Measurement of ϕ_s at LHCb

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on behalf of the LHCb collaboration

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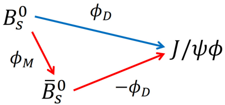
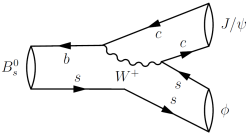
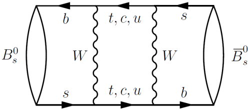
Introduction

- WHAT: interference between B_s^0 decay to $J/\psi\phi$ either directly or via B_s^0–$\overline{B}_s^0$ oscillation gives rise to a CP violating phase $\phi_s^{J/\psi\phi} \equiv \phi_s = \phi_M - 2\phi_D$







- WHY:
  1. in SM, $\phi_s \simeq -2\beta_s = -(0.0368 \pm 0.0014)\,\mathrm{rad}^{\dagger}$, $\beta_s = \arg\left(-V_{ts}V_{tb}^{*}/V_{cs}V_{cb}^{*}\right)$
  2. in presence of NP in the mixing box, ϕ_s can be larger

- HOW: tagged time-dependent angular analysis.
  Fit differential decay rates (for B_s^0 and $\overline{B}_s^0$):

$$\frac{\mathrm{d}^4\Gamma(B_s^0 \to J/\psi\phi)}{\mathrm{d}t\,\mathrm{d}\cos\theta_\mu\,\mathrm{d}\varphi_h\,\mathrm{d}\cos\theta_K} = f(\phi_s, \Delta\Gamma_s, \Gamma_s, \Delta m_s, |A_\perp|, |A_\parallel|, |A_S|, \delta_\perp, \delta_\parallel, \ldots)$$

† CKMfitter

Outline

1. Phenomenology
2. Selection of $B_s^0 \to J/\psi K^+ K^-$
3. Decay time
4. Angles
5. Initial flavour tagging
6. Fit and systematics
7. Conclusions and prospects

Phenomenology (I)

Time evolution of B_s^0–$\overline{B}_s^0$ system:

$$i\frac{d}{dt}\begin{pmatrix} |B_s^0(t)\rangle \\ |\overline{B}_s^0(t)\rangle \end{pmatrix} = \left(\hat{M} - \frac{i}{2}\hat{\Gamma}\right)\begin{pmatrix} |B_s^0(t)\rangle \\ |\overline{B}_s^0(t)\rangle \end{pmatrix}, \quad \hat{M} = \begin{pmatrix} M_{B_s^0} & M_{12} \\ M_{12}^* & M_{B_s^0} \end{pmatrix}, \quad \hat{\Gamma} = \begin{pmatrix} \Gamma_s & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_s \end{pmatrix}$$

Diagonalization of the mass and decay matrices gives the mass eigenstates:

$$B_{\mathrm{H}} = p|B_s^0\rangle + q|\overline{B}_s^0\rangle\, , B_{\mathrm{L}} = p|B_s^0\rangle - q|\overline{B}_s^0\rangle\, ; \quad |p|^2 + |q|^2 = 1$$

with the corresponding masses $M_{\mathrm{H}},\ M_{\mathrm{L}}$ and decay rates $\Gamma_{\mathrm{H}},\ \Gamma_{\mathrm{L}}$

We defined: $\Delta m_{\mathrm{s}} = M_{\mathrm{H}} - M_{\mathrm{L}}, \quad \Delta\Gamma_s = \Gamma_{\mathrm{L}} - \Gamma_{\mathrm{H}}, \quad \phi_M = \arg(M_{12})$

Phenomenology (II)

- $B_s^0 \to J/\psi K^+K^-$ proceeds predominantly via $B_s^0 \to J/\psi\phi$, with $\phi \to K^+K^-$, i.e. P-wave
- Small component with K^+K^- in S-wave
- Decay decomposed into 4 amplitudes: three P-waves, $A_0, A_\parallel, A_\perp$ and one S-wave, A_S. Final state is a mixture of CP-even (0, $\parallel$) and CP-odd ($\perp$, S)

$$\frac{\mathrm{d}^4\Gamma(B_s^0 \to J/\psi K^+K^-)}{\mathrm{d}t\ \mathrm{d}\Omega} \propto \sum_{k=1}^{10} h_k(t)\ f_k(\Omega)$$

$$h_k(t) = N_k e^{-\Gamma_s t}\left[a_k \cosh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + b_k \sinh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t)\right]$$

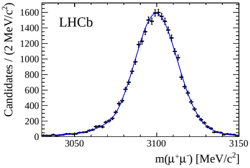
- N_k, a_k, b_k, c_k, d_k are functions of the 4 amplitudes, strong phases and ϕ_s
- For $\overline{B}_s^0$, change sign of c_k and d_k
  $\to$ significant gain when flavour tagging is used
- f_k are functions of 3 angles between the decaying particles
- Decay rates depend on 11 physics parameters
- Decay rates invariant under
  $(\phi_s, \Delta\Gamma_s, \delta_0, \delta_\parallel, \delta_\perp, \delta_\mathrm{S}) \longmapsto (\pi - \phi_s, -\Delta\Gamma_s, -\delta_0, -\delta_\parallel, \pi - \delta_\perp, -\delta_\mathrm{S})$
  $\to$ 2-fold ambiguity

Selection of $B_s^0 \to J/\psi(\mu^+\mu^-)K^+K^-$

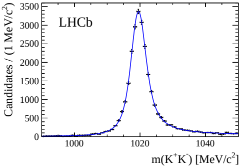
[PRD 87, 112010 (2013)]

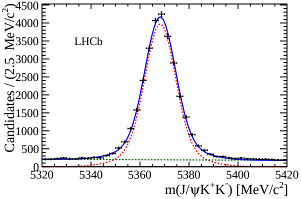
- Cut-based selection, using 1 fb^{-1} taken in 2011 at $\sqrt{s} = 7\,\mathrm{TeV}$
- Relies on excellent performances of the LHCb detector: $\sigma(IP) \sim 15\mu$m, $\delta p/p \sim 0.45\%$, very good $K-\pi$ separation

$J/\psi \to \mu^+\mu^-$ (2CB)



$\phi \to K^+K^-$ RPBW⊗G+pol



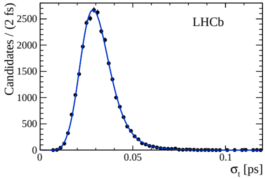


27 617 $B_s^0 \to J/\psi K^+K^-$ candidates, very small background

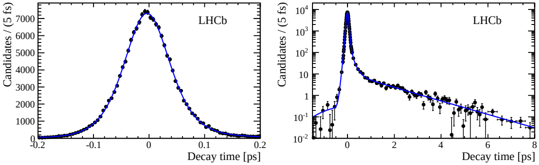
Decay time resolution

[PRD 87, 112010 (2013)]

Good decay time resolution essential to resolve the fast B_s^0–$\overline{B}_s^0$ oscillation ($2\pi/\Delta m_s \simeq 350\,\mathrm{fs}$).
Use per-event decay time error, with scale factor determined on real data, using prompt $J/\psi K^+K^-$ combinations



$B_s^0 \to J/\psi K^+K^-$ signal candidates



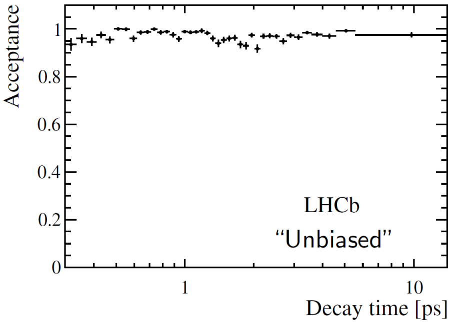
Prompt $J/\psi K^+K^-$ candidates

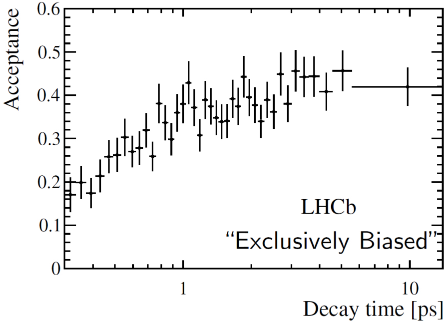
Effective decay time resolution is $45\,\mathrm{fs}$ ($\ll 2\pi/\Delta m_s$)

Decay time acceptance

[PRD 87, 112010 (2013)]

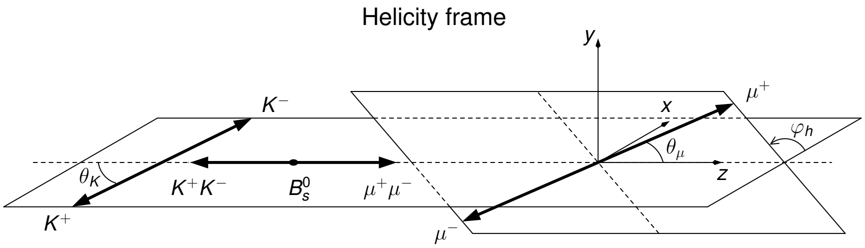
- 85% of our sample has a nearly flat decay time acceptance.
- 15% is exclusively triggered using muon IP cuts, which distort the decay time acceptance.
- Decay time acceptance determined using a prescaled unbiased trigger sample.



