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# Time dependent CP violation in b decays at LHCb

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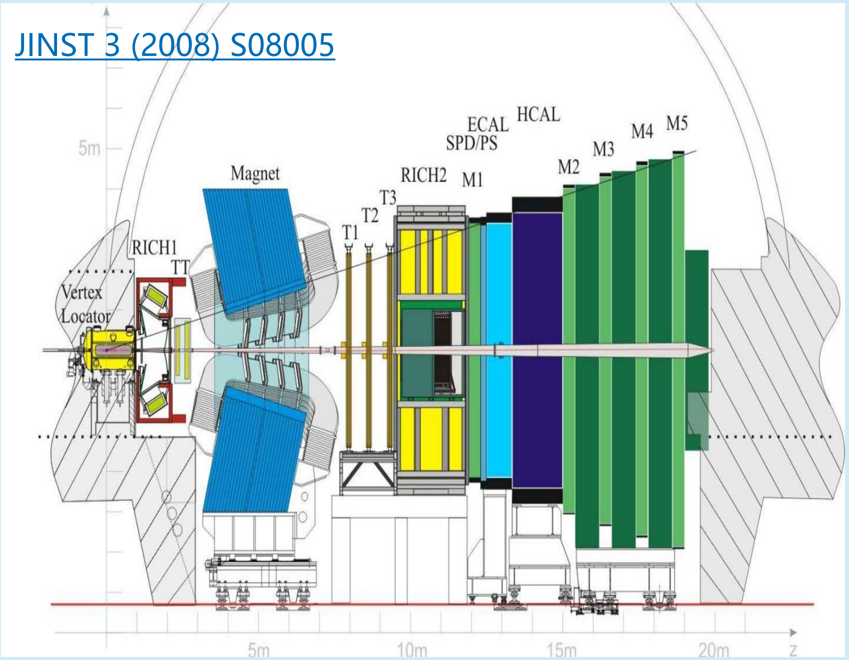
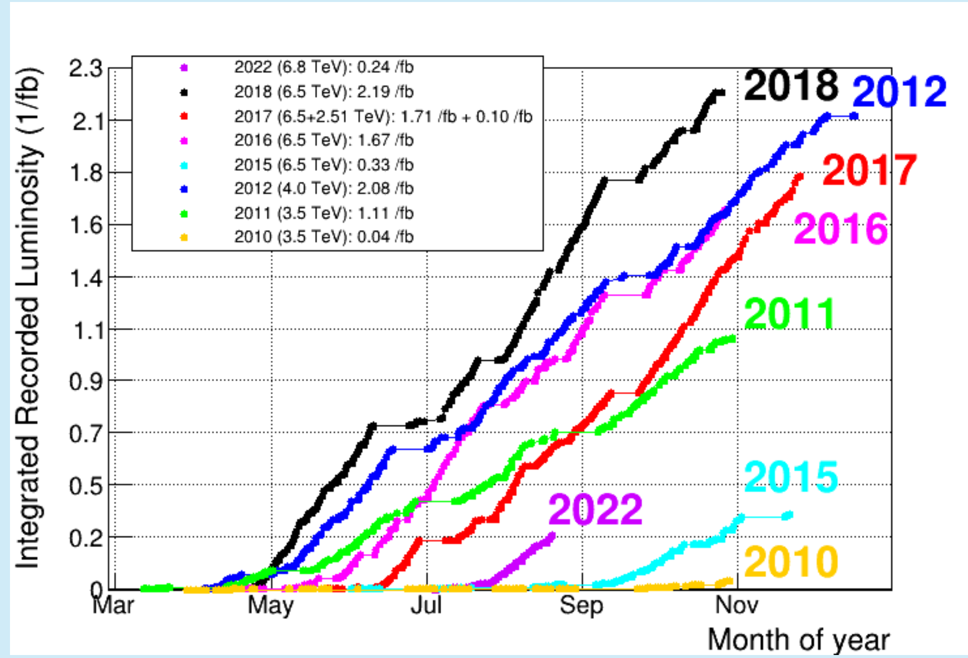
On behalf of the LHCb collaboration

