Current experimental status of $\Delta\Gamma$ and Δm

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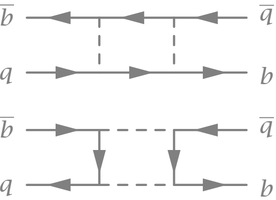
outline

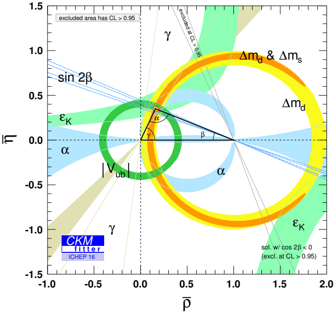
- $B^0_{d/s}$ mixing, $\Delta m_{d/s}$ and $\Delta\Gamma_{d/s}$
- measuring $\Delta m_{d/s}$
- measuring $\Delta\Gamma_{d/s}$
- conclusions

$B^0_{d/s}$ mixing



- mixing goes through box diagrams
  - $\Delta m_q \sim m_W^2 m_{B_q} \hat{\mathcal{B}}_q f_{B_q}^2 (V_{tq}^* V_{tb})^2 \qquad q = d, s$
  - $\Delta\Gamma_q \sim m_b^2 m_{B_q} \hat{\mathcal{B}}_q f_{B_q}^2 \Big((V_{tq}^* V_{tb})^2 + V_{tq}^* V_{tb} V_{cq}^* V_{cb} \mathcal{O}(m_c^2/m_b^2) + (V_{cq}^* V_{cb})^2 \mathcal{O}(m_c^4/m_b^4) \Big)$

- current WA: [HFLAV 2018]
  - $\Delta m_d = (0.5064 \pm 0.0019)\ \text{ps}^{-1}$
  - $\Delta\Gamma_d/\Gamma_d = (-0.2 \pm 1.0) \cdot 10^{-2}$
  - $\Delta m_s = (17.757 \pm 0.021)\ \text{ps}^{-1}$
  - $\Delta\Gamma_s/\Gamma_s = (0.132 \pm 0.008)$
- constrain apex of unitarity triangle:
  $\frac{\Delta m_s}{\Delta m_d} = \frac{m_{B_s}}{m_{B_d}} \xi^2 \left|\frac{V_{ts}}{V_{td}}\right|^2$
- get $\xi^2 = \frac{\hat{\mathcal{B}}_s f_{B_s}^2}{\hat{\mathcal{B}}_d f_{B_d}^2}$ from lattice QCD
  - $|V_{td}/V_{ts}| = 0.2053 \pm 0.0004(\text{exp}) \pm 0.0029(\text{lattice})$ [PDG2018]



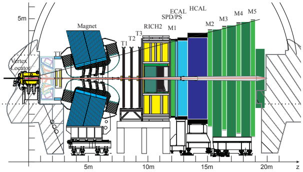
[CKMFitter 2016]

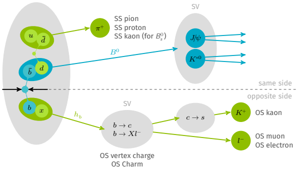
measuring Δm_q

measuring Δm_q

measuring $\Delta m_{d/s}$

- best precision from time dependent mixing analysis in flavour specific decays
- $A_{mix}^{th} = \dfrac{\Gamma_{\overline{B_q^0}\to\overline{f}}(t) - \Gamma_{B_q^0\to f}(t)}{\Gamma_{\overline{B_q^0}\to\overline{f}}(t) + \Gamma_{B_q^0\to f}(t)} \sim \cos(\Delta m_q t)$

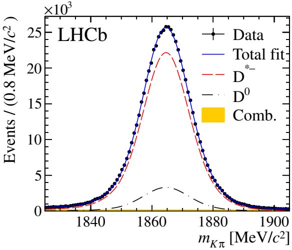




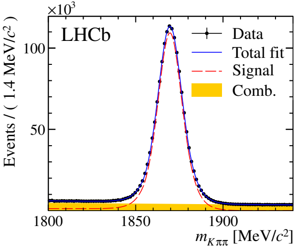
- experimental factors affecting significance:
  - signal yield: $\sqrt{N/2} f_{sig}$
    - large $b\bar{b}$ x-section, large data sample (so far, $\sim 5.5\,\mathrm{fb}^{-1}$ in run 2)
    - efficient trigger, reconstruction, excellent momentum and vertex resolution
    - excellent particle identification
  - diluted through time resolution: $e^{-(\Delta m_q \sigma_t)^2/2}$ ($\sigma_t \sim 45 - 55$ fs)
  - diluted through flavour tagging: $\sqrt{\epsilon_{tag}(1-2\omega)^2} \sim (3\ldots6)\%$
    - opposite side: e, μ, K,Vertex,charm
    - same side: π, p, K

