Lifetime, Mixing, and *CP* Violation Measurements in ATLAS

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CP Violation
in the Decay of Neutral Mesons

- First observed in the neutral kaon system: K^0 and its antiparticle $\bar{K}^0$ can oscillate into each other before they decay via weak interaction
- However K^0 and $\bar{K}^0$ are the *flavour* eigenstates of the system
- The two *mass* eigenstates (K^0_S and K^0_L) are quantum mechanical superpositions of the flavour eigenstates
- At first it was thought that the mass eigenstates were also CP eigenstates (only decays $K^0_S \rightarrow \pi\pi$ and $K^0_L \rightarrow \pi\pi\pi$ were observed)
- Precise measurement of upper limit for the CP violating decay $K^0_L \rightarrow \pi\pi$ (Cronin and Fitch, 1964 [1]) showed that the mass eigenstates are not equivalent to the CP eigenstates and thus established CP violation as a fact

Neutral Meson Mixing

- The time evolution of the wave function

$$|\psi(t)\rangle = a(t)|B_q^0\rangle + b(t)|\bar{B}_q^0\rangle \quad (1)$$

is governed by the time dependent Schrödinger's equation

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} |B_q^0\rangle \\ |\bar{B}_q^0\rangle \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} |B_q^0\rangle \\ |\bar{B}_q^0\rangle \end{pmatrix}, \quad (2)$$

where $\mathbf{M}$ and $\mathbf{\Gamma}$ are 2×2 hermitian matrices (mass and decay width respectively):

$$\mathbf{M} = \begin{pmatrix} \mathrm{M}_{11} & \mathrm{M}_{12} \\ \mathrm{M}_{12}^* & \mathrm{M}_{22} \end{pmatrix}, \quad \mathbf{\Gamma} = \begin{pmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_{22} \end{pmatrix} \quad (3)$$

- Diagonal elements of each of these matrices are the same (assuming *CPT* invariance): $\mathrm{M}_{11} = \mathrm{M}_{22} = \mathrm{M}$ and $\Gamma_{11} = \Gamma_{22} = \Gamma$.

Neutral Meson Mixing

- One can obtain the mass eigenstates from the equation 2 by diagonalizing the matrix $\left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)$.
- Heavy (B_H) and light (B_L) mass eigenstates can be thus written as

$$\begin{aligned} |B_H\rangle &\equiv p|B_q^0\rangle - q|\bar{B}_q^0\rangle \\ |B_L\rangle &\equiv p|B_q^0\rangle + q|\bar{B}_q^0\rangle \end{aligned} \tag{4}$$

with normalization $\sqrt{p^2 + q^2} = 1$ and $\frac{q}{p} = \sqrt{\frac{\mathrm{M}_{12}^* - \frac{i}{2}\Gamma_{12}^*}{\mathrm{M}_{12} - \frac{i}{2}\Gamma_{12}}}$.

- The real and imaginary parts of their corresponding eigenvalues $\omega_{H,L}$ represent their masses and decay widths

$$\omega_{H,L} = \mathrm{M} - \frac{i}{2}\Gamma \pm \frac{q}{p}\left(\mathrm{M}_{12} - \frac{i}{2}\Gamma_{12}\right). \tag{5}$$

Neutral Meson Mixing

- Mass difference $\Delta m_q = m_q^H - m_q^L = \Re(\omega_H - \omega_L)$ have been measured precisely [3]:

$$\Delta m_s = (17.757 \pm 0.021)\ \mathrm{ps}^{-1}, \Delta m_d = (0.5055 \pm 0.0020)\ \mathrm{ps}^{-1}$$

- Decay width difference $\Delta\Gamma_q = \Gamma_q^L - \Gamma_q^H = -2\Im(\omega_L - \omega_H)$ is predicted to be [4]:

$$\Delta\Gamma_s = (0.087 \pm 0.021)\ \mathrm{ps}^{-1}, \frac{\Delta\Gamma_d}{\Gamma_d} = (0.42 \pm 0.08) \times 10^{-2}$$

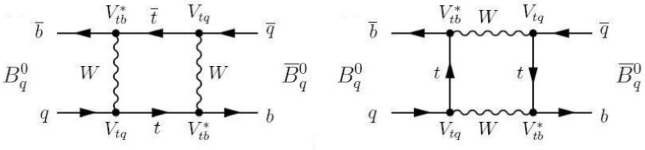


Figure: One loop Feynman diagrams for $B^0 - \bar{B}^0$ mixing.