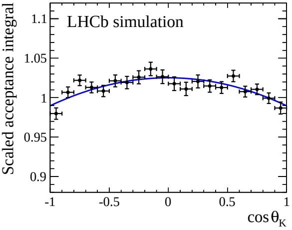


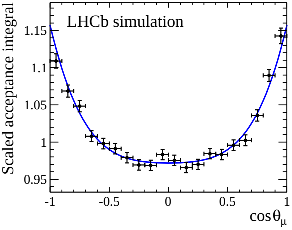
Angular acceptance

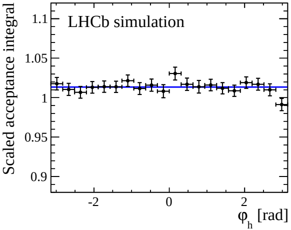
[PRD 87, 112010 (2013)]



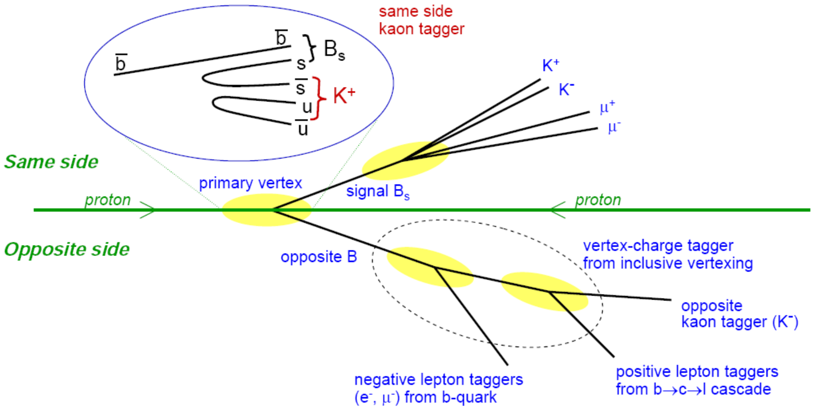
Forward geometry of LHCb + selection cuts ⇒ distorted angular acceptance
Determined using MC







Tag initial B_s^0 flavour



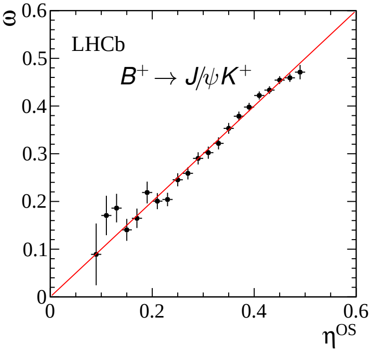
- $\varepsilon_{\rm tag} = \frac{R+W}{R+W+U}$, $\omega = \frac{W}{R+W}$, Tagging power = $\varepsilon_{\rm eff} = \varepsilon_{\rm tag} D^2 = \varepsilon_{\rm tag}(1-2\omega)^2$
  $\sim$ effective reduction of signal sample size due to imperfect tagging
- Mistag fraction, ω, estimated event by event
- Tagging algorithm optimized on MC and calibrated on real data with $B^0 \to D^{*-}\mu^+\nu_\mu$, $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^{*0}$ and $B_s^0 \to D_s^- \pi^+$

Flavour tagging calibration

[PRD 87, 112010 (2013)]

Calibration on real data, using flavor specific control channels

Measured true mistag versus estimated mistag probability:

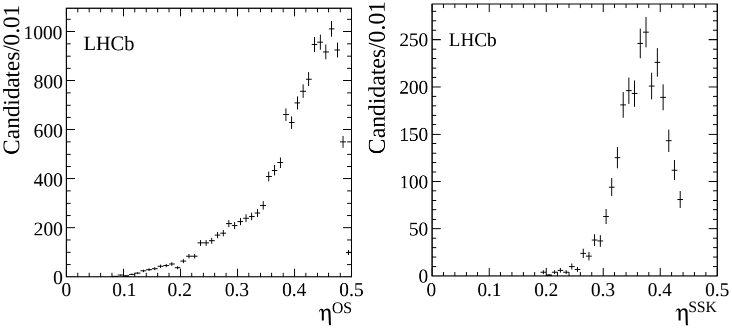


$$\omega(\eta) = p_0 + \frac{\Delta p_0}{2} + p_1(\eta - \langle\eta\rangle)\,, \qquad \bar{\omega}(\eta) = p_0 - \frac{\Delta p_0}{2} + p_1(\eta - \langle\eta\rangle)$$

Calibration	p_0	p_1	$\langle\eta\rangle$	Δp_0
OS	$0.392 \pm 0.002 \pm 0.008$	$1.000 \pm 0.020 \pm 0.012$	0.392	0.011 ± 0.003
SSK	$0.350 \pm 0.015 \pm 0.007$	$1.000 \pm 0.160 \pm 0.020$	0.350	-0.019 ± 0.005

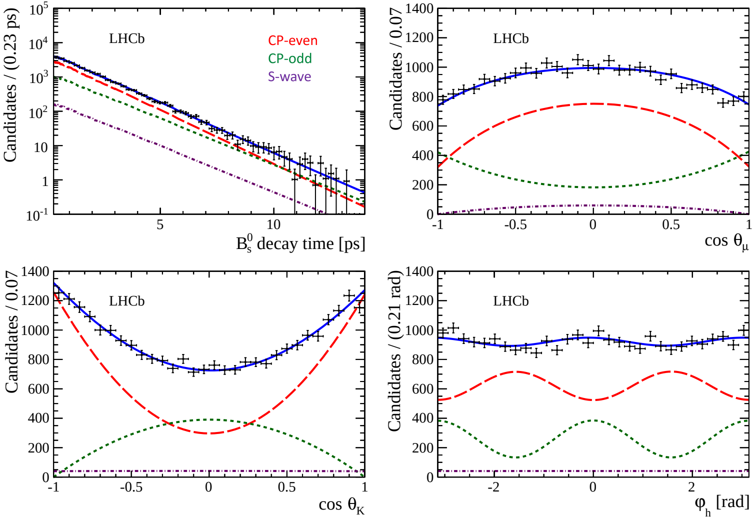
Flavour tagging performance

[PRD 87, 112010 (2013)]



	ε_{tag} (%)	ω (%)	$\varepsilon_{tag}(1-2\omega)^2$ (%)
OS	33.00	36.83	2.29
SSK	10.26	35.27	0.89
Combined	39.36	35.90	3.13

Unbinned maximum likelihood fit (*t*, *m*, angles, flavour)



Systematics

[PRD 87, 112010 (2013)]

Source	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$\|A_\perp(t)\|^2$	$\|A_0(t)\|^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	ϕ_s [rad]	$\|\lambda\|$
Stat. uncertainty	0.0048	0.016	0.0086	0.0061	$^{+0.13}_{-0.21}$	0.22	0.091	0.031
Background subtraction	0.0041	0.002	–	0.0031	0.03	0.02	0.003	0.003
$B^0 \to J/\psi K^{*0}$ background	–	0.001	0.0030	0.0001	0.01	0.02	0.004	0.005
Ang. acc. reweighting	0.0007	–	0.0052	0.0091	0.07	0.05	0.003	0.020
Ang. acc. statistical	0.0002	–	0.0020	0.0010	0.03	0.04	0.007	0.006
Lower decay time acc. model	0.0023	0.002	–	–	–	–	–	–
Upper decay time acc. model	0.0040	–	–	–	–	–	–	–
Length and mom. scales	0.0002	–	–	–	–	–	–	–
Fit bias	–	–	0.0010	–	–	–	–	–
Decay-time resolution offset	–	–	–	–	–	0.04	0.006	–
Quadratic sum of syst.	0.0063	0.003	0.0064	0.0097	0.08	0.08	0.011	0.022
Total uncertainties	0.0079	0.016	0.0107	0.0114	$^{+0.15}_{-0.23}$	0.23	0.092	0.038

Very small systematics uncertainty on ϕ_s

Results [PRD 87, 112010 (2013)]

- $B_s^0 \to J/\psi K^+ K^-$ alone:

$$\begin{aligned}
\phi_s &= 0.07 \pm 0.09 \text{ (stat)} \pm 0.01 \text{ (syst) rad} \\
\Gamma_s \equiv (\Gamma_\mathrm{L} + \Gamma_\mathrm{H})/2 &= 0.663 \pm 0.005 \text{ (stat)} \pm 0.006 \text{ (syst)}\ \mathrm{ps}^{-1} \\
\Delta\Gamma_s \equiv \Gamma_\mathrm{L} - \Gamma_\mathrm{H} &= 0.100 \pm 0.016 \text{ (stat)} \pm 0.003 \text{ (syst)}\ \mathrm{ps}^{-1}
\end{aligned}$$

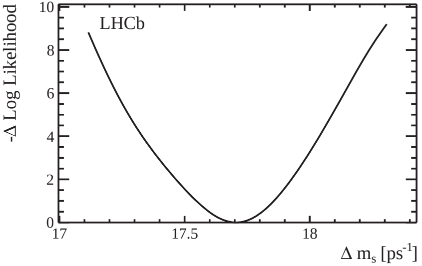
- World most precise measurements!

- Combined analysis with $B_s^0 \to J/\psi\pi^+\pi^-$ [PLB 713 (2012) 378]
  Final state is $> 98\%$ CP-odd [PRD86 052006 (2012)], no angular analysis required:

$$\begin{aligned}
\phi_s &= 0.01 \pm 0.07 \text{ (stat)} \pm 0.01 \text{ (syst) rad} \\
\Gamma_s &= 0.661 \pm 0.004 \text{ (stat)} \pm 0.006 \text{ (syst)}\ \mathrm{ps}^{-1} \\
\Delta\Gamma_s &= 0.106 \pm 0.011 \text{ (stat)} \pm 0.007 \text{ (syst)}\ \mathrm{ps}^{-1}
\end{aligned}$$

- Compatible with SM so far

By-product 1: standalone Δm_s measurement



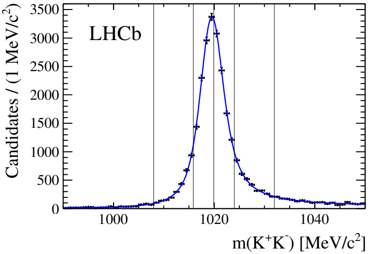
$$\Delta m_s = 17.70 \pm 0.10\ (\text{stat}) \pm 0.01\ (\text{syst})\ \text{ps}^{-1}$$ [PRD 87, 112010 (2013)]

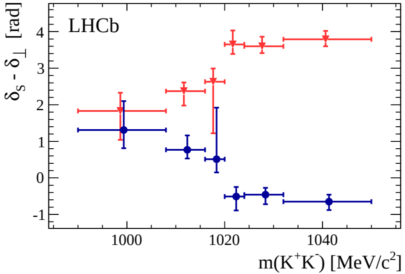
compatible with LHCb, New J. Phys. 15 (2013) 053021, 1 fb^{-1}, $B_s^0 \to D_s^- \pi^+$:

$$\Delta m_s = 17.768 \pm 0.023\ (\text{stat}) \pm 0.006\ (\text{syst})\ \text{ps}^{-1}$$

