High-precision measurement of the B_d^0 meson lifetime at the ATLAS experiment

Maria Smizanska,
Lancaster University
On behalf of the ATLAS collaboration

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ATLAS

A new record for precision on B-meson lifetimes

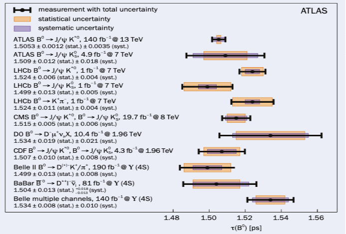
As direct searches for physics beyond the Standard Model continue to push frontiers at the LHC, the b-hadron physics sector remains a crucial source of insight for testing established theoretical models.

The ATLAS collaboration recently published a new measurement of the B^0 lifetime using $B^0 \to J/\psi K^{*0}$ decays from the entire Run-2 dataset it has recorded at 13 TeV. The result improves the precision of previous world-leading measurements by the CMS and LHCb collaborations by a factor of two.

Studies of b-hadron lifetimes probe our understanding of the weak interaction. The lifetimes of b-hadrons can be systematically computed within the heavy-quark expansion (HQE) framework, where b-hadron observables are expressed as a perturbative expansion in inverse powers of the b-quark mass.

ATLAS measures the "effective" B^0 lifetime, which represents the average decay time incorporating effects from mixing and CP contributions, as $\tau(B^0) = 1.5053 \pm 0.0012\,(\text{stat.}) \pm 0.0035\,(\text{syst.})$ ps. The result is consistent with previous measurements published by ATLAS and other experiments, as summarised in figure 1. It also aligns with theoretical predictions from HQE and lattice QCD, as well as with the experimental world average.

The analysis benefitted from the large Run-2 dataset and a refined trigger selection, enabling the collection of an extensive sample of 2.5 million $B^0 \to J/\psi K^{*0}$ decays. Events with a J/ψ meson decaying into two muons with sufficient transverse momentum are cleanly identified in the ATLAS Muon Spectrometer by the first-level hardware trigger. In the next-level software trigger, exploiting the full detector information, these muons are then combined with two tracks measured by the Inner Detector, ensuring they originate from the same vertex.



ATLAS Collab. 2024 arXiv:2411.09962

Fig. 1. *A comparison of the current ATLAS result for the B^0 lifetime with the previous ATLAS result in the $B^0 \to J/\psi K^0_S$ channel, and with those from other experiments.*

The B^0-meson lifetime is determined through a two-dimensional unbinned maximum-likelihood fit, utilising the measured B^0-candidate mass and decay time, and accounting for both signal and background components. The limited hadronic particle-identification capability of ATLAS requires careful modelling of the significant backgrounds from other processes that produce J/ψ mesons. The sensitivity of the fit is increased by estimating the uncertainty of the decay-time measurement provided by the ATLAS tracking and vertexing algorithms on a per-candidate basis. The resulting lifetime measurement is limited by systematic uncertainties, with the largest contributions arising from the correlation between B^0 mass and lifetime, and ambiguities in modelling the mass distribution.

ATLAS combined its measurement with the average decay width (Γ_s) of the light and heavy B_s-meson mass eigenstates, also measured by ATLAS, to determine the ratio of decay widths as $\Gamma_d/\Gamma_s = 0.9905 \pm 0.0022\,(\text{stat.}) \pm 0.0036\,(\text{syst.}) \pm 0.0057\,(\text{ext.})$. The result is consistent with unity and provides a stringent test of QCD predictions, which also support a value near unity.

Further reading

ATLAS Collab. 2024 arXiv:2411.09962.
ATLAS Collab. 2021 *Eur. Phys. J. C* **81** 342.

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- "Precision measurement of the B^0_d meson lifetime performed at the ATLAS using Run2 data " arXiv:2411.09962v1-hep-ex-15 Nov 2024; accepted by JHEP, April 2025.
- ATLAS B^0 lifetime is the most precise measurement to date
- Also measured the decay rate Γ_d of B^0
- Γ_d/Γ_s determined using ATLAS Γ_s measured in $B^0_s \to J/\psi\phi$ Eur. Phys. J. C 81 (2021) 342
- Recognised by ATLAS ATLAS Briefing ATLAS Briefing 25 November 2024
- Recognised by CERN LHC CERN Seminar and Article in CERN Courier p. 15).

