# Experimental status of lifetimes, mixing and CP violation

Durham 5th September 2017

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# Outline

- CP violation in $B_s$ mixing and $\phi_s$
- Intermezzo: Lifetimes
- sin 2β
- $\Delta\Gamma_d/\Gamma_d$
- Thoughts for the future

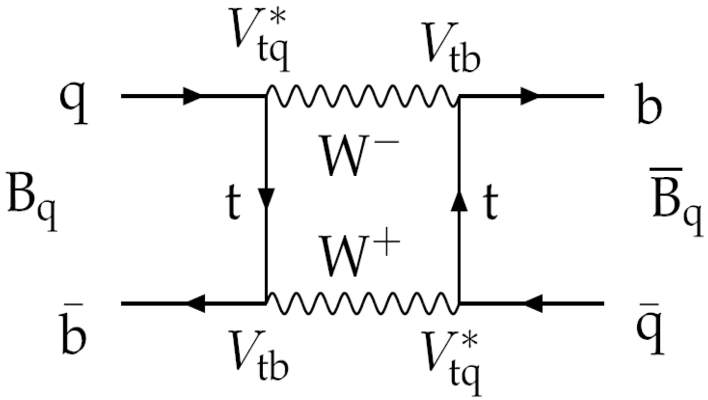
Interesting things not covered:

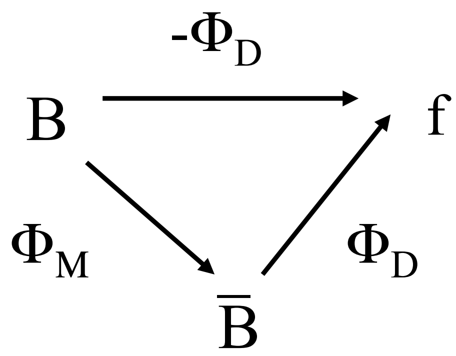
$B^0 \rightarrow \pi^+\pi^-$, $B_s \rightarrow K^+K^-$ (LHCb-CONF-2016-018)
$\sin 2\beta_{eff}$ with $B \rightarrow DD$ (PRL 117 (2016) 261801)
$\Gamma_D$ (EPJC 76 (2016) 412)

# CP violation in $B_s$ mixing

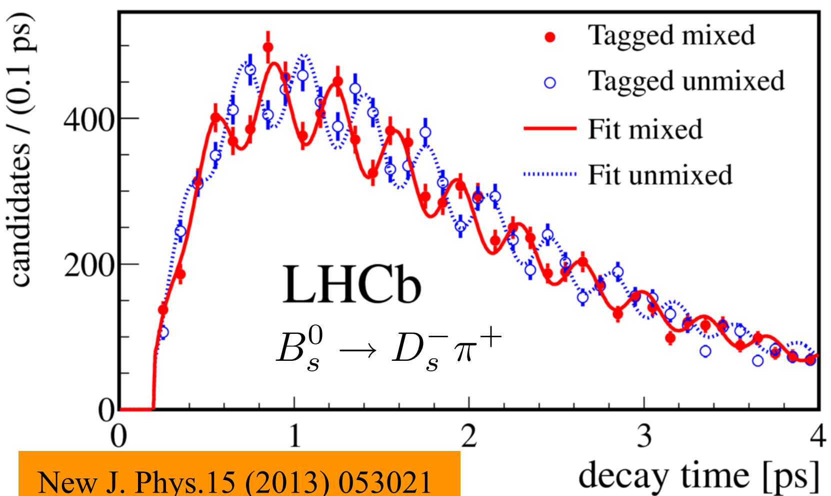
# $B_s$ mixing

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




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




New J. Phys.15 (2013) 053021

Excellent vertex detector needed to resolve fast $B_s$ oscillations

$$\text{Hflav} : \Delta m_s = 17.757 \pm 0.021\,\text{ps}^{-1}$$

cf SM 18.3 +/- 2.7

# CP violation in $B_s$ mixing

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

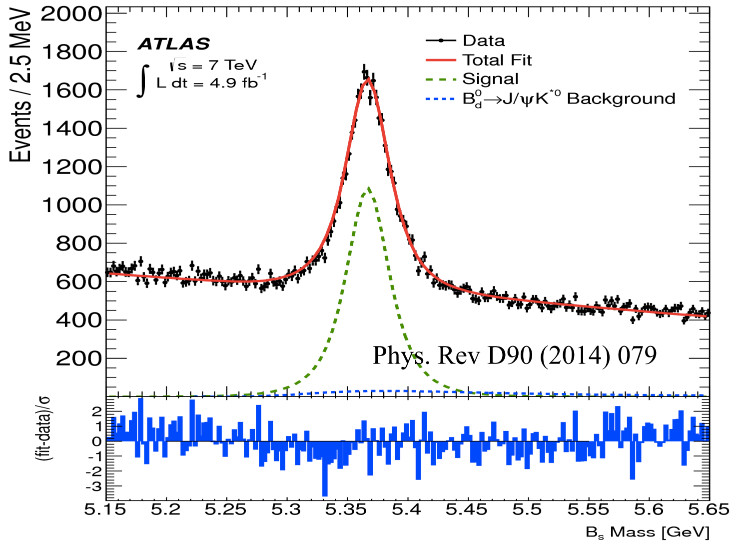
$$\Delta\Gamma_s = \Gamma_L - \Gamma_H$$

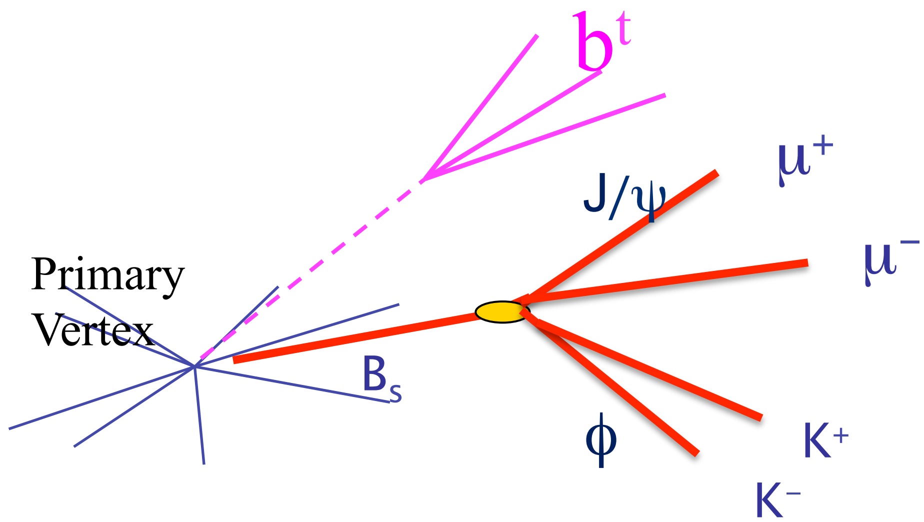
$$\Delta m_s = M_H - M_L$$

- Observable phase $\phi_s = -2\beta_s = \Phi_M - 2\,\Phi_D$
- In the Standard Model expected to be small $\phi_s = -0.04$ radian
- Larger values possible in models of New Physics

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

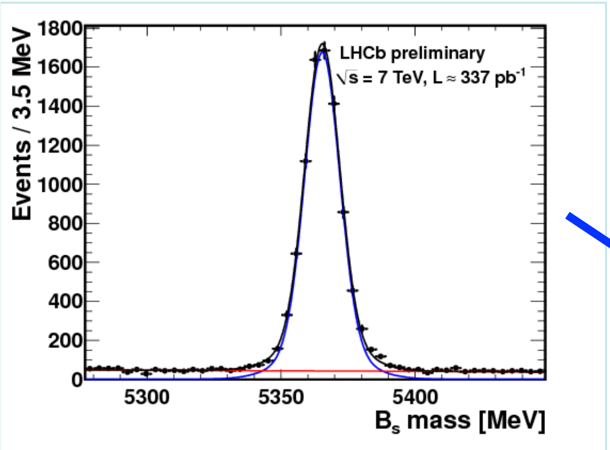
- LHCb also studied $B_S \to J/\psi\ K^+K^-$, $B_S \to J/\psi\ \pi^+\pi^-$, $B_S \to \psi(2s)\phi$, $B_S \to D_s^+D_s^-$

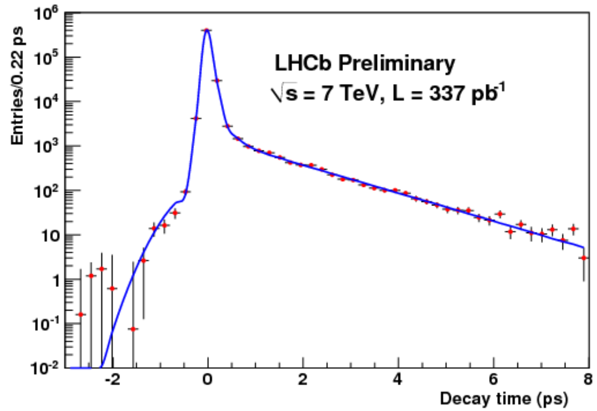


# Measuring $\phi_s$

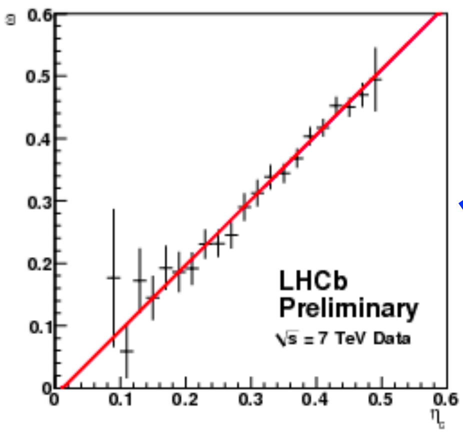
Mass distribution




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

Time acceptance due to cuts in the trigger + reconstruction effects

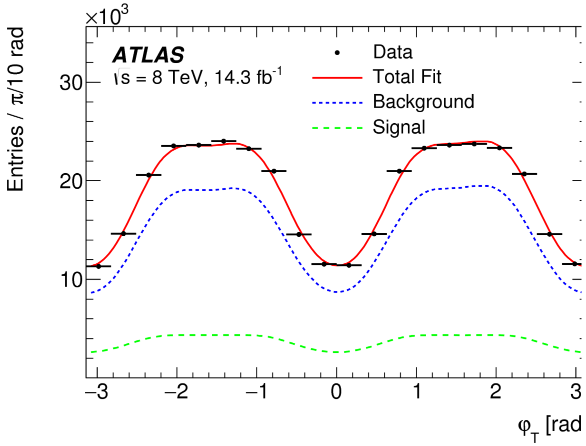
Angular acceptance for signal from simulation

