Time-dependent Measurements at LHCb & Belle(II)

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CEPC味物理-新物理与相关探测技术研讨会

2023-08-17

Outline

- Recap of CKM and CP violation
- Flavour tagging at LHCb & Belle II
- $\sin 2\beta$ measurements
- ϕ_s measurements
- $B^0_{(s)} \to h^+h^-$ & τ_L
- Prospects & summary

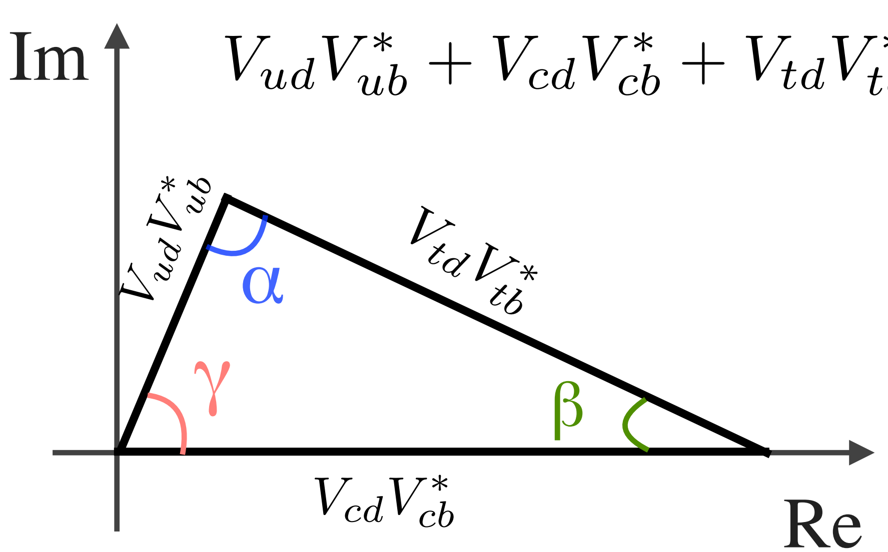
* Due to time limits, focusing on *B* decays only

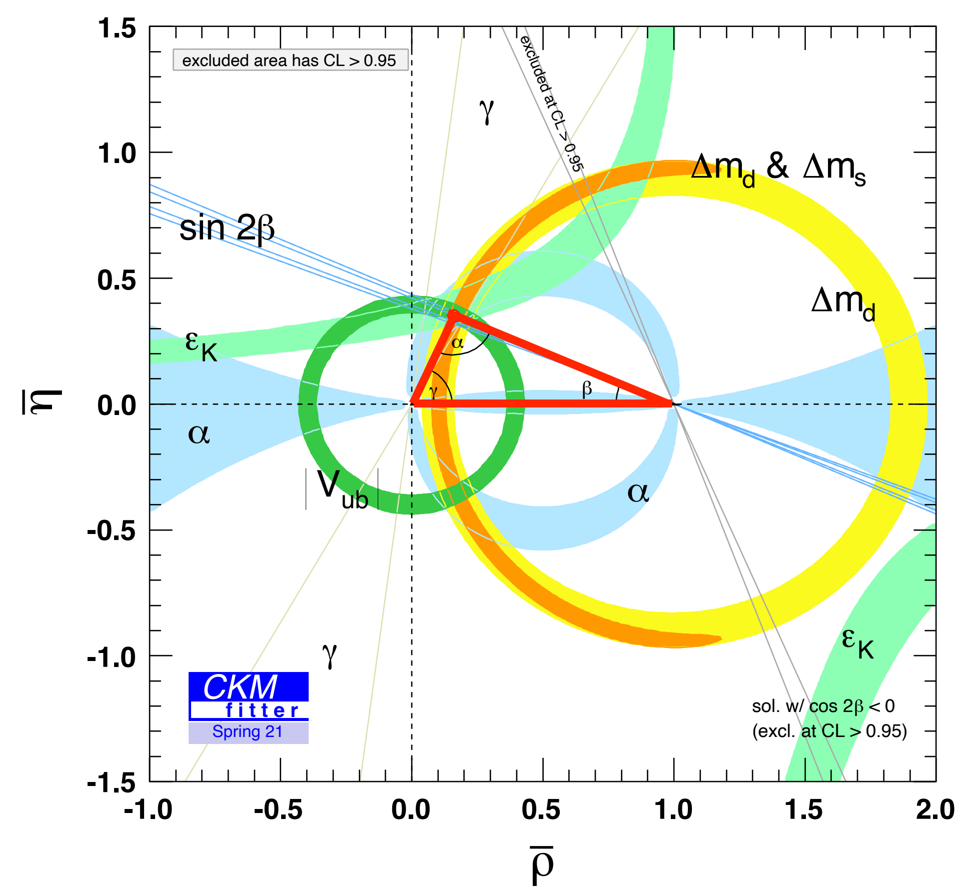
CKM matrix

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

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

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



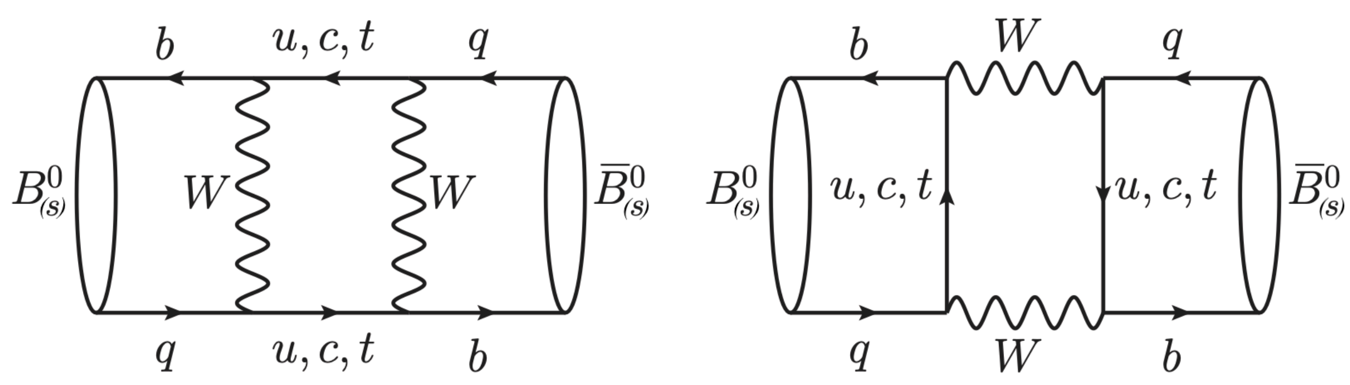


$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right), \quad \beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right), \quad \gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

see Yuexin Wang's talk for $B^0 \to \pi^0\pi^0$

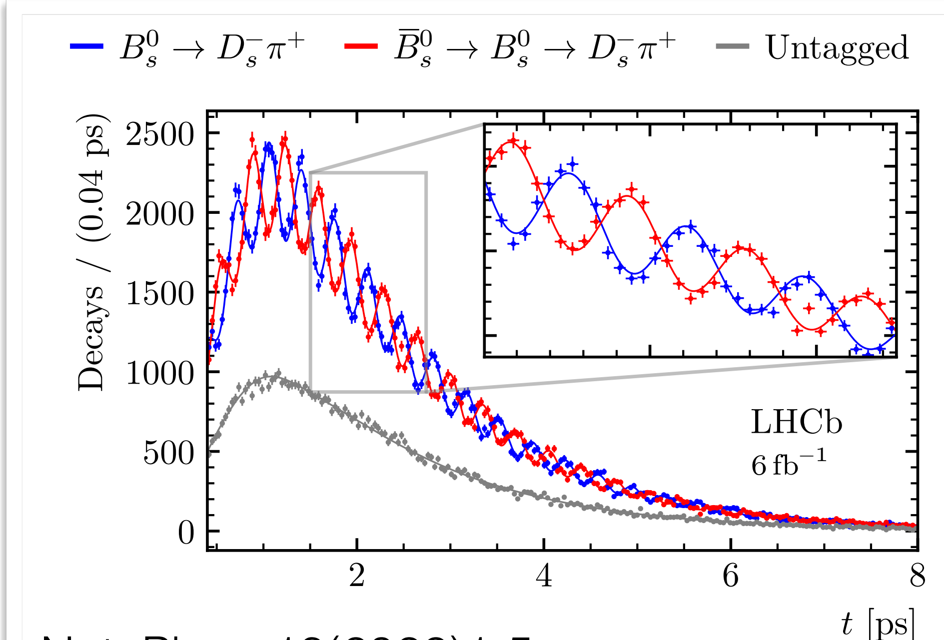
Neutral meson oscillation

- Neutral mesons can oscillate through box diagrams



Mixing and decay can be described by Schrödinger-like equation

$$i\frac{d}{dt}\begin{pmatrix}B\\ \bar{B}\end{pmatrix} = \tilde{\mathbf{H}}\begin{pmatrix}B\\ \bar{B}\end{pmatrix} = \begin{bmatrix} m-\frac{i}{2}\Gamma & m_{12}-\frac{i}{2}\Gamma_{12} \\ m_{12}^{*}-\frac{i}{2}\Gamma_{12}^{*} & m-\frac{i}{2}\Gamma\end{bmatrix}\begin{pmatrix}B\\ \bar{B}\end{pmatrix}$$



Nat. Phys. 18(2022)1-5

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

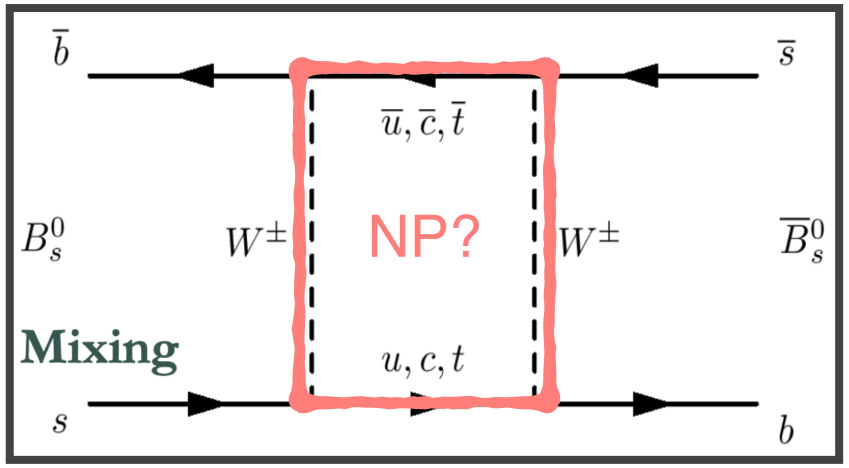
- Decay rate of initial B or $\bar{B}$

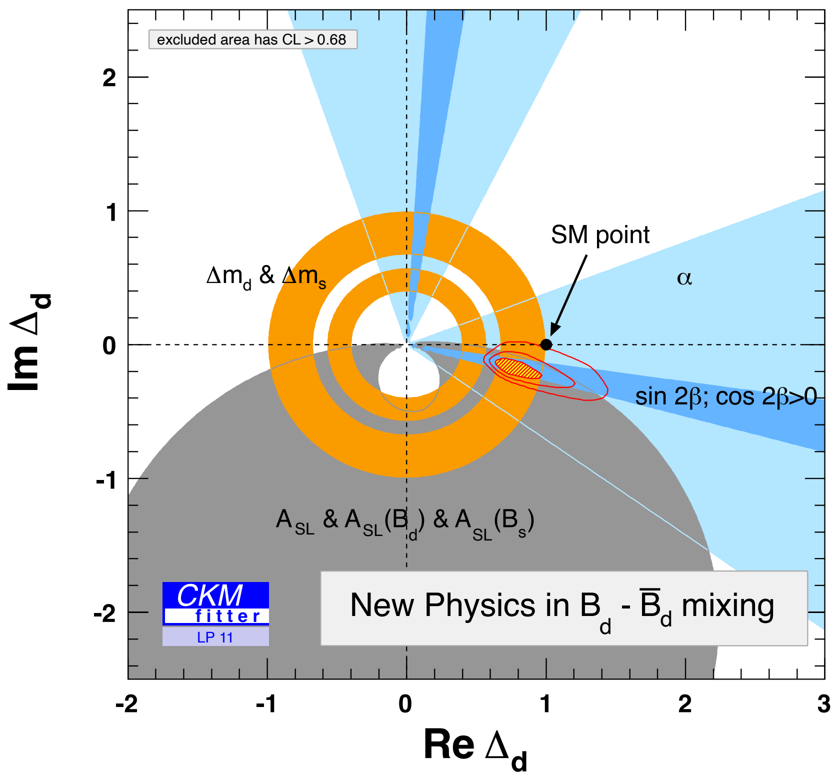
$$|\langle f|H|B\rangle|^2 = \frac{1}{2}e^{-\Gamma t}|A_f|^2\left\{ D\cosh\left(\frac{\Delta\Gamma}{2}t\right) + A_{\Delta\Gamma}\sinh\left(\frac{\Delta\Gamma}{2}t\right) \pm C\cos(\Delta m t) \mp S\sin(\Delta m t)\right\}$$

direct A_{CP} CP in mixing

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

Opportunities for new physics





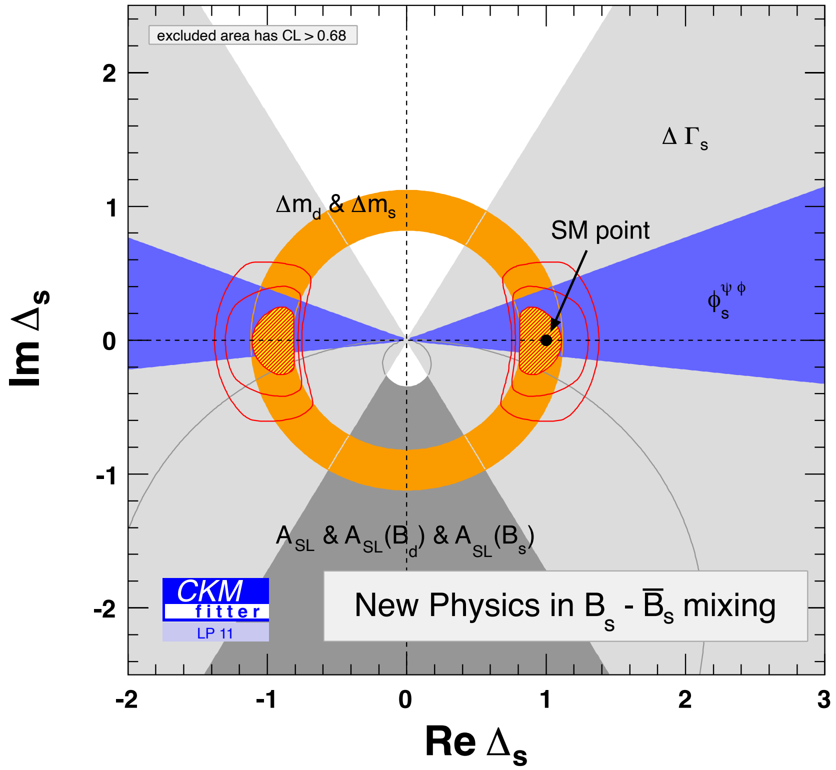
- New physics (NP) short-distance contributions can influence mixing

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

[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

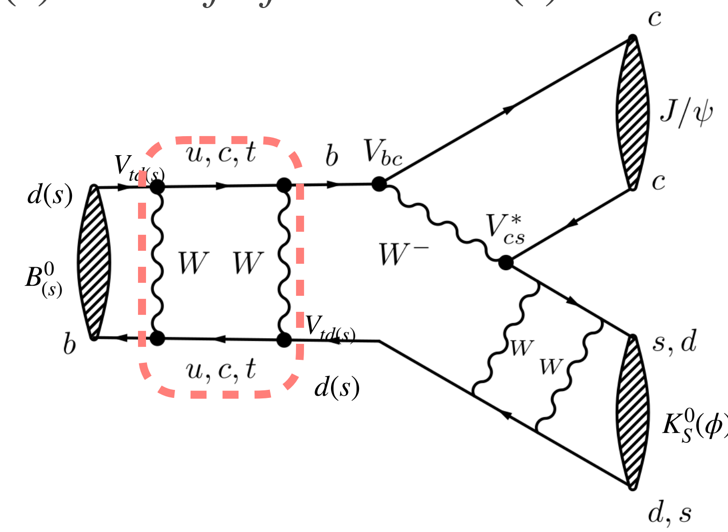
[PRD 89(2014)033016]



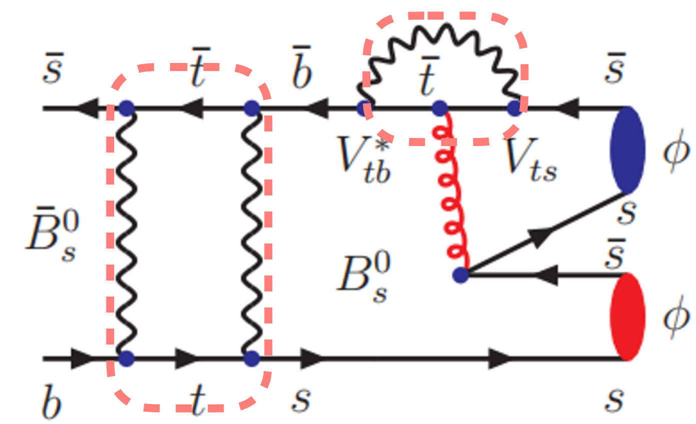
Time-dependent CP asymmetry

$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0_{(s)} \to f) - \Gamma(B^0_{(s)} \to f)}{\Gamma(\bar{B}^0_{(s)} \to f) + \Gamma(B^0_{(s)} \to f)} \propto C_f \cos(\Delta m_{(s)} t) + \eta_f S_f \sin(\Delta m_{(s)} t)$$