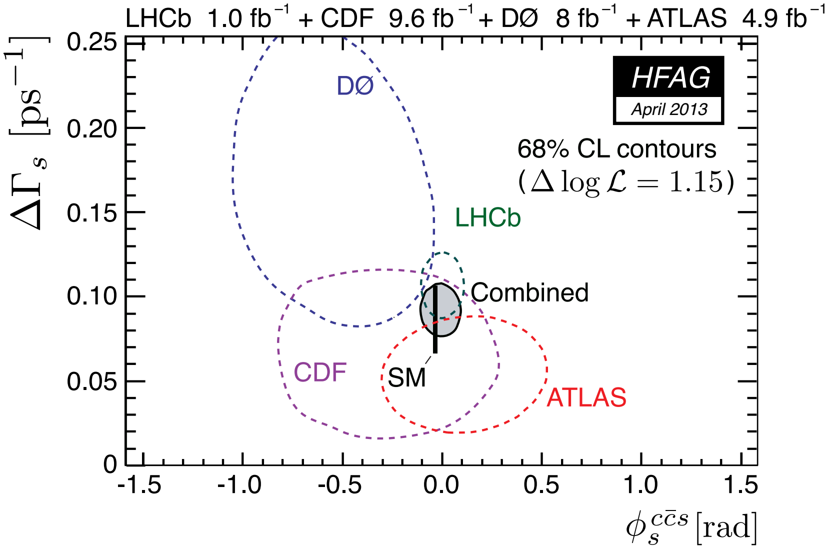
By-product 2: resolving the sign of $\Delta\Gamma_s$ [PRD 87, 112010 (2013)]

- Reminder: decay rates invariant under
  $(\phi_s, \Delta\Gamma_s, \delta_0, \delta_\parallel, \delta_\perp, \delta_S) \longmapsto (\pi - \phi_s, -\Delta\Gamma_s, -\delta_0, -\delta_\parallel, \pi - \delta_\perp, -\delta_S)$
- Expect:
  - P-wave phase increases rapidly with m_{KK}
  - S-wave phase varies slowly
  - hence $\delta_S - \delta_\perp$ decreases
- Observe:
  - falling phase trend (blue circles), hence $\Delta\Gamma_s > 0$





Comparison with other



[HFAG, preliminary]

Conclusions and prospects

- With 1 fb^{-1}, using $B_s^0 \to J/\psi K^+ K^-$ and $B_s^0 \to J/\psi \pi^+ \pi^-$, LHCb performed the world most precise measurements of:

$$\begin{aligned} \phi_s &= 0.01 \pm 0.07 \text{ (stat)} \pm 0.01 \text{ (syst) rad}, \\ \Gamma_s &= 0.661 \pm 0.004 \text{ (stat)} \pm 0.006 \text{ (syst) } \mathrm{ps}^{-1} \\ \Delta\Gamma_s &= 0.106 \pm 0.011 \text{ (stat)} \pm 0.007 \text{ (syst) } \mathrm{ps}^{-1} \end{aligned}$$

- Compatible with Standard Model so far
  $\longrightarrow$ Stronger constraints than ever on possible SM extensions in the B_s^0–$\overline{B}_s^0$ mixing phase and still room for NP!
- Expected total uncertainty on ϕ_s:
  - by the end of this year, using 3 fb^{-1}: ~ 0.05 rad
  - by the end of LHCb upgrade: ~ 0.008 rad

Backup

B mixing and lifetime I

The neutral B_q $(q = d, s)$ system is described by the following equation

$$i\frac{d}{dt}\begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix} = \left(\hat{M}^q - \frac{i}{2}\hat{\Gamma}^q\right)\begin{pmatrix} |B_q(t)\rangle \\ |\bar{B}_q(t)\rangle \end{pmatrix}$$

The famous box diagrams give rise to off-diagonal elements M_{12}^q and Γ_{12}^q in the mass matrix $\hat{M}^q$ and the decay rate matrix $\hat{\Gamma}^q$

Diagonalization of $\hat{M}^q$ and $\hat{\Gamma}^q$ gives the mass eigenstates

CP-odd: $B_H := p\,B + q\,\bar{B}$, CP-even: $B_L := p\,B - q\,\bar{B}$

with $|p|^2 + |q|^2 = 1$

with the corresponding masses M_H^q, M_L^q and decay rates Γ_H^q, Γ_L^q

B mixing and lifetime II

$|M_{12}^q|$, $|\Gamma_{12}^q|$ and $\phi_{12q} = \arg(-M_{12}^q/\Gamma_{12}^q)$ are related to three observables:

- **Mass difference:** $\Delta M_q := M_H^q - M_L^q = 2|M_{12}^q| \left(1 + \frac{1}{8}\frac{|\Gamma_{12}^q|^2}{|M_{12}^q|^2} \sin^2 \phi_{12q} + ...\right)$
  $|M_{12}^q|$: heavy virtual particles: t, SUSY, ...
- **Decay rate difference:**
  $\Delta\Gamma_q := \Gamma_L^q - \Gamma_H^q = 2|\Gamma_{12}^q| \cos \phi_{12q} \left(1 - \frac{1}{8}\frac{|\Gamma_{12}^q|^2}{|M_{12}^q|^2} \sin^2 \phi_{12q} + ...\right)$
  $|\Gamma_{12}^q|$: light real particles: u, c, ... no NP – below hadronic uncertainties
- **Flavour specific / semi leptonic CP asymmetries:**

$$a_{sl}^q = \mathrm{Im}\frac{\Gamma_{12}^q}{M_{12}^q} + \mathcal{O}\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right)^2 = \frac{\Delta\Gamma_q}{\Delta M_q} \tan \phi_{12q} + \mathcal{O}\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right)^2$$

New physics effects

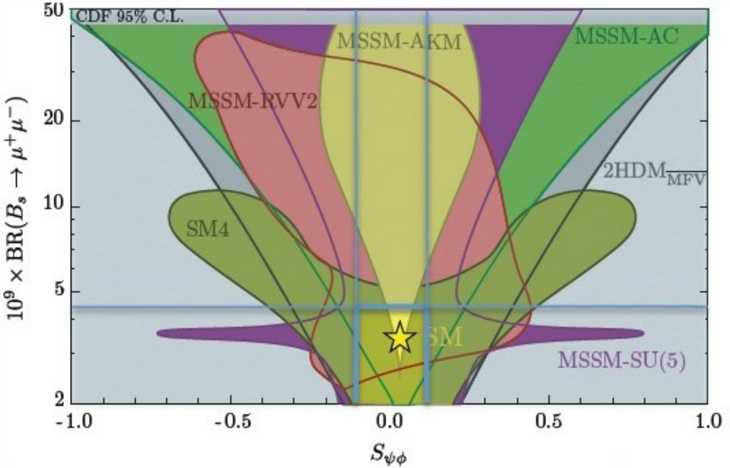
General parametrization of new physics effects in mixing

$$\Gamma_{12,s} = \Gamma_{12,s}^{\mathrm{SM}}\,, \qquad M_{12,s} = M_{12,s}^{\mathrm{SM}} \cdot \Delta_s\,; \qquad \Delta_s = |\Delta_s| e^{i\phi_s^\Delta}$$

leads to the following relations for observables

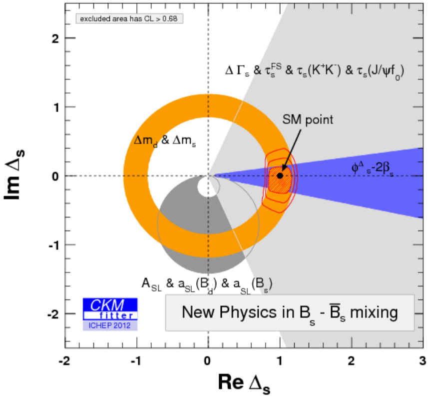
$$\begin{aligned}
\Delta M_s &= 2|M_{12,s}^{\mathrm{SM}}| \cdot |\Delta_s| \\
\Delta\Gamma_s &= 2|\Gamma_{12,s}| \cdot \cos\left(\phi_{12s}^{\mathrm{SM}} + \phi_s^\Delta\right) \\
a_{fs}^s &= \frac{|\Gamma_{12,s}|}{|M_{12,s}^{\mathrm{SM}}|} \cdot \frac{\sin\left(\phi_{12s}^{\mathrm{SM}} + \phi_s^\Delta\right)}{|\Delta_s|} \\
\phi_s^{J/\Psi\phi} &= -2\beta_s + \phi_s^\Delta + \delta_{\mathrm{Peng.}}^{\mathrm{SM}} + \delta_{\mathrm{Peng.}}^{\mathrm{NP}}
\end{aligned}$$

Remember: $\phi_{12s}^{\mathrm{SM}} = \arg(-M_{12}^s/\Gamma_{12}^s)$ and $\beta_s = \arg\left(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*\right)$



Correlation between the branching ratio of $B_s^0 \to \mu^+\mu^-$ and the mixing-induced CP asymmetry $-\sin\phi_s$ in the SM4, the two-Higgs doublet model with flavour blind phases and three SUSY favour models. The SM point is marked by a star.

NP in B_s^0 mixing



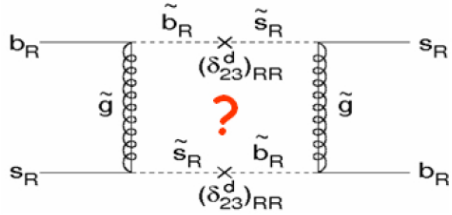
$$M_{12}^s = M_{12}^{\mathrm{SM},s} \Delta_s\,, \quad \Delta_s = |\Delta_s| e^{i\phi_s^\Delta}$$

$$Re(\Delta_s) = 0.940^{+0.199}_{-0.086} \text{ at } 68\% CL$$

$$Im(\Delta_s) = -0.04^{+0.11}_{-0.14} \text{ at } 68\% CL$$

[CKMfitter], after ICHEP2012, updated of arXiv:1203.0238v2. [LHCb-CONF-2012-022] ASLs included.

New physics in B_s^0-mixing



- **Examples of NP affecting Φ and being compatible with $\Delta m_s = 17.8 ps^{-1}$**
  - hep-ph/0703117 (little higgs model with T parity)
  - hep-ph/0703112 (susy, extra Z', little Higgs)
  - Hou et al., hep-ph/0810.3396 (4^{th} generation; top')
  - ...

