UNIVERSITY OF LIVERPOOL

Mass and Lifetime Measurements of Heavy Flavour Hadrons

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On behalf of the LHCb Collaboration

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Phenomenology Symposium

-

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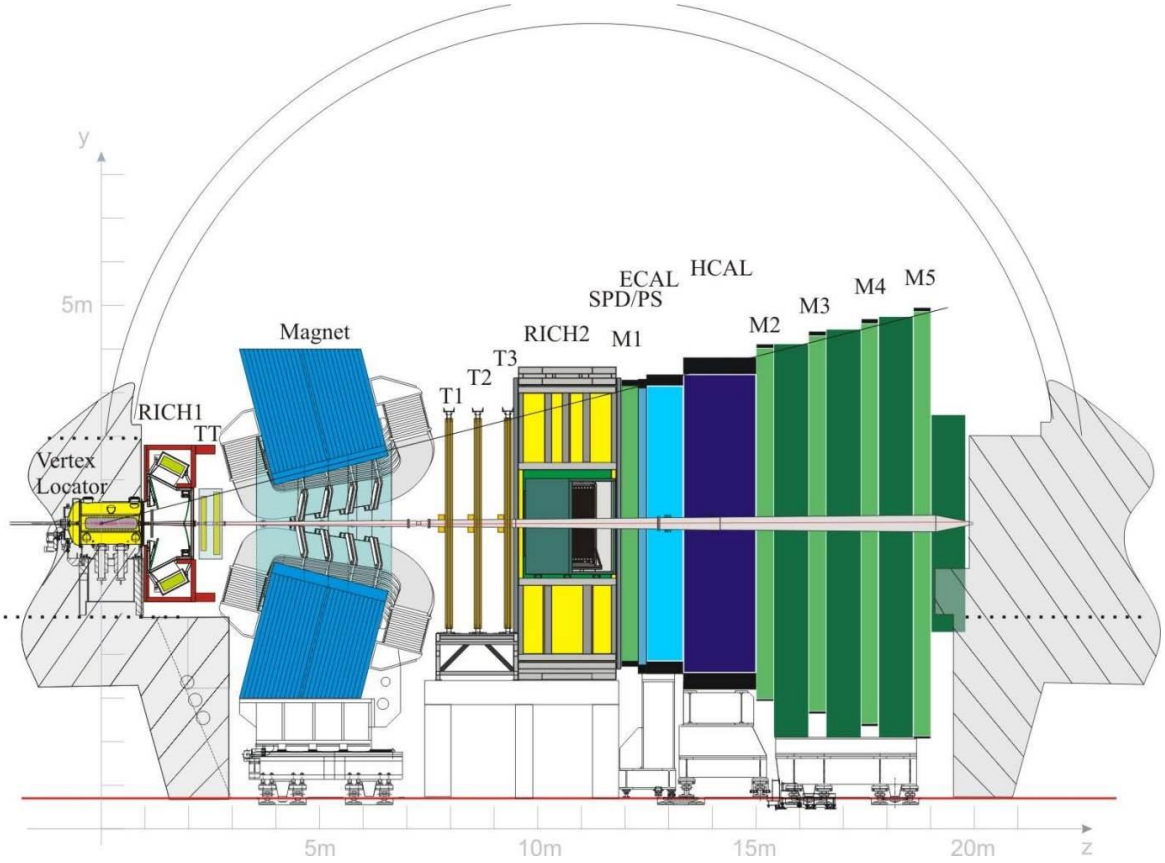
The LHCb Detector

- **VELO:** separation of displaced decay vertices, characteristic of b/c decays
- **RICH1/2:** K/π identification, crucial for fully hadronic final states
- **Muon detectors:** crucial for muon/dimuon final states

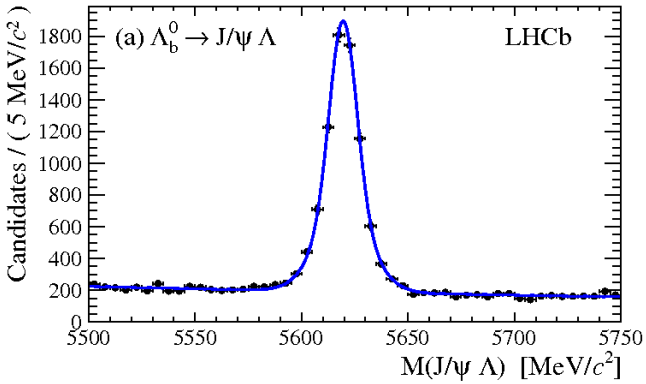


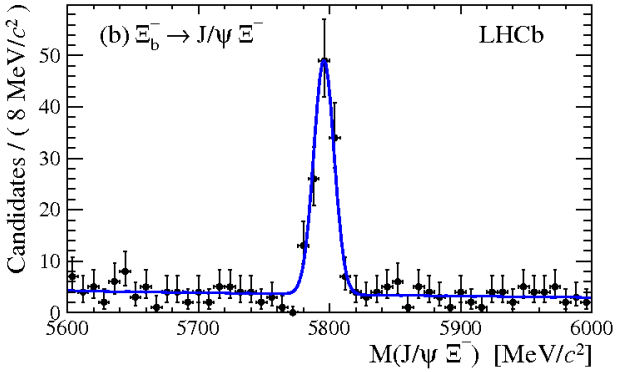
Mass Measurements

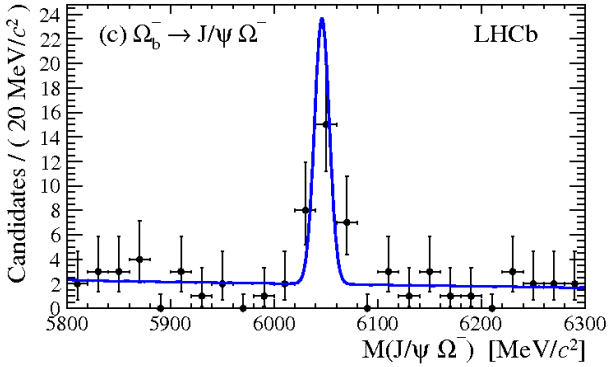
b Baryons ($1fb^{-1}$)

- **Important to measure b-baryon masses precisely as test of variety of QCD models**

