Time-dependent CP violation in B_s^0 decays at LHCb

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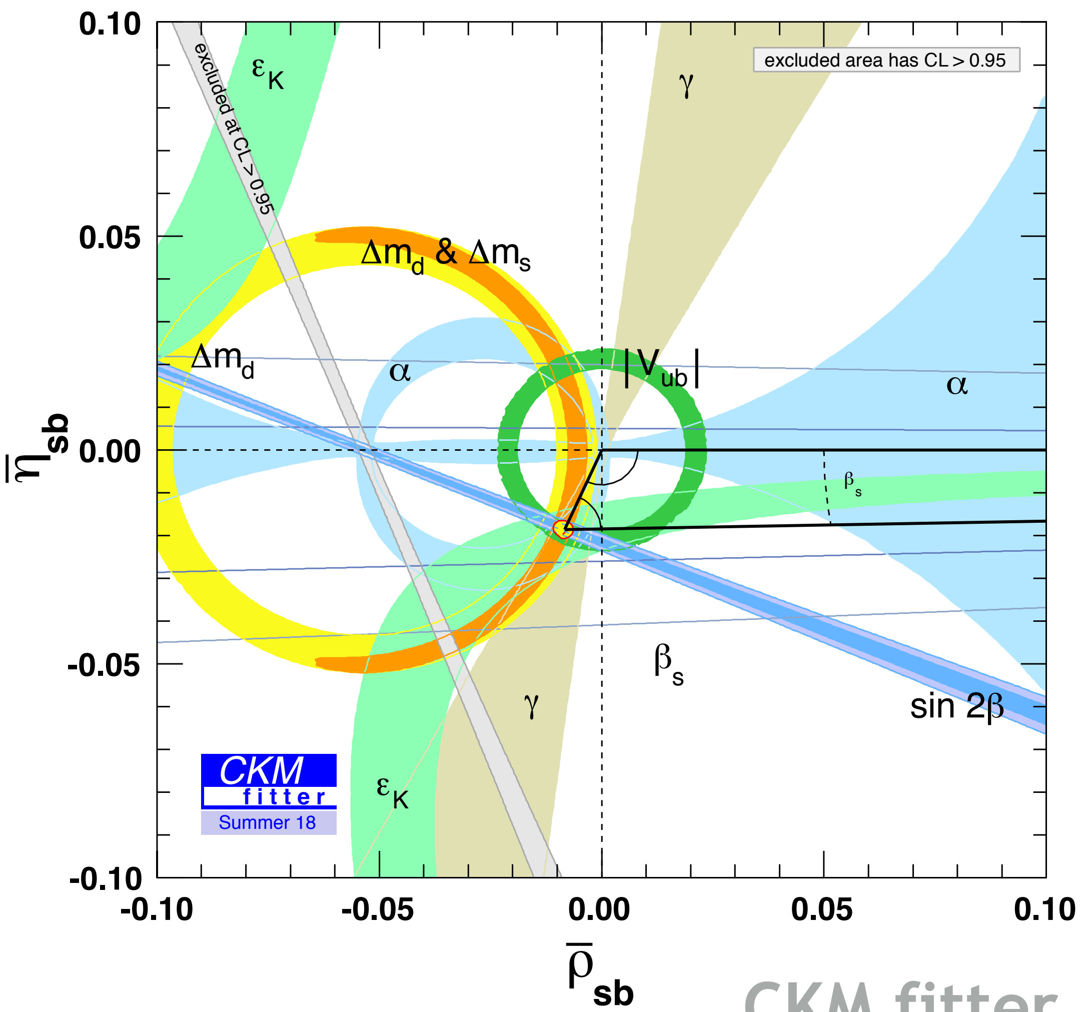
on behalf of the LHCb Collaboration

FPCP May 6-10 2019
Victoria, Canada

Motivation

The Standard Model (SM) fails to explain the matter-antimatter difference observed in our universe.
Looking for new sources of CP violation (CPV) can help explain this asymmetry.

B_s^0 mixing provides a sensitive probe to new physics.
Measurement of the CP violation phase, $\phi_s^{c\bar{c}s} = -2\beta_s$, allows for precision SM tests.

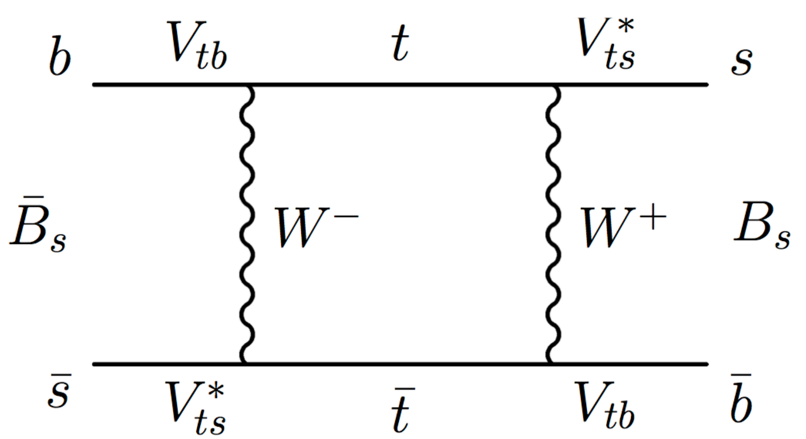


CKM fitter

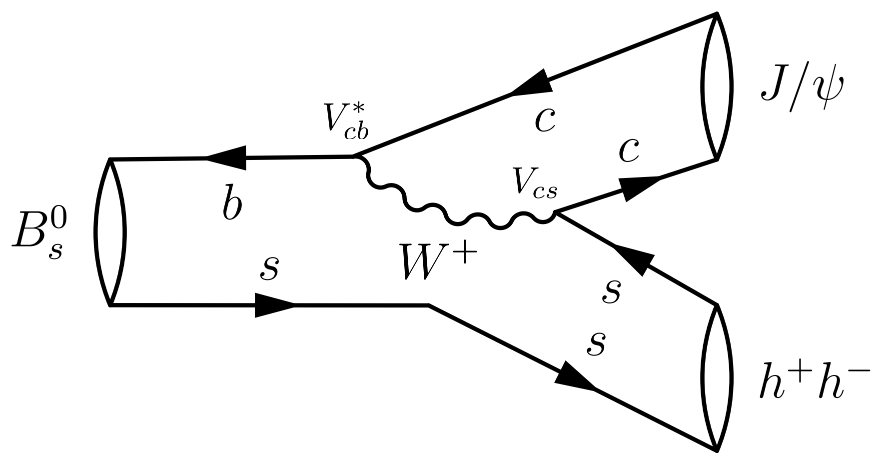
Motivation

- $\phi_s^{c\bar{c}s} = -2\beta_s$ measured in B_s^0 decays. Dependent on the CKM angle β_s.
- Analogous to CKM angle β in the B^0 system.

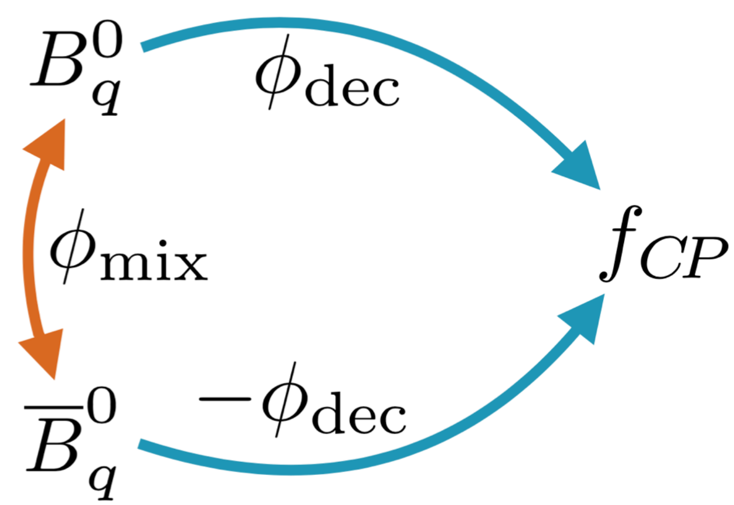
Mixing: $\phi_M = 2\arg(V_{ts}V_{tb}^*)$



Decay: $\phi_D = \arg(V_{cs}V_{cb}^*)$



$$\beta_s \equiv \arg\left(\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$



$$\phi_s \equiv \phi_{\text{mix}} - 2\phi_{\text{dec}}$$

- Interference between mixing and decay allows measurements of ϕ_s.

$B_s^0 \to \phi\phi$

Preliminary!!

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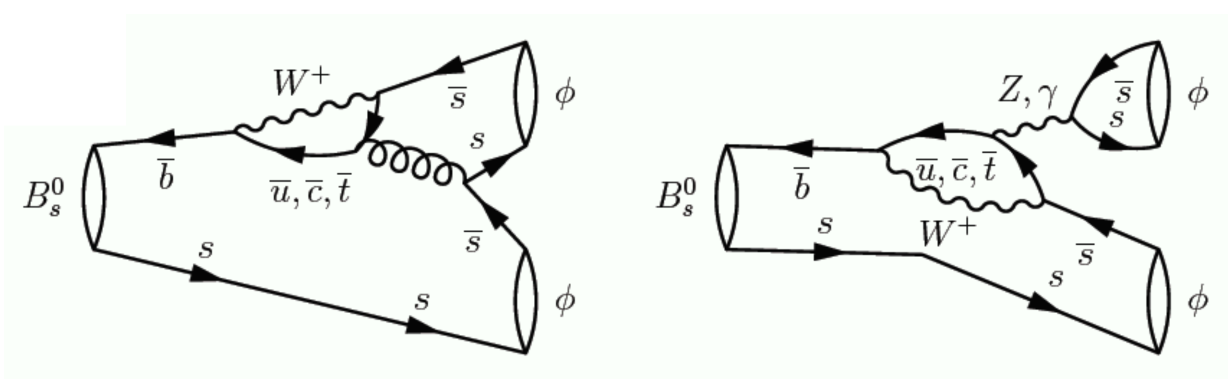
- Run 1 + 2015 + 2016 data

  [3.2 fb^{-1}] [0.3 fb^{-1}] [1.6 fb^{-1}]

Decay dominated by a penguin loop:

$\to$ Enhanced sensitivity to New Physics

Decay



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

Preliminary!!

