Experimental status of lifetimes, mixing and CP violation
Quo Vadis
Islay July 2023

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Outline

I decided to my brief interpret it as similar to a talk I gave in 2017 at a UK flavour workshop in Durham.

https://conference.ippp.dur.ac.uk/event/573/timetable/#20170905.detailed

I took plots for recent LHCb results from the LHC seminar https://indico.cern.ch/event/1281612/

Several plots lifted from papers published by Alex over the last few years

"The concept of progress acts as a protective mechanism to shield us from the terrors of the future."

Outline

- Introduction
- Neutral meson mixing
- Experimental overview
- $\phi_{s,}$ effective lifetimes and $\Delta\Gamma_s$
- sin 2β
- $\Delta\Gamma_d/\Gamma_d$
- Thoughts for the future

Standard Candles

Supporting Measurements

Standard Model tests

LHCb Run: Scorecard

Measurement	Run 1	Run 2
$\sin(2\beta)$	✔✔	✔✔
Δm_d	✔✔	×
$\Delta\Gamma_d$	✔✔	×
ϕ_s in $B_S \rightarrow J/\psi\ K^+K^-$	✔✔	✔✔
ϕ_s other modes	✔✔	✔
Δm_s	✔✔	✔✔
$\Delta\Gamma_s$	✔✔	✔✔
Penguin Pollution	✔✔	×
b-lifetimes	✔	×
τ_L	✔✔	✔

✔✔ All data, ✔ partial, × nothing

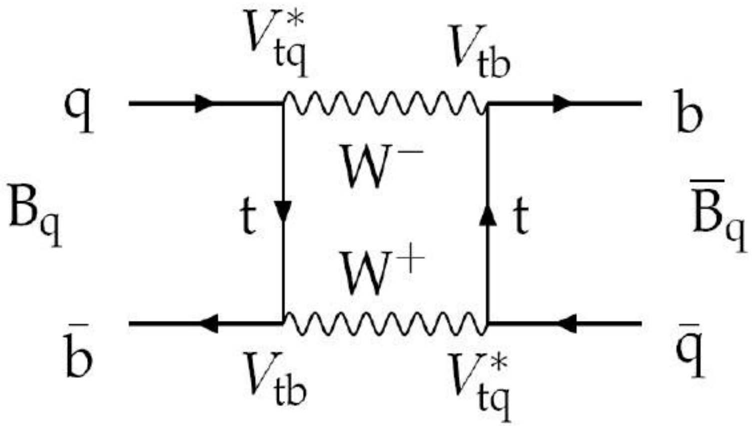
LHCb Run: Scorecard

Measurement	Run 1	Run 2
$B_S \to J/\psi\ K^+K^-$ around ϕ	✔✔	✔✔
$B_S \to J/\psi\ K^+K^-$ above ϕ	✔✔	✔
$B_S \to J/\psi\ K^+K^-$ (electrons)	✔✔	×
$B_S \to \psi(2s)\ K^+K^-$	✔✔	×
$B_S \to D_s^+ D_s^-$	✔✔	×

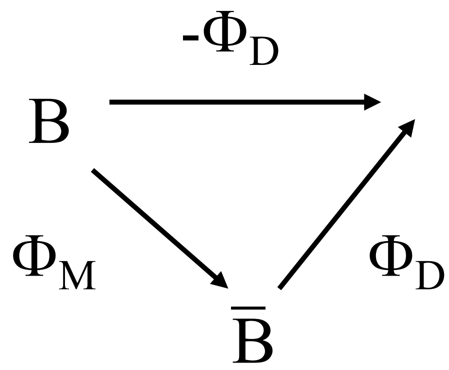
CP violation in B_s mixing

B_s mixing

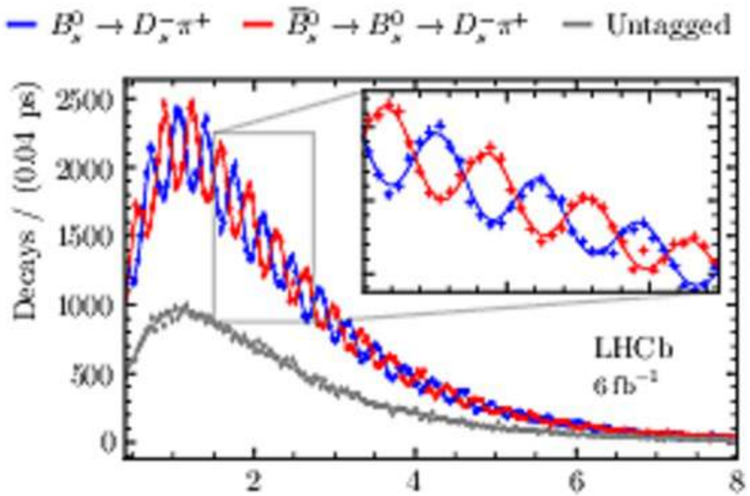
$$i\frac{\partial}{\partial t}\begin{pmatrix}|B_s^0(t)>\\ |\overline{B_s^0}(t)>\end{pmatrix} = \left(M - i\frac{\Gamma}{2}\right)\begin{pmatrix}|B_s^0(t)>\\ |\overline{B_s^0}(t)>\end{pmatrix}$$



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



- Flavour eigenstates mix to give physical states (see e.g. arxiv:1306.6474)
- Interference between decays with/without mixing gives measurable phase



Nature Physics 18, 1-5(2022)

Excellent vertex detector needed to resolve fast B_s oscillations

HFLAV $\Delta m_s = 17.765 \pm 0.006\,\mathrm{ps}^{-1}$

SM prediction JHEP 12 (2019) 009

$\Delta m_s = 18.4^{+0.7}_{-1.2}\,\mathrm{ps}^{-1}$

CP violation in B_s mixing

$$\phi_s = arg\left(-\frac{M_{12}}{\Gamma_{12}}\right)$$

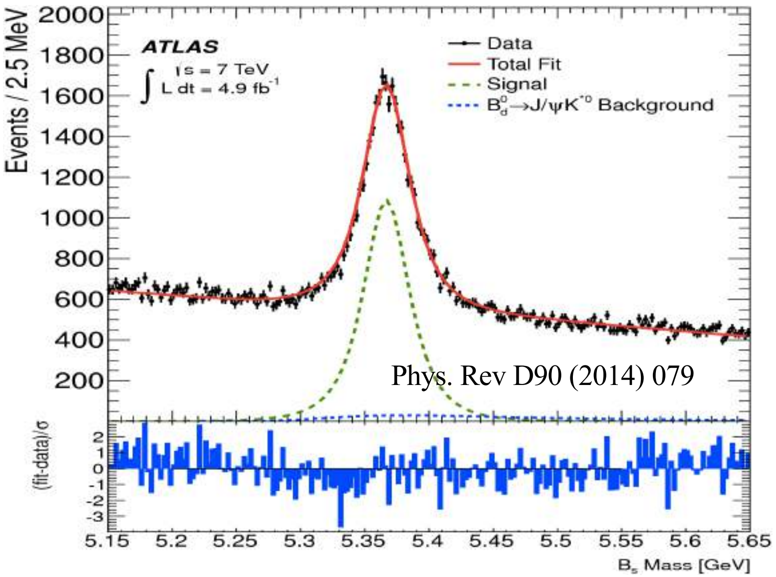
$$\Delta\Gamma_s = \Gamma_L - \Gamma_H$$

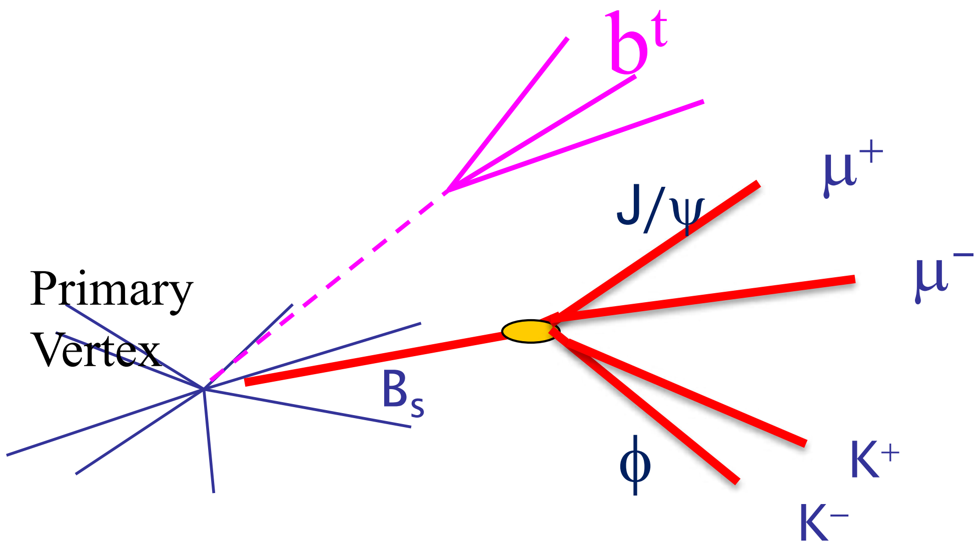
$$\Delta m_s = M_H - M_L$$

- Observable phase $\phi_s = -2\beta_s = \Phi_M - 2\,\Phi_D$
- In the Standard Model expected to be small $\phi_s = -\,0.0368$ radian
- Larger values possible in models of New Physics

Golden mode used by all LHC experiments $B_S \rightarrow J/\psi\ \phi$

- LHCb also studied $B_S \rightarrow J/\psi\ K^+K^-$, $B_S \rightarrow J/\psi\ \pi^+\pi^-$, $B_S \rightarrow \psi(2s)\phi$, $B_S \rightarrow D_s^+ D_s^-$

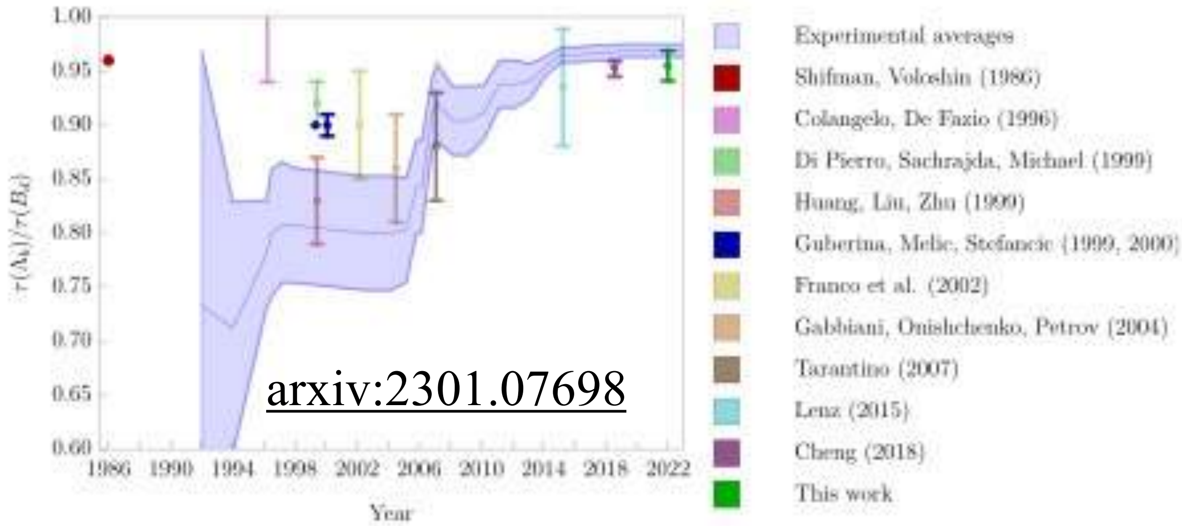


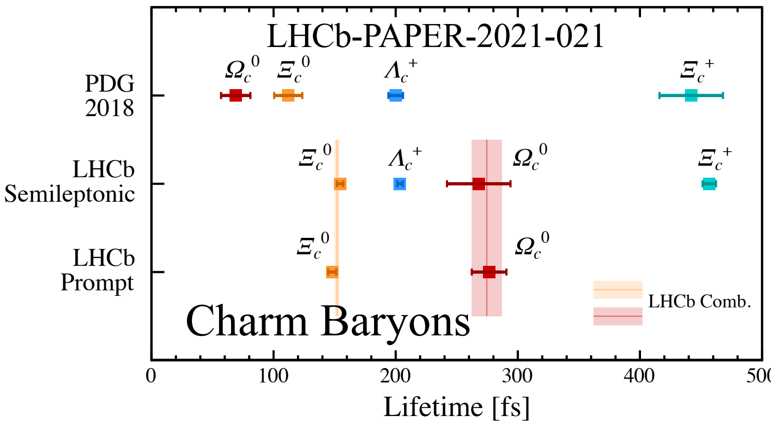


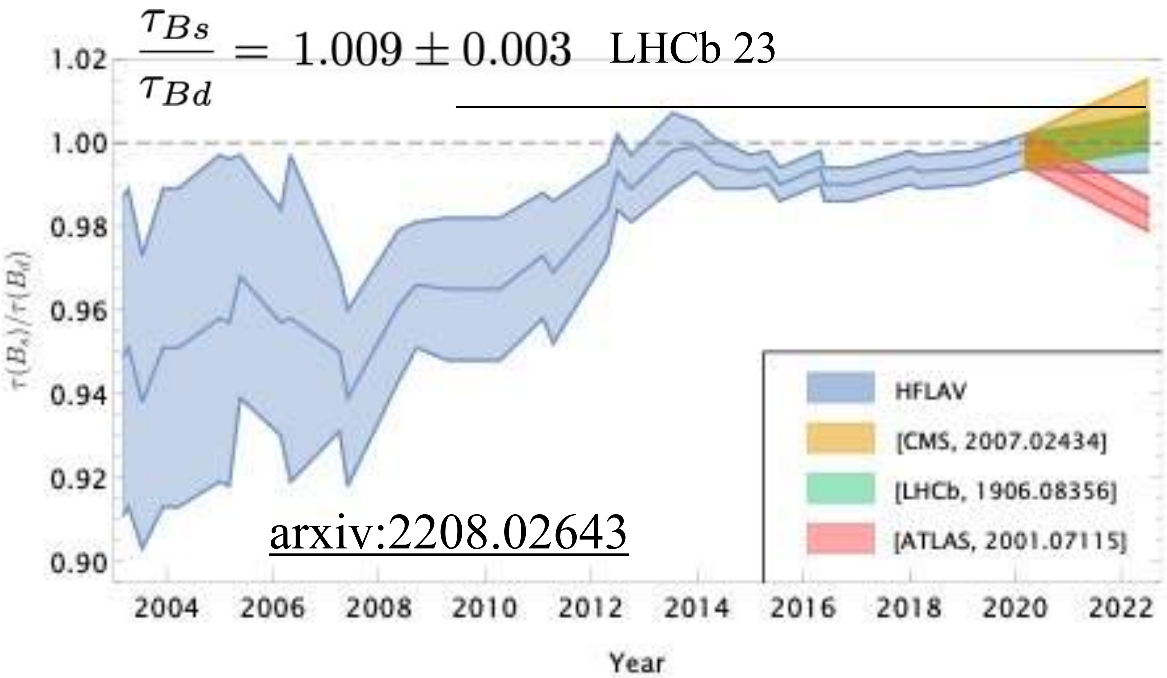
Time dependent studies

Understanding the decay-time distribution is critical for measurement of B-mixing parameters, particularly lifetimes

