MEASUREMENT OF CP-VIOLATION PARAMETERS IN DECAYS OF $B_s^0 \to J/\psi\phi$ WITH THE ATLAS DETECTOR

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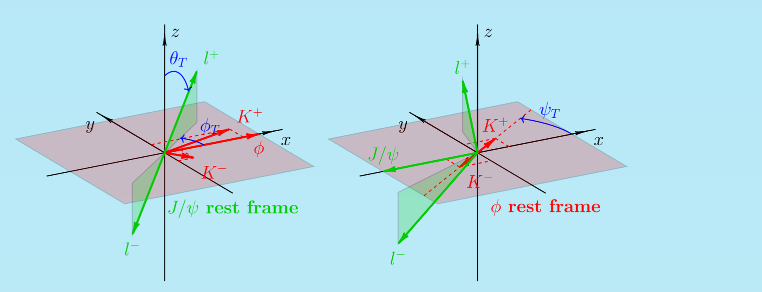
ANALYSIS STRATEGY

- $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decay
- Pseudo-scalar B_s decaying into vector-vector final state $\Longrightarrow$ 3 final states with $L = 0$, 1 or 2 + one more state with S-wave KK configuration. **Disentangled by angular analysis.** States with $L = 0, 2$ are CP-even, states with $L = 1$ and with S-wave KK system are CP-odd

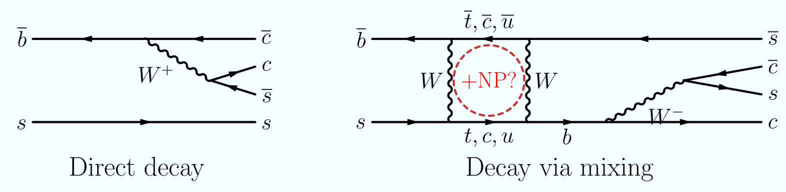


Fitted variables:

- **Three transversity angles** — disentangling CP-eigenstates
- **Invariant mass** — signal/background separation
- **Proper decay time** — information about Γ_s, $\Delta\Gamma_s$ and ϕ_s + signal/background separation

CP-VIOLATION IN $B_s^0 \to J/\psi\phi$ DECAY

- B_s-meson is electrically neutral and can **mix with its antiparticle**, just like neutral kaons do
- $B_s - \bar{B}_s$ mixing occurs due to weak flavour changing currents — through **loops with two W bosons**
- Hypothetical **new physics (NP)** particles **may affect the dynamics of this mixing**
- Since final state ($J/\psi\phi$) is common for both B_s and $\bar{B}_s$ there's **interference between decays with and without mixing**



- CP-violation occurs in this interference. It means that time-dependent decay probabilities are different for B_s and $\bar{B}_s$:

$$\Gamma^{\left[B_s^0(\rightsquigarrow \bar{B}_s^0)\to J/\psi\phi\right]}(t) \neq \Gamma^{\left[\bar{B}_s^0(\rightsquigarrow B_s^0)\to J/\psi\phi\right]}(t)$$

- **The amount of CP-violation is characterised by ϕ_s** — weak phase difference between the mixing amplitude and $b \to c\bar{c}s$ decay amplitude
- In the Standard Model (SM) ϕ_s is estimated by combining beauty and kaon physics observables:

$$\phi_s = -0.0363^{+0.0015}_{-0.0016}\ \text{rad}$$

- **NP contributions may alter this value**
- Other parameters describing B_s mixing and decay are mass difference

$$\Delta m_s = m_{\rm H} - m_{\rm L},$$

decay width difference

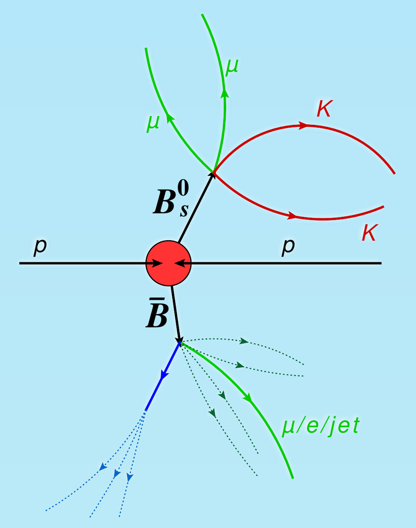
$$\Delta\Gamma_s = \Gamma_{\rm L} - \Gamma_{\rm H},$$