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$B_s^0 \to J/\psi \pi^+\pi^-$

arXiv:1903.05530

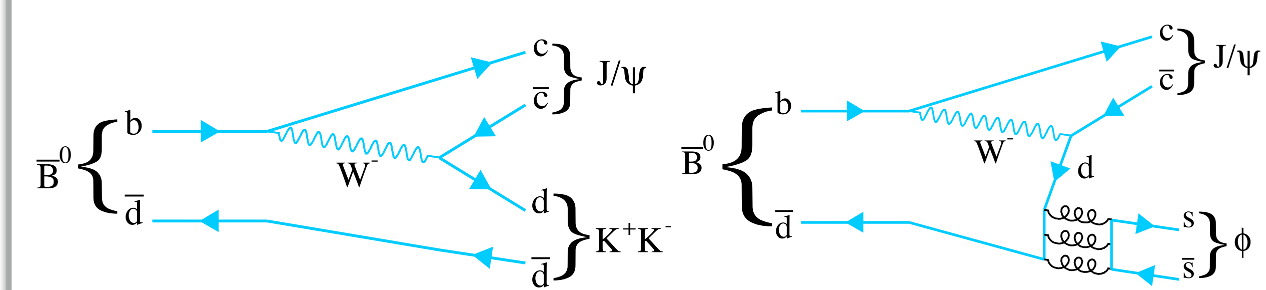
- 2015 + 2016 data

  [0.3 fb^{-1}] [1.6 fb^{-1}]

Two analyses on $B_s^0 \to J/\psi h^+h^-$:

- $h^+h^- = K^+K^-$ (ϕ mass region) $[0.99, 1.05]\mathrm{GeV}/c^2$
- $h^+h^- = \pi^+\pi^-$

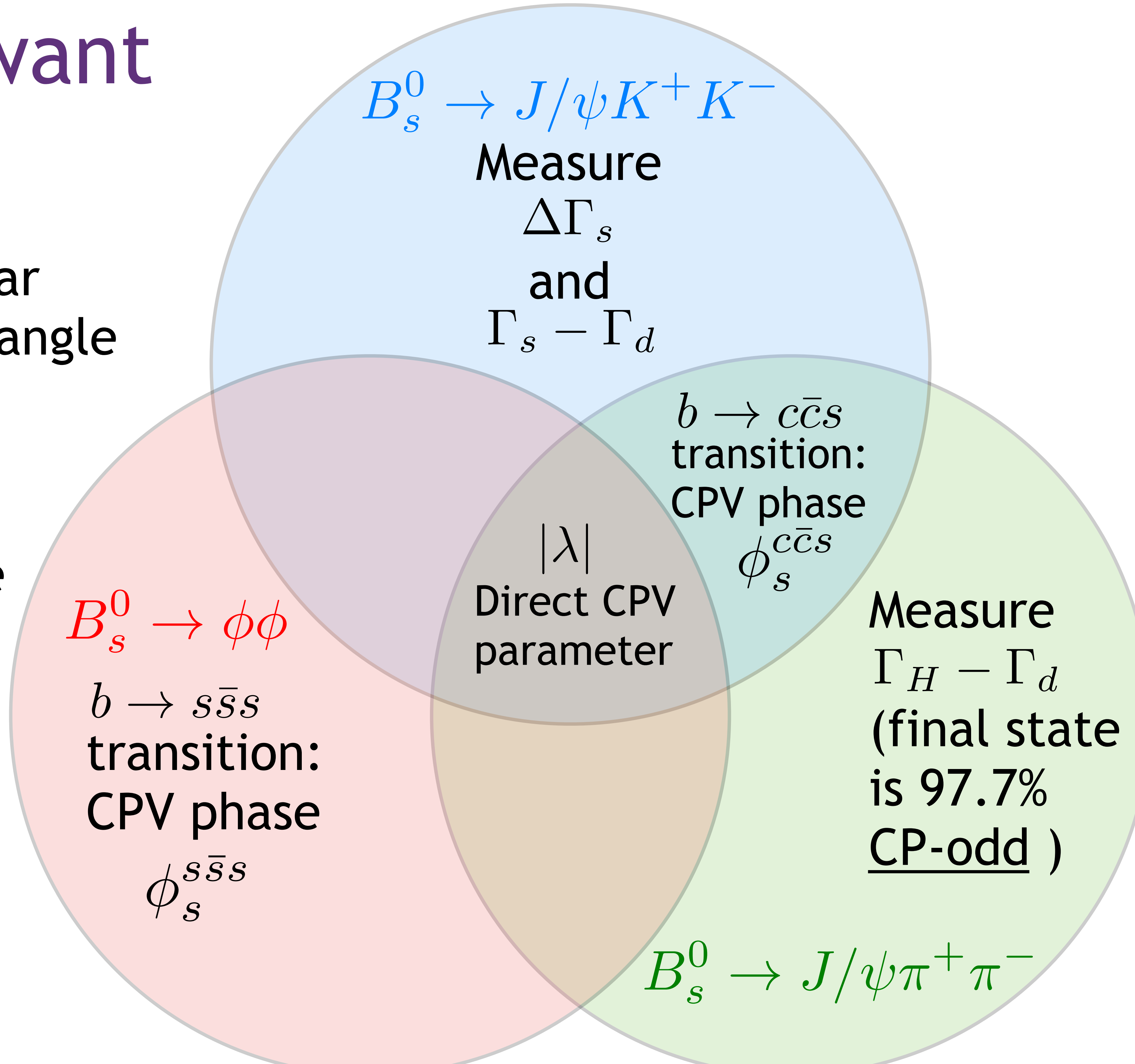
Decay



What do we want to measure?

Time-dependent angular analysis used to disentangle CP-even and CP-odd final states.

Simultaneous fit to the decay-time and three helicity angles performed to extract the fit parameters.



Predictions and Status

$B_s^0 \to \phi\phi$

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

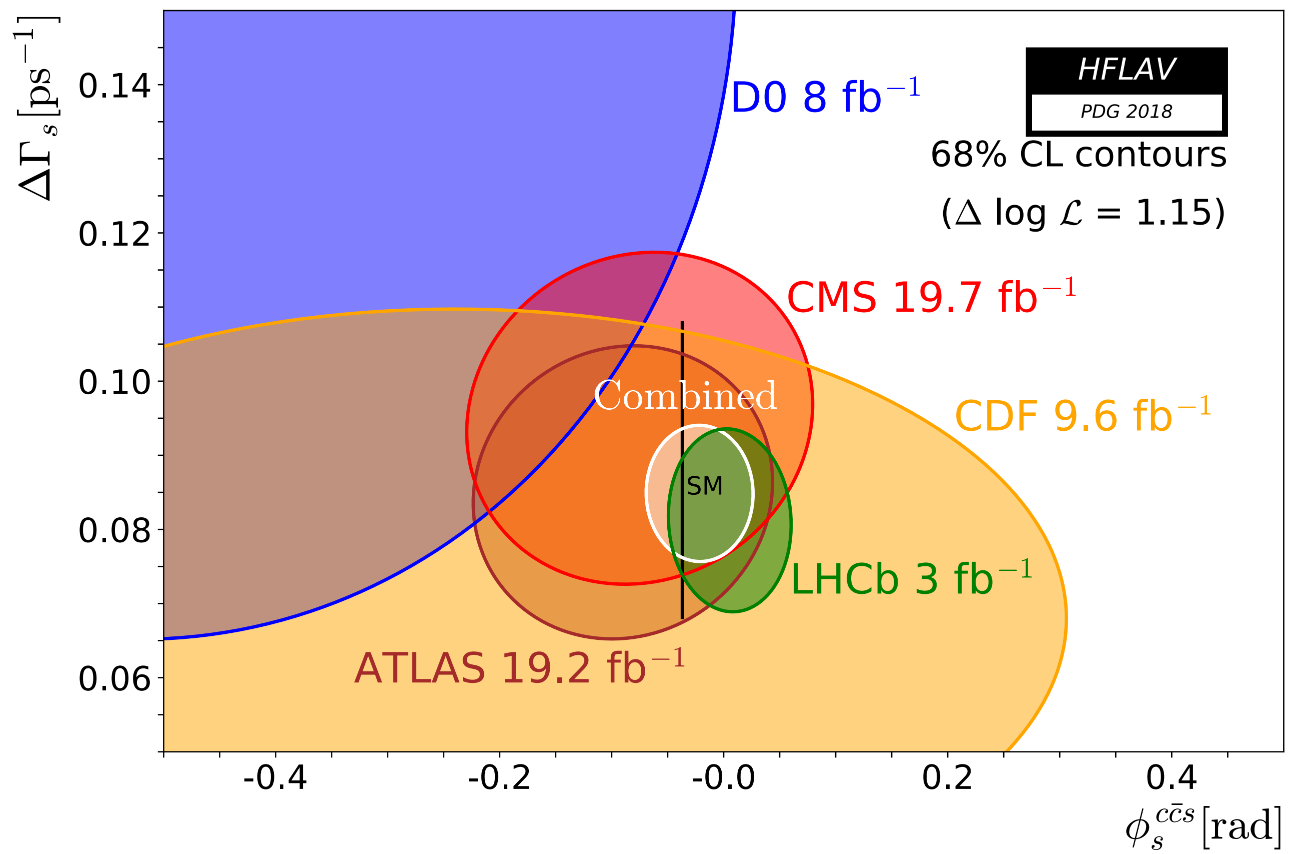
$B_s^0 \to J/\psi \pi^+ \pi^-$

SM predictions: $\phi_s^{s\bar{s}s}$ in context of QCD factorisation close to zero by SM, with errors of ~2%.
arXiv:0810.0249
Phys.Rev.D80:114026,2009

Certain BSM scenarios allow for significant CPV in $b \to s\bar{s}s$ penguin decays.
Phys.Lett. B493 (2000) 366-374
J.Phys.G32:835-848,2006
Phys.Lett.B671:256-262,2009

SM prediction: $\phi_s^{c\bar{c}s\ \mathrm{SM}} = -36.9^{+1.0}_{-0.7}$ [mrad]
CKMfitter

Experimental status: HFLAV 2018



Analysis ingredients

1. Selection
2. Decay-time resolution
3. Angular selection efficiency
4. Decay-time efficiency
5. Flavour tagging

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Signal selection

$B_s^0 \to \phi\phi$	$B_s^0 \to J/\psi K^+K^-$	$B_s^0 \to J/\psi \pi^+\pi^-$
LHCb-PAPER-2019-019	LHCb-PAPER-2019-013	arXiv:1903.05530

Neural network trained to remove background.

Boosted decision tree trained to remove background events.

