CP violation in the $B^0_{(s)}$ system at LHCb

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on behalf of the LHCb collaboration

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Outline

Highlights of LHCb results on $\not{CP}$ in neutral B mesons:

1. Polarization amplitudes and CP asymmetries in $B^0 \to \phi K^{*0}$;
2. Direct $\not{CP}$ in $B^0 \to \phi K^{*0}$;
3. Time dependent $\not{CP}$ in $B_s^0 \to K^+ K^-$;
4. $\not{CP}$ in semileptonic asymmetries a_{sl}^s;
5. CP-violating phase, ϕ_s, measurement;
6. $B_s^0 \to J/\psi\ \pi^+\pi^-$ amplitude analysis;
7. $\overline{B}_s^0 \to D_s^+ D_s^-$ effective lifetimes.

For other LHCb results:

Constraining the CKM angle gamma at LHCb: see Laurence Carson's talk.
Charm mixing and CP violation at LHCb: see Angelo di Canto's talk.
Latest results on rare decays from LHCb: see Mitesh Patel's talk.

$B^0_{(s)}$ - $\overline{B}^0_{(s)}$ mixing

Time development of the mixing described by effective Schroedinger equation:

$$i\frac{d}{dt}\begin{pmatrix} B^0_{(s)} \\ \overline{B}^0_{(s)} \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} B^0_{(s)} \\ \overline{B}^0_{(s)} \end{pmatrix}$$

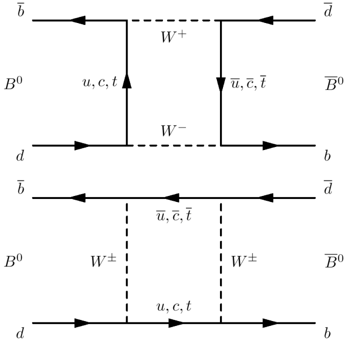
$$M = \begin{pmatrix} M_{11} & M_{12} \\ M^*_{12} & M_{22} \end{pmatrix}; \Gamma = \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma^*_{12} & \Gamma_{22} \end{pmatrix}$$

Diagonalizing it in terms of mass eigenstates:

$$i\frac{d}{dt}(B_L) = \left(m_L - \frac{i}{2}\Gamma_L\right)(B_L)$$
$$i\frac{d}{dt}(B_H) = \left(m_H - \frac{i}{2}\Gamma_H\right)(B_H)$$

Mass eigenstates $\neq$ flavour eigenstates:

$$|B_L\rangle = p\,|B^0_{(s)}\rangle + q\,|\overline{B}^0_{(s)}\rangle$$
$$|B_H\rangle = p\,|B^0_{(s)}\rangle - q\,|\overline{B}^0_{(s)}\rangle$$



Phenomenological mixing parameters:

- **Mass difference**: $\Delta m_{(s)} = m_H - m_L$
- **Lifetime difference**: $\Delta\Gamma_{(s)} = \Gamma_L - \Gamma_H$
- **Mixing phase**: $\phi_M = \arg(-M_{12}/\Gamma_{12})$

CP violation phenomenology in B mesons

Due to interfering amplitudes with different CKM phases in transitions of particles and antiparticles

CP violation in B decay (direct $\not{CP}$)

Difference decay amplitudes: $|\bar{\mathcal{A}}_{\bar{f}}/\mathcal{A}_f| \neq 1$

$$\Gamma(B \to f) \neq \Gamma(\overline{B} \to \bar{f})$$

possible also for charged B hadrons

Ex. $B^0_{(s)} \to K^+\pi^-$

CP violation in $B^0_{(s)}$ mixing

CP Violation in Mixing arises when:

$\mathcal{P}(B^0_{(s)} \to \overline{B}^0_{(s)}) \neq \mathcal{P}(\overline{B}^0_{(s)} \to B^0_{(s)})$
or $|q/p| \neq 1$

Ex. Semileptonic asymmetry $a^{s,d}_{sl}$

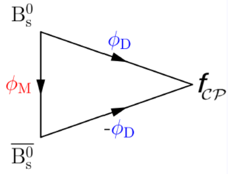
CP violation in interference between mixing and decays to CP eigenstates

Interference between $B^0_{(s)} \to f$ and $B^0_{(s)} \to \overline{B}^0_{(s)} \to f$.

Even if $|\bar{\mathcal{A}}_f/\mathcal{A}_f| = 1$ or $|q/p| = 1$, $\not{CP}$ is possible if:

$$\sin\phi_{d,s} = \mathrm{Im}\left(\left|\frac{q}{p}\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f}\right|\right) \neq 0$$

Ex. $\not{CP}$ phase ϕ_s, golden channel: $B^0_s \to J/\psi\phi$



$$\phi_{d,s} = \phi_M - 2\,\phi_D$$

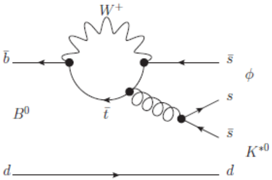
Direct $\not{CP}$

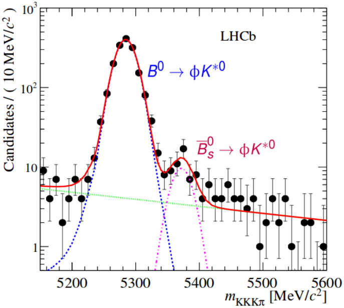
Polarization amplitudes and CP asymmetries in $B^0 \to \phi K^*(892)^0$ - $\mathcal{L} = 1\ \text{fb}^{-1}$

$B^0 \to \phi K^*(892)^0$

- $b \to s s\bar{s}$ FCNC decay, penguin in SM $\Longrightarrow$ sensitive to NP contributions in the loop.
- $B^0 \to K^+K^-K^+\pi^-$ final state studied.
- $N_{\text{sig}} = 1655 \pm 42$

[arXiv:1403.2888]

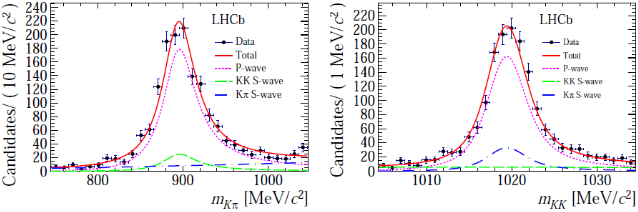


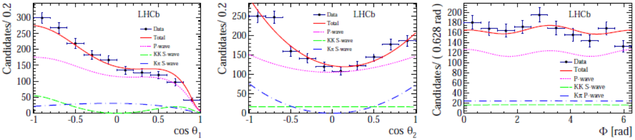


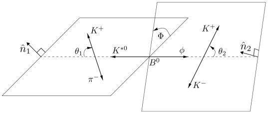
- **Angular analysis** of time-integrated decay rates to disentangle helicity structure of the $P \to VV$ decay (L= 0, 1, 2):
  - **P-wave**: longitudinal $\mathcal{A}_0$ and transverse, parallel $\mathcal{A}_{\parallel}$ and perpendicular $\mathcal{A}_{\perp}$;
  - **S-wave**: $\mathcal{A}_S(K\pi)$ ($B^0 \to \phi K^+\pi^-$) and $\mathcal{A}_S(KK)$ ($B^0 \to K^*(892)^0 K^- K^+$).

Polarization amplitudes and CP asymmetries in $B^0 \to \phi K^*(892)^0$ - $\mathcal{L} = 1\,\mathrm{fb}^{-1}$

[arXiv:1403.2888]







A_0^{CP}	= -0.003 ± 0.038 (stat) ± 0.005 (syst)
$A_\perp^{CP}$	= +0.047 ± 0.072 (stat) ± 0.009 (syst)
$A_{S(K\pi)}^{CP}$	= +0.073 ± 0.091 (stat) ± 0.035 (syst)
$A_{S(KK)}^{CP}$	= -0.209 ± 0.105 (stat) ± 0.012 (syst)

- B^0 and $\overline{B}^0$ decays are separated according to the charge of the kaon from the K^{*0}.
- CP-asymmetries consistent with zero.

