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Lifetimes of B^0, B_s and Λ_b

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on behalf of the LHCb collaboration

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Outline

- $B_s^0 \to D_s^- \pi^+$ — LHCb-PAPER-2014-037, To be submitted for publication — New!
- $B_s^0 \to D_s^- D_s^+$ — PRL 112, 111802 (2014)
- $B_s^0 \to K^+ K^-$ — arXiv:1406.7204, Submitted to journal — New!
- $B_s^0 \to J/\Psi f_0$ — PRL 109, 152002 (2012)
- $B_{(s)} \to J/\Psi X$ — JHEP04(2014)114
- $\Lambda_b \to J/\Psi p K^-$ — PLB, 734, (2014) 122
- Comparison of results: Γ_s - $\Delta\Gamma_s$ plane — New!

Topics NOT covered by this talk:

Semileptonic $B_c \to J/\psi \mu \nu (X)$: **Katharina Kreplin** (next talk)

Other beauty baryon lifetimes: **Steve Blusk** talk on Thursday!

Introduction

- Lifetimes are fundamental properties of particles
- Decays are essentially exponential:
  - But mixing can occur in neutral mesons
  - CP violation can occur
- Decay shape can be modified (not a pure exponential)

- Heavy Quark Expansion (HQE) predicts b-hadron lifetimes
- τ is expressed as an expansion in terms of mass(heavy quark)
- HQE can also be used to extract values of $|V_{ub}|$ & $|V_{cb}|$
- See the inspiring review by **A. Lenz: arXiv:1405.3601v1**

$$\frac{\tau(B^+)}{\tau(B_d)}^{\mathrm{HQE\,2014}} = 1.04^{+0.07}_{-0.03} ,$$

$$\frac{\tau(B_s)}{\tau(B_d)}^{\mathrm{HQE\,2014}} = 1.001 \pm 0.002 ,$$

$$\frac{\tau(\Lambda_b)}{\tau(B_d)}^{\mathrm{HQE\,2014}} = 0.935 \pm 0.054 ,$$

Effective Lifetime (1)

- **For charged B mesons** → decay is purely exponential
- **For neutral B mesons** → can oscillate + can have CP violation

in case of mixing and CP violation, equations become:

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

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

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

Extra term dependent on t
Shape is not purely exponential

CPV $A_{\Delta\Gamma} \equiv -2\left(1+\left|\lambda_f\right|^2\right)\mathrm{Re}\left(\lambda_f\right)$

$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

Effective Lifetime (2)

- **For B^0 mesons**: $\Delta\Gamma_d << \Gamma_d$
  simple exponential is a good approximation

- **For B_s^0 mesons**:
  $\Delta\Gamma_s$ is not small and $A_{\Delta\Gamma}$ depends on the mode considered

- **If $B_s^0 \rightarrow$ flavour specific**:
  decay is the exact sum of two exponential

$$\Gamma_s = \Gamma_{flavor\ specific}\left(1-\left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2\right) \Big/ \left(1+\left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2\right)$$

Result of a single exponential fit

Methods

We performed lifetime measurements with two different approaches

Relative measurement

- The lifetime is measured relative to a control mode with well known lifetime
- Signal mode and control mode have similar topology
- PROs: measure ratios → systematic uncertainties cancel
- CONSs: irreducible systematic uncertainty from input lifetime

Absolute measurement

- Fit decay distributions with exponentials convolved with resolution functions
- PROs: absolute measurement → no input needed
- CONSs: need to understand acceptance functions
- Data driven methods required to obtain desired precision

LHCb-PAPER-2014-037
To be submitted

$B_s \to D_s^- \pi^+$ Lifetime

New!

- Idea: measure signal yield in lifetime bins
- Signal decay distribution: Acceptance and convolution with resolution
- Measure the ratio of decay time distributions:

$$R(t) = \frac{F_{B_s}}{F_{B_x}} = \frac{A_{B_s}(t) \times [e^{-t/\tau_{B_s}} \otimes G(t, \sigma_{B_s})]}{A_{B_x}(t) \times [e^{-t/\tau_{B_x}} \otimes G(t, \sigma_{B_x})]}$$

- Fit the ratio ***R(t)***

$$\begin{aligned} R(t) &= R_0 e^{-t(1/\tau_{B_s} - 1/\tau_{B_x})} \\ &= R_0 e^{-t(\Gamma_{B_s} - \Gamma_{B_x})} \\ &= R_0 e^{-t\Delta_{B_s B_x}} \end{aligned}$$

Use Precise B^+, B^0 lifetimes as input

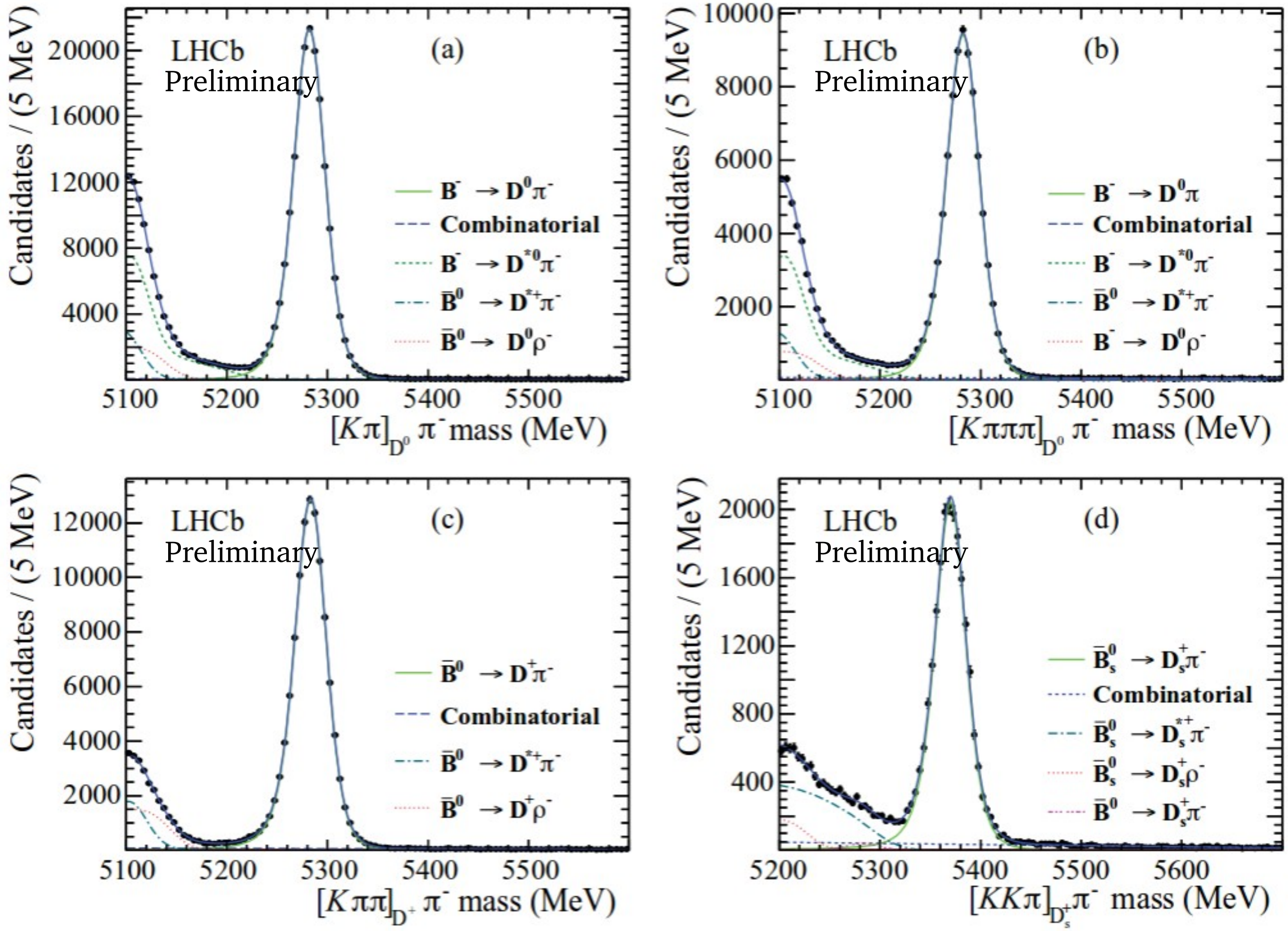
Relative lifetime between $B_s \to D_s^- \pi^+$, $D_s^- \to K^- K^+ \pi^-$ and
- $B^0 \to D^- \pi^+$, $D^- \to K^+ \pi^- \pi^-$
  (Same number of tracks, very different D lifetimes)
- $B^+ \to D^0 \pi^+$, $D^0 \to K^+ \pi^-$
  (Different number of tracks, similar D lifetimes)
- $B^+ \to D^0 \pi^+$, $D^0 \to K^+ \pi^- \pi^+ \pi^-$
  (Different number of tracks, similar D lifetimes)