Types of CP Violation

- CP **violation in decay** (or direct CP violation): decay amplitudes of $M \to f$ and $\bar{M} \to \bar{f}$ are different
- CP **violation in mixing** (or indirect CP violation): asymmetry in the particle antiparticle oscillations...

$$\frac{q}{p} \neq 1 \tag{6}$$

  In this case the CP eigenstates are not equivalent to the mass eigenstates.
- CP **violation in interference of mixing and decay** can only occur if M^0 and $\bar{M}^0$ decay into the same final state;
  The common final state is reached via two different decay chains: $M^0 \to f$ and $M^0 \to \bar{M}^0 \to f$ (case of $B_s^0 \to J/\psi\phi$)

Motivation: New Physics
(CPV in $B_s^0 \to J/\psi\phi$ [7] + [8] + [9])

- CP violating phase is defined as the weak phase difference between the $B_s^0 - \bar{B}_s^0$ mixing amplitude and the $b \to c\bar{c}s$ decay amplitude
- In the Standard Model (SM) it can be related to the CKM matrix

$$\phi_s \simeq -2\beta_s = -2\arg\left(\frac{V_{ts}V_{tb}^\star}{V_{cs}V_{cb}^\star}\right) \qquad (7)$$

  and then $\phi_s = -0.0363^{+0.0016}_{-0.0015}$ rad can be predicted
- A sizable deviation from this value would be a clear sign of beyond SM physics
- $\Delta\Gamma_s$ is not sensitive to New Physics, but can be used to test theoretical predictions
- The New Physics processes could introduce additional contributions to the box diagrams describing the B_s^0 mixing

Angular Analysis

- $B_s^0 \to J/\psi\phi$ = pseudoscalar to vector-vector
- Final state: admixture of CP-odd ($L = 1$) and CP-even ($L = 0, 2$) states
- Distinguishable through time-dependent angular analysis
- Non-resonant S-wave decay $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi f_0$ contribute to the final state
- Included in the differential decay rate due to interference with the $B_s^0 \to J/\psi(\mu^+\mu^-)\psi(K^+K^-)$ decay

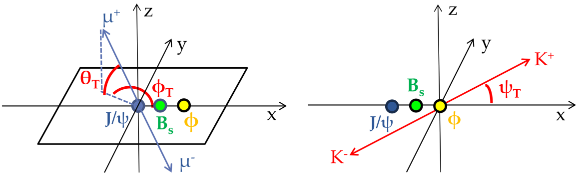


Figure: Angles between final state particles in transversity basis.

Decay Rate

- Ignoring detector effects, the distribution for the time and angles is given by the differential decay rate

$$\frac{\mathrm{d}^4\Gamma}{\mathrm{d}t\ \mathrm{d}\Omega} = \sum_{k=1}^{10} \mathcal{O}^{(k)}(t) g^{(k)}(\theta_T, \psi_T, \phi_T) \qquad (8)$$

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	$\lvert A_0(0)\rvert\lvert A_S(0)\rvert[\frac{1}{2}(e^{-\Gamma_{\mathrm{H}}^{(s)}t} - e^{-\Gamma_{\mathrm{L}}^{(s)}t})\sin\delta_S\sin\phi_s$ $\pm e^{-\Gamma_s t}(\cos\delta_S\cos(\Delta m_s t) + \sin\delta_S\cos\phi_s\sin(\Delta m_s t))]$	$\frac{4}{3}\sqrt{3}\cos\psi_T\left(1-\sin^2\theta_T\cos^2\phi_T\right)$