- In the Heavy Quark Expansion (HQE) theory the decay rate $\Gamma = 1/\tau$ is calculated:

$$\Gamma(\mathscr{B}_q) = \Gamma_3 + \delta\Gamma(\mathscr{B}_q)$$

leading → **Free b-quark decay:**

+ free of non-perturbative uncertainties
0 Looks like the muon decay

$$\Gamma_3 \propto \frac{G_F^2 m_b^5}{192\pi^3} V_{cb}^2$$

- Quark masses are difficult to define, huge dependence on definition can be reduced by higher order **perturbative corrections**

subleading → **Power-suppressed terms on the HQE:**

+ suppressed with at least 2 powers of $1/m_b \Rightarrow$ small
0 Individual contributions are products of **perturbative** Wilson coefficients and **non-perturbative matrix elements** (determined with lattice-QCD, sum rules and/or from fits of experimental data of inclusive semi-leptonic decays - V_{cb})

- Γ suffers from huge uncertainties of the leading term Γ_3; $\Gamma_d = 0.63^{+0.11}_{-0.07}\ \mathrm{ps}^{-1}$ Lenz, et al. 2023
- In rates ratios the leading term Γ_3 exactly cancels leaving just small uncertainties from sub-leading terms; $\Gamma_d/\Gamma_s = 1.003 \pm 0.006$ Lenz, Piscopo, Rusov 2023
- Lifetimes measurements also test models of New Physics (BSM) contributing to both leading and sub-leading terms. Excluding BSM effects larger than 5%, will already constrain many BSM scenarios Lenz2021
- Since the theory predictions are more precise for ratios - we also extracted Γ_d/Γ_s.

Method of derivation of decay rate Γ_d and ratio Γ_d/Γ_s from measured B_d^0 lifetime.

The lifetime we measured in $B^0 \to J/\psi K^{*0}$ is the effective lifetime $\tau_{B_d^0}$ related to decay widths: Γ_L, Γ_H of the light and heavy mass eigenstates of B_d^0–$\overline{B_d^0}$ system via: Fleischer et al, 2011

$$\tau_{B^0} = \frac{1}{\Gamma_d}\frac{1}{1-y^2}\left(\frac{1+2Ay+y^2}{1+Ay}\right), \qquad (1)$$

$\Gamma_d = (\Gamma_\mathrm{L}+\Gamma_\mathrm{H})/2$; $y = \Delta\Gamma_d/(2\Gamma_d) = (\Gamma_\mathrm{L}-\Gamma_\mathrm{H})/(2\Gamma_d)$. The asymmetry A:

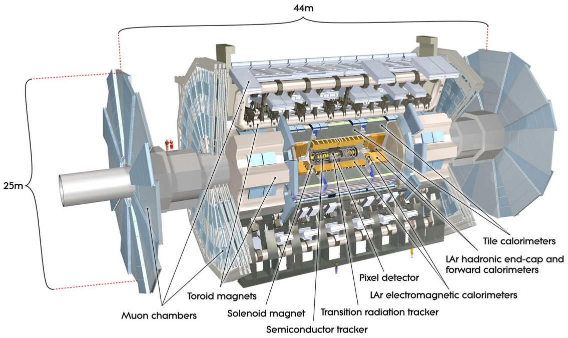
$$A = \frac{R_H^f - R_L^f}{R_H^f + R_L^f}.$$

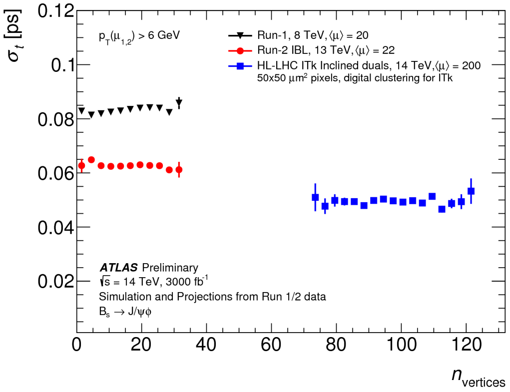
amplitudes R_L^f and R_H^f are defined via the summed decay rate of the members of the B_d^0–$\overline{B_d^0}$ system: Fleischer et al, 2011

$$\langle\Gamma(B^0(t))\rangle = \Gamma(B^0(t)) + \Gamma(\bar{B}^0(t)) = R_\mathrm{H}^f \exp\left(-\Gamma_\mathrm{H}\, t\right) + R_\mathrm{L}^f \exp\left(-\Gamma_\mathrm{L}\, t\right).$$

Using the values of y and A from Heavy Flavour Averaging group (HFLAV) Ref.HFLAV:2023, our $\tau_{B_d^0}$ value and Eq(1) allows Γ_d to be extracted.
ATLAS measured Γ_s = 0.6703±0.0014(stat.)±0.0018(syst.) ps^{-1} from $B_s^0 \to J/\psi\phi$ Eur. Phys. J. C 81 (2021) 342. This result combined with $B_d^0 \to J/\psi K^*$ allowed us to determine the ratio Γ_d/Γ_s.