Direct $\not{CP}$ in $B^0 \to \phi K^*(892)^0$ - $\mathcal{L} = 1\,\mathrm{fb}^{-1}$

[arXiv:1403.2888]

- Final state tagged by $K^{*0} \to K^+ \pi^-$ decay.
- Raw asymmetry measured from integrated rates:

$$A = \frac{N(\overline{B}^0 \to \phi \overline{K}^*(892)^0) - N(B^0 \to \phi K^*(892)^0)}{N(\overline{B}^0 \to \phi \overline{K}^*(892)^0) + N(B^0 \to \phi K^*(892)^0)}$$

- Correcting for production and detection asymmetries (determined using the control channel $B^0 \to J/\psi K^*(892)^0$):

$$A^{CP}(\phi K^{*0}) = (+1.5 \pm 3.2\,(\mathrm{stat}) \pm 0.5\,(\mathrm{syst}))\%$$

  - Systematic uncertainty from the difference in kinematic and trigger used to select $B^0 \to J/\psi K^*(892)^0$ events.

- No direct $\not{CP}$ in agreement with (and a factor of 2 more precise than):

$A^{CP}(\phi K^{*0}) = (+1 \pm 6\,(\mathrm{stat}) \pm 3\,(\mathrm{syst}))\%$ Babar [Phys.Rev.D 78, 092008(2008)]

$A^{CP}(\phi K^{*0}) = (-0.7 \pm 4.8\,(\mathrm{stat}) \pm 2.1\,(\mathrm{syst}))\%$ Belle [Phys.Rev.D 88, 072004(2013)]

Time dependent $\not{CP}$ in $B_s^0 \to K^+K^-$ - $\mathcal{L} = 1\ \mathrm{fb}^{-1}$

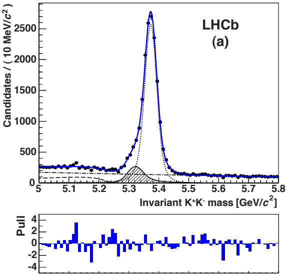
[J. High Energy Phys. 10 (2013) 183]

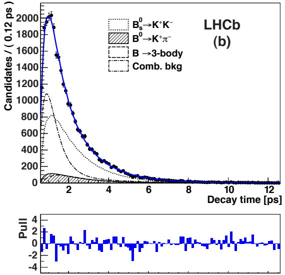
Time-dependent CP asymmetry:

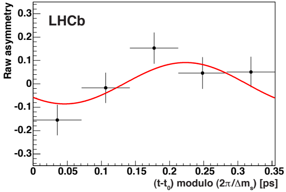
$$A^{CP}(t) = \frac{\Gamma_{\overline{B}_s^0 \to KK}(t) - \Gamma_{B_s^0 \to KK}(t)}{\Gamma_{\overline{B}_s^0 \to KK}(t) + \Gamma_{B_s^0 \to KK}(t)} = \frac{-C_{KK}\cos(\Delta m_s t) + S_{KK}\sin(\Delta m_s t)}{\cosh\left(\frac{\Delta\Gamma_s}{2}t\right) - \mathcal{A}_{KK}^{\Delta\Gamma_s}\sinh\left(\frac{\Delta\Gamma_s}{2}t\right)}$$

where C_{KK} = direct $\not{CP}$, S_{KK} = mixing-induced $\not{CP}$ and $\mathcal{A}_{KK}^{\Delta\Gamma_s}$ = $\not{CP}$ in interference.

Time-dependent analysis, flavour-tagging to identify initial B_s^0 flavour: calibrated using flavour-specific $B^0 \to K^+\pi^-$ events.







C_{KK}	$= 0.14 \pm 0.11 \pm 0.03$
S_{KK}	$= 0.30 \pm 0.12 \pm 0.04$

2.7 σ from (0, 0)

Time dependent $\not{C}\not{P}$ in $B^0 \to \pi^+\pi^-$ - $\mathcal{L} = 1\,\text{fb}^{-1}$

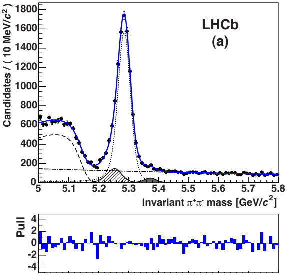
[J. High Energy Phys. 10 (2013) 183]

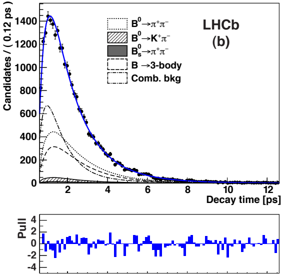
Time-dependent CP asymmetry:

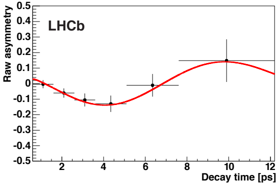
$$A^{CP}(t) = \frac{\Gamma_{\overline{B}^0 \to \pi\pi}(t) - \Gamma_{B^0 \to \pi\pi}(t)}{\Gamma_{\overline{B}^0 \to \pi\pi}(t) + \Gamma_{B^0 \to \pi\pi}(t)} = \frac{-C_{\pi\pi}\cos(\Delta m_d t) + S_{\pi\pi}\sin(\Delta m_d t)}{\cosh\left(\frac{\Delta\Gamma_d}{2}t\right) - \mathcal{A}_{\pi\pi}^{\Delta\Gamma_d}\sinh\left(\frac{\Delta\Gamma_d}{2}t\right)}$$

where $C_{\pi\pi}$ = direct $\not{C}\not{P}$, $S_{\pi\pi}$ = mixing-induced $\not{C}\not{P}$ and $\mathcal{A}_{KK}^{\Delta\Gamma_s}$ = $\not{C}\not{P}$ in interference.

Time-dependent analysis, flavour-tagging to identify initial B^0 flavour: calibrated using flavour-specific $B^0 \to K^+\pi^-$ events.







$C_{\pi\pi}$ = -0.38 $\pm$ 0.15 $\pm$ 0.02
$S_{\pi\pi}$ = -0.71 $\pm$ 0.13 $\pm$ 0.02

5.6 σ from (0, 0)

$\not{CP}$ in mixing

$\not{CP}$ in semileptonic asymmetries a_{sl}^s - $\mathcal{L} = 1\,\mathrm{fb}^{-1}$

- Consider a **flavour-specific** final state f:

$$B^0_{(s)} \to f \quad \text{or} \quad \overline{B}^0_{(s)} \to B^0_{(s)} \to f$$
$$\overline{B}^0_{(s)} \to \bar{f} \quad \text{or} \quad B^0_{(s)} \to \overline{B}^0_{(s)} \to \bar{f}$$

- $a_{sl} \equiv \frac{\Gamma(\overline{B}^0_{(s)}(t)\to f) - \Gamma(B^0_{(s)}(t)\to \bar{f})}{\Gamma(\overline{B}^0_{(s)}(t)\to f) + \Gamma(B^0_{(s)}(t)\to \bar{f})} \simeq \frac{\Delta\Gamma}{\Delta M}\tan\phi_M$

$\not{CP}$ in mixing is very small in the SM

$a_{sl}^d(B^0)^{SM}$	$= (-4.1 \pm 0.6)\cdot 10^{-4}$
$a_{sl}^s(B^0_s)^{SM}$	$= (+1.9 \pm 0.3)\cdot 10^{-5}$

[Lenz & Nierste, arXiv:1102.4274 [hep-ph]]

a_{sl}^s experimentally: untagged time-integrated asymmetry in **semileptonic flavour-specific** B^0_s decays (between $D_s^+ X \mu^- \overline{\nu}_\mu$ and $D_s^- X \mu^+ \nu_\mu$)

$$A^{CP}_{measured} = \frac{\Gamma[D_s^-\mu^+] - \Gamma[D_s^+\mu^-]}{\Gamma[D_s^-\mu^+] + \Gamma[D_s^+\mu^-]} = \frac{a_{sl}^s}{2} + \left[a_p - \frac{a_{sl}^s}{2}\right]\cdot \frac{\int e^{-\Gamma_s t}\cos(\Delta m_s t)\varepsilon(t)dt}{\int e^{-\Gamma_s t}\cosh(\Delta\Gamma_s/2t)\varepsilon(t)dt}$$

- $a_p \equiv (N(B^0_s) - N(\overline{B}^0_s))/(N(B^0_s) + N(\overline{B}^0_s))$;
- $\varepsilon(t)$ is the decay time acceptance;
- fast B^0_s mixing dilutes second term below precision of this measurement.

