# Mass and lifetime measurements of b-flavoured hadrons

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# Introduction

- Lifetimes and masses are fundamental properties of particles
- Decay time distribution is exponential:
  - Exception: in neutral mesons it can be modified due to mixing and CPV
- The decay rate for neutral B decays is: [Phys.Rev. D63 (2001) 114015]

(No production asymmetry assumed)

$$\Gamma[f,t] = \Gamma(B_s(t) \to f) + \Gamma(\overline{B}_s(t) \to f)$$

$$= \mathcal{N}_f \left[ e^{-\Gamma_L t} |\langle f | B_L \rangle|^2 + e^{-\Gamma_H t} |\langle f | B_H \rangle|^2 \right]$$

$$= \mathcal{N}_f \, |A_f|^2 \left[ 1 + |\lambda_f|^2 \right] e^{-\Gamma t} \left\{ \cosh \frac{\Delta\Gamma \, t}{2} + \sinh \frac{\Delta\Gamma \, t}{2} \mathcal{A}_{\Delta\Gamma} \right\}$$

$$\Delta\Gamma = \Gamma_L - \Gamma_H$$

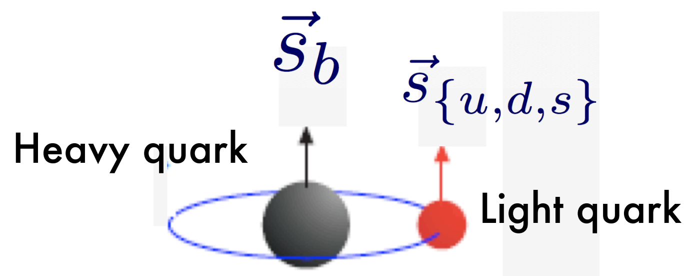
$$\mathcal{A}_{\Delta\Gamma} = \frac{|\langle f | B_H \rangle|^2 - |\langle f | B_L \rangle|^2}{|\langle f | B_H \rangle|^2 + |\langle f | B_L \rangle|^2}$$

Depends on mode considered

- For $B^0$ meson ($\bar{d}b$), the rate can be approximated as single exponential ($\Delta\Gamma_d/\Gamma_d << 1$)
- For $B_s^0$ meson ($\bar{s}b$), $\Delta\Gamma_s$ is not small and $A_{\Delta\Gamma}$ depends on the decay mode
- For flavour specific $B_s$ decays, the rate is the sum of two exponential and can be fitted by a single exponential with an "effective lifetime" $\tau_{\rm fs} \approx \frac{1}{\Gamma_s} \frac{1 + \left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2}{1 - \left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2}$

# Heavy Quark Expansion (HQE)

- Heavy Quark Effective Theory (HQET) describes hadrons with one heavy quark which is assumed to have infinite mass [arXiv:hep-ph/9611411]
- Precise measurements of the excited hadrons properties are a sensitive test of the validity of HQET




- The Heavy Quark Expansion (HQE) makes use of HQET for predicting lifetimes of hadrons containing a heavy quark [arXiv:1405.3601v1]
- Using optical theorem, Operator Product Expansion, and HQET:

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

  - Expressed in powers of the inverse of the mass of the heavy quark
  - Some theoretical uncertainties cancel calculating lifetime ratios

# Lifetime measurements

- Lifetimes measured in two different approaches:

1. **Absolute measurement:** fit directly the distribution of decay times taking into account acceptance correction
   - Acceptances must be well understood, data-driven methods needed

2. **Relative measurement:** measure lifetime relative to a control channel. Usually done with same decay topologies, e.g. $B_s \to J/\psi\ f_0$ compared with $B_0 \to J/\psi\ K^*$, where $f_0 \to \pi^+\pi^-$ and $K^* \to K^+\pi^-$
   - Many systematic uncertainties cancel in the ratio, but irreducible error from lifetime of control mode

# $B_s$ lifetime

# Lifetime with $B_s \to D_s \pi$ (1)

arXiv:1407.5873
(submitted to PRL)

- New measurement by LHCb
- $B_s \to D_s[KK\pi]\pi$ lifetime using 3 control samples:
  1. $B^0 \to D[K\pi\pi]\pi$ (same num. tracks, different D lifetime)
  2. $B^+ \to D^0[K\pi]\pi$ (different num. tracks, similar D lifetime)
  3. $B^+ \to D^0[K\pi\pi\pi]\pi$ (different num. tracks, similar D lifetime)
- Fit the ratio of the decay time distribution:

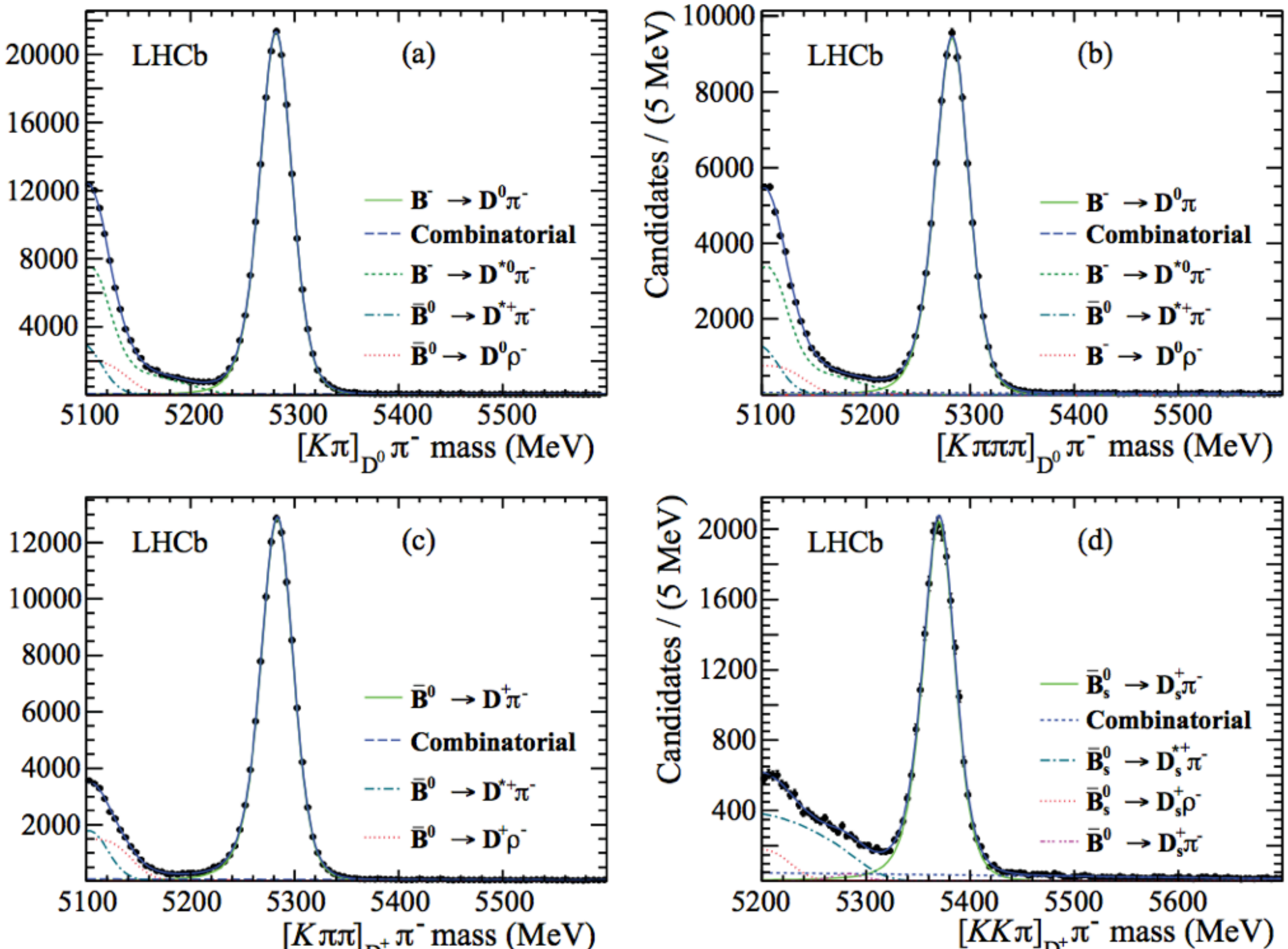
$$R(t) = \frac{\underbrace{A_{\bar{B}^0_s}(t)}_{\text{acceptance correction}} \times [\underbrace{e^{-t'/\tau_{\bar{B}^0_s}}}_{\text{exp. factor}} \otimes \underbrace{G(t-t', \sigma_{\bar{B}^0_s})}_{\text{resolution correction}}]}{A_{B_x}(t) \times [e^{-t'/\tau_{B_x}} \otimes G(t-t', \sigma_{B_x})]} \Rightarrow R(t) = \frac{A_{\bar{B}^0_s}(t)}{A_{B_x}(t)} e^{-t(1/\tau_{\bar{B}^0_s} - 1/\tau_{B_x})}$$

- Use precise $B^+$ and $B^0$ lifetimes as input

# Lifetime with $B_s \to D_s \pi$ (2)

arXiv:1407.5873
(submitted to PRL)

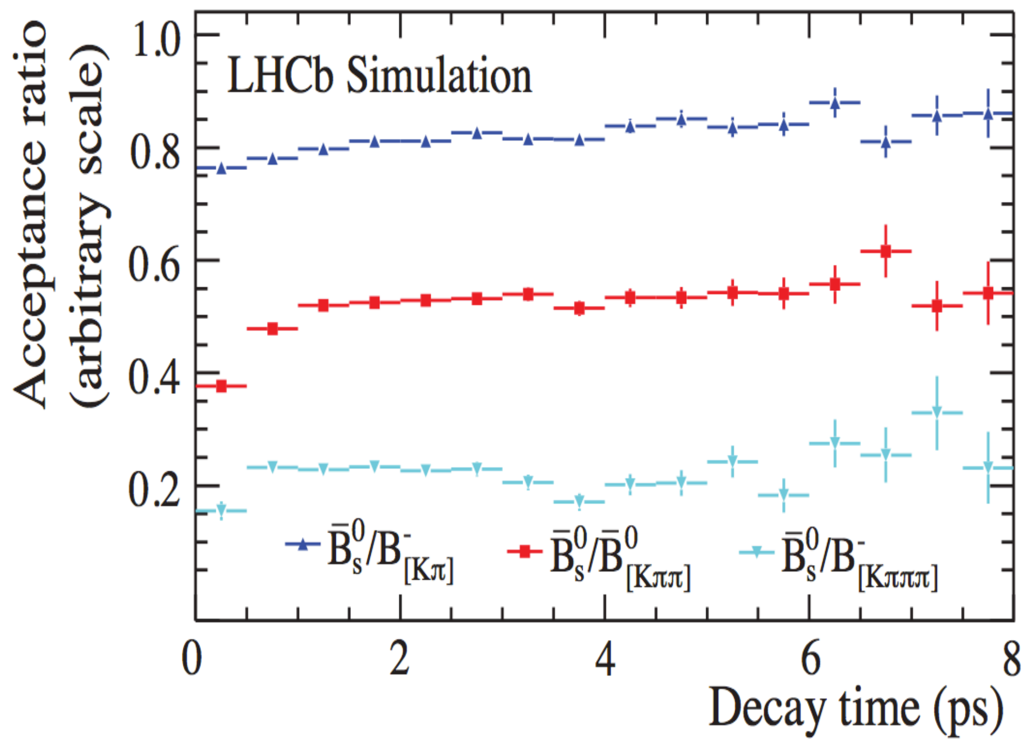
- 2011 data (1fb$^{-1}$)
- 21000 signal $B_s$ events



