Mass and lifetime at LHCb

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on behalf of the LHCb Collaboration

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BEACH 2014

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Introduction: the LHCb detector

Mass measurements

- b-hadron masses
- c-hadron masses

Lifetime measurements

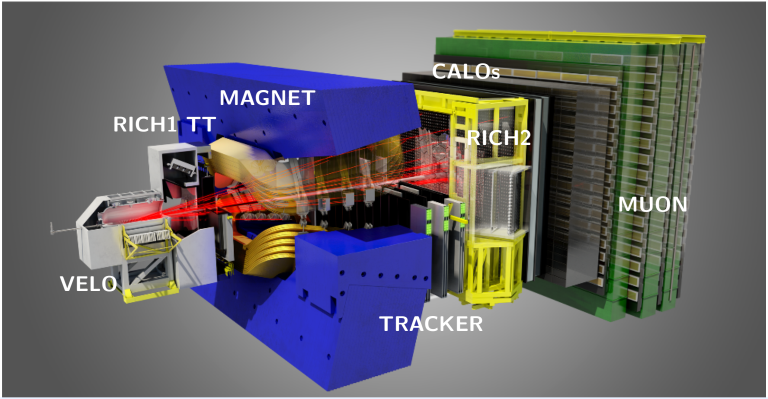
- Lifetime of b-baryon with decays to $J/\psi X$
- Lifetime$s$ of the $B^0_{(s)}$ meson

Conclusion and outlook

Recent measurements covered in other talks at BEACH 2014

B_c^+ mass and lifetime measurement	Xuhao Yuan
Ξ_b^0 lifetime measurement	Jimmy McCarthy

designed to enjoy the beauty (and the charm)



Already discussed yesterday by Ph. Ghez

Unique geometrical acceptance:	$2 < \eta < 5$ coverage
Excellent vertex locator (VELO):	$\sigma_{PV,xy} \sim 10\mu\text{m}$, $\sigma_{PV,z} \sim 60\mu\text{m}$
Tracking system:	$\Delta p/p : 0.35\% \div 0.55\%$
Muon system:	$\epsilon(\mu \to \mu) \sim 97\%$, MisID rate$(h \to \mu) \sim \mathcal{O}(1\%)$

Mass measurements

Measuring mass is easier with low-Q decays:

narrow peaks, less important momentum scale uncertainty.

Many uncertainties cancel in mass differences.

Dataset 1 fb^{-1}:

$$M(D^0) = 1864.75 \pm 015 \pm 0.11\ \text{MeV}/c^2$$

$$M(D^+) - M(D^0) = 4.76 \pm 0.12 \pm 0.07\ \text{MeV}/c^2$$

WORLD'S BEST MEASUREMENT!

$$M(D_s^+) - M(D^0) = 98.68 \pm 0.03 \pm 0.04\ \text{MeV}/c^2$$

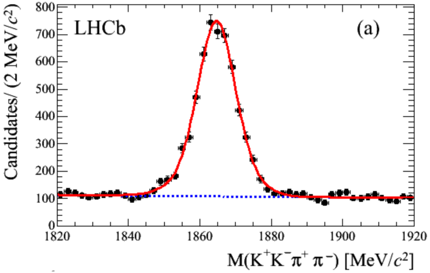
WORLD'S BEST MEASUREMENT!

Dataset 3 fb^{-1}:

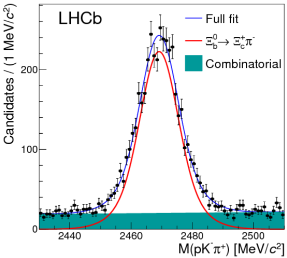
$$M(\Xi_c^+) - M(\Lambda_c^+) = 181.51 \pm 0.14 \pm 0.10\ \text{MeV}/c^2$$

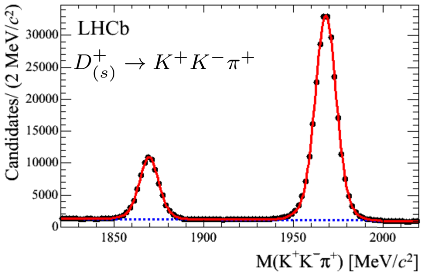
[arXiv:1405.7223] **WORLD'S BEST MEASUREMENT!**

