

Measurement of CP violation in $B_s^0 \rightarrow J/\psi \phi$ at LHCb

[LHCb-PAPER-2013-002, preliminary]

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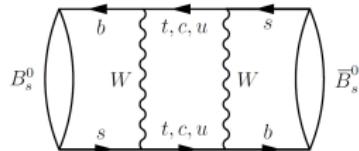
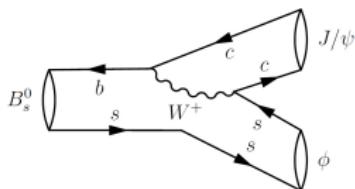
on behalf of the LHCb collaboration



Introduction

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

$$\begin{array}{c} B_s^0 \\ \phi_M \downarrow \\ \bar{B}_s^0 \end{array} \xrightarrow{\phi_D} J/\psi\phi$$



- **WHY:**

- 1 in SM, $\phi_s \simeq -2\beta_s = -(0.0364 \pm 0.0016)$ rad, $\beta_s = \arg(-V_{ts} V_{tb}^*/V_{cs} V_{cb}^*)$
- 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 \bar{B}_s^0):

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

Outline

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

Phenomenology

- $B_s^0 \rightarrow J/\psi K^+ K^-$ proceeds predominantly via $B_s^0 \rightarrow J/\psi \phi$, with $\phi \rightarrow K^+ K^-$, i.e. P-wave (P2VV, mixture of CP-even and CP-odd)
- Small component with $K^+ K^-$ in S-wave (CP-odd)
- Decay decomposed into 4 amplitudes: three P-waves, $A_0, A_{||}, A_{\perp}$ and one S-wave, A_S

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

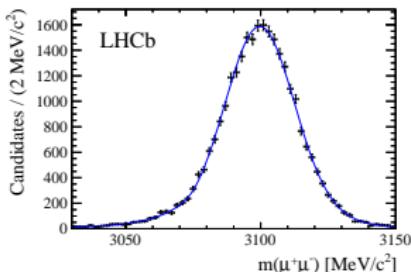
$$h_k(t) = N_k e^{-\Gamma_s t} [a_k \cosh(\tfrac{1}{2}\Delta\Gamma_s t) + b_k \sinh(\tfrac{1}{2}\Delta\Gamma_s t) + c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t)]$$

- $\Delta m_s = M_H - M_L, \quad \Delta\Gamma_s = \Gamma_L - \Gamma_H$
- N_k, a_k, b_k, c_k, d_k are functions of the 4 amplitudes, strong phases and ϕ_s
- For \bar{B}_s^0 , change sign of c_k and d_k
→ significant gain when flavour tagging is used
- Decay rates depend on 11 physics parameters
- Decay rates invariant under
 $(\phi_s, \Delta\Gamma_s, \delta_0, \delta_{||}, \delta_{\perp}, \delta_S) \mapsto (\pi - \phi_s, -\Delta\Gamma_s, -\delta_0, -\delta_{||}, \pi - \delta_{\perp}, -\delta_S)$
→ 2-fold ambiguity

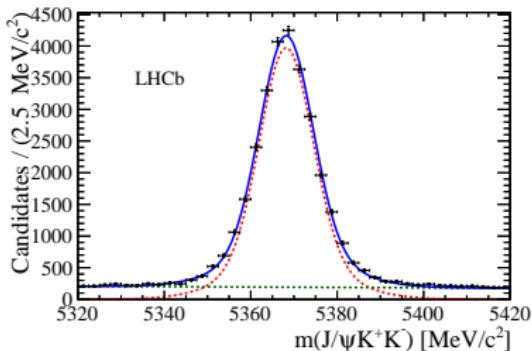
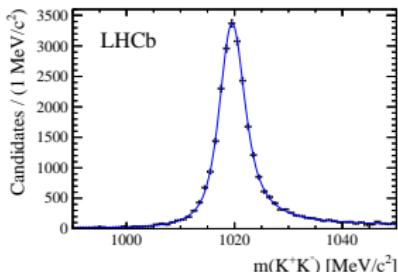
Selection of $B_s^0 \rightarrow J/\psi K^+ K^-$

Cut-based selection, using 1 fb^{-1} taken in 2011

$$J/\psi \rightarrow \mu^+ \mu^-$$



$$\phi \rightarrow K^+ K^-$$

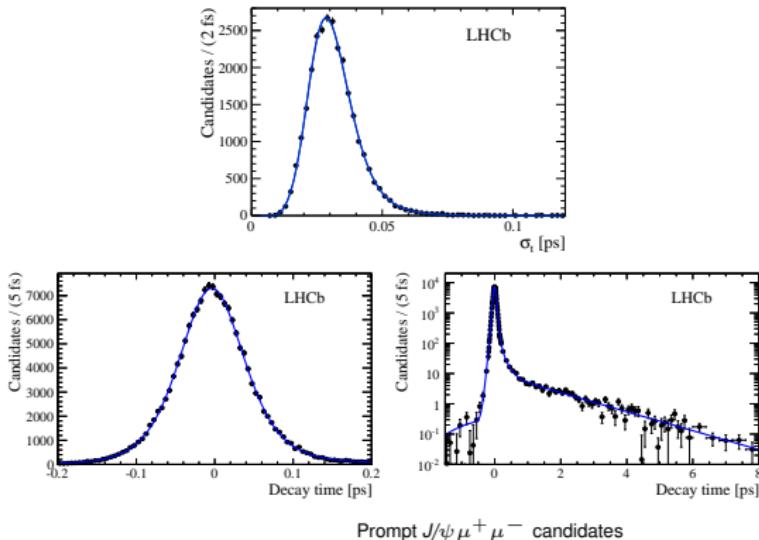


27 617 $B_s^0 \rightarrow J/\psi K^+ K^-$ candidates, very small background

Decay time resolution

Good decay time resolution essential to resolve the fast $B_s^0 - \bar{B}_s^0$ oscillation
($2\pi/\Delta m_s \simeq 350$ fs)

Use per-event decay time error, with scale factor determined on real data,
using prompt $J/\psi \mu^+ \mu^-$ combinations



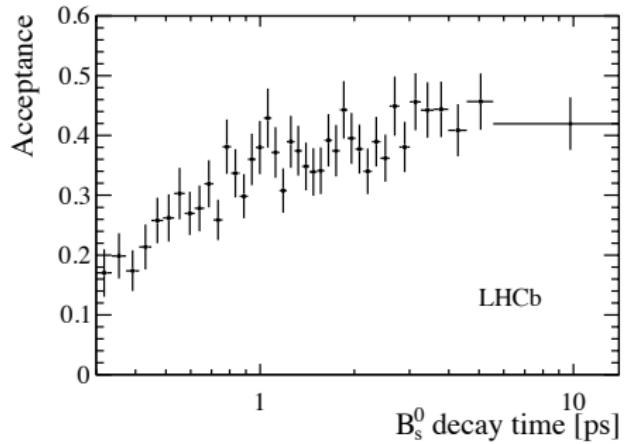
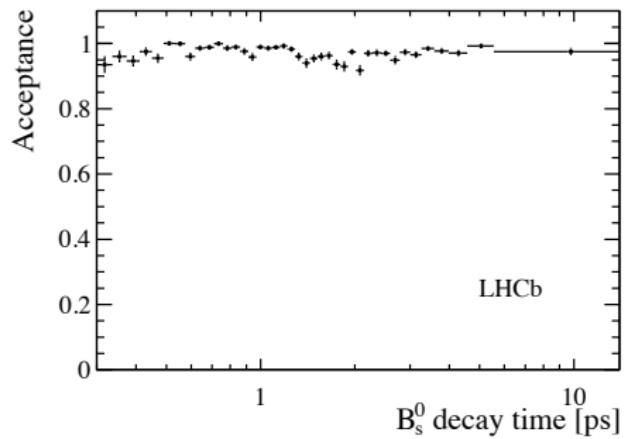
Effective decay time resolution is **45 fs** ($\ll 2\pi/\Delta m_s$)