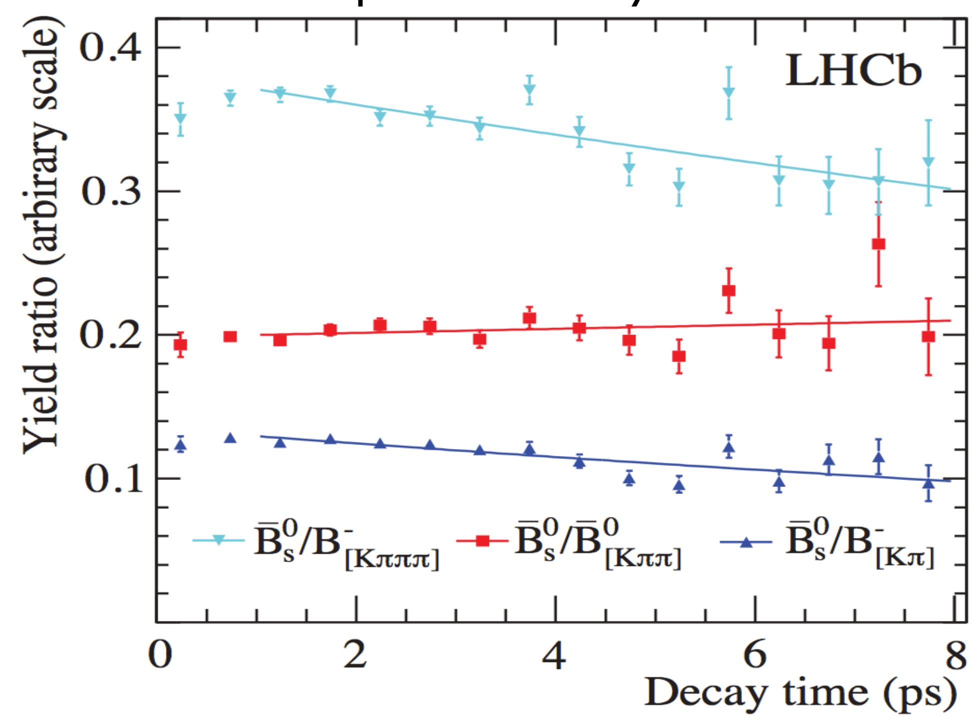
# Lifetime with $B_s \to D_s \pi$ (3)

arXiv:1407.5873

Acceptance ratio




Exponential fit to yield ratios




$$\tau_{\rm fs} = 1.535 \pm \underset{\text{stat.}}{0.015} \pm \underset{\text{syst.}}{0.012} \pm \underset{\text{PDG}}{0.007}\,\text{ps}$$

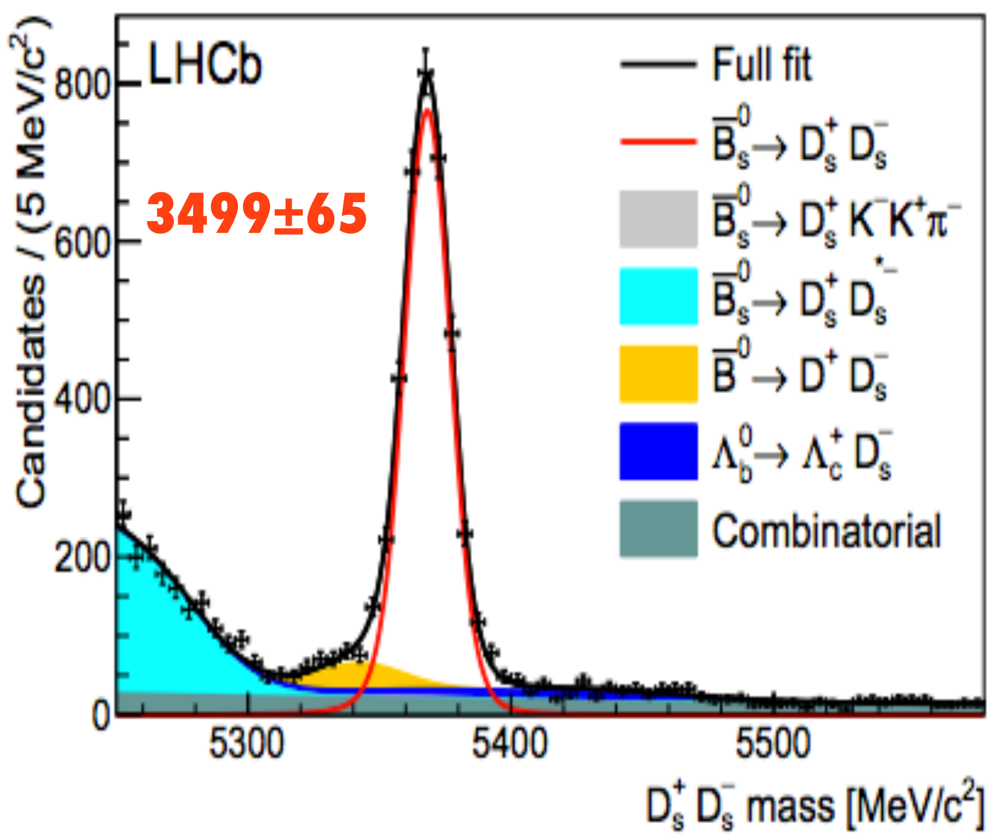
$$\tau_{\rm fs}(\overline{B}{}^0_s)/\tau(\overline{B}{}^0) = 1.010 \pm 0.010 \pm 0.008$$

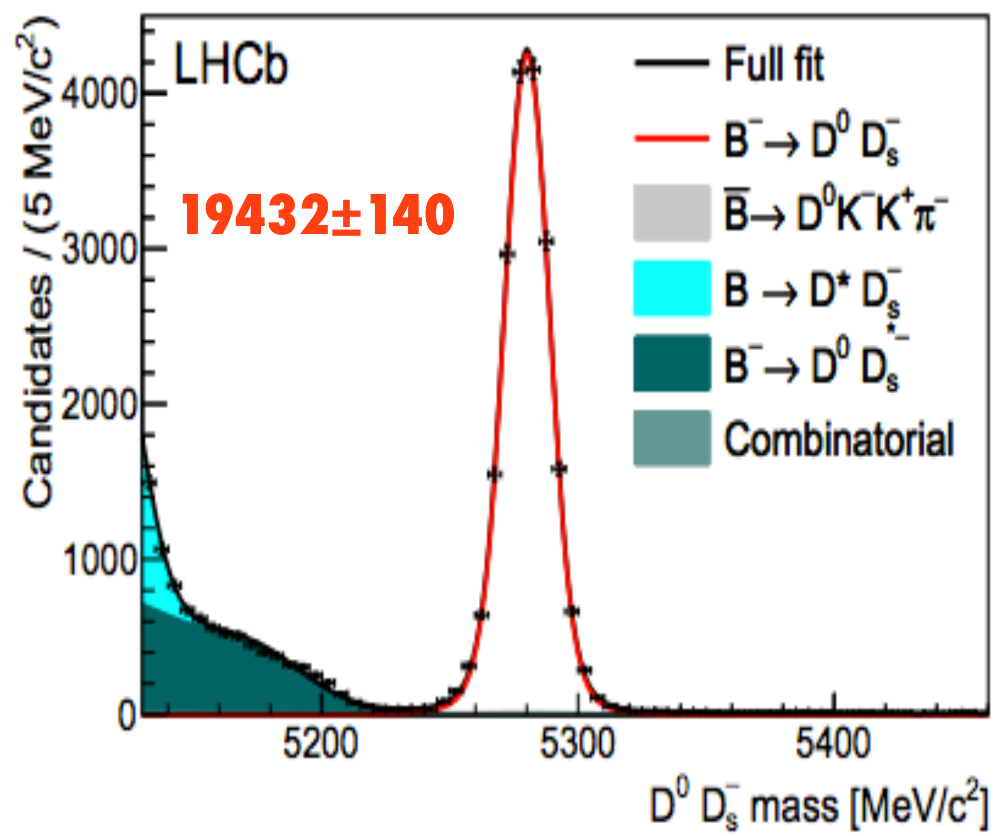
- This is the world best measurement
- $\tau(B_s)/\tau(B^0)$ consistent with HQE prediction 1.009±0.004
- Compatible with all previous flavour specific measurements

# Lifetime with $B_s \to D_s D_s$

PRL 112, 111802 (2014)
arXiv:1312.1217

- 2011 + 2012 datasets ($3fb^{-1}$)
- $D_s D_s$ is a CP even state
- Decay rate normalized to $B^- \to D^0 D_s^-$
- First lifetime measurement in this channel




$$\tau^{\text{eff}}_{\overline{B}^0_s \to D_s^- D_s^+} = 1.379 \pm 0.026 \pm 0.017 \text{ ps},$$

$$\Gamma_{\text{L}} = 0.725 \pm 0.014 \pm 0.009 \text{ ps}^{-1}$$

# Lifetime with $B_s \to KK$ (1)

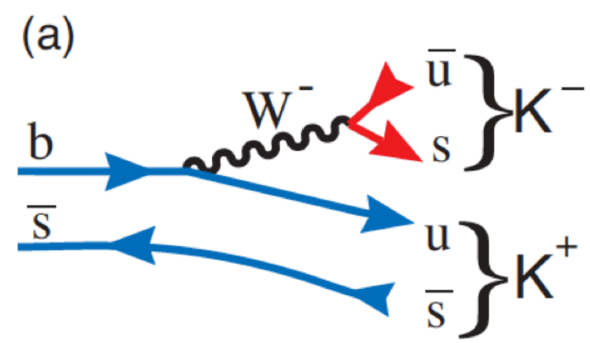
PLB 736, 446 (2014)

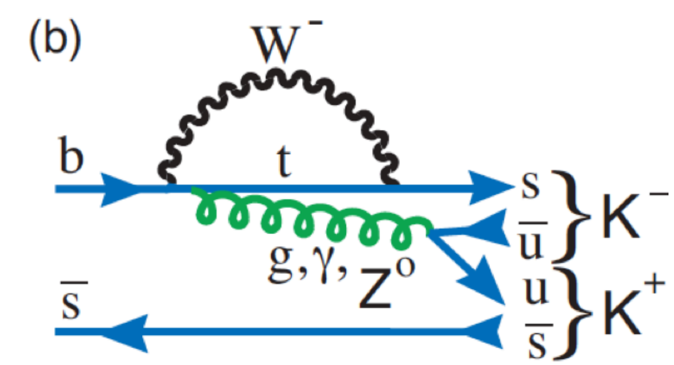
- 2011 data (1 $fb^{-1}$)
- CP-even, tree contribution gives CP violation

To first order:

$$\tau_{B_s^0 \to K^+K^-} \approx \frac{1}{\Gamma_s}\left(1 + \frac{\mathcal{A}_{\Delta\Gamma_s}\Delta\Gamma_s}{2\Gamma_s}\right)$$

$\approx -0.97$ (SM exp.)

