CP violation, mixing and semi-leptonic decays of beauty at the LHC

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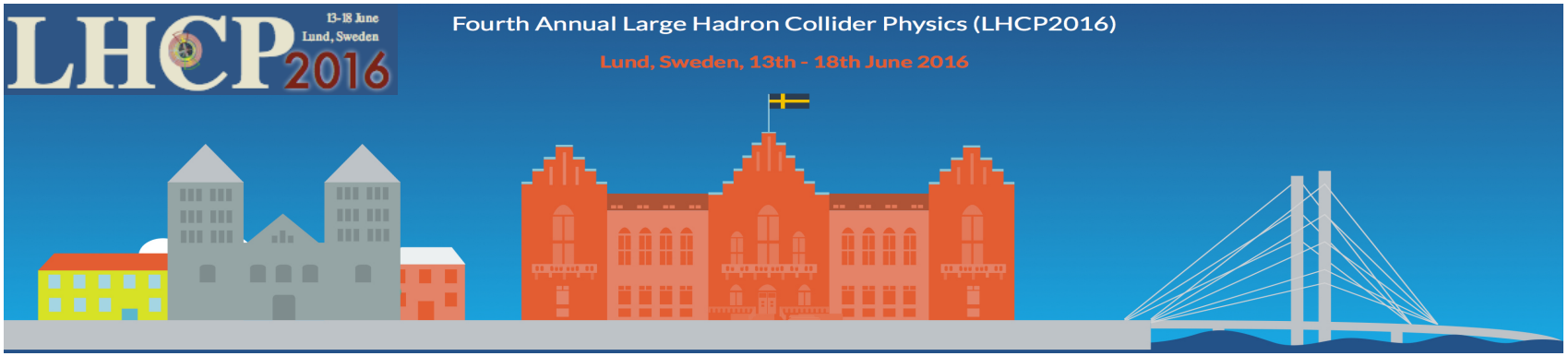
On behalf of the ATLAS, CMS and LHCb collaborations



Outline

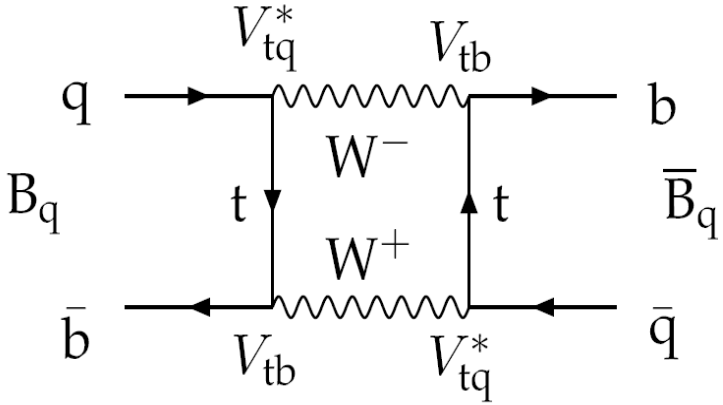
Review measurements of B mixing parameters at the LHC

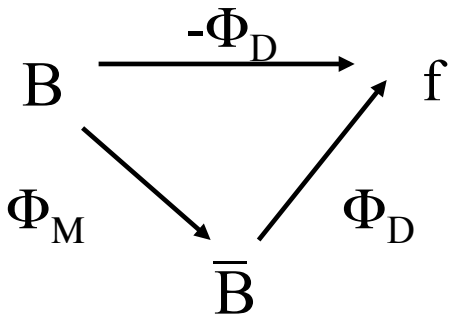
- B mixing
- B_s mixing phase, ϕ_s
- Semi-leptonic asymmetries: a_{sl}
- $\Delta\Gamma_d$ and Δm_d
- Summary

Huge number of Run 1 results
Impossible to present everything in 20 minutes. Focus on more recent results. Not covered sin2β and Δm_s

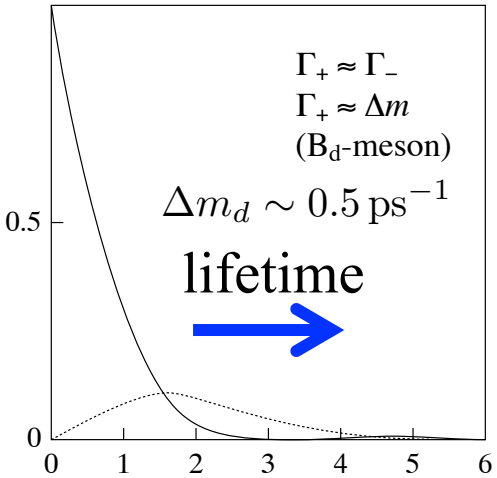
Neutral B meson mixing

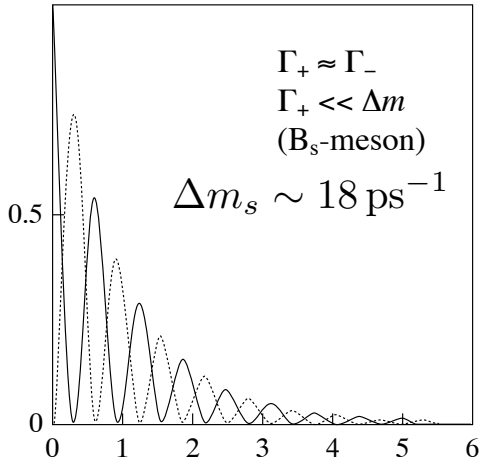
$$i\frac{\partial}{\partial t}\left(\frac{|B_s^0(t)>}{|\overline{B_s^0}(t)>}\right) = \left(M - i\frac{\Gamma}{2}\right)\left(\frac{|B_s^0(t)>}{|\overline{B_s^0}(t)>}\right)$$





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





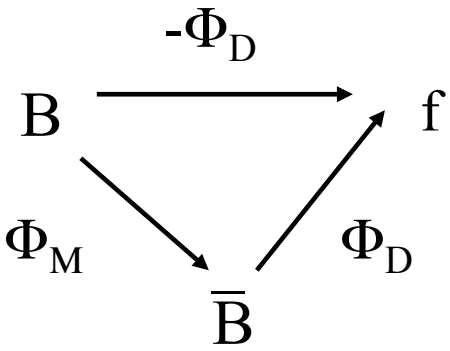
Slow B_d oscillations
Fast B_s oscillations

B_s meson mixing

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

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

$$\Delta m_s = M_H - M_L$$



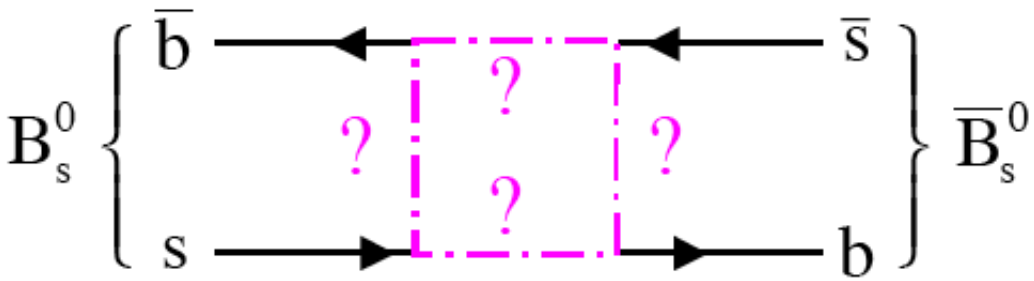
Physical states B_H and B_L

$\tau_L \sim 1.4$ ps, $\tau_H \sim 1.6$ ps

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 such as Supersymmetry and Little Higgs

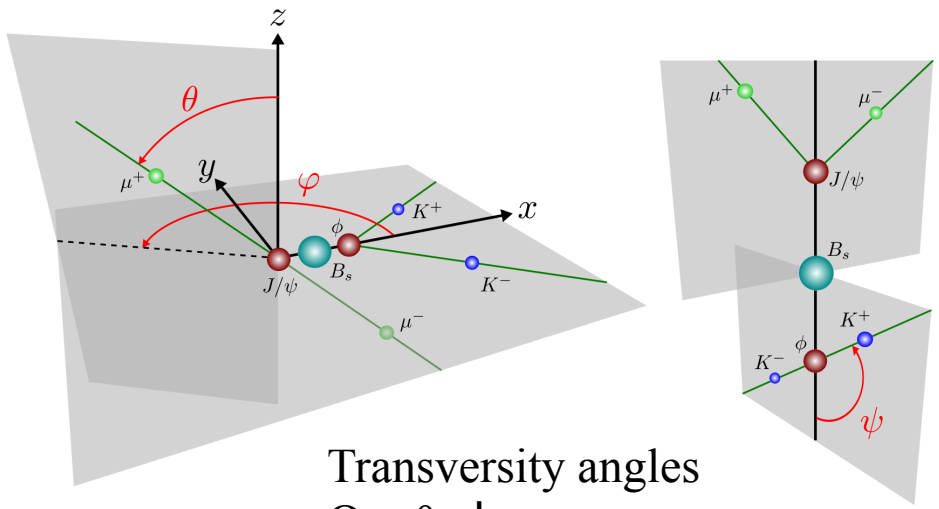


Measuring the B_s mixing phase

- Golden mode to Φs measure is $B_s \rightarrow J/\psi\varphi$
- Distinct experimental signature with low background
- But not CP eigenstate: Time dependent angular analysis needed

Polarization amplitudes

- A(perp) CP odd
- A_0 and A(para) CP even

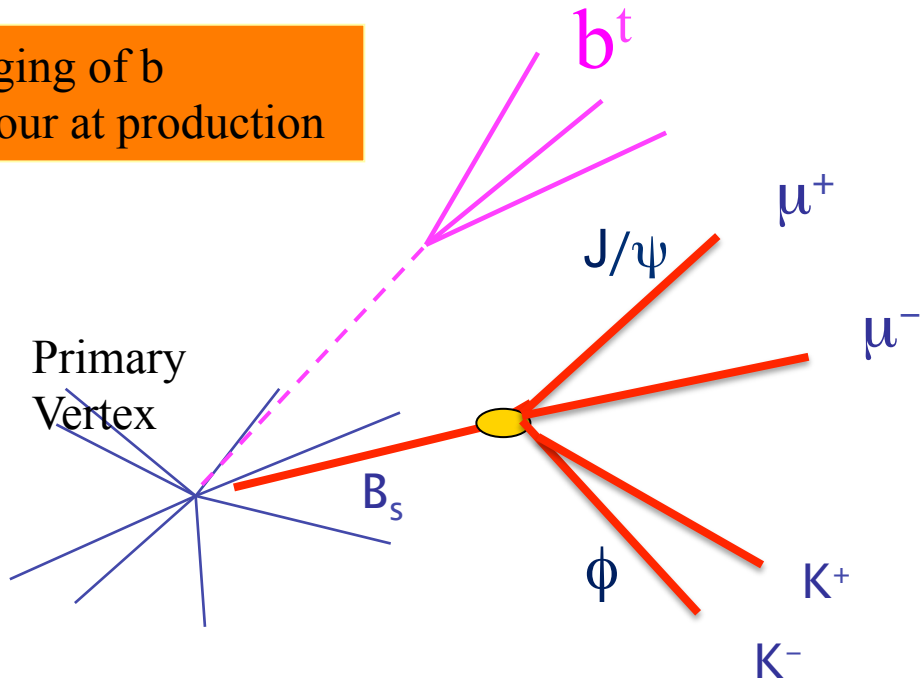


Transversity angles
$\Omega = \theta, \phi, \psi$

CP eigenstate modes also studied by LHCb ($B_s \rightarrow J/\psi f^0$, $B_s \rightarrow D_s^+ D_s^-$). No angular analysis but lower yields