- **Via decays to a J/Ψ and a hyperon**
  - $\Lambda_b^0 \rightarrow J/\Psi\Lambda$
  - $\Xi_b^- \rightarrow J/\Psi\Xi^-$
  - $\Omega_b^- \rightarrow J/\Psi\Omega^-$







$$M(\Lambda_b^0) = 5619.53 \pm 0.13 \pm 0.45\ MeV/c^2$$

$$M(\Xi_b^-) = 5795.8 \pm 0.9 \pm 0.4\ MeV/c^2$$

$$M(\Omega_b^-) = 6046.0 \pm 2.2 \pm 0.5\ MeV/c^2$$

PRL 110, 182001 (2013)

ATLAS: arXiv:1207.2284 (2012)
D0: PRL 101,232002 (2008)
D0: PRL 99,052001 (2007)
CDF: PRD 80.072003 (2009)
CDF: PRL 96,202001 (2006)
PDG: PRD 86,010001 (2012)

	$M(\Lambda_b^0)$	$M(\Xi_b^-)$	$M(\Omega_b^-)$
ATLAS	5619.7 ± 1.3	...	...
CDF	5619.7 ± 1.7	5790.9 ± 2.7	6054.4 ± 6.9
D0	...	5774 ± 19	6165 ± 16
PDG	5619.4 ± 0.7	5791.1 ± 2.2	6071 ± 40
LHCb	5619.5 ± 0.5	5795.8 ± 1.0	6046.0 ± 2.3

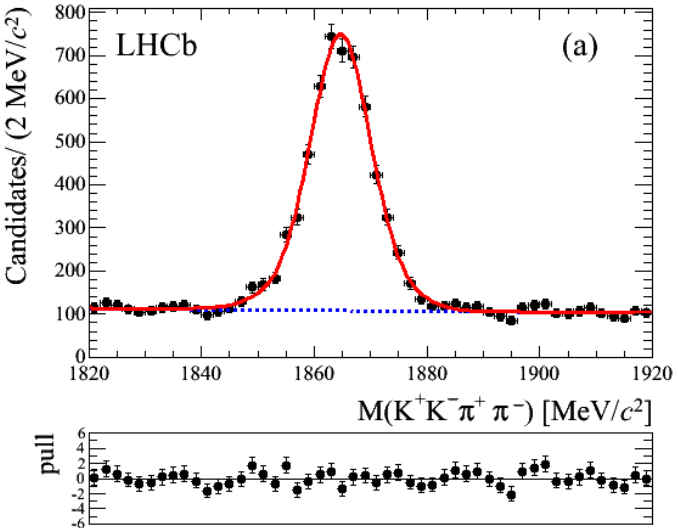
J/Ψ / hyperon channels only

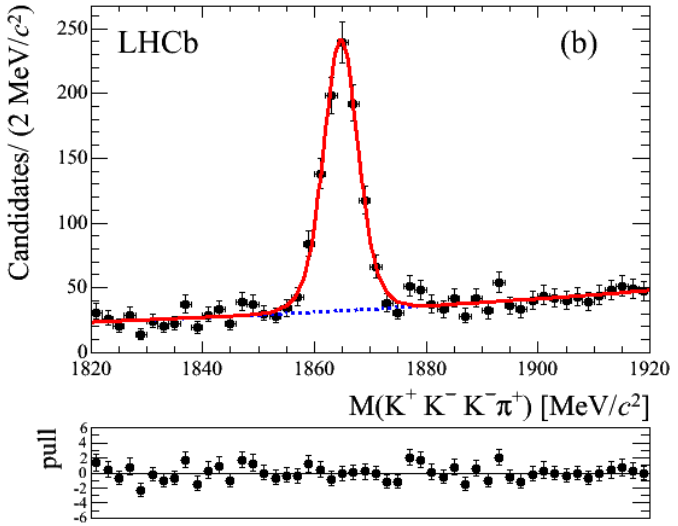
- **LHCb results most precise, in agreement with all previous measurements except for D0 Ω_b^- result**
- **See also mass and lifetime of Ξ_b^0 from $\Xi_b^0 \to \Xi_c^+ \pi^-$ covered in talk by J. McCarthy**

D Mesons ($1fb^{-1}$)

- **Important to know precisely:**
  - **Dominant systematic in measuring $B_c^0 \to J/\psi D_s^+$ mass**
  - **Help determine nature of X(3872) state**
- **Reconstruct D^0 candidates through**
  - ***a) $D^0 \to K^+ K^- \pi^+ \pi^-$***
  - ***b) $D^0 \to K^+ K^- K^- \pi^+$***

  (chosen as low energy release states)
- **Reconstruct $D_{(s)}^+$ candidates through**
  - ***$D_{(s)}^+ \to K^+ K^- \pi^+$***



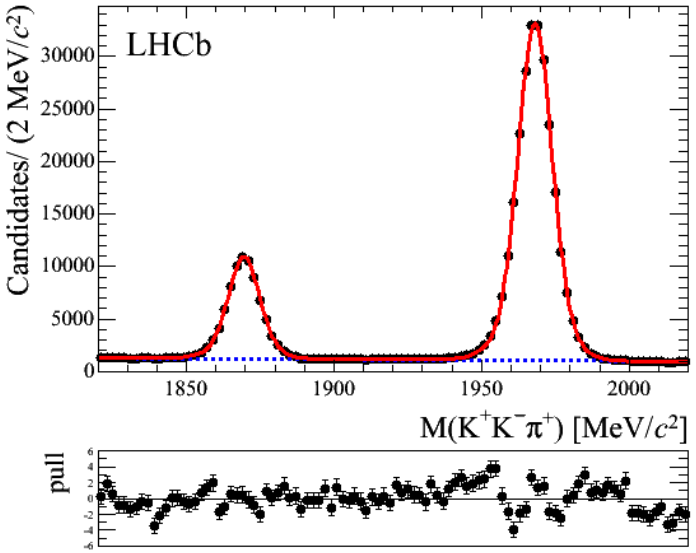


JHEP06(2013)065

$$M(D^0) = 1864.75 \pm 0.15 \pm 0.11\ MeV/c^2$$

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

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



Quantity	LHCb measurement	Best previous measurement	PDG fit
$M(D^0)$	1864.75 ± 0.19	1864.85 ± 0.18	1864.86 ± 0.13
$M(D^+) - M(D^0)$	4.76 ± 0.14	4.7 ± 0.3	4.76 ± 0.10
$M(D_s^+) - M(D^+)$	98.68 ± 0.05	98.4 ± 0.3	98.88 ± 0.25

