Latest Time-dependent Measurements of B decays at LHCb

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FIND论坛学术研讨会，USTC

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Outline

- Time-dependent CP violation
- Flavour tagging at LHCb
- $\sin 2\beta$ measurements
- ϕ_s measurements
- $B^0_{(s)} \to h^+h^-$ & $\tau^{\text{effective}}_{B^0_s}$
- Prospects & summary

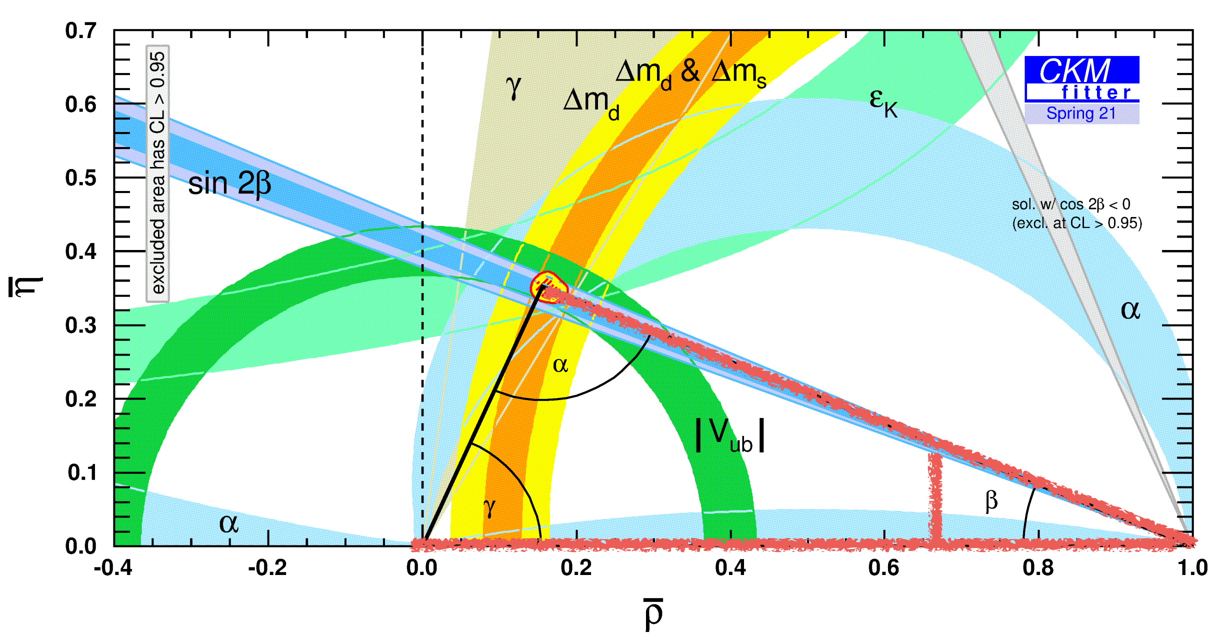
Chris Parkes

CKM matrix

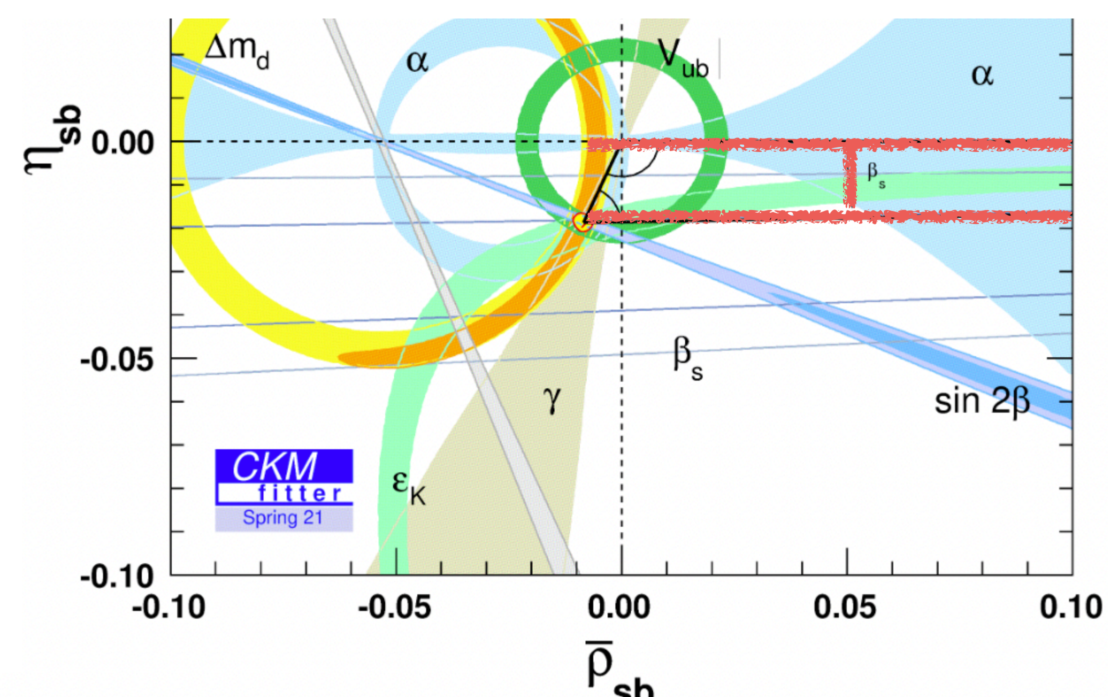
$$V_{CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix} + \mathcal{O}(\lambda^5) \sim \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

- Key test of the SM: Verify unitarity of CKM matrix
  - Magnitudes: branching fractions or mixing frequencies
  - Phases: CP violation measurement

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



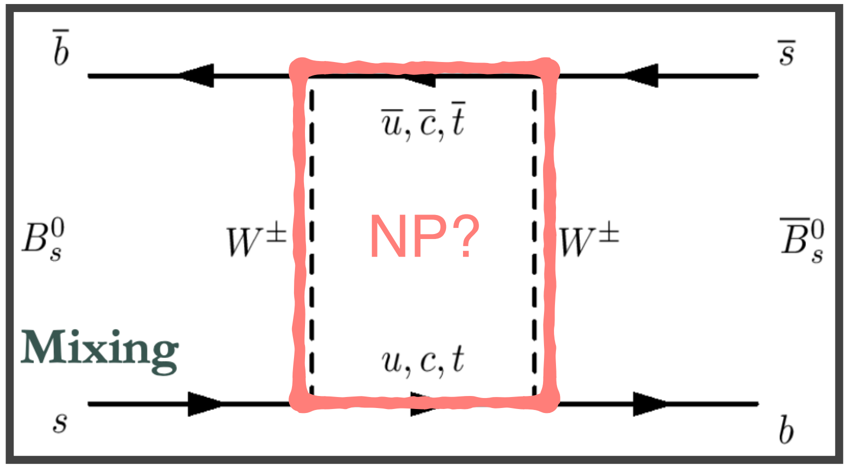
$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$



$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right), \beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right), \gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

$$\phi_s^{SM} \approx -2\beta_s = 2\arg\left(-\frac{V_{cs}V_{cb}^*}{V_{ts}V_{tb}^*}\right)$$

Opportunities for new physics



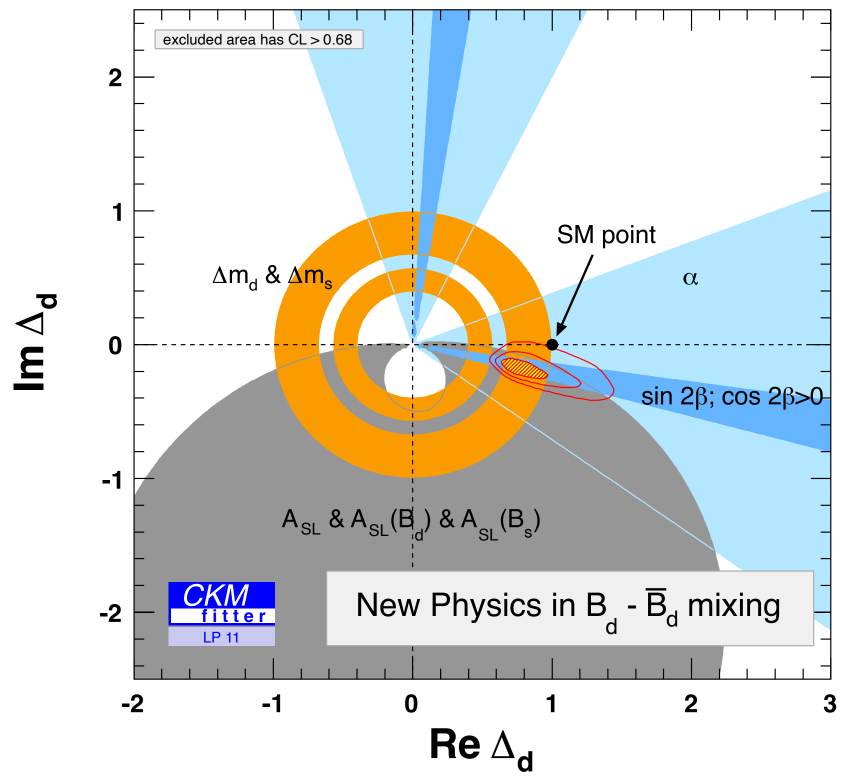
- New physics (NP) short-distance contributions can influence mixing

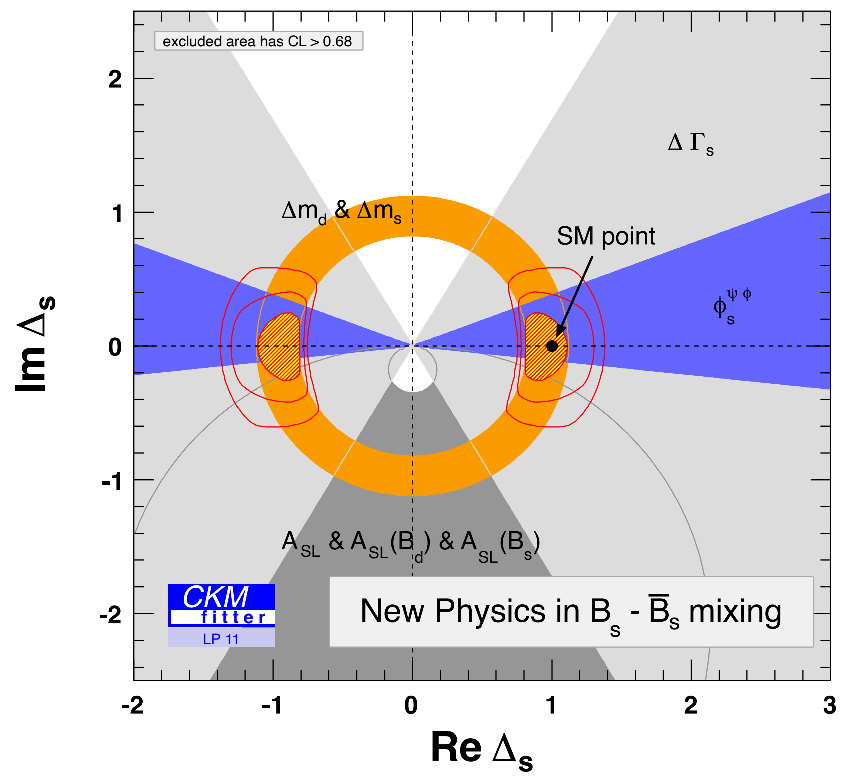
$$m_{12}^{q} = m_{12}^{SM,q} \cdot \Delta_{q}^{NP}$$

[PRD 86(2012)033008]

- Through B mixing, NP energy scales of up to 20 TeV for tree-level NP or 2 TeV for NP in loops can be probed

[PRD 89(2014)033016]



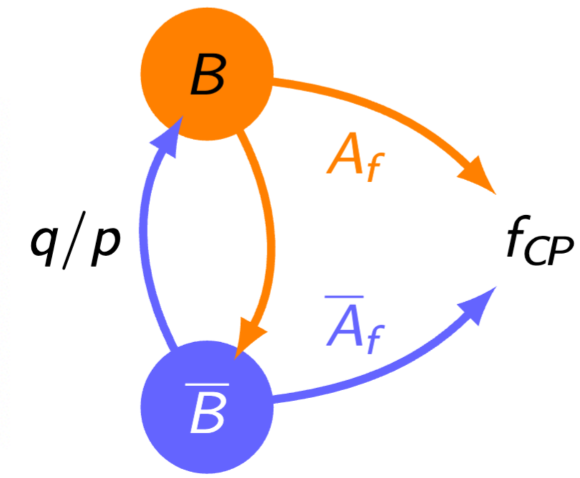


Decay of neutral B meson

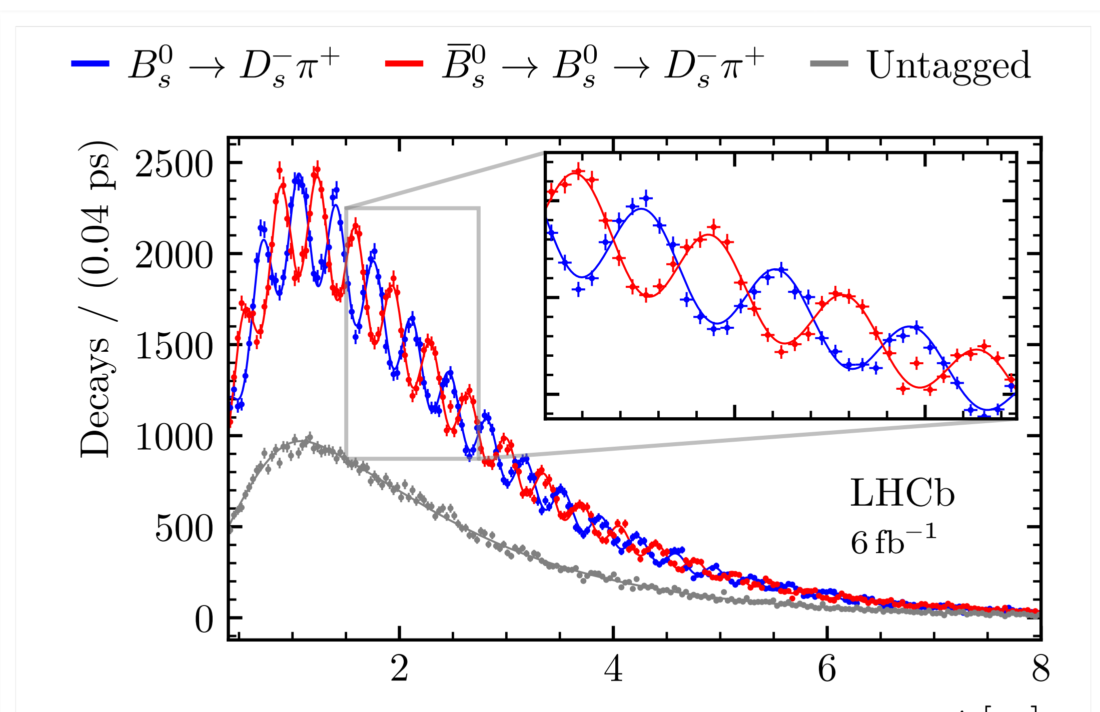
- Decay rate of initial B or $\bar{B}$

$$|\langle f|H|B\rangle|^2 = \frac{1}{2}e^{-\Gamma t}|A_f|^2\left\{D\cosh\left(\frac{\Delta\Gamma}{2}t\right) + A_{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma}{2}t\right) \pm C\cos(\Delta m t) \mp S\sin(\Delta m t)\right\}$$

direct CP — CP in interference of mixing & decay



- Mass difference $\Delta m_{(s)} = M_H - M_L = 2|M_{12}|$ → oscillation frequency!
- Decay-width difference $\Delta\Gamma_{(s)} = \Gamma_L - \Gamma_H = 2|\Gamma_{12}|cos\phi_{12}$



Nat. Phys. 18(2022)1-5

require time-dependent measurements!