There is experimental evidence these studies are hard







Measuring the decay-time

$$t = \frac{m}{p} \cdot l$$

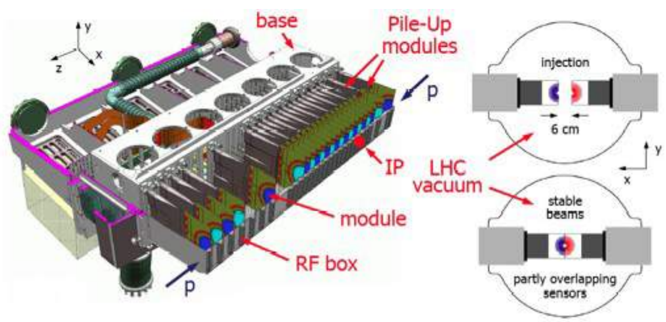
Critical to measure accurately and in unbiased way the decay length with the vertex detector

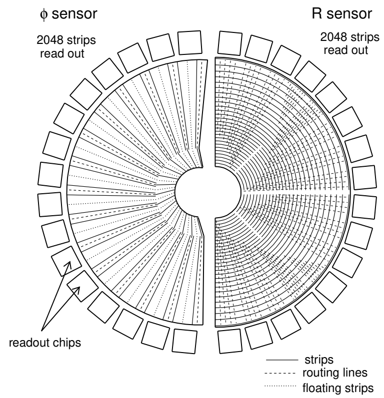
e.g. LHCb VELO (original version):

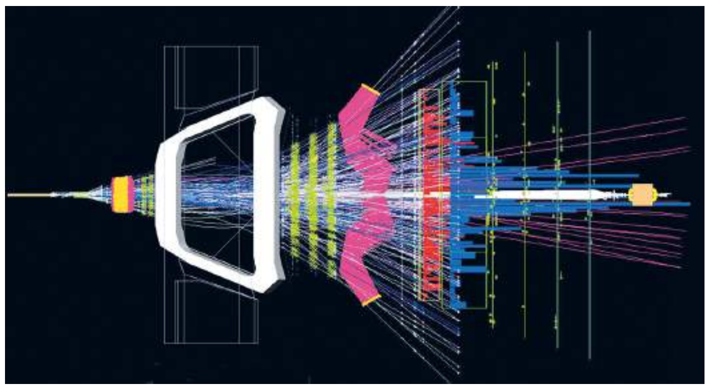
Two half detectors with modules with r and ϕ sensors

Track reconstruction for example combining projections in r-ϕ can lead to inefficiency at high times

Hadronic environment: cuts on decay-time related quantities to reduce rate







Modelling time acceptance

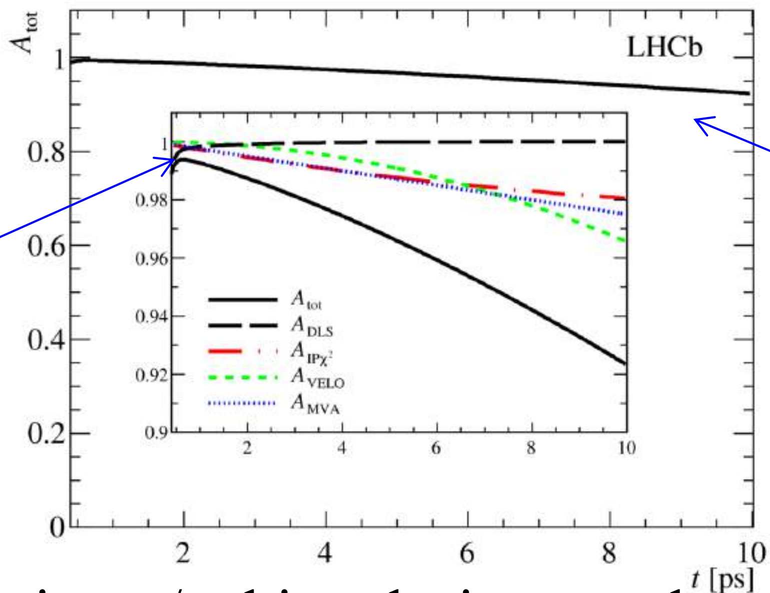
Two experimental approaches to understand decay time acceptance

Direct measurements

$B_s^0 \to J/\psi\eta$

Model + correct acceptance

Trigger/selection cuts



Velo efficiency IPCHI2 cuts

Use of data driven techniques/unbiased triggers where possible

Relative measurements

Use control channel with similar kinematics/trigger to signal to make relative measurement

ϕ_s: Looking back

- Extensive studies prior to first LHC running in 2009/10
- Golden mode $B_S \to J/\psi\ \phi$ extenstively studied but also many CP even modes
- CP odd modes (e.g $B_S \to J/\psi\ \pi^+\pi^-$) hardly considered

Channels	$\sigma(\phi_s)$ [rad]	Weight $(\sigma/\sigma_i)^2$ [%]
$B_s \to J/\psi\eta(\pi^+\pi^-\pi^0)$	0.142	2.3
$B_s \to D_sD_s$	0.133	2.6
$B_s \to J/\psi\eta(\gamma\gamma)$	0.109	3.9
$B_s \to \eta_c\phi$	0.108	3.9
Pure CP eigenstates	**0.060**	**12.7**
$B_s \to J/\psi\phi$	0.023	87.3
All CP eigenstates	**0.022**	**100.0**

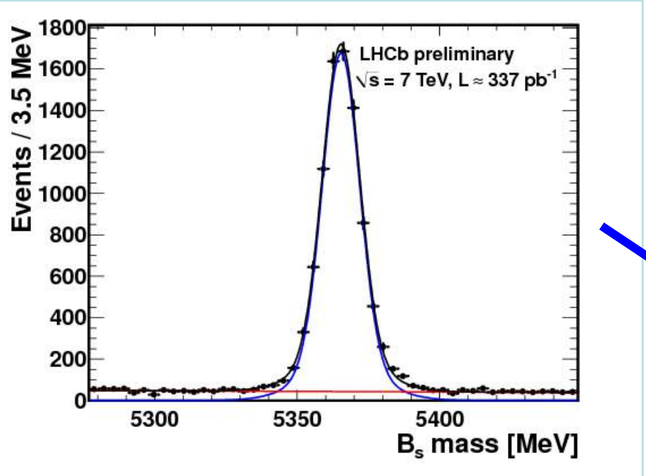
Thesis of Luis Fernandez
Summarized in LHCb-2006-047
Acta Phys. Pol. B 38 (2007) 931-940

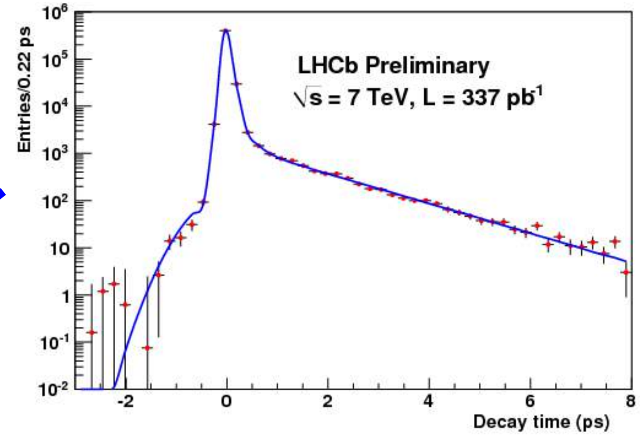
$2 fb^{-1}$

Reality – CP-odd studies turned out to be more favoured experimentally than CP-even

Measuring ϕ_s

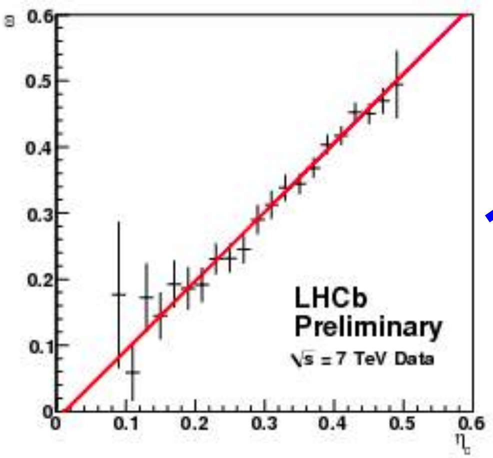
Mass distribution





Resolution model from prompt J/ψ Peak. Resolution ~ 50 fs

Unbinned maximum likelihood fit to mass, time and angles



Mistag rate measured using $B^+ \rightarrow J/\psi K^+$ calibration channel

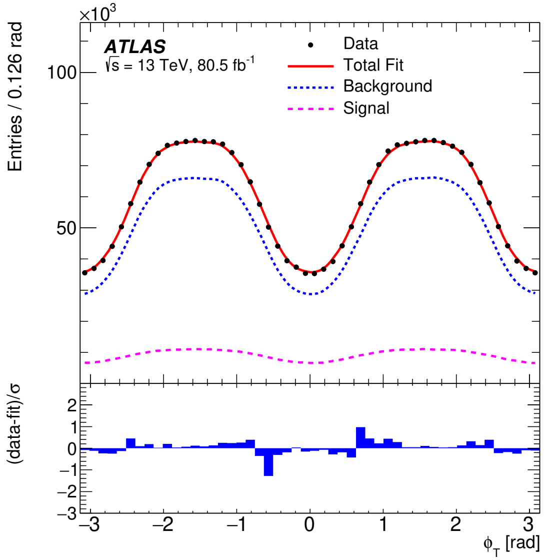
Angular acceptance for signal from simulation

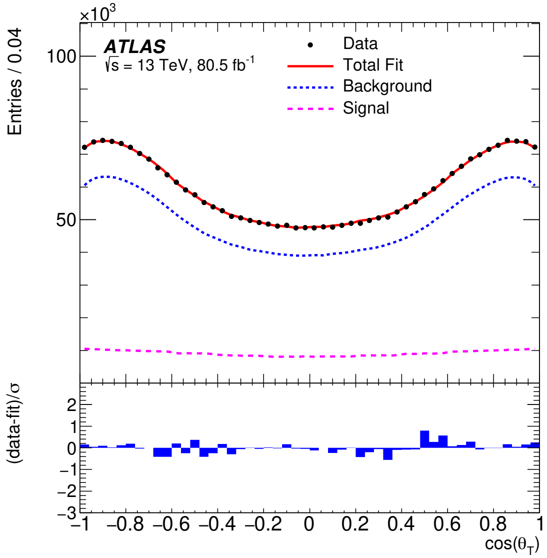
Time acceptance due to cuts in the trigger + reconstruction effects

