B decays to charmonia at LHCb

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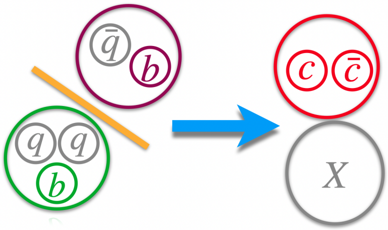
The 2022 Conference on Flavour Physics and CP Violation | May 23-27, Oxford, Mississippi (USA)

B decays to charmonia at LHCb

- B2CC specific working group at LHCb.
- Precise measurements on CKM sector
  $\Rightarrow$ stringent tests for SM.
- Mainly focused on CPV measurements, lifetime measurements, Branching Ratios...



Today´s menu:

1. Search for $B^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$.
2. CPV phase measurement in $B_s^0 \to J/\psi(e^+e^-)\phi(K^+K^-)$.
3. τ_L in $B_s^0 \to J/\psi(\mu^+\mu^-)\eta(\gamma\gamma)$.

Search for $B^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ [Chin. Phys. C45 (2021) 043001]

- $b \to c\bar{c}d$ transition $\to$ Cabibbo supressed.
- ϕ resonance produced by $\omega - \phi$ interference (small mixing angle supressed), or vacuum excitation (Okubo-Zweig-Iizuka supressed) [Phys. Lett. 5 (1963) 165].
- Predicted Branching Ratio: $(1.8 \pm 0.3) \times 10^{-7}$ [PLB666(2008)185188]
- Previous LHCb (@1 fb^{-1}): BR$< 1.9 \times 10^{-7}$ [Phys.Rev.D.88.072005]

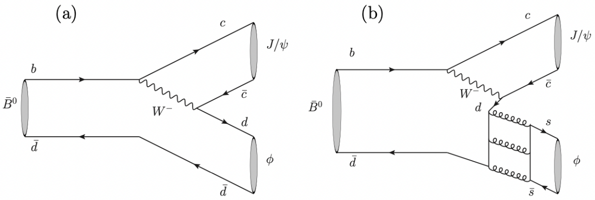


Figure 1: Feynman diagrams for the decay $B^0 \to J/\psi\phi$ via (a) $\omega - \phi$ mixing and (b) tri-gluon fusion.

Search for $B^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$

[Chin. Phys. C45 (2021) 043001]

- Full Run1+Run2 data. Control channel: $B_s^0 \to J/\psi\phi$.
- Correct MC variables to match background substracted data.
- BDT (Remove combinatorial background).
- Efficiency ratio ($B_{(s)} \to J/\psi KK$): $\frac{\epsilon_{B^0}}{\epsilon_{B_s^0}} = \frac{\epsilon^{acc}_{B^0}}{\epsilon^{acc}_{B_s^0}} \times \frac{\epsilon^{sel}_{B^0}}{\epsilon^{sel}_{B_s^0}} \times \frac{\epsilon^{m(KK)}_{B_s^0}}{\epsilon^{m(KK)}_{B^0}}$.

  $\to$ found compatible with 1.
- Sequential fits in $m(J/\psi K^+K^-)$ and $m(K^+K^-)$ to determine $B^0_{(s)} \to J/\psi\phi$.
  - Fit $m(J/\psi K^+K^-)$ and estimate yields and bkgs in $m(KK) \in [1000, 1050]$ MeV.
  - Fit $m(KK)$ in same region to distinguish $\phi(1020)$.
- Use Profile Likelihood Scan to set Upper Limit.

Search for $B^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$

[Chin. Phys. C45 (2021) 043001]

$m(K^+K^-)$ Fit strategy

$$N_{B^0} = N_{B_s^0} \times \frac{\mathcal{B}(B^0 \to J/\psi\phi)}{\mathcal{B}(B_s^0 \to J/\psi\phi)} \times \frac{\epsilon_{B^0}}{\epsilon_{B_s^0}} \times \frac{1}{fs/fd(\times f_{sc})}$$