- Benchmark for the flavor-tagged time-dependent measurement
- World-best measurement:

$$\Delta m_s = (17.7656 \pm 0.0057)\ ps^{-1}$$

Time-dependent *CP* asymmetry

$$A_{CP}(t) = \frac{\Gamma_{\bar{B}^0_{(s)}\to f}(t) - \Gamma_{B^0_{(s)}\to f}(t)}{\Gamma_{\bar{B}^0_{(s)}\to f}(t) + \Gamma_{B^0_{(s)}\to f}(t)} = \frac{-C_f \cos(\Delta m_{d(s)} t) + S_f \sin(\Delta m_{d(s)} t)}{\cosh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right) + A_f^{\Delta\Gamma} \sinh\left(\frac{\Delta\Gamma_{d(s)}}{2} t\right)}$$

$$C_f \equiv \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2}, \qquad S_f \equiv \frac{2\mathrm{Im}\lambda_f}{1 + |\lambda_f|^2}, \qquad A_f^{\Delta\Gamma} \equiv -\frac{2\mathrm{Re}\lambda_f}{1 + |\lambda_f|^2}$$

- CPV in decay or mixing if $|\lambda_f| \neq 1$

- For $b \to c\bar{c}q$ transition, $S_f \approx \sin 2\beta_{(s)}$

$$\lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

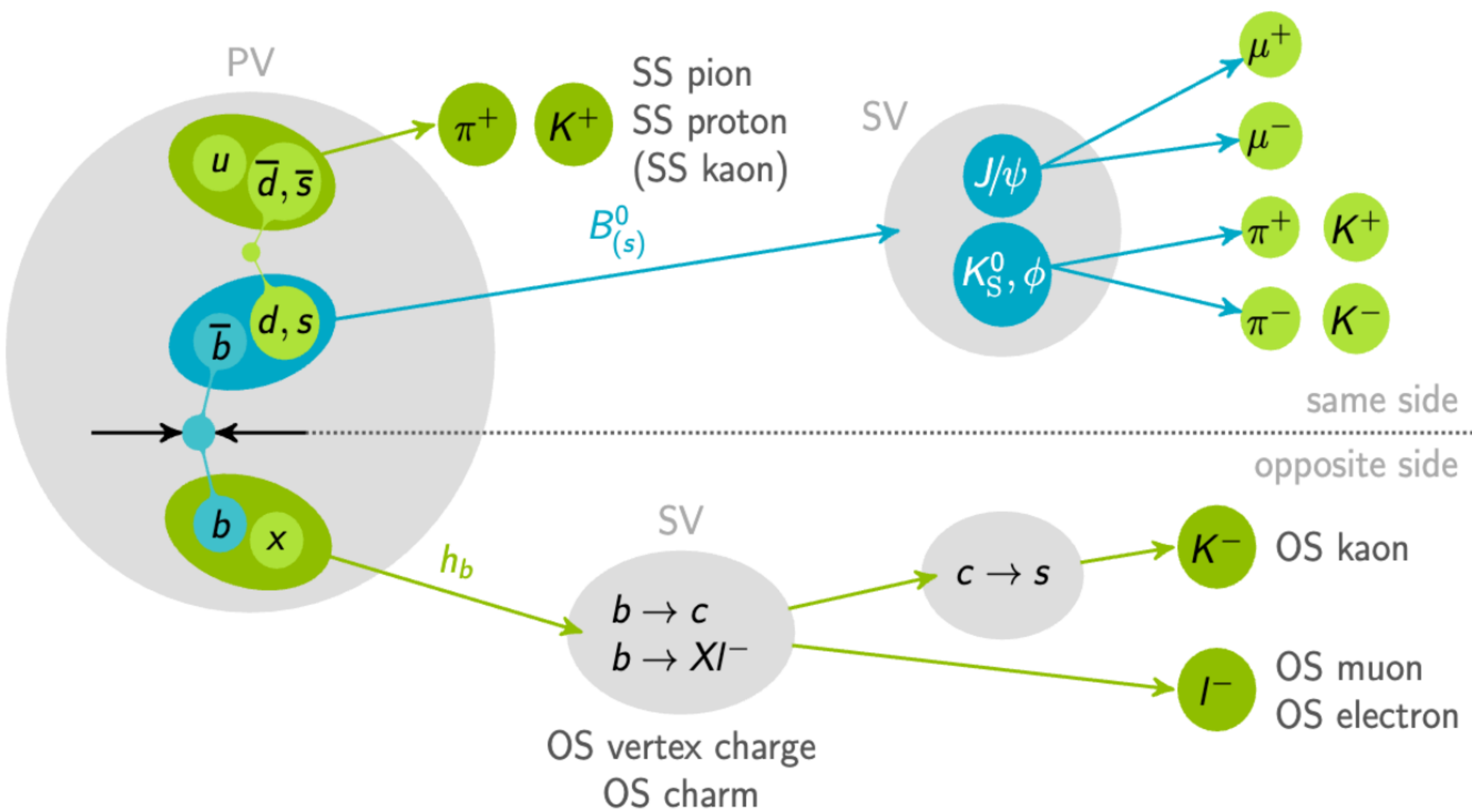
➡ Experimentally

$$A_{CP}(t) \propto e^{-\frac{1}{2}\Delta m_s^2 \sigma_t^2} \cdot (1 - 2\omega) \cdot (C_f \cos(\Delta m_{(s)} t) + \eta_f S_f \sin(\Delta m_{(s)} t))$$

- Flavour tagging of $B^0_{(s)}$ at production: probability of wrong tag ω
- Excellent decay-time resolution (vertex resolution)
- *CP* eigenvalue of the final state η_f

Flavour tagging

$$\mathcal{A}^{CP} = \frac{\Gamma(\overline{B}^0_{(s)} \to f_{CP}) - \Gamma(B^0_{(s)} \to f_{CP})}{\Gamma(\overline{B}^0_{(s)} \to f_{CP}) + \Gamma(B^0_{(s)} \to f_{CP})}$$



- Same-side (SS) tagging: Use charge of K/π produced in the fragmentation
- Opposite-side (OS) tagging: charge of leptons or hadrons from the other b hadrons

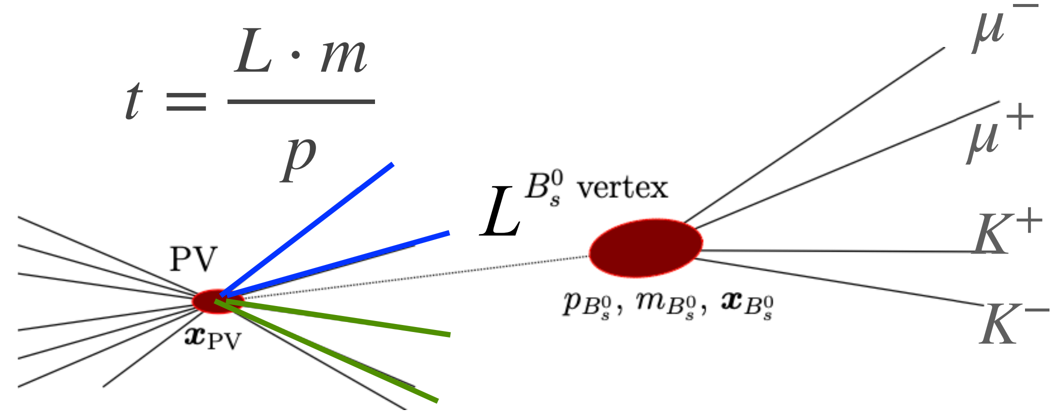
Tagging power	$B^0 \to \psi K^0_S$	$B^0_s \to J/\psi KK$	$B^0_s \to \phi\phi$
$\epsilon_{tag}(1-2\omega)^2$	(4-6)%	4.3%	6%

* tagging efficiency ϵ_{tag}, mistag rate ω

Decay-time resolution

- Decay time resolution dilutes oscillations, $\mathscr{D} = exp(-\frac{1}{2}\sigma_{\rm eff}^2\Delta m_s^2)$
- Significant for B_s^0 system, negligible for B^0

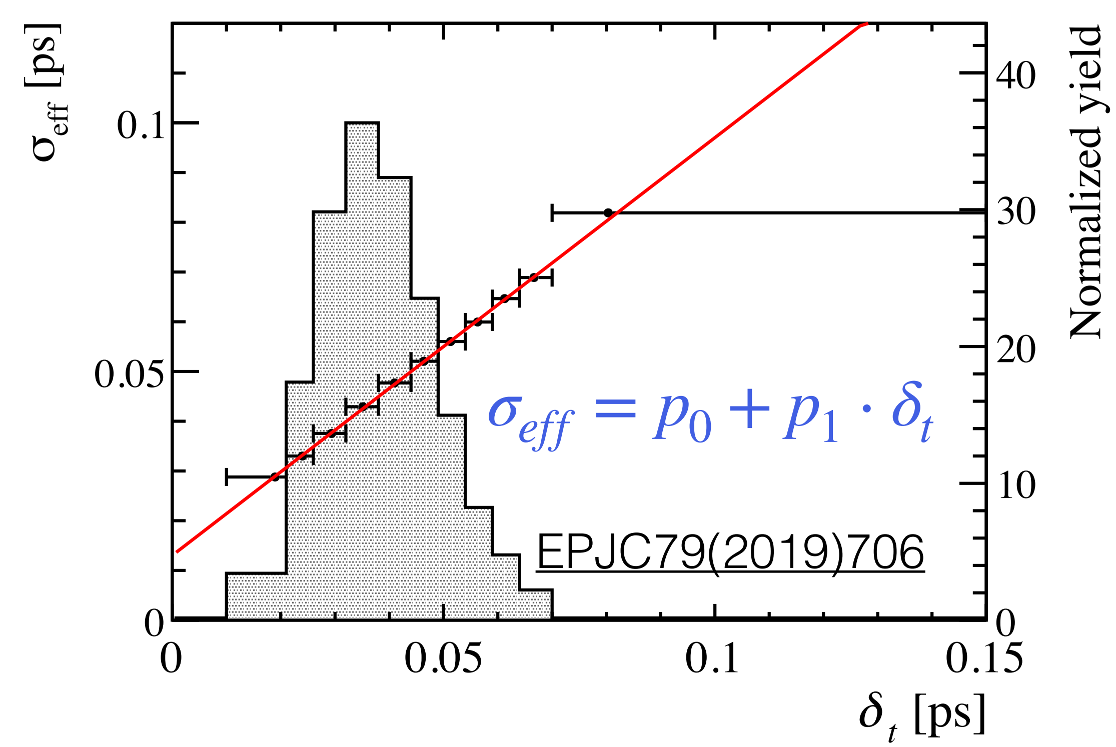
  - $B^0 \to \psi K_S^0$: $\sigma_{MC} \sim 60$ fs
  - $B_s^0 \to J/\psi KK$ & $B_s^0 \to \phi\phi$



$$\delta_t^2 = (\frac{m}{p})^2\sigma_L^2 + (\frac{t}{p})^2\sigma_p^2$$

$\sim 200\ \mu$m $\qquad \sigma_p/p \sim 0.4\,\%$

✓ Effective Gaussian resolution model:
σ_{eff} as a function of per-event δ_t (11 bins)

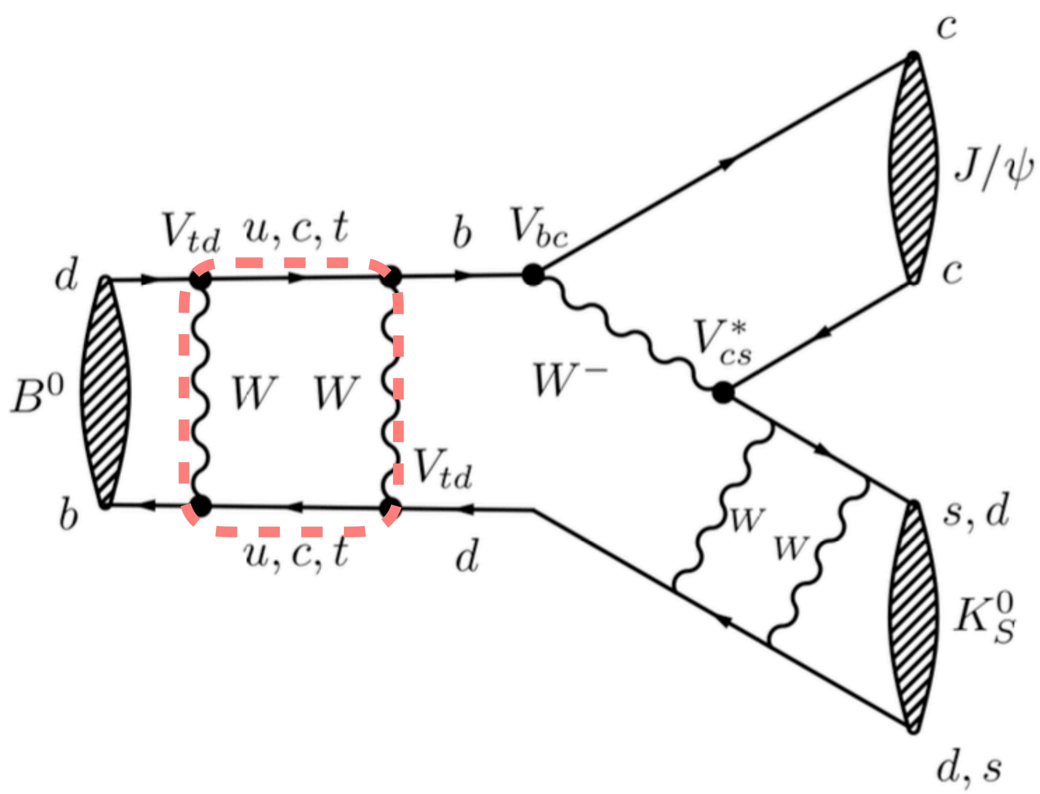


$\sigma_{eff} \sim 42(3)$ fs $\to \mathscr{D} = 0.757$

$\sin 2\beta$ in $B^0 \to \psi K_S^0$

LHCb-PAPER-2023-013
In preparation

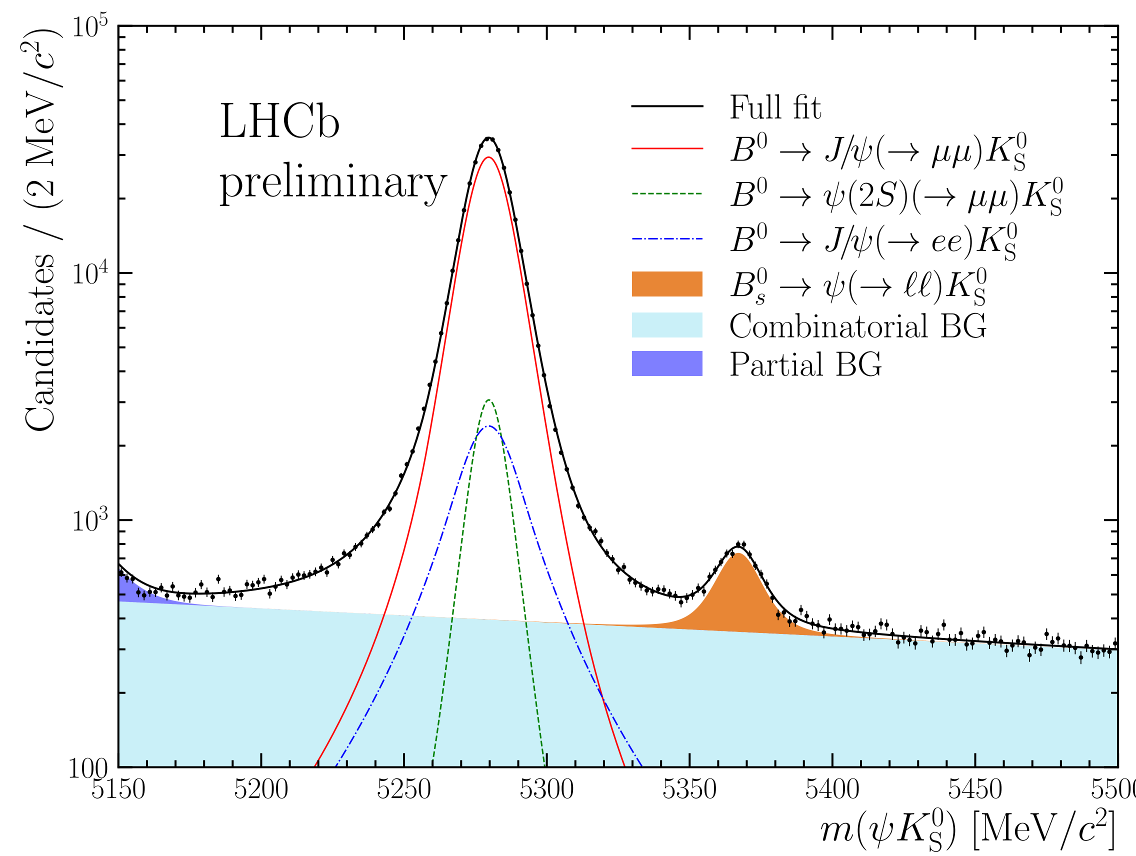
- Tree diagram dominated: NP in mixing
- Three decay modes in $B^0 \to \psi K_S^0$ *(CP-odd only)*



- $B^0 \to J/\psi(\mu^+\mu^-)K_s^0$ (85%)
- $B^0 \to J/\psi(e^+e^-)K_s^0$ (12%)
- $B^0 \to \psi(2S)(\mu^+\mu^-)K_s^0$ (6%)

sWeight from Mass fit to subtract background

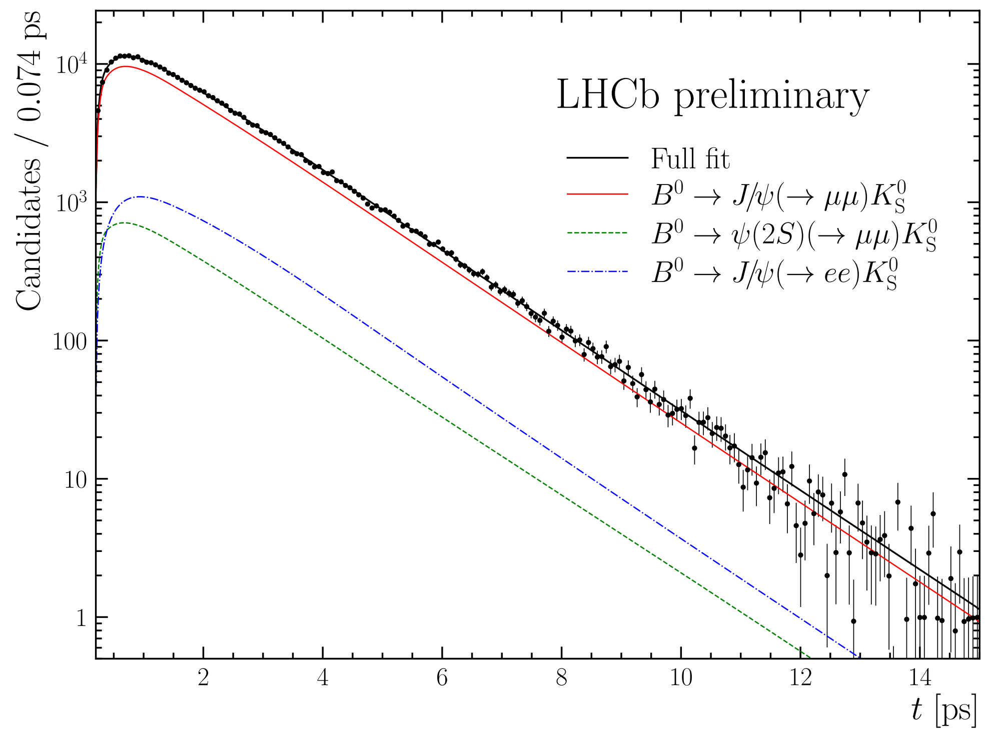
$$N_{J/\psi\,(\to\mu\mu)K_S^0} = 306\,322 \pm 619$$
$$N_{J/\psi\,(\to ee)K_S^0} = 42\,870 \pm 269$$
$$N_{\psi(2S)(\to\mu\mu)K_S^0} = 23\,570 \pm 164$$

