Beauty to charmonium decays at LHCb experiment

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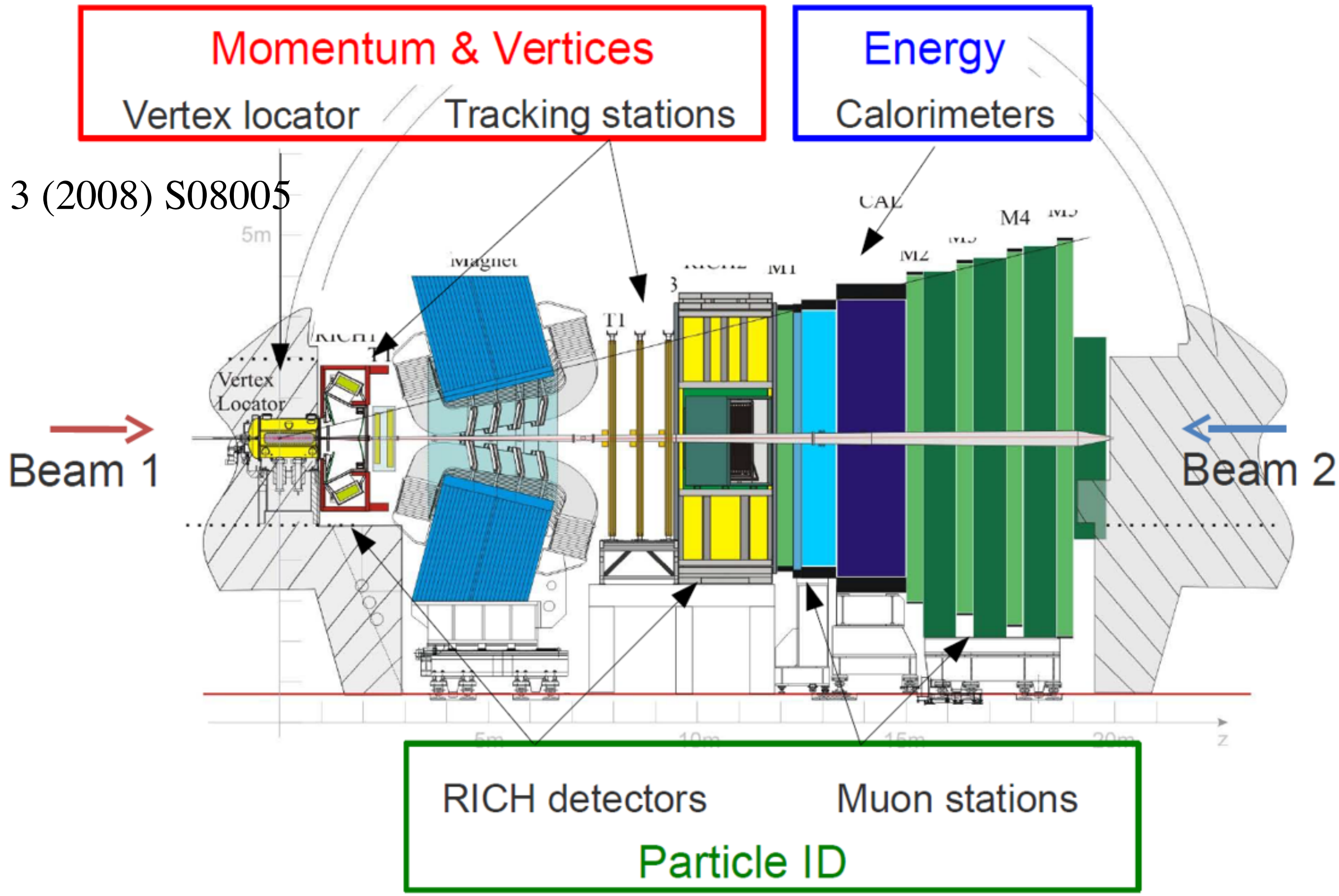
On behalf of LHCb collaboration
@ ICHEP meeting

ICHEP 2022 BOLOGNA

LHCb detector

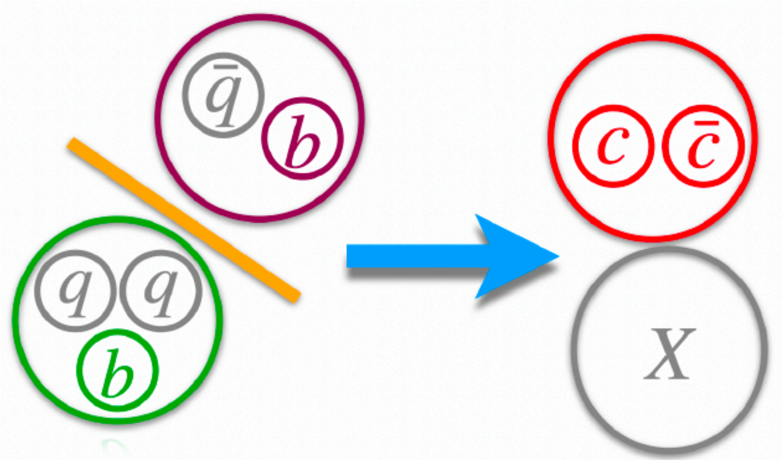
- Designed for beauty and charm physics, $2 < \eta < 5$
- Collected 3 fb^{-1} in 2011-2012 (Run 1), 6 fb^{-1} in 2015-2018 (Run 2)



JINST 3 (2008) S08005

Physics goals

- Beauty to charmonium decays
  - ✓ Mainly dominant by tree-level ($b \longrightarrow ccq$) $\Longrightarrow$ **stringent tests for SM,** such as mixing parameters in neutral B mesons
  - ✓ Focus on measurements of CPV, life time, Branching ratios…