measuring Δm_d at LHCb

- from semileptonic $B \to D^{(*)-}\mu^+\nu_\mu X$ decays
- large $BR \sim 2-5\%$
- reconstruct $D^{*-} \to \overline{D^0}(K^+\pi^-)\pi^-$ and $D^- \to K^+\pi^-\pi^-$
- $D^{(*)-}\mu^+$ form common vertex, missing ν_μ
  - cannot apply mass/kinematic cuts on B_d, only on D^0, D^{*-}, D^-
- veto mis-ID $J/\psi, \Lambda_c$
- BGs: D^0 from B, $B^+ \to D^{(*)-}\mu^+\pi^+\nu_\mu$, combinatorial



~ 0.8 M $B_d \to D^{*-}\mu^+\nu_\mu X$

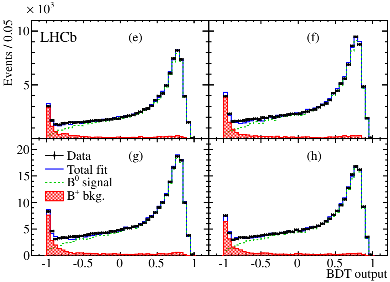


~ 1.4 M $B_d \to D^-\mu^+\nu_\mu X$

[Eur. Phys. J. C(2016) 76:412]

measuring Δm_d at LHCb

- physics BG: $B^+ \to D^{(*)-}\mu^+\pi^+\nu_\mu$
  - expected at $\sim 10\%$ level, but BR is only known with a precision of 10%
  - fraction of BG correlated with fitted value for Δm_d
  - model correctly, reduce BG for low systematic uncertainty
- train MVA classifier to discriminate this BG from signal
  - train on MC, in 4 separate tagging categories
  - inputs:
    - geometrical and kinematic info on $D^{(*)-}\mu$ system
    - isolation of tracks in cone around it
- use to suppress this BG by 70%
- use to evaluate remaining fraction (3%($D^{*-}\mu\nu_\mu X$)/6%($D^-\mu\nu_\mu X$)) on data



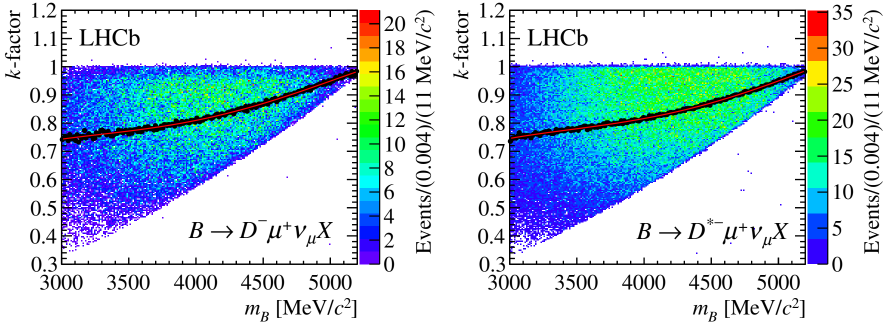
$B_d \to D^{*-}\mu^+\nu_\mu X$

[Eur. Phys. J. C(2016) 76:412]

measuring Δm_d at LHCb

- further complication: ν_μ escapes, X not reconstructed
- need to correct measured decay time: $t = \frac{M_{B_d} L}{p_{D^{(*)}\mu} c / k(m_B)}$
- with: $k(m_B) = \langle p_{D^{(*)}\mu} / p_{B_d}^{true} \rangle$

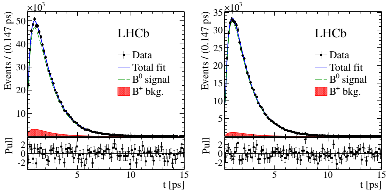
→ decay time is smeared, only average correction known