CLEO: PRL 98,092002 (2007)
KEDR: PLB 686,84 (2010)
BABAR: PRD 65,091104 (2002)
PDG: PRD 86,010001 (2012)

- **Reinforces conclusion that if X(3872) is $D^{*0}\overline{D}^0$ 'molecule', it is very loosely bound**

Lifetime Measurements

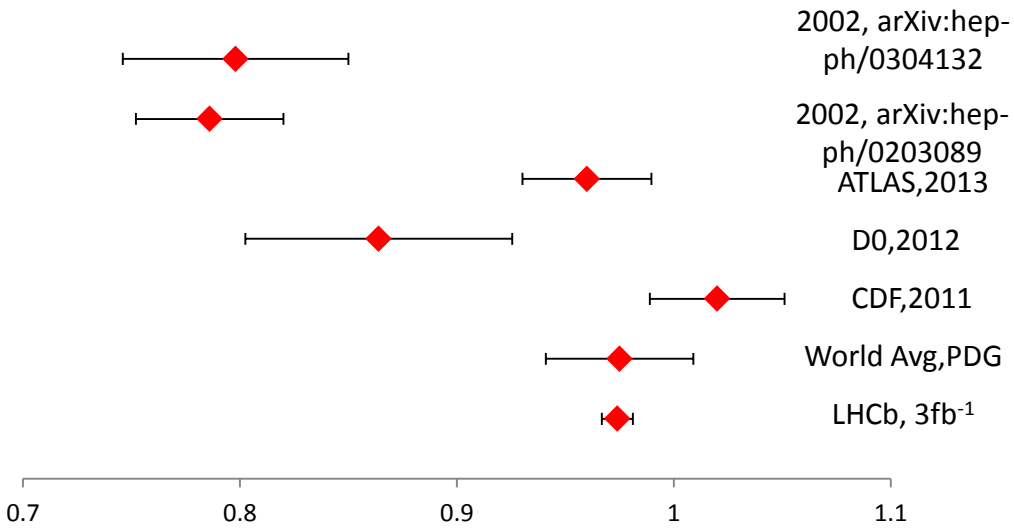
$\Lambda_b^0 \to J/\psi p K^-$ ($3fb^{-1}$)

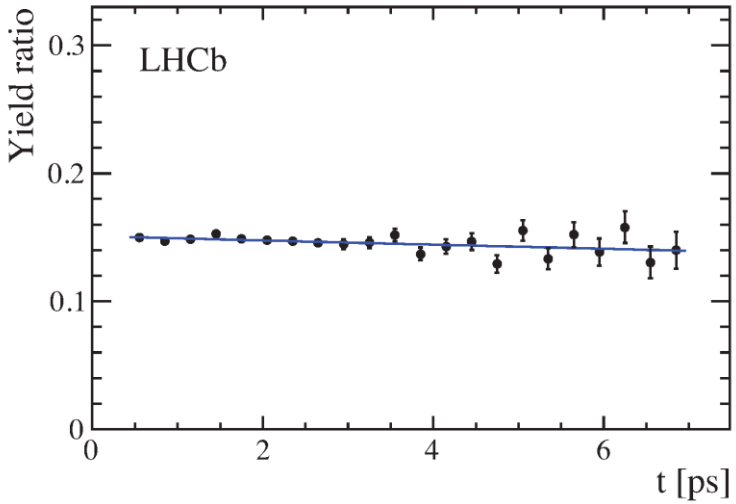
- Ratio of Λ_b^0 to B^0 lifetimes measured using $\Lambda_b^0 \to J/\psi p K^-$ and $B^0 \to J/\psi K^{*0}$ decays
- Heavy Quark Expansion Theory (HQE) predicts lifetimes differing by only a few percent
- Some discrepancy in past measurements

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

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

- Most precise to date, consistent with original predictions from HQE





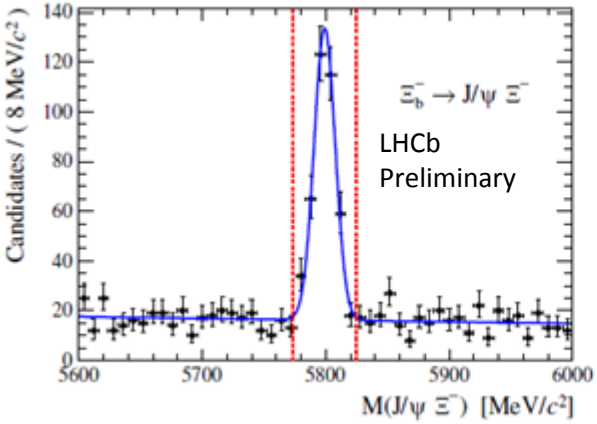
(arXiv:1402.6242, submitted to PLB)

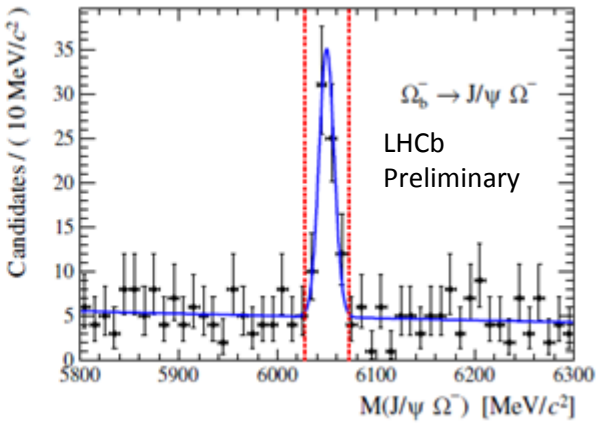
$\Xi_b^-, \Omega_b^- (3fb^{-1})$

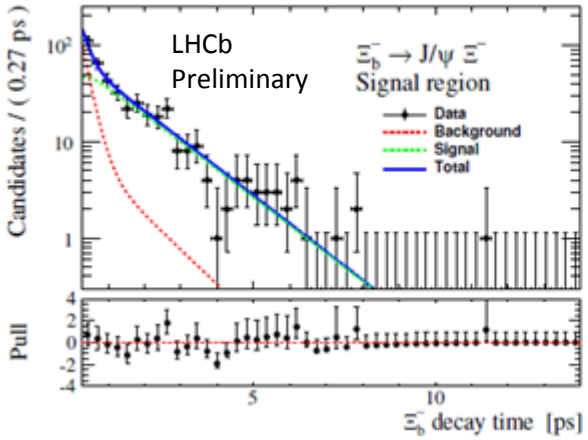
- **Few theoretical predictions for these lifetimes, range from 1.0ps - 1.7ps**