Decay time acceptance

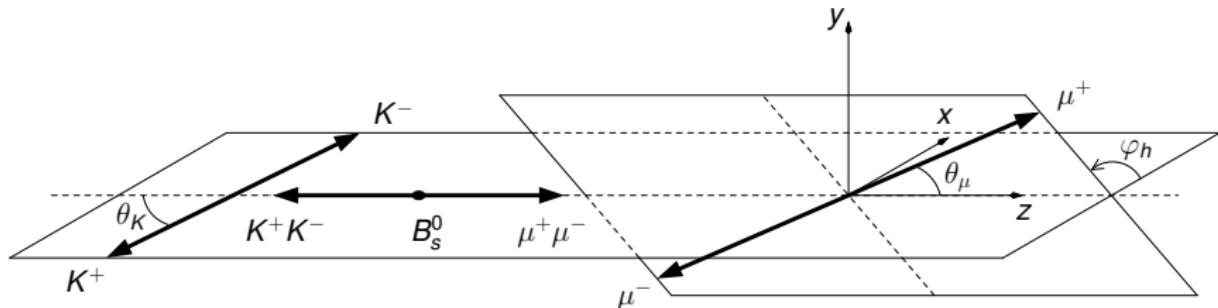
Decay time acceptance using a lifetime-unbiased trigger sample.

92% of our sample has a nearly flat decay time acceptance.

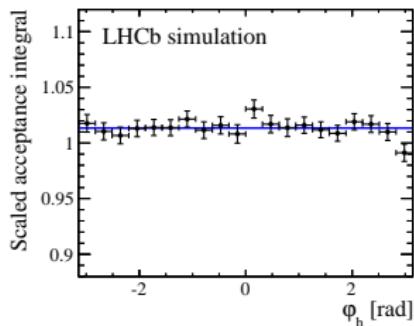
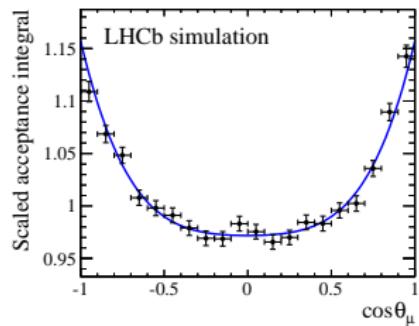
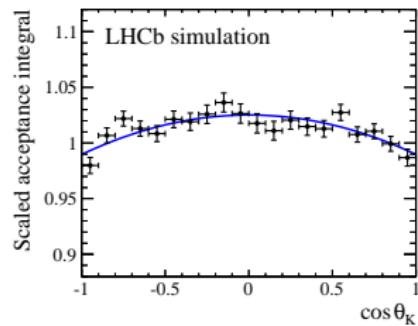
8% more difficult to handle, but added anyway for optimal used of the data



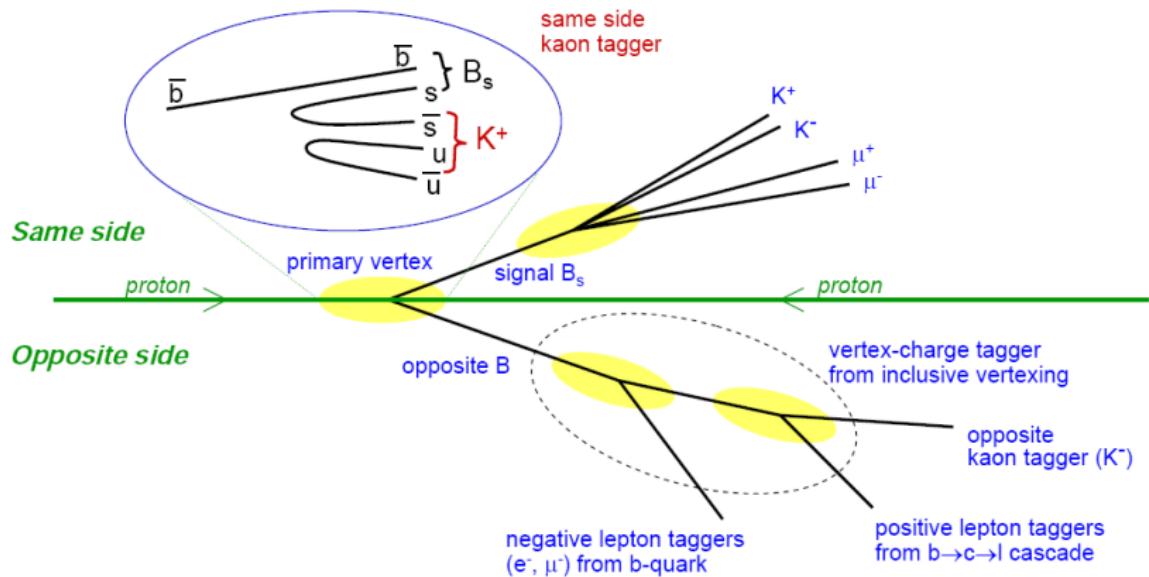
Angular acceptance



Forward geometry of LHCb + selections cuts \Rightarrow distorted angular acceptance
Determined using MC



Tag initial B_s^0 flavour

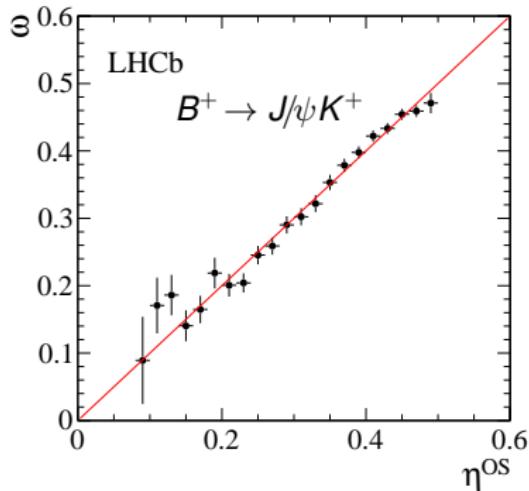


- $\varepsilon_{\text{tag}} = \frac{R+W}{R+W+U}$, $\omega = \frac{W}{R+W}$, Tagging power = $\varepsilon_{\text{eff}} = \varepsilon_{\text{tag}} D^2 = \varepsilon_{\text{tag}} (1 - 2\omega)^2$
 \sim effective reduction of signal sample size due to imperfect tagging
- Mistag fraction, ω , estimated event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