Used Data

- 4.9 fb^{-1} 7 TeV *pp* 2011 (untagged [7] + tagged [8])
- 14.3 fb^{-1} 8 TeV *pp* 2012 (statistically combined with 7 TeV to RUN1 tagged analysis [9])
- Collected by trigger based on identification of $J/\psi \to \mu^+\mu^-$ with $p_{\mathrm{T}}(\mu)$ threshold (vary over run periods)
- Two muon tracks and two tracks (no PID, but not muons), refitting, using only the best candidate in the event
- NO lifetime cut! Sig-Bck separation done by the fit

Flavour Tagging

- At the LHC B-mesons are produced in the hadronization of $b\bar{b}$ pair
- The majority of these pairs are produced either both in the forward or both in the backward direction of the detector
- Self-tagging $B^{\pm} \rightarrow J/\psi K^{\pm}$ channel used for calibration and performance estimation

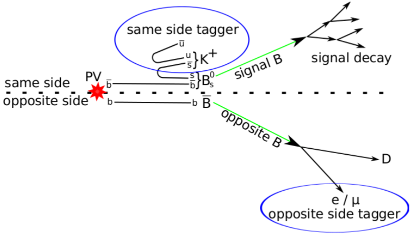


Figure: Same side vs. **opposite side taggers (OST)**

Flavour Tagging
Methods

- 3 tagging methods for the other B-meson (OST)
- Muon/electron tagging:
  - Use semi-leptonic decay of the B
  - $b \to \mu/e$ transition: b flavour given by lepton charge
  - Use momentum weighed charge of lepton and tracks around the lepton
  - Diluted by $b \to c \to l$ cascade decays and neutral B-meson oscillations
- Jet-charge tagging:
  - Used if the additional muon/electron is absent
  - Use momentum-weighted track-charge in jet

- From a calibration sample, the opposite-side charge is mapped to a Probability that the event is a B or $\bar{B}$, and put into the likelihood fit on per-candidate basis
- If there is no tagging information, $P = 0.5$ is assigned

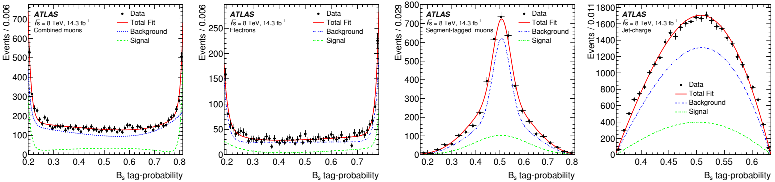


Figure: The tag-probability for tagging using (from left to right) combined-muons, electrons, segment-tagged muons, and jet-charge. Black dots are data after removing spikes, blue is a fit to the sidebands, green to the signal and red is a sum of both fits.

Flavour Tagging

Comparison with Untagged Analysis, 2011 Data

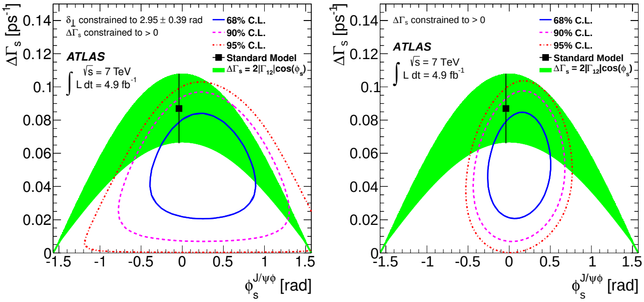


Figure: Likelihood contours in the $\phi_s - \Delta\Gamma_s$ plane for untagged (left) and tagged (right) analysis. Three contours show the 68%, 90%, and 95% confidence intervals (statistical errors only). The green band is the theoretical prediction of mixing-induced CP violation.

