Measurements of B mesons mixing phases at LHCb

Mary Richardson-Slipper
on behalf of the LHCb Collaboration

ICHEP 2024, Prague, Czech Republic

Outline

- Introduction
  - CKM matrix
  - The LHCb detector
- Measurement of $\sin(2\beta)$ with $B^0 \to J/\psi K_S^0$
- Measurement of ϕ_s with $B_s^0 \to J/\psi\phi$
- Measurement of $\phi_s^{s\bar{s}s}$ with $B_s^0 \to \phi\phi$
- Measurement of $\Delta\Gamma_s$ with $B_s^0 \to J/\psi\eta'$ and $B_s^0 \to J/\psi\pi^+\pi^-$
- Future prospects and summary

The CKM matrix

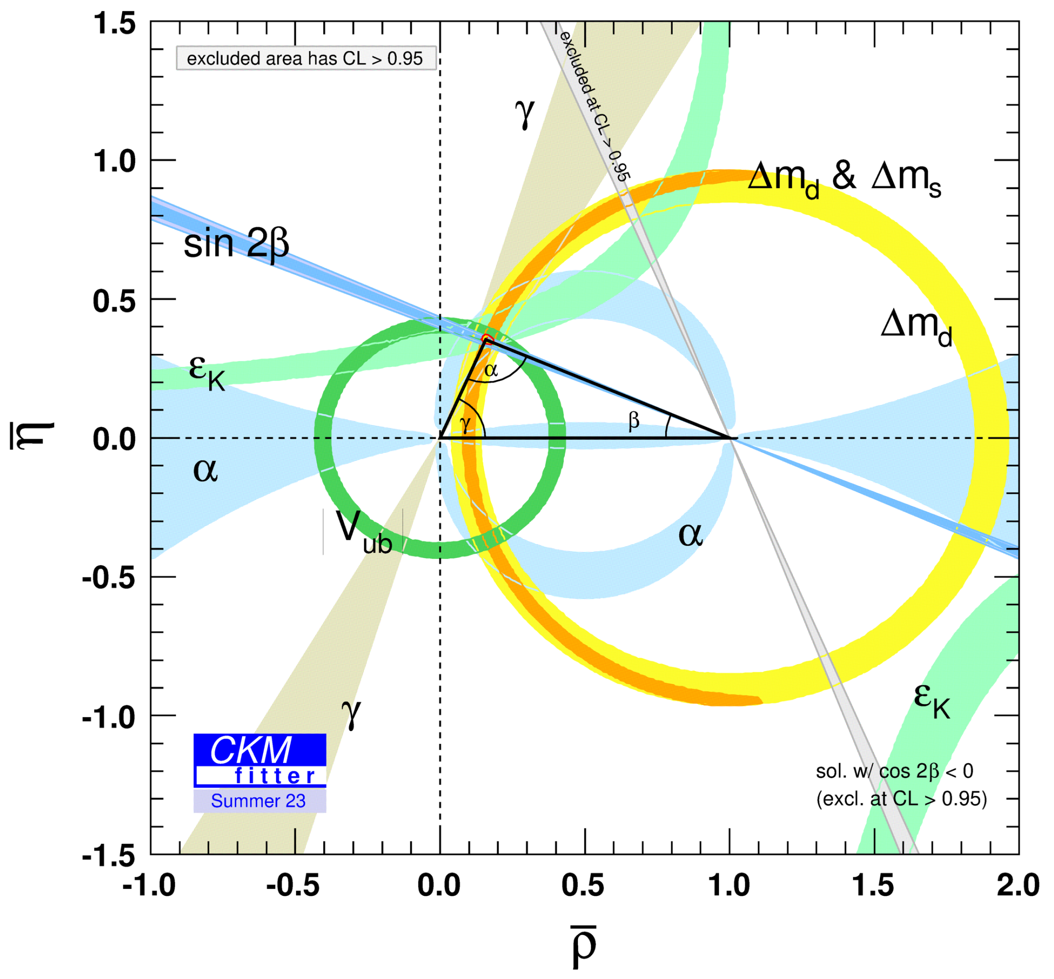
- Quark flavour mixing determined by the CKM matrix – connects weak eigenstates to mass eigenstates

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Unitarity of CKM matrix leads to the unitarity relations that form triangles in the complex plane

$$\sum_k V_{ik} V_{jk}^* = 0$$

- CP violation in the SM comes from complex phase in CKM matrix

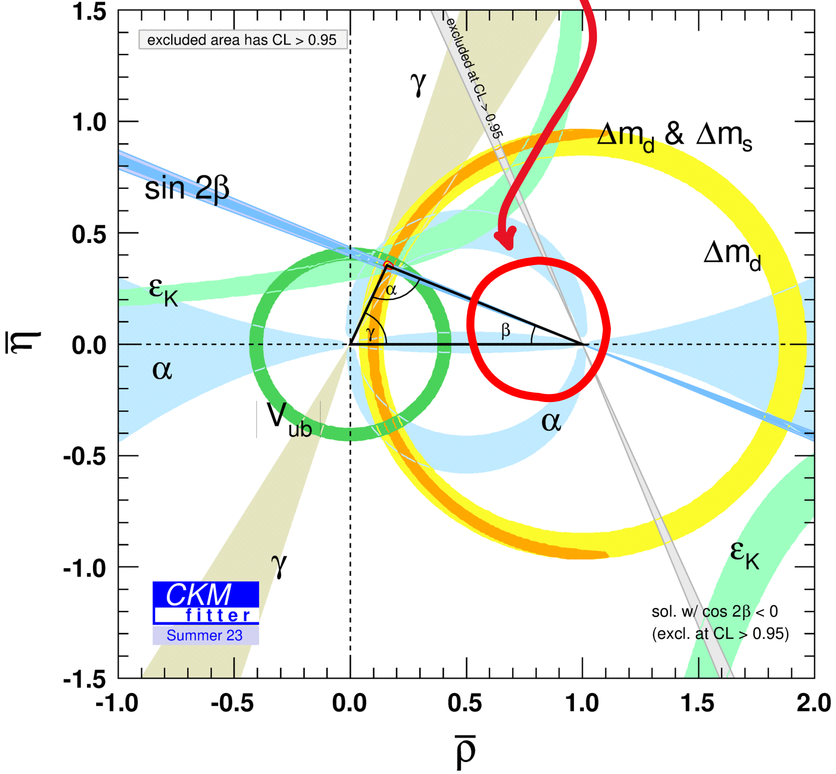


CKMfitter Group (J. Charles *et al.*), Eur. Phys. J. C41, 1-131 (2005) [hep-ph/0406184], updated results and plots available at: http://ckmfitter.in2p3.fr

