Lifetimes of flavoured hadrons at LHCb

B^0, B^+, B_s^0, B_c^+ and Λ_b

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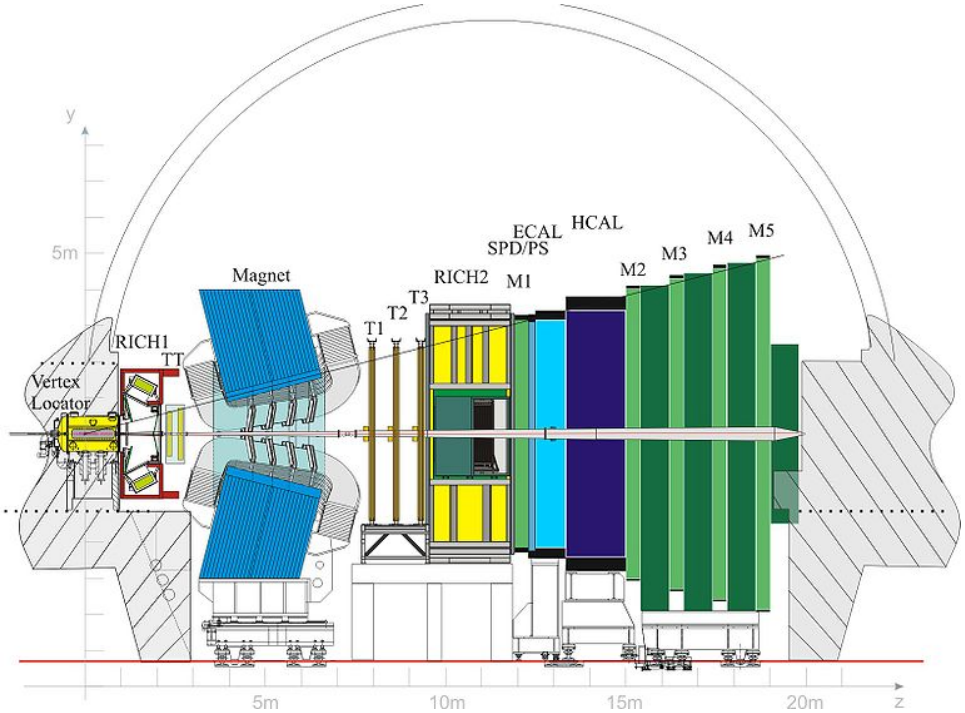
CONTENTS

LIFETIME MEASUREMENTS AT LHCB

- Lifetime measurements of B^0, B_s^0, B_c^+, Λ_b hadrons.
- Provides large number of improvements on previous precision measurements.
- Includes *CP* eigenstate and flavour-specific lifetimes of the B_s^0 meson.
- Allow us to test Heavy Quark Expansion (HQE) predictions.
- The methods used to extract the lifetime measurements differ.
- Data available: $1\,\mathrm{fb}^{-1}$ at $7\,\mathrm{TeV}$ and $2\,\mathrm{fb}^{-1}$ at $8\,\mathrm{TeV}$.

THE LHCB EXPERIMENT (JINST 3 S08005 (2008))

- Forward facing spectrometer which covers $\approx$ 2% full solid angle
- Within the solid angle $\approx$ 26% of $b\bar{b}$ pairs
- Include the full spectrum of B-hadrons produced by experiment (e.g. B^0, B_s^0, B_c^+, Λ_b).
- **Trigger** : Crucial for hadronic b-decay modes.
- **VELO** : Time dependent processes ($\approx$ 50 fs lifetime resolution).
- **RICH** : Hadronic final state identification.



B_s^0 LIFETIMES

- Neutral mesons split into two mass eigenstates $|B_L\rangle$ (light) and $|B_H\rangle$ (heavy).
- B_L and B_H have different lifetimes.
- Applicable to B^0 as well as B_s^0.

Without initial flavour (B_s^0 or $\bar{B}_s^0$) tagging

$$\Gamma(t) \propto \left[(1 - \mathcal{A}_{\Delta\Gamma_s})\, e^{-\Gamma_s - \frac{\Delta\Gamma_s}{2} t} + (1 + \mathcal{A}_{\Delta\Gamma_s})\, e^{-\Gamma_s + \frac{\Delta\Gamma_s}{2} t} \right],$$

where

$$\mathcal{A}_{\Delta\Gamma_s} = \frac{R_H - R_L}{R_H + R_L} \qquad \text{or} \qquad \mathcal{A}_{\Delta\Gamma_s} = \frac{2Re(\lambda_f)}{1+|\lambda_f|^2}, \qquad \lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

FLAVOUR SPECIFIC DECAY

$\mathcal{A}_{\Delta\Gamma_s} = 0$
Average lifetime measurement

DECAY TO *CP* EIGENSTATE

Sensitive to $\Delta\Gamma_s$, $\mathcal{A}_{\Delta\Gamma_s}$ and *CP* violating phases (ϕ_s)

B^0 AND Λ_b LIFETIMES

- HQE theory provides a description of hadrons containing heavy quarks.
- Lifetime measurements allow testing of theoretical predictions.
- Singly heavy B hadron lifetimes
  - Dominated by the weak decay of the b-quark
  - Small contribution from the spectator quarks
  - To first order: $\tau_{B^0} \sim \tau_{B^+} \sim \tau_{B_s^0} \sim \tau_{\Lambda_b}$
- Predictions made from series expansion ($m_b > \Lambda_{QCD}$)
  - AKA Heavy Quark Expansion (HQE)

$$\Gamma = \Gamma_0 + \frac{\Lambda}{m_b}\Gamma_1 + \frac{\Lambda^2}{m_b^2}\Gamma_2 + \frac{\Lambda^3}{m_b^3}\Gamma_3 + ...$$