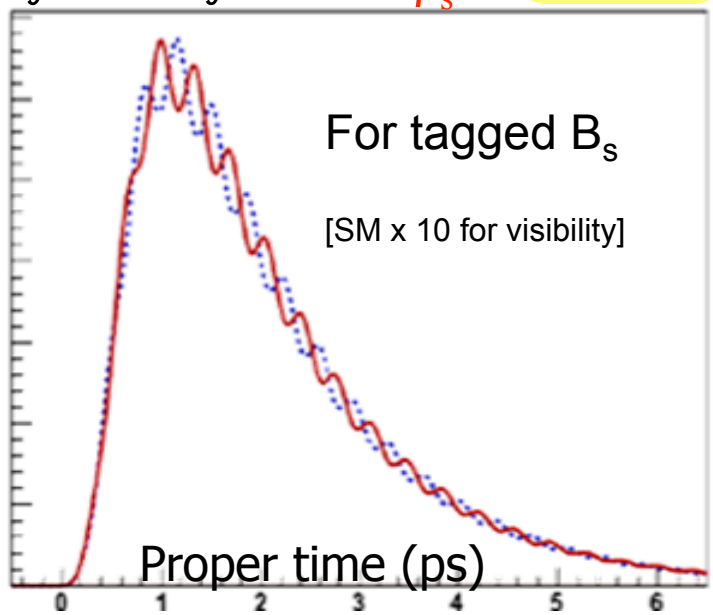
Measuring the B_s mixing phase

Tagging of b flavour at production



Mass + pointing constraints to reduce background

Asymmetry ∝ **sin** $2\beta_s$ × **sin** Δmt

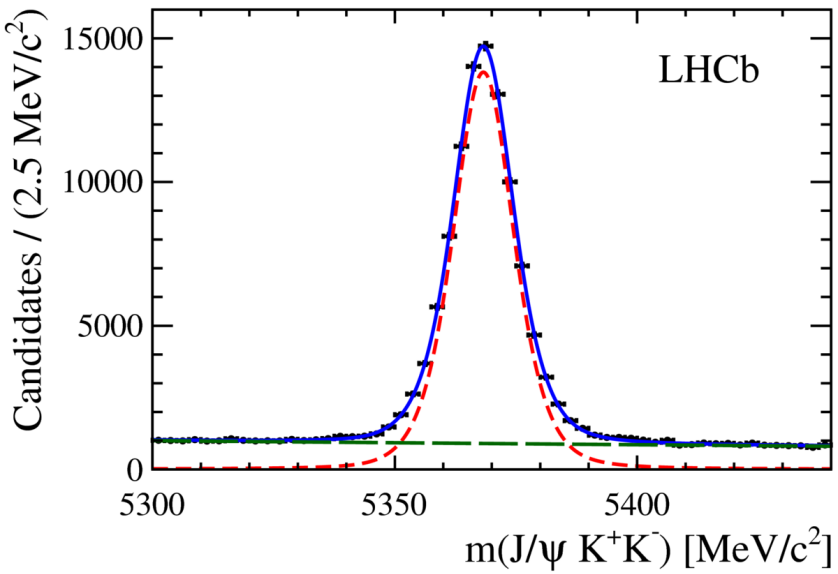


Good primary + secondary vertexing to measure proper time

Precision tracking crucial

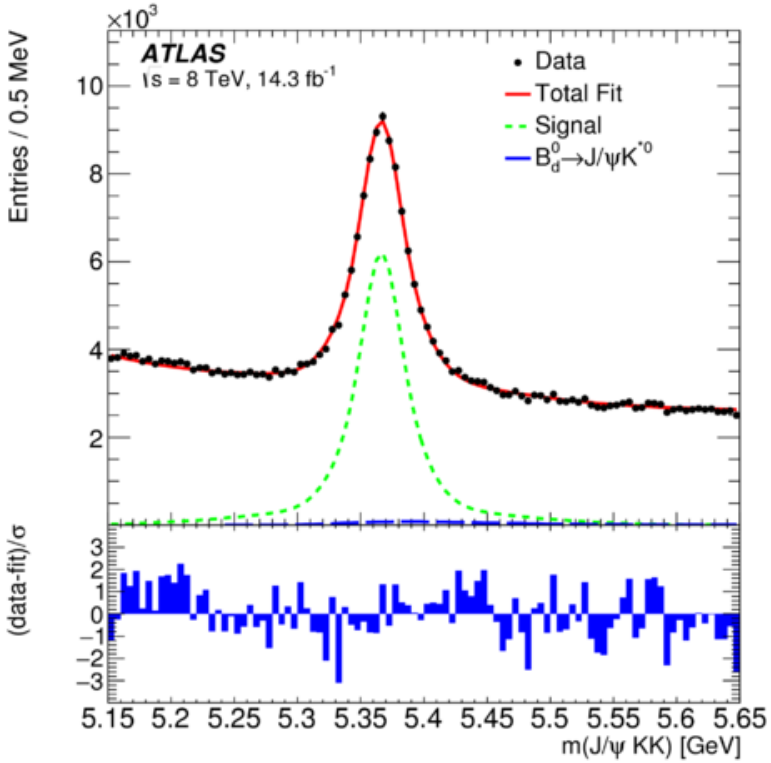
Measuring the B_s mixing phase

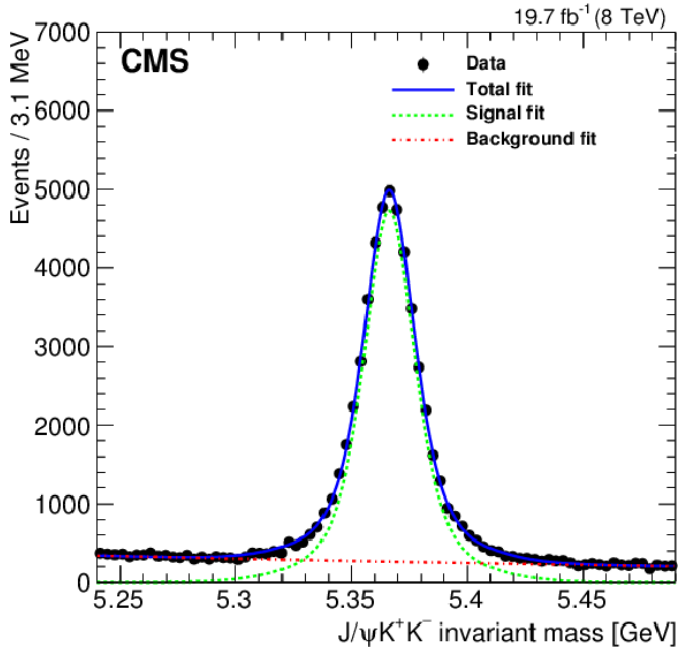
ATLAS, CMS, LHCb have all performed full angular analyses of $B_s \rightarrow J/\psi\varphi$ using full Run 1 dataset



PRL 114 (2015) 041801

arXiv:1601.03297





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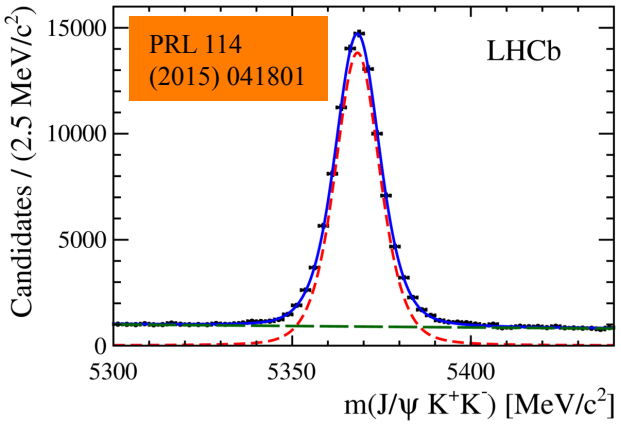
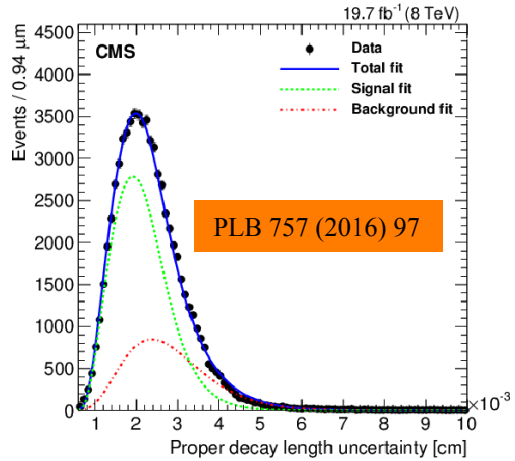
Measuring the B_s mixing phase

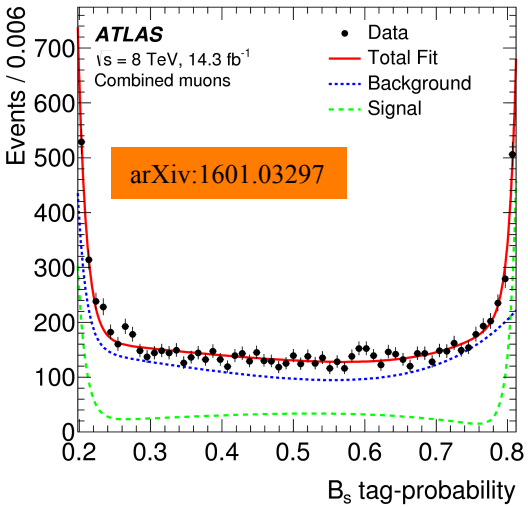


Mass distribution



Decay time Resolution model

Unbinned maximum likelihood fit to mass, time and angles



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

Decay time acceptance due to selection

Angular acceptance for signal from simulation

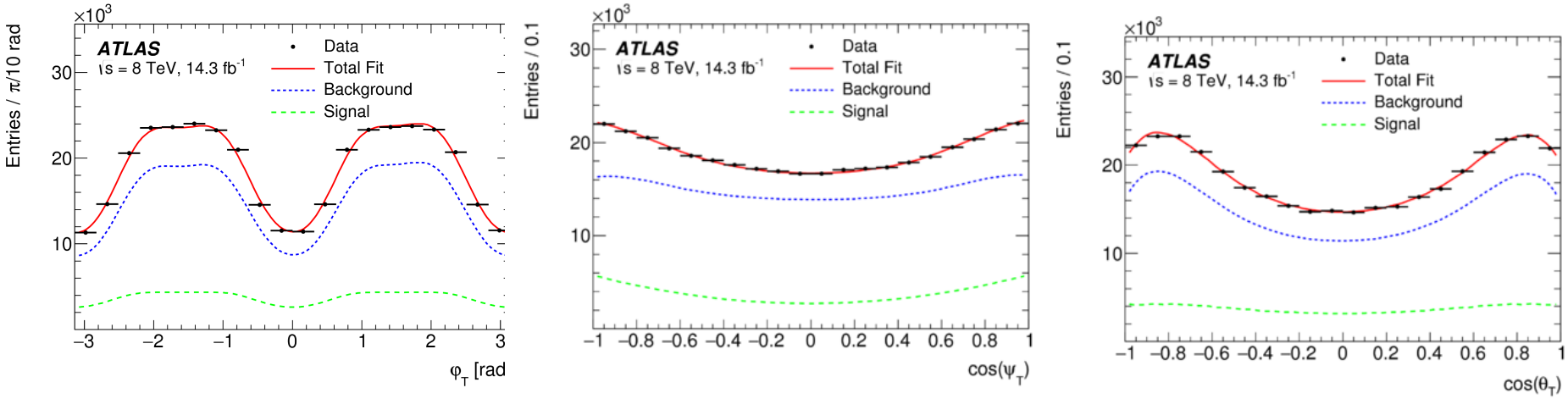
Mass sidebands or sWeight (arxiv: 0905.0724) technique to determine angular distribution of background