Measuring the CKM parameters

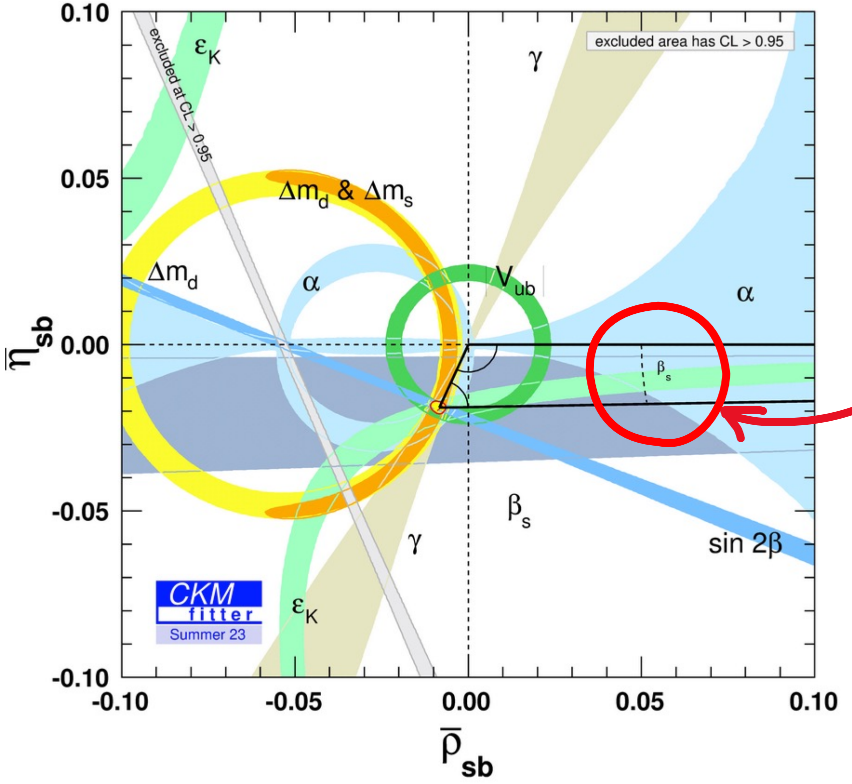
$B^0 \to J/\psi K_S^0$

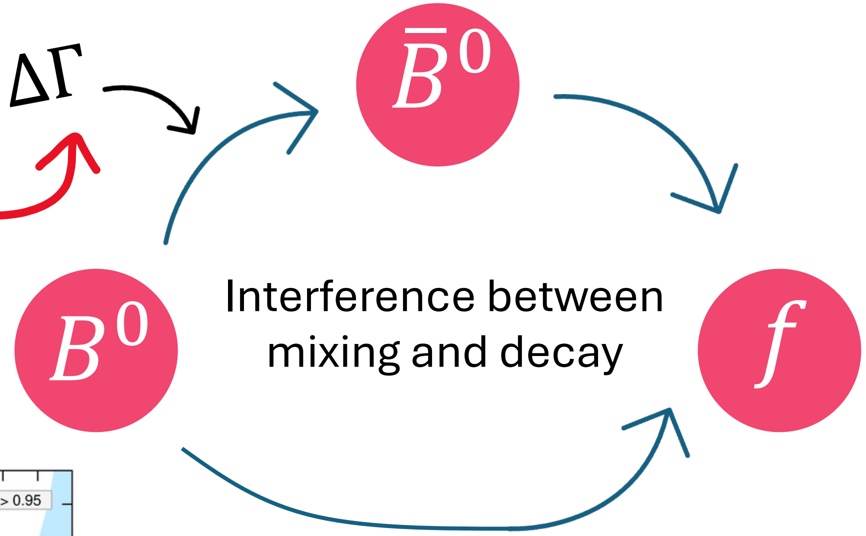
B^0 triangle



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

B_s^0 triangle

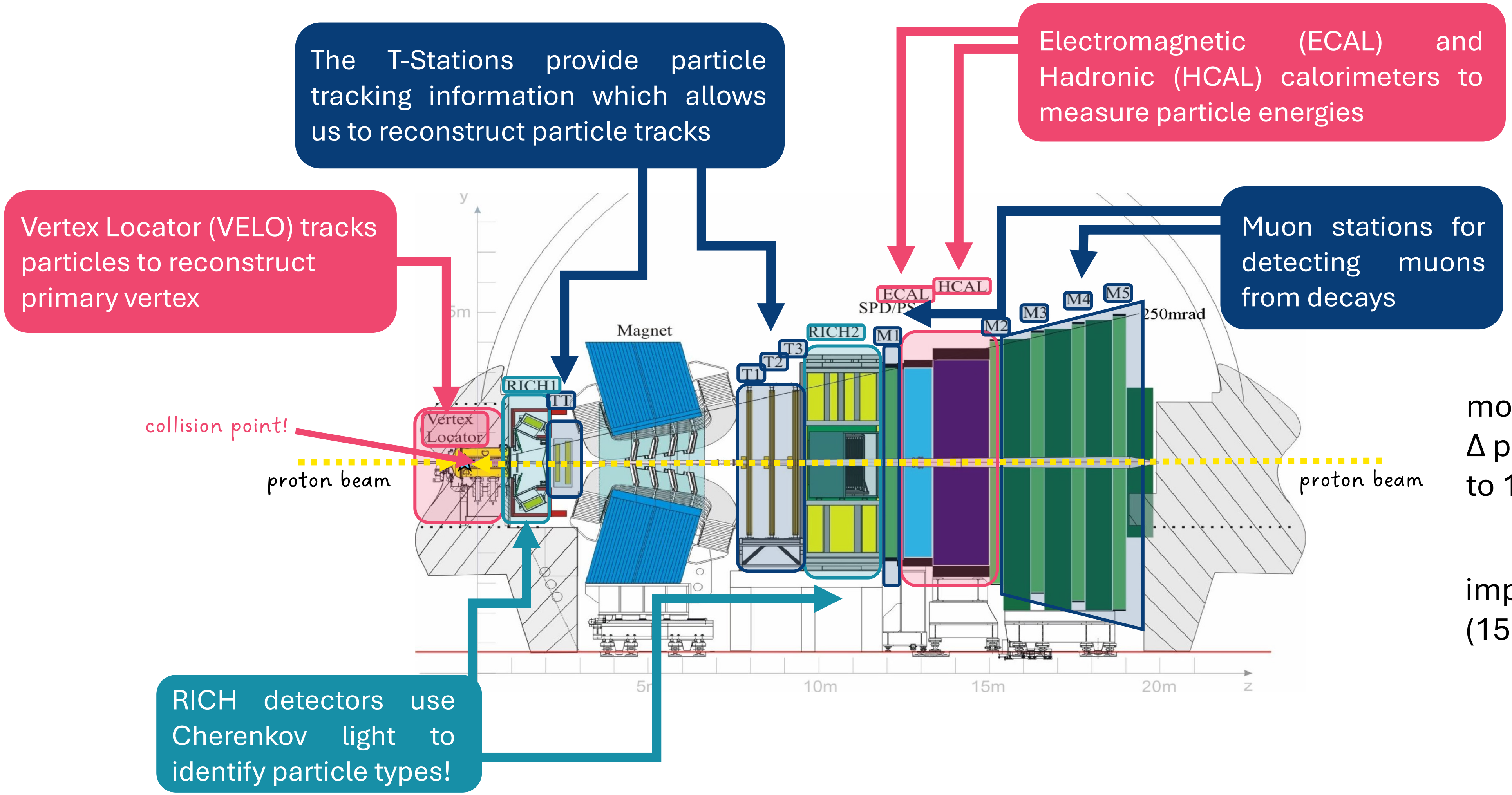




$B_s^0 \to J/\psi\phi$

Alves, A., & others (2008). The LHCb Detector at the LHC. *JINST, 3, S08005.*

The LHCb experiment – Run 1 and Run 2



momentum resolution:
$\Delta p / p$ = 0.5 % at low momentum to 1.0% at 200 GeV/c

impact parameter resolution:
(15 +29/pT[GeV]) μm

Phys. Rev. Lett. 132, 021801

Measurement of $\sin(2\beta)$ with $B^0 \to J/\psi K_S^0$

Using Run 2 data (6fb^{-1}). Three modes:

- $B^0 \to J/\psi(\to \mu^+\mu^-)K_S^0$, 306k events
- $B^0 \to J/\psi(\to e^+e^-)K_S^0$, 42k events
- $B^0 \to \psi(2S)(\to \mu^+\mu^-)K_S^0$, 23k events

measure CP violation parameters S and C

$$\mathcal{A}^{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to f) - \Gamma(B^0(t) \to f)}{\Gamma(\bar{B}^0(t) \to f) + \Gamma(B^0(t) \to f)} = \frac{S\sin(\Delta m_d t) - C\cos(\Delta m_d t)}{\cosh\left(\frac{1}{2}\Delta\Gamma_d t\right) + \mathcal{A}_{\Delta\Gamma}\sinh\left(\frac{1}{2}\Delta\Gamma_d t\right)}$$

CP violation parameters (S, C, $\mathcal{A}_{\Delta\Gamma}$)

$B^0 - \bar{B}^0$ mixing frequency (Δm_d)