and

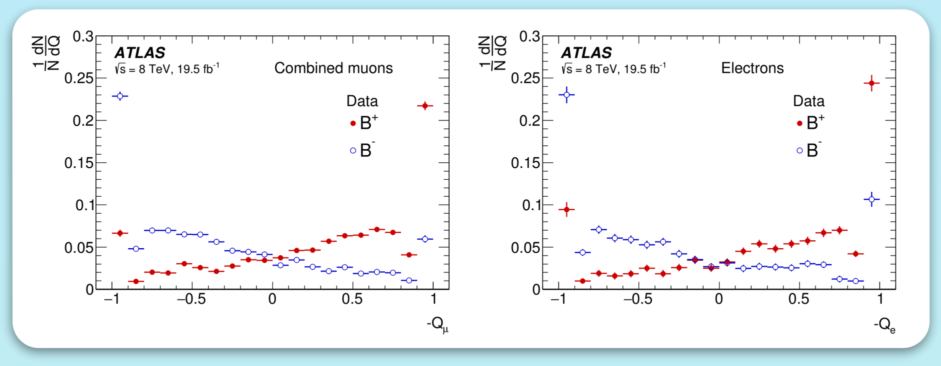
$$\Gamma_s = \frac{\Gamma_{\rm L} + \Gamma_{\rm H}}{2}$$

— mean of the two decay widths ("L" and "H" stand for light and heavy mass eigenstates respectively).

FLAVOUR TAGGING



- b-quarks are produced in **quark-antiquark pairs**
- Initial flavour is **correlated with the charge of decay product (e/μ/jet)**
- Measuring **weighted sum of charges** of tracks in a cone around an opposite-side e/μ/jet gives **information about B_s^0-meson flavour**
- Method calibrated with $B^+ \to J/\psi K^+$ decays



Unbinned maximum likelihood fit

$$\ln\mathscr{L} = \sum_{i=1}^{N}\Big\{w_i \cdot \ln\Big[f_s \cdot \mathscr{F}_s(m_i,t_i,\sigma_i,\Omega_i,P(B|Q),p_{{\rm T}i}) + f_s \cdot f_{B^0} \cdot \mathscr{F}_{B^0}(m_i,t_i,\sigma_i,\Omega_i,P(B|Q),p_{{\rm T}i}) + f_s \cdot f_{\Lambda_b^0} \cdot \mathscr{F}_{\Lambda_b^0}(m_i,t_i,\sigma_i,\Omega_i,P(B|Q),p_{{\rm T}i}) + (1 - f_s\cdot(1 + f_{B^0} + f_{\Lambda_b^0})) \cdot \mathscr{F}_{\rm bkg}(m_i,t_i,\sigma_i,\Omega_i,P(B|Q),p_{{\rm T}i})\Big]\Big\}$$

Trigger lifetime efficiency weights (w_i); Signal PDF ($\mathscr{F}_s$); B_d background PDF ($\mathscr{F}_{B^0}$); Λ_b^0 background PDF ($\mathscr{F}_{\Lambda_b^0}$); PDF for other background sources ($\mathscr{F}_{\rm bkg}$)

Backgrounds:

- $B_d \to J/\psi K^{*0}(K\pi)$ — estimated to be $(3.3 \pm 0.5)\%$ w.r.t. the signal
- $B_d \to J/\psi K\pi$ — $(0.7 \pm 0.5)\%$ w.r.t. the signal (not included in the fit, treated as systematic)
- $\Lambda_b^0 \to J/\psi pK$ — $(1.8 \pm 0.6)\%$ w.r.t. the signal

Tagging power and efficiency

Efficiency — number of tagged candidates divided by total number of candidates.