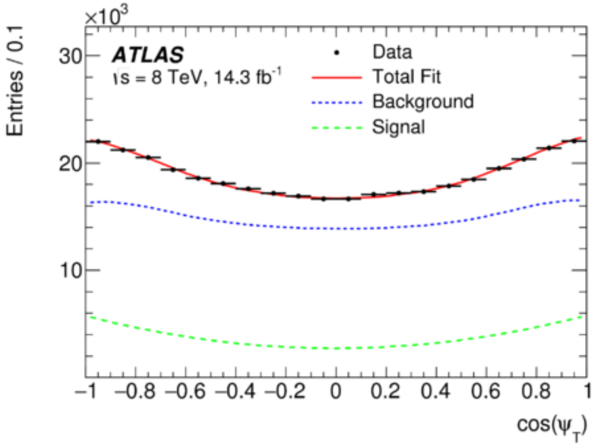
# $\phi_s$: ATLAS

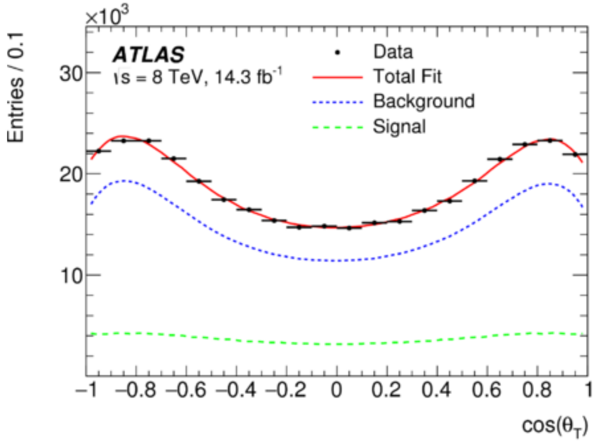
$B_s \to J/\psi\phi$

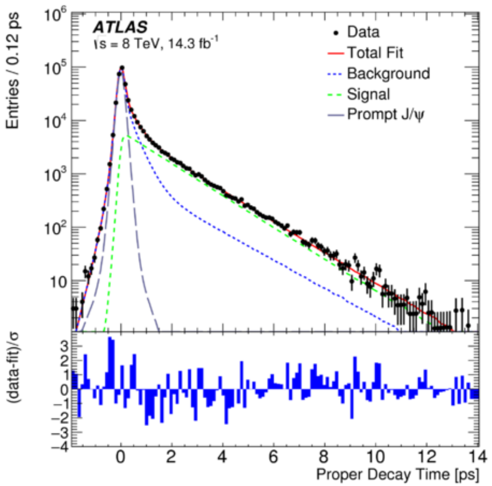
arXiv:1601.03297

Transversity angles



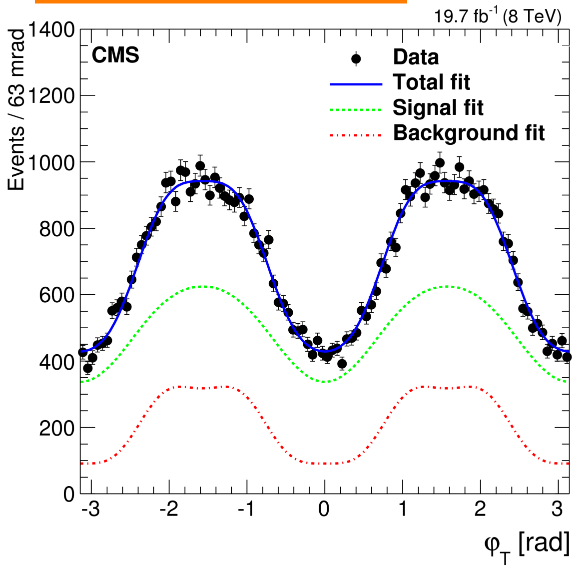



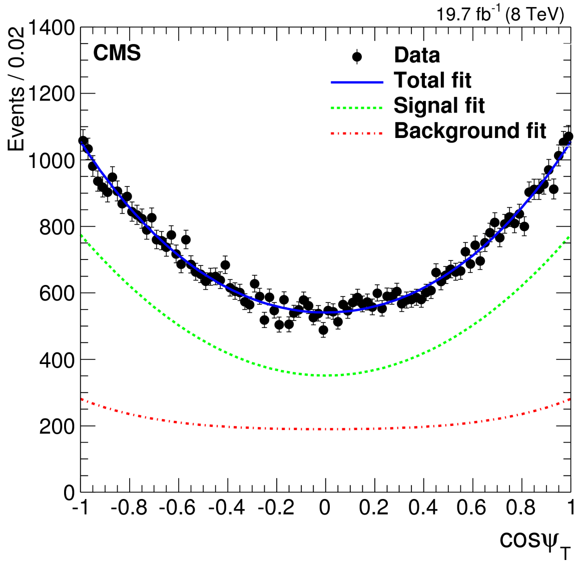

$$\begin{aligned}
\phi_s &= -0.098 \pm 0.084 \text{ (stat.)} \pm 0.040 \text{ (syst.) rad} \\
\Delta\Gamma_s &= 0.083 \pm 0.011 \text{ (stat.)} \pm 0.007 \text{ (syst.) ps}^{-1} \\
\Gamma_s &= 0.677 \pm 0.003 \text{ (stat.)} \pm 0.003 \text{ (syst.) ps}^{-1}.
\end{aligned}$$

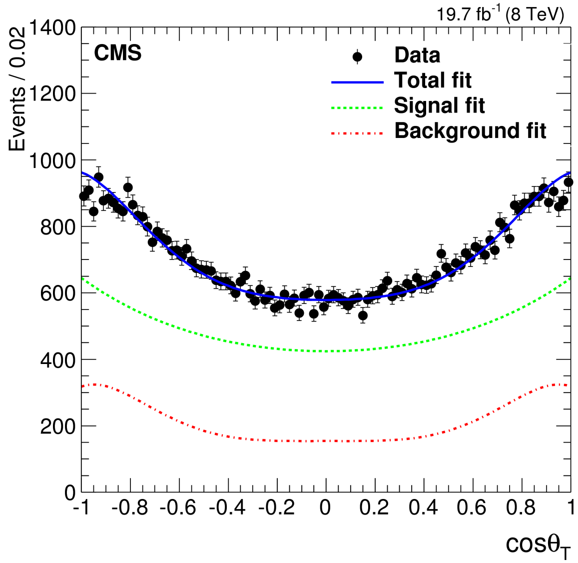
# $\phi_s$: CMS

$B_s \to J/\psi\phi$

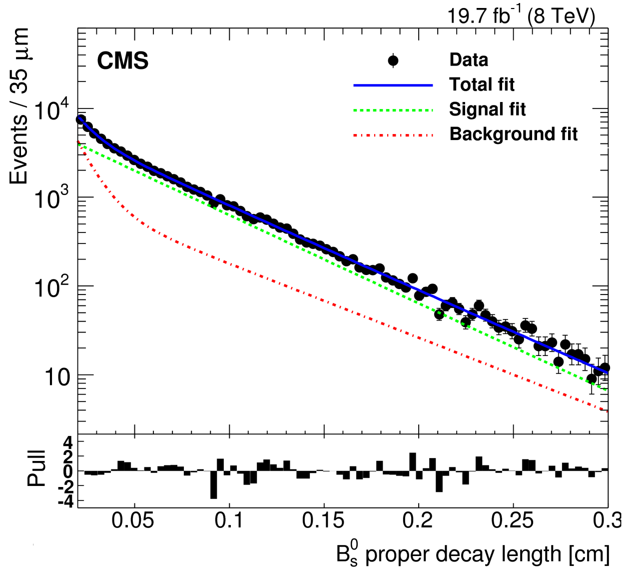
PLB 757 (2016) 97




Transversity angles

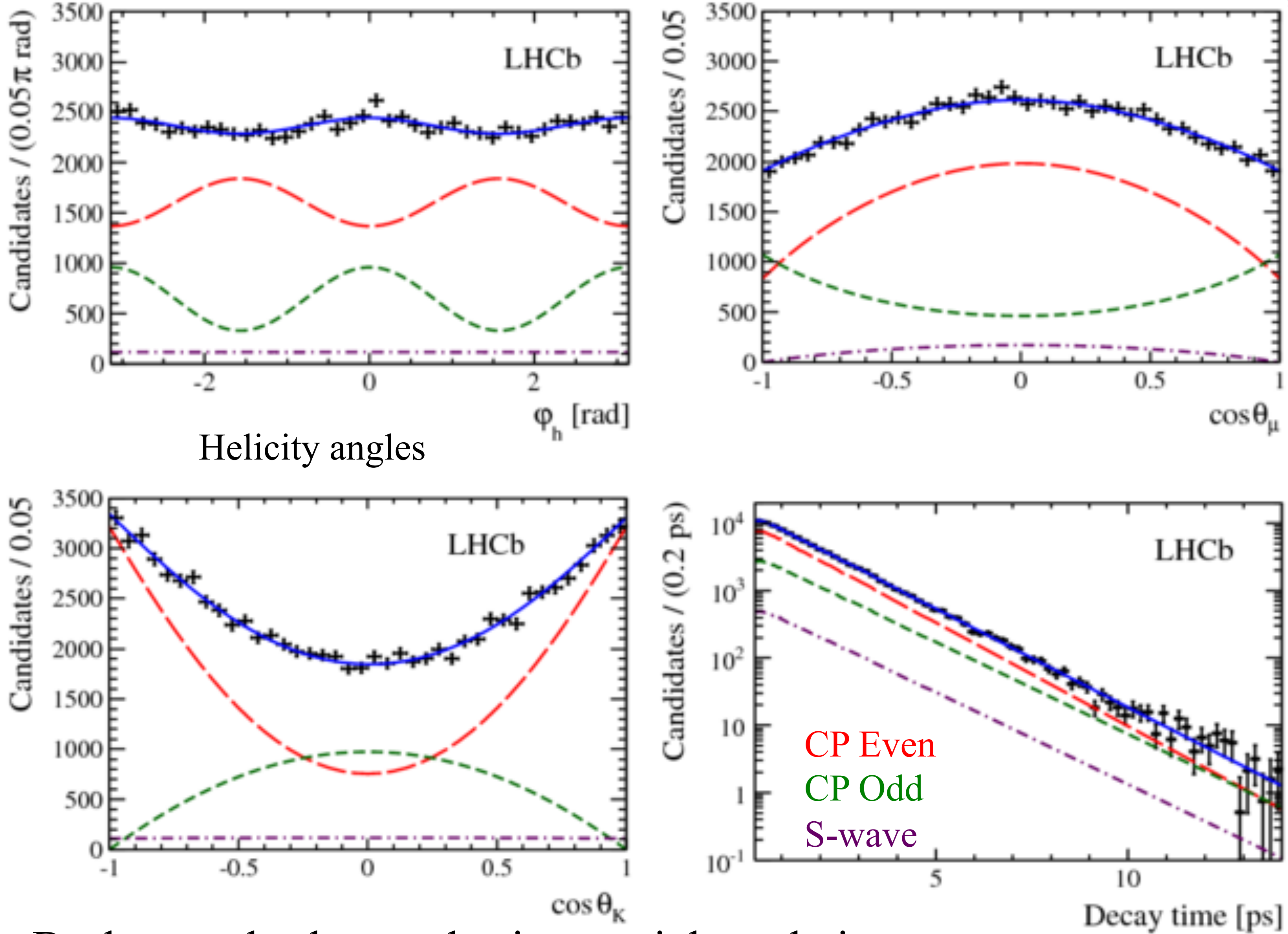



$$\phi_s = -0.075 \pm 0.097\,(\text{stat}) \pm 0.031\,(\text{syst})\,\text{rad},$$
$$\Delta\Gamma_s = 0.095 \pm 0.013\,(\text{stat}) \pm 0.007\,(\text{syst})\,\text{ps}^{-1}.$$