Flavour tagging calibration

Calibration on real data, using flavor specific control channels

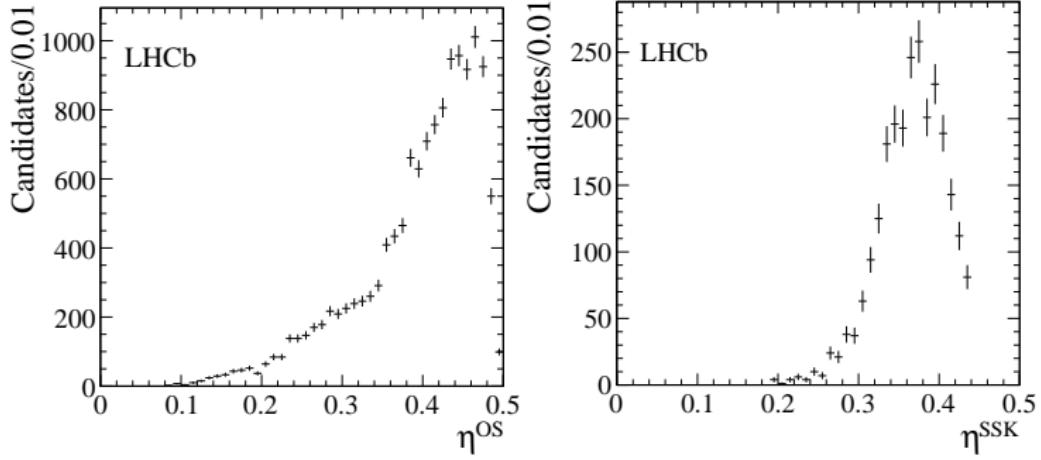
Measured true mistag versus estimated mistag probability:



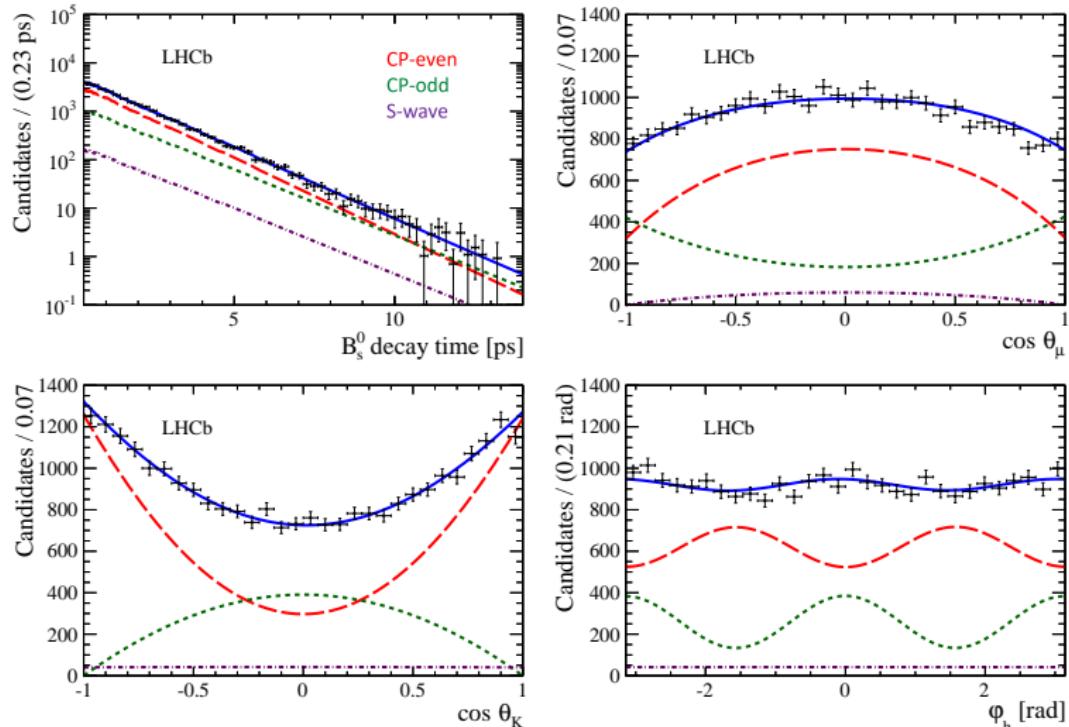
$$\omega(\eta) = p_0 + \frac{\Delta p_0}{2} + p_1(\eta - \langle\eta\rangle)$$

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



	$\varepsilon_{\text{tag}} \text{ (%)}$	$\omega \text{ (%)}$	$\varepsilon_{\text{tag}}(1 - 2\omega)^2 \text{ (%)}$
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)

Results [LHCb-PAPER-2013-002 preliminary]

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

$$\phi_s = 0.07 \pm 0.09 \text{ (stat)} \pm 0.01 \text{ (syst) rad},$$

$$\Gamma_s \equiv (\Gamma_L + \Gamma_H)/2 = 0.663 \pm 0.005 \text{ (stat)} \pm 0.006 \text{ (syst) ps}^{-1}$$

$$\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H = 0.100 \pm 0.016 \text{ (stat)} \pm 0.003 \text{ (syst) ps}^{-1}$$

- World most precise measurements!

- Combined analysis with $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$ [LHCb, PLB 713 (2012) 378]:

$$\phi_s = 0.01 \pm 0.07 \text{ (stat)} \pm 0.01 \text{ (syst) rad},$$

$$\Gamma_s = 0.661 \pm 0.004 \text{ (stat)} \pm 0.006 \text{ (syst) ps}^{-1}$$

$$\Delta\Gamma_s = 0.106 \pm 0.011 \text{ (stat)} \pm 0.007 \text{ (syst) ps}^{-1}$$

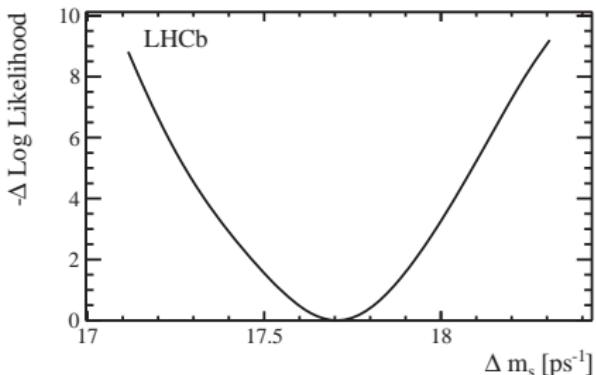
- Compatible with SM so far

Systematics

Source	Γ_s [ps $^{-1}$]	$\Delta\Gamma_s$ [ps $^{-1}$]	$ A_{\perp}(t) ^2$	$ A_0(t) ^2$	$\delta_{ }$ [rad]	δ_{\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
$B^0 \rightarrow J/\psi K^{*0}$ 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	–	–	–	–	–
Quadratic sum of syst.	0.0063	0.003	0.0064	0.0097	0.08	0.07	0.009	0.022
Total uncertainties	0.0079	0.016	0.0107	0.0114	$+0.15$ -0.23	0.23	0.091	0.038

Very small systematics uncertainty on ϕ_s

By-product 1: standalone Δm_s measurement



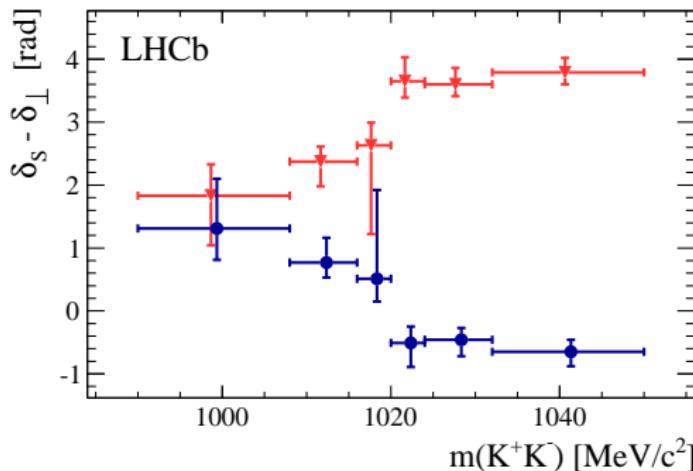
$$\Delta m_s = 17.70 \pm 0.10 \text{ (stat)} \pm 0.01 \text{ (syst)} \text{ ps}^{-1}$$

compatible with LHCb-PAPER-2013-006, 1 fb^{-1} , $B_s^0 \rightarrow D_s^- \pi^+$:

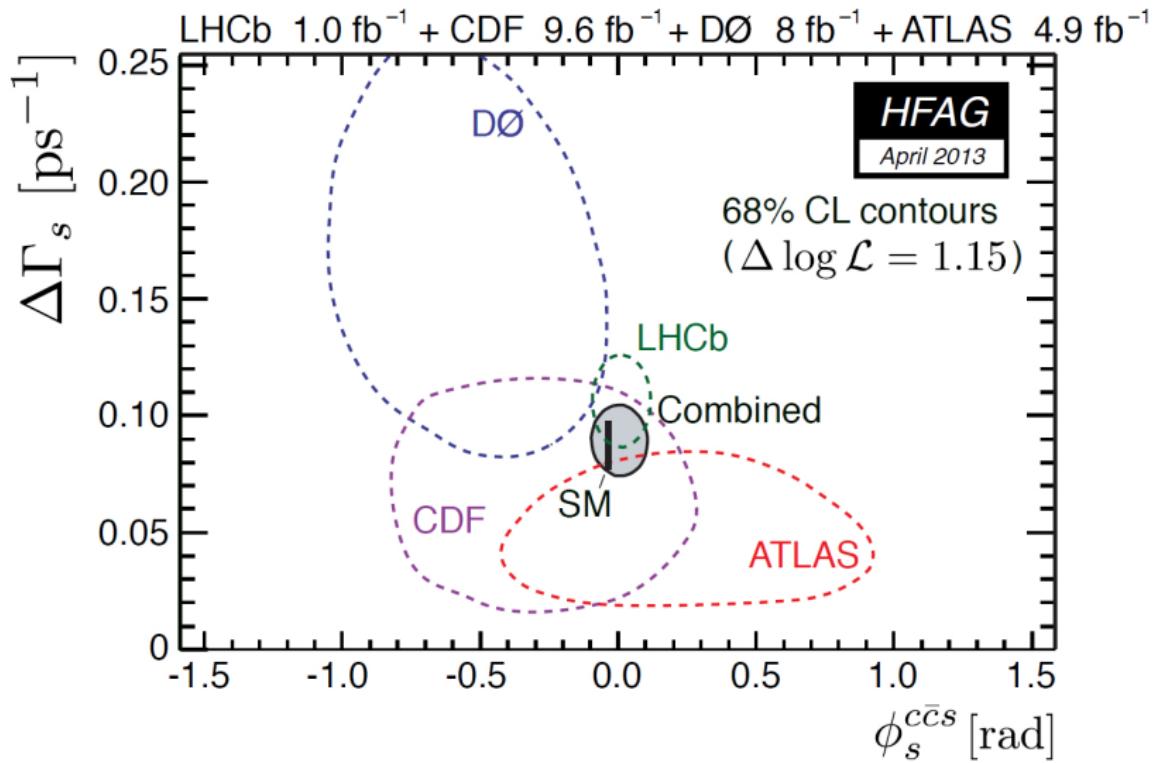
$$\Delta m_s = 17.68 \pm 0.023 \text{ (stat)} \pm 0.006 \text{ (syst)} \text{ ps}^{-1}$$

By-product 2: resolving the sign of $\Delta\Gamma_s$

- Reminder: decay rates invariant under $(\phi_s, \Delta\Gamma_s, \delta_0, \delta_{||}, \delta_{\perp}, \delta_s) \mapsto (\pi - \phi_s, -\Delta\Gamma_s, -\delta_0, -\delta_{||}, \pi - \delta_{\perp}, -\delta_s)$
- 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



Conclusions and prospects

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

$$\phi_s = 0.01 \pm 0.07 \text{ (stat)} \pm 0.01 \text{ (syst) rad,}$$

$$\Gamma_s = 0.661 \pm 0.004 \text{ (stat)} \pm 0.006 \text{ (syst) ps}^{-1}$$

$$\Delta\Gamma_s = 0.106 \pm 0.011 \text{ (stat)} \pm 0.007 \text{ (syst) ps}^{-1}$$

- Results preliminary, compatible with Standard Model so far
→ Stronger constraints than ever on possible SM extensions in $B_s^0 - \bar{B}_s^0$ mixing and still room for NP!
- Expected uncertainty on ϕ_s by the end of LHCb upgrade: $\sim 0.008 \text{ rad}$

Backup

Page 19 Phenomenology

Page 36 $B_s^0 \rightarrow J/\psi K^+ K^-$ analysis

Page 46 Upgrade

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

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

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

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

New physics effects

General parametrization of new physics effects in mixing

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

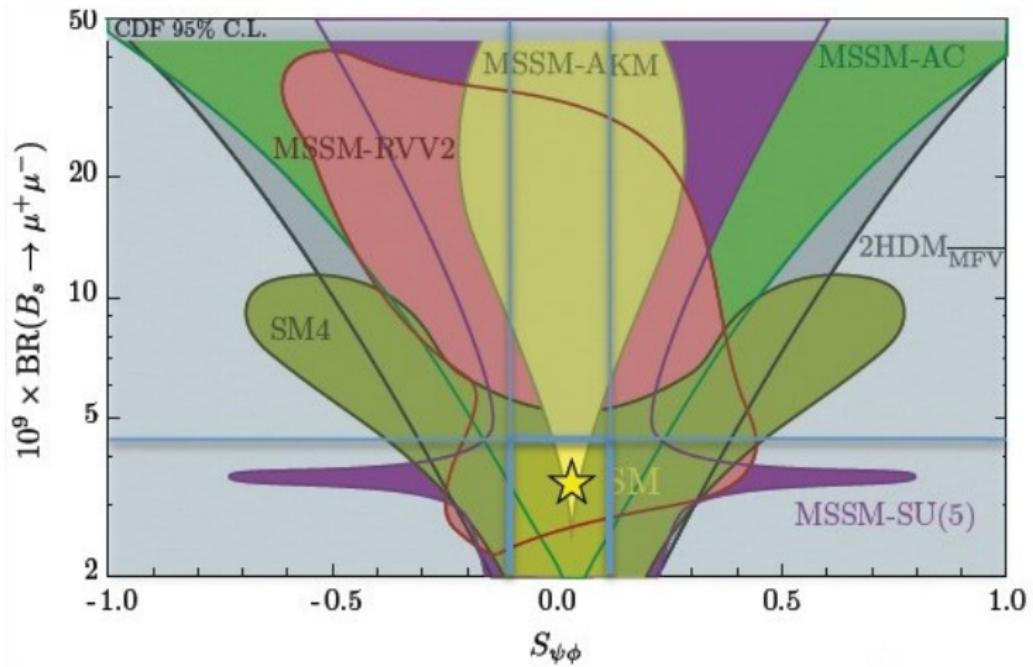
leads to the following relations for observables