- The terms are determined perturbatively and non-perturbatively
- Most precise predictions in lifetime ratios:

$$\frac{\tau_1}{\tau_2} = 1 + \frac{\Lambda^2}{m_b^2}\Gamma_2' + \frac{\Lambda^3}{m_b^3}\Gamma_3' + ...$$

- Γ_2' vanishes for τ_{B^+}/τ_{B^0} and $\tau_{B_s^0}/\tau_{B^0}$ but not for $\tau_{\Lambda_b}/\tau_{B^0}$

$\bar{B}^0_s \to D^-_s D^+_s$ AND $\bar{B}^0_s \to D^- D^+_s$ EFFECTIVE LIFETIME MEASUREMENTS (PHYS. REV. LETT. **112**, 111802 (2014))

$\bar{B}^0_s \to D^-_s D^+_s$ LIFETIME

- $\bar{B}^0_s \to D^-_s D^+_s$ is *CP*-even final state that allows the probing of Γ_L.
- $\bar{B}^0_s \to D^-_s D^+_s$ dominated by tree-level processes so clean measurement.
- Normalise using the topologically and kinematically similar $B^- \to D^0 D^-_s$ decay.
- To extract the lifetime use $\tau_{B^-} = 1.641 \pm 0.008\,\text{ps}$ (Phys. Rev. D**86**, 010001 (2012))

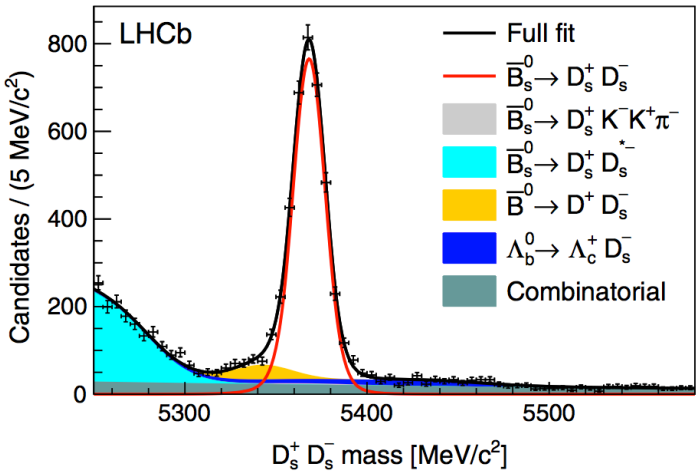
$\bar{B}^0_s \to D^- D^+_s$ LIFETIME

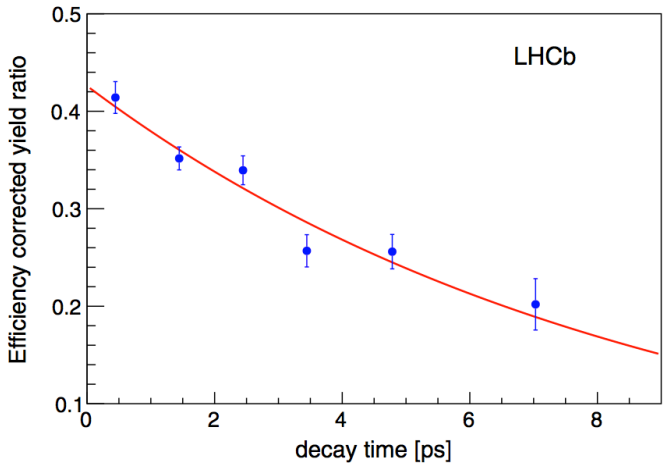
- $\bar{B}^0_s \to D^- D^+_s$ decay is flavour-specific.
- Mix of $|B_L\rangle$ (light) and $|B_H\rangle$ (heavy) mass eigenstates - average B^0_s lifetime.
- Normalisation channel chosen is the $B^0 \to D^- D^+_s$ decay.

$\bar{B}^0_s \to D^-_s D^+_s$ AND $\bar{B}^0_s \to D^- D^+_s$ LIFETIME RESULTS

LIFETIME MEASUREMENT METHOD

- Analysis performed with $3\,\text{fb}^{-1}$ of data.
- Lifetime ratio method employed on both decay channels.
- Acceptance and resolution effects cancel in the normalisation.





LHCB MEASUREMENTS (PHYS. REV. LETT. **112**, 111802 (2014))

- $\hat{\tau}_{\bar{B}^0_s \to D^-_s D^+_s} = 1.379 \pm 0.026\,(\text{stat}) \pm 0.017\,(\text{syst})$ ps
- $\Gamma^s_L = 0.725 \pm 0.014\,(\text{stat}) \pm 0.009\,(\text{syst})$ ps^{-1}
- $\hat{\tau}_{\bar{B}^0_s \to D^- D^+_s} = 1.52 \pm 0.15\,(\text{stat}) \pm 0.01\,(\text{syst})$ ps

Effective $B \to h^+h'^-$ Lifetimes

$B \to h^+h'^-$ Lifetimes

- Measure the effective lifetimes of the $B_s^0 \to K^+K^-$, $B^0 \to K^+\pi^-$ and $B_s^0 \to \pi^+K^-$ decays
- B^0, flavour-specific $B_s^0 \to \pi^+K^-$ and *CP*-eigenstate $B_s^0 \to K^+K^-$.
- Using 1 fb^{-1} of 2011 LHCb data.
- Proceed through both tree and loop processes.
- New physics could enter and compete with SM processes.