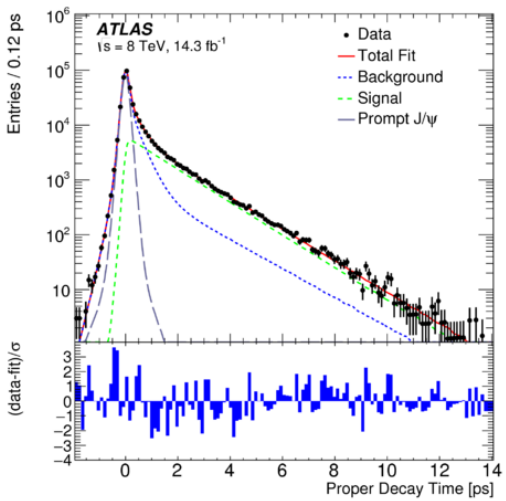
8

ATLAS: $B_s \rightarrow J/\psi\phi$

arXiv:1601.03297

Transversity angles





$$\phi_s = -0.098 \pm 0.084\ (\text{stat.}) \pm 0.040\ (\text{syst.})\ \text{rad}$$

$$\Delta\Gamma_s = 0.083 \pm 0.011\ (\text{stat.}) \pm 0.007\ (\text{syst.})\ \text{ps}^{-1}$$

$$\Gamma_s = 0.677 \pm 0.003\ (\text{stat.}) \pm 0.003\ (\text{syst.})\ \text{ps}^{-1}.$$

CMS: $B_s \rightarrow J/\psi\phi$

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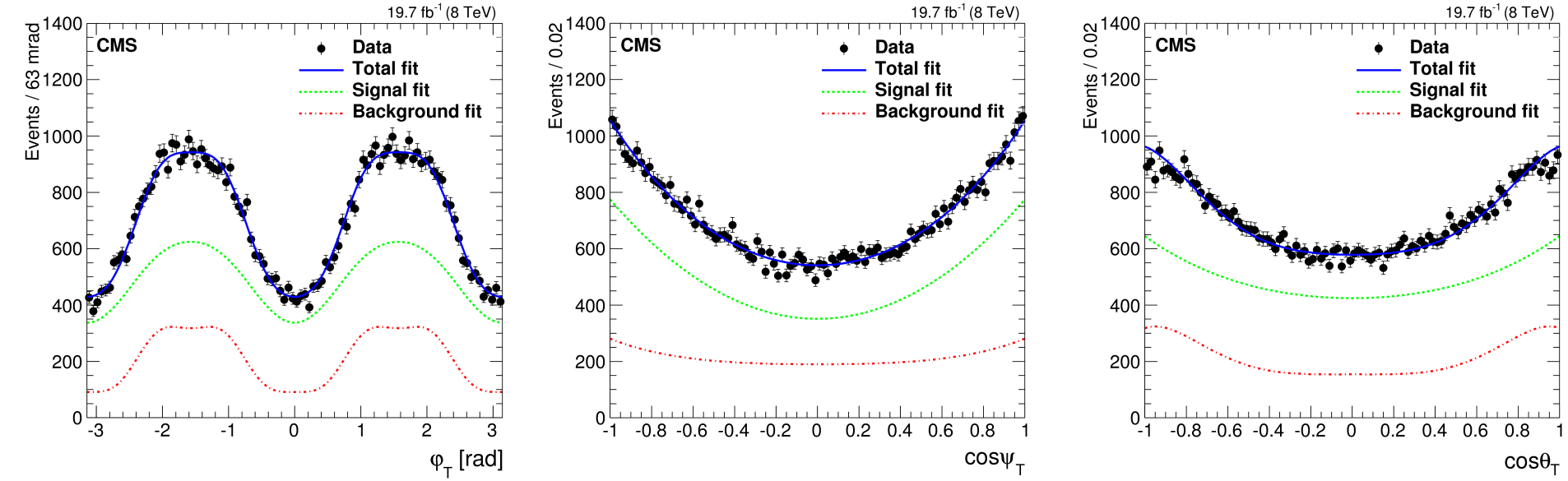
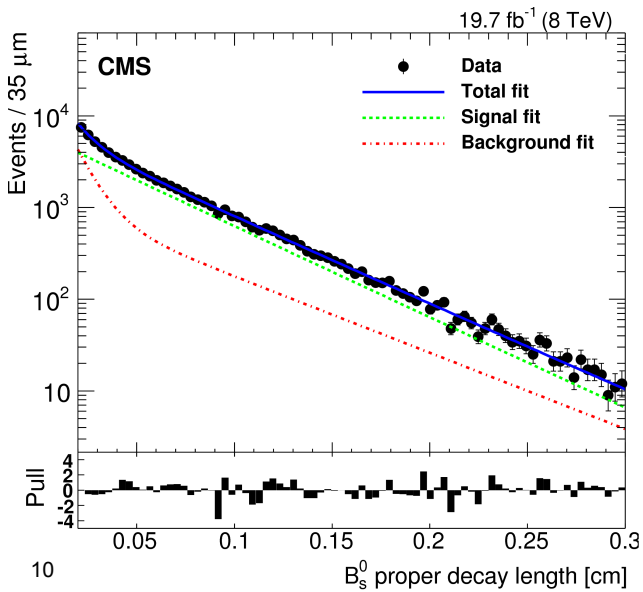


Transversity angles

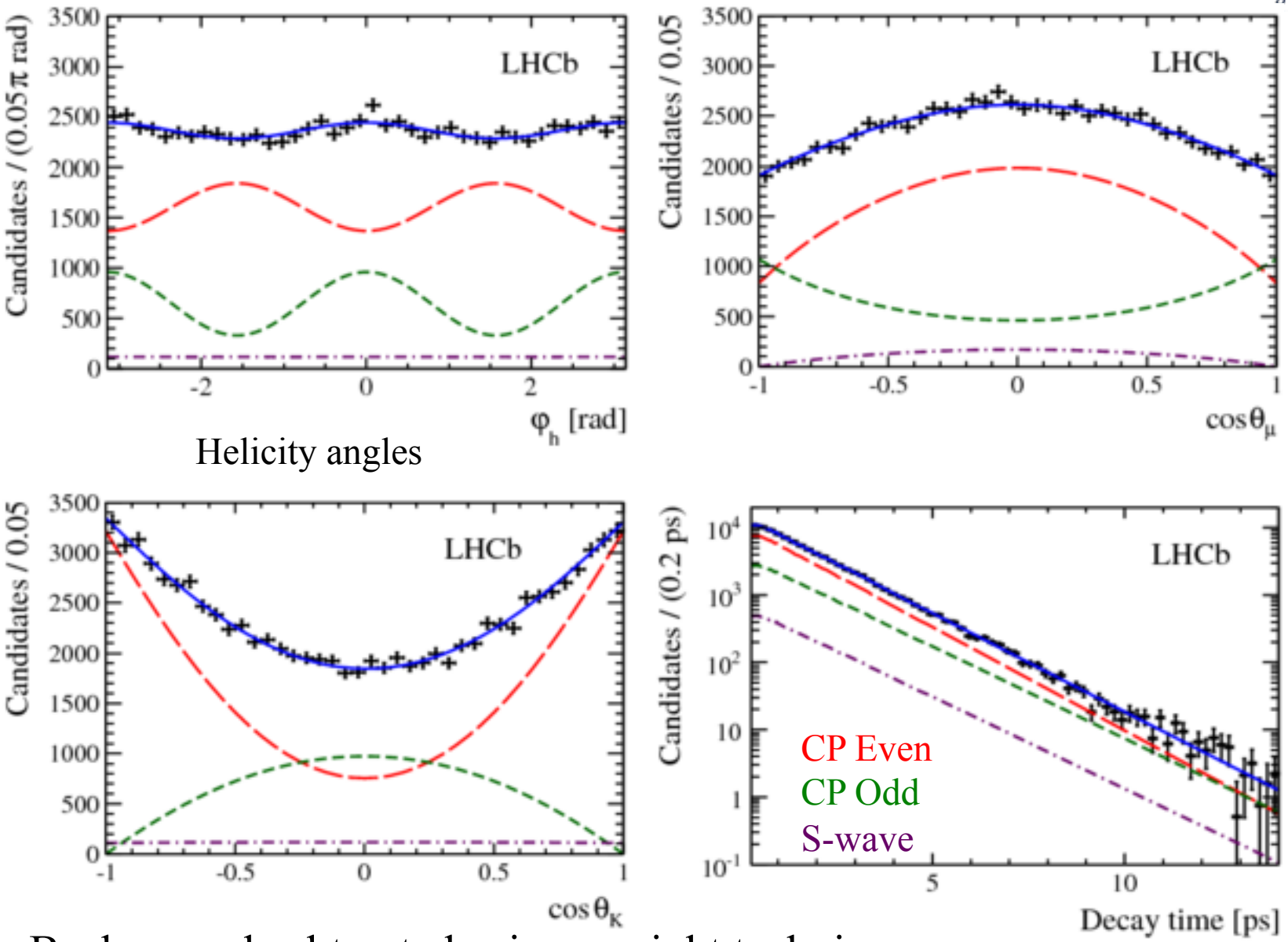


$$\phi_s = -0.075 \pm 0.097\,(\text{stat}) \pm 0.031\,(\text{syst})\,\text{rad},$$

