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

Meson2016

Andy Wharton,
On Behalf of the ATLAS Experiment

Lancaster University

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Introduction

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

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

Measurement of $\Delta\Gamma_d$

- arXiv:1605.07485
  - To be submitted to JHEP
- Motivation
- Method
- Results

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

Motivation

CP-Violation Phases

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

ATLAS Results

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

Event Selection

Event Selection

- 2012 data
  - $14.3\ \text{fb}^{-1}$, $\sqrt{s} = 8$ TeV
- Event selection:
  - Di-muon triggers with online J/ψ mass cut
  - Candidate reconstruction → Select single candidate per-event
  - 375,987 candidates selected for analysis

Daughter Particles

- $J/\psi \to \mu^+\mu^-$:
  - η dependent mass cuts
  - Vertex quality cut
- $\phi \to K^+K^-$:
  - Mass cut

Cuts

- Tracks:
  - Track quality cuts
  - $p_T(K^\pm) > 1.0$ [GeV]
- B_s^0:
  - Mass/vertex quality cuts

Method

Time-Dependent Angular Analysis

- Observables:
  - Mass, lifetime, p_T, transversity angles, initial flavour
  - Per-candidate errors
- UMLF $\rightarrow$ Physics parameters

Fitted PDF

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

Likelihood Fit

Mass Fits

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

Lifetime/Angle Fits

- $\mathcal{F}_{\rm s}$: Combined lifetime/angle/tagging PDF from theory
- $\mathcal{F}_{B_d^0}$:
  - Single Exponential, fixed from PDF lifetime
  - Spherical harmonic fit from MC
- $\mathcal{F}_{\rm bkg}$:
  - Prompt peak + negative exponential + two exponentials
  - Spherical harmonic fit from data
- Lifetime bias (-0.005 [ps^{-1}]) 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 $B^\pm \to J/\psi K^\pm$
- 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

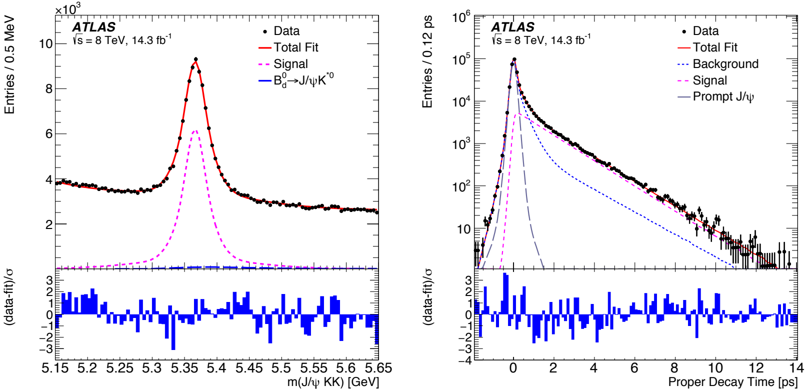

Figure: Mass (left) and lifetime (right) fit projections

Results - 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
$\lvert A_\parallel(0)\rvert^2$	0.230	0.005	0.006
$\lvert A_0(0)\rvert^2$	0.514	0.004	0.002
$\lvert A_S(0)\rvert^2$	0.090	0.008	0.020
$\delta_\perp$ [rad]	4.46	0.48	0.29
$\delta_\parallel$[rad]	3.15	0.13	0.05
$\delta_\perp - \delta_S$ [rad]	−0.08	0.04	0.01

Table: 2012 fit results

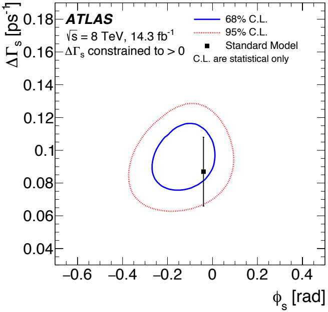

Figure: 2D likelihood scan in the ϕ_s - $\Delta\Gamma_s$ plane

Results - 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
$\lvert A_{\parallel}(0)\rvert^2$	0.227	0.004	0.006
$\lvert A_0(0)\rvert^2$	0.514	0.004	0.003
$\lvert A_S(0)\rvert^2$	0.071	0.007	0.017
$\delta_{\perp}$	4.13	0.33	0.16
$\delta_{\parallel}$	3.15	0.13	0.05
$\delta_{\perp} - \delta_S$	-0.08	0.04	0.01

Table: BLUE combination results for Run 1

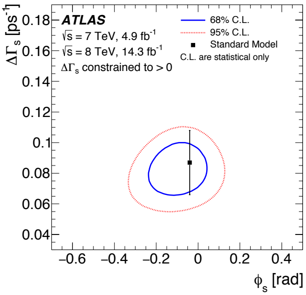

Figure: 2D likelihood scan in the ϕ_s - $\Delta\Gamma_s$ plane

Comparison with Other Experiments

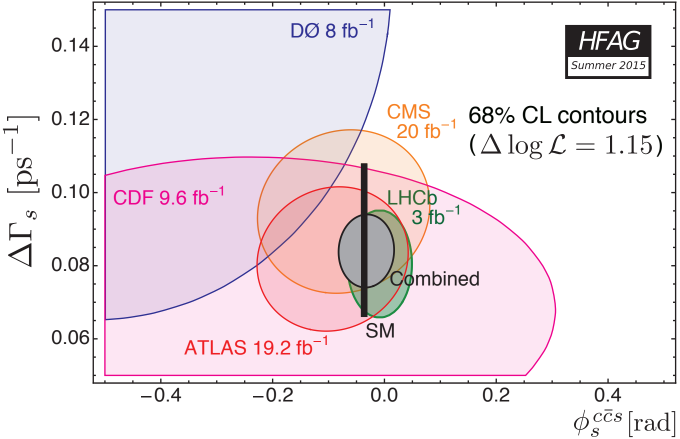

Figure: 2D likelihood scan in the ϕ_s - $\Delta\Gamma_s$ plane

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
  - $(\Delta\Gamma_d/\Gamma_d)_{\text{SM}} = 0.042 \pm 0.08 \times 10^{-2}$
- 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 $B \to f$ 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 arXiv:1605.07485