# $\phi_s$: LHCb

$B_s \to J/\psi\phi$

PRL 114 (2015) 041801

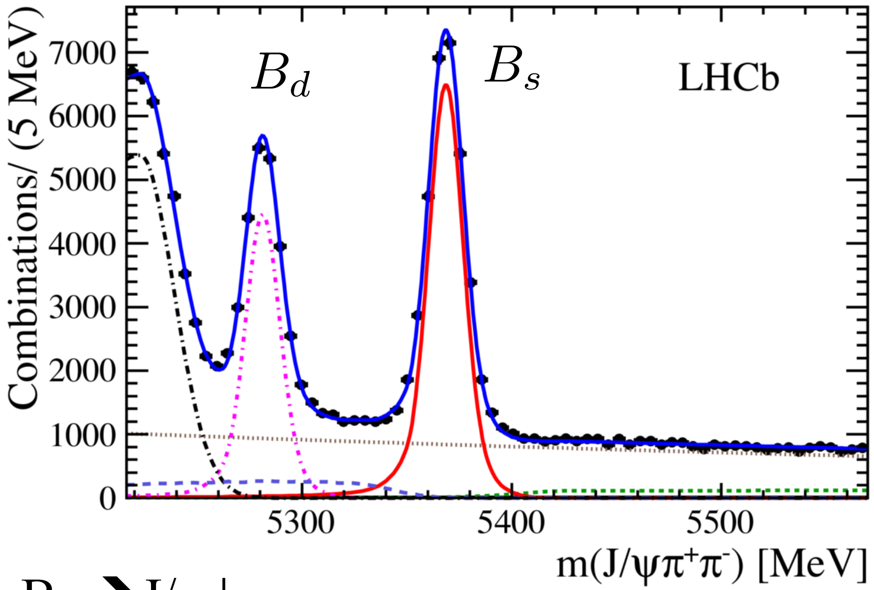


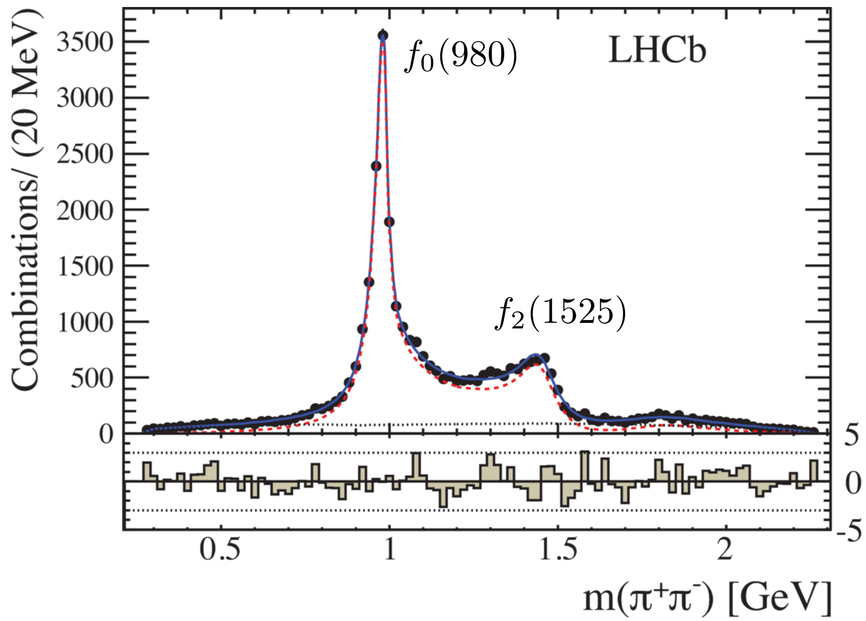

Background subtracted using sweight technique

# $\phi_s$: LHCb

PRL 114 (2015) 041801
PLB 736 (2014) 186

$B_s \rightarrow J/\psi\pi^+\pi^-$ contributes to overall LHCb sensitivity




$B_s \rightarrow J/\psi\phi$

$$\phi_s = -0.058 \pm 0.049 \pm 0.006 \text{ rad}$$

$$\Delta m_s = 17.711 \, ^{+0.055}_{-0.057} \pm 0.011 \text{ ps}^{-1}$$

$$\Gamma_s = 0.6603 \pm 0.0027 \pm 0.0015 \text{ ps}^{-1}$$

$$\Delta\Gamma_s = 0.0805 \pm 0.0091 \pm 0.0032 \text{ ps}^{-1}$$

$$|\lambda| = 0.964 \pm 0.019 \pm 0.007$$

$\phi_s = 75 \pm 67 \pm 8$ mrad. $B_s \rightarrow J/\psi\pi^+\pi^-$

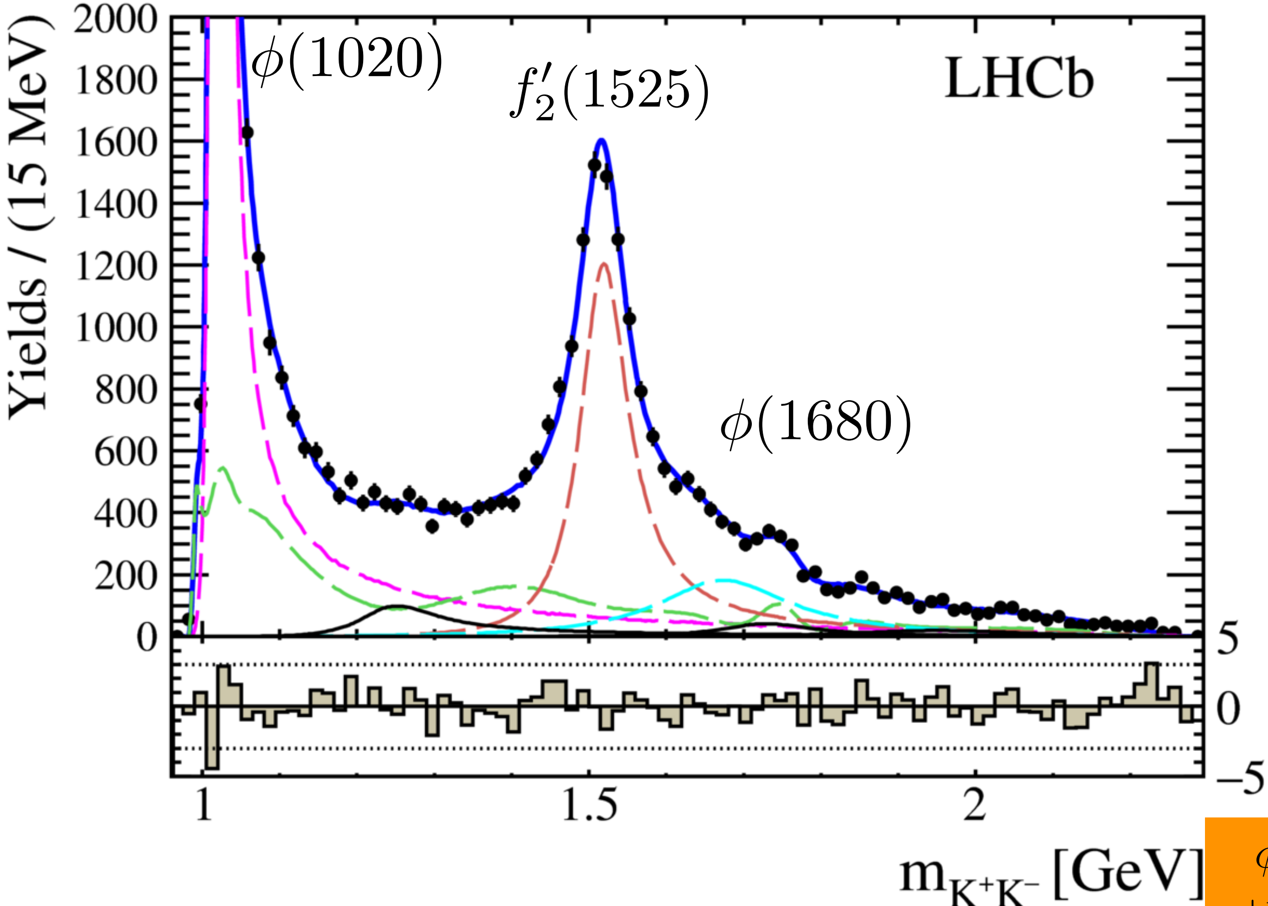
Combined

$$\phi_s = -0.010 \pm 0.039 \text{ rad}$$

# LHCb: High mass KK

New

JHEP08(2017)037




LHCb has studied CP violation using J/ψKK events above ϕ resonance

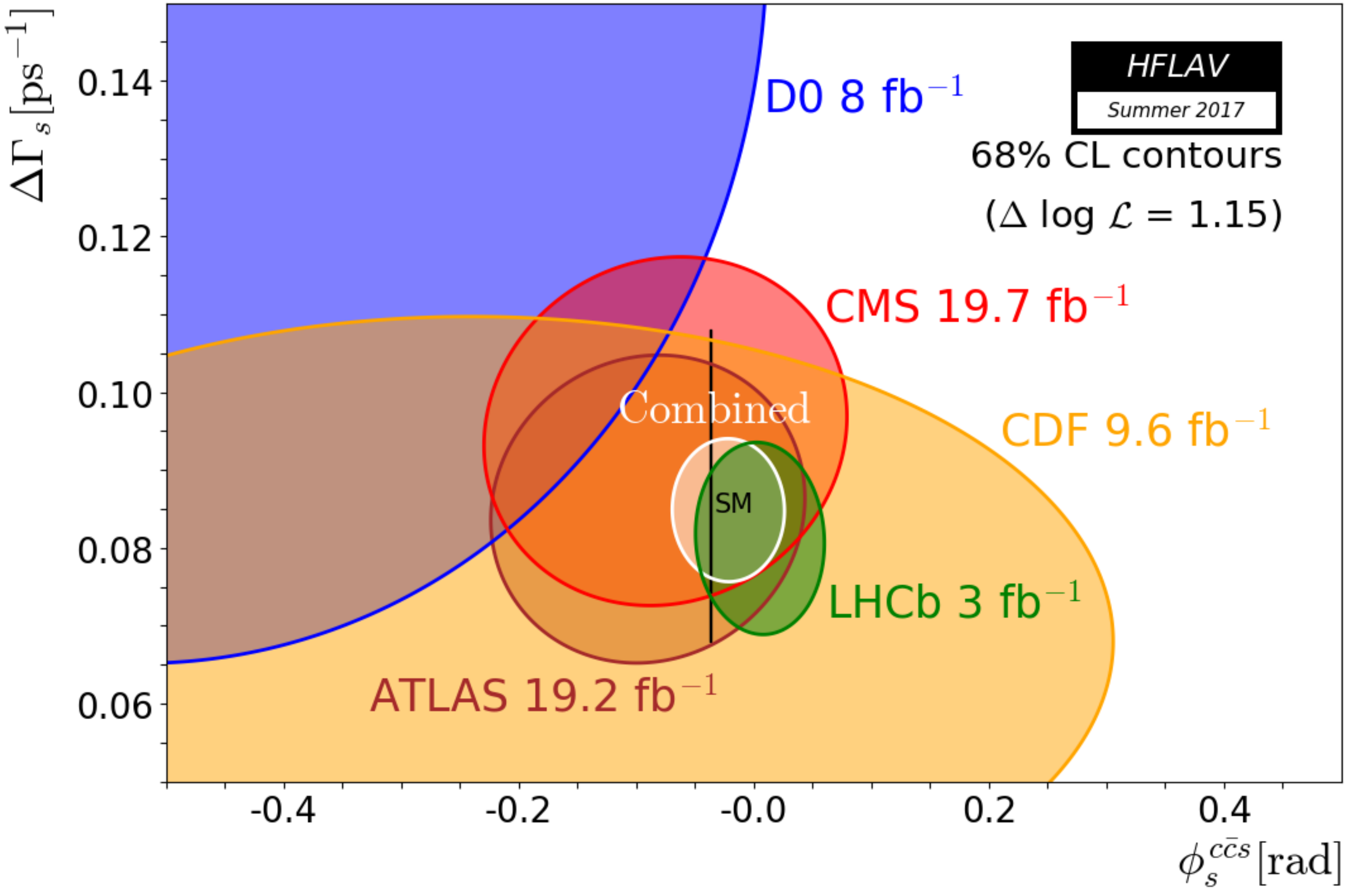
$$\phi_s = 119 \pm 107 \pm 34\,\text{mrad},$$
$$|\lambda| = 0.994 \pm 0.018 \pm 0.006,$$
$$\Gamma_s = 0.650 \pm 0.006 \pm 0.004\,\text{ps}^{-1}$$
$$\Delta\Gamma_s = 0.066 \pm 0.018 \pm 0.010\,\text{ps}^{-1}$$

LHCb average from J/ψKK, J/ψϕ , J/ψππ

$$\phi_s = 1 \pm 37\,\text{mrad}$$

# Summary of $\phi_s$

http://www.slac.stanford.edu/xorg/hflav/




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

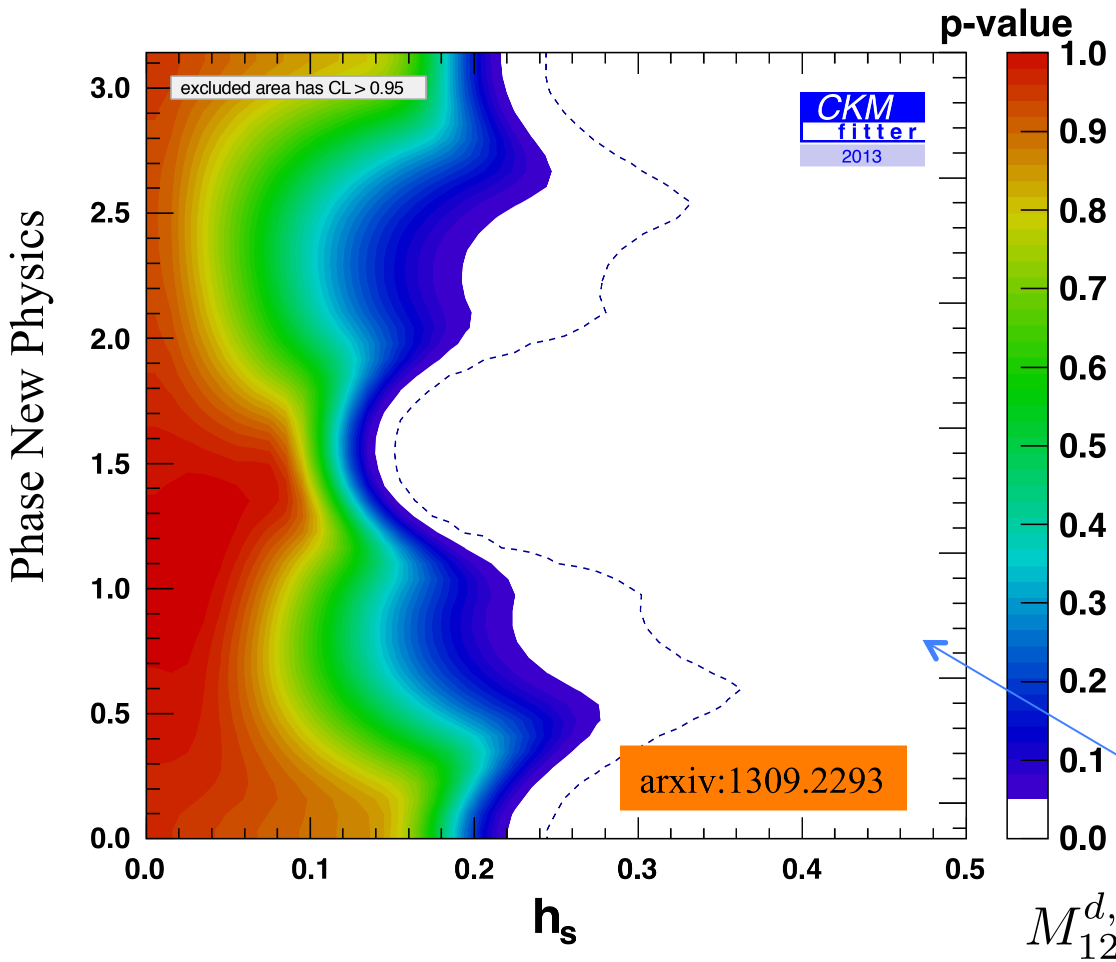
+ LHCb:
$B_S \to J/\psi\ K^+K^-$
$B_S \to J/\psi\ \pi^+\pi^-$
$B_S \to \psi(2s)\phi$
$B_S \to D_s^+D_s^-$

$$\Delta\Gamma_s = 0.085 \pm 0.06\,\mathrm{ps}^{-1}$$

$$\phi_s = -0.021 \pm 0.031\,\mathrm{rad}$$

# Summary of $\phi_s$

No sign of NP ☹
Still room for New Physics amplitude at level of 10 % in $B_s$ mixing (Similar story in $B_d$ sector) ☺



