Measurements of b-hadron and effective lifetimes at LHCb

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EPS 2013
20 July 2013
Stockholm, Sweden

Outline

1. Motivation
   - Probing QCD predictions
   - Probing CP violation
2. Effective Lifetime of $B_s^0 \to J/\psi K_S^0$
   - $1\ \text{fb}^{-1}$ data @ $\sqrt{s} = 7\ \text{TeV}$
3. Λ_b^0 Lifetime Measurement
   - $1\ \text{fb}^{-1}$ data @ $\sqrt{s} = 7\ \text{TeV}$
4. Summary

B Hadron Lifetime Predictions

- Singly heavy B hadron lifetimes
  - Dominated by the weak decay of the b-quark
  - Small contribution from the spectator quarks
  - To first order: $\tau_{B^0} \sim \tau_{B^+} \sim \tau_{B_s^0} \sim \tau_{\Lambda_b^0}$
- Predictions made from series expansion ($m_b > \Lambda_{QCD}$)
  - AKA Heavy Quark Expansion (HQE)

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

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

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

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

Theoretical predictions

$$\frac{\tau_{B_s^0}}{\tau_{B^0}} = 1.00 \pm 0.01 \qquad \frac{\tau_{\Lambda_b^0}}{\tau_{B^0}} = 0.88 \pm 0.05 \qquad [1]$$

$$\frac{\tau_{B_s^0}}{\tau_{B^0}} = 1.00 \pm 0.01 \qquad \frac{\tau_{\Lambda_b^0}}{\tau_{B^0}} = 0.86 \pm 0.05 \qquad [2]$$

Lifetimes are insensitive to BSM effects: *Test of QCD predictions*.

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The B_s^0 decay time distribution – finite value of $\Delta\Gamma_s$

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

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

Flavour specific decay

$\mathcal{A}_{\Delta\Gamma} = 0$

Average lifetime measurement

Decay to *CP* eigenstate

Sensitive to $\Delta\Gamma$ and *CP* violating phases (ϕ_s)

Effective lifetime measurements

Single eponential ML fit to the B_s^0 decay time distribution

$$\tau^{\text{eff}} = \frac{\int t \cdot \Gamma(t)}{\int \Gamma(t)} = \frac{\tau_{B_s^0}}{1-y_s^2} \frac{1+2\,\mathcal{A}_{\Delta\Gamma_s} y_s + y_s^2}{1+\mathcal{A}_{\Delta\Gamma_s} y_s},$$

where $y_s \equiv \frac{\Delta\Gamma_s}{2\Gamma_s}$ and $\tau_{B_s^0}$ is the average B_s^0 lifetime

Standard Model prediction

$$\begin{aligned} y_s &= 0.0802 \pm 0.0010 \text{ [3]} \\ \mathcal{A}_{\Delta\Gamma_s}^{B_s^0 \to J/\psi K_S^0} &= 0.944 \pm 0.066 \text{ [4]} \\ \tau^{\text{eff}}_{B_s^0 \to J/\psi K_S^0}\Big|_{\text{SM}} &= 1.639 \pm 0.022 \end{aligned}$$

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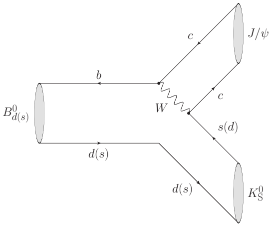
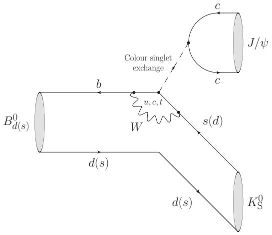
$B_s^0 \to J/\psi\, K_S^0$ – Motivation



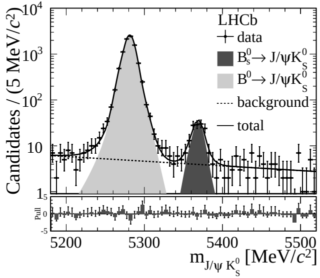


- CP-odd final state
  - Effective lifetime gives sensitivity to CP-violation
- Related to $B^0 \to J/\psi\, K_S^0$ by u-spin rotation
  - Golden mode for determining sin(2β)
  - $B^0 \to J/\psi\, K_S^0$: penguin pollution at % level
  - $B_s^0 \to J/\psi\, K_S^0$: penguins not CKM suppressed
- Time dependent asymmetries of $B_s^0 \to J/\psi\, K_S^0$ give a handle on the penguin contributions
- First: measure it's effective lifetime & branching ratio

