Mixing and CP violation in the B_s system

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On behalf of ATLAS collaboration

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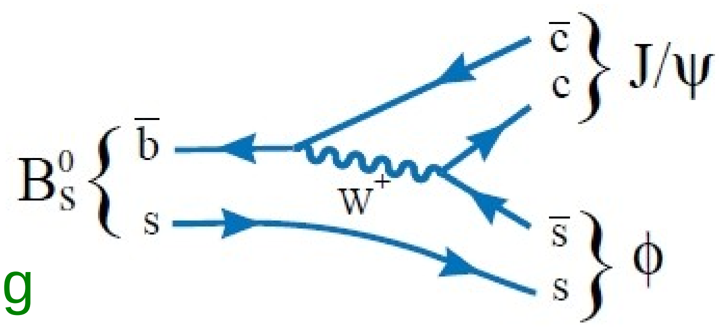
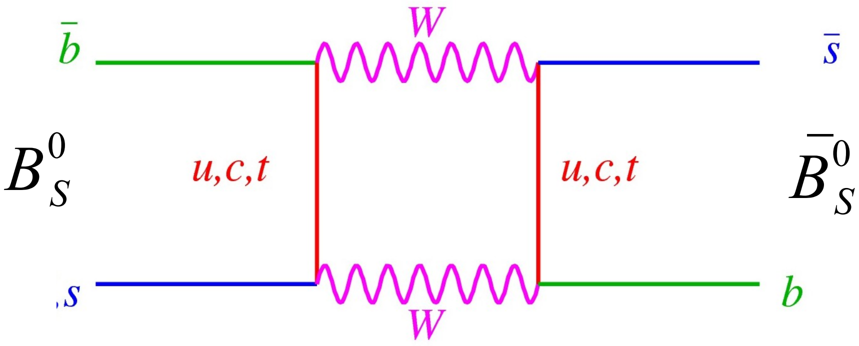
Motivation

→ CP violation in the $B_S^0 \to J/\psi\phi$ decay
occurs due to interference of direct decays
and decays occurring through $B_S^0 - \bar{B}_S^0$ mixing





oscillation frequency is characterized by Δm_s
– mass difference of heavy (B_H) and light (B_L)
mass eigenstates

→ quantities involved in $B_S^0 - \bar{B}_S^0$ mixing:

CP-violating phase ϕ_s – weak phase difference between amplitudes of
B-mixing and direct decay

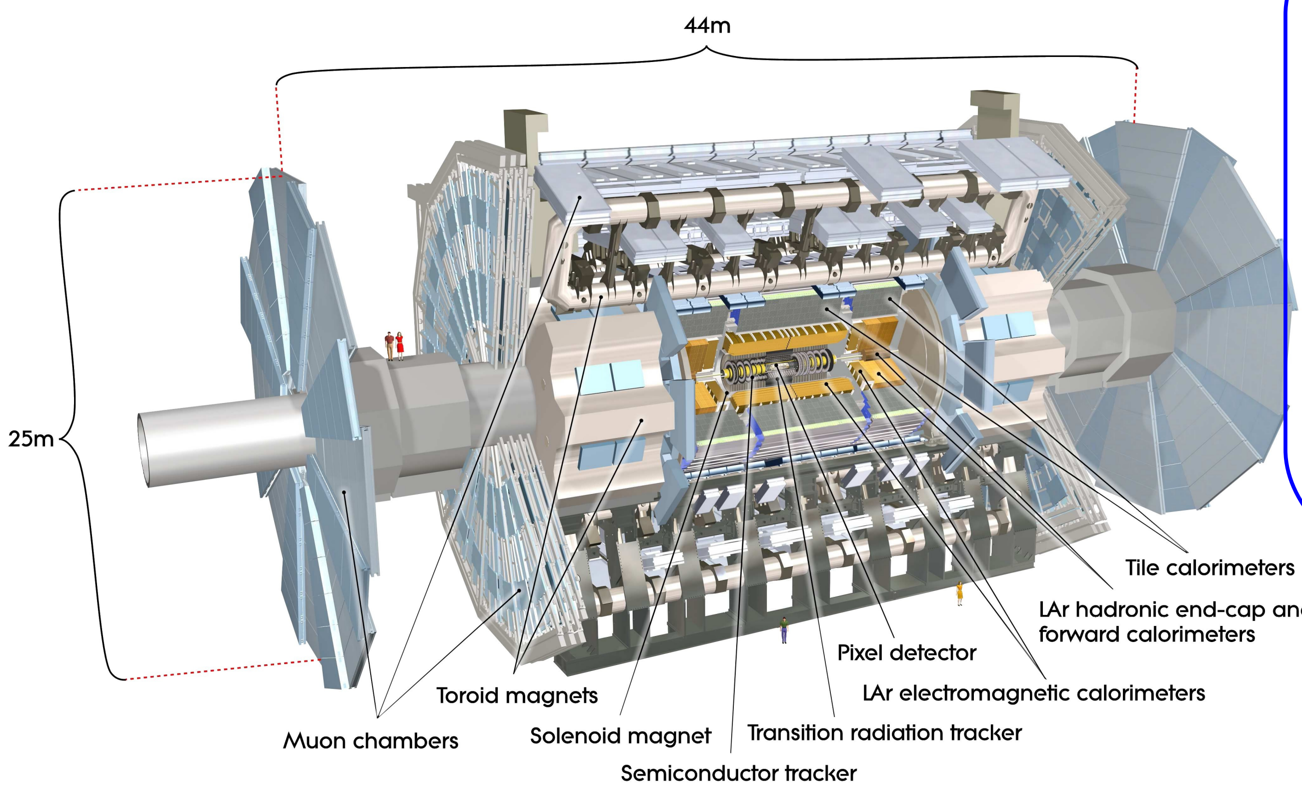
→ some New Physics models predict large values, while satisfying all
existing constrains