$D^0 \to K^+K^-\pi^+\pi^-$



$\Xi_c^+ \to pK^-\pi^+$





Baryon decaying to J/ψ

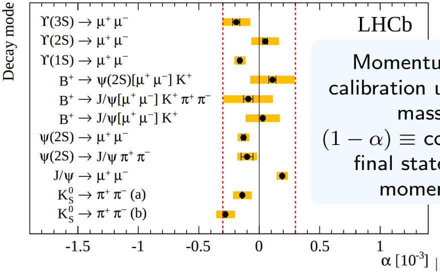
$$M(\Lambda_b^0) = 5619.53 \pm 0.13 \pm 0.45 \text{ MeV}/c^2 \qquad \Lambda_b^0 \to J/\psi\Lambda^0$$

$$M(\Xi_b^-) = 5795.8 \pm 0.9 \pm 0.4 \text{ MeV}/c^2 \qquad \Xi_b^- \to J/\psi\Xi^-$$

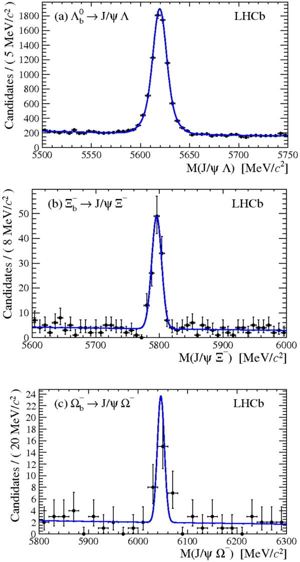
$$M(\Omega_b^-) = 6046.53 \pm 2.2 \pm 0.5 \text{ MeV}/c^2 \qquad \Omega_b^- \to J/\psi\Omega^-$$

WORLD'S BEST MEASUREMENTS

Dominant systematic: momentum scale calibration



Momentum scale calibration using PDG masses.
$(1-\alpha) \equiv$ correction to final state tracks momentum



Ξ_b^0 mass reported by LHCb studying $\Xi_b^0 \to \Xi_c^+\pi^-$ decays
$\longrightarrow$ analysis presented by J. Mc Carthy on Thursday.
`[arXiv:1405.7223]`

Lifetime measurements

Using *optical theorem*, *Operator Product Expansion*, and *HQET* one gets

$$\Gamma = \frac{G_F^2 m_b^5}{192\pi^3} V_{cb}^2 \left\{ c_{3,b} \left[1 - \frac{\mu_\pi^2 - \mu_G^2}{2m_b^2} + \mathcal{O}\left(\frac{1}{m_b^3}\right) \right] + 2c_{5,b} \left[\frac{\mu_G^2}{\mu_b^2} + \mathcal{O}\left(\frac{1}{m_b^3}\right) \right) + \frac{c_{6,b}}{m_b^3} \frac{\langle B|(\bar{b}q)_\Gamma(\bar{q}b)_\Gamma|B\rangle}{M_B} \right] + \ldots \right\}$$

meaning that corrections to the *free-quark* decay width are $\mathcal{O}\left(\frac{1}{m_b^2}\right)$!

Invented around 1986 is currently updated using Gauge Lattice QCD to determine matrix elements (including those in c_j parameters).

Some theoretical uncertainties cancel calculating lifetime ratios

Theoretical expectations on b-hadron lifetimes in this talk are obtained with HQE [Lenz'14, arXiv:1405.3601].

$\Xi_b \to J/\psi \Xi^-$

Signal candidates: 313 ± 20

$$\tau(\Xi_b^-) = 1.55^{+0.10}_{-0.09} \pm 0.03 \text{ ps}$$

WORLD'S BEST MEASUREMENT

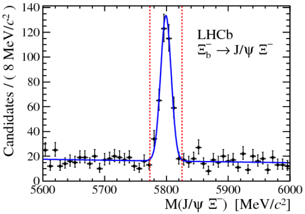
Theory [Lenz'14]: 1.56 ± 0.10 ps

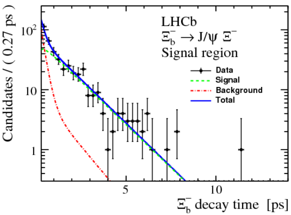
$\Omega_b^- \to J/\psi \Omega^-$

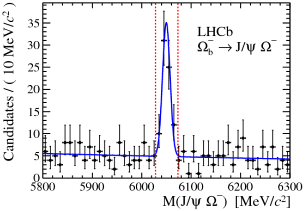
Signal candidates: 58 ± 8

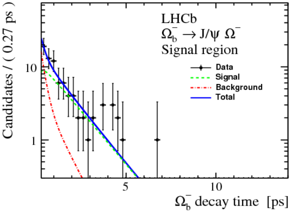
$$\tau(\Omega_b^-) = 1.54^{+0.26}_{-0.21} \pm 0.05 \text{ ps}$$

WORLD'S BEST MEASUREMENT

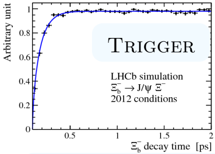


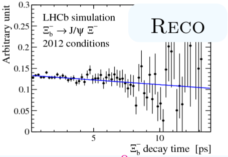






Systematic error dominated by the uncertainties on the acceptance function





Acceptance determined using Simulation and cross-checked with $B^0 \to J/\psi K^0_S$

Technique validated using $\Lambda_b^0 \to J/\psi \Lambda^0$ to measure $\tau(\Lambda_b^0)$ found consistent with W.A.

