

Mixing and CP-violation in the B_d^0 and B_s^0 systems at ATLAS

ICHEP - 2016

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Introduction

$$B_s^0 \rightarrow J/\psi(\mu^+\mu^-)\phi(K^+K^-)$$

- arXiv:1601.03297
 - Submitted to JHEP
- What, why, and how
- 2012 method/results
- Run1 results/comparison

Measurement of $\Delta\Gamma_d$

- JHEP 06 (2016) 081
- Motivation
- Method
- Results

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Motivation

CP-Violation Phases

- $B_s^0 \rightarrow J/\psi\phi$ expected to be extremely sensitive to BSM physics
- CP-violation phase: ϕ_s , predicted by SM to high precision
 - $\phi_{sSM} = (-0.0364 \pm 0.0016)$
- Pseudo-scalar \rightarrow Vector + Vector
 - 3 P-wave CP eigenstates
 - 2 S-wave contributions
 - Non-resonant $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)K^+K^-$
 - Resonant $B_s^0 \rightarrow J/\psi(\mu^+\mu^-)f_0(K^+K^-)$
- Requires time-dependent angular analysis to resolve CP eigenstates

ATLAS Results

- Two publications on CPV in $B_s^0 \rightarrow J/\psi\phi$ using 2011 data
 - [JHEP 12 \(2012\) 072](#); [Phys. Rev. D 90 \(2014\) 052007](#)
- 2012/Run 1 results submitted to JHEP, [arXiv:1601.03297](#)

Method

Time-Dependent Angular Analysis

- Observables:
 - Mass, lifetime, p_T , transversity angles, initial flavour
 - Per-candidate errors
- Unbinned maximum likelihood fit → Physics parameters

Fitted PDF

- $\ln \mathcal{L} = \sum_{i=1}^N \{w_i \cdot \ln(f_s(\mathcal{F}_s + f_{B_d^0} \cdot \mathcal{F}_{B_d^0}) + (1 - f_s \cdot (1 + f_{B_d^0}))\mathcal{F}_{bkg})\}$
- w_i is a per-candidate weight due to trigger/lifetime bias
- Fitted PDF has three components:
 - $\mathcal{F}_s = \text{Mass} \cdot \text{Lifetime/Angles/Tagging} \cdot \text{Acceptance} \cdot \text{Punzi}$
 - $\mathcal{F}_{B_d^0} = \text{Mass} \cdot \text{Lifetime} \cdot \text{Angles} \cdot \text{Punzi}$
 - $\mathcal{F}_{bkg} = \text{Mass} \cdot \text{Lifetime} \cdot \text{Angles} \cdot \text{Punzi}$
- Punzi terms for signal/background differences

Likelihood Fit

Mass Fits

- \mathcal{F}_s : Triple Gaussian
- $\mathcal{F}_{B_d^0}$: Landau function fitted from MC
- \mathcal{F}_{bkg} : Exponential

Lifetime/Angle Fits

- \mathcal{F}_s : Combined lifetime/angle/tagging PDF from theory
- $\mathcal{F}_{B_d^0}$:
 - Single exponential, fixed from PDG lifetime
 - Spherical harmonic fit from MC
- \mathcal{F}_{bkg} :
 - Prompt peak + negative exponential + two exponentials
 - Spherical harmonic fit from data
- Lifetime bias ($-0.005 \text{ [ps}^{-1}\text{]}$) corrected with per-event weight w_i

Flavour Tagging

OST Tagging

- Detect decay of pair-produced b
 - p_T weighted sum of charges from decay
- Per-event tagger/probability:
 - Muon, electron, jet-charge
- Calibrated with $B^\pm \rightarrow J/\psi K^\pm$
- Tagging applied probabilistically in fit

Tagger	Efficiency [%]	Dilution [%]	Tagging Power [%]
Combined muon	4.12 ± 0.02	47.4 ± 0.2	0.92 ± 0.02
Electrons	1.19 ± 0.01	49.2 ± 0.3	0.29 ± 0.01
Segment Tagged muon	1.20 ± 0.01	28.6 ± 0.2	0.10 ± 0.01
Jet charge	13.15 ± 0.03	11.85 ± 0.03	0.19 ± 0.01
Total	19.7 ± 0.04	27.6 ± 0.06	1.49 ± 0.02