Effective $B_s^0 \to K^+K^-$ Lifetime

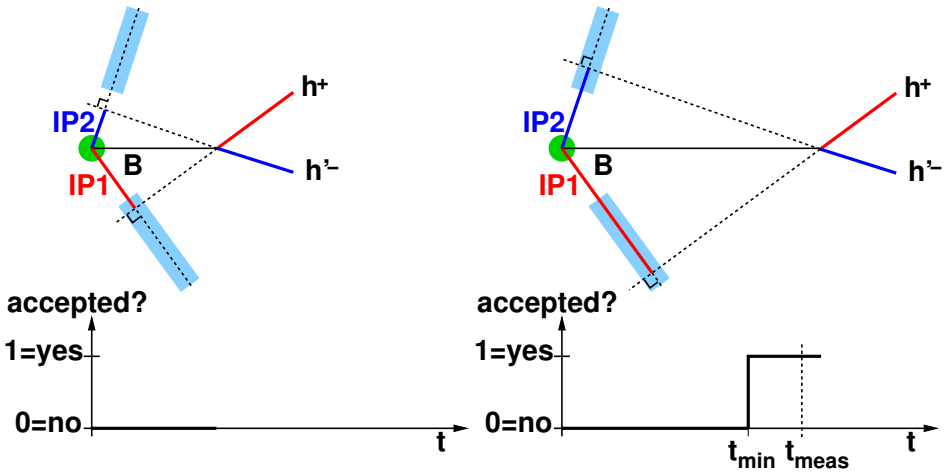
Decay into a *CP* even final state: K^+K^-

- Significant loop contributions in decay route
- *CP* conserved: only accessible from B_L, so measure Γ_L.
- *CP* violation: mix of B_L and B_H
- SM predicts very small *CP* violation, $A_{\Delta\Gamma}(B_s^0 \to K^+K^-) = -0.97^{+0.014}_{-0.009}$ (arXiv:1011.1096)

EFFECTIVE LIFETIME METHODOLOGY

Data driven method used to determine per-event acceptance function

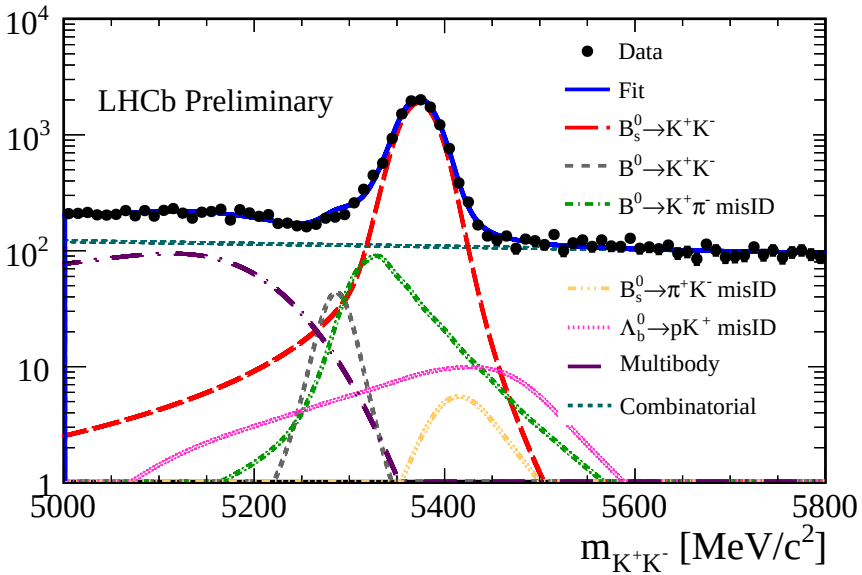
- Trigger and Selection re-run for all hypothetical lifetimes
- The step function is parameterised by the parameter t_{min}

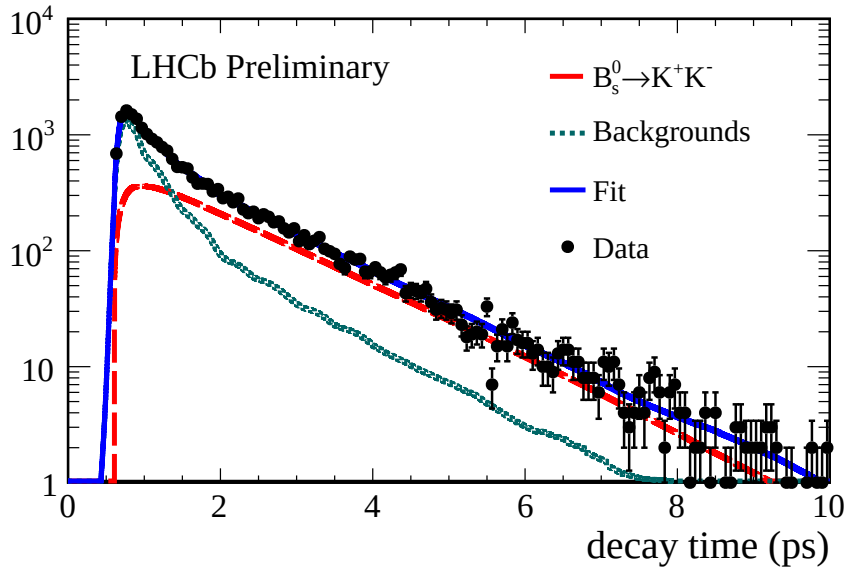


Fit methodology

- Fit factorised into invariant mass and reconstructed lifetime components
- Assumption that mass and lifetime are uncorrelated.
- Use *sWeights* to discriminate between signal and background.