$\not{CP}$ in semileptonic asymmetries a^s_{sl} - $\mathcal{L} = 1\,\mathrm{fb}^{-1}$

[Physics Letters B 728C (2014), pp. 607-615]

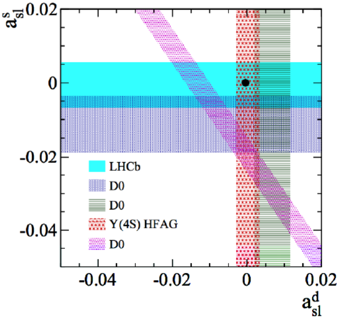
Experimentally: time-integrated asymmetry in semileptonic **flavour-specific f** B^0_s decays (between $D^+_s X\mu^-\overline{\nu}_\mu$ and $D^-_s X\mu^+\nu_\mu$)

$$A^{CP}_{measured} = \frac{\Gamma[D^-_s\mu^+] - \Gamma[D^+_s\mu^-]}{\Gamma[D^-_s\mu^+] + \Gamma[D^+_s\mu^-]} \simeq \frac{a^s_{sl}}{2}$$

- Correcting the raw-asymmetry for reconstruction and background asymmetries:

$$a^s_{sl} = [-0.06 \pm 0.50\,(\mathrm{stat}) \pm 0.36\,(\mathrm{syst})]\%$$

- Dominant systematic is from limited statistics in control sample
- 3σ tension with SM in the D0 result, not confirmed or excluded by LHCb.



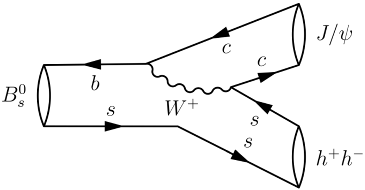
$\not{CP}$ in interference of mixing and decay

$B_s^0 \to J/\psi\ \phi$ - Introduction

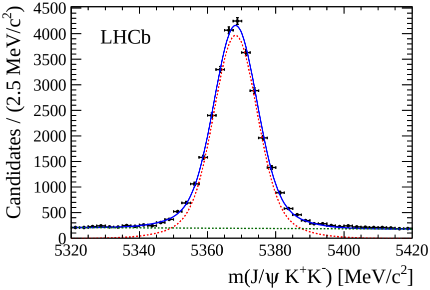
$B_s^0 \to J/\psi\ \phi$ via $b \to c\bar{c}s$ transitions:

- predominantly via $B_s^0 \to J/\psi\ \phi$, with $\phi \to K^+K^-$, i.e. P-wave.
- small non-resonant component with K^+K^- in S-wave.
- Angular analysis to disentangle CP even and CP odd final states.

Decay dominated by tree level diagram:



[Phys. Rev. D 87, 112010]



Analysed sample

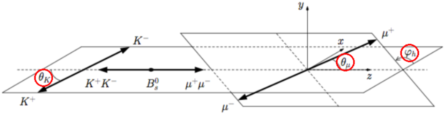
- Analysed 1 fb^{-1} of data;
- High statistics: **N $\sim$ 27600** signal events
- Low background: narrow J/ψ resonance plus cut on B_s^0 decay time

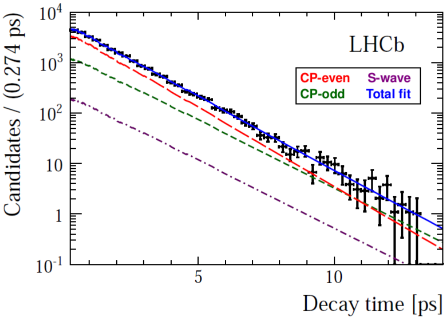
$B_s^0 \to J/\psi\ \phi$ angular and decay time projections

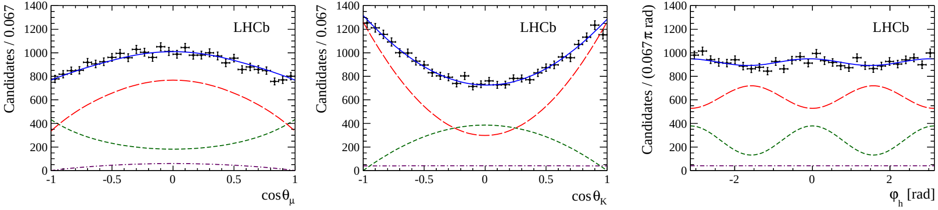
[Phys. Rev. D 87, 112010]

Unbinned maximum likelihood fit in 4 dimensions:

- clear separation of CP even and CP odd angular distributions.
- different lifetimes for CP odd and even components:
  $\Delta\Gamma_s = \Gamma_L - \Gamma_H \approx |\Gamma_{\mathrm{CP-odd}} - \Gamma_{\mathrm{CP-even}}|$

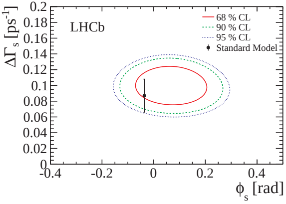






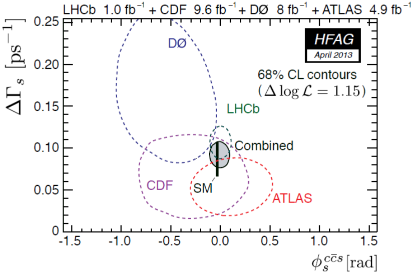
$B_s^0 \to J/\Psi\ \phi$ and $B_s^0 \to J/\Psi\ \pi^+\pi^-$ combined results

[Phys. Rev. D 87, 112010]



The results using $B_s^0 \to J/\psi\ \phi$ data corresponding to $\mathcal{L} = 1\,\text{fb}^{-1}$ are:

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



A simultaneous fit of $B_s^0 \to J/\Psi\ \phi$ and $B_s^0 \to J/\Psi\ \pi^+\pi^-$ gives:

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

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

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

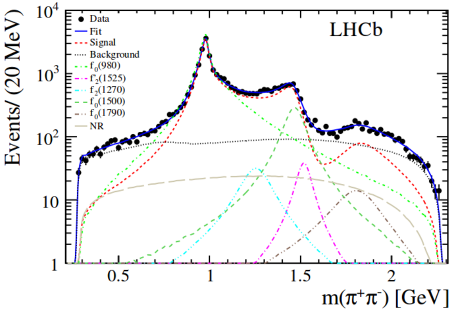
Ambiguity solved: sign of $\Delta\Gamma_s$ positive!

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

[arXiv:1402.6248 [hep-ex]]

New amplitude analysis with $\mathcal{L} = 3\,\mathrm{fb}^{-1}$!

- Precise study of CP content;
- Five interfering states required: $f_0(980)$, $f_0(1500)$, $f_0(1790)$, $f_2(1270)$, $f_2'(1525)$;
- Inclusion of non-resonant (NR) $J/\psi\pi^+\pi^-$ also provides a good description of data;
- CP-odd $> 97.7\%$ confirmed at 95% CL.



Mixing angle between the $f_0(500)$ and $f_0(980)$ resonances measured to be $|\phi_m| < 7.7^\circ$ at 90% CL

$\Longrightarrow$ most stringent limit ever reported!

$\Longrightarrow$ consistent with these states being tetraquarks.

Effective lifetime to test CP violation

Effective lifetime in CP eigenstates

[Eur.Phys.J. C71 (2011) 1789]

- In CP eigenstates the effective lifetime is sensitive to $\Delta\Gamma_s$ and ϕ_s (mixing induced $\not{C}\not{P}$ phase).