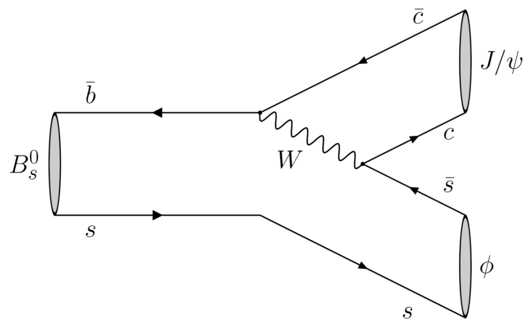

Updates to come with Run 2 data

Precision at <0.02 rad level by end of Run II

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

# Penguin Pollution

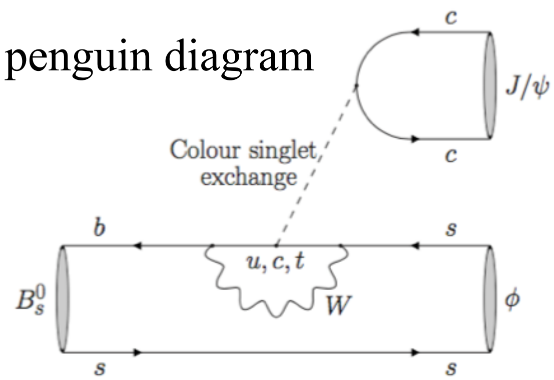
tree




Penguin contributions could mimic NP effects

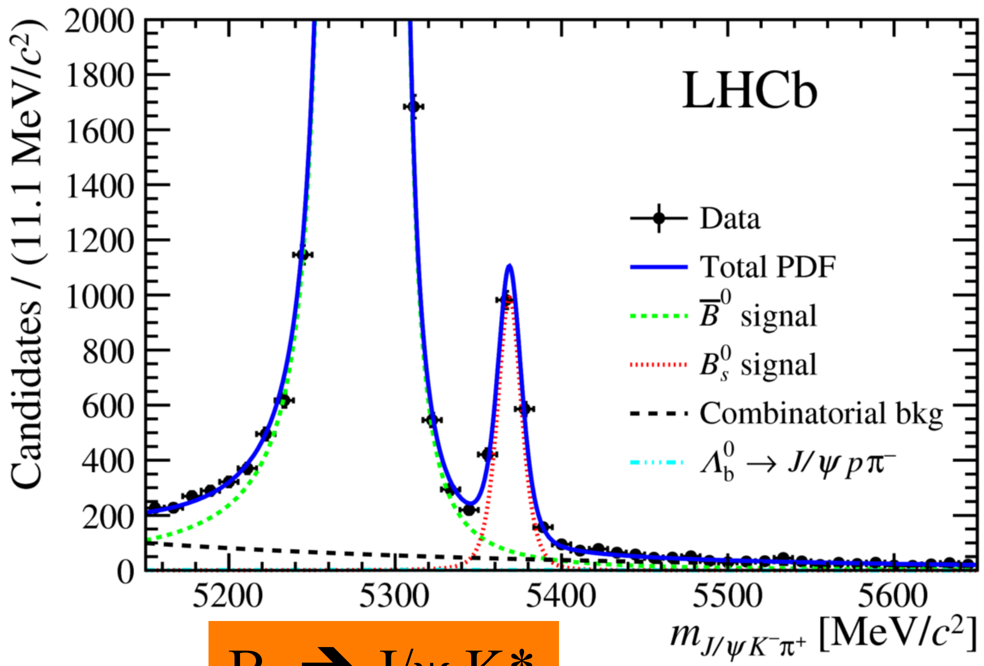
Study using other modes related by SU(3) symmetry to limit size using data
e.g. $B_s$ ➔ J/ψ K*, $B^0$ ➔ J/ψρ

penguin diagram




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

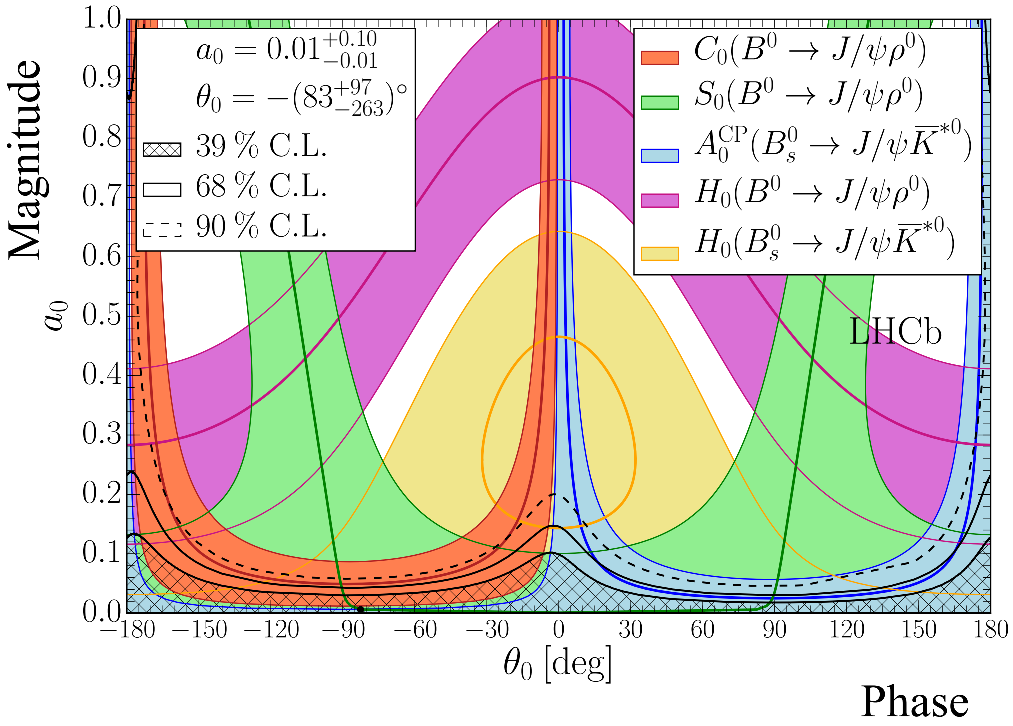
JHEP 11 (2015) 082
Phys Lett B742 (2015) 38




$B_s$ ➔ J/ψ K*

# Penguin Pollution

Fit to CP observables + polarization amplitudes in $B_s$ ➔ $J/\psi\, K^*$, $B^0$ ➔ $J/\psi\rho$



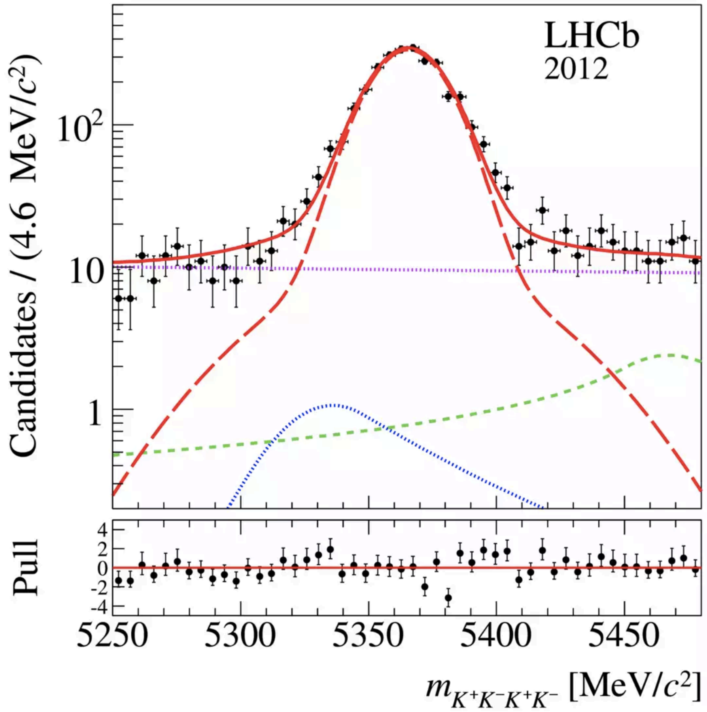

JHEP 11 (2015) 082
Phys Lett B742 (2015) 38

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

Effect of penguins bounded to be less than current uncertainties

# LHCb: and charmless…

JHEP 10 (2015) 053



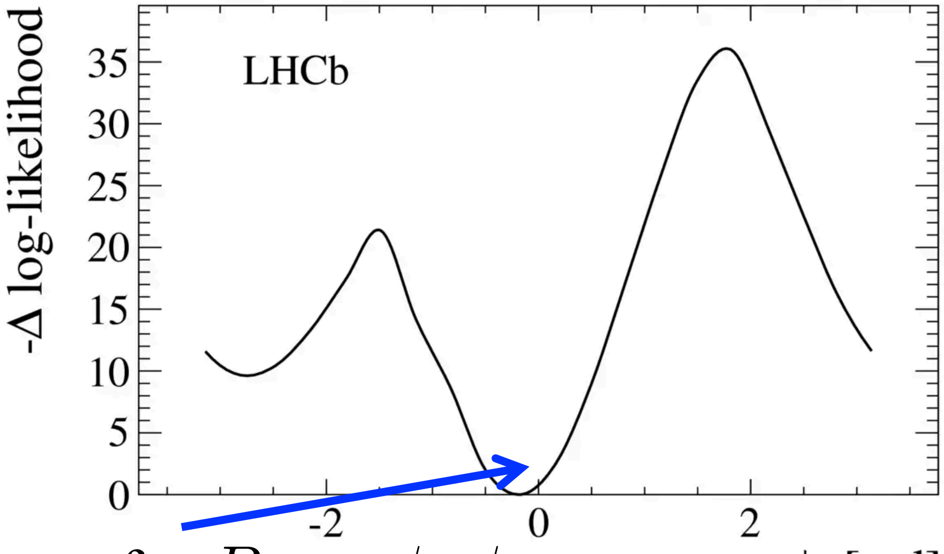

Can also look for CP violation in Bs mixing in loop diagrams

$B_s^0 \to \phi\phi$

Run 1

$\phi_s = -0.17 \pm 0.15\,(\text{stat}) \pm 0.03\,(\text{syst})\,\text{rad}$

Run 2 update soon




SM predicts ~zero for $B_s \to \phi_L\phi_L$

Other modes to study with Run 1/Run 2

$B_s^0 \to K^*\overline{K}^*$

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

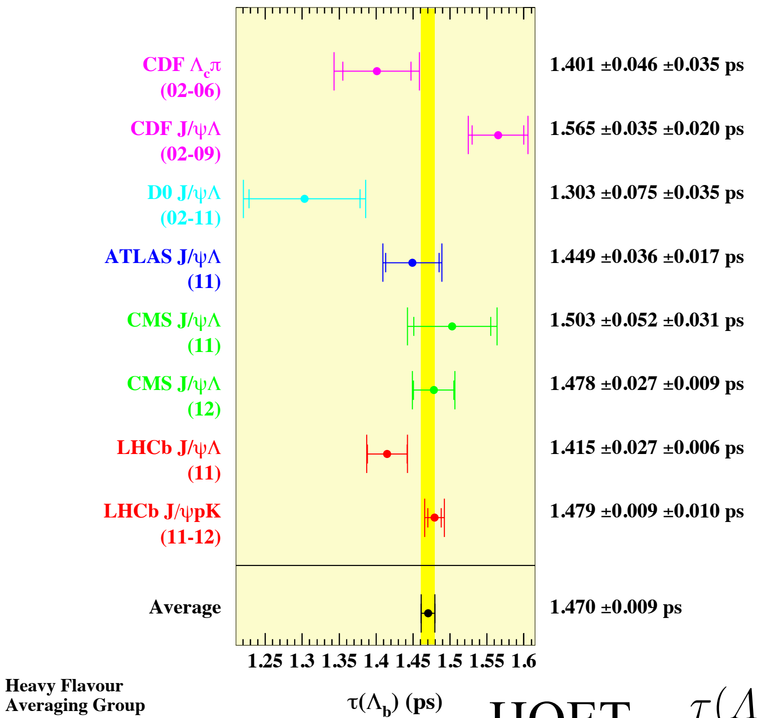
# Lifetime Measurements

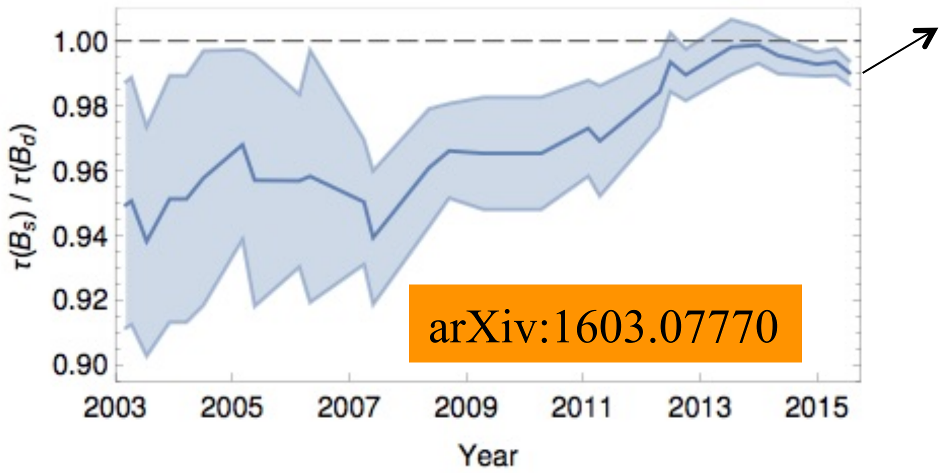
# Lifetime Measurements

As Alex just told lifetimes provide important test of Heavy Quark effective theory and duality assumptions