New Physics

Example of NP models compatible with all current measurements and modifying ϕ_s: A. J. Buras et al. arXiv:1211.1237
Other recent articles:
arXiv:1204.3872
arXiv:1207.0688

B_s^0 mixing phase

$$\phi_{12} = \arg\left[-M_{12}/\Gamma_{12}\right]$$
$$\Delta\Gamma_s = 2|\Gamma_{12}|\cos\phi_{12} + \mathcal{O}\left(\left|\frac{\Gamma_{12}}{M_{12}}\right|^2\right)$$
$$\phi_{12}^{\mathrm{SM}} = 0.0038 \pm 0.0010 \text{ [Lenz]}$$
$$\phi_{12} = \phi_{12}^{\mathrm{SM}} + \phi_{12}^{\mathrm{NP}}$$
$$A_{SL}^s = \Im\left(\frac{\Gamma_{12}}{M_{12}}\right) + \mathcal{O}\left(\left|\frac{\Gamma_{12}}{M_{12}}\right|^2\right) = \frac{\Delta\Gamma_s}{\Delta m_s}\tan\phi_{12} + \mathcal{O}\left(\left|\frac{\Gamma_{12}}{M_{12}}\right|^2\right)$$
$$(\phi_s^{c\bar{c}s})^{\mathrm{SM}} = -2\beta_s = -0.0368 \pm 0.0014, \quad \beta_s = \arg\left[-\left(V_{ts}V_{tb}^*\right)/\left(V_{cs}V_{cb}^*\right)\right]$$
$$\phi_s^{c\bar{c}s} = -2\beta_s + \phi_{12}^{\mathrm{NP}}$$
$$\phi_{12} = \phi_{12}^{\mathrm{SM}} + 2\beta_s + \phi_s^{c\bar{c}s}$$

$P \to VV$ decays

- B_s^0 is a pseudoscalar meson ($J^P = 1^-$), ϕ and J/ψ are vector mesons ($J^P = 1^-$)
- Total angular momentum conservation $\Rightarrow$ in the B_s^0 rest frame, ϕ and J/ψ have relative orbital momentum ℓ=0, 1, 2
- Since $CP|J/\psi\phi\rangle = (-1)^\ell|J/\psi\phi\rangle$, final state is a mixture of CP-even ($\ell = 0, 2$) and CP-odd ($\ell = 1$)
- Decompose decay amplitudes in terms of linear polarization, when J/ψ and ϕ are:
  - A_0: longitudinally polarized (CP-even)
  - $A_\perp$: transversely polarized and $\perp$ to each other (CP-odd)
  - $A_\|$: transversely polarized and $\|$ to each other (CP-even)
- $B_s^0 \to J/\psi K^+K^-$ can also be produced with K^+K^- pairs in an S-wave configuration (CP-odd).

- $\to$ 3 angles describe directions of final decay products $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$

Decay rate for $B_s^0 \to J/\psi K^+ K^-$

$$\frac{d^4\Gamma(B_s^0 \to J/\psi K^+K^-)}{dt\, d\Omega} \propto \sum_{k=1}^{10} h_k(t)\, f_k(\Omega)$$

$$h_k(t) = N_k e^{-\Gamma_s t} \left[a_k \cosh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + b_k \sinh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t)\right]$$

k	$f_k(\theta_\mu, \theta_K, \varphi_h)$	N_k	a_k	b_k	c_k	d_k
1	$2\cos^2\theta_K \sin^2\theta_\mu$	$\lvert A_0(0)\rvert^2$	1	D	C	$-S$
2	$\sin^2\theta_K \left(1-\sin^2\theta_\mu \cos^2\varphi_h\right)$	$\lvert A_\parallel(0)\rvert^2$	1	D	C	$-S$
3	$\sin^2\theta_K \left(1-\sin^2\theta_\mu \sin^2\varphi_h\right)$	$\lvert A_\perp(0)\rvert^2$	1	$-D$	C	S
4	$\sin^2\theta_K \sin^2\theta_\mu \sin 2\varphi_h$	$\lvert A_\parallel(0)A_\perp(0)\rvert$	$C\sin(\delta_\perp-\delta_\parallel)$	$S\cos(\delta_\perp-\delta_\parallel)$	$\sin(\delta_\perp-\delta_\parallel)$	$D\cos(\delta_\perp-\delta_\parallel)$
5	$\frac{1}{2}\sqrt{2}\sin 2\theta_K \sin 2\theta_\mu \cos\varphi_h$	$\lvert A_0(0)A_\parallel(0)\rvert$	$\cos(\delta_\parallel-\delta_0)$	$D\cos(\delta_\parallel-\delta_0)$	$C\cos(\delta_\parallel-\delta_0)$	$-S\cos(\delta_\parallel-\delta_0)$
6	$-\frac{1}{2}\sqrt{2}\sin 2\theta_K \sin 2\theta_\mu \sin\varphi_h$	$\lvert A_0(0)A_\perp(0)\rvert$	$C\sin(\delta_\perp-\delta_0)$	$S\cos(\delta_\perp-\delta_0)$	$\sin(\delta_\perp-\delta_0)$	$D\cos(\delta_\perp-\delta_0)$
7	$\frac{2}{3}\sin^2\theta_\mu$	$\lvert A_S(0)\rvert^2$	1	$-D$	C	S
8	$\frac{1}{3}\sqrt{6}\sin\theta_K \sin 2\theta_\mu \cos\varphi_h$	$\lvert A_S(0)A_\parallel(0)\rvert$	$C\cos(\delta_\parallel-\delta_S)$	$S\sin(\delta_\parallel-\delta_S)$	$\cos(\delta_\parallel-\delta_S)$	$D\sin(\delta_\parallel-\delta_S)$
9	$-\frac{1}{3}\sqrt{6}\sin\theta_K \sin 2\theta_\mu \sin\varphi_h$	$\lvert A_S(0)A_\perp(0)\rvert$	$\sin(\delta_\perp-\delta_S)$	$-D\sin(\delta_\perp-\delta_S)$	$C\sin(\delta_\perp-\delta_S)$	$S\sin(\delta_\perp-\delta_S)$
10	$\frac{4}{3}\sqrt{3}\cos\theta_K \sin^2\theta_\mu$	$\lvert A_S(0)A_0(0)\rvert$	$C\cos(\delta_0-\delta_S)$	$S\sin(\delta_0-\delta_S)$	$\cos(\delta_0-\delta_S)$	$D\sin(\delta_0-\delta_S)$

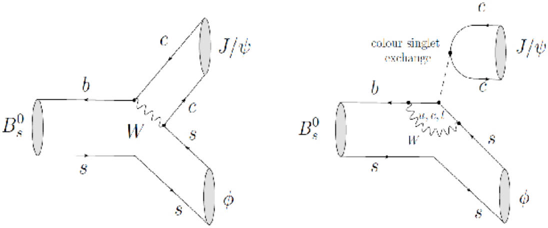
$$C \equiv \frac{1-|\lambda|^2}{1+|\lambda|^2}, \qquad S \equiv \frac{2\Im(\lambda)}{1+|\lambda|^2}, \qquad D \equiv \frac{-2\Re(\lambda)}{1+|\lambda|^2}.$$

$$\lambda_i \equiv \frac{q}{p}\frac{\bar{A}_i}{A_i}, \quad \eta_i = +1 \text{ for } i \in \{0, \parallel\} \text{ and } -1 \text{ for } i \in \{\perp, \mathrm{S}\}$$

$$\lambda_i = \eta_i \lambda, \quad \phi_s \equiv -\arg(\lambda)$$

Penguin pollution in $B_s^0 \to J/\psi\phi$

- In the SM, $B_s \to J/\psi\phi$ decay is dominated by a single weak phase: $V_{cs}V_{cb}^*$



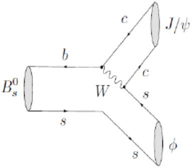
$$A(\bar{b} \to \bar{c}c\bar{s}) = V_{cs}V_{cb}^*(A_T + P_c) + V_{us}V_{ub}^*P_u + V_{ts}V_{tb}^*P_t$$
$$= V_{cs}V_{cb}^*(A_T + P_c - P_t) + V_{us}V_{ub}^*(P_u - P_t)$$

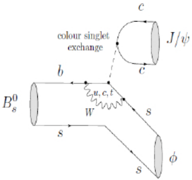
$V_{ts}V_{tb}^* = -V_{us}V_{ub}^* - V_{cs}V_{cb}^*$; $\sim A\lambda^2(1 - \lambda^2/2)$; $\sim A\lambda^4(\rho + i\eta)$

- Various penguin pollution estimates:
  - $\delta P \sim 10^{-4}$ [H. Boos et al., Phys.Rev. D70 (2004) 036006]
  - $\delta P \sim 10^{-3}$ [M. Gronau et al., arXiv:0812.4796]
  - δP up to ~0.1 [S. Faller et al., arXiv:0810.4248v1]

Penguin pollution in $B_s^0 \to J/\psi\phi$

[S. Faller et al. arXiv:0810.4248]

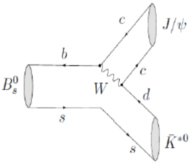


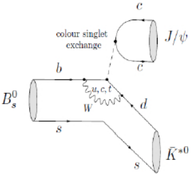


$\bar{b} \to \bar{s}c\bar{c}$

Penguins suppressed by λ^2

$$A(B_s^0 \to (J/\psi\phi)_f) = \left(1 - \frac{\lambda^2}{2}\right) \mathcal{A}_f \left[1 + \epsilon a_f e^{i\theta_f} e^{i\gamma}\right] \qquad \epsilon \equiv \lambda^2/(1-\lambda^2)$$





$\bar{b} \to \bar{d}c\bar{c}$

Penguins NOT suppressed wrt tree

$$A(B_s^0 \to (J/\psi \bar{K}^{*0})_f) = \lambda \mathcal{A}'_f \left[1 - a'_f e^{i\theta'_f} e^{i\gamma}\right]$$

Penguin pollution in $B_s^0 \to J/\psi\phi$

- In LHC, we have started to apply the method proposed in [S. Faller et al. arXiv:0810.4248]
- LHCb, PRD 86, 071102(R) (2012): using only $0.37\,\mathrm{fb}^{-1}$, we measure $\mathcal{B}(\mathrm{B_s^0} \to \mathrm{J/\psi \overline{K}^{*0}})$ = $(4.4^{+0.5}_{-0.4} \pm 0.8) \times 10^{-5}$ and the polarization fractions: $|A_0(0)|^2 = 0.50 \pm 0.08 \pm 0.02$, $|A_{\|}(0)|^2 = 0.19^{+0.10}_{-0.08} \pm 0.02$.
- Update with $3\,\mathrm{fb}^{-1}$ongoing and measurement of direct CPV in $B_s^0 \to J/\psi \overline{K}^{*0}$
- Other approaches to reduce penguin pollution:
  B. Bhattacharya et al., Int.J.Mod.Phys. A28 (2013) 1350063.
  M. Jung, arXiv:1212.4789.