- Tree diagram dominant: NP in mixing $S_f \approx \sin 2\beta_{(s)}$
  - $\sin 2\beta$: $B^0 \to \psi K^0_S / K^0_L$: CP-odd/even component
  - $\phi_s \approx \sin 2\beta_s$: $B^0_s \to J/\psi\phi$: a mixture of CP-even ($L = 0,2$) & CP-odd ($L = 1$)



- Penguin dominant: NP contributions in mixing & penguin diagrams
  - $\sin 2\beta$: $B^0 \to \phi K^0_S,\ K^0_S K^0_S K^0_S,\ K^0_S \pi^0$
  - $\phi_s^{s\bar{s}s}$: $B^0_s \to \phi\phi,\ K^{*0} K^{*0}$



➡ Experimentally

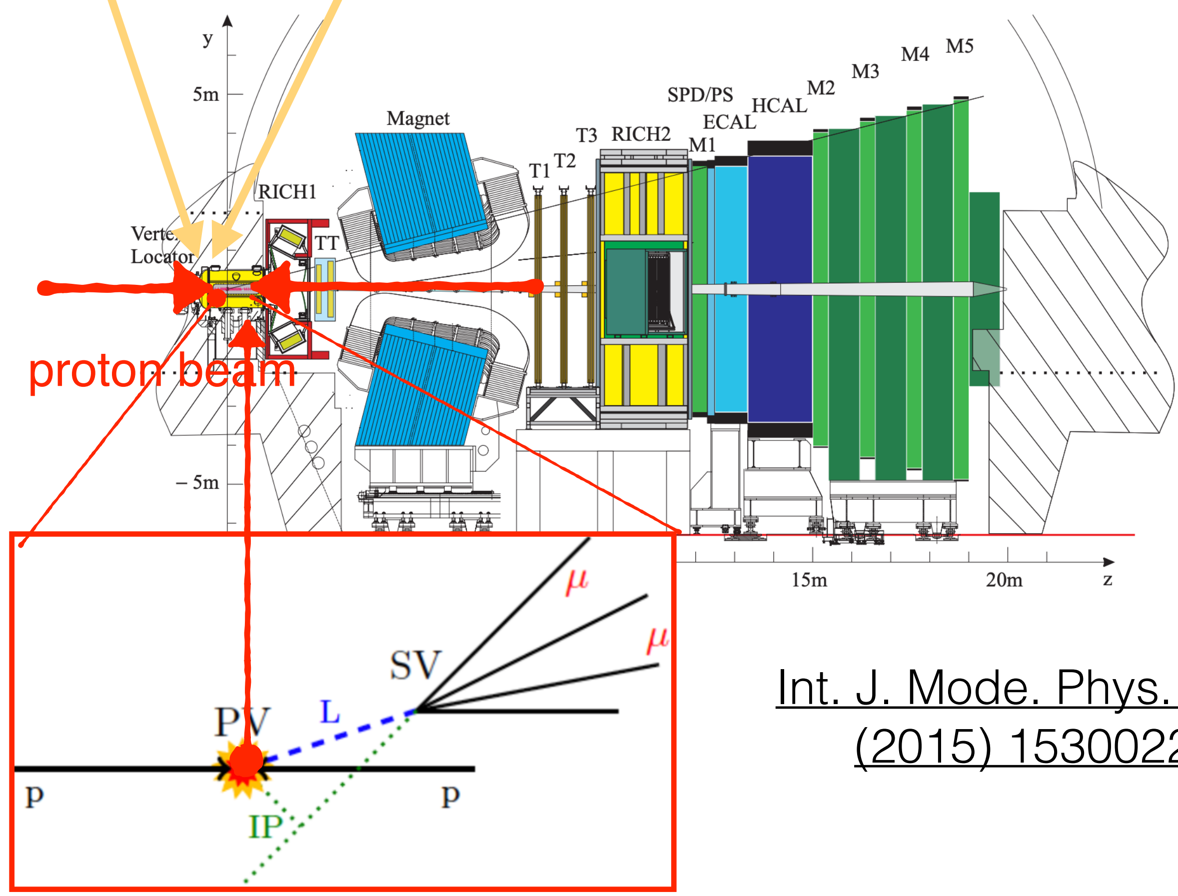
$$A_{CP}(t) \propto e^{-\frac{1}{2}\Delta m_s^2 \sigma_t^2} \cdot (1 - 2\omega) \cdot (C_f \cos(\Delta m_{(s)} t) + \eta_f S_f \sin(\Delta m_{(s)} t))$$

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

LHCb & Belle(II) detectors

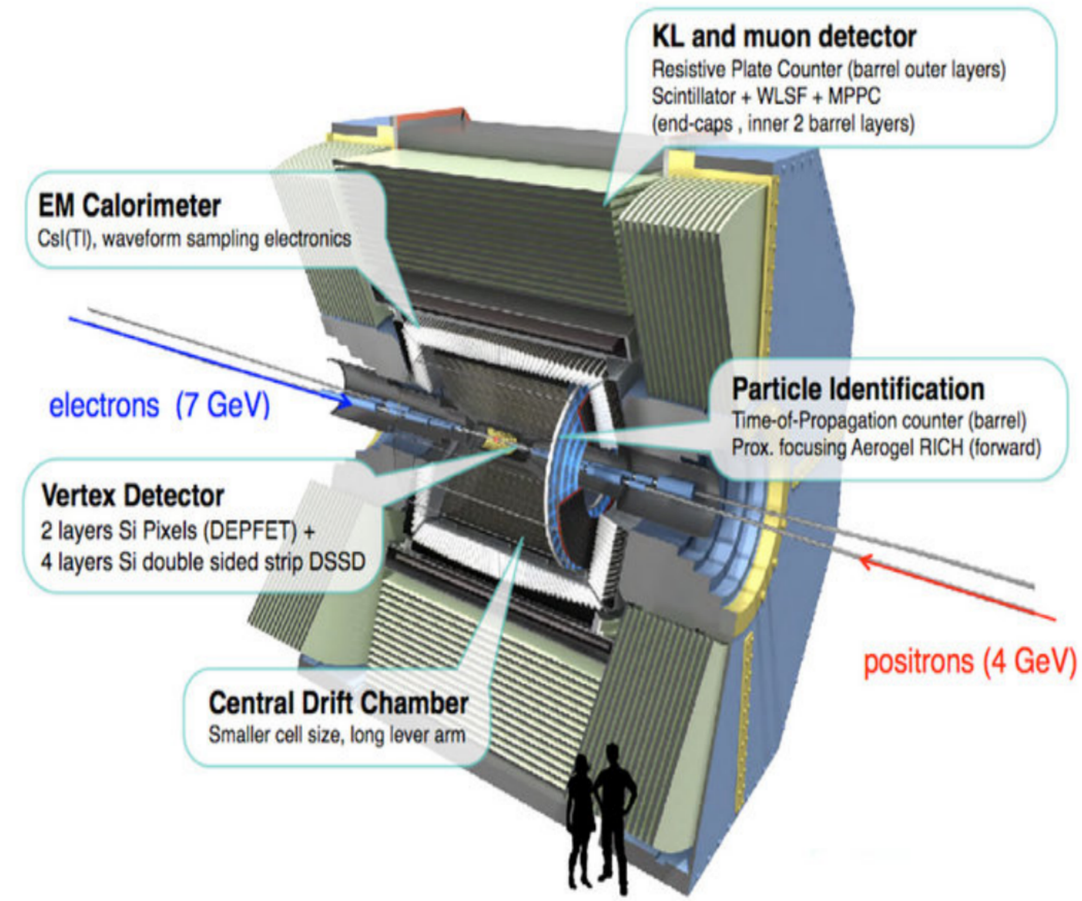
- Daughters of b & c hadron decays: $p_T \sim \mathcal{O}(1\ \mathrm{GeV}/c)$, flight distance L~1mm

Precise vertex measurements, $\sigma(IP_x)$~ 35 μm	Excellent decay time resolution ~ 43 fs for B_s^0



Int. J. Mode. Phys. A30 (2015) 1530022

- Asymmetric collider: e^- of 7 GeV with e^+ of 4 GeV

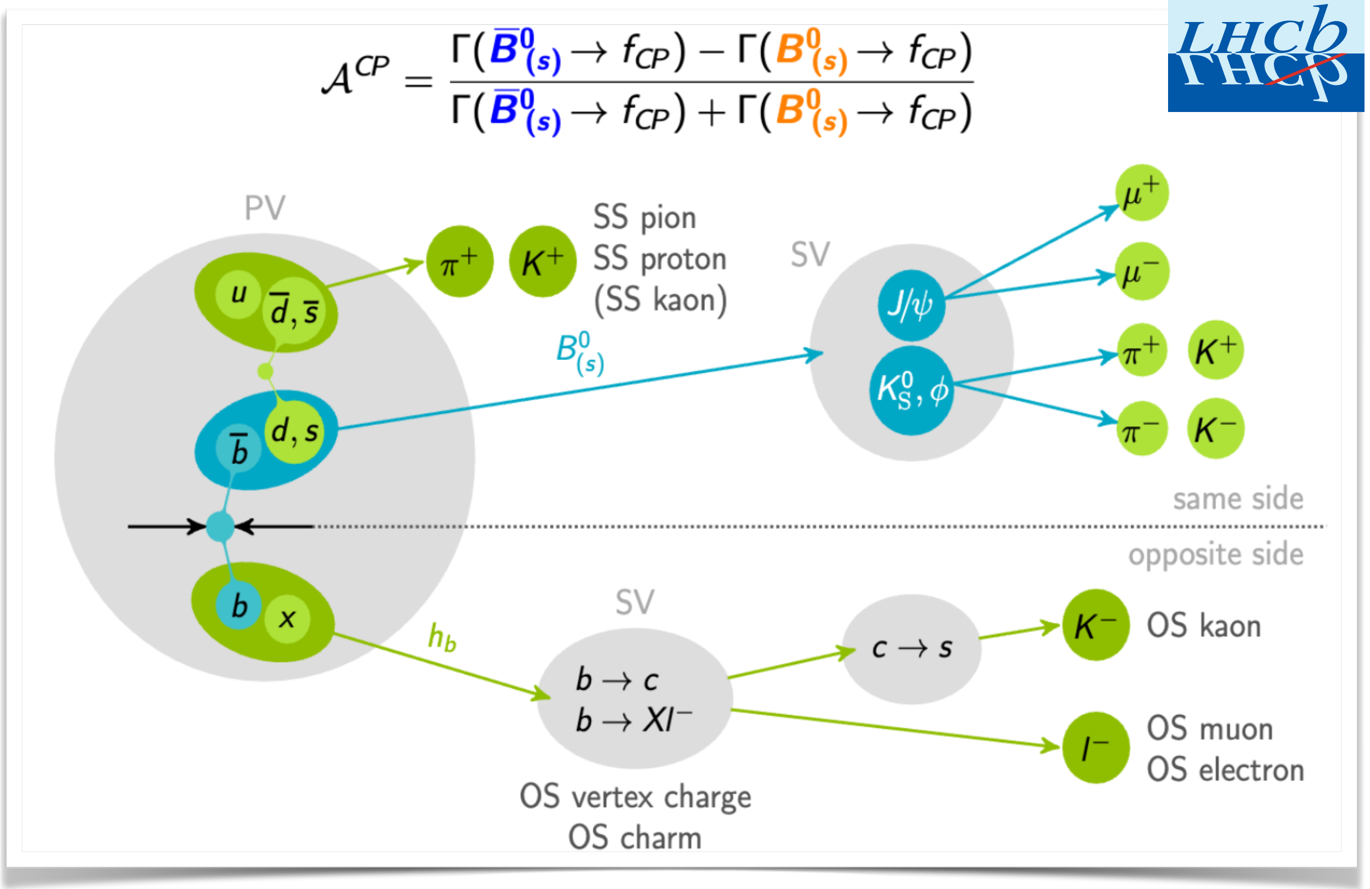


2x better vertex resolution than Belle

- pp collision: 3 fb^{-1} (7,8 TeV) + 6 fb^{-1} (13 TeV)
- $\sigma(b\bar{b})(7TeV) = 72.0 \pm 0.3 \pm 6.8\ \mu$b,
  $\sigma(b\bar{b})(13TeV) = 144 \pm 1 \pm 21\ \mu$b

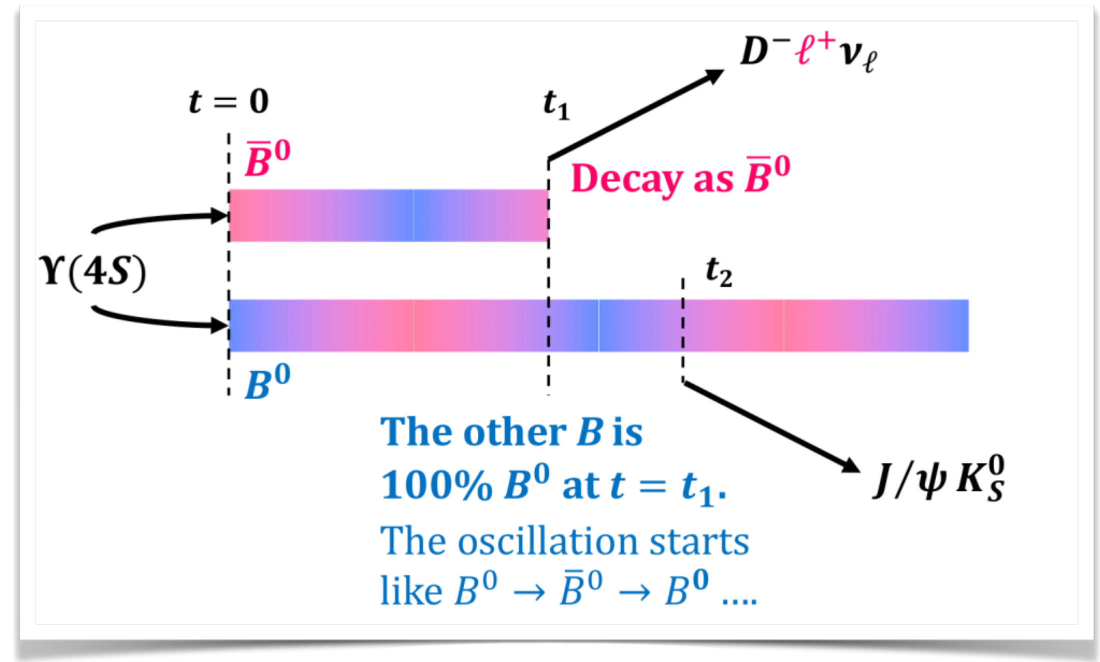
- e^+e^- collision: 362 fb^{-1} at $\Upsilon(4S)$
- $N(B\bar{B}) = 387 \times 10^6$

Flavour tagging



- 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 = (4~6)% (mode-dependent)
  $= \varepsilon_{tag} \cdot (1-\omega)^2$ (ω *is* mistag rate)

Coherent production of $B^0\bar{B}^0$



arXiv:2110.00790

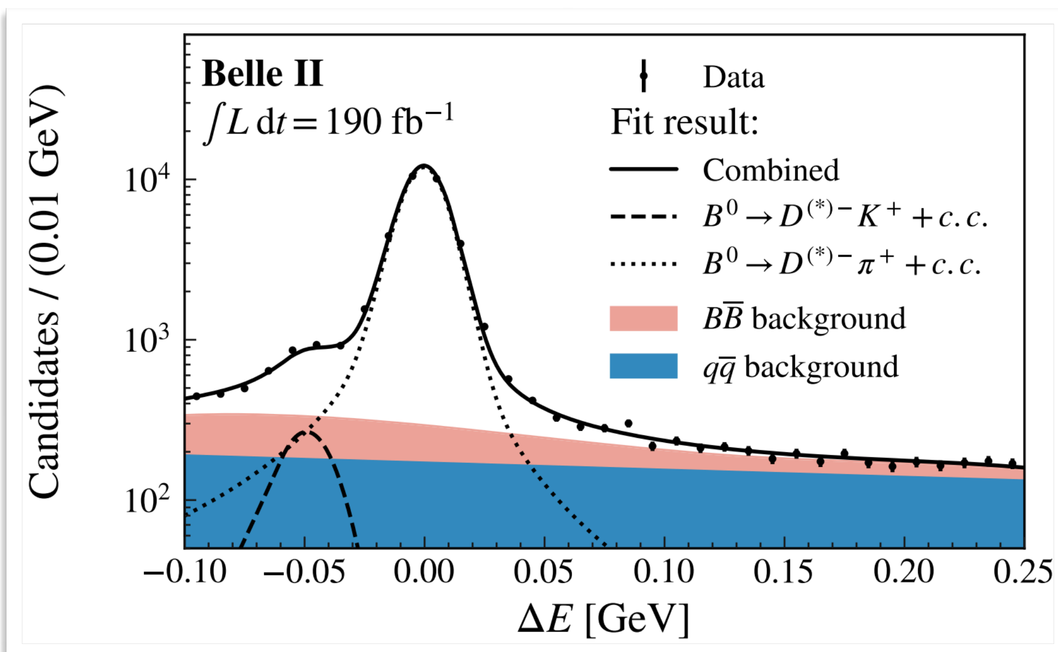
- Category-FT: Use inputs of kinematic, track hit and PID from the remaining tracks apart from the signal
- Tagging efficiency = (30±1.3)%
- wrong tagging probability $\omega = \frac{1-r}{2}$