B mass eigenstate decay width difference, compatible with zero ($\Delta\Gamma_d$)

$$\mathcal{A}^{CP}(t) \approx S\sin(\Delta m_d t) - C\cos(\Delta m_d t)$$

$$S = \sin(2\beta + \Delta\phi_d + \Delta\phi_d^{NP})$$

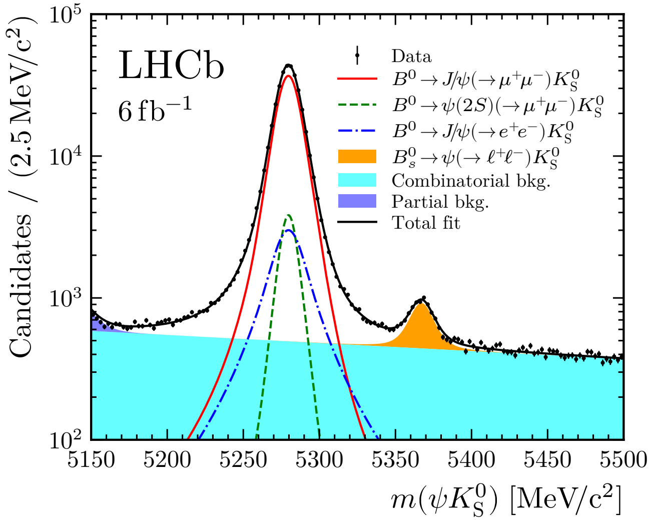
$\Delta\phi_d$: contributions from penguin topologies CKM suppressed: small in SM

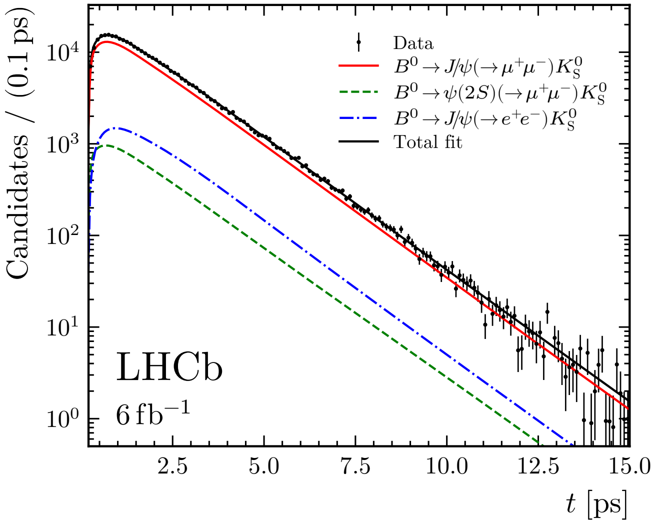
$\Delta\phi_d^{NP}$: possible contributions from new physics

Phys. Rev. Lett. 132, 021801

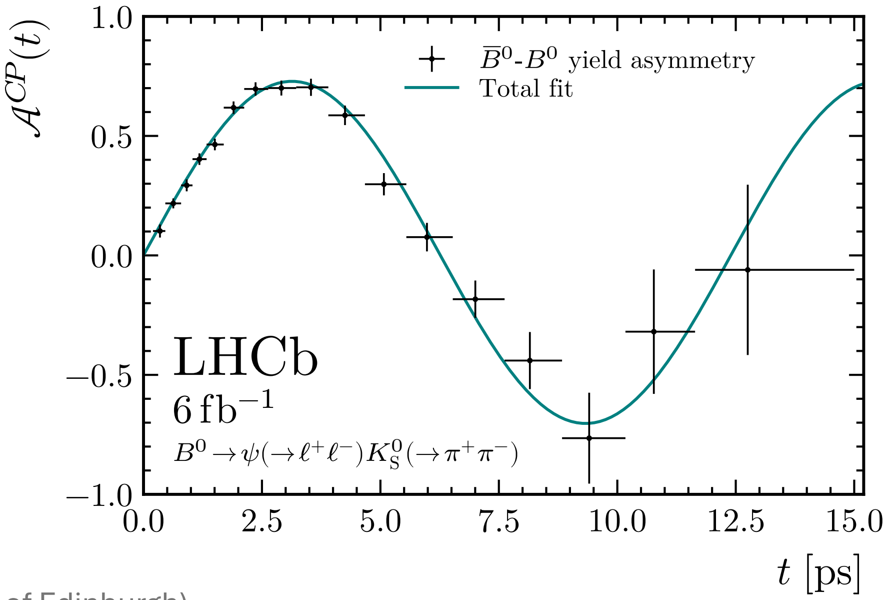
Measurement of $\sin(2\beta)$ with $B^0 \to J/\psi K_S^0$

Weighted fit to decay time distribution to extract S and C





Single most precise determination of CKM angle β – still statistics dominated



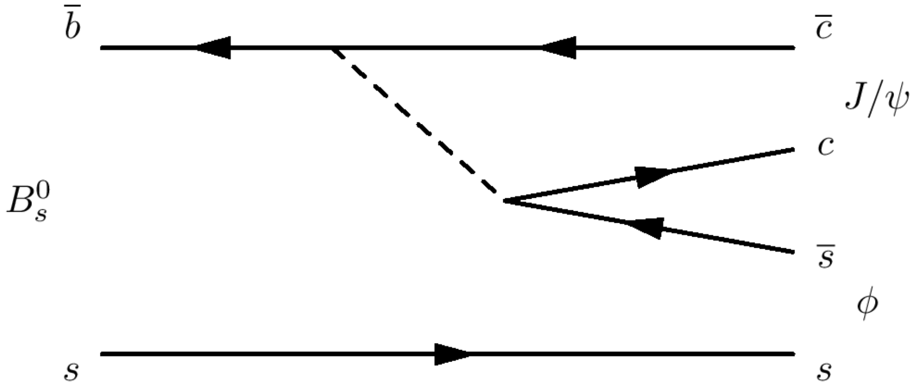
$$S_{\psi K_S^0} = 0.717 \pm 0.013(\text{stat}) \pm 0.008(\text{syst})$$
$$C_{\psi K_S^0} = 0.008 \pm 0.012(\text{stat}) \pm 0.003(\text{syst})$$

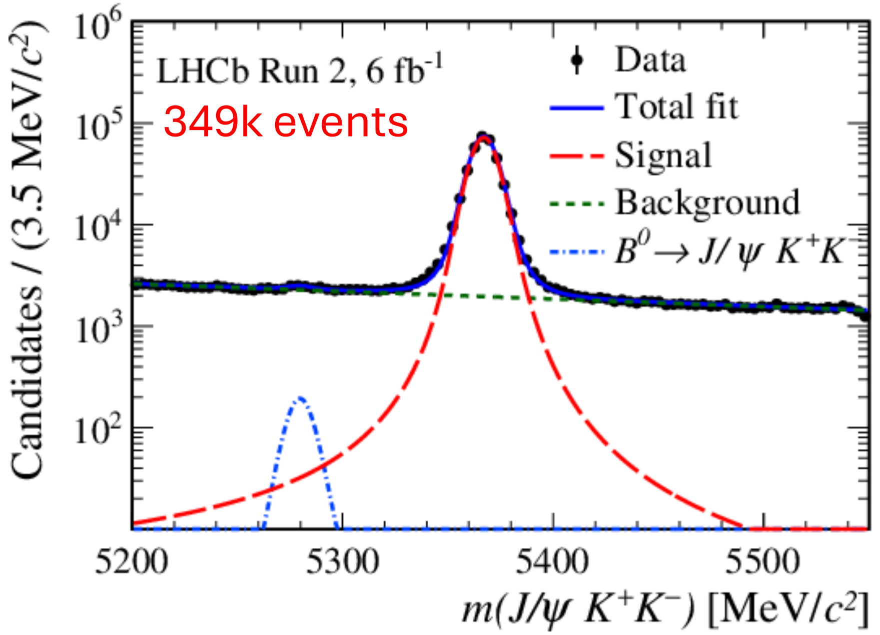
Phys. Rev. Lett. 132, 051802

Measurement of ϕ_s with $B_s^0 \to J/\psi\phi$

- A golden mode for study of CP violation
- Probe of CKM parameter β_s
  - Neglecting subleading loop contributions, CP violating phase $\phi_s^{c\bar{c}s} = -2\beta_s$
  - $\beta_s \equiv \arg[-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*)]$
- SM prediction very precise