EFFECTIVE $B \to h^+h'^-$ LIFETIME RESULTS





LHCB MEASUREMENTS (NEW RESULT FOR CONFERENCE, PAPER SUBMITTED SHORTLY)

- $\hat{\tau}_{B_s^0 \to K^+K^-} = 1.407 \pm 0.016\,(\text{stat}) \pm 0.007\,(\text{syst})$ ps
- $\Gamma_L^s = 0.711 \pm 0.008\,(\text{stat}) \pm 0.004\,(\text{syst})$ ps^{-1}
- $\mathcal{A}_{\Delta\Gamma}(B_s^0 \to K^+K^-) = -0.87 \pm 0.17\,(\text{stat}) \pm 0.13\,(\text{syst})$
- $\hat{\tau}_{B^0 \to K^+\pi^-} = 1.524 \pm 0.011\,(\text{stat}) \pm 0.004\,(\text{syst})$ ps
- $\hat{\tau}_{B_s^0 \to \pi^+K^-} = 1.60 \pm 0.06\,(\text{stat}) \pm 0.01\,(\text{syst})$ ps

LIFETIME MEASUREMENTS FROM $H_b \to J/\psi X$ (ARXIV:1402.2554)

B-HADRON LIFETIMES

- Measure the effective lifetimes of the exclusive $B^+ \to J/\psi K^+$, $B^0 \to J/\psi K^{*0}$, $B^0 \to J/\psi K^0_S$, $B^0_s \to J/\psi \phi$ and $\Lambda^0_b \to J/\psi \Lambda$ decays
- Using 1 fb^{-1} of 2011 LHCb data.
- Lifetime ratios to test HQE theory.
- Also determine $\Delta\Gamma_d/\Gamma_d$.

LIFETIME FIT METHODOLOGY

- Main challenge to control detector acceptance, reconstruction and selection efficiencies.
- Two-dimensional maximum likelihood fit to $m(J/\psi X)$ and t.
- Signal decay time PDF by single exponential function multiplied by t-dependent trigger and selection efficiency.
- Per-event correction for reconstruction efficiency applied in negative log-likelihood construction.

$H_b \to J/\psi X$ LIFETIME MEASUREMENT RESULTS

RESULTS

- All results compatible with world averages.
- Λ_b^0 smaller by $\approx 2\sigma$ from following LHCb measurement.
- Single most precise measurements of b-hadron lifetimes.

LHCB MEASUREMENTS (ARXIV:1402.2554)

- $\hat{\tau}_{B^+ \to J/\psi K^+} = 1.637 \pm 0.004\,(\text{stat}) \pm 0.003\,(\text{syst})$ ps
- $\hat{\tau}_{B^0 \to J/\psi K^{*0}} = 1.524 \pm 0.006\,(\text{stat}) \pm 0.004\,(\text{syst})$ ps
- $\hat{\tau}_{B^0 \to J/\psi K_s^0} = 1.499 \pm 0.013\,(\text{stat}) \pm 0.005\,(\text{syst})$ ps
- $\hat{\tau}_{B_s^0 \to J/\psi \phi} = 1.415 \pm 0.027\,(\text{stat}) \pm 0.006\,(\text{syst})$ ps
- $\hat{\tau}_{\Lambda_b^0 \to J/\psi \Lambda} = 1.480 \pm 0.011\,(\text{stat}) \pm 0.005\,(\text{syst})$ ps

$H_b \to J/\psi X$ ADDITIONAL RESULTS

ADDITIONAL MEASUREMENTS

- Lifetime ratios consistent with HQE predictions.
- Difference from unity of τ_{B^+}/τ_{B^-}, $\tau_{\Lambda_b^0}/\tau_{\bar{\Lambda}_b^0}$ or $\tau_{B^0 \to J/\psi K^{*0}}/\tau_{\bar{B} \to J/\psi \bar{K}^{*0}}$ would indicate violation of CPT invariance.
- For $B^0 \to J/\psi K^{*0}$ would indicate $\Delta\Gamma_d \neq 0$.
- Measurements of Γ_d, $\Delta\Gamma_d$ and $\Delta\Gamma_d/\Gamma_d$.

RATIOS AND OTHER RESULTS (ARXIV:1402.2554)

Ratio	Value	Prediction
$\tau_{B^+}/\tau_{B^0 \to J/\psi K^{*0}}$	$1.074 \pm 0.005 \pm 0.003$	1.063 ± 0.027 (Nucl.Phys. B633 (2002) 212)
$\tau_{B_s^0}/\tau_{B^0 \to J/\psi K^{*0}}$	$0.971 \pm 0.009 \pm 0.004$	1.00 ± 0.01 (Nucl.Phys. B633 (2002) 212)
$\tau_{\Lambda_b^0}/\tau_{B^0 \to J/\psi K^{*0}}$	$0.929 \pm 0.018 \pm 0.004$	$0.86 - 0.95$ (Nucl.Phys. B633 (2002) 212)
τ_{B^+}/τ_{B^-}	$1.002 \pm 0.004 \pm 0.002$	
$\tau_{\Lambda_b^0}/\tau_{\bar{\Lambda}_b^0}$	$0.940 \pm 0.035 \pm 0.006$	
$\tau_{B^0 \to J/\psi K^{*0}}/\tau_{\bar{B}^0 \to J/\psi \bar{K}^{*0}}$	$1.000 \pm 0.008 \pm 0.009$	
Other		
Γ_d	$0.656 \pm 0.003 \pm 0.002\ \text{ps}^{-1}$	
$\Delta\Gamma_d$	$-0.029 \pm 0.016 \pm 0.007\ \text{ps}^{-1}$	
$\Delta\Gamma_d/\Gamma_d$	$-0.044 \pm 0.025 \pm 0.011$	$(42 \pm 8) \times 10^{-4}$ (arXiv:hep-ph/1102.4274)