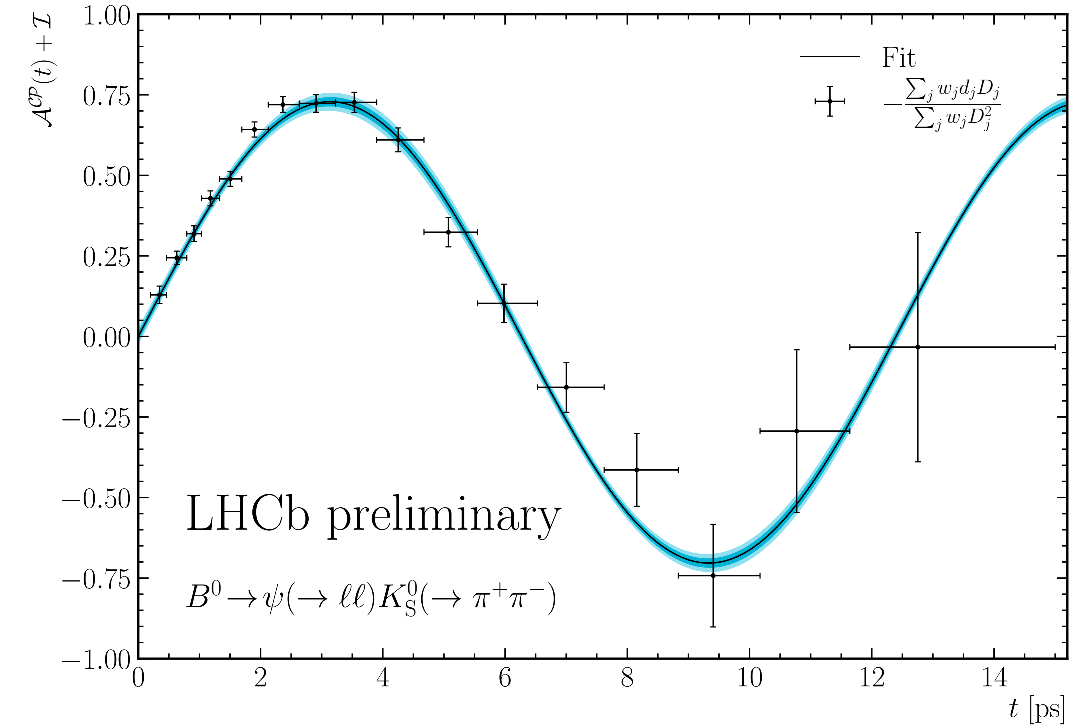


$\sin 2\beta$ in $B^0 \to \psi K^0_S$

LHCb-PAPER-2023-013
In preparation

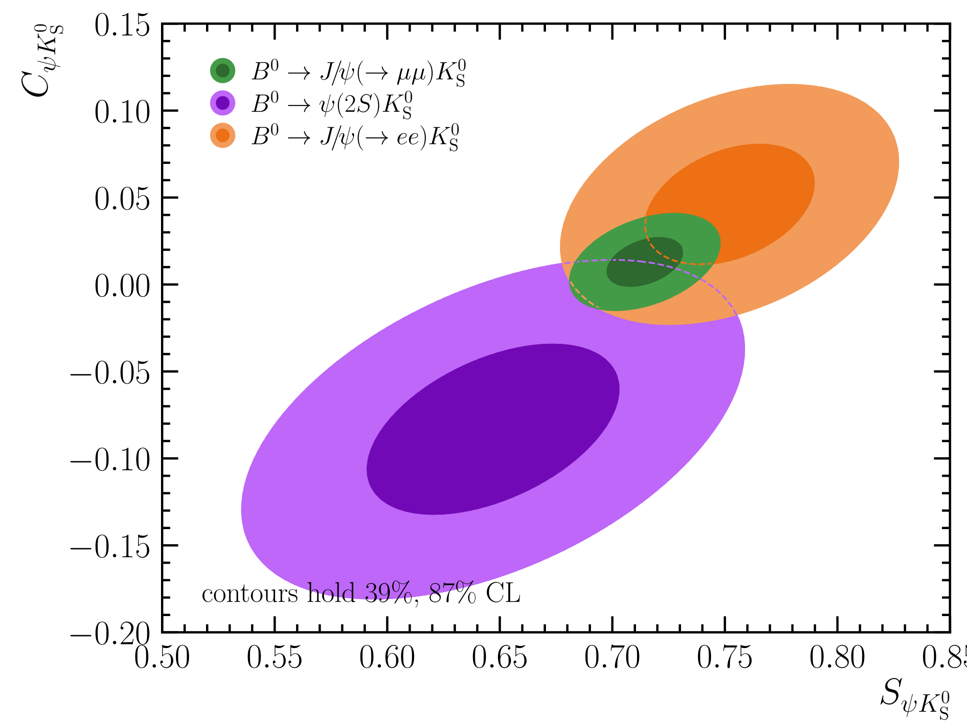
- Simultaneous fits to the decay time of B^0





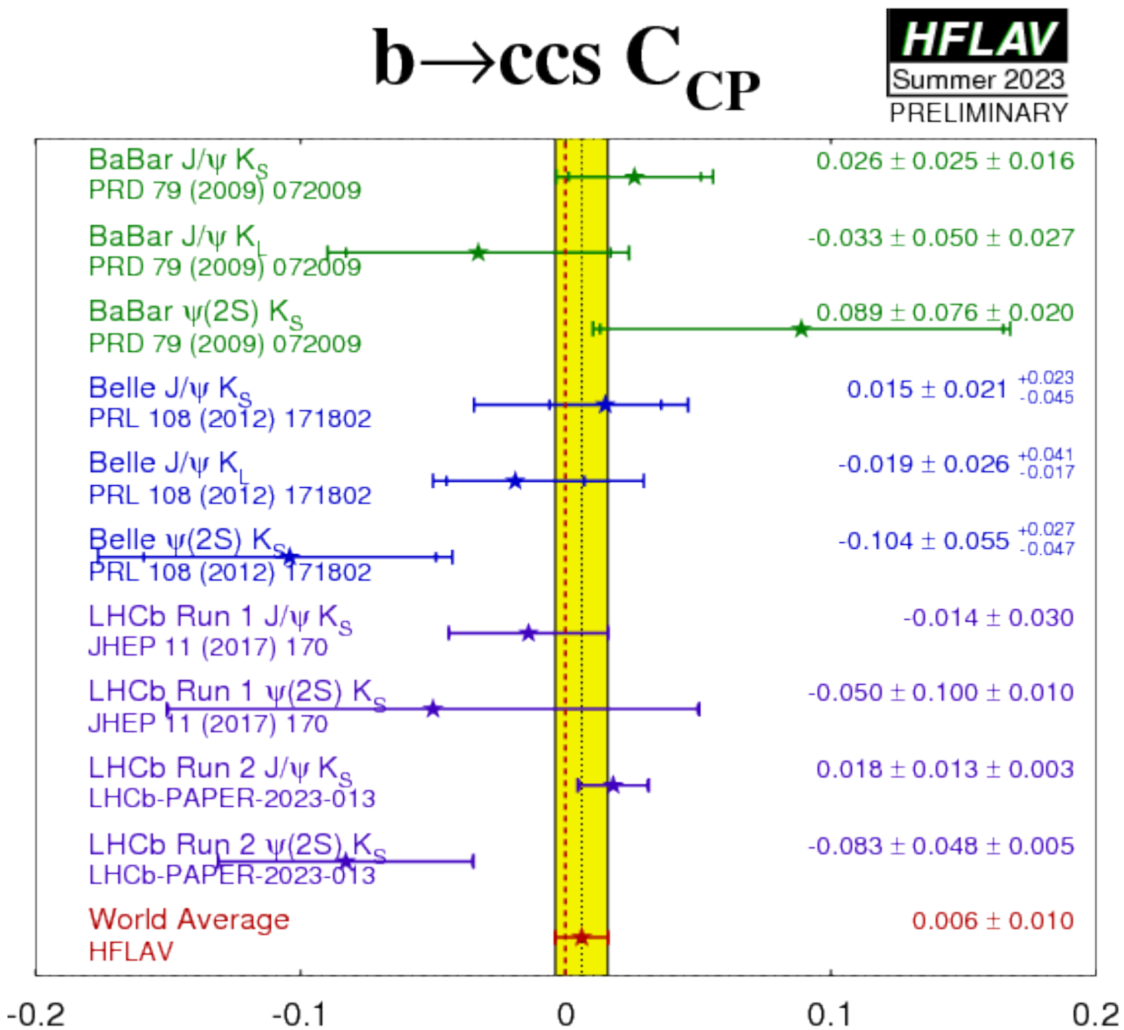
Combined fit result

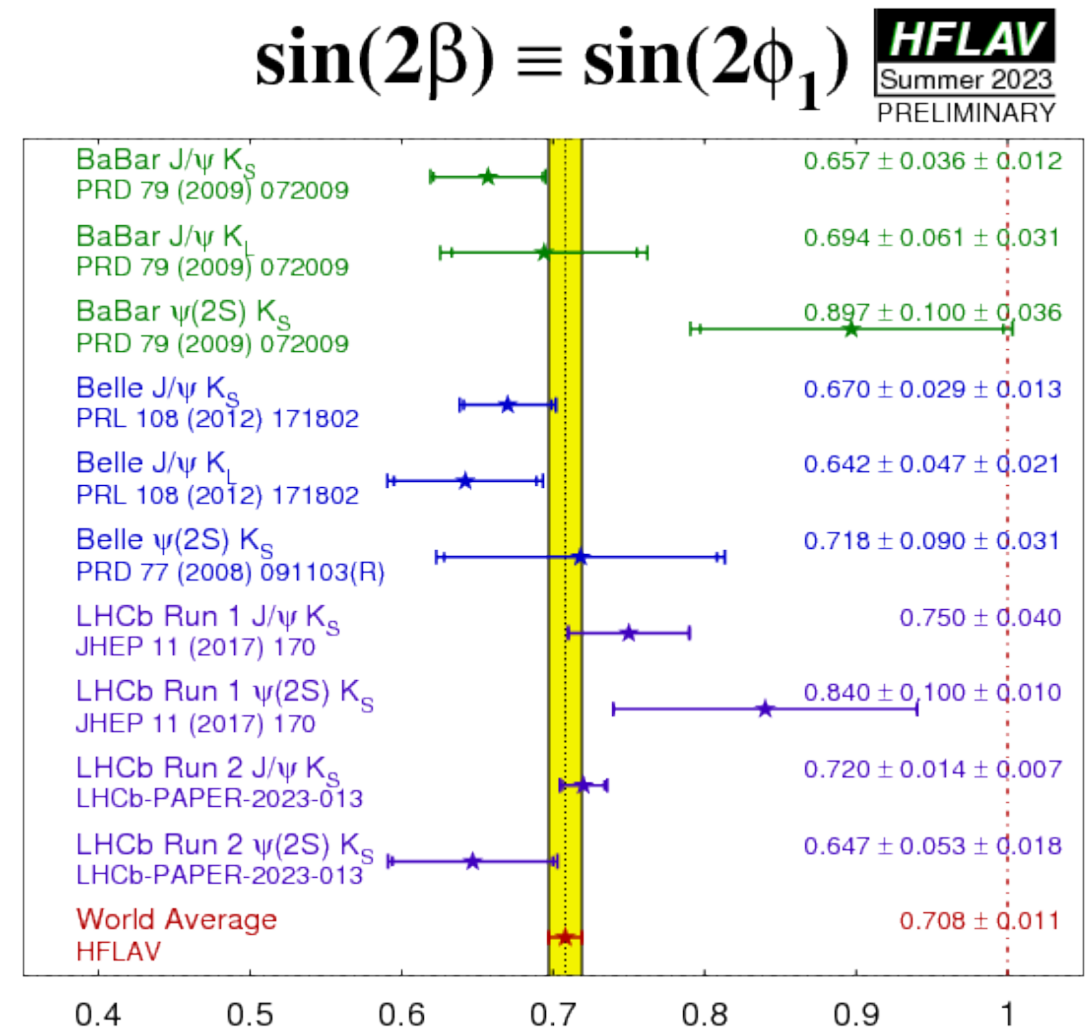
$$S^{\text{Run 2}}_{\psi K^0_S} = 0.716 \pm 0.013\,(\text{stat}) \pm 0.008\,(\text{syst})$$
$$C^{\text{Run 2}}_{\psi K^0_S} = 0.012 \pm 0.012\,(\text{stat}) \pm 0.003\,(\text{syst})$$



- The most precise measurement in single measurement to date

$\sin 2\beta$ combinations

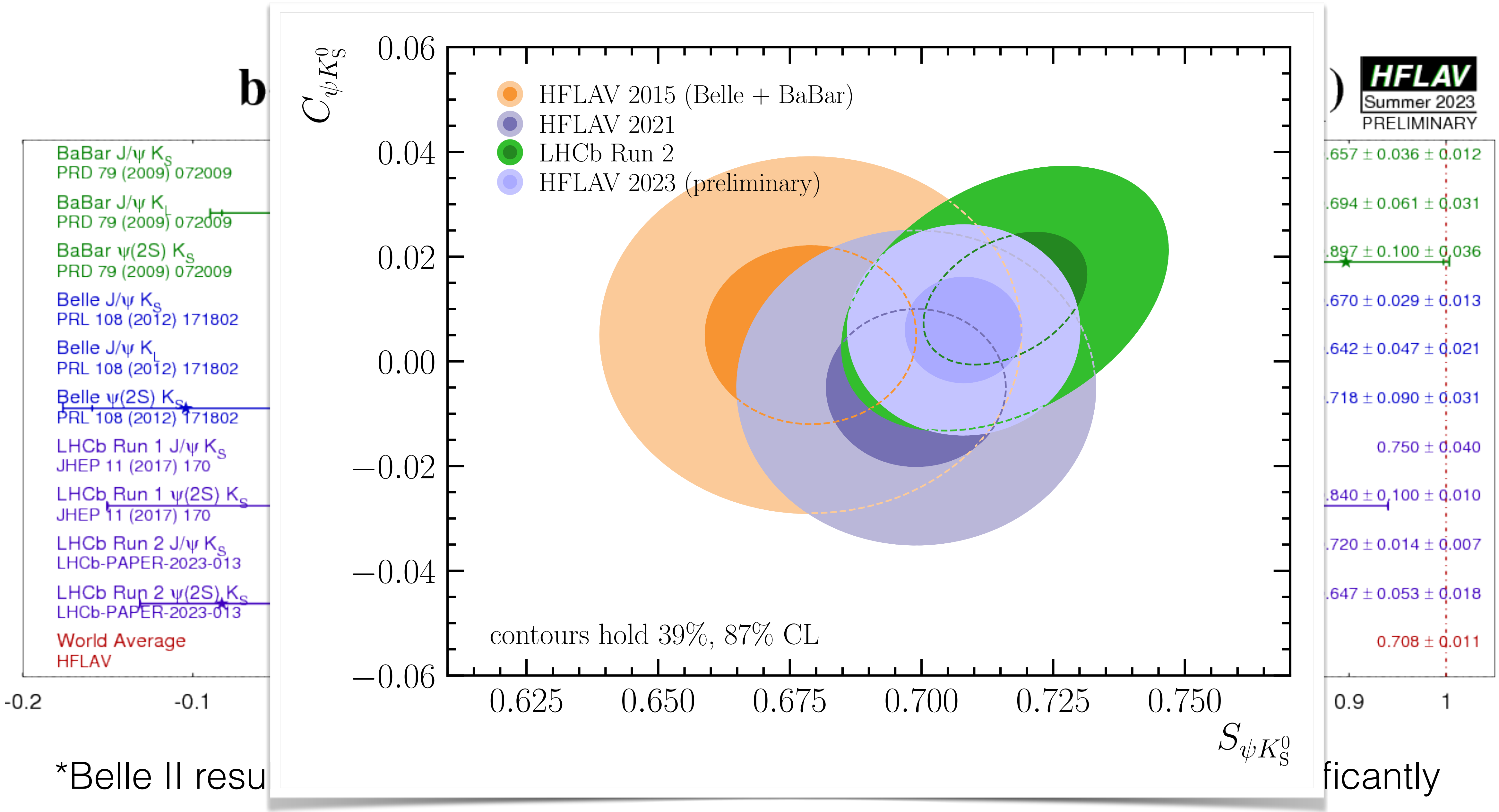




*Belle II results is not included, which should not affect the current WA significantly