Considering a $B^0_s(\overline{B}^0_s) \to f$ transition the untagged decay time distribution is:

$$\Gamma(t) \propto (1 - \mathcal{A}_{\Delta\Gamma_s})e^{-(\Gamma_L t)} + (1 + \mathcal{A}_{\Delta\Gamma_s})e^{-(\Gamma_H t)}$$

with $\mathcal{A}_{\Delta\Gamma_s}$ is a function of ϕ_s.
If we assume no $\not{C}\not{P}$ then for the CP eigenstates $\mathcal{A}_{\Delta\Gamma_s} = \pm 1$:

CP even: e.g. $\overline{B}^0_s \to D_s^+ D_s^- \Rightarrow \Gamma_L$

CP odd: e.g. $B^0_s \to J/\Psi f_0(980) \Rightarrow \Gamma_H$

Effective lifetime is the lifetime measured by describing the untagged decay time distribution with a single exponential. Expanding in $y_s = \Delta\Gamma_s/2\Gamma_s$ and using $\tau_{B^0_s} = 2/(\Gamma_L + \Gamma_H) = \Gamma_s^{-1}$:

$$\frac{\tau_f}{\tau_{B^0_s}} = 1 + \mathcal{A}_{\Delta\Gamma_s} y_s + [2 - (\mathcal{A}_{\Delta\Gamma_s})^2]y_s^2 + \mathcal{O}(y_s^3)$$

Alternative way to extract ϕ_s and $\Delta\Gamma_s$:
- *complementary to e.g. $B^0_s \to J/\Psi\phi$*
- *No flavour tagging needed*

$\overline{B}_s^0 \to D_s^+ D_s^-$ effective lifetime - $\mathcal{L} = 3\,\mathrm{fb}^{-1}$

[arXiv:1312.1217 [hep-ex]]

- Final state is CP-even, ϕ_s is small $\Longrightarrow \tau_{\mathrm{eff}} \approx 1/\Gamma_L$
- Measure lifetime relative to a similar final state topology decay, $B^- \to D^0 D_s^-$, with well-known lifetime:

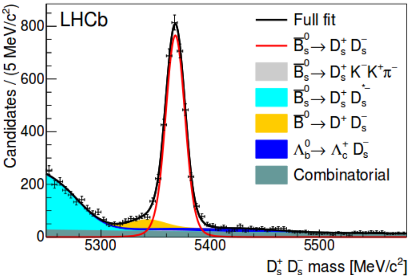
$$\tau_{B^-} = 1.641 \pm 0.008\ \mathrm{ps}$$

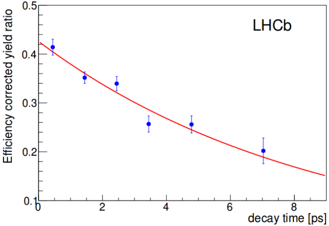
- The relative rate is given by:

$$\frac{\Gamma_{B_s^0(\overline{B}_s^0)\to D_s^+ D_s^-}(t)}{\Gamma_{B^-(B^+)\to D^0(\overline{D}^0)D_s^-(D_s^+)}(t)} \propto e^{-\alpha t}$$

where: $\alpha = 1/\tau_{\overline{B}_s^0\to D_s^+ D_s^-} - 1/\tau_{B^-}$

- Main systematic is from acceptance.





$$\tau^{\mathrm{eff}}_{\overline{B}_s^0\to D_s^+ D_s^-} = 1.379 \pm 0.026 \pm 0.017\ \mathrm{ps} \qquad \Gamma_L = 0.725 \pm 0.014 \pm 0.009\ \mathrm{ps}^{-1}$$

Conclusions

- Large variety of measurements of $\not{CP}$ in the neutral B sector coming from LHCb;
- All results in good agreement with SM;
- Majority of measurements still statistically limited;
- Some measurements still on partial data sample
  $\Longrightarrow$ full update coming soon!!
- LHC run 2 will start in 2015: center of mass energy $\sqrt{s} \rightarrow$ 13/14 TeV, so production cross section σ_{bb} doubles;
- Good prospects for the precision measurements in the LHCb upgrade phase: probe New Physics at the percentage level.

Thanks for your attention!

Backup Slides

Polarization amplitudes and CP asymmetries in $B^0 \to \phi K^*(892)^0$ - $\mathcal{L} = 1\,\mathrm{fb}^{-1}$

[LHCB-PAPER-2014-005]

P- and S-wave fractions are

$$F_{\mathrm{P}} = |A_0|^2 + |A_{\parallel}|^2 + |A_{\perp}|^2\,, \qquad F_{\mathrm{S}} = |A_{\mathrm{S}}^{K\pi}|^2 + |A_{\mathrm{S}}^{KK}|^2\,, \qquad F_{\mathrm{P}} + F_{\mathrm{S}} = 1\,, \tag{5}$$

and

$$\overline{F}_{\mathrm{P}} = |\overline{A}_0|^2 + |\overline{A}_{\parallel}|^2 + |\overline{A}_{\perp}|^2\,, \qquad \overline{F}_{\mathrm{S}} = |\overline{A}_{\mathrm{S}}^{K\pi}|^2 + |\overline{A}_{\mathrm{S}}^{KK}|^2\,, \qquad \overline{F}_{\mathrm{P}} + \overline{F}_{\mathrm{S}} = 1\,. \tag{6}$$

In addition, a convention is adopted such that the phases $\delta_{\mathrm{S}}^{K\pi}$ and δ_{S}^{KK} are defined as the difference between the P- and S-wave phases at the $K^*(892)^0$ and ϕ meson poles, respectively.

- Angular analysis at Babar and Belle show that the longitudinal and transverse components in the decay have roughly equal amplitudes:
  - similar results seen in other $B \to VV$ transitions;
  - in contrast with 3-level decays such as $B^0 \to \rho^+\rho^-$, where the V-A nature of the weak interactions means that the longitudinal component dominates;
  - possible interpretations: large contributions from penguin annihilation effects or final state interactions.

Polarization amplitudes and CP asymmetries in $B^0 \to \phi K^*(892)^0$ - $\mathcal{L} = 1\,\mathrm{fb}^{-1}$

Table 2: Parameters measured in the angular analysis. The first and second uncertainties are statistical and systematic, respectively.

Parameter	Definition	Fitted value
$f_{\rm L}$	$0.5(\|A_0\|^2/F_{\rm P} + \|\overline{A}_0\|^2/\overline{F}_{\rm P})$	$0.497 \pm 0.019 \pm 0.015$
$f_\perp$	$0.5(\|A_\perp\|^2/F_{\rm P} + \|\overline{A}_\perp\|^2/\overline{F}_{\rm P})$	$0.221 \pm 0.016 \pm 0.013$
$f_{\rm S}(K\pi)$	$0.5(\|A_{\rm S}^{K\pi}\|^2 + \|\overline{A}_{\rm S}^{K\pi}\|^2)$	$0.143 \pm 0.013 \pm 0.012$
$f_{\rm S}(KK)$	$0.5(\|A_{\rm S}^{KK}\|^2 + \|\overline{A}_{\rm S}^{KK}\|^2)$	$0.122 \pm 0.013 \pm 0.008$
$\delta_\perp$	$0.5(\arg A_\perp + \arg \overline{A}_\perp)$	$2.633 \pm 0.062 \pm 0.037$
$\delta_\parallel$	$0.5(\arg A_\parallel + \arg \overline{A}_\parallel)$	$2.562 \pm 0.069 \pm 0.040$
$\delta_{\rm S}(K\pi)$	$0.5(\arg A_{\rm S}^{K\pi} + \arg \overline{A}_{\rm S}^{K\pi})$	$2.222 \pm 0.063 \pm 0.081$
$\delta_{\rm S}(KK)$	$0.5(\arg A_{\rm S}^{KK} + \arg \overline{A}_{\rm S}^{KK})$	$2.481 \pm 0.072 \pm 0.048$
$\mathcal{A}_0^{CP}$	$(\|A_0\|^2/F_{\rm P} - \|\overline{A}_0\|^2/\overline{F}_{\rm P})/(\|A_0\|^2/F_{\rm P} + \|\overline{A}_0\|^2/\overline{F}_{\rm P})$	$-0.003 \pm 0.038 \pm 0.005$
$\mathcal{A}_\perp^{CP}$	$(\|A_\perp\|^2/F_{\rm P} - \|\overline{A}_\perp\|^2/\overline{F}_{\rm P})/(\|A_\perp\|^2/F_{\rm P} + \|\overline{A}_\perp\|^2/\overline{F}_{\rm P})$	$+0.047 \pm 0.074 \pm 0.009$
$\mathcal{A}_S(K\pi)^{CP}$	$(\|A_{\rm S}^{K\pi}\|^2 - \|\overline{A}_{\rm S}^{K\pi}\|^2)/(\|A_{\rm S}^{K\pi}\|^2 + \|\overline{A}_{\rm S}^{K\pi}\|^2)$	$+0.073 \pm 0.091 \pm 0.035$
$\mathcal{A}_S(KK)^{CP}$	$(\|A_{\rm S}^{KK}\|^2 - \|\overline{A}_{\rm S}^{KK}\|^2)/(\|A_{\rm S}^{KK}\|^2 + \|\overline{A}_{\rm S}^{KK}\|^2)$	$-0.209 \pm 0.105 \pm 0.012$
$\delta_\perp^{CP}$	$0.5(\arg A_\perp - \arg \overline{A}_\perp)$	$+0.062 \pm 0.062 \pm 0.005$
$\delta_\parallel^{CP}$	$0.5(\arg A_\parallel - \arg \overline{A}_\parallel)$	$+0.045 \pm 0.069 \pm 0.015$
$\delta_S(K\pi)^{CP}$	$0.5(\arg A_{\rm S}^{K\pi} - \arg \overline{A}_{\rm S}^{K\pi})$	$+0.062 \pm 0.062 \pm 0.022$
$\delta_S(KK)^{CP}$	$0.5(\arg A_{\rm S}^{KK} - \arg \overline{A}_{\rm S}^{KK})$	$+0.022 \pm 0.072 \pm 0.004$