Width difference $\Delta\Gamma_s$ = $\Gamma(B_L) - \Gamma(B_H)$:

→ should not be affected as significantly as ϕ_S by beyond-SM physics

Average decay width Γ_s = $[\Gamma(B_L) + \Gamma(B_H)] / 2$

Atlas detector



→ **Inner Detectors (ID)**
- → silicon pixel & strip tracker + transition radiation tracker
- → coverage $|\eta| < 2.5$
- → $\sigma / p_T \approx 0.05\%\, p_T \oplus 1.5\%$
- → impact parameter resolution ≈ 10 μm
- → inside 2T magnetic field

→ **Calorimetry**
- → high-granularity LAr EM calorimeter – $|\eta| < 2.5$
- → iron-scintillator tile calorimeter – $|\eta| < 4.9$

Muon Spectrometers (MS)
- → tracking chambers + detectors for triggering
- → inside toroidal magnetic field; coverage: $|\eta| < 2.7$; $\sigma / p_T \approx 2 - 7\ \%$

→ data collected during rising instantaneous luminosity and varying trigger conditions (2011)

Event selection (I)

→ using 4.9 fb^{-1} of data collected in 2011 in pp collisions with $\sqrt{s} = 7\,\mathrm{TeV}$

→ **trigger** based on $J/\psi \rightarrow \mu^+ \mu^-$ decay identification:

  → requires: – 1 muon with p_T > 4 GeV + another muon with p_T > 2 GeV

→ event has to contain ≥ 1 primary vertex (built from ≥ 4 ID tracks)

  ≥ 1 pair of oppositely charge muon candidates

→ **J/Ψ candidates reconstruction:**

  → muon tracks refitted to common vertex (χ^2/d.o.f. < 10)

  → di-muon invariant mass requirements:

invariant mass requirement		Muon 1: $\|\eta\| < 1.05$	Muon 1: $1.05 < \|\eta\| < 2.5$
Muon 2	$\|\eta\| < 1.05$	(2.959 – 3.229) GeV	(2.913 – 3.273) GeV
Muon 2	$1.05 < \|\eta\| < 2.5$	(2.913 – 3.273) GeV	(2.852 – 3.332) GeV

* due to varying mass resolution; 99.8% candidates are identified

Event selection (II)

→ $\phi \to K^+K^-$ **candidates reconstruction:**

→ reconstructed from all pairs of oppositely charged tracks (p_T > 0.5 GeV, $|\eta|$ < 2.5, not identified as μ)

→ **final selection:**

→ fitting the tracks for each combination of $J/\Psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$ to common vertex

→ fit constrain: J/Ψ mass (PDG world average: 3096.916 ± 0.011 MeV)

→ fit requirements:

1) fitted p_T of $\phi \to K^+K^-$ tracks > 1 GeV; m (K^+K^-) in [1.0085; 1.0305] GeV

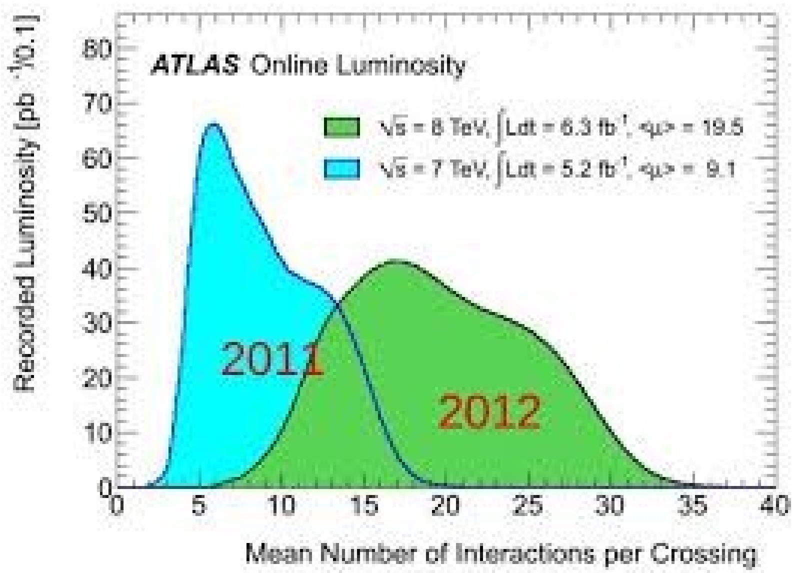
2) fit χ^2/d.o.f. < 3

Primary-vertex selection:

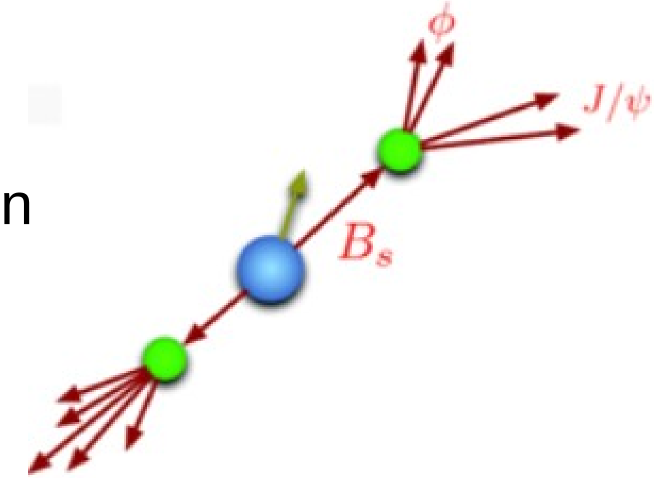
→ average # of interaction in selected events is 5.6

→ use primary vertex with smallest 3-dimensional impact parameter of the reconstructed B-momentum

→ 1% of wrong assignment



Flavour tagging



Opposite side tagging:

→ initial flavour of B_s is inferred from the other B meson

→ Calculate weighted sum of the charge of the tracks in a cone around:

a) additional muon in the event (originate near interaction point)

→ combined muon (combination of ID track and MS track

→ segment tagged muon (full ID track matched to track segment in MS)

b) b-jet axis (b-jet associated to same interaction point)

κ = 1.1

$$Q=\frac{\sum_{i}^{N\,tracks} q_i\cdot\left(p_T^i\right)^{\kappa}}{\sum_{i}^{N\,tracks}\left(p_T^i\right)^{\kappa}}$$

Tagger	Efficiency [%]	Dilution [%]	Tagging Power [%]
Segment Tagged muon	1.08 ± 0.02	36.7 ± 0.7	0.15 ± 0.02
Combined muon	3.37 ± 0.04	50.6 ± 0.5	0.86 ± 0.04
Jet charge	27.7 ± 0.1	12.68 ± 0.06	0.45 ± 0.03
Total	32.1 ± 0.1	21.3 ± 0.08	1.45 ± 0.05

Dilution D = 2*P(B|Q)-1 **Tagging power = εD^2**

Methods are studied and calibrated on $B^+\to J/\psi K^+$ and $B^-\to J/\psi K^-$ events

Methodology

→ **unbinned maximum likelihood fit** used to extract B_S^0 decay parameters

→ uses information of:

→ reconstructed mass ***m*** and its uncertainty

→ measured proper decay time and its uncertainty:

$$t = \frac{L_{xy} M_B}{c\, p_{T_B}}$$

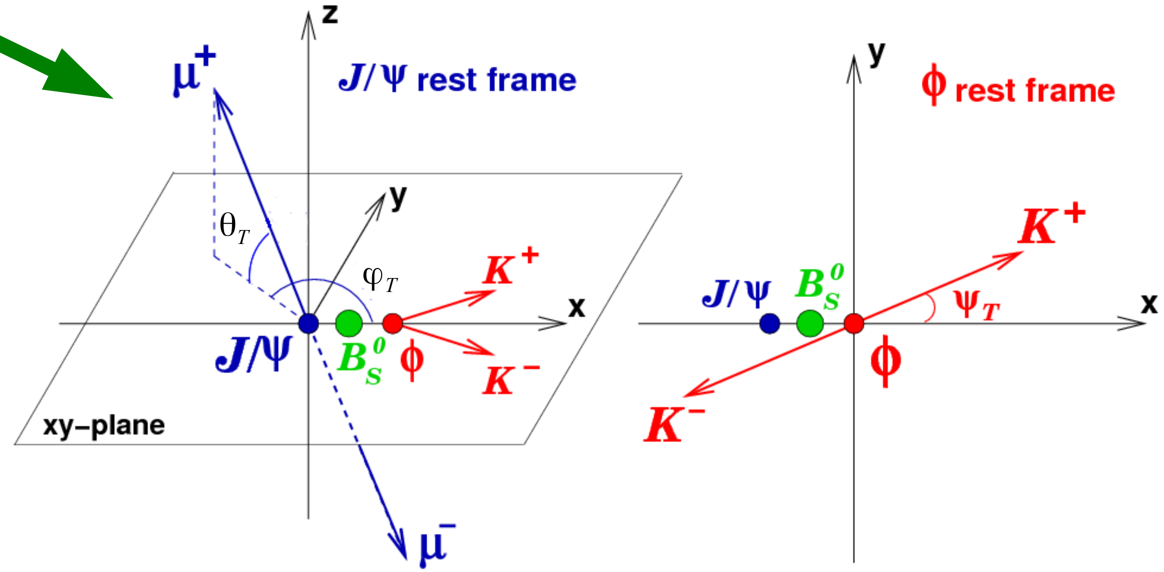
M_B = 5.3663 GeV (PDG, world average mass)

