Measurements of B lifetimes, mixing and CP violation at LHCb

Angelo Carbone
University of Bologna and INFN
on behalf of LHCb Collaboration

Pascos 2013, Taipei, Taiwan

November 20-26, 2013

Outline

- Overview of recent results on two-body decays
  - Direct CP asymmetries in $B^0 \rightarrow K^+\pi^-$ in $B_s^0 \rightarrow K^-\pi^+$ decays
    - First observation of CP violation in B_s^0 decays
  - Time-dependent CP asymmetries in $B^0 \rightarrow \pi^+\pi^-$ and $B_s^0 \rightarrow K^+K^-$ decays
    - First measurement with $B_s^0 \rightarrow K^+K^-$
- Overview of recent results on measurement of CP-violating mixing phase ϕ_s trough $b \rightarrow c\bar{c}s$ and $b \rightarrow s\bar{s}s$ transitions
  - Results on angular analysis with $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)K^+K^-$ and $B_s^0 \rightarrow \phi\phi$
  - $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\,\pi^+\pi^-$
- Measurements of B_s^0 effective lifetime
  - with $B_s^0 \rightarrow J/\psi\, f^0(980)$, $B_s^0 \rightarrow J/\psi\, K_s^0$ and $B_s^0 \rightarrow K^+K^-$
- Conclusions

CP violation with two-body charmless decays

Why search CPV in $B^0 \rightarrow h^+h^-$ decay?

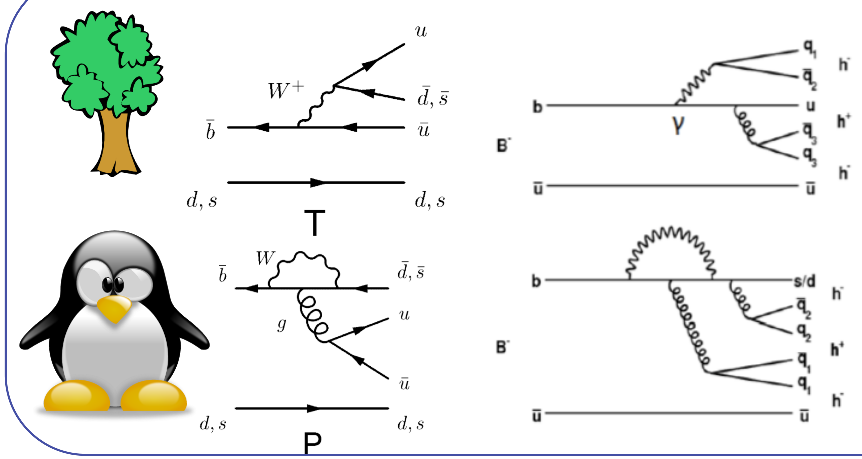
- They receive contributions from both tree and loop (penguin) diagrams
  - Relative phase between the diagrams → direct CP violation in time-integrated measurements
- Time-dependent CP violation in neutral B decays
- Improve knowledge of CKM matrix
- Valid theoretical tool to test QCD calculations
  - QCD factorization, pQCD, SCET, …
- Search for New Physics
  - CP-violation observables and branching fractions can differ from Standard Model predictions

Direct CP asymmetries

$$A_{CP} = \frac{\Gamma_{\bar{B}\to\bar{f}} - \Gamma_{B\to f}}{\Gamma_{\bar{B}\to\bar{f}} + \Gamma_{B\to f}}$$

Time-dependent CP asymmetries

$$A(t) = \frac{\Gamma_{\bar{B}\to f}(t) - \Gamma_{B\to f}(t)}{\Gamma_{\bar{B}\to f}(t) + \Gamma_{B\to f}(t)}$$

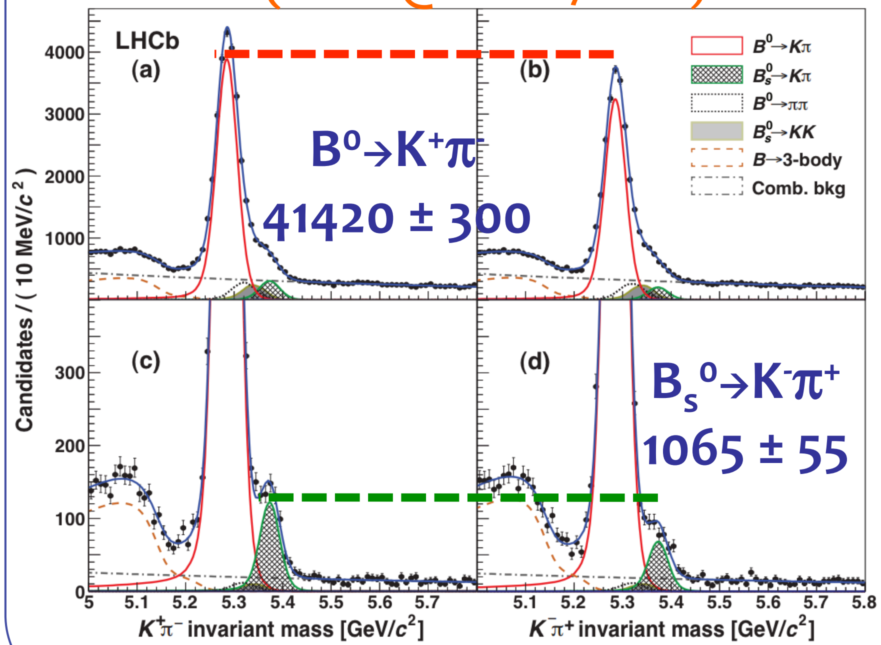


- As penguin topologies are generally sizeable, effects from New Physics in loops may be sizeable as well
- Theoretical interpretation is however not straightforward, because of unknown hadronic parameters in the amplitudes

Direct CP asymmetries in $B^0_{(s)} \to K\pi$ decays

PRL 110 (2013) 221601

$\mathcal{L}$ =(1 fb^{-1} @ √s = 7 TeV)



$$A_{raw} = \frac{N(\overline{B} \to K\pi) - N(B \to K\pi)}{N(\overline{B} \to K\pi) + N(B \to K\pi)}$$

$$A_{CP} = A_{raw} - A_D - \kappa A_P$$

Raw asymmetry from invariant mass fit

Detection asymmetry of final state particles

k dilution factor due to mixing

Asymmetry in production rates of B and $\overline{B}$ mesons

$$A_{CP}(B^0 \to K\pi) = -0.080 \pm 0.007(\text{stat}) \pm 0.003(\text{syst}),$$

Most precise measurement of this quantity to date, 10.5σ from zero

$$A_{CP}(B_s^0 \to K\pi) = 0.27 \pm 0.04(\text{stat}) \pm 0.01(\text{syst}).$$

First observation of CP violation in B_s^0 decays, with significance of 6.5σ

- Test using U-Spin in SM

$$\Delta = \frac{A_{CP}(B^0 \to K^+\pi^-)}{A_{CP}(B_s^0 \to K^-\pi^+)} + \frac{\mathcal{B}(B_s^0 \to K^-\pi^+)}{\mathcal{B}(B^0 \to K^+\pi^-)} \frac{\tau_d}{\tau_s} = 0$$

