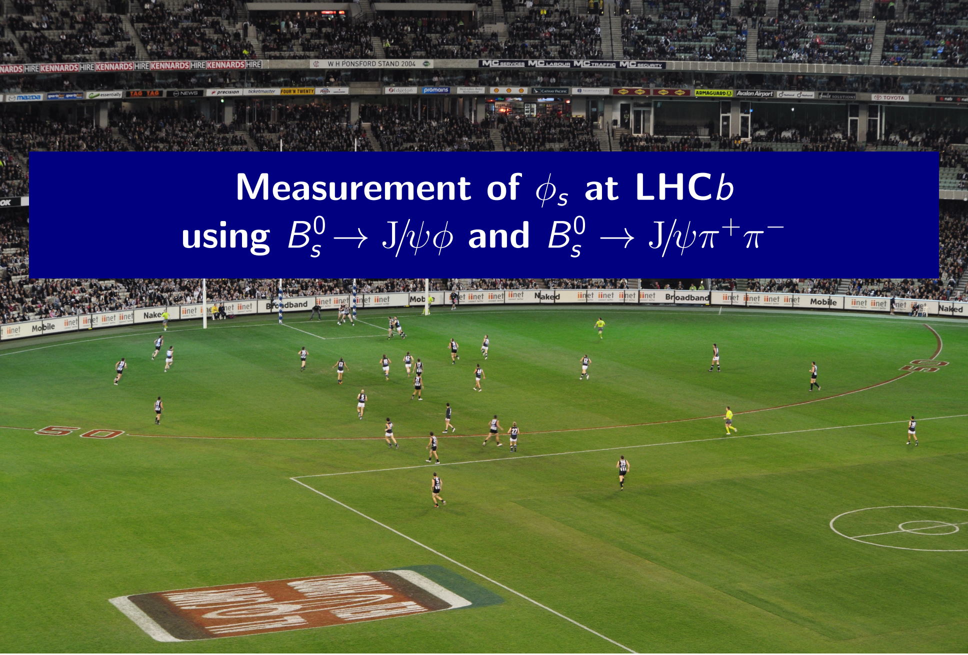
Measurement of ϕ_s at LHC*b* using $B_s^0 \to J/\psi\phi$ and $B_s^0 \to J/\psi\pi^+\pi^-$



Greig Cowan, on behalf of the LHCb collaboration

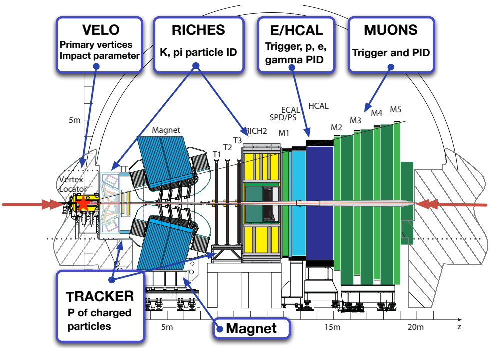
ICHEP, July 7th 2012

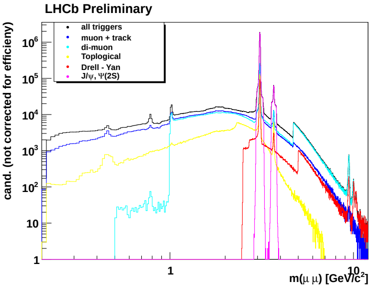
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

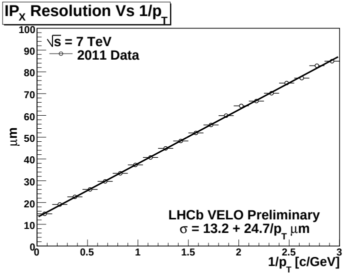
LHCb

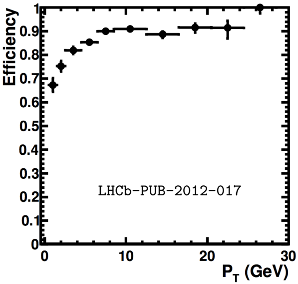
LHC*b* detector

2008 JINST 3 S08005





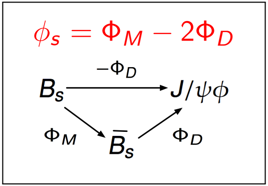




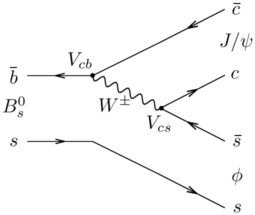
CP-violation in the B_s^0 system

- Interference between $\bar{b} \rightarrow \bar{c}c\bar{s}$ either directly or via mixing gives rise to a CP-violating phase