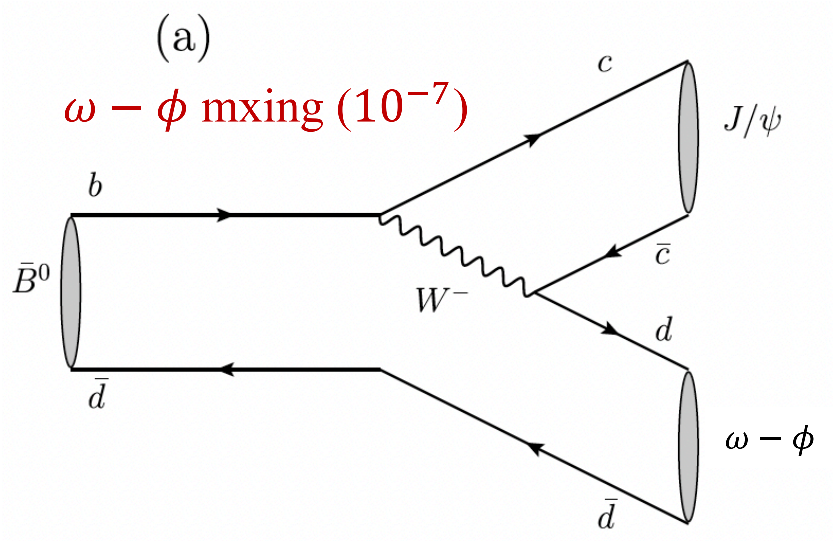


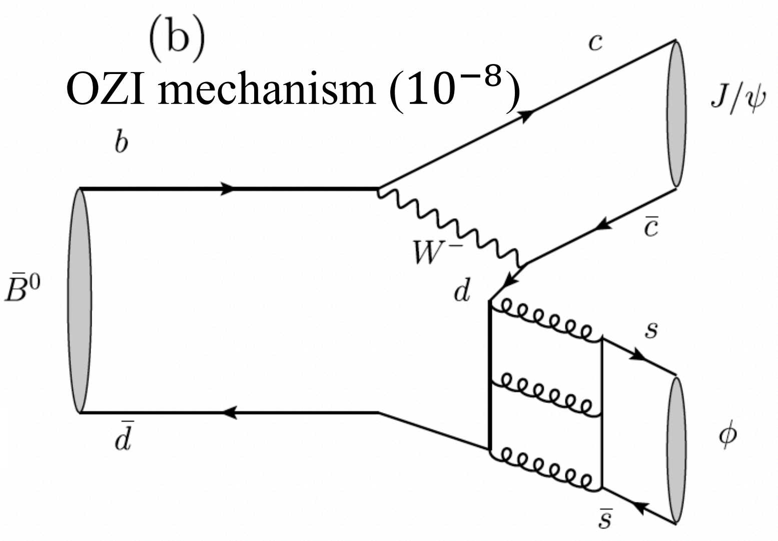
LHCb recent results

- ☐ Search for the rare decay $B^0 \to J/\psi\phi$
- ☐ Measure ϕ_s in $B_s^0 \to J/\psi(e^+e^-)\phi$ decay
- ☐ Measure τ_L in $B_s^0 \to J/\psi\eta$ decay

Search for the rare decay $B^0 \to J/\psi\phi$ [Chin. Phys. C45 (2021) 043001]

- $B^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ decay
  - ✓ Cabbibo suppressed $b \to c\bar{c}d$ transition
  - ✓ ϕ meson is produced by $\omega - \phi$ mixing or OZI mechanism **[Phys. Lett. B677 (2009) 278]**
  - ✓ Predicted BR : $(1.0 \pm 0.3)\times10^{-7}$ [PLB 666(2008)185188, PRD.88.072005]
  - ✓ Previous LHCb result @1 fb^{-1} : $\mathrm{BR} < 1.9\times10^{-7}$ [PRD.88.072005]





Search for the rare decay $B^0 \to J/\psi\phi$ [Chin. Phys. C45 (2021) 043001]

- Use full Run 1+2 data to search $B^0 \to J/\psi\phi$ decay, with control channel $B_s^0 \to J/\psi\phi$ decay

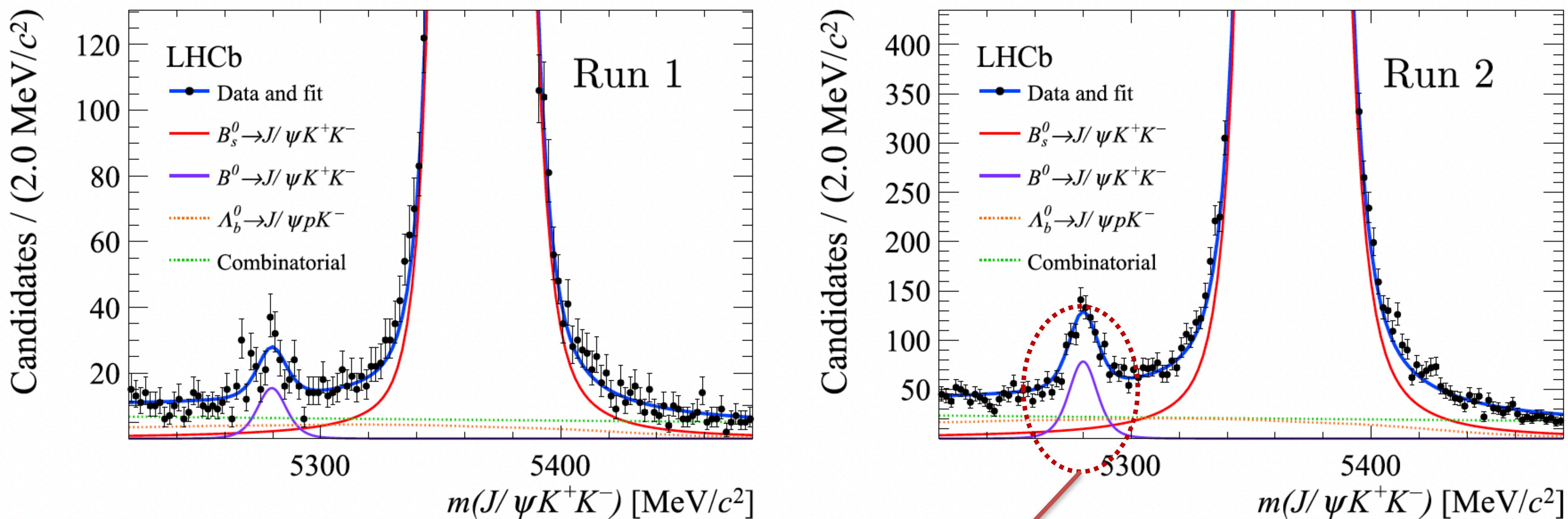
$$\mathcal{B}(B^0 \to J/\psi\phi) = \frac{N_{B^0}^{\phi}}{N_{B_s^0}^{\phi}} \times \mathcal{B}(B_s^0 \to J/\psi\phi) \times f_s/f_d (\times f_{scale}) \times \frac{\varepsilon_{B_s^0}}{\varepsilon_{B^0}}$$

- $\mathcal{B}(B_s^0 \to J/\psi\phi) = (\,10.50 \pm 0.13 \pm 0.64 \pm 0.82\ (f_s/f_d)\,) \times 10^{-3}$ [PhysRevD.87.072004]
- $f_s/f_d = 0.259 \pm 0.015$ [JHEP04(2013)001]
- $f_{scale} = 1.068 \pm 0.046$, scaling factor at 13 TeV [PRL. 118(2017)191801]
- $\varepsilon_{B^0}/\varepsilon_{B_s^0}$, efficiency ratio

- Perform sequential fits to $m(J/\psi K^+K^-)$ and $m(K^+K^-)$ due to correlation

- Use the PLS (Profile Likelihood Scan) method to set upper limit

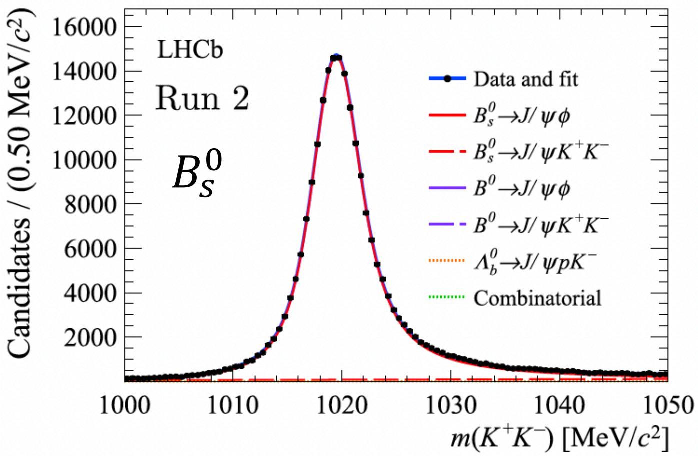
- Fit to $m(J/\psi K^+K^-)$
  - ✓ estimate the yields of each component in B^0 & B_s^0 signal regions
  - ✓ yields total ~800 $B^0 \to J/\psi K^+K^-$ signal events in B^0 signal region