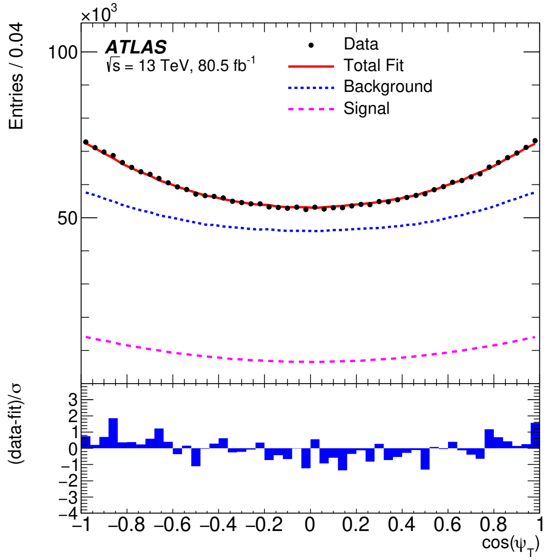
Eur. Phys. J. C 81 (2021) 342

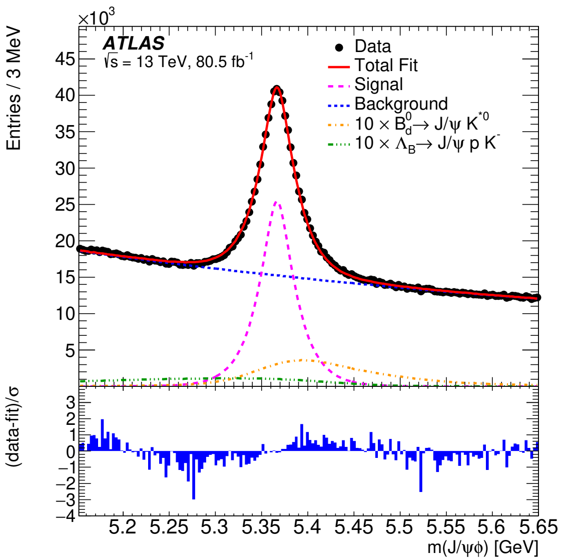
ϕ_s: ATLAS

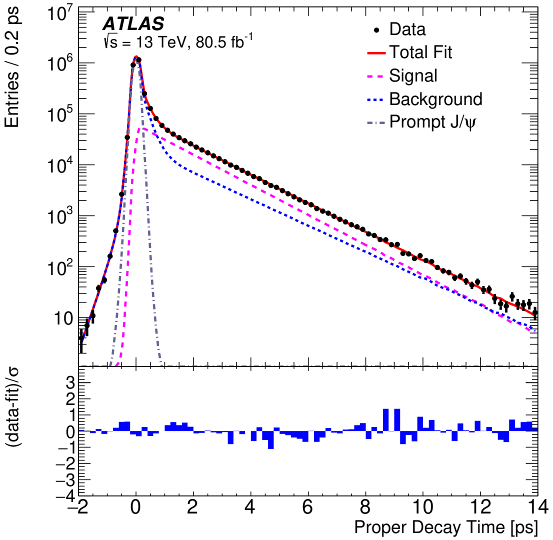
$B_s \to J/\psi\phi$











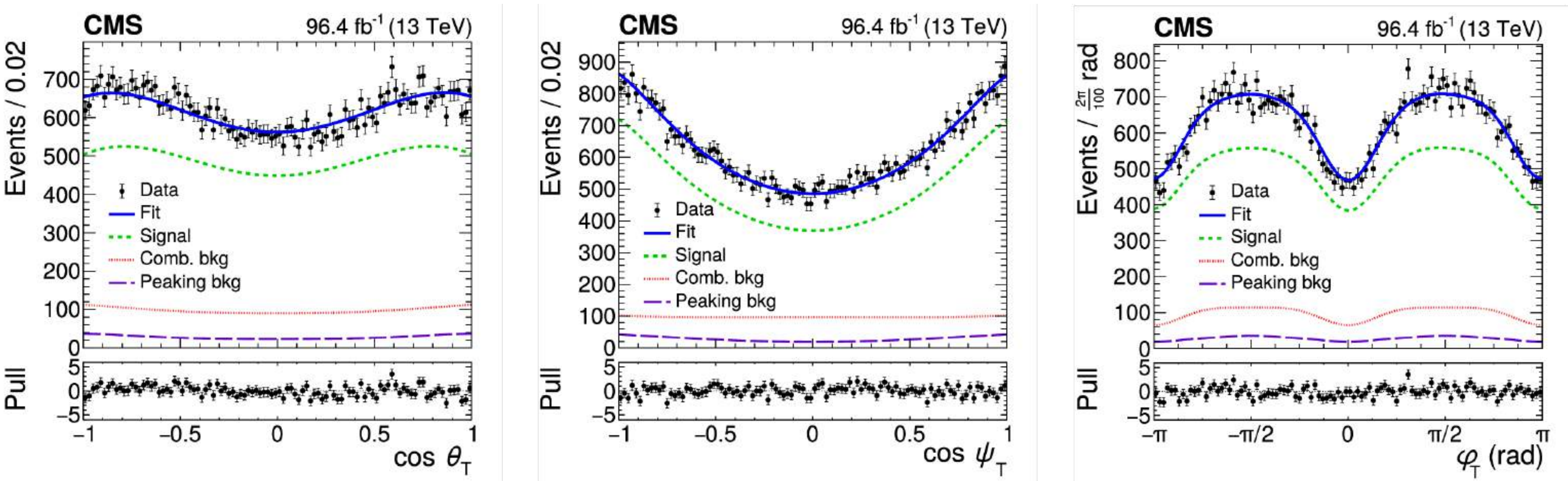
Data taken up to 2017

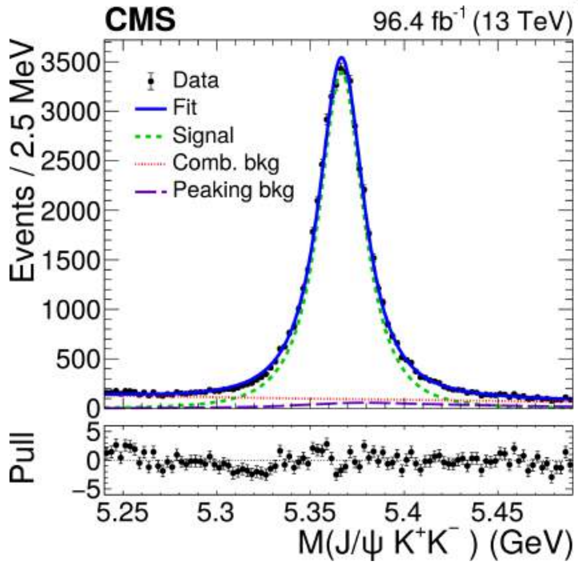
$$\phi_s = -0.087 \pm 0.036\ (\text{stat.}) \pm 0.021\ (\text{syst.})\text{rad}$$
$$\Delta\Gamma_s = 0.0657 \pm 0.0043(\text{stat.}) \pm 0.0037(\text{syst.})\text{ps}^{-1}$$
$$\Gamma_s = 0.6703 \pm 0.0014(\text{stat.}) \pm 0.0018(\text{syst.})\text{ps}^{-1}$$

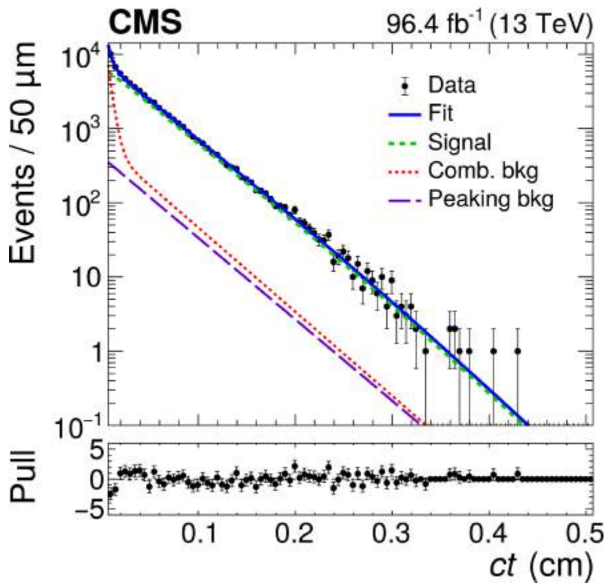
Phys. Lett. B 816 (2021) 136188

ϕ_s: CMS

$B_s \to J/\psi\phi$







8 TeV data plus

96.4 fb^{-1} up from 2017-18

$$\phi_s = -21 \pm 44\,(\text{stat}) \pm 10\,(\text{syst})\,\text{mrad},$$

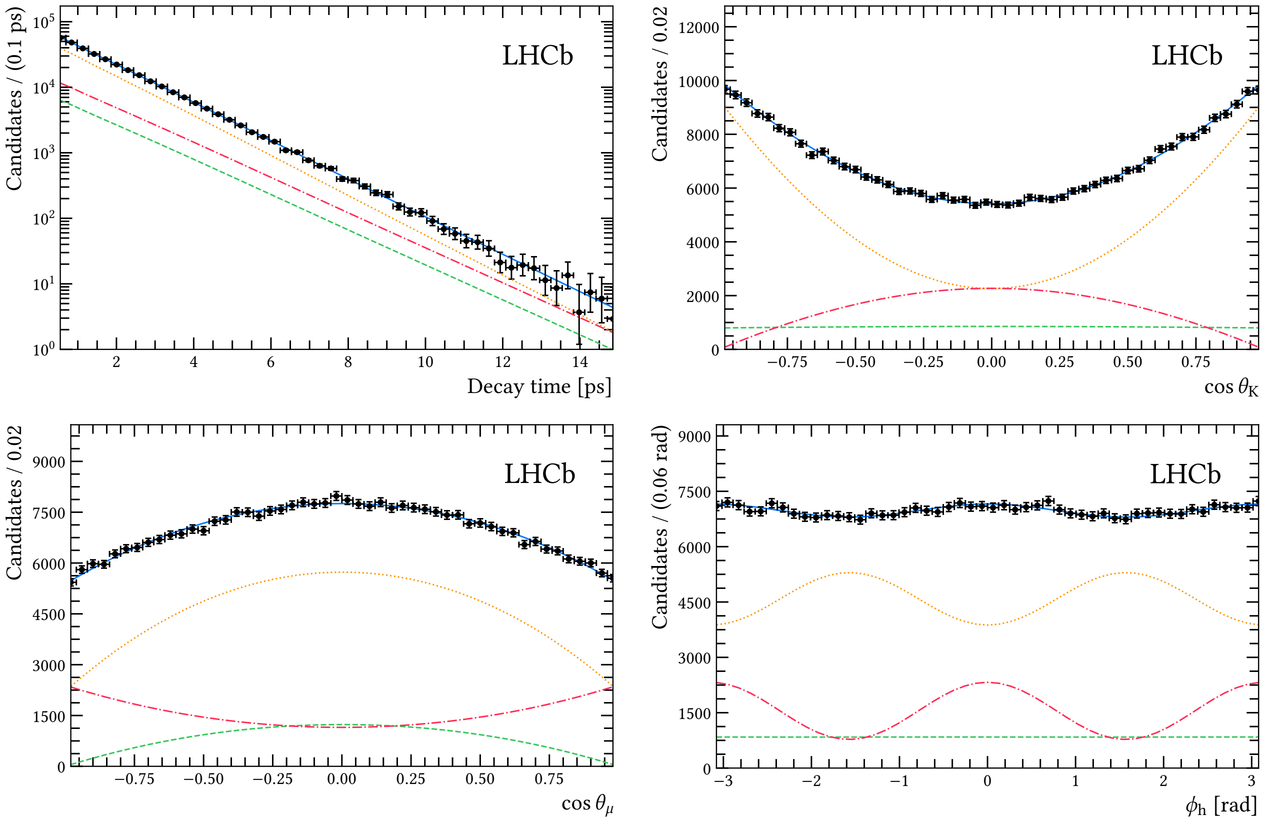
$$\Delta\Gamma_s = 0.1032 \pm 0.0095\,(\text{stat}) \pm 0.0048\,(\text{syst})\,\text{ps}^{-1}$$

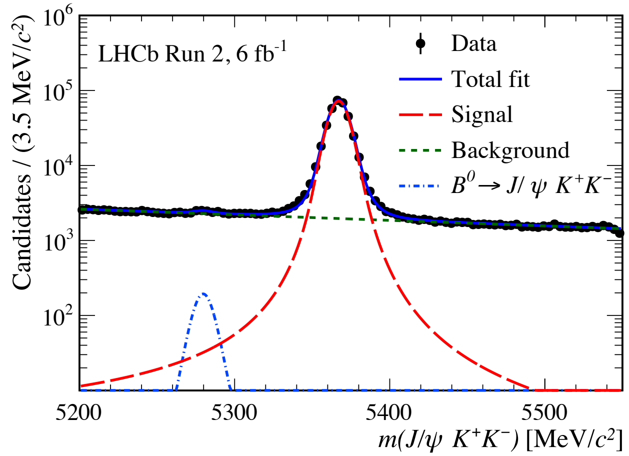
New

ϕ_s: LHCb

$B_s \to J/\psi\phi$

New LHCb result analysing full Run 2 dataset





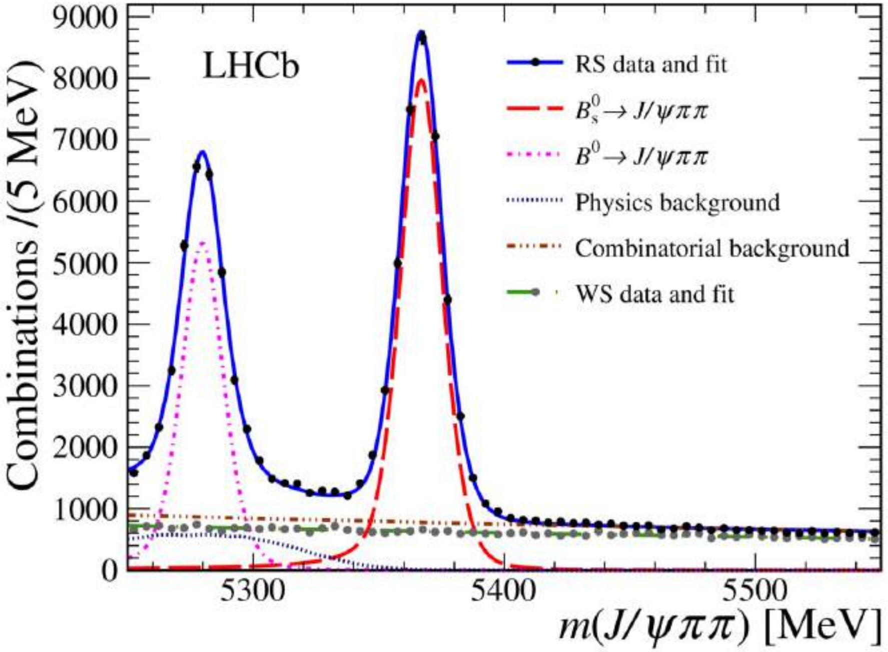
Parameters	Values [1]
ϕ_s [rad]	$-0.039 \pm 0.022 \pm 0.006$
$\lvert\lambda\rvert$	$1.001 \pm 0.011 \pm 0.005$
$\Gamma_s - \Gamma_d$ [ps^{-1}]	$-0.0056\,^{+0.0013}_{-0.0015} \pm 0.0014$
$\Delta\Gamma_s$ [ps^{-1}]	$0.0845 \pm 0.0044 \pm 0.0024$
Δm_s [ps^{-1}]	$17.743 \pm 0.033 \pm 0.009$
$\lvert A_\perp\rvert^2$	$0.2463 \pm 0.0023 \pm 0.0024$
$\lvert A_0\rvert^2$	$0.5179 \pm 0.0017 \pm 0.0032$
$\delta_\perp - \delta_0$ [rad]	$2.903\,^{+0.075}_{-0.074} \pm 0.048$
$\delta_\parallel - \delta_0$ [rad]	$3.146 \pm 0.060 \pm 0.052$

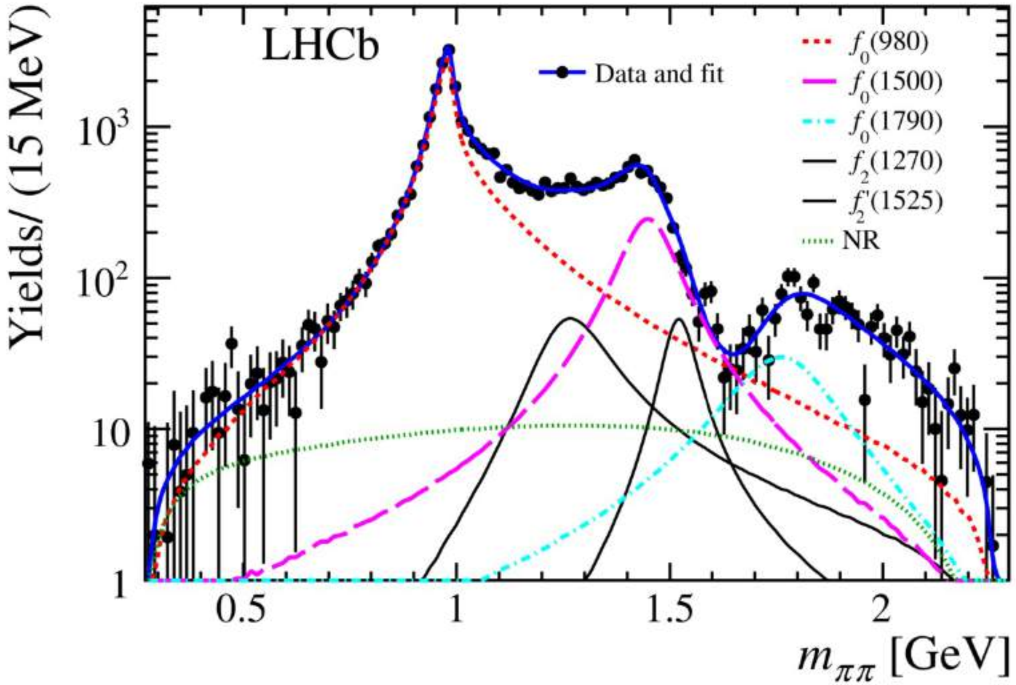
LHCb-Paper-2023-016

ϕ_s: LHCb

LHCb has also measured from a time dependent amplitude analysis of $B_S \to J/\psi\ \pi^+\pi^-$ using data up to 2016 used