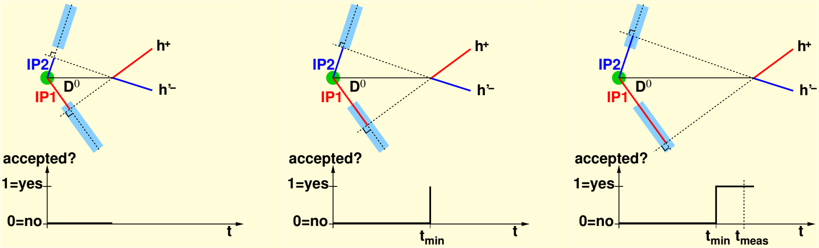
see also: $\tau(\Xi_b^0)$ determined with $\Xi_b^0 \to \Xi_c^+ \pi^-$ in J. McCarthy's talk (b-baryons)

Swimming

[JHEP 04 (2012) 129]

Data-driven technique called *swimming* widely used since 1985 [Z. Phys. C28 357]

Per-event acceptance determined by moving PV along $\vec{p}(\text{mother})$.



Measurement relative to known-τ particles decaying to similar final states

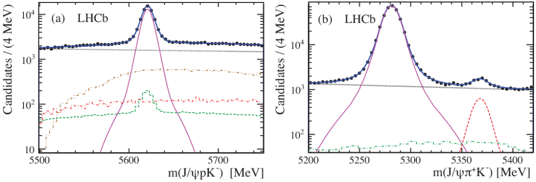
$$f_{B_1}(t) \propto \epsilon_1(t)\exp\left(-\Gamma_{B_1}t\right) \qquad f_{B_2}(t) \propto \epsilon_2(t)\exp\left(-\Gamma_{B_2}t\right)$$

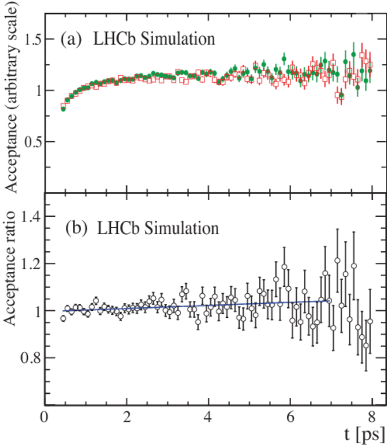
Measuring time-dependent yield ratio, get from fit $\delta\Gamma \equiv (\Gamma_{B_1} - \Gamma_{B_2})$

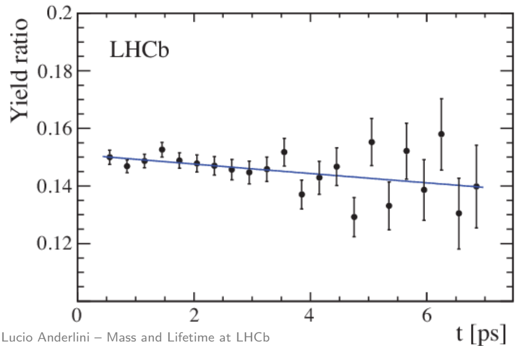
$$R(t) = \frac{N_{B_1}(t)}{N_{B_2}(t)} = \frac{\epsilon_1(t)}{\epsilon_2(t)}\exp(-\delta\Gamma t) \quad \text{with} \quad \frac{\epsilon_1(t)}{\epsilon_2(t)} = 1 + \textit{(small corrections from MC)}$$

Relative lifetime measurement: $\tau(\Lambda_b^0)/\tau(\bar{B}^0)$.