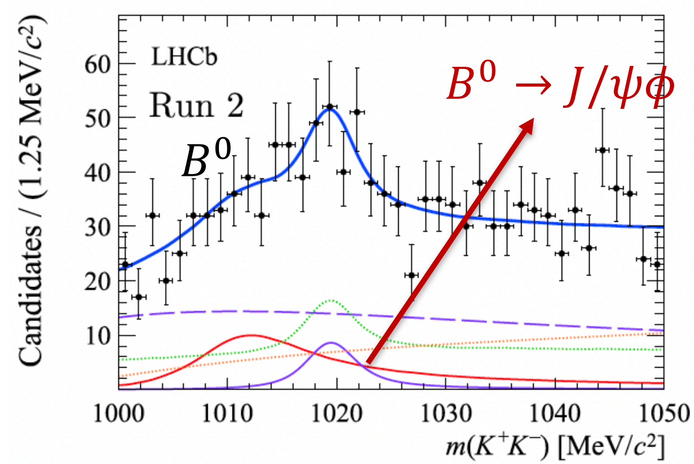


$B^0 \to J/\psi K^+K^-$

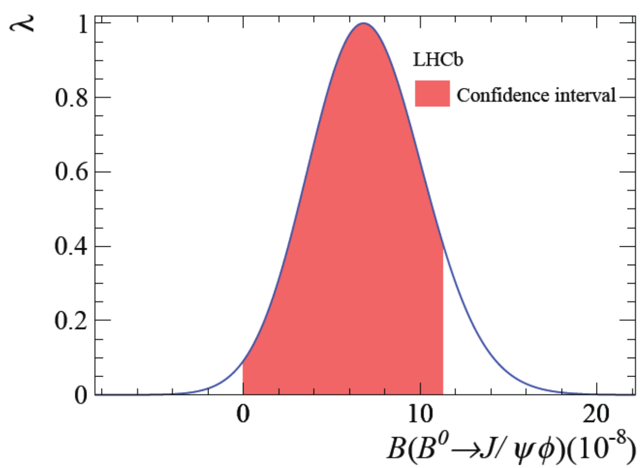
Search for the rare decay $B^0 \to J/\psi\phi$ [Chin. Phys. C45 (2021) 043001]

- Fit to m(K^+K^-) with ϕ shape determined from $B_s^0 \to J/\psi\phi$ decay
  - ✓ $\mathcal{B}(B^0 \to J/\psi\phi) = (6.9 \pm 3.0 \pm 0.9)\times 10^{-8}$, significance ~$2.3\sigma$





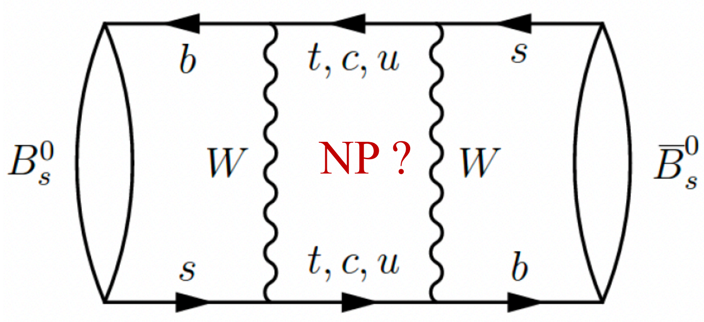
- Profile Likelihood Scan on $\mathcal{B}(B^0 \to J/\psi\phi)$

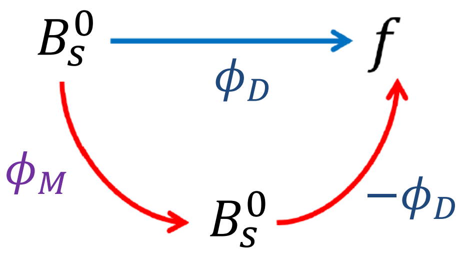


$\mathcal{B}(B^0 \to J/\psi\phi) <$ **1.1×10^{-7}**
at 90% C.L.
Improved upper limit, which is compatible with theoretical prediction.

Measure ϕ_s in $B_s^0 \to J/\psi(e^+e^-)\phi$ decay [Eur. Phys. J. C81 (2021) 1026]

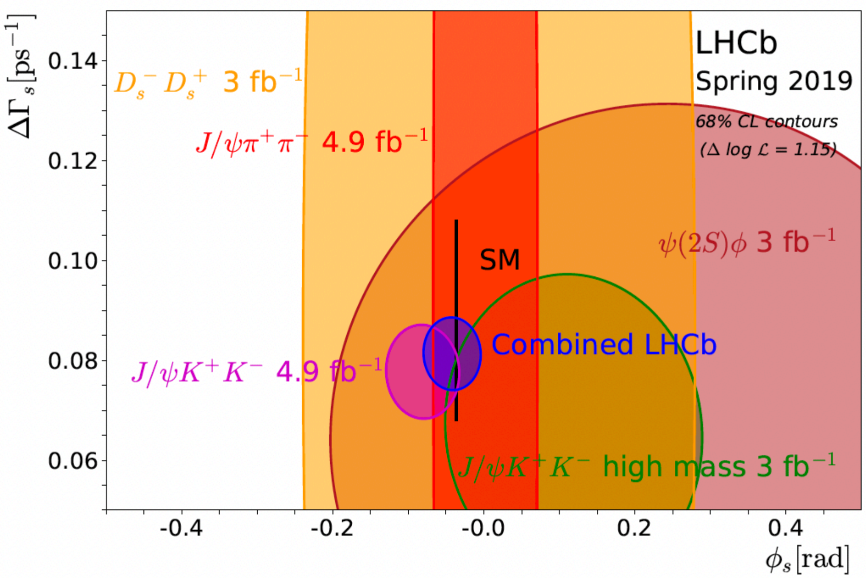
- CPV of interference between mixing and decay





Weak phase $\phi_s = \phi_M - 2\phi_D$

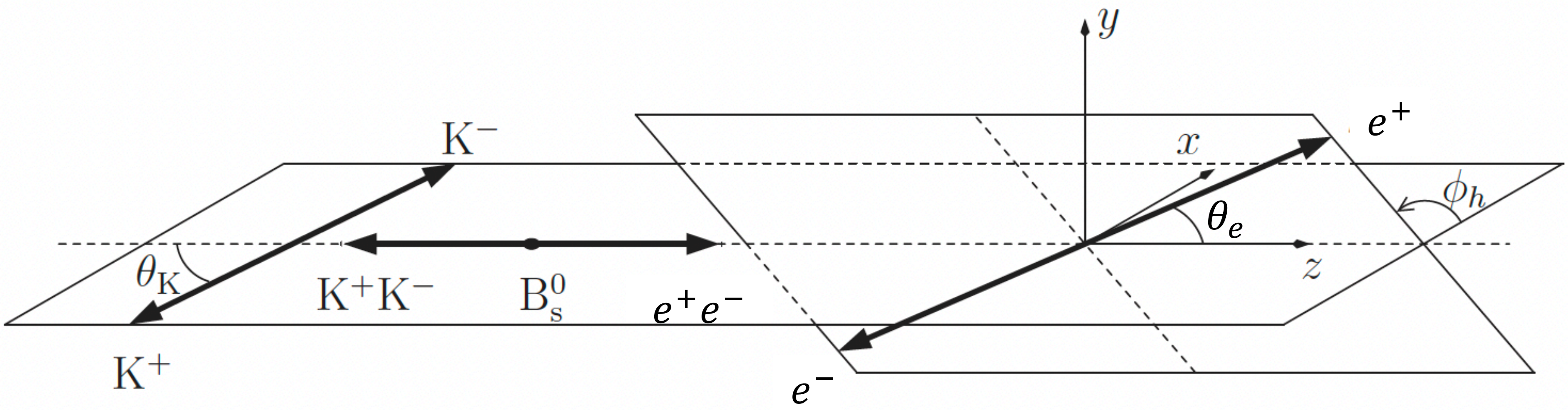
- Why is this interesting ?
  - ✓ excellent test for theoretical prediction
    $\phi_s = -2\beta_s = -37.0^{+0.8}_{-0.7}$ mrad [1]
  - ✓ sensitive to New Physics in B_s^0 mixing
  - ✓ LHCb results @ 4.9 fb^{-1} [2]:
    $\phi_s = 42 \pm 25$ mrad
    $\Delta\Gamma_s = 0.0813 \pm 0.0048\ \text{ps}^{-1}$
  - ✓ $B_s^0 \to J/\psi(e^+e^-)\phi$ is to be included