$f_s/f_d = 0.256 \pm 0.020$
JHEP04(2013)001

$f_{sc} = 1.068 \pm 0.046$ (13TeV) PRL. 118(2017)191801

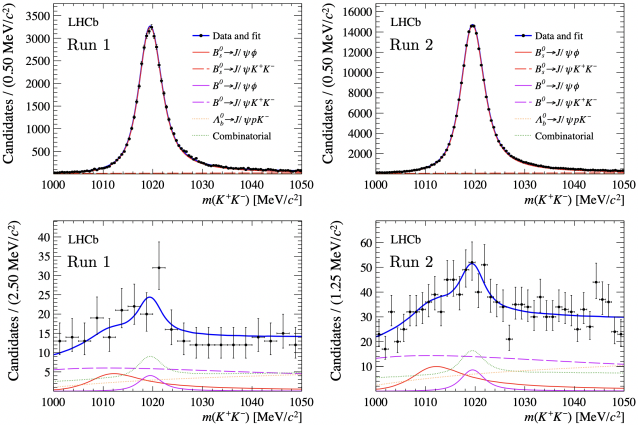
$\mathcal{B}(B_s^0 \to J/\psi\phi = (10.50 \pm 0.13 \pm 0.64 \pm 0.82)$
Phys.Rev.D87.072004

$\mathcal{B}(B^0 \to J/\psi\phi)$

$(6.8 \pm 3.0 \pm 0.9) \times 10^{-8}$ [2.3σ].

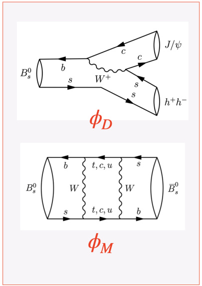
Upper Limit 1.1×10^{-7}.

Compatible with theoretical prediction.



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

[Eur. Phys. J. C81 (2021) 1026]



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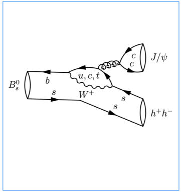

+

$$\phi_s^{meas.} = -2\beta_s + \Delta\phi_s^{peng} + \delta^{NP}$$

$-2\beta_s = -37^{+0.7}_{-0.8}$ mrad [1]

$\Delta\phi_s^{peng}$: $\sim (1 \pm 15)$ mrad (Run1)[2]

LHCb 4.9 fb^{-1}

[EUR. PHYS.J. C79 (2019)706]

$\phi_s = -42 \pm 25$ mrad

$\Delta\Gamma_s = 0.0813 \pm 0.0048\ \mathrm{ps}^{-1}$

$\Gamma_s = 0.6563 \pm 0.0021\ \mathrm{ps}^{-1}$

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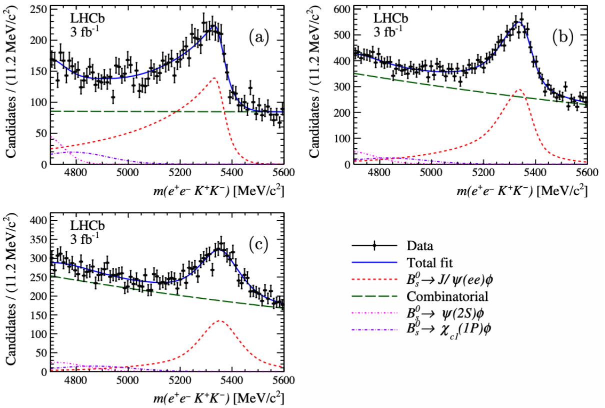
[1] CKMfitter, Phys. Rev. D84, 033005 (2011), updated with Summer 2019 results

[2] [TH:Kristof et al JHEP 1503 (2015) 145], [EXP:JHEP 11 (2015) 082]

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

[Eur. Phys. J. C81 (2021) 1026]

- Run1 analysis.
- First time ϕ_s is measured with e^+e^- in final state.
- Flavour tagged time dependent angular analysis.
- $P \to VV$
- $\approx 10\%$ of dimuon yield.
- Resolution of the reconstructed invariant mass affected by bremsstrahlung.



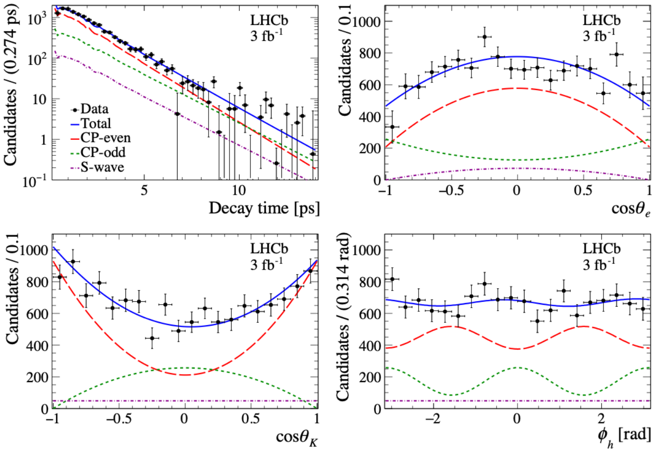
$$N_{sig} = \sum_{K=0}^{3} N_{K\gamma} = 12723 \pm 541$$
$$N_{cbkg} + N_{pbkg} = \sum_{K=0}^{3} N_{K\gamma} = 49558 \pm 1005$$