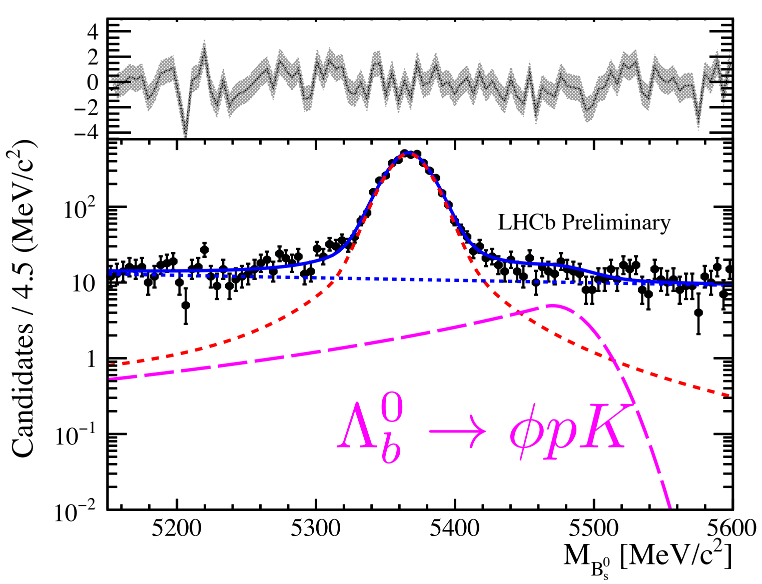
$\Lambda_b^0 \to J/\psi p K$ background subtracted using negative weighted MC.

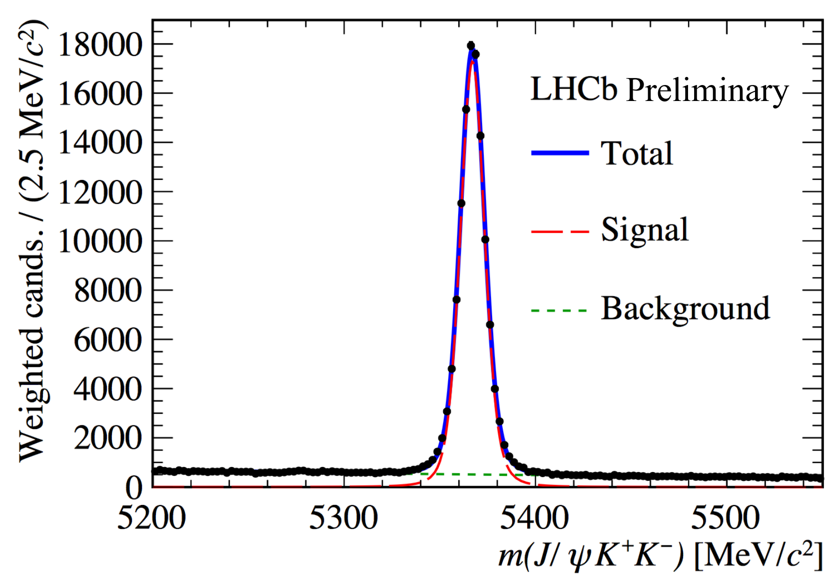
Wrong sign $(\pi^\pm\pi^\pm)$ combination used to determine combinatorial background shape.

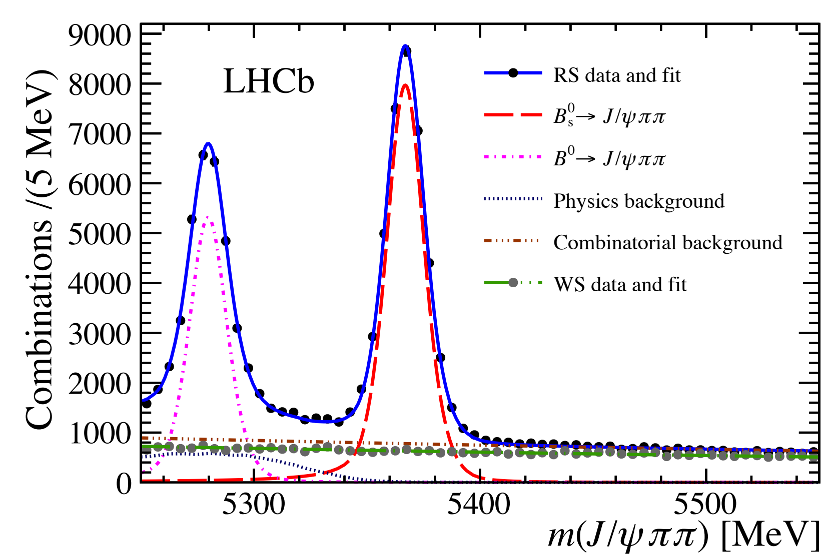
~8500 signal events.

~117 000 signal events.

~33 500 signal events.







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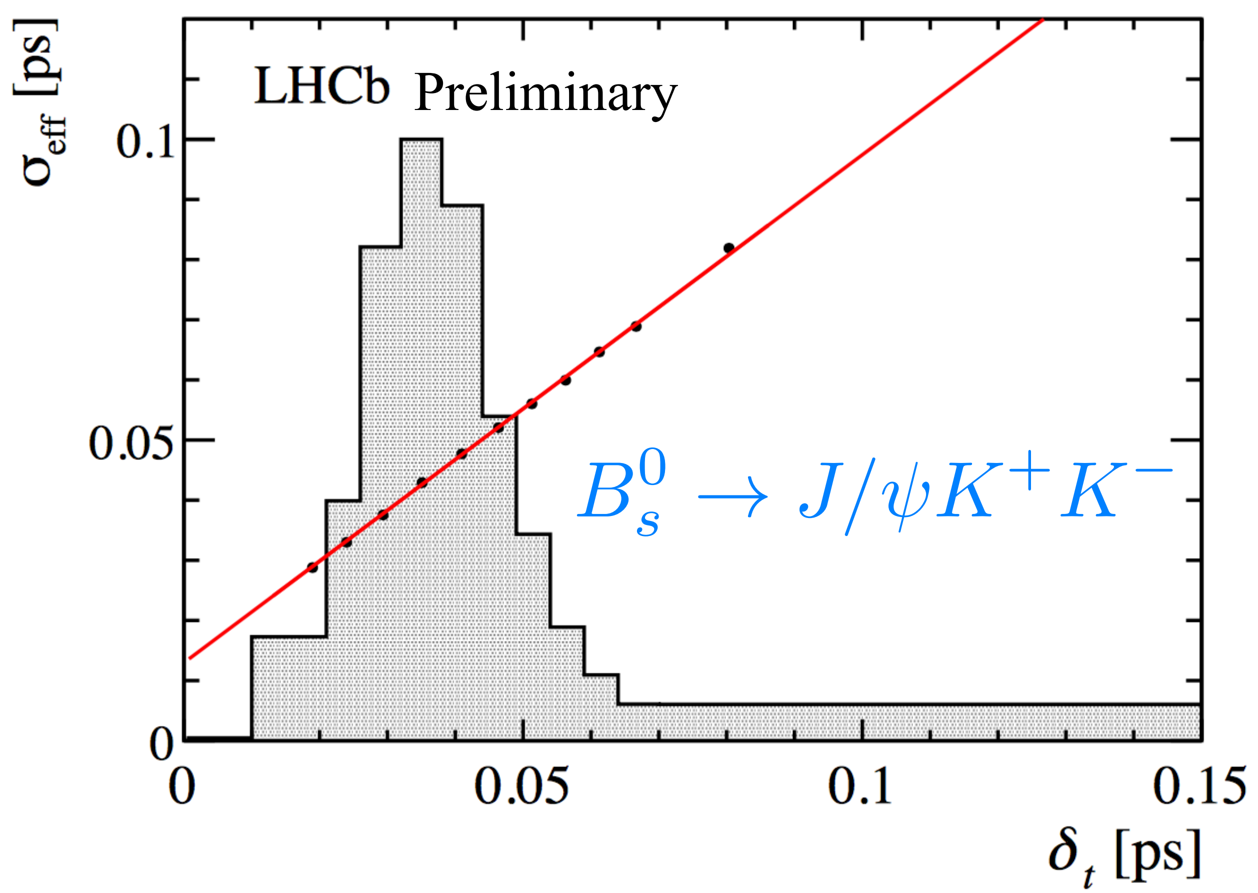
Decay-time resolution

Necessary to resolve the fast flavour oscillations induced by $B_s^0 - \bar{B}_s^0$ mixing.

Decay-time resolution of ~41-45 fs reached at LHCb.



$B_s^0 \to \phi\phi$	$B_s^0 \to J/\psi K^+ K^-$	$B_s^0 \to J/\psi \pi^+ \pi^-$
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Decay-time resolution calibrated on prompt pseudo-2-body samples.

Prompt J/ψ sample used to calibrate the decay-time resolution.

Analysis ingredients

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Angular efficiency

$B_s^0 \to \phi\phi$
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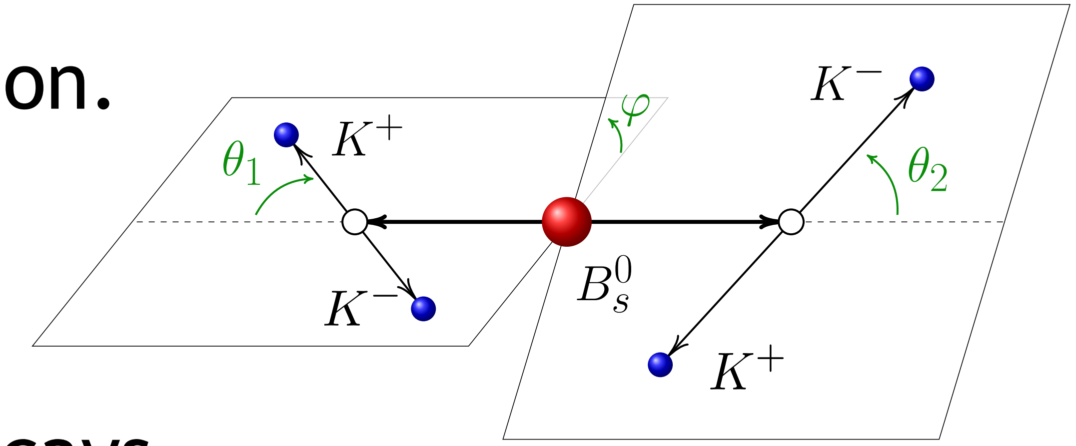
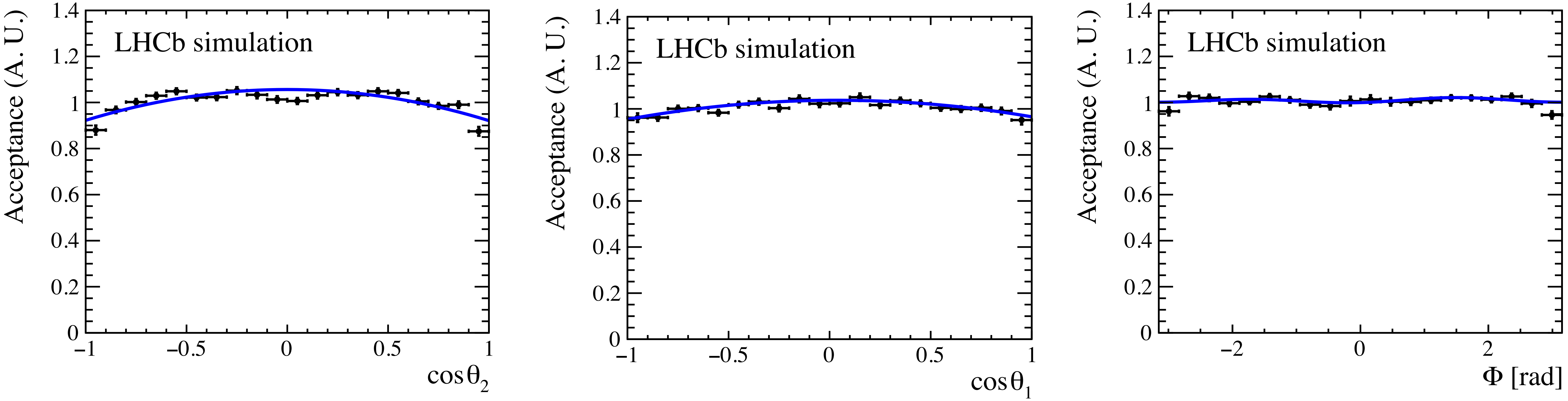