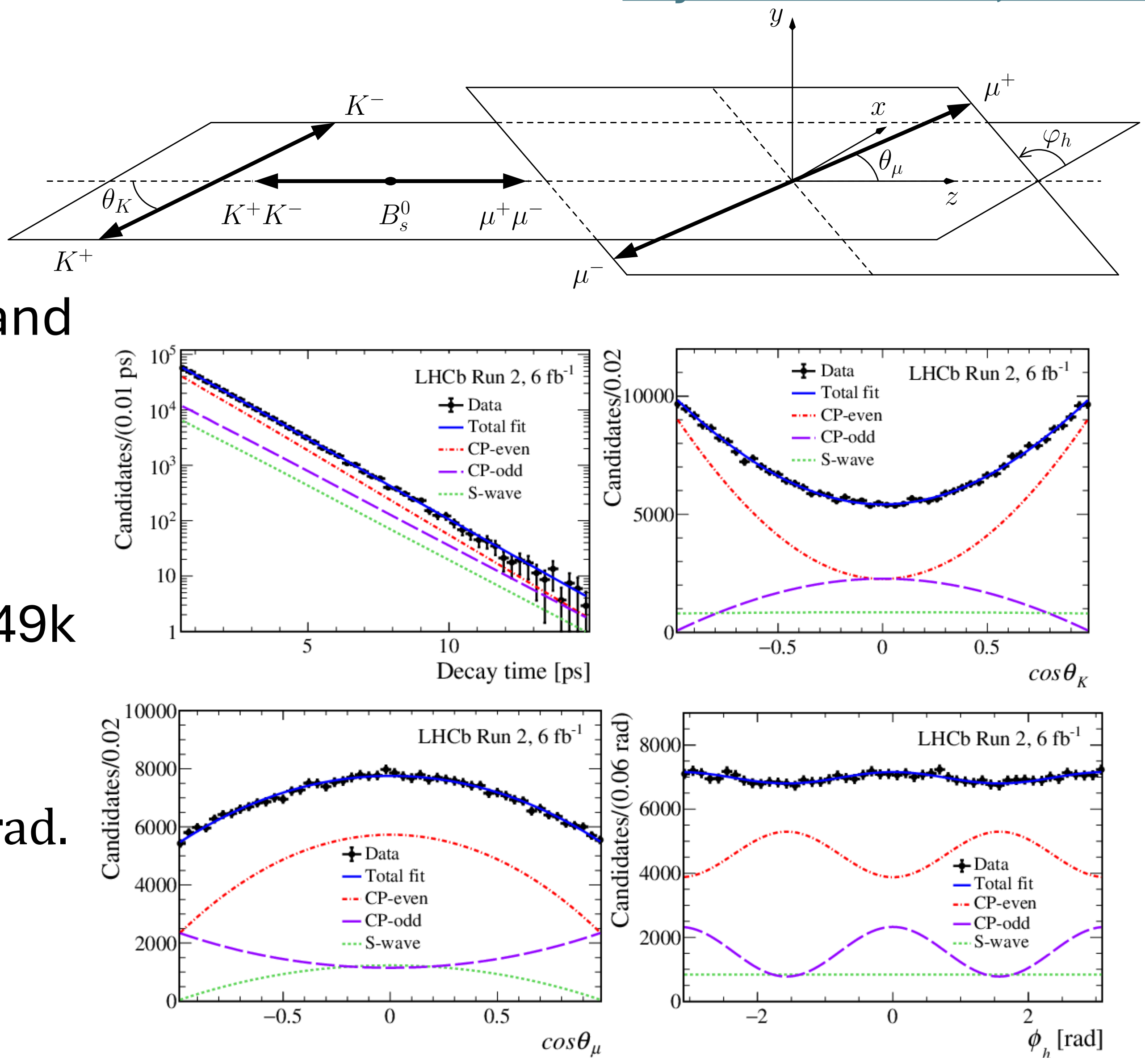
$$-2\beta_s^{SM} = -0.037 \pm 0.001 \text{ rad.}$$





Phys. Rev. Lett. 132, 051802

Measurement of ϕ_s with $B_s^0 \to J/\psi\phi$



- $\phi_s^{c\bar{c}s}$ extracted from 4D fit to decay time and three helicity angle distributions
    - Disentangle CP odd and even components
    - Flavour tagging and decay time acceptance accounted for
- Fit results using rull Run 2 dataset with 349k events:

$$\phi_s = -0.039 \pm 0.022(\text{stat.}) \pm 0.006(\text{syst.})\ \text{rad.}$$

- Most precise measurement of ϕ_s to date and consistent with the SM prediction

Phys. Rev. Lett. 131, 171802

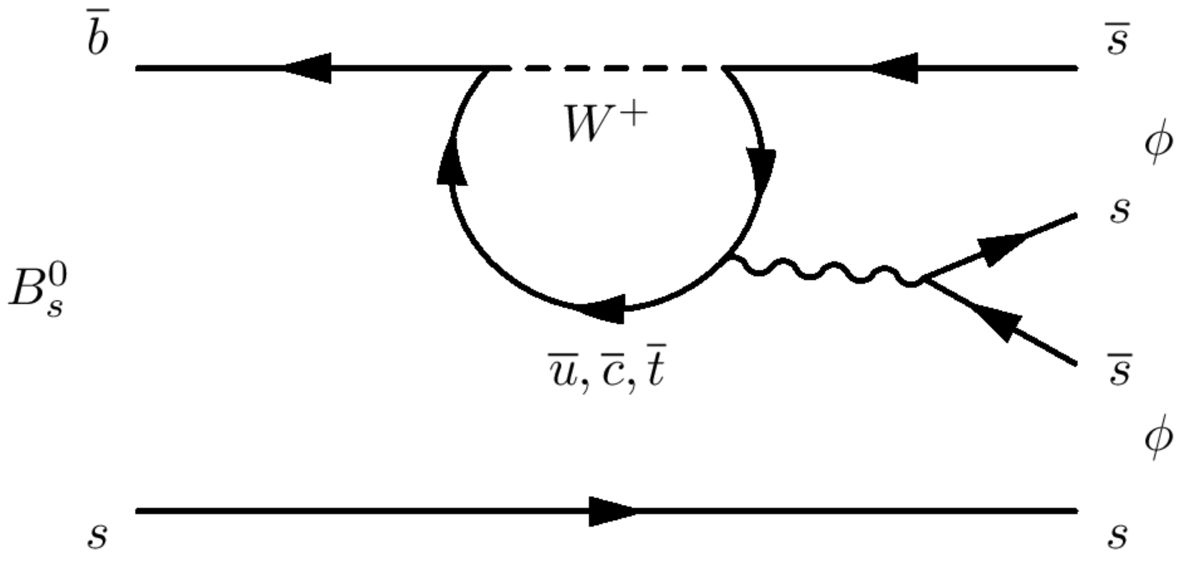
Measurement of $\phi_s^{s\bar{s}s}$ with $B_s^0 \to \phi\phi$

- Another golden mode of LHCb
- Probe of CP violation in penguin-dominated decays
- Experimentally clean
- CP violation in mixing and decay predicted to cancel in the SM

$$\phi_s^{s\bar{s}s} = \phi^M - \phi^D \approx 0$$

Upper limit: 0.02 rad.[1]

- Significant deviation from zero is clear signature of BSM physics



[1] Matthaeus Bartsch, Gerhard Buchalla, & Christina Kraus. (2008). B -> V_L V_L Decays at Next-to-Leading Order in QCD.