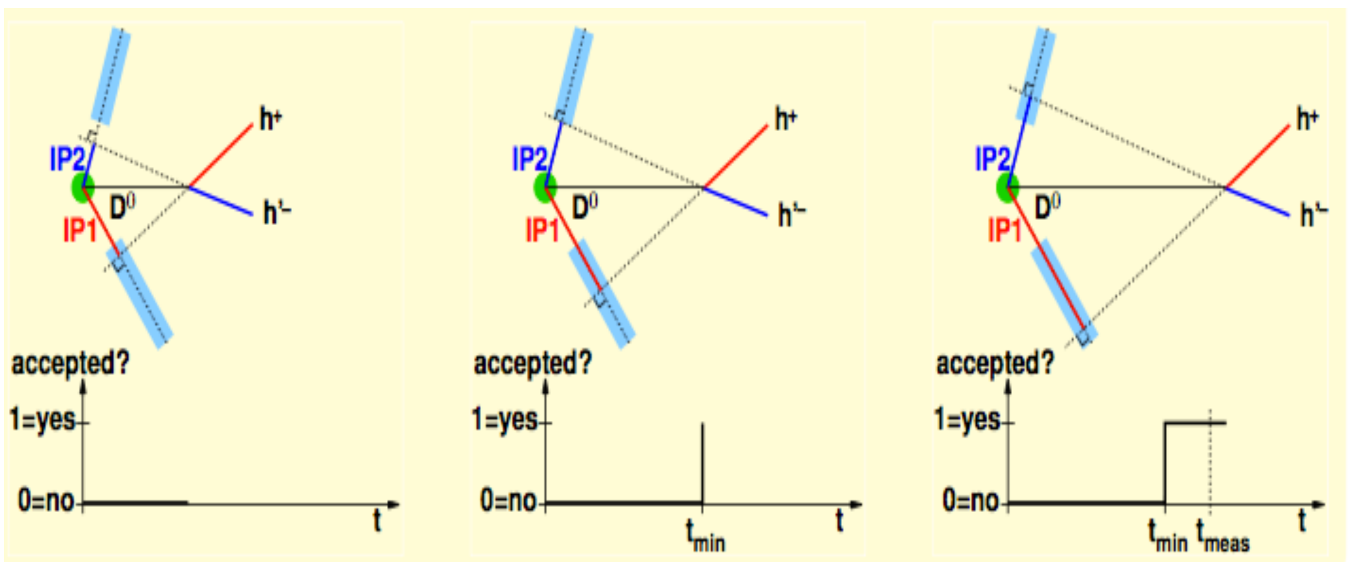



- Absolute lifetime measurement
- Decay acceptance from a data-driven approach ("swimming")

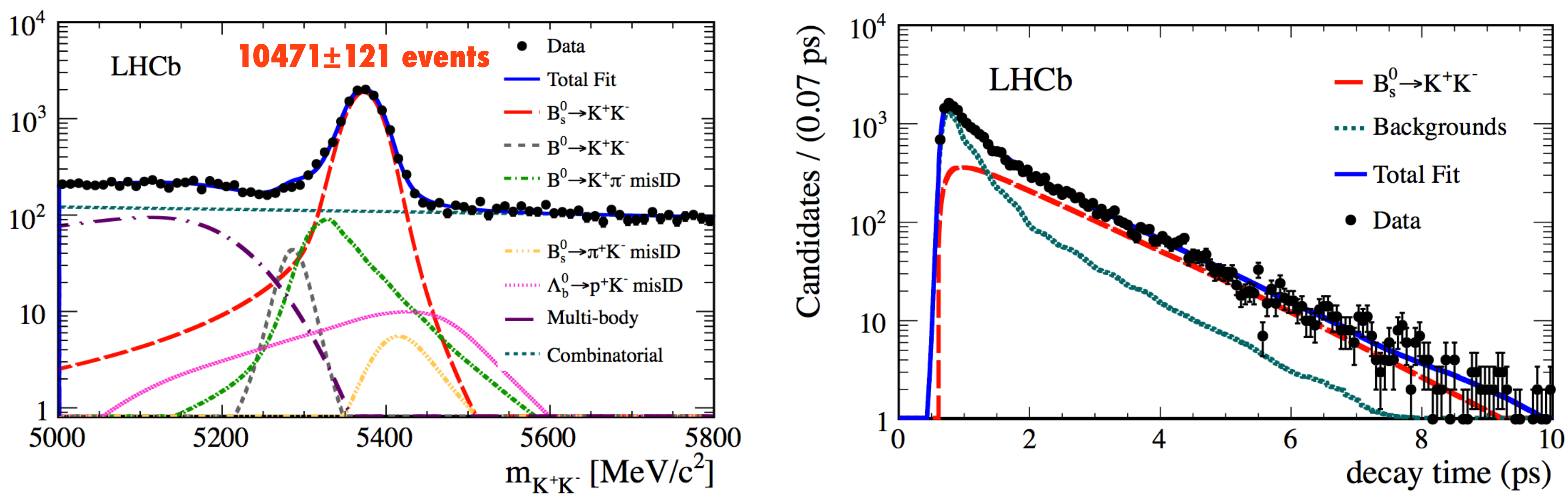
## "Swimming" method:

- A per-event acceptance function is determined by moving the primary vertex along the p vector of the B particle



# Lifetime with $B_s \to KK$ (2)

PLB 736, 446 (2014)




$$\tau_{B_s^0 \to K^+K^-} = 1.407 \pm 0.016\,(\text{stat}) \pm 0.007\,(\text{syst})\,\text{ps}$$

- This is the most precise determination of the effective lifetime in $B_s \to KK$ decay
- This measurement can be combined with LHCb results of $\Gamma_s$ and $\Delta\Gamma_s$ to obtain:

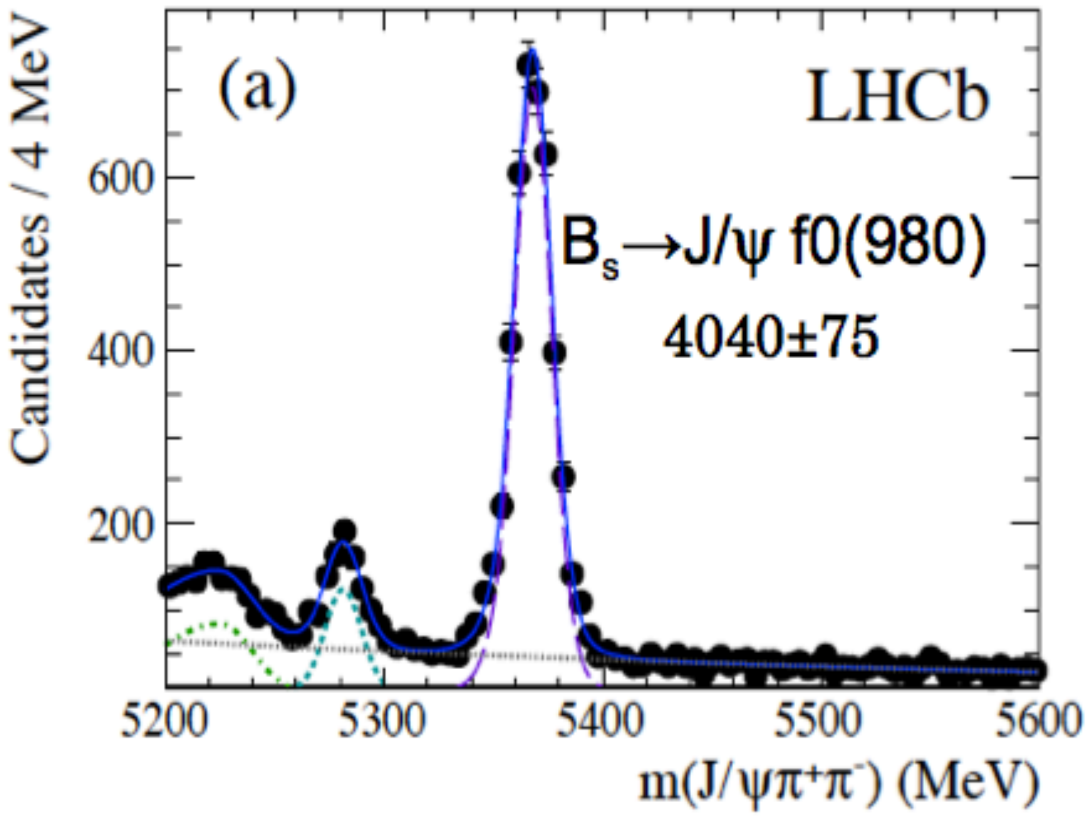
$$\mathcal{A}_{\Delta\Gamma_s} = -0.87 \pm 0.17\,(\text{stat}) \pm 0.13\,(\text{syst}) \qquad \mathcal{A}_{\Delta\Gamma} = \frac{|\langle f|\,B_H\rangle|^2 - |\langle f|\,B_L\rangle|^2}{|\langle f|\,B_H\rangle|^2 + |\langle f|\,B_L\rangle|^2}$$

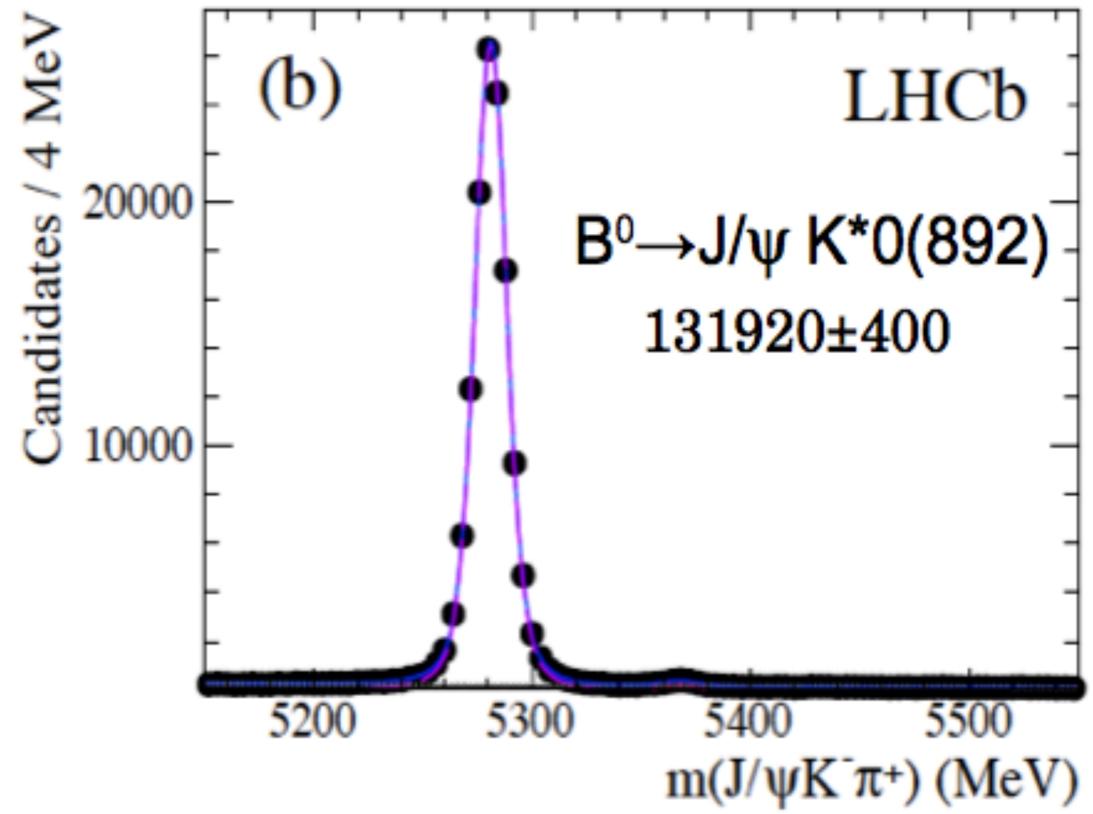
compatible with the SM prediction $A_{\Delta\Gamma} = -0.972$