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

[Eur. Phys. J. C81 (2021) 1026]

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

$$\phi_s = 0.00 \pm 0.28 \pm 0.07 \text{ rad}$$
$$\Delta\Gamma_s = 0.115 \pm 0.045 \pm 0.011 \; ps^{-1}$$
$$|\lambda| = 0.877^{+0.112}_{-0.116} \pm 0.031$$
$$\Gamma_s = 0.608 \pm 0.018 \pm 0.012 \; ps^{-1}$$



- Consistent with SM.
- ϕ_s consistent with 0.
- $|\lambda|$ consistent with 1.
- Statistically limited.
- More details on Marcos Romero Lamas talk! [16:00].

τ_L **in** $B_s^0 \to J/\psi(\mu^+\mu^-)\eta(\gamma\gamma)$ LHCb-PAPER-2022-010, PRELIMINARY!

- A sizable $\Delta\Gamma = \Gamma_L - \Gamma_H$ is predicted (L, H mass eigenstates).
- ϕ_s consistent with SM (very small) $\to$ CPV in mixing is small.
- Mass eigenstates $\approx$ CP eigenstates.
- Measure the effective lifetime on a pure *CP* even $\to$ direct access to $\tau_{eff} = 1/\Gamma_L$.
- Advantages: Not needed Angular/tagging analysis
- Disadvantages: Small statistics
- **SM prediction**: $\tau_L = \frac{\tau_{B_s^0}}{1-y_s^2}\left[\frac{1+2*A*y_s+y_s^2}{1+A*y_s}\right]$ [3]
  $y_s = \Delta\Gamma_s/2\Gamma_s$, $A = +1(-1)$ CP-odd (even).
  $\tau_L = (1.42 \pm 0.01)$ ps
  TH: $\tau_{B_s^0}/\tau_{B^0} = 1.0006 \pm 0.002$ and $\Delta\Gamma_s = (0.091 \pm 0.013)\,\mathrm{ps}^{-1}$ [4]
  EXP: $\tau_{B^0} = 1.519 \pm 0.004$ [PDG2020]

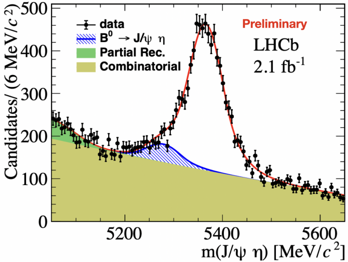
[3] Fleischer et al.,Eur.Phys.J. C71 (2011) 1789

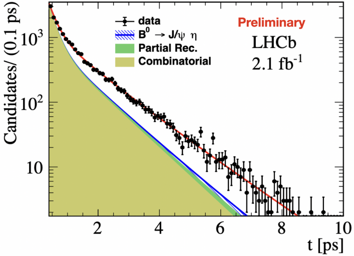
[4] Lenz et al. JHEP07(2020)177

τ_L in $B_s^0 \to J/\psi(\mu^+\mu^-)\eta(\gamma\gamma)$

LHCb-PAPER-2022-010, PRELIMINARY!

- Selection as lifetime unbiased as possible.
- **2D** (t,m) unbinned likelihood fit.
- **Mass fits**:
  1. signal: Double side Crystal Ball.
  2. $B^0 \to J/\psi\eta$: DSCB.
  3. Comb.: 2nd order Chebyshev pol.
  4. $B_s^0 \to J/\psi\phi(\eta\gamma)$: bifurcated Gaussian.
  5. $B_s^0 \to X_{c1,c2}(J/\psi\gamma)(\eta)$: erf(x).
- **Decay Time**: $Exp(t) * Res(t) * Acc(t)$.
  1. Triple Gaussian Model
  2. VELO misaligment found negligible (3.8 fs).