LHCb-PAPER-2014-037
To be submitted

$B_s \rightarrow D_s^- \pi^+$ Lifetime

New!

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



LHCb-PAPER-2014-037
To be submitted

$B_s \to D_s^- \pi^+$ Lifetime

New!

- 2011 data set (1 fb^{-1})
- 21000 signal Bs events

$$\tau_{\rm fs}(\overline{B}^0_s)/\tau(\overline{B}^0) = 1/\left(1+\tau(\overline{B}^0)\Delta_{B^0_s B^0}\right)$$

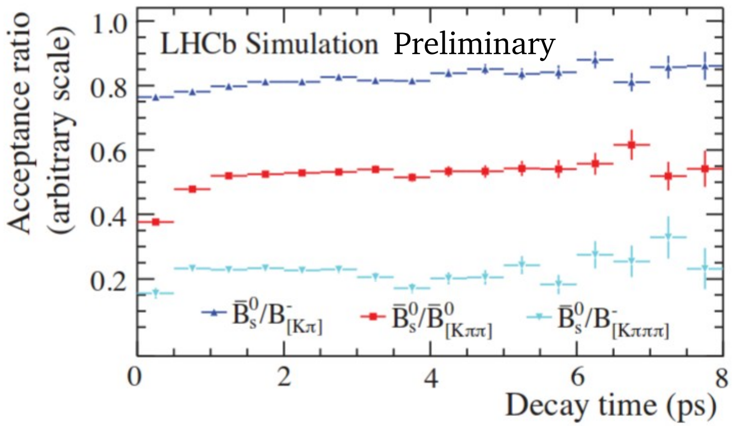
1.010 ± 0.010 ± 0.008

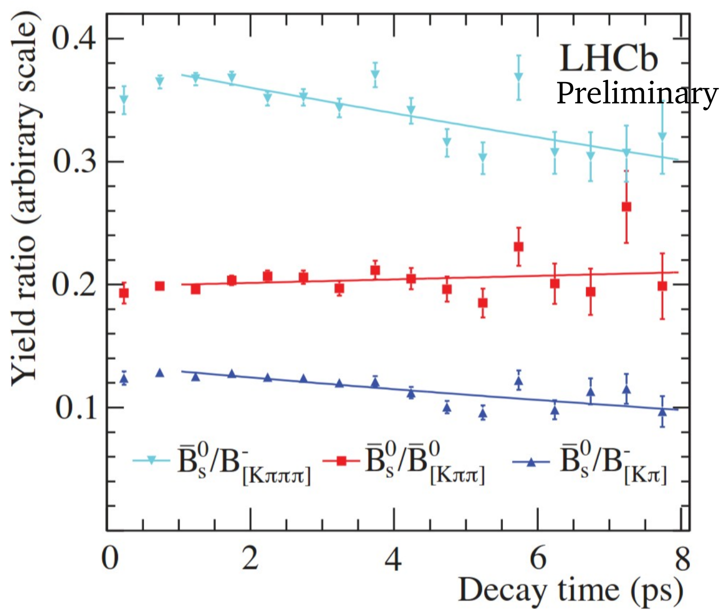
Consistent with HQE = 1.009 ± 0.004

$$\tau_{\rm fs} = 1.535 \pm 0.015 \pm 0.012 \pm 0.007\,{\rm ps}$$

Stat Sys PDG

- This is the most precise measurement to date
- Consistent with previously available flavour specific measurements

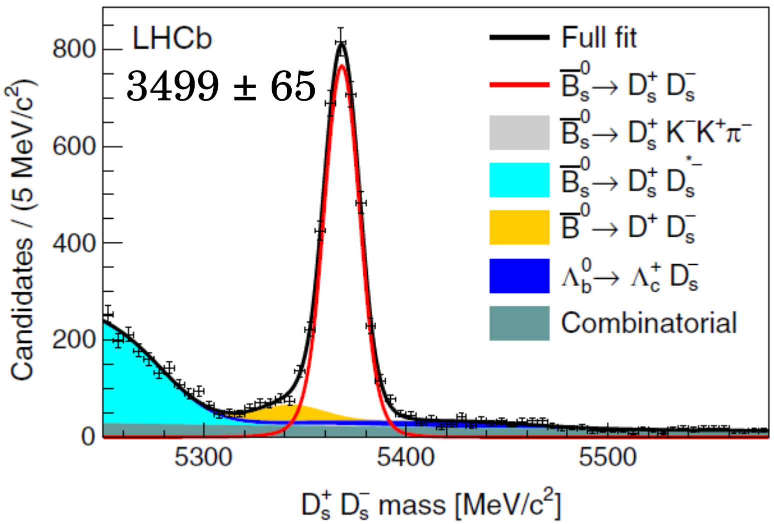


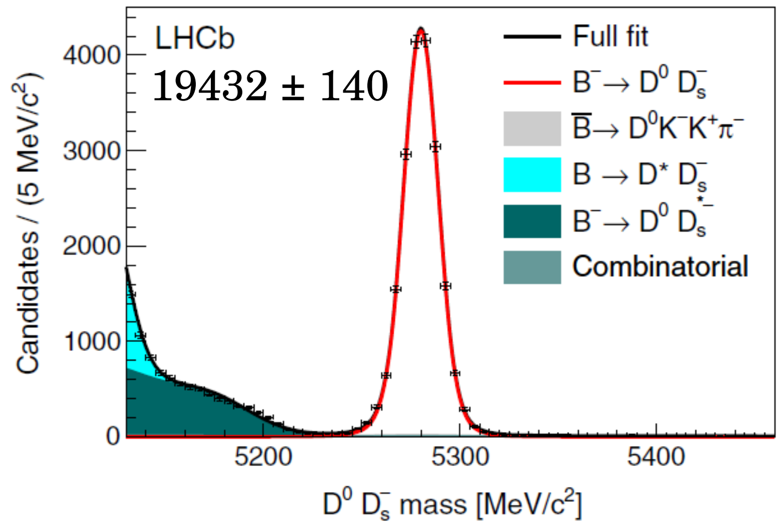


PRL 112, 111802 (2014)