# New results!

- Precision measurement of CP violation in the penguin-mediated decay $B_s^0 \to \phi\phi$ [arXiv:2304.06198]
  - Most precise result
- Measurement of CP violation in $B^0 \to \psi(\to l^+ l^-) K_S^0(\to \pi^+\pi^-)$ decays [LHCB-PAPER-2023-013-001]
  - Fresh-released & most precise result

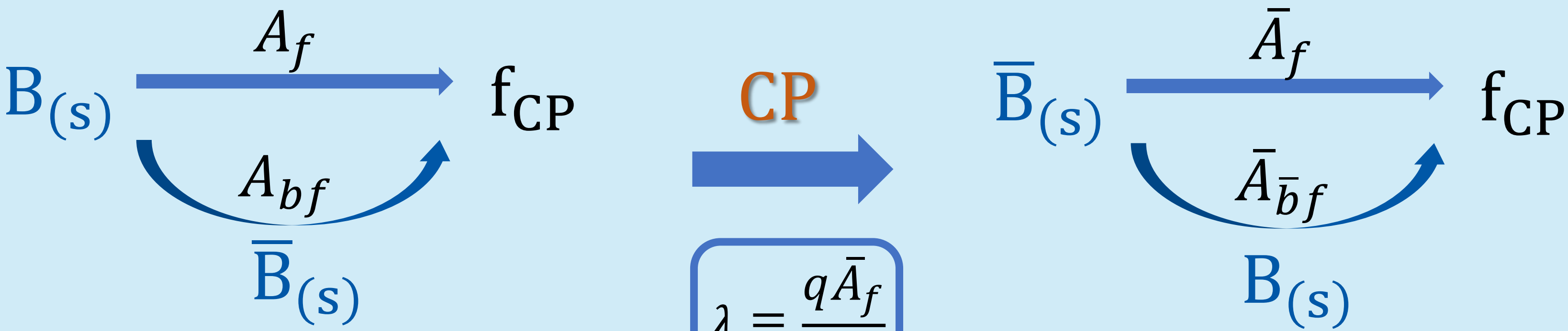
# LHCb: A flavour physics detector




- Acceptance $2 < \eta < 5$
- Angle (mrad) $10 < \theta < 300$
- $\Delta p/p = 0.5\%$ at low momentum
- $\Delta p/p = 1.0\%$ at 200GeV/c
- Forward spectrometer
- 9 $fb^{-1}$ data (Run1 + Run2)
- Excellent tracking and PID performance

# Time-dependent CP violation (CPV)




$$\Gamma_{B_{(s)}} = \left|A_f + A_{bf}\right|^2$$

$$\lambda \equiv \frac{q\bar{A}_f}{pA_f}$$

$$\Gamma_{\bar{B}_{(s)}} = \left|\bar{A}_f + \bar{A}_{\bar{b}f}\right|^2$$

- 2 kinds of CPV in time-dependent decay rate
  - Direct CPV:
    - $A \neq \bar{A}$
    - Parameters: $C$ (~0 in the SM), $|\lambda|$ (~1 in the SM)
  - Mixing-induced CPV:
    - $\arg(\frac{A_{bf}}{A_f}) \neq \arg\left(\frac{\bar{A}_{\bar{b}f}}{\bar{A}_f}\right)$ $(\Rightarrow \phi)$
    - Parameters: $S$ (~0 in the SM, with LO), $\phi$ (depend on channel)