ATLAS detector and feature important for this measurement



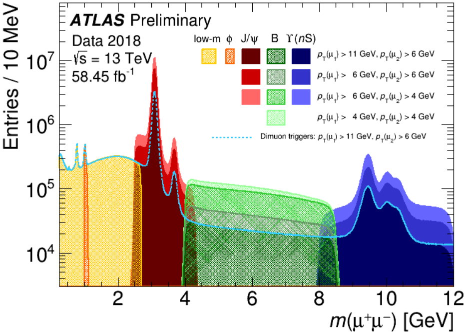


Time resolution of $B_s^0 \to J/\psi\phi$ for different numbers of reconstructed PV in the same bunch crossing ATL-PHYS-PUB-2013-010

- Inner Detector: PIX, SCT and TRT, $p_{\mathrm{T}} > 0.5\,\mathrm{GeV}$, $|\eta| < 2.5$
  - Run2: new IBL 25% improvement of time resolution with respect to Run1.
  - Time, mass resolutions remain stable within increasing pileup in Run 2
- Muon Spectrometer: triggering ($|\eta| < 2.4$), precision tracking ($|\eta| < 2.7$)

Data-taking conditions for this analysis

- The measurement uses 2015-2018 *pp* collision data at $\sqrt{s} = 13$ TeV.
- Triggers: $J/\psi \to \mu^+\mu^-$, the muon p_T thresholds varying: 4 GeV, 6 GeV and 11 GeV.
  - Low p_T thresholds were activated in the end of fills when the instantaneous luminosity decreases.
- For events accepted for this analysis, an average number of pp interactions per bunch crossing (pile-up) was 31.
- No displaced J/ψ vertex cuts applied. Trigger tracking: transverse impact parameter d0 $<$ 10mm on all tracks.



Extracting B_d^0 lifetime: Maximum-likelihood fit

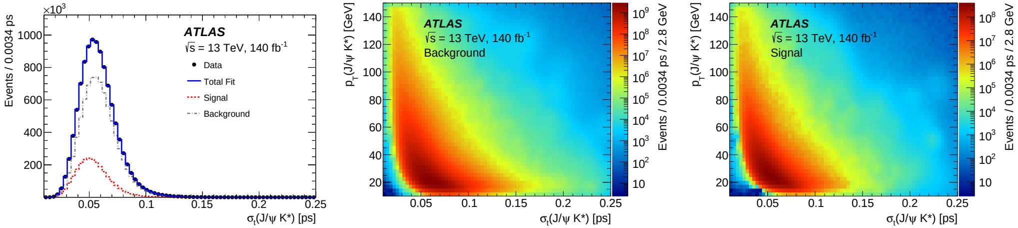
2D unbinned maximum-likelihood fit applied simultaneously to mass and proper decay time of B_d^0 candidates. Likelihood Function formula:

$$\ln L = \sum_{i=1}^{N} w(t_i) \ln[f_{\rm sig}\mathcal{M}_{\rm sig}(m_i)\mathcal{T}_{\rm sig}(t_i, \sigma_{t_i}, p_{\mathrm{T}_i}) + (1 - f_{\rm sig})\mathcal{M}_{\rm bkg}(m_i)\mathcal{T}_{\rm bkg}(t_i, \sigma_{t_i}, p_{\mathrm{T}_i})],$$

- $f_{\rm sig}$ - fraction of signal events in the total number of events, N.
- $\mathcal{M}_{\rm sig}$, $\mathcal{T}_{\rm sig}$ mass and time signal PDFs
- $\mathcal{M}_{\rm bkg}$, $\mathcal{T}_{\rm bkg}$ mass and time Backround PDFs
- The mass m_i, the proper decay time t_i, its uncertainty σ_i and the B_d^0 candidate transverse momentum $p_{\mathrm{T_i}}$ are the values measured from the data for each event i.
- Weight w_i accounts for event selection efficiency, based on MC.

- Per-candidate time errors σ_{t_i}, extracted from data in the vertex fit of each B_d^0 are used for deconvolution of proper decay times t_i.
- σ_{t_i} are different for signal and background, see fig Left. Same it true for p_{T} of B_d^0.
- To account for these differences, the 2D probability terms $C_j(\sigma_{t_i}, p_{\mathrm{T}_i})$ are introduced into Signal and Bg Time PDF terms $\mathcal{T}$. Method first used in G.Punzi

$$\mathcal{T}_j(t_i, \sigma_{t_i}, p_{\mathrm{T}_i}) = P_j(t_i, \sigma_{t_i}, p_{\mathrm{T}_i}) \cdot C_j(\sigma_{t_i}, p_{\mathrm{T}_i}), \quad (2)$$



Left: σ_{t_i} for Signal and Bg. Middle and Right: 2D probability terms $C_j(\sigma_{t_i}, p_{\mathrm{T}_i})$ for Bg. and Signal. The sPlot technique Pivk:2004ty is used to separate Signal and Bg.