$B_s^0 \to D_s^- D_s^+$

- 2011 + 2012 dataset (3 fb^{-1})
- Relative measurement wrt $B^0 \to D^0 Ds^-$
- First lifetime measurement in this final state
- Also observed $Bs \to D^- Ds^+$

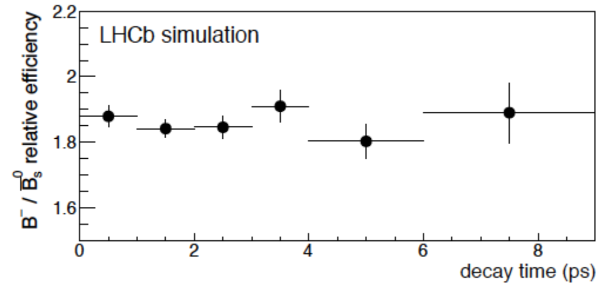




- **CP even final state**

$$1.379 \pm 0.026 \pm 0.017 \text{ ps}$$

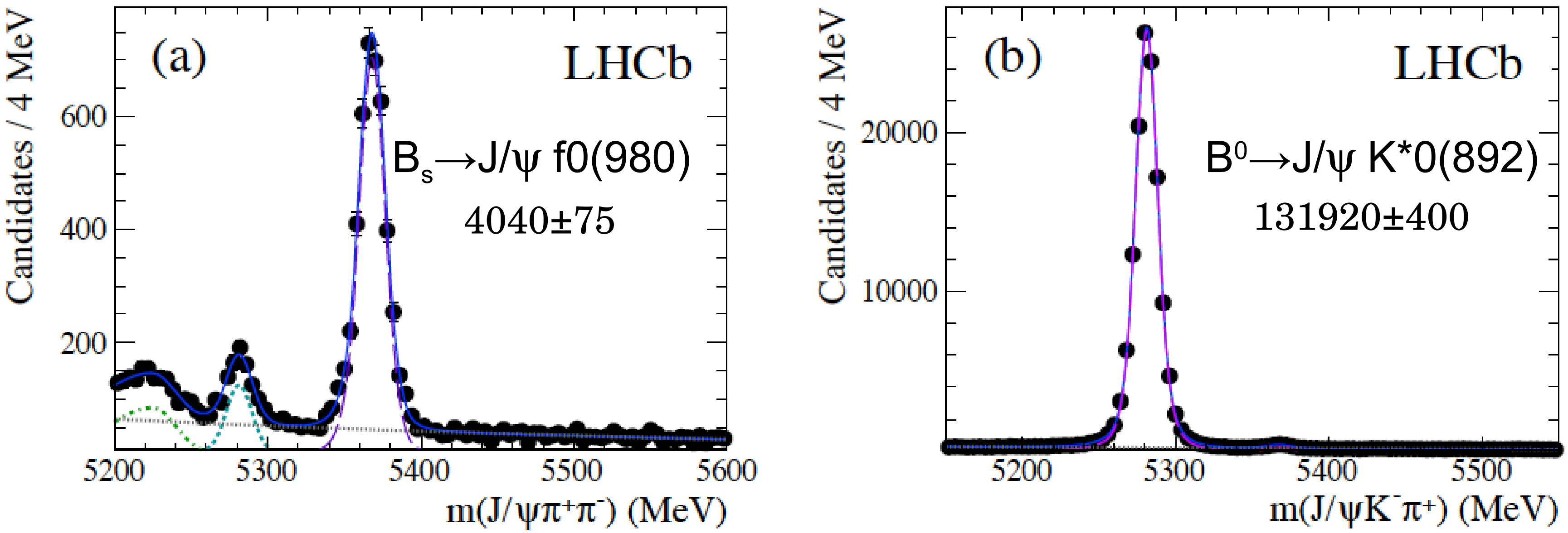
$$\Gamma_L = 0.725 \pm 0.014 \pm 0.009 \text{ ps}^{-1}$$



PRL 109, 152002 (2012)

$B_s^0 \rightarrow J/\Psi\ f_0$

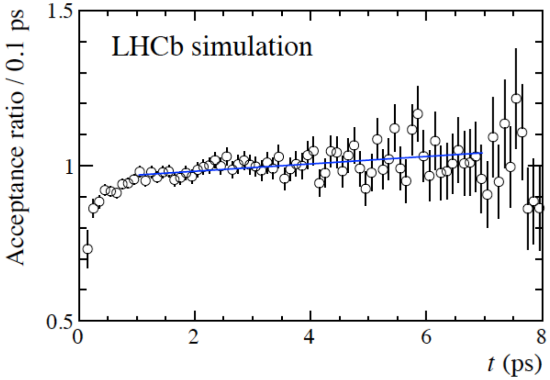
- 2011 dataset (1 fb^{-1})
- Relative measurement wrt $B^0 \rightarrow J/\psi\ K^{*0}(892)$



- Fit starts at 1ps where ratio of decay acceptances is linear
- Slope extracted from MC

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

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



arXiv:1406.7204
Submitted to PLB

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

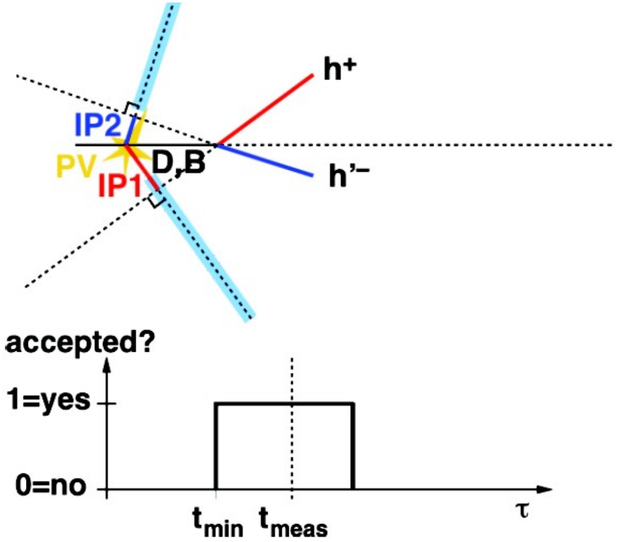
New!