L_{xy} – displacement of B_s^0 decay vertex from primary vertex In transverse plane

p_{TB} – reconstructed transverse momentum of B_s^0 candidate

→ transversity angles

$$\Omega = (\theta_T, \psi_T, \varphi_T)$$



→ flavour tagging

→ i.e. per-B_s candidate probability that the B_s was borned as B_s and not $\overline{B}_s$

Likelihood fit

of selected candidates

Weighting factor to account trigger efficiency

signal part

$$\ln \mathcal{L} = \sum_{i=1}^{N} \{ w_i \,.\, \ln \left(f_s \,.\, \mathcal{F}_S(m_i, t_i, \Omega_i) + f_s \,.\, f_{B^0} \,.\, \mathcal{F}_{B^0}(m_i, t_i, \Omega_i) \right.$$

$$\left. + (1 - f_s \,.\, (1 + f_{B^0})) \,.\, \mathcal{F}_{bckg}(m_i, t_i, \Omega_i) \right) \}$$

background part

$\mathcal{F}_x(m_i, t_i, \Omega_i)$

→ probability density function (PDF)

→ product of each quantity measured from data

→ for bckg: transversity angles are treated as uncorrelated

B^0 background part

mis-reconstruction of:

$B^0 \rightarrow J/\psi K^*$ … $f = (6.5 \pm 2.4)\%$

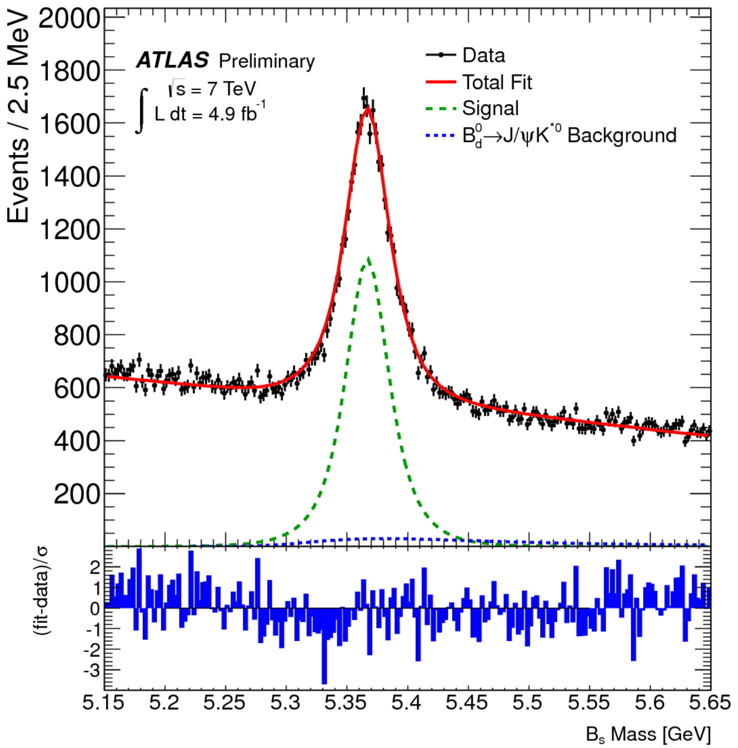
$B^0 \rightarrow J/\psi K^+\pi^-$ … $f = (4.5 \pm 2.8)\%$

→ fractions fixed in likelihood fit

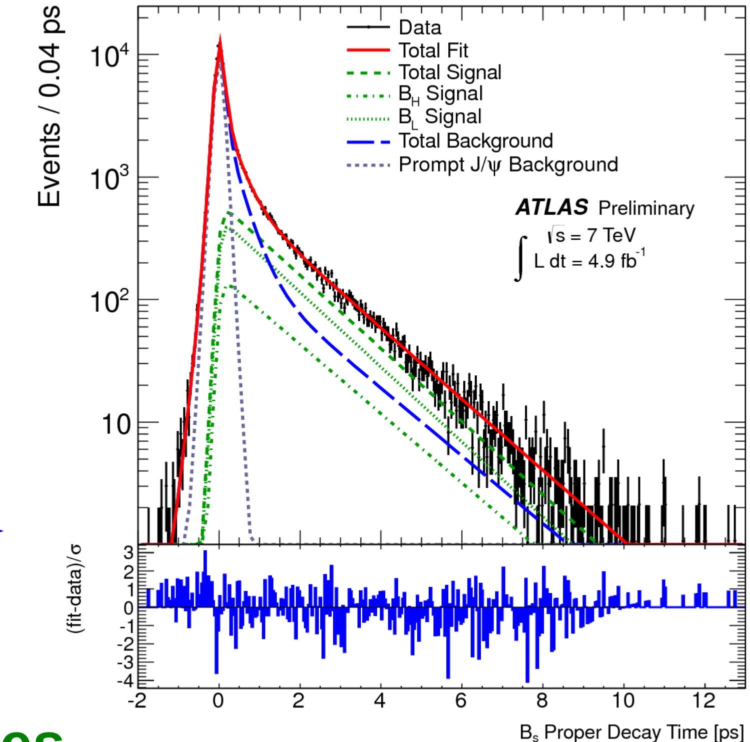
Flavour tagging enters the fit via the tag probability in the signal time-angular PDF, increasing sensitivity to ϕ_S and strong phase $\delta_\perp$