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

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

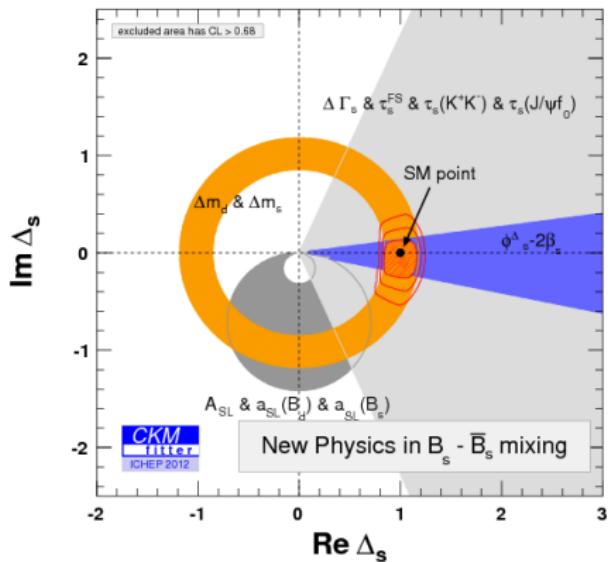
Constraints on New physics

[D. Straub, arXiv:1107.0266]



Correlation between the branching ratio of $B_s^0 \rightarrow \mu^+ \mu^-$ 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



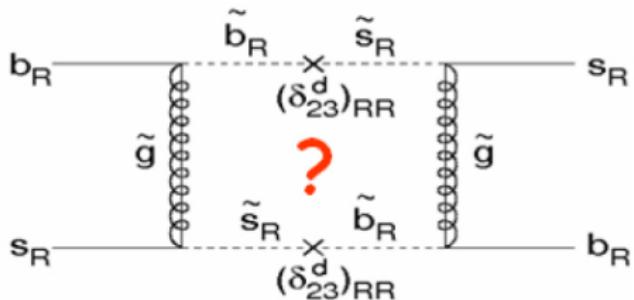
$$M_{12}^s = M_{12}^{\text{SM},s} \Delta_s, \quad \Delta_s = |\Delta_s| e^{i\phi_s^\Delta}$$

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

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

[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 $\Delta m_s = 17.8 \text{ ps}^{-1}$
 - hep-ph/0703117 (little higgs model with T parity)
 - hep-ph/0703112 (susy, extra Z' , little Higgs)
 - Hou et al., hep-ph/0810.3396 (4th 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](#)

CPV in B_s^0 and B^0 mixing

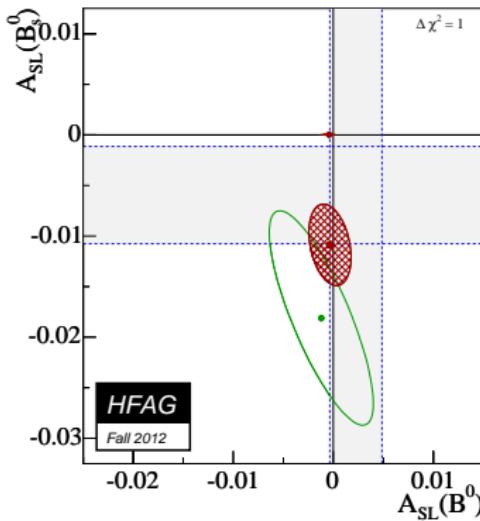
$$A_{SL}^d = \frac{N(\bar{B}^0(t) \rightarrow \ell^+ \nu_\ell X) - N(B^0(t) \rightarrow \ell^- \bar{\nu}_\ell X)}{N(\bar{B}^0(t) \rightarrow \ell^+ \nu_\ell X) + N(B^0(t) \rightarrow \ell^- \bar{\nu}_\ell X)} = \frac{|p/q|_d^2 - |q/p|_d^2}{|p/q|_d^2 + |q/p|_d^2}$$

DØ measures [PRD84, 052007 (2011)] :

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

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

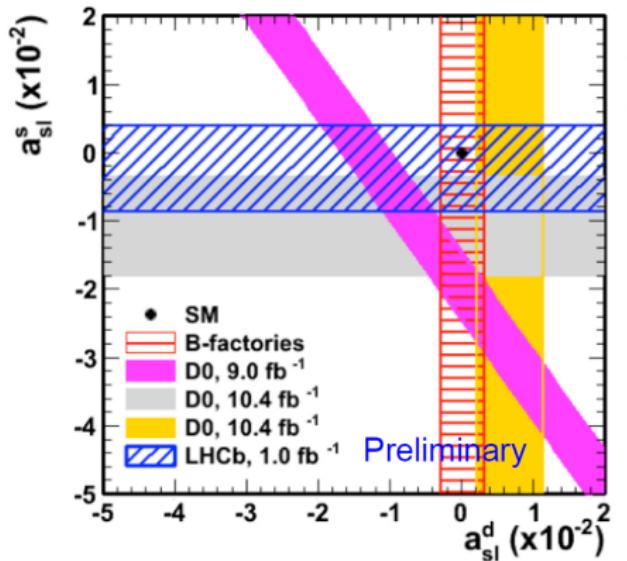


Direct measurements of A_{SL}^s and A_{SL}^d (B^0 average as the vertical band, B_s^0 average as the horizontal band, D0 dimuon result as the green ellipse), together with their two-dimensional average (red hatched ellipse). The red point close to $(0, 0)$ is the Standard Model prediction with error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

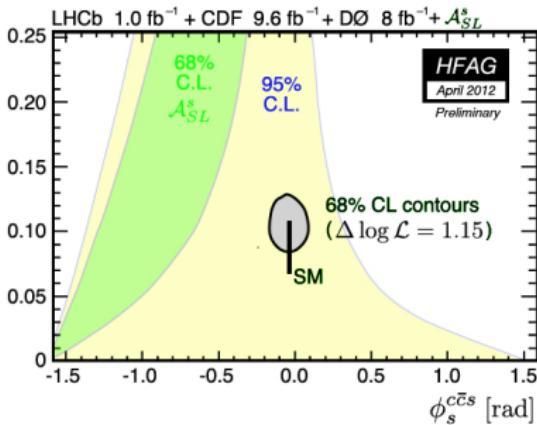
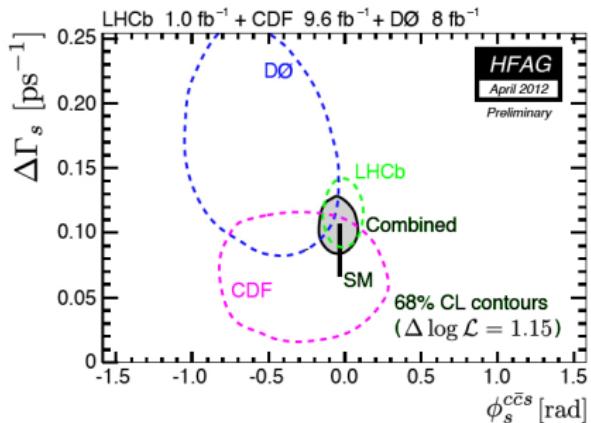
[HFAG 2012, preliminary]