PRECISION MEASUREMENT OF THE RATIO OF Λ_b TO B^0 LIFETIMES (ARXIV:1402.6242)

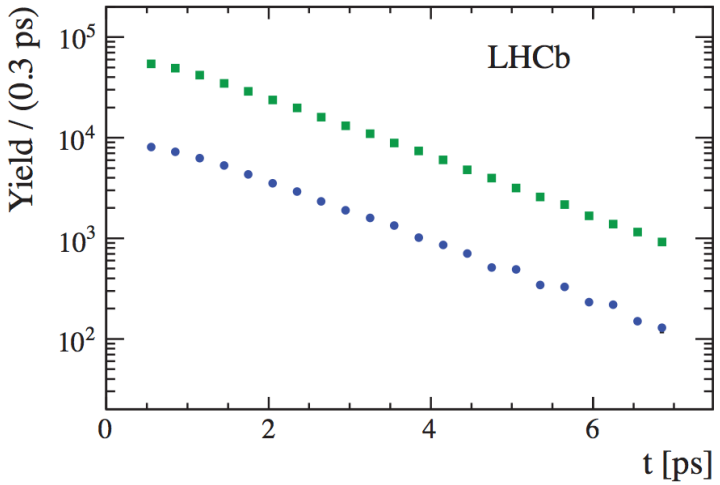
Λ_b TO B^0 LIFETIME RATIO

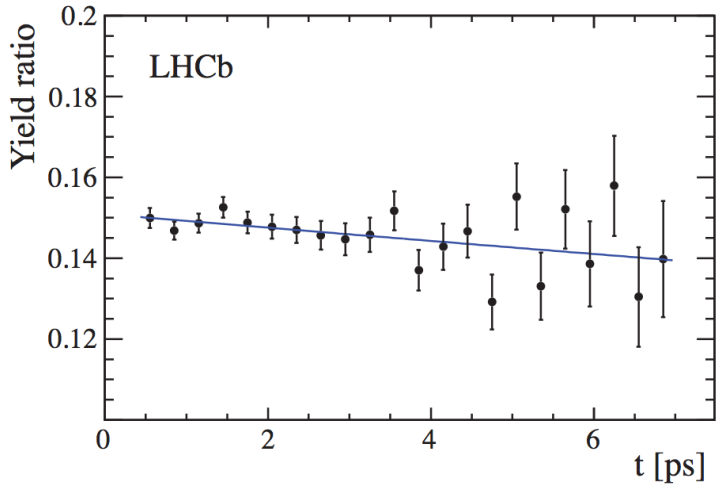
- Analysis uses total $3\,\text{fb}^{-1}$ from combined 2011 and 2012 LHCb data.
- 2011 data collected at centre of mass energy $7\,\text{TeV}$ and 2012 at $8\,\text{TeV}$.
- Decay Modes used are $\Lambda_b^0 \to J/\psi\, pK^-$ and $\bar{B}^0 \to J/\psi\, \pi^+ K^-$.

FIT METHOD

- Use the ratio of Λ_b^0 and $\bar{B}^0$ decay time distributions to remove decay time acceptances
- $\tau_{\Lambda_b^0}/\tau_{B^0}$ determined by the yield of b-hadrons from both decays.
- Unbinned maximum likelihood fit to b-hadron mass distribution in 22 bins of decay time within $0.4 - 7.0\,\text{ps}$.
- The world average of $\tau_{B^0} = 1.519 \pm 0.007\,\text{ps}$ (Phys.Rev. D86 (2012) 010001) is used to determine $\tau_{\Lambda_b^0}$.

Λ_b TO B^0 LIFETIME RATIO RESULT





RESULTS

- Most precise measurement to date of $\frac{\hat{\tau}_{\Lambda_b}}{\hat{\tau}_{B^0}}$ and consistent with HQE predictions $\gtrsim 0.9$ (arXiv:hep-ph/9804275).
- Most precise measurement of $\hat{\tau}_{\Lambda_b}$.

LHCB MEASUREMENTS (ARXIV:1402.6242)

- $\frac{\hat{\tau}_{\Lambda_b}}{\hat{\tau}_{B^0}} = 0.974 \pm 0.006\,(\text{stat}) \pm 0.004\,(\text{syst})$ ps
- $\hat{\tau}_{\Lambda_b} = 1.479 \pm 0.009\,(\text{stat}) \pm 0.010\,(\text{syst})$ ps

MEASUREMENTS OF THE B_c^+ LIFETIME (ARXIV:1401.6932)