$$C \equiv \frac{1-|\lambda|^2}{1+|\lambda|^2}$$

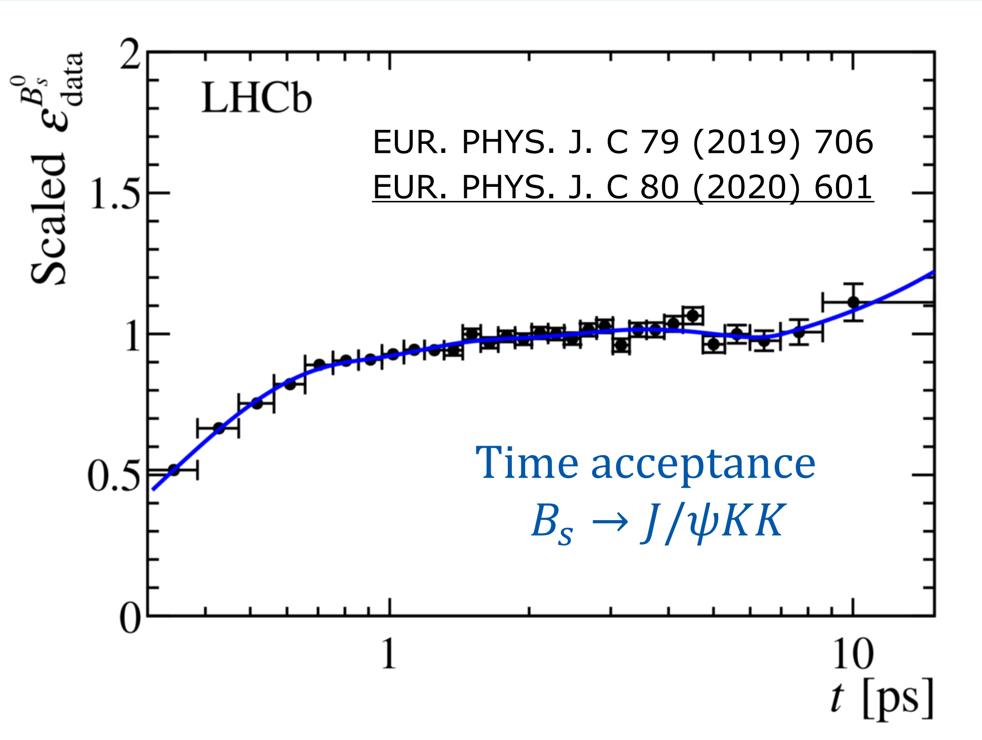
$$S \equiv \frac{2\mathrm{Im}\lambda}{1+|\lambda|^2}$$

# Detection effects

- Time and angular acceptance
  - Un-uniform reconstruction efficiency on time and angular
- Time resolution
  - Time reconstruction uncertainty
- Flavour tagging
  - $B$-$\bar{B}$ mixing

# Time and angular acceptance

- Estimated with signal MC and control channel
- Time acceptance
  - Modelling:
    - Cubic spline (generally)
  - Fit to the time distribution of signal MC or data samples




- Angular acceptance
  - Needed in time-dependent angular CPV measurement
  - $\xi_k \equiv \int [f_k(\vec{\Omega}) \frac{P_{\text{obs}}(\vec{\Omega}|t)}{P_{\text{gen}}(\vec{\Omega}|t)}] d\vec{\Omega}$
  - Determined with a data-driven method