A way to introduce β_s

V_{CKM} can be written with 4 independent parameters:

- the « usual » Wolfenstein parameters λ, A, ρ, η

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

- Or $|V_{us}|$, $|V_{ub}|$, $|V_{cb}|$, $|V_{td}|$ [Branco 1988]
- Or 4 independent phases: γ, β, β_s, β_K

$$\gamma = \arg\left(-\frac{V_{\mathrm{ud}}V_{\mathrm{ub}}^*}{V_{\mathrm{cd}}V_{\mathrm{cb}}^*}\right)$$

$$\beta = \arg\left(-\frac{V_{\mathrm{cd}}V_{\mathrm{cb}}^*}{V_{\mathrm{td}}V_{\mathrm{tb}}^*}\right)$$

$$\beta_{\mathrm{s}} = \arg\left(-\frac{V_{\mathrm{ts}}V_{\mathrm{tb}}^*}{V_{\mathrm{cs}}V_{\mathrm{cb}}^*}\right)$$

$$\beta_{\mathrm{K}} = \arg\left(-\frac{V_{\mathrm{us}}V_{\mathrm{ud}}^*}{V_{\mathrm{cs}}V_{\mathrm{cd}}^*}\right)$$

- References:

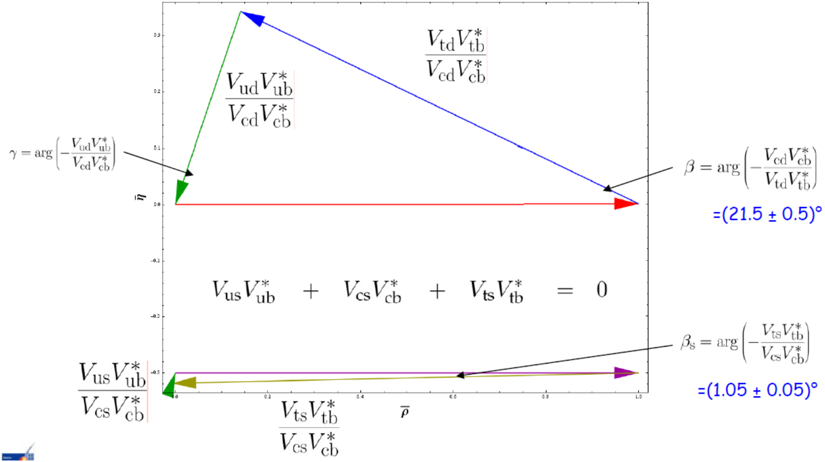
  - G. C. Branco and L. Lavoura, Phys. Lett. B 208, 123 (1988).
  - G. C. Branco et al., CP violation, Oxford University Press, (1999)
  - R. Aleksan, B. Kayser, and D. London. Determining the Quark Mixing Matrix from CP-Violating Asymmetries. *Phys. Rev. Lett.*, 73:18.20, 1994, hep-ph/9403341
  - See also: J. Silva, hep-ph/0410351

b–d and b–s unitarity triangles

SM values, both triangles on the same scale, bs triangle shifted by etabar-0.3 to be visible

b-d triangIde divided by VcdVcb*; while bs triangle divided by VcsVcb*

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



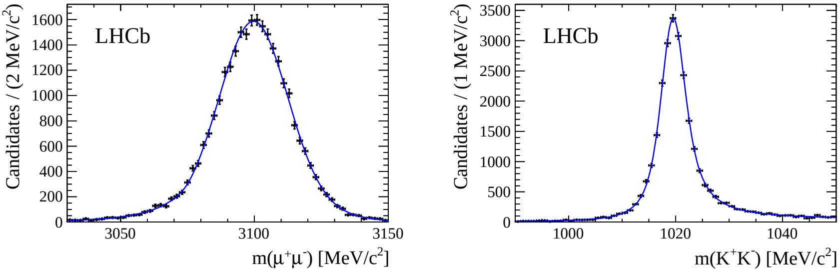
Selection of $B_s^0 \to J/\psi K^+ K^-$ candidates

[PRD 87, 112010 (2013)]

Decay mode	Cut parameter	Stripping	Final selection
all tracks	$\chi^2_{\rm track}/{\rm nDoF}$	< 5	< 4
	clone distance	–	> 5000
$J/\psi \to \mu^+\mu^-$	$\Delta \ln \mathcal{L}_{\mu\pi}$	> 0	> 0
	$min(p_{\rm T}(\mu^+), p_{\rm T}(\mu^-))$	–	> 0.5 GeV/c
	$\chi^2_{\rm vtx}/{\rm nDoF}(J/\psi)$	< 16	< 16
	$\lvert M(\mu^+\mu^-) - M(J/\psi)\rvert$	< 80 MeV/c^2	$\in$ [3030, 3150] MeV/c^2
$\phi \to K^+K^-$	$\Delta \ln \mathcal{L}_{K\pi}$	> -2	> 0
	$p_{\rm T}(\phi)$	> 1 GeV/c	> 1 GeV/c
	$M(\phi)$	$\in$ [980, 1050] MeV/c^2	$\in$ [990, 1050] MeV/c^2
	$\chi^2_{\rm vtx}/{\rm nDoF}(\phi)$	< 16	< 16
$B_s^0 \to J/\psi\phi$	$M(B_s^0)$	$\in$ [5200, 5550] MeV/c^2	$\in$ [5200, 5550] MeV/c^2
	$\chi^2_{\rm vtx}/{\rm nDoF}(B_s^0)$	< 10	< 10
	$\chi^2_{\rm DTF(B+PV)}/{\rm nDoF}(B_s^0)$	–	< 5
	$\chi^2_{\rm IP}(B_s^0)$	–	< 25
	$\chi_{\rm IP,next}(B_s^0)$	–	> 50
	$t(*)$	> 0.2 ps	[0.3, 14.0] ps

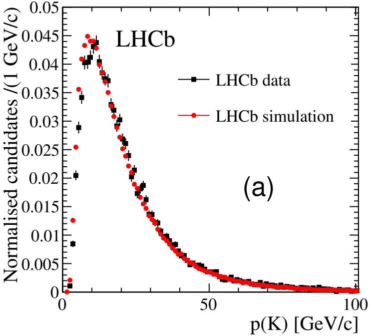
Selection

[PRD 87, 112010 (2013)]



Background subtracted invariant mass distributions of the $\mu^+\mu^-$ (left) and K^+K^- (right) systems in the selected sample of $B_s^0 \to J/\psi K^+K^-$ candidates (full $m(J/\psi K^+K^-)$ range). The solid blue line represents the fit to the data points.

Systematics related to angular acceptance [PRD 87, 112010 (2013)]



Background-subtracted kaon (a) and muon (b) momentum distributions for $B_s^0 \to J/\psi K^+ K^-$ signal events in data compared to simulated $B_s^0 \to J/\psi \phi$ signal events. The distributions are normalised to the same area. A larger deviation is visible for kaons.

Fit [PRD 87, 112010 (2013)]

- Unbinned maximum likelihhod fit

$$-\ln \mathcal{L} = -\alpha \sum_{\text{events } i} W_i \ln \mathcal{S}$$

- W_i = signal sWeights, using sPlot on the $B_s^0 \to J/\psi K^+ K^-$ invariant mass, fitted 2G+Exp
- $\alpha = \sum_i W_i / \sum_i W_i^2$ is used to include the effect of the weights in the determination of the uncertainties [arXiv:0905.0724]

$$S(\lambda, t, \Omega) = \epsilon(t, \Omega) \cdot \left[\left(\frac{1+qD}{2} \cdot P_B(\lambda, t, \Omega) + \frac{1-qD}{2} \cdot \overline{P_B}(\lambda, t, \Omega) \right) \otimes R_t \right]$$

Ingredients:

Proper time and angular acceptance ($\epsilon(t, \Omega)$) — tagging ($\frac{1+qD}{2}$, $\frac{1-qD}{2}$) — Proper time resolution (R_t)

$B_s^0 \to J/\psi K^+K^-$ fit, S-P correction factors [PRD 87, 112010 (2013)]

- In each m_{KK} bin, variation of the S-wave lineshape (assumed $\sim$ uniform) wrt the P-wave lineshape (relativistic Breit-Wigner)
- In each m_{KK} bin, compute:

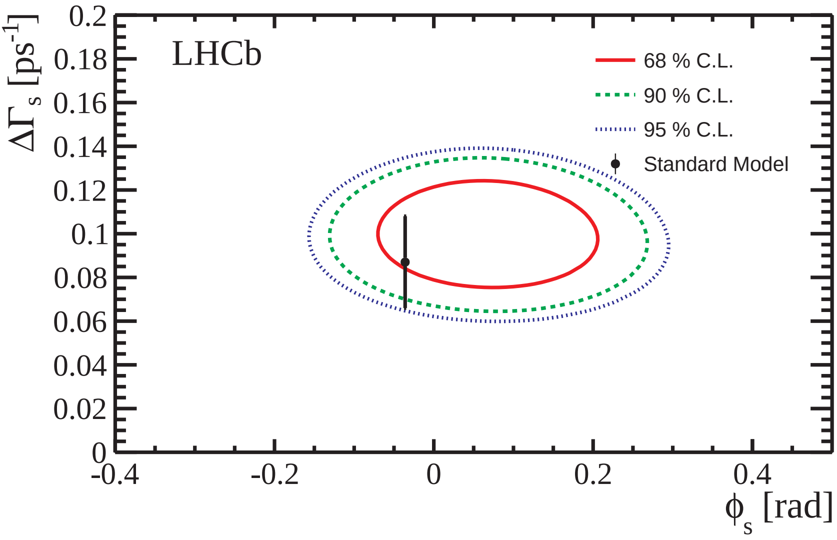
$$\int_{m^L}^{m^H} ps^* \; \mathrm{d}m(K^+K^-) = C_{\mathrm{SP}} e^{-i\theta_{\mathrm{SP}}}$$

- Multiply f_8, f_9, and f_{10} by C_{CP}
- θ_{SP} is absorbed in the measurements of $\delta_{\mathrm{S}} - \delta_{\perp}$

Bins of $m(K^+K^-)$ used in the analysis and the C_{SP} correction factors for the S-wave interference term, assuming a uniform distribution of non-resonant K^+K^- contribution and a non-relativistic Breit-Wigner shape for the decays via the ϕ resonance.