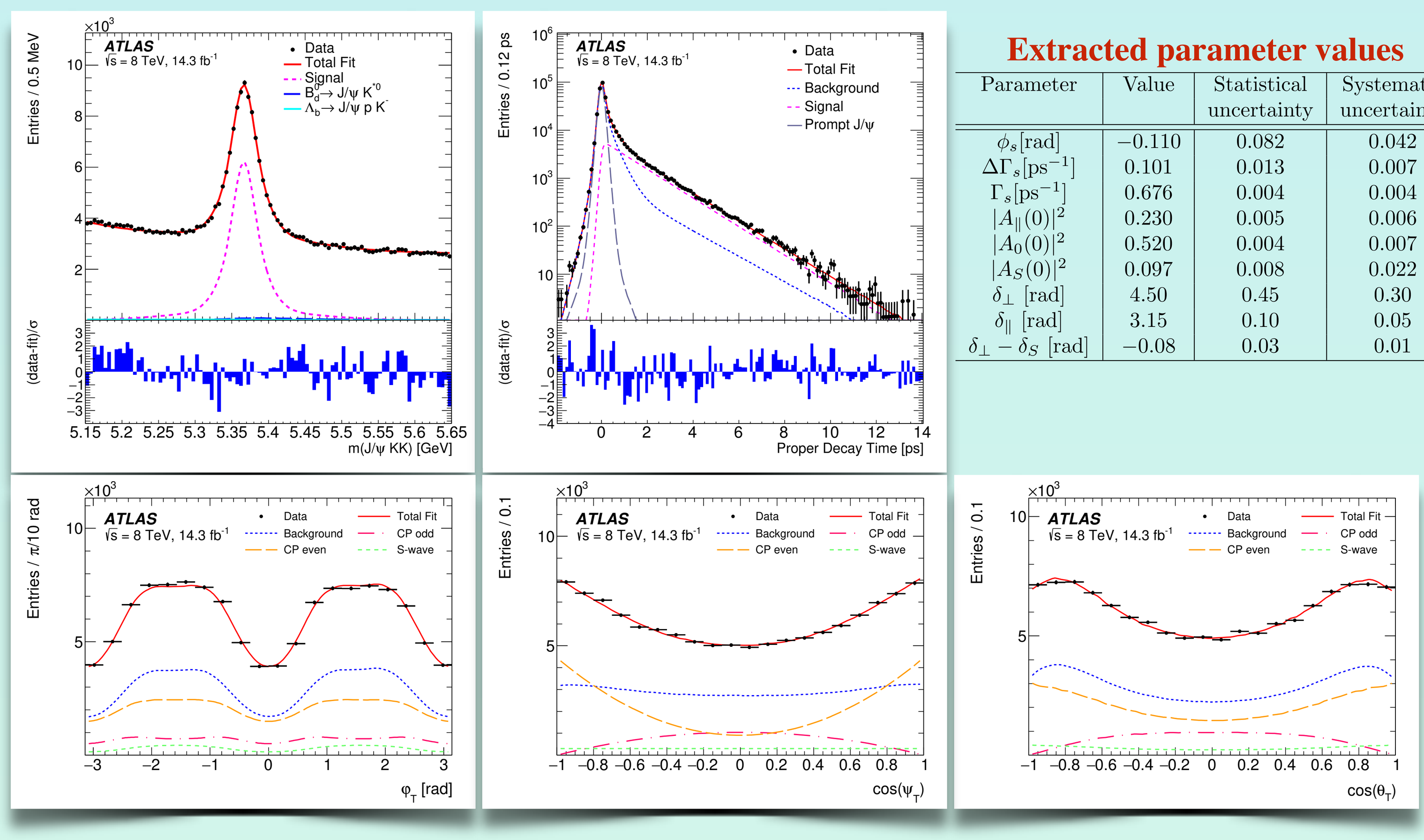
Dilution — difference between tagging probabilities $P(B|Q)$ and $P(\bar{B}|Q)$

