B-decays branching fractions, helicities & lifetimes in ATLAS

Radek Novotný
on behalf of the ATLAS collaboration

Beauty 2023, Clermont-Ferrand
July 6, 2023

ATLAS EXPERIMENT
THE UNIVERSITY OF NEW MEXICO

Outline

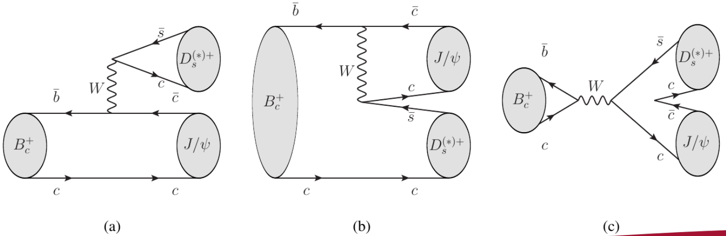
This talk will cover the following analyses:

- Study of $B_c^+ \to J/\psi D_s^{(*)+}$ decays in pp collisions at $\sqrt{s} = 13\,\text{TeV}$ .... JHEP 08 (2022) 087
- Overview of lifetime measurements performed by ATLAS
  - Measurement of the Λ_b^0 lifetime .... Phys. Rev. D 87 (2013) 032002
  - Measurement of the CP-violating phase in $B_s \to J/\psi\phi$ .... Eur. Phys. J. C 81 (2021) 342
  - Measurement of the relative width difference of the $B^0 - \bar{B}^0$ system .... JHEP 06 (2016) 081

$B_c^+ \to J/\psi D_s^{(*)+}$ (1/8)

JHEP 08 (2022) 087

- The ground state $B_c^+ \to J/\psi \pi^+$ was measured at the LHC Run1 Phys. Rev. D 104 (2021) 012010 and the new excited state $B_c(2S)$ was observed Phys. Rev. Lett. 113 (2014) 212004
- However, previous studies of rare processes were limited by the low B_c production cross-section
- Operating LHC experiments at a centre-of-mass energy $\sqrt{s} = 13$ TeV opens new opportunities to measure the properties of the B_c meson precisely
- These statistics allow measurement of $B_c^+ \to J/\psi D_s^+$ and $B_c^+ \to J/\psi D_s^{*+}$
- In this channel, B_c decays can occur through a weak transition of either heavy quark (a,b) as well as through a weak annihilation (c)



$B_c^+ \to J/\psi D_s^{(*)+}$ (2/8)

JHEP 08 (2022) 087

- The $B_c^+ \to J/\psi D_s^{(*)+}$ decays were studied at **ATLAS** using full Run 2 statistics corresponding to 139 fb^{-1} of integrated luminosity
- The $B_c^+ \to J/\psi D_s^{(*)+}$ decays are recosntructed in the following way:

J/ψ meson

- Reconstructed via its decay into a pair of oppositely charged muons

D_s^+ meson

- Reconstructed via the $D_s^+ \to \phi\pi^+$ decay, with the $\phi \to K^-K^+$
- The invariant mass of the ϕ candidate, $m(K^+K^-)$, is required to be within a ± 7 MeV range around the world average
- Only three-track combinations successfully fitted to a common vertex are accepted for further analysis

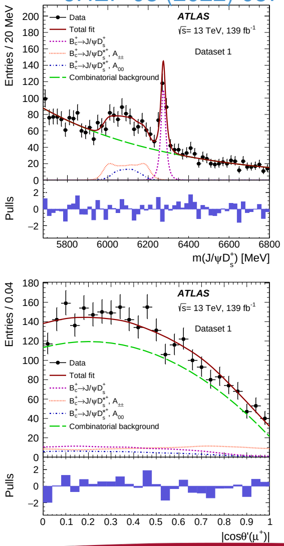
D_s^{*+} meson

- Decays into a D_s^+ meson and a soft photon or π^0 which is not reconstructed in the analysis
- The mass difference between D_s^+ and D_s^{*+} is sufficient for the two decay signals to be resolved as two distinct structures in the reconstructed mass of the $J/\psi D_s^+$ system

$B_c^+ \to J/\psi D_s^{(*)+}$ (3/8)