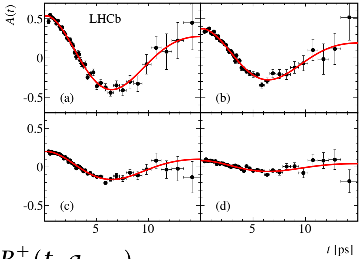
[Eur. Phys. J. C(2016) 76:412]

measuring Δm_d at LHCb

- $q_{mix} = \pm 1$: mixed/unmixed from μ charge and flavour tagging decision
  - 4 categories in mistag ω to gain sensitivity
  - tagging power $\epsilon(1-2\omega)^2 \sim 2.3 - 2.6\%$
- fit m_{D^-} and $m_{D^0}/\delta_m = m_{D*} - m_{D^0}$ distributions
- use to extract sWeights for signal + B^+ (subtracts combinatorial + D^0 from B):



[Eur. Phys. J. C(2016) 76:412]



$B_d \to D^- \mu^+ \nu_\mu X$

$$P(t, q_{mix}) = (1 - f_{B^+}) S(t, q_{mix}) + f_{B^+} B^+(t, q_{mix})$$
$$S(t, q_{mix}) = a(t) \left(e^{-t/\tau} (1 + q_{mix}(1-2\omega)\cos(\Delta m_d t)) \right) \otimes R(t) \otimes F(k)$$

- from data: acceptance $a(t)$, f_{B^+}, ω
- from simulation: resolution R(t), correction $F(k)$

measuring Δm_d at LHCb

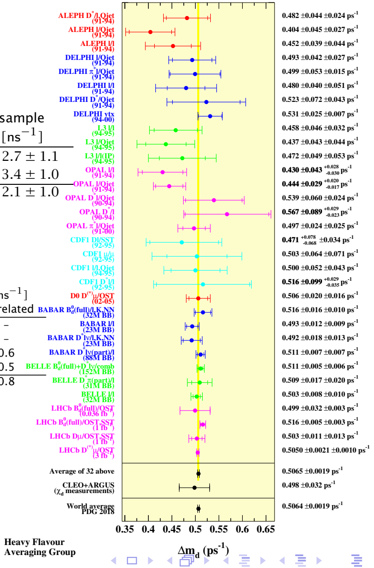
- result: [Eur. Phys. J. C(2016) 76:412]

Mode	2011 sample Δm_d [ns^{-1}]	2012 sample Δm_d [ns^{-1}]	Total sample Δm_d [ns^{-1}]
$B_d \to D^- \mu^+ \nu_\mu X$	506.2 ± 5.1	505.2 ± 3.1	$505.5 \pm 2.7 \pm 1.1$
$B_d \to D^{*-} \mu^+ \nu_\mu X$	497.5 ± 6.1	508.3 ± 4.0	$504.4 \pm 3.4 \pm 1.0$
combination			$505.0 \pm 2.1 \pm 1.0$

- systematic uncertainties:

Source of uncertainty	$B_d \to D^- \mu^+ \nu_\mu X$ [ns^{-1}]		$B_d \to D^{*-} \mu^+ \nu_\mu X$ [ns^{-1}]	
	Uncorrelated	Correlated	Uncorrelated	Correlated
B^+ background	0.4	0.1	0.4	–
Other backgrounds	–	0.5	–	–
k-factor distribution	0.4	0.5	0.3	0.6
Other fit-related	0.5	0.4	0.3	0.5
Total	0.8	0.8	0.6	0.8

- most precise measurement, dominates WA



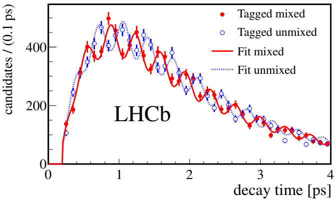
[Eur. Phys. J. C77 (2017) 895]

measuring Δm_s at LHCb

- decay rates for B_H and B_L to final state f can be different, so

$$\begin{aligned}\Gamma_{B_q\to f}(t) &= e^{-\Gamma_q t} \Big(\cosh(\Delta\Gamma_q t/2) + A^f_{\Delta\Gamma}\sinh(\Delta\Gamma t/2) + \\ &\quad A^{dir,f}_{CP}\cos(\Delta m_q t) + A^{mix,f}_{CP}\sin(\Delta m_q t)\Big) \\ \Gamma_{B_q\to f}(t) &= e^{-\Gamma_q t} \Big(\cosh(\Delta\Gamma_q t/2) + A^f_{\Delta\Gamma}\sinh(\Delta\Gamma t/2) - \\ &\quad A^{dir,f}_{CP}\cos(\Delta m_q t) - A^{mix,f}_{CP}\sin(\Delta m_q t)\Big)\end{aligned}$$