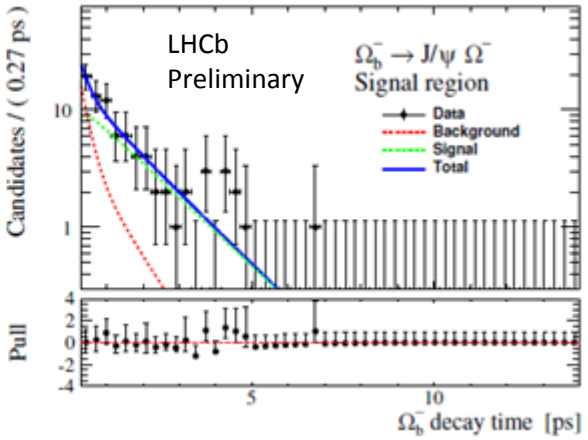
PRD 56,2783 (1997)
PTP 99,271 (1998)
arXiv:hep-ph/9508408

- **Measured in the decays:**
  - $\Xi_b^- \to J/\Psi \Xi^-$
  - $\Omega_b^- \to J/\Psi \Omega^-$









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

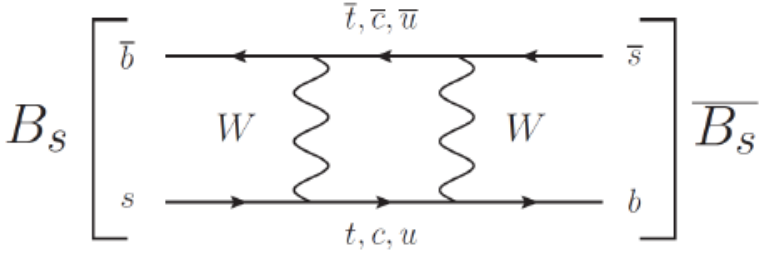
$$\tau(\Omega_b^-) = 1.54^{+0.26}_{-0.21} \pm 0.05\ ps$$

Both most precise determinations to date

LHCb-PAPER-2014-010 (in preparation)

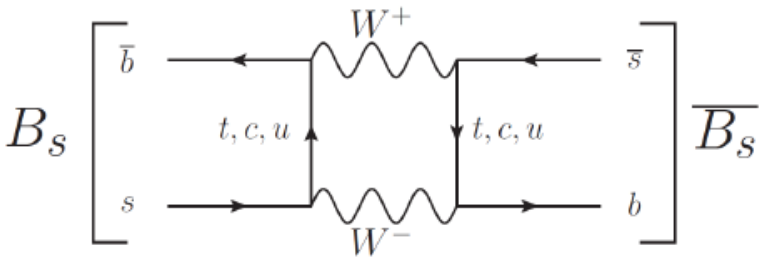
$B_{(s)}^0$ oscillations

- $B_{(s)}^0$ oscillates continuously between particle anti-particle



- Mass and CP eigenstates are linear combinations of the two states:

$$|B_{H,L}\rangle = p|B_s^0\rangle \mp q|\bar{B}_s^0\rangle$$



- Decay as some mixture of particle and anti-particle, so actually measure effective lifetimes to specific final states

$\Gamma_{s/d}$: average decay width of eigenstates

$\Gamma_{s/d}$: difference in decay widths

$\Gamma_{H/L}$: decay width of heavy/light eigenstate

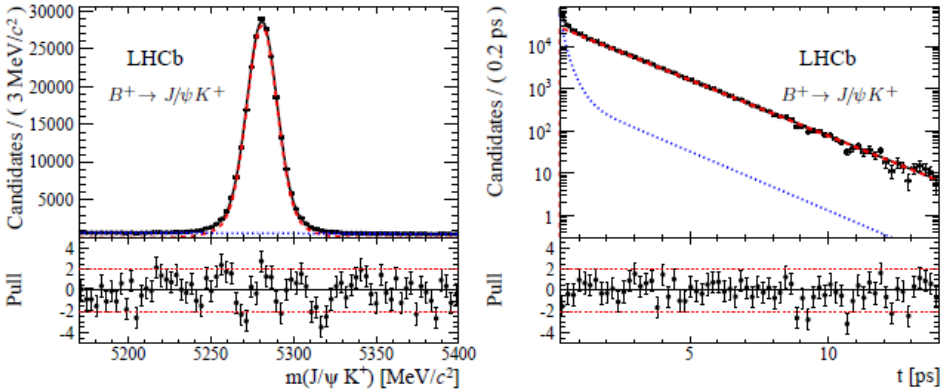
$\varphi_{s/d}$: CP violating phase, interference between direct decay and oscillation then decay

$B^+, B^0, B_s{}^0, \Lambda_b{}^0$ ($1fb^{-1}$)

- Data, signal and background shown in each plot (mass on left, decay time on right)
- Lifetime ratios used as test of Heavy Quark Expansion (HQE)