Tagging power — efficiency times dilution squared

Tagger	Efficiency [%]	Dilution [%]	Tagging Power [%]
Combined μ	4.12 ± 0.02	47.4 ± 0.2	0.92 ± 0.02
Electron	1.19 ± 0.01	49.2 ± 0.3	0.29 ± 0.01
Segment-tagged μ	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	19.66 ± 0.04	27.56 ± 0.06	1.49 ± 0.02

FIT RESULTS (8 TEV DATA, 14.3 FB^{-1})

Fit projections



Extracted parameter values

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s[rad]	-0.110	0.082	0.042
$\Delta\Gamma_s$[ps^{-1}]	0.101	0.013	0.007
Γ_s[ps^{-1}]	0.676	0.004	0.004
$\lvert A_\parallel(0)\rvert^2$	0.230	0.005	0.006
$\lvert A_0(0)\rvert^2$	0.520	0.004	0.007
$\lvert A_S(0)\rvert^2$	0.097	0.008	0.022
$\delta_\perp$ [rad]	4.50	0.45	0.30
$\delta_\parallel$ [rad]	3.15	0.10	0.05
$\delta_\perp - \delta_S$ [rad]	-0.08	0.03	0.01

SYSTEMATIC UNCERTAINTIES

- **Flavour tagging**
  Alternative tagging probability fits for the calibration sample $B^+ \to J/\psi K^+$ performed
- **Angular acceptance**
  Alternative binning for angular acceptance calculation
- **Inner detector alignment**
  A possible bias on the impact parameter d_0 was evaluated to be 0.14% in barrel and 0.55% in endcap. These values were used to modify d_0 in alternative fits.
- **Trigger efficiency**
  The uncertainty of trigger efficiency weights propagated to the main fit (effect found to be negligible)
- **Background angular model**
  Alternative p_T binning and alternative sideband mass regions taken to fit the background angular shapes

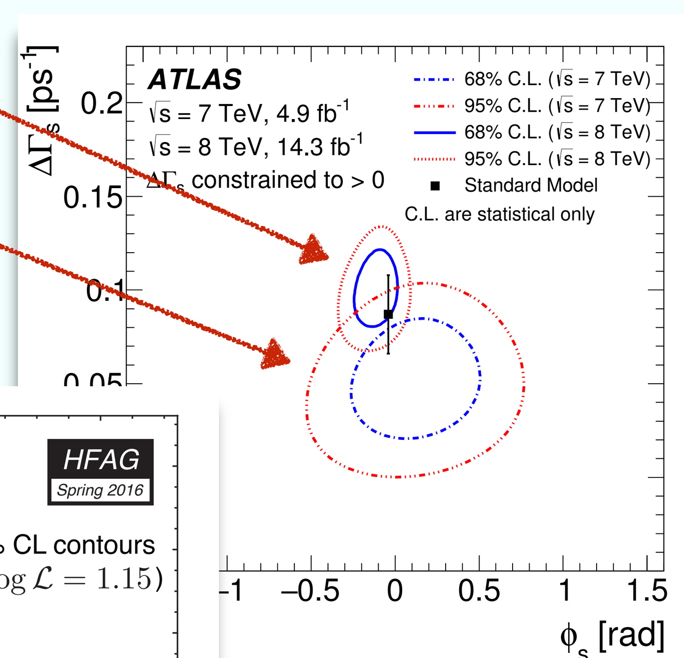
	ϕ_s [rad]	$\Delta\Gamma_s$ [ps^{-1}]	Γ_s [ps^{-1}]	$\lvert A_\parallel(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_\perp$ [rad]	$\delta_\parallel$ [rad]	$\delta_\perp - \delta_S$ [rad]
Tagging	0.025	0.003	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	0.001	0.236	0.014	0.004
Acceptance	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	0.003	$<10^{-3}$	0.001	0.004	0.008	$<10^{-3}$
Inner detector alignment	0.005	$<10^{-3}$	0.002	$<10^{-3}$	$<10^{-3}$	$<10^{-3}$	0.134	0.007	$<10^{-3}$
Background angles model:									
Choice of $p_{\rm T}$ 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
Λ_b background model	0.011	0.002	0.001	0.001	0.007	0.009	0.045	0.006	0.007
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	0.042	0.007	0.004	0.006	0.007	0.022	0.30	0.05	0.01