- time-dependent analyses of B^0_q decays give access to
  - Δm_q
  - sometimes also $\Delta\Gamma_q$ (we'll see in a bit…)
- often a flavour-specific channel like $B_s \to D_s\pi$ will give the best results
- will look into $B_s \to J/\psi K^+K^-$, since it's newer…

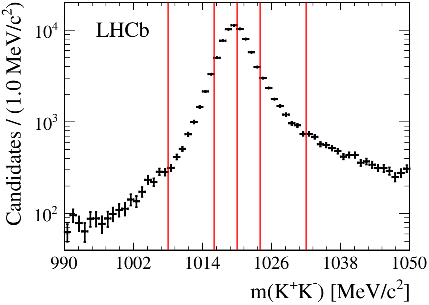


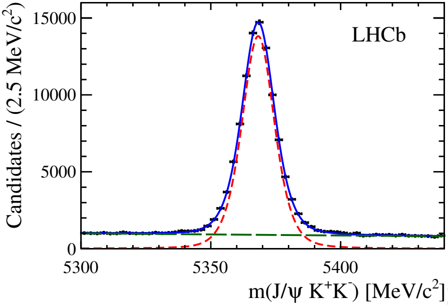
Δm_s from $B^0_s \to D_s\pi$

[New J. Phys. 15 (2013) 053021]

measuring Δm_s at LHCb

- do a time-dependent analysis of $B_s \to J/\psi K^+ K^-$:
  - usually people do this to learn about mixing phase ϕ_s
  - complicated angular analysis
- corresponding to a data set of $3\,\text{fb}^{-1}$
- $>$ 95k $B_s \to J/\psi K^+ K^-$ candidates, very clean
- main BG: combinatorial, K/π mis-ID, subtracted using sWeights
- flavour tagging: opposite side + same side Kaon, $\epsilon(1-2\omega)^2 = (3.73 \pm 0.15)\%$

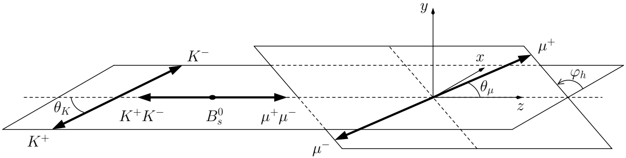




[Phys. Rev. Lett. 114, 041801 (2015)]

measuring Δm_s at LHCb

- final state $J/\psi K^+K^-$ is mixture of CP eigenstates
  - depends on relative angular momentum of J/ψ and K^+K^--system
  - to learn about ϕ_s, need to disentangle CP-even and CP-odd component (for details, see talks by Maria, Varvara, Pavel)
- analyse decay rate as function of helicity angles $\cos(\theta_K), \cos(\theta_\mu), \phi_h$

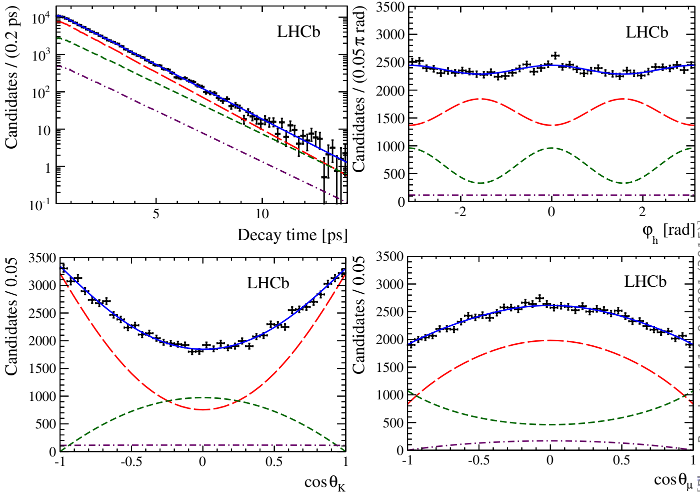


[Phys. Rev. D 87, 112010 (2013)]

  - forward geometry of LHCb cuts into these angles
  - model 3D angle-dependent efficiency using simulation
- helps to disentangle $B_{s,H}$ and $B_{s,L}$

measuring Δm_s at LHCb

- simultaneous fit in decay time and angular analysis
- long- and short-lived component separated thanks to different angular dependence!

