CP violation in Bs to J/psi phi : update from ATLAS

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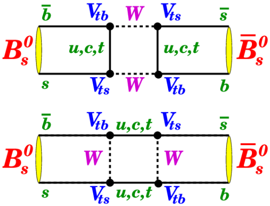
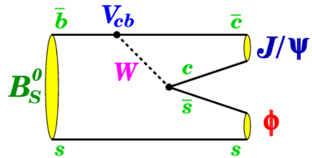
Motivation

- Interference of direct decay and decay with mixing into the same final state of $B_s^0 \to J/\psi\phi$ gives rise to time-dependent CP violation (CPV)





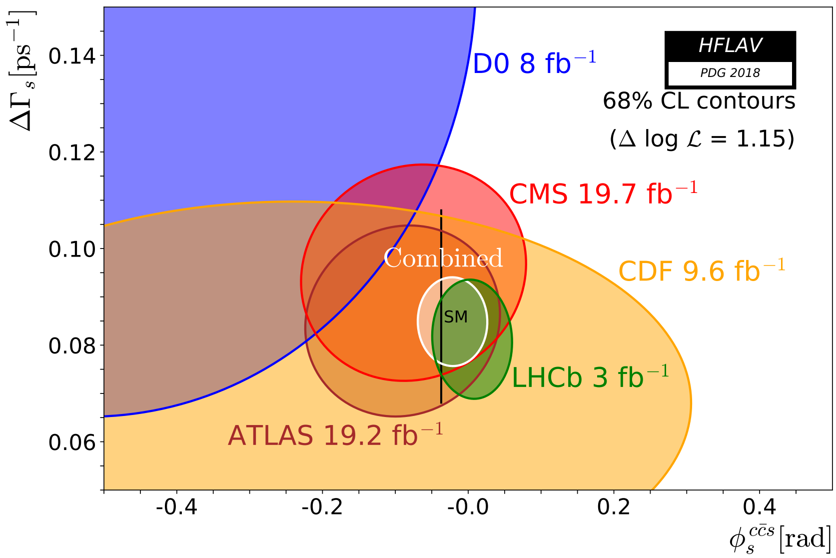
- CPV phase ϕ_s is the weak phase difference between the $B_s^0 - \bar{B}_s^0$ mixing amplitude and the direct $b \to c\bar{c}s$ decay amplitude
- In the Standard Model (SM) the ϕ_s is related to the CKM matrix and is small:

$$\phi_s \simeq -2\beta_s = -2arg\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*} = -0.0363^{+0.0016}_{-0.0015}\,\mathrm{rad}$$

- New Physics (NP) processes could contribute to the mixing box diagrams, potentially allowing for large deviations in ϕ_s from the SM prediction

- Alongside ϕ_s, other quantities are describing the differential decay rate:
  - Decay widths of the two mass eigenstates
  - CP even/odd state amplitudes and phases

Experimental Status: CPV in $B_s^0 \to J/\psi\phi$



- LHC Run 1 results consistent with the Standard Model prediction
- Search for New Physics needs increase of the ϕ_s precision

Data and Monte Carlo simulation samples

Run 2 Data:

- Uses 80.5 fb^{-1} of pp 2015 (4.9 fb^{-1}) 2016 (31.3 fb^{-1}) and 2017 (44.3 fb^{-1}) data (13 TeV)
- Statistically combined with Run1 ATLAS results:
  4.9 fb^{-1} (7 TeV, 2011)
  14.3 fb^{-1} (8 TeV, 2012)
- 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

MC samples:

- $B_s^0 \to J/\psi\phi$ MC events (2015-2017)
- MC samples for peaking backgrounds
  $B_d^0 \to J/\psi K^{*0}$, $B_d^0 \to J/\psi K\pi$ and $\Lambda_b^0 \to J/\psi Kp$
- MC samples for tagging calibration channel $B^\pm \to J/\psi K^\pm$
  (systematics and cross-checks only, data used for calibration)

Reconstruction and candidate selection

Event

- Triggers (previous slide) and Good Data selection
- At least one primary vertex (PV) formed from at least 4 inner detector (ID) tracks
- At least one pair of ID+MS (muon spectrometer) identified $\mu^+\mu^-$

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

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

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

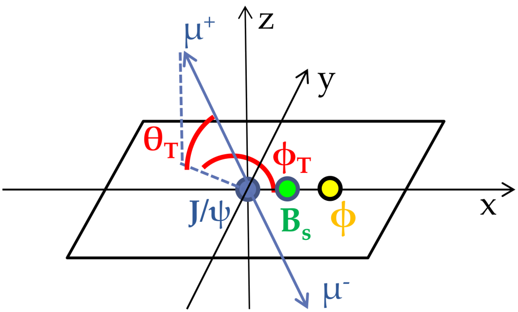
- $p_\mathrm{T}(K) > 1\ \mathrm{GeV}$
- $1008.5\ \mathrm{MeV} < m(KK) < 1030.5\ \mathrm{MeV}$

