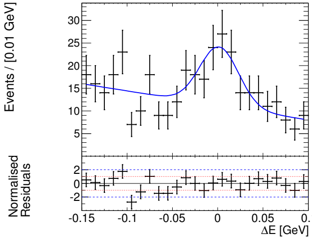
$B^0 \to D^-\rho^+$, with $D^- \to K_S^0\pi^-$ and $\rho^+ \to \pi^0\pi^+$

Neutral Charm Model (peaking background)

Neutral Charm model (peaking background) correlation matrix

	ΔE	$\mathcal{F}_{\mathrm{B\bar{B}/q\bar{q}}}$	$m_{3\pi}$	$\mathcal{H}_{3\pi}$	Δt
ΔE	1	-0.019	0.066	-0.05	-0.041
$\mathcal{F}_{\mathrm{B\bar{B}/q\bar{q}}}$		1	0.018	0.066	-0.033
$m_{3\pi}$			1	-0.043	0.065
$\mathcal{H}_{3\pi}$				1	0.019
Δt					1

Peaking Background ΔE and $\mathcal{F}_{B\bar{B}/q\bar{q}}$

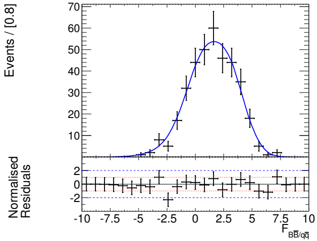


ΔE peaking background

First order Chebyshev + Gaussian

$$\mathcal{P}^{\mathrm{Charm,\,pb}}_{B^0\bar{B}^0}(\Delta E) =$$

$$fG(\Delta E;\, \mu,\, \sigma) + (1-f)\sum_{i=0}^{1} c_i C_i(\Delta E)$$

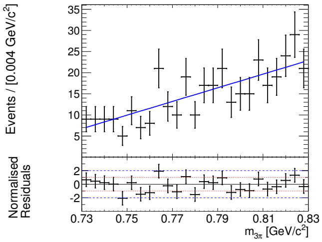


$\mathcal{F}_{\mathrm{B\bar{B}/q\bar{q}}}$ peaking background

Shape fixed from signal MC, free main mean $\mu_{1,\mathrm{l}}$

$$\begin{aligned}\mathcal{P}^{\mathrm{Charm,\,pb,\,l}}_{B^0\bar{B}^0}(\mathcal{F}_{\mathrm{B\bar{B}/q\bar{q}}}) = f_1 G(\mathcal{F}_{\mathrm{B\bar{B}/q\bar{q}}};\, \mu_{1,\mathrm{l}},\, \sigma_{1,\mathrm{l}}) \\ + f_2 G(\Delta E;\, \mu_{2,\mathrm{l}},\, \sigma_{2,\mathrm{l}}) \\ + (1 - f_1 - f_2) G(\Delta E;\, \mu_{3,\mathrm{l}},\, \sigma_{3,\mathrm{l}})\end{aligned}$$

Neutral charm $m_{3\pi}$ and $\mathcal{H}_{3\pi}$

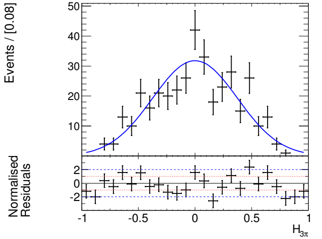


$m_{3\pi}$ peaking background

Shape fixed from signal MC, Chebyshev 1st order added

$$\mathcal{P}^{\mathrm{Charm,\,pb}}_{B^0\bar{B}^0}(m_{3\pi}) =$$

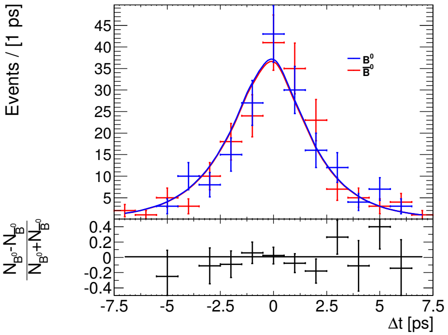
$$f\mathcal{P}_{\mathrm{Sig}}(m_{3\pi}) + (1-f)\sum_{i=0}^{1} c_i C_i(m_{3\pi})$$



$\mathcal{H}_{3\pi}$ peaking background

Gaussian

$$\mathcal{P}^{\mathrm{Charm,\,pb}}_{B^0\bar{B}^0}(\mathcal{H}_{3\pi}) = G(\mathcal{H}_{3\pi};\, \mu,\, \sigma)$$



Δt peaking background, $\mathcal{A} = 0$, $\mathcal{S} = 0$

$$\mathcal{P}^{\text{Charm, pb}}_{B^0\bar{B}^0}(\Delta t, q) = (1 - f_{ol})\frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \cdot \left[1 - q\Delta w + q(1-2w)\left(\mathcal{A}_{CP}\cos(\Delta m \Delta t) + \mathcal{S}_{CP}\sin(\Delta m \Delta t)\right)\right] \otimes R_{B^0\bar{B}^0} + f_{ol}\mathcal{P}_{ol}$$