Phys. Rev. Lett. 131, 171802

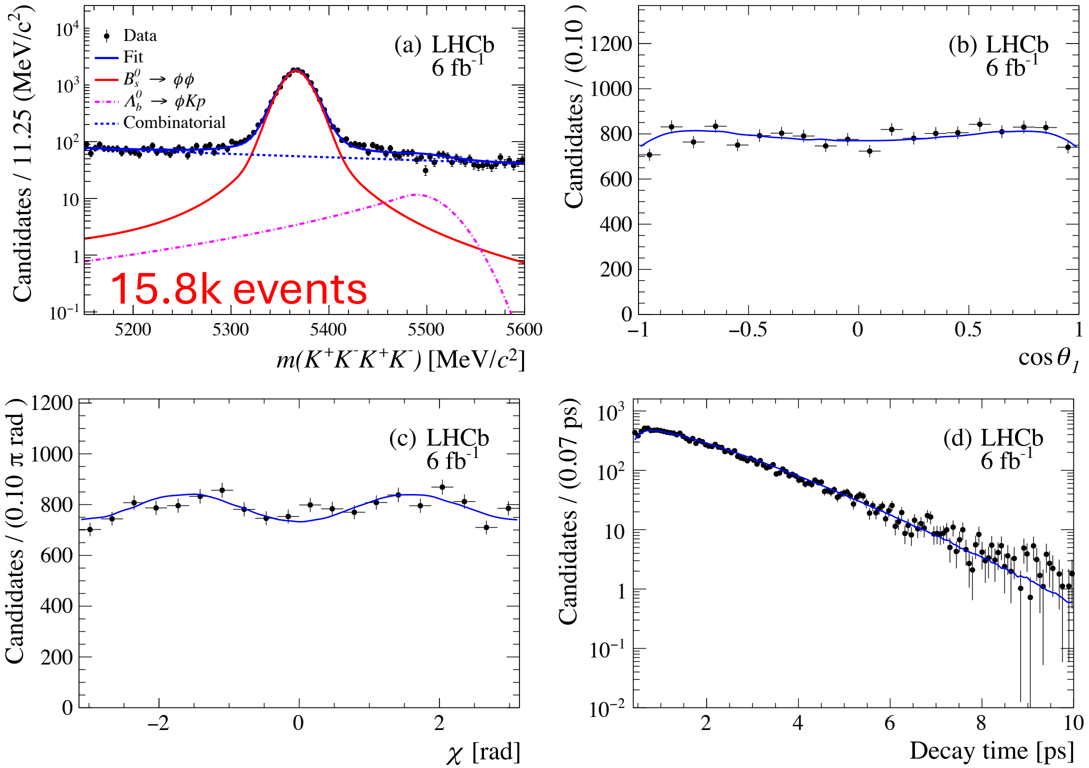
Measurement of $\phi_s^{s\bar{s}s}$ with $B_s^0 \to \phi\phi$

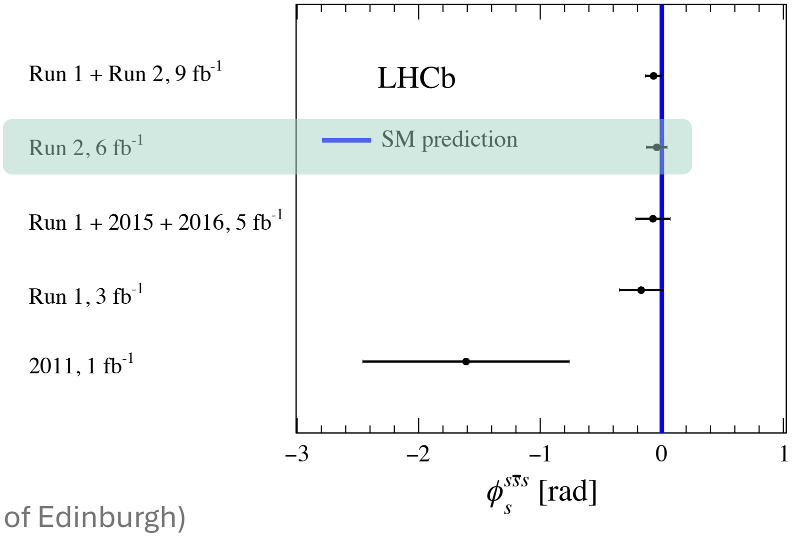
- Value of $\phi_s^{s\bar{s}s}$ extracted from 4D fit to decay time and three helicity angle distributions

- Fit results using full Run 2 dataset with 15.8k events:

$$\phi_s^{s\bar{s}s} = -0.042 \pm 0.075\ (\text{stat.}) \pm 0.009\ (\text{syst.})\ \text{rad}$$

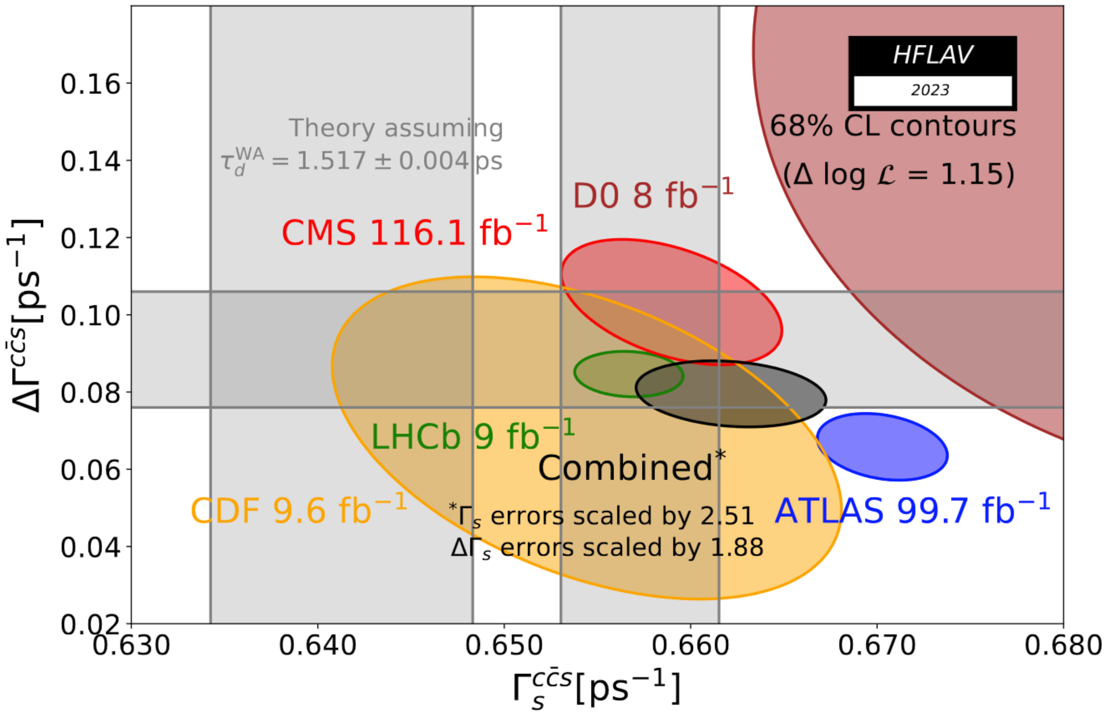
- Most precise measurement of time-dependent CP asymmetry in penguin dominated B decays to date and consistent with the SM prediction





Measurement of $\Delta\Gamma_s$ with $B_s^0 \to J/\psi\eta'$ and $B_s^0 \to J/\psi\pi^+\pi^-$

Tensions exist in measurements of $\Delta\Gamma_s$ using $B_s^0 \to J/\psi\phi$ from LHCb, ATLAS and CMS



Amhis, Y., et. al. (2024). For the 2024 edition of the Review of Particle Physics by the Particle Data Group