[1] CKM Fitter
[2] Eur. Phys. J. C 80 (2020) 601

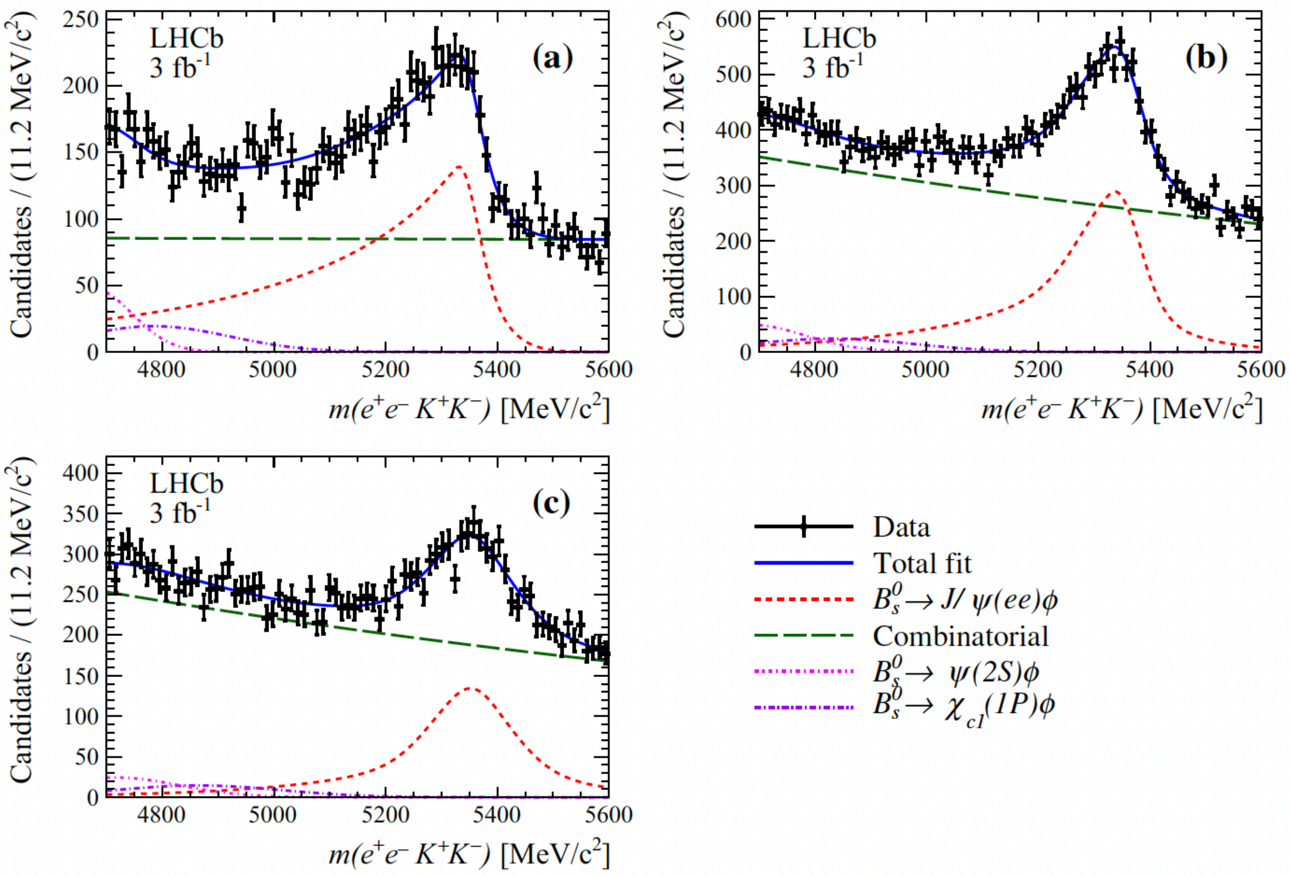
Measure ϕ_s in $B_s^0 \to J/\psi(e^+e^-)\phi$ decay [Eur. Phys. J. C81 (2021) 1026]

- First time to measure ϕ_s in this decay, 3 fb^{-1} (Run 1)
- Perform a flavour tagged time-dependent angular analysis in helicity basis, with distinguished final states: *CP* odd and even, s-wave



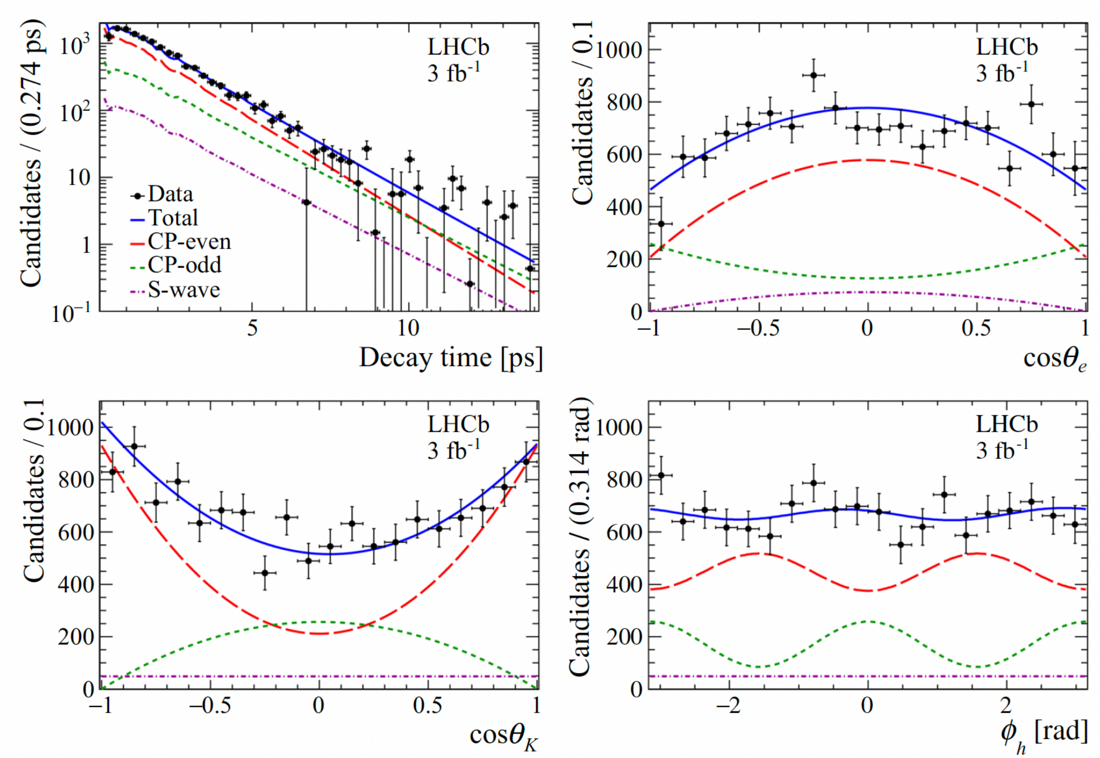
Measure ϕ_s in $B_s^0 \to J/\psi(e^+e^-)\phi$ decay [Eur. Phys. J. C81 (2021) 1026]