PHYS. LETT. B797 (2019) 134789



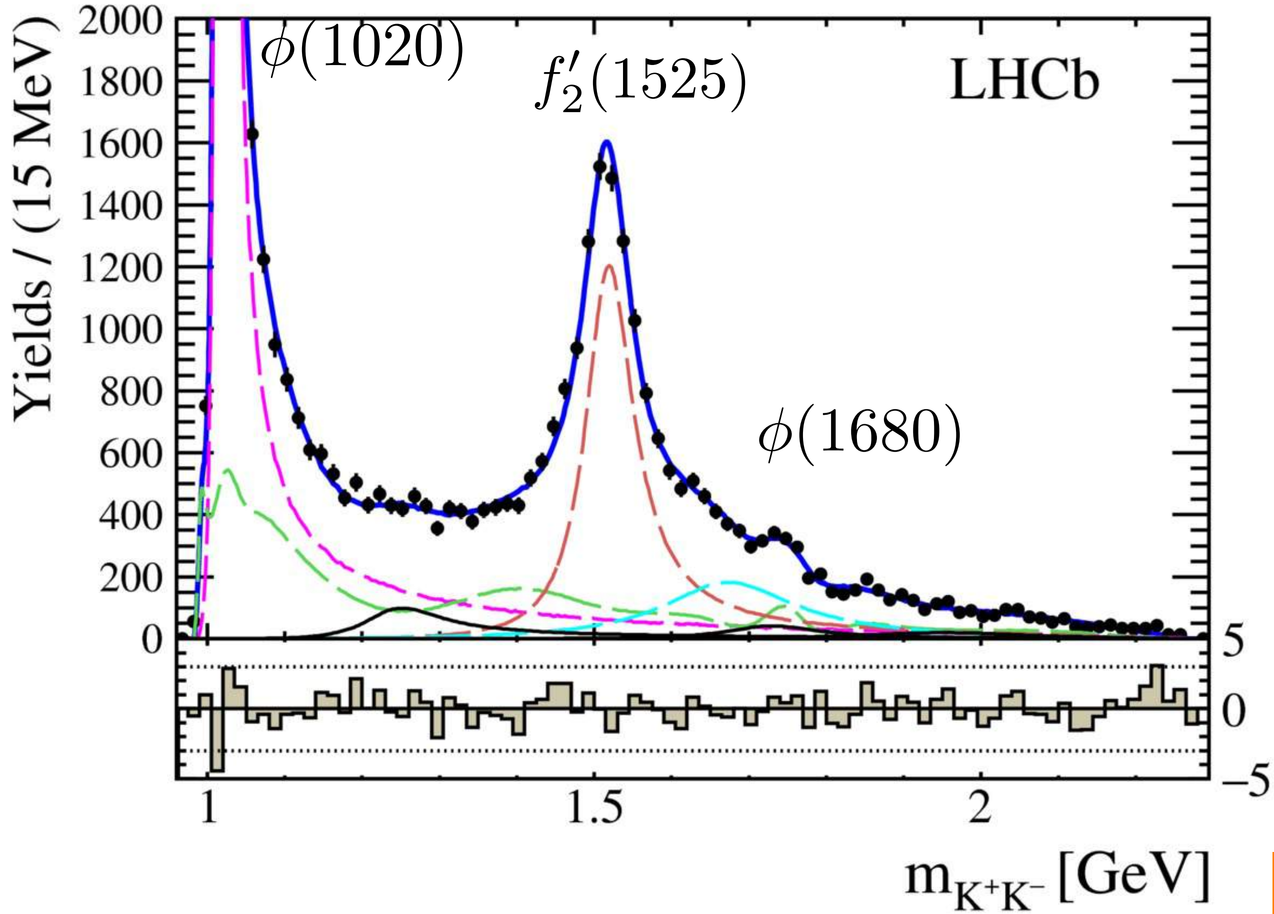


	Fit result	Correlation		
Parameter		$\Gamma_H - \Gamma_{B^0}$	$\lvert\lambda\rvert$	ϕ_s
$\Gamma_H - \Gamma_{B^0}$ (ps^{-1})	$-0.050 \pm 0.004 \pm 0.004$	1.000	0.022	0.038
$\lvert\lambda\rvert$	$1.01^{+0.08}_{-0.06} \pm 0.03$	0.022	1.000	0.065
ϕ_s (rad)	$-0.057 \pm 0.060 \pm 0.011$	0.038	0.065	1.000

Uncertainty on Γ_{B0} similar size

LHCb: High mass KK

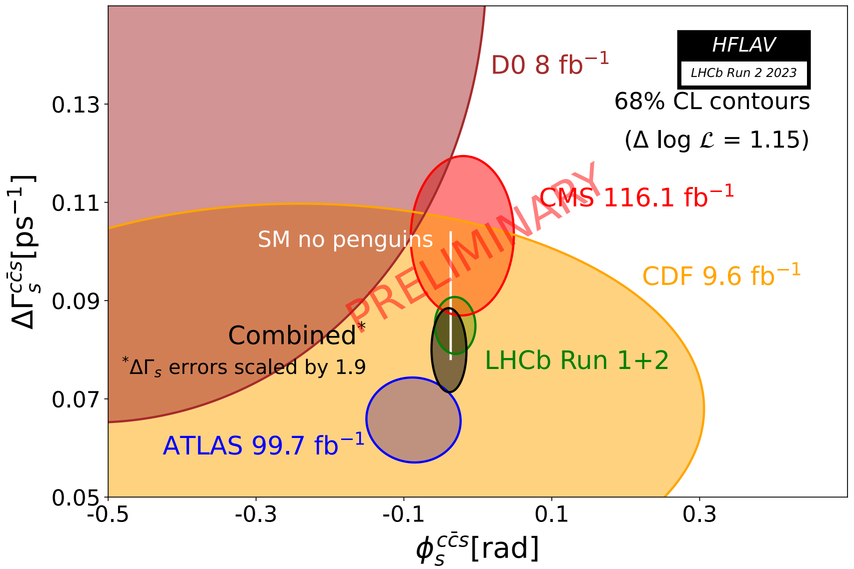
JHEP08(2017)037



LHCb has studied CP violation using J/ψKK events above ϕ resonance with Run 1 data

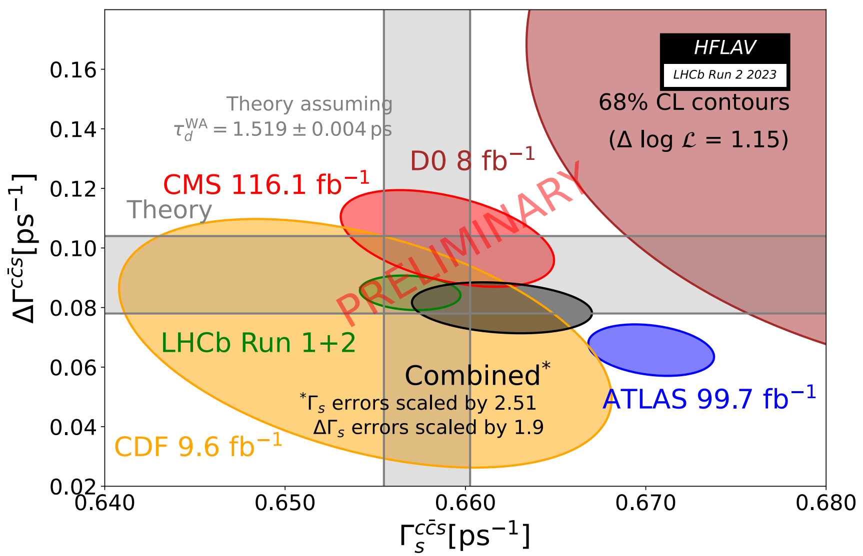
$$\phi_s = 119 \pm 107 \pm 34\,\text{mrad},$$
$$|\lambda| = 0.994 \pm 0.018 \pm 0.006,$$
$$\Gamma_s = 0.650 \pm 0.006 \pm 0.004\,\text{ps}^{-1}$$
$$\Delta\Gamma_s = 0.066 \pm 0.018 \pm 0.010\,\text{ps}^{-1}$$

Summary of ϕ_s



$B_S \to J/\psi\phi$
ATLAS
CMS
LHCb
CDF
D0

LHCb:
$B_S \to J/\psi\ K^+K^-$
$B_S \to J/\psi(ee)\ K^+K^-$
$B_S \to J/\psi\ \pi^+\pi^-$
$B_S \to \psi(2s)\phi$
$B_S \to D_s^+D_s^-$



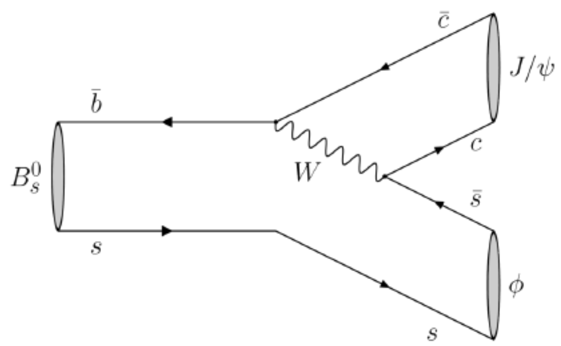
$$\phi_s^{J/\psi KK} = -0.050 \pm 0.017\,\text{rad}$$

$$\phi_s^{c\bar{c}s} = -0.039 \pm 0.016\,\text{rad}$$

In agreement with the SM predictions
Note large scale factor on $\Delta\Gamma_s$, Γ_s
reflecting tensions in experimental data

Penguin Pollution

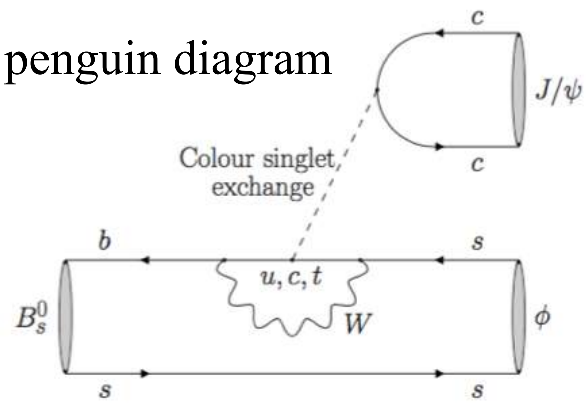
tree



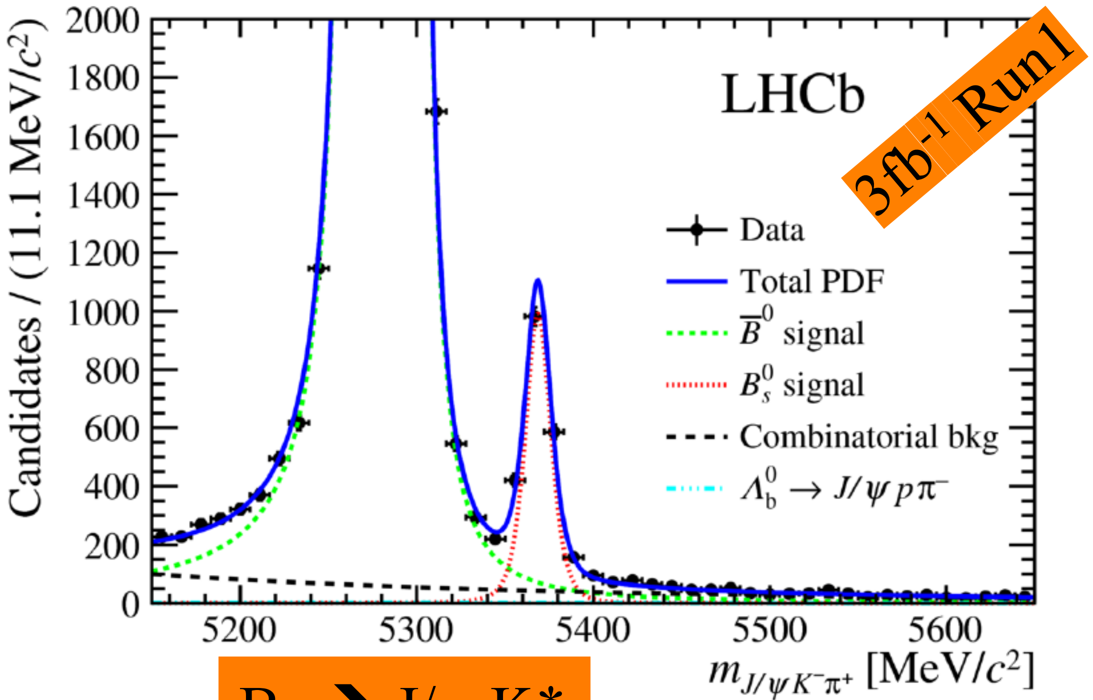
Penguin contributions could mimic NP effects

Study using other modes related by SU(3) symmetry to limit size using data
e.g. B_s ➔ J/ψ K*, B^0 ➔ $J/\psi\rho$

penguin diagram



$$A\left(B_s^0 \to (J/\psi\, \overline{K}^{*0})_i\right) = -\lambda \mathcal{A}_i \left[1 - a_i e^{\mathrm{i}\theta_i} e^{\mathrm{i}\gamma}\right]$$