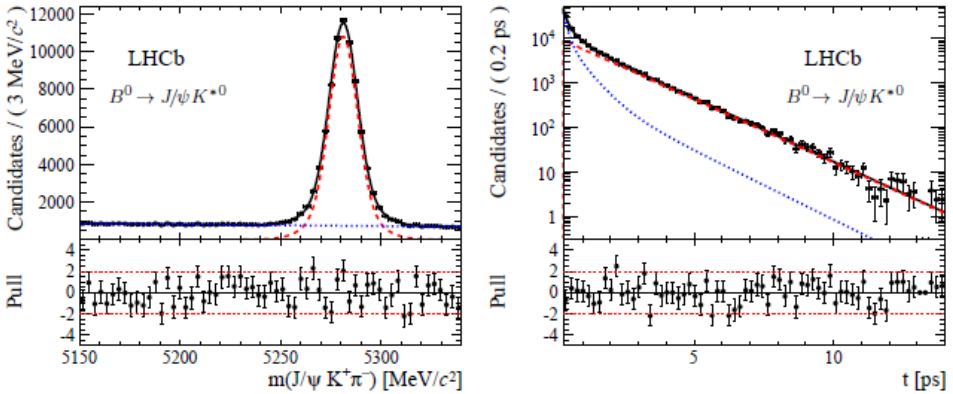
$B^+ \rightarrow J/\psi K^+$

$\tau = 1.637 \pm 0.004 \pm 0.003\ ps$



$B^0 \rightarrow J/\psi K^{*0}$

$\tau_{eff} = 1.524 \pm 0.006 \pm 0.004\ ps$



$B^0 \rightarrow J/\psi K_s{}^0$

$\tau_{eff} = 1.499 \pm 0.013 \pm 0.005\, ps$

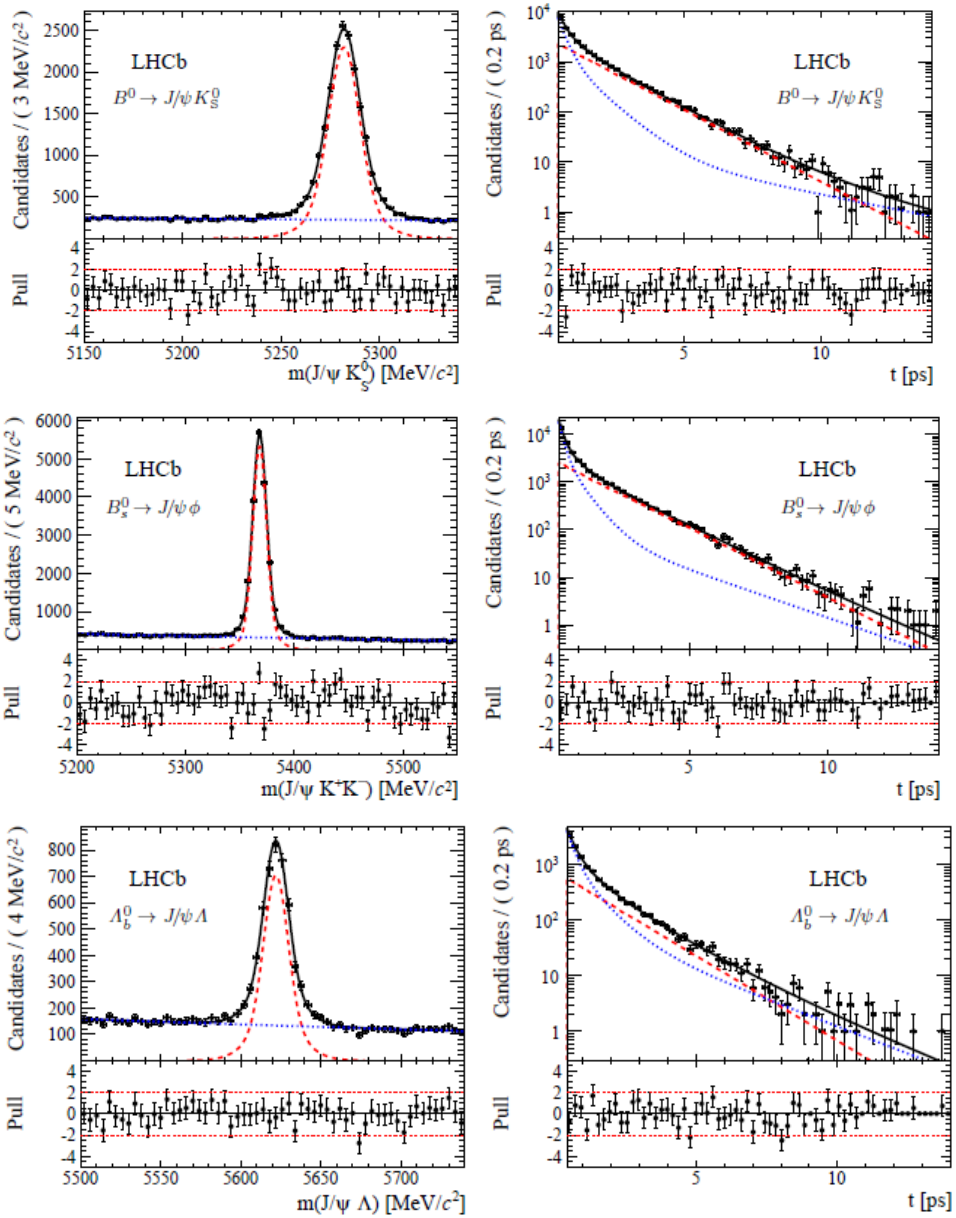
$B_s{}^0 \rightarrow J/\psi\phi$

$\tau_{eff} = 1.480 \pm 0.011 \pm 0.005\, ps$

$\Lambda_b{}^0 \rightarrow J/\psi\Lambda$

$\tau = 1.415 \pm 0.027 \pm 0.006\, ps$

(*arXiv:1402.2554, submitted to JHEP*)



Observable	Prediction	World average
τ_{B^+} [ps]	–	1.641 ± 0.008
τ_{B^0} [ps]	–	1.519 ± 0.007
$\tau_{B_s^0}$ [ps]	–	1.516 ± 0.011
$\tau_{\Lambda_b^0}$ [ps]	–	1.429 ± 0.024
τ_{B^+}/τ_{B^0}	1.063 ± 0.027	1.079 ± 0.007
$\tau_{B_s^0}/\tau_{B^0}$	1.00 ± 0.01	0.998 ± 0.009
$\tau_{\Lambda_b^0}/\tau_{B^0}$	0.86–0.95	0.941 ± 0.016

Many references, included in backup

Ratio	Value
$\tau_{B^+}/\tau_{B^0 \to J/\psi K^{*0}}$	$1.074 \pm 0.005 \pm 0.003$
$\tau_{B_s^0}/\tau_{B^0 \to J/\psi K^{*0}}$	$0.971 \pm 0.009 \pm 0.004$
$\tau_{\Lambda_b^0}/\tau_{B^0 \to J/\psi K^{*0}}$	$0.929 \pm 0.018 \pm 0.004$

- **Most precise measurements in these channels, consistent with previous measurements**
- **Ratios consistent with HQE predictions**

- $B^0 \to J/\psi K^{*0}$ and $B^0 \to J/\psi K_S{}^0$ also used to calculate values for Γ_d and $\Delta\Gamma_d$

$$\Gamma_d = 0.656 \pm 0.003 \pm 0.002\ ps$$

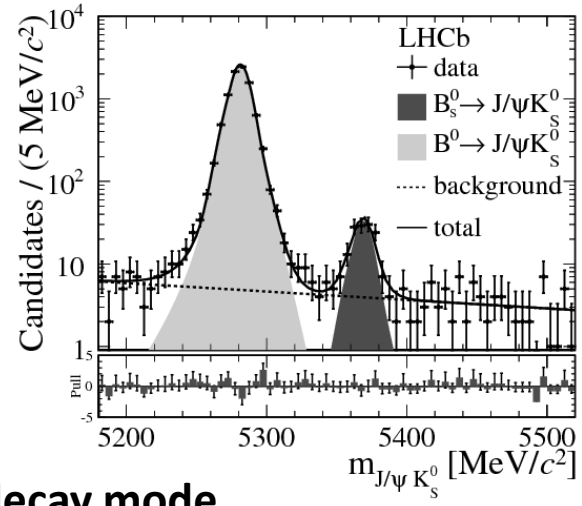
$$\Delta\Gamma_d = -0.029 \pm 0.016 \pm 0.007\ ps$$