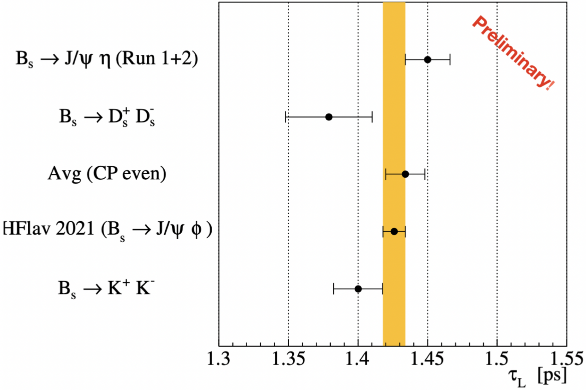




τ_L in $B_s^0 \to J/\psi(\mu^+\mu^-)\eta(\gamma\gamma)$

LHCb-PAPER-2022-010, PRELIMINARY!

τ_L [ps]
Run2
$1.445 \pm 0.016(stat) \pm 0.008(syst)$
Comb
$1.452 \pm 0.016(stat + uc) \pm 0.002(syst)$
PDG(*tree level average)
1.437 ± 0.014[5]
SM
1.42 ± 0.01
HFLAV
1.426 ± 0.008[6]
(*based upon $B_s^0 \to J/\psi\phi$)



[5] PDG2020

[6] HFLAV

Summary

1. Update in the Upper limit for the $\mathcal{B}(B^0 \to J/\psi\phi) < 1.1 \times 10^{-7}$.
2. First measurement of ϕ_s in $B_s^0 \to J/\psi(e^+e^-)\phi(K^+K^-)$, compatible with no CPV, consistent with SM prediction and consistent with $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$.
3. Update in the lifetime measurement τ_L, using $B_s^0 \to J/\psi\eta$ to be $\tau_{eff} = 1.449 \pm 0.016 \pm 0.001$ ps $\left(@9\ \mathrm{fb}^{-1}\right)$.
4. Stay tuned for many interesting new results!

BACKUP

Fit results of $m(J/\psi K^+K^-)$

Table 1: Measured yields of all contributions from the fit to $J/\psi K^+K^-$ mass distribution, showing the results for the full mass range and for the B_s^0 and B^0 regions.

Data	Category	Full	B_s^0 region	B^0 region
Run 1	$B_s^0 \to J/\psi K^+K^-$	55498 ± 238	51859 ± 220	35 ± 6
	$B^0 \to J/\psi K^+K^-$	127 ± 19	0	119 ± 18
	$\Lambda_b^0 \to J/\psi pK^-$	407 ± 26	55 ± 8	61 ± 8
	Combinatorial background	758 ± 55	85 ± 11	94 ± 11
Run 2	$B_s^0 \to J/\psi K^+K^-$	249670 ± 504	233663 ± 472	153 ± 12
	$B^0 \to J/\psi K^+K^-$	637 ± 39	0	596 ± 38
	$\Lambda_b^0 \to J/\psi pK^-$	1943 ± 47	261 ± 16	290 ± 17
	Combinatorial background	2677 ± 109	303 ± 20	331 ± 21

$m(K^+K^-)$ fit strategy

$$P^{tot}_{s/d} = N^{\phi}_{s/d} \times S_{\phi}(m) + N^{non}_{s/d} \times S_{non}(m) + N^{\Lambda}_{s/d} \times B_{\Lambda}(m) + N^{com}_{s/d} \times B_{com}(m) + N^{B^0_s}_{d} \times T_{B^0_s}(m)$$

S_{ϕ} same lineshape for $B_{s/d} \to J/\psi\phi$ decays

S_{non}, $f_0(980)/a_0(980)$+nonres. for $B^0_{s/d} \to J/\psi K^+K^-$ decays.

$B_{\Lambda}\&B_{com}$ shapes of Λ^b_0 and comb bkg (3th & 2th Chebyshev).

$T_{B^0_s}$, B^0_s tail shape under B^0 peak.

$N^{\Lambda}_{s/d}$, $N^{com}_{s/d}$, $N^{B^0_s}_{d}$ fixed from $m(J/\psi K^+K^-)$ fit.

ϕ: BF * $|A_{BW}|^2 \circledast$ G

BF: Barrier factor, A_{BW} Breit-winger, G gaussian

non-ϕ K^+K^-: $P_B P_R F_B^2(\frac{P_B}{m_B})^{2L_B} \left|A_R \times e^{i\delta} + A_{NR}\right|^2$

A_R Flatte model, A_{NR} a constant for nonresonance Phys. Lett. B 63 (1976) 228.