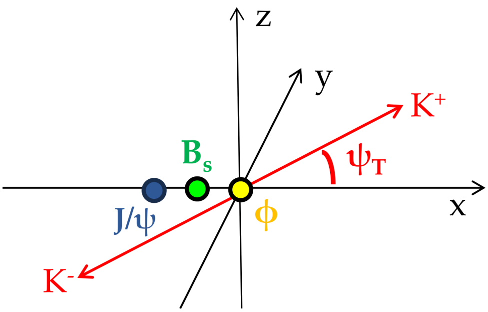
$B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$

- $p_\mathrm{T}(B_s^0) > 10\ \mathrm{GeV}$
- Four-track vertex fit $\chi^2/\mathrm{d.o.f.} < 3$ (J/ψ mass constrained)
- Keep only the candidate with best vertex fit $\chi^2/\mathrm{d.o.f.}$ in event
- $5150\ \mathrm{MeV} < m(B_s^0) < 5650\ \mathrm{MeV} \to$ **in total 2 977 526 B_s^0 candidates**

Angular analysis

- $B_s^0 \to J/\psi\phi$ decay = decay of 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 $B_s^0 \to J/\psi K^+K^-$ contributes to the final state and is included in the differential decay rate due to interference with the signal $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decay
- The transversity angles, $\Omega = (\Theta_T, \Psi_T, \phi_T)$ are defined as below





Mass-lifetime-angular fit

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

$$
\begin{aligned}
\ln \mathcal{L} = \sum_{i=1}^{N} \{ w_i \cdot \ln(f_{\mathrm{s}} \cdot \mathcal{F}_{\mathrm{s}}(m_i, t_i, \sigma_{m_i}, \sigma_{t_i}, \Omega_i, P(B|Q), p_{\mathrm{T}_i}) \\
+ f_{\mathrm{s}} \cdot f_{B^0} \cdot \mathcal{F}_{B^0}(m_i, t_i, \sigma_{m_i}, \sigma_{t_i}, \Omega_i, P(B|Q), p_{\mathrm{T}_i}) \\
+ f_{\mathrm{s}} \cdot f_{\Lambda_b} \cdot \mathcal{F}_{\Lambda_b}(m_i, t_i, \sigma_{m_i}, \sigma_{t_i}, \Omega_i, P(B|Q), p_{\mathrm{T}_i}) \\
+ (1 - f_{\mathrm{s}} \cdot (1 + f_{B^0} + f_{\Lambda_b})) \mathcal{F}_{\mathrm{bkg}}(m_i, t_i, \sigma_{m_i}, \sigma_{t_i}, \Omega_i, P(B|Q), p_{\mathrm{T}_i}) \}
\end{aligned}
$$

Physics parameters

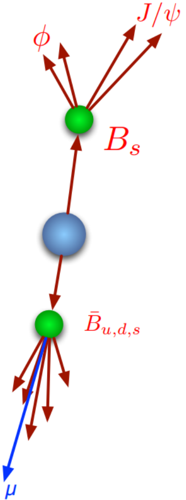
- CPV phase: ϕ_s
- Decay widths: $\Delta\Gamma_s$, Γ_s
- Decay amplitudes: $|A_0(0)|^2$, $|A_{||}(0)|^2$, $\delta_{||}$, $\delta_{\perp}$
- S-wave: $|A_S(0)|^2$, δ_S
- Δm_s fixed to PDG, $|\lambda|$ fixed to 1

Observables

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

Opposite side tagging

- Uses b-$\bar{b}$ correlation to determine initial signal flavour from the other B-meson in the event
  - $b \to l$ transitions give a clean tagging method
  - $b \to c \to l$ and neutral B-meson oscillations dilute the tagging
- Provides probability $P(B|Q)$ of signal candidate to be B_s^0 or $\bar{B}_s^0$



Tagger types

- tight muon, low-p_{T} muon, electron, b-tagged jet

- Signal flavour probability derived from charge of p_{T} weighted tracks in a cone around the opposite side primary object ($e^{\pm}$, $\mu^{\pm}$, b-jet)

$$Q_x = \frac{\sum_i^{N\ \mathrm{tracks}} q_i \cdot (p_{\mathrm{T}i})^{\kappa}}{\sum_i^{N\ \mathrm{tracks}} (p_{\mathrm{T}i})^{\kappa}}$$

- Search order based on best purity:
  tight muons, electrons, low-p_{T} muons, b-jets