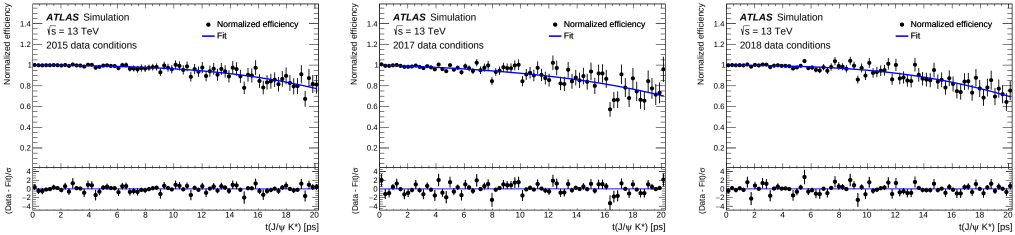
Efficiencies and corrections

- Trigger, offline reconstruction, event selections bias the reconstructed proper-decay time distribution.
- Trigger and offline tracking impose $|d_0| < 10$ mm, for all four final-state tracks of $B^0 \to J/\psi K^{*0}$, resulting in inefficiency at large times.
- Inefficiencies determined by signal MC, passed through simulation of detector response & triggers, offline tracking and event selections - as data.

Ratio of proper decay time distributions before and after the whole chain, were fitted by:

$$1/w(t_i) = p_0 \cdot [1 - p_1 \cdot (\mathrm{Erf}((t_i - p_3)/p_2) + 1)] \quad (3)$$

Erf is error function, p_0, p_1, p_2 , p_3 determined in the fit. Weights $w(t_i)$ are used to re-weight each event in Likelihood fit.



Systematic uncertainties

Source of uncertainty	Systematic uncertainty [ps]
ID alignment	0.00108
Choice of mass window	0.00104
Time efficiency	0.00130
Best-candidate selection	0.00041
Mass fit model	0.00152
Mass-time correlation	0.00229
Proper decay time fit model	0.00010
Conditional probability model	0.00070
Fit model test with pseudo-experiments	0.00002
Total	0.0035

- The statistical error of this B_d^0 lifetime measurement is 0.0012 $(\mathrm{stat.})$ ps.

Systematic uncertainties: Inner detector alignment

- ID misalignment effects: dominated by global length scale biases originating from ID geometry radial and longitudinal distortions along track trajectory.
- These manifest themselves as a shift in the reconstructed masses of known resonances, e.g. $J/\psi \to \mu^+\mu^-$ Eur. Phys. J. C 80 (2020) 1194.

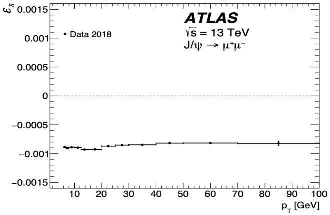
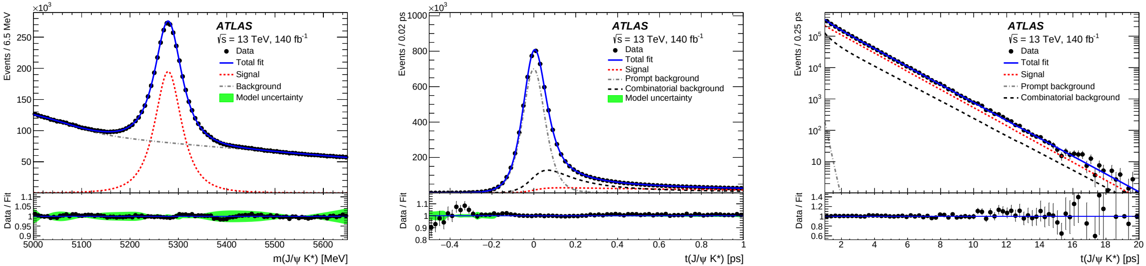


Fig showing a bias of the $J/\psi \to \mu^+\mu^-$ mass, measured as a relative difference from PDG value, as a function of a muon track p_T.

- In our analysis B_d^0 tracks are re-fitted with the J/ψ mass constrained to PDG, effectively removing the misalignment effect. The impact of misalignment - estimated by alternative fit: B_d^0 vertex re-fitted without PDG constrain.
- Additionally, to account for the momentum bias affecting hadrons from K^{*0} - their p_T are altered by -0.085% Eur. Phys. J. C 80 (2020) 1194.
- The two effects summed in quadrature, give the systematics: 0.9 σ_{stat}

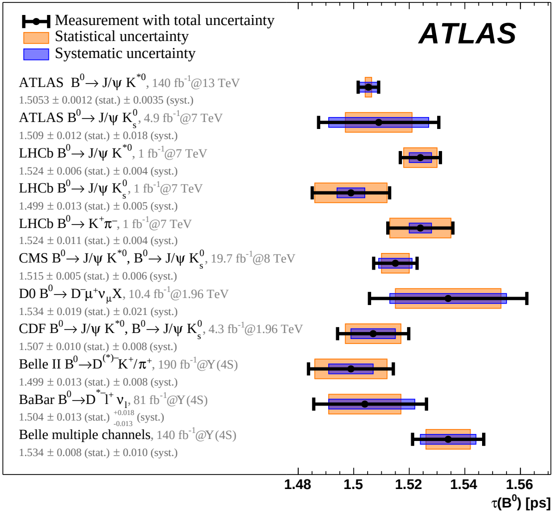
The B^0 effective lifetime value measured with a total of $2\,450\,500 \pm 2400$ $B^0 \to J/\psi K^{*0}$ signal events The measured effective lifetime is

$$\tau = 1.5053 \pm 0.0012\,(\text{stat.}) \pm 0.0035\,(\text{syst.})\ \text{ps}.$$