Table: Tagging power estimated from calibration sample

Fit Projections

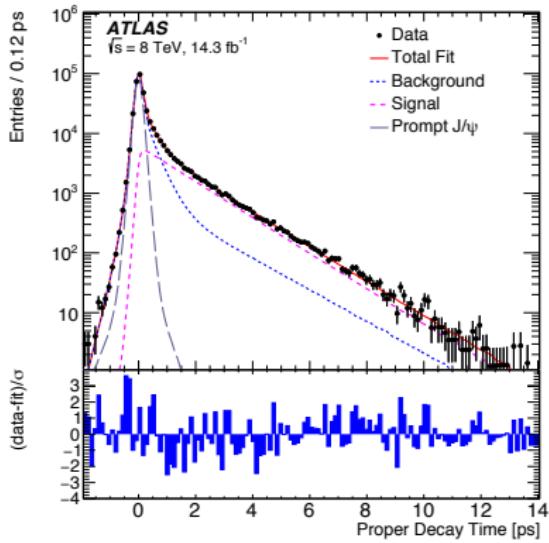
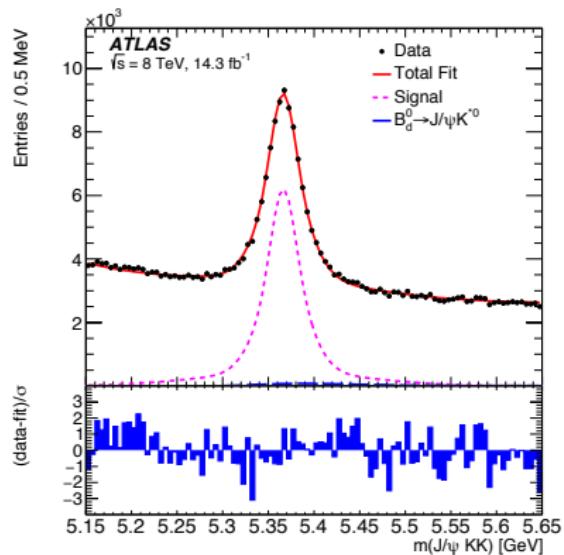


Figure: Mass (left) and lifetime (right) fit projections

Results - Run1

BLUE Combination

- BLUE method used to combine 2011/2012 results
 - Combined result is statistically limited
 - Precision determined by lifetime resolution

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	-0.098	0.084	0.040
$\Delta\Gamma_s$ [ps $^{-1}$]	0.083	0.011	0.007
Γ_s [ps $^{-1}$]	0.677	0.003	0.003
$ A_{ }(0) ^2$	0.227	0.004	0.006
$ A_0(0) ^2$	0.514	0.004	0.003
$ A_S(0) ^2$	0.071	0.007	0.017
δ_{\perp}	4.13	0.33	0.16
$\delta_{ }$	3.15	0.13	0.05
$\delta_{\perp} - \delta_S$	-0.08	0.04	0.01