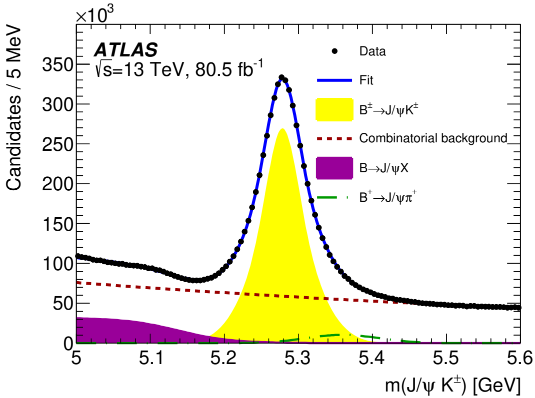
Tagging calibration

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

- Self-tagging non-oscillating channel
- Dimuon 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
- $\tau(B^\pm) > 0.2$ ps^{-1} reducing prompt combinatorial background

Tagging performance

- Efficiency $\epsilon = N_\mathrm{tagged}/N_\mathrm{Bcand.}$ (fraction of tagged signals)
- Dilution $D = (1 - 2w)$ (w is mistag probability)
- Tagging power $TP = \epsilon D^2$ (figure of merit of tagger performance)

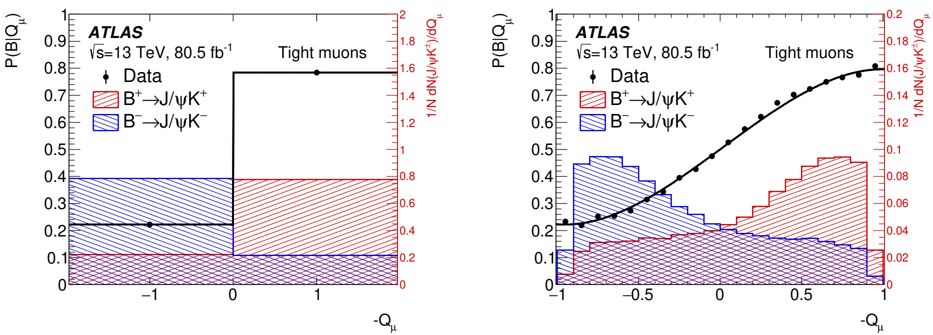


Tagging performance

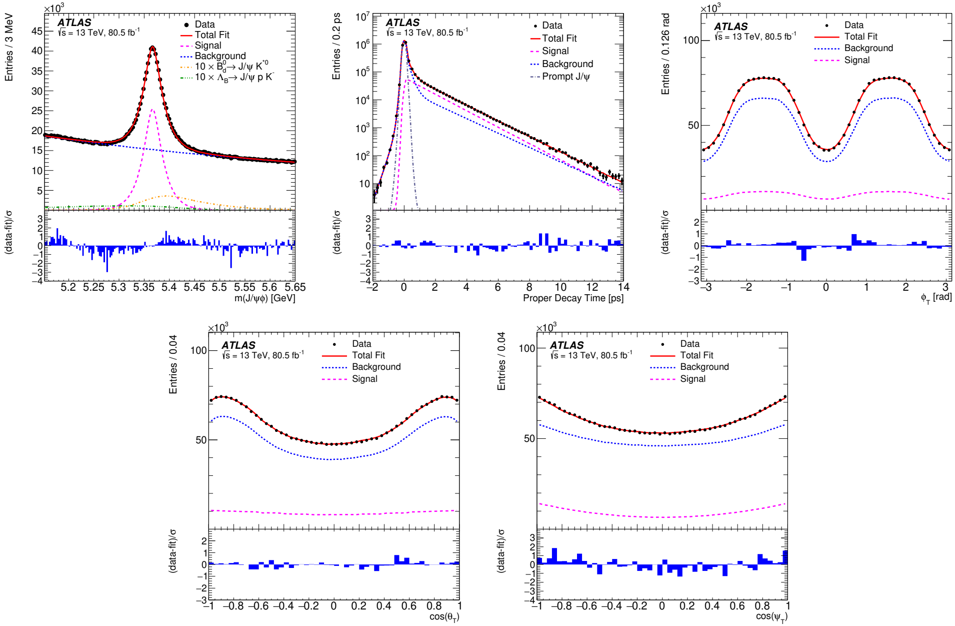
- Tagging performance in the $B^{\pm}$ channel

Tag method	ϵ_x [%]	D_x [%]	T_x [%]
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	12.04 ± 0.02	16.6 ± 0.1	0.334 ± 0.006
Total	21.23 ± 0.03	28.7 ± 0.1	1.75 ± 0.01

- Tag charge (Q_{μ}) distribution and calibration curve (for tight muons)