The CP asymmetries in both the amplitudes and the phases are consistent with zero.

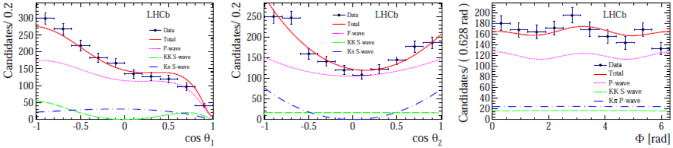
Polarization amplitudes and CP asymmetries in $B^0 \to \phi K^*(892)^0$ - $\mathcal{L} = 1\,\mathrm{fb}^{-1}$

Systematic contributions:

- **Acceptance of the detector**: the angular acceptance is obtained from simulated events and the syst takes into account the limited size of MC.
- **Mass model**: used to determine the s-weights for the angular analysis, a) for signal DG instead of DG+CB b) for bkg first order poly instead of expo c) additional inclusive and exclusive backgrounds d) contributions from Λ_b mis.id. bkg added e) lower bound of the range varied. Largest difference assigned as a syst.
- **S-wave**: alternative model of the s-wave considered.
- **Data/MC**: s-wave component not included in MC, simulated events are reweighted and then used to calculate again angular acceptances.

Polarization amplitudes and CP asymmetries in $B^0 \to \phi K^*(892)^0$ - $\mathcal{L} = 1\,\mathrm{fb}^{-1}$

[LHCB-PAPER-2014-005]



f_L	= 0.497 $\pm$ 0.019 (stat) $\pm$ 0.015 (syst)
$f_\perp$	= 0.221 $\pm$ 0.016 (stat) $\pm$ 0.013 (syst)
$f_S(K\pi)$	= 0.143 $\pm$ 0.013 (stat) $\pm$ 0.012 (syst)
$f_S(KK)$	= 0.122 $\pm$ 0.013 (stat) $\pm$ 0.008 (syst)

- Longitudinal and transverse polarizations have similar size ($\sim$ 0.5), in agreement with Babar [PRD 78, 092008] and Belle [PRD 88, 072004]
- Significant S-wave contribution

Polarization amplitudes and CP asymmetries in $B^0 \to \phi K^*(892)^0$ - Triple product asymmetries

- Non-zero triple product asymmetries arise either due to a *T*-violating phase (*CP*-violation) or a *CP*-conserving phase and final-state interactions.
- For the P-wave decay two triple product asymmetries are calculated:

$$A_T^1 = \frac{\Gamma(\sin \pm \Phi > 0) - \Gamma(\sin \pm \Phi > 0)}{\Gamma(\sin \pm \Phi > 0) + \Gamma(\sin \pm \Phi > 0)} \quad A_T^2 = \frac{\Gamma(\sin 2\Phi > 0) - \Gamma(\sin 2\Phi > 0)}{\Gamma(\sin 2\Phi > 0) + \Gamma(\sin 2\Phi > 0)}$$

  where $+$ is used for $\cos\theta_1 \cos\theta_2 > 0$ and otherwise.
- data can be separated into B^0 and $\overline{B}^0$:

$$A^i_{\mathrm{true}} = \frac{A^i_T + \overline{A}^i_T}{2} \qquad A^i_{\mathrm{fake}} = \frac{A^i_T - \overline{A}^i_T}{2}$$

  - in SM A^i_{true} predicted to be 0;
  - large values of A^i_{fake} reflect the importance of strong final-state phases.
- Presence of *S*-wave allows two additional TP asymmetries.

Polarization amplitudes and CP asymmetries in $B^0 \to \phi K^*(892)^0$ - Triple product asymmetries

Table 3: Triple-product asymmetries. The first and second errors on the measured statistical and systematic, respectively.

Asymmetry	Measured value
A_T^1(true)	$-0.007 \pm 0.012 \pm 0.002$
A_T^2(true)	$+0.004 \pm 0.014 \pm 0.002$
A_T^3(true)	$+0.004 \pm 0.006 \pm 0.001$
A_T^4(true)	$+0.002 \pm 0.006 \pm 0.001$
A_T^1(fake)	$-0.105 \pm 0.012 \pm 0.006$
A_T^2(fake)	$-0.017 \pm 0.014 \pm 0.003$
A_T^3(fake)	$-0.063 \pm 0.006 \pm 0.005$
A_T^4(fake)	$-0.019 \pm 0.006 \pm 0.007$

- The true asymmetries are consistent with zero, showing no evidence for physics beyond the Standard Model.
- In contrast, all but one of the fake asymmetries are significantly different from zero, indicating the presence of final-state interactions.

Time dependent $\not{CP}$ in $B_s^0 \to K^+K^-$ - $\mathcal{L} = 1\,\mathrm{fb}^{-1}$

- CP-violation in charmless two-body decays is a good test of CKM;
- quantitative SM predictions for CP violation are challenging because of the presence of (loop) penguin amplitudes, in addition to tree level
  $\Longrightarrow$ knowledge of hadronic factors required
  $\Longrightarrow$ necessary to combine several measurements using approximate flavour symmetries in order to cancel uncertainties on hadronic factors.
- Belle and Babar performed isospin analysis of $B \to \pi\pi$, determining the phase of the CKM matrix;
- hadronic parameters entering $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$ are related by U-spin symmetry $\Longrightarrow$ experimental knowledge of $B_s^0 \to K^+K^-$ can improve the determination of the CKM phase.
- LHCb performed measurements of time integrated CP asymmetries in $B^0 \to K^+\pi^-$ and $B_s^0 \to K^-\pi^+$, plus several BR.