Δm_d and τ_{B^0} in $B^0 \to D^{(*)-}\pi^+$

PRD107(2023)L091102

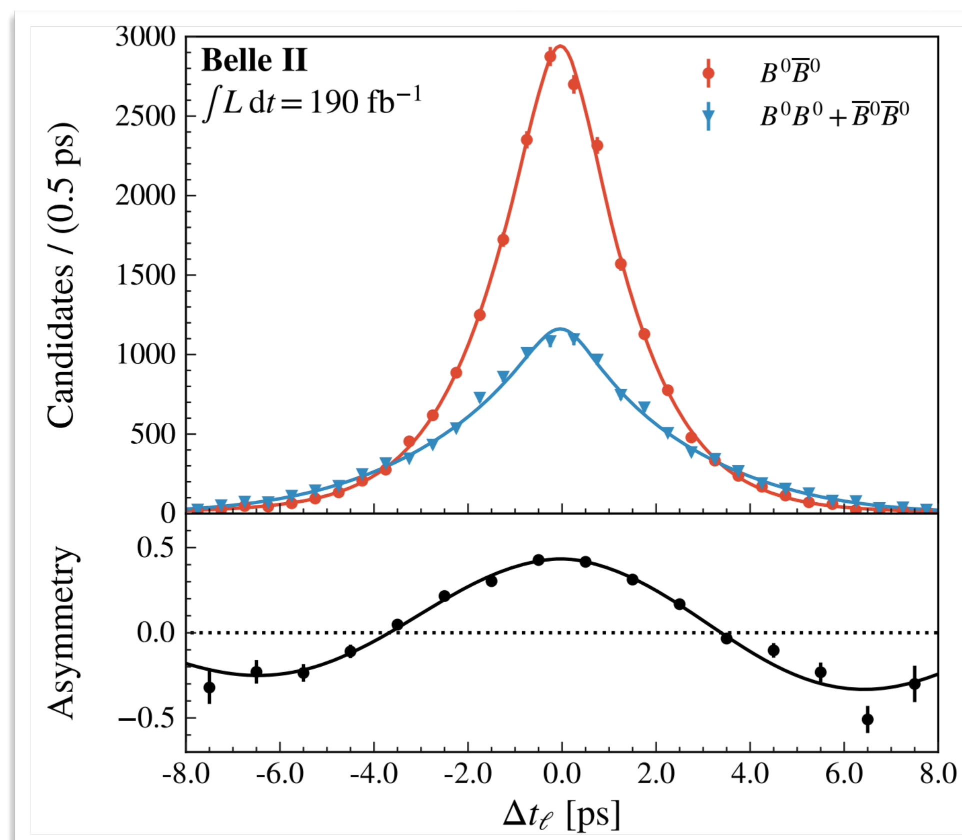
- $190\ \text{fb}^{-1}\ e^+e^- \to \Upsilon(4S) \to B\bar{B}$: $N(B\bar{B}) = 200 \times 10^6$
- Entangled quantum states: knowledge of the B^0 tag flavour determines the B_{CP} flavour at that time $\Delta t \equiv t_{CP} - t_{\text{tag}}$
- Benchmark for time-dependent measurements
- Fit to background-subtracted Δt distribution to extract Δm_d and τ_{B^0}

$$P(\Delta t, q_f|\tau_{B^0}, \Delta m_d) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}[1 + q_f\cos(\Delta m_d \Delta t)]$$



$$\tau_{B^0} = (1.499 \pm 0.013 \pm 0.008)\ \text{ps},$$

$$\Delta m_d = (0.516 \pm 0.008 \pm 0.005)\ \text{ps}^{-1}$$

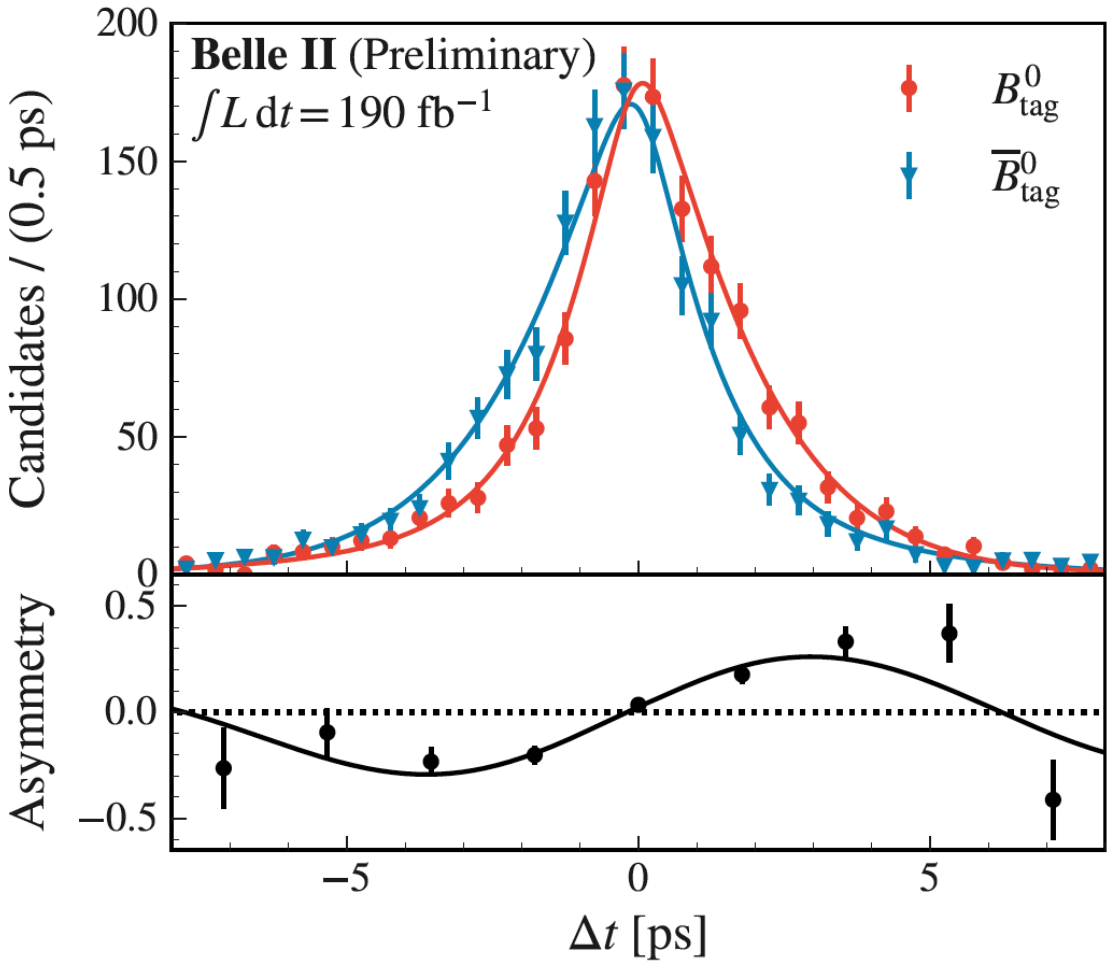


$\sin 2\beta$ in $B^0 \to J/\psi K_S^0$

arXiv:2302.12898

- $190\ \text{fb}^{-1}\ e^+e^- \to \Upsilon(4S) \to B\bar{B}$: $N(B\bar{B}) = 200 \times 10^6$
- Entangled quantum states: Fit to background-subtracted $\Delta t \equiv t_{CP} - t_{\text{tag}}$

$$P(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{2\tau_{B^0}}\{1 + q[S_{CP}\sin(\Delta m_d \Delta t) + A_{CP}\cos(\Delta m_d \Delta t)]\}$$



$$S_{CP} = 0.720 \pm 0.062(\text{stat}) \pm 0.016(\text{syst})$$
$$A_{CP} = 0.094 \pm 0.044(\text{stat}) {}^{+0.042}_{-0.017}(\text{syst})$$

(Statistical uncertainty dominant!)

Consistent with Belle results:

$$S_{CP} = 0.667 \pm 0.023(\text{stat}) \pm 0.012(\text{syst})$$
$$A_{CP} = 0.006 \pm 0.016(\text{stat}) \pm 0.012(\text{syst})$$

Agree with the World average:

$$A_{CP} = 0.699 \pm 0.017, \quad S_{CP} = 0.005 \pm 0.015$$

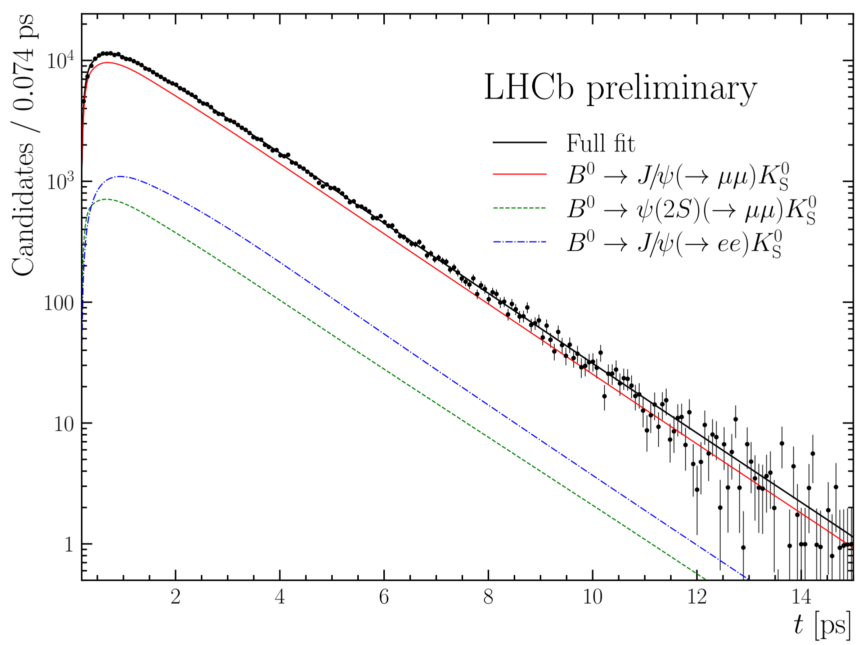
2755 $B^0 \to J/\psi K_S^0$ signal (4x less than Belle data)

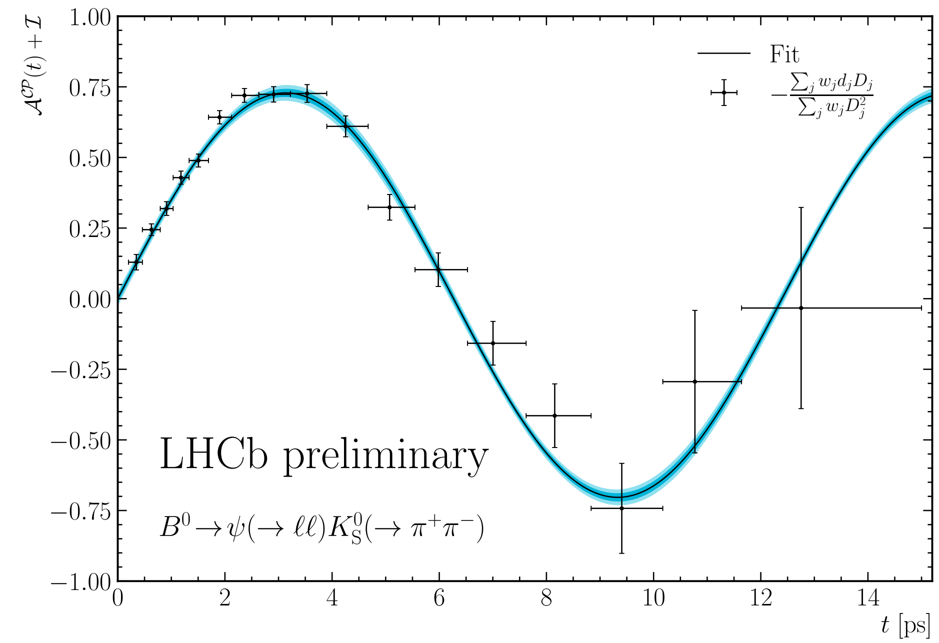
$\sin 2\beta$ in $B^0 \to \psi K_S^0$

LHCb-PAPER-2023-013
In preparation

- Three decay modes in $B^0 \to \psi K_S^0$
- Simultaneous fits to the decay time of B^0

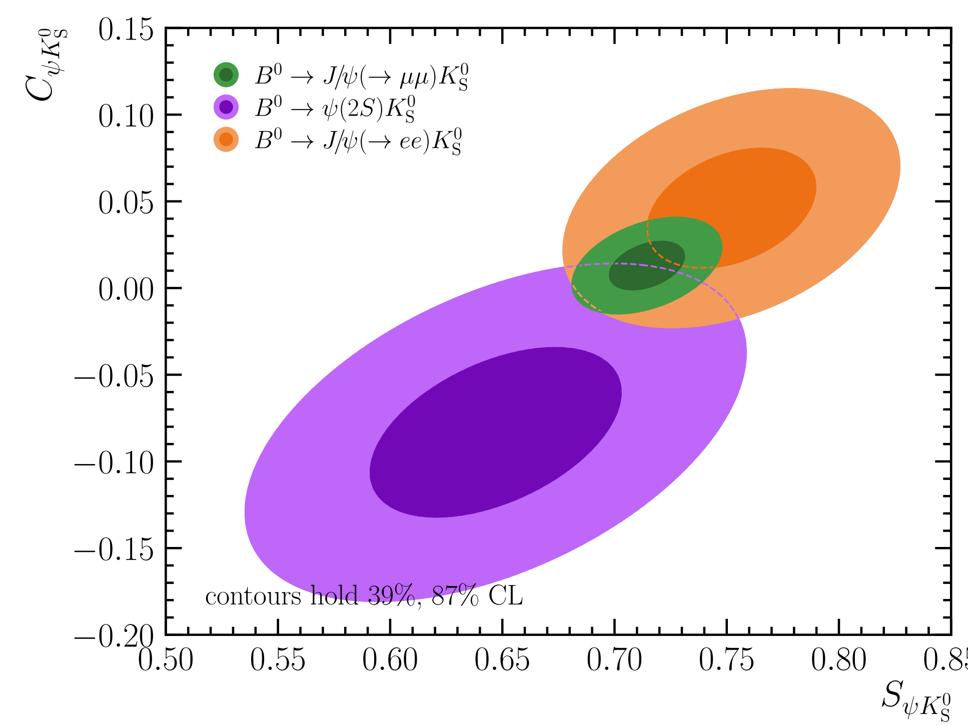
$B^0 \to J/\psi(\mu^+\mu^-)K_s^0(\to \pi^+\pi^-)$
$B^0 \to \psi(2S)(\mu^+\mu^-)K_s^0(\to \pi^+\pi^-)$
$B^0 \to J/\psi(e^+e^-)K_s^0(\to \pi^+\pi^-)$