Need to account for non-uniform selection efficiency in decay angles as a result of detector acceptance and kinematic selection.

- Simulated events with same selection as data events to determine the efficiency correction.
- Similar procedure for $B_s^0 \to J/\psi h^+ h^-$ decays.



Analysis ingredients

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Decay-time efficiency

$B_s^0 \to \phi\phi$
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$B_s^0 \to J/\psi\pi^+\pi^-$
arXiv:1903.05530

$B_s^0 \to J/\psi K^+K^-$
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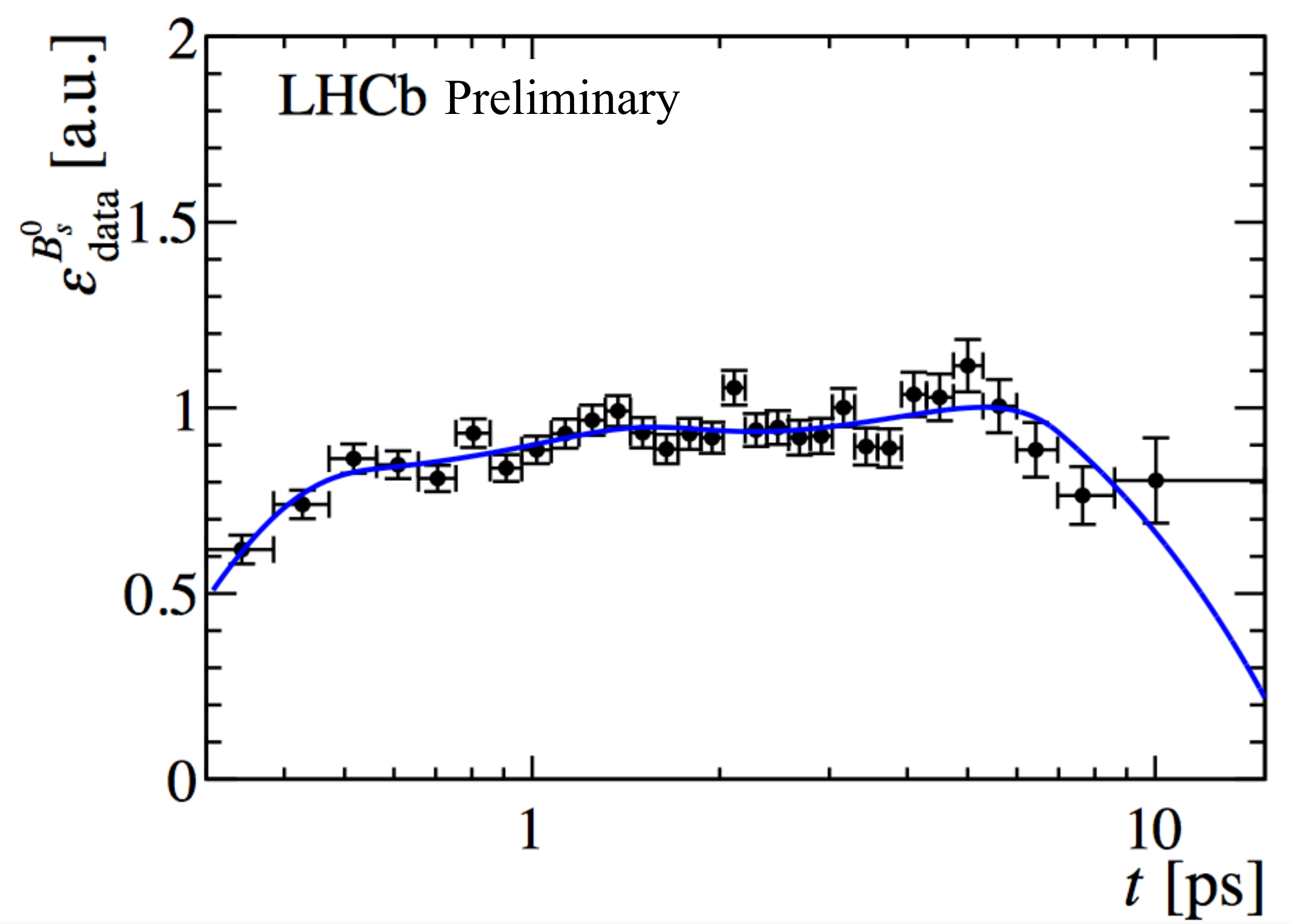
Run 1: $B_s^0 \to D_s^-\pi^+$

Run 2: $B^0 \to J/\psi K^{*0}$

Different control samples used in Run 1 and Run 2 due to difference in the High Level Trigger (HLT).

$B^0 \to J/\psi K^{*0}$ used as control mode.



Analysis ingredients

1. Selection
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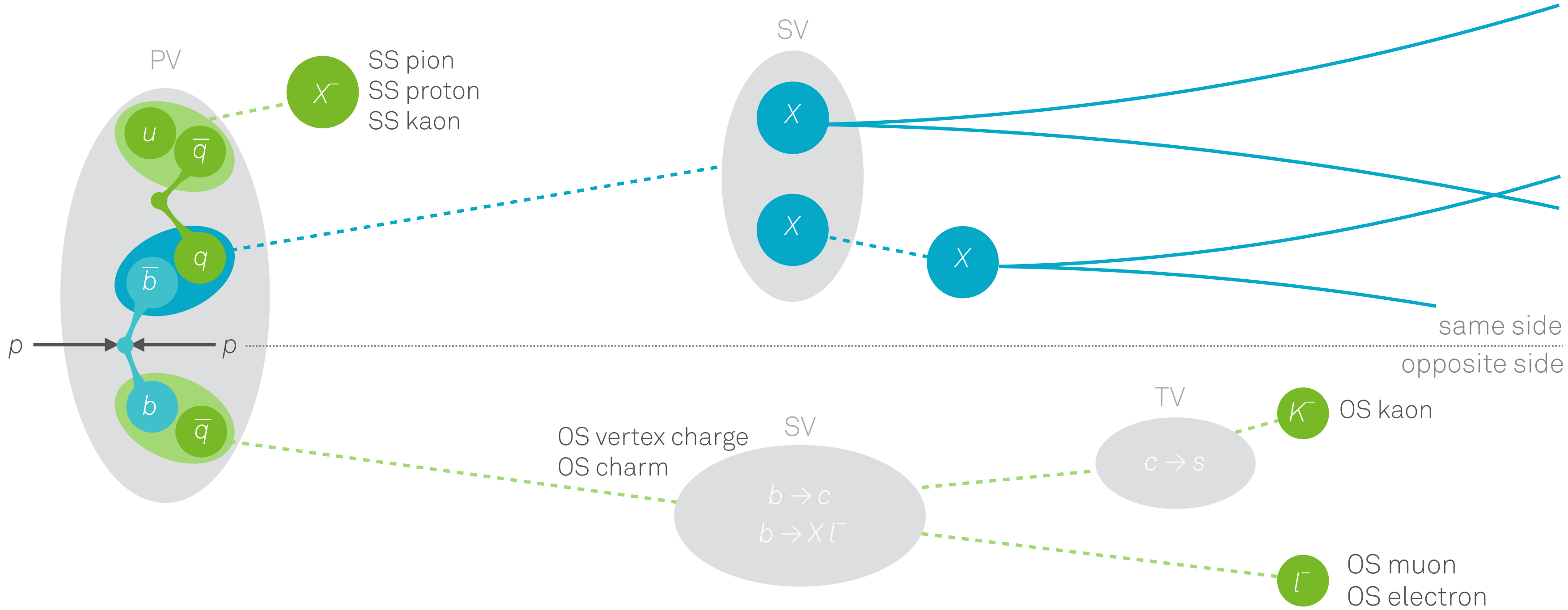
5. Flavour tagging

Flavour tagging



- Aim: tag the flavour of the B meson at production.
- Precision of ϕ_s measurement scales with the tagging power.
- Tagging algorithms calibrated using modes with known flavour. E.g. $B^+ \to J/\psi K^+$, $B_s^0 \to D_s^- \pi^+$.