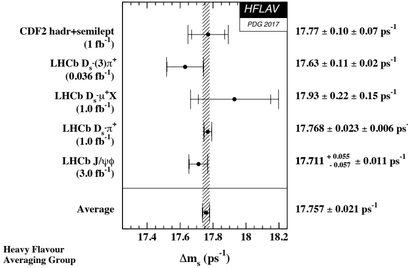


[Phys. Rev. Lett. 114, 041801 (2015)]

measuring Δm_s at LHCb

Parameter	Value
Γ_s [ps^{-1}]	$0.6603 \pm 0.0027 \pm 0.0015$
$\Delta\Gamma_s$ [ps^{-1}]	$0.0805 \pm 0.0091 \pm 0.0032$
$\lvert A_\perp \rvert^2$	$0.2504 \pm 0.0049 \pm 0.0036$
$\lvert A_0 \rvert^2$	$0.5241 \pm 0.0034 \pm 0.0067$
δ [rad]	$3.26^{+0.10}_{-0.17}{}^{+0.06}_{-0.07}$
$\delta_\perp$ [rad]	$3.08^{+0.14}_{-0.15} \pm 0.06$
ϕ_s [rad]	$-0.058 \pm 0.049 \pm 0.006$
$\lvert\lambda\rvert$	$0.964 \pm 0.019 \pm 0.007$
Δm_s [ps^{-1}]	$17.711^{+0.055}_{-0.057} \pm 0.011$

[Phys. Rev. Lett. 114, 041801 (2015)]



[Eur. Phys. J. C77 (2017) 895]

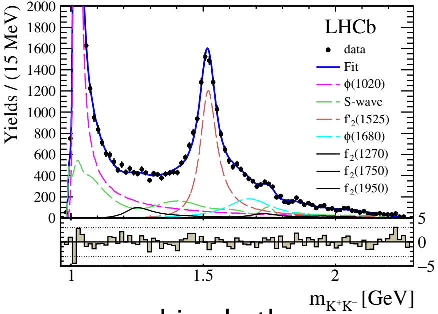
- hugely complex fix, but gives access to
  - Δm_s
  - Γ_s, $\Delta\Gamma_s$
  - mixing phase ϕ_s
  - amplitudes and phases of different angular components
- LHCb measurements in $B_s^0 \to D_s\pi$ and $B_s^0 \to J/\psi K^+K^-$ dominate the WA

measuring $\Delta\Gamma_q$

measuring $\Delta\Gamma_q$

measuring $\Delta\Gamma_s$ at LHCb

- have already seen $B_s \to J/\psi K^+K^-$ with K^+K^- in the $\phi(1020)$ region [Phys. Rev. Lett. 114, 041801 (2015)]
- similar example: use higher K^+K^- invariant masses: [JHEP 08 (2017) 037]
  - also uses $3\,\text{fb}^{-1}$
  - similar to analysis with K^+K^- in the ϕ region
  - more than 33k candidates with $m_{KK} > 1.05\,\text{GeV}$



$$\phi_s = 119 \pm 107 \pm 34\,\text{mrad},$$
$$|\lambda| = 0.994 \pm 0.018 \pm 0.006,$$
$$\Gamma_s = 0.650 \pm 0.006 \pm 0.004\text{ps}^{-1},$$
$$\Delta\Gamma_s = 0.066 \pm 0.018 \pm 0.010\text{ps}^{-1}$$

[JHEP 08 (2017) 037]