CPV in the mixing

LHCb-CONF-2012-022



B_s^0 mixing phase



$$\phi_{12} = \arg [-M_{12}/\Gamma_{12}]$$

$$\Delta\Gamma_s = 2|\Gamma_{12}| \cos \phi_{12} + \mathcal{O}\left(\left|\frac{\Gamma_{12}}{M_{12}}\right|^2\right)$$

$$\phi_{12}^{\text{SM}} = 0.0038 \pm 0.0010 \text{ [Lenz]}$$

$$\phi_{12} = \phi_{12}^{\text{SM}} + \phi_{12}^{\text{NP}}$$

$$A_{SL}^s = \Im\left(\frac{\Gamma_{12}}{M_{12}}\right) + \mathcal{O}\left(\left|\frac{\Gamma_{12}}{M_{12}}\right|^2\right) = \frac{\Delta\Gamma_s}{\Delta m_s} \tan \phi_{12} + \mathcal{O}\left(\left|\frac{\Gamma_{12}}{M_{12}}\right|^2\right)$$

$$(\phi_s^{c\bar{c}s})^{\text{SM}} = -2\beta_s = -0.0364 \pm 0.0016, \quad \beta_s = \arg [-(V_{ts} V_{tb}^*) / (V_{cs} V_{cb}^*)]$$

$$\phi_s^{c\bar{c}s} = -2\beta_s + \phi_{12}^{\text{NP}}$$

$$\phi_{12} = \phi_{12}^{\text{SM}} + 2\beta_s + \phi_s^{c\bar{c}s}$$

$P \rightarrow VV$ 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 $\ell=0, 1, 2$
- 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)
- $B_s^0 \rightarrow J/\psi K^+ K^-$ can also be produced with $K^+ K^-$ pairs in an S-wave configuration (CP-odd).
- \rightarrow 3 angles describe directions of final decay products $J/\psi \rightarrow \mu^+ \mu^-$ and $\phi \rightarrow K^+ K^-$

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

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

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

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

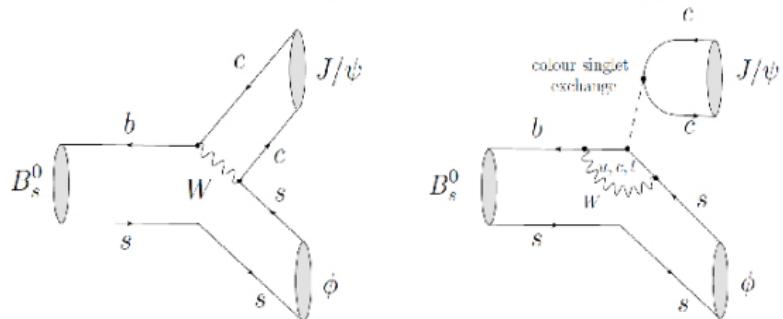
$$C \equiv \frac{1 - |\lambda|^2}{1 + |\lambda|^2}, \quad S \equiv \frac{2\Im(\lambda)}{1 + |\lambda|^2}, \quad D \equiv \frac{-2\Re(\lambda)}{1 + |\lambda|^2}.$$

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

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

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

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



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

$$V_{ts} V_{tb}^* = -V_{us} V_{ub}^* - V_{cs} V_{cb}^*$$

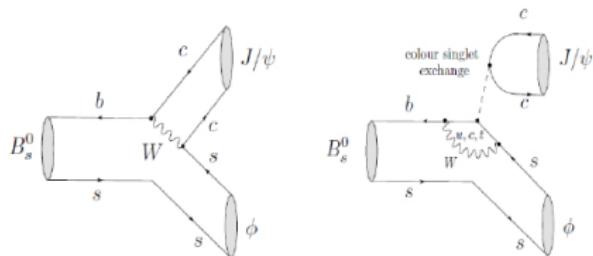
$$\sim A\lambda^2(1 - \lambda^2/2)$$

$$\sim A\lambda^4(\rho + i\eta)$$

- 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 $B_s^0 \rightarrow J/\psi \phi$

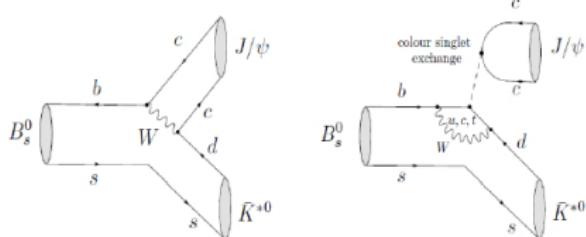
[S. Faller et al. arXiv:0810.4248v1]



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

Penguins suppressed by λ^2

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



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

Penguins NOT suppressed wrt tree

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

A way to introduce β_s

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

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

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

- Or $|V_{us}|, |V_{ub}|, |V_{cb}|, |V_{td}|$ [Branco 1988]
- Or 4 independent phases: $\gamma, \beta, \beta_s, \beta_K$

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

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

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

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

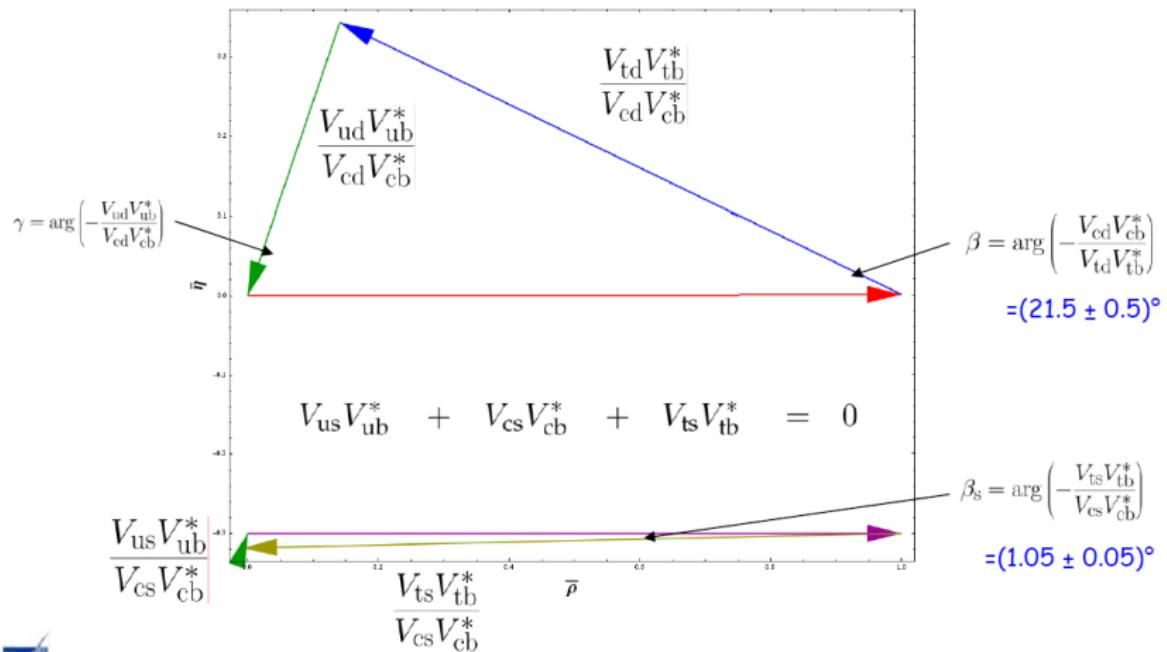
References:

- G. C. Branco and L.avoura, 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 $\bar{\rho} - 0.3$ to be visible
b-d triangle divided by $V_{cd}V_{cb}^*$; while bs triangle divided by $V_{cs}V_{cb}^*$