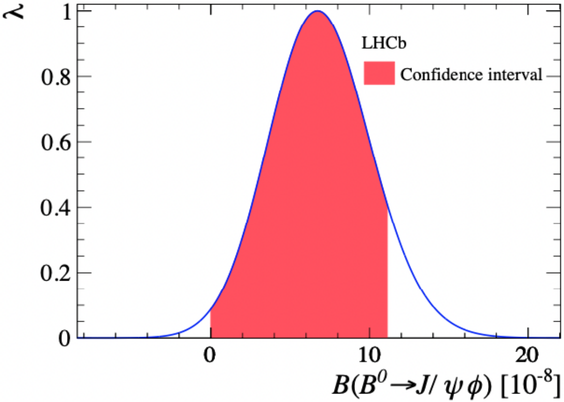
δ constrained based on $B_{s/d} \to J/\psi K^+K^-$ amplitude analysis PhysRevD.87.072004.

Syst. in $B^0 \to J/\psi\phi$

Table 2: Systematic uncertainties on $\mathcal{B}(B^0 \to J/\psi\phi)$ for multiplicative and additive sources.

Multiplicative uncertainties	Value (%)
$\mathcal{B}(B_s^0 \to J/\psi\phi)$	6.2
Scaling factor for f_s/f_d	3.4
$\varepsilon_{B^0}/\varepsilon_{B_s^0}$	1.8
Total	7.3
Additive uncertainties	**Value (10^{-8})**
$m(J/\psi K^+K^-)$ model of combinatorial background	0.03
Fixed yields of Λ_b^0 in $m(K^+K^-)$ fit	0.05
Fixed yields of combinatorial background in $m(K^+K^-)$ fit	0.61
Fixed yields of B_s^0 contribution in $m(K^+K^-)$ fit	0.24
Constant d	0.01
$m(K^+K^-)$ shape of B_s^0 contribution	0.29
$m(K^+K^-)$ shape of Λ_b^0	0.28
$m(K^+K^-)$ shape of combinatorial background	0.16
$m(K^+K^-)$ shape of non-ϕ	0.06
Total	0.80

PLS in $B^0 \to J/\psi\phi$



MF in $B_s^0 \to J/\psi(e^+e^-)\phi(K^+K^-)$

- MF for B_s^0:
  1. Signal: Double CB.
  2. Comb: Exponential.
  3. $B_s^0 \to \Psi(2S)\phi$ (part.) double Gaussian.
  4. $B_s^0 \to \chi_{c1}(1P)\phi$ (part.) Gaussian.
- MF for B^0 (Control Channel):
  1. Signal: Double CB.
  2. Comb: Exponential.
  3. $B_s^0 \to \Psi(2S)K^*$ (part.) double Gaussian.
  4. $B_s^0 \to \chi_{c1}(1P)K^*$ (part.) Gaussian.
  5. $B_s^0 \to J/\psi K_1(1270)$ (part.) Double CB.

MF in $B_s^0 \to J/\psi(e^+e^-)\phi(K^+K^-)$

Table 7: The results of the fit to the $m(e^+e^-K^+K^-)$ distribution in the data sample divided into three Bremsstrahlung categories. The scale parameter is a difference between sigma of the first and second Crystal Ball function and $n_1 = n_2 = n$. The shape of the partially reconstructed background is fixed to MC fit discribed in Sec. 5.2.

Parameter	0γ	1γ	2γ	
α_1	0.134±0.005	0.199±0.006	0.37±0.01	fixed to MC fit
α_2	-1.28±0.3	-0.742±0.02	-0.546±0.02	fixed to MC fit
$\sigma_1[\mathrm{MeV}/c^2]$	31.4±4.3	45.0±4.	72.5±8.8	float
scale	1.15±0.1	1.5±0.05	0.96±0.03	fixed to MC fit
$\mu[\mathrm{MeV}/c^2]$	5337.6±4.4	5336.4±2.5	5351.9±5.3	float
f_{CB1}	0.987±0.008	0.7±0.006	0.59±0.01	fixed to MC fit
n	5.3±0.5	30.0±6.0	21.0±5.0	fixed to MC fit
bkg slope	-0.00023±0.00014	-0.00046±0.00006	-0.00046±0.00010	float
$\mathrm{N}_{\mathrm{cbkg}}$	7697±452	22752±453	16625±594	
$f_{B_s^0\to\psi(2S)\phi}$	0.387±0.014	0.432±0.008	0.453±0.010	float
$\mathrm{N}_{B_s^0\to\psi(2S)\phi}$	210±60	508±134	347±163	
$\mathrm{N}_{B_s^0\to\chi_{c1}(1P)\phi}$	333±164	666±336	420±394	
$\mathrm{N}_{\mathrm{sig}}$	3374±325	6289±215	3060±375	