Time dependent $\not{CP}$ in $B_s^0 \to K^+K^-$ - $\mathcal{L} = 1\,\mathrm{fb}^{-1}$

$$
\begin{aligned}
A_{CP} &= \frac{\mathcal{B}\left(\overline{B} \to \bar{f}\right) - \mathcal{B}\left(B \to f\right)}{\mathcal{B}\left(\overline{B} \to \bar{f}\right) + \mathcal{B}\left(B \to f\right)}, \\
A_f &= \frac{\varepsilon_{\mathrm{rec}}\left(\bar{f}\right) - \varepsilon_{\mathrm{rec}}\left(f\right)}{\varepsilon_{\mathrm{rec}}\left(\bar{f}\right) + \varepsilon_{\mathrm{rec}}\left(f\right)}, \\
A_{\mathrm{P}} &= \frac{\mathcal{R}\left(\overline{B}\right) - \mathcal{R}\left(B\right)}{\mathcal{R}\left(\overline{B}\right) + \mathcal{R}\left(B\right)},
\end{aligned}
$$

- ϵ_{rec} is zero if $f = \bar{f}$
- A fit to the $K^{\pm}\pi^{\mp}$ mass and time spectra is performed to determine the performance of the flavour tagging and the B^0 and B_s^0 production asymmetries.
- Average tagging power (OST): $\epsilon_{eff} = (2.45 \pm 0.25)\%$ (no significant asymmetries between $B^0_{(s)}$ and $\overline{B}^0_{(s)}$)
- Production asymmetries: $A_P(B^0) = (0.6 \pm 0.9)\%$ and $A_P(B_s^0) = (7 \pm 5)\%$
- Decay time resolution: correcting $J/\psi \to \mu\mu$ resolution with a correction factor taken from MC we get 50 ± 0 fs (with a bias of less than 2 fs).

Time dependent $\not{C}\not{P}$ in $B_s^0 \to K^+K^-$ - $\mathcal{L} = 1\,\mathrm{fb}^{-1}$

Systematic uncertainty		C_{KK}	S_{KK}	$C_{\pi\pi}$	$S_{\pi\pi}$
Particle identification		0.003	0.003	0.002	0.004
Flavour tagging		0.008	0.009	0.010	0.011
Production asymmetry		0.002	0.002	0.003	0.002
Signal mass:	final state radiation	0.002	0.001	0.001	0.002
	shape model	0.003	0.004	0.001	0.004
Bkg. mass:	combinatorial	< 0.001	< 0.001	< 0.001	< 0.001
	cross-feed	0.002	0.003	0.002	0.004
Sig. decay time:	acceptance	0.010	0.018	0.002	0.003
	resolution width	0.020	0.025	< 0.001	< 0.001
	resolution bias	0.009	0.007	< 0.001	< 0.001
	resolution model	0.008	0.015	< 0.001	< 0.001
Bkg. decay time:	cross-feed	< 0.001	< 0.001	0.005	0.002
	combinatorial	0.008	0.006	0.015	0.011
	three-body	0.001	0.003	0.003	0.005
Ext. inputs:	Δm_s	0.015	0.018	-	-
	Δm_d	-	-	0.013	0.010
	Γ_s	0.004	0.005	-	-
Total		0.032	0.042	0.023	0.021

$\not{CP}$ in semileptonic asymmetries a_{sl}^s

The measurement can be affected by a detection charge-asymmetry, which may be induced by event selection, tracking, and muon selection.

$$A_{CP}^{measured} = A_{\mu}^{c} + A_{track} - A_{bkg}$$

where:

$$A_{\mu}^{c} = \frac{N(D_s^- \mu^+) - N(D_s^+ \mu^-) \times \frac{\epsilon(\mu^+)}{\epsilon(\mu^-)}}{N(D_s^- \mu^+) + N(D_s^+ \mu^-) \times \frac{\epsilon(\mu^+)}{\epsilon(\mu^-)}}$$

- $N(D_s^- \mu^+)$ and $N(D_s^+ \mu^-)$ are the measured yields of $D_s \mu$ pairs;
- $\epsilon(\mu^{\pm})$ are efficiency corrections accounting for trigger and muon identification effects;
- A_{track} is the track-reconstruction asymmetry of charged particles, due to the magnet that bends particles of different charge in different detector halves;
- A_{bkg} accounts for asymmetries induced by backgrounds.

$\not{CP}$ in semileptonic asymmetries a_{sl}^s

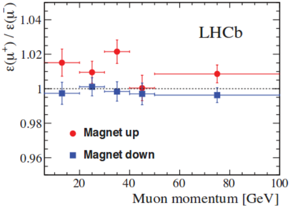


Figure 3: Relative muon efficiency as a function of muon momentum determined using the kinematically-selected J/ψ sample.

- relative efficiencies for triggering and identifying muons.
- constistent with being independent of momentum.
- small 1% differences due to alignment of the muon stations, which affects predominantly the hardware muon trigger.

$\not{CP}$ in semileptonic asymmetries a_{sl}^s

A_{track} is the track-reconstruction asymmetry of charged particles, due to the magnet that bends particles of different charge in different detector halves

- $A_{track}^{\pi\mu} = (+0.01 \pm 0.13)\%$: small because the pion and muon asymmetries are the same but they have opposite sign ($D_s^{\pm}(\phi\pi^{\pm})\mu^{\mp}$);
- $A_{track}^{KK} = (+0.012 \pm 0.004)\%$: residual charge asymmetries in K reconstruction due to a slight momentum mismatch between the two kaons from the ϕ arising from the interference with the S-wave component.
- The total tracking asymmetry is: $A_{track} = (+0.02 \pm 0.13)\%$
- The total background asymmetry is: $A_{back} = (+0.05 \pm 0.05)\%$

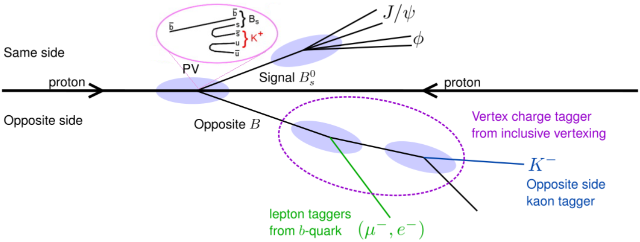
$\not{CP}$ in semileptonic asymmetries a_{sl}^{s}

Table 3: Sources of systematic uncertainty on A_{meas}.

Source	$\sigma(A_{\text{meas}})[\%]$
Signal modelling and muon correction	0.07
Statistical uncertainty on the efficiency ratios	0.08
Background asymmetry	0.05
Asymmetry in track reconstruction	0.13
Field-up and field-down run conditions	0.01
Software trigger bias (topological trigger)	0.05
Total	0.18

Flavour tagging - B_s^0 or $\overline{B}_s^0$? [Eur.Phys.J. C72(2012) 2022] [LHCb-CONF-2012-033]

Tagging: determine flavour of decaying B_s^0-meson at production.



Needs precise knowledge of mistag probability, $\omega_{\rm mistag}$:

$$A_{CP}(t) = -\eta_{CP} \cdot D_{\rm tag}(\omega_{\rm mistag}) \cdot D_{\rm tres}(\sigma_t) \cdot \sin(\phi_s) \cdot \sin(\Delta m_s t)$$

$$D_{\rm tag} = (1 - 2\omega_{\rm mistag})$$

Using SSK and OS tagging algorithms fully optimized and calibrated on data $\omega_{\rm mistag} \approx 36\%$:

- **effective tagging power** $\epsilon_{tag} D^2_{\rm tag} = (3.13 \pm 0.12 \pm 0.20)\%$

Same tagging power as a dataset containing $\epsilon_{tag} D^2_{\rm tag} N$ perfectly tagged events.

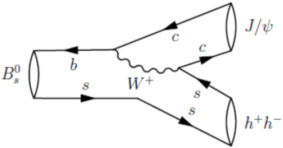
$B_s^0 \to J/\psi\ \phi$ systematics

Table 9: Statistical and systematic uncertainties.