# Lifetime with $B_s \to J/\Psi\ f^0$

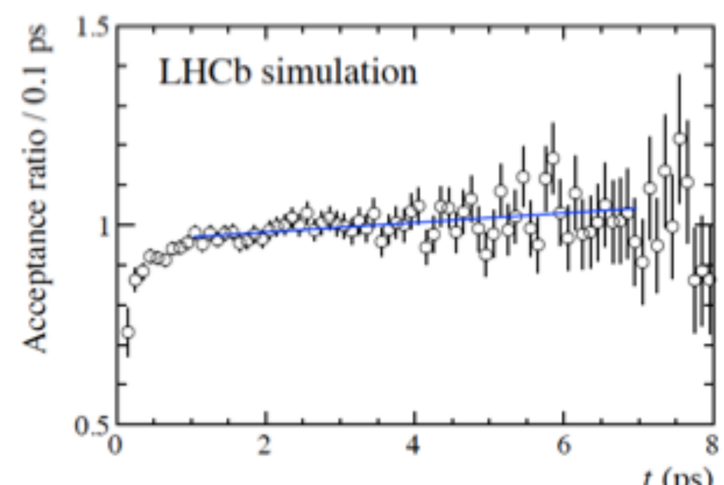
PRL 109, 152002 (2012)

- 2011 data ($1 fb^{-1}$)
- CP-odd final state
- Relative measurement wrt $B^0 \to J/\Psi K^{0*}(892)$




$$1.700 \pm 0.040 \pm 0.026 \text{ ps}$$

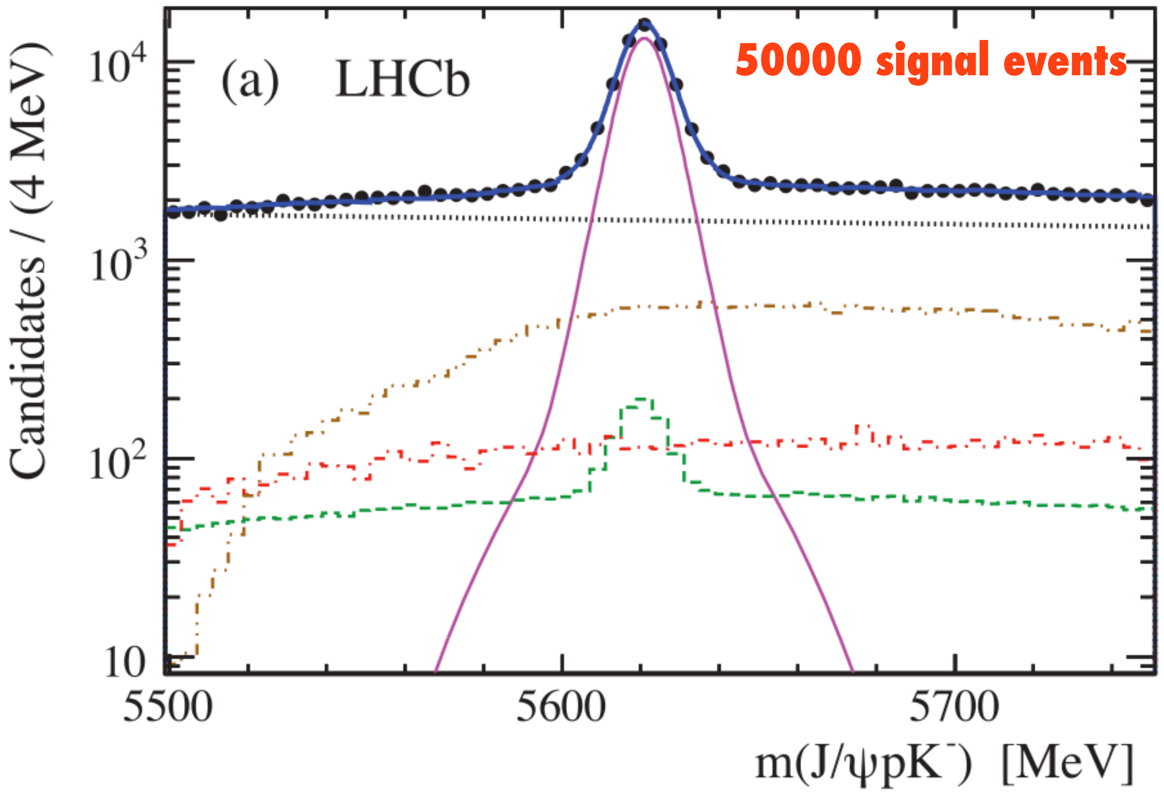


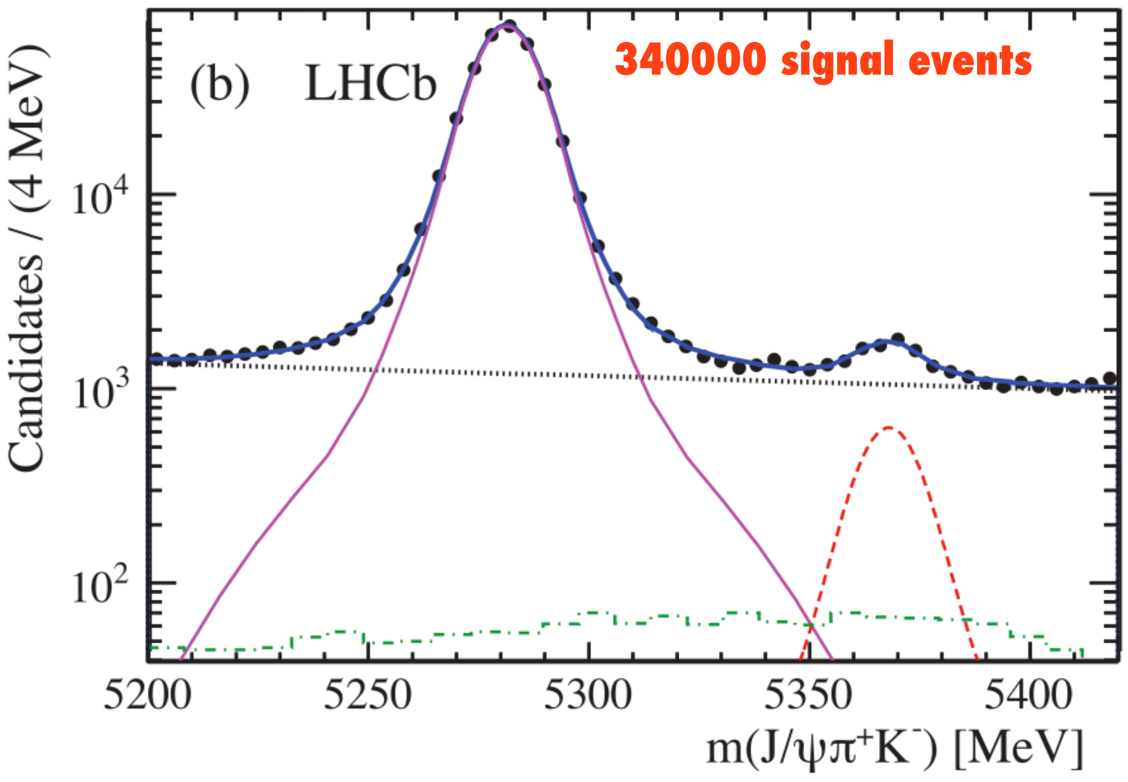
# Lifetime of b-baryons

# $\Lambda_b^0$ lifetime (1)

PLB 734, 122 (2014)

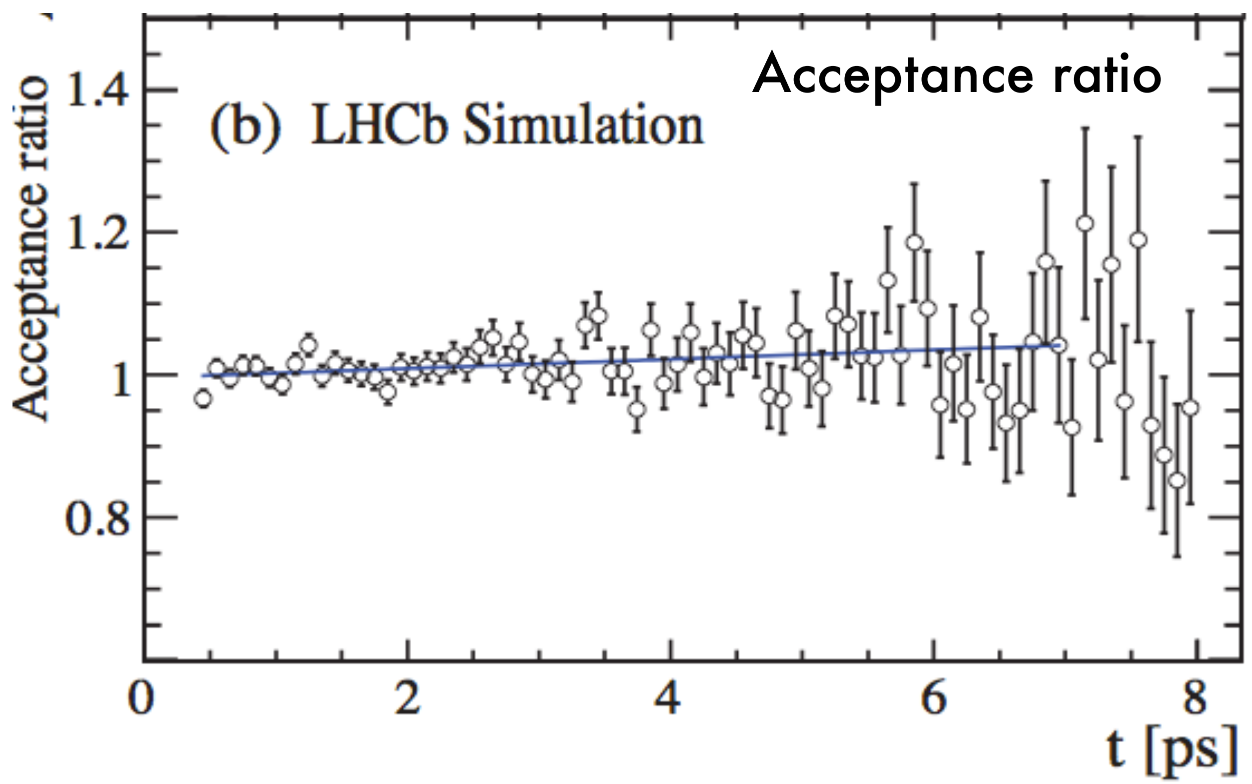
- HQE predicts b-hadron lifetimes close to each other within few percent: $\tau_{Bs}/\tau_{B0} \approx 1.0$, $\tau_{B-}/\tau_{B0} \approx 1.1$, $\tau_{\Lambda b}/\tau_{B0} \approx 0.94$
- Early $\Lambda_b^0$ lifetime measurements yielded values smaller than HQE predictions
- LHCb measured $\tau_{B-}/\tau_{B0}$ directly using the newly observed $B^0 \rightarrow J/\Psi Kp$ decay
- Relative measurement wrt $B^0 \rightarrow J/\Psi K^{0*}$
- 2011 + 2012 data ($3fb^{-1}$)