Maximum Likelihood Fit

- Observed variables:
  - B_s mass m_i
  - B_s proper decay time t_i and its uncertainty; $t = \frac{L_{xy}\, m_B}{p_\mathrm{T}}$
  - 3 angles between final state particles in transversity basis $\Omega_i(\theta_{Ti}, \phi_{Ti}, \psi_{Ti})$
  - B_s momentum $p_{\mathrm{T}i}$
  - B_s tag probability $P(B|Q_i)$ and tagging method M_i
- Determine 9 physics variables to describe $B_s \to J/\psi\phi$ and S-wave: $\Delta\Gamma_s, \phi_s, \Gamma_s, |A_0(0)|^2, |A_{||}(0)|^2, |A_S(0)|^2, \delta_{||}, \delta_\perp, \delta_S$

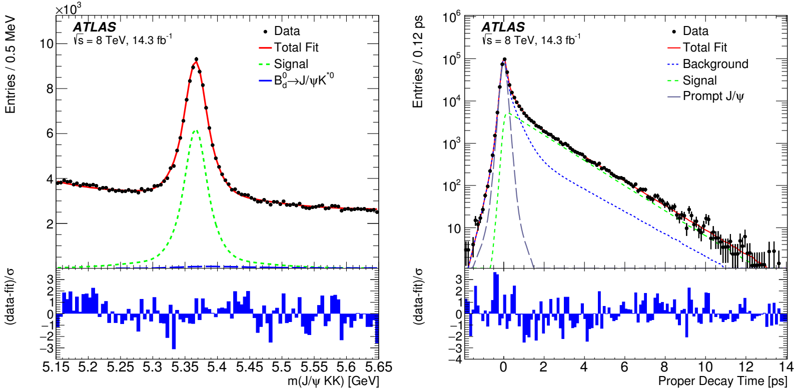
$$\begin{aligned}\ln\ \mathcal{L} = \sum_{i=1}^{N}\{ & w_i \cdot \ln(f_\mathrm{s} \cdot \mathcal{F}_\mathrm{s}(m_i, t_i, \sigma_t, \Omega_i, P(B|Q)) + \\ & + f_\mathrm{s} \cdot f_{B^0} \cdot \mathcal{F}_{B^0}(m_i, t_i, \sigma_t, \Omega_i) + \\ & + (1 - f_\mathrm{s} \cdot (1 + f_{B^0})) \cdot \mathcal{F}_\mathrm{bkg}(m_i, t_i, \Omega_i))\}\end{aligned} \tag{9}$$

Maximum Likelihood Fit

- Signal PDF consists of:
  - **Mass PDF**: 3 gaussians with same mean
  - **Time-angular PDF** convolved with time resolution function $G(t, \sigma(t_i))$. Flavor-dependent terms weighted by the corresponding tagging probability
  - Angular **acceptance** (from MC, in bins of p_{T})
  - **Punzi terms**: empirical distributions of $\sigma(t_i)$, p_{T}, and $P(B|Q)$
- Background PDF:
  - **Mass PDF**: exponential + const.
  - **Time PDF**: delta-function + 3 exponentials convolved with time resolution function $G(t, \sigma(t_i))$
  - **Angular PDF**: Legendre polynomial functions

Fit Projection
2012 Data

- Fit projection to all data passing selections
- $74,900 \pm 400$ signal B_s from the fit



Systematic Uncertainties

2012 Data

	ϕ_s [rad]	$\Delta\Gamma_s$ [ps^{-1}]	Γ_s [ps^{-1}]	$\lvert A_{\parallel}(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_\perp$ [rad]	$\delta_\parallel$ [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

- Variation of **tagging calibration** parametrization
- Uncertainty estimated form **MC tests** of **acceptance** fitting method
- Variation of physics **background fractions**
- Pseudo-experiments with **variations of parameterizations**

Results in RUN1

- Ambiguity in sign of $\Delta\Gamma_s$:

$$\{\phi_s, \Delta\Gamma_s, \delta_\perp, \delta_\parallel\} \rightarrow \{\pi - \phi_s, -\Delta\Gamma_s, \pi - \delta_\perp, 2\pi - \delta_\parallel\}, \quad (10)$$

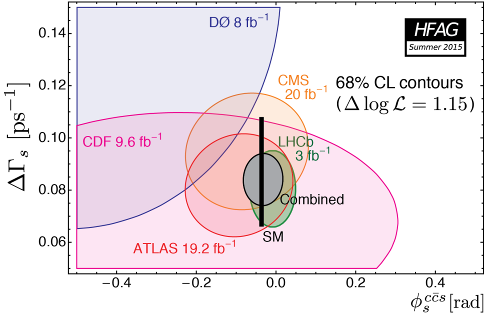
$\Delta\Gamma_s > 0$ constrained by LHC*b* (PRL 108 (2012) 241801)