- Fit to $m(e^+e^-K^+K^-)$
  - ✓ Fit B_s^0 mass with 0, 1 and 2 electrons applied with bremsstrahlung correction
  - ✓ Yield total ~13 k signal events, with a tagging power ~5% and a time resolution ~46 fs



Measure ϕ_s in $B_s^0 \to J/\psi(e^+e^-)\phi$ decay [Eur. Phys. J. C81 (2021) 1026]

➢ Fit projections and measured results



Par.	Value
ϕ_s	$0.00 \pm 0.28 \pm 0.07$ rad
$\Delta\Gamma_s$	$0.115 \pm 0.045 \pm 0.011$ ps^{-1}
$\|\lambda\|$	$0.877^{+0.112}_{-0.116} \pm 0.031$
Γ_s	$0.608 \pm 0.018 \pm 0.012$ ps^{-1}

- ☐ Statistical uncertainty is dominant
- ☐ Consistent with SM and previous results
- ☐ No CPV is found

Measure τ_L in $B_s^0 \to J/\psi\eta(\gamma\gamma)$ decay [arXiv:2206.03088]

- $\Delta\Gamma_s$ and τ_L in B_s^0 system
  - ✓ Sizeable prediction of $\Delta\Gamma_s = \Gamma_L - \Gamma_H = 0.091 \pm 0.013\ \text{ps}^{-1}$ [1]
  - ✓ $\Delta\Gamma_s$ can be directly measured or inferred from measured τ_L & τ_H
  - ✓ Precise measurement of τ_L gives stringent tests of consistency between two cases, and also SM prediction of $\tau_L = 1.422 \pm 0.013$ ps [1,2]

[1] Eur.Phys.J. C71 (2011) 1789
[2] JHEP07(2020)177

- τ_L in $B_s^0 \to J/\psi\eta(\gamma\gamma)$ decay
  - ✓ Mass eigenstates ≈ *CP* eigenstates due to small CPV in mixing
  - ✓ Pure *CP* even final state ⟹ TD angular analysis is not needed

□ $\tau_L = \tau_{\text{eff}}$ is accessible by a decay-time fit

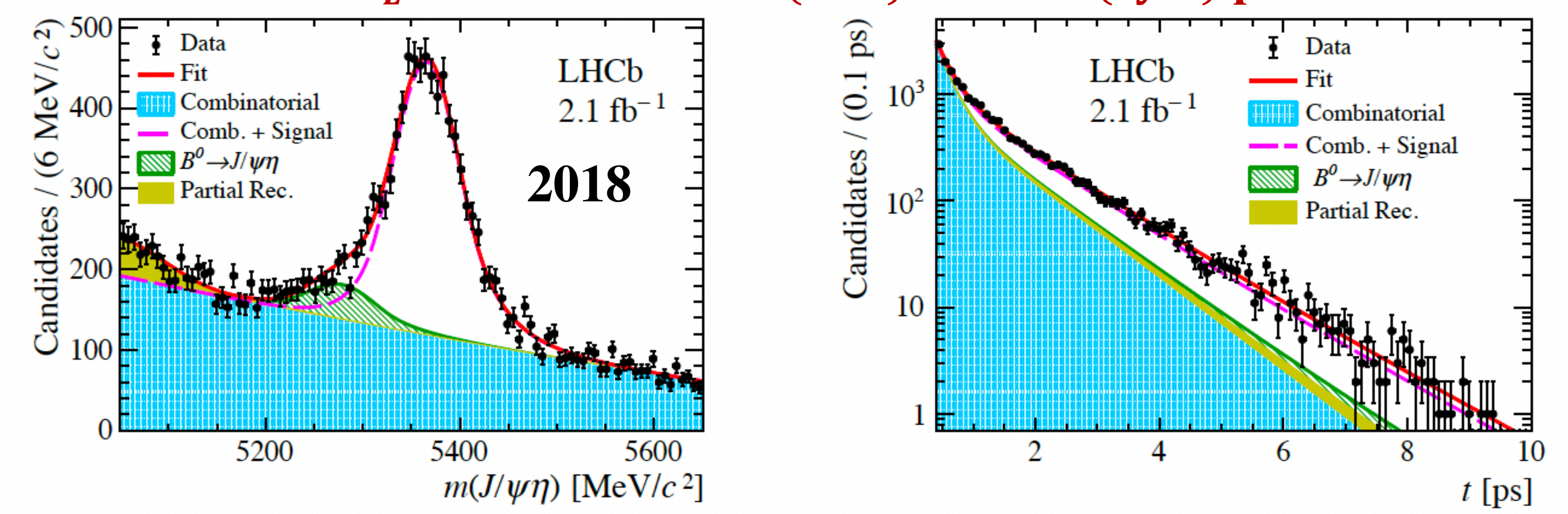
□ Update τ_L measurement with full Run 2 data

Measure τ_L in $B_s^0 \to J/\psi\eta(\gamma\gamma)$ decay [arXiv:2206.03088]

- Perform a 2D fit to $m(J/\psi\eta)$ and decay-time
  - ✓ **Mass fit:**
    - B_s^0 & B^0 peaks by double sided Crystal Ball, comb. bkg. by 2nd Chebyshv
    - partially rec. bkg. by the models determined from simulations
  - ✓ **Decay-time fit:** $[e^{-t/\tau_L} \otimes \mathrm{Res}(t)] \times \mathrm{Acc}(t)$
    - $\mathrm{Res}(t)$, single gaussian with an average width ~52 fs
    - $\mathrm{Acc}(t)$, efficiency function determined from simulations