- Two diagrams contributing to the same final state
- CP violation can contribute
- Lifetime formula slightly modified by extra term

$$\Gamma[f,t] \propto e^{-\Gamma t}\left[1+\frac{1}{2}\left(\frac{\Delta\Gamma}{2}t\right)^2 + A_{\Delta\Gamma}\left(\frac{\Delta\Gamma}{2}t\right)\right]$$

Expected ~ -1

- Absolute measurement
- Uses the so-called "swimming" technique
- Method pioneered by CDF
- Data driven method to get decay acceptance function
- A per-event acceptance function is determined
- Idea is to move the PV along the momentum
- vector of B and see when particle is accepted



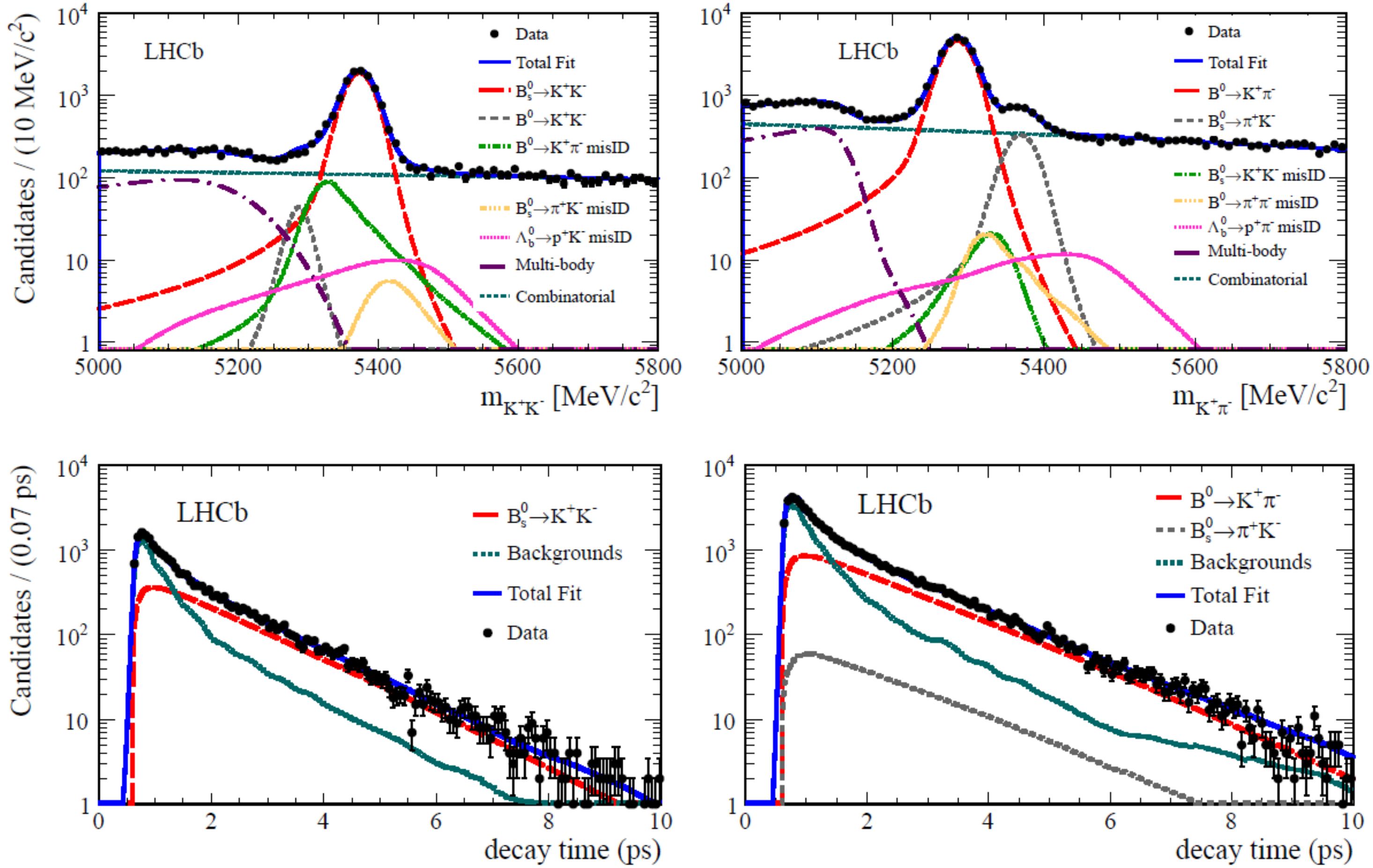
- Measure also lifetime of decays with similar topology

arXiv:1406.7204
Submitted to PLB

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

New!

- 2011 dataset (1 fb^{-1})

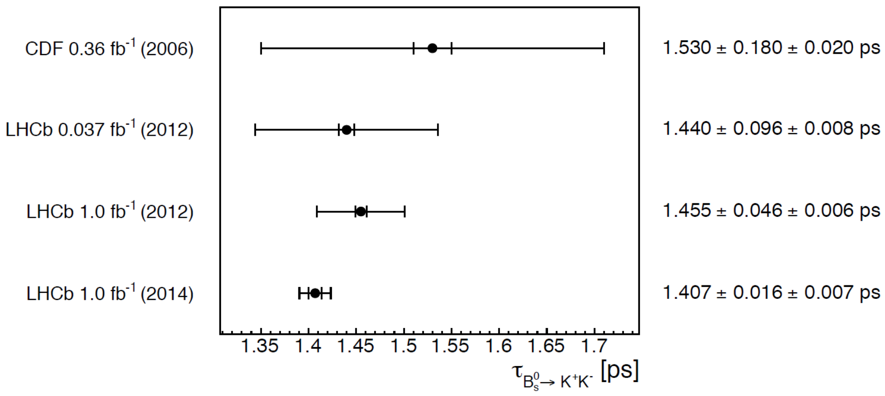


arXiv:1406.7204
Submitted to PLB

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

New!

- 2011 dataset (1 fb^{-1})



$$\tau_{B_s^0 \to K^+K^-} = 1.407 \pm 0.016\ (\text{stat}) \pm 0.007\ (\text{syst})\ \text{ps},$$
$$\tau_{B^0 \to K^+\pi^-} = 1.524 \pm 0.011\ (\text{stat}) \pm 0.004\ (\text{syst})\ \text{ps},$$
$$\tau_{B_s^0 \to \pi^+K^-} = 1.60 \pm 0.06\ (\text{stat}) \pm 0.01\ (\text{syst})\ \text{ps}.$$

- Can be used to extract:

$$\mathcal{A}_{\Delta\Gamma_s} = \frac{2\Gamma_s^2}{\Delta\Gamma_s}\tau_{B_s^0 \to K^+K^-} - \frac{2\Gamma_s}{\Delta\Gamma_s}$$

$$\mathcal{A}_{\Delta\Gamma_s} = -0.87 \pm 0.17\,(\text{stat}) \pm 0.13\,(\text{syst})$$

Consistent with SM expectation:

$$\mathcal{A}_{\Delta\Gamma_s}(B_s^0 \to K^+K^-) = -0.972^{+0.014}_{-0.009}$$

JHEP04(2014)114

$B \to J/\Psi X$

- Set of lifetime measurements
- Absolute measurements in final stated containing J/Ψ
- 2011 data set (1 fb^{-1})
- Most precise measurements to date!