Since ϕ_s small, to good approximation

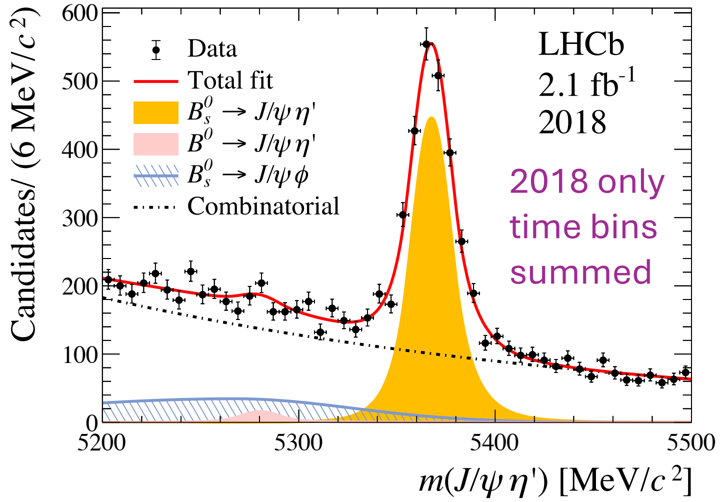
- CP-even measures light lifetime
- CP-odd measures heavy lifetime

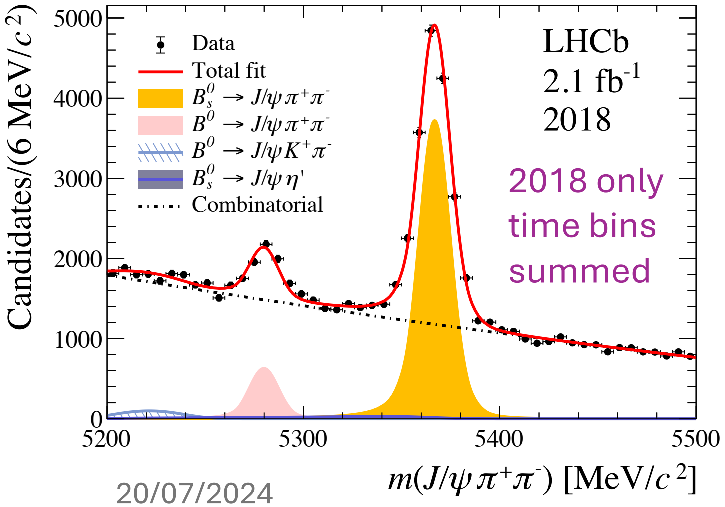
$\Delta\Gamma_s$ is measured from decay-width difference between

- CP-even decay $B_s^0 \to J/\psi\eta'$ and
- $B_s^0 \to J/\psi\pi^+\pi^-$ which is CP-odd via the $f_0(980)$ resonance

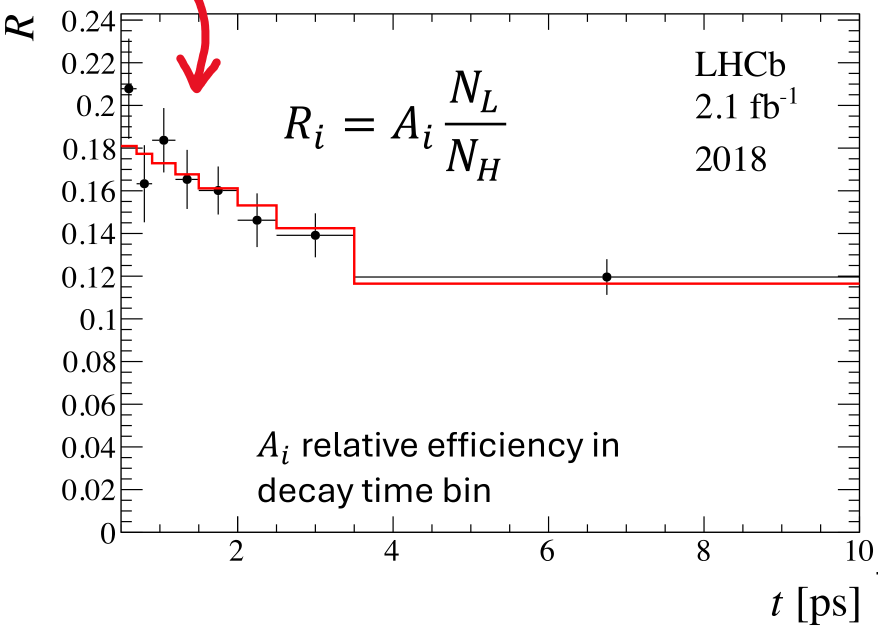
Independent cross-check!

Measurement of $\Delta\Gamma_s$ with $B_s^0 \to J/\psi\eta'$ and $B_s^0 \to J/\psi\pi^+\pi^-$





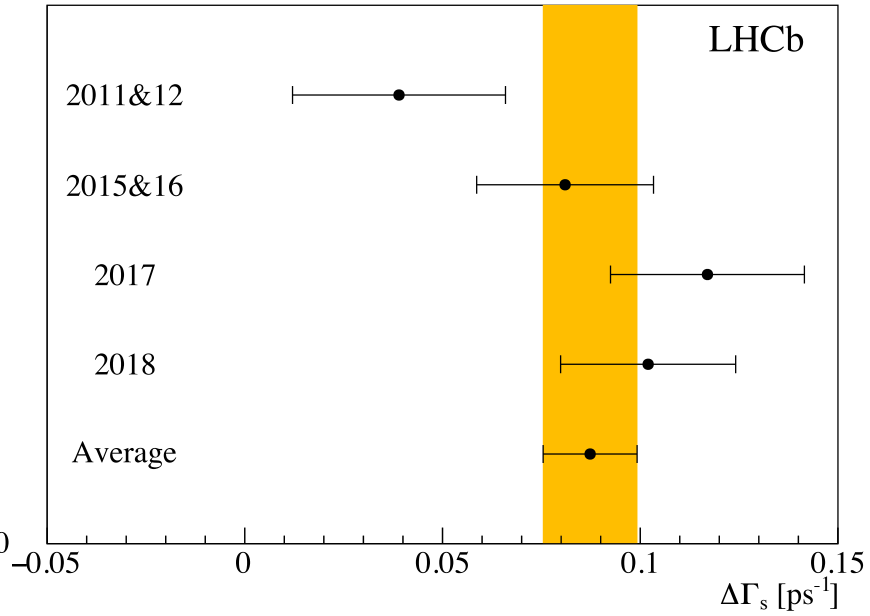
$\Delta\Gamma_s$ extracted from fit!



Weighted average with systematics

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

In agreement with LHCb $B_s^0 \to J/\psi\phi$ result!



Future prospects

- Measurements statistically limited
- Exciting era of **LHCb Upgrade I**
  - Taking data at higher instantaneous luminosity and with fully software trigger

	LHCb Upgrade I
$\sin 2\beta$, with $B^0 \to J/\psi K^0_S$	0.011
ϕ_s, with $B^0_s \to J/\psi\phi$	14 mrad
$\phi_s^{s\bar{s}s}$, with $B^0_s \to \phi\phi$	39 mrad

Table adapted from Aaij, R., & others (2018). Physics case for an LHCb Upgrade II - Opportunities in flavour physics, and beyond, in the HL-LHC era.

