CP violation in $B_s \to J/\psi\phi$ in ATLAS using 80.5 fb^{-1} of Run 2 data

Maria Smizanska
on behalf of the ATLAS collaboration

Lancaster University

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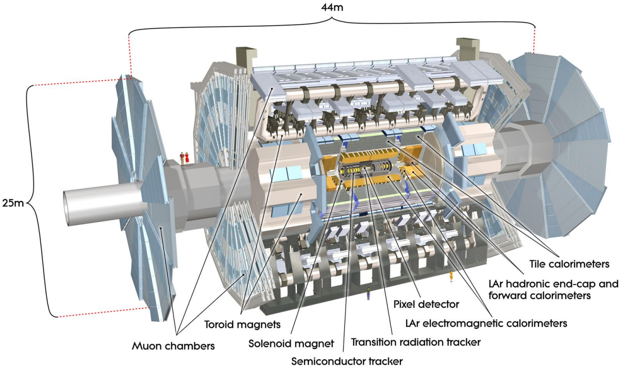
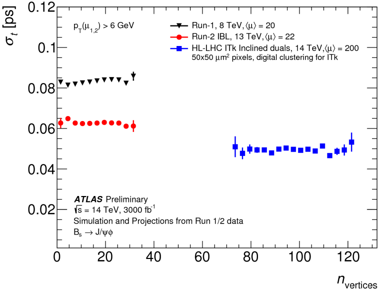
Motivation

- $B_s^0 \to J/\psi\phi$ is used to measure CP-violation phase ϕ_s potentially sensitive to New Physics
- In SM ϕ_s is related to the CKM elements $\phi_s \simeq 2\arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$ and predicted with high precision
  - $\phi_s = -0.03696^{+0.00072}_{-0.00082}$ rad by CKMFitter group PhysRevD.91.073007
  - $\phi_s = -0.03700 \pm 0.00104$ rad according to UTfit Collaboration arXiv: hep-ph/0606167 [hep-ph].
- After LHC Run1 a combined : $\phi_s = -0.021 \pm 0.031$ rad - a precision of SM was 30 times better - still room for New physics
- LHC Run2 results needed to tighten the ϕ_s value
- ATLAS results presented here are based on 80.5 fb^{-1} of 13 TeV pp collision data from 2015-2017 and Statistically combined with Run1
- Other quantity related to B_s^0 mixing extracted along with ϕ_s is $\Delta\Gamma_s = \Gamma_s^L - \Gamma_s^H$, where Γ_s^L and Γ_s^H are the decay widths of the different mass eigenstates. $\Delta\Gamma_s$ is not sensitive to New Physics, however measurement is interesting to test a theory.

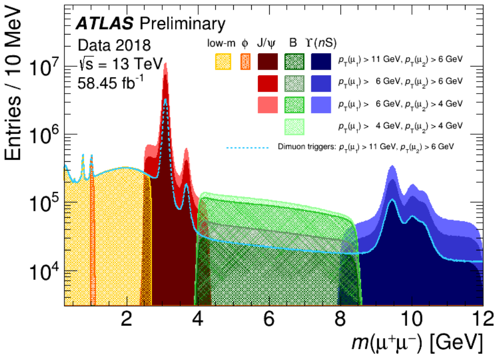




- Inner Detector: PIX, SCT and TRT, $p_{\mathrm{T}} > 0.4\,\mathrm{GeV}$, $|\eta| < 2.5$
  - Run2: new IBL 25% improvement of time resolution with respect to Run1.
  - time resolution remains stable within increasing pileup in Run 2
- Muon Spectrometer: triggering ($|\eta| < 2.4$), precision tracking ($|\eta| < 2.7$)

Trigger system

- Events collected with mixture of triggers based on $J/\psi \to \mu^+\mu^-$ identification, with muon p_{T} thresholds of either 4 GeV or 6 GeV (vary over run periods)
- No lifetime or impact parameter cut at HLT level



