Measurement of CP Violation in $B_s^0 \to \phi\phi$ decays

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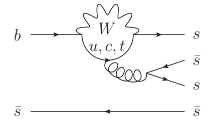
Introduction

Theory and Motivation



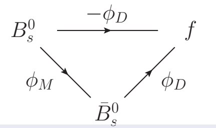


Figure: **Left:** $B_s^0 \to \phi\phi$ via gluonic penguin
Right: Mixing and decay phases

- $b \to s\bar{s}s$ FCNC transition
- Sensitive to new physics.
- Measure CPV in interference

$$\phi_s = \phi_{\text{Mix}} - 2\phi_{\text{Decay}}$$

- SM prediction: $|\phi_s| < 0.02$ rad
- Large CPV would suggest new physics
- Also measure direct CPV parameter

$$|\lambda| = \left| \frac{q}{p} \cdot \frac{\bar{A}_f}{A_f} \right|$$

Selection and Mass Fit

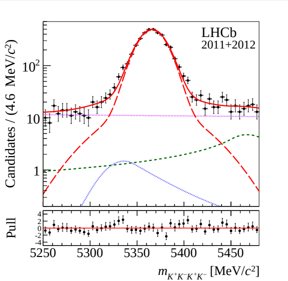
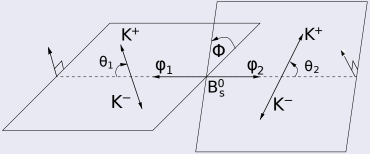


Figure: Fit to $K^+K^-K^+K^-$ invariant mass
Black points: event candidates
Red long-dashed: $B_s^0 \to \phi\phi$
Purple dotted: combinatoric
Green dashed: $\Lambda_b \to \phi pK$
Blue dotted: $B^0 \to \phi K^*$

- 3 fb^{-1} of pp collisions in LHCb
- $K^+K^-K^+K^-$ final state
- BDT used to optimise the selection
- Two peaking backgrounds: $\Lambda_b \to \phi Kp$ and $B^0 \to \phi K^*$
- ∼3950 signal event candidates selected

Analysis

Angular Analysis



- Pseudoscalar to two vectors
- Three P-wave amplitudes:
  A_0 & $A_{||}$ (CP-even) $A_\perp$ (CP-odd)
- Two S-wave amplitudes:

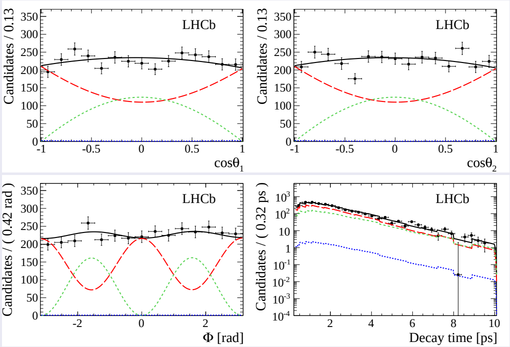
A_S (ϕf_0 CP-odd) A_{SS} ($f_0 f_0$ CP-even)

- Fit full differential decay rate with 15-term PDF of the form:

$$\frac{d^4\Gamma}{dt d\theta_1 d\theta_2 d\Phi} \propto \sum_{i=1}^{15} K_i(t) f_i(\theta_1, \theta_2, \Phi)$$

- CP observables contained in K_i

1D Fit Projections



Black points: background-subtracted data
Black solid: time-dependent angular fit
Red long-dashed: CP-even *P*-wave
Green short-dashed: CP-odd *P*-wave
Blue dotted: *S*-wave

Results and Conclusions

CP Observables

Parameter	Value $\pm$ Stat $\pm$ Syst
ϕ_s (rad)	$-0.17 \pm 0.15 \pm 0.03$
$\lvert\lambda\rvert$	$1.04 \pm 0.07 \pm 0.03$
$\lvert A_0\rvert^2$	$0.364 \pm 0.012 \pm 0.009$
$\lvert A_\perp\rvert^2$	$0.305 \pm 0.013 \pm 0.005$

- Error on ϕ_s dominated by the statistical uncertainty.
- Main systematics from decay time and angular acceptance.