Channel	Yield
$B^+ \to J/\psi K^+$	$229\,434 \pm 503$
$B^0 \to J/\psi K^{*0}$	$70\,534 \pm 312$
$B^0 \to J/\psi K^0_S$	$17\,045 \pm 175$
$B^0_s \to J/\psi \phi$	$18\,662 \pm 152$
$\Lambda^0_b \to J/\psi \Lambda$	$3\,960 \pm 89$

$$\tau_{B^+\to J/\psi K^+} = 1.637 \pm 0.004 \pm 0.003\, ps,$$
$$\tau_{B^0\to J/\psi K^{*0}} = 1.524 \pm 0.006 \pm 0.004\, ps,$$
$$\tau_{B^0\to J/\psi K^0_s} = 1.499 \pm 0.013 \pm 0.005\, ps,$$
$$\tau_{\Lambda^0_b\to J/\psi \Lambda} = 1.415 \pm 0.027 \pm 0.006\, ps,$$
$$\tau_{B^0_s\to J/\psi \phi} = 1.480 \pm 0.011 \pm 0.005\, ps,$$

$$\Delta\Gamma_d/\Gamma_d = -0.044 \pm 0.025 \pm 0.011$$ LHCb only

0.015±0.018 by B factories

Prediction arXiv:0412007:

$$(\Delta\Gamma/\Gamma)_{B_d} = (3 \pm 1.2) \cdot 10^{-3}$$

PLB, 734, (2014) 122

$\Lambda_b \to J/\Psi p K^-$

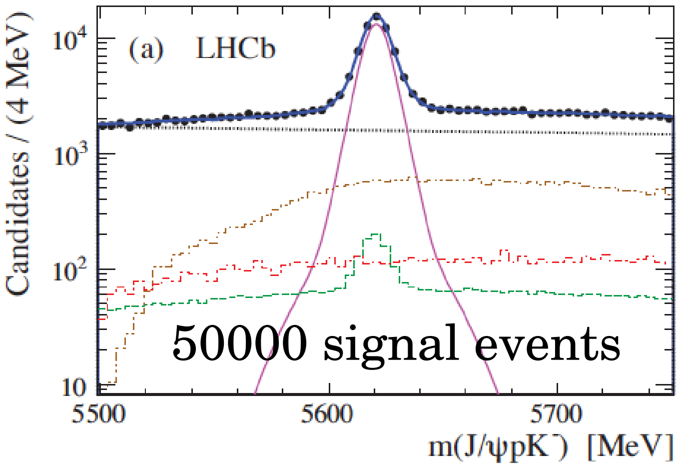
- HQE prediction of the ratio $\tau(\Lambda_b)/\tau(B^0) = 0.935 \pm 0.054$
- Problem of the Λ_b lifetime:long standing puzzle
- Need a precision measurement

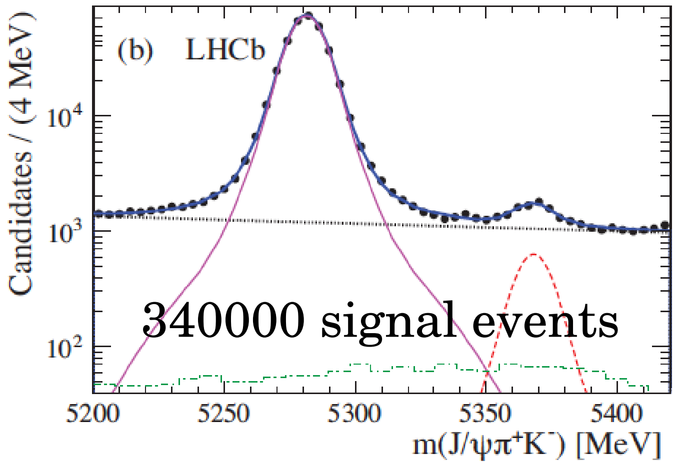
Year	Exp	Decay	$\tau(\Lambda_b)$ [ps]	$\tau(\Lambda_b)/\tau(B_d)$
2010	CDF	$J/\psi\Lambda$	1.537 ± 0.047	1.020 ± 0.031
2009	CDF	$\Lambda_c + \pi^-$	1.401 ± 0.058	0.922 ± 0.038
2007	D0	$\Lambda_c \mu\nu X$	1.290 ± 0.150	0.849 ± 0.099
2007	D0	$J/\psi\Lambda$	1.218 ± 0.137	0.802 ± 0.090
2006	CDF	$J/\psi\Lambda$	1.593 ± 0.089	1.049 ± 0.059
2004	D0	$J/\psi\Lambda$	1.22 ± 0.22	0.87 ± 0.17

- LHCb measures ratio of lifetime directly
- Uses newly observed Λ_b mode
- Updated to 2011 + 2012 dataset (3 fb^{-1})

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

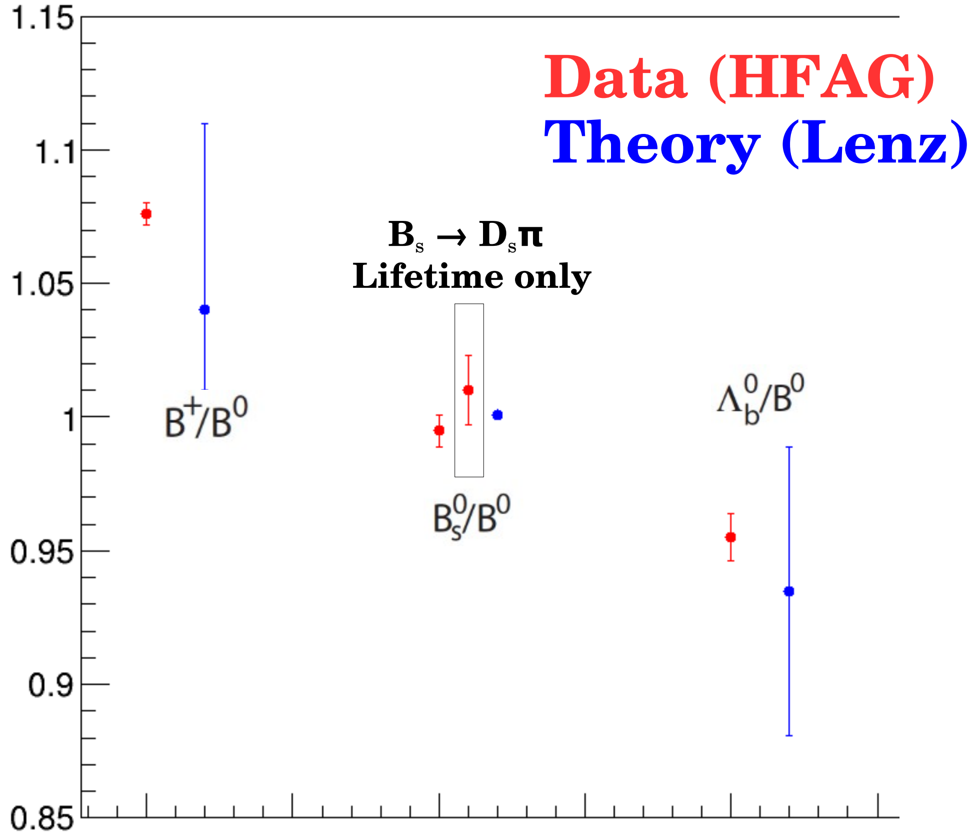
$$\tau(\Lambda_b^0) = 1.479 \pm 0.009 \pm 0.010 \text{ ps}$$