Data and Monte Carlo simulation samples

Data:

- $80.5\,\text{fb}^{-1}$ of 13 TeV pp collision data from 2015-2017
- Statistically combined with Run1 ATLAS results:
  - $4.9\,\text{fb}^{-1}$ (7 TeV, pp 2011)
  - $14.3\,\text{fb}^{-1}$ (8 TeV, pp 2012)

MC samples:

- Signal $B_s^0 \to J/\psi\phi$ MC events
- MC samples for peaking backgrounds $B_d^0 \to J/\psi K^{*0}$, $B_d^0 \to J/\psi K\pi$, $\Lambda_b^0 \to J/\psi Kp$
- MC samples for tagging calibration channel $B^{\pm} \to J/\psi K^{\pm}$
  (systematics and cross-checks only, real data used for calibration)

Reconstruction and candidate selection

Event:

- Triggers (previous slide) and good quality data
- At least one PV formed from at least 4 ID tracks
- At least one pair of ID+MS identified $\mu^+\mu^-$

$J/\psi \to \mu^+\mu^-$

- Dimuon vertex fit $\chi^2/d.o.f. < 10$
- Three dimuon invariant mass windows for BB/BE/EE (barrel, endcap) muon combinations

$\phi \to K^+K^-$

- $p_T(K) > 1$ GeV
- $1008.5\,\text{MeV} < m(KK) < 1030.5\,\text{MeV}$

$B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$

- $p_T(B_s^0) > 10$ GeV
- Four-track vertex fit $\chi^2/d.o.f. < 3$ (J/ψ mass constrained)
- Keep only the candidate with best vertex fit $\chi^2/d.o.f.$ in event
- $5150\,\text{MeV} < m(B_s^0) < 5650\,\text{MeV} \to$ in total 3 210 429 B_s^0 candidates

- $B_s^0 \to J/\psi\phi$ = 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 $B_s^0 \to J/\psi K^+K^-$ 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

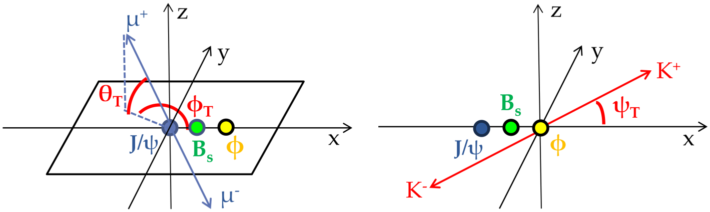


Figure: Angles between final state particles in transversity basis.

Mass-lifetime-angular fit

We perform unbinned maximum likelihood fit simultaneously for B_s^0 mass, decay time and the decay angles:

$$
\begin{aligned}
\ln\ \mathcal{L} = \sum_{i=1}^{N} \{ & w_i \cdot \ln(f_s \cdot \mathcal{F}_s(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), p_{T_i}) \\
& + f_s \cdot f_{B_d^0} \cdot \mathcal{F}_{B_d^0}(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), p_{T_i}) \\
& + f_s \cdot f_{\Lambda_b} \cdot \mathcal{F}_{\Lambda_b}(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), p_{T_i}) \\
& + (1 - f_s \cdot (1 + f_{B_d^0} + f_{\Lambda_b})) \cdot \mathcal{F}_{\rm bkg}(m_i, t_i, \sigma_m, \sigma_t, \Omega_i, P(B|Q), p_{T_i}))\}
\end{aligned}
$$

Physics parameters

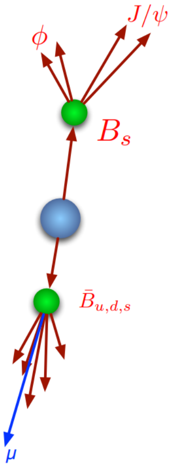
- CPV phase ϕ_s
- Decay widths: $\Delta\Gamma_s$, Γ_s
- Decay amplitudes: $|A_0(0)|^2$, $|A_{||}(0)|^2$, $\delta_{||}$, $\delta_{\perp}$
- S-wave: $|A_S(0)|^2$, δ_S
- Δm_s fixed to PDG