Fit projections

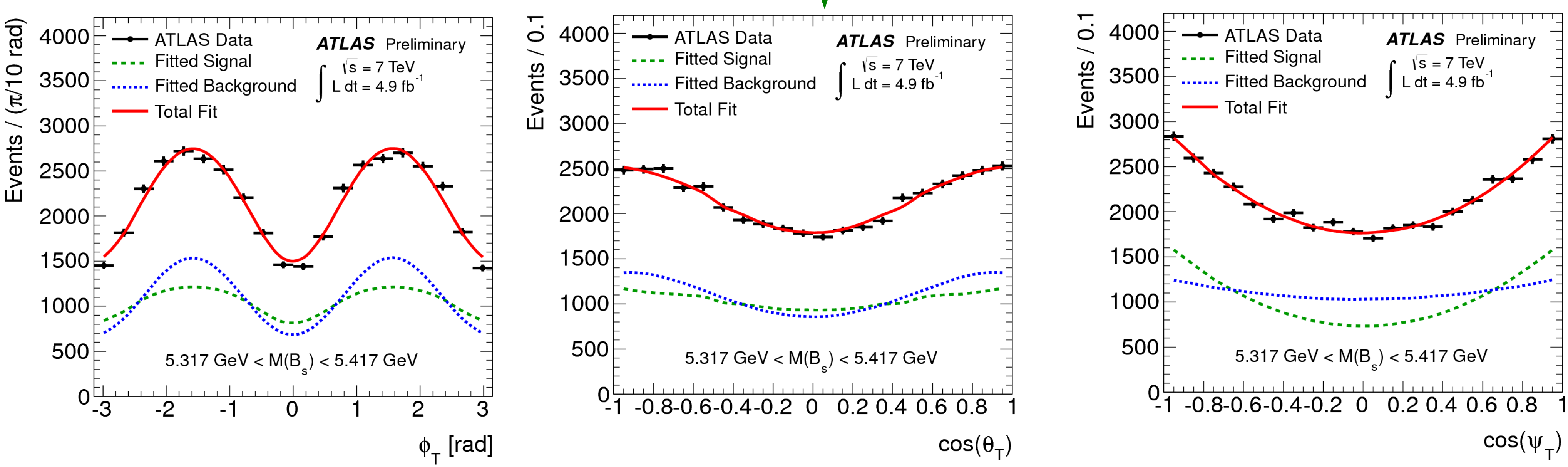
Mass



Proper decay time



Transversity angles



Systematics

	ϕ_s (rad)	$\Delta\Gamma_s$ (ps^{-1})	Γ_s (ps^{-1})	$\|A_{\|\|}(0)\|^2$	$\|A_0(0)\|^2$	$\|A_S(0)\|^2$	$\delta_\perp$ (rad)	$\delta_{\|\|}$ (rad)	$\delta_\perp - \delta_S$ (rad)
ID alignment	$<10^{-2}$	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	-	$<10^{-2}$	$<10^{-2}$	-
Trigger efficiency	$<10^{-2}$	$<10^{-3}$	0.002	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	$<10^{-2}$	$<10^{-2}$	$<10^{-2}$
B_d^0 contribution	0.03	0.001	$<10^{-3}$	$<10^{-3}$	0.005	0.001	0.02	$<10^{-2}$	$<10^{-2}$
Tagging	0.10	0.001	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	0.002	0.05	$<10^{-2}$	$<10^{-2}$
Models:									
default fit	$<10^{-2}$	0.002	$<10^{-3}$	0.003	0.002	0.006	0.07	0.01	0.01
signal mass	$<10^{-2}$	0.001	$<10^{-3}$	$<10^{-3}$	0.001	$<10^{-3}$	0.03	0.04	0.01
background mass	$<10^{-2}$	0.001	0.001	$<10^{-3}$	$<10^{-3}$	0.002	0.06	0.02	0.02
resolution	0.02	$<10^{-3}$	0.001	0.001	$<10^{-3}$	0.002	0.04	0.02	0.01
background time	0.01	0.001	$<10^{-3}$	0.001	$<10^{-3}$	0.002	0.01	0.02	0.02
background angles	0.02	0.008	0.002	0.008	0.009	0.027	0.06	0.07	0.03
Total	0.11	0.009	0.003	0.009	0.011	0.028	0.13	0.09	0.04

ID alignment – effect of residual misalignment studied in signal MC

Trigger efficiency – uncertainty in trigger selection efficiency

B_d^0 contribution – uncertainty in relative fraction of B^0 background

Tagging – Uncertainty in the calibration of the tag probability

Models – uncertainties of fit model derived in pseudo-experiment studies

Results

The PDFs describing B_s^0 decay is **invariant under following transformations:**

$$\{\phi_s, \Delta\Gamma_s, \delta_\perp, \delta_\parallel\} \rightarrow \{\pi - \phi_s, -\Delta\Gamma_s, \pi - \delta_\perp, 2\pi - \delta_\parallel\}$$