ϵ = tagging efficiency
D = dilution factor

Tagging power achieved:

$B_s^0 \to J/\psi \pi^+\pi^-$
arXiv:1903.05530

$$\epsilon D^2 = 5.06 \pm 0.38\%$$

$B_s^0 \to J/\psi K^+K^-$
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$$\epsilon D^2 = 4.73 \pm 0.34\%$$

$B_s^0 \to \phi\phi$
LHCb-PAPER-2019-019

$$\epsilon D^2 = 5.74 \pm 0.43\%$$

Analysis ingredients

1. Selection
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Fit projections

$B_s^0 \to \phi\phi$

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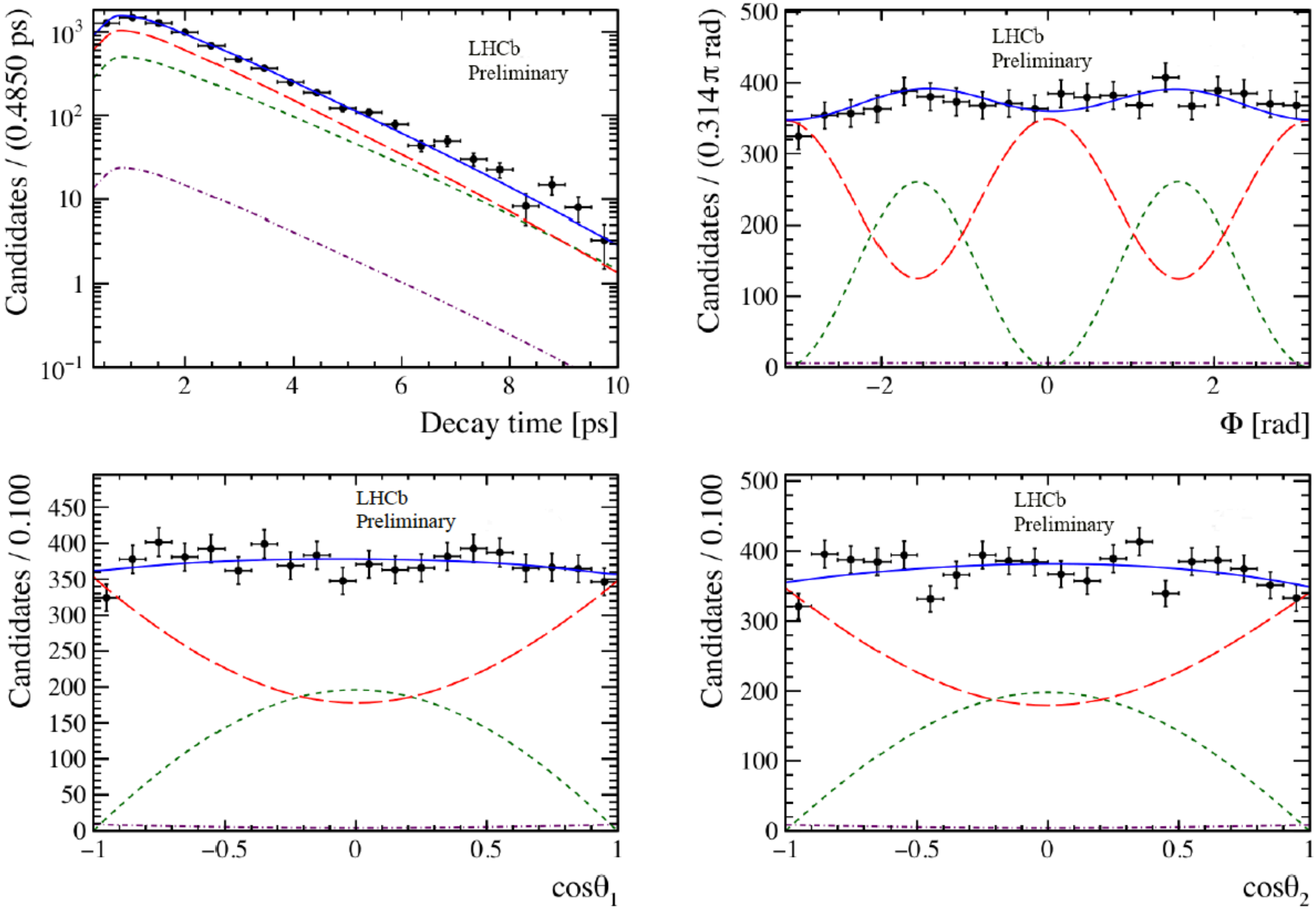
Simultaneous fit to decay time and helicity angles.



Total fit

CP-even P-wave

CP-odd P-wave

S-wave combined with double S-wave

S-wave component stems from the $f^0(980)$ resonance (close to the $\phi(1020)$ in mass)

Fit projections

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

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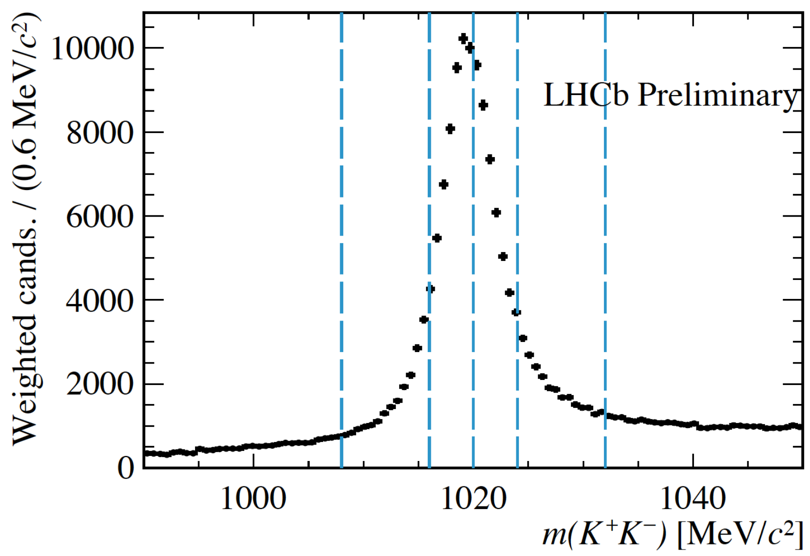
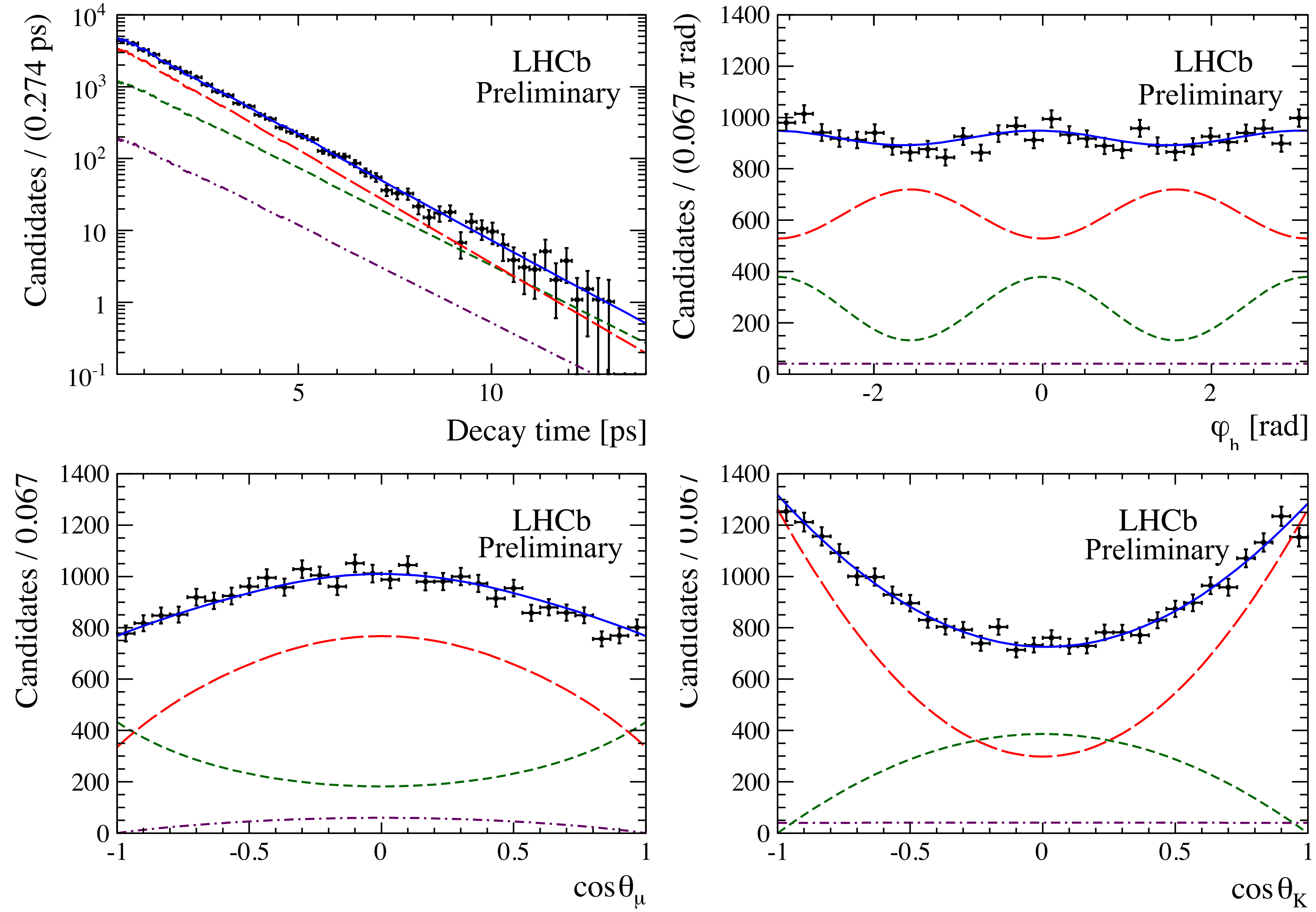
Simultaneous fit to decay time and helicity angles in 6 $m(K^+K^-)$ bins.





Fit binned in $m(K^+K^-)$ to control interference between S-wave and P-wave contributions.