- Consistent with other measurements, still statistical uncertainty limited
- LHCb results dominate the latest World Average

$\sin 2\beta$ combinations



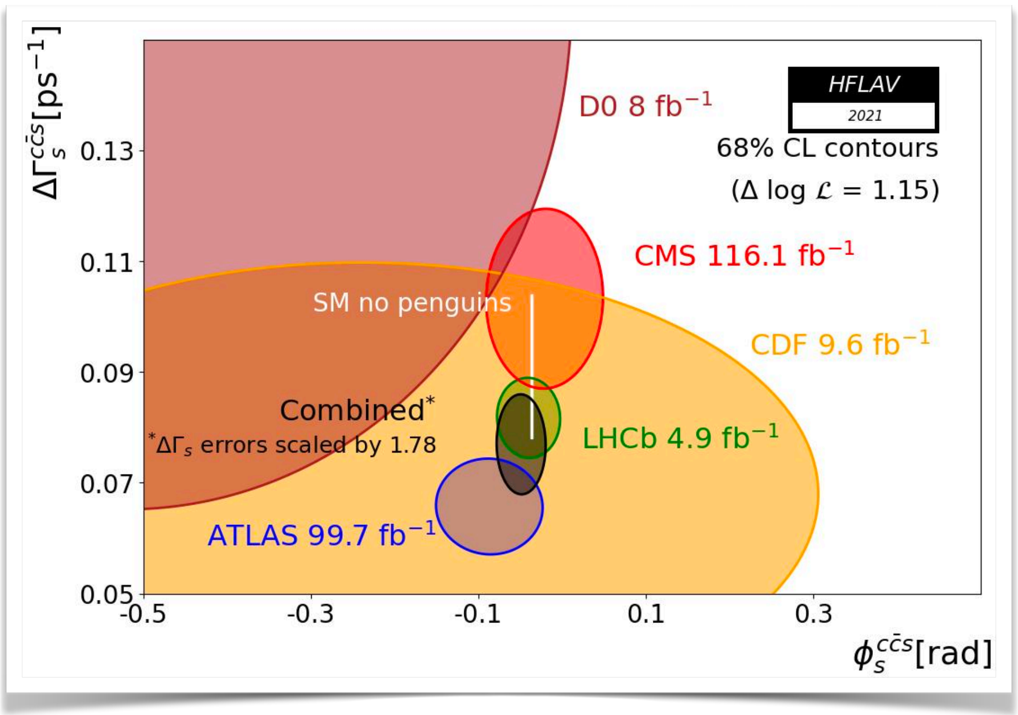
*Belle II resu ... ficantly

- Consistent with other measurements, still statistical uncertainty limited
- LHCb results dominate the latest World Average

ϕ_s in $B_s^0 \to J/\psi\phi(KK)$

arXiv: 2308.01468
submitted to PRL

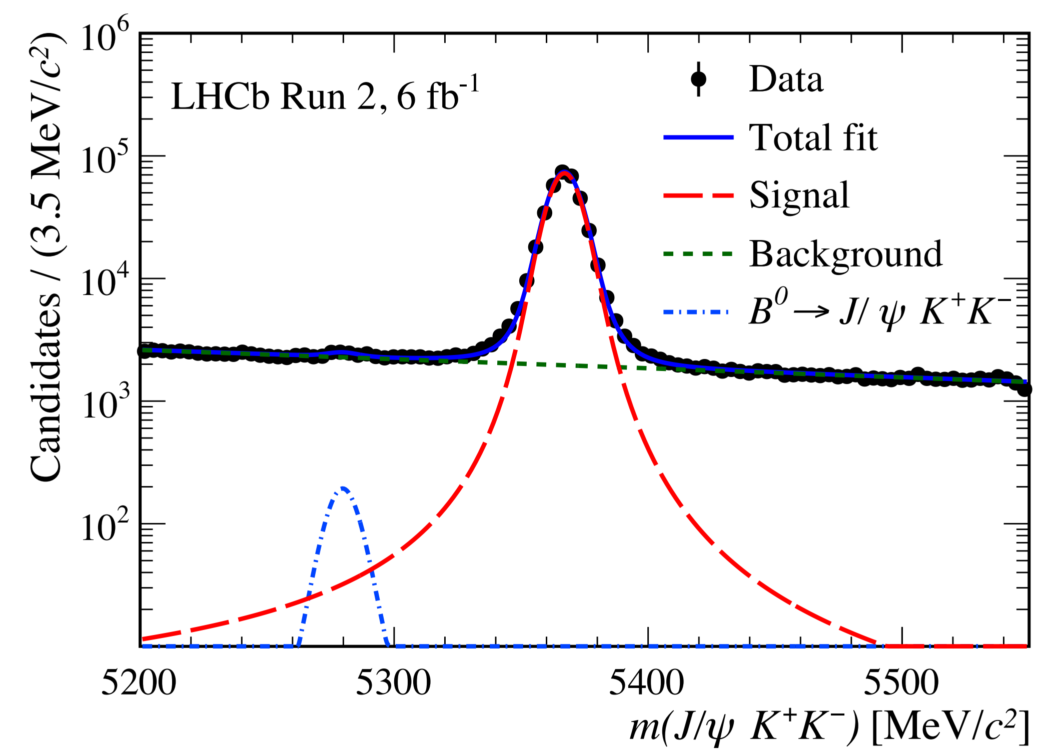
- Golden model to measure ϕ_s : $b \to c\bar{c}s$ transition process $B_s^0 \to J/\psi\phi(KK)$
- Sensitive to New Physics, small contribution could be clearly visible



- $-\beta_s^{\rm SM} = -0.0368^{+0.0009}_{-0.0006}$ rad
- 2022 world average: $\phi_s^{c\bar{c}s,WA} = (-0.049 \pm 0.019)$ rad
- Tension between $\Delta\Gamma_s$ measurements from different experiments

sWeight from Mass fit to subtract background

Total signal candidates ~349000

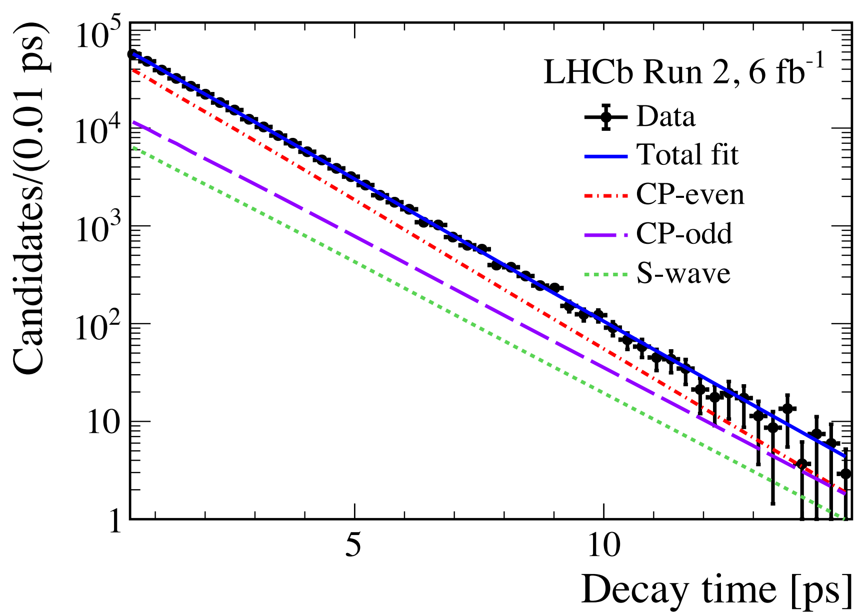


ϕ_s in $B_s^0 \to J/\psi\phi(KK)$

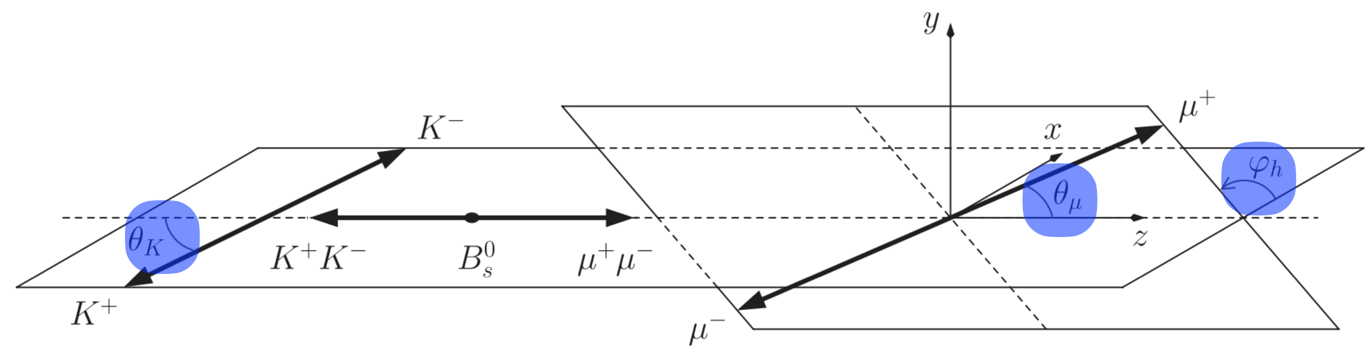
arXiv: 2308.01468
submitted to PRL

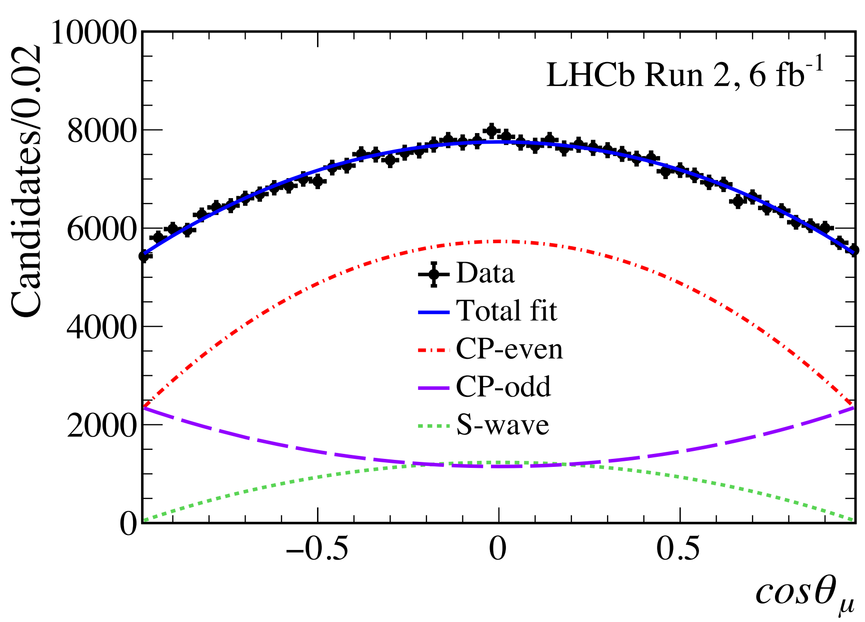
- Time-dependent flavour-tagged angular analysis for $B_s^0 \to VV$

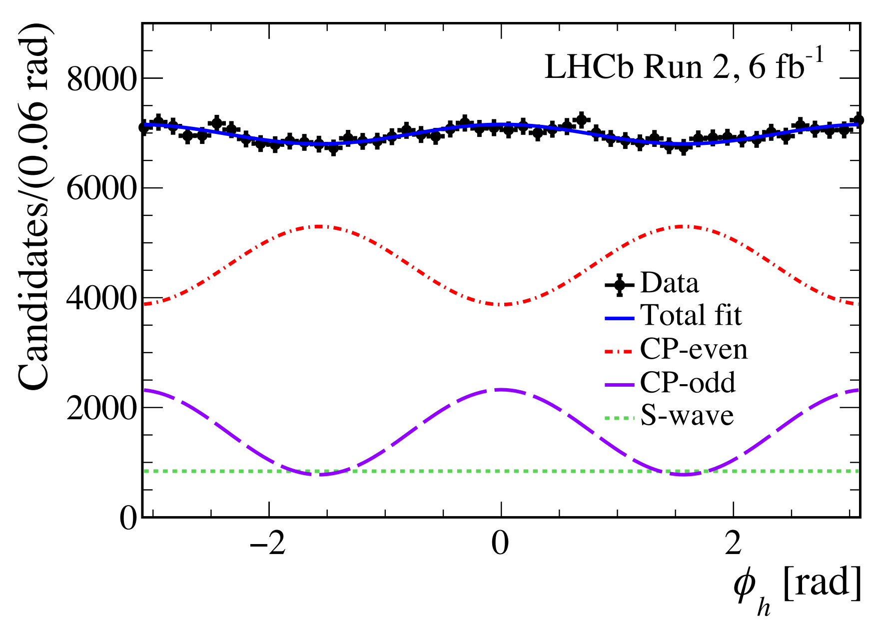
$$\mathscr{P}(t, \theta_K, \theta_\mu, \phi_h \,|\, \delta_t) \propto \sum_{k=1}^{10} N_k h_k(t) f_k(\theta_K, \theta_\mu, \phi_h) \;\; \to \phi_s, \Delta m_s, \Delta\Gamma_s, \Gamma_s - \Gamma_d$$

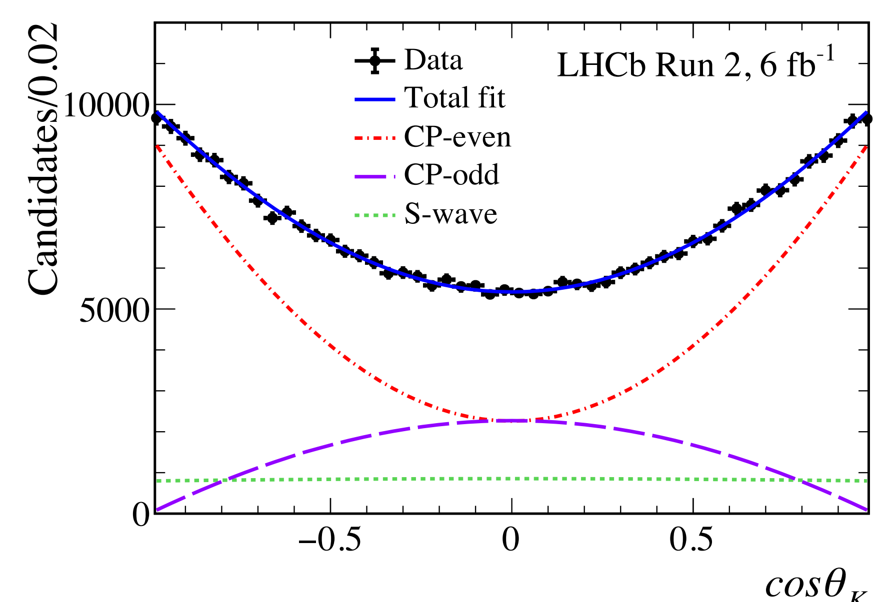


* Amplitudes f_k based on helicity frame to disentangle CP-odd and CP-even components





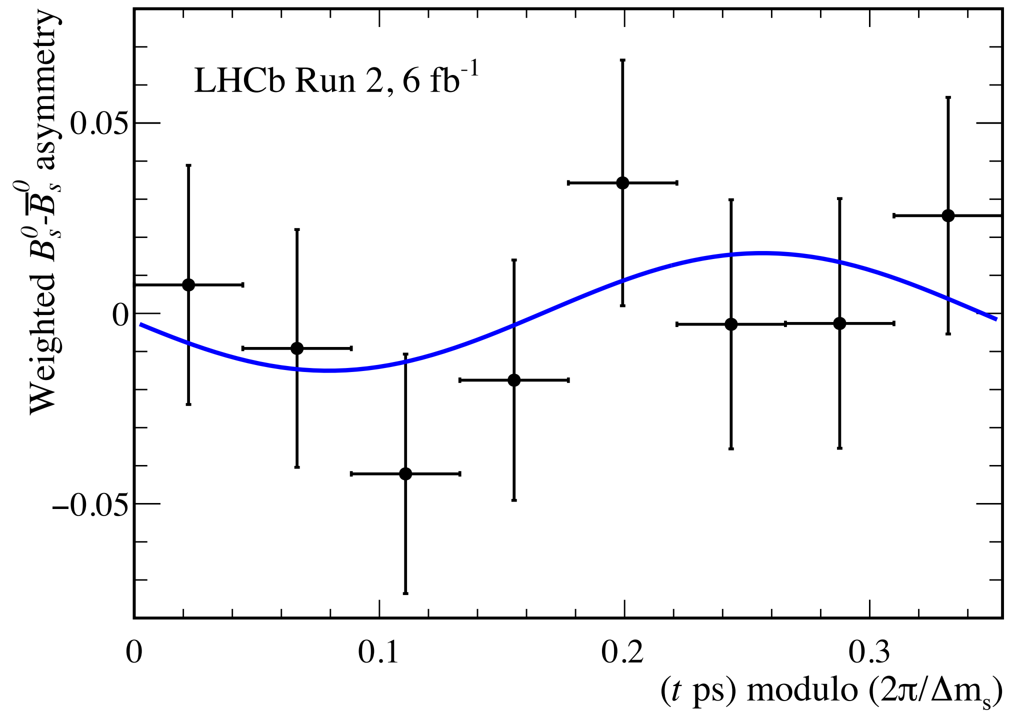




ϕ_s in $B_s^0 \to J/\psi KK$

arXiv: 2308.01468
submitted to PRL

Parameters	Values [1]
ϕ_s [rad]	$-0.039 \pm 0.022 \pm 0.006$
$\lvert\lambda\rvert$	$1.001 \pm 0.011 \pm 0.005$
$\Gamma_s - \Gamma_d$ [ps^{-1}]	$-0.0057 {}^{+0.0013}_{-0.0015} \pm 0.0014$
$\Delta\Gamma_s$ [ps^{-1}]	$0.0846 \pm 0.0044 \pm 0.0024$
Δm_s [ps^{-1}]	$17.743 \pm 0.033 \pm 0.009$
$\lvert A_\perp\rvert^2$	$0.2463 \pm 0.0023 \pm 0.0024$
$\lvert A_0\rvert^2$	$0.5179 \pm 0.0017 \pm 0.0032$
$\delta_\perp - \delta_0$ [rad]	$2.903 {}^{+0.075}_{-0.074} \pm 0.048$
$\delta_\parallel - \delta_0$ [rad]	$3.146 \pm 0.060 \pm 0.052$