JHEP 08 (2022) 087

- $B_c^+ \to J/\psi D_s^{*+}$ decay is a pseudoscalar meson into two vector states (can be described in terms of three helicity amplitudes: A_{--}, A_{++} and A_{00})
- The extended unbinned maximum-likelihood fit to the two-dimensional distribution of $m(J/\psi D_s^+)$ and $|\cos\theta'(\mu^+)|$ is performed
- The signal extraction is performed in two (non-overlapping) datasets:
  - Dataset 1: candidates in the events collected by the standard di-muon triggers or by three-muon triggers without requirements on the additional ID tracks
  - Dataset 2: candidates collected only by the dedicated $B_s^0 \to \mu^+\mu^-\phi$ triggers and not by other ones used in the analysis
- Dataset 1 and Dataset 2 are fitted simultaneously
- The signal and background probability density functions (PDFs) for the fit are assumed to be uncorrelated for $m(J/\psi D_s^+)$ and $|\cos\theta'(\mu^+)|$



$B_c^+ \to J/\psi D_s^{(*)+}$ (4/8)

JHEP 08 (2022) 087

- $B_c^+ \to J/\psi D_s^{*+}$ decay can be described in terms of three helicity amplitudes
- The $m(J/\psi D_s^+)$ and $|\cos\theta'(\mu^+)|$ spectra are the same for the A_{++} and A_{--} amplitudes (that is confirmed with the MC simulation) so it can be parametrized by $A_{\pm\pm}$ and A_{00} only
- The $f_{\pm\pm}$ corresponds to the $A_{\pm\pm}$ components fraction in the total yield
- The $m(J/\psi D_s^+)$ and $|\cos\theta'(\mu^+)|$ shapes of the two helicity components of the $B_c^+ \to J/\psi D_s^{*+}$ signal are described using templates made from the MC simulated events with the adaptive kernel estimation technique
- Since the datasets are fitted simultaneously, two yields $N^{DS1}_{B_c^+\to J/\psi D_s^+}$ and $N^{DS2}_{B_c^+\to J/\psi D_s^+}$ are published

Parameter	Value
$m_{B_c^+}$ [MeV]	6274.8 ± 1.4
$\sigma_{B_c^+}$ [MeV]	11.5 ± 1.5
$r_{D_s^{*+}/D_s^+}$	1.76 ± 0.22
$f_{\pm\pm}$	0.70 ± 0.10
$N^{\mathrm{DS1}}_{B_c^+\to J/\psi D_s^+}$	193 ± 20
$N^{\mathrm{DS2}}_{B_c^+\to J/\psi D_s^+}$	49 ± 10
$N^{\mathrm{DS1}}_{B_c^+\to J/\psi D_s^{*+}}$	338 ± 32
$N^{\mathrm{DS1\&2}}_{B_c^+\to J/\psi D_s^+}$	241 ± 28
$N^{\mathrm{DS1\&2}}_{B_c^+\to J/\psi D_s^{*+}}$	424 ± 46

$B_c^+ \to J/\psi D_s^{(*)+}$ (5/8)

JHEP 08 (2022) 087

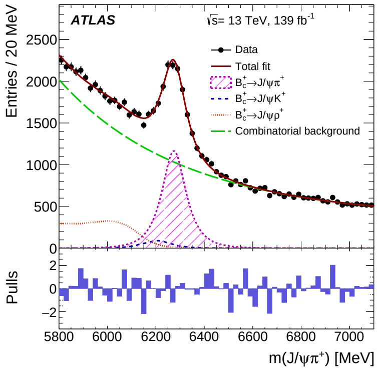
- $B_c^+ \to J/\psi\pi^+$ decay is used as a reference to measure the branching fractions ratios:

$$R_{D_s^{(*)+}/\pi^+} = \frac{\mathcal{B}(B_c^+ \to J/\psi D_s^{(*)+})}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}$$

and

$$R_{D_s^{*+}/D_s^+} = \frac{\mathcal{B}(B_c^+ \to J/\psi D_s^{*+})}{\mathcal{B}(B_c^+ \to J/\psi D_s^+)}$$

- The yield is extracted with an extended unbinned maximum-likelihood fit
- Partially reconstructed B_c^+ decays (PRDs), $B_c^+ \to J/\psi X$, as well as the peaking background from $B_c^+ \to J/\psi K^+$ are modelled by the MC simulation shapes



Parameter	Value
$m_{B_c^+}$ [MeV]	6274.5 ± 1.5
$\sigma_{B_c^+}$ [MeV]	47.5 ± 2.5
$N_{B_c^+\to J/\psi\pi^+}$	8440^{+550}_{-470}

- Overall efficiencies are important to measure relative production ratio
- The total efficiency is a product of kinematic acceptance and reconstruction efficiency and they are calculated for Dataset 1 and for the full dataset
- They are different for the $A_{\pm\pm}$ and A_{00} components hence the efficiency for this mode is given by

$$\epsilon_{B_c^+ \to J/\psi D_s^{*+}} = \frac{1}{f_{\pm\pm}/\epsilon_{B_c^+ \to J/\psi D_s^{*+}, A_{\pm\pm}} + (1 - f_{\pm\pm})/\epsilon_{B_c^+ \to J/\psi D_s^{*+}, A_{00}}}$$