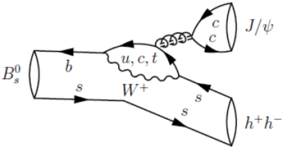
Source	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$\lvert A_\perp\rvert^2$	$\lvert A_0\rvert^2$	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	ϕ_s [rad]	$\lvert\lambda\rvert$
Stat. uncertainty	0.0048	0.016	0.0086	0.0061	$^{+0.13}_{-0.21}$	0.22	0.091	0.031
Background subtraction	0.0041	0.002	–	0.0031	0.03	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

[Phys. Rev. D 87, 112010]

$B_s^0 \to J/\psi\ \phi$ penguin pollutions



(a) tree



(b) penguin

- Standar Model prediction is obtained ignoring penguin pollutions
- Experimentally an angular analysis in $B_s^0 \to J/\psi\ K^{*0}$ can give information about penguin contributions to $B_s^0 \to J/\psi\ \phi$

First step: *"Measurement of the $B_s^0 \to J/\psi K^{*0}$ branching fraction and angular amplitudes"*

[Phys. Rev. D 86, 071102(R) (2012)]

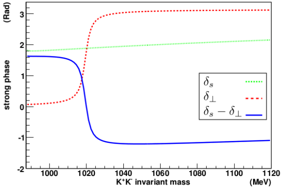
$$BR = (4.4^{+0.5}_{-0.4} \pm 0.8) \times 10^{-5}$$

Determining the sign of $\Delta\Gamma_s$

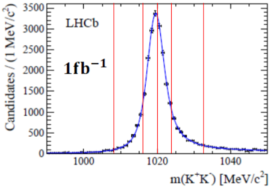
Two solutions to the decay rates in $B_s^0 \to J/\Psi\ \phi$:

[Phys. Rev. D 87, 112010]

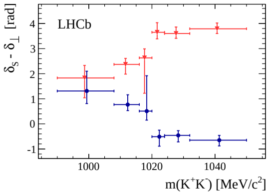
Solution I	Solution II
$\delta - \delta_0$	$\delta_0 - \delta$
$\delta_\perp - \delta_0$	$\pi - \delta_0 - \delta_\perp$
$\delta_s - \delta_0$	$\delta_0 - \delta_s$
ϕ_s	$\pi - \phi_s$
$\Delta\Gamma_s$	$-\Delta\Gamma_s$



- P-wave phase ($\delta_\perp$) increases rapidly across $\phi(1020)$ mass resonance, S-wave (δ_s) varies slowly.
- Measuring $\delta_s - \delta_\perp$ in bins of $M(K^+K^-)$ resolves the ambiguity.
- LHCb results using $\mathcal{L} = 1\text{fb}^{-1}$ in 6 bins of $M(K^+K^-)$:



The **physical solution** has to decrease in bins of $M(K^+K^-)$



Solution I confirmed $\Longrightarrow$ positive $\Delta\Gamma_s$ fits expectations.

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

- Resonances that decay into a $\pi^+\pi^-$ pair must be isoscalar (I=0), because $s\bar{s}$ system has I=0.
- To test it the isospin-1 $\rho(770)$ meson is added.
- The non-resonance (NR) is assumed to be S-wave.
- In previous analysis a resonant-state at (1475±6) MeV was observed and identified as $f_0(1370)$. Now identified with $f_0(1500)$.
- New structure visible around 1800 MeV ⇒ could be $f_0(1790)$ observed by BES [Phys.Lett.B607:243-253 (2005)]

Table 2: Possible resonance candidates in the $\overline{B}_s^0 \to J/\psi\pi^+\pi^-$ decay mode and their parameters used in the fit.

Resonance	Spin	Helicity	Resonance formalism	Mass (MeV)	Width (MeV)	Source
$f_0(500)$	0	0	BW	471 ± 21	534 ± 53	LHCb [19]
$f_0(980)$	0	0	Flatté	see text		
$f_2(1270)$	2	$0, \pm 1$	BW	1275.1 ± 1.2	$185.1^{+2.9}_{-2.4}$	PDG [6]
$f_0(1500)$	0	0	BW	see text		
$f_2'(1525)$	2	$0, \pm 1$	BW	1522^{+6}_{-3}	84^{+12}_{-8}	LHCb [28]
$f_0(1710)$	0	0	BW	1720 ± 6	135 ± 8	PDG [6]
$f_0(1790)$	0	0	BW	1790^{+40}_{-30}	270^{+60}_{-30}	BES [27]
$\rho(770)$	1	$0, \pm 1$	BW	775.49 ± 0.34	149.1 ± 0.8	PDG [6]

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

- In order to compare different models quantitatively an estimate of the goodness of fit is calculated:

$$\chi^2 = 2\sum_{i=1}^{N_{bin}}\left[x_i - n_i + n_i ln\left(\frac{n_i}{x_i}\right)\right]$$

where n_i is the number of events in the four dimensional bin i and x_i is the expected number of events according to the fitted likelihood function.

- 5R: $f_0(980)$, $f_0(1500)$, $f_0(1790)$, $f_2(1270)$, $f_2'(1525)$
- Solution I: minima with no significant NR, Solution II: minima with significant NR

Table 3: Fit $-\ln\mathcal{L}$ and χ^2/ndf of different resonance models.

Resonance model	$-\ln\mathcal{L}$	χ^2/ndf
5R (Solution I)	−93738	2005/1822 = 1.100
5R+NR (Solution I)	−93741	2003/1820 = 1.101
5R+$f_0(500)$ (Solution I)	−93741	2004/1820 = 1.101
5R+$f_0(1710)$ (Solution I)	−93744	1998/1820 = 1.098
5R+$\rho(770)$ (Solution I)	−93742	2004/1816 = 1.104
5R+NR (Solution II)	−93739	2008/1820 = 1.103
5R+NR+$f_0(500)$ (Solution II)	−93741	2004/1818 = 1.102
5R+NR+$f_0(1710)$ (Solution II)	−93745	2004/1818 = 1.102
5R+NR+$\rho(770)$ (Solution II)	−93746	1998/1814 = 1.101

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

- For both Solution I and II dominant contribution is S-wave including: $f_0(980)$, $f_0(1500)$, $f_0(1790)$;
- D-wave $f_2(1270)$, $f_2'(1525)$ is only 2.3% for both solutions.

Table 4: Fit fractions (%) of contributing components for both solutions.

Component	Solution I	Solution II
$f_0(980)$	$70.3 \pm 1.5^{+0.4}_{-5.1}$	$92.4 \pm 2.0^{+\ 0.8}_{-16.0}$
$f_0(1500)$	$10.1 \pm 0.8^{+1.1}_{-0.3}$	$9.1 \pm 0.9 \pm 0.3$
$f_0(1790)$	$2.4 \pm 0.4^{+5.0}_{-0.2}$	$0.9 \pm 0.3^{+2.5}_{-0.1}$
$f_2(1270)_0$	$0.36 \pm 0.07 \pm 0.03$	$0.42 \pm 0.07 \pm 0.04$
$f_2(1270)_\parallel$	$0.52 \pm 0.15^{+0.05}_{-0.02}$	$0.42 \pm 0.13^{+0.11}_{-0.02}$
$f_2(1270)_\perp$	$0.63 \pm 0.34^{+0.16}_{-0.08}$	$0.60 \pm 0.36^{+0.12}_{-0.09}$
$f_2'(1525)_0$	$0.51 \pm 0.09^{+0.05}_{-0.04}$	$0.52 \pm 0.09^{+0.05}_{-0.04}$
$f_2'(1525)_\parallel$	$0.06^{+0.13}_{-0.04} \pm 0.01$	$0.11^{+0.16+0.03}_{-0.07-0.04}$
$f_2'(1525)_\perp$	$0.26 \pm 0.18^{+0.06}_{-0.04}$	$0.26 \pm 0.22^{+0.06}_{-0.05}$
NR	-	$5.9 \pm 1.4^{+0.7}_{-4.6}$
Sum	85.2	110.6
$-\ln\mathcal{L}$	-93738	-93739
χ^2/ndf	2005/1822	2008/1820

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

- $f_0(500)$ states does not have a significant fit fraction
- Upper limit for the fit fraction ratio between $f_0(500)$ and $f_0(980)$ of 0.3% from Solution I and 3.4% from Solution II at 90% CL
- $\rho(770)$ states does not have a significant fit fraction
- $\rho(770)$ fit fraction $0.60 \pm 0.30^{+0.08}_{-0.14}$ from Solution I and $1.02 \pm 0.36^{+0.09}_{-0.15}$ from Solution II.
- mass of $f_0(1790)$ in good agreement with BES result.