Method

Time dependence of the decay B $\to f$

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

Method

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

$\Delta\Gamma_d$ 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, $\Gamma[f,t] \to \Gamma[f, L_{\text{prop}}]$
  - 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

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

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

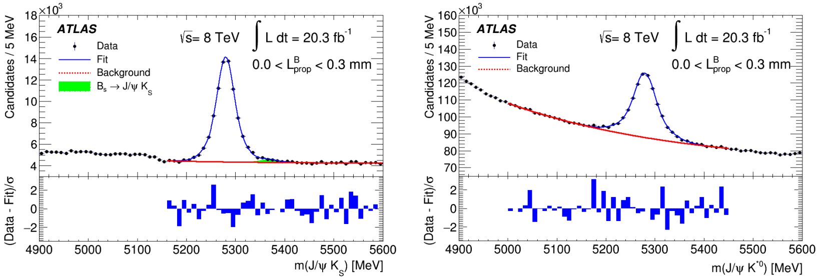

Figure: Invariant mass fits for the CP-specific $B^0_d \rightarrow J/\psi K^0_S$ decay (right) and the flavour specific $B^0_d \rightarrow J/\psi K^*$ decay (left)

Production Cross Sections

Flavour Decays

- Initial B_d^0 flavour not tagged
  - Sum over $B_d^0 \to f$ and anti-particle processes
- Observed asymmetry determined from event counts
- Expected asymmetry due to:
  - Detector asymmetry (K^* v's $\overline{K^*}$ 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}

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

Production Asymmetry

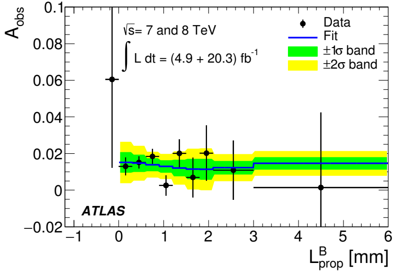

Figure: Fitted $B^0_d / \overline{B^0_d}$ flavour specific decay ratios

Fitted Values

- $\chi^2 = 6.50$, d.o.f $= 7$
- $A_{det} = (1.33 \pm 0.24 \pm 0.30) \times 10^{-2}$
  - 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

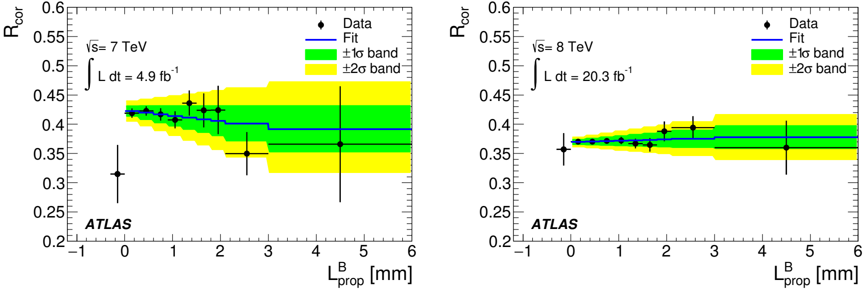

Figure: CP/Flavour specific decay ratios for 2011 (left) and 2012 (right)

Fitted Values

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

$$
\begin{aligned}
\phi_s &= (-0.098 \pm 0.084(\text{stat}) \pm 0.040(\text{syst}))\ [\text{rad}] \\
\Delta\Gamma_s &= (0.083 \pm 0.011(\text{stat}) \pm 0.007(\text{syst}))\ [\text{ps}^{-1}] \\
\Delta\Gamma_d/\Gamma_d &= (-0.1 \pm 1.1(\text{stat}) \pm 0.9(\text{syst})) \times 10^{-2}
\end{aligned}
$$

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

- 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

Signal PDF

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

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

Comparison with Other Experiments

$$\begin{aligned}
\Delta\Gamma_d/\Gamma_d &= (-0.1 \pm 1.1 \pm 0.9) \times 10^{-2} \text{ (ATLAS)} \\
\Delta\Gamma_d/\Gamma_d &= (-4.4 \pm 2.5 \pm 1.1) \times 10^{-2} \text{ (LHCb)} \\
\Delta\Gamma_d/\Gamma_d &= (+1.7 \pm 1.8 \pm 1.1) \times 10^{-2} \text{ (Belle)} \\
\Delta\Gamma_d/\Gamma_d &= (+0.8 \pm 3.7 \pm 1.8) \times 10^{-2} \text{ (BaBar)} \\
\Delta\Gamma_d/\Gamma_d &= (0.42 \pm 0.08) \times 10^{-2} \text{ (SM)}
\end{aligned}$$

Comparison

- ATLAS result is consistent with SM prediction