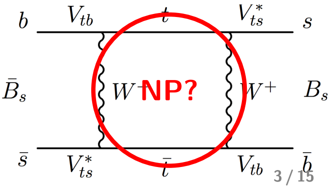
$$\phi_s^{SM} = -2\beta_s + \delta P = -0.036 \pm 0.002\,\mathrm{rad} + \delta\mathrm{P}$$



- $\bar{b} \rightarrow \bar{c}c\bar{s}$ dominated by tree-level transitions, $\Phi_D = \arg(V_{cs}V_{cb}^*)$.
  - Small penguin pollution, $\delta P \sim 10^{-3} - 10^{-4}$.



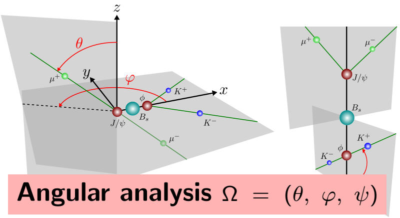
- Mixing phase $\Phi_M = 2\arg(V_{ts}V_{tb}^*) \approx -2\beta_s$.
  - New physics can modify: $\phi_s \rightarrow \phi_s^{SM} + \phi_s^{NP}$.



Measuring ϕ_s using $B_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$

- $P \to VV$: final state is admixture of CP-odd ($\ell = 1$) and CP-even ($\ell = 0, 2$) with different lifetimes.
- 3 K^+K^- P-wave, 1 S-wave
- Unbinned log-likelihood fit to statistically disentangle final states.

$$\mathrm{CP}|\, J/\psi\phi\rangle_\ell = \eta_f |\, J/\psi\phi\rangle_\ell = (-1)^\ell |\, J/\psi\phi\rangle_\ell$$



Angular analysis $\Omega = (\theta, \varphi, \psi)$

$$\mathcal{S}(\lambda, \mathrm{m}, \mathrm{t}, \Omega) = \mathcal{G}(\mathrm{m}) \cdot \epsilon(\mathrm{t}, \Omega) \cdot \left(\frac{1 + \mathrm{qD}}{2} \cdot \mathrm{s}(\lambda, \mathrm{t}, \Omega) + \frac{1 - \mathrm{qD}}{2} \cdot \bar{\mathrm{s}}(\lambda, \mathrm{t}, \Omega) \right) \otimes \mathrm{R_t}$$

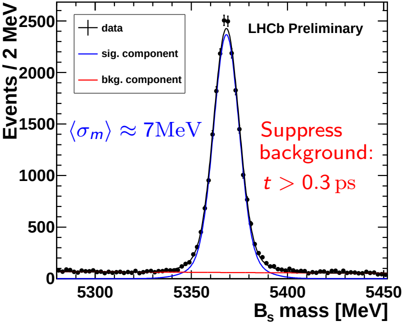
- Acceptance, flavour tagging, time resolution.
- **Physics**: $\lambda = (\phi_s,\ \Gamma_s,\ \Delta\Gamma_s,\ \Delta m_s,\ \delta_\parallel,\ \delta_\perp,\ \delta_S,\ |A_\parallel|^2,\ |A_\perp|^2,\ |A_S|^2)$

$B_s^0 \to J/\psi\phi$ analysis of $1\,\mathrm{fb}^{-1}$

LHCb-CONF-2012-002

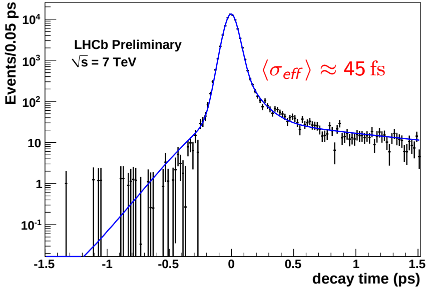
Selection

- Di-muon trigger: $p_{\mathrm{T}} > 0.5\,\mathrm{GeV}/c$.
- Simple kinematic selection: ~ 21200 candidates



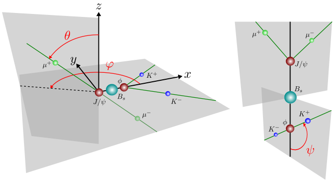
Decay time resolution

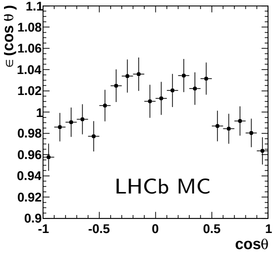
- Use prescaled sample of prompt-J/ψ events to extract resolution scale factor.