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

LHCb: $B_s \rightarrow J/\psi\phi$

PRL 114 (2015) 041801



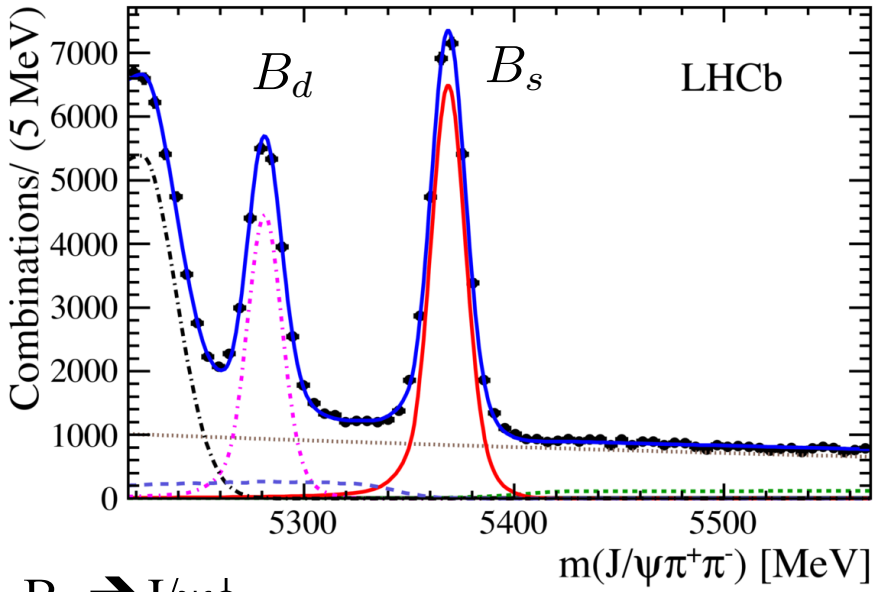
Helicity angles

Background subtracted using sweight technique

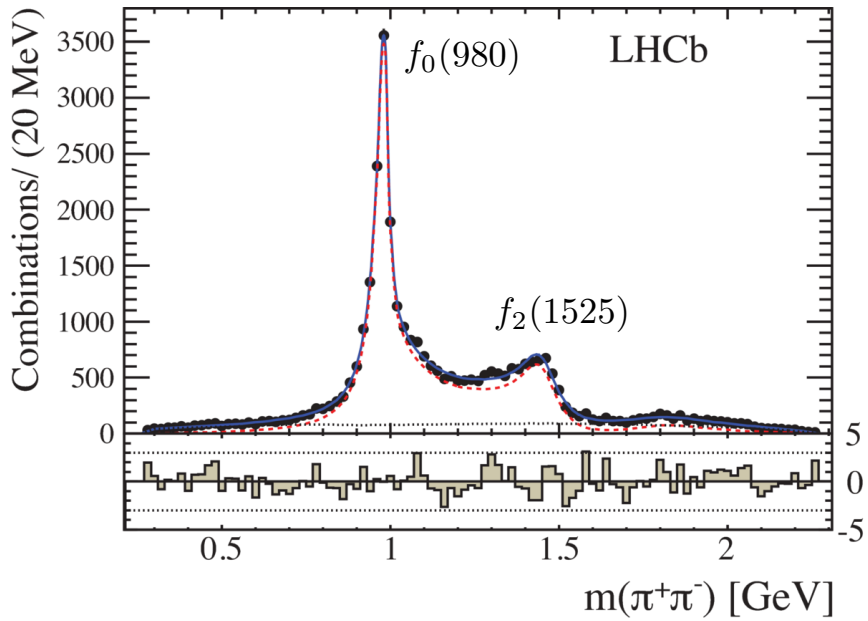
LHCb: $B_s \rightarrow J/\psi\pi^+\pi^-$

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

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



$B_s \rightarrow J/\psi\phi$



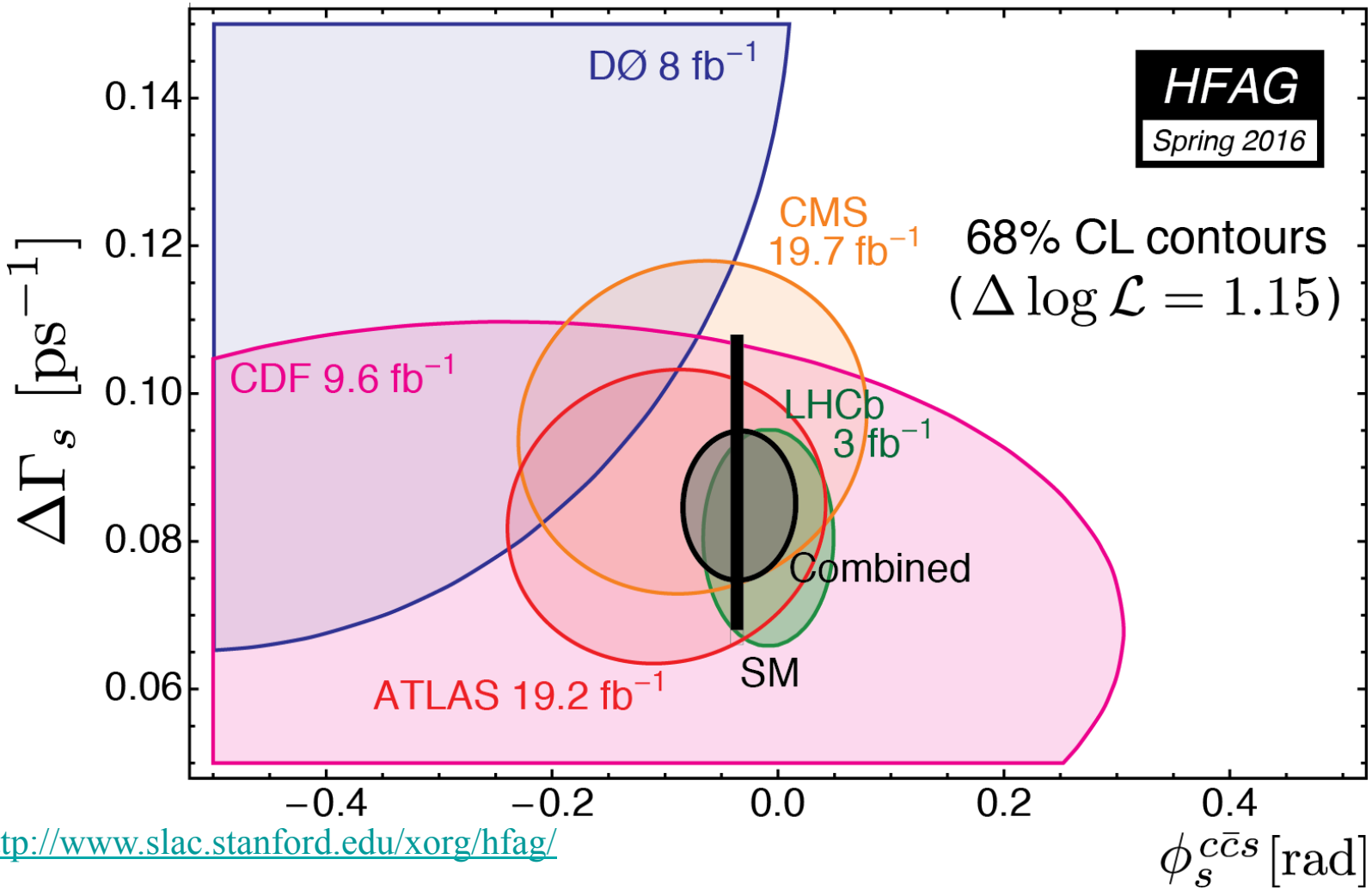
$$\phi_s = -0.058 \pm 0.049 \pm 0.006 \text{ rad}$$
$$\Delta m_s = 17.711\ ^{+0.055}_{-0.057} \pm 0.011 \text{ ps}^{-1}$$
$$\Gamma_s = 0.6603 \pm 0.0027 \pm 0.0015 \text{ ps}^{-1}$$
$$\Delta\Gamma_s = 0.0805 \pm 0.0091 \pm 0.0032 \text{ ps}^{-1}$$
$$|\lambda| = 0.964 \pm 0.019 \pm 0.007$$

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

Combined

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

ϕ_s status

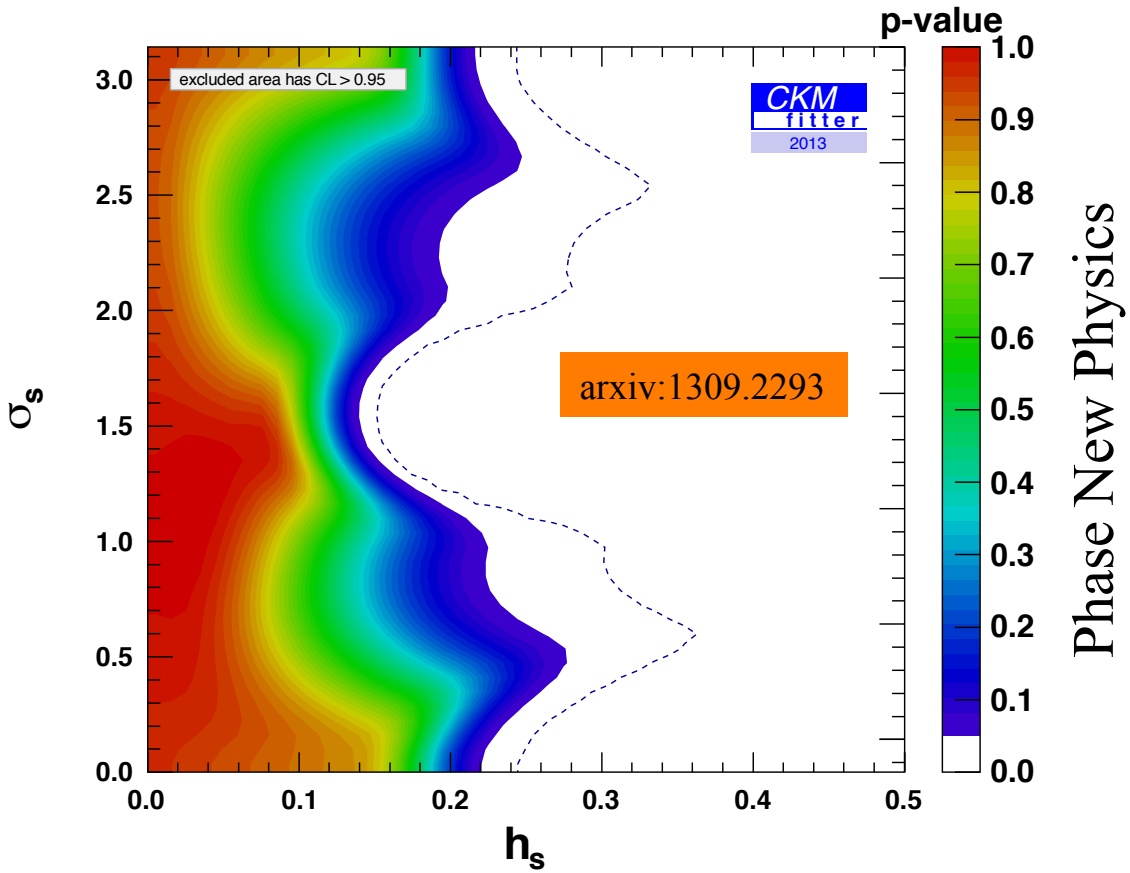


http://www.slac.stanford.edu/xorg/hfag/

Results consistent with Standard Model

ϕ_s outlook

Still room for New Physics amplitude at level of 10 % in B_s mixing
(Similar story in B_d sector)