Run 1: $\tau_L = 1.479 \pm 0.034(\mathrm{stat}) \pm 0.011(\mathrm{syst})$ ps

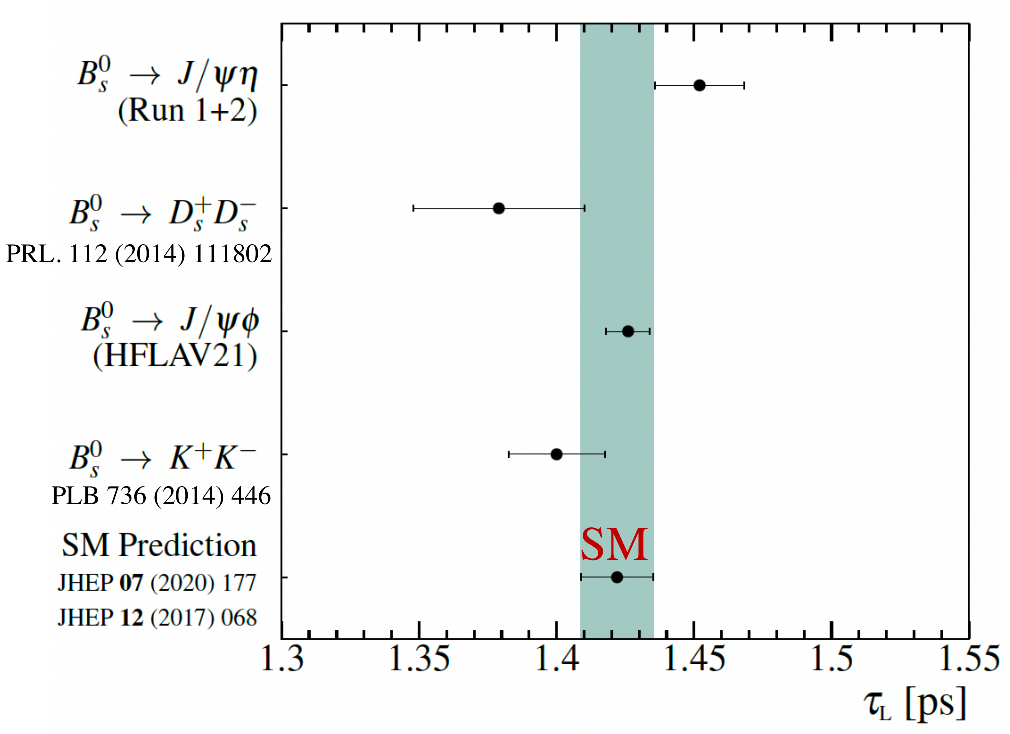
Run 2: $\tau_L = 1.445 \pm 0.016(\mathrm{stat}) \pm 0.008(\mathrm{syst})$ ps



Measure τ_L in $B_s^0 \to J/\psi\eta(\gamma\gamma)$ decay [arXiv:2206.03088]

Measured results

- More precise than results in $B_s^0 \to D_s^+ D_s^-$ and $B_s^0 \to K^+K^-$ analyses
- Consistent with previous HFLAV 2021 result and SM prediction
- All results are compatible



Mode	τ_L [ps]
Run 1+2	$1.452 \pm 0.014 \pm 0.008$
$B_s^0 \to D_s^+ D_s^-$	$1.379 \pm 0.026 \pm 0.017$
$B_s^0 \to K^+K^-$	$1.407 \pm 0.016 \pm 0.007$
HFLAV2021	1.426 ± 0.008
SM	1.422 ± 0.013

Summary

- Update a search for the rare decay $B^0 \to J/\psi\phi$ (@9 fb^{-1}), and obtain an improved upper limit of $\mathcal{B}(B^0 \to J/\psi\phi) < 1.1\times10^{-7}$.

- First measurement of ϕ_s in $B_s^0 \to J/\psi(e^+e^-)\phi$ decay (@3 fb^{-1}). The obtained results are consistent with previous results and SM.

- Update measurement of lifte time τ_L in $B_s^0 \to J/\psi\eta$ decay, and obtain combined $\tau_L = 1.452 \pm 0.014 \pm 0.008$ ps (@9 fb^{-1}), which is consistent with other LHCb results and SM.

Stay tuned for many interesting new results !

Backup

LHCb performance numbers

Integrated luminosity	2011: 1.0 fb-1
	2012: 2.0 fb-1
	2015: 0.30 fb-1
	2016: 1.6 fb-1
	2017: 1.7 fb-1
	2018: 2.1 fb-1
Geometrical acceptance	pseudorapidity: $2 < \eta < 5$
	angle: $10 < \theta < 300$ / 250 mrad (bending /non bending plane)

LHCb performance numbers

Resolutions	momentum resolution: $\Delta p / p$ = 0.5 % at low momentum to 1.0% at 200 GeV/c (see the detector performance paper for a plot)
	ECAL resolution (nominal): 1 % + 10 %/ $\sqrt{(E[GeV])}$
	impact parameter resolution: (15 +29/pT[GeV]) μm
	invariant mass resolution: ~8 MeV/c^2 for $B \to J/\psi X$ decays with constraint on J/ψ mass ~22 MeV/c^2 for two-body B decays ~100 MeV/c^2 for $B_s \to \varphi \gamma$, dominated by photon contribution
	decay time resolution: ~45 fs for $B_s \to J/\psi \varphi$ and for $B_s \to D_s \pi$
Efficiencies	percentage of working detector channels: ~99 % for all sub-detectors
	data taking efficiency:90 % (good for analyses: 99%)
	trigger efficiencies: ~ 90 % for dimuon channels ~ 30 % for multi-body hadronic final states
	track reconstruction efficiency: ~ 96 % for long tracks
	Particle ID efficiency: Electron ID ~ 90 % for ~ 5 % $e \to h$ mis-id probability Kaon ID ~ 95 % for ~ 5 % $\pi \to K$ mis-id probability Muon ID ~ 97 % for 1-3 % $\pi \to \mu$ mis-id probability

m($J/\psi K^+K^-$) fit results in $B^0 \to J/\psi\phi$ analysis

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

- Simultaneous fit of Run 1 and Run 2 samples

$$\mathrm{P}_{s/d}^{tot} = N_{s/d}^{\phi}\times\mathrm{S}_{\phi}(m) + N_{s/d}^{non}\times\mathrm{S}_{non}(m) + N_{s/d}^{\Lambda_b^0}\times\mathrm{B}_{\Lambda_b^0}(m)$$
$$+N_{s/d}^{com}\times\mathrm{B}_{com}(m) + N_{d}^{B_s^0}\times\mathrm{T}_{B_s^0}(m)$$

- S_{ϕ}, same lineshape for $B_{s/d}^0 \to J/\psi\phi$ decays
- S_{non}, $f_0(980)/a_0(980)$+nonresonance for $B_{s/d}^0 \to J/\psi K^+K^-$ decays
- $\mathrm{B}_{\Lambda_b^0}$ & B_{com}, shapes of Λ_b^0 and comb. bkg.
- $\mathrm{T}_{B_s^0}$, B_s^0 tail shape under B^0 peak
- fix the $N_{s/d}^{\Lambda_b^0}$, $N_{s/d}^{com}$, $N_{d}^{B_s^0}$ obtained from m($J/\psi K^+K^-$) fit

Systematics in $B^0 \to J/\psi\phi$ analysis

Multiplicative uncertainties	Value ($\% \times \mathcal{B}$)
$\mathcal{B}(B_s^0 \to J/\psi\phi)$	6.2
Scaling factor for f_s/f_d	3.4
$\varepsilon_{B^0}/\varepsilon_{B_s^0}$	1.8
Total	$\mathbf{k = 7.3}$
Additive uncertainties	**Value (10^{-8})**
$m(J/\psi K^+K^-)$ model of comb. bkg.	0.03
Fixed yields of Λ_b^0 in $m(K^+K^-)$ fit	0.05
Fixed yields of comb. bkg. in $m(K^+K^-)$ fit	0.62
Fixed yields of B_s^0 tail in $m(K^+K^-)$ fit	0.25
Constant d	0.01
$m(K^+K^-)$ shape of B_s^0 tail	0.29
$m(K^+K^-)$ shape of Λ_b^0	0.29
$m(K^+K^-)$ shape of comb. bkg.	0.17
$m(K^+K^-)$ shape of none-ϕ	0.06
Total	$\sigma_{\mathbf{model}} = \mathbf{0.83}$