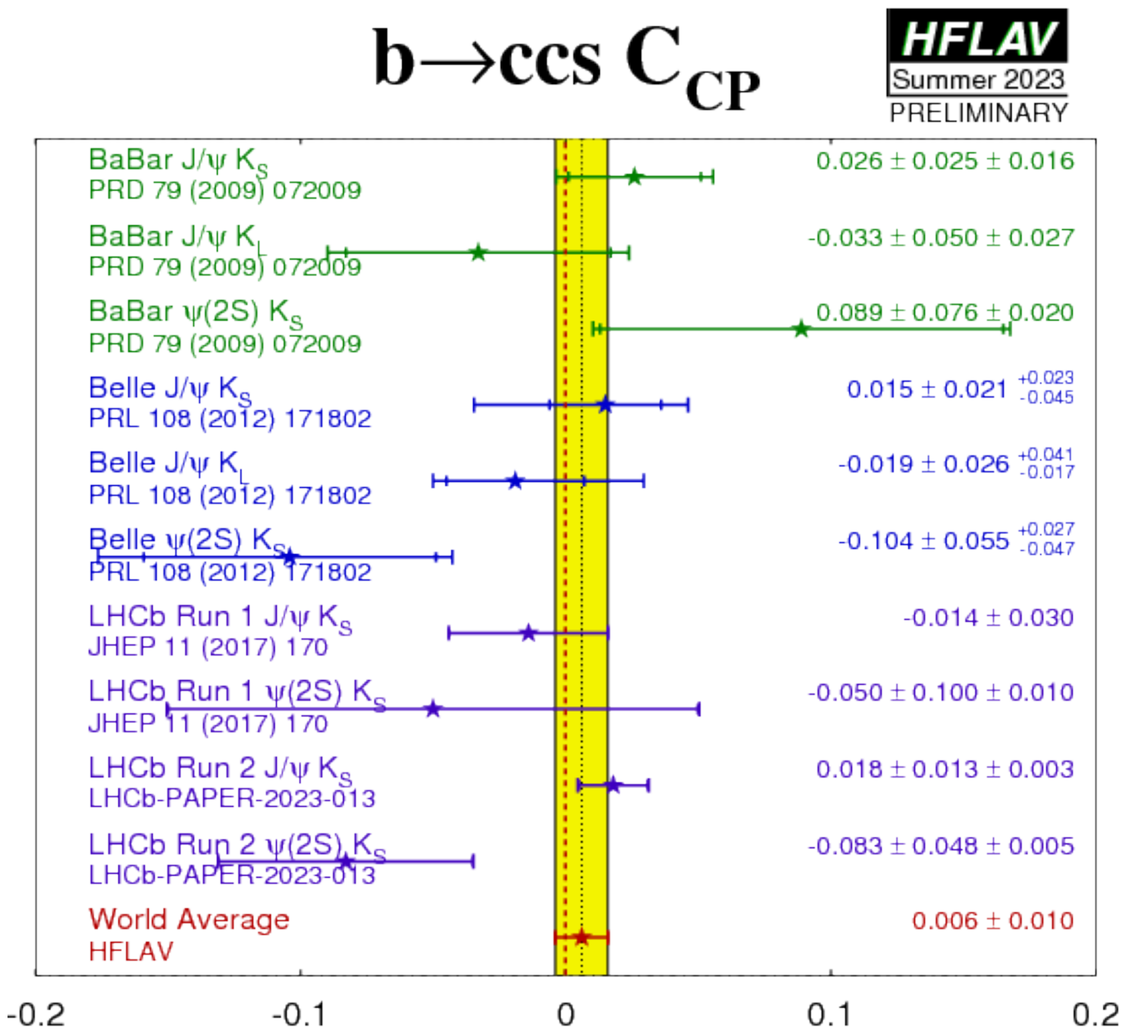
Combined fit result

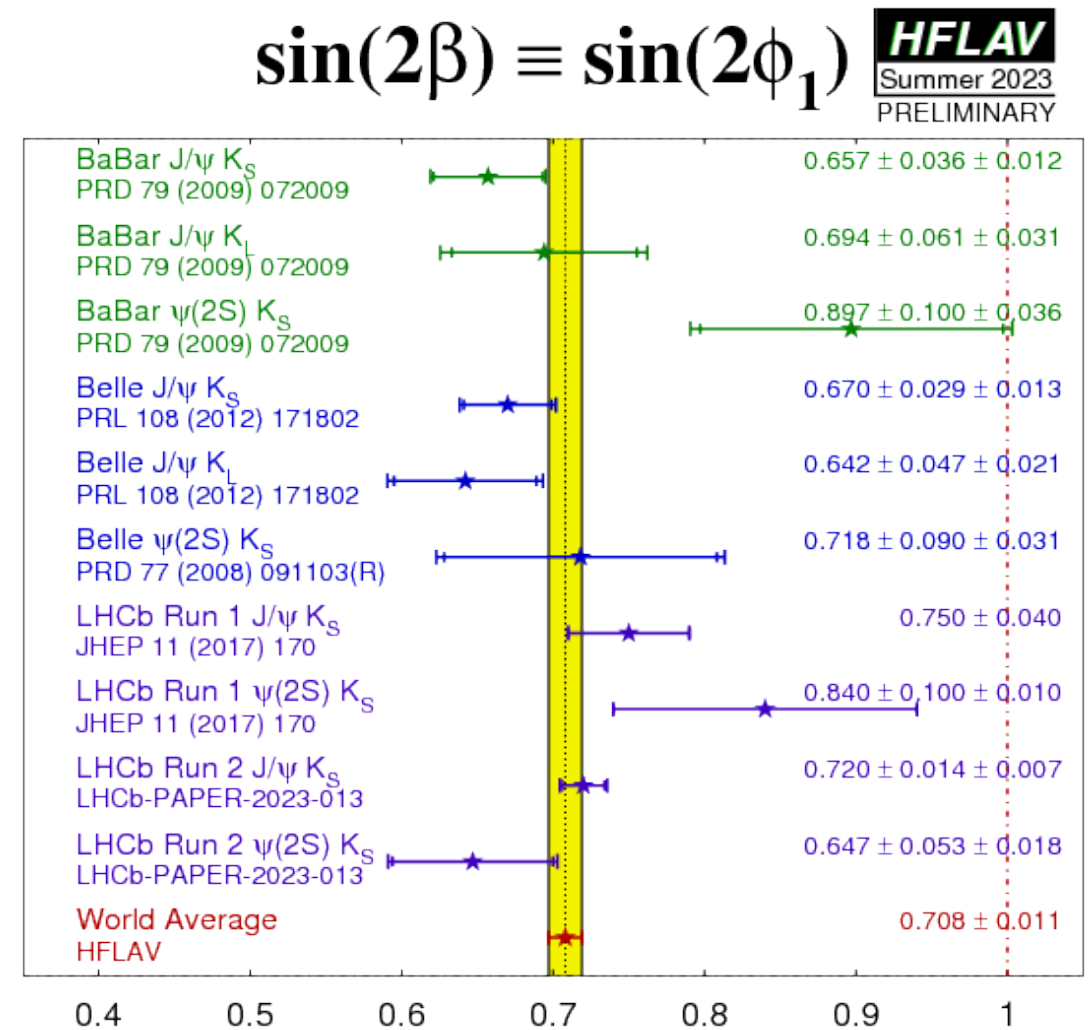
$$S^{\text{Run 2}}_{\psi K^0_S} = 0.716 \pm 0.013\,(\text{stat}) \pm 0.008\,(\text{syst})$$
$$C^{\text{Run 2}}_{\psi K^0_S} = 0.012 \pm 0.012\,(\text{stat}) \pm 0.003\,(\text{syst})$$



- The **most precise measurement** in single measurement to date

$\sin 2\beta$ combinations



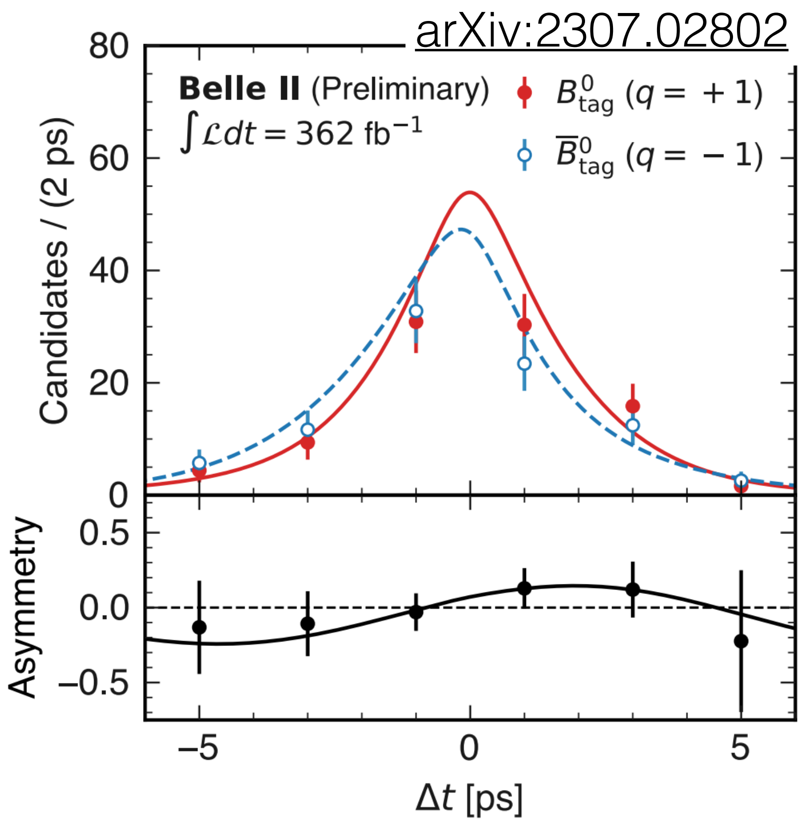


*Belle II results is not included, which should not affect the current WA significantly

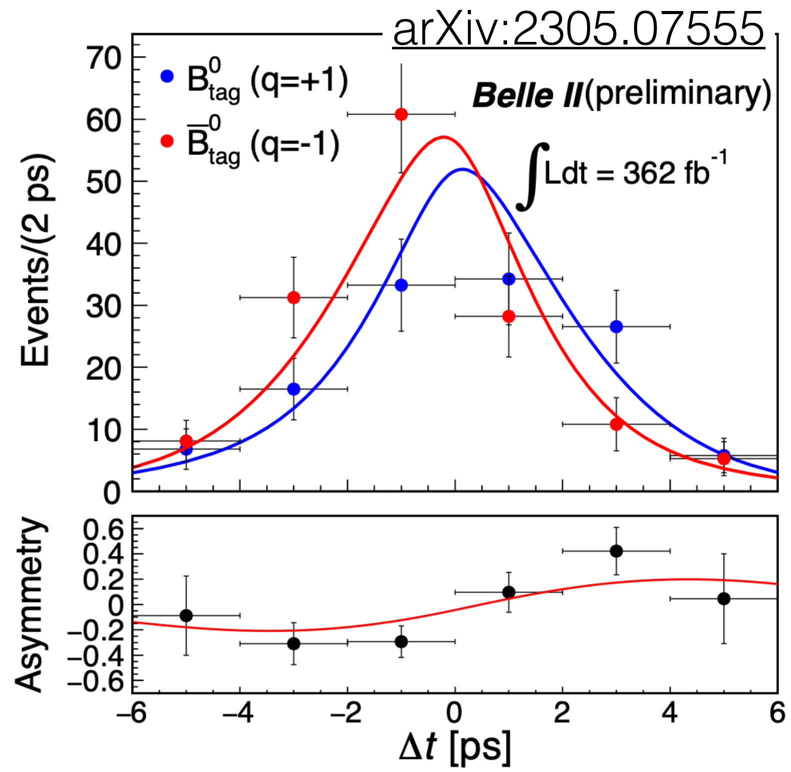
- Consistent with other measurements, still statistical uncertainty limited
- LHCb results dominate the latest World Average

Penguin dominated decay $B^0 \to \phi K_S^0$, $K_S^0\pi^0$, $K_S^0K_S^0K_S^0$

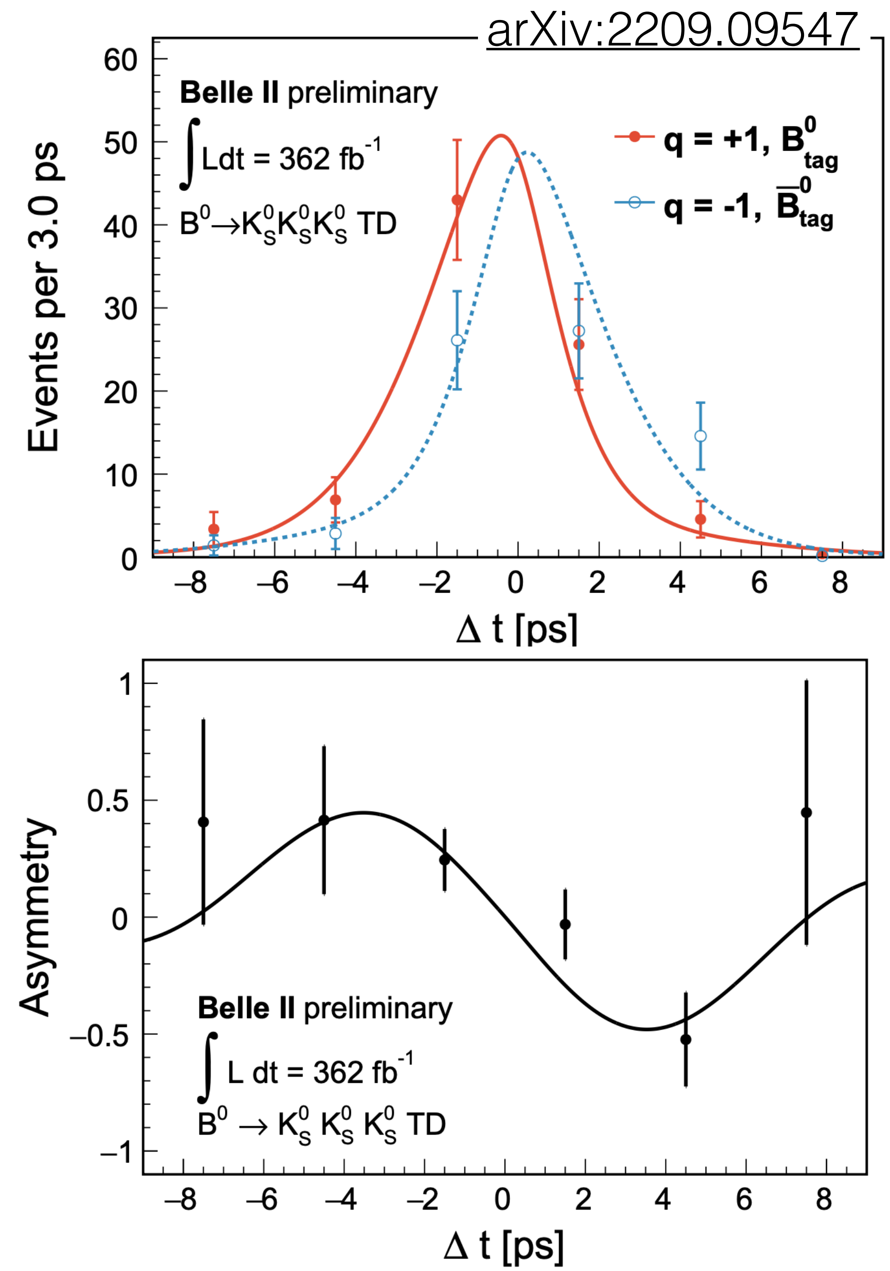
$B^0 \to \phi K_S^0$



$B^0 \to K_S^0\pi^0$



$B^0 \to K_S^0K_S^0K_S^0$



Observable		Belle II (362 fb^{-1})	World Average
$B^0 \to \phi K_S^0$	A	$0.31 \pm 0.20^{+0.05}_{-0.06}$	-0.01 ± 0.14
	S	$0.54 \pm 0.26^{+0.06}_{-0.08}$	$0.74^{+0.11}_{-0.13}$
$B^0 \to K_S^0K_S^0K_S^0$	A	$0.07^{+0.15}_{-0.20} \pm 0.02$	0.15 ± 0.12
	S	$-1.37^{+0.35}_{-0.45} \pm 0.03$	-0.83 ± 0.17
$B^0 \to K_S^0\pi^0$	A	$0.04^{+0.15}_{-0.14} \pm 0.05$	-0.01 ± 0.10
	S	$0.75^{+.20}_{-0.23} \pm 0.04$	0.57 ± 0.17

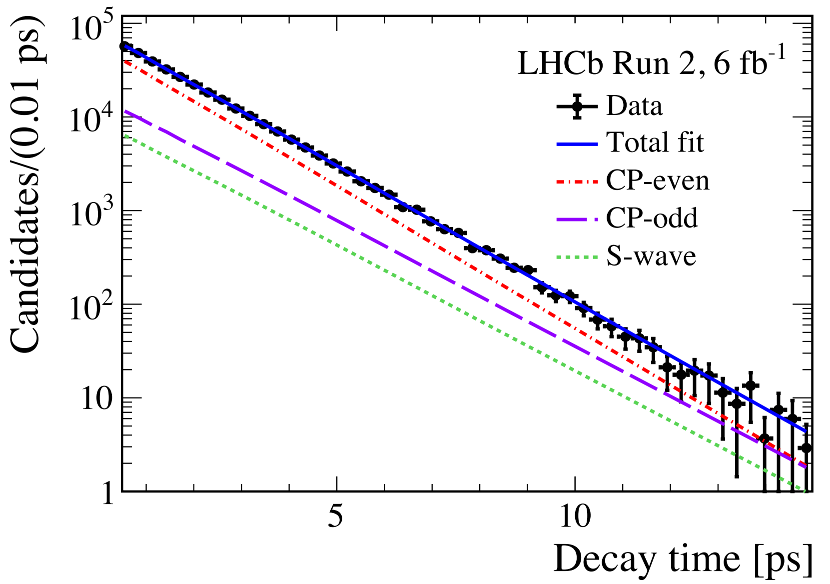
- Good agreement with the WA, more data needed!
- Belle II is in the unique position to measurements involving neutral particles

ϕ_s in $B_s^0 \to J/\psi\phi(KK)$

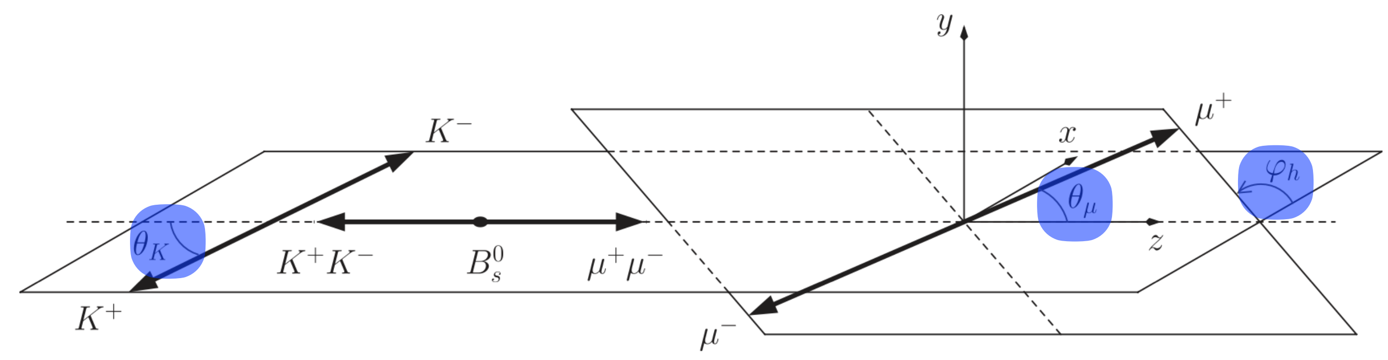
arXiv: 2308.01468
submitted to PRL

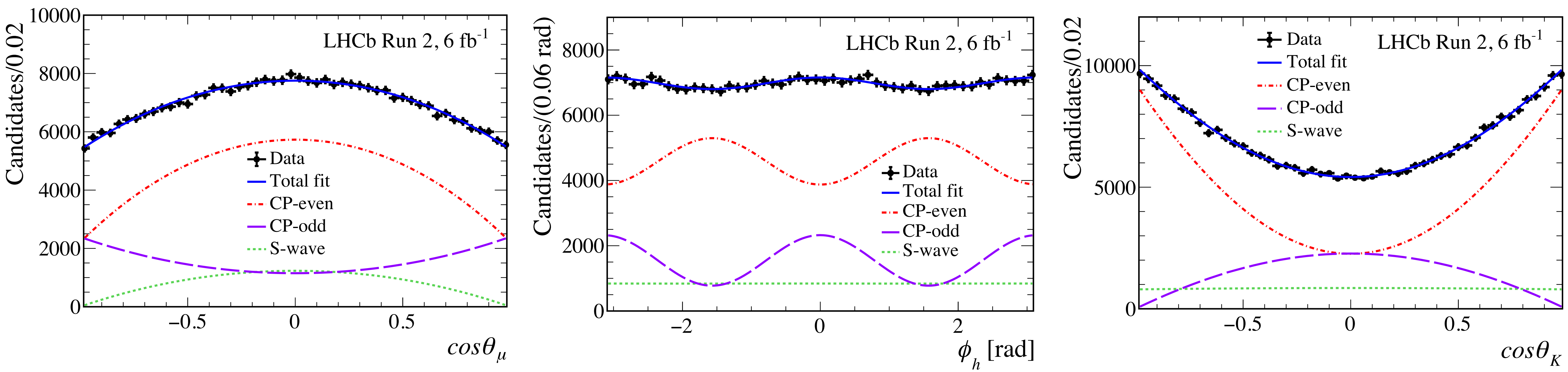
- Time-dependent flavour-tagged angular analysis for $B_s^0 \to VV$