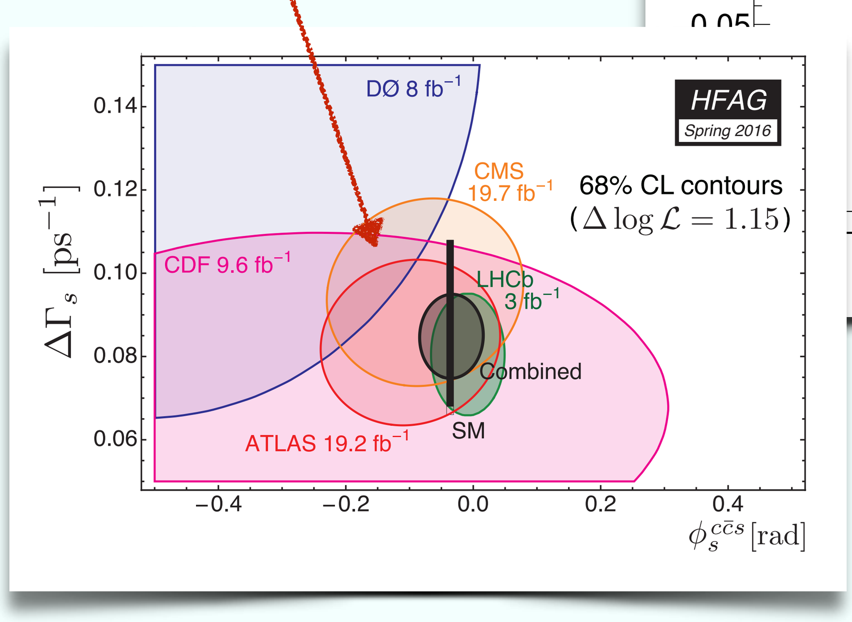
- **B_d contribution**
  Impact of the uncertainties of the fitted parameters taken into account (negligible effect)
  Alternative fit including $B_d \to J/\psi K\pi$ contribution performed
- **Λ_b contribution**
  Impact of the uncertainties of mass, angular and lifetime shapes as well as relative fraction and resonant pK invariant mass structure taken into account
- **Fit model variations**
  Pseudo-experiments generated with alternate models are fitted with the default model
- **Default fit model**
  Pseudo-experiments generated and fitted with the default model

RUN-1 COMBINED ATLAS RESULT

Par	Run1 combined Value	Stat	Syst
ϕ_s[rad]	-0.090	0.078	0.041
$\Delta\Gamma_s$[ps^{-1}]	0.085	0.011	0.007
Γ_s[ps^{-1}]	0.675	0.003	0.003
$\lvert A_\parallel(0)\rvert^2$	0.227	0.004	0.006
$\lvert A_0(0)\rvert^2$	0.522	0.003	0.007
$\lvert A_S\rvert^2$	0.072	0.007	0.018
$\delta_\perp$ [rad]	4.15	0.32	0.16
$\delta_\parallel$ [rad]	3.15	0.10	0.05
$\delta_\perp - \delta_S$ [rad]	-0.08	0.03	0.01

- **14.3 fb^{-1} from 8 TeV data**
- **4.9 fb^{-1} from 7 TeV data**
- **Combined 7 & 8 TeV ATLAS result**





- **8 TeV result is consistent with 7 TeV result**
- **Combined ATLAS Run-1 measurement agrees with other experiments and with SM prediction**
- **World combination (HFAG) is consistent with SM**

These results are published in:
The ATLAS collaboration, Aad, G., et al. J. High Energ. Phys. (2016) 2016: 147. doi:10.1007/JHEP08(2016)147