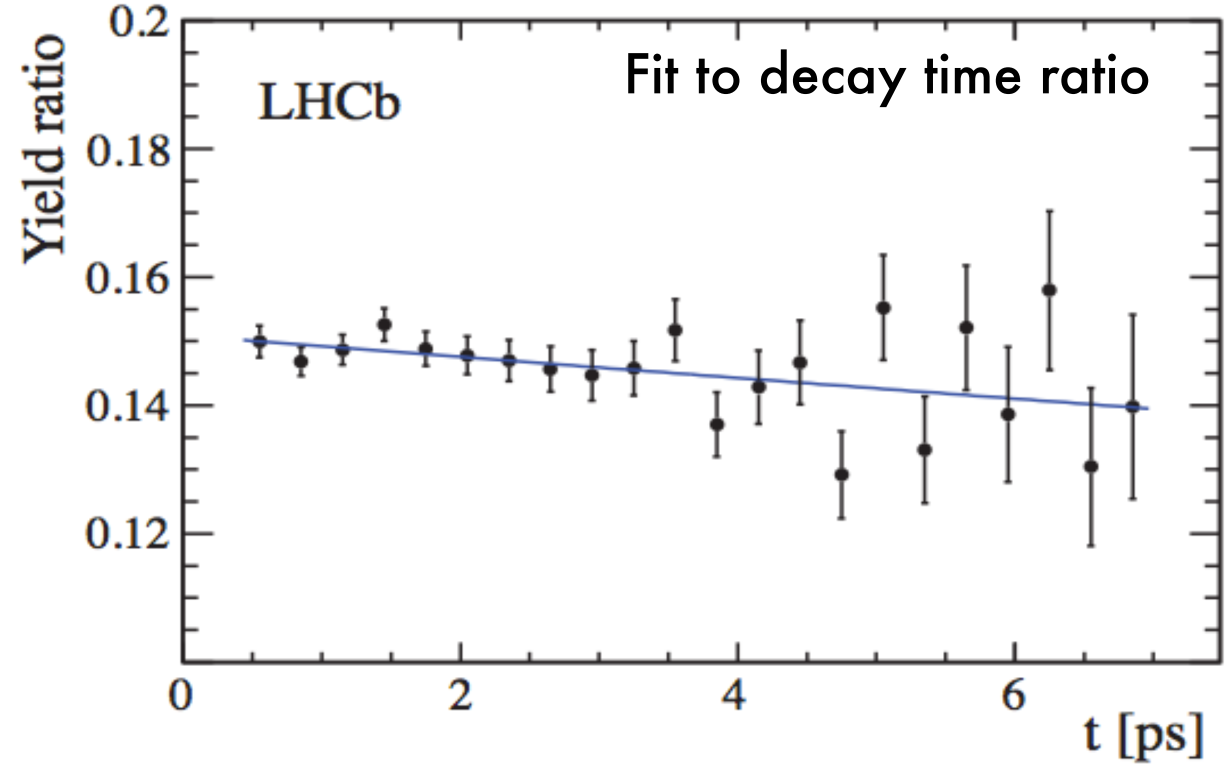


# $\Lambda_b^0$ lifetime (2)

PLB 734, 122 (2014)




$$\tau_{\Lambda_b^0} = 1.479 \pm 0.009 \pm 0.010 \text{ ps}$$

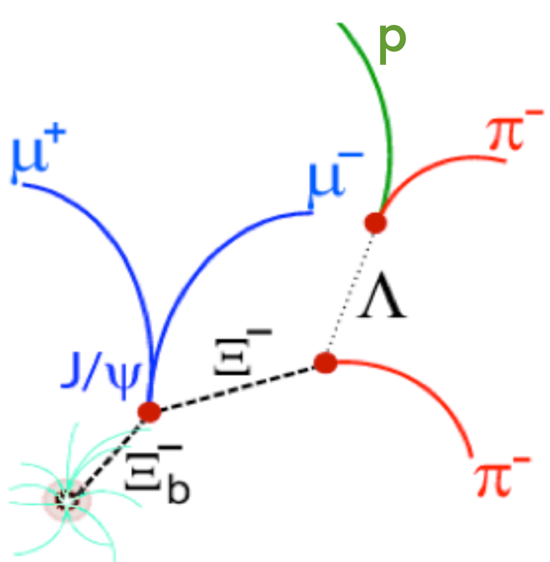
$$\frac{\tau_{\Lambda_b^0}}{\tau_{B^0}} = 0.974 \pm 0.006 \pm 0.004$$

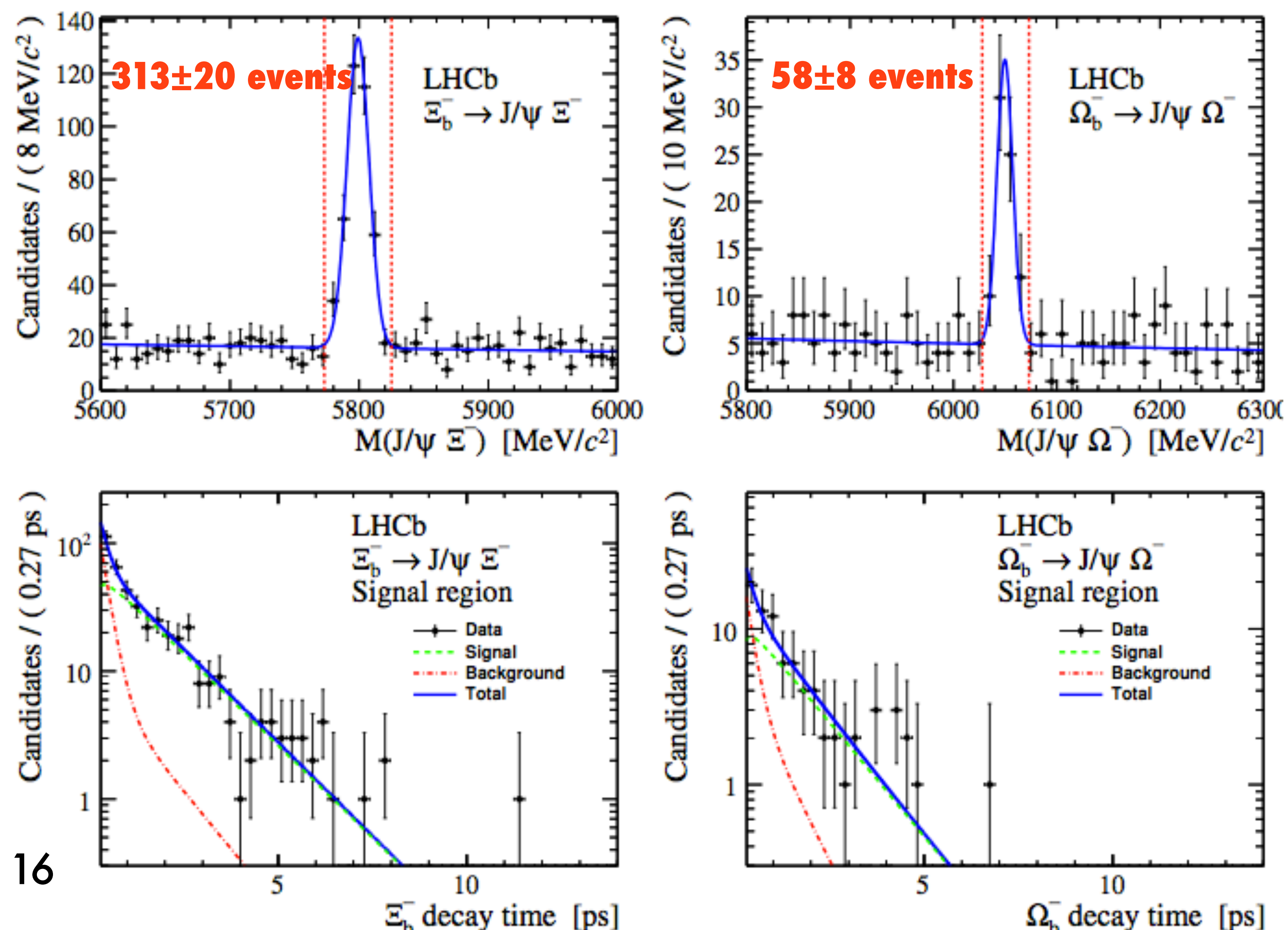
- This is the most precise measurements of $\Lambda_b^0$ lifetime to date
- The result is consistent with HQE prediction

# $\Xi_b^-$ and $\Omega_b^-$ lifetimes (1)

arXiv:1405.1543 (2014) (submitted to PLB)

- So far, only the most abundantly produced $\Lambda_b^0$ (udb) has been studied in detail
- Less information exists on strange b-baryons such as $\Xi_b$ (dsb) or $\Omega_b$(ssb)
- Previous measurement by CDF only [Phys. Rev. D89 (2014) 072014]
- New absolute measurements by LHCb using $\Xi_b^- \rightarrow J/\Psi\ \Xi^-$ and $\Omega_b^- \rightarrow J/\Psi\Omega^-$
- 2011 + 2012 data (3 $fb^{-1}$)



# $\Xi_b^-$ and $\Omega_b^-$ lifetimes (2)

arXiv:1405.1543 (2014)
(submitted to PLB)