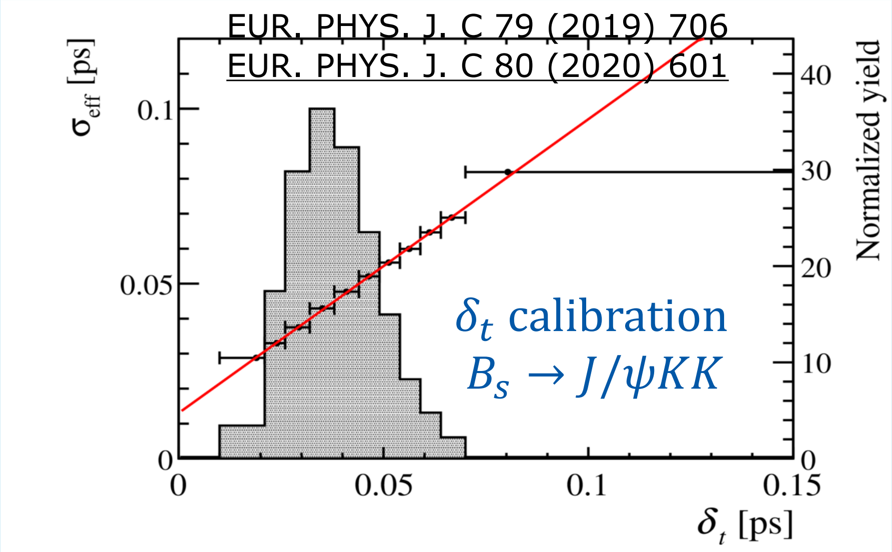
$f_k(\vec{\Omega})$: Angular function for different polarization states

# Per-event time resolution

- Extract time resolution $\Delta t$ in prompt data sample or signal MC sample with multi-Gaussian resolution model $R(t, t')$
- Convolve $R(t, t')$ on time PDF

Or:

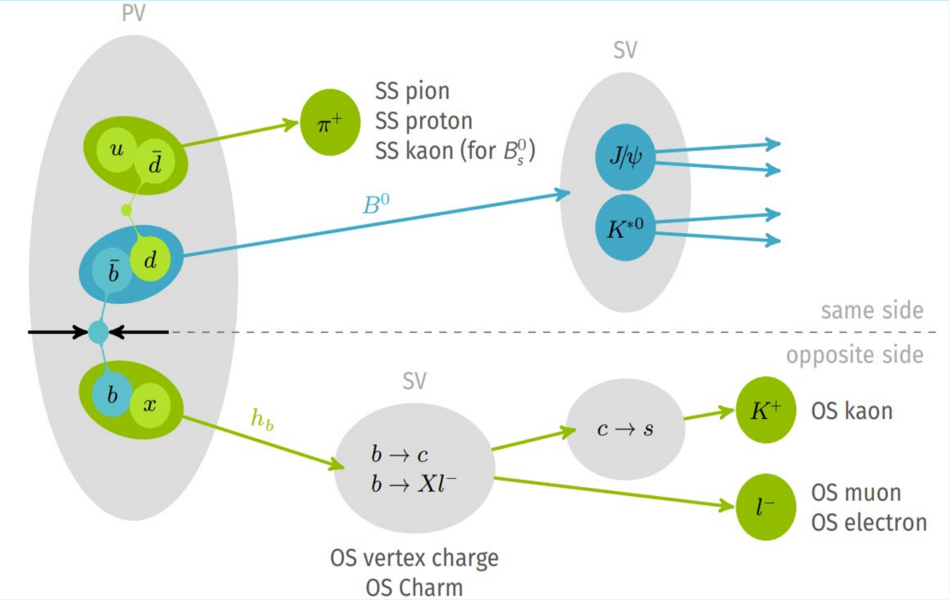
- Calculate the $\sigma_{\text{eff}}$ from $R(t, t')$
- Calibrate the time resolution of signal channel $\delta t$ by $\sigma_{\text{eff}}$ with linear function
- Use single-Gaussian resolution model with calibrated $\delta t$ as the width, convolute it on the decay time PDF.