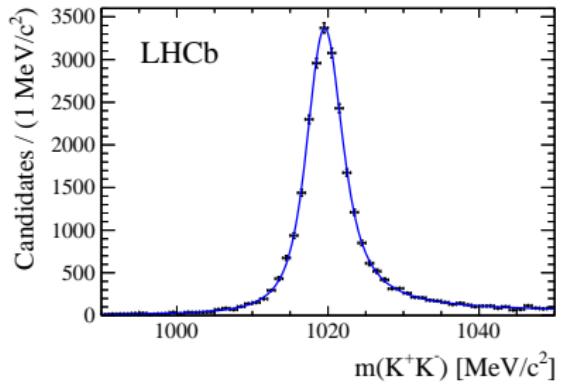
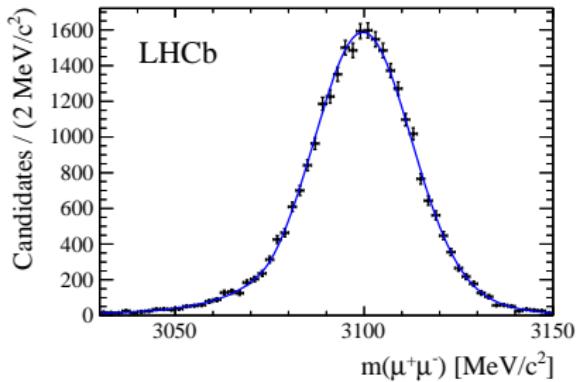
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



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

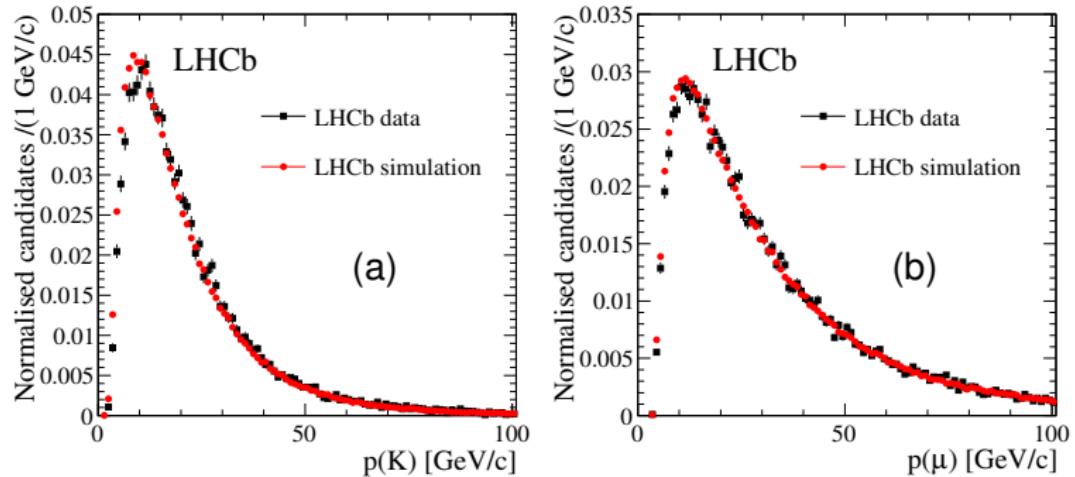
Decay mode	Cut parameter	Stripping	Final selection
all tracks	$\chi_{\text{track}}^2 / \text{nDoF}$ clone distance	< 5 -	< 4 > 5000
$J/\psi \rightarrow \mu^+ \mu^-$	$\Delta \ln \mathcal{L}_{\mu\pi}$ $\min(p_T(\mu^+), p_T(\mu^-))$ $\chi_{\text{vtx}}^2 / \text{nDoF}(J/\psi)$ $ M(\mu^+ \mu^-) - M(J/\psi)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

Selection



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

Systematics related to angular acceptance



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

Unbinned maximum likelihood fit

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

W_i = signal sWeights

$\alpha = \sum_i W_i / \sum_i W_i^2$ is used to include the effect of the weights in the determination of the uncertainties [arXiv:0905.0724]

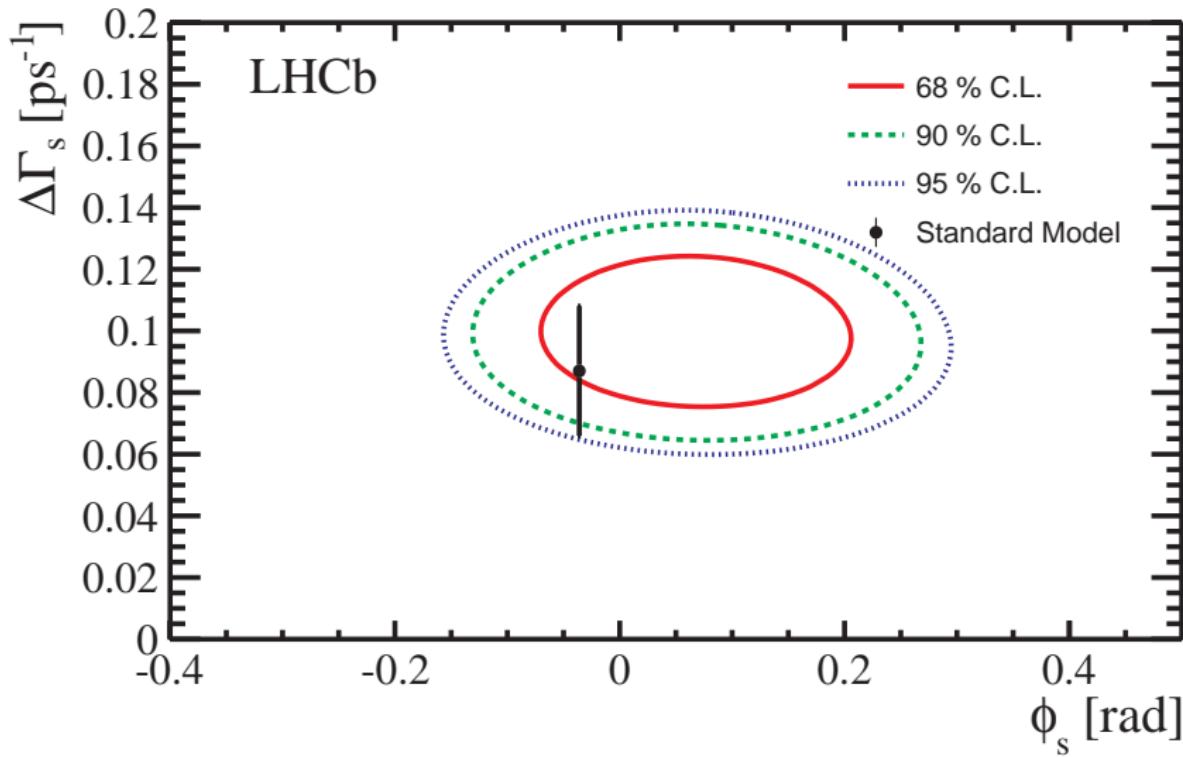
$$S(\lambda, t, \Omega) = \epsilon(t, \Omega) \cdot \left[\left(\frac{1+qD}{2} \cdot P_B(\lambda, t, \Omega) + \frac{1-qD}{2} \cdot \overline{P}_B(\lambda, t, \Omega) \right) \otimes R_t \right]$$

↑ ↗ ↗ ↑

Ingredients: tagging Proper time resolution

Proper time and angular acceptance

Results [LHCb-PAPER-2013-002]



Results [LHCb-PAPER-2013-002]