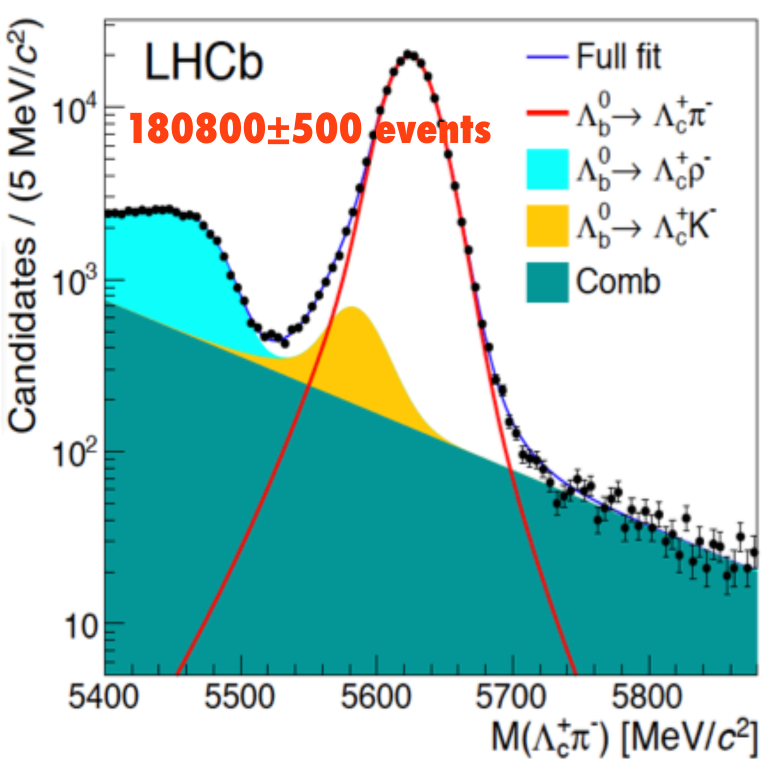
$$\tau(\Xi_b^-) = 1.55\,^{+0.10}_{-0.09}\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})\ \mathrm{ps}$$

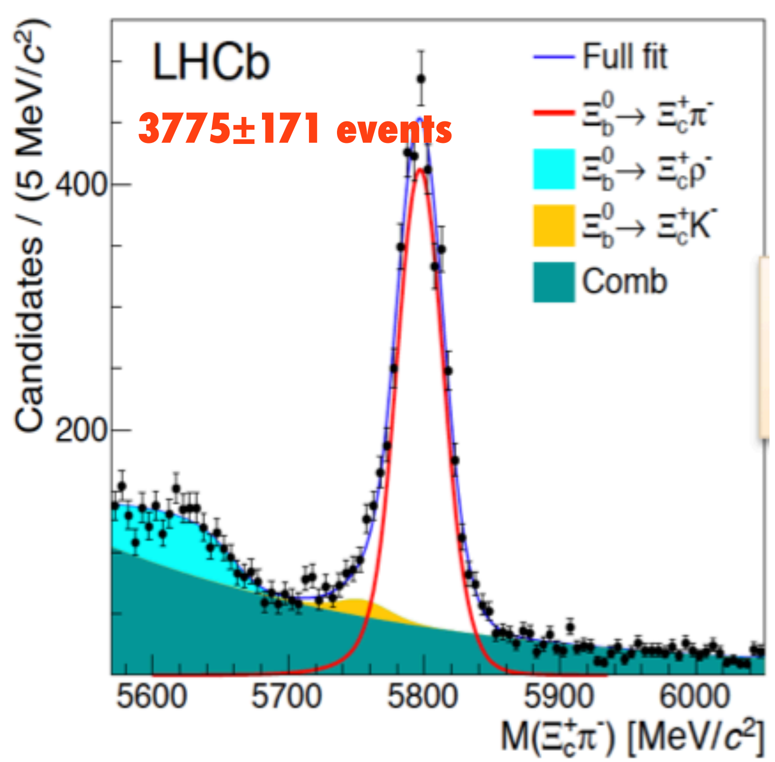
$$\tau(\Omega_b^-) = 1.54\,^{+0.26}_{-0.21}\,(\mathrm{stat}) \pm 0.05\,(\mathrm{syst})\ \mathrm{ps}$$

- This is the most precise measure of the lifetime in these b-baryons to date
- Measurements in agreement with CDF result and theoretical predictions

PRL 113, 032001 (2014)

- $\Xi_b^0/\Lambda_b^0$ lifetimes ratio measured by LHCb using $\Lambda_b^0 \to \Lambda_c^+ \pi$ and $\Xi_b^0 \to \Xi_c^+ \pi$