→ $\Delta\Gamma_s$ has been determined to be positive **(LHCb: PRL 108 (2012), 241801)**

=> unique solution

→ **SM prediction:**

$$\phi_s \simeq -2\beta_s = -0.0368 \pm 0.0018\,\text{rad}$$

$$\beta_s = \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$$

$$\Delta\Gamma_s = 0.087 \pm 0.021\,\text{ps}^{-1}$$

PRL 97 (2006), 151803

→ **RESULTS:**

ATLAS-CONF-2013-039

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s(rad)	0.12	0.25	0.11
$\Delta\Gamma_s$(ps^{-1})	0.053	0.021	0.009
Γ_s(ps^{-1})	0.677	0.007	0.003
$\lvert A_\parallel(0)\rvert^2$	0.220	0.008	0.009
$\lvert A_0(0)\rvert^2$	0.529	0.006	0.011
$\lvert A_S\rvert^2$	0.024	0.014	0.028
$\delta_\perp$	3.89	0.46	0.13
$\delta_\parallel$	[3.04-3.23]		0.09
$\delta_\perp - \delta_S$	[3.02-3.25]		0.04

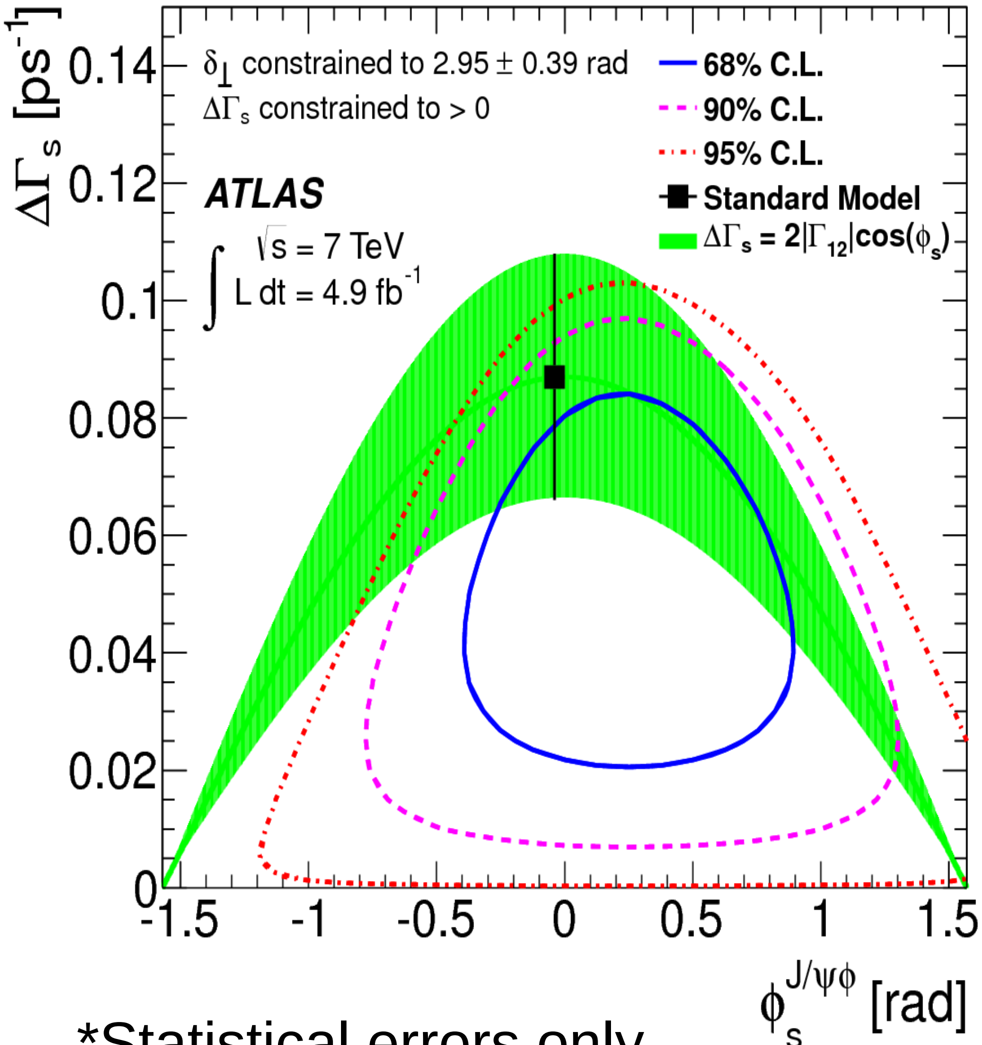
Transversity amplitudes (describe admixture of CP even and odd eigenstates)

Amplitude describing $B_s \rightarrow J/\psi K^+K^-$ decays (f_0)