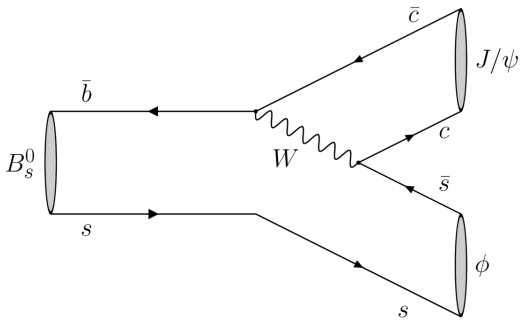
Magnitude New Physics

Can expect updates with Run 2 data

Precision at <0.02 rad level by end of Run II

Penguin pollution

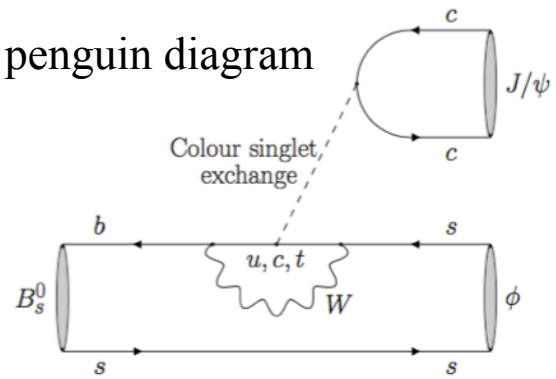
tree



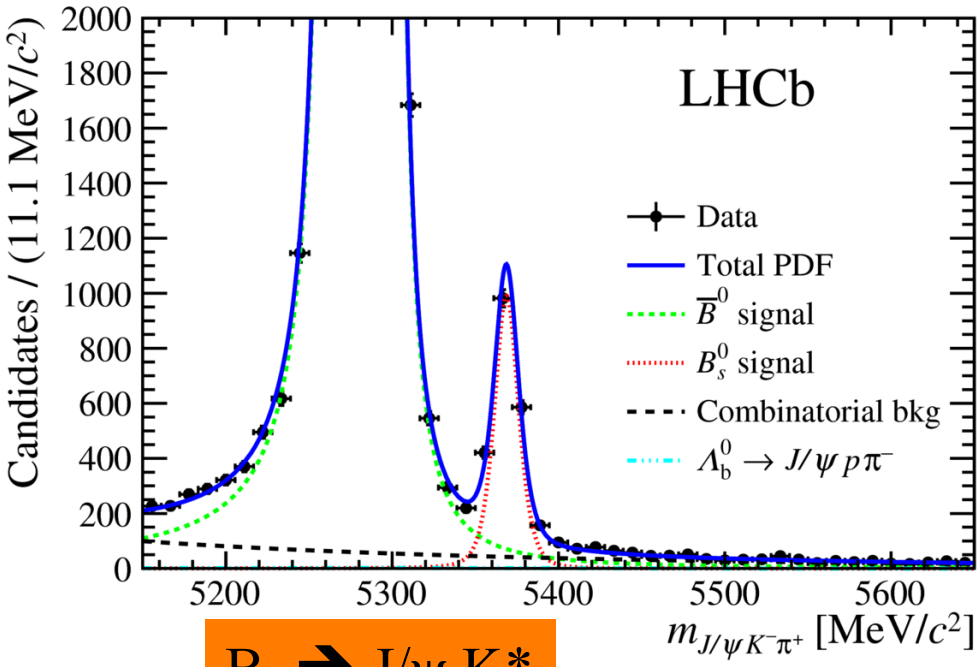
Penguin contributions could mimic NP effects

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

penguin diagram



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

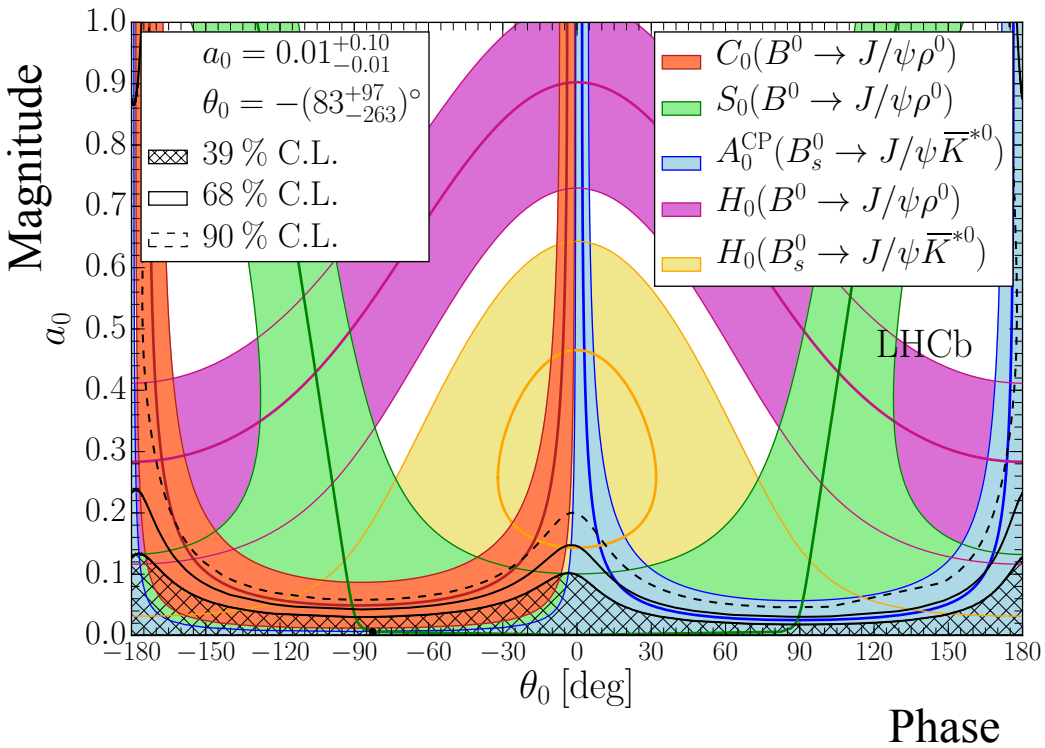


$B_s \rightarrow J/\psi\, K^*$

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

ϕ_s: Penguin pollution

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



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

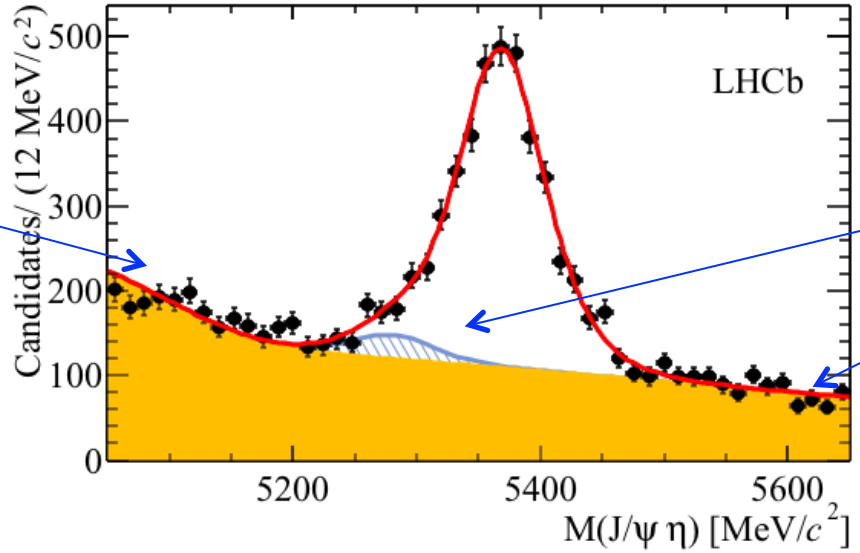
$$\Delta\phi_{s,0}^{J/\psi\phi} = 0.000^{+0.009}_{-0.011}\,(\text{stat})\ \ ^{+0.004}_{-0.009}\,(\text{syst})\,\text{rad}\,,$$
$$\Delta\phi_{s,\parallel}^{J/\psi\phi} = 0.001^{+0.010}_{-0.014}\,(\text{stat})\,\pm 0.008\,(\text{syst})\,\text{rad}\,,$$
$$\Delta\phi_{s,\perp}^{J/\psi\phi} = 0.003^{+0.010}_{-0.014}\,(\text{stat})\,\pm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

Effect of penguins bounded to be less than current uncertainties

$B_s \rightarrow J/\psi\eta$ effective lifetime

New

$B_s \rightarrow J/\psi X$



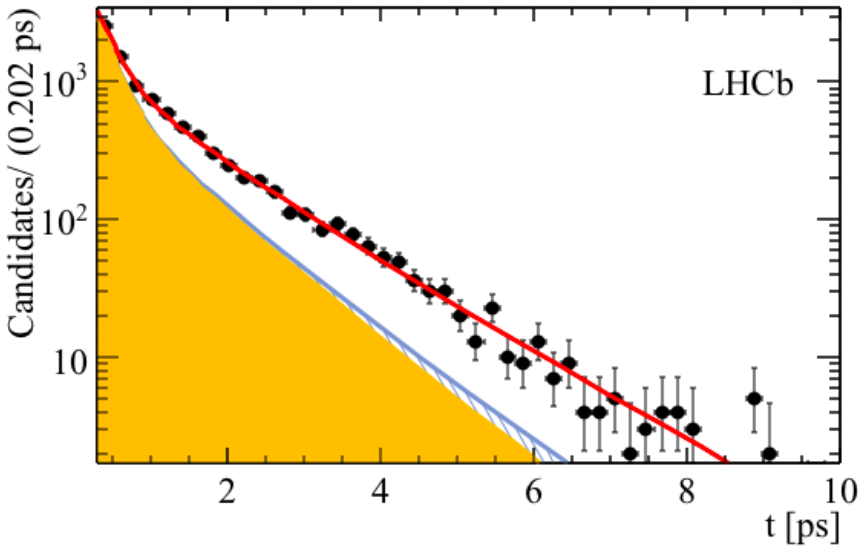
$B_d \rightarrow J/\psi\eta$

combinatorial

LHCb-PAPER-2016-017

Use $\eta \rightarrow \gamma\gamma$ decay mode

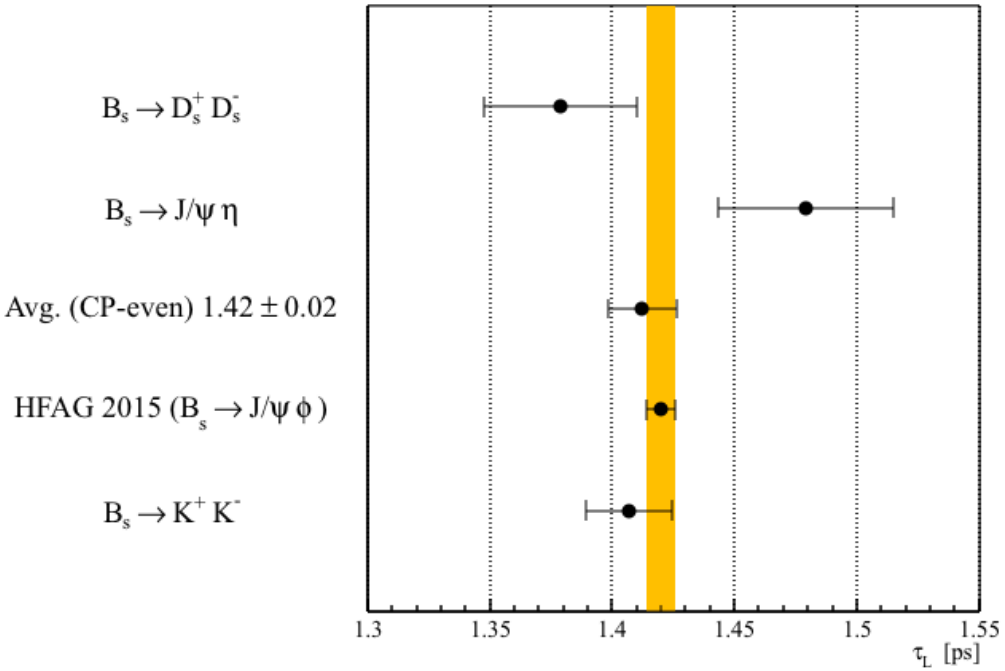
3021 +/- 73 signal candidates.
Extract Effective lifetime from 2-D fit to mass and lifetime distributions.