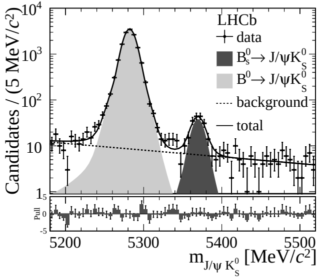
Signal yield & branching ratio (1 fb^{-1} @ $\sqrt{s} = 7$ TeV)

- Multivariate selection of $B^0_{(s)} \to J/\psi(\to \mu^+\mu^-)K_S^0(\to \pi^+\pi^-)$
- Two candidate classes: if the K_S^0 decays inside or after the vertex detector
  - Labelled *long* (left plot) or *downstream* (right plot) K_S^0
- Measure the ratio of branching fractions of the B^0 and B_s^0 decays

$N_{B^0} = 9\,031 \pm 96$, $N_{B_s^0} = 115 \pm 12$



$N_{B^0} = 14\,391 \pm 122$, $N_{B_s^0} = 158 \pm 15$



$$\frac{\mathcal{B}(B_s^0 \to J/\psi K_S^0)}{\mathcal{B}(B^0 \to J/\psi K_S^0)} = 0.0439 \pm 0.0032\ (\text{stat}) \pm 0.0015\ (\text{syst}) \pm 0.0034\ (f_s/f_d)$$

Method

Lifetime determined from a 2D maximum likelihood fit

- Requires descriptions of the decay time acceptance of the signal and of the decay time distribution of the background

Decay time acceptance

- Assumed to be identical for the two modes
- Modelled with the function

$$f_{\mathrm{Acc}}(t) = \frac{1 + \beta\, t}{1 + (\lambda\, t)^{-\kappa}}$$

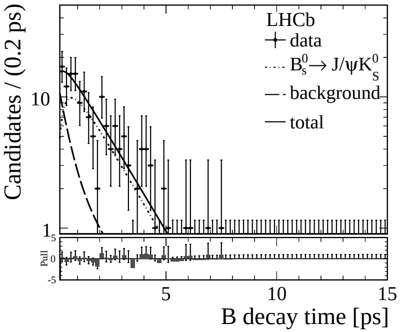
- τ_{B^0} well known: fit for the parameters with $B^0 \to J/\psi K_S^0$ data
- Separate parameters for *long* and *downstream* candidates

Background modelling

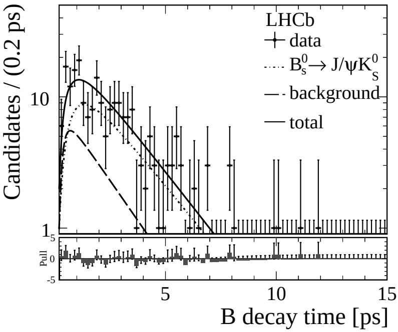
- Decay time distribution extracted with *sPlot*s
- Modelled with two (one) exponentials for *long* (*downstream*) candidates

Decay time fit and results

Long K_S^0 candidates



Downstream K_S^0 candidates



$$\tau^{\text{eff}}_{B_s^0 \to J/\psi K_S^0} = 1.75 \pm 0.12\,(\text{stat})\ 0.07\,(\text{syst}),$$ compared to

$$\left.\tau^{\text{eff}}_{B_s^0 \to J/\psi K_S^0}\right|_{\text{SM}} = 1.639 \pm 0.022$$

Published in Nucl. Phys. **B** 873 (2012) p 875 [5]

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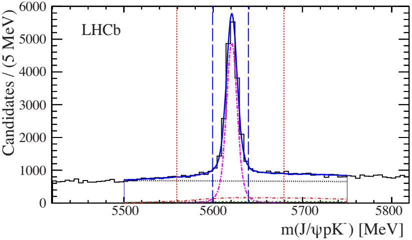
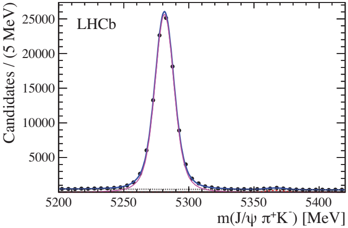
Λ_b^0 lifetime from $\Lambda_b^0 \to J/\psi\, pK^+$ (1 fb^{-1} @ $\sqrt{s} = 7$ TeV)

$N_{\Lambda_b^0 \to J/\psi\, pK^+} = 15\,581 \pm 178$



$N_{B^0 \to J/\psi\, K^{*0}} = 97\,506 \pm 447$



- Multi-variate selection
- First observation of the decay mode $\Lambda_b^0 \to J/\psi\,(\to \mu^+\mu^-)pK^-$
- $\mathcal{B}$ measurement in preparation

- Lifetime measured relative to $B^0 \to J/\psi\,(\to \mu^+\mu^-)K^{*0}(\to \pi^+K^-)$
- Only differ in PID selection
- Well-known lifetime and $\mathcal{B}$