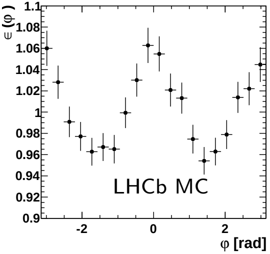


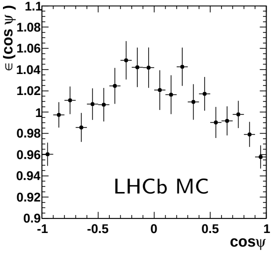
Angular acceptance

- Angular acceptance of $\pm 5\%$ due to detector geometry ($10 < \Theta < 400\,\mathrm{mrad}$) and implicit momentum cuts on final state particles.
- Evaluate using MC.
- Apply to fit via angular "moments" of the PDF or 3D analytic parameterisation of orthogonal polynomials.





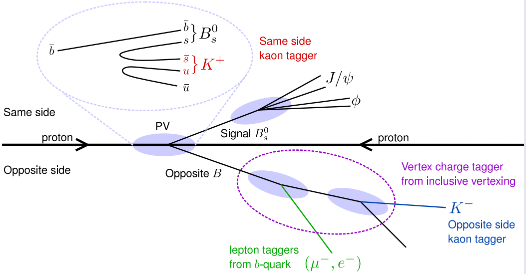




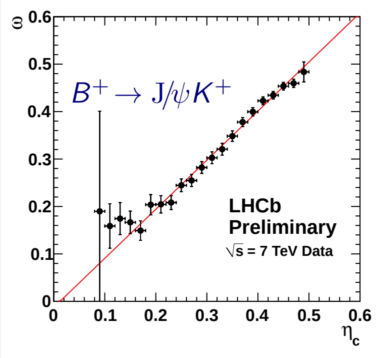
Flavour tagging

LHCb-CONF-2012-002, LHCb-CONF-2012-026

- Sensitivity to ϕ_s comes from events tagged as B_s^0 or $\bar{B}_s^0$.
- Specialised tagging algorithms analyse event to determine initial flavour (talk from S. Vecchi).
- Effective OS tagging efficiency of $\varepsilon_{\rm tag}\mathcal{D}^2 = (2.29 \pm 0.27)\%$