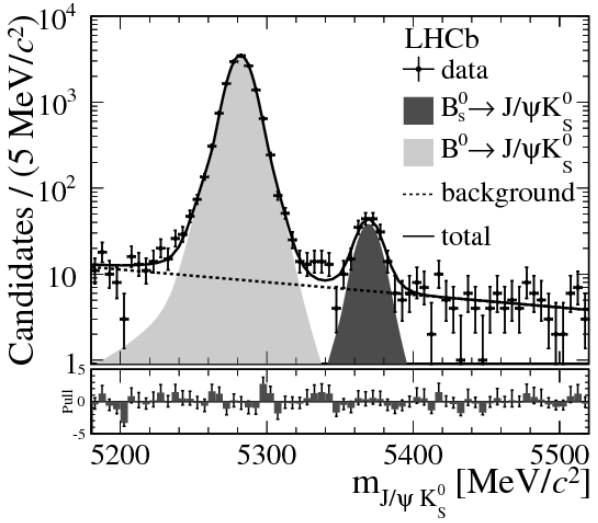
$$\frac{\Delta\Gamma_d}{\Gamma_d} = -0.044 \pm 0.025 \pm 0.011$$

SM Prediction: $\frac{\Delta\Gamma_d}{\Gamma_d} = -0.0042 \pm 0.0008$ A.Lenz, U.Nierste arXiv:1102.4274

- Consistent with SM prediction

$B_s^0 \rightarrow J/\psi K_s^0$ ($1fb^{-1}$)





- **CP Odd decay mode**
- **Sample split into K_s^0 candidates with (left) and without (right) hits in the VELO for analysis**
- **Lifetimes combined in weighted average**

$$\tau_{eff} = 1.75 \pm 0.12 \pm 0.07\ ps$$

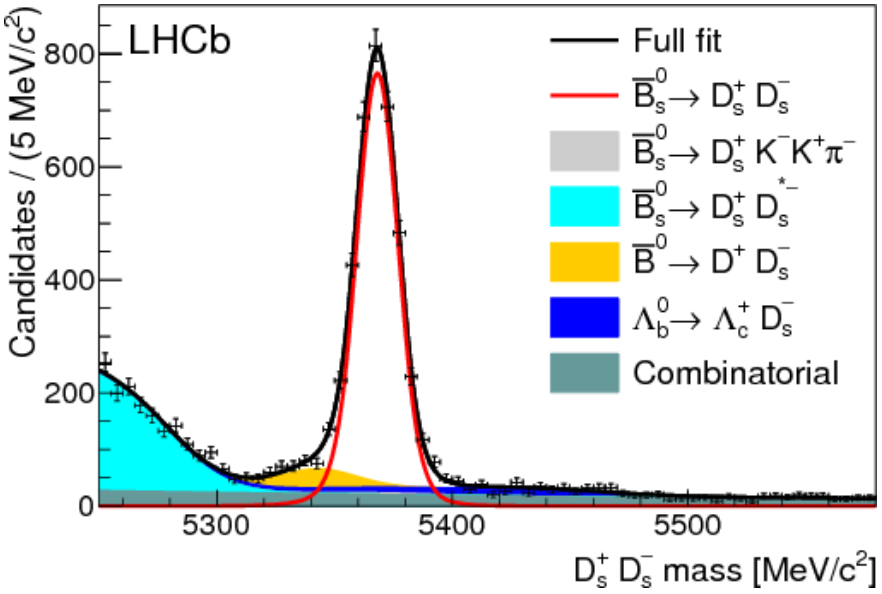
SM: $\tau_{eff} = 1.639 \pm 0.022\ ps$

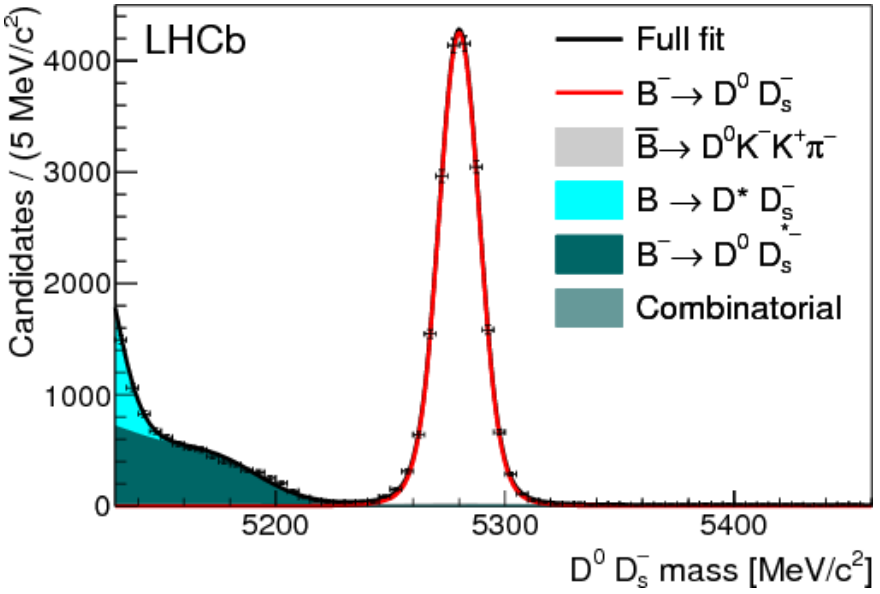
R. Fleischer, Penguin effects in $\phi_{d,s}$ determinations, arXiv:1212.2792.