- The most precise measurement in single channel to date
- Compatible with prediction assuming the SM $-\beta_s^{SM} = -0.0368^{+0.0009}_{-0.0006}$ rad
- No evidence of CP violation
- Consistent and combined with all LHCb measurements
  $(B_s^0 \to J/\psi hh, D_s^+ D_s^-, \psi(2S)KK)$ $\phi_s = -0.031 \pm 0.018$ rad

ϕ_s polarisation dependent fit

arXiv: 2308.01468
submitted to PRL

- New physics effects can vary in different polarisation states
  - Allow $|\lambda|$ and ϕ_s to differ in polarisation states
  - Shows no evidence for any polarisation dependence

Parameters	Values (stat. unc. only)
ϕ_s^0 [rad]	-0.034 ± 0.023
$\phi_s^{\parallel} - \phi_s^0$ [rad]	-0.002 ± 0.021
$\phi_s^{\perp} - \phi_s^0$ [rad]	$-0.001\,^{+\,0.020}_{-\,0.021}$
$\phi_s^{S} - \phi_s^0$ [rad]	$0.022\,^{+\,0.027}_{-\,0.026}$
$\|\lambda^0\|$	$0.969\,^{+\,0.025}_{-\,0.024}$
$\|\lambda^{\parallel}/\lambda^0\|$	$0.982\,^{+\,0.055}_{-\,0.052}$
$\|\lambda^{\perp}/\lambda^0\|$	$1.107\,^{+\,0.081}_{-\,0.075}$
$\|\lambda^{S}/\lambda^0\|$	$1.121\,^{+\,0.085}_{-\,0.078}$

ϕ_s combinations in $b \to c\bar{c}s$ transition

Previous World Average:

$\phi_s^{c\bar{c}s} = -0.049 \pm 0.019$ rad

$\phi_s^{J/\psi KK} = -0.070 \pm 0.022$ rad

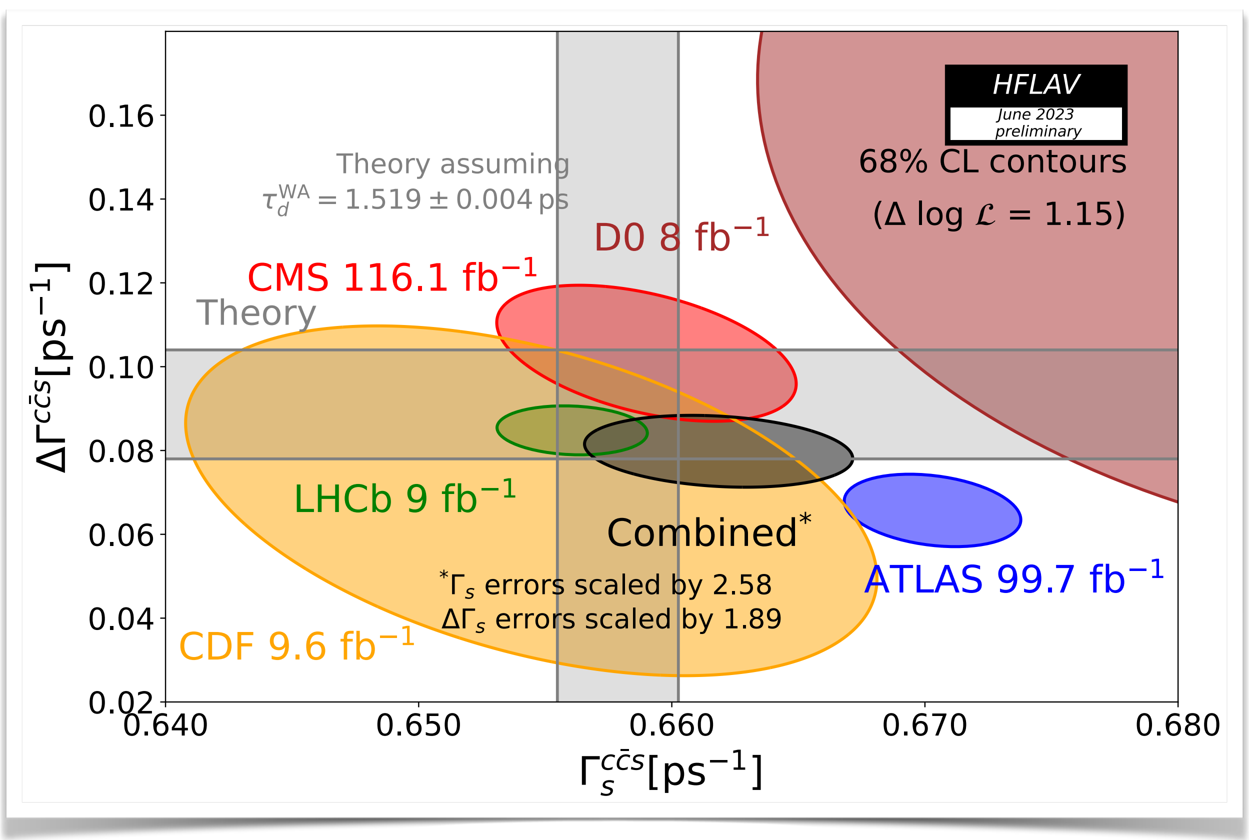
New World Average: (preliminary)

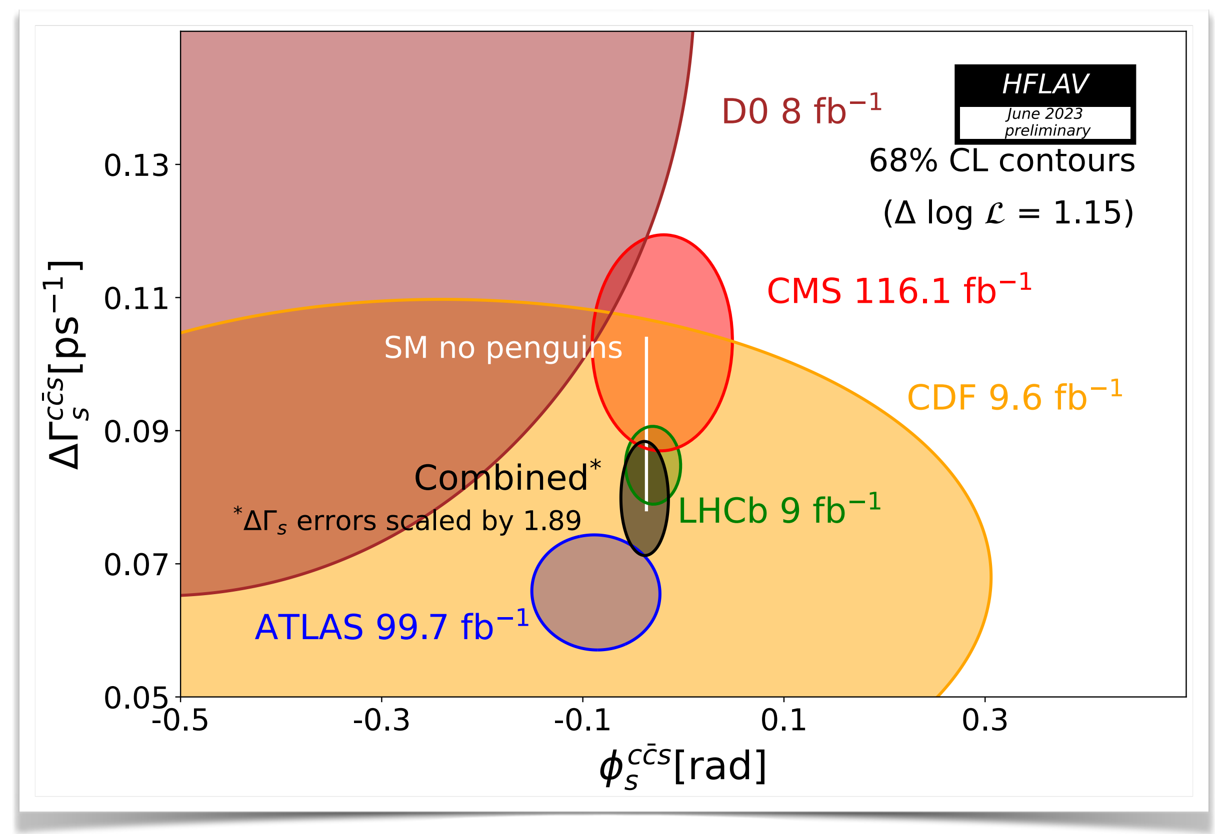
$\phi_s^{c\bar{c}s} = -0.050 \pm 0.016$ rad (16%)

$\phi_s^{J/\psi KK} = -0.039 \pm 0.017$ rad (23%)

- Consistent with the Global fits with SM assumption

$$\phi_s^{\text{CKMFitter}} \approx -2\beta_s = (-0.0368^{+0.0006}_{-0.0009})\ \text{rad} \qquad \phi_s^{\text{UTFitter}} = (-0.0370 \pm 0.0010)\ \text{rad}$$

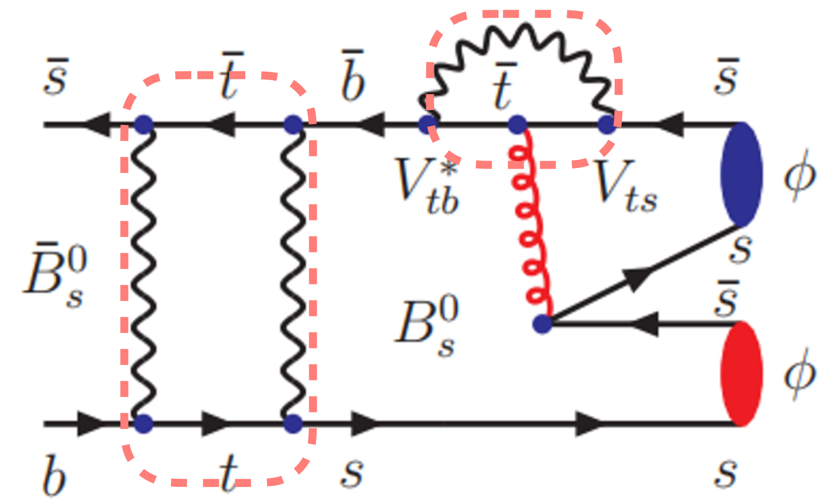




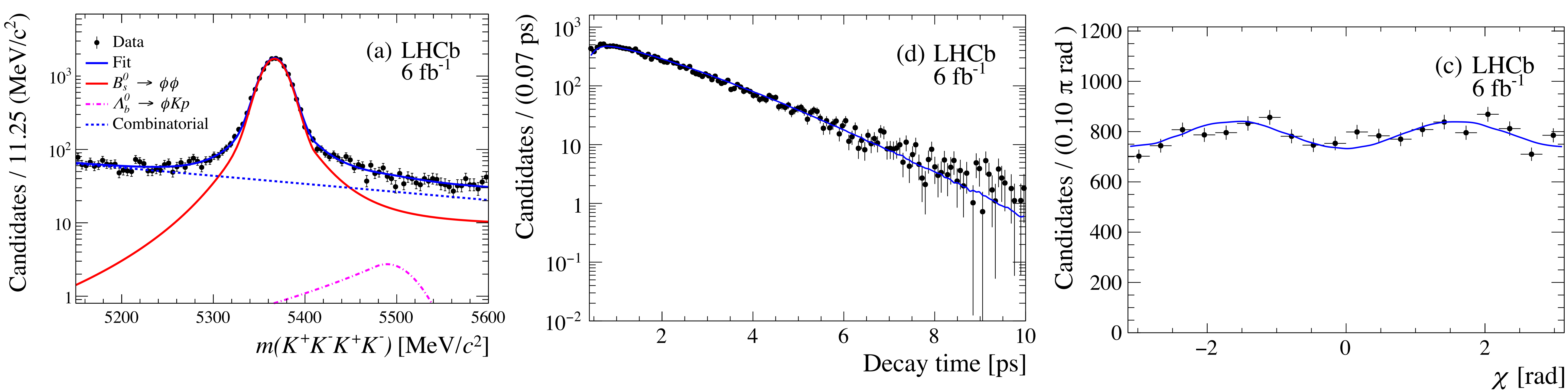
ϕ_s in $b \to s\bar{s}s$ transition

LHCb-PAPER-2023-001

- Benchmark channel $B_s^0 \to \phi(KK)\phi(KK)$ proceeds via $b \to s\bar{s}s$ transition
  - Penguin dominated decay
  - NP contributes in penguin or mixing process



- Similar analysis strategy as $B_s^0 \to J/\psi\phi(KK)$
  → flavour-tagged time-dependent angular analysis