Table: BLUE combination results for Run 1

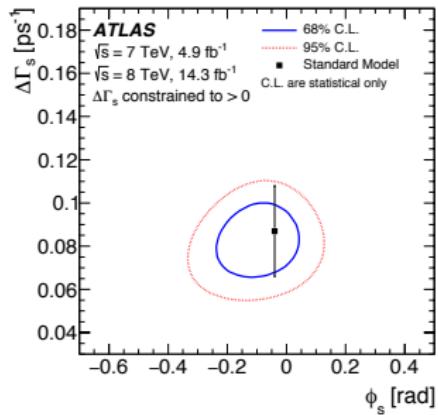


Figure: 2D likelihood scan in the ϕ_s - $\Delta\Gamma_s$ plane

Comparison with Other Experiments

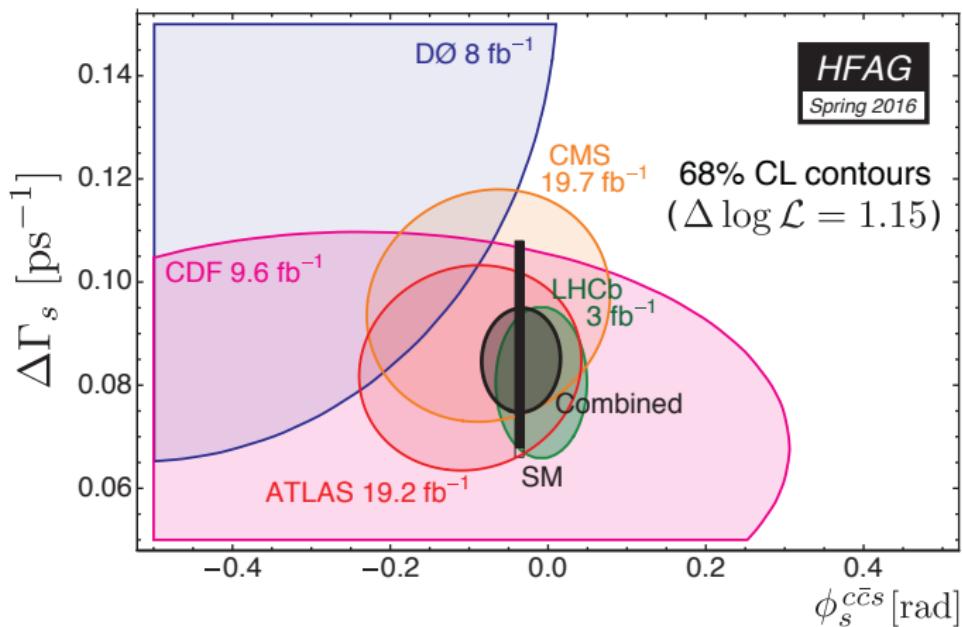


Figure: 2D likelihood scan in the ϕ_s - $\Delta\Gamma_s$ plane

Measurement of $\Delta\Gamma_d$

Motivation

Motivation

- $\Delta\Gamma_d$ is one of the least measured parameters in the B mass system
- Small value predicted by the SM
 - $(\Delta\Gamma_d/\Gamma_d)_{\text{SM}} = 0.42 \pm 0.08 \times 10^{-2}$
- However current experimental precision much worse
 - $(\Delta\Gamma_d/\Gamma_d)_{\text{PDG}} = 0.1 \pm 1.0 \times 10^{-2}$
- Presents useful opportunity to search for new physics

Decay Rates

- Decays rate from light/heavy eigenstates to a final state f may differ
 - Time dependence of the decay $B \rightarrow f$ is sensitive to f
- Selecting flavour/CP specific states f allows determination of $\Delta\Gamma_d/\Gamma_d$

ATLAS Result

- Run 1 results given in [JHEP 06 \(2016\) 081](#)

Method

Time dependence of the decay $B \rightarrow f$

$$\Gamma[f, t] \propto e^{-\Gamma_q t} \left[\cosh \frac{\Delta\Gamma_q t}{2} + A_P A_{CP}^{\text{dir}} \cos(\Delta m_q t) + A_{\Delta\Gamma} \sinh \frac{\Delta\Gamma_q t}{2} + A_P A_{CP}^{\text{mix}} \sin(\Delta m_q t) \right]$$

Method

- A_P is the particle/anti-particle production asymmetry
- A_{CP}^{dir} , $A_{\Delta\Gamma}$, and A_{CP}^{mix} are well defined for CP/flavour eigenstates
- The CP specific decay $B_d^0 \rightarrow J/\psi K_S^0$
 - $A_{CP}^{\text{dir}} = 0$, $A_{\Delta\Gamma} = \cos 2\beta$, $A_{CP}^{\text{mix}} = -\sin 2\beta$
- The flavour specific decay $B_d^0 \rightarrow J/\psi K^*$
 - $A_{CP}^{\text{dir}} = 1$, $A_{\Delta\Gamma} = 0$, $A_{CP}^{\text{mix}} = 0$
- The ratio between the CP/flavour eigenstates allows a fit of $\Delta\Gamma_d$
 - In bins of proper decay length

Signal Extraction

Event Counts

- Determine signal counts in bins of proper decay length
 - Decay length bins into 10 bins between $-0.3 \rightarrow 6.0$ mm
 - Event counts determined through mass fits
 - Corrected for per-bin detector acceptance