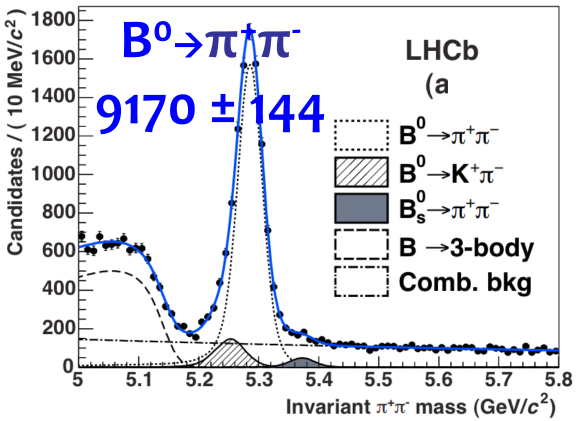
- Also using LHCb results for branching ratios [JHEP 10 (2012) 037]

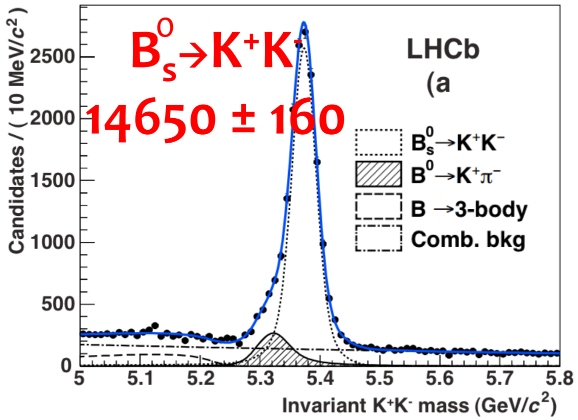
$$\Delta = -0.02 \pm 0.05 \pm 0.04$$

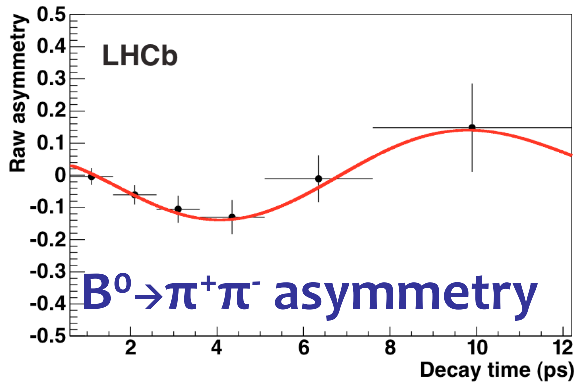
Time dependent CPV in $B^0 \to \pi^+\pi^-$ and $B_s^0 \to K^+K^-$

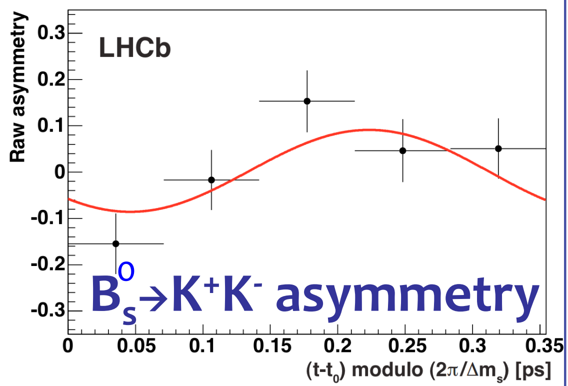
JHEP 10 (2013) 183

$\mathcal{L}$ = (1 fb^{-1} @ $\sqrt{s}$ = 7 TeV)









$$\mathcal{A}(t) = \frac{-C_f \cos(\Delta m_{d(s)} t) + S_f \sin(\Delta m_{d(s)} t)}{\cosh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right) - A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right)}$$

C → direct CP violation

S → mixing-induced CP violation

$$C_{\pi\pi} = -0.38 \pm 0.15\,(\text{stat}) \pm 0.02\,(\text{syst}),$$
$$S_{\pi\pi} = -0.71 \pm 0.13\,(\text{stat}) \pm 0.02\,(\text{syst}),$$

Results are compatible with previous measurements from BaBar and Belle

$$C_{KK} = 0.14 \pm 0.11\,(\text{stat}) \pm 0.03\,(\text{syst}),$$
$$S_{KK} = 0.30 \pm 0.12\,(\text{stat}) \pm 0.04\,(\text{syst}),$$

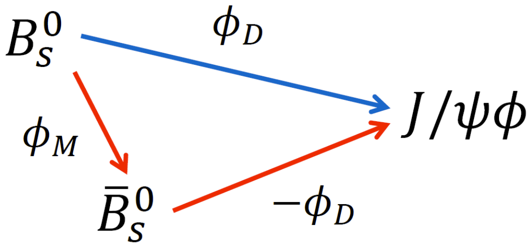
First measurement ever

significance for (C_{KK}, S_{KK}) to differ from (0, 0) is 2.7σ

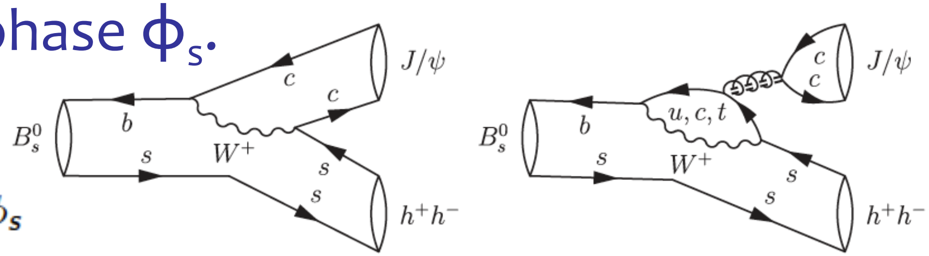
Search for new physics in B_s^0 mixing

ϕ_s with $B_s^0 \to J/\psi(\mu^+\mu^-)h^+h^-$

The interference between B_s^0 meson decay amplitudes to CP eigenstates, directly (ϕ_D) or via mixing (ϕ_M-ϕ_D), gives rise to a measurable CP-violating phase ϕ_s.