Total fit

CP-odd P-wave

CP-even P-wave

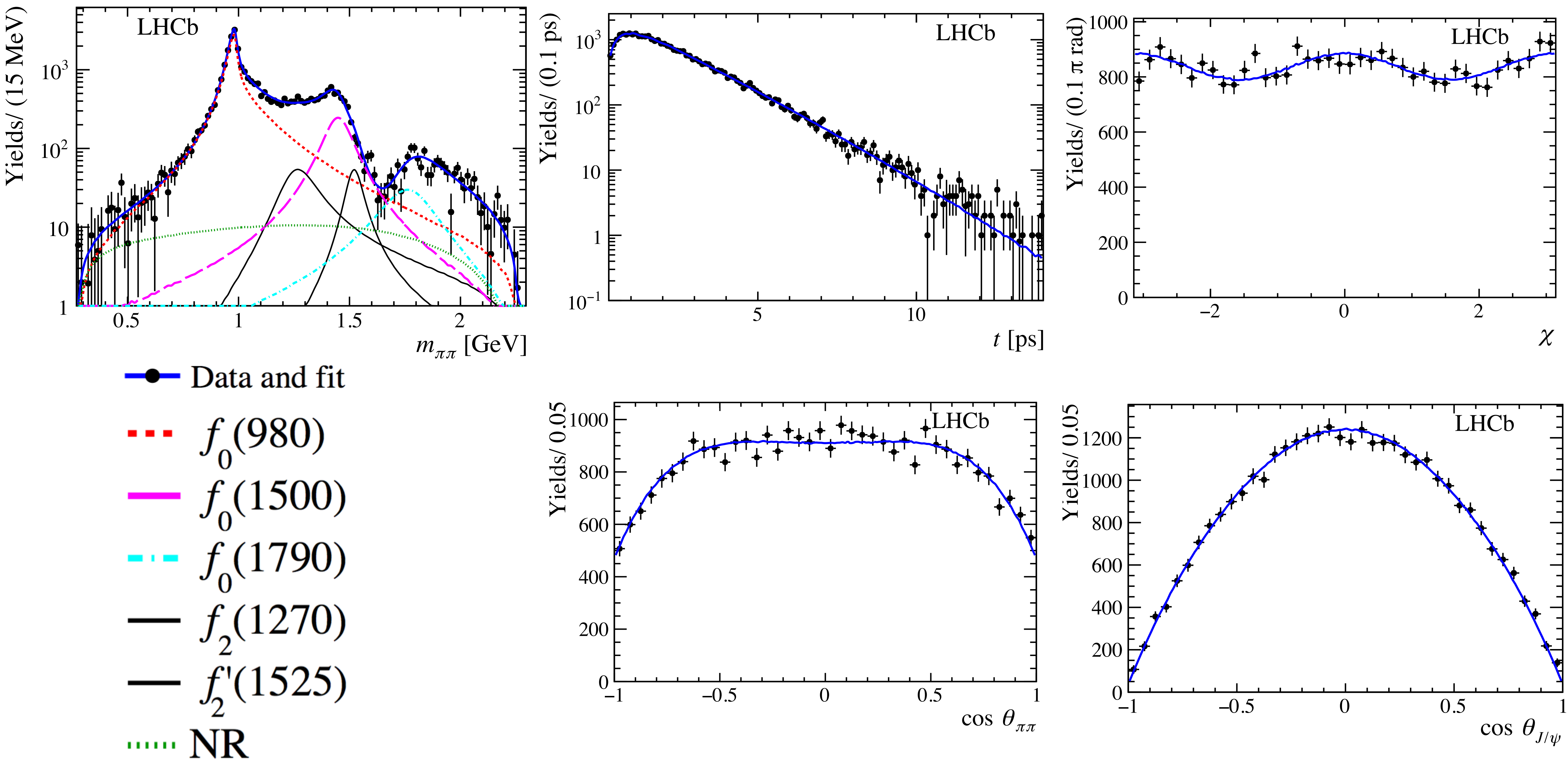
S-wave

Fit projections

$B_s^0 \to J/\psi\pi^+\pi^-$

arXiv:1903.05530

Simultaneous fit to decay time, helicity angles and $m(\pi^+\pi^-)$.



Results

$$B_s^0 \to \phi\phi$$

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Polarisation independent fit

$$\phi_s^{s\bar{s}s} = -0.073 \pm 0.115 \pm 0.027 \ \text{[rad]}$$

$$|\lambda| = -0.99 \pm 0.05 \pm 0.01$$

Most precise measurements to date in this decay mode. Measurements dominated by statistical error.

Results in agreement with SM predictions.

$$B_s^0 \to \phi\phi$$

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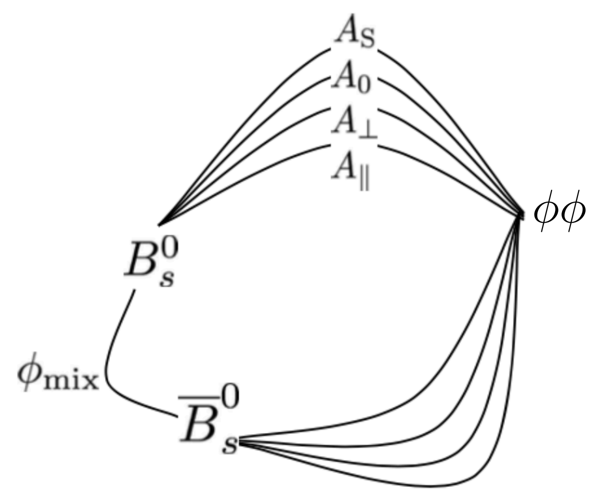
Polarisation dependent fit



Assumptions (due to limited statistics):

- $\phi_{s,0}$ is CP conserving
- No direct CPV

$$\phi_{s,\parallel} = 0.014 \pm 0.055 \pm 0.011 \ \text{[rad]}$$

$$\phi_{s,\perp} = 0.044 \pm 0.059 \pm 0.019 \ \text{[rad]}$$

Stay tuned for update full Run 2 data result!

Results

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

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$$\phi_s^{c\bar{c}s} = -0.083 \pm 0.041 \pm 0.006 \ \text{[rad]}$$
$$|\lambda| = 1.012 \pm 0.016 \pm 0.006$$
$$\Gamma_s - \Gamma_d = -0.0041 \pm 0.0024 \pm 0.0015 \ [\text{ps}^{-1}]$$
$$\Delta\Gamma_s = -0.0772 \pm 0.0077 \pm 0.0026 \ [\text{ps}^{-1}]$$

Most precise single measurement of $\phi_s^{c\bar{c}s}$, $\Delta\Gamma_s$ and $\Gamma_s - \Gamma_d$.

All results are in agreement with SM predictions.

$$B_s^0 \to J/\psi \pi^+ \pi^-$$

arXiv:1903.05530

$$\phi_s^{c\bar{c}s} = -0.057 \pm 0.060 \pm 0.011 \ \text{[rad]}$$
$$|\lambda| = 1.01^{+0.08}_{-0.06} \pm 0.03$$
$$\Gamma_H - \Gamma_d = -0.050 \pm 0.004 \pm 0.004 \ [\text{ps}^{-1}]$$

Combination

LHCb have performed many analyses measuring $\phi_s^{c\bar{c}s}$.

LHCb Run 1 analyses

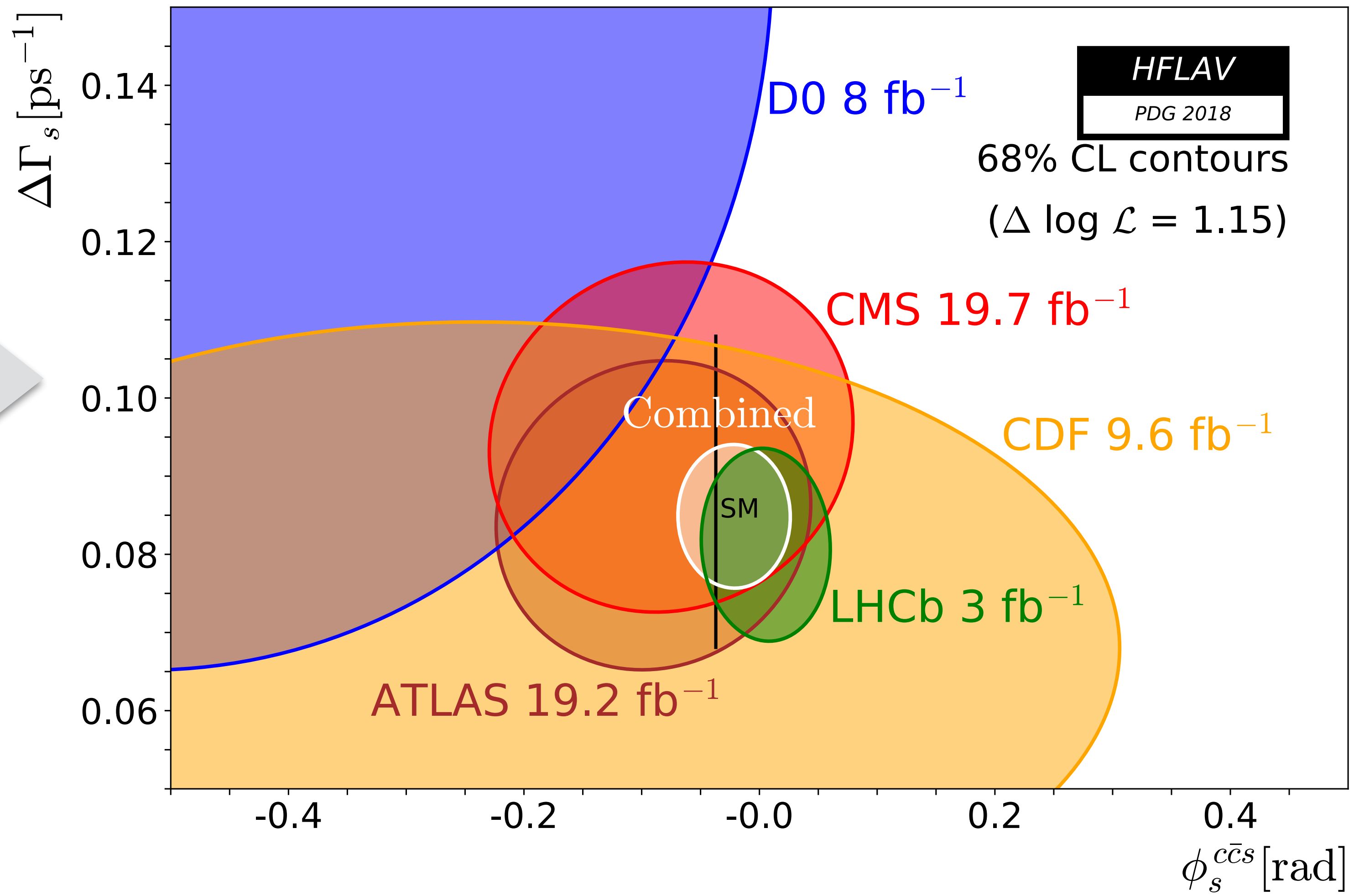
[1] $B_s^0 \to \psi(2S)\phi$

[2] $B_s^0 \to D_s^+ D_s^-$

[3] $B_s^0 \to J/\psi K^+ K^-$ (high mass range)