- The total efficiencies for all decay modes are shown in the following table

Mode	$\epsilon^{\mathrm{DS1}}_{B_c^+ \to J/\psi X}$ [%]	$\epsilon^{\mathrm{DS1\&2}}_{B_c^+ \to J/\psi X}$ [%]
$B_c^+ \to J/\psi D_s^+$	0.971 ± 0.012	1.163 ± 0.013
$B_c^+ \to J/\psi D_s^{*+}$, A_{00}	0.916 ± 0.012	1.088 ± 0.012
$B_c^+ \to J/\psi D_s^{*+}$, $A_{\pm\pm}$	0.868 ± 0.010	1.049 ± 0.011
$B_c^+ \to J/\psi \pi^+$	2.169 ± 0.018	–

- The fraction of transverse polarization in the $B_c^+ \to J/\psi D_s^{*+}$ decay $\Gamma_{\pm\pm}/\Gamma$ is also measured

$$\Gamma_{\pm\pm}/\Gamma = f_{\pm\pm} \frac{\epsilon^{DS1\&2}_{B_c^+ \to J/\psi D_s^{*+}}}{\epsilon_{B_c^+ \to J/\psi D_s^{*+}, A_{\pm\pm}}}$$

$B_c^+ \to J/\psi D_s^{(*)+}$ (7/8)

JHEP 08 (2022) 087

- The ratios of the branching fractions for $B_c^+ \to J/\psi D_s^{(*)+}$ and $B_c^+ \to J/\psi \pi^+$ are found to be

$$R_{D_s^+/\pi^+} = 2.76 \pm 0.33 \pm 0.29 \pm 0.16$$

$$R_{D_s^{*+}/\pi^+} = 5.33 \pm 0.61 \pm 0.67 \pm 0.32,$$

  where the third error corresponds to the uncertainty in the branching fraction of the $D_s^+ \to \phi(K^+K^-)\pi^+$ decay

- The ratio of the branching fractions for $B_c^+ \to J/\psi D_s^{*+}$ and $B_c^+ \to J/\psi D_s^+$ is found to be:

$$R_{D_s^{*+}/D_s^+} = 1.93 \pm 0.24 \pm 0.09$$

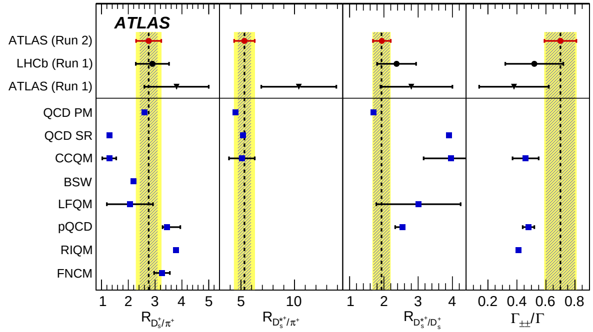
- The fraction of transverse polarization in the $B_c^+ \to J/\psi D_s^{*+}$ decay

$$\Gamma_{\pm\pm}/\Gamma = 0.70 \pm 0.10 \pm 0.04$$

$B_c^+ \to J/\psi D_s^{(*)+}$ (8/8)

JHEP 08 (2022) 087

- All results are consistent with the earlier measurements by ATLAS[1] and LHCb[2]
- Results compared with the theory predictions
- A QCD (PM) relativistic potential model agrees well



$R_{D_s^+/\pi^+}$	$R_{D_s^{*+}/\pi^+}$	$R_{D_s^{*+}/D_s^+}$	$\Gamma_{\pm\pm}/\Gamma$	Reference
2.76 ± 0.47	5.33 ± 0.96	1.93 ± 0.26	0.70 ± 0.11	ATLAS Run 2
2.90 ± 0.62	–	2.37 ± 0.57	0.52 ± 0.20	LHCb Run 1
3.8 ± 1.2	10.4 ± 3.5	$2.8^{+1.2}_{-0.9}$	0.38 ± 0.24	ATLAS Run 1
2.6	4.5	1.7	–	QCD potential model
1.3	5.2	3.9	–	QCD sum rules
1.29 ± 0.26	5.09 ± 1.02	3.96 ± 0.80	0.46 ± 0.09	CCQM
2.2	–	–	–	BSW
2.06 ± 0.86	–	3.01 ± 1.23	–	LFQM
$3.45^{+0.49}_{-0.17}$	–	$2.54^{+0.07}_{-0.21}$	0.48 ± 0.04	pQCD
3.7832	–	–	0.410	RIQM
3.257 ± 0.293	–	–	–	FNCM
1.67 ± 0.36	3.49 ± 0.52	2.09 ± 0.52	–	$B^+ \to \bar{D}^{*0} D_s^{(*)+} / \bar{D}^{*0}\pi^+$
2.92 ± 0.42	6.46 ± 0.60	2.21 ± 0.35	0.48 ± 0.05	$B^0 \to D^{*-} D_s^{(*)+} / D^{*-}\pi^+$
–	7.2 ± 2.1	–	0.94 ± 0.18	$B_s^0 \to D_s^{*-} D_s^+ / D_s^{*-}\pi^+$
–	–	1.402 ± 0.083	0.396 ± 0.023	$B^+ \to J/\psi K^{(*)+}$
–	–	1.425 ± 0.065	0.429 ± 0.007	$B^0 \to J/\psi K^{(*)0}$
–	–	–	0.4774 ± 0.0034	$B_s^0 \to J/\psi \phi$