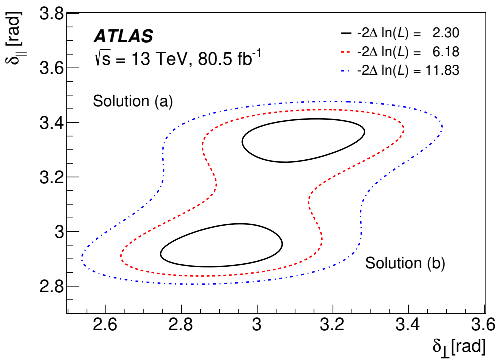
Projections of the mass-lifetime-angular fit



- Pull plots include both statistical and systematical uncertainties
- Deviations within 2σ and thus covered by declared systematics

Two Solutions of Likelihood Function

- While for most of the physics parameters, including ϕ , $\Delta\Gamma$, Γ, the fit determines a single solution, for the strong-phases $\delta_\perp$ and $\delta_{||}$ two well separated local maxima of the likelihood are found, and shown as solution (a) and (b) in the table of results.
- The difference in likelihood values, between the two solutions is equal to 0.03, favouring (a) but without ruling out (b).



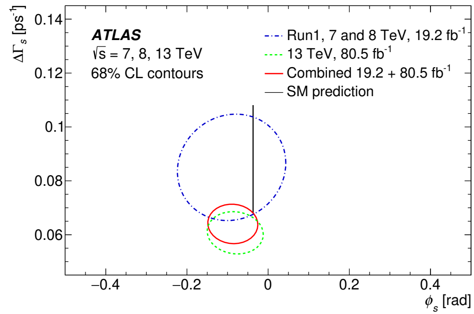
Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s [rad]	−0.081	0.041	0.020
$\Delta\Gamma_s$ [ps^{-1}]	0.0607	0.0047	0.0022
Γ_s [ps^{-1}]	0.6687	0.0015	0.0018
$\lvert A_{\parallel}(0)\rvert^2$	0.2213	0.0019	0.0022
$\lvert A_0(0)\rvert^2$	0.5131	0.0013	0.0034
$\lvert A_S(0)\rvert^2$	0.0321	0.0033	0.0044
$\delta_\perp - \delta_S$ [rad]	−0.25	0.05	0.04
Solution (a)			
$\delta_\perp$ [rad]	3.12	0.11	0.05
$\delta_{\parallel}$ [rad]	3.35	0.05	0.08
Solution (b)			
$\delta_\perp$ [rad]	2.91	0.11	0.05
$\delta_{\parallel}$ [rad]	2.94	0.05	0.08

Systematic uncertainties

- Systematics assumed uncorrelated $\rightarrow \text{Total} = \sqrt{\sum_i \text{syst}_i^2}$