[4] $B_s^0 \to J/\psi K^+ K^-$

[5] $B_s^0 \to J/\psi \pi^+ \pi^-$



Combination

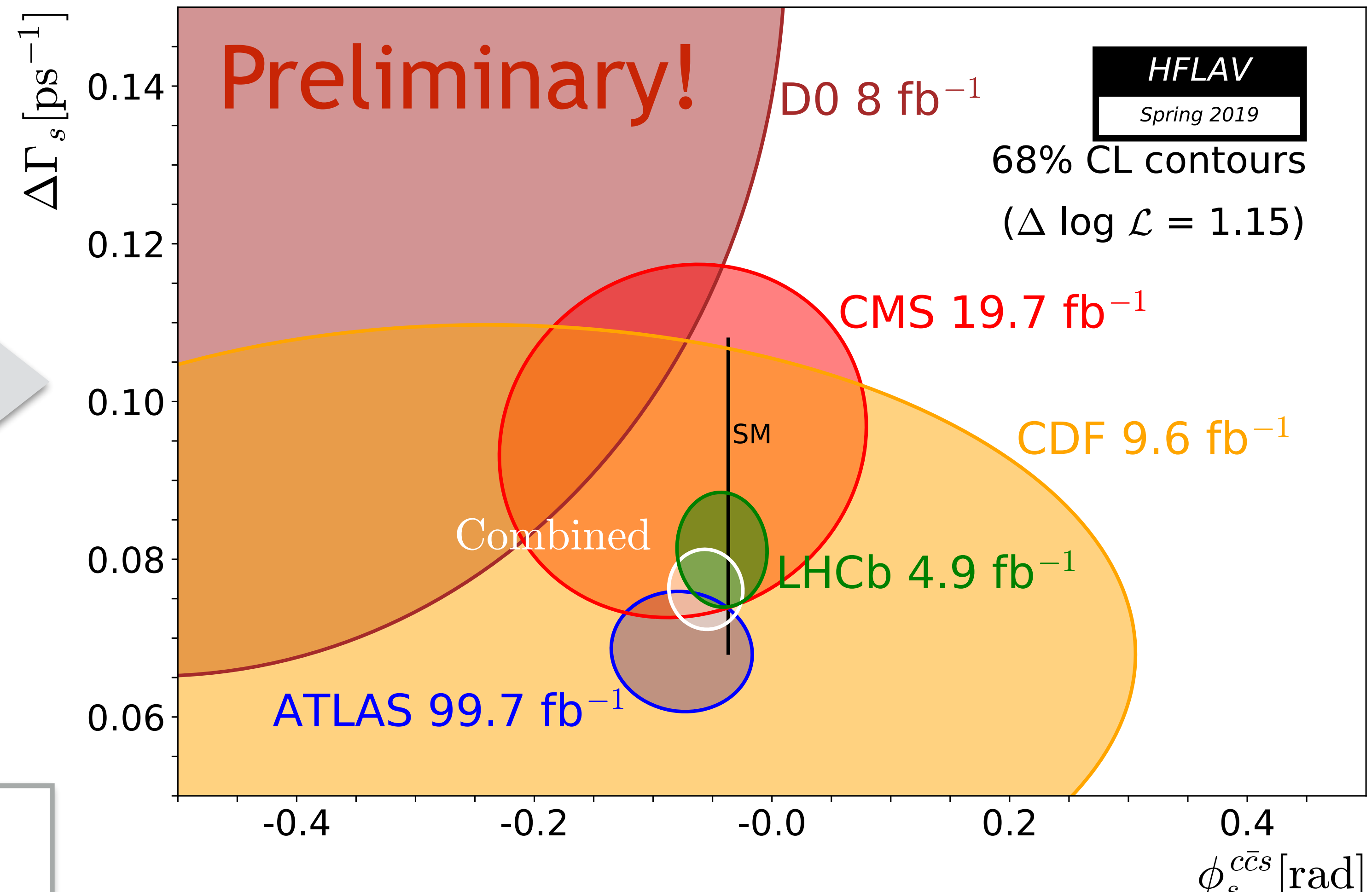
LHCb have performed many analyses measuring $\phi_s^{c\bar{c}s}$.

Including the LHCb Run 2 analyses

+ $B_s^0 \to J/\psi K^+ K^-$
  LHCb-PAPER-2019-013

+ $B_s^0 \to J/\psi \pi^+ \pi^-$
  arXiv:1903.05530

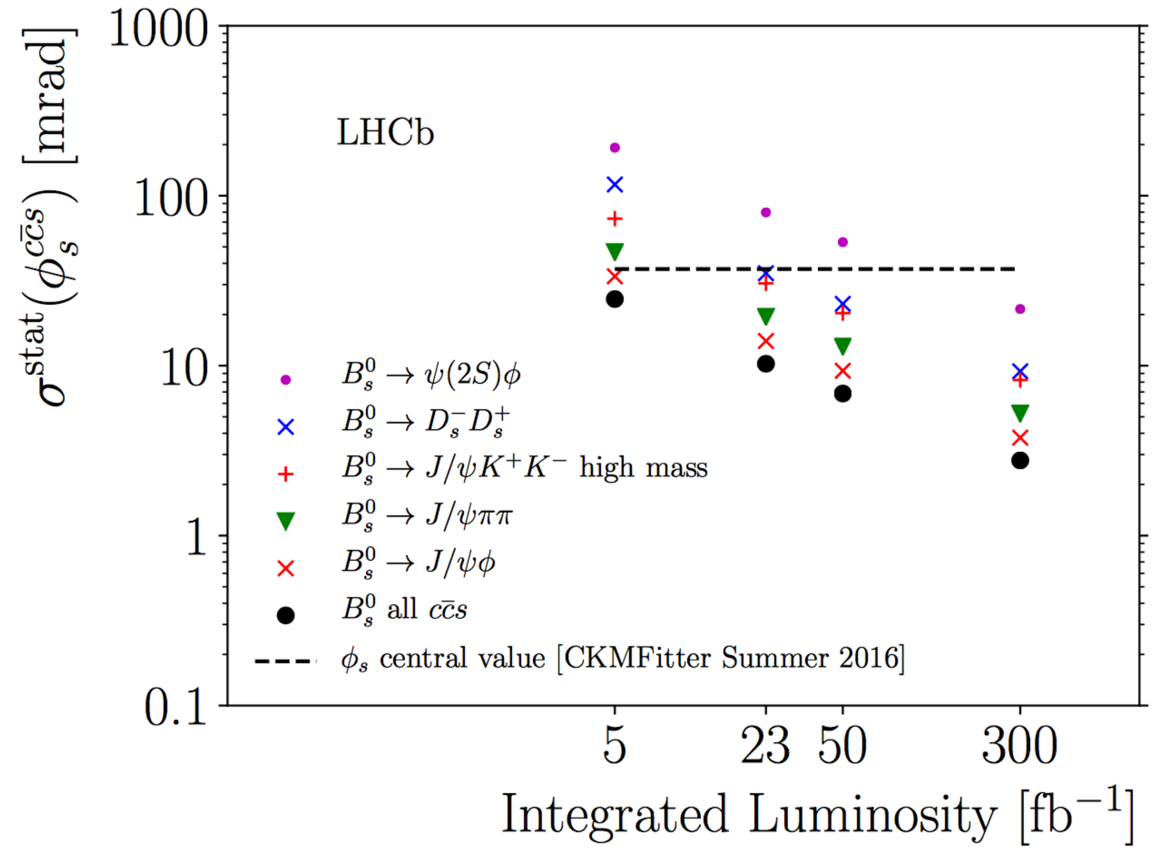
$$\phi_s^{c\bar{c}s} = -0.040 \pm 0.025 \text{ [rad]}$$
$$|\lambda| = 0.991 \pm 0.010$$
$$\Delta\Gamma_s = 0.0816 \pm 0.0048 \text{ [ps}^{-1}\text{]}$$
$$\Gamma_s - \Gamma_d = -0.0024 \pm 0.0018 \text{ [ps}^{-1}\text{]}$$

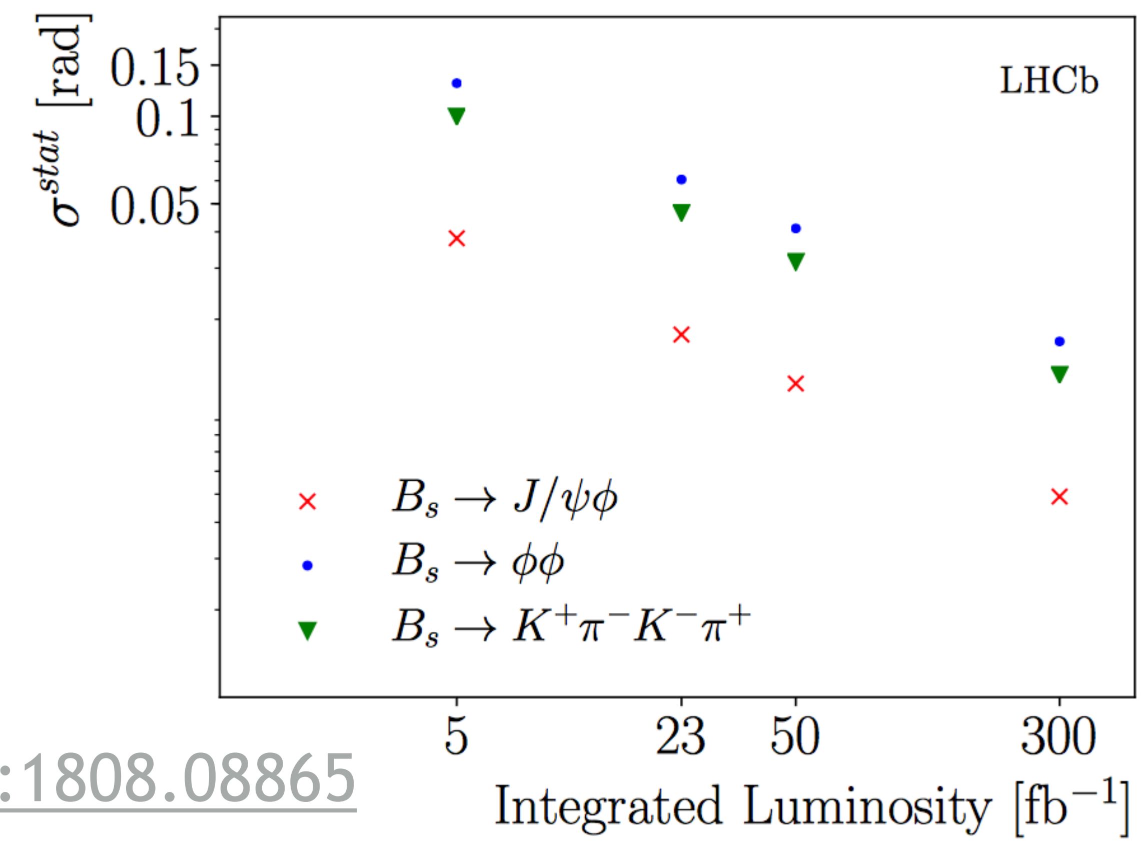


Preliminary ATLAS result:
ATLAS-CONF-2019-009

Conclusion

- The latest CP violation measurements presented have made a tremendous improvement in the experimental precision.
- Currently LHCb is producing some of the world's most precise ϕ_s measurements.
- With the ongoing upgrade and more Run 2 data to analyse, the statistical precision of these measurements will increase further.





arXiv:1808.08865

Thank you for your attention.