$m(K^+K^-)$ bin [MeV/c^2]	C_{SP}
990 – 1008	0.966
1008 – 1016	0.956
1016 – 1020	0.926
1020 – 1024	0.926
1024 – 1032	0.956
1032 – 1050	0.966

Results [PRD 87, 112010 (2013)]



Results [PRD 87, 112010 (2013)]

Parameter	Value	σ_{stat}	σ_{sys}
Γ_s [ps^{-1}]	0.661	0.004	0.006
$\Delta\Gamma_s$ [ps^{-1}]	0.106	0.011	0.007
$\lvert A_\perp(t)\rvert^2$	0.246	0.007	0.006
$\lvert A_0(t)\rvert^2$	0.523	0.005	0.010
$\delta_\parallel$ [rad]	3.32	$^{+0.13}_{-0.21}$	0.08
$\delta_\perp$ [rad]	3.04	0.20	0.07
ϕ_s [rad]	0.01	0.07	0.01
$\lvert\lambda\rvert$	0.93	0.03	0.02

Results of combined fit to the $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi\pi^+\pi^-$ datasets.

Results [PRD 87, 112010 (2013)]

Results of the maximum likelihood fit for the S-wave parameters, with asymmetric statistical and symmetric systematic uncertainties.

$m(K^+K^-)$ bin [MeV/c^2]	Parameter	Value	σ_{stat} (asymmetric)	σ_{syst}
990 – 1008	F_S	0.227	$+0.081, -0.073$	0.020
	$\delta_S - \delta_\perp$ [rad]	1.31	$+0.78, -0.49$	0.09
1008 – 1016	F_S	0.067	$+0.030, -0.027$	0.009
	$\delta_S - \delta_\perp$ [rad]	0.77	$+0.38, -0.23$	0.08
1016 – 1020	F_S	0.008	$+0.014, -0.007$	0.005
	$\delta_S - \delta_\perp$ [rad]	0.51	$+1.40, -0.30$	0.20
1020 – 1024	F_S	0.016	$+0.012, -0.009$	0.006
	$\delta_S - \delta_\perp$ [rad]	-0.51	$+0.21, -0.35$	0.15
1024 – 1032	F_S	0.055	$+0.027, -0.025$	0.008
	$\delta_S - \delta_\perp$ [rad]	-0.46	$+0.18, -0.26$	0.05
1032 – 1050	F_S	0.167	$+0.043, -0.042$	0.021
	$\delta_S - \delta_\perp$ [rad]	-0.65	$+0.18, -0.22$	0.06

Results [PRD 87, 112010 (2013)]

Statistical and systematic uncertainties for S-wave fractions in bins of $m(K^+K^-)$.

Source	bin 1 F_S	bin 2 F_S	bin 3 F_S	bin 4 F_S	bin 5 F_S	bin 6 F_S
Stat. uncertainty	$^{+0.081}_{-0.073}$	$^{+0.030}_{-0.027}$	$^{+0.014}_{-0.007}$	$^{+0.012}_{-0.009}$	$^{+0.027}_{-0.025}$	$^{+0.043}_{-0.042}$
Background subtraction	0.014	0.003	0.001	0.002	0.004	0.006
$B^0 \rightarrow J/\psi K^{*0}$background	0.010	0.006	0.001	0.001	0.002	0.018
Angular acc. reweighting	0.004	0.006	0.004	0.005	0.006	0.007
Angular acc. statistical	0.003	0.003	0.002	0.001	0.003	0.004
Fit bias	0.009	–	0.002	0.002	0.001	0.001
Quadratic sum of syst.	0.020	0.009	0.005	0.006	0.008	0.021
Total uncertainties	$^{+0.083}_{-0.076}$	$^{+0.031}_{-0.029}$	$^{+0.015}_{-0.009}$	$^{+0.013}_{-0.011}$	$^{+0.028}_{-0.026}$	$^{+0.048}_{-0.047}$

Results [PRD 87, 112010 (2013)]

Statistical and systematic uncertainties for S-wave phases in bins of $m(K^+K^-)$.

Source	bin 1 $\delta_S - \delta_\perp$ [rad]	bin 2 $\delta_S - \delta_\perp$ [rad]	bin 3 $\delta_S - \delta_\perp$ [rad]	bin 4 $\delta_S - \delta_\perp$ [rad]	bin 5 $\delta_S - \delta_\perp$ [rad]	bin 6 $\delta_S - \delta_\perp$ [rad]
Stat. uncertainty	$^{+0.78}_{-0.49}$	$^{+0.38}_{-0.23}$	$^{+1.40}_{-0.30}$	$^{+0.21}_{-0.35}$	$^{+0.18}_{-0.26}$	$^{+0.18}_{-0.22}$
Background subtraction	0.03	0.02	–	0.03	0.01	0.01
$B^0 \to J/\psi K^{*0}$background	0.08	0.04	0.08	0.01	0.01	0.05
Angular acc. reweighting	0.02	0.03	0.12	0.13	0.03	0.01
Angular acc. statistical	0.033	0.023	0.067	0.036	0.019	0.015
Fit bias	0.005	0.043	0.112	0.049	0.022	0.016
C_{SP} factors	0.007	0.028	0.049	0.025	0.021	0.020
Quadratic sum of syst.	0.09	0.08	0.20	0.15	0.05	0.06
Total uncertainties	$^{+0.79}_{-0.50}$	$^{+0.39}_{-0.24}$	$^{+1.41}_{-0.36}$	$^{+0.26}_{-0.38}$	$^{+0.19}_{-0.26}$	$^{+0.19}_{-0.23}$

Correlation matrix for the principal physics parameters, $B_s^0 \to J/\psi K^+K^-$ only

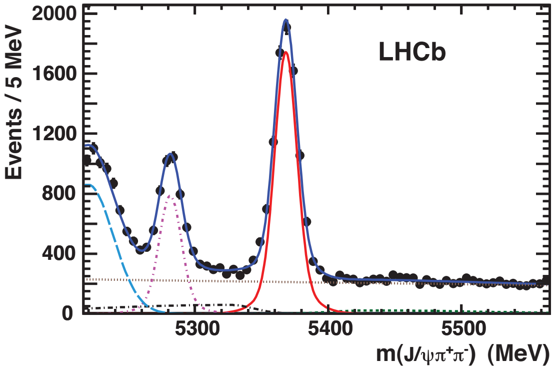
[LHCb, PRD 87, 112010 (2013)]

	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$\lvert A_\perp(t)\rvert^2$	$\lvert A_0(t)\rvert^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	ϕ_s [rad]	$\lvert\lambda\rvert$
Γ_s [ps^{-1}]	1.00	**−0.39**	**0.37**	**−0.27**	−0.09	−0.03	0.06	0.03
$\Delta\Gamma_s$ [ps^{-1}]		1.00	**−0.68**	**0.63**	0.03	0.04	−0.04	0.00
$\lvert A_\perp(t)\rvert^2$			1.00	**−0.58**	**−0.28**	−0.09	0.08	−0.04
$\lvert A_0(t)\rvert^2$				1.00	−0.02	−0.00	−0.05	0.02
$\delta_\parallel$ [rad]					1.00	**0.32**	−0.03	0.05
$\delta_\perp$ [rad]						1.00	**0.28**	0.00
ϕ_s [rad]							1.00	0.04
$\lvert\lambda\rvert$								1.00

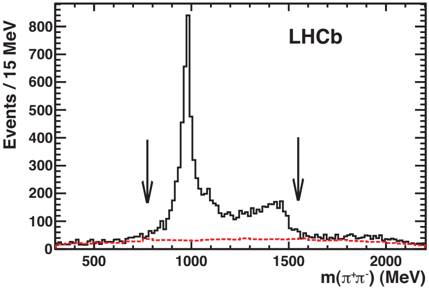
More on systematics [LHCb, PRD 87, 112010 (2013)]

- Acceptance at high decay time is due to time-dependent VELO reconstruction inefficiencies and some selection cuts.
- This acceptance is parametrised as $(1 + \beta t)$ with $\beta = (-8.3 \pm 4.0) \times 10^{-3}\,\mathrm{ps}^{-1}$, obtained from a mix of data and MC samples.
- Flavour tagging and time resolution uncertainties are included in the statistical errors.

1 fb^{-1}, 7421 $\pm$ 105 $B_s^0 \to J/\psi\pi^+\pi^-$ signal candidates



Mass distribution of the selected $J/\psi\pi^+\pi^-$ combinations in the $f_{\rm odd}$ region. The blue solid curve shows the result of a fit with a double Gaussian signal (red solid curve) and several background components: combinatorial background (brown dotted line), background from $B^- \to J/\psi K^-$ and $J/\psi\pi^-$ (green short-dashed line), $\overline{B}^0 \to J/\psi\pi^+\pi^-$ (purple dot-dashed), $\overline{B}_s^0 \to J/\psi\eta'$ and $\overline{B}_s^0 \to J/\psi\phi$ when $\phi \to \pi^+\pi^-\pi^0$ (black dot-long-dashed), and $\overline{B}^0 \to J/\psi K^-\pi^+$ (light-blue long-dashed).

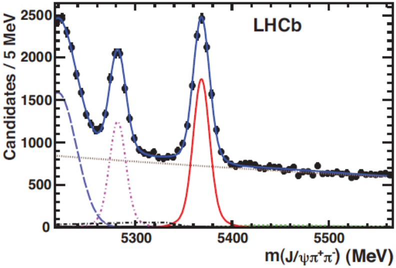


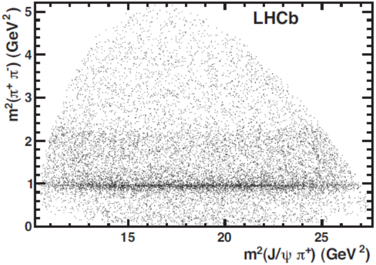
- $B_s^0 \to J/\psi\pi^+\pi^-$ final state is $> 98\%$ CP-odd, [LHCb, PRD86 052006 (2012)]
- No angular analysis required
- $\phi_s = -0.14^{+0.17}_{-0.16} \pm 0.01\,\mathrm{rad}$
- Main systematics: direct CP parameter fixed to 1, mass signal-background and decay time background PDF parameters fixed

Phys. Rev. **D86** (2012) 052006

- With 1 fb^{-1}, $B_s^0 \to J/\psi\pi^+\pi^-$ candidates are reconstructed in the full $\pi\pi$ mass range.