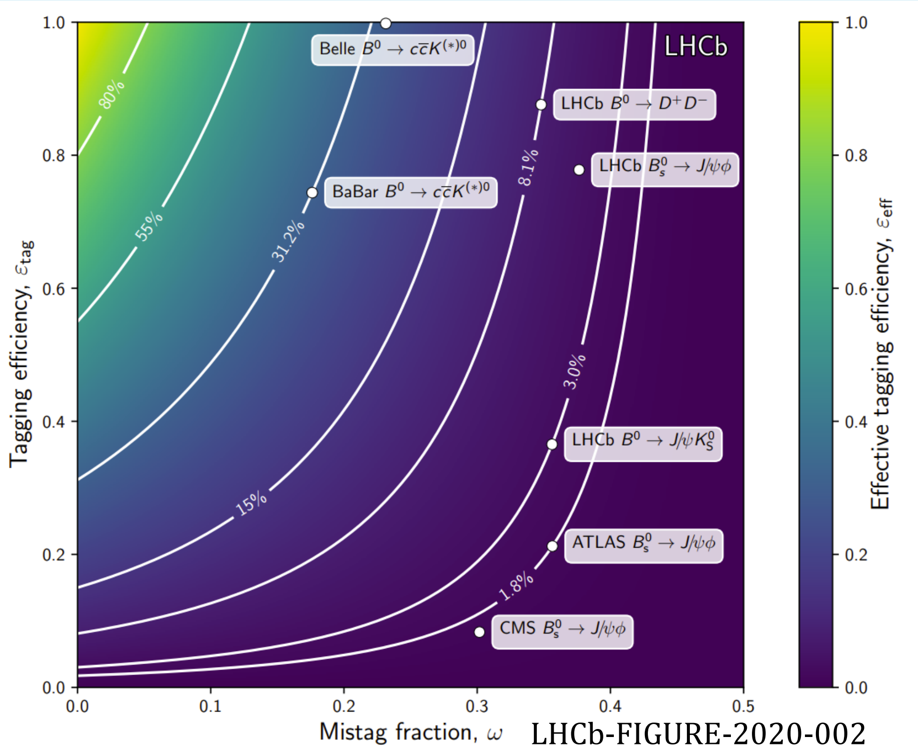



- ~60 fs for $B^0 \to \psi K_S$
- ~44 fs for $B_s^0 \to \phi\phi$

# Flavour tagging

- Taggers
  - "Same side(SS)": produced with signal B meson
  - "Opposite side(OS)": produced from related $\bar{b}$-hadron to signal B meson
- $\epsilon_{\text{eff}} \propto 1/\sigma_{stat}^2$