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



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

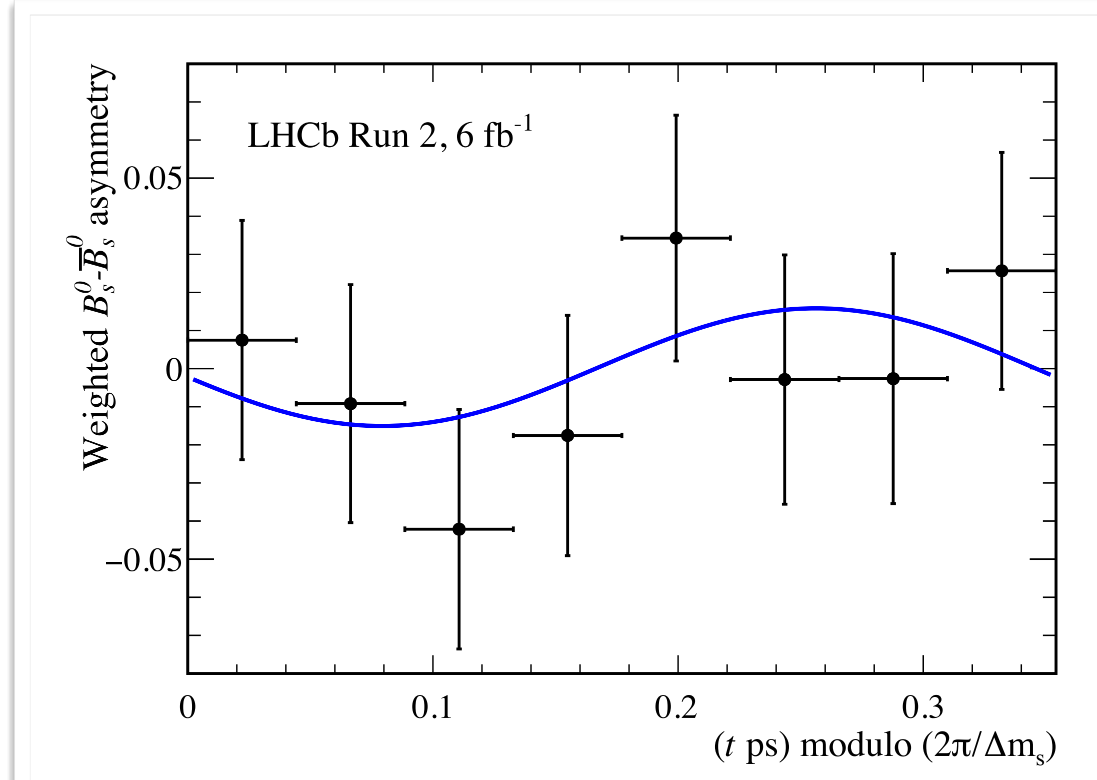




ϕ_s in $B_s^0 \to J/\psi KK$

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 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

⇨

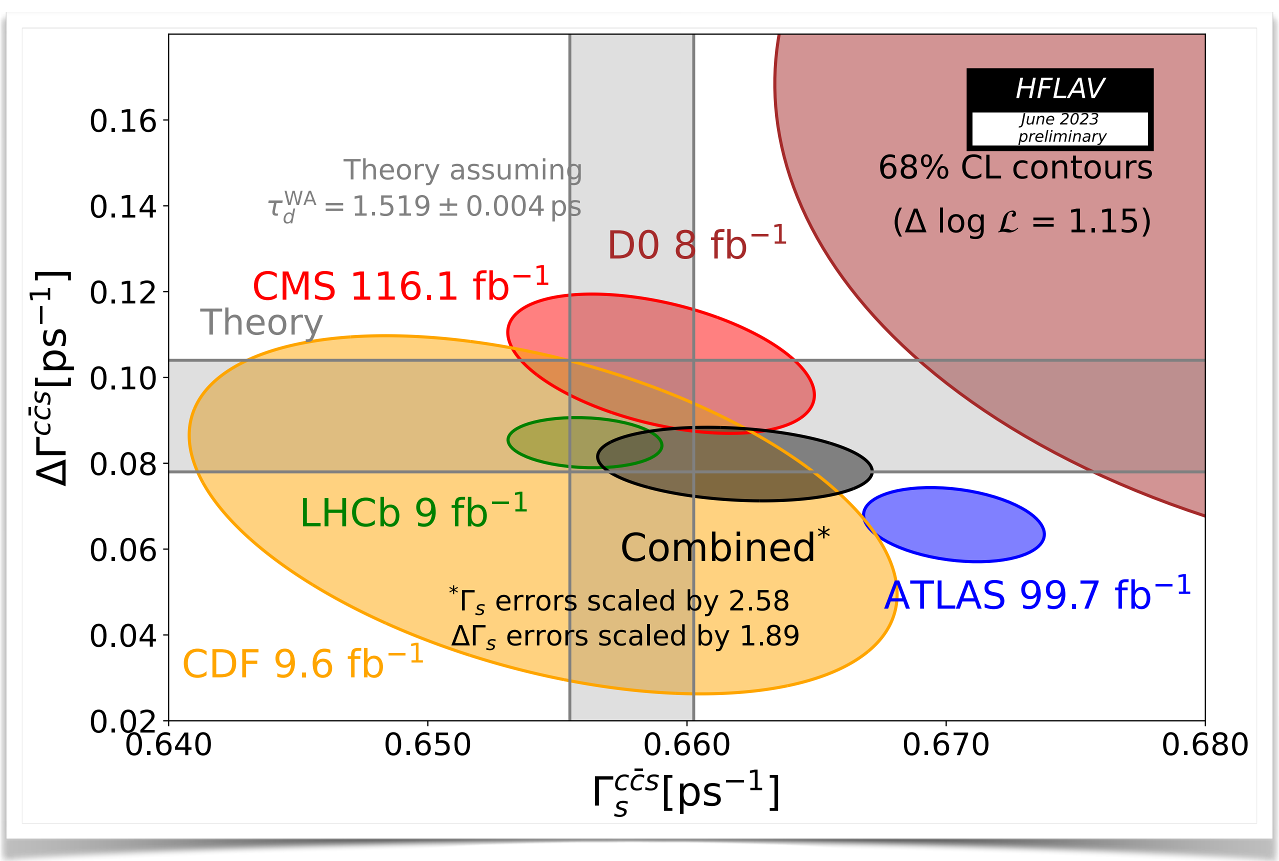
New World Average: (preliminary)

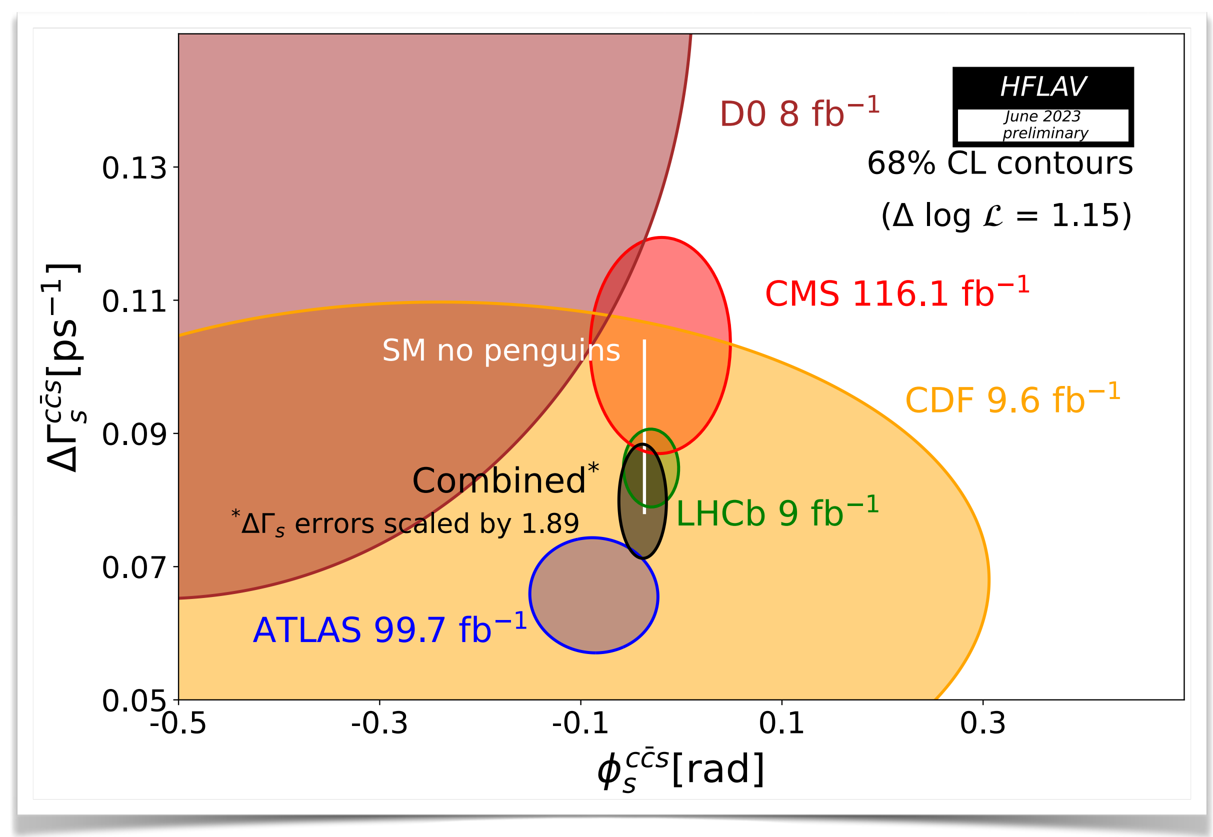
$\phi_s^{c\bar{c}s} = -0.050 \pm 0.016$ rad (16%)

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

- Consistent with the Global fits with SM assumption

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





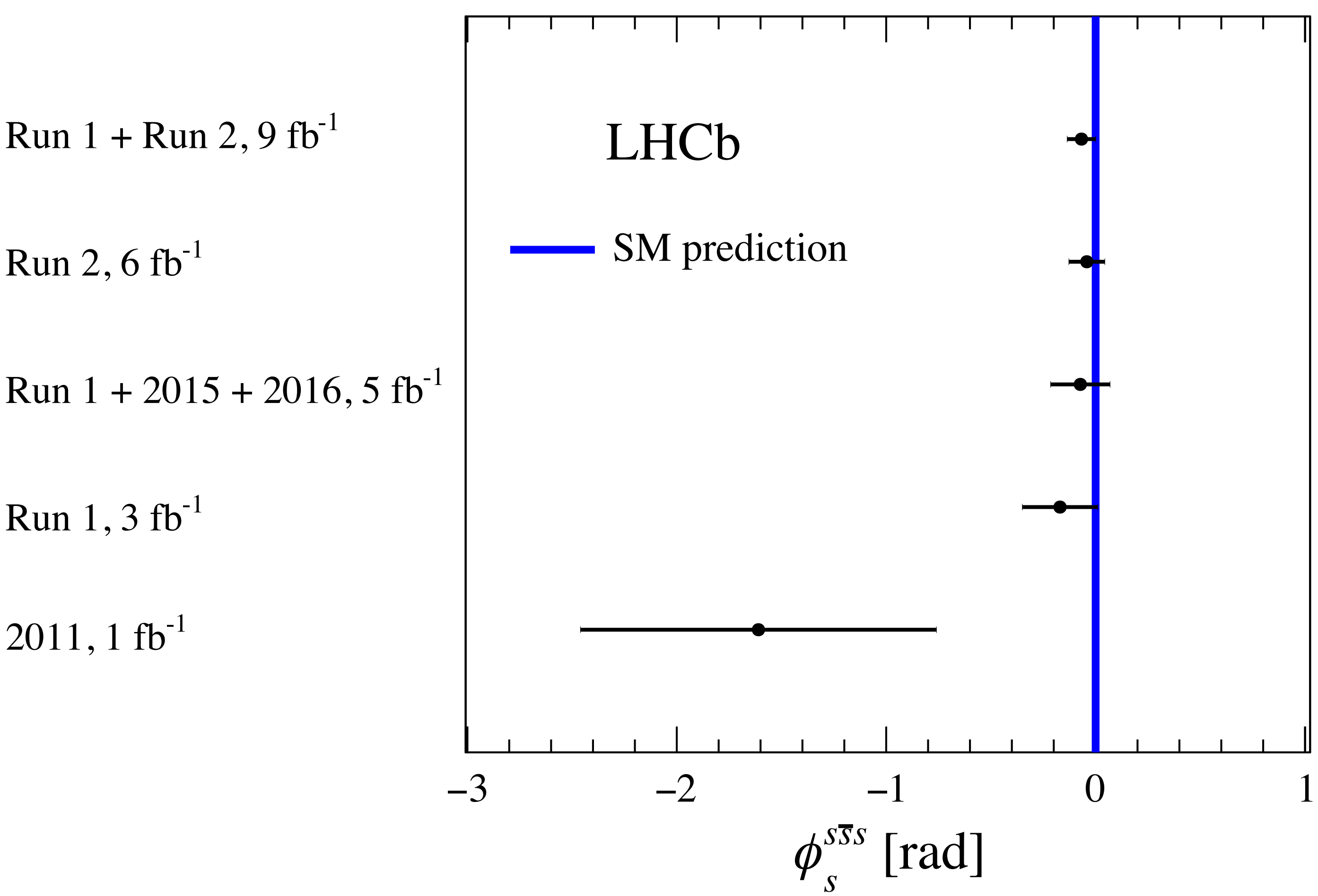
ϕ_s in $b \to s\bar{s}s$ transition

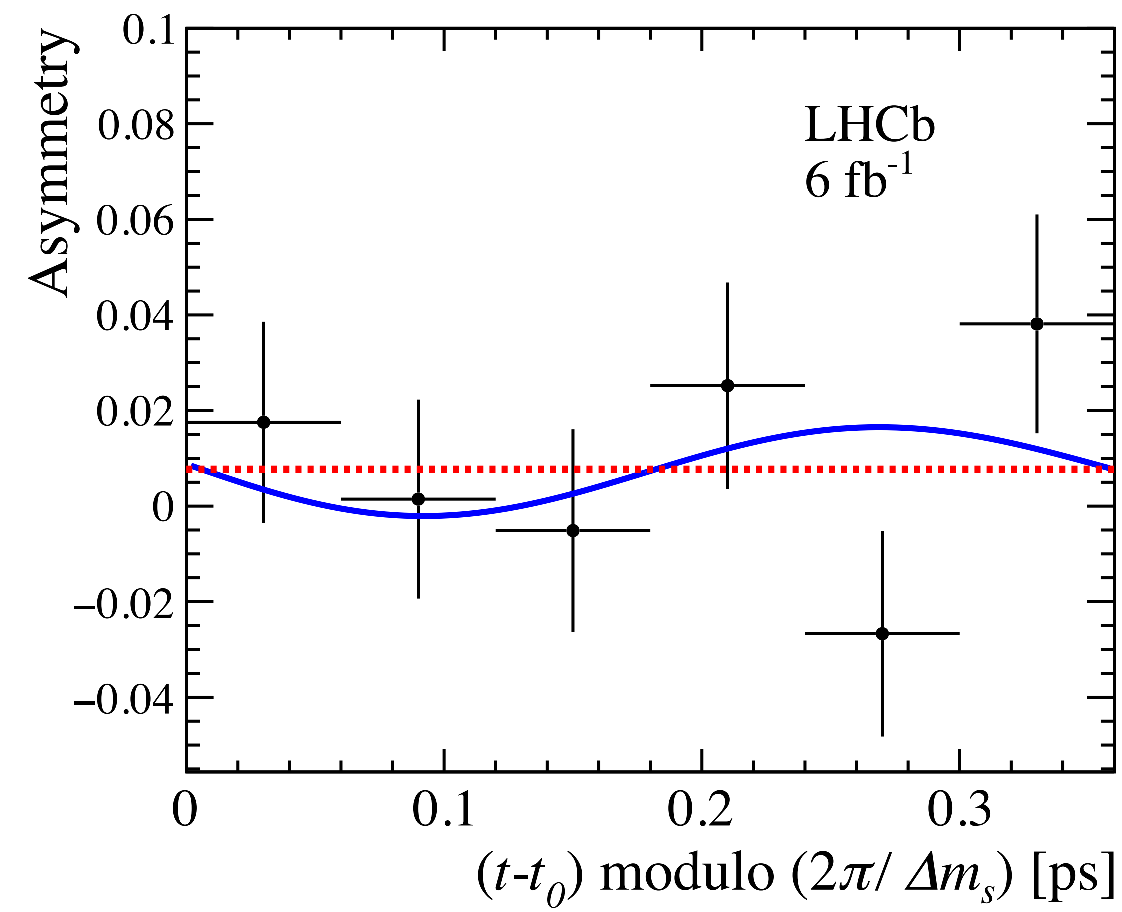
LHCb-PAPER-2023-001
accepted by PRL

- Penguin dominant decay $B_s^0 \to \phi\phi$
- Similar time-dependent flavour-tagged angular analysis as $B_s^0 \to J/\psi KK$