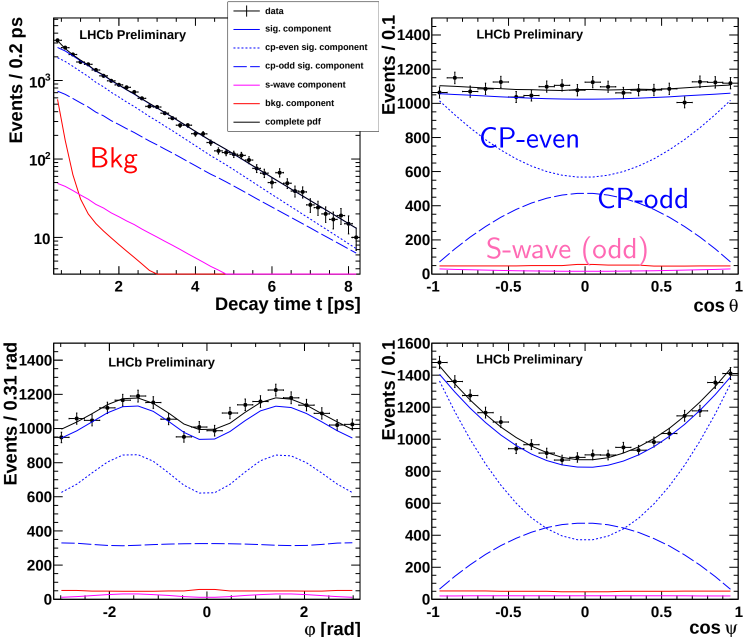


OS calibration: $\omega = p_0 + p_1(\eta_c - \langle\eta_c\rangle)$



Projection of time dependent angular fit

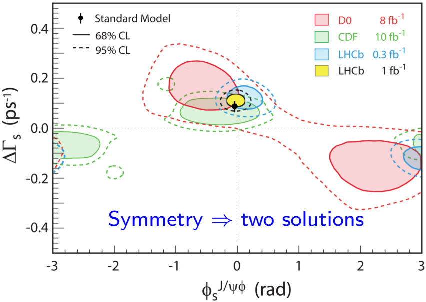
LHCb-CONF-2012-002



Projection of time dependent angular fit

LHCb-CONF-2012-002

Preliminary			
Parameter	Value	Stat.	Syst.
Γ_s [ps^{-1}]	0.6580	0.0054	0.0066
$\Delta\Gamma_s$ [ps^{-1}]	0.116	0.018	0.006
$\lvert A_\perp(0)\rvert^2$	0.246	0.010	0.013
$\lvert A_0(0)\rvert^2$	0.523	0.007	0.024
F_S	0.022	0.012	0.007
$\delta_\perp$ [rad]	2.90	0.36	0.07
$\delta_\parallel$ [rad]	[2.81, 3.47]		0.13
δ_s [rad]	2.90	0.36	0.08
ϕ_s [rad]	-0.001	0.101	0.027



Systematics

- Neglecting potential CPV in mixing and decay.
- Knowledge of angular acceptance.
- Background description.
- Decay time acceptance.

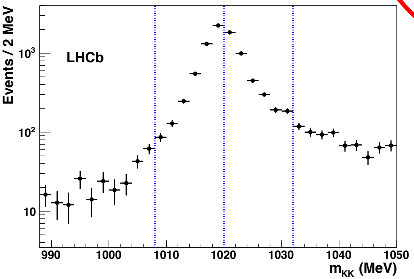
Ongoing studies to reduce these for publication

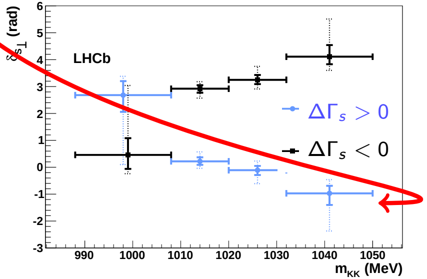
Resolving the ambiguity

Phys. Rev. Lett. 108 (2012) 241801

$$(\phi_s, \Delta\Gamma_s, \delta_{\parallel} - \delta_0, \delta_{\perp} - \delta_0, \delta_{\rm S} - \delta_0) \leftrightarrow (\pi - \phi_s, -\Delta\Gamma_s, \delta_0 - \delta_{\parallel}, \pi + \delta_0 - \delta_{\perp}, \delta_0 - \delta_{\rm S})$$

- Perform angular fit in 4 bins of K^+K^- mass.
- $\delta_{\rm S\perp} = \delta_{\rm S} - \delta_{\perp}$ should fall across $\phi(1020)$ mass.

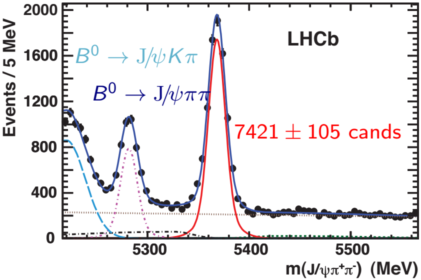


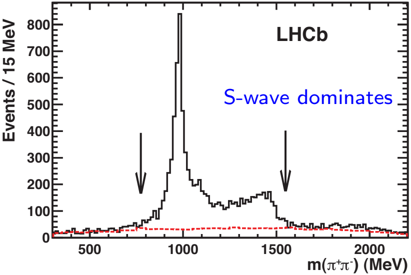


ϕ_s from $B_s^0 \to J/\psi\pi^+\pi^-$

arXiv:1204.5675v3, submitted to Phys. Lett. B

- $B_s^0 \to J/\psi\pi^+\pi^-$ is another $\bar{b} \to \bar{c}c\bar{s}$.
- Not vector-vector final state $\Rightarrow$ no complex angular analysis!
- $\pi^+\pi^-$ is $> 97.7\%$ CP-odd @ 95% Conf. Level (see talk from C. Linn).

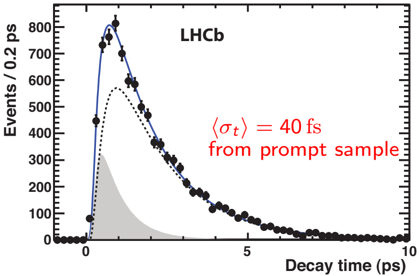


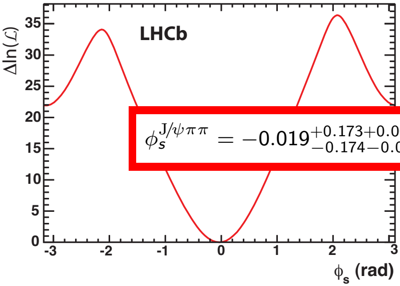


ϕ_s from $B_s^0 \to J/\psi\pi^+\pi^-$

arXiv:1204.5675v3, submitted to Phys. Lett. B

- $\Gamma_s, \Delta\Gamma_s$ constrained from $B_s^0 \to J/\psi\phi$ analysis (see talk from A. Phan on B_s^0 lifetimes)
- Δm_s from LHCb (Phys. Lett. B709 (2012) 177).