LHCb-FIGURE-2020-002

- (4.62-6.48)% for $B^0 \to \psi K_S$
- (5.7-6.3)% for $B_s \to \phi\phi$

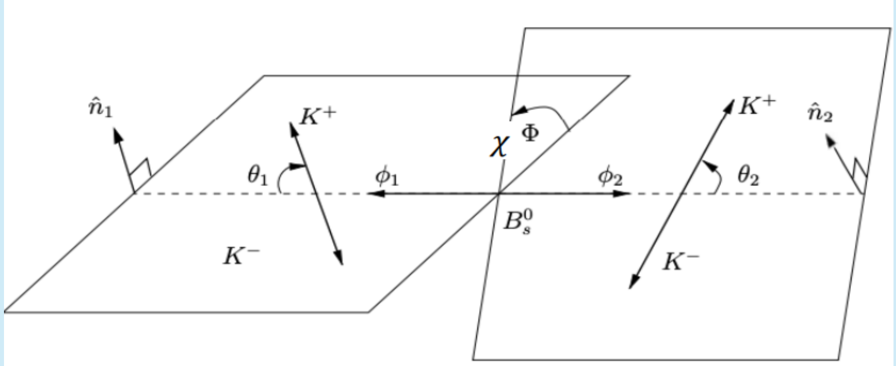
# $B_s \to \phi\phi$

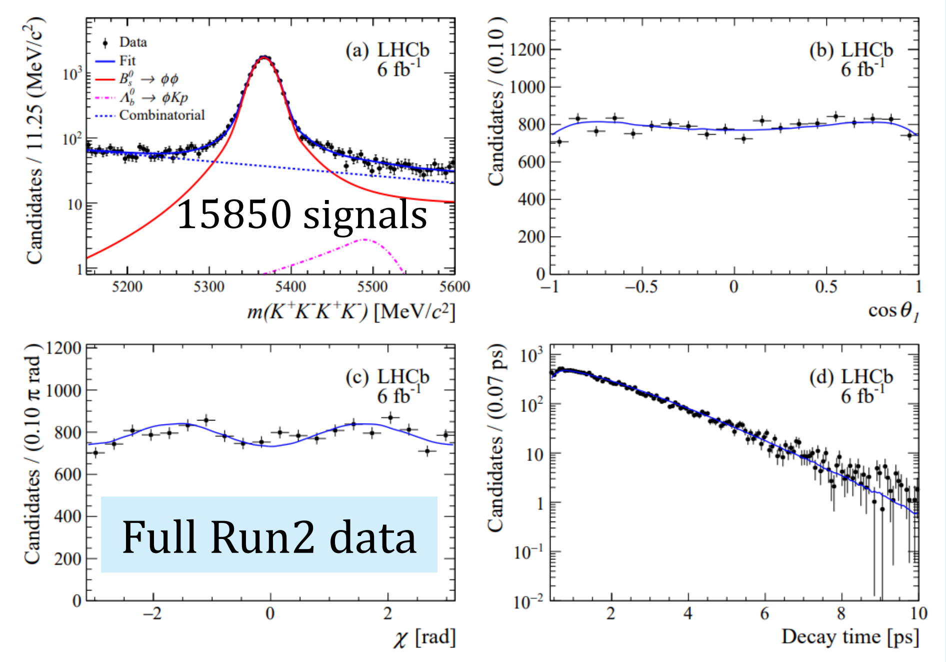
arXiv: 2304.06198

- Use sPlot to subtract background
- First polarization-dependent CPV parameter measurement
  - $\frac{d^4\Gamma(t,\vec{\Omega})}{dt d\vec{\Omega}} \propto \sum_{k=1}^{6} h_k(t) f_k(\vec{\Omega})$

B decay rate (t)

Angular function



# $B_s \to \phi\phi$

arXiv: 2304.06198

- Use sPlot to subtract background
- First polarization-dependent CPV parameter measurement

- $\phi_s^{s\bar{s}s} = -0.042 \pm 0.075 \pm 0.009$ rad
- $|\lambda| = 1.004 \pm 0.030 \pm 0.009$
- $|A_0|^2 = 0.384 \pm 0.007 \pm 0.003$
- $|A_\perp|^2 = 0.310 \pm 0.006 \pm 0.003$
- $\delta_\parallel - \delta_0 = 2.463 \pm 0.029 \pm 0.009$ rad
- $\delta_\perp - \delta_0 = 2.769 \pm 0.105 \pm 0.011$ rad

- $\phi_{s,0} = -0.18 \pm 0.09$ rad
- $\phi_{s,\parallel} - \phi_{s,0} = 0.12 \pm 0.09$ rad
- $\phi_{s,\perp} - \phi_{s,0} = 0.17 \pm 0.09$ rad