Questions?

Backup

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

Phys. Rev. Lett. 114, 041801

Run 1 results

Parameter	Value
Γ_s (ps^{-1})	$0.6603 \pm 0.0027 \pm 0.0015$
$\Delta\Gamma_s$ (ps^{-1})	$0.0805 \pm 0.0091 \pm 0.0032$
$\lvert A_\perp\rvert^2$	$0.2504 \pm 0.0049 \pm 0.0036$
$\lvert A_0\rvert^2$	$0.5241 \pm 0.0034 \pm 0.0067$
$\delta_\parallel$ (rad)	$3.26^{+0.10+0.06}_{-0.17-0.07}$
$\delta_\perp$ (rad)	$3.08^{+0.14}_{-0.15} \pm 0.06$
ϕ_s (rad)	$-0.058 \pm 0.049 \pm 0.006$
$\lvert\lambda\rvert$	$0.964 \pm 0.019 \pm 0.007$
Δm_s (ps^{-1})	$17.711^{+0.055}_{-0.057} + 0.011$

$B_s^0 \to J/\psi \pi^+\pi^-$

Phys. Lett. B736 (2014) 186

Run 1 results

$$\phi_s = 70 \pm 68 \pm 8 \text{ mrad}$$

$$|\lambda| = 0.89 \pm 0.05 \pm 0.01$$

$B_s^0 \to \phi\phi$

Phys. Rev. D 90, 052011

Run 1 results

Parameter	Best fit value
ϕ_s (rad)	-0.17 ± 0.15
$\lvert\lambda\rvert$	1.04 ± 0.07
$\lvert A_\perp\rvert^2$	0.305 ± 0.013
$\lvert A_0\rvert^2$	0.364 ± 0.012
δ_1 (rad)	0.13 ± 0.23
δ_2 (rad)	2.67 ± 0.23
Γ_s (ps^{-1})	0.662 ± 0.006
$\Delta\Gamma_s$ (ps^{-1})	0.102 ± 0.012
Δm_s (ps^{-1})	17.774 ± 0.024

Predictions arXiv:1309.2293

7 fb^{-1} 50 fb^{-1}

	2003	2013	Stage I		Stage II	
$\lvert V_{ud}\rvert$	0.9738 ± 0.0004	$0.97425 \pm 0 \pm 0.00022$	id		id	
$\lvert V_{us}\rvert$ $(K_{\ell 3})$	$0.2228 \pm 0.0039 \pm 0.0018$	$0.2258 \pm 0.0008 \pm 0.0012$	0.22494 ± 0.0006		id	
$\lvert\epsilon_K\rvert$	$(2.282 \pm 0.017) \times 10^{-3}$	$(2.228 \pm 0.011) \times 10^{-3}$	id		id	
Δm_d [ps^{-1}]	0.502 ± 0.006	0.507 ± 0.004	id		id	
Δm_s [ps^{-1}]	> 14.5 [95% CL]	17.768 ± 0.024	id		id	
$\lvert V_{cb}\rvert \times 10^3$ $(b \to c\ell\bar{\nu})$	$41.6 \pm 0.58 \pm 0.8$	$41.15 \pm 0.33 \pm 0.59$	42.3 ± 0.4	[17]	42.3 ± 0.3	[17]
$\lvert V_{ub}\rvert \times 10^3$ $(b \to u\ell\bar{\nu})$	$3.90 \pm 0.08 \pm 0.68$	$3.75 \pm 0.14 \pm 0.26$	3.56 ± 0.10	[17]	3.56 ± 0.08	[17]
$\sin 2\beta$	0.726 ± 0.037	0.679 ± 0.020	0.679 ± 0.016	[17]	0.679 ± 0.008	[17]
α (mod π)	—	$(85.4^{+4.0}_{-3.8})^\circ$	$(91.5 \pm 2)^\circ$	[17]	$(91.5 \pm 1)^\circ$	[17]
γ (mod π)	—	$(68.0^{+8.0}_{-8.5})^\circ$	$(67.1 \pm 4)^\circ$	[17, 18]	$(67.1 \pm 1)^\circ$	[17, 18]
β_s	—	$0.0065^{+0.0450}_{-0.0415}$	0.0178 ± 0.012	[18]	0.0178 ± 0.004	[18]
$\mathcal{B}(B \to \tau\nu) \times 10^4$	—	1.15 ± 0.23	0.83 ± 0.10	[17]	0.83 ± 0.05	[17]
$\mathcal{B}(B \to \mu\nu) \times 10^7$	—	—	3.7 ± 0.9	[17]	3.7 ± 0.2	[17]
$A^d_{\rm SL} \times 10^4$	10 ± 140	23 ± 26	-7 ± 15	[17]	-7 ± 10	[17]
$A^s_{\rm SL} \times 10^4$	—	-22 ± 52	0.3 ± 6.0	[18]	0.3 ± 2.0	[18]
$\bar{m}_c$	$1.2 \pm 0 \pm 0.2$	$1.286 \pm 0.013 \pm 0.040$	1.286 ± 0.020		1.286 ± 0.010	
$\bar{m}_t$	167.0 ± 5.0	$165.8 \pm 0.54 \pm 0.72$	id		id	
$\alpha_s(m_Z)$	$0.1172 \pm 0 \pm 0.0020$	$0.1184 \pm 0 \pm 0.0007$	id		id	
B_K	$0.86 \pm 0.06 \pm 0.14$	$0.7615 \pm 0.0026 \pm 0.0137$	0.774 ± 0.007	[19, 20]	0.774 ± 0.004	[19, 20]
f_{B_s} [GeV]	$0.217 \pm 0.012 \pm 0.011$	$0.2256 \pm 0.0012 \pm 0.0054$	0.232 ± 0.002	[19, 20]	0.232 ± 0.001	[19, 20]
B_{B_s}	1.37 ± 0.14	$1.326 \pm 0.016 \pm 0.040$	1.214 ± 0.060	[19, 20]	1.214 ± 0.010	[19, 20]
f_{B_s}/f_{B_d}	$1.21 \pm 0.05 \pm 0.01$	$1.198 \pm 0.008 \pm 0.025$	1.205 ± 0.010	[19, 20]	1.205 ± 0.005	[19, 20]
B_{B_s}/B_{B_d}	1.00 ± 0.02	$1.036 \pm 0.013 \pm 0.023$	1.055 ± 0.010	[19, 20]	1.055 ± 0.005	[19, 20]
$\tilde{B}_{B_s}/\tilde{B}_{B_d}$	—	$1.01 \pm 0 \pm 0.03$	1.03 ± 0.02		id	
$\tilde{B}_{B_s}$	—	$0.91 \pm 0.03 \pm 0.12$	0.87 ± 0.06		id	

Decay-time resolution

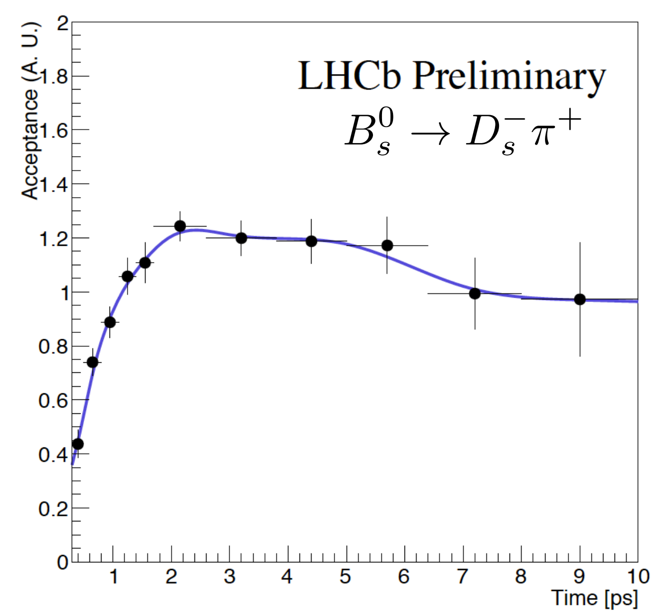
$B_s^0 \to \phi\phi$
LHCb-PAPER-2019-019

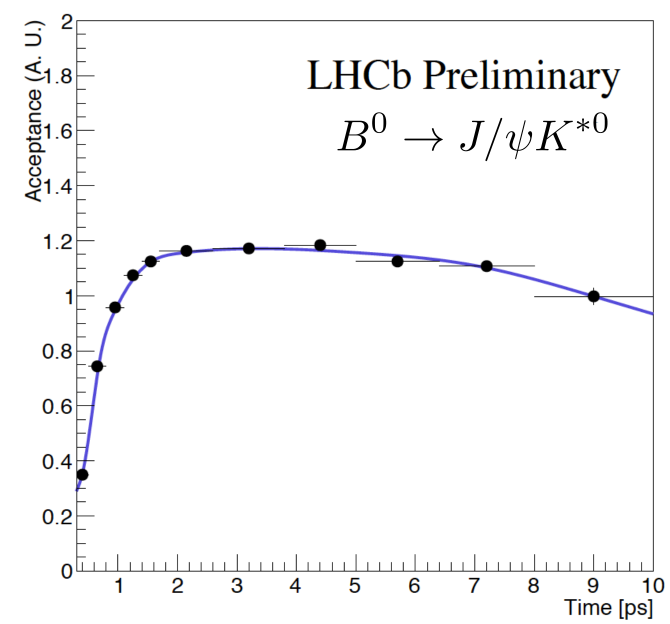
Want a decay-time unbiased control sample.
Run 1: stripping line for control sample is BDT based (same bias as our decay).
Run 2: completely decay-time unbiased stripping/trigger selection.

Run 1: $B_s^0 \to D_s^- \pi^+$

Run 2: $B^0 \to J/\psi K^{*0}$

Different samples used in Run 1 and Run 2 due to difference in the Higher Level Trigger (HLT).





External Inputs

$B_s^0 \to \phi\phi$

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B_s^0 decay width, Γ_s, and decay width difference, $\Delta\Gamma_s$, Gaussian constrained to values measured in Run 1 $B_s^0 \to J/\psi\phi$ and $B_s^0 \to J/\psi\pi\pi$ combination (arXiv:1411.3104).

With enough control over the decay time acceptance, the mode could also provide an important measurement of $\Delta\Gamma_s$.

External inputs of the B_s^0 oscillation frequency improves the accuracy of the measurement (arXiv:1304.4741).