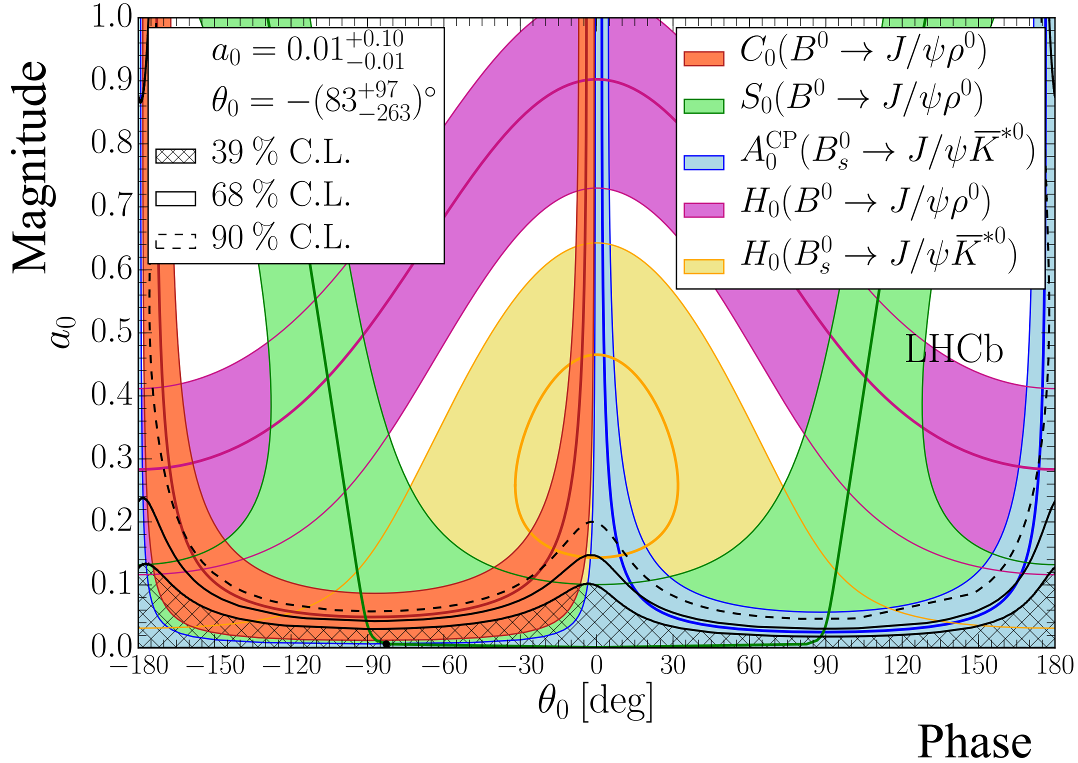


JHEP 11 (2015) 082
Phys Lett B742 (2015) 38

B_s ➔ J/ψ K*

Penguin Pollution

Fit to CP observables + polarization amplitudes in B_s ➔ J/ψ K*, B^0 ➔ J/ψρ

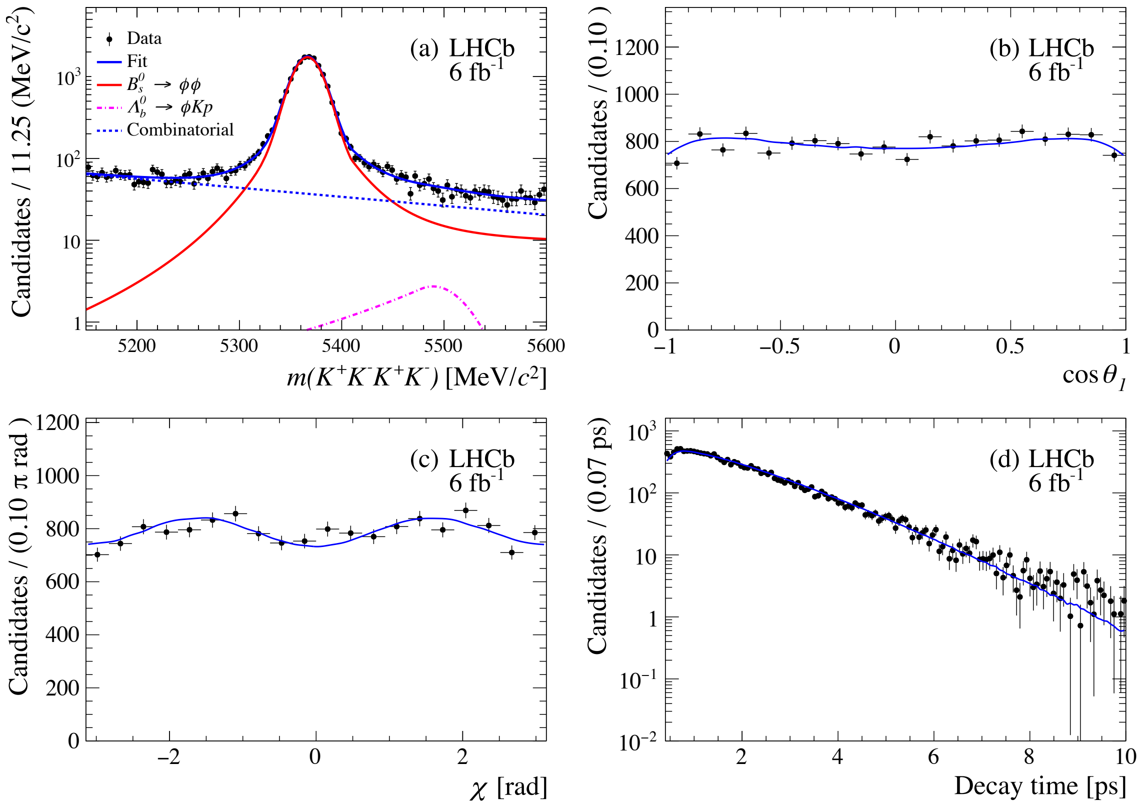


JHEP 11 (2015) 082
Phys Lett B742 (2015) 38

$$\Delta\phi_{s,0}^{J/\psi\phi} = 0.000^{+0.009}_{-0.011}\,(\text{stat})\ ^{+0.004}_{-0.009}\,(\text{syst})\,\text{rad}\,,$$
$$\Delta\phi_{s,\parallel}^{J/\psi\phi} = 0.001^{+0.010}_{-0.014}\,(\text{stat}) \pm 0.008\,(\text{syst})\,\text{rad}\,,$$
$$\Delta\phi_{s,\perp}^{J/\psi\phi} = 0.003^{+0.010}_{-0.014}\,(\text{stat}) \pm 0.008\,(\text{syst})\,\text{rad}\,.$$

Effect of penguins bounded to be less than current uncertainties

LHCb: and charmless…



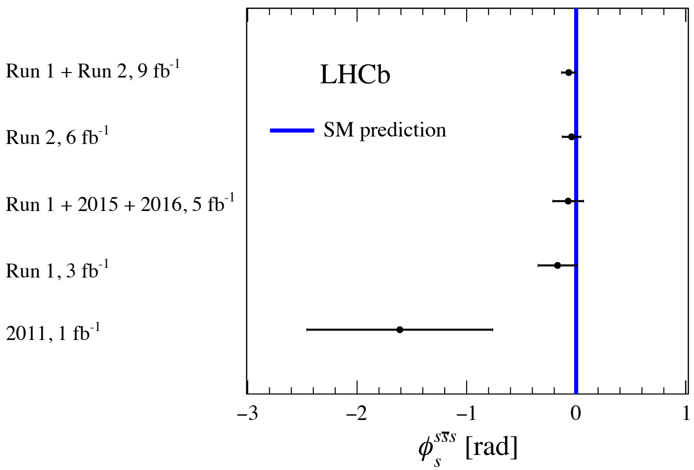
Can also look for CP violation in B_s mixing in loop diagrams

e.g $B_s^0 \to \phi\phi$

Run 2 update this Spring

$$\phi_s^{s\bar{s}s} = -0.043 \pm 0.075 \pm 0.009\,\text{rad}$$

$$\phi_s^{s\bar{s}s} = -0.074 \pm 0.069\,\text{rad}$$



Lots of other modes to explore

$B_s^0 \to K^* \overline{K}^*$ studied with Run 1

$B_s^0 \to \phi\pi^+\pi^-$ observed in Run 1

arxiv: 2304.06198

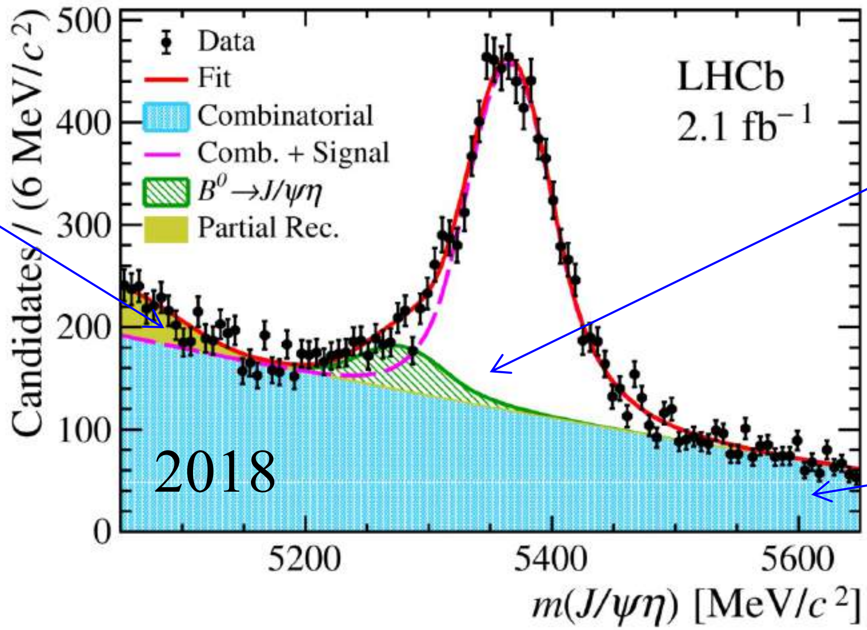
Untagged Measurements

arxiv: 2206.03088

$B_s \rightarrow J/\psi\eta$ lifetime: Run 2

$B_s^0 \rightarrow J/\psi\eta X$

$B_d^0 \rightarrow J/\psi\eta$

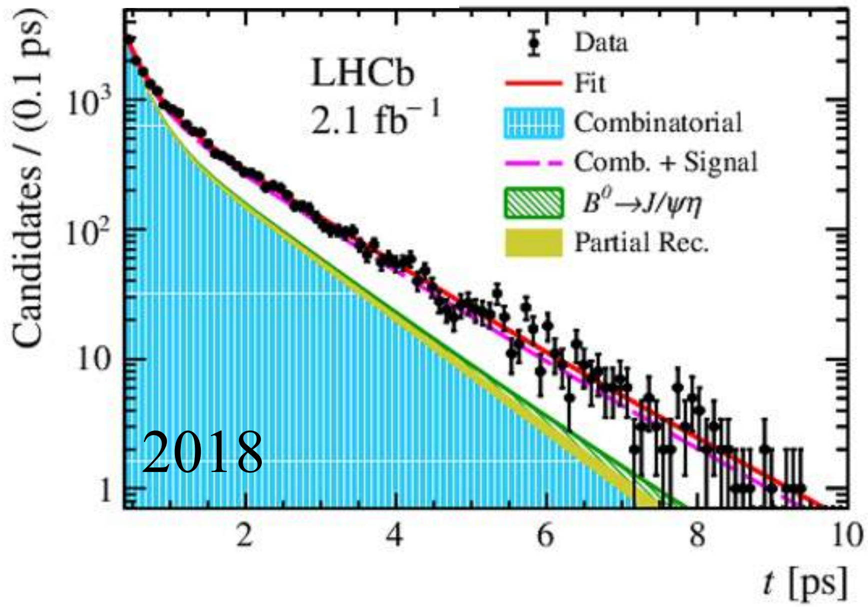


combinatorial

Effective lifetime in this channel previously studied with Run 1 data

Update study to Run 2

~ 15k candidates in Run 2 data



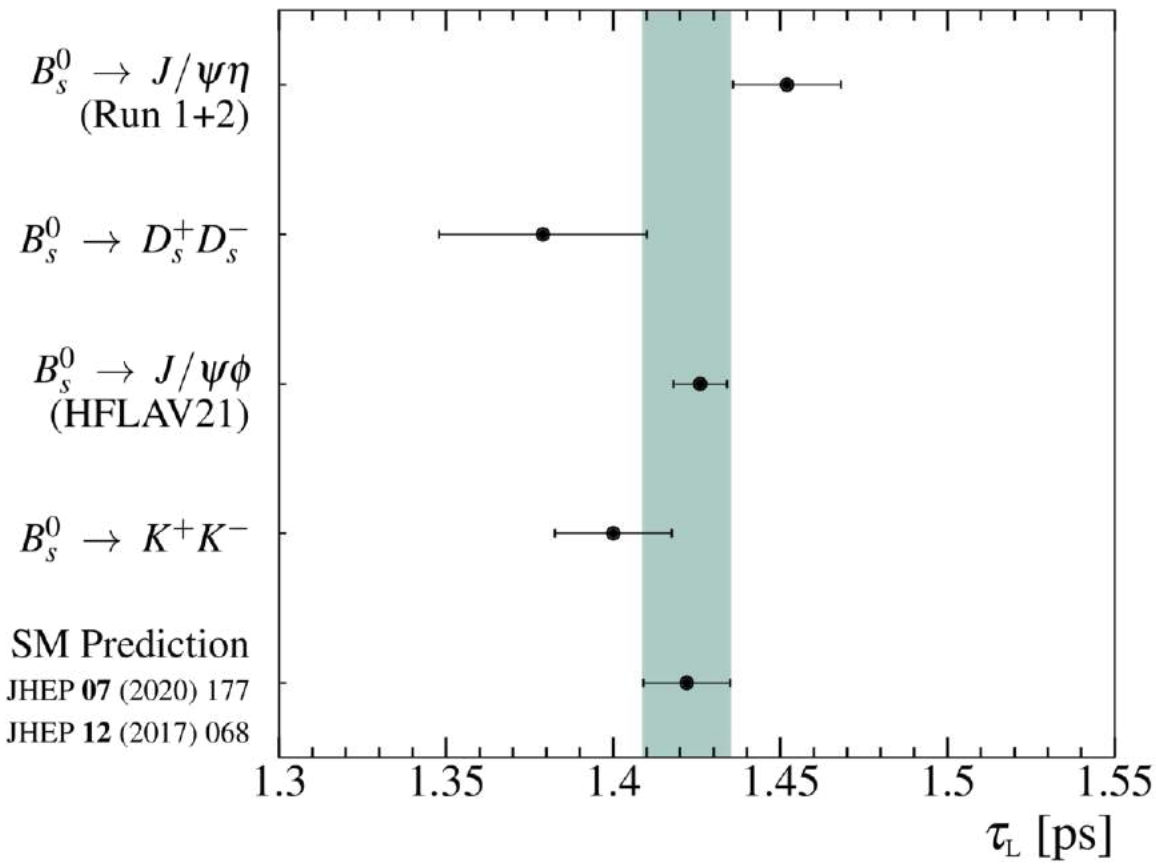
Accepted by EJPC

arxiv: 2206.03088

$B_s \rightarrow J/\psi\eta$ lifetime: Run 2

Run 2 $\tau_L = 1.445 \pm 0.016(\text{stat}) \pm 0.008(\text{syst})$ ps.