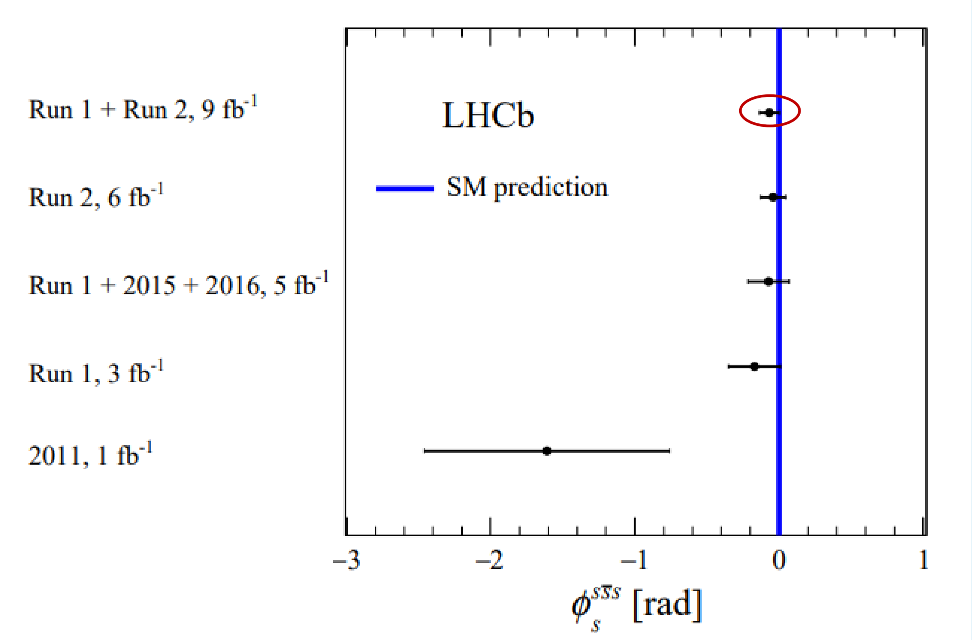
- $|\lambda_0| = 1.02 \pm 0.07$
- $|\lambda_\perp/\lambda_0| = 0.97 \pm 0.22$
- $|\lambda_\parallel/\lambda_0| = 0.78 \pm 0.21$

- $\phi_s^{s\bar{s}s} \sim 0$ in the SM
- No obvious difference between the CPV parameters in each polarization states

# $B_s \to \phi\phi$

arXiv: 2304.06198

- Combined with Run1 result
  - $\phi_s^{s\bar{s}s} = -0.074 \pm 0.069$ rad
  - $|\lambda| = 1.009 \pm 0.030$
- The most precise result in penguin-dominated B meson decay



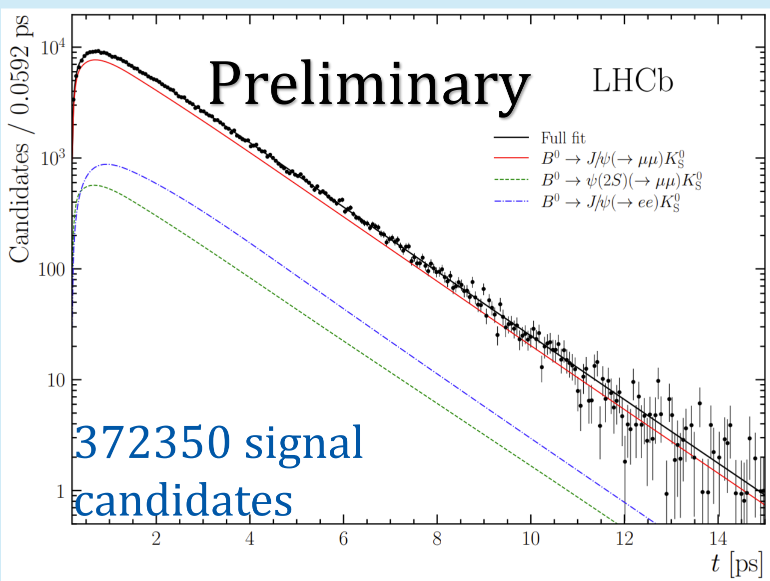

- Consistent with the previous measurement
- Agrees with the SM expectation
- Can be used to further constrain $b \to s$ transitions