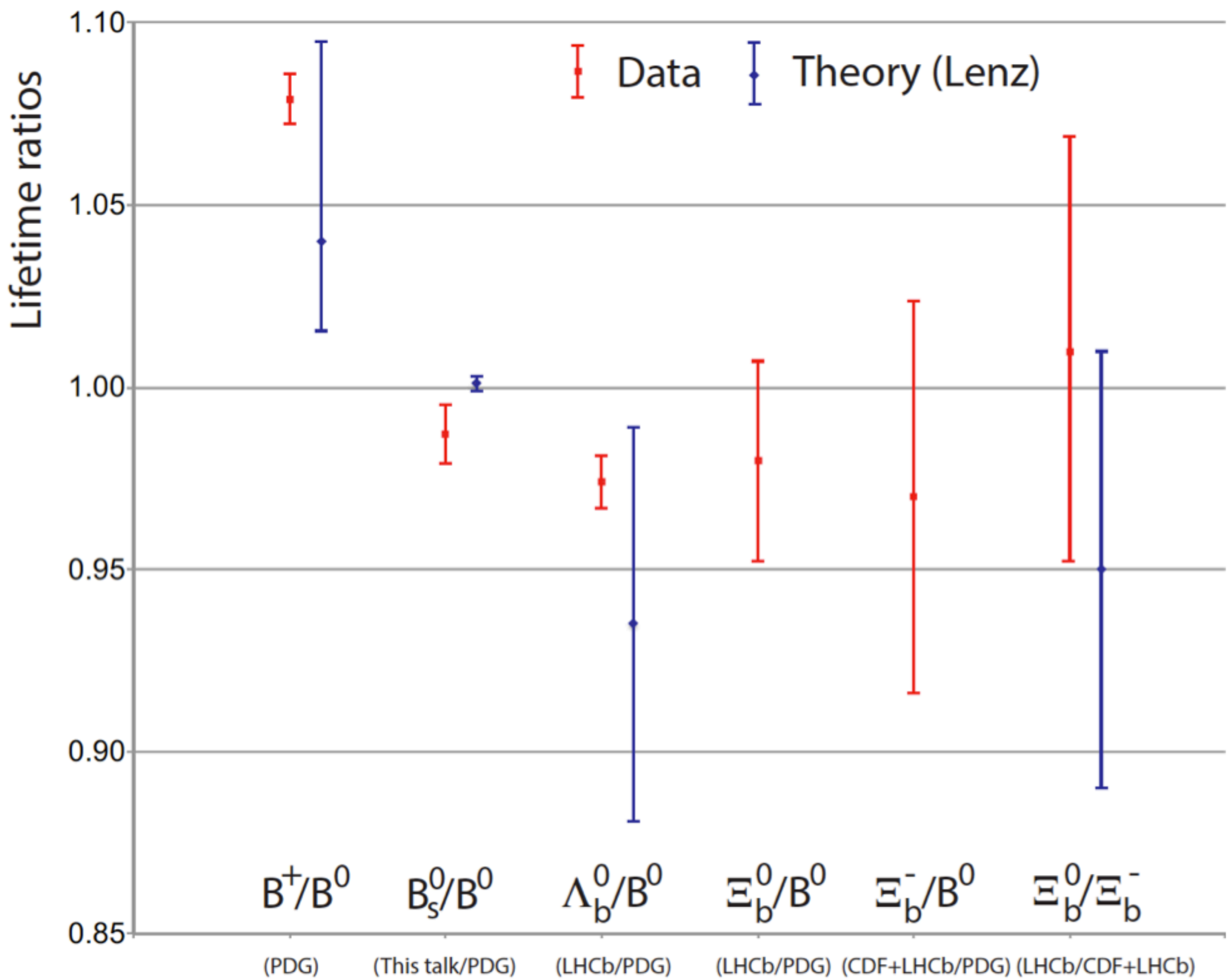



$$\frac{\tau(\Xi_b^0)}{\tau(\Lambda_b^0)} = 1.006 \pm 0.018 \pm 0.010$$

$$\tau(\Xi_b^0) = 1.477 \pm 0.026 \pm 0.014 \pm 0.013\ \mathrm{ps}$$

# Lifetimes ratios: data vs HQE




- Good agreement of lifetimes ratio measurements with HQE

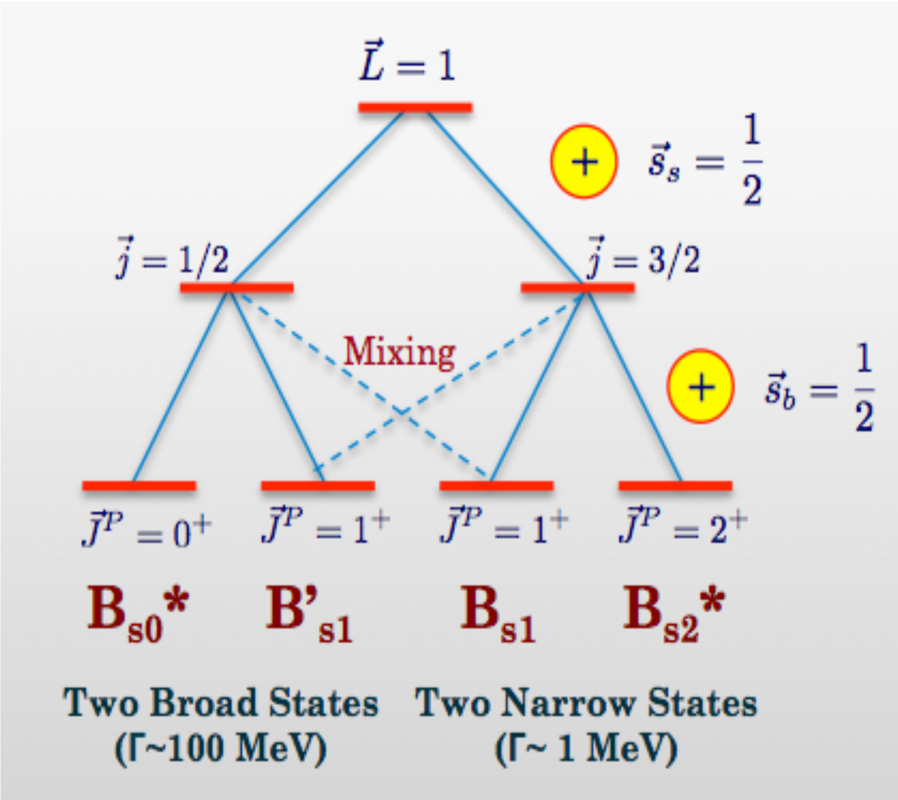
# Mass measurements

# Mass of excited $B_s$ mesons (1)

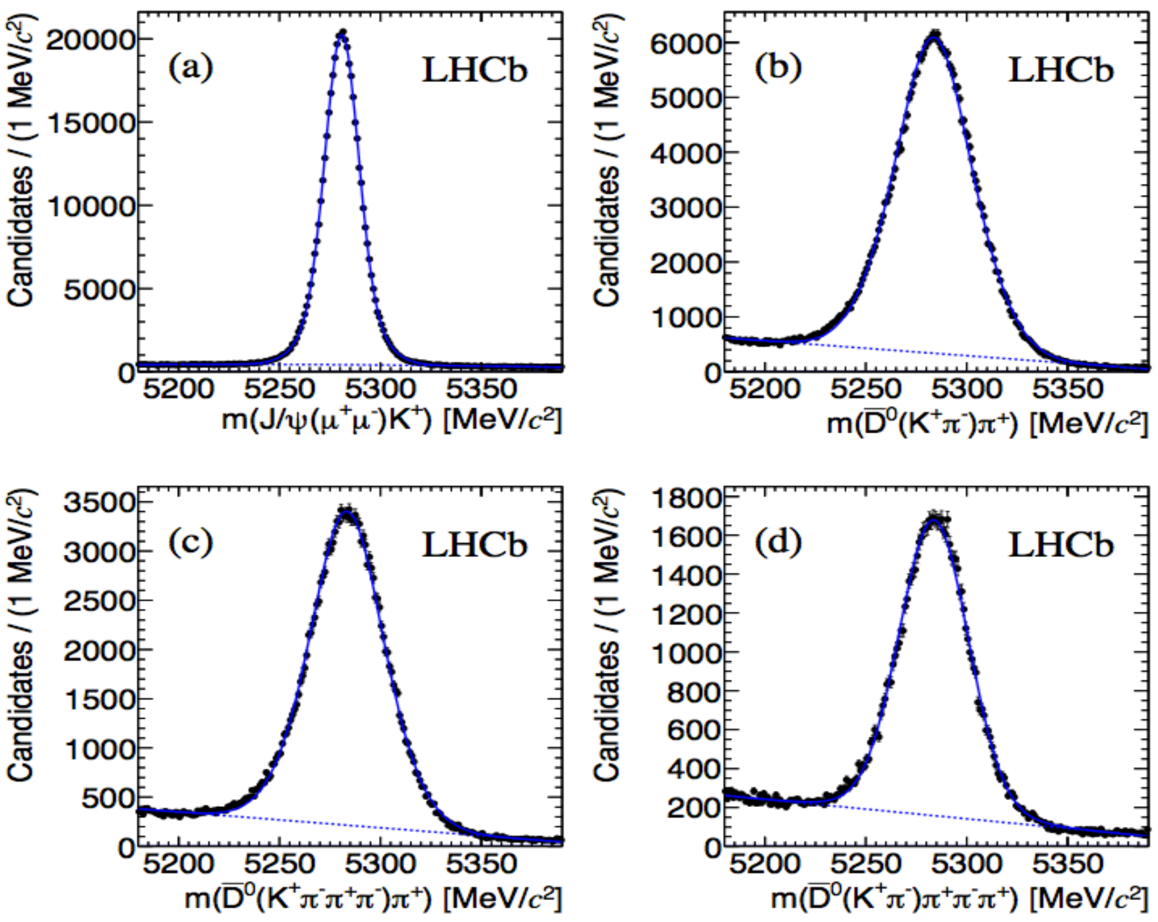
PRL 110, 151803 (2013)

- Precise measurements of excited B-hadron properties are important tests for HQET
- In HQET, $B_s$ mesons characterized by the relative a.m of the two quarks (L), the a.m. of the light quark (j) and the total a.m. of B-meson (J)
- First observation of two narrow $B_s$ excited states by CDF [PRL 100, 082001 (2008)]
- Precise mass measurements by LHCb using 2011 data (1 $fb^{-1}$)

For L=1, four possible $B_s$ excited states decaying in $B^+K^-$ and/or $B^{*+}K^-$



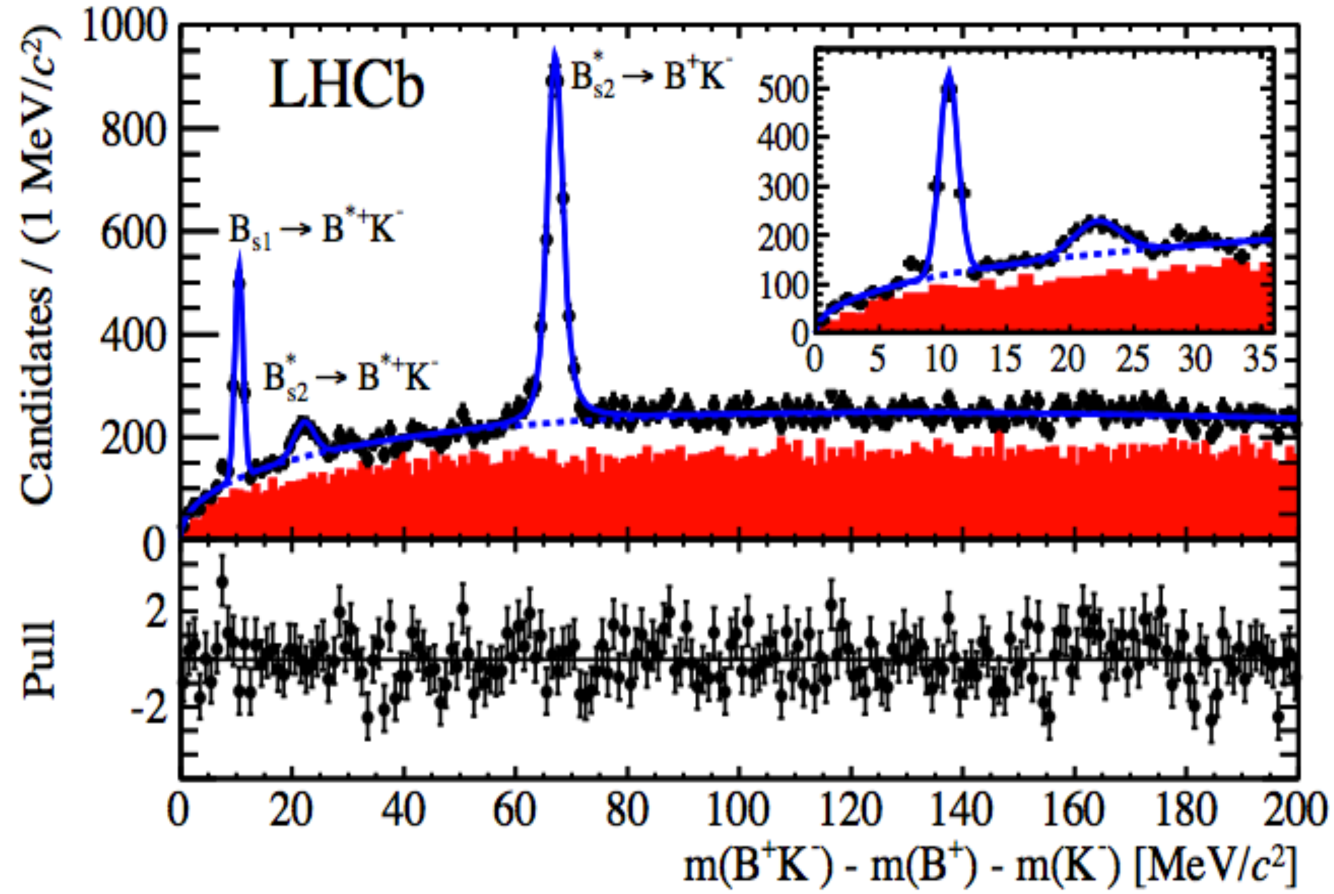

$B^+$ meson selected using four modes



# Mass of excited $B_s$ mesons (2)

PRL 110, 151803 (2013)

- Relativistic Breit-Wigner convolved with Gaussian resolution from simulation
- Threshold function for the combinatorial background $f(Q)= Q^{\alpha}\, e^{\beta Q+\gamma}$ validated with wrong sign events




$$m(B^{*+}) = 5324.26 \pm 0.30 \pm 0.23 \pm 0.17\ \mathrm{MeV}/c^2$$

$$m(B_{s1}) = 5828.40 \pm 0.04 \pm 0.04 \pm 0.41\ \mathrm{MeV}/c^2$$

$$m(B_{s2}^{*}) = 5839.99 \pm 0.05 \pm 0.11 \pm 0.17\ \mathrm{MeV}/c^2$$

$$\Gamma(B_{s2}^{*}) \quad 1.56 \pm 0.13 \pm 0.47\ \mathrm{MeV}/c^2$$

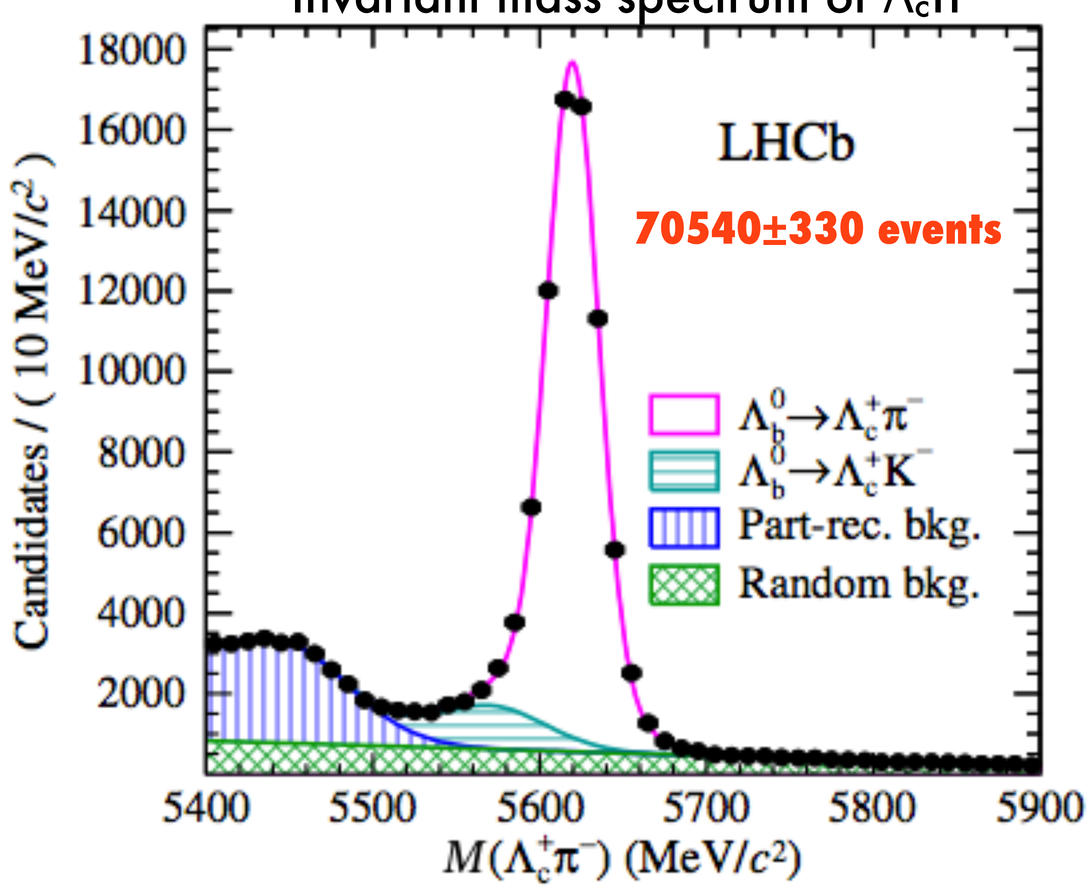
- $B_{s2}^{*} \to B^{*+}K^{-}$ observed for the first time and first measurement of $\Gamma(B_{s2}^{*})$
- This is the most precise measurement of $B_{s1}$, $B_{s2}^{*}$, $B^{*}$ masses to date