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

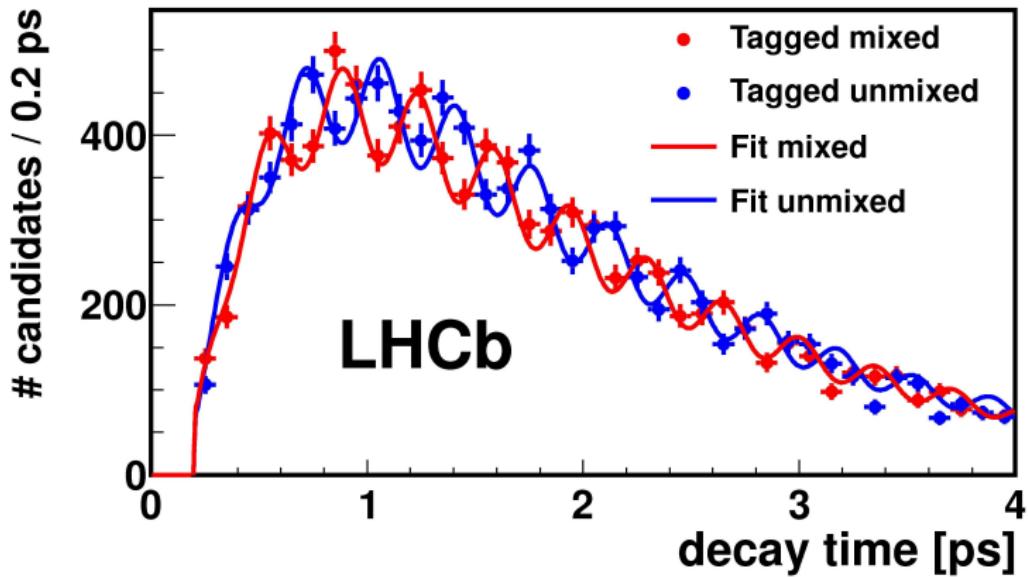
Results of combined fit to the $B_s^0 \rightarrow J/\psi K^+ K^-$ and $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$ datasets.

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

	Γ_s [ps $^{-1}$]	$\Delta\Gamma_s$ [ps $^{-1}$]	$ A_{\perp}(t) ^2$	$ A_0(t) ^2$	$\delta_{ }$ [rad]	δ_{\perp} [rad]	ϕ_s [rad]	$ \lambda $
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
$ A_{\perp}(t) ^2$			1.00	-0.58	-0.28	-0.09	0.08	-0.04
$ A_0(t) ^2$				1.00	-0.02	-0.00	-0.05	0.02
$\delta_{ }$ [rad]					1.00	0.32	-0.03	0.05
δ_{\perp} [rad]						1.00	0.28	0.00
ϕ_s [rad]							1.00	0.04
$ \lambda $								1.00

Correlation matrix for statistical uncertainties on combined results

	Γ_s [ps $^{-1}$]	$\Delta\Gamma_s$ [ps $^{-1}$]	$ A_{\perp}(t) ^2$	$ A_0(t) ^2$	$\delta_{ }$ [rad]	δ_{\perp} [rad]	ϕ_s [rad]	$ \lambda $
Γ_s [ps $^{-1}$]	1.00	0.10	0.08	0.03	-0.08	-0.04	0.01	0.00
$\Delta\Gamma_s$ [ps $^{-1}$]		1.00	-0.49	0.47	0.00	0.00	0.00	-0.01
$ A_{\perp}(t) ^2$			1.00	-0.40	-0.37	-0.14	0.02	-0.05
$ A_0(t) ^2$				1.00	-0.05	-0.03	-0.01	0.01
$\delta_{ }$ [rad]					1.00	0.39	-0.01	0.13
δ_{\perp} [rad]						1.00	0.21	0.03
ϕ_s [rad]							1.00	0.06
$ \lambda $								1.00

$1 \text{ fb}^{-1} \ B_s^0 \rightarrow D_s^- \pi^+$ 

$$\Delta m_s = 17.68 \pm 0.023 \text{ (stat)} \pm 0.006 \text{ (syst)} \text{ ps}^{-1}$$

Comparison with other

LHCb-PAPER-2013-002 (1 fb^{-1} , this talk):

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

Experiment	Dataset [fb^{-1}]	Ref.	$\phi_s [\text{rad}]$	$\Delta\Gamma_s [\text{ps}^{-1}]$
LHCb ($B_s^0 \rightarrow J/\psi \phi$)	0.4	LHCb2011	$0.15 \pm 0.18 \pm 0.06$	$0.123 \pm 0.029 \pm 0.011$
LHCb ($B_s^0 \rightarrow J/\psi \pi^+ \pi^-$)	1.0	LHCb-PAPER-2012-006	$-0.019^{+0.173}_{-0.174}{}^{+0.004}_{-0.003}$	-
LHCb (combined)	$0.4+1.0$	LHCb-PAPER-2012-006	$0.06 \pm 0.12 \pm 0.06$	-
ATLAS	4.9	ATLAS2012	$0.22 \pm 0.41 \pm 0.10$	$0.053 \pm 0.021 \pm 0.010$
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	$[-0.60, 0.12] \text{ at 68\% CL}$	$0.068 \pm 0.026 \pm 0.009$

ATLAS and CMS do not use flavour tagging (yet)

Expected performances of LHCb upgrade

CERN-LHCC-2012-007

Type	Observable	Current precision	LHCb 2018	Upgrade (50 fb^{-1})	Theory uncertainty
B_s^0 mixing	$2\beta_s (B_s^0 \rightarrow J/\psi \phi)$	0.10 [9]	0.025	0.008	~ 0.003
	$2\beta_s (B_s^0 \rightarrow J/\psi f_0(980))$	0.17 [10]	0.045	0.014	~ 0.01
	$A_{fs}(B_s^0)$	6.4×10^{-3} [18]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguin	$2\beta_s^{\text{eff}} (B_s^0 \rightarrow \phi \phi)$	—	0.17	0.03	0.02
	$2\beta_s^{\text{eff}} (B_s^0 \rightarrow K^{*0} \bar{K}^{*0})$	—	0.13	0.02	< 0.02
	$2\beta_s^{\text{eff}} (B^0 \rightarrow \phi K_S^0)$	0.17 [18]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\text{eff}} (B_s^0 \rightarrow \phi \gamma)$	—	0.09	0.02	< 0.01
	$\tau^{\text{eff}} (B_s^0 \rightarrow \phi \gamma) / \tau_{B_s^0}$	—	5 %	1 %	0.2 %
Electroweak penguin	$S_3(B^0 \rightarrow K^{*0} \mu^+ \mu^-; 1 < q^2 < 6 \text{ GeV}^2/c^4)$	0.08 [14]	0.025	0.008	0.02
	$s_0 A_{FB}(B^0 \rightarrow K^{*0} \mu^+ \mu^-)$	25 % [14]	6 %	2 %	7 %
	$A_I(K \mu^+ \mu^-; 1 < q^2 < 6 \text{ GeV}^2/c^4)$	0.25 [15]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \rightarrow \pi^+ \mu^+ \mu^-) / \mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)$	25 % [16]	8 %	2.5 %	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$	1.5×10^{-9} [2]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) / \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$	—	$\sim 100\%$	$\sim 35\%$	$\sim 5\%$
Unitarity triangle angles	$\gamma (B \rightarrow D^{(*)} K^{(*)})$	$\sim 10\text{--}12^\circ$ [19, 20]	4°	0.9°	negligible
	$\gamma (B_s^0 \rightarrow D_s K)$	—	11°	2.0°	negligible
	$\beta (B^0 \rightarrow J/\psi K_S^0)$	0.8° [18]	0.6°	0.2°	negligible
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 fb^{-1} by the upgraded experiment. Systematic uncertainties are expected to be non-negligible for the most precisely measured quantities.