- $\Lambda_b^0 \to J/\psi p K^-$
- $\bar{B}^0 \to J/\psi \bar{K}^{*0} \to J/\psi K^- \pi^+$







Result

$$\tau(\Lambda_b^0)/\tau(\bar{B}^0) = 0.974 \pm 0.006 \pm 0.004$$

$$\tau(\Lambda_b^0) = (1.479 \pm 0.009 \pm 0.010)\ \text{ps}$$

WORLD'S BEST MEASUREMENT

Theory: $\tau(\Lambda_b^0) = 1.41 \pm 0.08$ ps

Lifetimes of the B_s^0 meson

B_s flavour eigenstates (B_s^0 and $\bar{B_s^0}$) are superposition of mass eigenstates $B^0_{s,H}$ and $B^0_{s,L}$. In absence of CP violation,

$$\mathsf{CP}|B^0_{s,L}\rangle = |B^0_{s,L}\rangle \qquad \mathsf{CP}|B^0_{s,H}\rangle = -|B^0_{s,H}\rangle$$

$$(\mathsf{CP}\ \text{even}) \qquad (\mathsf{CP}\ \text{odd})$$

Defined the quantities: $\Gamma_s = \left(\frac{\Gamma_{s,H}+\Gamma_{s,L}}{2}\right)$; and $\Delta\Gamma_s = \Gamma_{s,L} - \Gamma_{s,H}$, the following *lifetimes* are defined:

- as measured in CP-odd final states $\tau_H = \tau_- = \frac{1}{\Gamma_H}$,
- as measured in CP-even final states $\tau_L = \tau_+ = \frac{1}{\Gamma_L}$,

Flavour eigenstate decay with a non-exponential low approximated by:

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

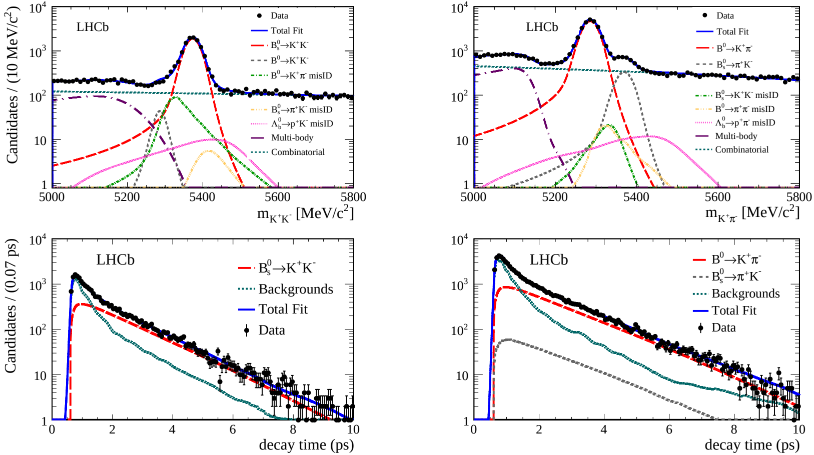
- when fitted with a simple exponential $\tau_{\text{fs}} \approx \frac{1}{\Gamma_s}\frac{1+\left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2}{1-\left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2}$.

(The latter assumes $\Delta\Gamma_s \ll \Gamma_s$ and no production asymmetry: $\sigma(B_s^0) = \sigma(\bar{B_s^0})$)

Absolute lifetime measurement

Dataset: $1\ \text{fb}^{-1}$

Acceptance w/ *swimming*



Analysis technique

1. fit mass *pdf* $f(m) = \sum_{\text{class}} f(m|\text{class})P(\text{class})$
2. fit lifetime

$$f(t;\tau|m) = \sum_{\text{class}} f(t;\tau|\text{class}) \frac{P(\text{class})f(m|\text{class})}{f(m)}$$

Results

$$\tau_{B^0_s \to K^+K^-} = 1.407 \pm 0.016 \pm 0.007 \text{ ps}$$

WORLD'S BEST MEASUREMENT

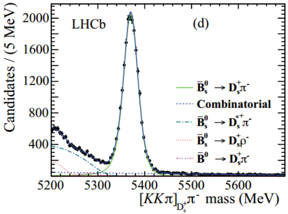
$$\tau_{B^0 \to K^+\pi^-} = 1.524 \pm 0.011 \pm 0.004 \text{ ps}$$

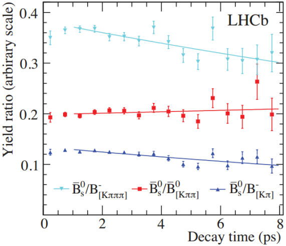
$$\tau_{B^0_s \to \pi^+K^-} = 1.60 \pm 0.06 \pm 0.01 \text{ ps}$$

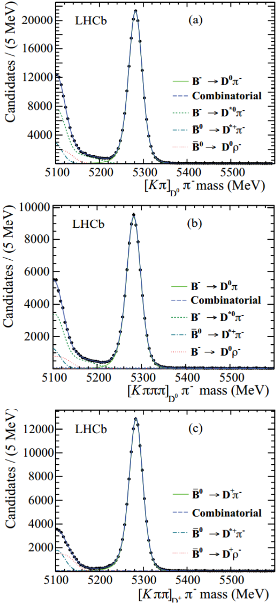
Using 3 normalization channels:

Dataset: 3 fb^{-1}

- $[B^-_{[K\pi]}]$ $B^- \to D^0\pi^+$ with $D^0 \to K^-\pi^+$
- $[B^-_{[K\pi\pi\pi]}]$ $B^- \to D^0\pi^+$ with $D^0 \to K^-\pi^+\pi^-\pi^+$
- $[\bar{B}^0_{[K\pi\pi]}]$ $\bar{B}^0 \to D^+\pi^-$ with $D^+ \to K^-\pi^+\pi^+$





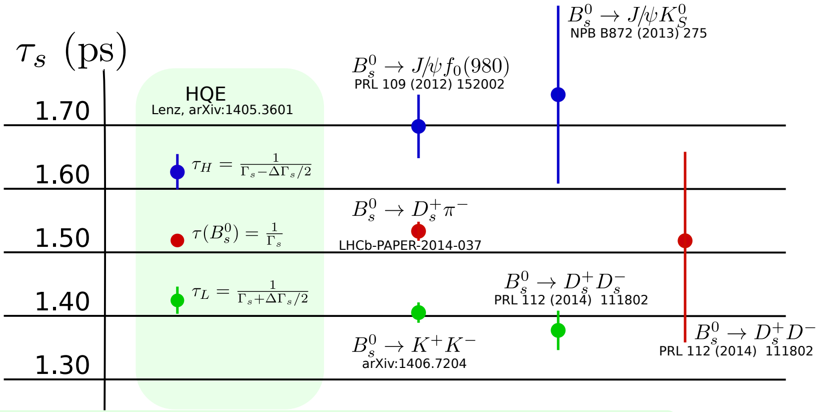


Result (fully correlated uncertainties)

- $\tau_{[B^-_{[K\pi]}]} = 1.540 \pm 0.015 \pm 0.012 \pm 0.008(\tau_{B^0})$ ps
- $\tau_{[\bar{B}^0_{[K\pi\pi]}]} = 1.535 \pm 0.015 \pm 0.012 \pm 0.007(\tau_{B^-})$ ps
  WORLD'S BEST MEASUREMENT
- $\tau_{[B^-_{[K\pi\pi\pi]}]} = 1.535 \pm 0.016 \pm 0.018 \pm 0.008(\tau_{B^0})$ ps

Validation: $B^-/\bar{B}^0$ lifetime ratios found consistent with WA

Recent LHCb Contributions to B_s^0 lifetime measurements

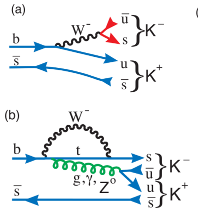


Overview of recent LHCb contribution on B_s^0 lifetimes

- Good experimental understanding of B_s^0 lifetime and width difference.
- Impressive consistency of experimental results with HQE predictions
- Limits on new physics come from effective lifetime comparisons *e.g.*

$$\tau_L|_{B_s^0 \to D_s^+ D_s^-} \quad vs. \quad \tau_L|_{B_s^0 \to K^+ K^-}$$

(Tree-level) (Penguin-polluted)



Conclusion and outlook

Conclusion and outlook

LHC and LHCb excellent performance allowed to collect excellent data in 2011/12!

Many world-leading mass and lifetime measurement of b- and c-hadrons achieved

Major improvements in B_s^0, B_c^+ and $b-$baryon systems.

Heavy Quark Expansion (HQE) has been found to predict well all the measured b-hadron lifetimes.

	HQE	LHCb	
Λ_b^0	1.41 ± 0.08 ps	$1.479 \pm 0.009 \pm 0.010$ ps	[PLB, 734 (2014) 122]
Ξ_b^-	1.56 ± 0.10 ps	$1.55^{+0.10}_{-0.09} \pm 0.03$ ps	[arXiv:1405.1543]
$\bar{B}_s^0$	1.521 ± 0.008 ps	$1.535 \pm 0.015 \pm 0.012 \pm 0.007(\tau_{B-})$ ps	[LHCb-PAPER-2014-037]
Ξ_b^0	—	$1.477 \pm 0.026 \pm 0.014 \pm 0.013(\tau_{\Lambda_b})$ ps	[arXiv:1405.7223]

More to come

Next year LHCb will take data at higher energy (larger σ) and luminosity.

Improved precision and new measurements are planned and expected!