Run 1+ 2 avg $\tau_L = 1.452 \pm 0.014 \pm 0.007 \pm 0.002$ ps

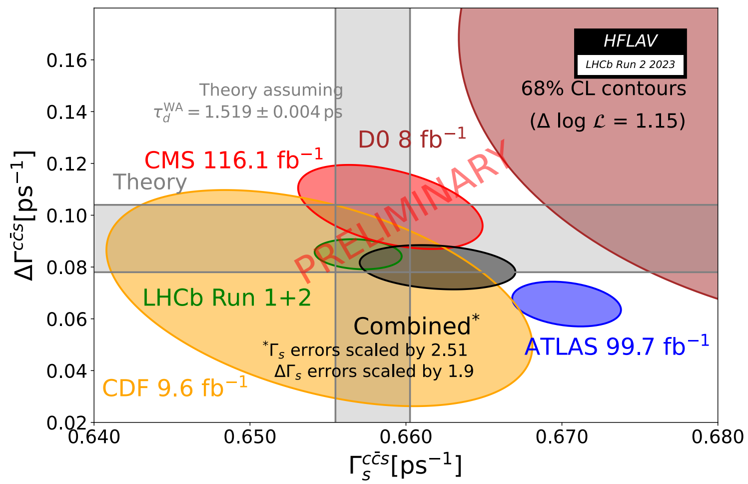


Result in good agreement with SM prediction and other decay modes

Statistically limited. Room for improvement in Run 3

B_s lifetime summary

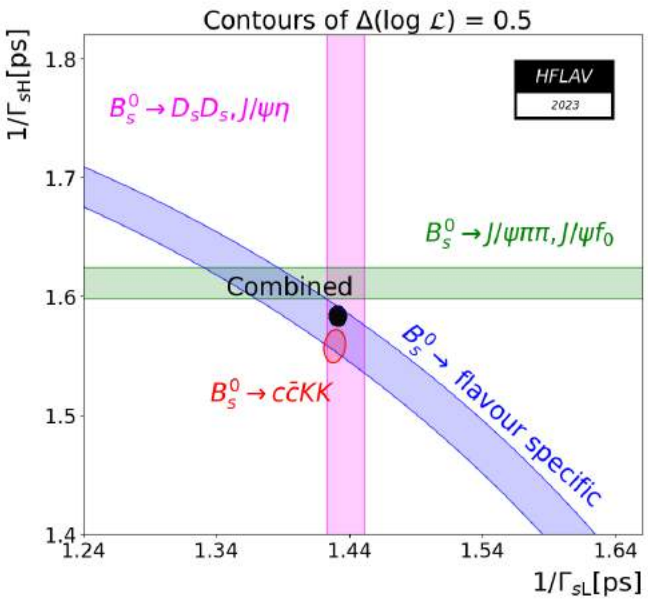
Effective lifetimes less precise but consistent with $B_s \to J/\psi\phi$

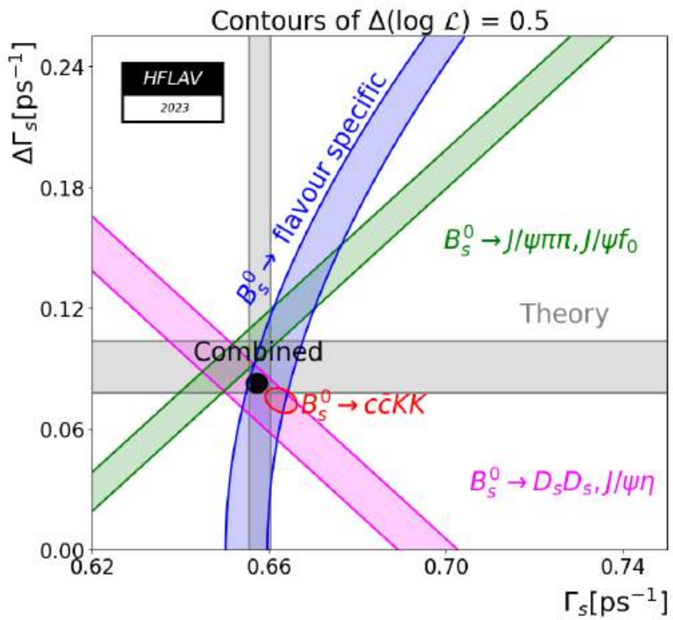


Tension in measurements of both $\Delta\Gamma_s$ and Γ_s using $B_s \to J/\psi\phi$ by the LHC collaborations

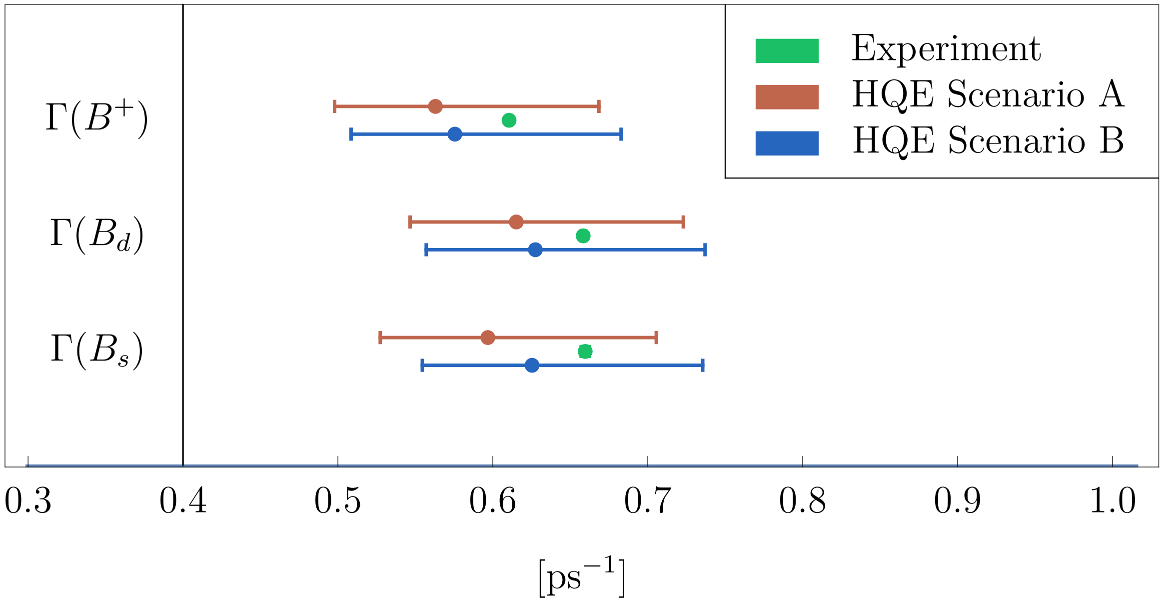
Effective lifetimes tend to favour $\Delta\Gamma_s$ higher than ATLAS

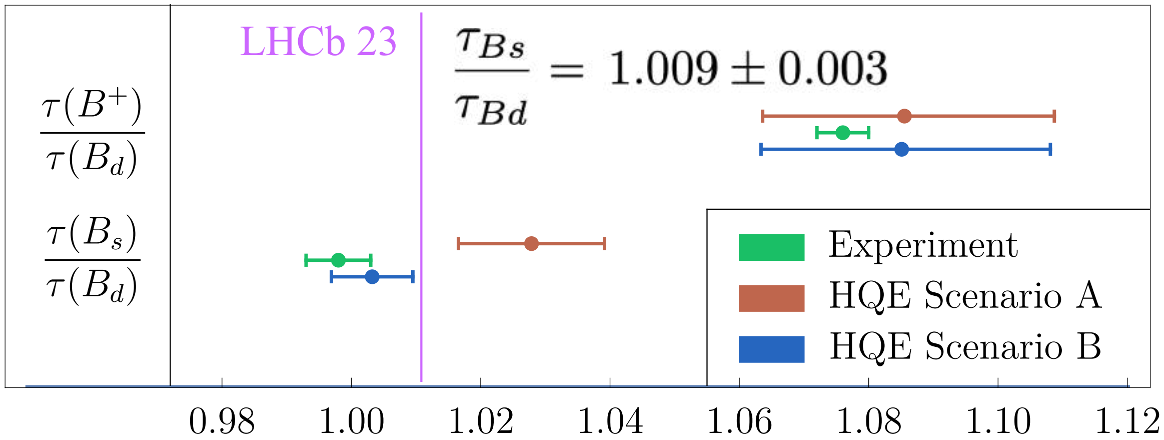
Maybe largely aesthetic at moment but if you dig deep working out where/how Bd lifetime goes into effective lifetimes is a bit of a mess.





B_s lifetime summary





Observable	HQE Scenario A	HQE Scenario B	Exp. value
$\Gamma(B^+)[\mathrm{ps}^{-1}]$	$0.563^{+0.106}_{-0.065}$	$0.576^{+0.107}_{-0.067}$	0.6105 ± 0.0015
$\Gamma(B_d)[\mathrm{ps}^{-1}]$	$0.615^{+0.108}_{-0.069}$	$0.627^{+0.110}_{-0.070}$	0.6583 ± 0.0017
$\Gamma(B_s)[\mathrm{ps}^{-1}]$	$0.597^{+0.109}_{-0.069}$	$0.625^{+0.110}_{-0.071}$	0.6596 ± 0.0026
$\tau(B^+)/\tau(B_d)$	$1.0855^{+0.0232}_{-0.0219}$	$1.0851^{+0.0230}_{-0.0217}$	1.076 ± 0.004
$\tau(B_s)/\tau(B_d)$	$1.0279^{+0.0113}_{-0.0113}$	$1.0032^{+0.0063}_{-0.0063}$	0.998 ± 0.005

arxiv: 2208.02643

CP even modes: Other possibilities

As mentioned before data taking many CP-even modes were studied in the context of ϕ_s

$$\eta' \to \rho^0\gamma$$
$$\eta' \to \eta\pi^+\pi^-$$
$$\eta \to \pi^0\pi^+\pi^-$$

Branching fraction measurements made using these modes e.g. JHEP 01 (2015) 024 that probe SU(3), $\eta - \eta'$ mixing
Modes with 2 photons are clean but limited statistics, order 1000 - 2000 events
Single photons good statistics, more challenging backgrounds

$\eta' \to \rho^0\gamma$ has reasonable statistics and can be used to measure $\Delta\Gamma_s$ independent of B^0 lifetime in combination with $B_S \to J/\psi\ \pi^+\pi^-$

Other modes with small branching fractions, feasible but not explored

$$\eta \to \pi^+\pi^-\gamma \qquad \eta' \to \gamma\gamma$$

Branching fraction measurements of ψ(2S) modes made with Run 1 (see NUCL. PHYS. B871 (2013) 403), No studies of effective lifetimes

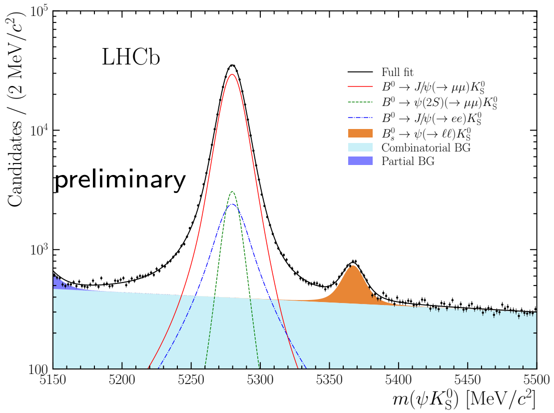
$\sin 2\beta$

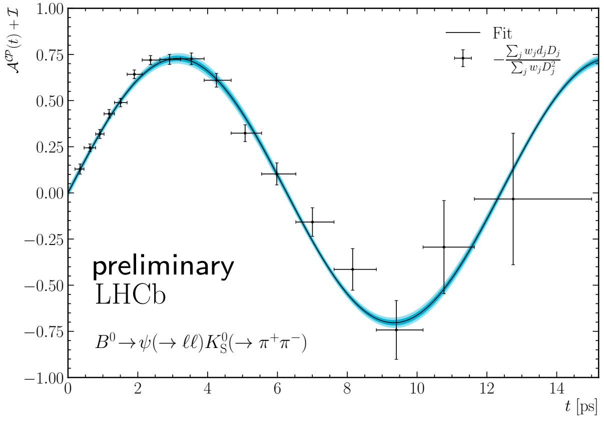
sin 2β

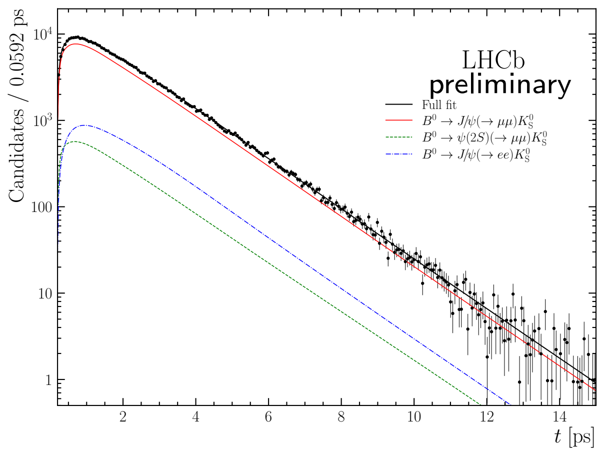
New

LHCb-Paper-2023-013

New LHCb Run 2 results using $B_d \to J/\psi K_s$ (both muons and electrons) and $B_d \to \psi(2S)K_s$