Observables

- Basic observables : m_i, t_i, Ω_i
- Conditional observables per-candidate:
  - resolutions: σ_{m_i}, σ_{t_i}
  - tagging probability and method: $P(B|Q)$

Flavour tagging

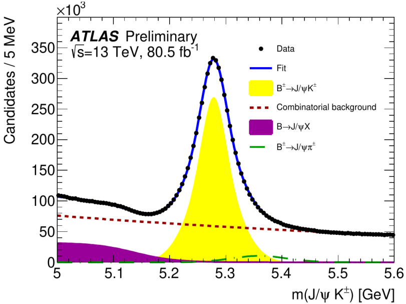
- Opposite side tagging
  - Use $b - \bar{b}$ pair correlation to infer initial signal flavour from the other B meson
  - Provide the probability of signal candidate to be B_s^0 or $\overline{B}_s^0$ at production
- Muon and Electron Tagging
  - $b \rightarrow l$ transitions are clean tagging method
  - $b \rightarrow c \rightarrow l$ and neutral B-meson oscillations dilute the tagging
- Jet-Charge
  - information from tracks in b-tagged jet, when no lepton is found
- Calibration using $B^{\pm} \rightarrow J/\psi K^{\pm}$ data



Tag calibration

Calibration using $B^{\pm} \to J/\psi K^{\pm}$ events (real data)

- self tagging non oscillating channel
- Di-muon candidates in range $2.8 < m(\mu\mu) < 3.4$ GeV
- $p_{\mathrm{T}}(\mu) > 4$ GeV, $p_{\mathrm{T}}(K^{\pm}) > 1$ GeV
- Invariant mass in range $5.0 < m(\mu\mu K^{\pm}) < 5.6$ GeV
- $\tau(B) > 0.2$ ps - to reduce prompt component of the combinatorial background



- Opposite side lepton or jet, with tracks in cone $\Delta R < 0.5$

$$Q = \frac{\sum_i^{N_tracks} q^i (p_{\mathrm{T}}^i)^{\kappa}}{\sum_i^{N_tracks} q^i (p_{\mathrm{T}}^i)^{\kappa}} \to P(Q|B^{\pm}) \qquad Q \in < -1; 1 >$$

Tagging performance

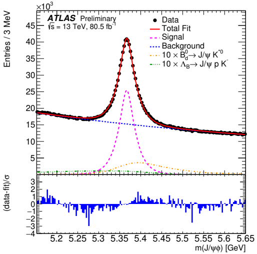
Tag method	Efficiency [%]	Effective Dilution [%]	Tagging Power [%]
Tight muon	4.50 ± 0.01	43.8 ± 0.2	0.862 ± 0.009
Electron	1.57 ± 0.01	41.8 ± 0.2	0.274 ± 0.004
Low-p_T muon	3.12 ± 0.01	29.9 ± 0.2	0.278 ± 0.006
Jet	5.54 ± 0.01	20.4 ± 0.1	0.231 ± 0.005
Total	14.74 ± 0.02	33.4 ± 0.1	1.65 ± 0.01

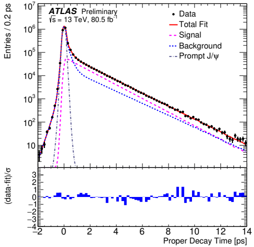
- **Efficiency**: Fraction of signals with specific tagger, $\varepsilon = \frac{N_{\text{tagged}}}{N_{\text{Bcand}}}$
- **Dilution**: $D = (1 - 2w)$, where w is the miss-tag probability
- **Tagging Power**: figure of merit of tagger performance
  - Depends on dilution and efficiency:

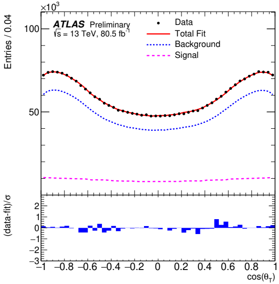
$$TP = \varepsilon D^2 = \varepsilon(1 - 2w)^2$$

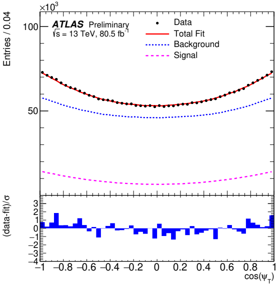
Projection and results of the mass-lifetime-angular fit

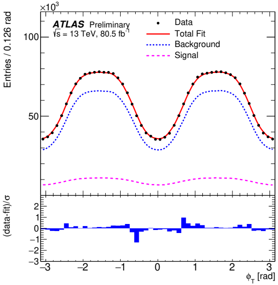
Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s[rad]	−0.068	0.038	0.018
$\Delta\Gamma_s$[ps^{-1}]	0.067	0.005	0.002
Γ_s[ps^{-1}]	0.669	0.001	0.001
$\|A_{\|\|}(0)\|^2$	0.219	0.002	0.002
$\|A_0(0)\|^2$	0.517	0.001	0.004
$\|A_S(0)\|^2$	0.046	0.003	0.004
$\delta_\perp$ [rad]	2.946	0.101	0.097
$\delta_{\|\|}$ [rad]	3.267	0.082	0.201
$\delta_\perp - \delta_S$ [rad]	−0.220	0.037	0.010







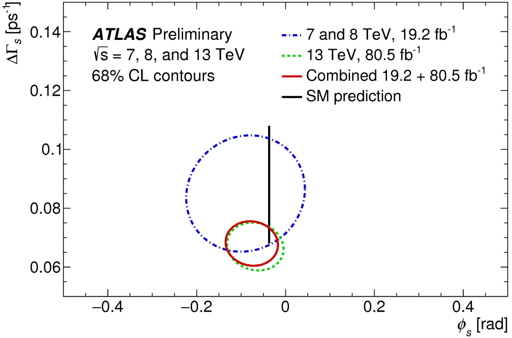




Combination of the results with the previous from Run 1

- A Best Linear Unbiased Estimate (BLUE) combination is performed to combine the current result with the Run 1 measurement
- The BLUE combination uses the measured values and uncertainties of the parameters as well as the correlations between them

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s[rad]	–0.076	0.034	0.019
$\Delta\Gamma_s$[ps^{-1}]	0.068	0.004	0.003
Γ_s[ps^{-1}]	0.669	0.001	0.001
$\lvert A_{\parallel}(0)\rvert^2$	0.220	0.002	0.002
$\lvert A_0(0)\rvert^2$	0.517	0.001	0.004
$\lvert A_S\rvert^2$	0.043	0.004	0.004
$\delta_\perp$ [rad]	3.075	0.096	0.091
$\delta_\parallel$ [rad]	3.295	0.079	0.202
$\delta_\perp - \delta_S$ [rad]	–0.216	0.037	0.010



Summary

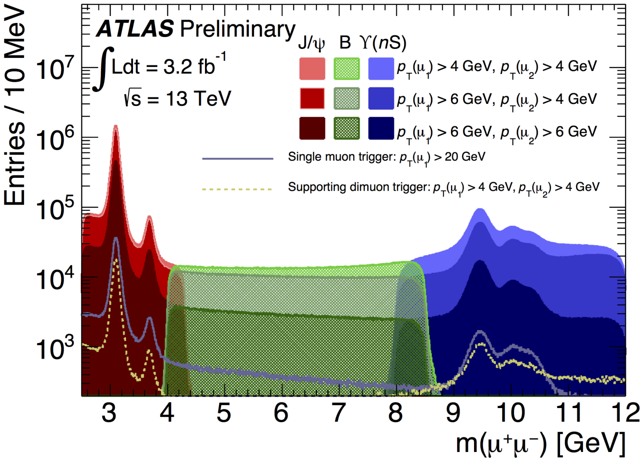
- Analysis of the 2015+2016+2017 ATLAS data performed
- Results combined with Run1 results
- Compatible with LHCb and CMS and the SM prediction
- Complete Run2 analysis ongoing (60 fb^{-1} more data)
- Overview of latest LHC results on ϕ_s