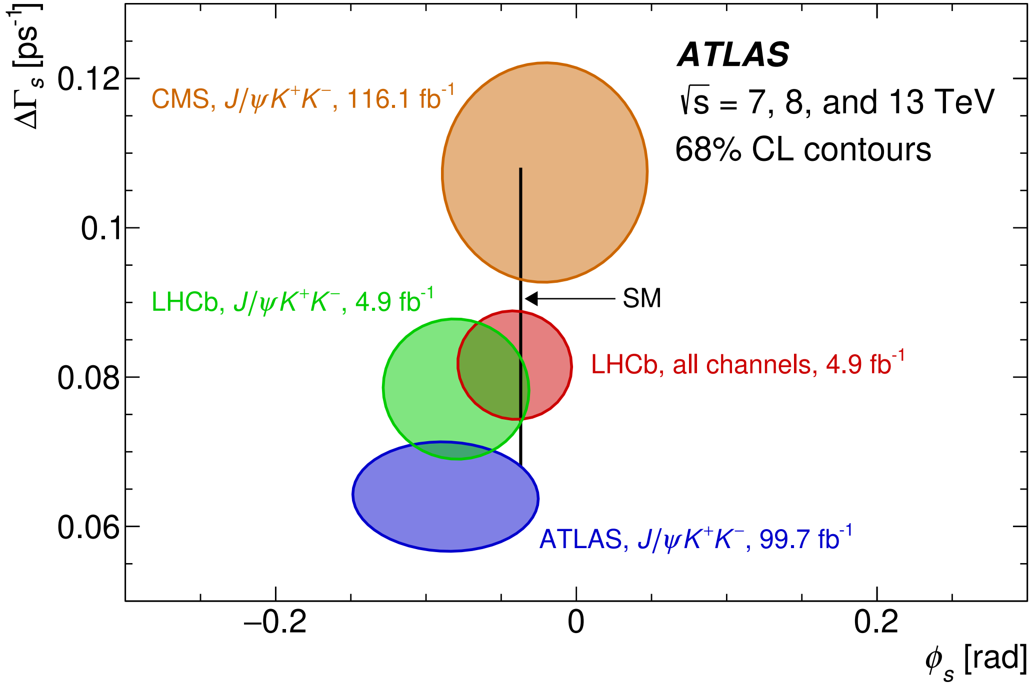
	ϕ_s [10^{-3} rad]	$\Delta\Gamma_s$ [10^{-3} ps^{-1}]	Γ_s [10^{-3} ps^{-1}]	$\lvert A_\parallel(0)\rvert^2$ [10^{-3}]	$\lvert A_0(0)\rvert^2$ [10^{-3}]	$\lvert A_S(0)\rvert^2$ [10^{-3}]	$\delta_\perp$ [10^{-3} rad]	$\delta_\parallel$ [10^{-3} rad]	$\delta_\perp - \delta_S$ [10^{-3} rad]
Tagging	19	0.4	0.3	0.2	0.2	1.1	17	19	2.3
Acceptance	0.5	< 0.1	< 0.1	1.0	0.8	2.6	33	56	7.0
ID alignment	0.8	0.2	0.5	< 0.1	< 0.1	< 0.1	11	7.2	< 0.1
Best candidate selection	0.5	0.4	0.7	0.5	0.2	0.2	12	17	7.5
Background angles model:									
Choice of fit function	2.5	< 0.1	0.3	1.1	< 0.1	0.6	12	0.9	1.1
Choice of p_{T} bins	1.3	0.5	< 0.1	0.4	0.5	1.2	1.5	7.2	1.0
Choice of mass interval	0.4	0.1	0.1	0.3	0.3	1.3	4.4	7.4	2.3
Dedicated backgrounds:									
B_d^0	2.3	1.1	< 0.1	0.2	3.0	1.5	10	23	2.1
Λ_b	1.6	0.3	0.2	0.5	1.2	1.8	14	30	0.8
Alternate Δm_s	1.0	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	15	4.0	< 0.1
Fit model:									
Time res. sig frac	1.4	1.1	0.5	0.5	0.6	0.8	12	30	0.4
Time res. p_{T} bins	0.7	0.5	0.8	0.1	0.1	0.1	2.2	14	0.7
S-wave phase	0.3	< 0.1	< 0.1	< 0.1	< 0.1	0.2	8	15	37
Fit bias	5.7	1.3	1.2	1.3	0.4	1.1	3.3	19	0.3
Total	20	2.2	1.8	2.2	3.4	4.4	51	84	38

- 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	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
$\lvert A_\parallel(0)\rvert^2$	0.2221	0.0017	0.0022	0.2218	0.0017	0.0022
$\lvert A_0(0)\rvert^2$	0.5149	0.0012	0.0031	0.5149	0.0012	0.0031
$\lvert A_S\rvert^2$	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

Updated overview of the experimental results



Conclusions

- Analysis of the 2015+2016+2017 data of $80.5\,\mathrm{fb}^{-1}$ performed
- Results combined with those from the previous Run 1 analysis
- Results are compatible with LHCb and CMS ones as well as with the Standard Model prediction
- Our new measurement improves precision of the parameters

Current results on ϕ_s from LHC

	ϕ_s [rad]
LHC Combined Run 1	-0.021 ± 0.031 (stat)
LHCb 4.9 fb^{-1} EUR. PHYS. J. C 79 (2019)	-0.0042 ± 0.025 (stat)
ATLAS Run 1 JHEP08, 147	-0.090 ± 0.078 (stat) $\pm$ 0.041 (syst)
CMS 96.4 fb^{-1} CMS-PAS-BPH-20-001	-0.021 ± 0.045 (stat)
ATLAS 2015/16/17 ($80.5\,\mathrm{fb}^{-1}$) $\oplus$ Run 1 ($19.2\,\mathrm{fb}^{-1}$)	-0.087 ± 0.037 (stat) $\pm$ 0.019 (syst)

Backup slides

Probability density functions

$$\ln \mathcal{L} = \sum_{i=1}^{N} \{ w_i \cdot \ln (f_{\rm s} \mathcal{F}_{\rm s} + f_{\rm s} f_{B^0} \mathcal{F}_{B^0} + f_{\rm s} f_{\Lambda_b} \mathcal{F}_{\Lambda_b} + (1 - f_{\rm s}(1 + f_{B^0} + f_{\Lambda_b})) \mathcal{F}_{\rm bkg} \}$$

Signal PDFs

- Mass: Gaussian with per-candidate width and scalefactor
- Time-angles: signal decay 4D function
  - Convolved with per-candidate time resolution
  - Flavour-dependent terms weighted by tagging probability $P(B|Q)$
  - Applied B-$p_{\rm T}$ dependent angular acceptance