Challenging both to theory and experiment

Long saga of $\Lambda_b$ lifetime




Ratio of $B_s$ and $B_d$ lifetimes should be 1 to good precision
[versus experiment 0.994 +/- 0.004]

⟷ HQET $\tau(\Lambda_b^0)/\tau(B^0)^{\mathrm{HQE2014}} = 0.935 \pm 0.054$

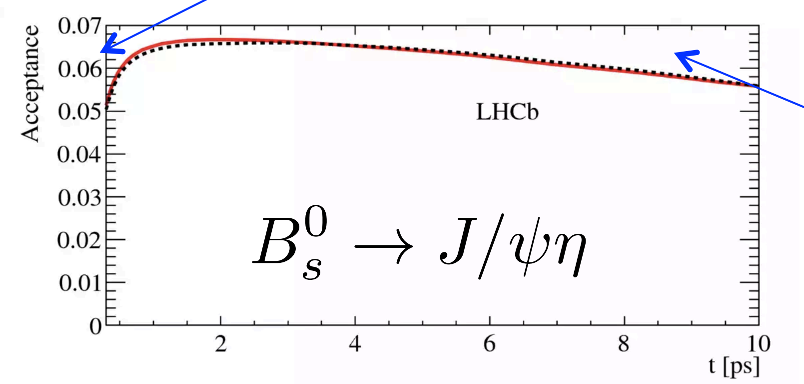
# Lifetime Measurements

Two experimental approaches to understand decay time acceptance

## Direct measurements

Trigger/selection cuts

Model + correct acceptance




Velo efficiency

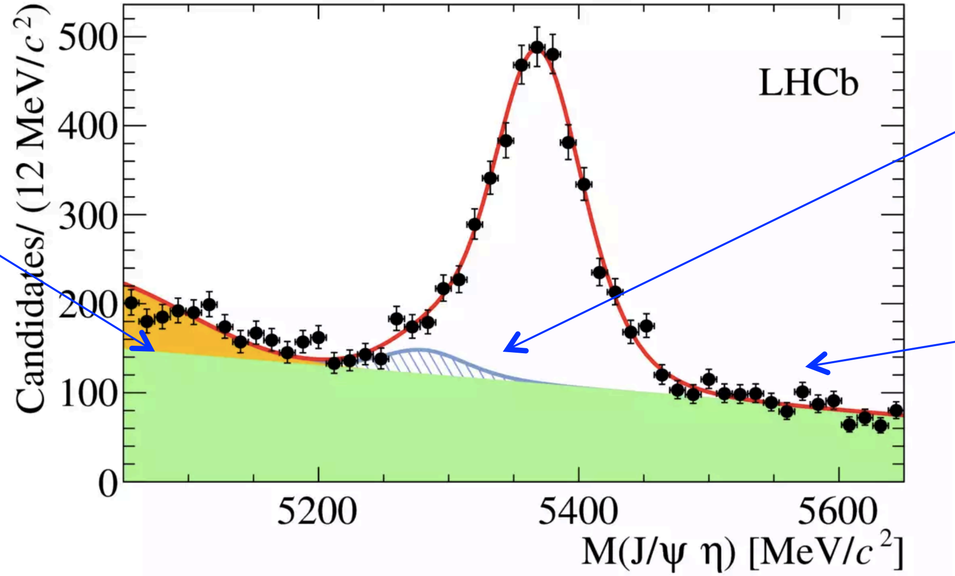
Use of data driven techniques/unbiased triggers where possible

## Relative measurements

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

# $B_s \to J/\psi\eta$ lifetime

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

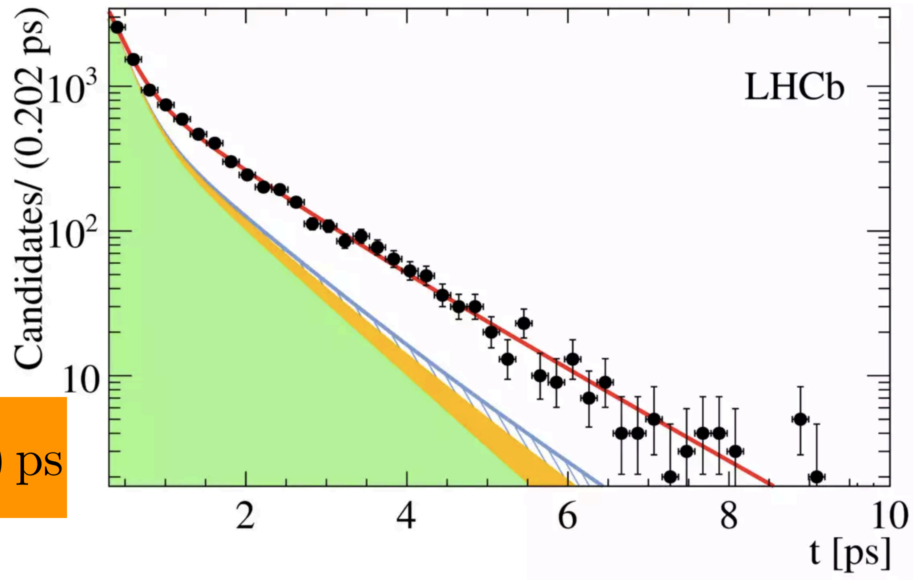



$B_d^0 \to J/\psi \eta$

combinatorial

Measurement statistically limited

3021 +/- 73 candidates in Run 1 data

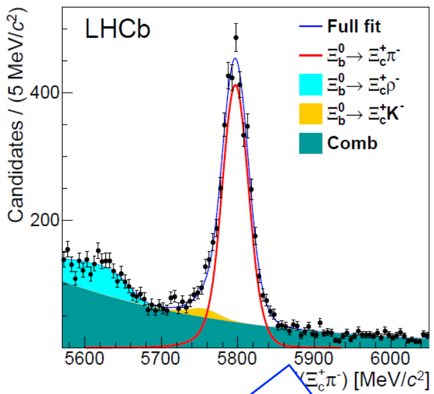


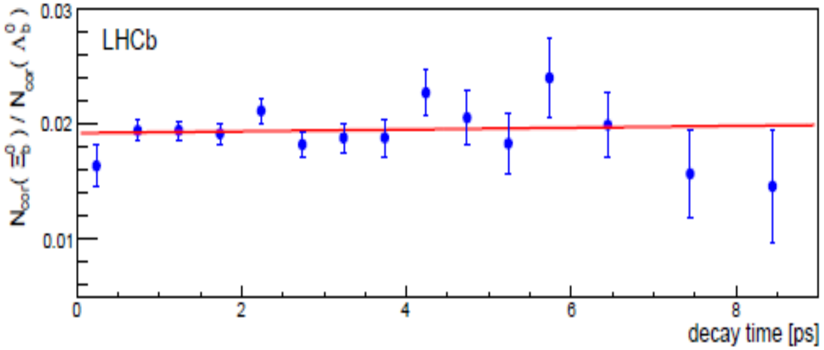

$\tau_{\text{eff}} = 1.479 \pm 0.034\ (\text{stat}) \pm 0.011\ (\text{syst})\ \text{ps}$

Phys. Lett. B 762C (2016) 484-492

# Baryons: e.g $\Xi_b^0$ lifetime

$\Xi_b^0 \rightarrow \Xi_c^+ \pi^-$



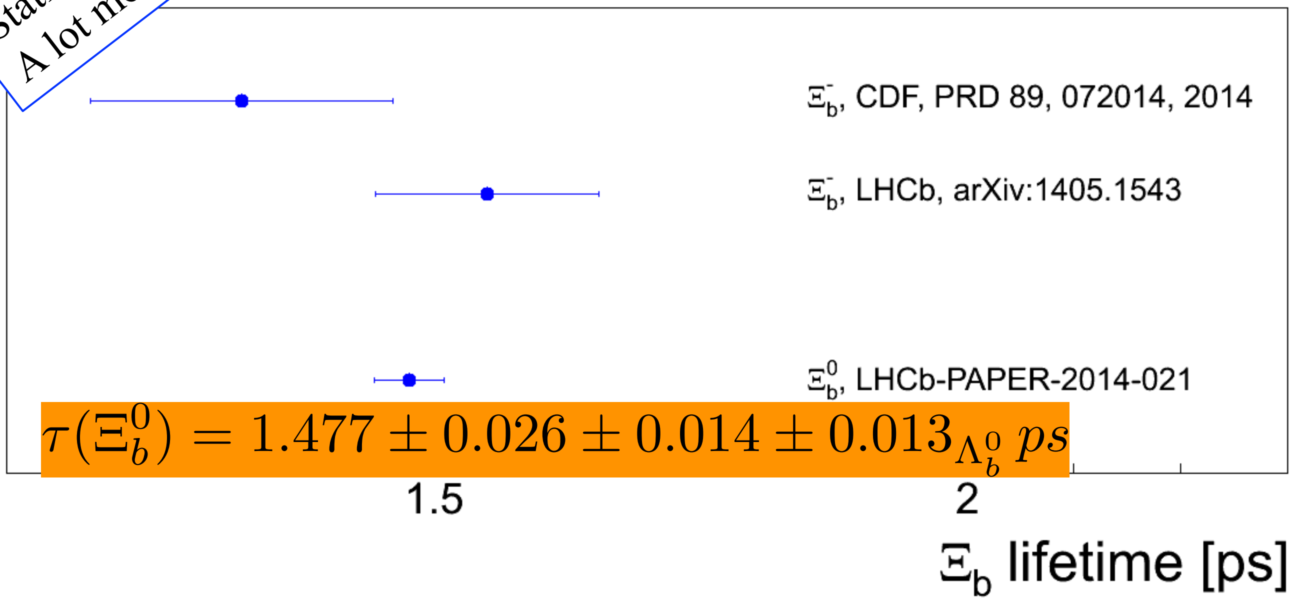




$$\frac{N_{cor}(\Xi_b^0)}{N_{cor}(\Lambda_b)} \sim e^{\beta t}$$

$$\frac{1}{\beta} = \frac{1}{\tau_{\Lambda_b}} - \frac{1}{\tau_{\Xi_b^0}}$$

$$\frac{\tau(\Xi_b^0)}{\tau(\Lambda_b)} = 1.006 \pm 0.018 \pm 0.01$$

Statistics dominate
A lot more to come !