[1] ATLAS Collaboration: Eur. Phys. J. C 76 (2016) 4

[2] LHCb Collaboration: Phys. Rev. D 87 (2013) 112012, [Addendum: Phys. Rev. D 89 (2014) 019901]

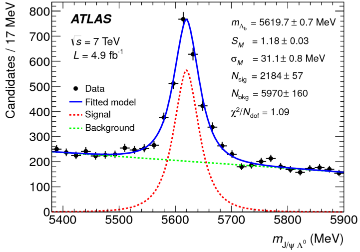
Overview of the lifetime measurements (1/4)

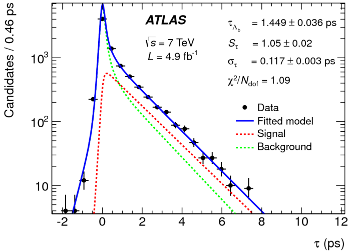
Λ_b^0 lifetime measurement: Phys. Rev. D 87 (2013) 032002

- The most direct measurement of the lifetime was performed by ATLAS in the Λ_b^0 baryon decay where the Λ_b^0 was reconstructed in the decay chain $\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda^0(p\pi^-)$
- The analysis uses data from Run 1

Parameter	Value	Par.	Value
m_{Λ_b}	5619.7 ± 0.7 MeV	$\chi^2/N_{\rm dof}$	1.09
τ_{Λ_b}	1.449 ± 0.036 ps	$N_{\rm sig}$	2184 ± 57
$f_{\rm sig}$	0.268 ± 0.007	$N_{\rm bkg}$	5970 ± 160
S_m	1.18 ± 0.03	σ_m	31.1 ± 0.8 MeV
S_τ	1.05 ± 0.02	σ_τ	0.117 ± 0.003 ps

- The cross-check with $B_d^0 \to J/\psi(\mu^+\mu^-)K_S^0(\pi^+\pi^-)$ (that contribute to Λ_b^0 decay contamination) was also made, the result $\tau_{B_d} = 1.509 \pm 0012(\text{stat.}) \pm 0.018(\text{syst.})$ ps was measured and leads to the ratio:
$R = \tau_{\Lambda_b}/\tau_{B_d} = 0.960 \pm 0.025(\text{stat.}) \pm 0.016(\text{syst.})$

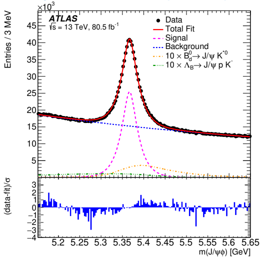


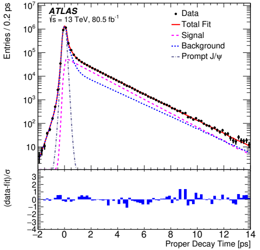


Overview of the lifetime measurements (2/4)

Measurement of the CP-violating phase in $B_s \to J/\psi\phi$- Eur. Phys. J. C 81 (2021) 342

- The most recent analysis is focusing on a CP violation measurement in the $B_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ channel
- It uses partial Run 2 data sample with 80.5 fb^{-1} of integrated luminosity
- The B_s^0 mixing also is described by $\Delta\Gamma_s = \Gamma_s^L - \Gamma_s^H$, where Γ_s^L and Γ_s^H are the decay widths of the different mass eigenstates, and $\Gamma_s = (\Gamma_s^L + \Gamma_s^H)/2$ their average.
- It uses opposite side tagging to identify initial signal flavour from the other B meson
- An unbinned maximum likelihood fit was performed to extract parameters describing $B_s \to J/\psi\phi$ and S-wave: $\phi_s, \Delta\Gamma_s, \Gamma_s, |A_0(0)|^2, |A_{||}(0)|^2, |A_S(0)|^2, \delta_{||}, \delta_\perp$ *and* δ_S