- **First measurement, consistent with SM expectation**

***Nucl. Phys. B* 873 (2013) 275-292**

$B_s^0 \to D_s^+ D_s^-$ ($3fb^{-1}$)





PRL 112, 111802 (2014)

- **CP Even decay, lifetime translates as measurement of Γ_L if $\phi_s \approx 0$**
- **Measuring τ_{eff} in CP specific final states probes ($\Delta\Gamma_S$, ϕ_s) parameter space; complementary to direct measurements**
- **Normalised to $B^- \to D^0 D_s^-$; similar final state topology/kinematics, precisely measured lifetime**

- $D_s \rightarrow K^+K^-\pi^\pm / K^\pm\pi^-\pi^+ / \pi^+\pi^-\pi^\pm$

- **Measure lifetime ratio (bottom) after correcting for relative efficiencies (top)**

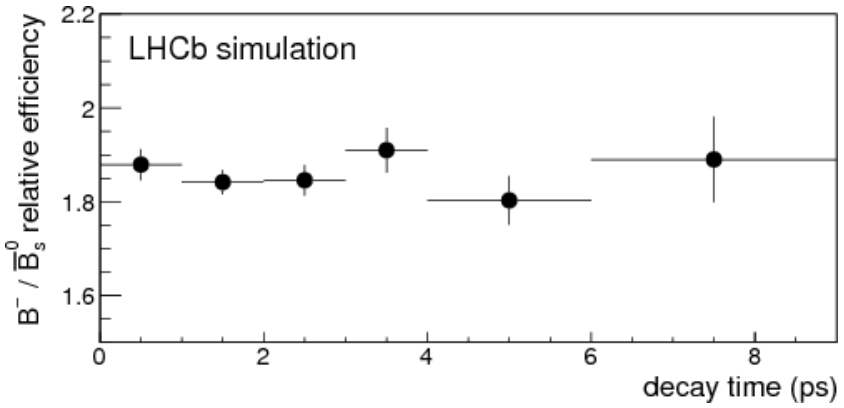
$$\frac{\Gamma_{\bar{B}_s^0 \to D_s^- D_s^+}(t) + \Gamma_{B_s^0 \to D_s^+ D_s^-}(t)}{\Gamma_{B^- \to D^0 D_s^-}(t) + \Gamma_{B^+ \to \bar{D}^0 D_s^+}(t)} \propto e^{-\alpha_{su} t}$$

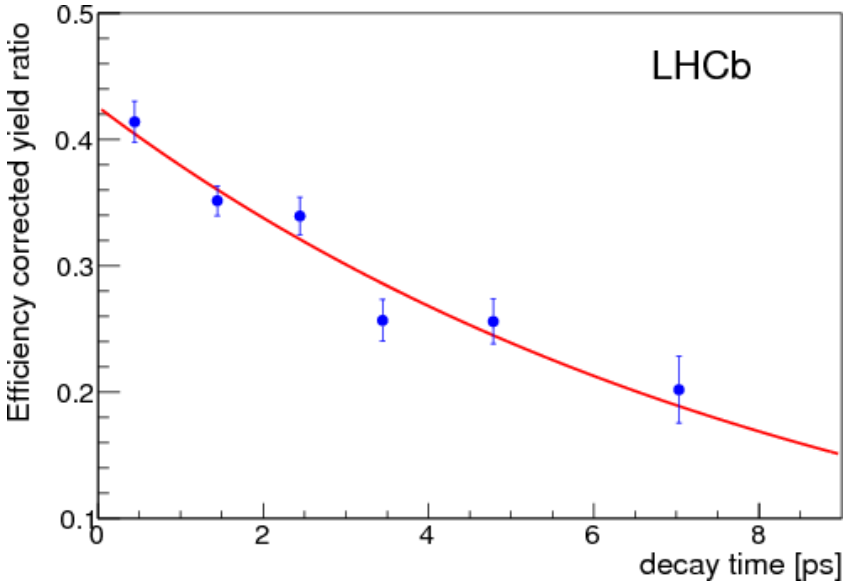
$$\alpha_{su} = 1/\tau^{\text{eff}}_{\bar{B}_s^0 \to D_s^- D_s^+} - 1/\tau_{B^-}$$

- **Measuring α_{su} determines lifetime**

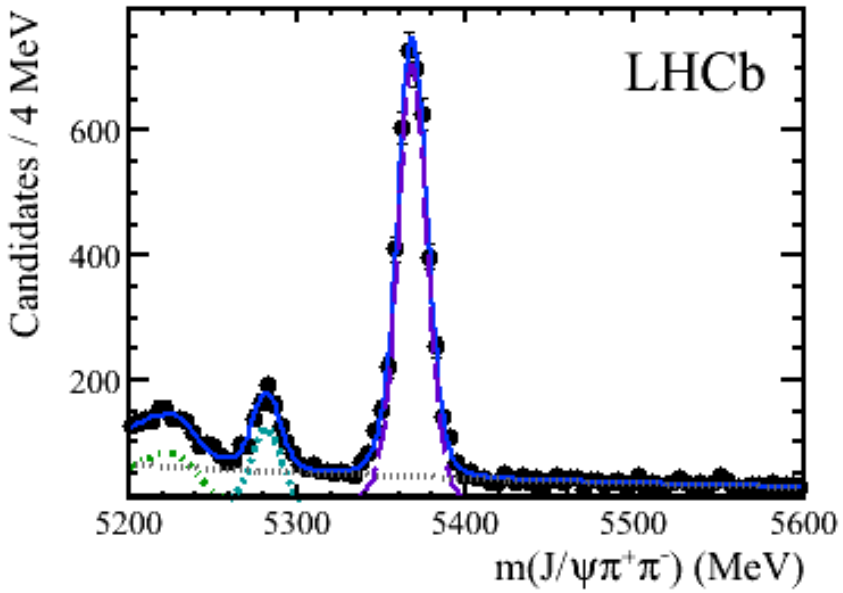
$$\tau_{eff} = 1.379 \pm 0.026 \pm 0.017\ ps$$