- Mass fit projection (left). Proper decay time fit projections in two different ranges: $(-0.5; 1.0)$ ps (Middle) and $(1; 20)$ ps (Right).
- Solid blue line - total fit, dashed red line - signal.
- The lower panels: ratio of data point to the fit value. The green band - the envelope of model variations included in the systematic uncertainty, the bars on the data points indicate statistical uncertainties. Plot -right - the model variation band too small to be visible.

A comparison ATLAS B^0 lifetime with the latest results of other experiments.



- The current ATLAS result in $B^0 \to J/\psi K^{*0}$ channel.
- The previous ATLAS result Phys. Rev. D 87 (2013) 032002 in the $B^0 \to J/\psi K^0_S$ channel.
- Latest LHCb results JHEP 04 (2014) 114 in $B^0 \to J/\psi K^{*0}$ and $B^0 \to J/\psi K^0_S$ decays and Phys. Lett. B 736 (2014) 446 in the $B^0 \to K^+\pi^-$.
- Latest CMS Eur. Phys. J. C 78 (2018) 457 combined result for $B^0 \to J/\psi K^{*0}$ and $B^0 \to J/\psi K^0_S$ decays.
- Tevatron experiments: D0 Phys. Rev. Lett. 114 (2015) 062001 in the $B^0 \to D^-\mu^+\nu_\mu$ channel, and CDF Phys. Rev. Lett. 106 (2011) 121804 with a combined result for $B^0 \to J/\psi K^{*0}$ and $B^0 \to J/\psi K^0_S$.
- e^+e^- colliders: Belle II Phys. Rev. D 107 (2023) L091102 in the $B^0 \to D^{(*)-}K^+/\pi^+$ channel and the last result from BaBar Phys. Rev. D 73 (2006) 012004 in the $B^0 \to D^{*+}\ell^-\bar{\nu}_\ell$. Belle PhysRevD.71.07990, 2005 this combination includes B^0_d decays to $D^{*-}\ell^+\nu$, $D^{*-}\pi^+$, $D^-\pi^+$, $D^{*-}\rho^+$, $J/\psi K^{*0}$, $J/\psi K^0_S$.

Results: Determination of the B_d^0 average decay width Γ_d and the ratio Γ_d/Γ_s

Γ_d

- We determine Γ_d from our measured effective lifetime τ_{B^0}, using Eq (1) and input values $2y = \Delta\Gamma_d/\Gamma_d = 0.001 \pm 0.010$ and asymmetry $A = -0.578 \pm 0.136$ from HFLAV:2023:

$$\Gamma_d = 0.6639 \pm 0.0005\,(\text{stat.}) \pm 0.0016\,(\text{syst.}) \pm 0.0038\,(\text{ext.})\ \text{ps}^{-1}$$

  The uncertainty denoted 'ext.' originates from the HFLAV.
- The value Γ_d is in agreement with HQE theory of $0.63^{+0.11}_{-0.07}\ \text{ps}^{-1}$ Lenz et al. 2023

Γ_d/Γ_s

- Using $\Gamma_s = 0.6703 \pm 0.0014\,(\text{stat.}) \pm 0.0018\,(\text{syst.})\ \text{ps}^{-1}$ measured by the ATLAS Eur. Phys. J. C 81 (2021) 342 the resulting Γ_d/Γ_s ratio is

$$\Gamma_d/\Gamma_s = 0.9905 \pm 0.0022\,(\text{stat.}) \pm 0.0036\,(\text{syst.}) \pm 0.0057\,(\text{ext.})$$

- The statistical, systematic and external uncertainties are propagated from the quantities above. In Γ_d/Γ_s - systematic uncertainties of the ATLAS measurements of τ_{B^0} and Γ_s primarily come from different sources. They are therefore treated as uncorrelated.
- Γ_d/Γ_s agrees with theory HQE and lattice QCD models prediction.

- ATLAS preformed a measurement of B_d^0 effective lifetime and the average decay width Γ_d using $B^0 \to J/\psi K^{*0}$ events reconstructed from a 140 fb^{-1} data sample of pp collisions collected with the ATLAS detector during the $\sqrt{s}$=13 TeV LHC run.
- The B^0 effective lifetime is measured to be $1.5053 \pm 0.0012(\text{stat}) \pm 0.0035(\text{syst})$ ps. This results is compatible with other experimental measurements and is the most precise measurement to date.
- The measured average decay width of the heavy and light B^0 mass eigenstates is $\Gamma_d = 0.6639 \pm 0.0005\ (\text{stat.}) \pm 0.0016\ (\text{syst.}) \pm 0.0038\ (\text{ext.})\ \text{ps}^{-1}$ This value is in good agreement with the theory prediction.
- The measured average decay width Γ_d is combined with the average decay width Γ_s measured previously by ATLAS to obtain the ratio $\Gamma_d/\Gamma_s = 0.9905 \pm 0.0022\ (\text{stat.}) \pm 0.0036\ (\text{syst.}) \pm 0.0057\ (\text{ext.})$ This result is compatible with the theory predictions from HQE and lattice QCD calculations as well as with the experimental average.