Decay time correction

- Correction of bias in the proper decay time by weighting events

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

- Extracted from MC separately for data periods and trigger selection
- Typically $10 - 20\ \mathrm{fs}^{-1}$, in more biased periods $70\ \mathrm{fs}^{-1}$

Probability density functions

$$\ln \mathcal{L} = \sum_{i=1}^{N} \{ w_i \cdot \ln(f_\mathrm{s} \mathcal{F}_\mathrm{s} + f_\mathrm{s} f_{B^0} \mathcal{F}_{B^0} + f_\mathrm{s} f_{\Lambda_b} \mathcal{F}_{\Lambda_b} + (1 - f_\mathrm{s}(1 + f_{B^0} + f_{\Lambda_b})) \mathcal{F}_\mathrm{bkg} \}$$

Peaking backgrounds

- Contributions from $B_d^0 \to J/\psi K^{*0}$, $B_d^0 \to J/\psi K\pi$ and $\Lambda_b^0 \to J/\psi K p$
- Shapes of distributions changed due to wrong mass assignment (KK)
- PDFs extracted from MC and then fixed in the main fit
- Fractions calculated from:
  - Efficiencies and acceptance from MC
  - BR from PDG
  - Fragmentation fractions from other measurements

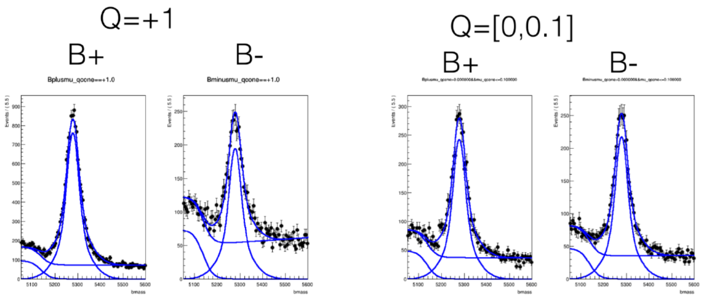
Combinatorial background PDFs

- Mass: exponential + constant
- Time: delta-function and 3 exponentials convolved with per-candidate time resolution
- Angles: Legendre polynomials from sidebands; fixed in the main fit

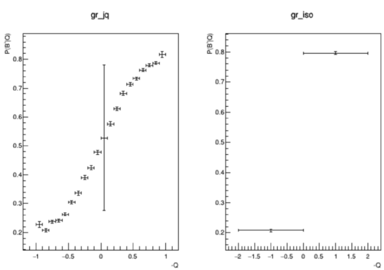
Signal time-angular PDF

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

- For Muons and Jets, now use fits to mass distribution in bins of Q-variable
- Result of the fit provide $N_B \pm^{Q=i}$; $P(Q|B+) = N(B+|Q)/N(B+)$



- Calibration curve separated into *Continuous part* and *Discrete part*
- Converts Q-values into a Probability:



$$P(\bar{b}|Q) = \frac{P(Q|\bar{b})P(\bar{b})}{P(Q|\bar{b})P(\bar{b}) + P(Q|b)P(b)} = \frac{P(Q|\bar{b})}{P(Q|\bar{b}) + P(Q|b)},$$

Tag "Punzi" distributions - discrete

- Fraction of tag-charge equal to ± 1 in signal and background events

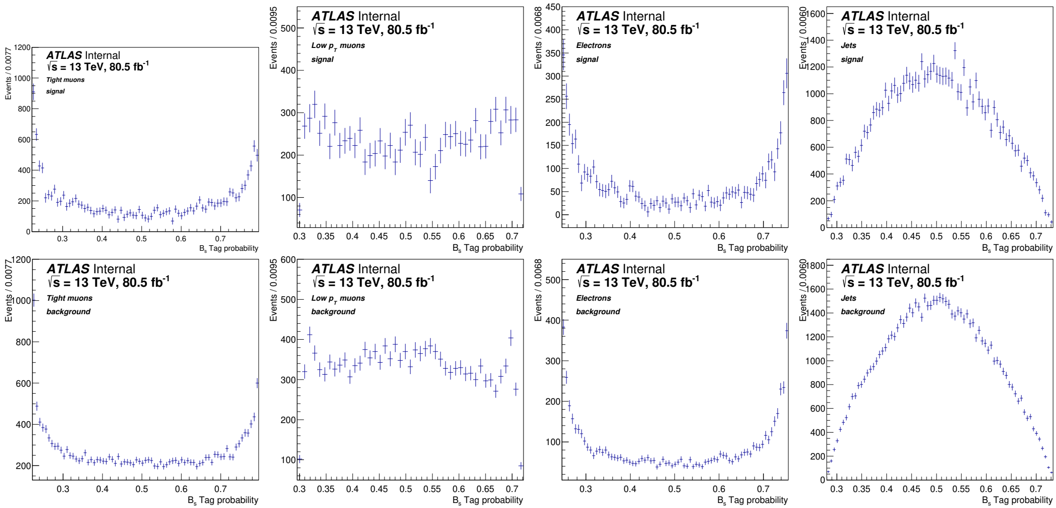
Tag method	Signal		Background	
	f_{+1}	f_{-1}	f_{+1}	f_{-1}
Tight μ	0.069 ± 0.003	0.075 ± 0.003	0.047 ± 0.001	0.049 ± 0.001
Electron	0.20 ± 0.01	0.19 ± 0.01	0.168 ± 0.002	0.173 ± 0.002
Low-pt μ	0.109 ± 0.005	0.117 ± 0.005	0.070 ± 0.001	0.076 ± 0.001
Jets	0.0451 ± 0.0015	0.0458 ± 0.0016	0.0376 ± 0.0003	0.0386 ± 0.0003