Conclusions and Prospects

- Values of ϕ_s and $|\lambda|$ found to be consistent with hypothesis of CP conservation
- After Run II, expect factor of 2 improvement on precision of ϕ_s
- After upgrade, expect error on ϕ_s to be comparable to theoretical uncertainty
- Paper submitted to Phys. Rev. D. available at arXiv:1407.2222 [hep-ex]

Backup Slides

Time-dependent Angular Fit PDF

i	K_i	f_i
1	$\lvert A_0(t)\rvert^2$	$4\cos^2\theta_1\cos^2\theta_2$
2	$\lvert A_\parallel(t)\rvert^2$	$\sin^2\theta_1\sin^2\theta_2(1+\cos 2\Phi)$
3	$\lvert A_\perp(t)\rvert^2$	$\sin^2\theta_1\sin^2\theta_2(1-\cos 2\Phi)$
4	$Im(A_\parallel^*(t)A_\perp(t))$	$-2\sin^2\theta_1\sin^2\theta_2\sin 2\Phi$
5	$Re(A_\parallel^*(t)A_0(t))$	$\sqrt{2}\sin 2\theta_1\sin 2\theta_2\cos\Phi$
6	$Im(A_0^*(t)A_\perp(t))$	$-\sqrt{2}\sin 2\theta_1\sin 2\theta_2\sin\Phi$
7	$\lvert A_{SS}(t)\rvert^2$	$\frac{4}{9}$
8	$\lvert A_S(t)\rvert^2$	$\frac{4}{3}(\cos\theta_1+\cos\theta_2)^2$
9	$Re(A_S^*(t)A_{SS}(t))$	$\frac{8}{3\sqrt{3}}(\cos\theta_1+\cos\theta_2)$
10	$Re(A_0(t)A_{SS}^*(t))$	$\frac{8}{3}\cos\theta_1\cos\theta_2$
11	$Re(A_\parallel(t)A_{SS}^*(t))$	$\frac{4\sqrt{2}}{3}\sin\theta_1\sin\theta_2\cos\Phi$
12	$Im(A_\perp(t)A_{SS}^*(t))$	$-\frac{4\sqrt{2}}{3}\sin\theta_1\sin\theta_2\sin\Phi$
13	$Re(A_0(t)A_S^*(t))$	$\frac{8}{\sqrt{3}}\cos\theta_1\cos\theta_2(\cos\theta_1+\cos\theta_2)$
14	$Re(A_\parallel(t)A_S^*(t))$	$\frac{4\sqrt{2}}{\sqrt{3}}\sin\theta_1\sin\theta_2(\cos\theta_1+\cos\theta_2)\cos\Phi$
15	$Im(A_\perp(t)A_S^*(t))$	$-\frac{4\sqrt{2}}{\sqrt{3}}\sin\theta_1\sin\theta_2(\cos\theta_1+\cos\theta_2)\sin\Phi$

P-wave (ϕϕ)

CP-even S-wave (f0f0)

CP-odd S-wave (ϕf0)

f0f0– ϕf0 interference

ϕϕ-f0f0 interference

ϕϕ-ϕf0 interference

$$A(t,\theta_1,\theta_2,\Phi) = A_0(t)\cos\theta_1\cos\theta_2 + \frac{A_\parallel(t)}{\sqrt{2}}\sin\theta_1\sin\theta_2\cos\Phi$$

$$+\,i\frac{A_\perp(t)}{\sqrt{2}}\sin\theta_1\sin\theta_2\sin\Phi + \frac{A_S(t)}{\sqrt{2}}(\cos\theta_1+\cos\theta_2) + \frac{A_{SS}(t)}{3}$$

Extracting CP observables

$$K_i(t) = N_i e^{-\Gamma_s t}\left[a_i \cosh\left(\Delta\Gamma_s t/2\right) + b_i \sinh\left(\Delta\Gamma_s t/2\right) + c_i \cos(\Delta m_s t) + d_i \sin(\Delta m_s t)\right]$$

Table: Coefficients of the time dependent terms used in above equation. Amplitudes are defined at $t = 0$.