Backup Slides - 1 More details on $B^0 \to J/\psi K^{*0}$ ATLAS analysis

Event reconstruction and selection

$B^0 \rightarrow J/\psi K^{*0}$ candidates

- At least one $J/\psi \rightarrow \mu^+\mu^-$ with χ^2ndof < 10; within mass window retaining 99.7% J/ψ candidates.
- K^*: Out of two hypothesis $K^+\pi^-$ / $K^-\pi^+$ the one closer to K^* PDG mass selected.
- J/ψ and K^* - fitted to a common vertex, constrained by fixing di-muon mass to J/ψ PDG. Only χ^2/ndof $<$3 retained.
- 10% events have multiple $J/\psi K^*$ candidates (in average 2.1); the one with smallest χ^2/ndof selected.

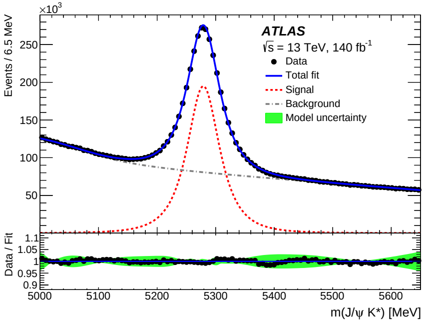
Primary vertex (PV) selection

- For selected events the average pileup is 31: need to choose the best PV candidate where B_d^0 is produced.
- PV positions are recalculated after removing any tracks used in the B_d^0.
- The PV candidate with the smallest 3D impact parameter, a_0 (min. distance between PV and the line extrapolated from the B_d^0 vertex in B_d^0 momentum direction), is used.

For each B_d^0 candidate, the proper decay time t is determined:

$$t = \frac{L_{xy}\ m_B}{p_{\mathrm{T}_B}}, \quad (4)$$

p_{T_B} is transverse momentum of m_B = PDG B_d^0 mass. The transverse decay length, L_{xy}, is the distance in the transverse plane from PV to the B_d^0 decay vertex, projected onto p_{T_B}.



Signal mass is modelled with a Johnson S_U-distribution Johnson

$$\mathcal{M}_{\text{sig}}(m_i) = \frac{\delta}{\lambda\sqrt{2\pi}\sqrt{1+\left(\frac{m_i-\mu}{\lambda}\right)^2}} \exp\left[-\frac{1}{2}\left(\gamma + \delta \sinh^{-1}\left(\frac{m_i-\mu}{\lambda}\right)\right)^2\right]$$

where μ, γ, δ and λ are free parameters of fit.

Background has two components: 1. prompt - J/ψ produced in $\mathrm{pp} \to \mathrm{J}/\psi\mathrm{X}$, combined with random K^*. 2. combinatorial - J/ψ from any b-hadron decay combined with random K^*. They are modelled by sum of linear and sigmoid functions:

$$\mathcal{M}_{\text{bkg}}(m_i) = f_{\text{poly}}(1 + p_0 \cdot m_i) + (1 - f_{\text{poly}})\left(1 - \frac{s(m_i - m_0)}{\sqrt{1 + (s(m_i - m_0))^2}}\right)$$

where f_{poly} relative size of the two components and m_0, s and p_0 are parameters of the fit.

Signal PDF: exponential function convolved by Resolution function *R*.

$$P_{\mathrm{sig}}(t_i|\sigma_{t_i}, p_{\mathrm{T}_i}) = E(t', \tau_{B^0}) \otimes R(t' - t_i, \sigma_{t_i})$$

$E(t', \tau_{B^0}) = (1/\tau_{B^0}) \exp(-t'/\tau_{B^0})$ for $t' \geq 0$, with τ_{B^0} - the fitted B_d^0 lifetime.

Background PDF:

$$P_{\mathrm{bkg}}(t_i|\sigma_{t_i}, p_{\mathrm{T}_i}) = \left(f_{\mathrm{prompt}} \cdot \delta_{\mathrm{Dirac}}(t') + (1 - f_{\mathrm{prompt}}) \sum_{k=1}^{3} b_k \prod_{l=1}^{k-1} (1 - b_l) E(t', \tau_{\mathrm{bkg}_k}) \right) \otimes R(t' - t_i, \sigma_{t_i})$$

Dirac function δ_{Dirac}: direct background; 3 exponentials $E(t', \tau_{\mathrm{bkg}_k})$: components of combinatorial background; τ_{bkg_k}, and fractions: f_{prompt} and b_k are free parameters of fit.