$B_s \rightarrow J/\psi KK$	ϕ_s [rads]
LHCb 4.9 fb^{-1} combined with 3 other channels, Eur. Phys. J. C (2019) 79	-0.041 ± 0.025
CMS 96.4 fb^{-1} Run2 combined with Run1, CMS-PAS-BPH-20-001	-0.021 ± 0.045
ATLAS 80.5 fb^{-1} combined with Run1, arXiv: 2001.07115 [hep-ex]	$-0.076 \pm 0.034(\textit{stat}) \pm 0.019(\textit{syst})$

Backup Slides

Full likelihood function

k	$\mathcal{O}^{(k)}(t)$	$g^{(k)}(\theta_T, \psi_T, \phi_T)$
1	$\frac{1}{2}\|A_0(0)\|^2 \left[(1+\cos\phi_s)\, e^{-\Gamma_{\mathrm{L}}^{(s)}t} + (1-\cos\phi_s)\, e^{-\Gamma_{\mathrm{H}}^{(s)}t} \pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$2\cos^2\psi_T(1-\sin^2\theta_T\cos^2\phi_T)$
2	$\frac{1}{2}\|A_\parallel(0)\|^2 \left[(1+\cos\phi_s)\, e^{-\Gamma_{\mathrm{L}}^{(s)}t} + (1-\cos\phi_s)\, e^{-\Gamma_{\mathrm{H}}^{(s)}t} \pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\sin^2\psi_T(1-\sin^2\theta_T\sin^2\phi_T)$
3	$\frac{1}{2}\|A_\perp(0)\|^2 \left[(1-\cos\phi_s)\, e^{-\Gamma_{\mathrm{L}}^{(s)}t} + (1+\cos\phi_s)\, e^{-\Gamma_{\mathrm{H}}^{(s)}t} \mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\sin^2\psi_T\sin^2\theta_T$
4	$\frac{1}{2}\|A_0(0)\|\|A_\parallel(0)\|\cos\delta_\parallel \left[(1+\cos\phi_s)\, e^{-\Gamma_{\mathrm{L}}^{(s)}t} + (1-\cos\phi_s)\, e^{-\Gamma_{\mathrm{H}}^{(s)}t} \pm 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin^2\theta_T\sin 2\phi_T$
5	$\|A_\parallel(0)\|\|A_\perp(0)\|[\frac{1}{2}(e^{-\Gamma_{\mathrm{L}}^{(s)}t} - e^{-\Gamma_{\mathrm{H}}^{(s)}t})\cos(\delta_\perp-\delta_\parallel)\sin\phi_s \pm e^{-\Gamma_s t}(\sin(\delta_\perp-\delta_\parallel)\cos(\Delta m_s t) - \cos(\delta_\perp-\delta_\parallel)\cos\phi_s\sin(\Delta m_s t))]$	$-\sin^2\psi_T\sin 2\theta_T\sin\phi_T$
6	$\|A_0(0)\|\|A_\perp(0)\|[\frac{1}{2}(e^{-\Gamma_{\mathrm{L}}^{(s)}t} - e^{-\Gamma_{\mathrm{H}}^{(s)}t})\cos\delta_\perp\sin\phi_s \pm e^{-\Gamma_s t}(\sin\delta_\perp\cos(\Delta m_s t) - \cos\delta_\perp\cos\phi_s\sin(\Delta m_s t))]$	$\frac{1}{\sqrt{2}}\sin 2\psi_T\sin 2\theta_T\cos\phi_T$
7	$\frac{1}{2}\|A_S(0)\|^2 \left[(1-\cos\phi_s)\, e^{-\Gamma_{\mathrm{L}}^{(s)}t} + (1+\cos\phi_s)\, e^{-\Gamma_{\mathrm{H}}^{(s)}t} \mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\frac{2}{3}\left(1-\sin^2\theta_T\cos^2\phi_T\right)$
8	$\alpha\|A_S(0)\|\|A_\parallel(0)\|[\frac{1}{2}(e^{-\Gamma_{\mathrm{L}}^{(s)}t} - e^{-\Gamma_{\mathrm{H}}^{(s)}t})\sin(\delta_\parallel-\delta_S)\sin\phi_s \pm e^{-\Gamma_s t}(\cos(\delta_\parallel-\delta_S)\cos(\Delta m_s t) - \sin(\delta_\parallel-\delta_S)\cos\phi_s\sin(\Delta m_s t))]$	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin^2\theta_T\sin 2\phi_T$
9	$\frac{1}{2}\alpha\|A_S(0)\|\|A_\perp(0)\|\sin(\delta_\perp-\delta_S) \left[(1-\cos\phi_s)\, e^{-\Gamma_{\mathrm{L}}^{(s)}t} + (1+\cos\phi_s)\, e^{-\Gamma_{\mathrm{H}}^{(s)}t} \mp 2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s\right]$	$\frac{1}{3}\sqrt{6}\sin\psi_T\sin 2\theta_T\cos\phi_T$
10	$\alpha\|A_0(0)\|\|A_S(0)\|[\frac{1}{2}(e^{-\Gamma_{\mathrm{H}}^{(s)}t} - e^{-\Gamma_{\mathrm{L}}^{(s)}t})\sin\delta_S\sin\phi_s \pm e^{-\Gamma_s t}(\cos\delta_S\cos(\Delta m_s t) + \sin\delta_S\cos\phi_s\sin(\Delta m_s t))]$	$\frac{4}{3}\sqrt{3}\cos\psi_T\left(1-\sin^2\theta_T\cos^2\phi_T\right)$