Acceptances in $B_s^0 \to J/\psi(e^+e^-)\phi(K^+K^-)$

$$\epsilon_{data}^{B_s^0} = \epsilon_{data}^{B^0} \times \frac{\epsilon_{MC}^{B_s^0}}{\epsilon_{MC}^{B^0}}$$

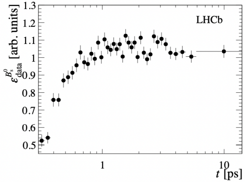


Figure 4: Signal efficiency as a function of the decay time, $\varepsilon_{\rm data}^{B_s^0}(t)$, scaled by the average

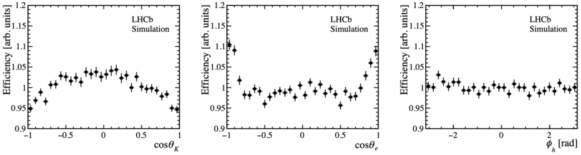


Figure 5: Efficiency projected onto (left) $\cos\theta_K$, (middle) $\cos\theta_e$ and (right) ϕ_h obtained from a simulated $B_s^0 \to J/\psi\phi$ sample, scaled by the average efficiency.

Syst. $B_s^0 \to J/\psi(e^+e^-)\phi$

Table 4: Statistical and systematic uncertainties. A dash corresponds to systematic uncertainties that are negligible. Systematic uncertainties from different sources are added in quadrature.

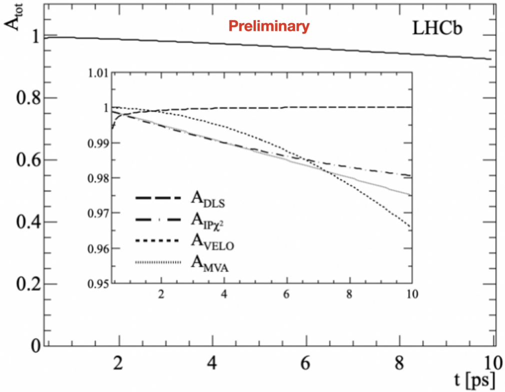
Source	Γ_s [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	$A_\perp^2$	A_0^2	$\delta_\parallel$ [rad]	$\delta_\perp$ [rad]	ϕ_s [rad]	$\lvert\lambda\rvert$	F_S	δ_S [rad]
Stat. uncertainty	0.018	0.045	0.034	0.029	$^{+0.08}_{-0.07}$	$^{+0.43}_{-0.42}$	0.28	$^{+0.112}_{-0.116}$	$^{+0.042}_{-0.051}$	$^{+0.25}_{-0.27}$
Mass factorisation	0.003	0.003	0.005	0.007	0.01	0.03	0.02	0.011	0.017	0.01
Mass model	0.011	0.005	0.004	0.005	0.02	0.14	0.05	0.011	0.007	0.04
Ang. acceptance	–	–	0.002	0.001	–	0.02	0.01	0.005	0.003	0.02
Time resolution	0.002	0.008	0.004	0.002	0.06	0.02	0.03	0.003	0.002	0.01
Time acceptance	0.003	0.003	0.001	0.001	–	–	–	0.001	–	–
MC (time acc.)	0.001	0.001	0.001	–	–	–	–	–	–	–
MC (ang. acc.)	–	–	0.001	0.001	0.01	0.01	0.02	0.017	0.003	–
Λ_b^0 background	0.001	0.001	0.001	0.001	0.01	–	0.01	0.005	0.01	–
Ang. resolution	–	0.002	0.002	0.003	–	0.01	–	–	0.005	–
B_c^+ background	0.003	–	–	–	–	–	–	–	–	–
Fit bias	–	–	–	0.009	–	–	–	0.020	–	–
Syst. uncertainty	0.012	0.011	0.008	0.013	0.07	0.15	0.07	0.031	0.022	0.05
Total uncertainty	0.022	0.046	0.035	0.032	0.10	$^{+0.46}_{-0.45}$	0.29	$^{+0.117}_{-0.121}$	$^{+0.047}_{-0.056}$	$^{+0.26}_{-0.28}$