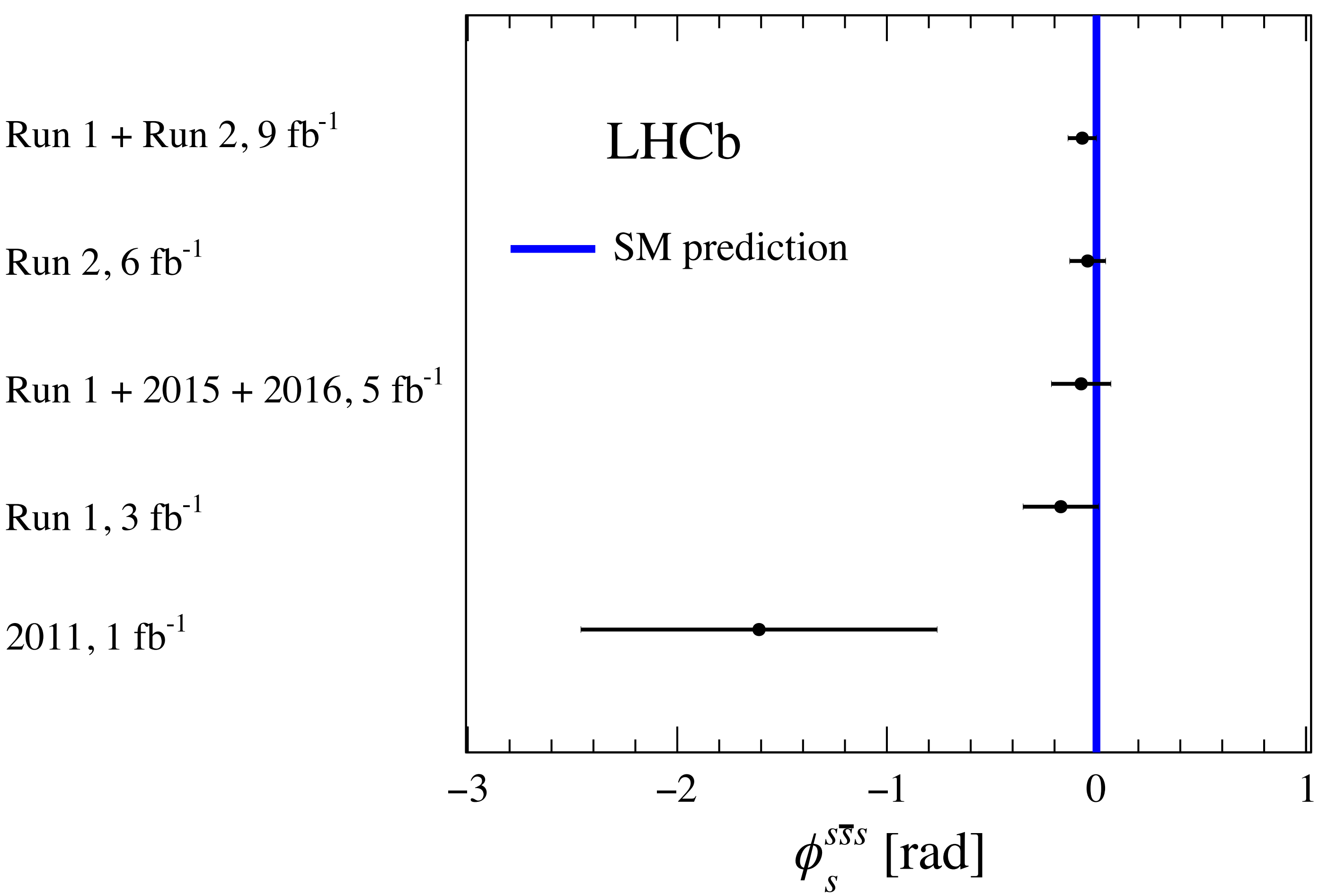


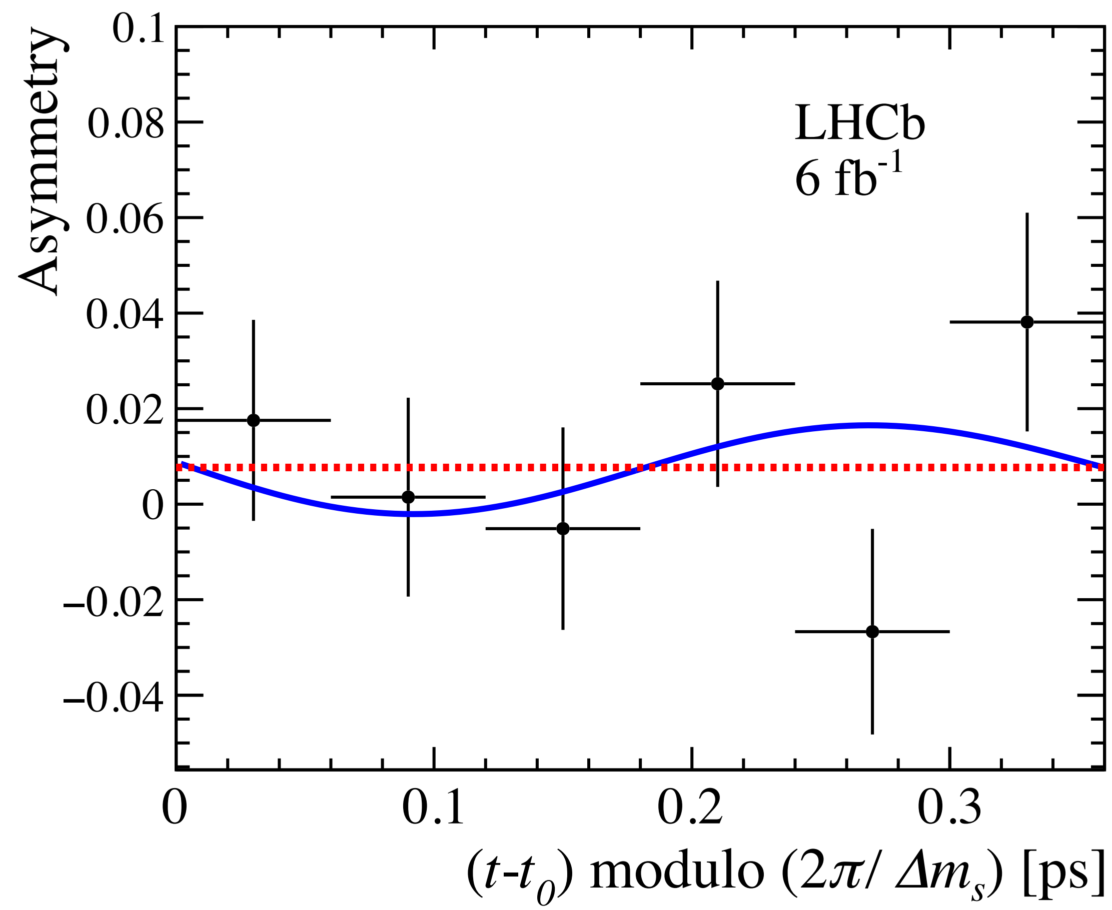
ϕ_s in $b \to s\bar{s}s$ transition

LHCb-PAPER-2023-001
accepted by PRL

$$\phi_s^{s\bar{s}s} = -0.042 \pm 0.075 \pm 0.009 \text{ rad}, \ |\lambda| = 1.004 \pm \pm 0.030 \pm 0.009$$

- The most precise measurement in any penguin dominated B decays
- No polarisation dependence is observed

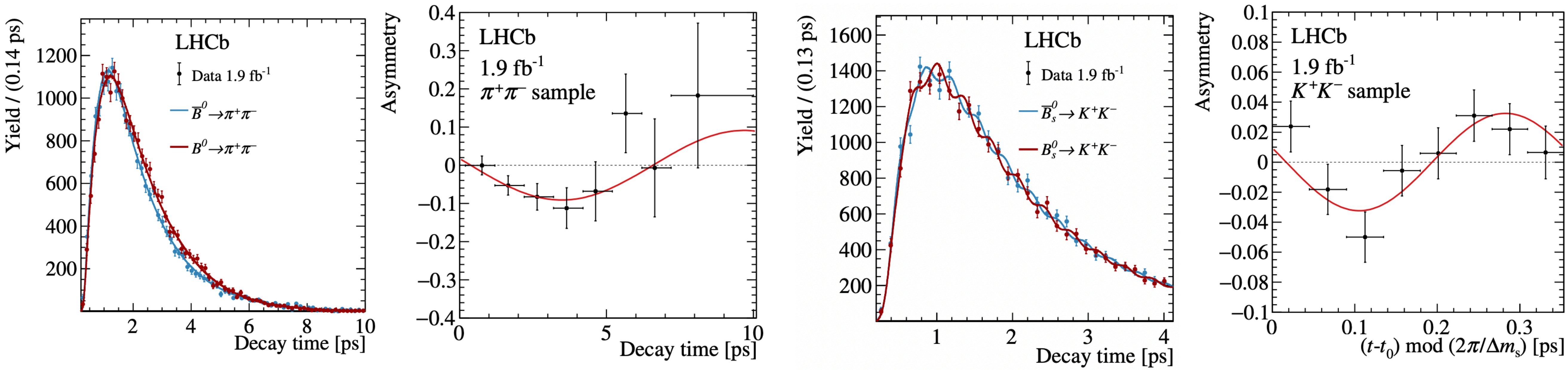




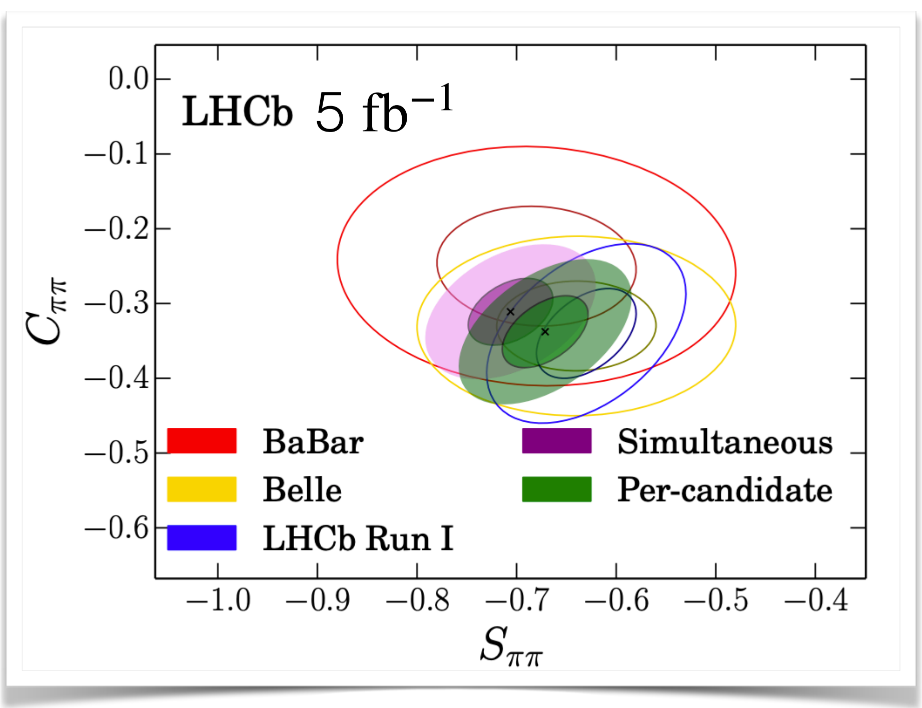
CP asymmetry in $B^0_{(s)} \to h^+h^-$

JHEP03(2021)075

- Simultaneous fit to the invariant mass, $B^0_{(s)}$ decay time and tagging decision for $B^0 \to \pi^+\pi^-$, $B^0_s \to K^+K^-$, $B^0_{(s)} \to K\pi$, providing constraints to α, γ, $\sin 2\beta_s$
- The first observation of time-dependent CP violation in B^0_s decay



Analysis of full Run 2 data in progress

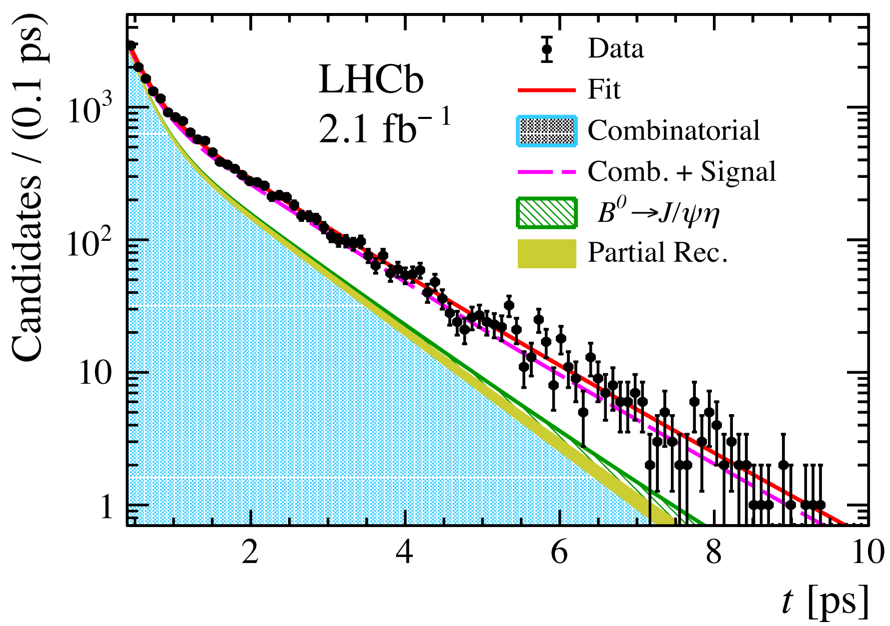


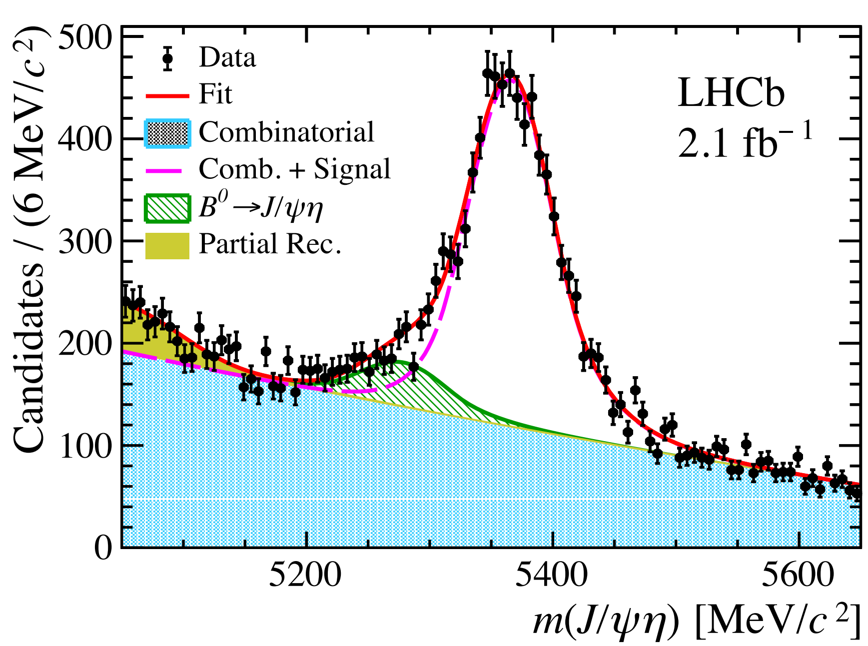
$$
\begin{aligned}
C_{\pi\pi} &= -0.311 \pm 0.045 \pm 0.015,\\
S_{\pi\pi} &= -0.706 \pm 0.042 \pm 0.013,\\
A_{CP}^{B^0} &= -0.0824 \pm 0.0033 \pm 0.0033,\\
A_{CP}^{B^0_s} &= 0.236 \pm 0.013 \pm 0.011,\\
C_{KK} &= 0.164 \pm 0.034 \pm 0.014,\\
S_{KK} &= 0.123 \pm 0.034 \pm 0.015,\\
\mathcal{A}_{KK}^{\Delta\Gamma} &= -0.83 \pm 0.05 \pm 0.09,
\end{aligned}
$$

Effective lifetime measurements in $B_s^0 \to J/\psi\eta$

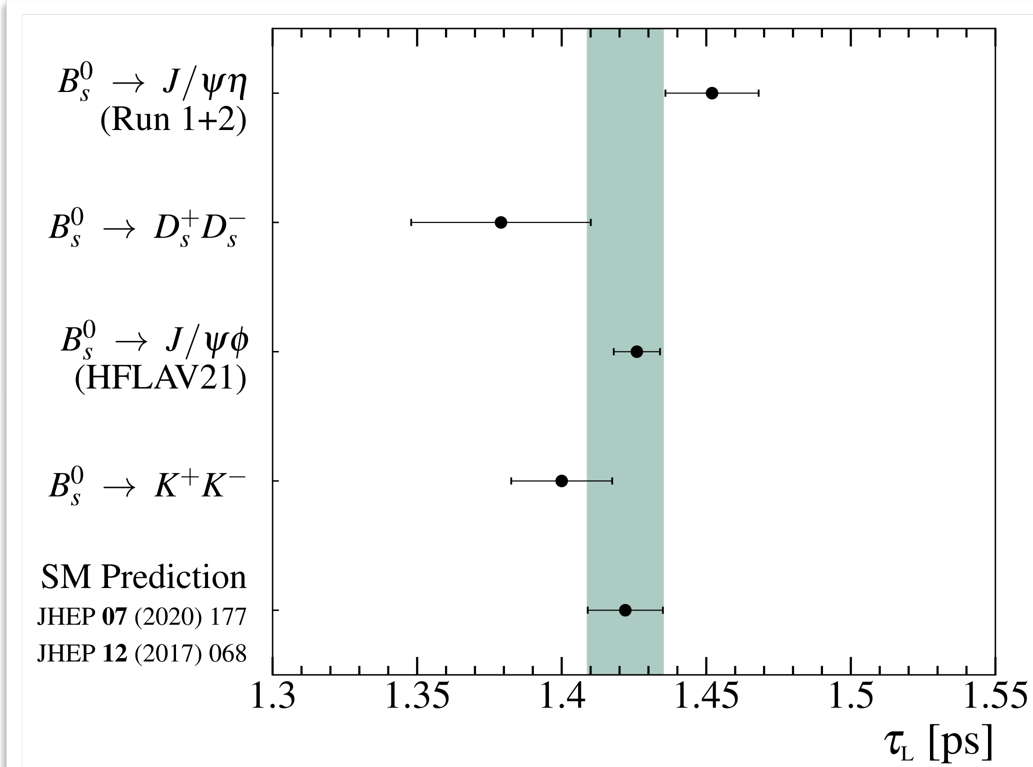
EPJC83 (2023) 629

- CP-even decay $B_s^0 \to J/\psi(\mu^+\mu^-)\eta(\gamma\gamma)$ allows to determine $\tau_L = 1/\Gamma_L$
- Simultaneous fit to invariant mass and decay time





$$\tau_L = 1.452 \pm 0.014 \pm 0.007 \pm 0.002\ \text{ps}$$



Agree with the SM prediction and other measurements

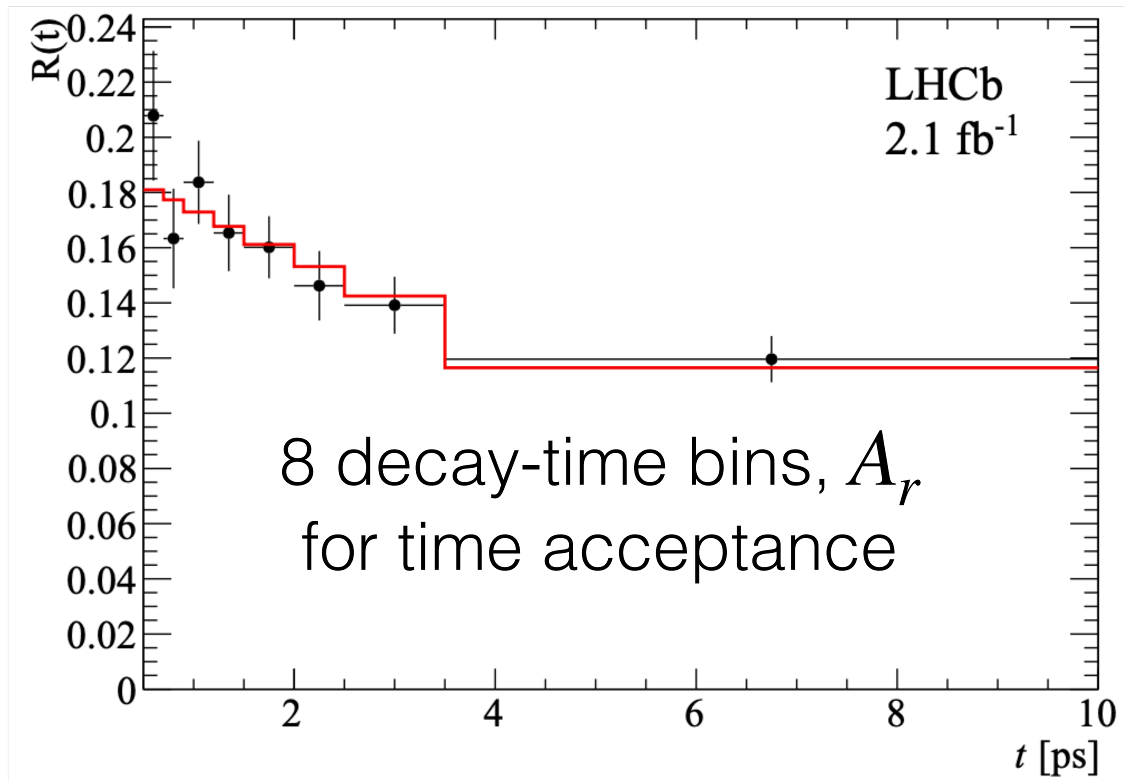
Effective lifetime measurements in $B_s^0 \to J/\psi\eta'$