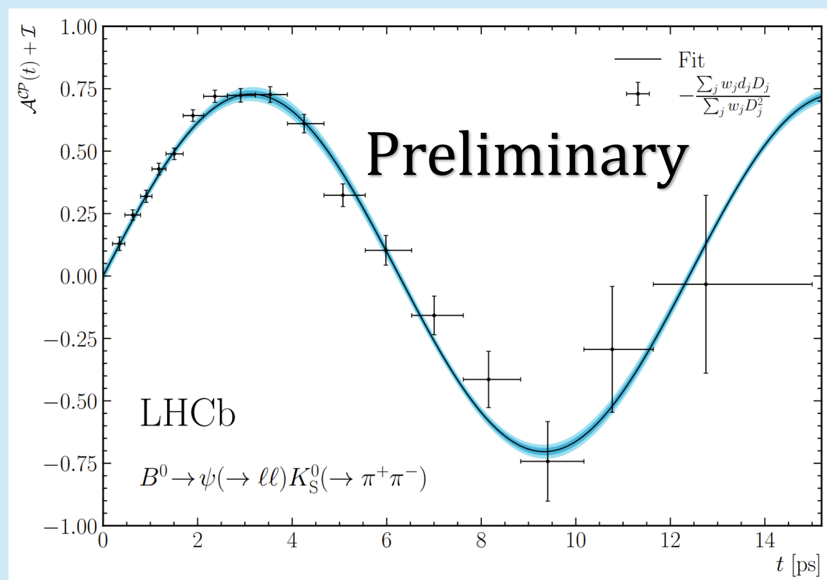
# CPV in $B^0 \to \psi K^0_S$

New!

LHCb-PAPER-2023-013 [in preparation]

- $b \to c\bar{c}s$ tree-level dominates, golden channel to measure CKM angle $\beta$ ($\phi^{c\bar{c}s} \sim 2\beta$)
- Run2 data with 3 $\psi$ decay modes
  - $\psi(2S) \to \mu^+\mu^-, J/\psi \to e^+e^-(\mu^+\mu^-)$
- Simultaneous fit on different decay modes is performed for final result



# CPV in $B^0 \rightarrow \psi K_S^0$

New!

LHCb-PAPER-2023-013

- C and S result in different decay modes and simultaneous result

| Mode | $S$ | $C$ |
|---|---|---|
| $J/\psi_{\mu\mu}K_S$ | $0.714 \pm 0.015 \pm 0.007$ | $0.013 \pm 0.014 \pm 0.003$ |
| $J/\psi_{ee}K_S$ | $0.752 \pm 0.037 \pm 0.084$ | $0.046 \pm 0.034 \pm 0.008$ |
| $\psi(2S)K_S$ | $0.647 \pm 0.053 \pm 0.018$ | $-0.083 \pm 0.048 \pm 0.005$ |
| All | $0.716 \pm 0.013 \pm 0.008$ | $0.012 \pm 0.012 \pm 0.003$ |
| HFLAV | $0.699 \pm 0.017$ | $-0.005 \pm 0.015$ |

- Agree with the current world average
- Precision from all channels is higher than the current average
- Best precision!

# Summary

- The new & most precise $\phi_s^{s\bar{s}s}$ measurement in $B_s$ decay shows agreement with the SM
- The CPV parameters of $B^0 \rightarrow \psi K_S$ are measured
  - The most precise result!
  - Will dominate the precision of world average
  - Push the precision border of CKM triangle
- Stay tuned for coming results with full Run2 data

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Thanks for your attention!

# Back up

# How do we combine Run1 result

1. Take all principle parameters, their statistical uncertainties, and correlation matrix
2. Label the systematics of Run1 and Run2 according to the sources
3. Determine the correlation of systematics
   1. Assume the parameters are fully-correlated.
   2. Assume the correlated source from Run1 and Run2 is fully-correlated
4. Do a simultaneous $\chi^2$ fit to get the average result

# Time bias

- Time bias is observed in time resolution fit
  - Due to detector mis-alignment
- Time can be calibrated with the mean bias in resolution fit by polynomial model (in $B^0 \rightarrow \psi K_S$)
- Possibly can be neglected if the bias is not large
  - In $B_s^0 \rightarrow \phi\phi$, the bias is ~5fs, the effect on CPV parameters is neglected