In Standard Model: ϕ_s
$= \phi_{s,M} - 2\phi_{s,D} =$
$= -2\beta_s + \phi_s^{\text{penguin}} \approx$
$\approx -2\beta_s$



SM, for $b \to c\bar{c}s$ transitions and ignoring subleading penguin contributions, predicts

$$\phi_s = -2\beta_s = (-0.036 \pm 0.002) \text{ rad}$$

$\rightarrow \phi_s = \phi_s^{SM} + \phi_s^{NP}$

ϕ_s^{SM} small

$\rightarrow \phi_s$ can be enlarged by ϕ_s^{NP}

Theoretically clean tree-dominating decay

Two modes:

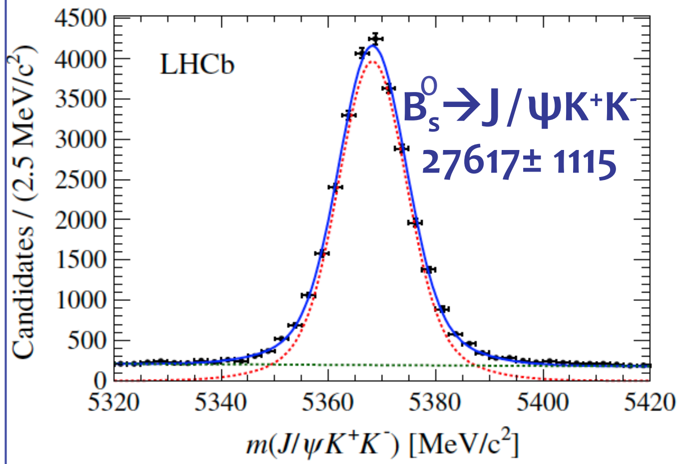
$B_s^0 \to J/\psi K^+K^-$, manly trough $B_s^0 \to J/\psi\phi$, more statistic, angular decomposition needed

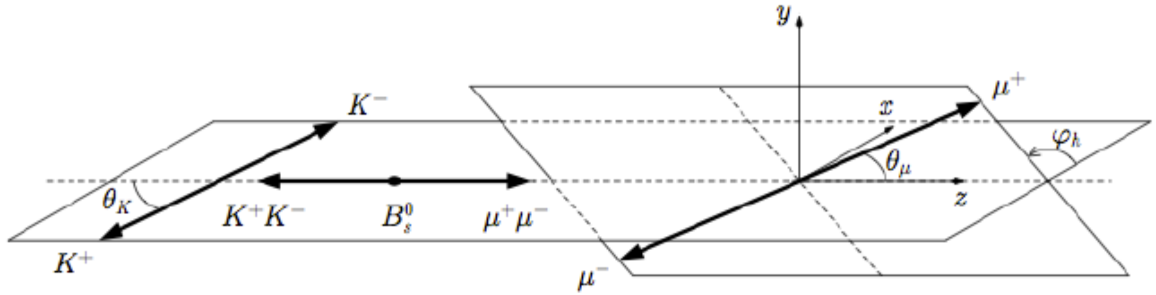
$B_s^0 \to J/\psi\pi^+\pi^-$, less statistics, no angular decomposition needed

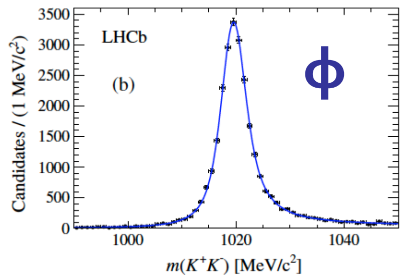
Time dependent analysis of $B_s^0 \rightarrow J/\psi K^+K^-$

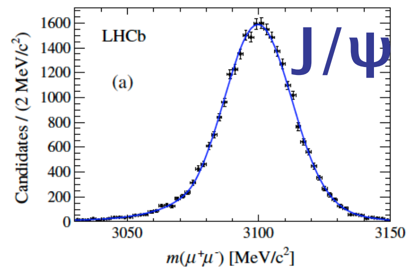
PRD 87 (2013) 112010

Angular analysis to statistically separate CP eigenstates









$\mathcal{L}$ = (1 fb^{-1} @ √s = 7 TeV)

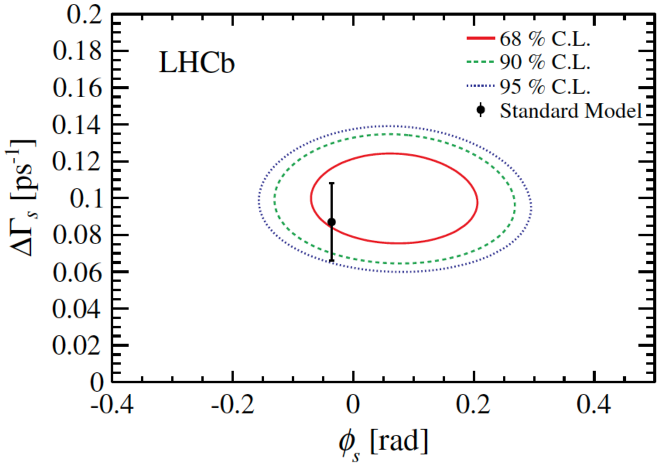
Main contribution from $\phi \rightarrow K^+K$

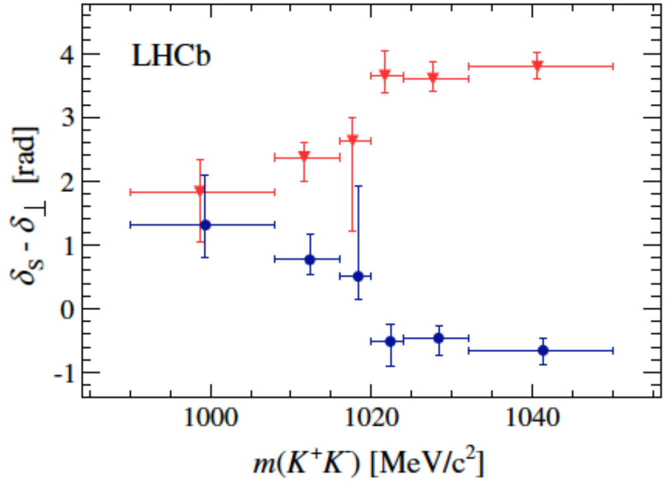
- Flavour tagging used to determine flavour at the production
  - Tagging calibrated on data using $B^0 \to D^{*-}\mu\nu_\mu$, $B^+ \rightarrow J/\psi K^+$ (opposite side), $B_s^0 \rightarrow D_s^-\pi^+$ (same side)
  - Effective tagging power (3.13±0.23)% (OS+SS)
- Decay time resolution calibrated with prompt $\mu^+\mu^-K^+K^-$ events that have a true decay time of zero → <σ> = 45 fs