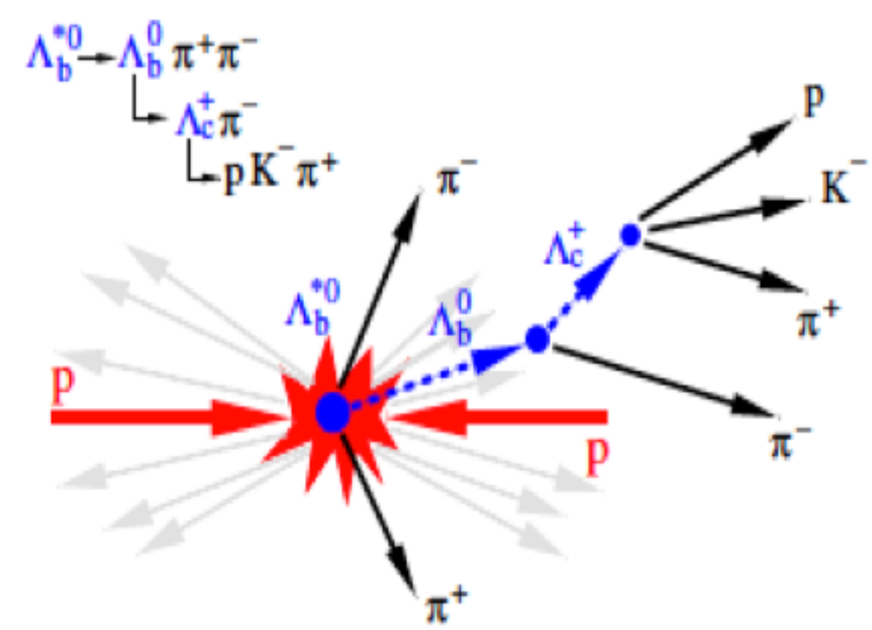
# Mass of excited $\Lambda_b^0$ baryons (1)

PRL 109, 172003 (2012)

- Quark model predicts the existence of two orbitally excited (L=1) $\Lambda_b^0$ states decaying into $\Lambda_b^0\,\pi^-\pi^+$ or $\Lambda_b^0\,\gamma$
- First observation of excited $\Lambda_b$ baryons by LHCb
- $\Lambda_b^0$ reconstructed using $\Lambda_b^0 \to \Lambda_c^+\pi^-$ with $\Lambda_c^+ \to pK^-\pi^+$, is coupled to a pair of pions coming from primary vertex (PV)
- 2011 dataset (1fb$^{-1}$)

Invariant mass spectrum of $\Lambda_c\pi$

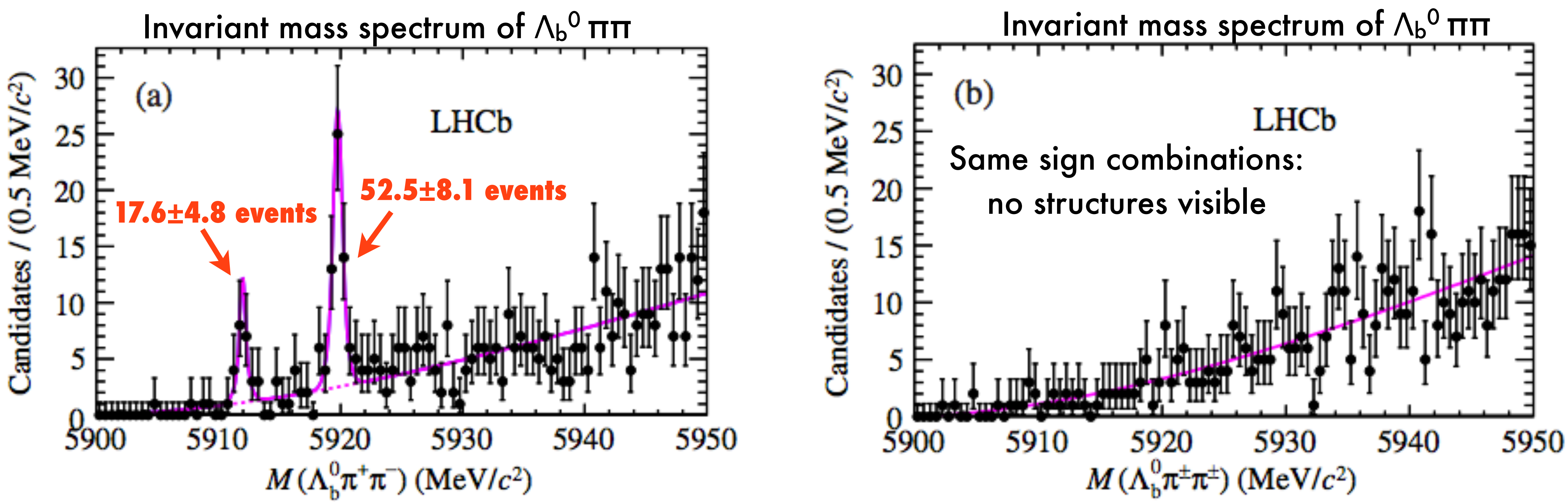



- Kinematic fit to constrain the $\Lambda_b^0$ mass to PDG value, and the $\Lambda_b^0$ and the pions to PV

# Mass of excited $\Lambda_b^0$ baryons (2)

PRL 109, 172003 (2012)




- The two peaks are interpreted as orbitally excited states $\Lambda_b^*(5912)$ and $\Lambda_b^*(5920)$

$$M_{\Lambda_b^{*0}(5912)} = 5911.97 \pm 0.12 \pm 0.02 \pm 0.66 \text{ MeV}/c^2$$

$$M_{\Lambda_b^{*0}(5920)} = 5919.77 \pm 0.08 \pm 0.02 \pm 0.66 \text{ MeV}/c^2$$

Error on knowledge of $\Lambda_b$ mass

$$\Gamma_{\Lambda_b^{*0}(5912)} < 0.66 \text{ MeV} \qquad \Gamma_{\Lambda_b^{*0}(5920)} < 0.63 \text{ MeV}$$ @90 CL

- The observation of the state $\Lambda_b^*(5920)$ confirmed also by CDF [PRD 88, 071101 (2014)]

# Conclusions

- The measurements of b-flavored hadron lifetimes have been improved significantly in the last few years
- $B^0$, $B^-$ and $B_s$ lifetimes are well known now. Several b-baryon lifetimes are also know
- HQE prediction of lifetime ratios has been found to be consistent with data

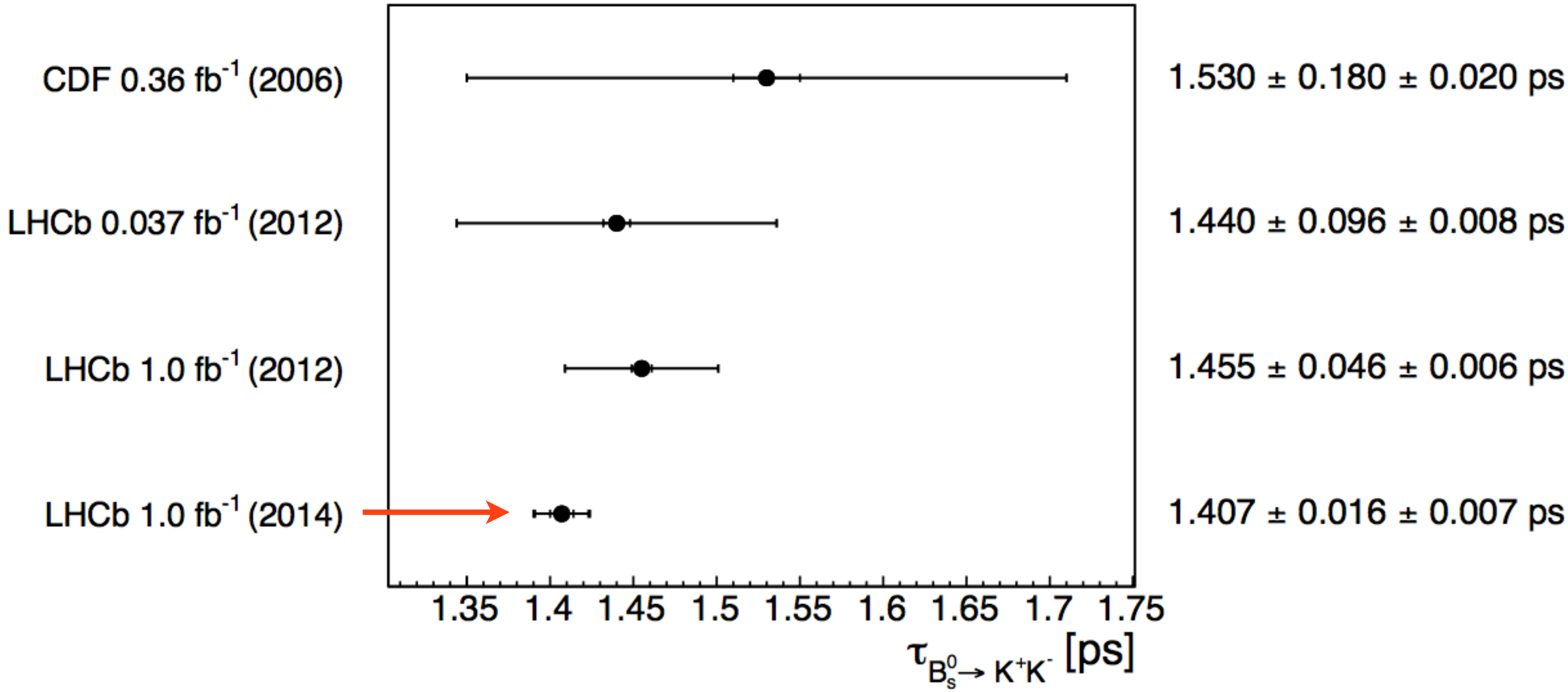
| | HQE | LHCb | |
|---|---|---|---|
| $\Lambda_b^0$ | $1.41 \pm 0.08$ ps | $1.479 \pm 0.009 \pm 0.010$ ps | [PLB, 734 (2014) 122] |
| $\Xi_b^-$ | $1.56 \pm 0.10$ ps | $1.55^{+0.10}_{-0.09} \pm 0.03$ ps | [arXiv:1405.1543] |
| $\bar{B}_s^0$ | $1.521 \pm 0.008$ ps | $1.535 \pm 0.015 \pm 0.012 \pm 0.007(\tau_{B^-})$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

- First observations of excited states of b-hadrons $B_{s1}$, $B_{s2}^*$, $\Lambda_b^*$ have been made, and the respective masses and decay widths measured

# Backup

# Lifetime with $B_s \to KK$ (3)

- Evolution of the effective $B_s \to KK$ lifetime measurements



# Constraints on $\Phi_s$ and $\Delta\Gamma_s$

- Constraints on the mixing phase between the $B_s$ and $\overline{B}_s$ ($\Phi_s$) and decay width difference ($\Delta\Gamma_s$) using 3 recent measurements from LHCb

Plot done using formalism in EPJ C71, 1789 (2011)