- Fraction of tag-methods in signal and background events

Tag method	Signal	Background
Tight μ	0.0400 ± 0.0006	0.0316 ± 0.0001
Electron	0.0187 ± 0.0004	0.01479 ± 0.0001
Low-pT μ	0.0291 ± 0.0005	0.0264 ± 0.0001
Jets	0.144 ± 0.001	0.1196 ± 0.0002
Untagged	0.767 ± 0.003	0.8077 ± 0.0005

Tag "Punzi" distributions - continuous

Tight muons | Low-p_{T} muons | Electrons | Jets



Fit correlations between the physical parameters

- Fit correlations between the physical parameters of interest, obtained from the fit for solution (a)

	$\Delta\Gamma$	Γ_s	$\lvert A_{\parallel}(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_{\parallel}$	$\delta_{\perp}$	$\delta_{\perp}-\delta_S$
ϕ_s	−0.080	0.017	−0.003	−0.004	−0.007	0.007	0.004	−0.007
$\Delta\Gamma$	1	−0.586	0.090	0.095	0.051	0.032	0.005	0.020
Γ_s		1	−0.125	−0.045	0.080	−0.086	−0.023	0.015
$\lvert A_{\parallel}(0)\rvert^2$			1	−0.341	−0.172	0.522	0.133	−0.052
$\lvert A_0(0)\rvert^2$				1	0.276	−0.103	−0.034	0.070
$\lvert A_S(0)\rvert^2$					1	−0.362	−0.118	0.244
$\delta_{\parallel}$						1	0.254	−0.085
$\delta_{\perp}$							1	0.001

- Fit correlations between the physical parameters of interest, obtained from the fit for solution (b)

	$\Delta\Gamma$	Γ_s	$\lvert A_{\parallel}(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_{\parallel}$	$\delta_{\perp}$	$\delta_{\perp}-\delta_S$
ϕ_s	−0.084	0.019	−0.011	−0.003	−0.006	0.007	0.005	−0.006
$\Delta\Gamma$	1	−0.586	0.090	0.096	0.057	−0.029	−0.010	0.021
Γ_s		1	−0.116	−0.048	0.071	0.070	0.017	0.015
$\lvert A_{\parallel}(0)\rvert^2$			1	−0.338	−0.110	−0.444	−0.106	−0.052
$\lvert A_0(0)\rvert^2$				1	0.269	0.080	0.017	0.070
$\lvert A_S(0)\rvert^2$					1	0.291	0.060	0.251
$\delta_{\parallel}$						1	0.235	0.097
$\delta_{\perp}$							1	0.056

Correlation matrix of the BLUE combination

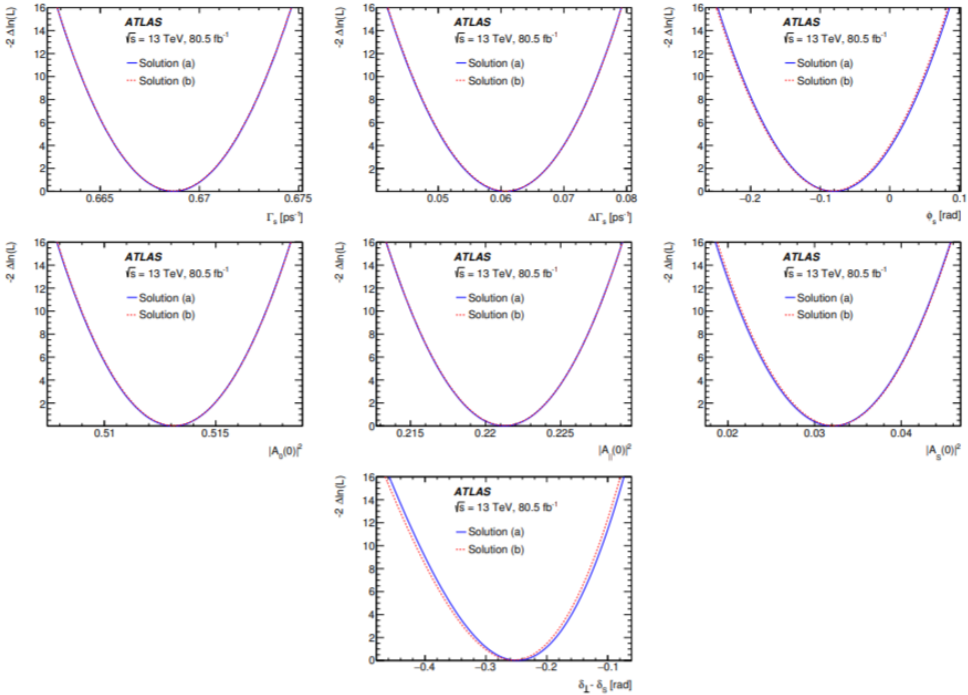
- Correlation matrix of the BLUE combination of the 7 TeV and 8 TeV results and the solution (a) of the 13 TeV result