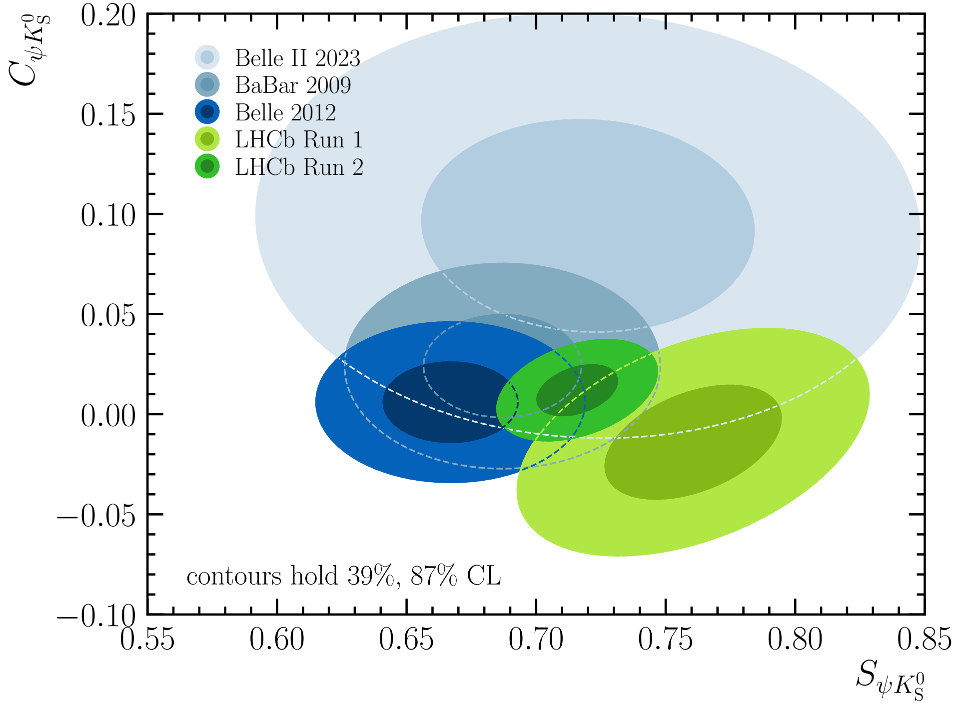


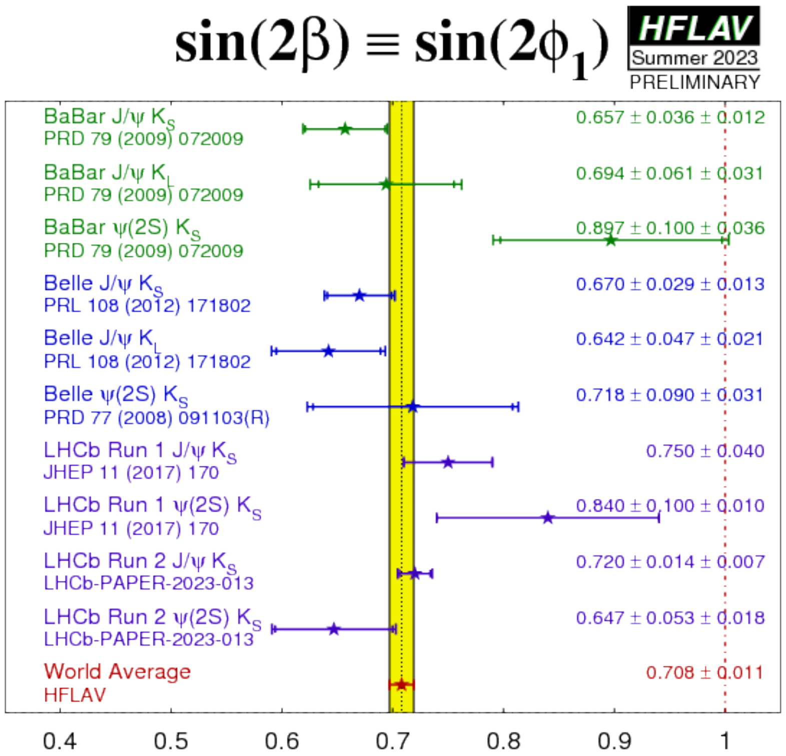


$$N_{J/\psi(\to\mu\mu)K^0_S} = 306\,322 \pm 619$$
$$N_{J/\psi(\to ee)K^0_S} = 42\,870 \pm 269$$
$$N_{\psi(2S)(\to\mu\mu)K^0_S} = 23\,570 \pm 164$$

$$S^{\text{Run 2}}_{J/\psi(\to\mu^+\mu^-)K^0_S} = 0.714 \pm 0.015\,(\text{stat}) \pm 0.007\,(\text{syst})$$
$$C^{\text{Run 2}}_{J/\psi(\to\mu^+\mu^-)K^0_S} = 0.013 \pm 0.014\,(\text{stat}) \pm 0.003\,(\text{syst})$$
$$S^{\text{Run 2}}_{\psi(2S)K^0_S} = 0.647 \pm 0.053\,(\text{stat}) \pm 0.018\,(\text{syst})$$
$$C^{\text{Run 2}}_{\psi(2S)K^0_S} = -0.083 \pm 0.048\,(\text{stat}) \pm 0.005\,(\text{syst})$$
$$S^{\text{Run 2}}_{J/\psi(\to e^+e^-)K^0_S} = 0.752 \pm 0.037\,(\text{stat}) \pm 0.084\,(\text{syst})$$
$$C^{\text{Run 2}}_{J/\psi(\to e^+e^-)K^0_S} = 0.046 \pm 0.034\,(\text{stat}) \pm 0.008\,(\text{syst})$$

sin 2β





LHCb Run 2 result most precise to date

Still dominated by statistical uncertainty

Important systematic from $\Delta\Gamma_d$

Source	$\sigma(S)$	$\sigma(C)$
Fitter validation	0.0004	0.0006
$\Delta\Gamma_d$ uncertainty	0.0055	0.0017
FT calibration portability	0.0053	0.0001
FT $\Delta\epsilon_{tag}$ portability	0.0014	0.0017
Decay-time bias model	0.0007	0.0013

sin 2β: Looking back

PROCEEDINGS OF THE WORKSHOP ON STANDARD MODEL PHYSICS (AND MORE) AT THE LHC

Tagging method	ATLAS		CMS		LHCb	
	$\mu^+\mu^-$	e^+e^-	$\mu^+\mu^-$	e^+e^-	$\mu^+\mu^-$	e^+e^-
Lepton	0.039	0.031	0.031		n/a	n/a
B–π	0.026	n/a	0.023		n/a	n/a
SS Jet charge	n/a	n/a	0.021		n/a	n/a
OS Jet charge	n/a	n/a	0.023		n/a	n/a
Lepton and kaon	n/a	n/a	n/a		0.023	0.051
Total	0.017		0.015		0.021	

LHCb numbers for 2fb^{-1}

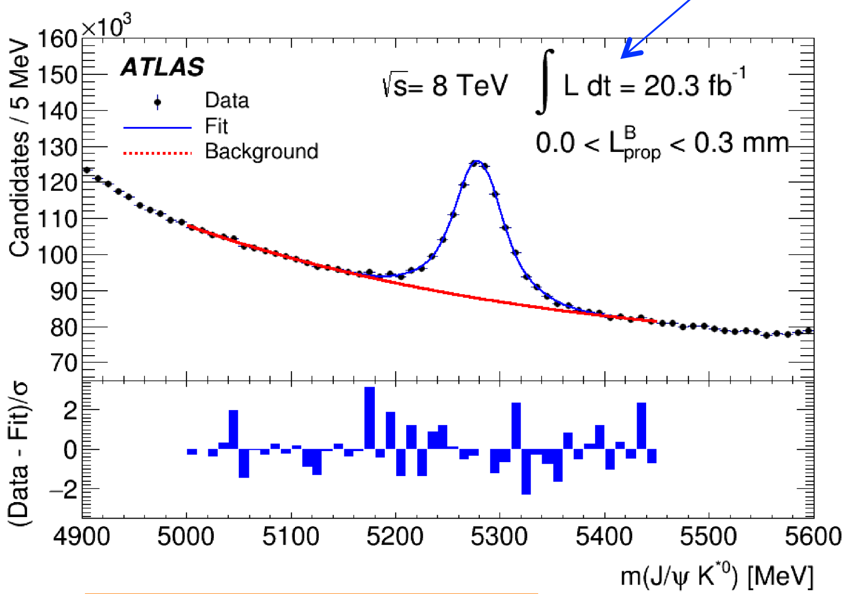
- Expected LHCb precision with 6 fb^{-1}(back in 2000) was 0.012
- Achieved 0.015, which is remarkably close
  - Especially considering the reoptimization of the detector led to less acceptance for K_s

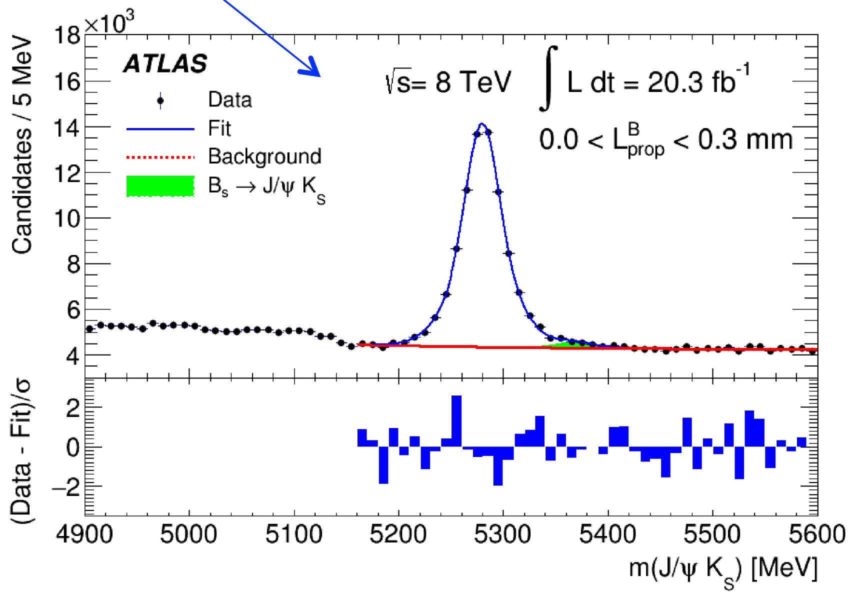
$\Delta\Gamma_d$

$\Delta\Gamma_d$

Tension between D0 like-sign dimuon measurement and SM led to renewed interested in $\Delta\Gamma_d$ a decade or so ago.
Important systematic in $\sin 2\beta$ measurement
Measurements from all three LHC collaborations. Most precise experimental result from ATLAS

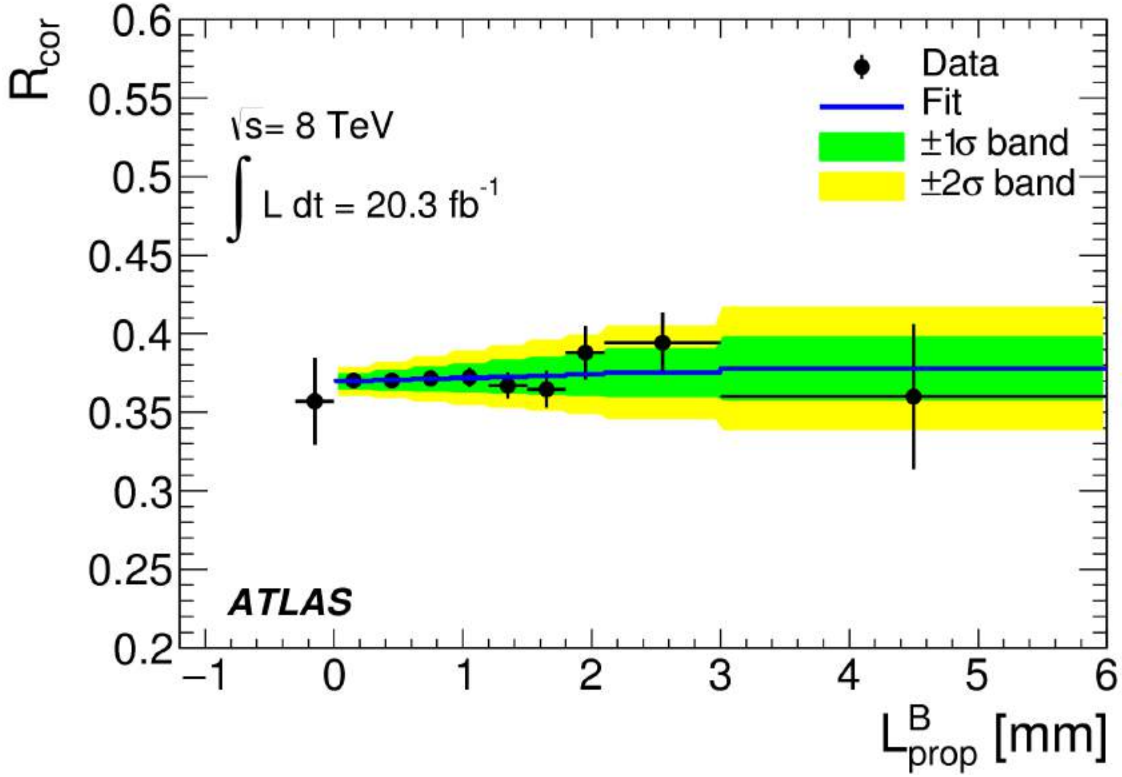
Compare lifetimes in B ➔ J/ψ K* and B ➔ J/ψ K_s





arXiv:1605.07485

$\Delta\Gamma_d$



Fit yields of the channels in bins of decay length

$$R_{i,\mathrm{uncor}} = \frac{N_i(J/\psi K_S)}{N_i(J/\psi K^{*0})}$$

Correct for detector efficiency

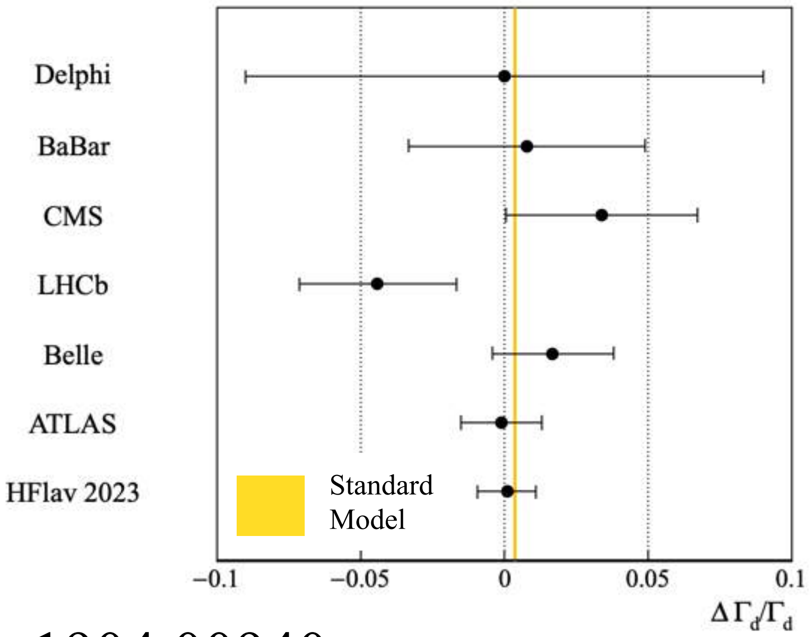
$$R_{i,\mathrm{cor}} = \frac{R_{i,\mathrm{uncor}}}{R_{i,\mathrm{eff}}}$$

Takes proper account of production asymmetry

$$\Delta\Gamma_d/\Gamma_d = (-0.1 \pm 1.1\ (\mathrm{stat.}) \pm 0.9\ (\mathrm{syst.})) \times 10^{-2}$$