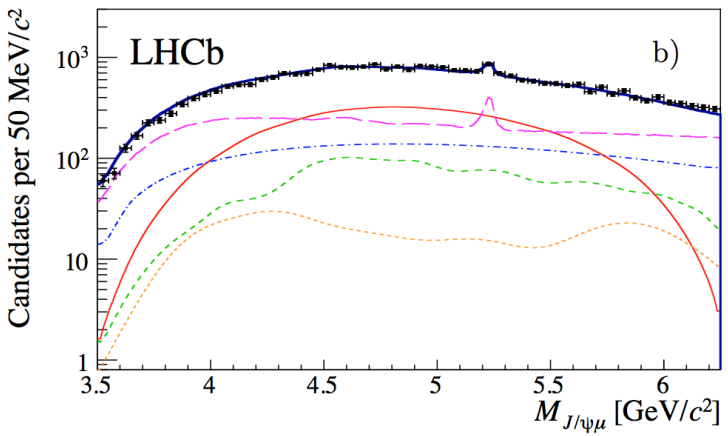
B_c^+ LIFETIME MEASUREMENT

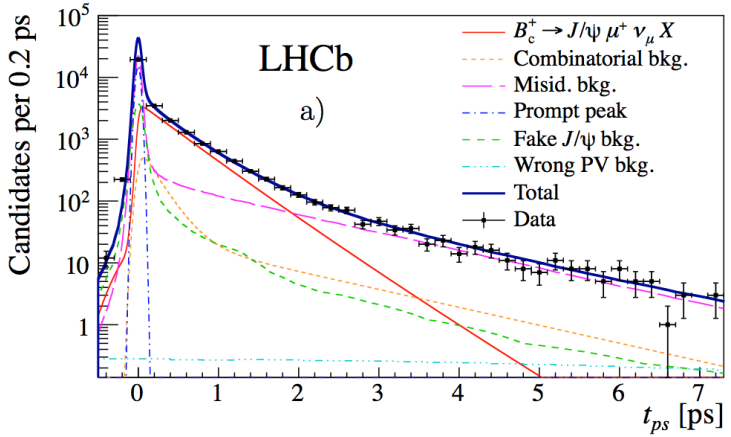
- Lifetime measurement using the $B_c^+ \to J/\psi\, \mu^+ \nu_\mu X$.
- Total integrated luminosity of $2\,fb^{-1}$ from 2012 data.
- B_c^+ is the heaviest ground state charged meson in the SM.
- Precise measurement of $\tau_{B_c^+}$ provides tests of theoretical models of its dynamics.
- $\tau_{B_c^+}$ is largest uncertainty in relative branching fraction measurements.

LIFETIME MEASUREMENT METHOD

- Semileptonic decay means partial reconstruction.
- Need simulation to correct for missing energy, this correction method is called the k-factor.
- PDF model for t is obtained by convoluting simulated $\tau_{B_c^+}$ distribution with k-factor and resolution functions.
- Further details presented in "Properties and decays of the B_c^+ meson" by L.Anderlini.

B_c^+ LIFETIME RESULTS





RESULTS

- Most precise measurement of the B_c^+ lifetime
- Computations with different frameworks predict $300 < \tau_{B_c^+} < 700$ fs.
- Current world average 452 ± 33 fs (Phys.Rev. D86 (2012) 010001)

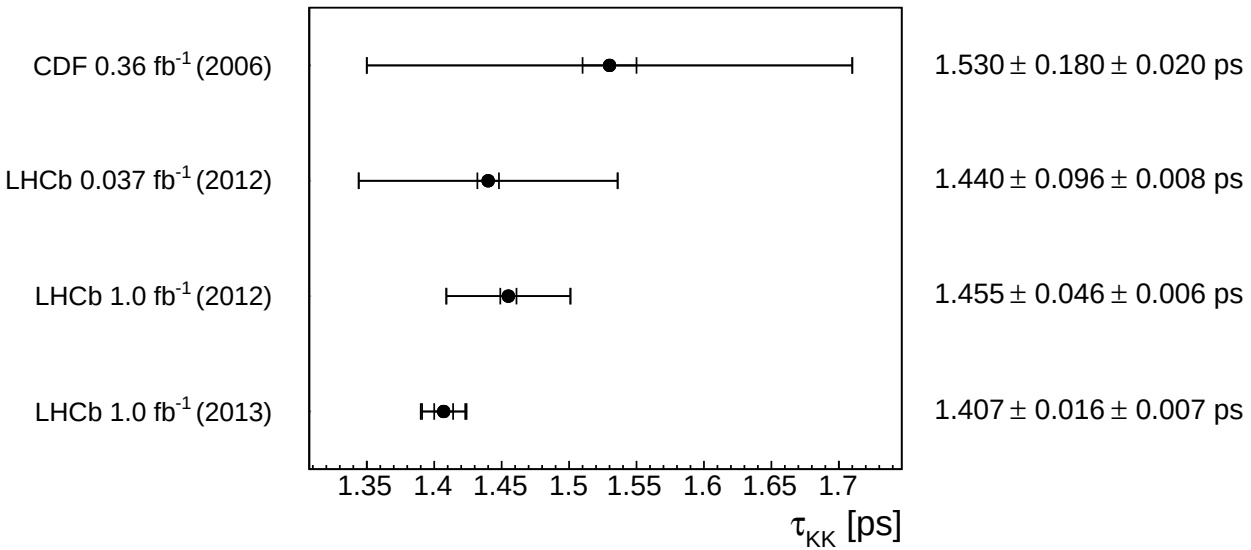
LHCB MEASUREMENTS (ARXIV:1402.6242)

- $\hat{\tau}_{B_c^+ \to J/\psi\,\mu^+\nu_\mu X} = 509 \pm 8\,(\text{stat}) \pm 12\,(\text{syst})$ fs

RESULTS IMPLICATIONS - *CP* EIGENSTATE B_s^0

$1/\Gamma_L^s$ RESULTS

- Two compatible measurements of $1/\Gamma_L^s$ using different channels.
- Worlds best measurement using $B_s^0 \to K^+K^-$ channel.