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

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



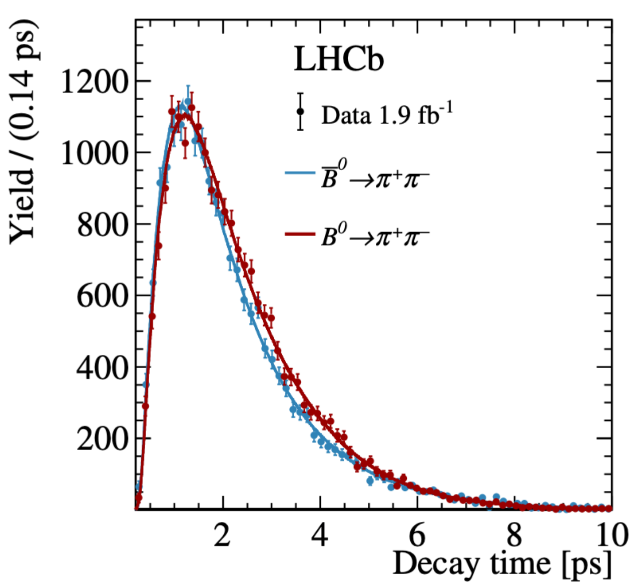


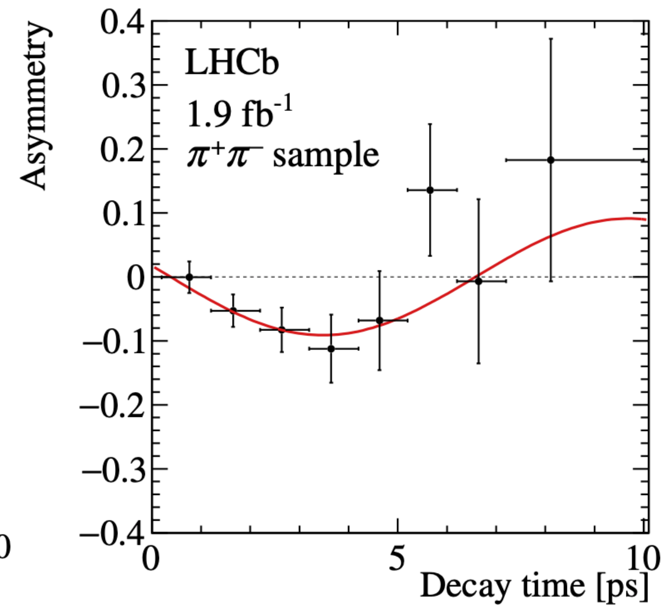
CP asymmetry in $B^0_{(s)} \to h^+h^-$

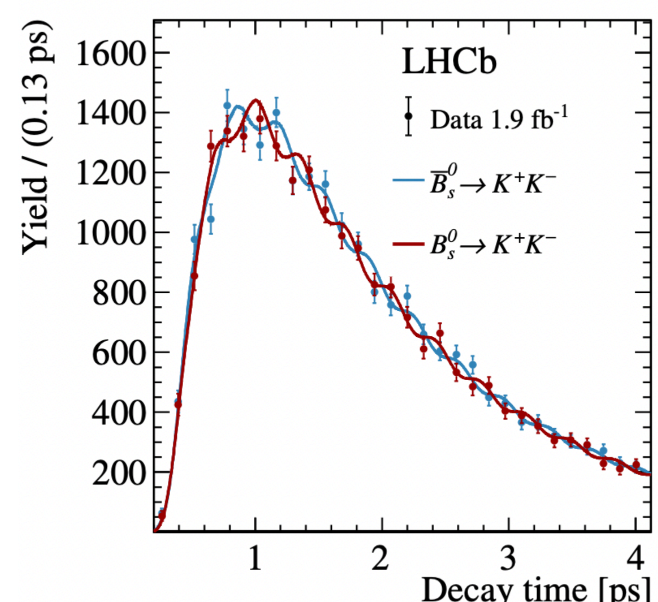
JHEP03(2021)075

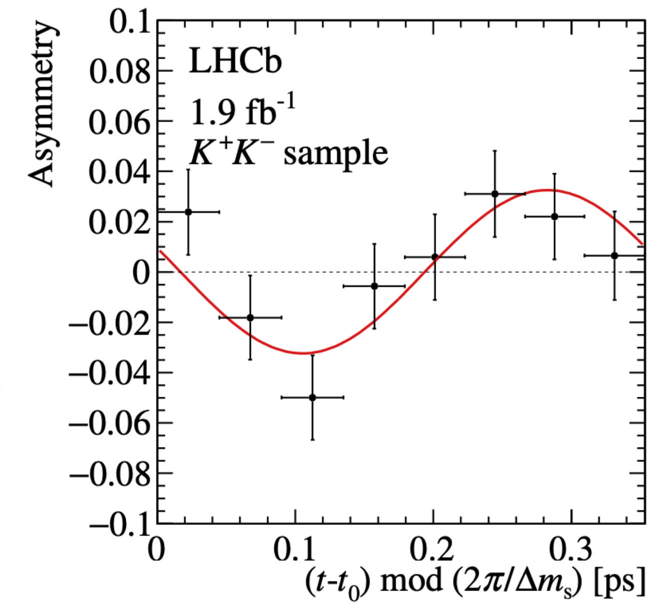
- Simultaneous fit to the invariant mass, $B^0_{(s)}$ decay time and tagging decision for $B^0 \to \pi^+\pi^-$, $B^0_s \to K^+K^-$, $B^0_{(s)} \to K\pi$, providing inputs to α, γ, $\sin 2\beta_s$
- The first observation of time-dependent CP violation in B^0_s decay

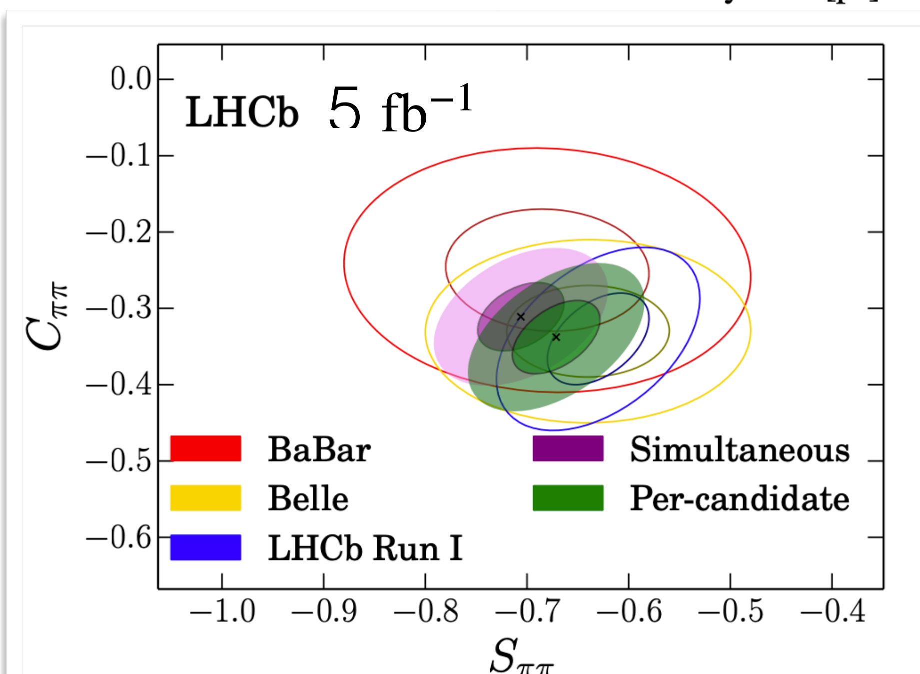
see Yuexin Wang's talk for $B^0 \to \pi^0\pi^0$









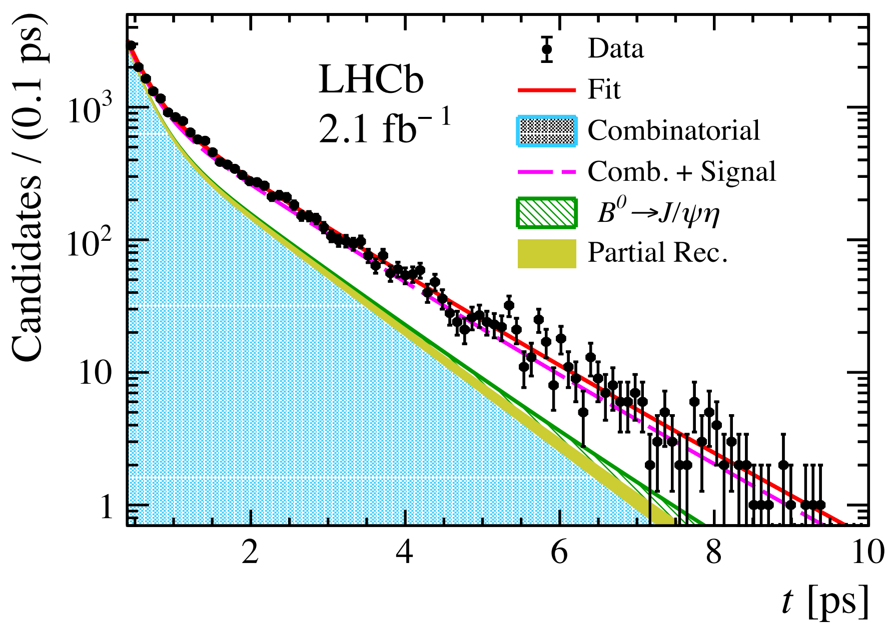


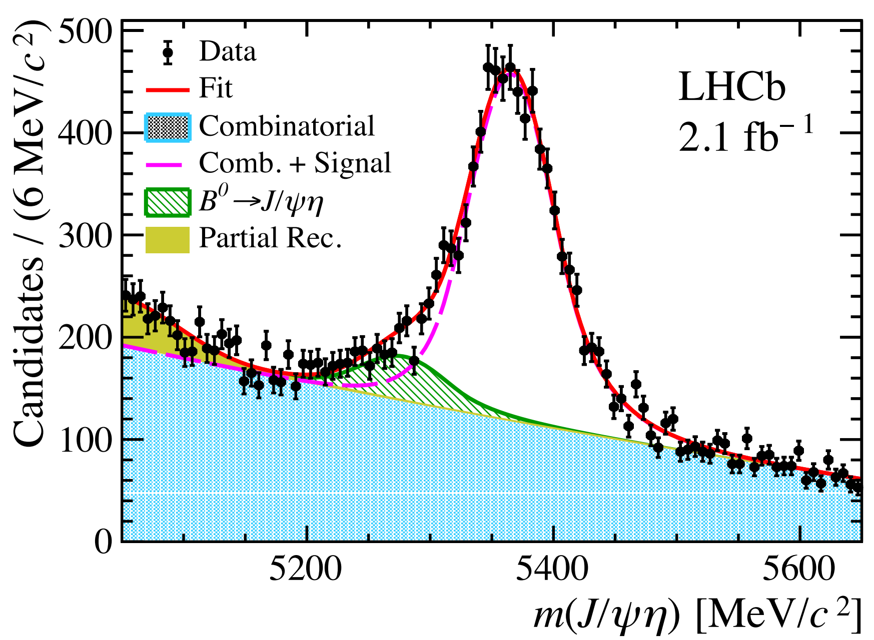
$$
\begin{aligned}
C_{\pi\pi} &= -0.311 \pm 0.045 \pm 0.015, \\
S_{\pi\pi} &= -0.706 \pm 0.042 \pm 0.013, \\
A_{CP}^{B^0} &= -0.0824 \pm 0.0033 \pm 0.0033, \\
A_{CP}^{B^0_s} &= 0.236 \pm 0.013 \pm 0.011, \\
C_{KK} &= 0.164 \pm 0.034 \pm 0.014, \\
S_{KK} &= 0.123 \pm 0.034 \pm 0.015, \\
\mathcal{A}_{KK}^{\Delta\Gamma}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

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

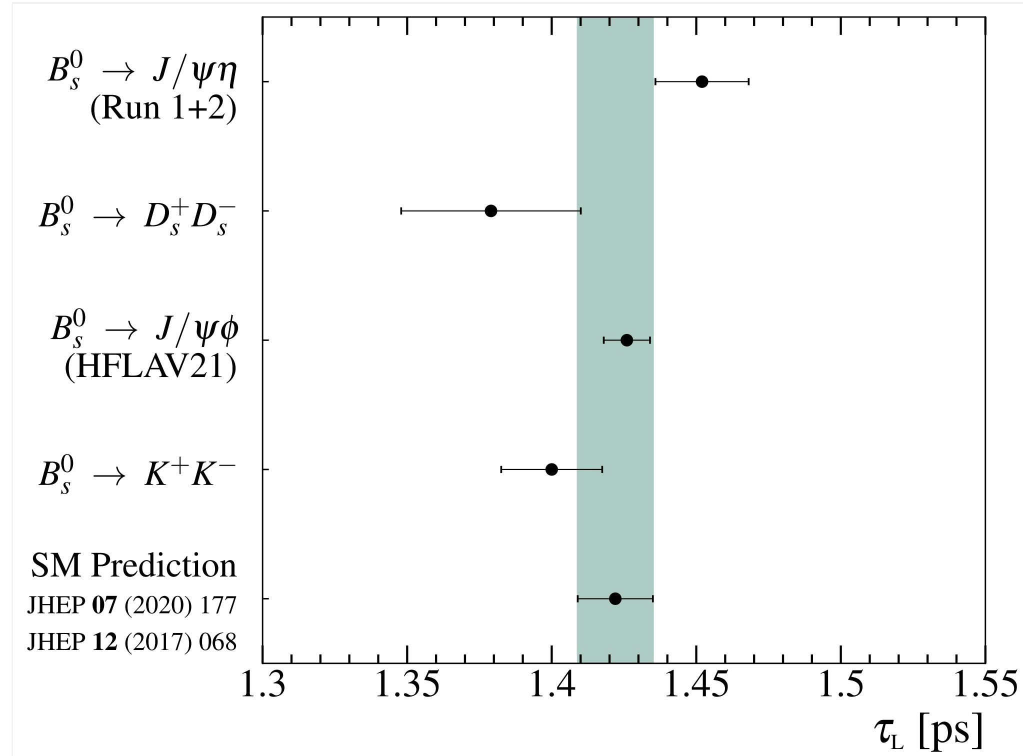
EPJC83 (2023) 629

- 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





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



Better reconstruction of η and $J/\psi(e^+e^-)$ at CEPC? + $B_s^0 \to J/\psi\eta'(\pi^0)$

Looking at future

see Lingfeng Li's talk

Particle	Belle II	LHCb (300 fb^{-1})	CEPC (4×Tera-Z)
B^0, $\bar{B}^0$	5.4×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}	4.8×10^{11}
$B^\pm$	5.7×10^{10} (50 ab^{-1} on $\Upsilon(4S)$)	3×10^{13}	4.8×10^{11}
B_s^0, $\bar{B}_s^0$	6.0×10^{8} (5 ab^{-1} on $\Upsilon(5S)$)	1×10^{13}	1.2×10^{11}
$B_c^\pm$	-	1×10^{11}	7.2×10^{8}
Λ_b^0, $\bar{\Lambda}_b^0$	-	2×10^{13}	1×10^{11}

see Mingrui Zhao's talk

	Belle II	LHCb	CEPC
tagging power	(30~35)%	(4~6)%	20 %
time resolution	…	43 fs	4.7 fs
e/neutral particles	***	*	***

- Belle II, LHCb & CEPC compensate each other
- CEPC & Belle II have advantages in decays with neutral particles