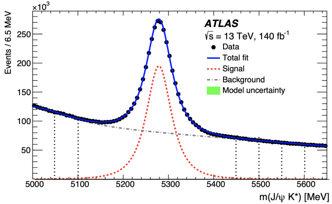
Resolution function *R*: modelled as a sum of three Gaussian distributions with widths: $S^{(k)} \sigma_{\tau_i}$

$$R(t' - t_i, \sigma_{t_i}) = \sum_{k=1}^{3} f_{\mathrm{res}}^{(k)} \frac{1}{\sqrt{2\pi}\, S^{(k)} \sigma_{t_i}} \exp\left(\frac{-(t' - t_i)^2}{2(S^{(k)} \sigma_{t_i})^2} \right)$$

three $f_{res}^{(k)}$ fractions and scale factors $S^{(k)}$ are free parameters of fit, σ_{τ_i} is the per-candidate time error, extracted from data in the vertex fit of each $B^0 \to J/\psi K^{*0}$.

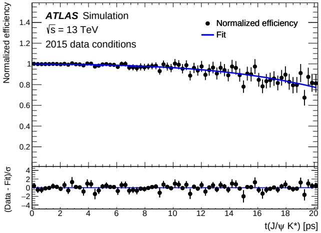
Systematic uncertainties: Mass-time correlation systematics

- Correlations between the invariant mass and the pseudo-proper decay time, and their potential impact on the fit results, are studied.
- No mass-time correlation in signal PDF proven by MC.
- For background the correlations are studied in data. First, applying the default time Background PDF $P_{\rm bkg}(t_i, \sigma_i, p_{{\rm T}_i})$ fit in each of the 6 mass sideband bins in data. Fractions $f_{\rm prompt}$ and b_1, b_2 determined in each bin were then fitted to extract their dependence on mass. The best description - achieved by linear functions.



- Based on this information, an alternative fit model, in which the background PDF term $P_{\rm bkg}(t_i, \sigma_i, p_{{\rm T}_i})$ is constructed with the parameters accounting for mass-dependence:
  $f_{\rm prompt}(m_i) = a + b(m_i - 5.279\ \text{GeV})$, $b_1(m_i) = c_1 + d_1(m_i - 5.279\ \text{GeV})$ and
  $b_2(m_i) = c_2 + d_2(m_i - 5.279\ \text{GeV})$. a, b, c_1, d_1, c_2 and d_2 are free parameters of the fit. A difference of lifetime w.r.t default fit is 0.00228 ps (1.9 σ)

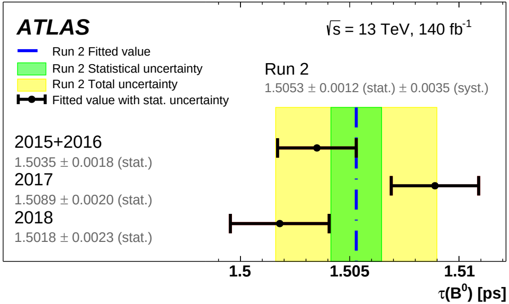
Time efficiency correction systematics



- Two alternative functions fitting the time efficiency histogram, replacing the default error function, were: hyperbolic tangent function or $(x^2+1)^{-1/2}$. The larger of the changes in the fitted lifetime, of size $0.5\sigma_{\mathrm{stat}}$ - taken as a systematic uncertainty.
- Systematic effects due to limited MC statistic, used to build the time efficiency histogram, was estimated by repeating the fit with a large number of alternative time efficiency functions, obtained by smearing the number of MC events in the time bins, leading to $0.5\sigma_{\mathrm{stat}}$.
- An alternative fit using data events with $t < 8$ ps, is performed to validate the modelling of the efficiency for high lifetimes, where the efficiency decrease is large, lead to small systematics $0.5\sigma_{\mathrm{stat}}$.

Results: A consistency and stability test over data taking periods

As a consistency and stability test, the B^0 lifetime value was fitted separately for each data-taking period (2015+2016, 2017 and 2018). Figure shows the degree of stability over time. The *p*-value for consistency of the three individual results, accounting for just statistical uncertainties is 0.038.



The fitted values of the B^0 lifetime, measured with $B^0 \rightarrow J/\psi K^{*0}$ decays, for the 2015+2016, 2017 and 2018 subsamples compared to the value for the whole sample. The B^0 lifetime value for each subsample is shown by a black point, with the error bar indicating the statistical uncertainty.