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

$\mathcal{L}$ = (1 fb^{-1} @ √s = 7 TeV)

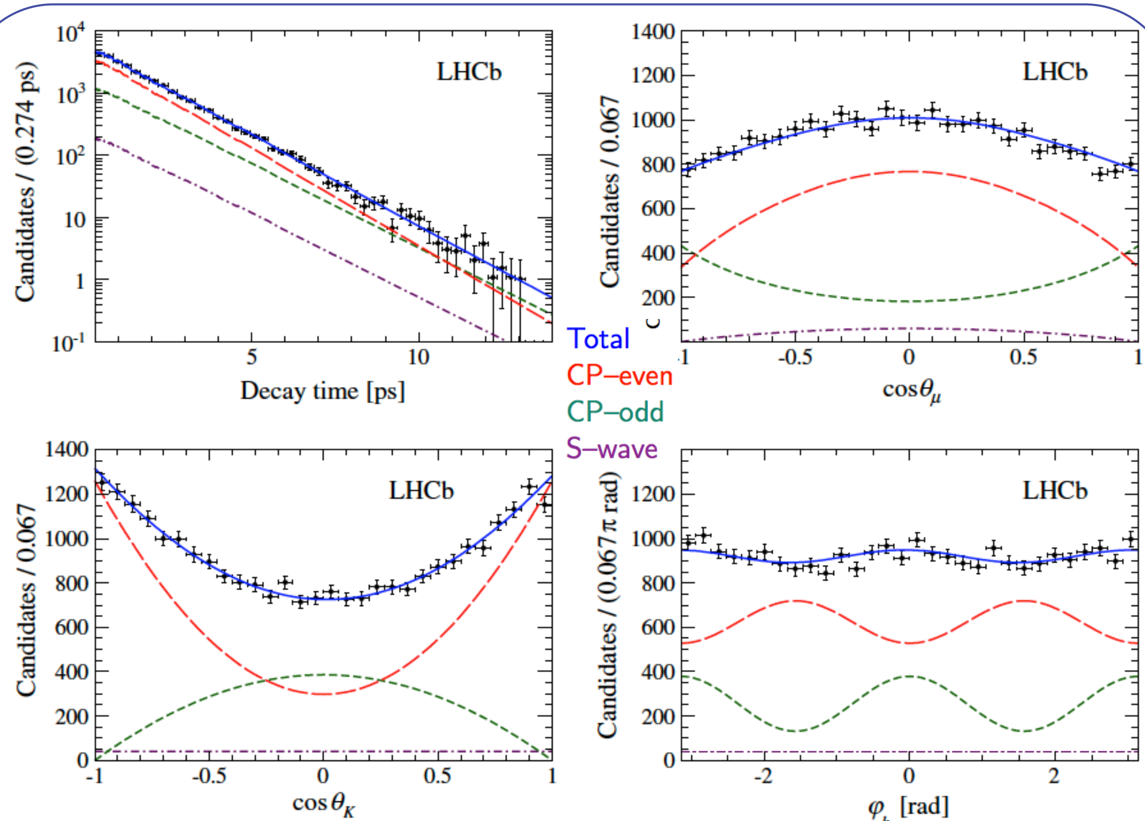
PRD 87 (2013) 112010





$\Delta\Gamma_s > 0$ confirmed

[A. Lenz, U. Nierste arXiv 1102.4274]



ϕ_s = 0.07 ± 0.09 (stat) ± 0.01(syst) rad

$\Delta\Gamma_s$ = 0.100 ± 0.016 (stat) ± 0.003 (syst) ps^{-1}

$\Gamma_s = (\Gamma_H+\Gamma_L)/2$ = 0.663 ± 0.005 ± 0.006 ps^{-1}

In good agreement with SM expectation

Time dependent analysis of $B_s^0 \to J/\psi\pi^+\pi^-$

PLB 713 (2012) 378

Also a $b \to c\bar{c}s$ process

97.5% pure CP odd decay

[PRD 86 (2012) 052006, arXiv: 1204.5643]

Γ_s and $\Delta\Gamma_s$ constrained to result from $B_s^0 \to J/\psi K^+K^-$

$$\phi_s = -0.14^{+0.17}_{-0.16} \pm 0.01 \text{ rad}$$

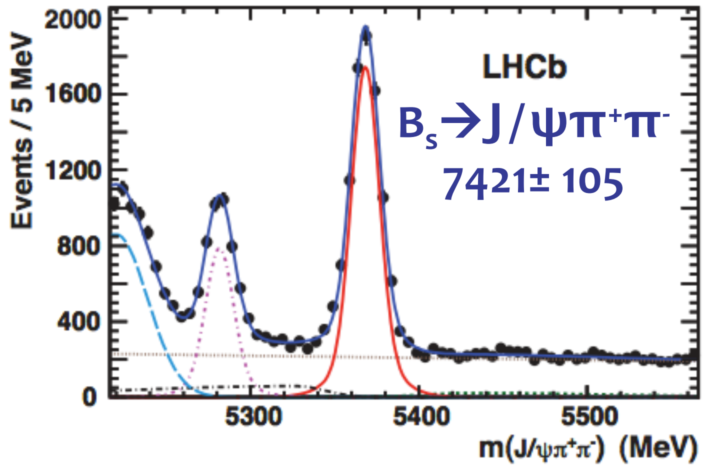
Combined results $B_s^0 \to J/\psi h^+h^-$

$$\phi_s^{c\bar{c}s} = 0.01 \pm 0.07 \pm 0.01 \text{ rad}$$

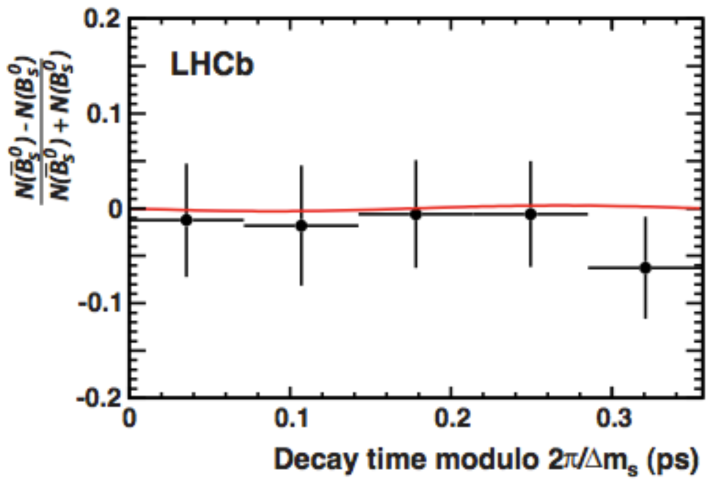
$$\Delta\Gamma_s = 0.106 \pm 0.011 \pm 0.007 \text{ ps}^{-1}$$