ATLAS Preliminary
∫Ldt = 3.2 fb^-1
√s = 13 TeV
J/ψ B ϒ(nS)
pT(μ1) > 4 GeV, pT(μ2) > 4 GeV
pT(μ1) > 6 GeV, pT(μ2) > 4 GeV
pT(μ1) > 6 GeV, pT(μ2) > 6 GeV
Single muon trigger: pT(μ1) > 20 GeV
Supporting dimuon trigger: pT(μ1) > 4 GeV, pT(μ2) > 4 GeV
Entries / 10 MeV
10^7
10^6
10^5
10^4
10^3
3 4 5 6 7 8 9 10 11 12
m(μ+μ−) [GeV]

Systematic uncertainties

- Systematics assumed uncorrelated → Total = $\sqrt{\sum_i \mathrm{syst}_i^2}$
- Tagging systematics dominant for ϕ_s
  - Accounting for pile-up dependence, calibration curves model and MC precision, "Punzi" PDFs variations, difference between $B^{\pm}$ and B_s^0 kinematics
- Fit-model time resolution systematics dominant for Γ_s and $\Delta\Gamma_s$

	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	1.7×10^{-2}	0.4×10^{-3}	0.3×10^{-3}	0.2×10^{-3}	0.2×10^{-3}	2.3×10^{-3}	1.9×10^{-2}	2.2×10^{-2}	2.2×10^{-3}
Acceptance	0.7×10^{-3}	$<10^{-4}$	$<10^{-4}$	0.8×10^{-3}	0.7×10^{-3}	2.4×10^{-3}	3.3×10^{-2}	1.4×10^{-2}	2.6×10^{-3}
ID alignment	0.7×10^{-3}	0.1×10^{-3}	0.5×10^{-3}	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$	1.0×10^{-2}	7.2×10^{-3}	$<10^{-4}$
S–wave phase	0.2×10^{-3}	$<10^{-4}$	$<10^{-4}$	0.3×10^{-3}	$<10^{-4}$	0.3×10^{-3}	1.1×10^{-2}	2.1×10^{-2}	8.3×10^{-3}
Background angles model:									
Choice of fit function	1.8×10^{-3}	0.8×10^{-3}	$<10^{-4}$	1.4×10^{-3}	0.7×10^{-3}	0.2×10^{-3}	8.5×10^{-2}	1.9×10^{-1}	1.8×10^{-3}
Choice of p_T bins	1.3×10^{-3}	0.5×10^{-3}	$<10^{-4}$	0.4×10^{-3}	0.5×10^{-3}	1.2×10^{-3}	1.5×10^{-3}	7.2×10^{-3}	1.0×10^{-3}
Choice of mass interval	0.4×10^{-3}	0.1×10^{-3}	0.1×10^{-3}	0.3×10^{-3}	0.3×10^{-3}	1.3×10^{-3}	4.4×10^{-3}	7.4×10^{-3}	2.3×10^{-3}
Dedicated backgrounds:									