Conclusions (1)

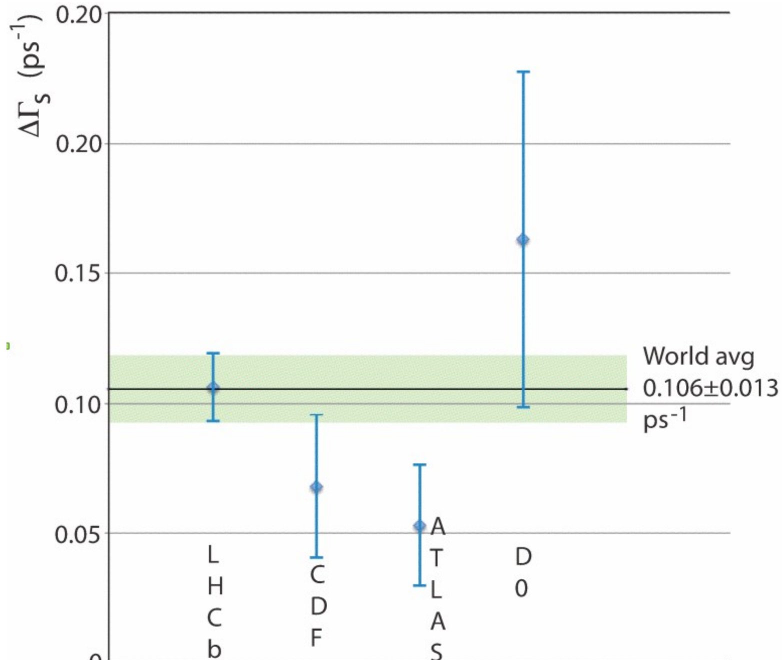
- Recent measurement give a consistent picture of b-hadron lifetimes
- HQE gives very reliable predictions
- Lifetimes ratios known to striking precision



Conclusions (2)

- B_s sector shows good agreement and it is consistent with SM
- From $B_s \rightarrow J/\Psi\ (\pi\pi, KK)$
- Average does not include recent CMS result (ICHEP)

Exp.	$\int$**L** (fb^{-1})	Γ_s (ps^{-1})	**ArXiv**
ATLAS	4.9	0.6700±0.0070±0.0040	1208.0572
CDF	9.6	0.6545±0.0081±0.0039	1208.2967
D0	8.0	0.6930±0.0182	1109.3166
LHCb	1	0.6610±0.0040±0.0060	1324.2600
Average		0.666±0.0045	

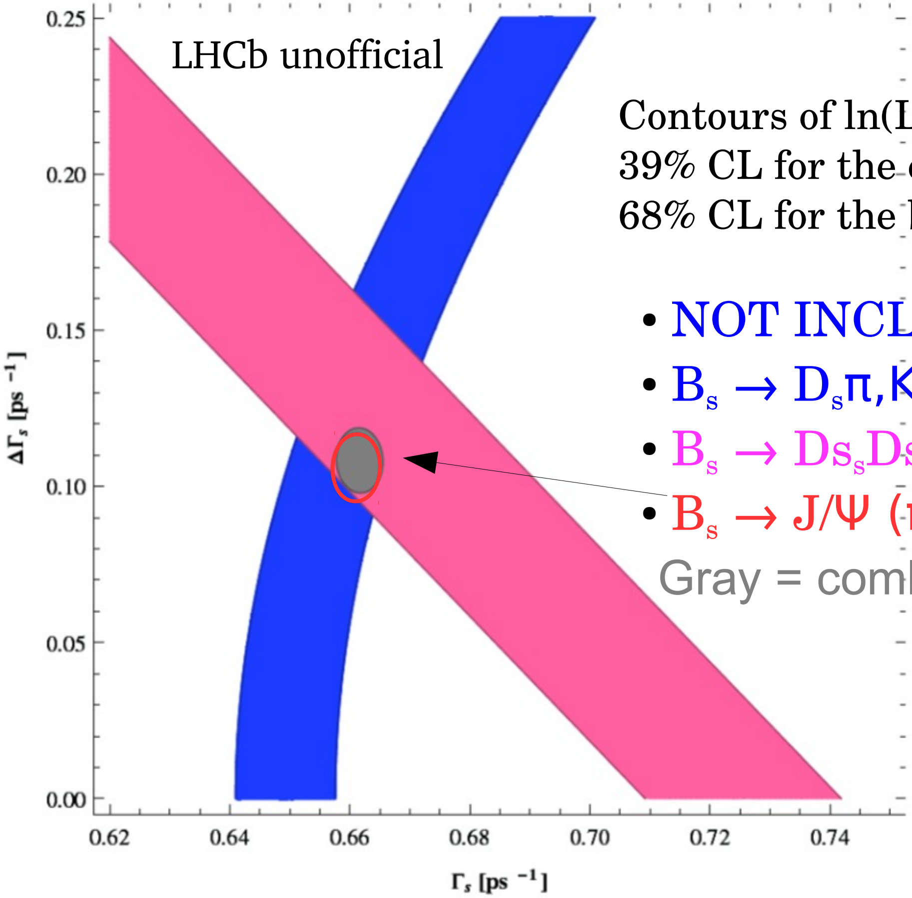


CMS PAS BPH-13-012
2012 data only, 20fb^{-1}, 49k $B_s \rightarrow \psi\varphi$

$\Delta\Gamma_s = 0.096 \pm 0.014 \pm 0.007$
previous central value was 0.048!