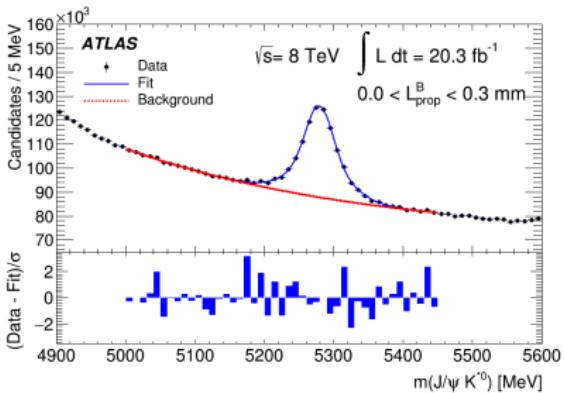
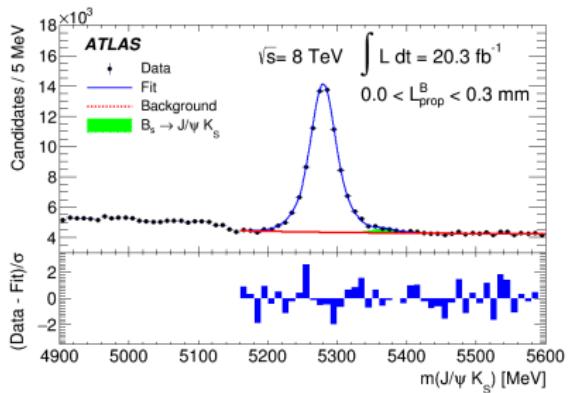


Figure: Invariant mass fits for the CP-specific $B_d^0 \rightarrow J/\psi K_s^0$ decay (left) and the flavour specific $B_d^0 \rightarrow J/\psi K^*$ decay (right)

Production Asymmetry

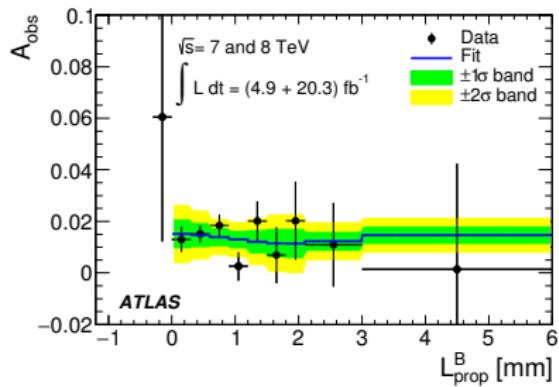


Figure: Fitted B_d^0 / \bar{B}_d^0 flavour specific decay ratios

$$A_{\text{obs},i} = \frac{K_i^* - \bar{K}_i^*}{K_i^* + \bar{K}_i^*}$$

$$A_{\text{exp},i} = (A_{\text{det}} + A_{\text{osc},i})(1 - 2W)$$

Fitted Values

- $\chi^2 = 6.50, \text{ d.o.f} = 7$
- $A_{\text{det}} = (1.33 \pm 0.24 \pm 0.30) \times 10^{-2}$
 - Checked against MC
- $A_p = (0.25 \pm 0.48 \pm 0.05) \times 10^{-2}$
 - Checked against LHCb results

Production Asymmetry

- First measurement of production asymmetry in central rapidity region

Fitted Ratios

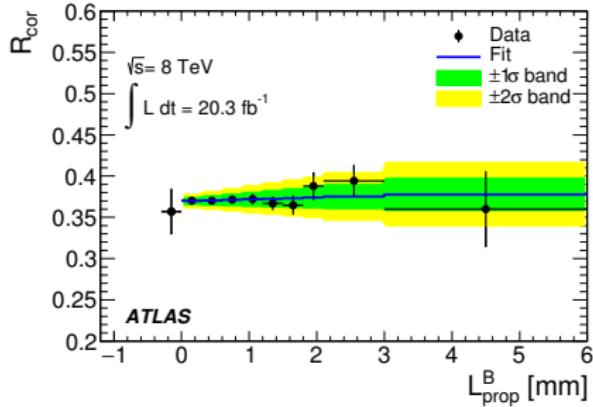
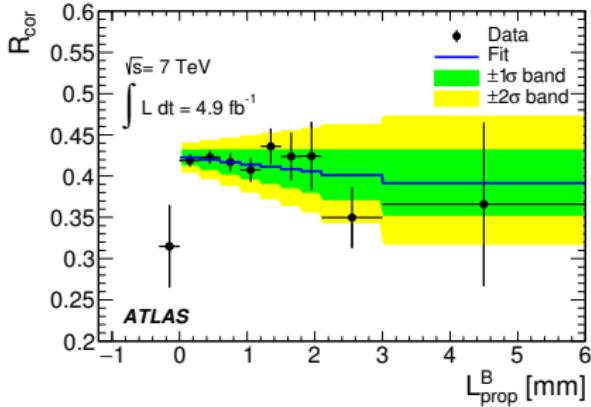