i	N_i	a_i	b_i	c_i	d_i
1	$\lvert A_0\rvert^2$	1	D	C	$-S$
2	$\lvert A_\parallel\rvert^2$	1	D	C	$-S$
3	$\lvert A_\perp\rvert^2$	1	$-D$	C	S
4	$\lvert A_\parallel\rvert\lvert A_\perp\rvert$	$C\sin\delta_1$	$S\cos\delta_1$	$\sin\delta_1$	$D\cos\delta_1$
5	$\lvert A_\parallel\rvert\lvert A_0\rvert$	$\cos(\delta_{2,1})$	$D\cos(\delta_{2,1})$	$C\cos\delta_{2,1}$	$-S\cos(\delta_{2,1})$
6	$\lvert A_0\rvert\lvert A_\perp\rvert$	$C\sin\delta_2$	$S\cos\delta_2$	$\sin\delta_2$	$D\cos\delta_2$
7	$\lvert A_{SS}\rvert^2$	1	D	C	$-S$
8	$\lvert A_S\rvert^2$	1	$-D$	C	S
9	$\lvert A_S\rvert\lvert A_{SS}\rvert$	$C\cos(\delta_S - \delta_{SS})$	$S\sin(\delta_S-\delta_{SS})$	$\cos(\delta_{SS}-\delta_S)$	$D\sin(\delta_{SS}-\delta_S)$
10	$\lvert A_0\rvert\lvert A_{SS}\rvert$	$\cos\delta_{SS}$	$D\cos\delta_{SS}$	$C\cos\delta_{SS}$	$-S\cos\delta_{SS}$
11	$\lvert A_\parallel\rvert\lvert A_{SS}\rvert$	$\cos(\delta_{2,1}-\delta_{SS})$	$D\cos(\delta_{2,1}-\delta_{SS})$	$C\cos(\delta_{2,1}-\delta_{SS})$	$-S\cos(\delta_{2,1}-\delta_{SS})$
12	$\lvert A_\perp\rvert\lvert A_{SS}\rvert$	$C\sin(\delta_2 - \delta_{SS})$	$S\cos(\delta_2 - \delta_{SS})$	$\sin(\delta_2-\delta_{SS})$	$D\cos(\delta_2-\delta_{SS})$
13	$\lvert A_0\rvert\lvert A_S\rvert$	$C\cos\delta_S$	$-S\sin\delta_S$	$\cos\delta_S$	$-D\sin\delta_S$
14	$\lvert A_\parallel\rvert\lvert A_S\rvert$	$C\cos(\delta_{2,1} - \delta_S)$	$S\sin(\delta_{2,1} - \delta_S)$	$\cos(\delta_{2,1}-\delta_S)$	$D\sin(\delta_{2,1} - \delta_S)$
15	$\lvert A_\perp\rvert\lvert A_S\rvert$	$\sin(\delta_2 - \delta_S)$	$-D\sin(\delta_2 - \delta_S)$	$C\sin(\delta_2 - \delta_S)$	$S\sin(\delta_2 - \delta_S)$

$$C \equiv \frac{1-|\lambda|^2}{1+|\lambda|^2} \quad S \equiv -\frac{2|\lambda|\sin\phi_s}{1+|\lambda|^2} \quad D \equiv -\frac{2|\lambda|\cos\phi_s}{1+|\lambda|^2} \quad \delta_1 \equiv \delta_\perp - \delta_\parallel \quad \delta_2 \equiv \delta_\perp - \delta_0 \quad \delta_{2,1} \equiv \delta_2 - \delta_1$$

Time-dependent Angular Fit Results

Parameter	Best fit value
ϕ_s (rad)	-0.17 ± 0.15
$\lvert\lambda\rvert$	1.04 ± 0.07
$\lvert A_\perp\rvert^2$	0.305 ± 0.013
$\lvert A_0\rvert^2$	0.364 ± 0.012
δ_1 (rad)	0.13 ± 0.23
δ_2 (rad)	2.67 ± 0.23
Γ_s (ps^{-1})	0.662 ± 0.006
$\Delta\Gamma_s$ (ps^{-1})	0.102 ± 0.012
Δm_s (ps^{-1})	17.774 ± 0.024

Table: Results of the decay time dependent fit.

Systematics

Parameter	$\lvert A_0\rvert^2$	$\lvert A_\perp\rvert^2$	δ_1 (rad)	δ_2 (rad)	(rad)	$\lvert\lambda\rvert$
Mass model	–	–	0.03	0.04	–	0.02
AA (statistical)	0.003	0.004	0.02	0.02	0.02	0.02
AA (tagging)	0.006	0.002	–	0.01	–	0.01
Fit bias	–	–	0.02	–	–	–
Time acceptance	0.005	0.003	0.02	0.05	0.02	–
Peaking background	–	–	0.01	0.01	–	0.01
Total	0.009	0.005	0.05	0.07	0.03	0.03

Table: Summary of systematic uncertainties for physics parameters in the decay time dependent measurement, where AA denotes angular acceptance.