$$\Gamma_s = 0.661 \pm 0.004 \pm 0.006 \text{ ps}^{-1}$$

$\mathcal{L} = (1 \text{ fb}^{-1} @ \sqrt{s} = 7 \text{ TeV})$

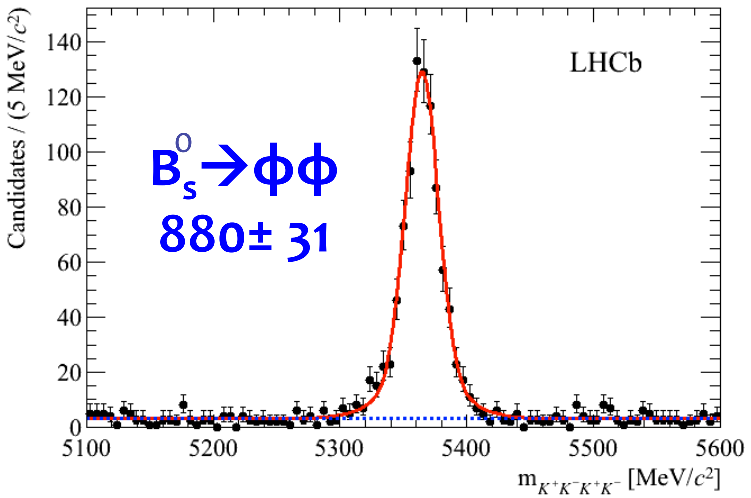


Background-subtracted CP asymmetry

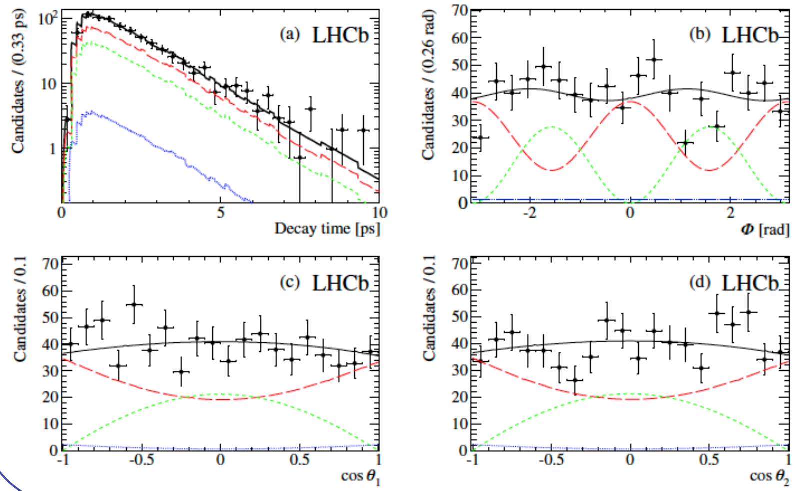


Time dependent analysis of $B_s^0 \rightarrow \phi\phi$

PRL 110 (2013) 241802

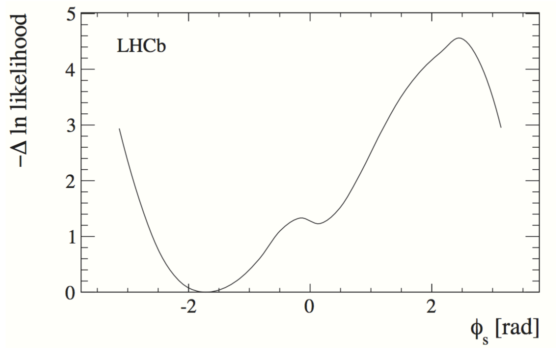


$\mathcal{L}$ = (1 fb^{-1} @ $\sqrt{s}$ = 7 TeV)