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

- **Acceptance**: fit repeated in data 100 times with the acceptance randomly generated according to the corresponding error matrix.
- **Background modeling**: fit repeated in data 100 times with the background function randomly generated according to the corresponding error matrix.
- **Fit model**: a) possible contributions of resonances in slide 44 but not used in the baseline solution, b) hadron scale *r* parameters in the Blatt-Weisskopf barrier factors varied from 5.0 GeV^{-1} to 3.0 GeV^{-1} for B meson and from 1.5 GeV^{-1} to 3.0 GeV^{-1} for R resonance, c) using F_{KK}=1 in the Flattè function.
  $\Rightarrow$ largest deviation taken as a systematic.
- **Resonance parameters**: repeating data fit by varying the mass and width of resonances within their errors one at time and add the changes in quadrature.
- **Negligible:** value of ϕ_s, efficiency function $\epsilon(t)$, Γ_s and $\Delta\Gamma_s$ uncertianties, L_B choice[1].

[1] for $\tau = \perp$ amplitude, the L_B value of a spin-1 (or 2) resonance is 1 (or 2); the other transversity components (0 and $\|$) have two possible L_B values of 0 and 2 (or 1 and 3) for spin-1 (or 2) resonances. In this analysis the lower one is used.

$B_s^0 \to J/\psi\pi^+\pi^-$ mixing angles

When the σ and f_0 are considered as $q\bar{q}$ states there is the possibility of their being mixtures of light and strange quarks that is characterized by a 2×2 rotation matrix with a single parameter, the angle ϕ, so that their wave-functions are

$$\begin{aligned} |f_0\rangle &= \cos\phi|s\bar{s}\rangle + \sin\phi|n\bar{n}\rangle \\ |\sigma\rangle &= -\sin\phi|s\bar{s}\rangle + \cos\phi|n\bar{n}\rangle, \\ \text{where } |n\bar{n}\rangle &\equiv \frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle + |d\bar{d}\rangle\right). \end{aligned} \tag{1}$$

While there have been several attempts to measure the mixing angle ϕ, the model dependent results give a wide range of values. We describe here only a few examples. $D^\pm$ and $D_s^\pm$ decays into $f_0(980)\pi^\pm$ and $f_0(980)K^\pm$ give values of $31^\circ \pm 5^\circ$ or $42^\circ \pm 7^\circ$ [10]. $D_s^+ \to \pi^+\pi^+\pi^-$ transitions give a range $35^\circ < |\phi| < 55^\circ$ [11]. In light meson radiative decays two solutions are found either $4^\circ \pm 3^\circ$ or $136^\circ \pm 6^\circ$ [12]. Resonance decays from both $\phi \to \gamma\pi^0\pi^0$ and $J/\psi \to \omega\pi\pi$ give a value of $\simeq 20^\circ$. On the basis of SU(3), a value of $19^\circ \pm 5^\circ$ is provided [13]. Finally, Ochs [14], averaging over several processes, finds $30^\circ \pm 3^\circ$

When these states are viewed as $q\bar{q}q\bar{q}$ states the wave functions becomes

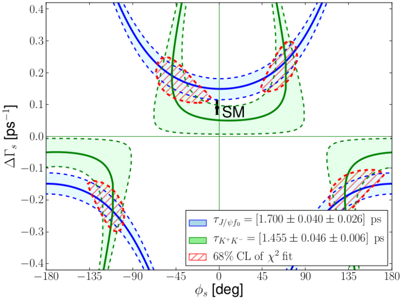
$$|f_0\rangle = \frac{1}{\sqrt{2}}\left([su][\bar{s}\bar{u}] + [sd][\bar{s}\bar{d}]\right), \quad |\sigma\rangle = [ud][\bar{u}\bar{d}]. \tag{2}$$

In this Letter we assume the tetraquark states are unmixed, for which there is some justification [2,10,15], with a mixing angle estimate of $< 5^\circ$ [9].

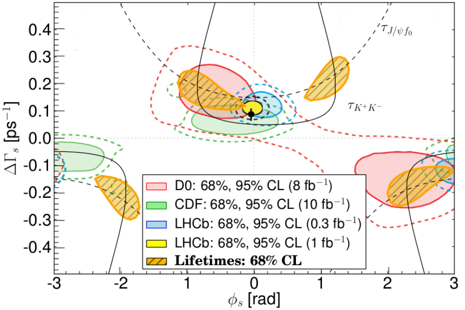
How effective lifetime can constrain ϕ_s

Fleischer, Kneijens [arXiv:1209.3206]

Using effective lifetime to constrain $\Delta\Gamma_s$ and ϕ_s



Inluding direct measurement



Using:

$\tau_{K^+K^-} = [1.455 \pm 0.046$ (stat) ± 0.006 (syst)$]$ ps

[Phys.Lett. **B716 (2012) 393-400**]

$\tau_{J/\Psi f_0} = [1.700 \pm 0.040$ (stat) ± 0.026 (syst)$]$ ps

[LHCb-PAPER-2012-017, arXiv: **1207.0878**]

Using:

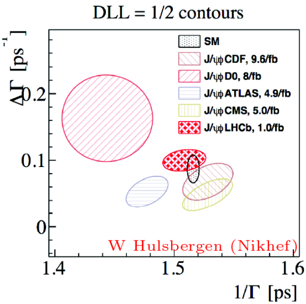
$\phi_s = -0.002 \pm 0.083$ (stat) ± 0.027 (syst) rad

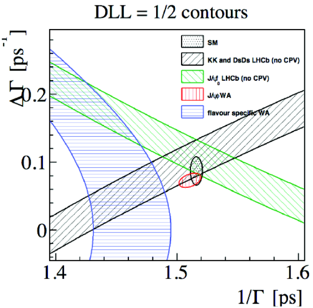
$\Delta\Gamma_s = 0.116 \pm 0.018$ (stat) ± 0.006 (syst) ps^{-1}

[LHCb-CONF-**2012-002**]

$\overline{B}_s^0 \to D_s^+ D_s^-$ effective lifetime - $\mathcal{L} = 3\,\mathrm{fb}^{-1}$

Channel	CP	τ^{eff} [ps]	Ref.
$\overline{B}_s^0 \to D_s^+ D_s^-$	even	$1.379 \pm 0.026 \pm 0.017$	arxiv:1312.1217, PRL
$\overline{B}_s^0 \to K^+ K^-$	even	$1.455 \pm 0.046 \pm 0.006$	PLB 716 (2012) 393-400
$\overline{B}_s^0 \to J/\psi f_0(980)$	odd	$1.700 \pm 0.040 \pm 0.026$	PRL 109 (2012) 152002
$\overline{B}_s^0 \to J/\psi K_S^0$	odd	$1.75 \pm 0.12 \pm 0.07$	Nucl. Phys. B 873 (2013) 275-292
$\overline{B}_s^0 \to D^- D_s^+$	FS	$1.52 \pm 0.15 \pm 0.01$	arxiv:1312.1217, PRL





- Perform naive combination of these lifetimes and results on $\Delta\Gamma_s$ and Γ_s from $B_s^0 \to J/\psi\phi$ and $B_s^0 \to J/\psi\pi\pi$
- Everything in agreement with SM+HQE predictions.

LHCb upgrade

		End of Run2			
		$\int L dt = 3\ fb^{-1}$	$\int L dt = 8\ fb^{-1}$	$\int L dt = 50\ fb^{-1}$	
Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.05	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.09	0.05	**0.016**	~ 0.01
	$A_{sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic penguin	$\phi_s^{eff}(B_s^0 \to \phi\phi)$ (rad)	0.18	0.12	**0.026**	0.02
	$\phi_s^{eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.029**	< 0.02
	$2\beta^{eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.04**	0.02
Right-handed currents	$\phi_s^{eff}(B_s^0 \to \phi\gamma)$	0.20	0.13	**0.030**	< 0.01
	$\tau^{eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.8%**	0.2%
Electroweak penguin	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
	$q_0^2\, A_{FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_I(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.14	0.07	**0.024**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs penguin	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\%$
Unitarity triangle angles	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**1.1°**	negligible
	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.4°**	negligible
	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm *CP* violation	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.5**	–
	ΔA_{CP} (10^{-3})	0.8	0.5	**0.12**	–