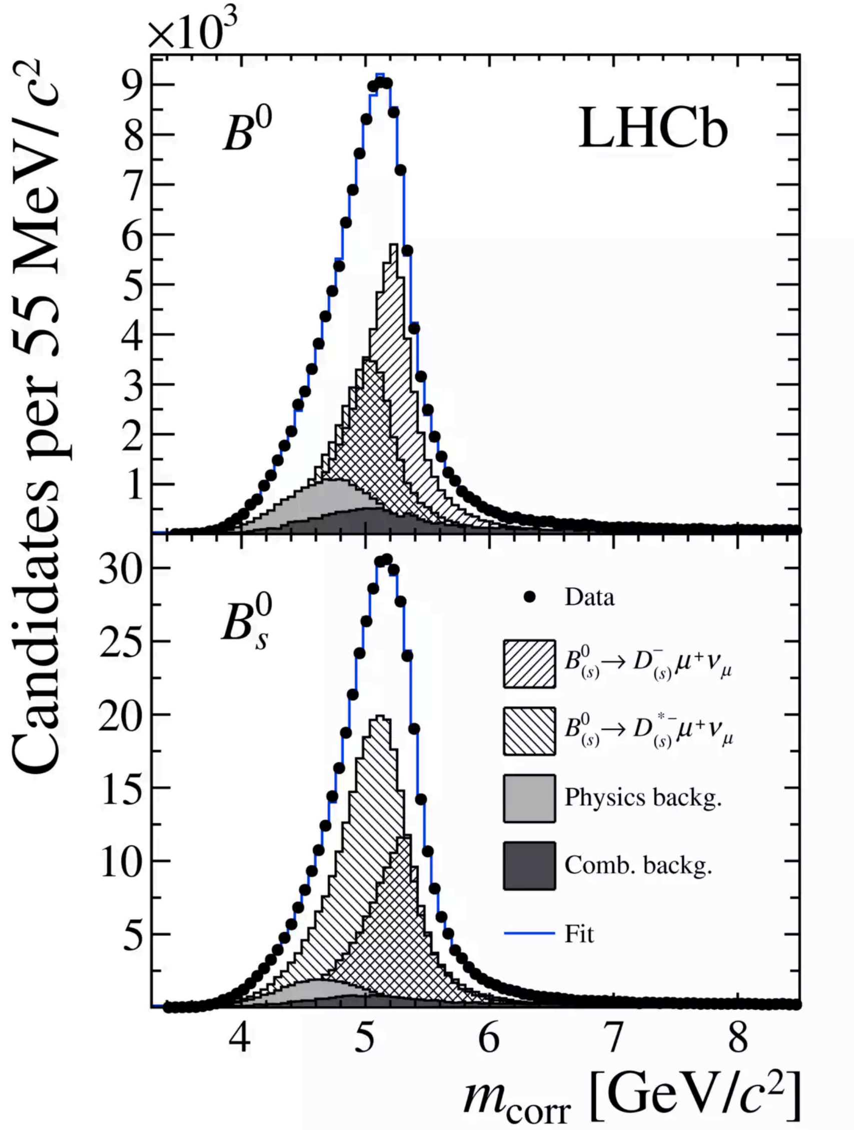



$$\tau(\Xi_b^0) = 1.477 \pm 0.026 \pm 0.014 \pm 0.013_{\Lambda_b^0}\ ps$$

$\Xi_b^0$ and $\Lambda_b$ lifetime consistent to 2 % as Expected from HQE

# Semileptonic decays

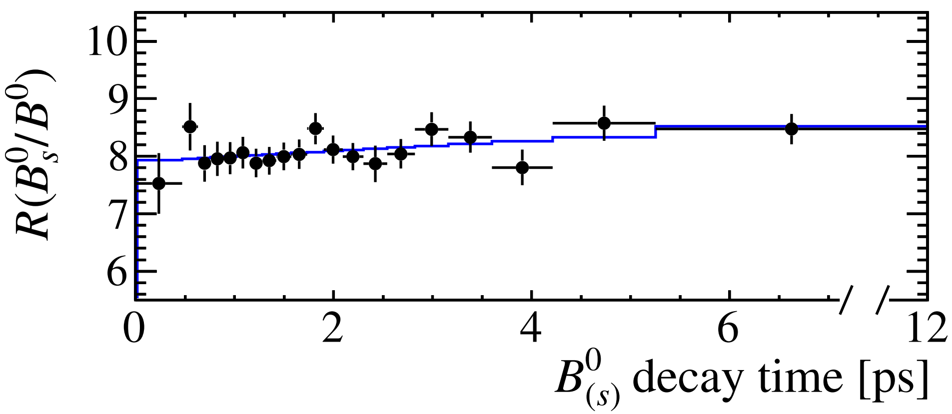
arXiv:1705.03475




LHCb has also measured with $B_s$ Lifetime with semileptonic decays

Large statistics, worse resolution

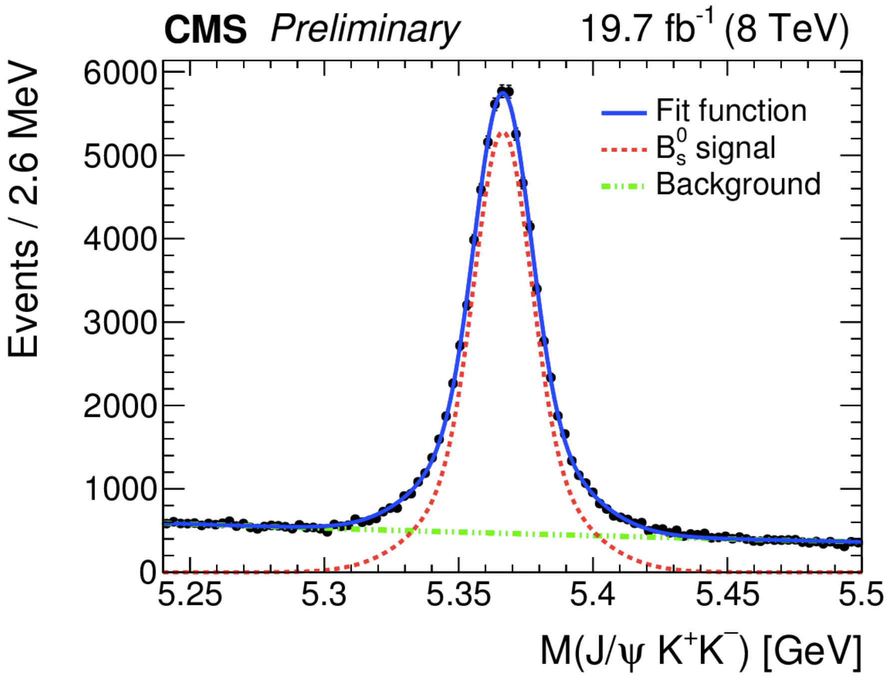
Complementary measurements

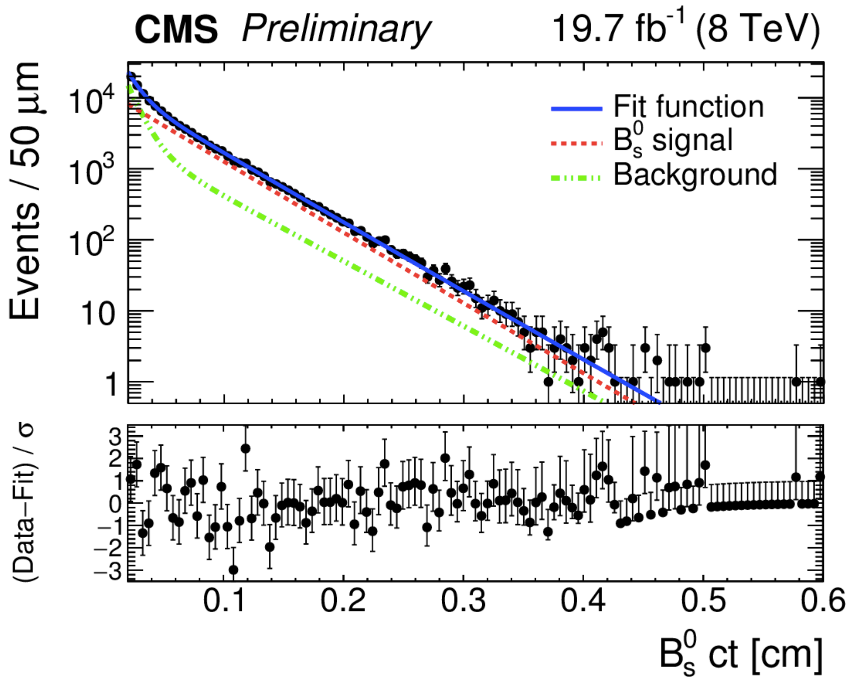



$$\tau^{fs}_{B^0_s} = 1.547 \pm 0.013\,(\mathrm{stat}) \pm 0.010\,(\mathrm{syst}) \pm 0.004\,(\tau_B)\ \mathrm{ps}$$

# CMS lifetime results

CMS-PAS-BPH-13-008

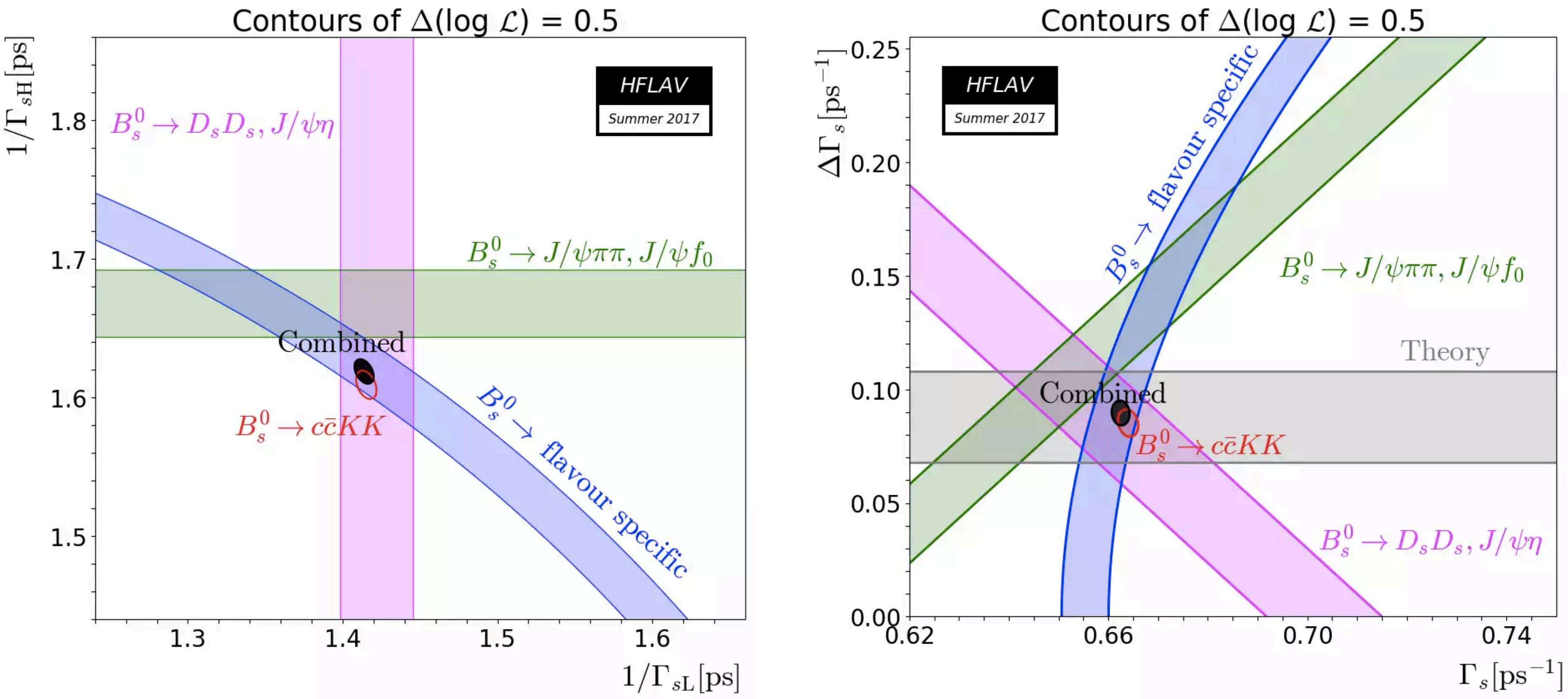



CMS recently presented preliminary results on b-hadron hadron lifetimes

$$c\tau_{B^0} = 453.0 \pm 1.6\,(\text{stat}) \pm 1.5\,(\text{syst})\,\mu\text{m (in } J/\psi K^*(892)^0),$$
$$c\tau_{B^0} = 457.8 \pm 2.7\,(\text{stat}) \pm 2.7\,(\text{syst})\,\mu\text{m (in } J/\psi K^0_S),$$
$$c\tau_{B^0_s} = 504.3 \pm 10.5\,(\text{stat}) \pm 3.7\,(\text{syst})\,\mu\text{m (in } J/\psi \pi^+\pi^-),$$
$$c\tau_{B^0_s} = 443.9 \pm 2.0\,(\text{stat}) \pm 1.2\,(\text{syst})\,\mu\text{m (in } J/\psi \phi(1020)),$$
$$c\tau_{\Lambda^0_b} = 443.1 \pm 8.2\,(\text{stat}) \pm 2.7\,(\text{syst})\,\mu\text{m}.$$