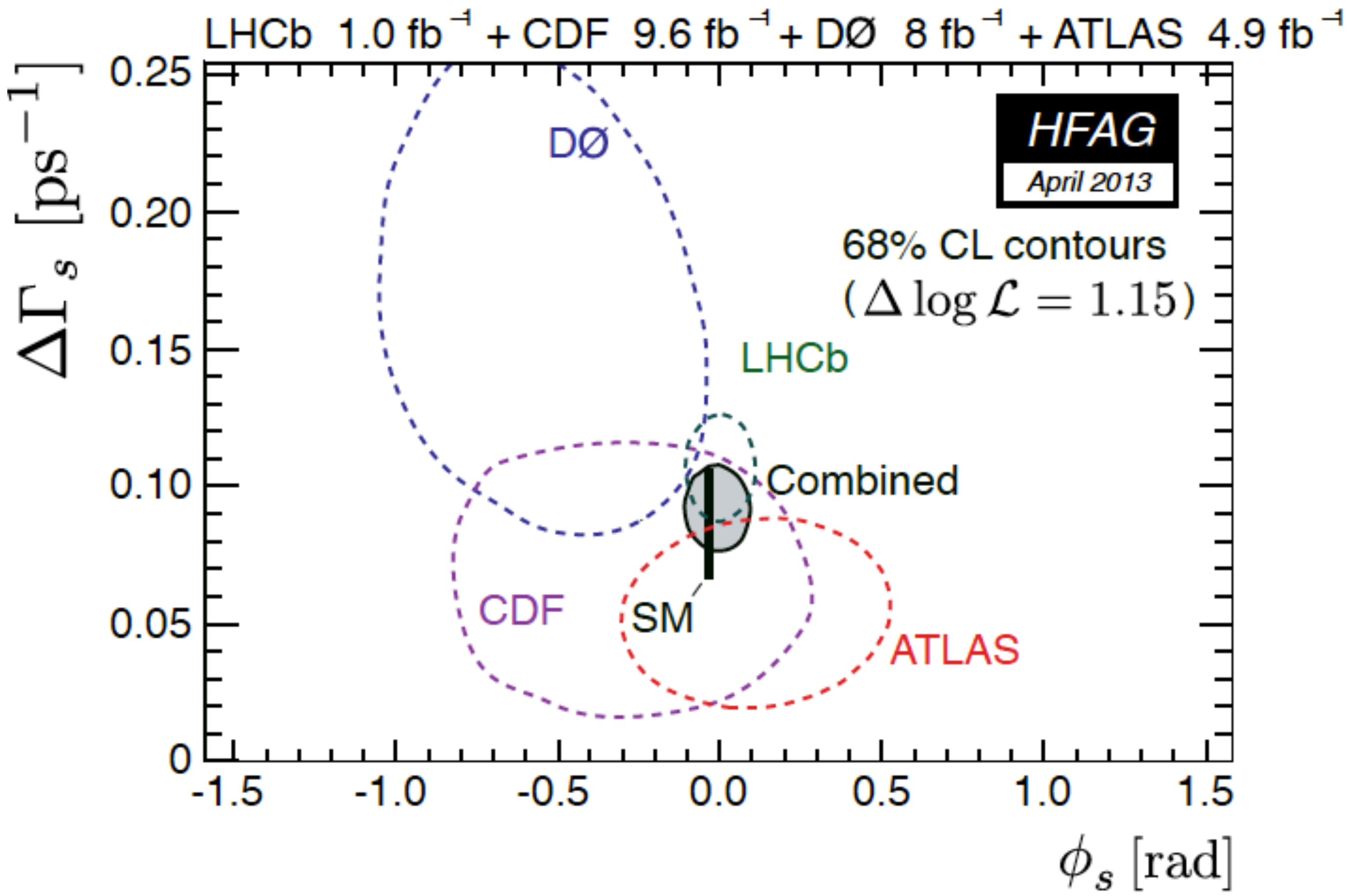


- $B_s^0 \rightarrow \phi\phi$ is forbidden at the tree level in the SM and proceeds via a gluonic $b \rightarrow s\bar{s}s$ process
- SM predicts CP-violating phase to be small (decay dependent)
- Calculations using QCD factorization provide an upper limit of 0.02 rad
- Null test of the SM!
- Largest systematic error due to S- wave contribution
- Total systematic uncertainties 0.22 rad

$$\phi_s^{\phi\phi} \in [-2.46, -0.76] \text{ rad at } 68\ \%\ \text{CL}$$



Comparison with the other experiment



LHCb measurement is most precise and dominating
Precision improvement crucial for further test of the SM

B_s^0 effective lifetime

Introduction to effective lifetime

- In CP eigenstates the effective lifetime is sensitive to Γ_s and ϕ_s (mixing induced CP phase). Considering a B_s^0 ($\bar{B}_s^0$)→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 $\mathcal{A}_{\Delta\Gamma_s}$ function of ϕ_s.
- If there is no CP violation $\mathcal{A}_{\Delta\Gamma_s} = \pm 1$

Effective lifetime is the lifetime measured by describing the untagged decay time distribution with a single exponential. At the first order in $y_s=2\Delta\Gamma_s/\Gamma_s$

$$\tau^{\text{eff}} = \tau_{B_s^0}\left(1 + \mathcal{A}_{\Delta\Gamma_s} y_s + \mathcal{O}(y_s^2)\right)$$

- CP-even decays in SM are dominated by the light mass eigenstate $\tau^{\text{eff}} \sim \Gamma_L^{-1}$
  - for exaple B_s^0→KK. SM expectation: $\mathcal{A}_{\Delta\Gamma_s} = -0.972 \pm 0.012$ $\tau_{KK} = 1.40 \pm 0.02$ ps.
- CP-odd decays in SM are dominated by the heavy mass eigenstate $\tau^{\text{eff}} \sim \Gamma_H^{-1}$
  - for exaple B_s^0→J/ψK_s. SM expectation: $\mathcal{A}_{\Delta\Gamma_s} = 0.944 \pm 0.066$ $\tau^{\text{eff}}_{J/\psi K_S^0}|_{\text{SM}} = 1.639 \pm 0.022$ ps

Alternative way to extract $\Delta\Gamma_s$ and ϕ_s

[R. Fleischer and R. Knegjens, Eur. Phys. J. C (2011) 1789]

$B_s^0 \to K^+K^-$ effective lifetime

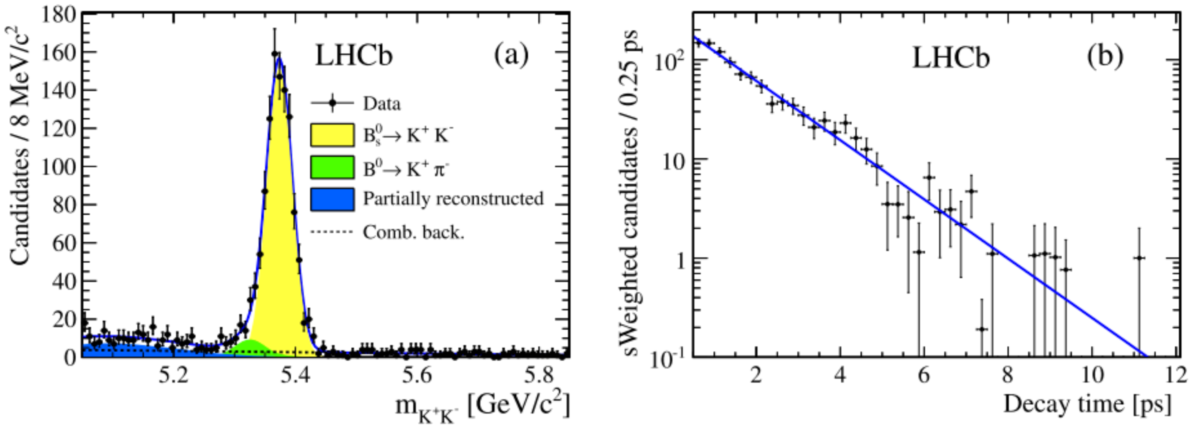
PLB 716 (2012) 393

CP-even eigenstate

- Analysis uses minimal lifetime biasing selection
  - No selections on lifetime biasing variables like impact parameters or flight distance
  - decay time >0.5 ps is used to avoid the potential edge effect introduced by the trigger requirement decay time >0.3 ps
- Trigger and event selections are based on the Neural Network
- Flat acceptance verified on simulation

$\mathcal{L}$ = (1 fb^{-1} @ $\sqrt{s}$ = 7 TeV)

$B_s^0 \to KK$ 997± 34



τ_{KK} = 1.455 ± 0.046 ± 0.006 ps

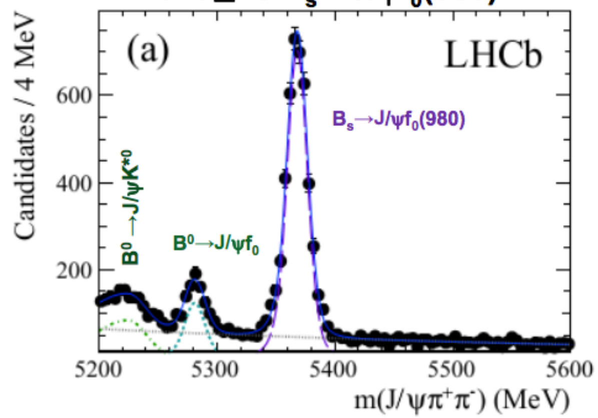
Agrees the SM prediction very well

$\tau_{KK} = 1.40 \pm 0.02$ ps.