Γ_s - $\Delta\Gamma_s$ plane (LHCb only)

- Combine all the LHCb results
- Plot done in a similar way as HFAG: http://www.slac.stanford.edu/xorg/hfag/osc/spring_2014/
- Systematics assumed uncorrelated



Contours of ln(L) = 0.5
39% CL for the enclosed 2D regions
68% CL for the bands

- NOT INCLUDING $B_s \to KK$
- $B_s \to D_s\pi, K\pi$
- $B_s \to Ds_s Ds_s$
- $B_s \to J/\Psi\ (\pi\pi, KK)$

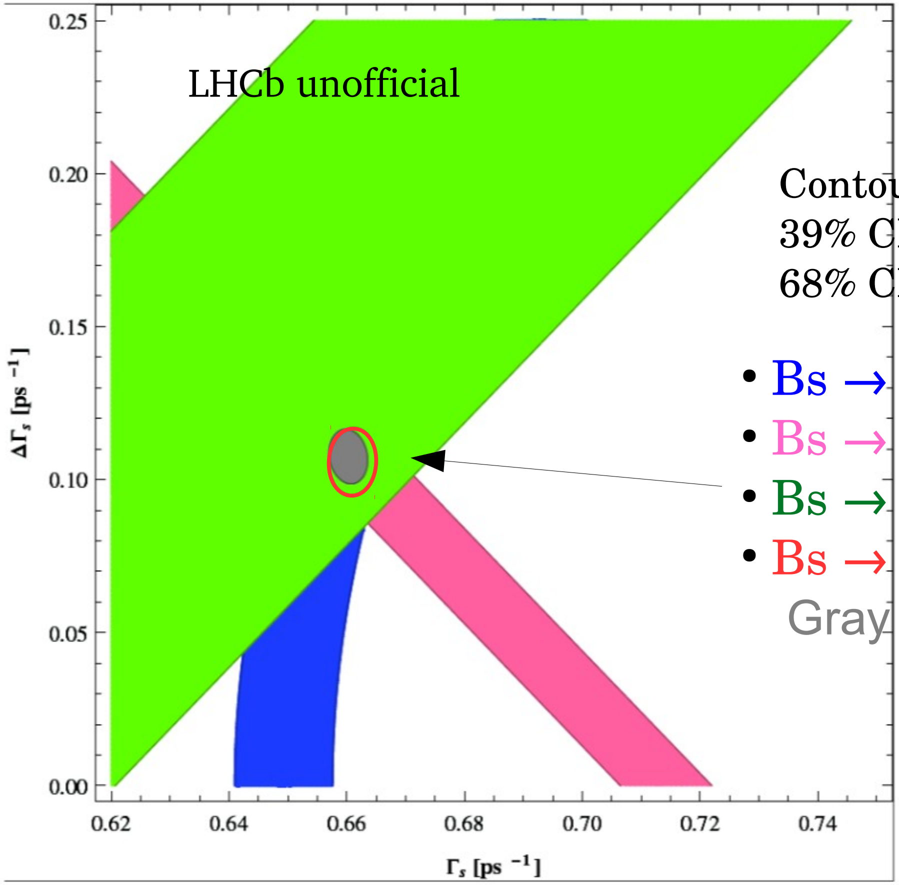
Gray = combination

VERY NICE AGREEMENT!

Backup Slides

Γ_s - $\Delta\Gamma_s$ plane

- Combine all the LHCb results
- Plot done à la HFAG: http://www.slac.stanford.edu/xorg/hfag/osc/spring_2014/
- Systematics uncorrelated + No direct CP + ϕ_s=0



Contours of ln(L) = 0.5
39% CL for the enclosed 2D regions
68% CL for the bands

- $B_s \to D_s\pi, K\pi$
- $B_s \to D_sD_s$, KK
- $B_s \to J/\Psi\ K_s$
- $B_s \to J/\Psi\ (\pi\pi, KK)$

Gray = combination

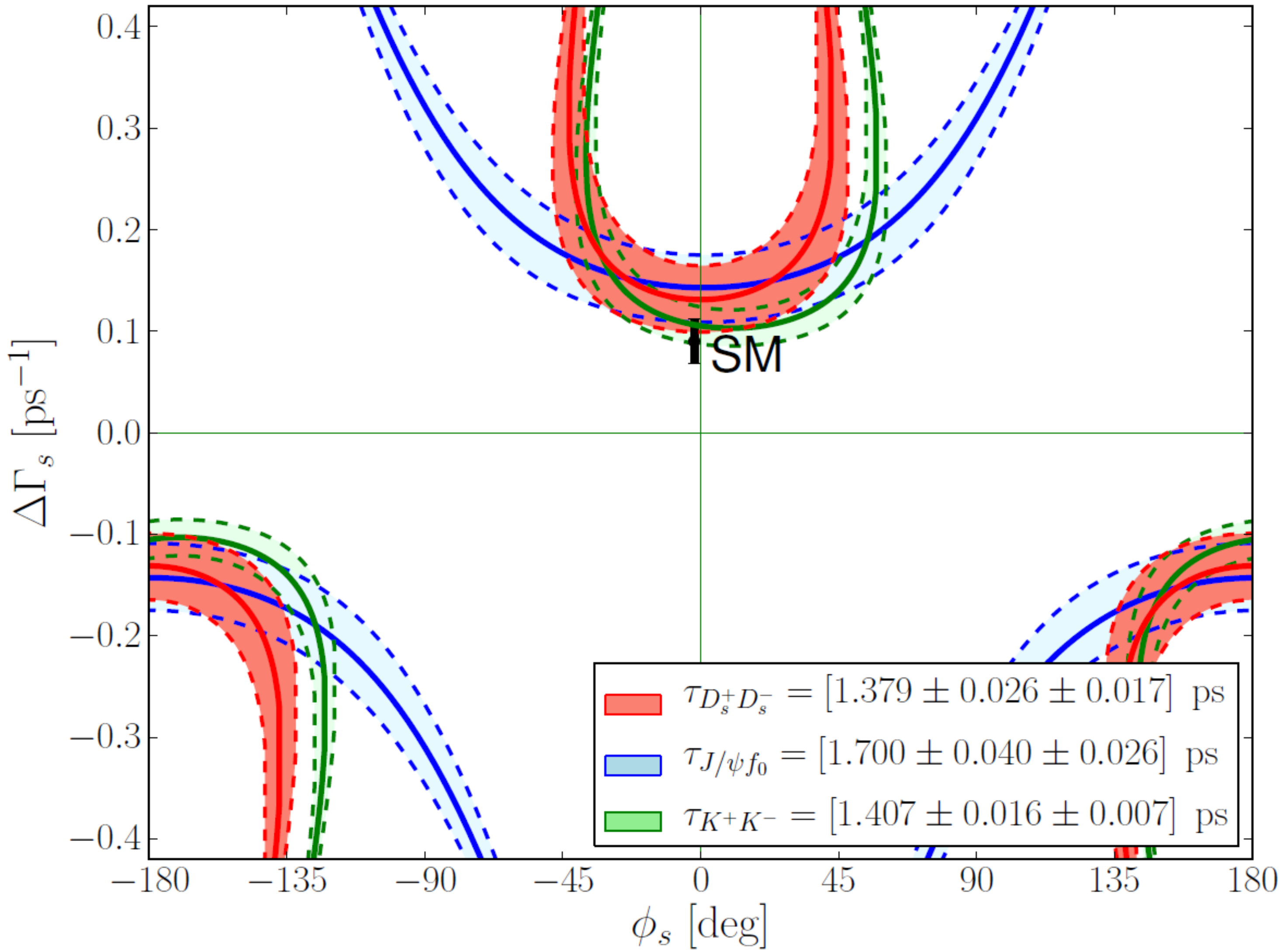
Γ_s - $\Delta\Gamma_s$ plane: numerical results

- Combine all the LHCb results
- Plot done à la HFAG: http://www.slac.stanford.edu/xorg/hfag/osc/spring_2014/
- Systematics uncorrelated + No direct CP + ϕ_s=0
- LHCb Unofficial