Figure: CP/Flavour specific decay ratios for 2011 (left) and 2012 (right)

Fitted Values

- $\chi^2 = 4.34, \text{d.o.f} = 7$ [2011]
- $\chi^2 = 2.81, \text{d.o.f} = 7$ [2012]

Results

Results

- $\Delta\Gamma_d/\Gamma_d = (-2.8 \pm 2.2(\text{stat.}) \pm 1.5(\text{MC stat.})) \times 10^{-2}$ [2011]
- $\Delta\Gamma_d/\Gamma_d = (0.8 \pm 1.3(\text{stat.}) \pm 0.5(\text{MC stat.})) \times 10^{-2}$ [2012]

LHC Results

- Results from the two years are consistent
 - $\Delta\Gamma_d/\Gamma_d = (-0.1 \pm 1.1(\text{stat.}) \pm 0.9(\text{syst.})) \times 10^{-2}$
- The current LHCb result is
 - $\Delta\Gamma_d/\Gamma_d = (-4.4 \pm 2.5(\text{stat.}) \pm 1.1(\text{syst.})) \times 10^{-2}$

Conclusion

- ATLAS results are consistent with SM predictions
- The Combined ATLAS result is consistent with current LHCb results
 - The ATLAS result currently the most precise measurement!

Summary

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

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

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

$B_s^0 \rightarrow J/\psi(\mu^+ \mu^-) \phi(K^+ K^-)$

- Run1 results show no significant deviation from SM predictions

Measurement of $\Delta\Gamma_d$

- ATLAS has obtained the most precise single measurement of $\Delta\Gamma_d$

Backup

Event Selection

2012 Data

- 14.3 fb^{-1} , $\sqrt{s} = 8 \text{ TeV}$

Event Selection

- Di-muon triggers with online J/ψ mass cut
- Tracks:
 - Track quality cuts, $p_T(K^\pm) > 1.0 \text{ [GeV]}$
- $J/\psi \rightarrow \mu^+\mu^-$: (From trigger matched objects)
 - η dependent mass cuts, vertex quality cut
- $\phi \rightarrow K^+K^-$: (From all pairs of opposite charge tracks)
 - Mass cut
- B_s^0 :
 - Mass/vertex quality cuts
- 375,987 candidates selected for analysis