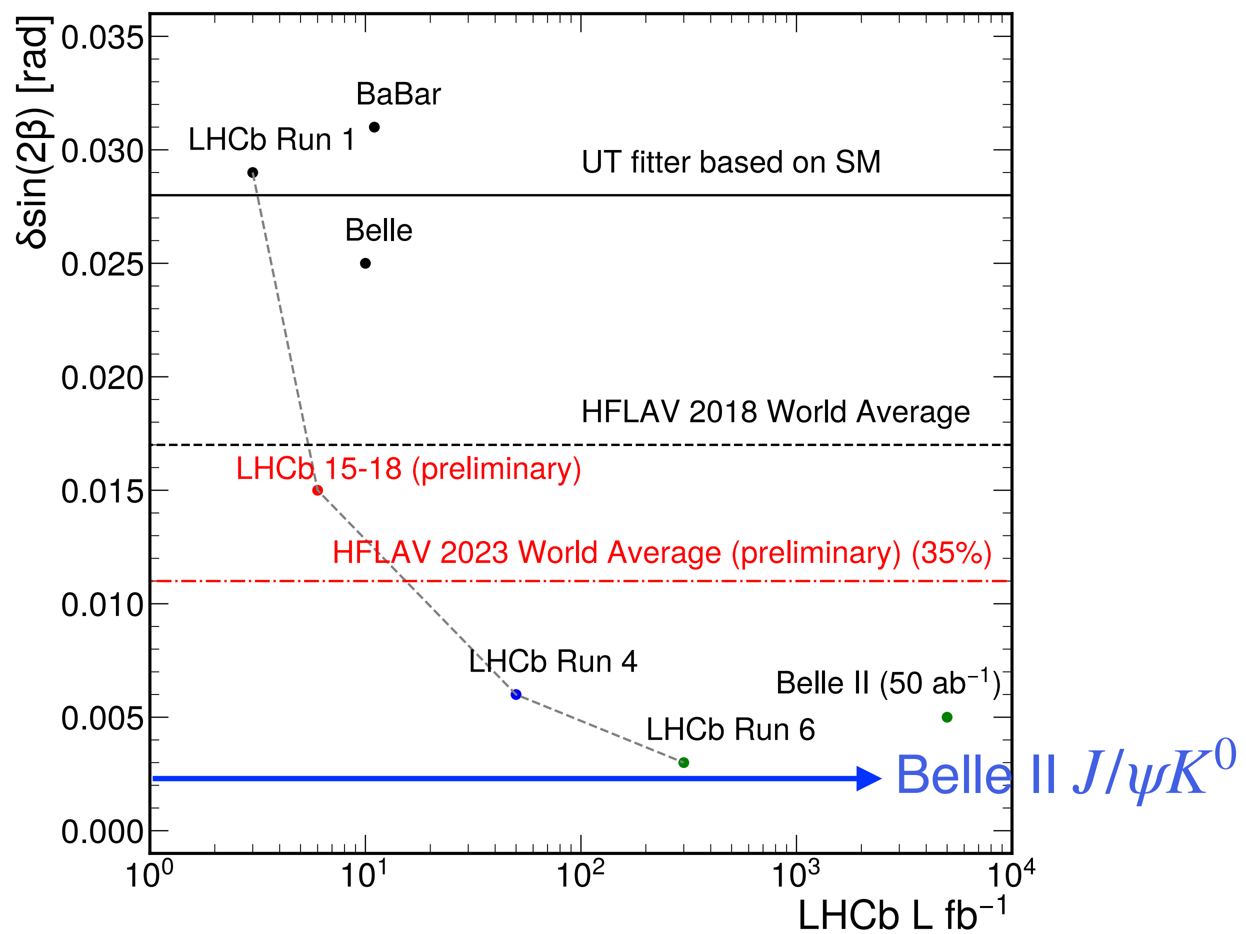
  →See Yuexin Wang's talk for α measurement with $B^0 \to \pi^0\pi^0$

Looking at future for $\sin 2\beta$

- Belle II good at $J/\psi \to e^+e^-$, K_L^0, π^0 reconstruction than LHCb

Could CEPC make great contributions for these with η' and π^0?

	WA		$5\,\mathrm{ab}^{-1}$		$50\,\mathrm{ab}^{-1}$	
Channel	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$
$J/\psi K^0$	0.22	0.21	0.012	0.011	0.0052	0.0090
$\eta' K^0$	0.06	0.04	0.032	0.020	0.015	0.008
ϕK^0	0.12	0.14	0.048	0.035	0.020	0.011
ωK_S^0	0.21	0.14	0.08	0.06	0.024	0.020
$K_S^0\pi^0\gamma$	0.20	0.12	0.10	0.07	0.031	0.021
$K_S^0\pi^0$	0.17	0.010	0.09	0.06	0.028	0.018

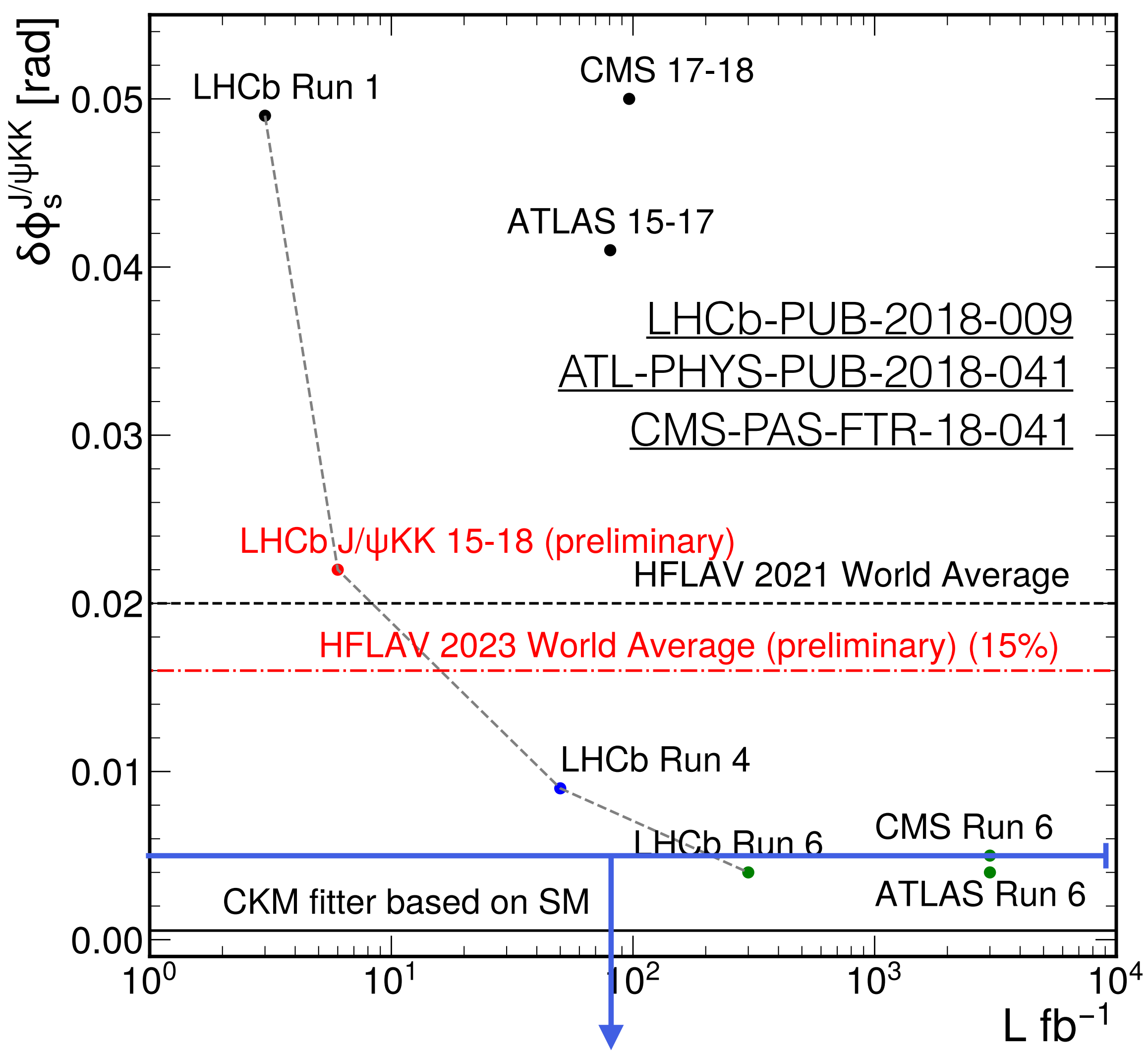


LHCb-PUB-2018-009

BelleII physics book

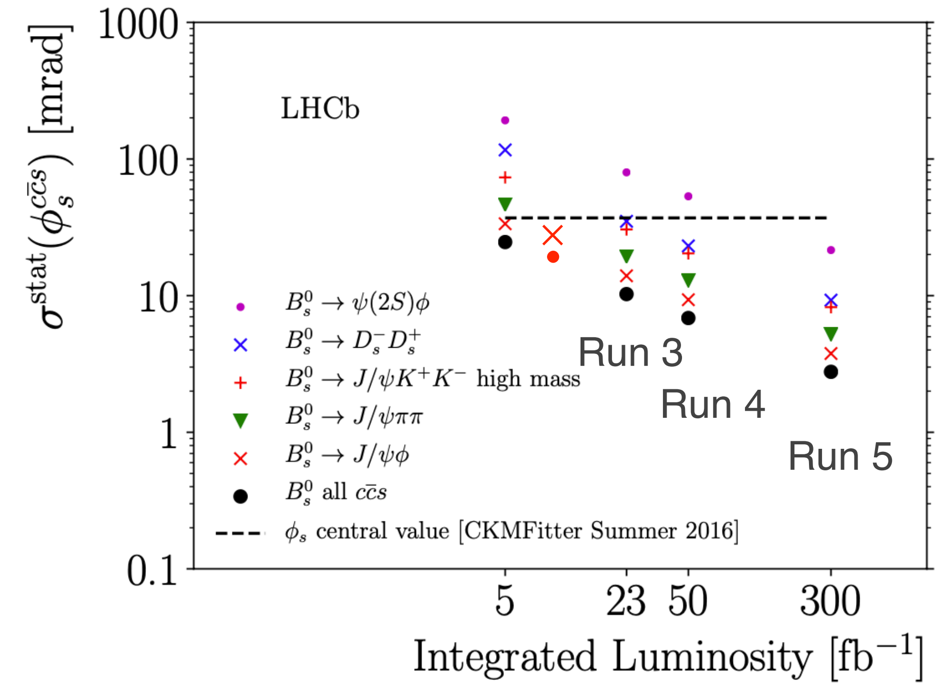
Looking at future for ϕ_s

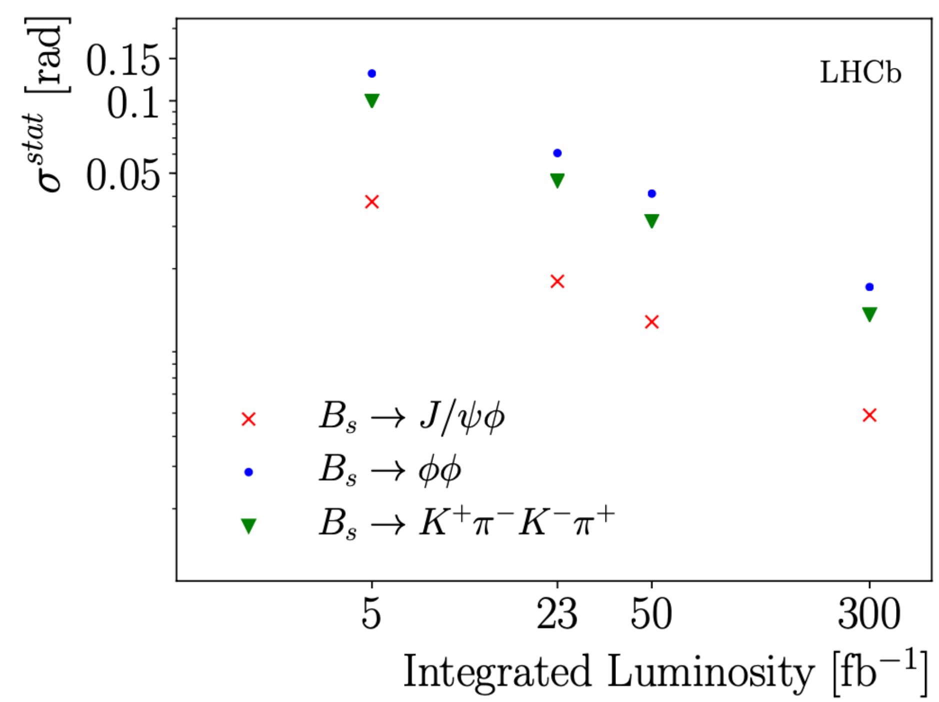
- B_s^0 production at Belle II is limited
- Significant contribution from CEPC possible!



CEPC (Tera-Z)~0.0046 rad

see Mingrui Zhao's talk



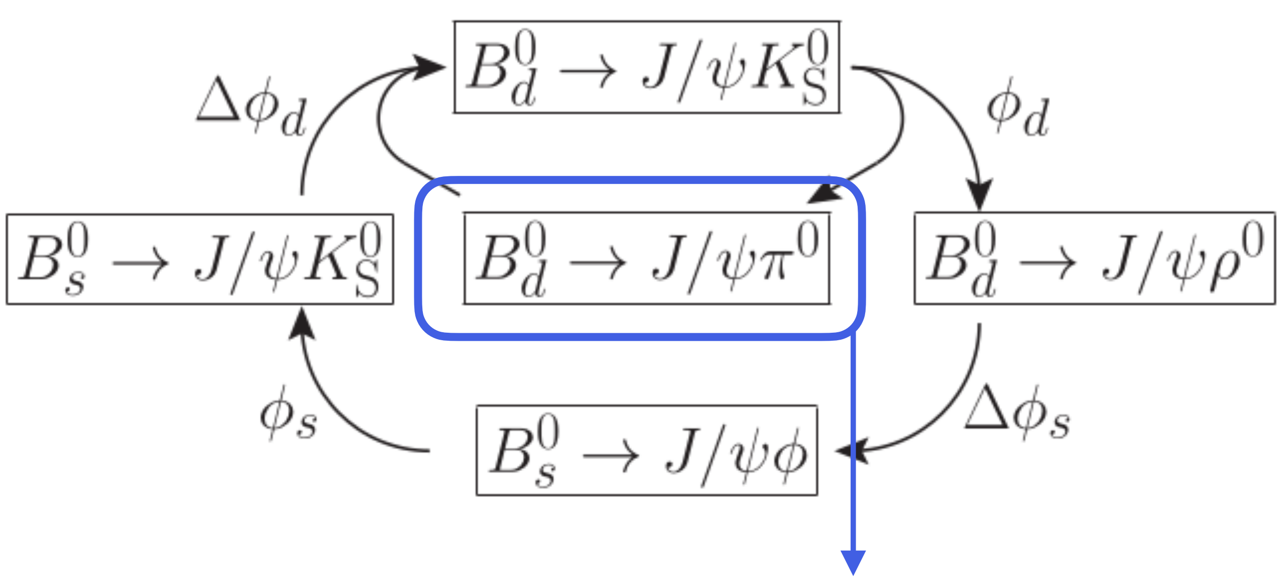


Control of penguin contribution

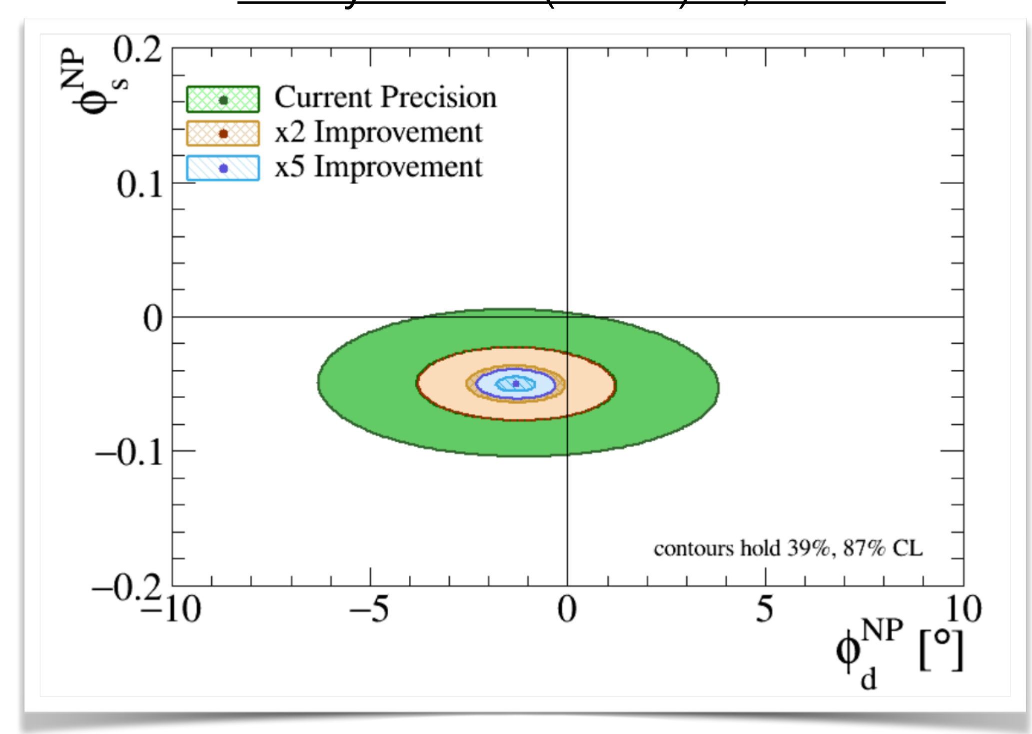
- $\sigma(\phi_s) \sim 0.016$ comparable with the estimation of $\Delta\phi_s^{penguin} \sim 1^\circ \approx 0.017$, better control of penguin effect necessary
- Combined analysis of penguin contributions in ϕ_s and ϕ_d $(\sin 2\beta)$, using SU(3) flavor symmetry

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

$$\phi_s = \phi_s^{\text{tree}} + \Delta\phi_s^{\text{penguin}} + \phi_s^{NP}$$



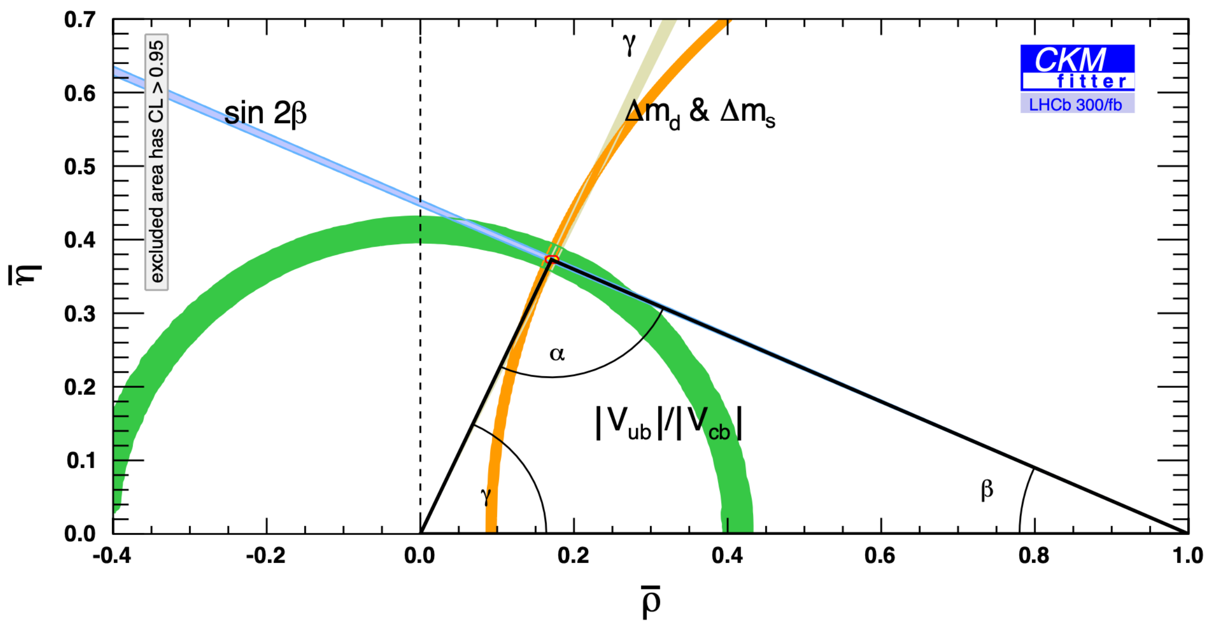
J.Phys.G 48 (2021) 6, 065002



Could be good opportunity for CEPC?