Method

- Yields determined in 16 decay time bins
- Ratio of yield fitted as a function of time

$$R(t) = \frac{N_{\Lambda_b^0}(0)}{N_{\bar{B}^0}(0)} \frac{e^{-t/\tau_{\Lambda_b^0}}}{e^{-t/\tau_{\bar{B}^0}}} = R(0)e^{-t\Delta_{\Lambda B}}, \qquad \Delta_{\Lambda B} = \frac{1}{\tau_{\Lambda_b^0}} - \frac{1}{\tau_{B^0}}$$

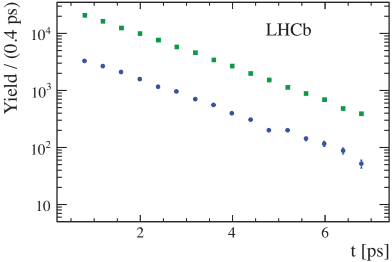
- Topologically identical decays
  - Acceptance cancels to first order
- Allow for a linear difference in acceptance

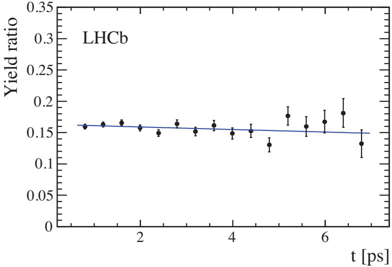
$$R(t) = R(0)[1 + a \cdot t]e^{-t\Delta_{\Lambda B}}$$

- Parameter *a* determined from simulations

$$a = 0.0033 \pm 0.0024\ \mathrm{ps}^{-1}$$

Signal yields versus decay time





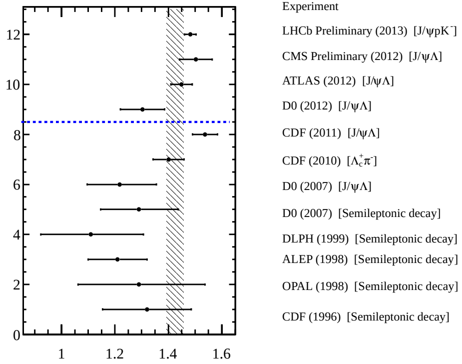
$\Lambda_b^0 \to J/\psi\, pK^+$ $\quad$ $B^0 \to J/\psi\, K^{*0}$

$$\Delta_{\Lambda B} = 16.4 \pm 8.2 \pm 4.4\ \mathrm{ns}^{-1}$$

$$\frac{\tau_{\Lambda_b^0}}{\tau_{B^0}} = \frac{1}{1 + \tau_{B^0}\Delta_{\Lambda B}} = 0.976 \pm 0.012 \pm 0.006$$

Paper submitted to Phys. Rev. Lett. arXiv:1307.2476 [6]

Comparison with previous results



- Agrees with previous world average
- Most precise measurement to date
- Using the current world average for τ_{B^0} [7] gives:

$$\tau_{\Lambda_b^0} = 1.482 \pm 0.018 \pm 0.012 \ \text{ps}$$

Comparison with prediction:

$$\left.\frac{\tau_{\Lambda_b^0}}{\tau_{B^0}}\right|_{\text{LHCb}_{\Lambda_b^0 \to J/\psi\, pK^+}} = 0.976 \pm 0.012 \pm 0.006$$

$$\left.\frac{\tau_{\Lambda_b^0}}{\tau_{B^0}}\right|_{\text{theory}} = 0.86 - 88 \pm 0.05$$

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Summary

- Theoretical motivation for B hadron lifetime measurements
  - Test of QCD predictions
  - Constraining *CP* violation
- Two lifetime measurements from LHCb presented
  - Using $1\ \text{fb}^{-1}$ data collected @ $\sqrt{s} = 7\ \text{TeV}$ in 2011
- Effective lifetime measurement of $B_s^0 \to J/\psi K_s^0$
  - First measurement of this quantity
- Precision measurement of the Λ_b^0 lifetime with $\Lambda_b^0 \to J/\psi pK^+$
  - Most precise measurement to date

Bibliography

[1] Eur. Phys. J. **C33**, S895 (2004)

[2] Phys. Rev. **D70**, 094031 (2004)

[3] Phys. Rev. **D87**, 112010 (2013)

[4] Proceedings from CKM 2012 (arXiv:1212.2792)

[5] LHCb-PAPER-2013-032 (2013) (arXiv:1307.2476)

[6] Phys. Rev **D86** (2012)