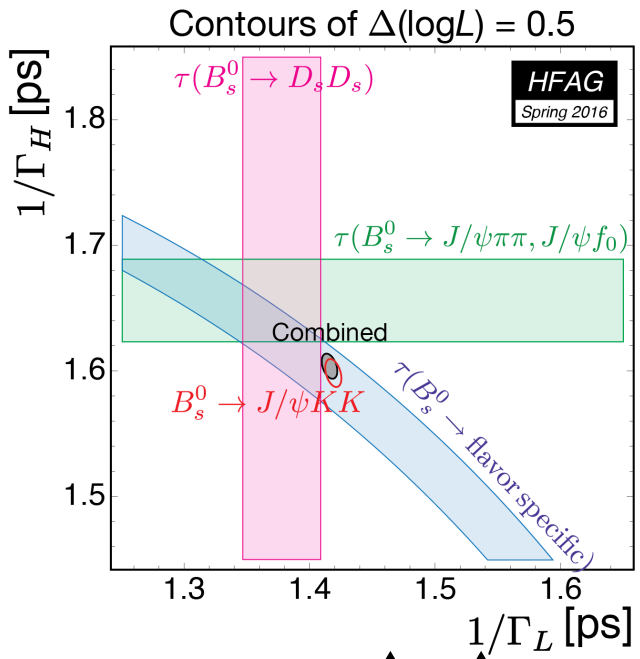


$B_s \rightarrow J/\psi\eta$ effective lifetime

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

Agrees with measurements in other modes and theory expectations



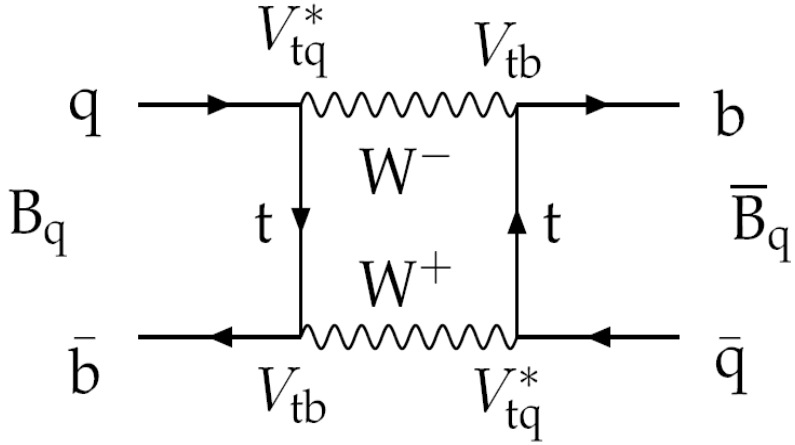


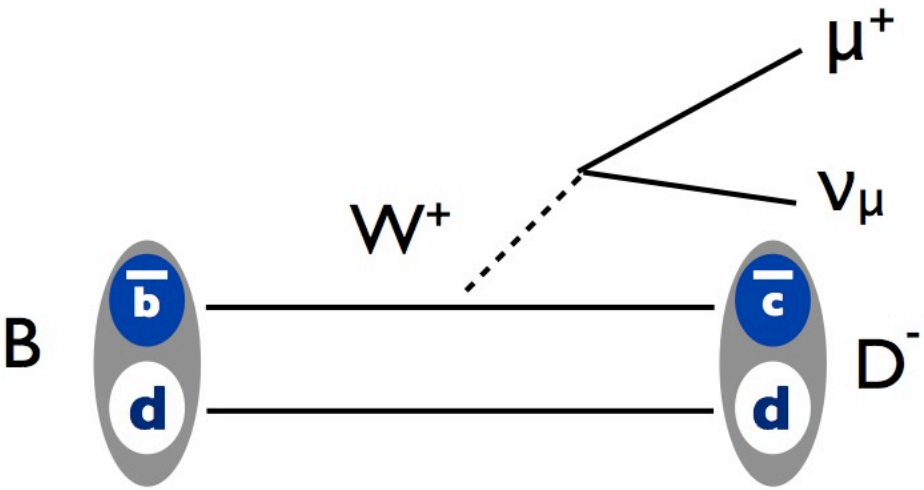
$B_s \rightarrow J/\psi\eta$

CP violation in B mixing

$$\mathcal{P}(B_q \to \overline{B}_q) \neq \mathcal{P}(\overline{B}_q \to B_q)$$

$$a_{\rm sl} \equiv \frac{\Gamma(\overline{B} \to f) - \Gamma(B \to \bar{f})}{\Gamma(\overline{B} \to f) + \Gamma(B \to \bar{f})} \approx \frac{\Delta\Gamma}{\Delta m} \tan\phi_{12}$$





Probe with semileptonic decays (flavour specific)

$$B_d^0 \to D^- \mu^+ \nu_\mu X \quad a_{sl}^d$$

$$B_s^0 \to D_s^- \mu^+ \nu_\mu X \quad a_{sl}^s$$

$$a_{sl}^d = (-4.7 \pm 0.6) \times 10^{-4}$$

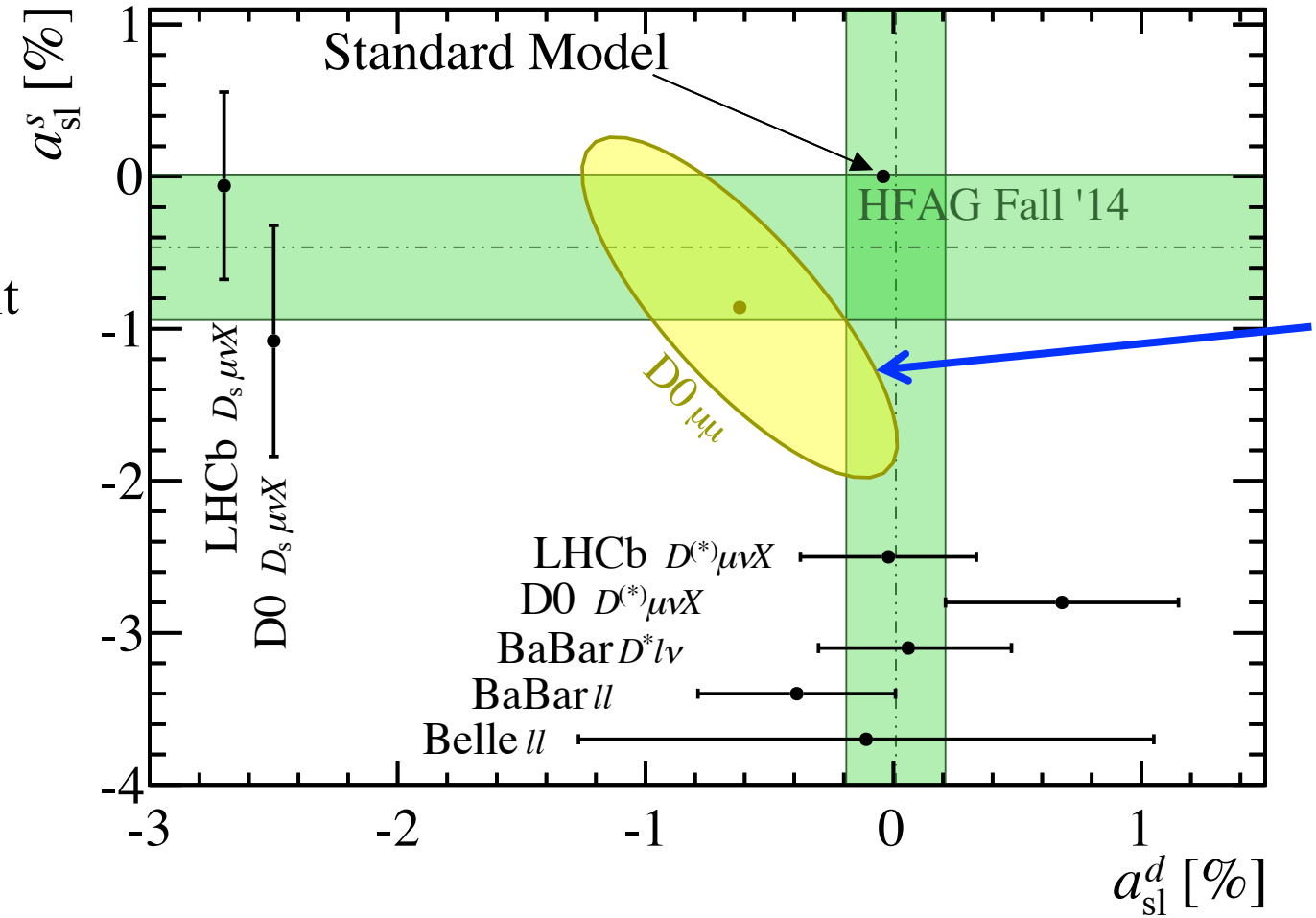
$$a_{sl}^s = (2.22 \pm 0.27) \times 10^{-5}$$

SM values
Artuso, Borissov and Lenz
arXiv: 1511.09466

Story so far…

Status at start of this year….