LHCb Upgrade II also on the horizon for HL-LHC

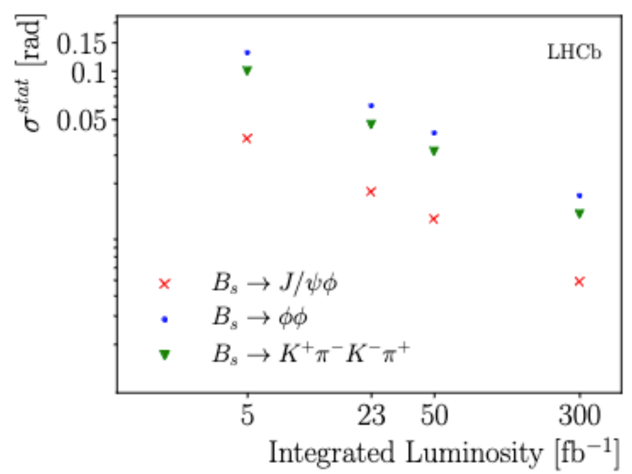


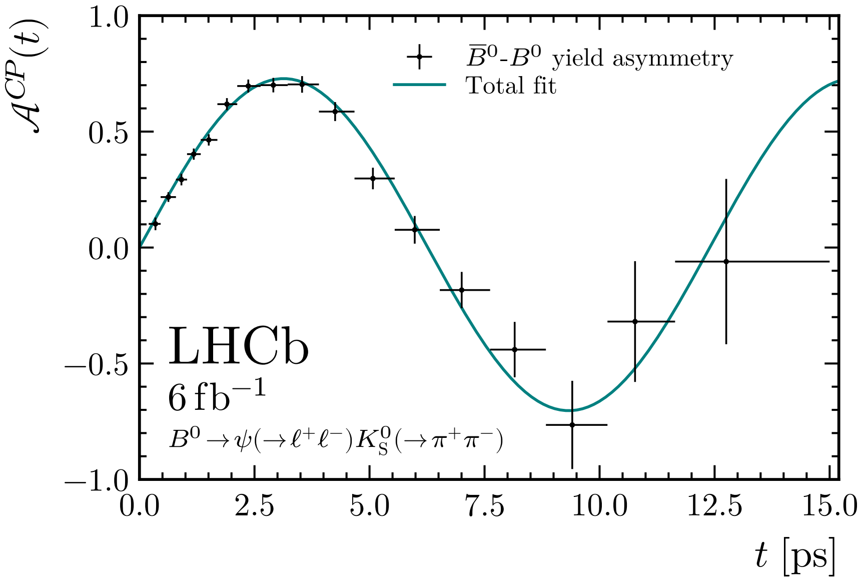
Table 3.1: Statistical sensitivity on $\phi_s^{s\bar{s}s}$ and $\phi_s^{d\bar{d}s}$.

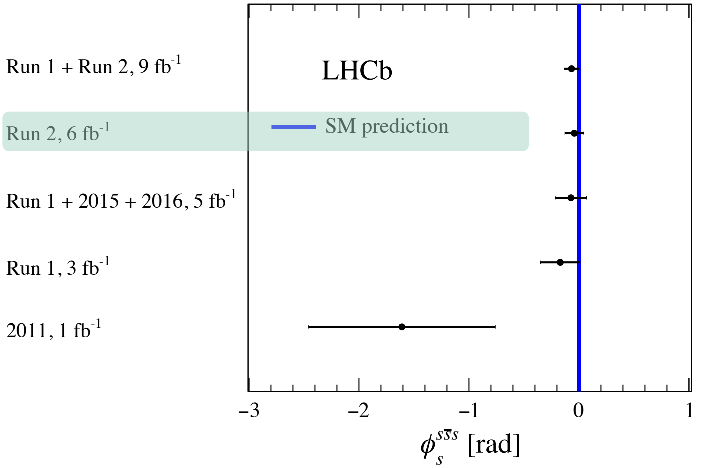
Decay mode	σ(stat.) [rad]			
	3 fb^{-1}	23 fb^{-1}	50 fb^{-1}	300 fb^{-1}
$B^0_s \to \phi\phi$	0.154	0.039	0.026	0.011
$B^0_s \to (K^+\pi^-)(K^-\pi^+)$ (inclusive)	0.129	0.033	0.022	0.009
$B^0_s \to K^*(892)^0\overline{K}^*(892)^0$	–	0.127	0.086	0.035

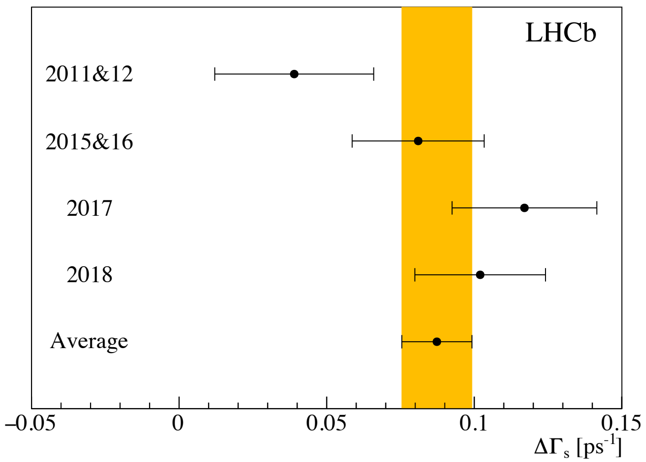
Aaij, R., & others (2018). Physics case for an LHCb Upgrade II - Opportunities in flavour physics, and beyond, in the HL-LHC era.

Summary

- World-leading sensitivity from LHCb measurements of B meson mixing phases
- CKM picture is holding strong for now
- So far, no evidence for new physics
- Exciting times ahead with LHCb Upgrade I underway and Upgrade II to come







Backup slides

Measurement of $\sin(2\beta)$ with $B^0 \to J/\psi K_S^0$

Time dependent decay rate expressed as

$$\mathcal{P}(t,d,n) \propto e^{-\Gamma_d t/\hbar}\{[1+d(1-2\omega^+(\eta))]P_{B^0}(t) + [1+d(1-2\omega^-(\eta))]P_{\bar{B}^0}(t)\}$$

With

$$P_{B^0,\bar{B}^0}(t) \propto (1 \mp \alpha)(1 \mp \Delta\epsilon_{\text{tag}})[1 \mp S\sin(\Delta m_d t) \pm C\cos(\Delta m_d t)]$$

CP asymmetry as function of decay time

$$\mathcal{A}_{\text{int}}^{CP} = -\left(\Sigma_j^N \kappa_j d_j D_j\right)/\left(\Sigma_j^N \kappa_j D_j^2\right)$$

Where $D_j = (1 - \omega_j^+ - \omega_j^-)$ is tagging dilution, d_j is tagging decision and κ_j is the signal event weight

$B_s^0 \to J/\psi\phi$ differential decay rate

$$\frac{\mathrm{d}^4\Gamma(B_s^0 \to J/\psi K^+K^-)}{\mathrm{d}t\ \mathrm{d}\Omega} \propto \sum_{k=1}^{10} h_k(t)\ f_k(\Omega)\,.$$

The time-dependent functions $h_k(t)$ can be written as

$$h_k(t) = N_k e^{-\Gamma_s t}\left[a_k \cosh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + b_k \sinh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t)\right]$$

k	$f_k(\theta_\mu, \theta_K, \varphi_h)$	N_k	a_k	b_k	c_k	d_k
1	$2\cos^2\theta_K \sin^2\theta_\mu$	$\|A_0\|^2$	1	D	C	$-S$
2	$\sin^2\theta_K\left(1-\sin^2\theta_\mu\cos^2\varphi_h\right)$	$\|A_\parallel\|^2$	1	D	C	$-S$
3	$\sin^2\theta_K\left(1-\sin^2\theta_\mu\sin^2\varphi_h\right)$	$\|A_\perp\|^2$	1	$-D$	C	S
4	$\sin^2\theta_K\sin^2\theta_\mu\sin 2\varphi_h$	$\|A_\parallel A_\perp\|$	$C\sin(\delta_\perp-\delta_\parallel)$	$S\cos(\delta_\perp-\delta_\parallel)$	$\sin(\delta_\perp-\delta_\parallel)$	$D\cos(\delta_\perp-\delta_\parallel)$
5	$\frac{1}{2}\sqrt{2}\sin 2\theta_K\sin 2\theta_\mu\cos\varphi_h$	$\|A_0 A_\parallel\|$	$\cos(\delta_\parallel-\delta_0)$	$D\cos(\delta_\parallel-\delta_0)$	$C\cos(\delta_\parallel-\delta_0)$	$-S\cos(\delta_\parallel-\delta_0)$
6	$-\frac{1}{2}\sqrt{2}\sin 2\theta_K\sin 2\theta_\mu\sin\varphi_h$	$\|A_0 A_\perp\|$	$C\sin(\delta_\perp-\delta_0)$	$S\cos(\delta_\perp-\delta_0)$	$\sin(\delta_\perp-\delta_0)$	$D\cos(\delta_\perp-\delta_0)$
7	$\frac{2}{3}\sin^2\theta_\mu$	$\|A_\mathrm{S}\|^2$	1	$-D$	C	S
8	$\frac{1}{3}\sqrt{6}\sin\theta_K\sin 2\theta_\mu\cos\varphi_h$	$\|A_\mathrm{S} A_\parallel\|$	$C\cos(\delta_\parallel-\delta_\mathrm{S})$	$S\sin(\delta_\parallel-\delta_\mathrm{S})$	$\cos(\delta_\parallel-\delta_\mathrm{S})$	$D\sin(\delta_\parallel-\delta_\mathrm{S})$
9	$-\frac{1}{3}\sqrt{6}\sin\theta_K\sin 2\theta_\mu\sin\varphi_h$	$\|A_\mathrm{S} A_\perp\|$	$\sin(\delta_\perp-\delta_\mathrm{S})$	$-D\sin(\delta_\perp-\delta_\mathrm{S})$	$C\sin(\delta_\perp-\delta_\mathrm{S})$	$S\sin(\delta_\perp-\delta_\mathrm{S})$
10	$\frac{4}{3}\sqrt{3}\cos\theta_K\sin^2\theta_\mu$	$\|A_\mathrm{S} A_0\|$	$C\cos(\delta_0-\delta_\mathrm{S})$	$S\sin(\delta_0-\delta_\mathrm{S})$	$\cos(\delta_0-\delta_\mathrm{S})$	$D\sin(\delta_0-\delta_\mathrm{S})$