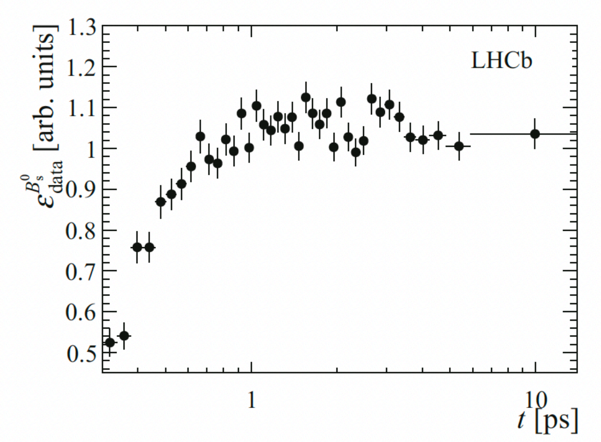
Relative uncertainties

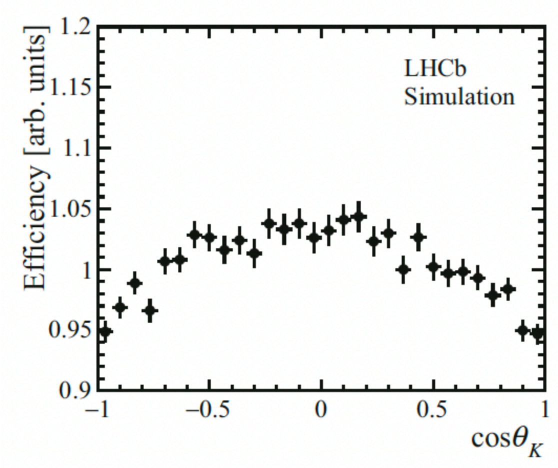
(1) m($J/\psi K^+K^-$) model
(2) Yields of bkground

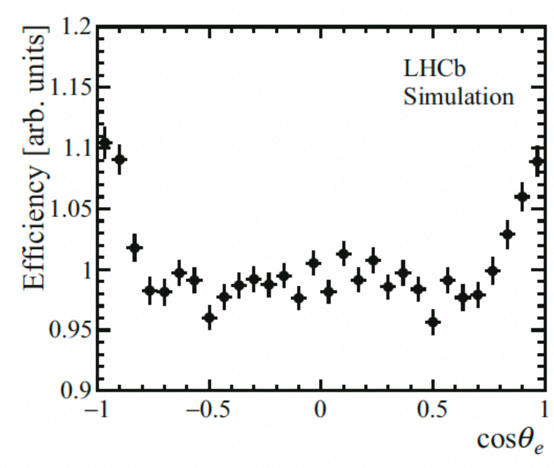
m(K^+K^-) shapes

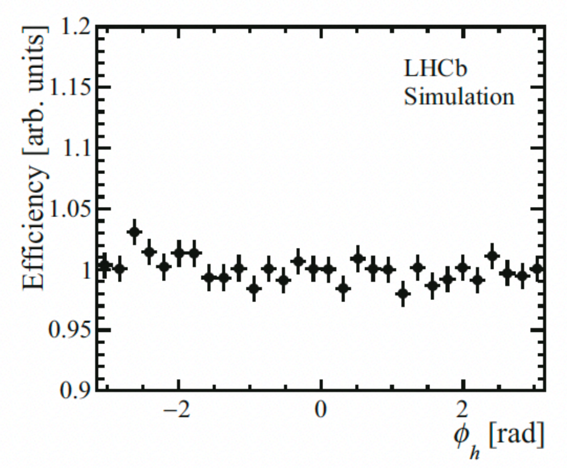
Compared to statistical uncertainty 3.1×10^{-8}, they are small

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









Systematics in $B_s^0 \to J/\psi\eta$ analysis

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	$^{+0.117}_{-0.121}$	$^{+0.047}_{-0.056}$	$^{+0.26}_{-0.28}$

τ_L prediction in $B_s^0 \to J/\psi\eta$ analysis

- **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]