- To analyse the resonant component, a modified Dalitz plot analysis of the final states has been used:
  - $s_{13} = m^2(J/\psi\pi^+)$
  - $s_{23} = m^2(\pi^+\pi^-)$
  - Helicity angle $\theta_{J/\psi}$

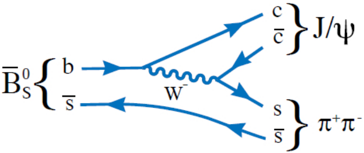




$B_s^0 \to J/\psi\pi^+\pi^-$, resonance models

[LHCb, PRD 86 (2012) 052006]

- $s\bar{s}$ system is in an isoscalar state at leading order.
- $\pi\pi$ wavefunction must be symmetric. $\rightarrow$ Only spin-0 and -2 mesons.
- $\rho(770)$ component added to test high order processes.
- Several scenarios have been tried to get the best significant Poisson likelihood χ^2 (goodness-of-fit).



Resonance	Spin	Helicity	Resonance formalism
$f_0(600)$	0	0	BW
$\rho(770)$	1	$0, \pm1$	BW
$f_0(980)$	0	0	Flatté
$f_2(1270)$	2	$0, \pm1$	BW
$f_0(1370)$	0	0	BW
$f_0(1500)$	0	0	BW

Name	Components
Single R	$f_0(980)$
2R	$f_0(980) + f_0(1370)$
3R	$f_0(980) + f_0(1370) + f_2(1270)$
3R + NR	$f_0(980) + f_0(1370) + f_2(1270)$ + nonresonant
3R + NR + $\rho(770)$	$f_0(980) + f_0(1370) + f_2(1270)$ + nonresonant + $\rho(770)$
3R + NR + $f_0(1500)$	$f_0(980) + f_0(1370) + f_2(1270)$ + nonresonant + $f_0(1500)$
3R + NR + $f_0(600)$	$f_0(980) + f_0(1370) + f_2(1270)$ + nonresonant + $f_0(600)$

$B_s^0 \to J/\psi\pi^+\pi^-$, results

[LHCb, PRD 86 (2012) 052006]

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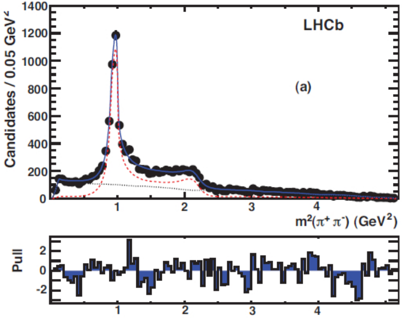
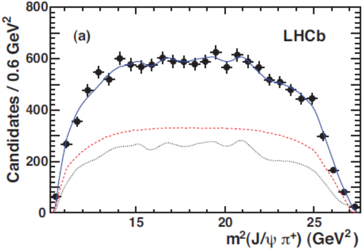
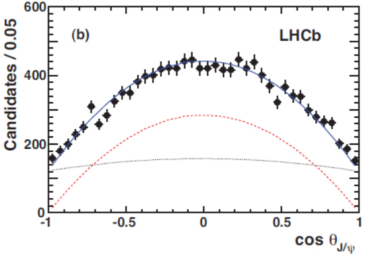
- The background PDF is parametrised from a wrong-sign $J/\psi\pi^\pm\pi^\pm$ sample and random $J/\psi + \rho(770)$ from MC.
- The best significant χ^2 is obtained with the $f_0(980)$+$f_2(1270)$+$f_0(1370)$ and non-resonant model.
- Existence of $B_s^0 \to J/\psi f_0(1370)$ clearly established now.







CPV in B_s^0 and B^0 mixing

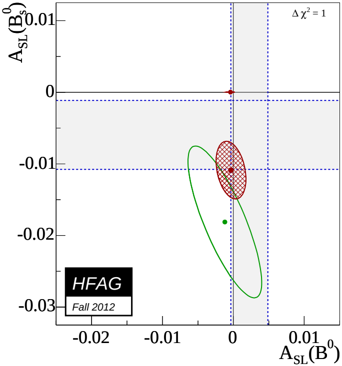
$$A_{SL}^d = \frac{N(\overline{B}^0(t) \to \ell^+ \nu_\ell X) - N(B^0(t) \to \ell^- \bar{\nu}_\ell X)}{N(\overline{B}^0(t) \to \ell^+ \nu_\ell X) + N(B^0(t) \to \ell^- \bar{\nu}_\ell X)} = \frac{|p/q|_d^2 - |q/p|_d^2}{|p/q|_d^2 + |q/p|_d^2}$$

DØ measures [PRD84, 052007 (2011)] :

$$A_{SL}^b = \frac{f_d Z_d A_{SL}^d + f_s Z_s A_{SL}^s}{f_d Z_d + f_s Z_s} \quad = \quad -0.00787 \pm 0.00172(\text{stat}) \pm 0.00093(\text{syst})$$

where $Z_q = 1/(1 - y_q^2) - 1/(1 + x_q^2) = 2\chi_q/(1 - y_q^2)$, $q = d, s$

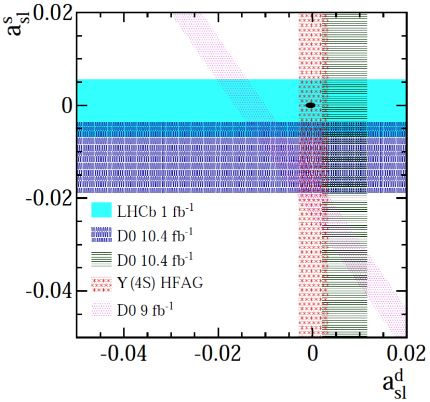
CPV in B_s^0 and B^0 mixing



Direct measurements of A_{SL}^s and A_{SL}^d (B^0 average as the vertical band, B_s^0 average as the horizontal band, D0 dimuon result as the green ellipse), together with their two-dimensional average (red hatched ellipse). The red point close to $(0,0)$ is the Standard Model prediction with error bars multiplied by 10. The prediction and the experimental average deviate from each other by 2.4σ.

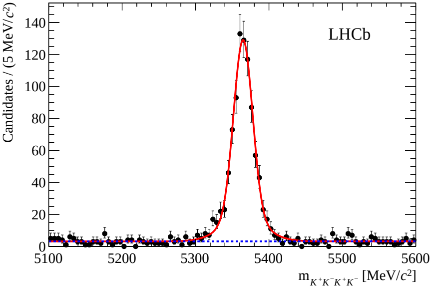
[HFAG 2012, preliminary]

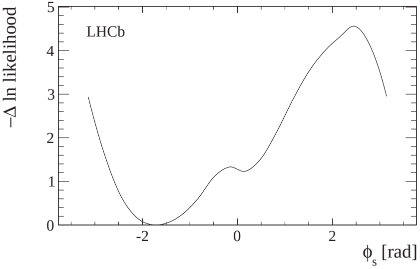
LHCb-PAPER-2013-033, arXiv:1308.1048, submitted to PLB



$a^s_{sl} = (-0.06 \pm 0.50 \pm 0.36)\%$ [LHCb-PAPER-2013-033]

$B_s^0 \to \phi\phi$ [PRL 110, 241802 (2013)]

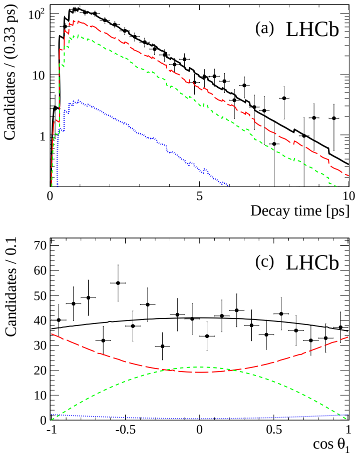


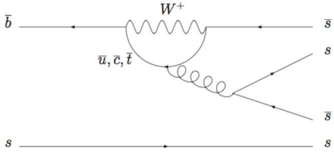


- Pure $b \to s\bar{s}s$ penguin mode
- SM expectation for CP violating weak phase $|\phi_s^{s\bar{s}s}| < 0.02^\dagger$
- Tagged time-dependent angular analysis, 1 fb^{-1} 880 $B_s^0 \to \phi\phi$ candidates
- $\phi_s^{s\bar{s}s} \in [-2.46, -0.76]\,\mathrm{rad}$ at 68% CL

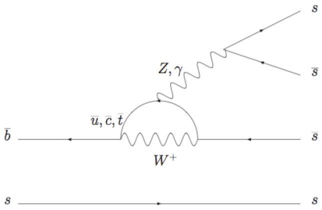
† Bartsch et al., arXiv:8010.0249, Beneke et al., Nucl.Phys. B774 (2007)64, Cheng et al., PRD 80 (2009) 114026.