Backup slides - 2 Other B lifetimes measured in ATLAS

Earlier ATLAS B-hadron lifetime measurements

- Measurement of effective lifetime in $B^0_{(s)} \to \mu^+\mu^-$
  JHEP 09 (2023) 199 W
- Measurement of Λ^0_b lifetime in $\Lambda^0_b \to J/\psi\Lambda^0$ and B^0_d lifetime in $B^0_d \to J/\psi K^0_S$ decays
  PhysRevD.87.032002, 2013
- Measurement of the relative width difference $\Delta\Gamma_d/\Gamma_d$ of the B^0_d-$\overline{B^0_d}$ system with the ATLAS detector
  JHEP06(2016)081
- Measurement of the CP-violating phase, the width difference $\Delta\Gamma_s$ between the meson mass eigenstates and the average decay width Γ_s in the $B_s \to J/\psi\phi$ decay.
  Eur. Phys. J. C 81 (2021) 342

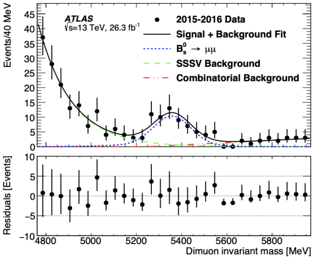
- In Standard Model (SM) only the *CP*-odd heavy-mass eigenstate in the $B_s^0 - \bar{B}_s^0$ pair decays into $\mu^+\mu^-$ M. Beneke JHEP 10 (2019) 232 and errata JHEP 11 (2022) 099.
- Beyond the Standard Model (BSM) such as minimal supersymmetric Standard Model extensions D. M. Straub Il Nuovo Cimento C 35 (2012) 249 can potentially perturb the effective lifetime in $B_{(s)}^0 \to \mu^+\mu^-$ decays. These perturbations can be significant also in absence of measurable BSM effects on the $B_{(s)}^0 \to \mu^+\mu^-$ branching fraction (BR).
- The effective $B_{(s)}^0 \to \mu^+\mu^-$ lifetime is defined as

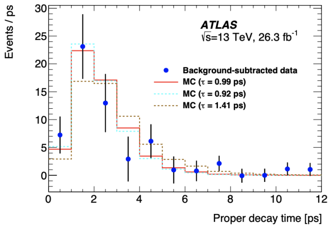
$$\tau_{\mu\mu} = \frac{\int_0^\infty t\Gamma(B_s^0(t)\to\mu\mu)\,dt}{\int_0^\infty \Gamma(B_s^0(t)\to\mu\mu)\,dt},\ \text{where: } \Gamma\left(B_s\left(t\right) \to \mu\mu\right) = \Gamma\left(B_s^0\left(t\right) \to \mu\mu\right) + \Gamma\left(\bar{B}_s^0\left(t\right) \to \mu\mu\right)$$

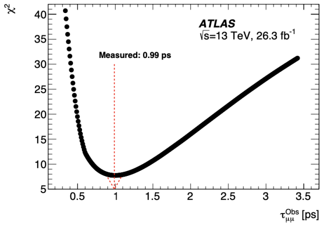
  and t is the proper decay time of the B_s^0 and $\bar{B}_s^0$ mesons.
- In the SM hypothesis $\tau_{\mu\mu}$ coincides with the lifetime of the heavy B_s^0 eigenstate $\tau_{B_s^H}$.
- The experimental average of the B_s^0 - $\bar{B}_s^0$ lifetimes and their difference Phys. Rev. D 107 (2023) 052008 yields the prediction $\tau_{\mu\mu}^{SM} = (1.624 \pm 0.009)$ ps, with new physics effects perturbing it at most by the difference between the heavy and light eigenstate lifetimes (0.193 ps).

Measurement of effective lifetime in $B^0_{(s)} \to \mu^+\mu^-$, cont 1

- Data from 2015-2016 are used in this measurement.
- Un-binned maximum likelihood fit to candidates in the [4766 – 5966] MeV mass region (Left Fig) , yielding 58 ± 13 (stat. only) $B^0_{(s)} \to \mu^+\mu^-$ signal events.
- Signal and backgrounds weights calculated from the result of the mass fit are used to construct the proper decay time data histogram - background-subtracted employing per-event weights calculated according to the *sPlot* technique (Middle Fig).
- The lifetime measurement is obtained by minimising the binned χ^2 between the data histogram and lifetime-dependent pure signal MC templates extracted from MC simulated samples, as illustrated in the Middle and Right Fig.







- The statistical uncertainty is derived from the Neyman CL band construction Figure Left. The χ^2 minimum and the Neyman belt construction yield $\tau_{\mu\mu} = 0.99^{+0.42}_{-0.07}$ (stat) ps. The imbalance between positive and negative statistical uncertainties is already suggested by the asymmetry in the χ^2 scan.
- The systematic errors are dominated by data-MC discrepancies, followed by uncertainties in backgrounds lifetime modelling.
- The result using 2015-2016 data is $\tau_{\mu\mu} = 0.99^{+0.42}_{-0.07}$ (stat.) $\pm$ 0.17 (syst.) ps. It is consistent with the SM prediction $\tau^{SM}_{\mu\mu} = (1.624 \pm 0.009)$ ps Phys. Rev. D 107 (2023) 052008 as well as with the other available experimental results.