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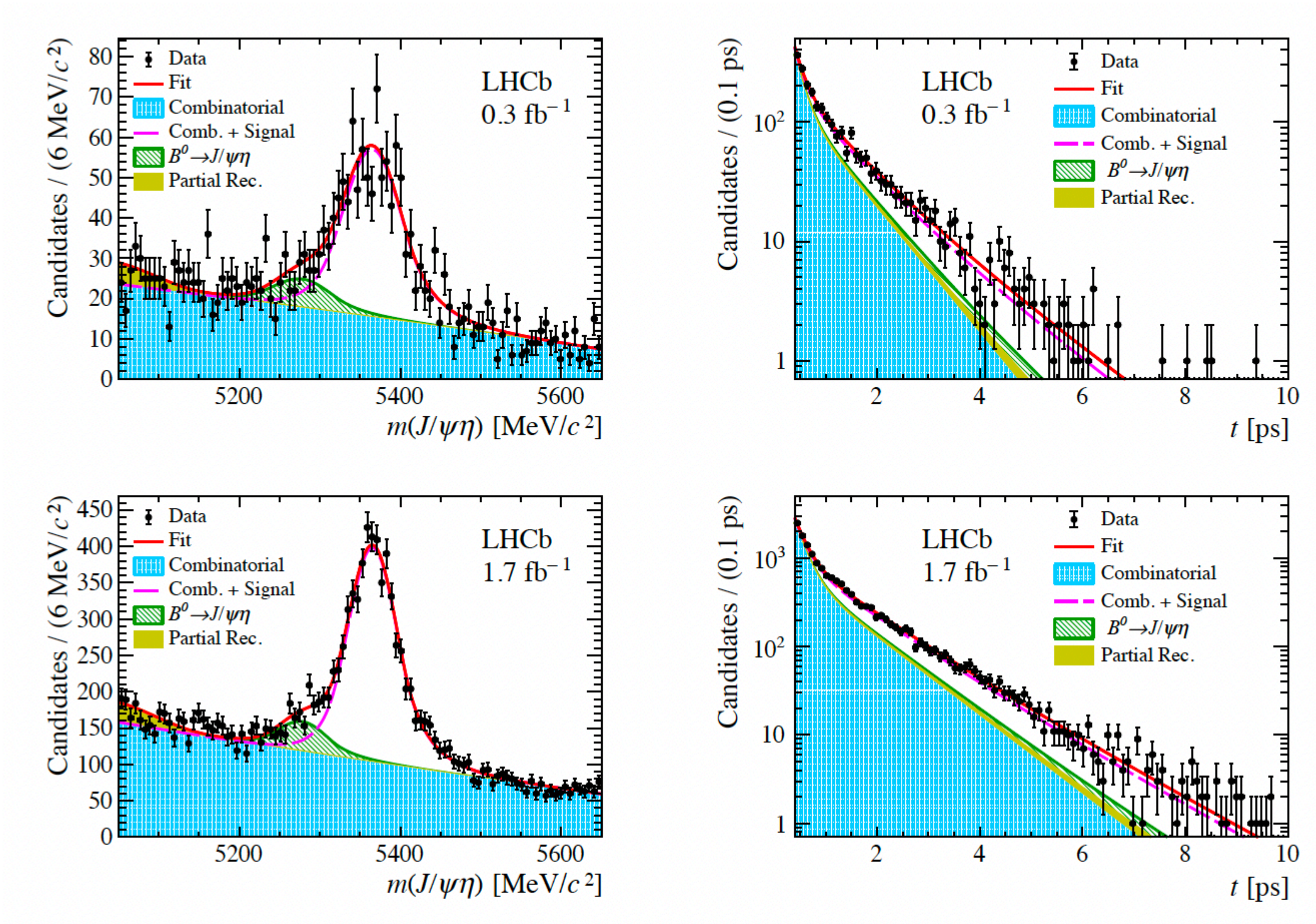
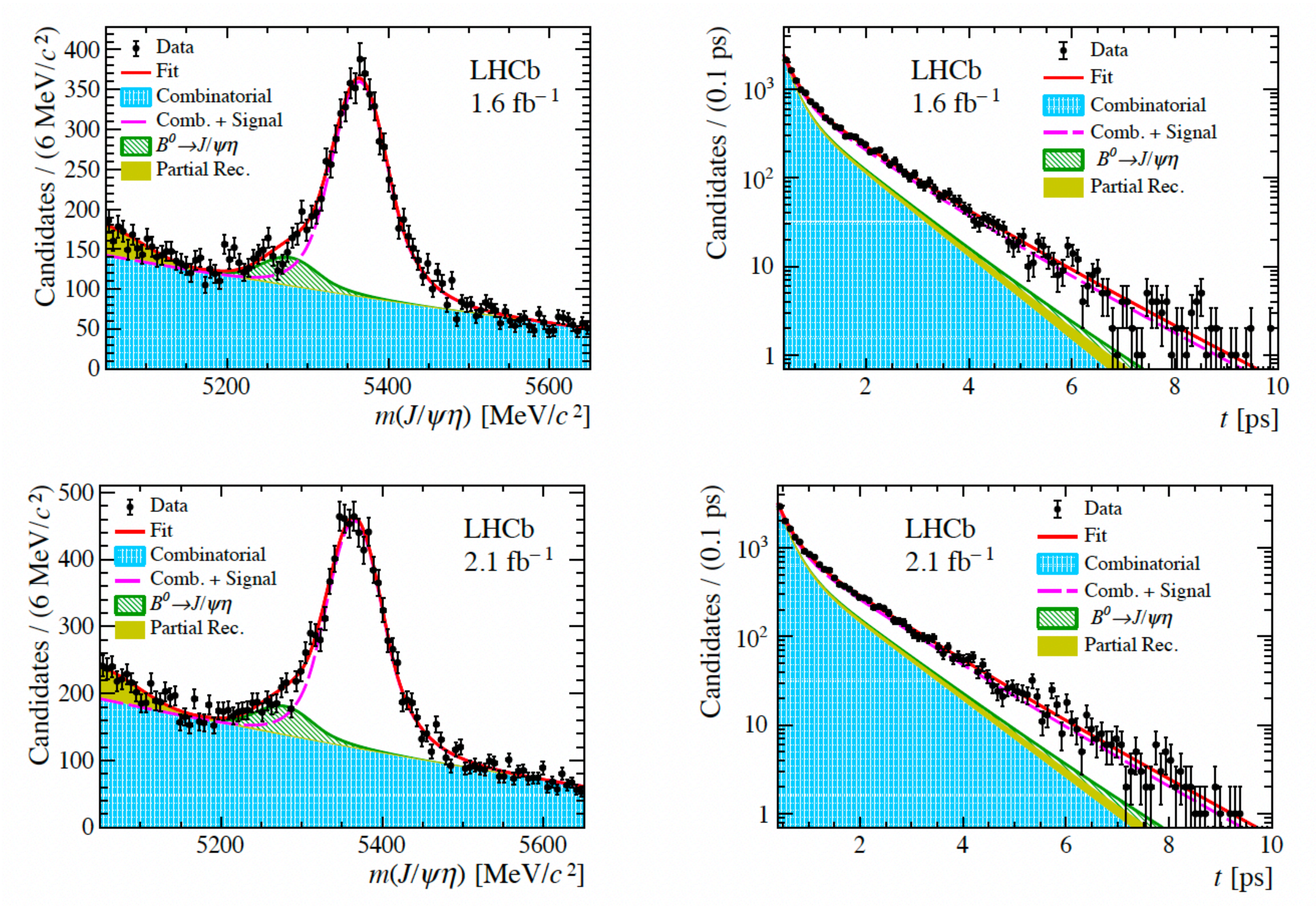
[3] Fleischer et al.,Eur.Phys.J. C71 (2011) 1789

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

Fit results in $B_s^0 \to J/\psi\eta$ analysis



Fit results in $B_s^0 \to J/\psi\eta$ analysis



Decay-time efficiency in $B_s^0 \to J/\psi\eta$ analysis

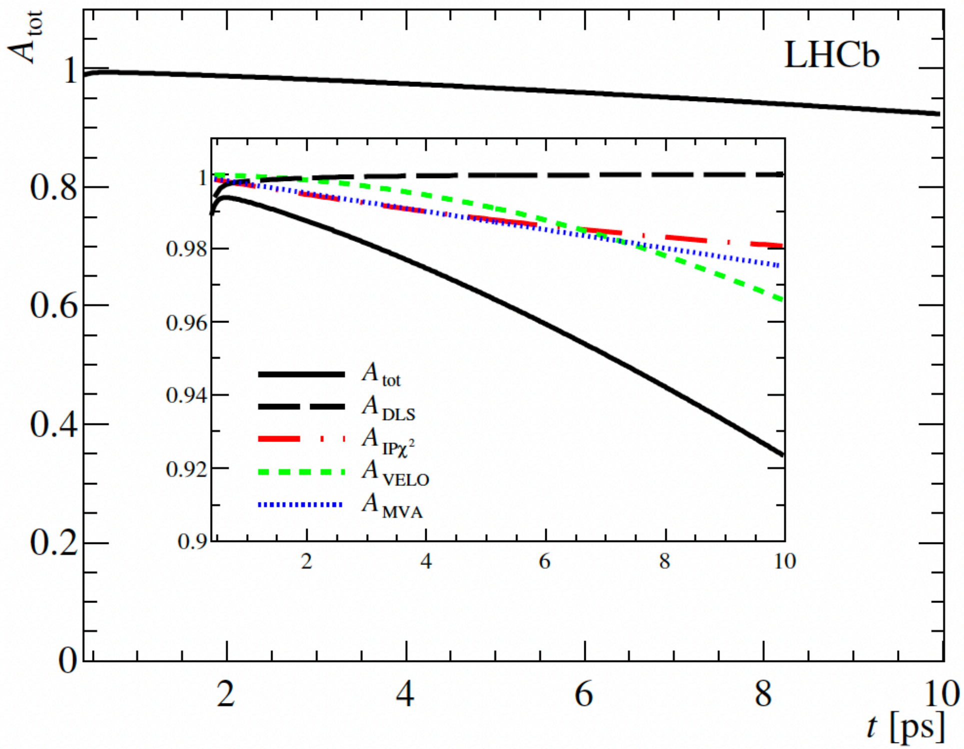


Figure 2: Total acceptance function, A_{tot} for the 2016 data taking period. The insert shows the four individual components of the acceptance that are multiplied to give A_{tot}. The acceptance functions for the other years are similar.

Systematics in $B_s^0 \to J/\psi\eta$ analysis

Source	Uncertainty [fs]
Simulated sample sizes	5.2
A_{VELO}	1.1
A_{DLS}	–
$A_{\mathrm{IP}\chi^2}$	0.4
A_{MVA}	1.7
B^+ lifetime	4.0
Time resolution model	0.3
VELO half alignment	3.8
τ for $B_s^0 \to \chi_c\eta$ component	0.7
Mass model	0.8
B^0 component	0.4
Momentum scale	–
z-scale	0.3
Data-simulation χ^2_{IP} differences	0.1
Mass-time correlation	0.5
B_c^+ component	1.0
Quadrature sum	8.0