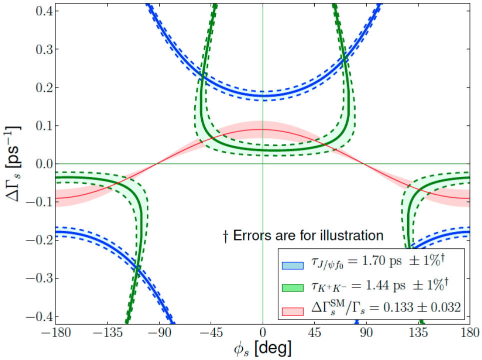
[7] Nucl. Phys. **B** 873 (2012) p 875

Backup Slides

Constraining *CP* Violation

B_s^0 effective lifetime measurement

- Fit single exponential distribution
- Compare *CP* even and *CP* odd lifetimes



- $B_s^0 \to K^+K^-$: *CP* even
- $B_s^0 \to J/\psi f_0$: *CP* odd
- Current central values but 1% illustrative errors

Single Exponential Maximum Likelihood Fit

Likelihood function (n events with lifetime t^i)

$$L(\Gamma) = \prod_{i=0}^{n-1} \Gamma e^{-\Gamma t^i} = \Gamma^n e^{-\Gamma \sum_{i=0}^{n-1} t^i}$$

$$ln(L(\Gamma)) = n \cdot ln(\Gamma) - \Gamma \sum_{i=0}^{n-1} t^i$$

Maximum is found at

$$\frac{d}{d\Gamma}(ln(L(\Gamma))) = n(\frac{1}{\Gamma} - \frac{1}{n}\sum_{i=0}^{n-1} t^i) = n(\frac{1}{\Gamma} - \bar{t}) = 0$$

$$\Rightarrow \frac{1}{\Gamma} = \bar{t}$$

Double Exponential without Acceptance

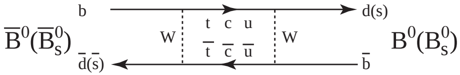
Hence fitting the $B_s^0 \to K^+K^-$ lifetime with a single exponential PDF, ignoring acceptance, yields

$$
\begin{aligned}
\frac{1}{\hat{\Gamma}} = \bar{t} &= \frac{\int_0^\infty t \cdot f_{B_s^0 \to K^+K^-}(t)\,\mathrm{d}t}{\int_0^\infty f_{B_s^0 \to K^+K^-}(t)\,\mathrm{d}t} \\
&= \frac{\int_0^\infty t(R_H e^{-\Gamma_H t} + R_L e^{-\Gamma_L t})\,\mathrm{d}t}{\int_0^\infty (R_H e^{-\Gamma_H t} + R_L e^{-\Gamma_L t})\,\mathrm{d}t} \\
&= \frac{\frac{R_H}{\Gamma_H^2} + \frac{R_L}{\Gamma_L^2}}{\frac{R_H}{\Gamma_H} + \frac{R_L}{\Gamma_L}} \\
&= \frac{1}{\Gamma + \frac{\Delta\Gamma}{2}} + \frac{1}{\Gamma - \frac{\Delta\Gamma}{2}} - \frac{1}{\Gamma + A_{\Delta\Gamma}\frac{\Delta\Gamma}{2}}
\end{aligned}
$$

This is the expression commonly used in literature and is only valid in absence of resolution and acceptance effects.

Neutral Meson Mixing

Neutral mesons mix via common states



Solution to the 2 × 2 Schrödinger equation:

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

Time evolution: Mass and lifetime difference

$$\Delta m^{(s)} = m_H^{(s)} - m_L^{(s)}$$
$$\Delta\Gamma^{(s)} = \Gamma_L^{(s)} - \Gamma_H^{(s)}$$

Phase shift introduced by the mixing

ϕ_s or β_s

Oscillation and Decay to final state f

Decay amplitude $A_f = \langle f|T|B^0_{(s)}\rangle$ and oscillation parameter $\lambda_f = \frac{q\bar{A}_f}{pA_f}$

$$\Gamma_{B^0_{(s)}\to f} = |A_f|^2(1+|\lambda_f|^2)\frac{e^{-\Gamma_{d,s}t}}{2}\Big(A_{dir}cos(\Delta m_{d,s}t) + A_{mix}sin(\Delta m_{d,s}t) + cosh(\frac{\Delta\Gamma_{d,s}t}{2}) + A_{\Delta\Gamma}sinh(\frac{\Delta\Gamma_{d,s}t}{2}) \Big)$$

- $A_{dir} = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}$ Direct *CP* violation
- $A_{mix} = \frac{2Im\lambda_f}{1+|\lambda_f|^2}$ Mixing-induced *CP* violation
- $A_{\Delta\Gamma} = \frac{2Re\lambda_f}{1+|\lambda_f|^2}$ Decay rate asymmetry