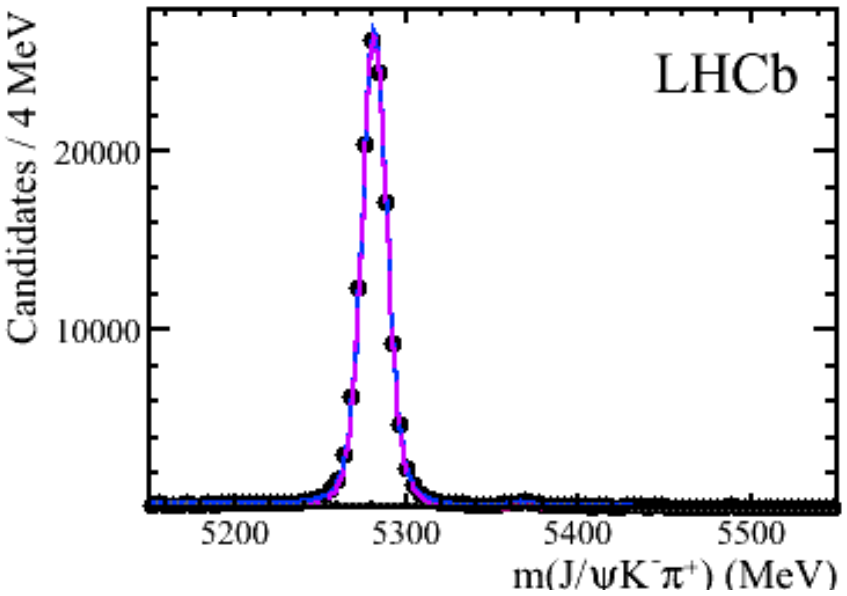
$$\Gamma_L = 0.725 \pm 0.014 \pm 0.009\ ps^{-1}$$





$B_s^0 \to J/\psi f_0(980)$ ($1fb^{-1}$)

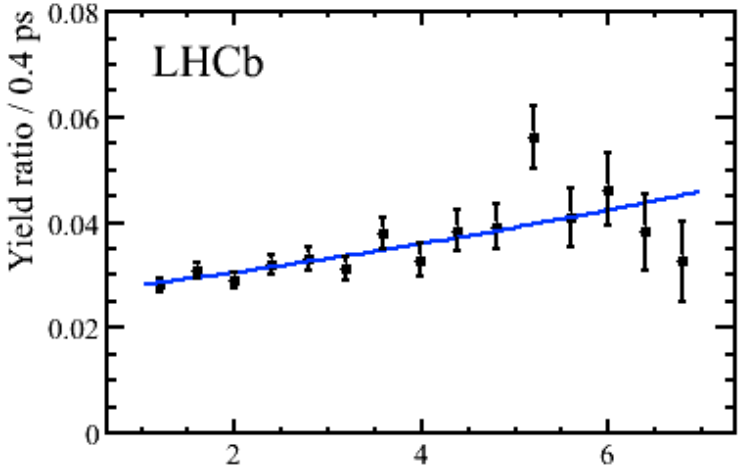




- **CP Odd decay channel**
- **Measure τ ratio to $B_s^0 \to J/\psi K^{*0}(K^-\pi^+)$**

$$\tau_{eff} = 1.700 \pm 0.040 \pm 0.026\ ps$$

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



PRL 109, 152002 (2012)

Results

$B_s^0 \to D_s^+ D_s^-$ (3fb^{-1})

$\tau_{eff} = 1.379 \pm 0.026 \pm 0.017\ ps$

$\Gamma_L = 0.725 \pm 0.014 \pm 0.009\ ps^{-1}$

$B_s^0 \to K^+K^-$ (1fb^{-1})

$\tau_{eff} = 1.407 \pm 0.016 \pm 0.007\ ps$

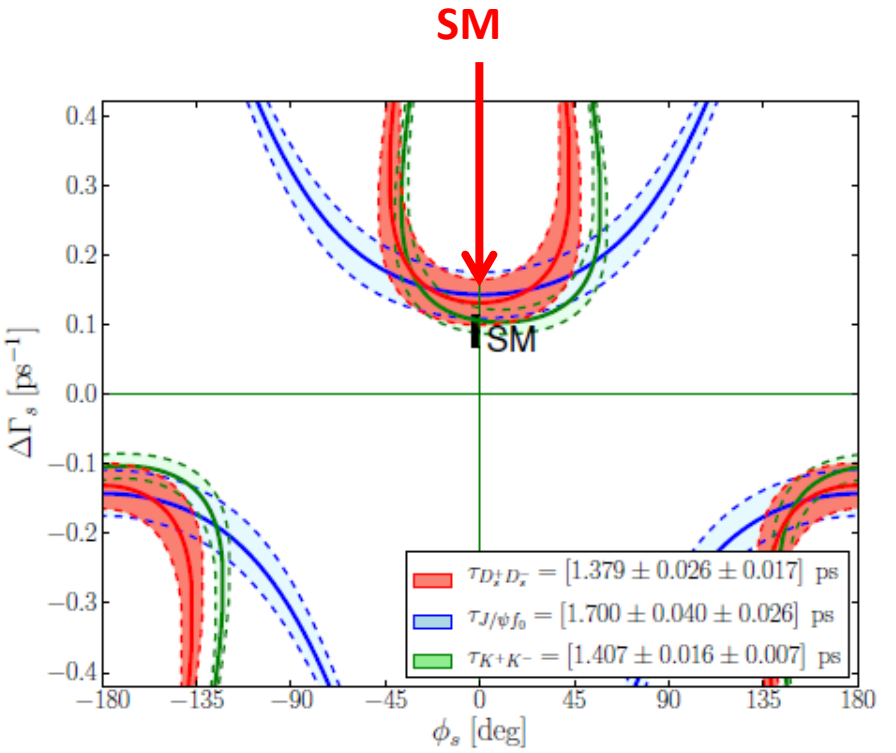
$\Gamma_L = 0.711 \pm 0.008 \pm 0.004\ ps^{-1}$

(interesting as loop dominated – see talk by J. Prisciandaro for further details)

$B_s^0 \to J/\psi f_0(980)$ (1fb^{-1})

$\tau_{eff} = 1.700 \pm 0.040 \pm 0.026\ ps$

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



Produced using method described by R. Fleischer, R. Knegjens in **Eur. Phys. J. C71 (2011) 1789**

- **CP Even lifetimes are consistent**
- **All measurements consistent with SM predictions**

Conclusions

- **LHCb has made many world-leading mass and lifetime measurements of heavy flavoured hadrons**

- ***Achieved many goals already:***
  - **Resolved long standing discrepancy in Λ_b^0 lifetime**
  - **Resolved previous discrepancy in Ω_b^- mass**
  - **Closely scrutinised HQE theory and predictions**
  - **Measured $\Delta\Gamma_s$, φ_s in a way complementary to direct methods**

- ***More to come:***
  - **More heavy baryons to be studied**
  - **Greater precision with more luminosity, even closer examination of theory**

- **Thanks for listening!**

$B^+, B^0, B_s{}^0, \Lambda_b{}^0$ References

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