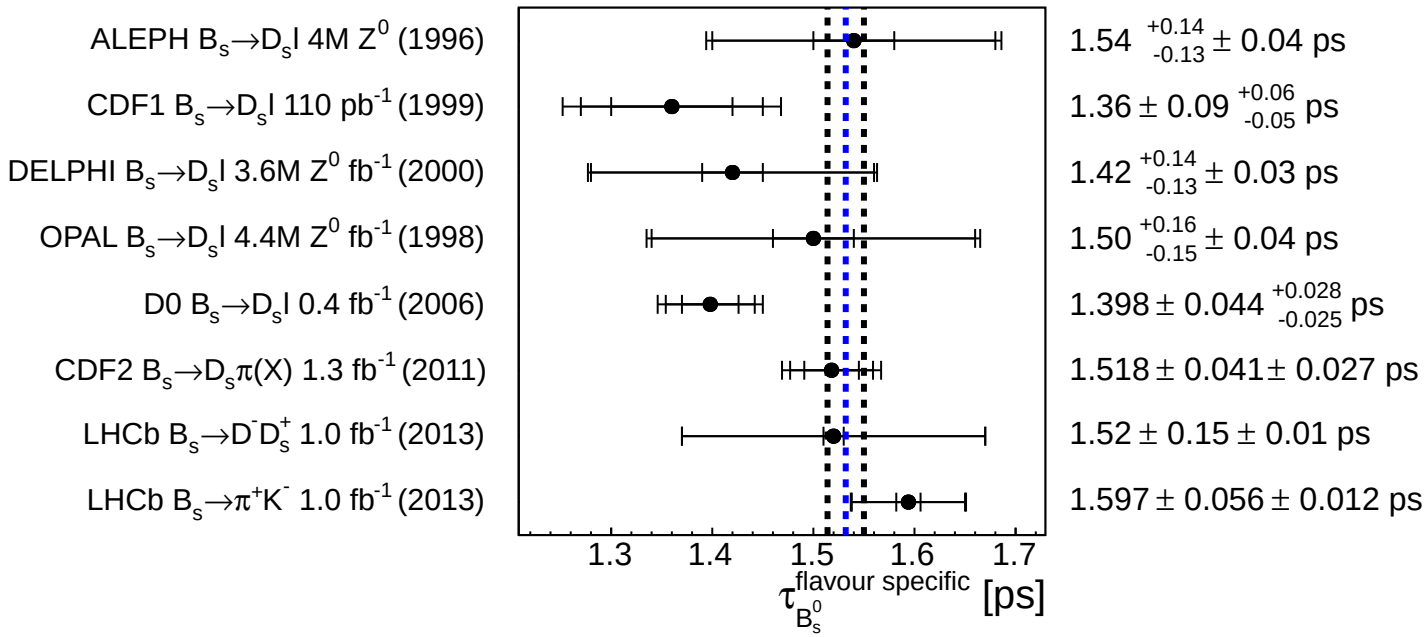
SM CHECKS

- $\mathcal{A}_{\Delta\Gamma}(B_s^0 \to K^+K^-) = -0.87 \pm 0.17\,(\text{stat}) \pm 0.13\,(\text{syst})$
- Consistent with SM prediction of $A_{\Delta\Gamma}(B_s^0 \to K^+K^-) = -0.97^{+0.014}_{-0.009}$ (arXiv:1011.1096)

RESULTS IMPLICATIONS - FLAVOUR SPECIFIC B_s^0

FLAVOUR SPECIFIC B_s^0 RESULTS

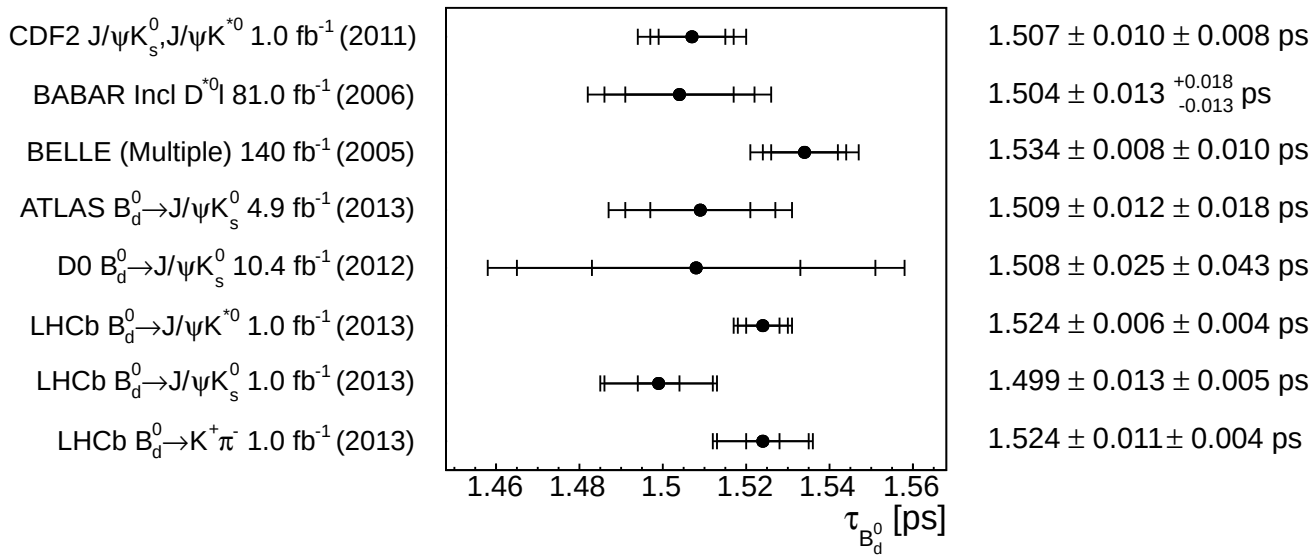
- LHCb results are compatible with the flavour specific lifetime predicted by $\Delta\Gamma_s$ and Γ_s from $B_s^0 \to J/\psi\,\phi$ (Phys.Rev. D87 (2013) 112010)
- Blue line is central value, black lines are uncertainties.