Strong phases

$\phi s - \Delta\Gamma$ *contour plot*

JHEP 12 (2012) 072
Analysis with no flavour tagging



*Statistical errors only

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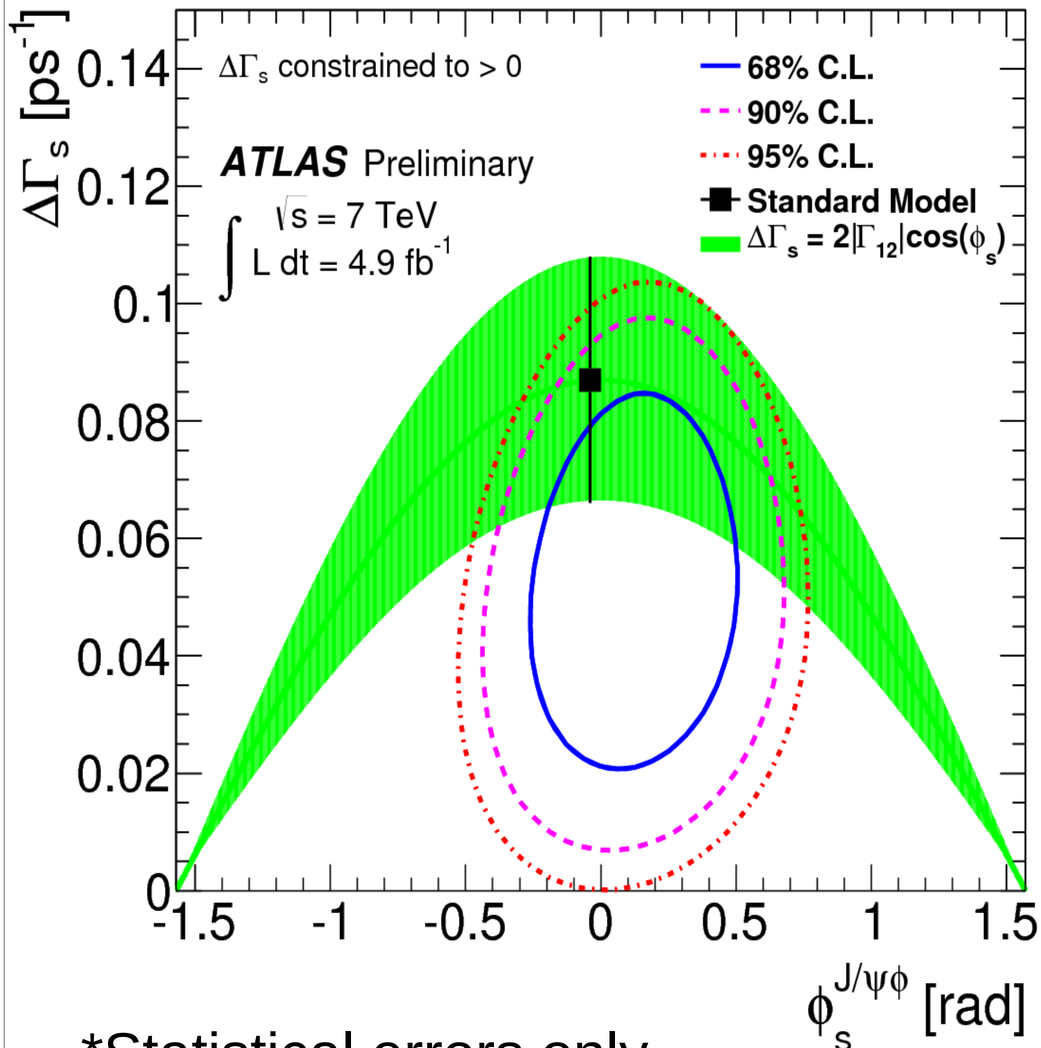
Analysis with flavour tagging



*Statistical errors only

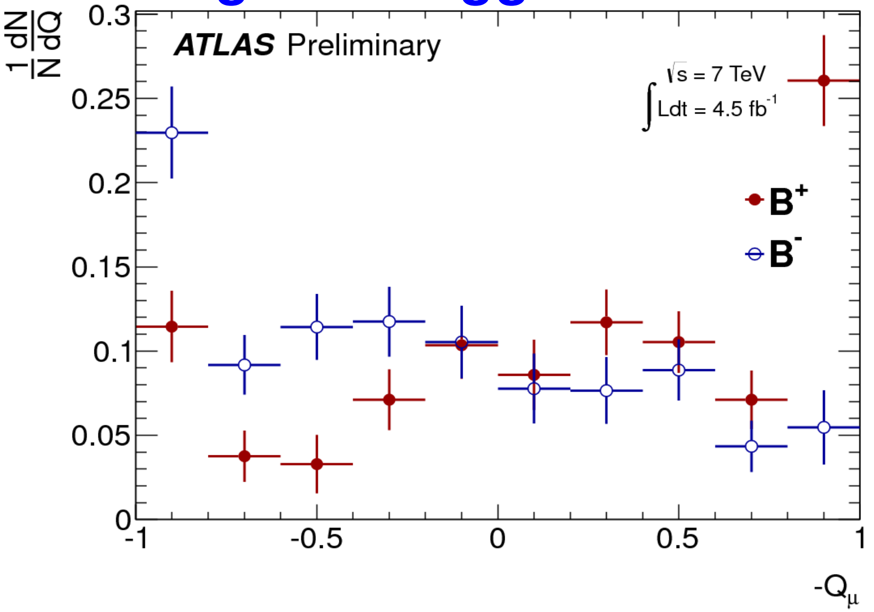
Thank you!