Signal PDF

k	$\mathcal{O}^{(k)}(t)$	$g^{(k)}(\theta_T, \psi_T, \phi_T)$
1	$\frac{1}{2} A_0(0) ^2 \left[(1 + \cos \phi_s) e^{-\Gamma_L^{(s)} t} + (1 - \cos \phi_s) e^{-\Gamma_H^{(s)} t} \pm 2e^{-\Gamma_s t} \sin(\Delta m_s t) \sin \phi_s \right]$	$2 \cos^2 \psi_T (1 - \sin^2 \theta_T \cos^2 \phi_T)$
2	$\frac{1}{2} A_{ }(0) ^2 \left[(1 + \cos \phi_s) e^{-\Gamma_L^{(s)} t} + (1 - \cos \phi_s) e^{-\Gamma_H^{(s)} t} \pm 2e^{-\Gamma_s t} \sin(\Delta m_s t) \sin \phi_s \right]$	$\sin^2 \psi_T (1 - \sin^2 \theta_T \sin^2 \phi_T)$
3	$\frac{1}{2} A_{\perp}(0) ^2 \left[(1 - \cos \phi_s) e^{-\Gamma_L^{(s)} t} + (1 + \cos \phi_s) e^{-\Gamma_H^{(s)} t} \mp 2e^{-\Gamma_s t} \sin(\Delta m_s t) \sin \phi_s \right]$	$\sin^2 \psi_T \sin^2 \theta_T$
4	$\frac{1}{2} A_0(0) A_{ }(0) \cos \delta_{ }$ $\left[(1 + \cos \phi_s) e^{-\Gamma_L^{(s)} t} + (1 - \cos \phi_s) e^{-\Gamma_H^{(s)} t} \pm 2e^{-\Gamma_s t} \sin(\Delta m_s t) \sin \phi_s \right]$	$-\frac{1}{\sqrt{2}} \sin 2\psi_T \sin^2 \theta_T \sin 2\phi_T$
5	$ A_{ }(0) A_{\perp}(0) [\frac{1}{2}(e^{-\Gamma_L^{(s)} t} - e^{-\Gamma_H^{(s)} t}) \cos(\delta_{\perp} - \delta_{ }) \sin \phi_s$ $\pm e^{-\Gamma_s t} (\sin(\delta_{\perp} - \delta_{ }) \cos(\Delta m_s t) - \cos(\delta_{\perp} - \delta_{ }) \cos \phi_s \sin(\Delta m_s t))]$	$\sin^2 \psi_T \sin 2\theta_T \sin \phi_T$
6	$ A_0(0) A_{\perp}(0) [\frac{1}{2}(e^{-\Gamma_L^{(s)} t} - e^{-\Gamma_H^{(s)} t}) \cos \delta_{\perp} \sin \phi_s$ $\pm e^{-\Gamma_s t} (\sin \delta_{\perp} \cos(\Delta m_s t) - \cos \delta_{\perp} \cos \phi_s \sin(\Delta m_s t))]$	$\frac{1}{\sqrt{2}} \sin 2\psi_T \sin 2\theta_T \cos \phi_T$
7	$\frac{1}{2} A_S(0) ^2 \left[(1 - \cos \phi_s) e^{-\Gamma_L^{(s)} t} + (1 + \cos \phi_s) e^{-\Gamma_H^{(s)} t} \mp 2e^{-\Gamma_s t} \sin(\Delta m_s t) \sin \phi_s \right]$	$\frac{2}{3} (1 - \sin^2 \theta_T \cos^2 \phi_T)$
8	$ A_S(0) A_{ }(0) [\frac{1}{2}(e^{-\Gamma_L^{(s)} t} - e^{-\Gamma_H^{(s)} t}) \sin(\delta_{ } - \delta_S) \sin \phi_s$ $\pm e^{-\Gamma_s t} (\cos(\delta_{ } - \delta_S) \cos(\Delta m_s t) - \sin(\delta_{ } - \delta_S) \cos \phi_s \sin(\Delta m_s t))]$	$\frac{1}{3} \sqrt{6} \sin \psi_T \sin^2 \theta_T \sin 2\phi_T$
9	$\frac{1}{2} A_S(0) A_{\perp}(0) \sin(\delta_{\perp} - \delta_S)$ $\left[(1 - \cos \phi_s) e^{-\Gamma_L^{(s)} t} + (1 + \cos \phi_s) e^{-\Gamma_H^{(s)} t} \mp 2e^{-\Gamma_s t} \sin(\Delta m_s t) \sin \phi_s \right]$	$\frac{1}{3} \sqrt{6} \sin \psi_T \sin 2\theta_T \cos \phi_T$
10	$ A_0(0) A_S(0) [\frac{1}{2}(e^{-\Gamma_H^{(s)} t} - e^{-\Gamma_L^{(s)} t}) \sin \delta_S \sin \phi_s$ $\pm e^{-\Gamma_s t} (\cos \delta_S \cos(\Delta m_s t) + \sin \delta_S \cos \phi_s \sin(\Delta m_s t))]$	$\frac{4}{3} \sqrt{3} \cos \psi_T (1 - \sin^2 \theta_T \cos^2 \phi_T)$

Table: Lifetime/angular signal PDF. The first term has been colour coded to show the **amplitude**, **lifetime**, **initial flavour**, and angular components

Results - 2012

2012 Results

- 9 physics parameters
 - ϕ_s , $\Delta\Gamma_s$, Γ_s , 3 amplitudes, 3 phases

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	-0.123	0.089	0.041
$\Delta\Gamma_s$ [ps $^{-1}$]	0.096	0.013	0.007
Γ_s [ps $^{-1}$]	0.678	0.004	0.004
$ A_{ }(0) ^2$	0.230	0.005	0.006
$ A_0(0) ^2$	0.514	0.004	0.002
$ A_S(0) ^2$	0.090	0.008	0.020
δ_{\perp} [rad]	4.46	0.48	0.29
$\delta_{ }$ [rad]	3.15	0.13	0.05
$\delta_{\perp} - \delta_S$ [rad]	-0.08	0.04	0.01