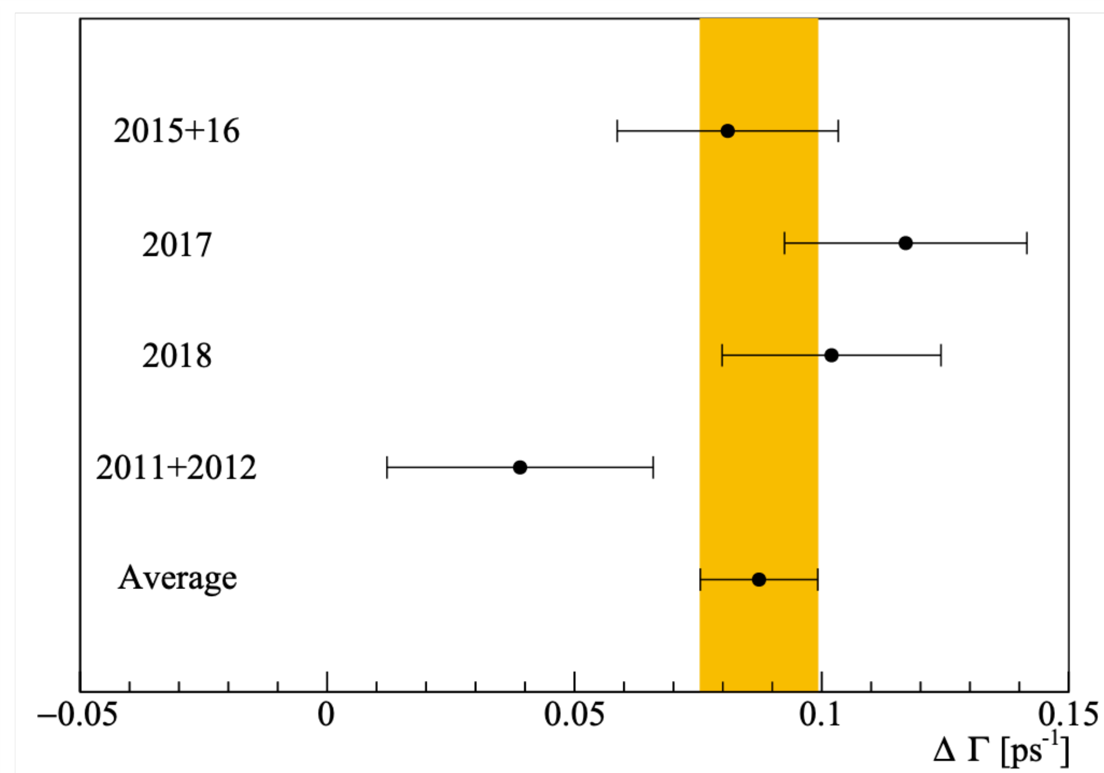
- Simultaneous analysis of CP-even decay $B_s^0 \to J/\psi(\mu^+\mu^-)\eta'(\pi^+\pi^-\gamma)$ and CP-odd decay $B_s^0 \to J/\psi\rho^0$ to determine $\Delta\Gamma_s$
- Fit to the ratio of decay time $R(t)$ in 8 bins

LHCb-PAPER-2023-025
in preparation

$$R(t) = A_r(t) \cdot \frac{N_L}{N_H}$$

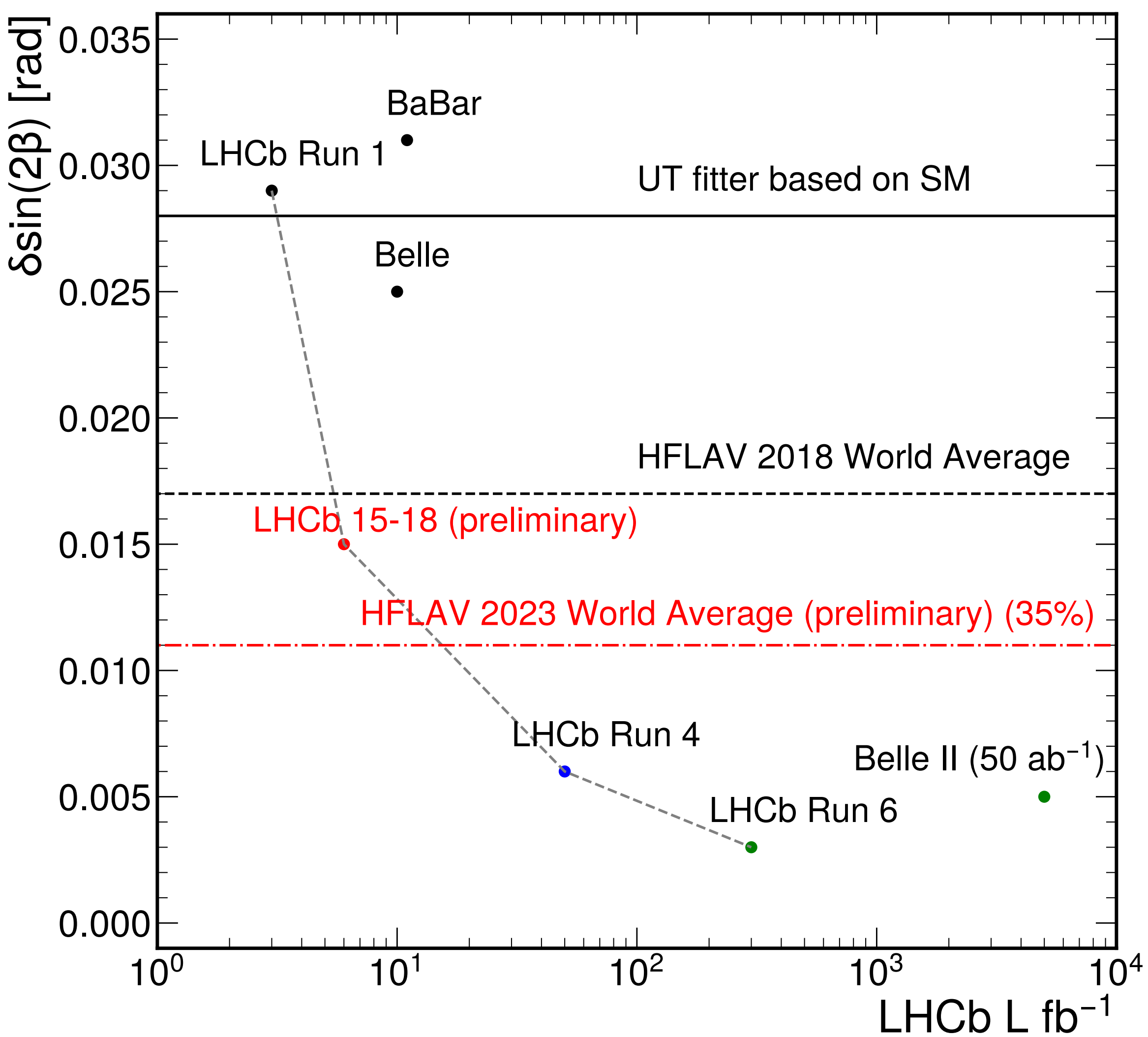
$$\Delta\Gamma_s = 0.087 \pm 0.012 \pm 0.009 \text{ ps}^{-1}$$

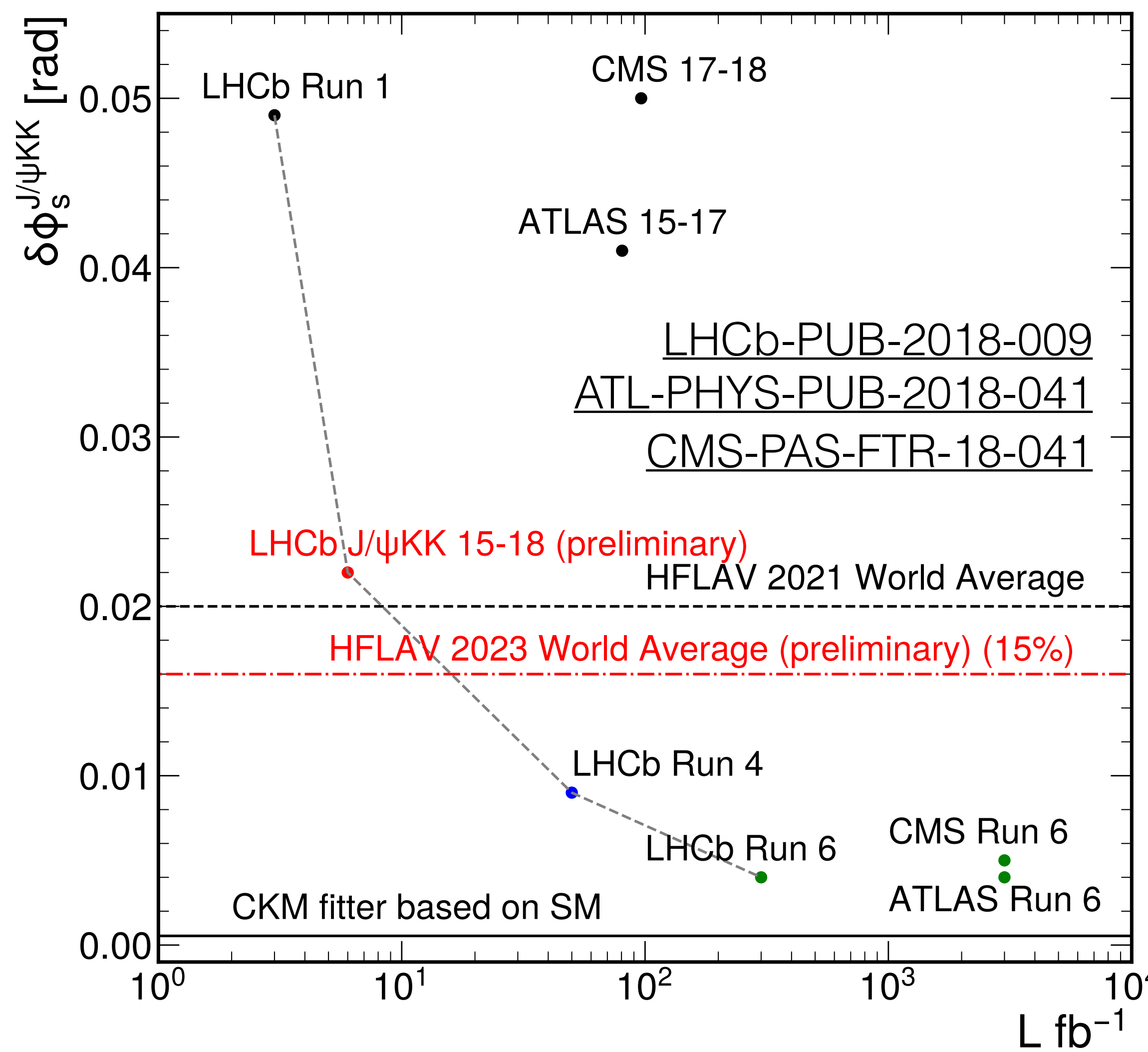




Agree with the World Average: $0.074 \pm 0.006 \text{ ps}^{-1}$

Looking at future





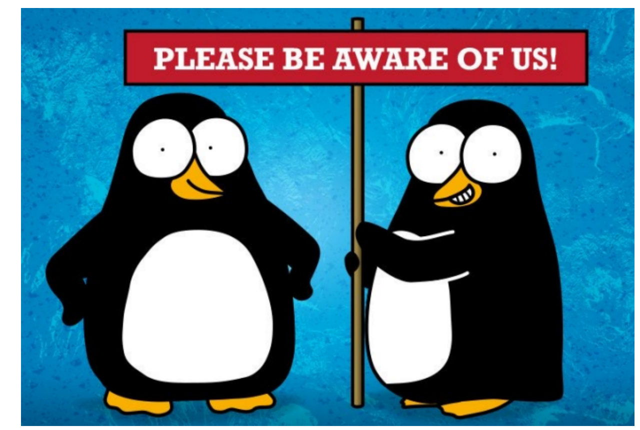
LHCb-PUB-2018-009
BelleII physics book

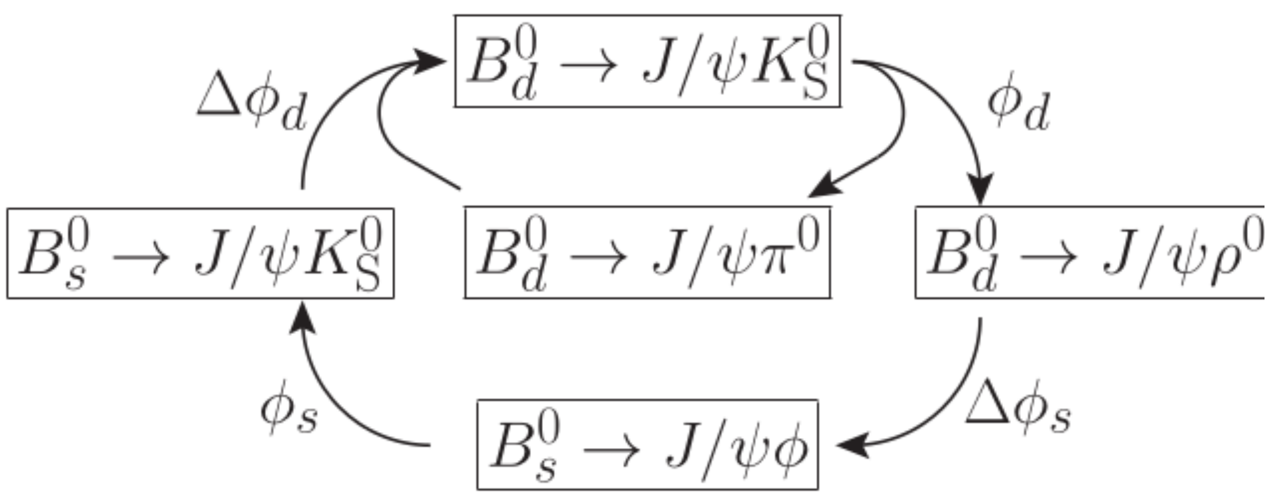
- Further precision improvement with more data and more decay modes
- Great opportunities to search for NP indirectly, up to > TeV scale

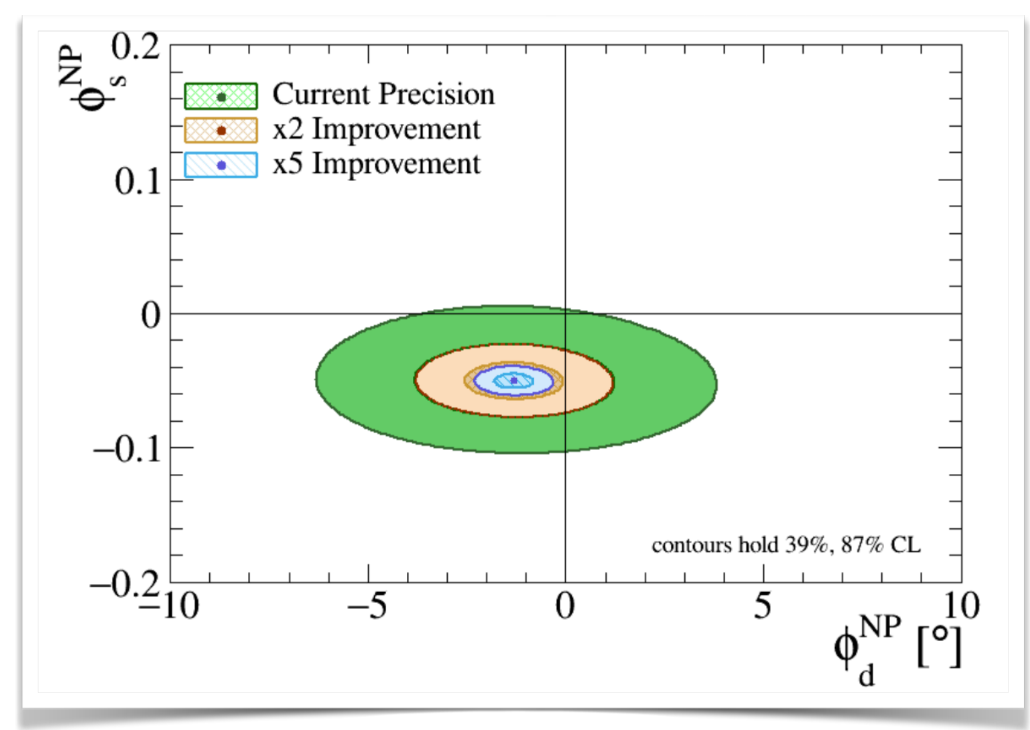
Control of penguin contribution

- $\sigma(\phi_s) \sim 0.016$ comparable with the theoretical estimation of $\Delta\phi_s^{penguin} \sim 1^\circ \approx 0.017$, better control of penguin effect necessary
- Combined analysis of penguin contributions in ϕ_s and ϕ_d $(\sin 2\beta)$, using SU(3) flavor symmetry

$$\phi_d = \sin(2\beta^{\text{tree}}) + \Delta\phi_d{}^{\text{penguin}} + \phi_d{}^{\text{NP}}$$
$$\phi_s = \phi_s^{\text{tree}} + \Delta\phi_s^{\text{penguin}} + \phi_s^{NP}$$