	8 TeV data			7 TeV data			Run1 combined		
Par	Value	Stat	Syst	Value	Stat	Syst	Value	Stat	Syst
ϕ_s[rad]	−0.123	0.089	0.041	0.12	0.25	0.05	−0.098	0.084	0.040
$\Delta\Gamma_s$[ps^{-1}]	0.096	0.013	0.007	0.053	0.021	0.010	0.083	0.011	0.007
Γ_s[ps^{-1}]	0.678	0.004	0.004	0.677	0.007	0.004	0.677	0.003	0.003
$\|A_\parallel(0)\|^2$	0.230	0.005	0.006	0.220	0.008	0.009	0.227	0.004	0.006
$\|A_0(0)\|^2$	0.514	0.004	0.002	0.529	0.006	0.012	0.514	0.004	0.003
$\|A_S\|^2$	0.090	0.008	0.020	0.024	0.014	0.028	0.071	0.007	0.017
$\delta_\perp$ [rad]	4.46	0.48	0.29	3.89	0.47	0.11	4.13	0.33	0.16
$\delta_\parallel$ [rad]	3.15	0.13	0.05	[3.04, 3.23]		0.09	3.15	0.13	0.05
$\delta_\perp - \delta_S$ [rad]	−0.08	0.04	0.01	[3.02, 3.25]		0.04	−0.08	0.04	0.01

Comparison

	Lumi	ϕ_s [rad]
ATLAS RUN1	19.2 fb^{-1}	$-0.098 \pm 0.084 \pm 0.040$
LHCb RUN1	3.0 fb^{-1}	$-0.058 \pm 0.049 \pm 0.006$
CMS 2012	19.7 fb^{-1}	$-0.075 \pm 0.097 \pm 0.031$
Standard Model	-	-0.037 ± 0.002

No sign for physics beyond the Standard Model :-(



Motivation: Test of the SM
(Relative Width Difference in $B^0 - \bar{B}^0$ system [13])

- The relative value of $\frac{\Delta\Gamma_d}{\Gamma_d}$ is reliably predicted in the SM [4]:

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

- It has been shown [14] that a relatively large variation of $\Delta\Gamma_d$ due to a possible new physics contribution would not contradict other existing SM results
- Precise measurement would therefore provide a stringent test of the underlying theory, complementary to other searches
- Current experimental uncertainty on $\Delta\Gamma_d$ is much larger than the SM central value: $\frac{\Delta\Gamma_d}{\Gamma_d} = (0.1 \pm 1.0) \times 10^{-2}$ (World avg.)
- Furthermore, the measurements of $\Delta\Gamma_d$ made by Belle [15] and LHC*b* [16] differ by more than 1.5σ
- Therefore, more precise measurements of $\Delta\Gamma_d$ are needed to establish its value and perform an important test of the SM

Measurement Method

- The decay rate of the light and heavy mass eigenstates (B_d^L and B_d^H) to a given final f state can be different. Therefore the time dependence of the decay rate of $B^0 \to f$ is sensitive to f
- The untagged time-dependant decay rate of a B^0 meson into final state f is given by:

$$\Gamma(f,t) \propto \mathrm{e}^{-\Gamma_d t}\{\cosh\frac{\Gamma_d t}{2} + A_p A_{\mathrm{CP}}^{\mathrm{dir}} \cos(\Delta m_d t) + + A_{\Delta\Gamma} \sinh\frac{\Gamma_d t}{2} + A_p A_{\mathrm{CP}}^{\mathrm{mix}} \sin(\Delta m_d t)\} \quad (11)$$