RESULTS IMPLICATIONS - B^0 AND Λ_b

B^0 RESULTS

- B^0 measurements all consistent with world average, 1.519 ± 0.007 ps (Phys.Rev. D86 (2012) 010001)



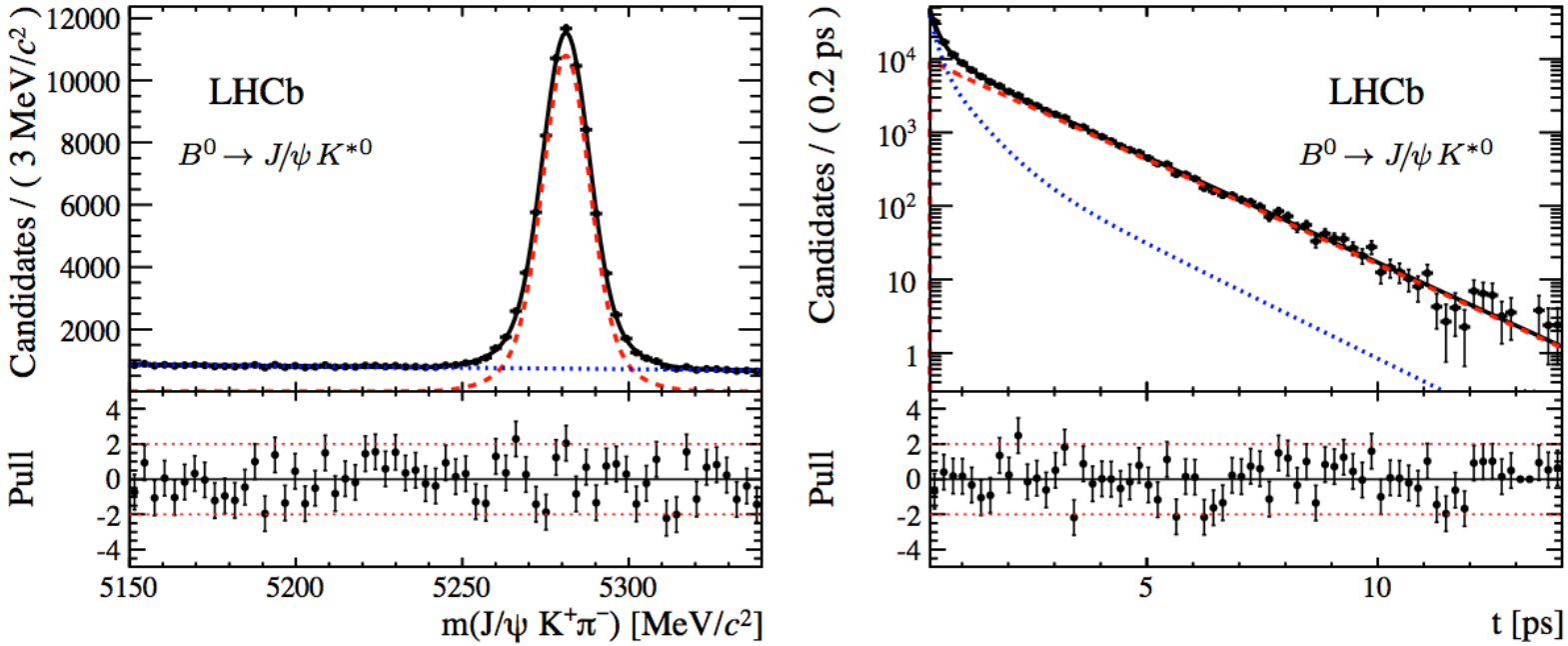
Λ_b RESULTS

- $\hat{\tau}_{\Lambda_b}$ lifetime within $\approx 2\sigma$ world average of 1.429 ± 0.024 ps (Phys.Rev. D86 (2012) 010001)
- $\frac{\hat{\tau}_{\Lambda_b}}{\hat{\tau}_{B^0}}$ in agreement with theoretical predictions of $\gtrsim 0.9$ (arXiv:hep-ph/9804275)

WRAP UP

- LHCb has a rich program of lifetime studies
- Theoretical motivations of lifetime include testing HQE and constraining CP-violation.
- Five lifetime analysis presented
  - Measurements of B^+, B^0, B_s^0, B_c^+ and Λ_b lifetimes and lifetime ratios presented.
  - Worlds best measurements of $1/\Gamma_L^s$ and other compatible measurements.
  - Precision measurement of $\tau_{\Lambda_b^0}/\tau_{B_d^0}$.
  - World best measurement of B_c^+ lifetime.
- Flavour specific B_s^0 lifetime from $\mathrm{B}_s^0 \to \mathrm{D}_s^+\pi^-$ decay and update to effective $\mathrm{B} \to \mathrm{h}^+\mathrm{h}^{'-}$ lifetimes being conducted.
- Future updates of all 1 fb^{-1} analyses with 3 fb^{-1}.

BACKUP SLIDES - $H_b \to J/\psi X$ FITS



BACKUP SLIDES - B_c^+ LIFETIME FITS