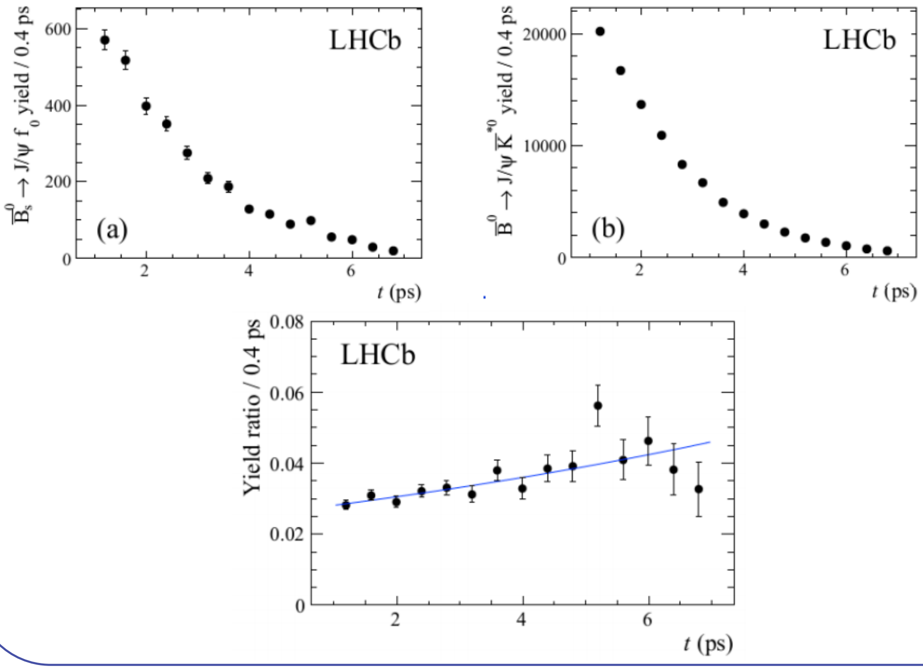
$B_s^0 \to J/\psi\, f^0(980)$ effective lifetime

- The final state $J/\psi\, f^0(980)$ is a CP-odd eigenstate
- Lifetime measured relative to $B^0 \to J/\psi K^{*0}$
  - Both decay channels have similar kinematics, hence most of the systematic cancel in ratio
- Multivariate selections are used
- Compare the signal yields in 15 bins of decay time

$4040 \pm 75\ B_s^0 \to J/\psi f_0(980)$



$131920 \pm 400\ B^0 \to J/\psi K^{*0}$



PRL 109 (2012) 152002

$\mathcal{L}$ = (1 fb^{-1} @ $\sqrt{s}$ = 7 TeV)

Fit for the width difference, $1/\tau_{J/\psi f0} - 1/\tau_{J/\psi K^*}$

$$1/\tau_{J/\psi f0} - 1/\tau_{J/\psi K^*} = -0.070 \pm 0.014 \pm 0.001\ \text{ps}^{-1}$$

$$\tau_{J/\psi f0} = 1.700 \pm 0.040 \pm 0.026\ \text{ps}$$

World's best

$$\Gamma_H = 0.588 \pm 0.014 \pm 0.009\ \text{ps}^{-1}$$

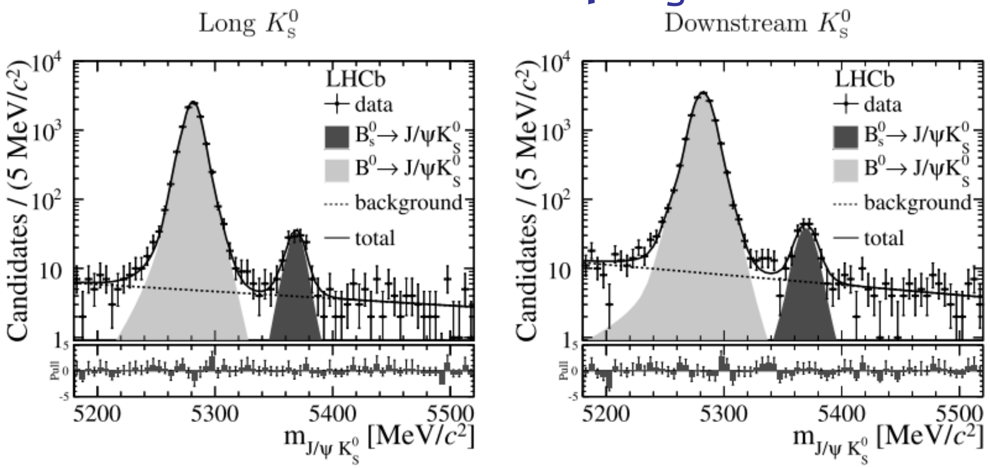
(included systematic due to possible non-zero ϕ_s)

$B_s^0 \to J/\psi K_s^0$ effective lifetime

NPB 873 (2013) 275

$\mathcal{L}$ = (1 fb^{-1} @ $\sqrt{s}$ = 7 TeV)

The final state $J/\psi K_s^0$ is another CP-odd eigenstate.



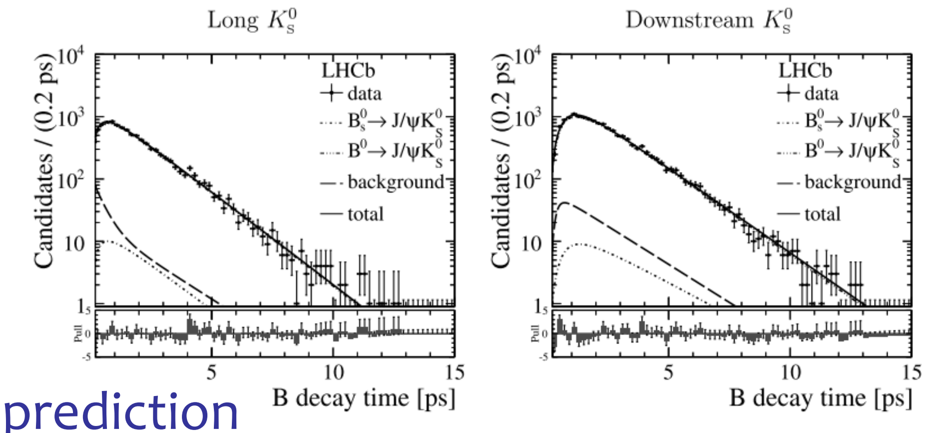
Long K_s^0: reconstructed with hits in all the LHCb tracking system