B_d^0	2.3×10^{-3}	1.1×10^{-3}	$<10^{-4}$	0.2×10^{-3}	3.1×10^{-3}	1.4×10^{-3}	1.0×10^{-2}	2.3×10^{-2}	2.1×10^{-3}
Λ_b	1.6×10^{-3}	0.4×10^{-3}	0.2×10^{-3}	0.5×10^{-3}	1.2×10^{-3}	1.8×10^{-3}	1.4×10^{-2}	2.9×10^{-2}	0.8×10^{-3}
Fit model:									
Time res. sig frac	1.4×10^{-3}	1.1×10^{-3}	$<10^{-4}$	0.5×10^{-3}	0.6×10^{-3}	0.6×10^{-3}	1.2×10^{-2}	3.0×10^{-2}	0.4×10^{-3}
Time res. p_T bins	3.3×10^{-3}	1.4×10^{-3}	0.1×10^{-2}	$<10^{-4}$	$<10^{-4}$	0.5×10^{-3}	6.2×10^{-3}	5.2×10^{-3}	1.1×10^{-3}
Total	1.8×10^{-2}	0.2×10^{-2}	0.1×10^{-2}	0.2×10^{-2}	0.4×10^{-2}	0.4×10^{-2}	9.7×10^{-2}	2.0×10^{-1}	0.1×10^{-1}

Mass-lifetime-angular fit

Tau weight — Signal — Peaking background — Combinatorial background

$$\ln \mathcal{L} = \sum_{i=1}^{N} \{ \underbrace{w_i}_{\text{Tau weight}} \cdot \ln(\underbrace{f_s \cdot \mathcal{F}_s}_{\text{Signal}} + \underbrace{f_s \cdot f_{B_d^0} \cdot \mathcal{F}_{B_d^0} + f_s \cdot f_{\Lambda_b} \cdot \mathcal{F}_{\Lambda_b}}_{\text{Peaking background}} + \underbrace{(1 - f_s \cdot (1 + f_{B_d^0} + f_{\Lambda_b})) \cdot \mathcal{F}_{\mathrm{bkg}}}_{\text{Combinatorial background}})\}$$

- Data are corrected by the decay time correction
- Mass as well as lifetime use per-candidate width and scale factor, with flavour-dependent terms weighted by tagging probability $P(B|Q)$
- Contributions from $B_d^0 \to J/\psi K^{*0}$, $B_d^0 \to J/\psi K\pi$ and $\Lambda_b^0 \to J/\psi Kp$ due to wrong mass assignment (KK)
  - Efficiencies and acceptance from MC
  - BR from PDG
  - Fragmentation fractions from other measurements
- Combinatorial background for angular distribution use Legendre polynomials from sidebands; fixed in the main fit