- can combine both:

$$\phi_s = -25 \pm 45 \pm 8\,\text{mrad} \qquad \Gamma_s = 0.6588 \pm 0.0022 \pm 0.0015\text{ps}^{-1}$$
$$|\lambda| = 0.978 \pm 0.013 \pm 0.003 \qquad \Delta\Gamma_s = 0.0813 \pm 0.0073 \pm 0.0036\text{ps}^{-1}$$

measuring $\Delta\Gamma_q$

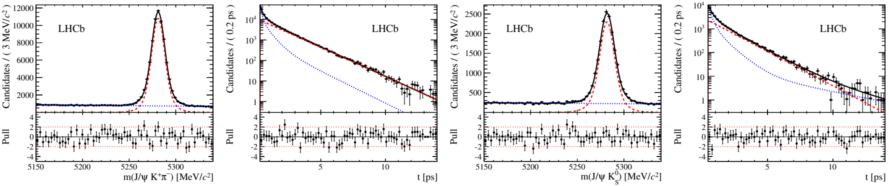
- have already seen how to get $\Delta\Gamma_q$ from time-dependent mixing analyses
- other method: effective lifetime depends on $y_q = 2\Delta\Gamma_q/\Gamma_q$:

$$\tau^{eff}_{B_q\to f} = \frac{1}{\Gamma_q}\frac{1}{1-y_q^2}\frac{1+2A^f_{\Delta\Gamma}y_q+y_q^2}{1+A^f_{\Delta\Gamma}y_q}$$

  - can use different decay channels (different $A^f_{\Delta\Gamma}$) (e.g. [JHEP04(2014)114])
    - $B^0 \to J/\psi K^{*0}$ ($A^f_{\Delta\Gamma} = 0$)
    - $B^0 \to J/\psi K^0_S$ ($A^f_{\Delta\Gamma} = \cos(2\beta)$)
- can use measurements of $\Delta\Gamma_q$ for many things on the theory side
  - e.g. to derive bounds on quark-hadron duality, to mention a recent example [arXiv:1603.07770v2]

measuring $\Delta\Gamma_d$ at LHCb

- idea is to measure effective lifetimes of e.g.
  - $B^0 \to J/\psi K^{*0}$
  - $B^0 \to J/\psi K_S^0$
- trigger on μ, $3\,\mathrm{fb}^{-1}$ data sample
- minimise decay time biasing selection criteria
- fully reconstruct decay, model efficiencies with MC and control channels
- fit time and invariant mass

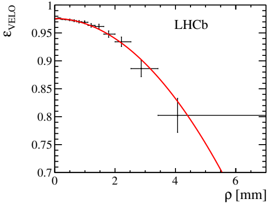


$\sim$ 71k $B^0 \to J/\psi K^*$ $\sim$ 17k $B^0 \to J/\psi K_S^0$

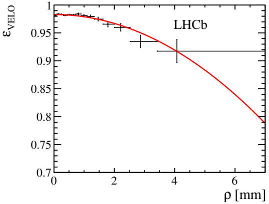
[JHEP04(2014)114]

measuring $\Delta\Gamma_d$ at LHCb

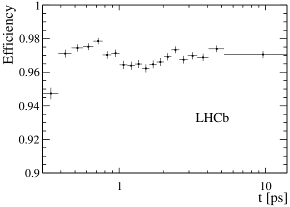
- of course, (effective) lifetime measurements require precise control of efficiency as function of decay time (and flight distance)
- two main contributions:
  - VELO reconstruction efficiency as one moves away from beamline radially (ρ)
  - combined trigger and selection efficiency as a function of time



online reco



offline reco



combined trigger + selection eff.

[JHEP04(2014)114]

measuring $\Delta\Gamma_d$ at LHCb

- results: [JHEP04(2014)114]

  $\tau_{B^0\to J/\psi K^*} = 1.524 \pm 0.006 \pm 0.004$ ps

  $\tau_{B^0\to J/\psi K^0_S} = 1.499 \pm 0.013 \pm 0.005$ ps

- use $\tau^{eff}_{B_q\to f} = \frac{1}{\Gamma_q}\frac{1}{1-y_q^2}\frac{1+2A^f_{\Delta\Gamma}y_q+y_q^2}{1+A^f_{\Delta\Gamma}y_q}$
  - $A^f_{\Delta\Gamma} = 0$ for flavour specific decays
  - $A^f_{\Delta\Gamma} = \cos(2\beta)$ for $B^0 \to J/\psi K^0_S$

- combine from these results:

  $\Gamma_d = 0.656 \pm 0.003 \pm 0.002 \text{ps}^{-1}$

  $\Delta\Gamma_d = -0.029 \pm 0.016 \pm 0.007 \text{ps}^{-1}$

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

Source	τ_{B^+}/τ_{B^0}	$\tau_{B^0_s}/\tau_{B^0}$	$\tau_{\Lambda_b}/\tau_{B^0}$	τ_{B^+}/τ_{B^-}	$\tau_{\Lambda_b}/\tau_{\Lambda_{\overline{b}}}$	$\tau_{B^0}/\tau_{\overline{B}^0}$	$\Delta\Gamma_d/\Gamma_d$
Statistical uncertainty	5.0	8.5	18.0	4.0	35.0	8.0	25.0
VELO reconstruction	1.6	1.7	1.1	–	–	–	4.1
Simulation sample size	2.0	2.2	2.8	2.1	5.3	3.0	6.3
Mass-time correlation	1.6	1.2	2.3	–	–	–	4.7
Trigger and selection eff.	1.1	1.8	1.5	–	–	–	4.0
Background modelling	0.3	0.1	1.5	0.2	3.0	1.4	3.8
Mass modelling	0.2	0.4	0.2	0.1	0.2	0.2	0.8
Peaking background	–	0.3	0.7	–	–	–	0.5
Effective lifetime bias	–	1.0	–	–	–	–	–
B^0 production asym.	–	–	–	–	–	8.5	1.9
Total systematic	3.2	3.7	4.4	2.1	6.1	9.1	10.7

- ATLAS has a decay-length dependent analysis with $\sim$ 139k $B^0 \to J/\psi K^0_s$ and $\sim$ 685k $B^0 \to J/\psi K^{*0}$, yielding $\Delta\Gamma_d/\Gamma_d = -0.001 \pm 0.011 \pm 0.009$

[JHEP06 (2016) 081]

conclusion

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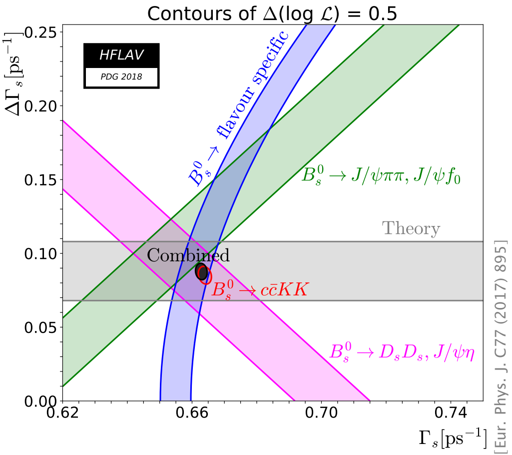
- LHCb measurements of Δm_d, Δm_s still dominate WA
  - experimental status similar to that of last CKM
  - help constrain CKM matrix → important test of SM
  - more and more of run 2 data is analysed
  - new results are being produced
  - stay tuned for more!
- also some progress on $\Delta\Gamma_s$ in the last year or so
  - also stay tuned for more!
- theory limits current precision of $|V_{ts}|$ and $|V_{td}|$
  - looking forward for the lattice to become even better

backup

backup

Γ_s versus $\Delta\Gamma_s$



- $B_s^0 \to D\mu X$ [Phys. Rev. Lett. 119, 101801 (2017)]
- $B_s^0 \to D_s\pi$ [Phys. Rev. Lett. 113, 172001 (2014)]
- $B_s^0 \to J/\psi f_0$ [Phys. Rev. Lett. 109, 152002 (2012)]
- $B_s^0 \to J/\psi\phi$ [Phys. Rev. Lett. 114, 041801 (2015)]
- $B_s^0 \to J/\psi KK$ [JHEP 08 (2017) 037]
- $B_s^0 \to \psi(2S)\phi$ [PLB 762 (2016) 253]
- $B_s^0 \to J/\psi\eta$ [Physics Letters B 762C (2016) pp. 484-492]
- $B_s^0 \to D_sD_s$ [Phys. Rev. Lett. 112, 111802 (2014)]

- many lifetime measurements in B_s^0 sector by LHCb, pinning down Γ_s and $\Delta\Gamma_s$
- excellent laboratory to test quantitative understanding of $\Delta\Gamma_s$ from first principles