Mass fit in τ_L measurement

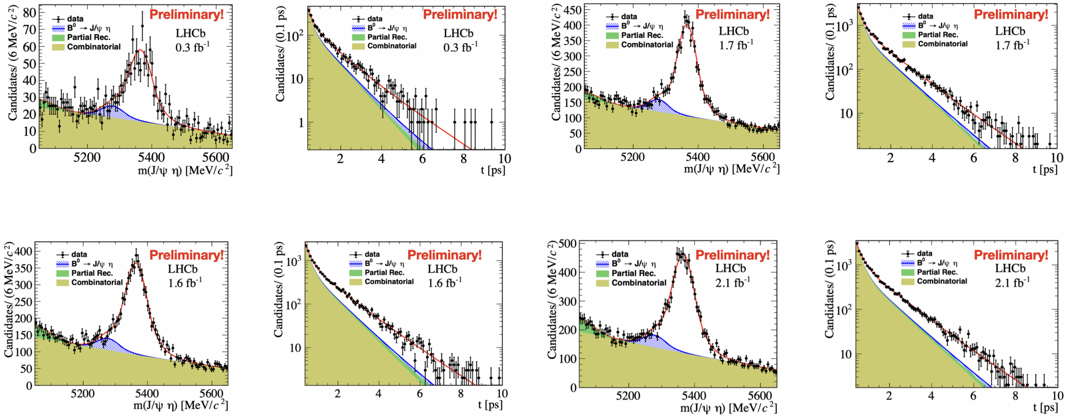
- $B_s^0 \to J/\psi\eta$: Double sided crystal Ball (tail parameters from MC)
- $B^0 \to J/\psi\eta$: Double sided crystal Ball (it overlaps w/ signal mode, differences of mass peaks to known value $87.22 \pm 0.16\mathrm{MeV/c^2}$).
- Combinatorial bkg: 2nd order Chebyshev polinomial.
- $B_s^0 \to J/\psi\phi(\eta\gamma)$: bifurcated Gaussian function.
- $B_s^0 \to X_{c1,c2}(J/\psi\gamma)(\eta)$: Error function based on simulation (unknown lifetime left free in the fit).

Decay time fit in τ_L measurement

1. All (exc. comb bkg) $Exp(t) \circledast Res(t) \circledast Acc(t)$ *Comb bkg = Sum of two exps.
2. σ in Res(t)=52fs from simulation.
3. $Acc(t) = A_{DLS} * A_{VELO} * A_{IP} * A_{MVA}$
4. A_{DLS}: Decay Length significance (by trigger requirements). Modeled using simulation and calibrated on $B^+ \to J/\psi K^+$ data.
5. A_{IP}: Requirements on χ^2_{IP}, modeled using simulated signal decays.
6. A_{VELO}: Less efficiency when Distance of closest approach increases. (1/3 respect to Run1). Calibration of order 2 fror simulation $(1 - \beta t - \gamma t^2)$.
7. A_{MVA}: χ^2_{IP} in MVA. Linear acceptance correction.
8. Fit bias with/without A $\to$ 18fs.



Fit τ_L


data
B0 → J/ψ η
Partial Rec.
Combinatorial
Preliminary!
LHCb
0.3 fb-1
1.7 fb-1
1.6 fb-1
2.1 fb-1
Candidates/ (6 MeV/c2)
Candidates/ (0.1 ps)
m(J/ψ η) [MeV/c2]
t [ps]

Syst in τ_L measurement

Table 1: Systematic uncertainties on the lifetime measurement in fs. Uncertainties less than 0.1 fs are indicated with a dash.

Source	Uncertainty [fs]
Simulated sample sizes	5.2
A_β	1.1
$A_{\chi^2_{\text{IP}}}$	0.4
A_{DLS}	–
MVA acceptance	1.7
B^+ lifetime	4.0
Time resolution model	0.3
VELO half alignment	3.8
τ for $B^0_s \to \chi_c \eta$ component	0.7
Mass model	0.8
Momentum scale	–
z-scale	0.3
B^0 component	0.4
Data-MC χ^2_{IP} differences	0.1
Mass-time correlation	0.5
B_c^+ component	1
Quadrature sum	8.0

Preliminary!