$B_s^0 \to \phi\phi$ [PRL 110, 241802 (2013)]

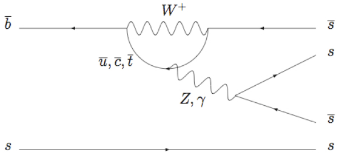




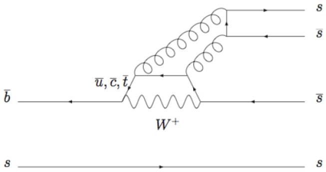
(a) gluonic penguin



(b) colour-allowed electroweak penguin



(c) colour-suppressed electroweak penguin



(d) singlet penguin

Comparison $B_s^0 \to J/\psi\phi$, $B^0 \to J/\psi K^{*0}$

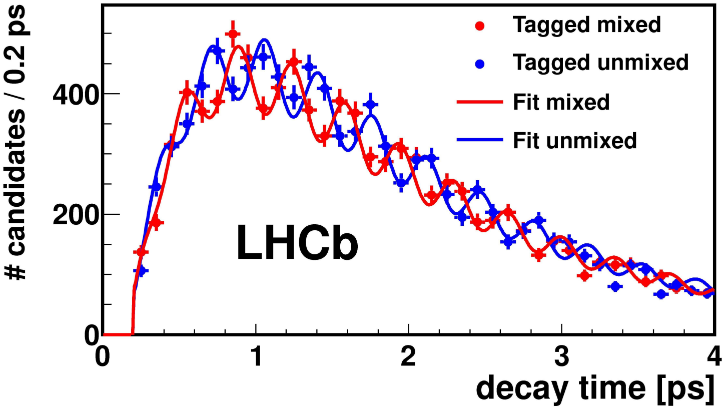
$B_s^0 \to J/\psi\phi$: LHCb, PRD 87, 112010 (2013)
$B^0 \to J/\psi K^{*0}$: LHCb, arXiv:1307.2782

	$\|A_0\|^2$	$\|A_\perp\|^2$	$\|A_\parallel\|^2$
$B_s^0 \to J/\psi\phi$	$0.521 \pm 0.006 \pm 0.010$	$0.249 \pm 0.009 \pm 0.006$	$0.230 \pm 0.007 \pm 0.012$
$B^0 \to J/\psi K^{*0}$	$0.572 \pm 0.003 \pm 0.014$	$0.201 \pm 0.004 \pm 0.008$	$0.227 \pm 0.004 \pm 0.011$

$|A_0|^2$: compatible at 2.8σ
$|A_\perp|^2$: 3.4σ
$|A_\parallel|^2$: compatible at 0.2σ

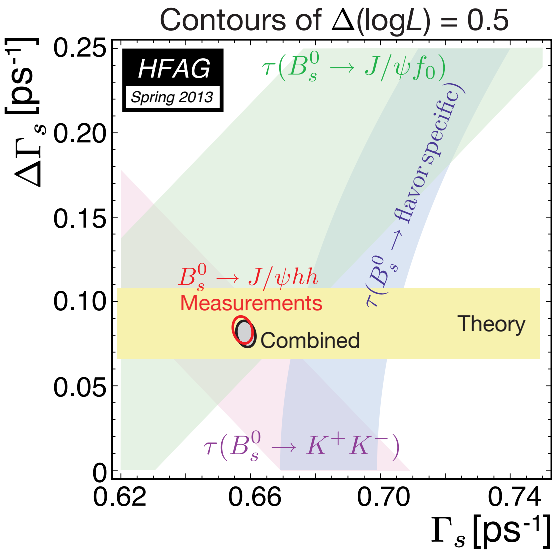
LHCb, New J. Phys. 15 (2013) 053021

$1\,\mathrm{fb}^{-1}\ B_s^0 \to D_s^- \pi^+$



$$\Delta m_s = 17.768 \pm 0.023\ (\text{stat}) \pm 0.006\ (\text{syst})\,\mathrm{ps}^{-1}$$

$\Delta\Gamma_s$, Γ_s, HFAG averages



Comparison with other

[PRD 87, 112010 (2013)] (1 fb^{-1}, this talk):

$$\begin{aligned}
\phi_s &= 0.01 \pm 0.07 \text{ (stat)} \pm 0.01 \text{ (syst) rad},\\
\Gamma_s &= 0.661 \pm 0.004 \text{ (stat)} \pm 0.006 \text{ (syst) } \mathrm{ps}^{-1},\\
\Delta\Gamma_s &= 0.106 \pm 0.011 \text{ (stat)} \pm 0.007 \text{ (syst) } \mathrm{ps}^{-1}.
\end{aligned}$$

Experiment	Dataset [fb^{-1}]	Ref.	ϕ_s[rad]	$\Delta\Gamma_s$[ps^{-1}]
LHCb ($B_s^0 \to J/\psi\,\phi$)	0.4	LHCb2011	$0.15 \pm 0.18 \pm 0.06$	$0.123 \pm 0.029 \pm 0.011$
LHCb ($B_s^0 \to J/\psi\pi^+\pi^-$)	1.0	LHCb-PAPER-2012-006	$-0.019^{+0.173+0.004}_{-0.174-0.003}$	–
LHCb (combined)	0.4+1.0	LHCb-PAPER-2012-006	$0.06 \pm 0.12 \pm 0.06$	–
ATLAS	4.9	ATLAS2012tagged	$0.12 \pm 0.25 \pm 0.11$	$0.053 \pm 0.021 \pm 0.010$
CMS	5.0	CMS2012	–	$0.048 \pm 0.024 \pm 0.003$
D0	8.0	D02011	$-0.55^{+0.38}_{-0.36}$	$0.163^{+0.065}_{-0.064}$
CDF	9.6	CDF2012	$[-0.60,\ 0.12]$ at 68% CL	$0.068 \pm 0.026 \pm 0.009$

CMS does not use flavour tagging (yet)

Comparison with other

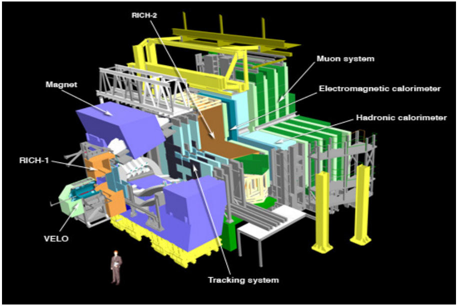
	CDF	D0	LHCb	ATLAS	CMS$^{*)}$
$\int \mathcal{L}$ [fb^{-1}]	9.6	8.0	1.0	4.9	5.0
# $B_s \to J/\psi KK(f_0)$	11k	5.6k	27.6k (7.4k)	22.7k	14.5k
ϵD^2 OS [%]	1.39 $\pm$ 0.05	2.48 $\pm$ 0.22	2.29$\pm$0.22	1.45$\pm$0.05	-
ϵD^2 SS [%]	3.5$\pm$1.4	-	0.89$\pm$0.18	-	-
σ_t [fs]	100	100	48	100	-
Reference	PRL 109(2012) 171802	PRD85(2012) 032006	PRD87(2013) 112010	ATLAS-CONF-2013.029	CMS-PAS BPH-11-006

* CMS: $\Delta\Gamma$ only: 0.048$\pm$0.024$\pm$0.003 ps^{-1}

[S. Hansmann-Menzemer at EPS'2013]

LHCb detector at the LHC

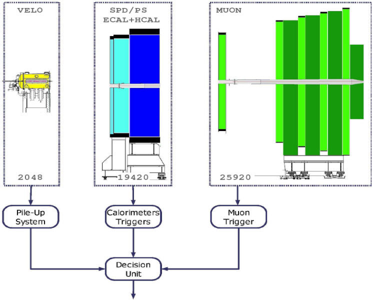
- LHC: p–p collider, $\sqrt{s} = 7\,\mathrm{TeV}$ (2011), $8\,\mathrm{TeV}$ (2012)
- LHCb: single-arm forward spectrometer:
  - Tracking system
    IP resolution $\sim$ 15μm (at high p_T)
    $\delta p/p \sim$ 0.45%
  - RICH system
    Very good $K - \pi$ identification for
    $p \sim 2 - 100\,\mathrm{GeV}/c$
  - Calorimeter
    Energy measurement, identify π^0,γ,e
    + trigger
  - Muon detector
    muon identification + trigger



- Integrated lumi $1\,\mathrm{fb}^{-1}$ (2011), $2\,\mathrm{fb}^{-1}$ (2012)

Trigger

- L0 hardware trigger:
  - Find lepton, hadron with high p_T
  - Reduce the rate from 40 MHz to 1 MHz
- HLT1 software trigger:
  - Finds vertexes in VELO
  - Tracks with high IP & p_T
- HLT2 software trigger:
  - Reconstruct all tracks in event
  - Select inclusive/exclusive B meson
  - Output rate = 5 kHz

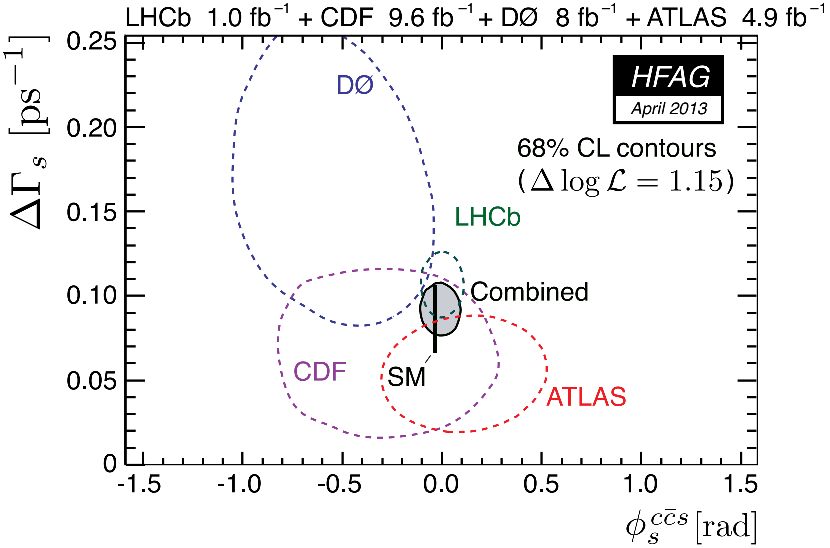


Expected performances of LHCb upgrade CERN-LHCC-2012-007

Type	Observable	Current precision	LHCb 2018	Upgrade ($50\,\text{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\,\phi$)	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\, f_0(980)$)	0.17 [10]	0.045	0.014	~ 0.01
	$A_{\rm fs}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\rm eff}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\rm eff}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,\text{GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [16]	8 %	2.5 %	~ 10 %
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	~ 10–12° [19, 20]	4°	0.9°	negligible
	γ ($B_s^0 \to D_s K$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\, K_S^0$)	0.8° [18]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [18]	0.40×10^{-3}	0.07×10^{-3}	–
	ΔA_{CP}	2.1×10^{-3} [5]	0.65×10^{-3}	0.12×10^{-3}	–

Table 1: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the current sensitivity is compared to that which will be achieved by LHCb before the upgrade, and that which will be achieved with $50\,\text{fb}^{-1}$ by the upgraded experiment. Systematic uncertainties are expected to be non-negligible for the most precisely measured quantities.

Comparison with other, April 2013



Comparison with other, LHCb upgrade projections