- Considered final states are:
  - $J/\psi(\mu^-\mu^+)K^{*0}(K^+\pi^-)$ with $A_{\mathrm{CP}}^{\mathrm{dir}} = \pm 1$, $A_{\Delta\Gamma} = 0$, $A_{\mathrm{CP}}^{\mathrm{mix}} = 0$,
  - $J/\psi(\mu^-\mu^+)K_S(\pi^-\pi^+)$ with $A_{\mathrm{CP}}^{\mathrm{dir}} = 0$, $A_{\Delta\Gamma} = \cos 2\beta$, $A_{\mathrm{CP}}^{\mathrm{mix}} = -\sin 2\beta$, where β is the Unitarity Triangle angle measured as $\sin 2\beta = 0.679 \pm 0.020$
- A_p is the production asymmetry of B^0 and $\bar{B}^0$

Measurement Method

- The value of $\Delta\Gamma_d$ can be determined by measuring the experimental ratio of proper decay lengths L^B_{prop} of the two channels

$$R(L^B_{\mathrm{prop}}) = \frac{N(B^0 \to J/\psi K_S, L^B_{\mathrm{prop}})}{N(B^0 \to J/\psi K^{*0}, L^B_{\mathrm{prop}})}, \qquad (12)$$

where $N(B^0 \to J/\psi K_S, L^B_{\mathrm{prop}})$ and $N(B^0 \to J/\psi K^{*0}, L^B_{\mathrm{prop}})$ are the number of reconstructed B^0 decays to the specified final state as a function of L^B_{prop}

Measurement Method

- The predicted decay rate as a function of L^B_{prop} for the decay $B^0 \to f$ is

$$\Gamma(f, L^B_{\mathrm{prop}}) = \int_0^\infty G(L^B_{\mathrm{prop}} - ct, f)\Gamma(f, t)\mathrm{d}t \qquad (13)$$

  where $G(L^B_{\mathrm{prop}} - ct, f)$ is the function describing the resolution of L^B_{prop} for a given channel f
- $R(L^B_{\mathrm{prop}})$ is dependent on $\Delta\Gamma_d$ which can therefore be measured by fitting $R(L^B_{\mathrm{prop}})$ using the predicted decay rates of the $J/\psi K_S$ and $J/\psi K^{*0}$ channels

Measurement of B^0 Proper Decay Length

- The technique used to measure the proper decay length (L^B_{prop}) is designed to use the same input information for both the $B^0 \to J/\psi K_S$ and $B^0 \to J/\psi K^{*0}$ channels
- This reduces the experimental bias in $R(L^B_{\mathrm{prop}})$
- The origin of the B^0 $(x^{\mathrm{PV}}, y^{\mathrm{PV}})$ is measured using a PV fit in which the decay products of the B^0 are removed
- Position of the B^0 decay is defined by the J/ψ decay vertex $(x^{J/\psi}, y^{J/\psi})$
- For each reconstructed $B^0 \to J/\psi K_S$ and $B^0 \to J/\psi K^{*0}$ candidate, the proper decay length is constructed

$$L^B_{\mathrm{prop}} = \frac{(x^{J/\psi} - x^{\mathrm{PV}})p^B_{\mathrm{T},x} + (y^{J/\psi} - y^{\mathrm{PV}})p^B_{\mathrm{T},y}}{p^B_{\mathrm{T}^2}} m^0_B \qquad (14)$$

Measurement of B^0 Proper Decay Length

- The proper decay length distribution is obtained by first dividing the range of L^B_{prop} between -0.3 and 6.0 mm into ten bins
- In each bin, distributions of the invariant mass of $J/\psi K_S$ and $J/\psi K^{*0}$ are produced and the number of signal B^0 in each bin is determined by a fit to these distributions
- The ratio of the number of B^0 candidates in the two channels in each L^B_{prop} bin gives the experimental ratio

$$R_{i,\mathrm{uncor}}(L^B_{\mathrm{prop}}) = \frac{N_i(J/\psi K_S)}{N_i(J/\psi K^{*0})} \qquad (15)$$