# $B_s$ lifetime summary




Does not include LHCb semileptonics or CMS results

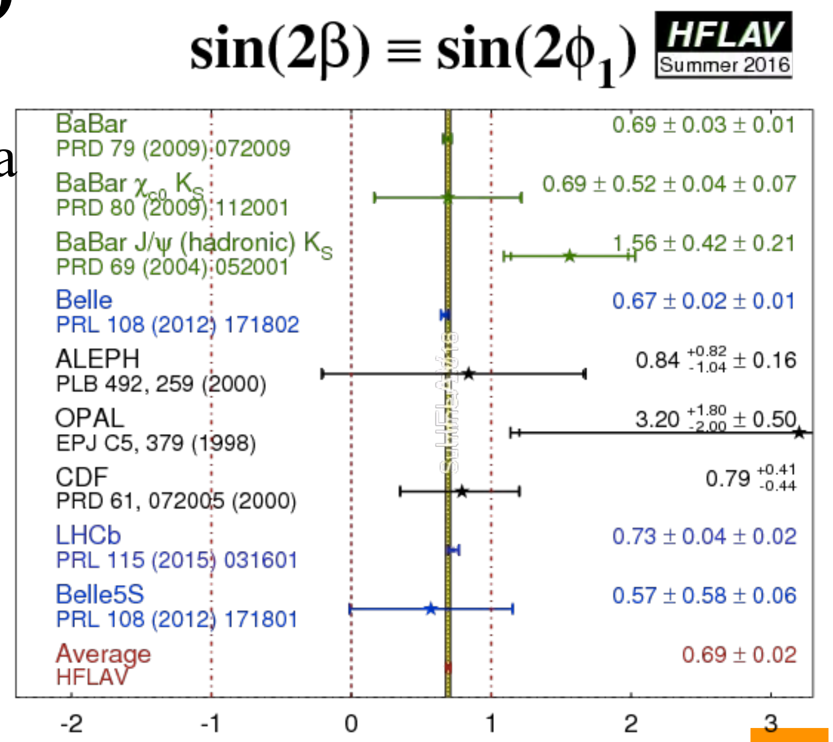
# $\sin 2\beta$

# sin 2β

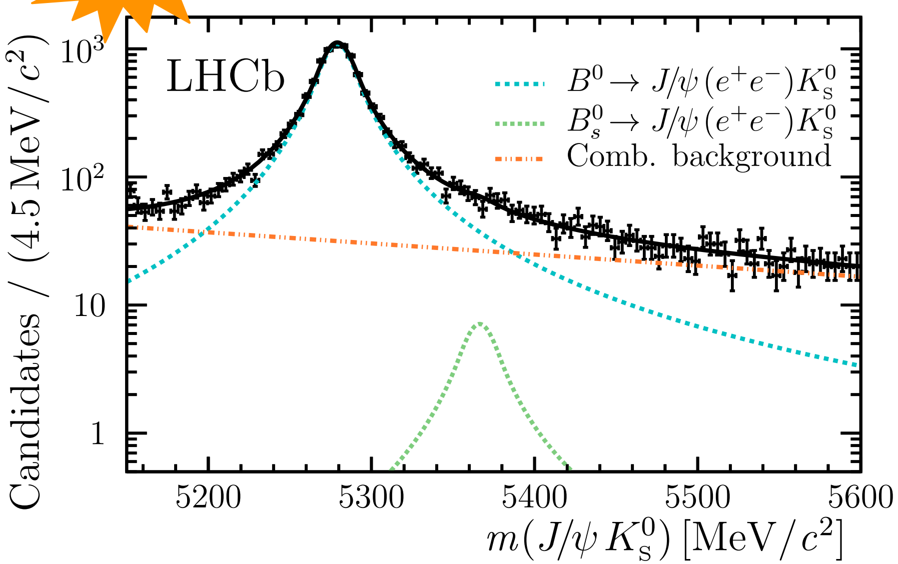
LHCb has measured sin 2β using Run 1 data

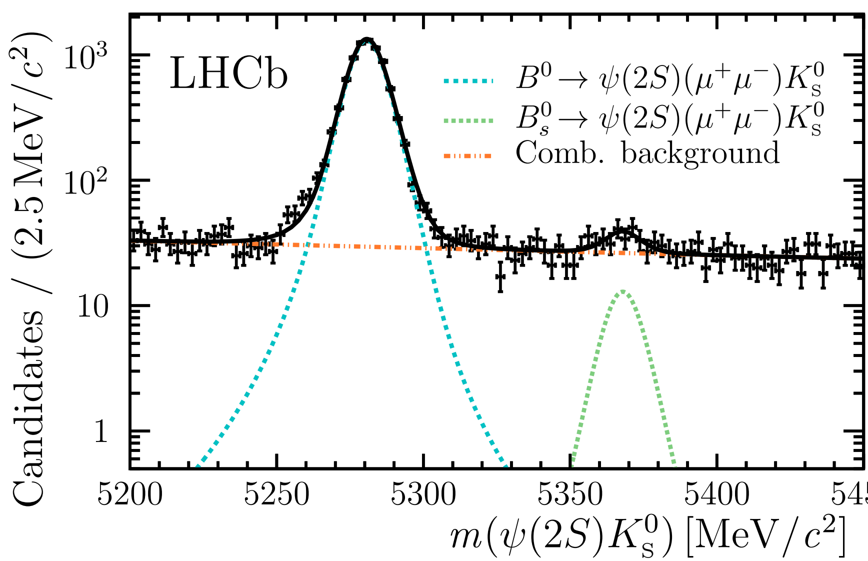
Result reduces tension between direct + indirect determinations from global fit

New LHCb Run 1 results using ψ(2S) and electron modes




New

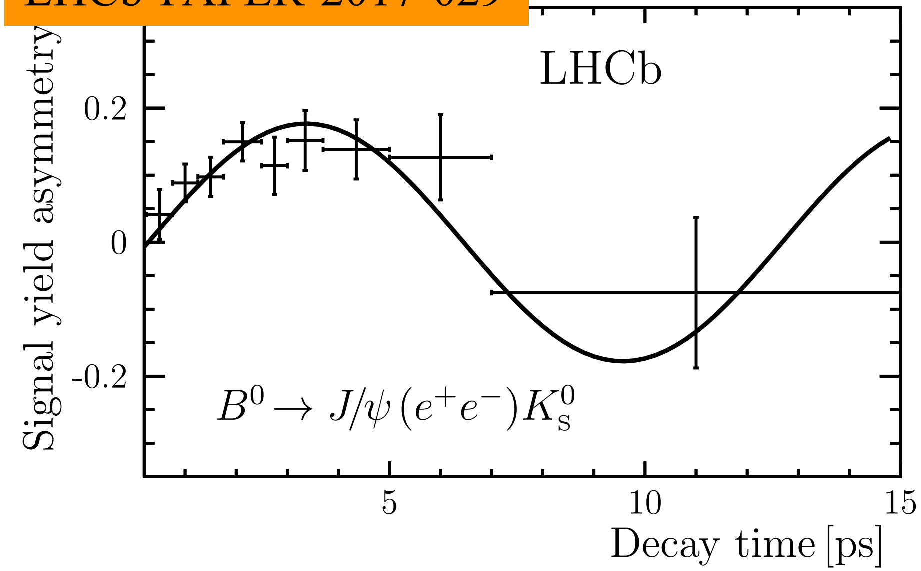


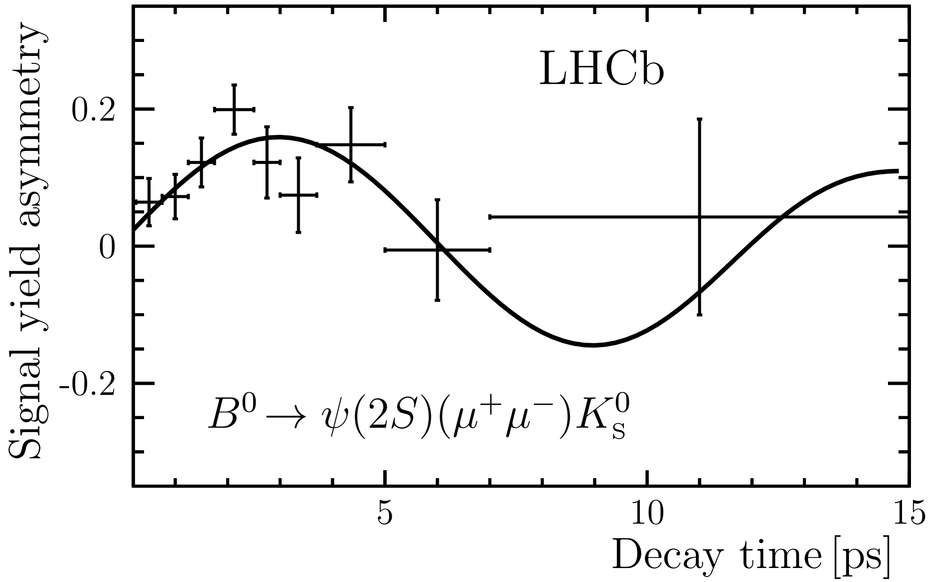




LHCb-PAPER-2017-029

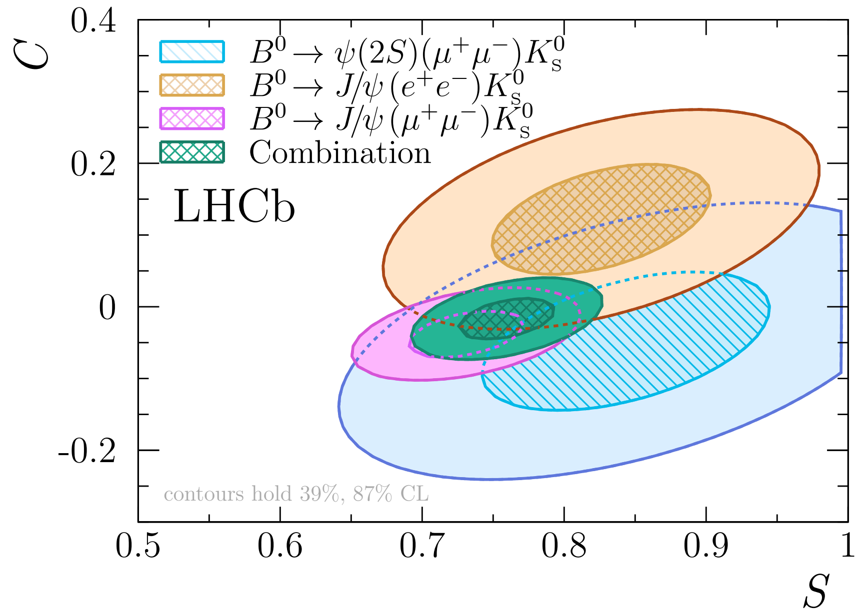
# sin 2β

LHCb-PAPER-2017-029




$$C(B^0 \to J/\psi\,(e^+e^-)K^0_S) = 0.12\,^{+0.07}_{-0.07}\,(\text{stat}) \pm 0.02\,(\text{syst})$$
$$S(B^0 \to J/\psi\,(e^+e^-)K^0_S) = 0.83\,^{+0.07}_{-0.08}\,(\text{stat}) \pm 0.01\,(\text{syst})$$
$$C(B^0 \to \psi(2S)(\mu^+\mu^-)K^0_S) = -0.05\,^{+0.10}_{-0.10}\,(\text{stat}) \pm 0.01\,(\text{syst})$$
$$S(B^0 \to \psi(2S)(\mu^+\mu^-)K^0_S) = 0.84\,^{+0.10}_{-0.10}\,(\text{stat}) \pm 0.01\,(\text{syst})$$




LHCb uncertainty reduced by 20 %

$$C(B^0 \to [c\bar{c}]K^0_S) = -0.017 \pm 0.029$$
$$S(B^0 \to [c\bar{c}]K^0_S) = 0.760 \pm 0.034$$

# $\Delta\Gamma_d$

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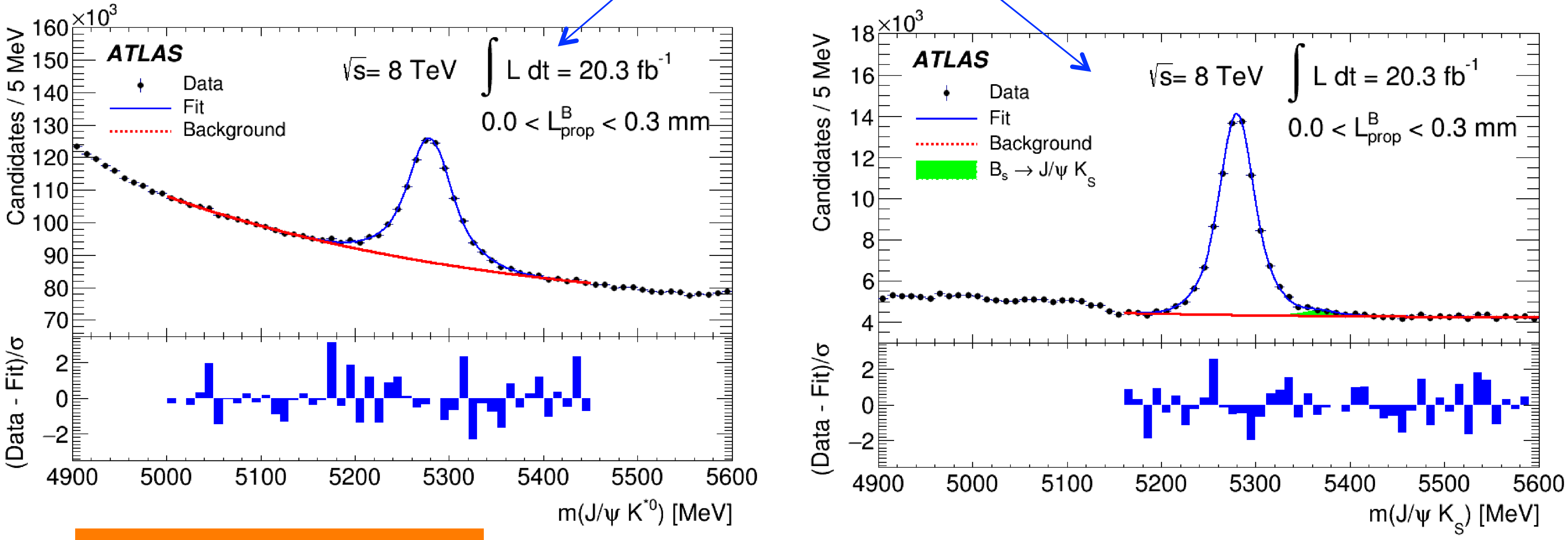
Tension between D0 like-sign dimuon measurement and SM (see Mika's talk) led to renewed interested in $\Delta\Gamma_d$. Important to constrain new physics in this observable (arXiv:1404.2531)