1fb^{-1} result



Known tension of D0 like sign dimuon measurement with SM

arXiv:1605.09768

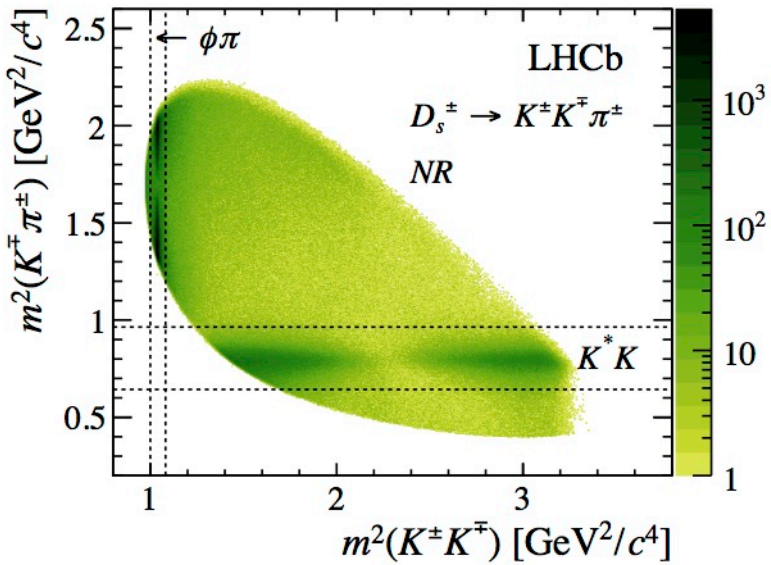
Measuring a_{sl}

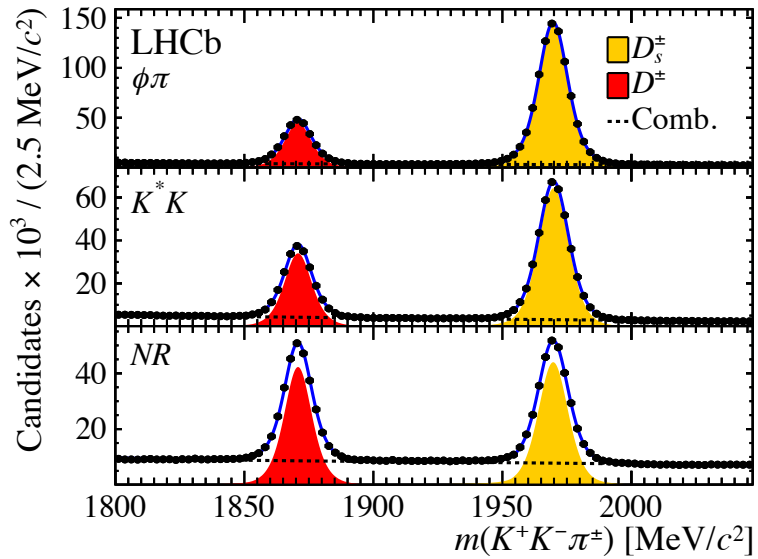
Untagged time integrated counting experiment

$$A_{\text{raw}} = \frac{N(D_s^- \mu^+) - N(D_s^+ \mu^-)}{N(D_s^- \mu^+) + N(D_s^+ \mu^-)}$$

$$a_{\text{sl}}^s = \frac{2}{1 - f_{\text{bkg}}}(A_{\text{raw}} - A_{\text{det}} - f_{\text{bkg}} A_{\text{bkg}})$$

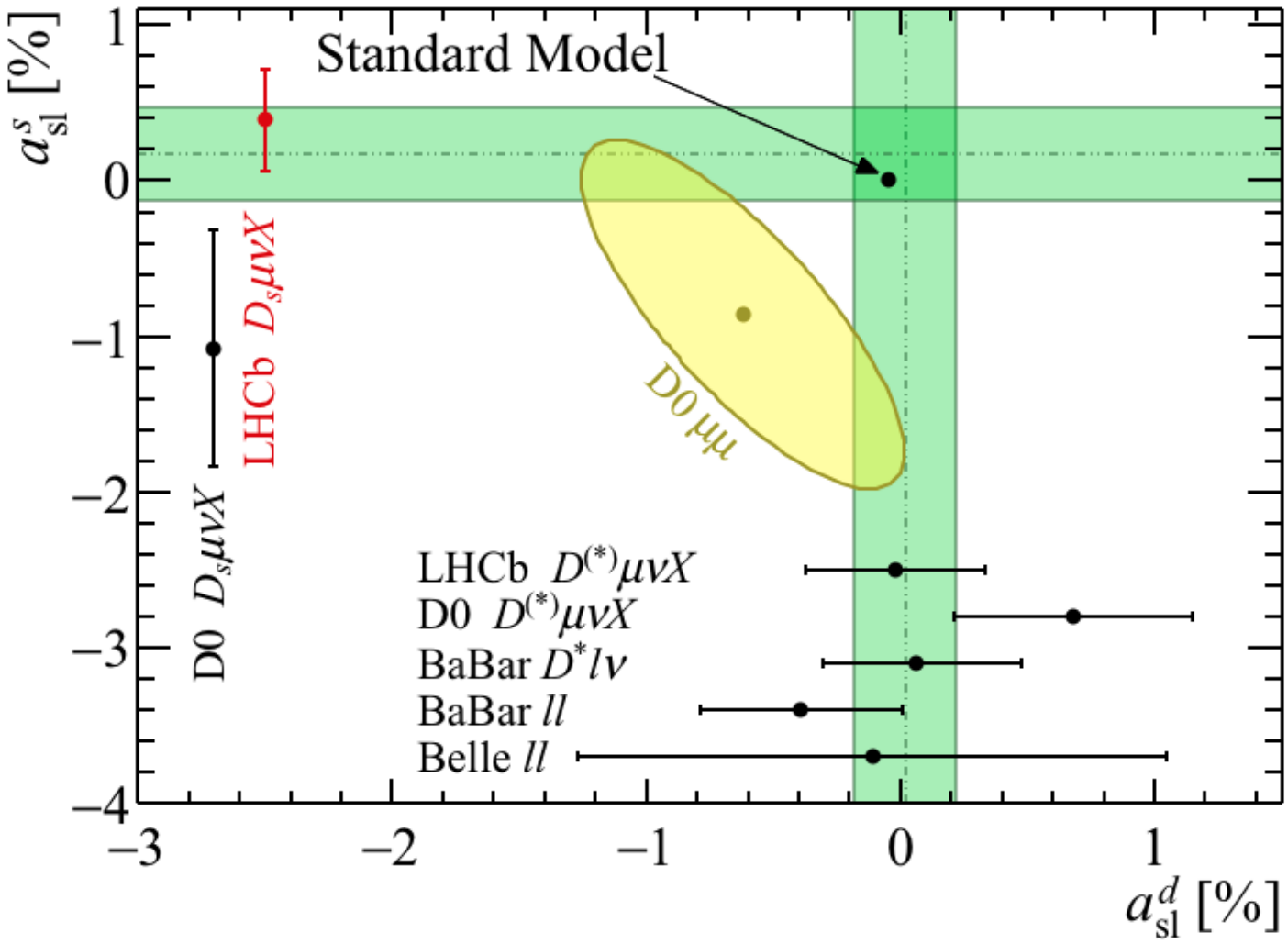
A_{det} is determined using data driven methods





Results

LHCb-PAPER-2016-013



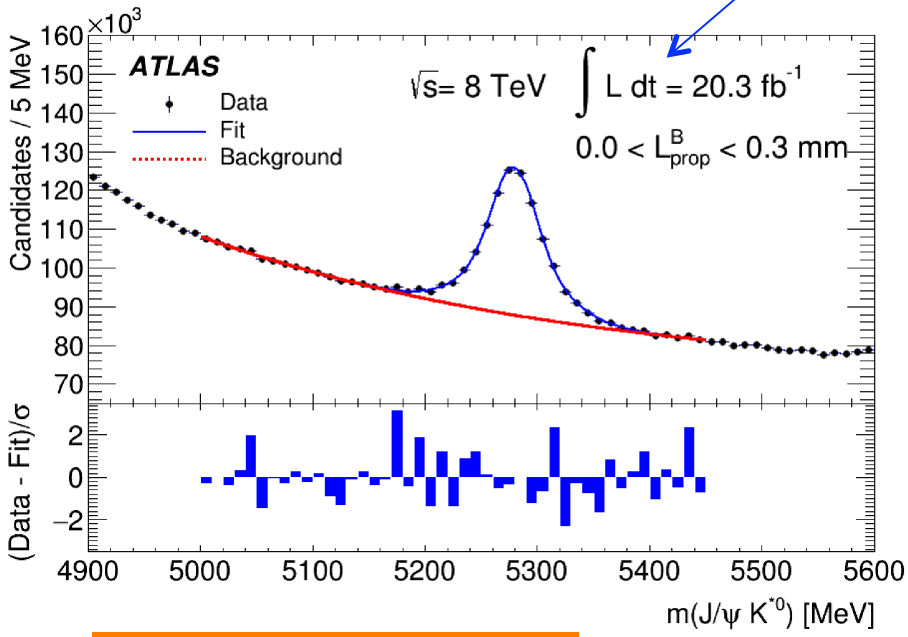
$$a^s_{\rm sl} = (0.39 \pm 0.26 \pm 0.20)\%$$

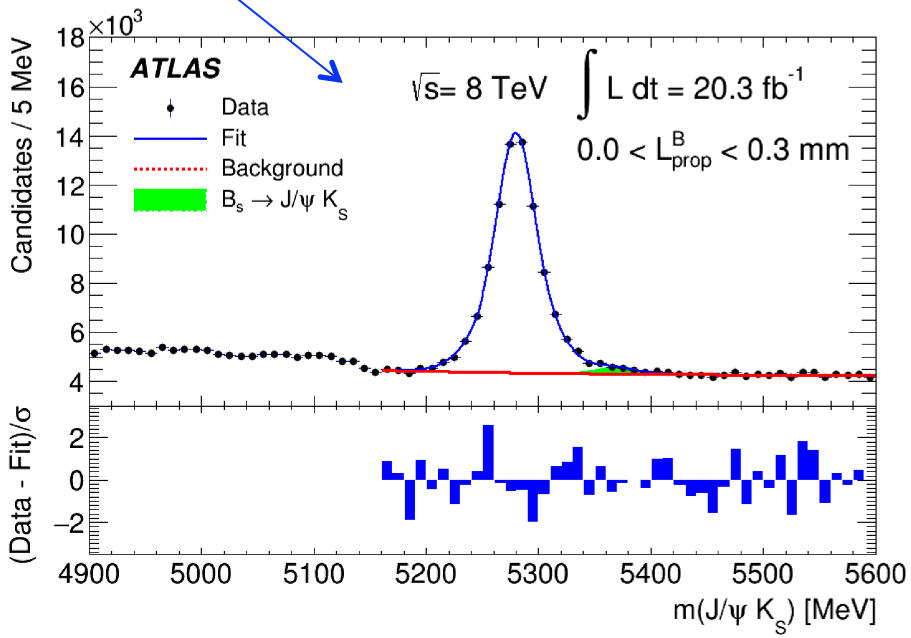
$\Delta\Gamma_d$

Discrepancy of D0 result to SM led to suggestion that it could be due to New Physics in $\Delta\Gamma_d$ as this is relatively poorly constrained (arXiv:1404.2531)