Table: 2012 fit results

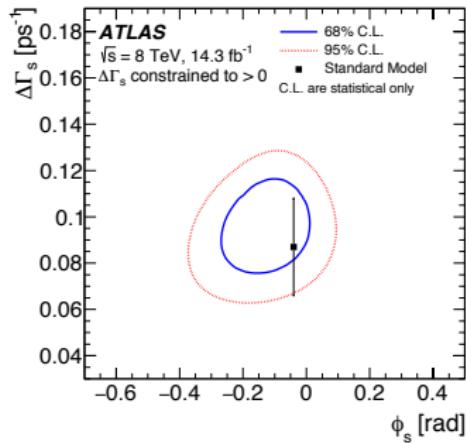


Figure: 2D likelihood scan in the ϕ_s - $\Delta\Gamma_s$ plane

Results - 2012

	ϕ_s [rad]	$\Delta\Gamma_s$ [ps $^{-1}$]	Γ_s [ps $^{-1}$]	$ A_{ }(0) ^2$	$ A_0(0) ^2$	$ A_S(0) ^2$	δ_\perp [rad]	$\delta_{ }$ [rad]	$\delta_\perp - \delta_S$ [rad]
Tagging	0.025	0.003	<10 $^{-3}$	<10 $^{-3}$	<10 $^{-3}$	0.001	0.236	0.014	0.004
Acceptance	<10 $^{-3}$	<10 $^{-3}$	<10 $^{-3}$	0.003	<10 $^{-3}$	0.001	0.004	0.008	<10 $^{-3}$
Inner detector alignment	0.004	<10 $^{-3}$	0.002	<10 $^{-3}$	<10 $^{-3}$	<10 $^{-3}$	0.112	0.006	<10 $^{-3}$
Background angles model:									
Choice of p_T bins	0.020	0.006	0.003	0.003	<10 $^{-3}$	0.008	0.004	0.006	0.008
Choice of mass interval	0.008	0.001	0.001	<10 $^{-3}$	<10 $^{-3}$	0.002	0.021	0.005	0.003
B_d^0 background model	0.023	0.001	<10 $^{-3}$	0.002	0.002	0.017	0.090	0.011	0.009
Fit model:									
Mass signal model	0.004	<10 $^{-3}$	<10 $^{-3}$	0.002	<10 $^{-3}$	0.001	0.015	0.017	<10 $^{-3}$
Mass background model	<10 $^{-3}$	0.002	<10 $^{-3}$	0.002	<10 $^{-3}$	0.002	0.027	0.038	<10 $^{-3}$
Time resolution model	0.003	<10 $^{-3}$	0.001	0.002	<10 $^{-3}$	0.002	0.057	0.011	0.001
Default fit model	0.001	0.002	<10 $^{-3}$	0.002	<10 $^{-3}$	0.002	0.025	0.015	0.002
Total	0.041	0.007	0.004	0.006	0.002	0.020	0.29	0.05	0.01

Table: 2012 fit systematics

Lifetime Error Distributions

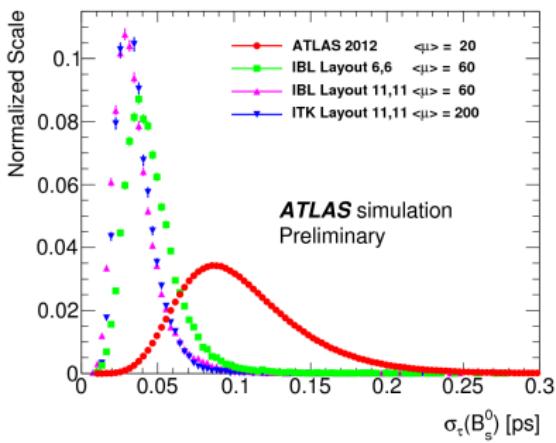
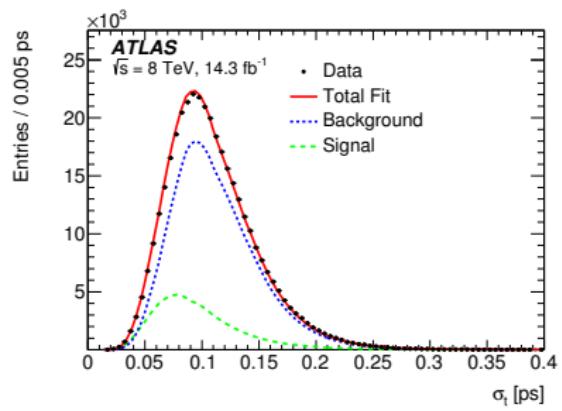