$\Delta\Gamma_d$

$$\Delta\Gamma_d/\Gamma_d = (1 \pm 1) \times 10^{-2}\,\mathrm{ps}^{-1}$$

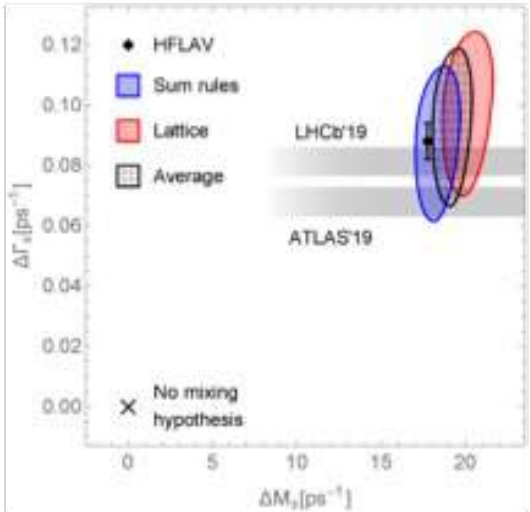


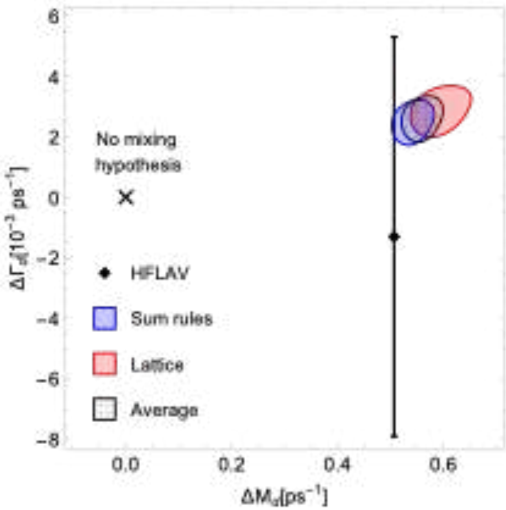
$$\Delta\Gamma_d^{SM} = (2.6 \pm 0.4) \times 10^{-3}\,\mathrm{ps}^{-1}$$

arxiv: 2211.02724

LHCb result is only with fraction of Run 1 dataset: Run 2 update would be interesting

arxiv 1904.00940





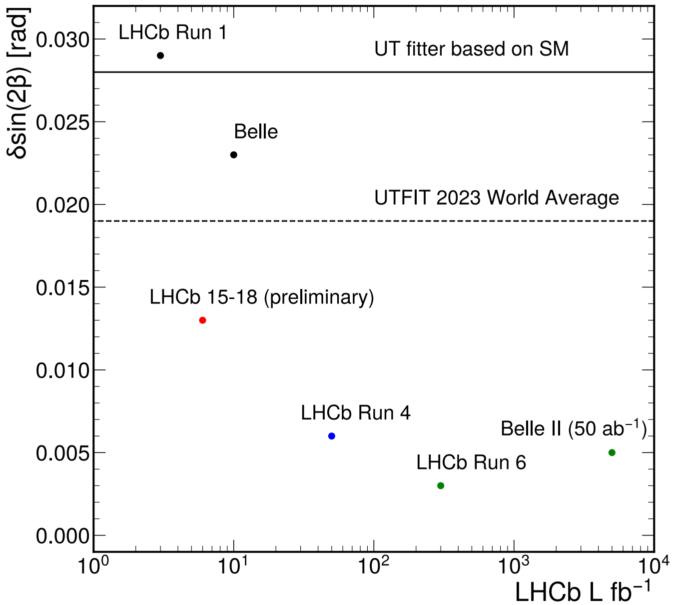
With 300 fb^{-1} precision of 0.001 on could be achieved on $\Delta\Gamma_d/\Gamma_d$ By LHCb Upgrade 2. Potential to pin down to be non-zero/precision SM tests

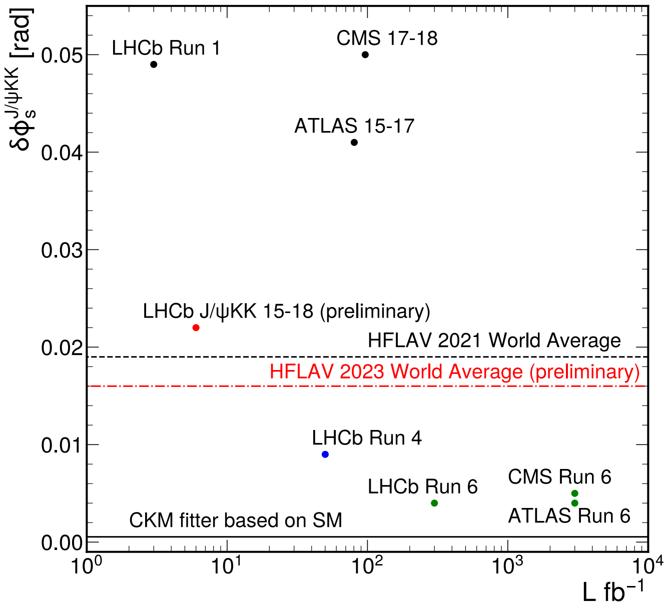
see arxiv:1808.08865

Thoughts

Prospects for B-mixing

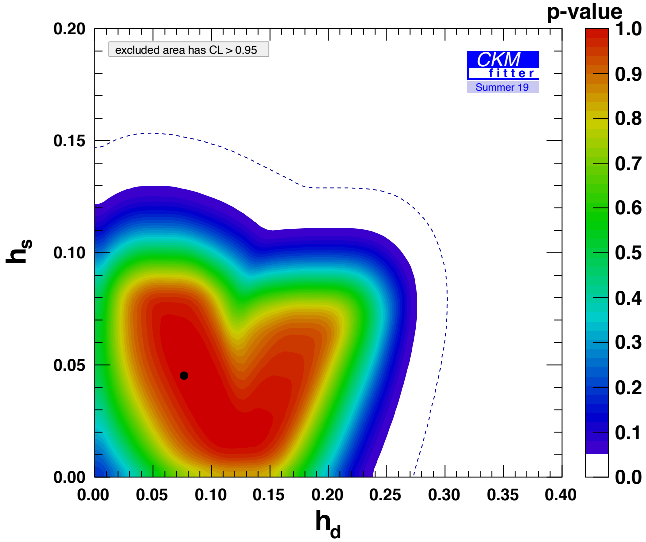
No sign of NP ☹
Still room for New Physics amplitude at level of 10 % in B_d, B_s mixing ☺
In the next decades move from 10 fb^{-1} to 300 fb^{-1} with LHCb upgrades plus ATLAS/CMS/Belle 2





LHCb-PUB-2018-009, ATL-PHYS-PUB-2018-041,
CMS-PAS-FTR-18-041, https://pos.sissa.it/294/005/pdf

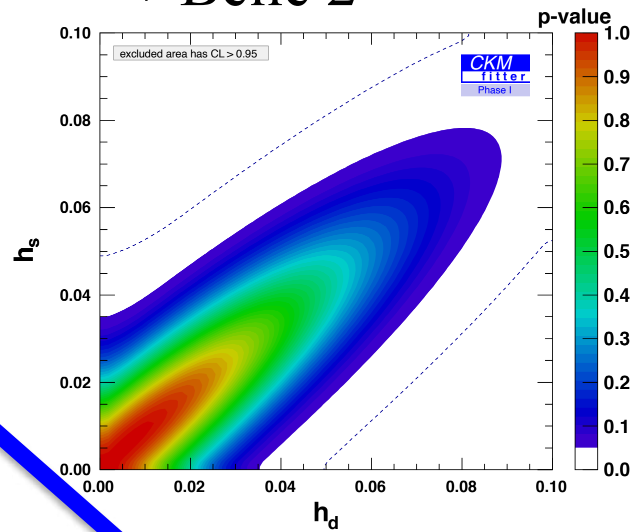
Prospects for B-mixing



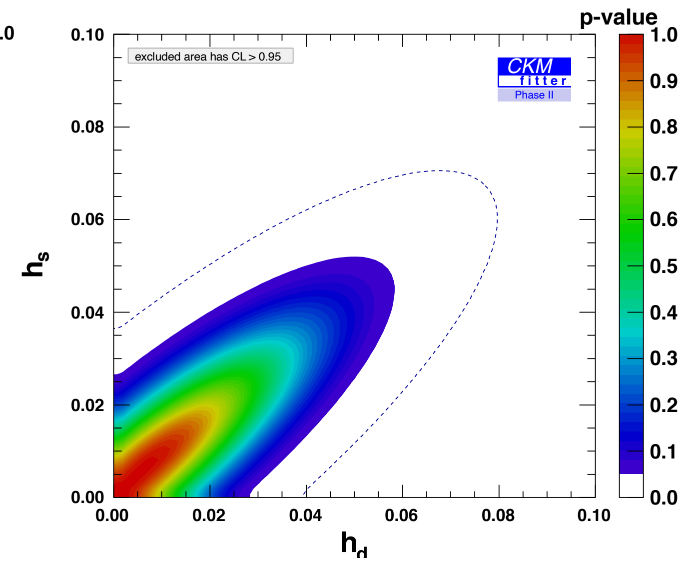
2019

arxiv:2006.04824

LHCb Upgrade I
+ Belle 2



LHCb
Upgrade 2



$$M_{12}^{d,s} = (M_{12}^{d,s})_{\rm SM} \times \left(1 + h_{d,s}\, e^{2i\sigma_{d,s}}\right)$$

Thoughts

The Run 1+2 era is ending

A lot was achieved ☺ , close to pre-LHC expectations

Some things were not in the pre-LHC program: e.g. high J/ψ KK, $J/\psi\pi\pi$ ☺

Some things were not fully exploited: CP even eigenstates ☹

Several measurements still to be updated to full dataset: important to exploit power of Run 1+2 datasets of all LHC experiments (while balancing that Run 3 is the future)

Entering the era of the LHC upgrades and Belle 2

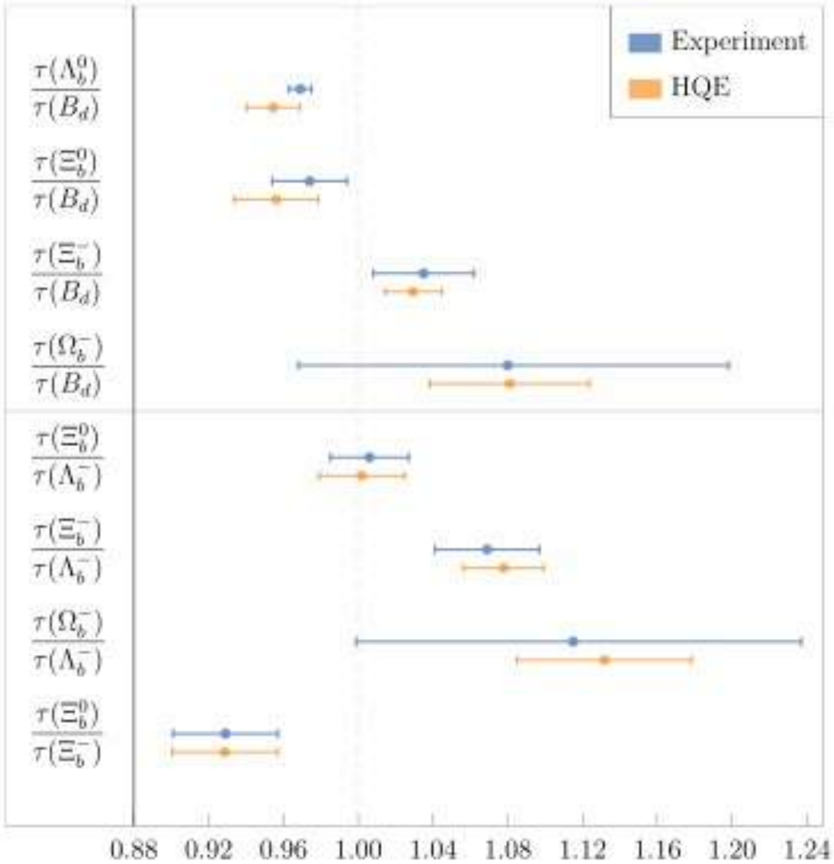
Thoughts

Personal top 3 pick of things
still to be done with Run 2

B^+ and B^0 lifetime: Improve precision of standard candles. With Run 2 LHCb alone statistical precision of 1 ps can be achieved for B^+

$\Delta\Gamma_d$: Many good reasons to measure better

b-baryon lifetimes: a lot of progress in Run 1, but no Run 2 results?



Thoughts

The upgrade era is (almost) here

Early days of LHCb upgrade will provide many interesting opportunities

Lifetimes then $\Delta m_{s,}$ Δm_d ideal early program measurements to demonstrate new detector capabilities (as was case in 2010)
Bonus: New pixel detector with different systematic uncertainties

Since systematics are important mandatory to cross-check results with different modes, techniques and experiments

Run 3 provides opportunity to make precision measurement of b baryon/hadron lifetimes, testing HQET

Summary

B_s mixing parameters known with precision after Run 1+2

- No sign of New Physics ☹

Still more Run 2 to come

- Both tree-level and with charmless decays

Important to exploit precision by controlling theoretical uncertainties with data driven approaches

- Ensure that less high impact supporting measurements and cross-checks get done

Run 3: will give even larger datasets, with new and more precise detectors

“Lanark said irritably, "You seem to understand my questions, but your answers make no sense to me."
"That's typical of life, isn't it?”

Backup

Predictions for $\Delta\Gamma_s$

Value [$\times 10^{-2}\text{ps}^{-1}$]	Renormalization scheme	Reference
7.7 ± 2.2	Pole mass	Asatrian *et. al.* [1]
8.8 ± 1.8	$\overline{MS}$	Asatrian *et. al.* [1]
9.2 ± 1.4	$\overline{MS}$	Davies *et. al.* [2]
9.1 ± 1.3	$\overline{MS}$	Lenz *et. al.* [3]
7.6 ± 1.7	Avg. $\overline{MS}$ + PS	Gerlach *et. al.* [4]

[1] Hrachia M. Asatrian et al. Penguin contribution to the width difference and asymmetry in mixing. *Phys. Rev. D*, 102(3):033007, 2020.

[2] Christine T. H. Davies et al. Lattice qcd matrix elements for the $B_s^0 - \bar{B}_s^0$ width difference. *Phys. Rev. Lett.*, 124(8):082001, 2020.

[3] Alexander Lenz and Gilberto Tetlalmatzi-Xolocotzi. Model-independent bounds on new physics effects. *JHEP*, 07:177, 2020.

[4] Marvin Gerlach et al. The width difference in $B - \bar{B}$ mixing at order α_s and beyond. *JHEP*, 04:006, 2022.