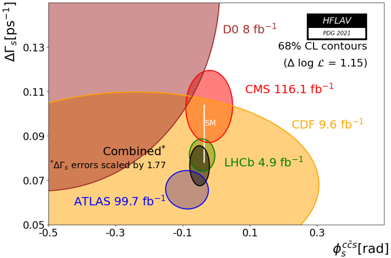


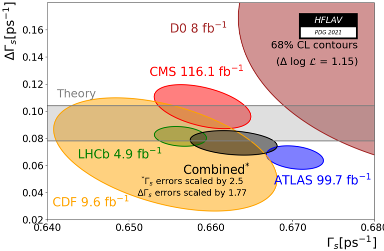


Overview of the lifetime measurements (3/4)

Measurement of the CP-violating phase in $B_s \to J/\psi\phi$- Eur. Phys. J. C 81 (2021) 342

- In Run2 for the strong-phases $\delta_\perp$ and $\delta_\parallel$ two well separated local maxima of the likelihood are found
- Their difference in likelihood values is minimal
- The current results were combined with those from the previous analysis in Run1
- Consistent with SM prediction and other LHC experiments with only small tensions



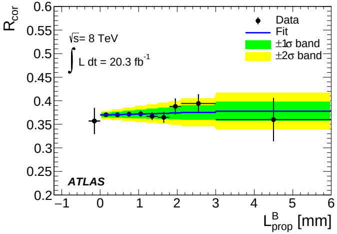


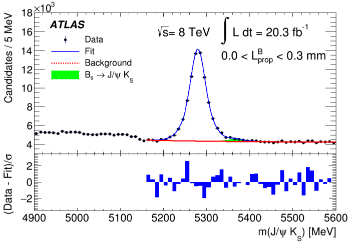
Parameter	Solution (a) Value	Solution (a) Statistical uncertainty	Solution (a) Systematic uncertainty	Solution (b) Value	Solution (b) Statistical uncertainty	Solution (b) Systematic uncertainty
ϕ_s [rad]	−0.087	0.036	0.019	−0.088	0.036	0.019
$\Delta\Gamma_s$ [ps^{-1}]	0.0641	0.0043	0.0024	0.0640	0.0043	0.0024
Γ_s [ps^{-1}]	0.6697	0.0014	0.0015	0.6698	0.0014	0.0015
$\|A_\parallel(0)\|^2$	0.2221	0.0017	0.0022	0.2218	0.0017	0.0022
$\|A_0(0)\|^2$	0.5149	0.0012	0.0031	0.5149	0.0012	0.0031
$\|A_S\|^2$	0.0343	0.0031	0.0044	0.0348	0.0031	0.0044
$\delta_\perp$ [rad]	3.22	0.10	0.05	3.03	0.10	0.05
$\delta_\parallel$ [rad]	3.36	0.05	0.08	2.95	0.05	0.08
$\delta_\perp - \delta_S$ [rad]	−0.24	0.05	0.04	−0.24	0.05	0.04

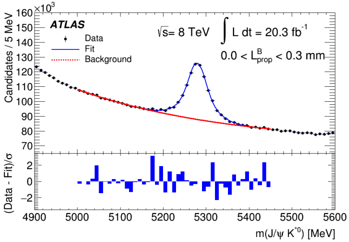
Overview of the lifetime measurements (4/4)

$B^0 - \bar{B}^0$ **width difference** : JHEP 06 (2016) 081

- $B^0 - \bar{B}^0$ width difference measurement was made using Run 1 data
- $\Delta\Gamma$ is one of the parameters describing the time evolution of the $B^0 - \bar{B}^0$ system
- It is measured through production asymmetry in the $B^0 \to J/\psi K_S$ and $B^0 \to J/\psi K^{*0}$ decays in dependence on the proper decay time L^B_{prom} after correction for detector effects







- $\Delta\Gamma_d/\Gamma_d = (-0.1 \pm 1.1(\text{stat.}) \pm 0.9(\text{syst})) \times 10^{-2}$ agrees well with the SM prediction and is consistent with other measurements

Summary

- ATLAS has an extensive research program focusing on various aspects of the heavy flavour decays
- ATLAS has conducted a precise measurement of CP-violation and lifetime parameters as well as the study of rare decays such as $B_c^+ \to J/\psi D_s^{(*)+}$
- It provides valuable results for the theory predictions and also helps to validate various models

Clermont-Ferrand