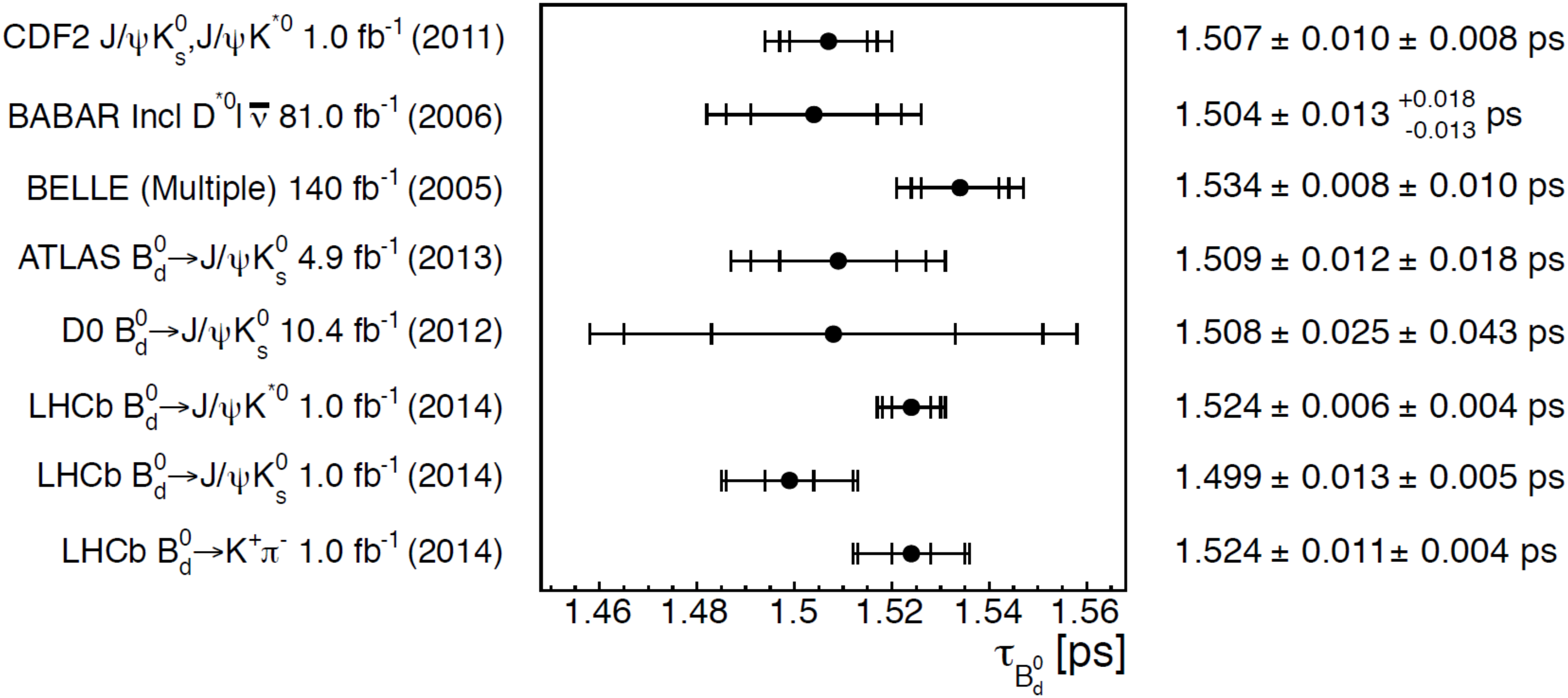
	J/ψ hh	+eff. lifetime	ALL	removing KK and $J/\psi\, K^0_S$
$\Delta\Gamma_s(\mathrm{ps}^{-1})$	0.106 ± 0.011	$0.106815^{+0.00918222}_{-0.00916179}$	$0.107544^{+0.00890455}_{-0.00891088}$	$0.108291^{+0.0103867}_{-0.0103722}$
$\Gamma_s(\mathrm{ps}^{-1})$	0.661 ± 0.004	$0.660773^{+0.00363879}_{-0.00363541}$	$0.660268^{+0.00329061}_{-0.00327979}$	$0.661624^{+0.00387548}_{-0.00387389}$
$\rho(\Gamma_s, \Delta\Gamma_s)$	0.047	-0.223708	-0.136227	-0.0384904
$\tau_s = 1/\Gamma_s(\mathrm{ps})$	1.5129 ± 0.0092	$1.51338^{+0.00833398}_{-0.00832625}$	$1.51454^{+0.00754808}_{-0.00752325}$	$1.51143^{+0.00885326}_{-0.00884964}$
$\tau_L = 1/\Gamma_L(\mathrm{ps})$	1.4006 ± 0.0136	1.40021 ± 0.0101491	1.40048 ± 0.0101239	1.3971 ± 0.0124061
$\tau_H = 1/\Gamma_H(\mathrm{ps})$	1.6447 ± 0.01798	1.64646 ± 0.01751	1.64882 ± 0.0159949	1.64615 ± -0.0178713
$\Delta\Gamma_s/\Gamma_s$	0.1604 ± 0.0166	0.161651 ± 0.0141065	0.162879 ± 0.0136251	0.163674 ± 0.0157539

Column1: only Bs → J/Ψ (ππ,KK)
Column2: J/Ψ(ππ,KK) + KK + DsDs + J/ΨKs
Column3: J/Ψ(ππ,KK) + KK + DsDs + J/ΨKs + Dsπ + Kπ
Column4: J/Ψ(ππ,KK) + DsDs + Dsπ + Kπ

Constraints on φ_s and $\Delta\Gamma_s$



B_d Lifetime



CDF2 $J/\psi K^0_s, J/\psi K^{*0}$ 1.0 fb^{-1} (2011)
BABAR Incl $D^{*0} l \bar{\nu}$ 81.0 fb^{-1} (2006)
BELLE (Multiple) 140 fb^{-1} (2005)
ATLAS $B^0_d \to J/\psi K^0_s$ 4.9 fb^{-1} (2013)
D0 $B^0_d \to J/\psi K^0_s$ 10.4 fb^{-1} (2012)
LHCb $B^0_d \to J/\psi K^{*0}$ 1.0 fb^{-1} (2014)
LHCb $B^0_d \to J/\psi K^0_s$ 1.0 fb^{-1} (2014)
LHCb $B^0_d \to K^+\pi^-$ 1.0 fb^{-1} (2014)
1.46
1.48
1.5
1.52
1.54
1.56
$\tau_{B^0_d}$ [ps]
$1.507 \pm 0.010 \pm 0.008$ ps
$1.504 \pm 0.013 ^{+0.018}_{-0.013}$ ps
$1.534 \pm 0.008 \pm 0.010$ ps
$1.509 \pm 0.012 \pm 0.018$ ps
$1.508 \pm 0.025 \pm 0.043$ ps
$1.524 \pm 0.006 \pm 0.004$ ps
$1.499 \pm 0.013 \pm 0.005$ ps
$1.524 \pm 0.011 \pm 0.004$ ps

B_s Flavour Specific (other measurements)