Figure: Lifetime error distributions for 2012 data (left) and MC for Run 1/2/3 (right)

$\Delta\Gamma_d$ Extraction

CP/Flavour Ratio

- Observed CP/flavour decay ratio in bins of proper decay length
 - Event counts corrected by per-bin efficiency factors
- Expected ratio given from theory (as a function of t)
 - Convolute by detector resolution, $\Gamma[f, t] \rightarrow \Gamma[f, L_{\text{prop}}]$
 - Integrate over each bin to determine expected event counts
 - Take ratio for bin i , as a function of $\Delta\Gamma_d/\Gamma_d$
- χ^2 minimisation to determine $\Delta\Gamma_d/\Gamma_d$
 - CP decay sets shape, flavour decay sets normalisation

$$\frac{\Gamma[\text{CP}, t]}{\Gamma[\text{Flavour}, t] + \Gamma[\overline{\text{Flavour}}, t]} \propto \frac{e^{-\Gamma_d t} \left[\cosh \frac{\Delta\Gamma_d t}{2} + \cos 2\beta \sinh \frac{\Delta\Gamma_d t}{2} - A_P \sin 2\beta \sin(\Delta m_d t) \right]}{e^{-\Gamma_d t} \left[\cosh \frac{\Delta\Gamma_d t}{2} \right]}$$

Production Cross Sections

Flavour Decays

- Initial B_d^0 flavour not tagged
 - Sum over $B_d^0 \rightarrow f$ and anti-particle processes
- Observed asymmetry determined from event counts
- Expected asymmetry due to:
 - Detector asymmetry (K^* v's \bar{K}^* reconstruction), A_{det}
 - Offset from 0
 - Dominated by K^\pm iteration cross section differences at low p
 - Flavour oscillation, $A_{\text{osc},i}$
 - Mis-tagging of decay products, W
- Used to fit A_P and A_{det}

$$A_{\text{obs},i} = \frac{N(J/\psi K^*, i) - N(J/\psi \bar{K}^*, i)}{N(J/\psi K^*, i) + N(J/\psi \bar{K}^*, i)} \quad A_{\text{exp},i} = (A_{\text{det}} + A_{\text{osc},i})(1 - 2W)$$

Systematic Errors

Source	$\delta(\Delta\Gamma_d/\Gamma_d)$, 2011	$\delta(\Delta\Gamma_d/\Gamma_d)$, 2012
K_S decay length	0.21×10^{-2}	0.16×10^{-2}
K_S pseudorapidity	0.14×10^{-2}	0.01×10^{-2}
$B_d^0 \rightarrow J/\psi K_S$ mass range	0.47×10^{-2}	0.59×10^{-2}
$B_d^0 \rightarrow J/\psi K^{*0}$ mass range	0.30×10^{-2}	0.15×10^{-2}
Background description	0.16×10^{-2}	0.09×10^{-2}
$B_s^0 \rightarrow J/\psi K_S$ contribution	0.11×10^{-2}	0.08×10^{-2}
L_{prop}^B resolution	0.29×10^{-2}	0.29×10^{-2}
Fit bias (Toy MC)	0.07×10^{-2}	0.07×10^{-2}
B_d^0 production asymmetry	0.01×10^{-2}	0.01×10^{-2}
MC sample	1.54×10^{-2}	0.45×10^{-2}
Total uncertainty	1.69×10^{-2}	0.84×10^{-2}

Table: 2012 fit systematics

Comparison with Other Experiments

$$\Delta\Gamma_d/\Gamma_d = (-0.1 \pm 1.1 \pm 0.9) \times 10^{-2} \text{ (ATLAS)}$$

$$\Delta\Gamma_d/\Gamma_d = (-4.4 \pm 2.5 \pm 1.1) \times 10^{-2} \text{ (LHCb)}$$

$$\Delta\Gamma_d/\Gamma_d = (+1.7 \pm 1.8 \pm 1.1) \times 10^{-2} \text{ (Belle)}$$

$$\Delta\Gamma_d/\Gamma_d = (+0.8 \pm 3.7 \pm 1.8) \times 10^{-2} \text{ (BaBar)}$$

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

Comparison

- ATLAS result is consistent with SM prediction