[J.Phys.G 48 (2021) 6, 065002](https://doi.org/)

Summary

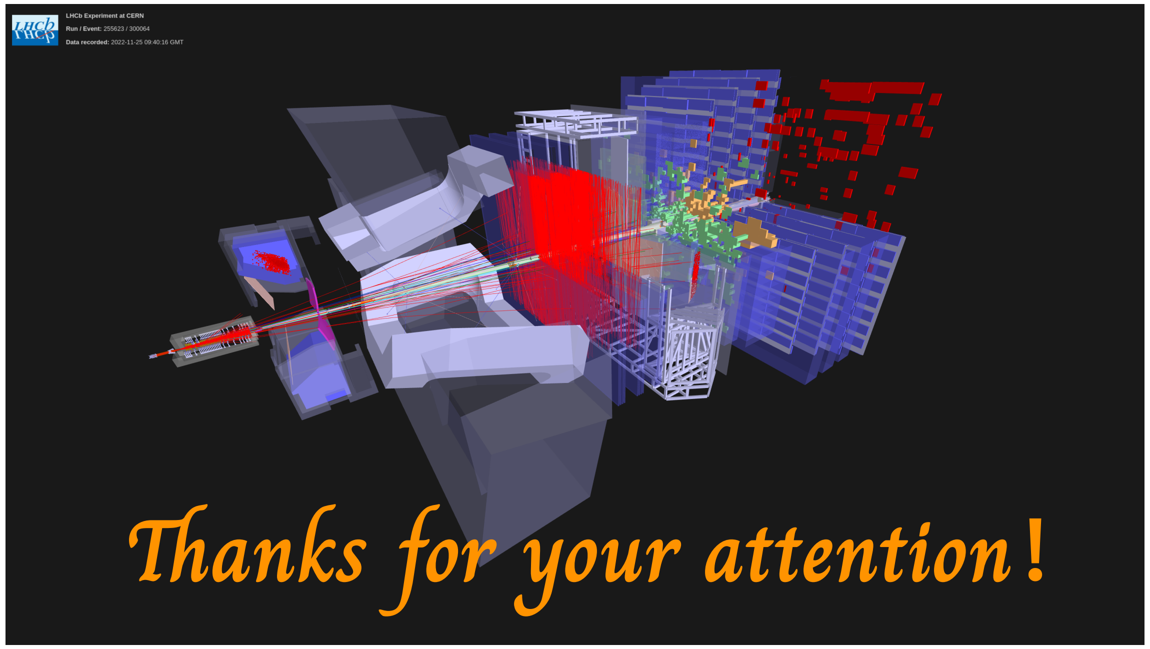
✓ LHCb dominates the world average of many CPV measurements

✓ Flag-ship time-dependent measurements of CP violation in B-meson decays with full LHCb data sample, providing the most precise results for

- ✓ ϕ_s in $b \to c\bar{c}s$ transition, $\sigma(\phi_s) \sim 20$ mrad
- ✓ $\phi_s^{s\bar{s}s}$ in penguin dominant B decays
- ✓ $\sin 2\beta = 0.716 \pm 0.013(\text{stat.}) \pm 0.008(\text{syst.})$

✓ New results for $\Delta\Gamma_s$ and Γ_L

✓ Looking forward to further test of the SM and search for new physics with more data from Upgrade I & II



Back up slides

Systematics for $\sin 2\beta$

LHCb-PAPER-2023-013
in preparation

Source	$\sigma(S)$	$\sigma(C)$
Fitter validation	0.0004	0.0006
$\Delta\Gamma_d$ uncertainty	0.0055	0.0017
FT calibration portability	0.0053	0.0001
FT $\Delta\epsilon_{\text{tag}}$ portability	0.0014	0.0017
Decay-time bias model	0.0007	0.0013

$$S^{\text{Run 2}}_{J/\psi(\to\mu^+\mu^-)K^0_S} = 0.714 \pm 0.015\,(\text{stat}) \pm 0.0074\,(\text{syst})$$

$$C^{\text{Run 2}}_{J/\psi(\to\mu^+\mu^-)K^0_S} = 0.013 \pm 0.014\,(\text{stat}) \pm 0.0025\,(\text{syst})$$

$$S^{\text{Run 2}}_{\psi(2S)K^0_S} = 0.647 \pm 0.053\,(\text{stat}) \pm 0.018\,(\text{syst})$$

$$C^{\text{Run 2}}_{\psi(2S)K^0_S} = -0.083 \pm 0.048\,(\text{stat}) \pm 0.0053\,(\text{syst})$$

$$S^{\text{Run 2}}_{J/\psi(\to e^+e^-)K^0_S} = 0.752 \pm 0.037\,(\text{stat}) \pm 0.084\,(\text{syst})$$

$$C^{\text{Run 2}}_{J/\psi(\to e^+e^-)K^0_S} = 0.046 \pm 0.034\,(\text{stat}) \pm 0.0077\,(\text{syst})$$

Time-dependent angular fit

EPJC79(2019)706

$$\mathscr{P}(t,\theta_K,\theta_\mu,\phi_h|\delta_t) \propto \sum_{k=1}^{10} N_k h_k(t) f_k(\theta_K,\theta_\mu,\phi_h) \quad \rightarrow \phi_s,\ \Delta m_s,\ \Delta\Gamma_s,\ \Gamma_s-\Gamma_d$$

$$\mathcal{P}\left(t,\Omega|\mathfrak{q}^{\mathrm{OS}},\mathfrak{q}^{\mathrm{SSK}},\eta^{\mathrm{OS}},\eta^{\mathrm{SSK}},\delta_t\right) \propto \sum_{k=1}^{10} C_{\mathrm{SP}}^{k} N_k f_k(\Omega)\varepsilon_{\mathrm{data}}^{B_s^0}(t) \cdot \left\{\left[\mathcal{Q}\left(\mathfrak{q}^{\mathrm{OS}},\mathfrak{q}^{\mathrm{SSK}},\eta^{\mathrm{OS}},\eta^{\mathrm{SSK}}\right)h_k\left(t|B_s^0\right) + \bar{\mathcal{Q}}\left(\mathfrak{q}^{\mathrm{OS}},\mathfrak{q}^{\mathrm{SSK}},\eta^{\mathrm{OS}},\eta^{\mathrm{SSK}}\right)h_k\left(t|\bar{B}_s^0\right)\right] \otimes \mathcal{R}\left(t-t'|\delta_t\right)\right\}$$

Angular amplitudes

C_{SP}^{k} account for the interference between P- and S- wave

flavor tagging

time-dependent oscillation

decay-time efficiency

decay-time resolution

$$h_k(t|B_s^0) = \frac{3}{4\pi}e^{-\Gamma t}\left(a_k\cosh\frac{\Delta\Gamma t}{2} + b_k\sinh\frac{\Delta\Gamma t}{2} + c_k\cos(\Delta m t) + d_k\sin(\Delta m t)\right),$$

$$h_k(t|\bar{B}_s^0) = \frac{3}{4\pi}e^{-\Gamma t}\left(a_k\cosh\frac{\Delta\Gamma t}{2} + b_k\sinh\frac{\Delta\Gamma t}{2} - c_k\cos(\Delta m t) - d_k\sin(\Delta m t)\right),$$

a_k, b_k, c_k, d_k involve strong and weak phases (δ,ϕ_s) of each component

k	A_k	$f_k(\theta_\mu,\theta_K,\varphi_h)$
1	$\lvert A_0\rvert^2$	$2\cos^2\theta_K\sin^2\theta_\mu$
2	$\lvert A_\parallel\rvert^2$	$\sin^2\theta_k(1-\sin^2\theta_\mu\cos^2\varphi_h)$
3	$\lvert A_\perp\rvert^2$	$\sin^2\theta_k(1-\sin^2\theta_\mu\sin^2\varphi_h)$
4	$\lvert A_\parallel A_\perp\rvert$	$\sin^2\theta_k\sin^2\theta_\mu\sin 2\varphi_h$
5	$\lvert A_0 A_\parallel\rvert$	$\frac{1}{2}\sqrt{2}\sin 2\theta_k\sin 2\theta_\mu\cos\varphi_h$
6	$\lvert A_0 A_\perp\rvert$	$-\frac{1}{2}\sqrt{2}\sin 2\theta_k\sin 2\theta_\mu\sin\varphi_h$
7	$\lvert A_S\rvert^2$	$\frac{2}{3}\sin^2\theta_\mu$
8	$\lvert A_S A_\parallel\rvert$	$\frac{1}{3}\sqrt{6}\sin\theta_k\sin 2\theta_\mu\cos\varphi_h$
9	$\lvert A_S A_\perp\rvert$	$-\frac{1}{3}\sqrt{6}\sin\theta_k\sin 2\theta_\mu\sin\varphi_h$
10	$\lvert A_S A_0\rvert$	$\frac{4}{3}\sqrt{3}\cos\theta_K\sin^2\theta_\mu$

Systematics for ϕ_s

arXiv: 2308.01468
submitted to PRL

* Uncertainties ($\times 0.01$) Dominated sys. Sub-dominated sys. Stat. limited

Source	$\lvert A_0\rvert^2$	$\lvert A_\perp\rvert^2$	ϕ_s [rad]	$\lvert\lambda\rvert$	$\delta_\perp - \delta_0$ [rad]	$\delta_\parallel - \delta_0$ [rad]	$\Gamma_s - \Gamma_d$ [ps^{-1}]	$\Delta\Gamma_s$ [ps^{-1}]	Δm_s [ps^{-1}]
Mass parametrization	0.04	0.03	0.03	0.02	0.15	0.12	0.02	0.04	0.03
Mass: shape statistical	0.04	0.04	0.05	0.09	0.62	0.33	0.02	0.01	0.11
Mass factorization	0.11	0.10	0.42	0.19	0.54	0.60	0.12	0.16	0.18
B_c^+ contamination	0.04	0.05	—	0.02	—	0.17	(0.07)	(0.03)	—
D–wave component	0.04	0.04	0.02	—	0.07	0.13	0.01	0.03	0.02
Bkgcat 60	0.07	0.04	0.02	0.10	0.18	0.18	0.02	—	0.01
Multiple candidates	0.01	—	0.27	0.22	0.90	0.41	0.01	0.01	0.24
Particle identification	0.06	0.09	0.27	0.27	1.31	0.51	0.05	0.15	0.46
$C_{\rm SP}$ factors	—	0.01	0.01	0.03	0.73	0.41	—	0.01	0.04
DTR model portability	—	—	0.08	0.03	0.26	0.09	—	—	0.09
DTR calibration	—	—	0.03	0.02	0.11	0.07	—	—	0.05
Time bias correction	0.04	0.05	0.06	0.05	0.77	0.11	0.03	0.05	0.44
Angular efficiency	0.05	0.14	0.25	0.32	0.42	0.44	0.01	0.02	0.13
Angular resolution	0.01	0.01	0.02	0.01	0.02	0.08	—	0.01	0.02
Kinematic weighting	0.24	0.09	0.01	0.01	0.98	0.86	0.02	0.03	0.31
Momentum uncertainty	0.08	0.04	0.04	—	0.07	0.11	0.01	—	0.13
Longitudinal scale	0.07	0.04	0.04	—	0.10	0.09	0.02	—	0.31
Neglected correlations	—	—	—	—	4.20	4.96	—	—	—
Total sys. unc.	0.32	0.24	0.6	0.5	4.8	5.2	0.14	0.24	0.9
Stat. unc.	0.17	0.23	2.2	1.1	7.5	6.0	0.14	0.44	3.3

- ϕ_s, $\lvert\lambda\rvert$, $\Delta\Gamma_s$, Δm_s are statistically limited

Systematics for $\phi_s^{s\bar{s}s}$

LHCb-PAPER-2023-001
accepted by PRL

Source	$\phi_s^{s\bar{s}s}$	$\|\lambda\|$	$\|A_0\|^2$	$\|A_\perp\|^2$	$\delta_\parallel - \delta_0$	$\delta_\perp - \delta_0$
Time resolution	4.9	2.6	0.8	0.8	0.1	3.4
Flavor tagging	4.8	4.7	0.9	1.3	1.2	9.7
Angular acceptance	3.9	4.9	1.4	1.7	4.7	1.2
Time acceptance	2.3	1.7	0.1	0.1	5.6	0.7
Mass fit & factorization	2.2	4.4	1.9	2.3	2.3	2.5
MC truth match	1.1	0.2	0.1	0.1	0.2	0.3
Fit bias	0.8	0.7	0.9	0.3	3.6	0.7
Candidate multiplicity	0.3	0.2	0.1	0.8	0.2	0.1
Total	8.8	8.6	2.7	3.3	8.5	10.7

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

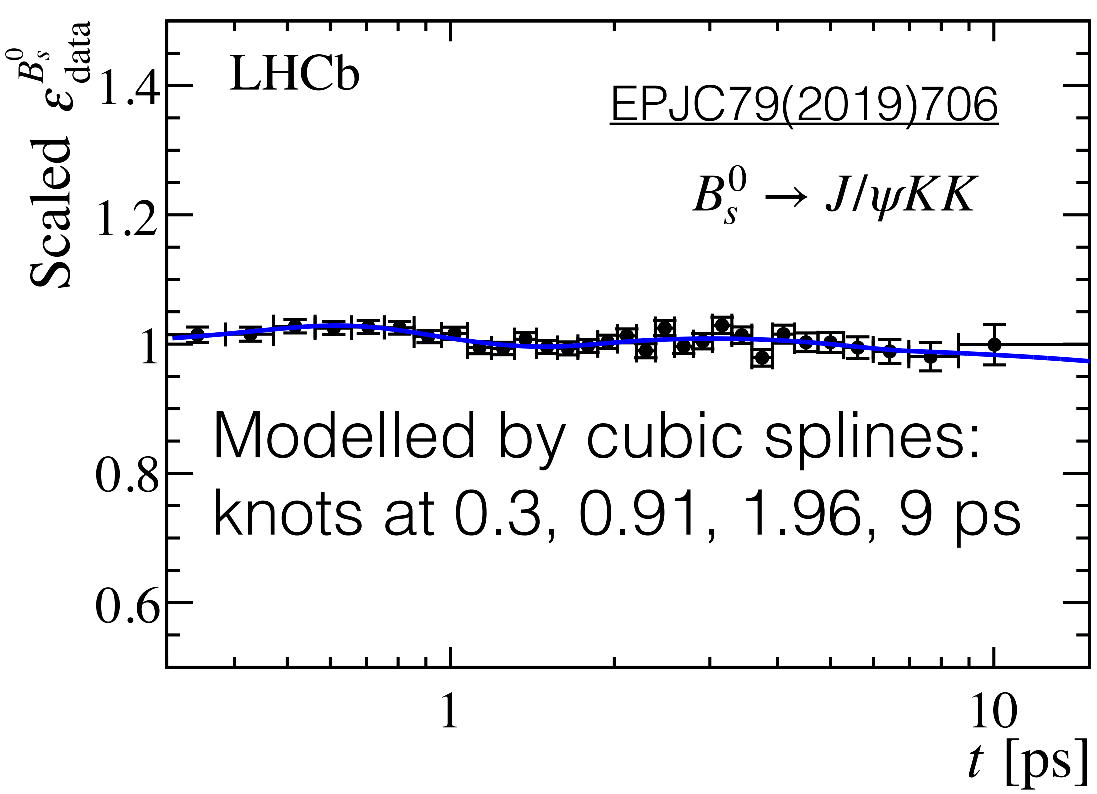
Decay time & angular efficiencies

- Reconstruction and selection criteria introduce non-uniform efficiency

- Decay-time efficiencies:

  Data driven method

$$\varepsilon^{B_s^0}_{\rm data}(t) = \varepsilon^{B^0}_{\rm data}(t) \times \frac{\varepsilon^{B_s^0}_{\rm sim}(t)}{\varepsilon^{B^0}_{\rm sim}(t)}$$



$$f(t) \propto \varepsilon(t) \cdot e^{-t/\tau} \otimes G(0,\sigma_t)$$

- Angular efficiencies for B_s^0 decays estimated with simulation