Summary

- ✓ LHCb & Belle II are leading the efforts in the time-dependent measurements of CP violation
- ✓ Most of the measurements are / will be statistical limited
- ✓ CEPC & Belle II have advantages in measurements with neutral particles, e.g. $B^0 \to \pi^0\pi^0,\ B^0 \to J/\psi\pi^0$ etc
- ✓ With higher flavor tagging & better time resolution than LHCb, CEPC could definitely make significant contribution to such time-dependent measurements
- ✓ Looking forward to further test of the SM and search for new physics



Thanks for your attention!

Back up slides

Fit pdf at Belle II

arXiv:2302.12898

Fit to Δt distribution in 7 bins of tag quality r :

$$P_{CP}(\Delta t,\ q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{2\tau_{B^0}}\{1 - q\Delta w + q\mu(1-2w) + [q(1-2w) + \mu(1-q\Delta w)][S_{CP}\sin(\Delta m_d \Delta t) + A_{CP}\cos(\Delta m_d \Delta t)]\}$$

flavor tagging

convolved by decay-time resolution

$$\mathcal{R}(\mathrm{d}\Delta\tau;\sigma_{\Delta t}) = f_{\mathrm{core}} G(\mathrm{d}\Delta\tau; m_{\mathrm{core}}\sigma_{\Delta t}, s_{\mathrm{core}}\sigma_{\Delta t}) + f_{\mathrm{tail}}\mathcal{R}_{\mathrm{tail}}(\mathrm{d}\Delta\tau; m_{\mathrm{tail}}\sigma_{\Delta t}, s_{\mathrm{tail}}\sigma_{\Delta t}, c/\sigma_{\Delta t}, f_{>}, f_{<}) + f_{\mathrm{OL}} G(\mathrm{d}\Delta\tau; 0, \sigma_{\mathrm{OL}}),$$

Flavor tagging calibrated with $D^0 \to D^{(*)-}\pi^+$:

$$P_{\mathrm{flav}}(\Delta t,\ q,\ q_\pi) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}}\{1 - q\Delta w + q\mu(1-2w) - q_\pi[q(1-2w) + \mu(1-q\Delta w)]\cos(\Delta m_d \Delta t)\}$$

Systematic uncertainties

arXiv:2302.12898

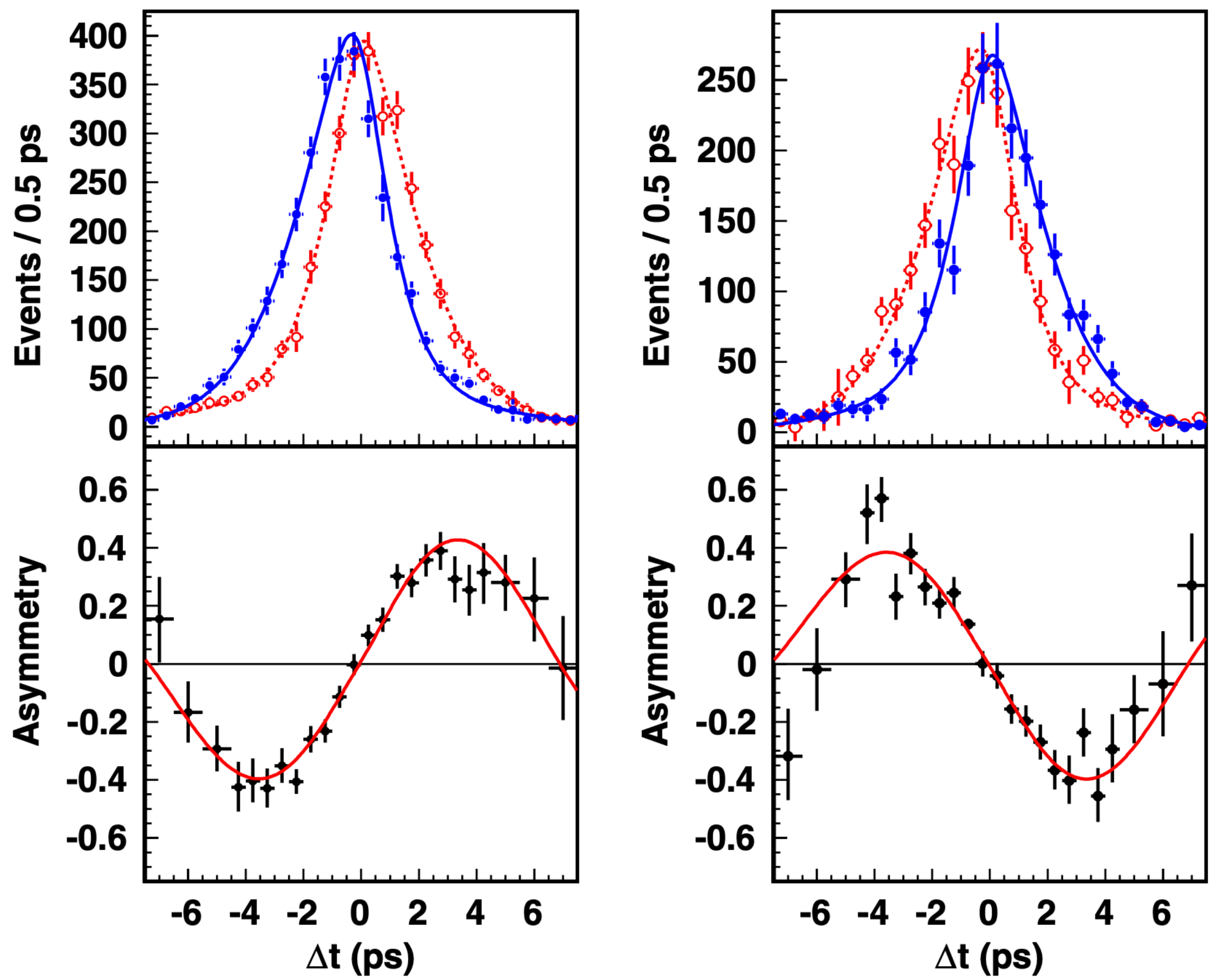
Dominant contribution due to samples size, could be reduced with more data!

TABLE II. Summary of the individual sources of uncertainties

Source	$\sigma(S_{CP})$	$\sigma(A_{CP})$
Statistical	0.0622	0.0439
Calibration with $B^0 \to D^{(*)-}\pi^+$decays		
$B^0 \to D^{(*)-}\pi^+$sample size	0.0111	0.0093
Signal charge-asymmetry	0.0027	0.0126
$w_6^+ = 0$ limit	0.0014	0.0001
Fit model		
Analysis bias	0.0080	0.0020
Fixed resolution parameters	0.0039	0.0008
$\sigma_{\Delta t}$ binning	0.0050	0.0051
τ_{B^0}, Δm_d	0.0007	0.0002
Δt measurement		
Alignment	0.0020	0.0042
Beam spot	0.0024	0.0020
Momentum scale	0.0005	0.0013
$B^0 \to J/\psi K_S^0$ ΔE background shape	0.0037	0.0015
Multiple candidates	0.0005	0.0008
CP violation in $B^0_{\rm tag}$ decays	0.0020	$^{+0.0380}_{-0.0000}$
Total systematic	0.0163	$^{+0.0418}_{-0.0174}$

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

PRL108(2012)171802



Decay mode	$\sin 2\phi_1 \equiv -\xi_f \mathcal{S}_f$	$\mathcal{A}_f$
$J/\psi K_S^0$	$+0.670 \pm 0.029 \pm 0.013$	$-0.015 \pm 0.021^{+0.045}_{-0.023}$
$\psi(2S) K_S^0$	$+0.738 \pm 0.079 \pm 0.036$	$+0.104 \pm 0.055^{+0.047}_{-0.027}$
$\chi_{c1} K_S^0$	$+0.640 \pm 0.117 \pm 0.040$	$-0.017 \pm 0.083^{+0.046}_{-0.026}$
$J/\psi K_L^0$	$+0.642 \pm 0.047 \pm 0.021$	$+0.019 \pm 0.026^{+0.017}_{-0.041}$
All modes	$+0.667 \pm 0.023 \pm 0.012$	$+0.006 \pm 0.016 \pm 0.012$

Systematics for $\sin 2\beta$

LHCb-PAPER-2023-016
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

$$S^{\text{Run 2}}_{J/\psi(\to\mu^+\mu^-)K^0_S} = 0.714 \pm 0.015\,(\text{stat}) \pm 0.0074\,(\text{syst})$$
$$C^{\text{Run 2}}_{J/\psi(\to\mu^+\mu^-)K^0_S} = 0.013 \pm 0.014\,(\text{stat}) \pm 0.0025\,(\text{syst})$$
$$S^{\text{Run 2}}_{\psi(2S)K^0_S} = 0.647 \pm 0.053\,(\text{stat}) \pm 0.018\,(\text{syst})$$
$$C^{\text{Run 2}}_{\psi(2S)K^0_S} = -0.083 \pm 0.048\,(\text{stat}) \pm 0.0053\,(\text{syst})$$
$$S^{\text{Run 2}}_{J/\psi(\to e^+e^-)K^0_S} = 0.752 \pm 0.037\,(\text{stat}) \pm 0.084\,(\text{syst})$$
$$C^{\text{Run 2}}_{J/\psi(\to e^+e^-)K^0_S} = 0.046 \pm 0.034\,(\text{stat}) \pm 0.0077\,(\text{syst})$$

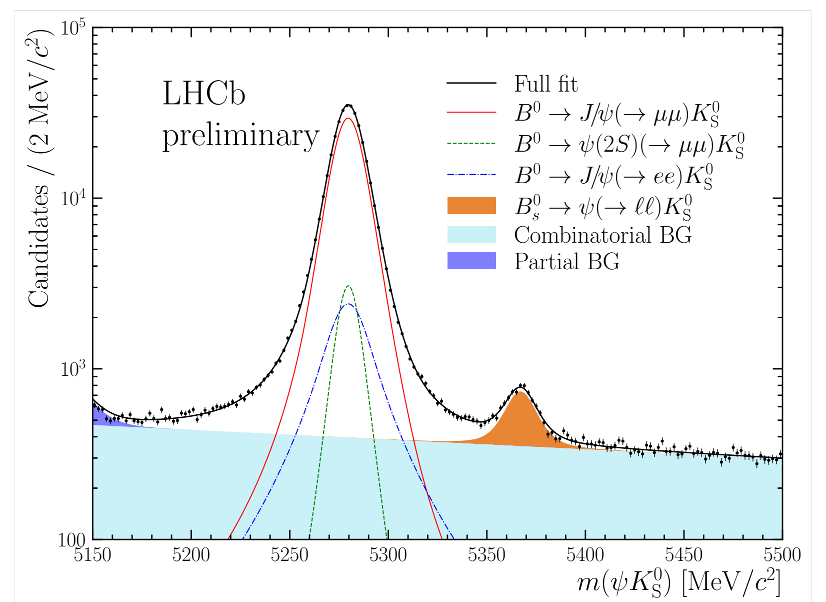
Mass fit

- *sPlot technique* to subtract combinatorial background:
  → perform fits to invariant mass distribution

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

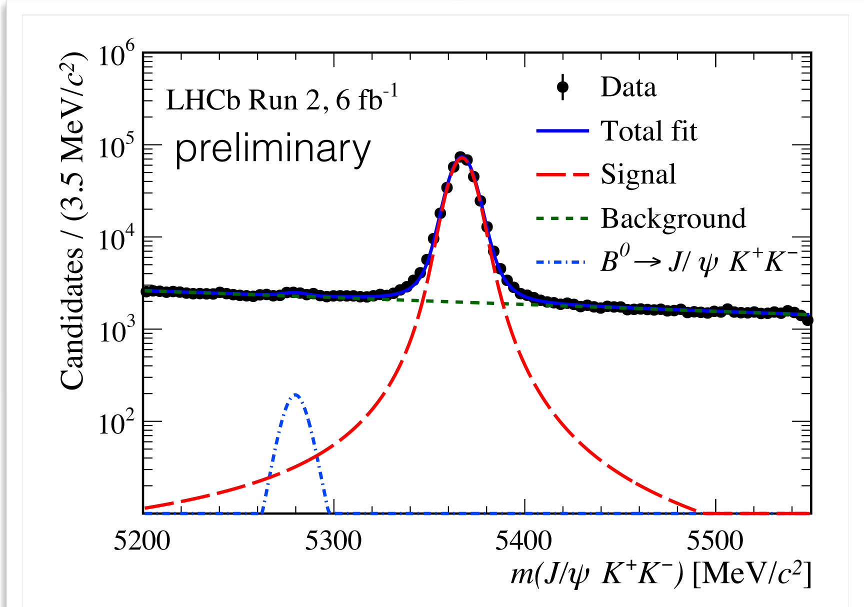
- $B_s^0 \to J/\psi K^+K^-$

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



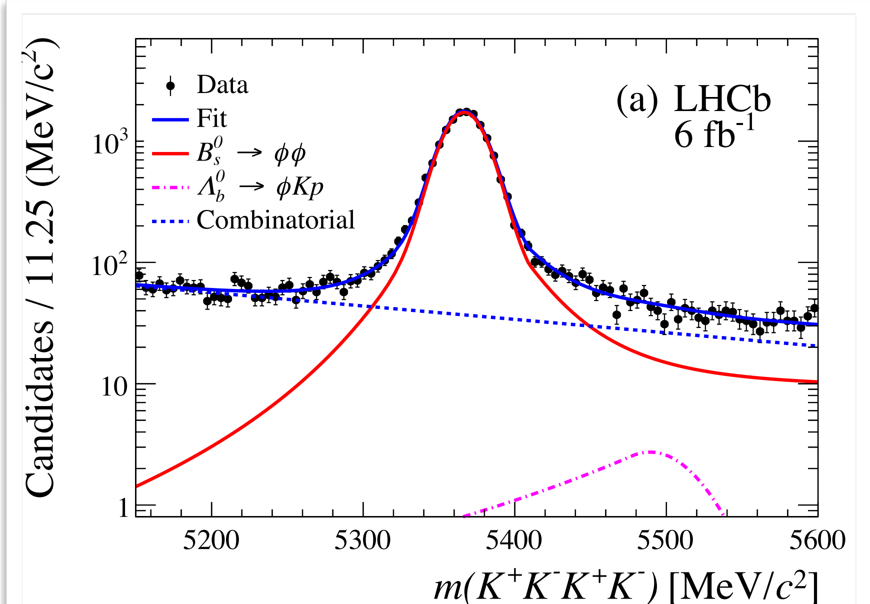
Total signal candidates
~306090 + 42700 + 23560

LHCb-PAPER-2023-013
In preparation



Total signal candidates
~349000

LHCb-PAPER-2023-016
In preparation



Total signal candidates
~15840

LHCb-PAPER-2023-001

ϕ_s polarisation dependent fit

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

LHCb-PAPER-2023-016

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]	$0.022 ^{+0.027}_{-0.026}$
$\lvert\lambda^0\rvert$	$0.969 ^{+0.025}_{-0.024}$
$\lvert\lambda^{\parallel}/\lambda^0\rvert$	$0.982 ^{+0.055}_{-0.052}$
$\lvert\lambda^{\perp}/\lambda^0\rvert$	$1.107 ^{+0.081}_{-0.075}$
$\lvert\lambda^{S}/\lambda^0\rvert$	$1.121 ^{+0.085}_{-0.078}$

Systematics for ϕ_s

LHCb

* 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 $\phi_s^{s\bar{s}s}$

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]	$2.769 \pm 0.105 \pm 0.011$

Time-dependent angular fit

EPJC79(2019)706

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

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

Angular amplitudes

C^k_{SP} account for the interference between P- and S- wave

flavor tagging

time-dependent oscillation

decay-time efficiency

decay-time resolution

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

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

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	$\lvert A_S A_0\rvert$	$\frac{4}{3}\sqrt{3}\cos\theta_K\sin^2\theta_\mu$