	$\Delta\Gamma$	Γ_s	$\lvert A_{\parallel}(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_{\parallel}$	$\delta_{\perp}$	$\delta_{\perp}-\delta_S$
ϕ_s	−0.039	0.002	0.001	0.000	−0.002	0.003	0.004	−0.004
$\Delta\Gamma$	1	−0.342	0.050	0.032	0.025	0.013	0.003	0.013
Γ_s		1	−0.052	−0.012	0.031	−0.027	−0.012	0.007
$\lvert A_{\parallel}(0)\rvert^2$			1	−0.076	−0.056	0.158	0.067	−0.023
$\lvert A_0(0)\rvert^2$				1	0.054	−0.017	−0.010	0.017
$\lvert A_S(0)\rvert^2$					1	−0.105	−0.057	0.109
$\delta_{\parallel}$						1	0.111	−0.033
$\delta_{\perp}$							1	0.001

- Correlation matrix of the BLUE combination of the 7 TeV and 8 TeV results and the solution (b) of the 13 TeV result

	$\Delta\Gamma$	Γ_s	$\lvert A_{\parallel}(0)\rvert^2$	$\lvert A_0(0)\rvert^2$	$\lvert A_S(0)\rvert^2$	$\delta_{\parallel}$	$\delta_{\perp}$	$\delta_{\perp}-\delta_S$
ϕ_s	−0.041	0.003	−0.003	0.001	−0.001	0.003	0.004	−0.003
$\Delta\Gamma$	1	−0.342	0.050	0.032	0.028	−0.012	−0.007	0.013
Γ_s		1	−0.048	−0.012	0.028	0.022	0.009	0.007
$\lvert A_{\parallel}(0)\rvert^2$			1	−0.075	−0.035	−0.135	−0.052	−0.023
$\lvert A_0(0)\rvert^2$				1	0.053	0.014	0.005	0.017
$\lvert A_S(0)\rvert^2$					1	0.085	0.028	0.112
$\delta_{\parallel}$						1	0.103	0.038
$\delta_{\perp}$							1	0.037

1D log-likelihood scans



Systematic uncertainties

- Tagging systematics:
  - calibration function (tag probability vs. tag charge)
  - pile-up dependence (calibration for three N_{PV} bins)
  - variation of tag probability and tag method "Punzi" terms (functions, histograms)
  - stat. uncertainty due to $B^{\pm} \to J/\psi K^{\pm}$ data sample included in overall stat. err.
- Angular acceptance (binned fit of MC) by changing the bin widths and central values
- Inner detector alignment: Residual misalignment affects tracks impact parameter, effect in fit results in systematics
- S-wave phase by varying correction factor α that accounts for mass-dependence of phase difference between S and P waves
- Background angles model varying Legendre polynomials describing sidebands data:
  - their degree
  - B-p_{T} dependence (binning)
  - size of B_s^0 mass sidebands
- Contributions from peaking backgrounds $B_d^0 \to J/\psi K^{*0}$, $B_d^0 \to J/\psi K\pi$ and $\Lambda_b^0 \to J/\psi Kp$, accounting for:
  - production fraction uncertainties
  - uncertainties in modeling of decay angles (including S/P wave interference)
  - in the Λ_b^0 case also uncertainties in $\Lambda_b^0 \to J/\psi \Lambda^*$ BRs
  - uncertainties of fit-function describing the mass-time-angular PDFs
- Signal fit model:
  - adding second mass scale factor
  - varying B-p_{T} binning (decay time per-candidate errors sensitive to that)
  - varying signal fraction when determining the decay time "Punzi" terms