$$\phi_s \equiv -\arg\lambda$$

$$C \equiv \frac{1-|\lambda|^2}{1+|\lambda|^2}\,, \qquad S \equiv \frac{2\Im(\lambda)}{1+|\lambda|^2}\,, \qquad D \equiv -\frac{2\Re(\lambda)}{1+|\lambda|^2}\,,$$

$B_s^0 \to \phi\phi$ differential decay rate

$$\frac{\mathrm{d}^4\Gamma(t,\vec{\Omega})}{\mathrm{d}t\mathrm{d}\vec{\Omega}} \propto \sum_{k=1}^{6} h_k(t) f_k(\vec{\Omega})$$

$$h_k(t) = N_k e^{-\Gamma_s t}\left[a_k \cosh\left(\frac{\Delta\Gamma_s}{2}t\right) + b_k \sinh\left(\frac{\Delta\Gamma_s}{2}t\right) + Q c_k \cos(\Delta m_\mathrm{s}\, t) + Q d_k \sin(\Delta m_\mathrm{s}\, t)\right]$$

i	N_i	a_i	b_i	c_i	d_i	f_i
1	$\lvert A_0\rvert^2$	$1+\lvert\lambda_0\rvert^2$	$-2\lvert\lambda_0\rvert\cos(\phi)$	$1-\lvert\lambda_0\rvert^2$	$2\lvert\lambda_0\rvert\sin(\phi)$	$4\cos^2\theta_1\cos^2\theta_2$
2	$\lvert A_\parallel\rvert^2$	$1+\lvert\lambda_\parallel\rvert^2$	$-2\lvert\lambda_\parallel\rvert\cos(\phi_{s,\parallel})$	$1-\lvert\lambda_\parallel\rvert^2$	$2\lvert\lambda_\parallel\rvert\sin(\phi_{s,\parallel})$	$\sin^2\theta_1\sin^2\theta_2(1+\cos 2\Phi)$
3	$\lvert A_\perp\rvert^2$	$1+\lvert\lambda_\perp\rvert^2$	$2\lvert\lambda_\perp\rvert\cos(\phi_{s,\perp})$	$1-\lvert\lambda_\perp\rvert^2$	$-2\lvert\lambda_\parallel\rvert\sin(\phi_{s,\perp})$	$\sin^2\theta_1\sin^2\theta_2(1-\cos 2\Phi)$
4	$\frac{\lvert A_\parallel\rvert\lvert A_\perp\rvert}{2}$	$\sin(\delta_\parallel-\delta_\perp)-\lvert\lambda_\parallel\rvert\lvert\lambda_\perp\rvert\cdot$ $\sin(\delta_\parallel-\delta_\perp-\phi_{s,\parallel}+\phi_{s,\perp})$	$-\lvert\lambda_\parallel\rvert\sin(\delta_\parallel-\delta_\perp-\phi_{s,\parallel})$ $+\lvert\lambda_\perp\rvert\sin(\delta_\parallel-\delta_\perp+\phi_{s,\perp})$	$\sin(\delta_\parallel-\delta_\perp)+\lvert\lambda_\parallel\rvert\lvert\lambda_\perp\rvert\cdot$ $\sin(\delta_\parallel-\delta_\perp-\phi_{s,\parallel}+\phi_{s,\perp})$	$\lvert\lambda_\parallel\rvert\cos(\delta_\parallel-\delta_\perp-\phi_{s,\parallel})$ $+\lvert\lambda_\perp\rvert\cos(\delta_\parallel-\delta_\perp+\phi_{s,\perp})$	$-2\sin^2\theta_1\sin^2\theta_2\sin 2\Phi$
5	$\frac{\lvert A_\parallel\rvert\lvert A_0\rvert}{2}$	$\cos(\delta_\parallel-\delta_0)+\lvert\lambda_\parallel\rvert\lvert\lambda_0\rvert\cdot$ $\cos(\delta_\parallel-\delta_0-\phi_{s,\parallel}+\phi)$	$-\lvert\lambda_\parallel\rvert\cos(\delta_\parallel-\delta_0-\phi_{s,\parallel})$ $+\lvert\lambda_0\rvert\cos(\delta_\parallel-\delta_0+\phi)$	$\cos(\delta_\parallel-\delta_0)-\lvert\lambda_\parallel\rvert\lvert\lambda_0\rvert\cdot$ $\sin(\delta_\parallel-\delta_0-\phi_{s,\parallel}+\phi)$	$-\lvert\lambda_\parallel\rvert\sin(\delta_\parallel-\delta_0-\phi_{s,\parallel})$ $+\lvert\lambda_0\rvert\sin(\delta_\parallel-\delta_0+\phi)$	$\sqrt{2}\sin 2\theta_1\sin 2\theta_2\cos\Phi$
6	$\frac{\lvert A_0\rvert\lvert A_\perp\rvert}{2}$	$\sin(\delta_0-\delta_\perp)-\lvert\lambda_0\rvert\lvert\lambda_\perp\rvert\cdot$ $\sin(\delta_0-\delta_\perp-\phi+\phi_{s,\perp})$	$-\lvert\lambda_0\rvert\sin(\delta_0-\delta_\perp-\phi)$ $+\lvert\lambda_\perp\rvert\sin(\delta_0-\delta_\perp+\phi_{s,\perp})$	$\sin(\delta_0-\delta_\perp)+\lvert\lambda_0\rvert\lvert\lambda_\perp\rvert\cdot$ $\sin(\delta_0-\delta_\perp-\phi+\phi_{s,\perp})$	$\lvert\lambda_0\rvert\cos(\delta_0-\delta_\perp-\phi)$ $+\lvert\lambda_\perp\rvert\cos(\delta_0-\delta_\perp+\phi_{s,\perp})$	$-\sqrt{2}\sin 2\theta_1\sin 2\theta_2\sin\Phi$

$\Delta\Gamma_s$ with $B_s^0 \to J/\psi\eta'$ and $B_s^0 \to J/\psi\pi^+\pi^-$

$$R_i \propto \frac{\left[e^{-\Gamma_s t(1+y)}\right]_{t_1}^{t_2}}{\left[e^{-\Gamma_s t(1-y)}\right]_{t_1}^{t_2}} \times \frac{(1-y)}{(1+y)} \;, y = \frac{\Delta\Gamma_s}{2\Gamma_s}$$

$$R_i = A_i \frac{N_L^{RAW}}{N_H^{RAW}}$$