New measurement by ATLAS

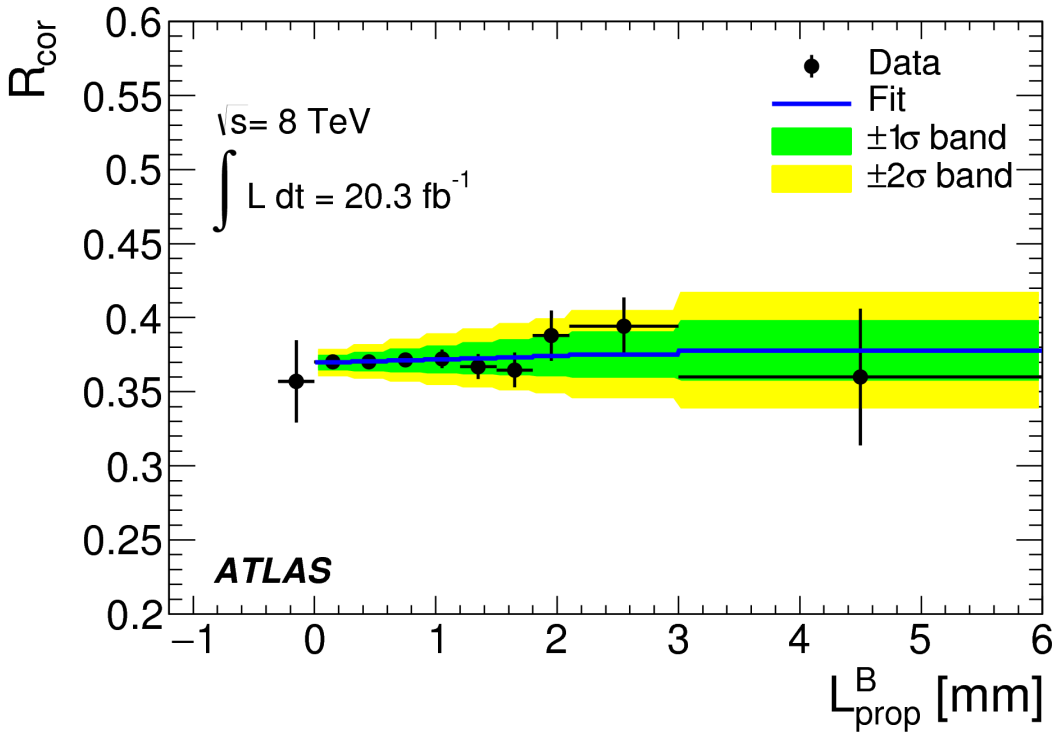
Compare lifetimes in B ➔ J/ψ K* and B ➔ J/ψ K_s





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

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

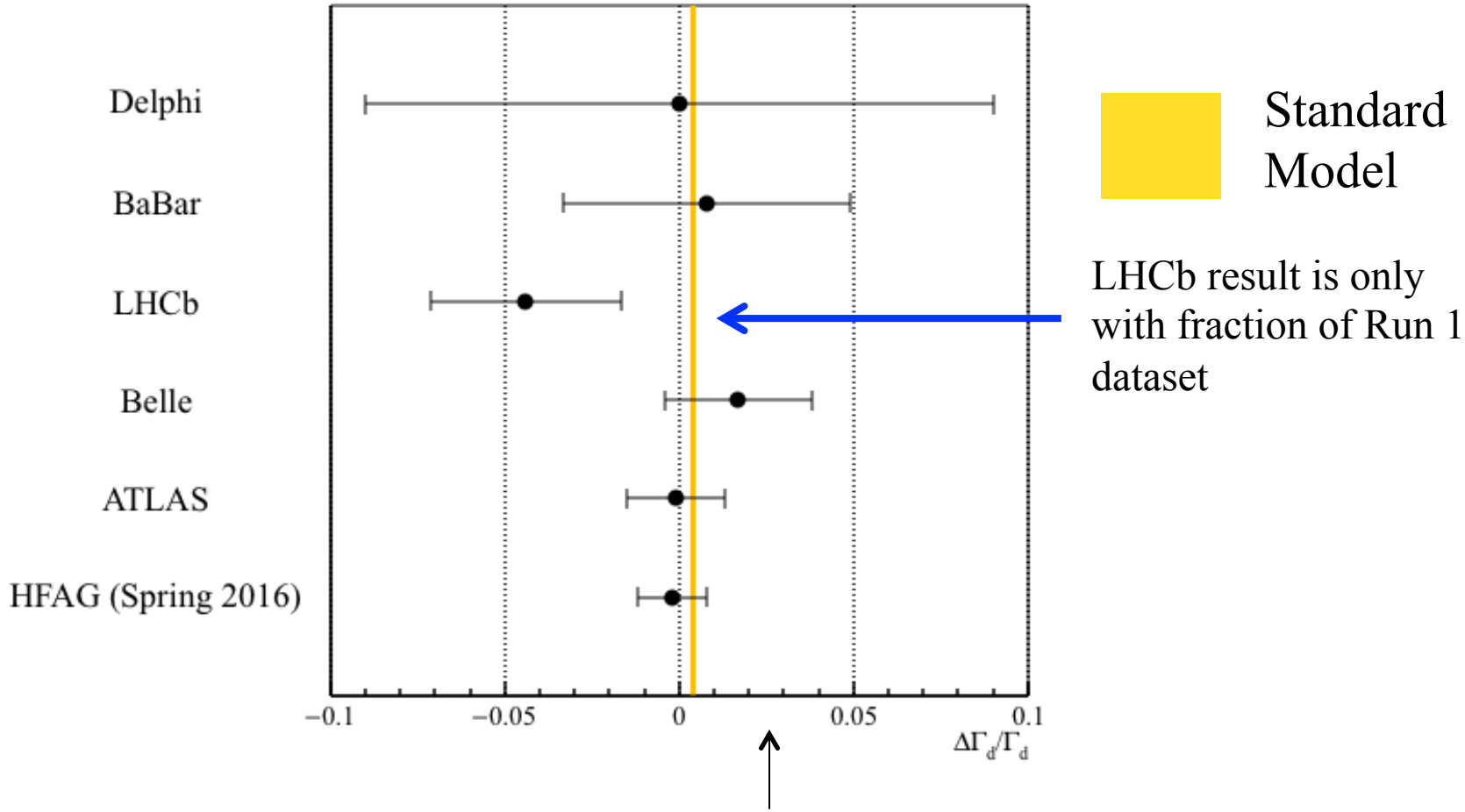
Takes proper account of production asymmetry

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

$\Delta\Gamma_d$

ATLAS result consistent with SM + previous measurements

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



arXiv:1604.03475

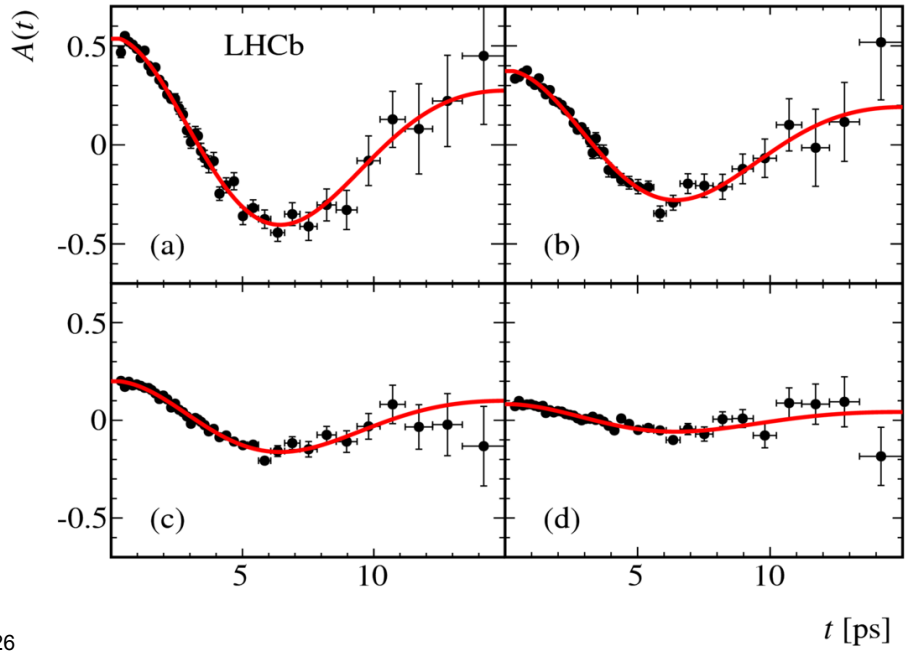
Δm_d

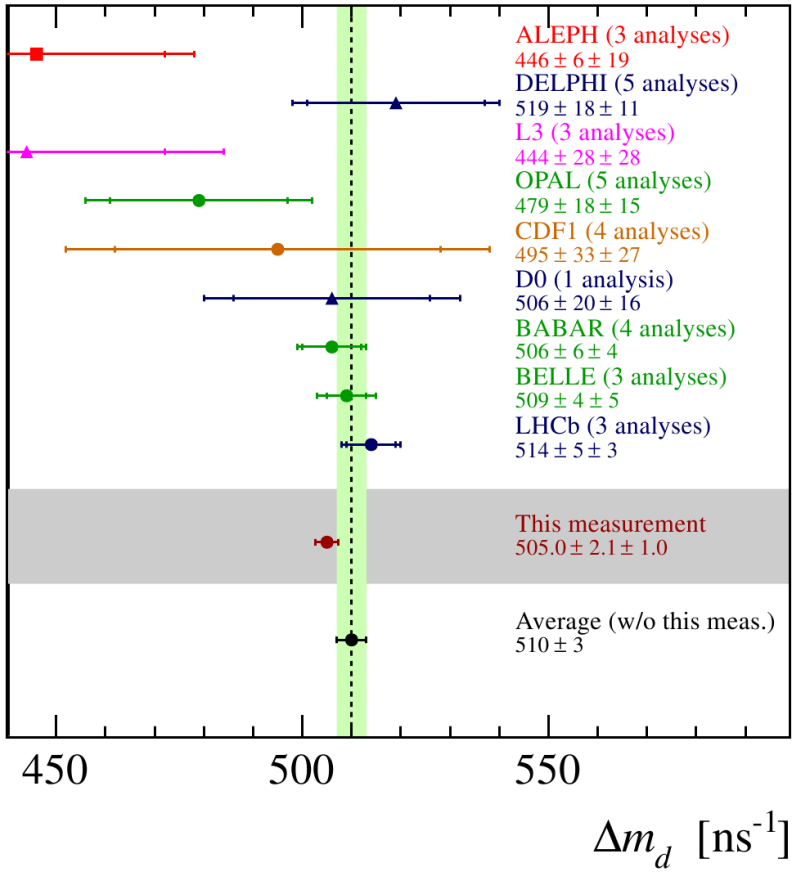
Δm_s now precisely known

$$\Delta m_s = 17.757 \pm 0.021\ \mathrm{ps}^{-1}$$

Limitation on knowledge of UT sides from lattice (improving fast) and Δm_d

New LHCb measurement uses $B^0 \to D(*)^- \mu\nu$ decays





$$\Delta m_d = (505.0 \pm 2.1\,(\mathrm{stat}) \pm 1.0\,(\mathrm{syst}))\ \mathrm{ns}^{-1}$$

LHCb Single most precise measurement

Summary

- Measurements of all $B_{(s)}$ mixing parameters made during Run 1 of LHC
  - Not covered in this talk: Δm_s , $\sin 2\beta$
  - LHC experiments producing high precision results with low systematic uncertainties
- Run 1 measurements still coming out, e.g. $B_s \rightarrow J/\psi\eta$, τ_{eff}
- Run 1 results consistent with Standard Model
  - But still room for new physics at 10 % level
- Significant improvement coming with Run II and beyond

Backup