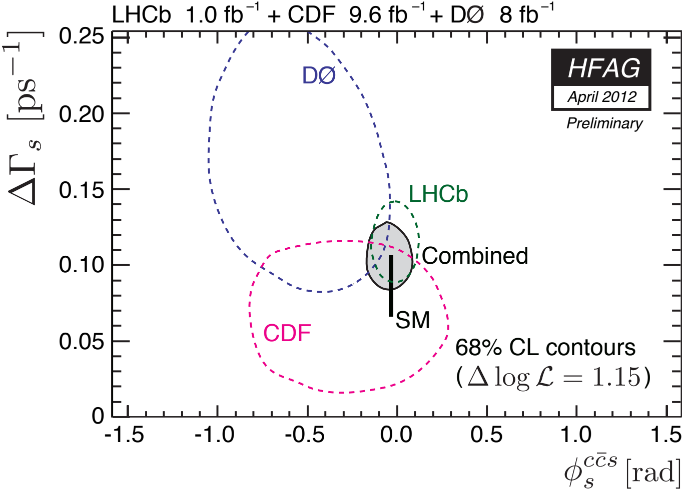
$$\phi_s^{J/\psi\pi\pi} = -0.019^{+0.173+0.004}_{-0.174-0.003}\ \mathrm{rad}$$

Simultaneous fit of $B_s^0 \to J/\psi\phi$ and $B_s^0 \to J/\psi\pi^+\pi^-$

$$\phi_s = -0.002 \pm 0.083 \pm 0.027\ \mathrm{rad}$$

Latest ϕ_s combination

arXiv:1207.1158

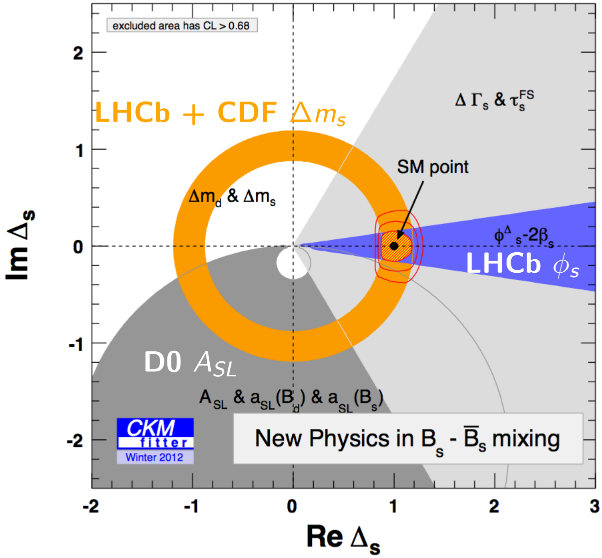


$$\phi_s = -0.044^{+0.090}_{-0.085}\,\mathrm{rad}, \qquad \Delta\Gamma_s = +0.105 \pm 0.015\,\mathrm{ps}^{-1}$$

Impact on New Physics

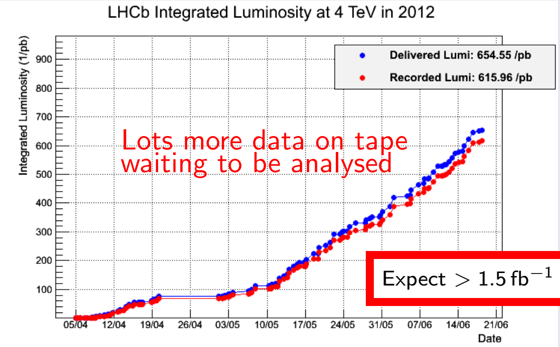
Lenz et al. arXiv:1203.0238v2 [hep-ph]

- Model independent analysis places strong constraints on size of NP in M_{12}.
- **Need** independent $\mathrm{a}_{\mathrm{fs}}^{\mathrm{s}}$ measurement (see talk from M. Artuso).
- **Need** increased precision on ϕ_s.