Ratio of Reconstruction Ef

- $R_{i,\mathrm{uncor}}(L^B_{\mathrm{prop}})$ must be corrected to account for the difference in the reconstruction efficiencies of the two channels
- This difference is the largest source of experimental bias in $R_{\mathrm{uncor}}(L^B_{\mathrm{prop}})$ and it can be assessed only with MC
- Measure the ratio of reconstruction efficiencies in MC defined as

$$R_{i,\mathrm{eff}}(L^B_{\mathrm{prop}}) = \frac{\epsilon_i(B^0 \to J/\psi K_S, L^B_{\mathrm{prop}})}{\epsilon_i(B^0 \to J/\psi K^{*0}, L^B_{\mathrm{prop}})} \qquad (16)$$

- $R_{i,\mathrm{uncor}}(L^B_{\mathrm{prop}})$ is then divided by $R_{i,\mathrm{eff}}(L^B_{\mathrm{prop}})$ to obtain the corrected ratio $R_{i,\mathrm{cor}}(L^B_{\mathrm{prop}})$

Production Asymmetry

- The B^0 production asymmetry A_p is measured from the charge asymmetry of the $B^0 \to J/\psi K^{*0}$ decay, measured as a function of L^B_{prop}

$$A_{\mathrm{obs}} = \frac{N(J/\psi K^{*0}) - N(J/\psi \bar{K}^{*0})}{N(J/\psi K^{*0}) + N(J/\psi \bar{K}^{*0})} \quad (17)$$

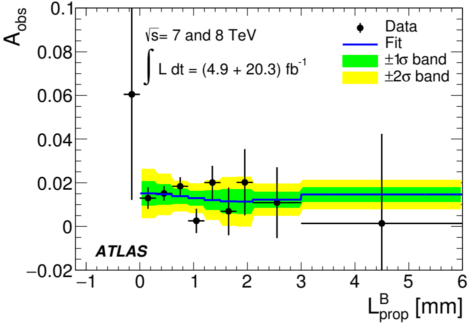
- The charge asymmetry is has two main contributions:
  - The detector asymmetry A_{det}
  - The production asymmetry A_p, which should oscillate

Production Asymmetry

- The ATLAS results are

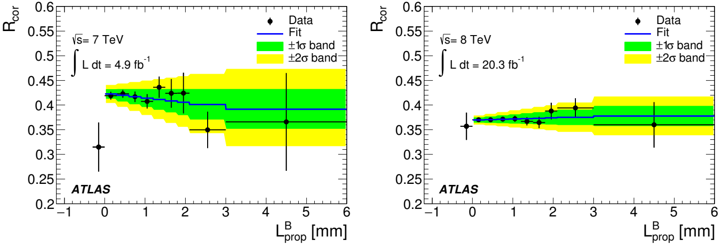
$$A_{\mathrm{det}} = (+1.33 \pm 0.24 \pm 0.30) \times 10^{-2}$$

$$A_p = (+0.25 \pm 0.48 \pm 0.05) \times 10^{-2}$$



$\Delta\Gamma_d/\Gamma_d$ Results

- The corrected $R_{i,\mathrm{cor}}(L^B_{\mathrm{prop}})$ is fitted by the expected number of events in each channel, in each bin
- Two separate results for the 2011 (7 TeV) and 2012 (8 TeV) datasets are
  - 2011: $\frac{\Delta\Gamma_d}{\Gamma_d} = (-2.8 \pm 2.2(\mathrm{stat.}) \pm 1.7(\mathrm{syst.})) \times 10^{-2}$
  - 2012: $\frac{\Delta\Gamma_d}{\Gamma_d} = (+0.8 \pm 1.3(\mathrm{stat.}) \pm 0.8(\mathrm{syst.})) \times 10^{-2}$



$\Delta\Gamma_d/\Gamma_d$ Results

- The results from the two years are consistent and are combined

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

- The combined result is in agreement with the SM prediction
- It is also consistent with other measurements at other experiments performed by BaBar, Belle, and LHC*b*

Conclusion

- The results of the $B_s^0 \to J/\psi\phi$ analysis performed using data collected by ATLAS during RUN1 of the LHC are

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

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

- These results are consistent with the SM prediction and results from other experiments... but some room for new physics in CPV in this channel is still there
- The measurement of the B^0 width difference is

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

- This is currently the most precise **single** measurement of this quantity and is consistent with the SM expectation and results from other experiments

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