Downstream K_s^0: reconstructed without hits in the Vertex Locator detector

Lifetime determined from a 2D maximum likelihood fit

Simultaneous fit to $B_s^0 \to J/\psi K_s^0$ and $B^0 \to J/\psi K_s^0$

Lifetime acceptance parameters determined from the fit by fixing B^0 lifetime

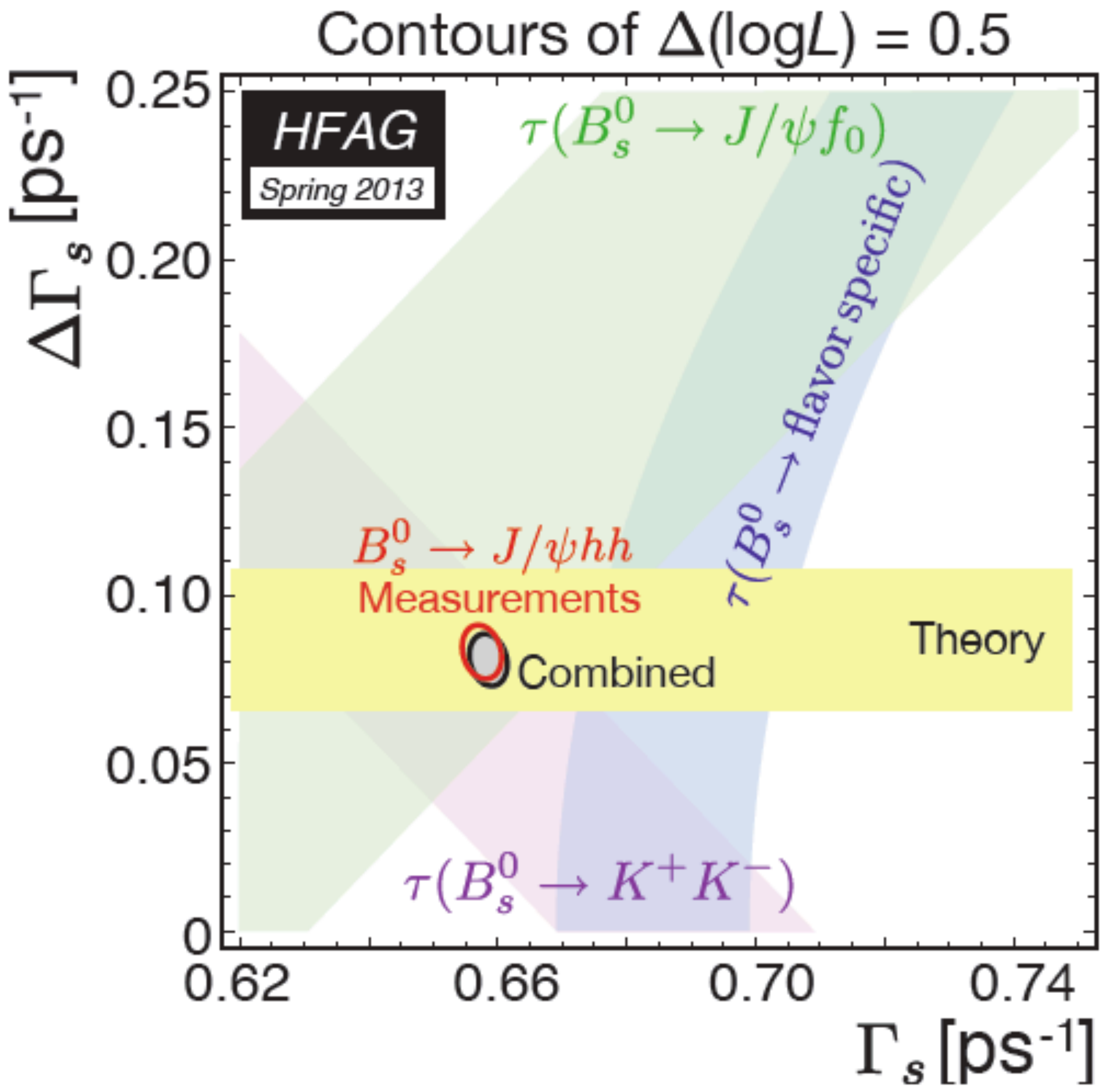


$$\tau_{J/\psi Ks} = 1.75 \pm 0.12 \pm 0.07 \text{ ps}$$

Measurement is consistent with the SM prediction

$\tau_{J/\psi K_S^0}$ = 1.639±0.022 ps (Eur. Phys.J C71,1532)

Impact of effective lifetime



Conclusions (I)

- LHCb has recently obtained several results regarding searches of CPV and New Physics
- Measurement of direct CP asymmetries in $B^0 \to K^+\pi^-$ and $B^0_s \to \pi^+K^-$ decays
  - World's best measurement of $A_{CP}(B^0 \to K^+\pi^-)$ with 10.5σ significance
  - First observation of direct CP violation in B^0_s decays with 6.5σ significance
- Measurements of CP-violation and decay width difference with

$B^0_s \to J/\psi h^+h^-$

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

$B^0_s \to \phi\phi$

$$\phi_s^{\phi\phi} \in [-2.46, -0.76]\ \text{rad at 68 \% CL}$$

Total systematic uncertainties 0.22 rad

- Measurement of B^0_s effective lifetime
  - $B^0_s \to K^+K^-$ $\tau_{KK} = 1.455 \pm 0.046 \pm 0.006$ ps CP-even
  - $B^0_s \to J/\psi\, f^0(980)$ $\tau_{J/\psi f0} = 1.700 \pm 0.040 \pm 0.026$ ps
  - $B^0_s \to J/\psi K^0_s$ $\tau_{J/\psi Ks} = 1.75 \pm 0.12 \pm 0.07$ ps

  CP-odd ($\tau_{J/\psi f0}$, $\tau_{J/\psi Ks}$)

Conclusions (II)

- Other recent results not show today
  - time-dependent analysis on $B^0 \rightarrow J/\psi K^{*0}$ (including amplitudes analysis), $B^0 \rightarrow J/\psi K_s$
  - B^0 and B_s oscillation frequency with $B^0 \rightarrow D^- \pi^+$, $B^0 \rightarrow J\psi K^{*0}$ and $B_s^0 \rightarrow D_s^- \pi^+$
  - B_c lifetime with $\rightarrow J/\psi \pi^+$
- All the results shown today are based on L=1 fb^{-1}, we have additional L=2 fb^{-1} on tape

watch this space and stay tuned!