Back up

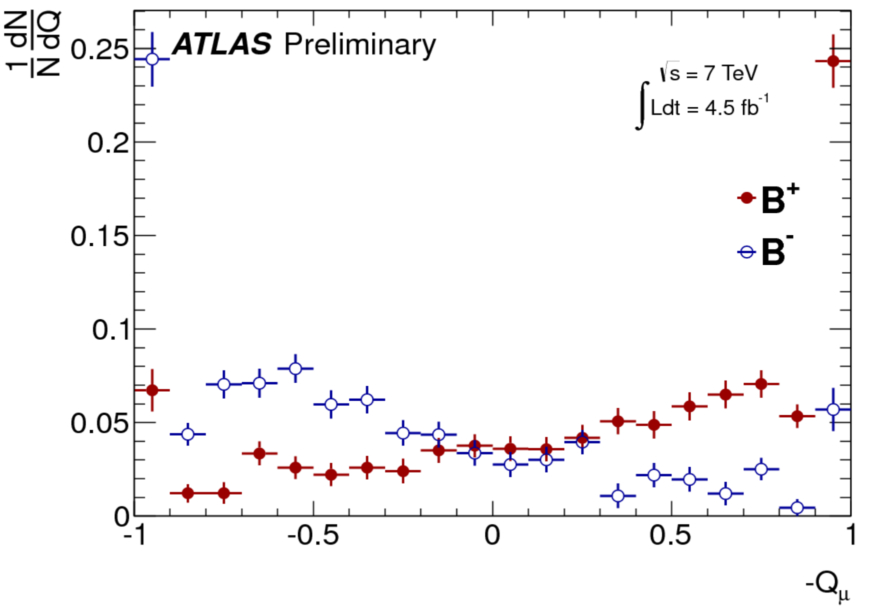
Tagging power of flavour tagging methods

Muon cone charge

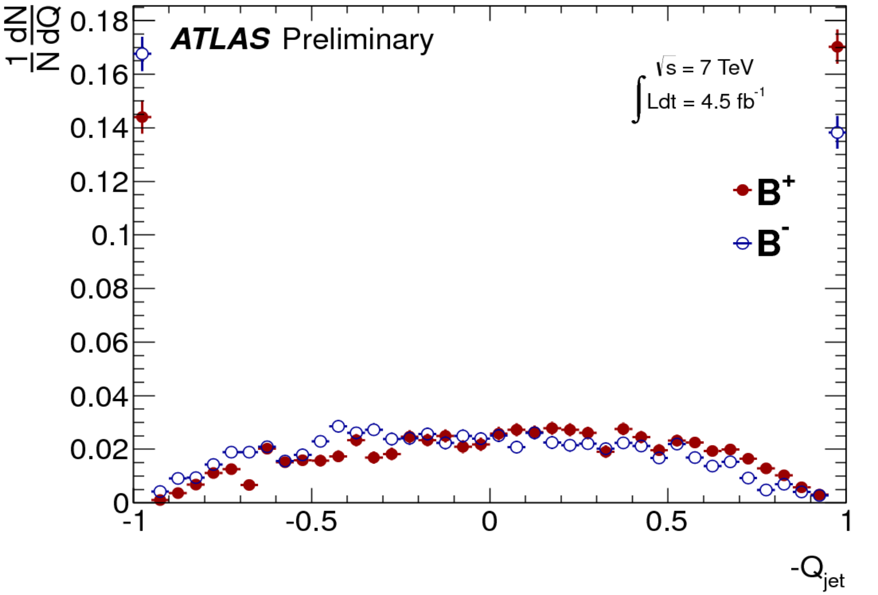
segment tagged muons



combined muons



jet - charge



Correlations between physics parameters

	ϕ_s	$\Delta\Gamma$	Γ_s	$\|A_{\|\|}(0)\|^2$	$\|A_0(0)\|^2$	$\|A_S(0)\|^2$	$\delta_{\|\|}$	$\delta_\perp$	$\delta_\perp - \delta_S$
ϕ_s	1.000	0.107	0.026	0.010	0.002	0.029	0.021	-0.043	-0.003
$\Delta\Gamma$		1.000	-0.617	0.105	0.103	0.069	0.006	-0.017	0.001
Γ_s			1.000	-0.093	-0.063	0.034	-0.003	0.001	-0.009
$\|A_{\|\|}(0)\|^2$				1.000	-0.316	0.077	0.008	0.005	-0.010
$\|A_0(0)\|^2$					1.000	0.283	- 0.003	-0.016	-0.025
$\|A_S(0)\|^2$						1.000	-0.011	-0.054	-0.098
$\delta_{\|\|}$							1.000	0.038	0.007
$\delta_\perp$								1.000	0.081
$\delta_\perp - \delta_S$									1.000