Summary

- Excellent dectector performance:
  1. Clean signals.
  2. Decay time resolution: $\sim 45\,\mathrm{fs}$.
  3. OS tagging: $\varepsilon_{\text{tag}}\mathcal{D}^2 = (2.29 \pm 0.27)\%$.
- LHCb made most precise measurement of ϕ_s ($B_s^0 \to \mathrm{J}/\psi\phi$, $\mathrm{J}/\psi\pi\pi$).
- First direct observation of non-zero $\Delta\Gamma_\mathrm{s} \Rightarrow$ resolved sign ambiguity.

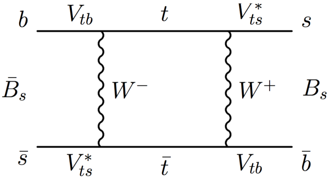


Expect $> 1.5\,\mathrm{fb}^{-1}$ by end 2012

Backup

Brief introduction to B_s^0-meson mixing and decay

$$i\frac{\partial}{\partial t}\begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix} = \left(\mathbf{M} - i\frac{\mathbf{\Gamma}}{2}\right)\begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix}$$



$$|B_{s,\mathrm{L}}^0\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle$$
$$|B_{s,\mathrm{H}}^0\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle$$

Some relevant parameters

$$\mathrm{M}_{\mathrm{B_s^0}} = \frac{\mathrm{M_H} + \mathrm{M_L}}{2}, \qquad \Gamma_\mathrm{s} = \frac{\Gamma_\mathrm{L} + \Gamma_\mathrm{H}}{2}$$

$$\Delta \mathrm{m_s} = \mathrm{M_H} - \mathrm{M_L} \approx 2\mathrm{M}_{12}, \qquad \Delta\Gamma_\mathrm{s} = \Gamma_\mathrm{L} - \Gamma_\mathrm{H} \approx 2\Gamma_{12}\cos\varphi$$

$$\varphi = \arg\left(-\frac{\mathrm{M}_{12}}{\Gamma_{12}}\right)$$

Systematics

Source	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$A_\perp^2$	A_0^2	F_S	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	δ_s [rad]	ϕ_s [rad]
Description of background	0.0010	0.004	-	0.002	0.005	0.04	0.04	0.06	0.011
Angular acceptances	0.0018	0.002	0.012	0.024	0.005	0.12	0.06	0.05	0.012
t acceptance model	0.0062	0.002	0.001	0.001	-	-	-	-	-
z and momentum scale	0.0009	-	-	-	-	-	-	-	-
Prod. asymmetry ($\pm$ 10%)	0.0002	0.002	-	-	-	-	-	-	0.008
CPV mixing & decay ($\pm$ 5%)	0.0003	0.002	-	-	-	-	-	-	0.020
Fit bias	-	0.001	0.003	-	0.001	0.02	0.02	0.01	0.005
Quadratic sum	0.0066	0.006	0.013	0.024	0.007	0.13	0.07	0.08	0.027

ϕ_s

1. Neglecting potential CPV in mixing and decay.
   - Fit for $|\lambda|$ shows that $\Delta(|\lambda|^2) = \pm 5\%$ is a reasonable variation.
   - Evaluate using toys generating with $|\lambda|^2 = 0.95, 1.05$ and fitting with $|\lambda|^2 = 1$.
2. Knowledge of angular acceptance.

Systematics

Source	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$A_\perp^2$	A_0^2	F_S	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	δ_s [rad]	ϕ_s [rad]
Description of background	0.0010	0.004	-	0.002	0.005	0.04	0.04	0.06	0.011
Angular acceptances	0.0018	0.002	0.012	0.024	0.005	0.12	0.06	0.05	0.012
t acceptance model	0.0062	0.002	0.001	0.001	-	-	-	-	-
z and momentum scale	0.0009	-	-	-	-	-	-	-	-
Prod. asymmetry ($\pm$ 10%)	0.0002	0.002	-	-	-	-	-	-	0.008
CPV mixing & decay ($\pm$ 5%)	0.0003	0.002	-	-	-	-	-	-	0.020
Fit bias	-	0.001	0.003	-	0.001	0.02	0.02	0.01	0.005
Quadratic sum	0.0066	0.006	0.013	0.024	0.007	0.13	0.07	0.08	0.027

$\Delta\Gamma_s, \Gamma_s$

1. Background description.
2. Upper decay time acceptance affects Γ_s.
3. Trigger acceptance affects $\Delta\Gamma_s$, amplitudes.