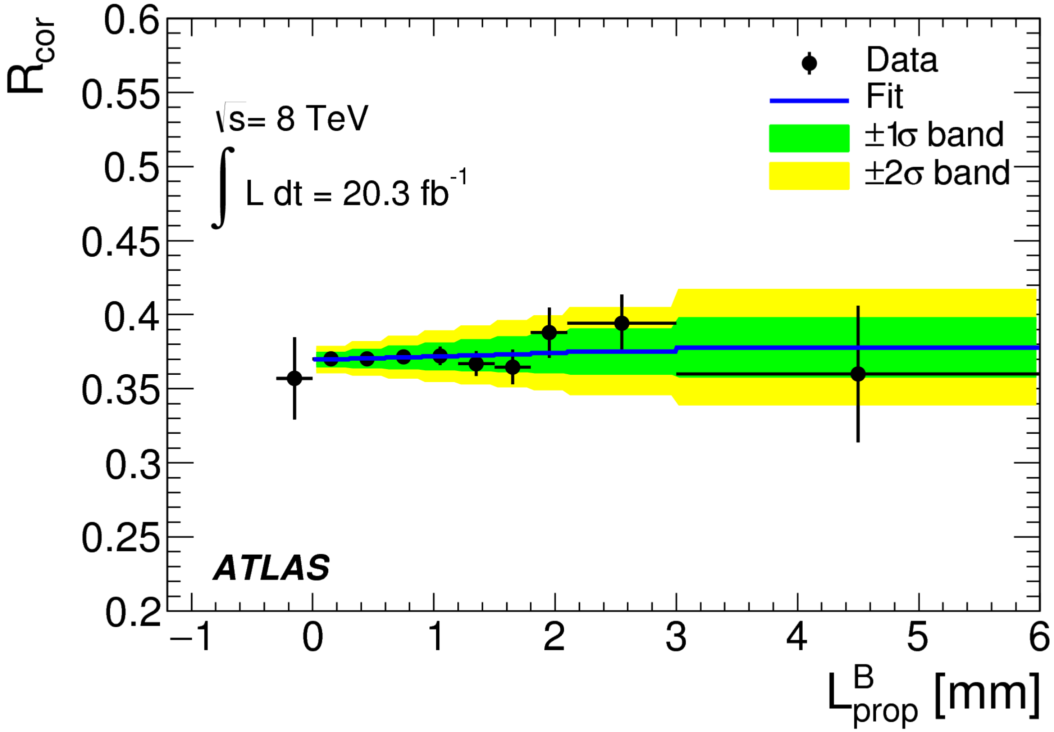
Recent ATLAS measurement

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

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

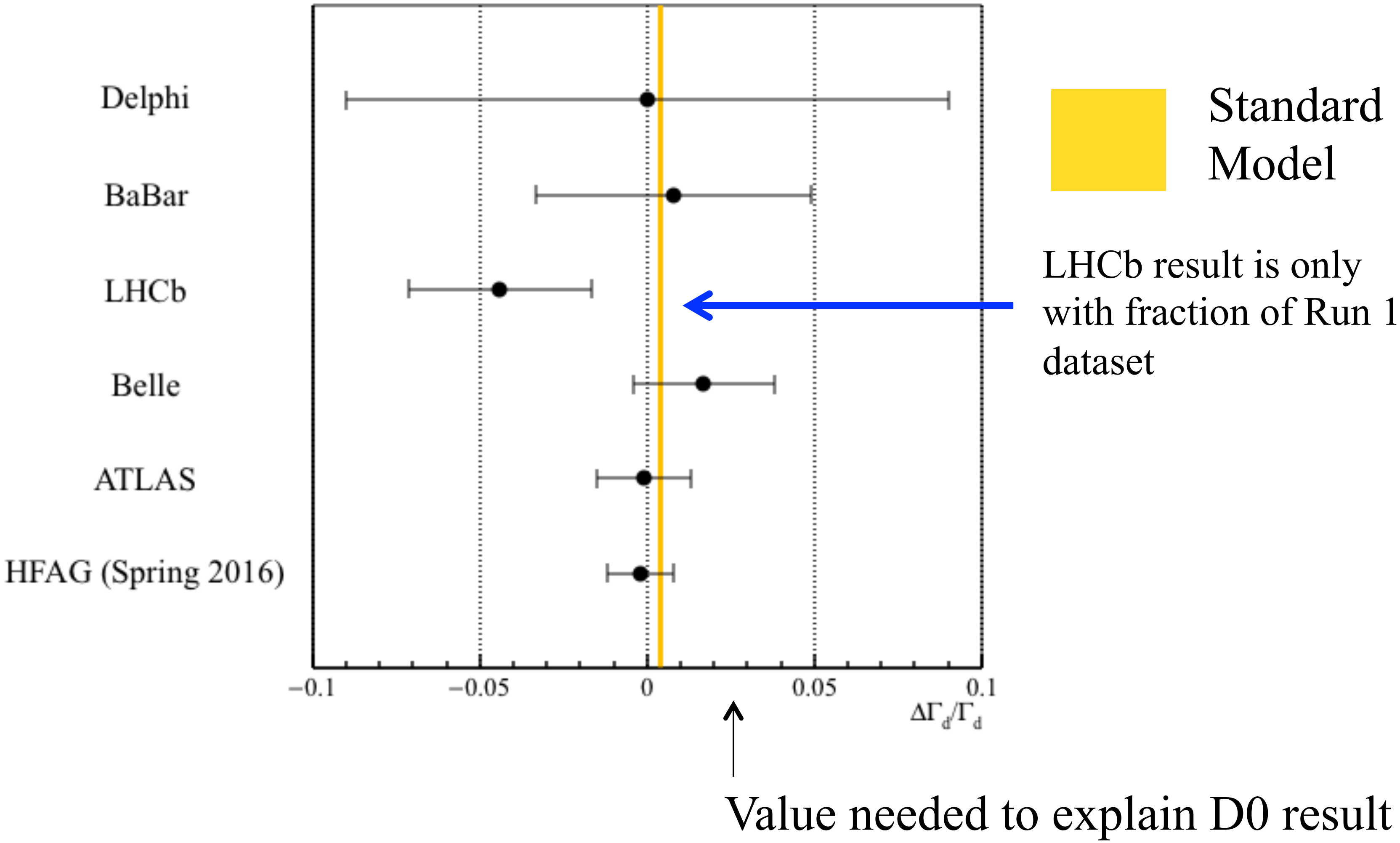
Takes proper account of production asymmetry

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

# $\Delta\Gamma_d$

ATLAS result consistent with SM + previous measurements

$$\Delta\Gamma_d/\Gamma_d\ (\mathrm{SM}) = (0.42 \pm 0.08) \times 10^{-2}$$



# Thoughts

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**The Run 1 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/ψππ ☺

Some things were so far not exploited: electrons for $\phi_s$, CP even eigenstates ☹

**Run 2 analyses will come soon**

LHCb 2015+2016 dataset comparable in size to Run 1, adding 2017 will double in size

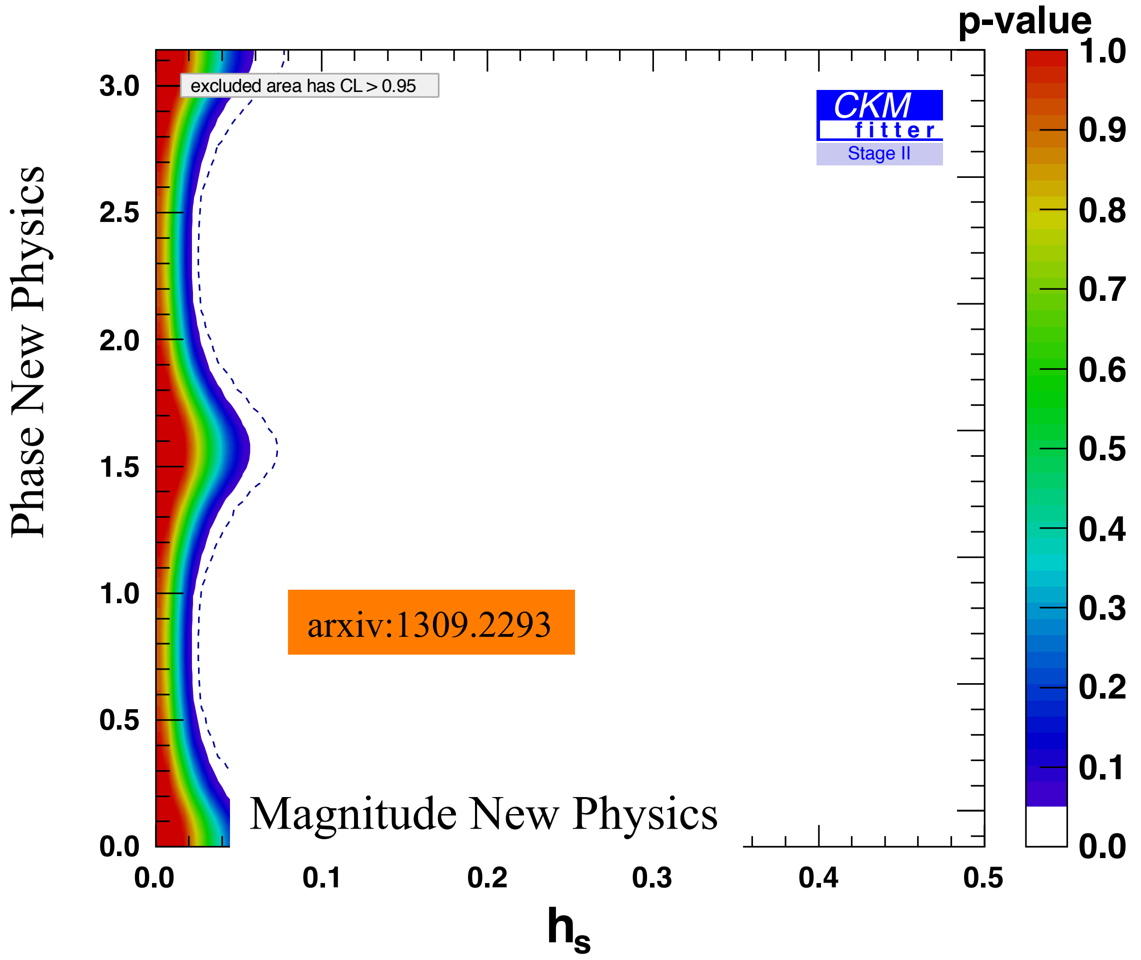
Measurements especially lifetimes will be increasingly systematics limited

Avoid monoculture: supporting and complementary measurements are important since NP small, e.g. lifetimes in $B_s \rightarrow J/\psi\eta$

# Thoughts

The upgrade era is starting

ATLAS IBL , new CMS pixel detector are in LHCb upgrade after LS2 in ~2020




LHC upgrade era $\phi_s$ will be measured to 0.2°

Limit New Physics amplitude to the % level

# Thoughts

The upgrade era is around the corner

Early days of LHCb upgrade provides many interesting opportunities

Lifetimes, $\Delta m_s$ ideal first measurements to demonstrate new detector capabilities (as was case in 2010)

Bonus: New pixel detector with better performance very different systematic uncertainties

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

Run 2 and Run 3 provide opportunity to make precision measurement of b baryon/hadron lifetimes, testing HQET

# Summary

$B_s$ mixing parameters known with precision after Run 1

- No sign of New Physics ☹

Run 2 results expected soon: improved precision

- Both tree-level and with charmless decays

Important to exploit precision by controlling theoretical uncertainties and exploiting data driven approaches to this

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

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

# Backup

# $B_s$ mixing

http://www.slac.stanford.edu/xorg/hflav/