Precision measurement of CP violation in penguin-mediated decay $B_s \rightarrow \phi\phi$

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Shanghai

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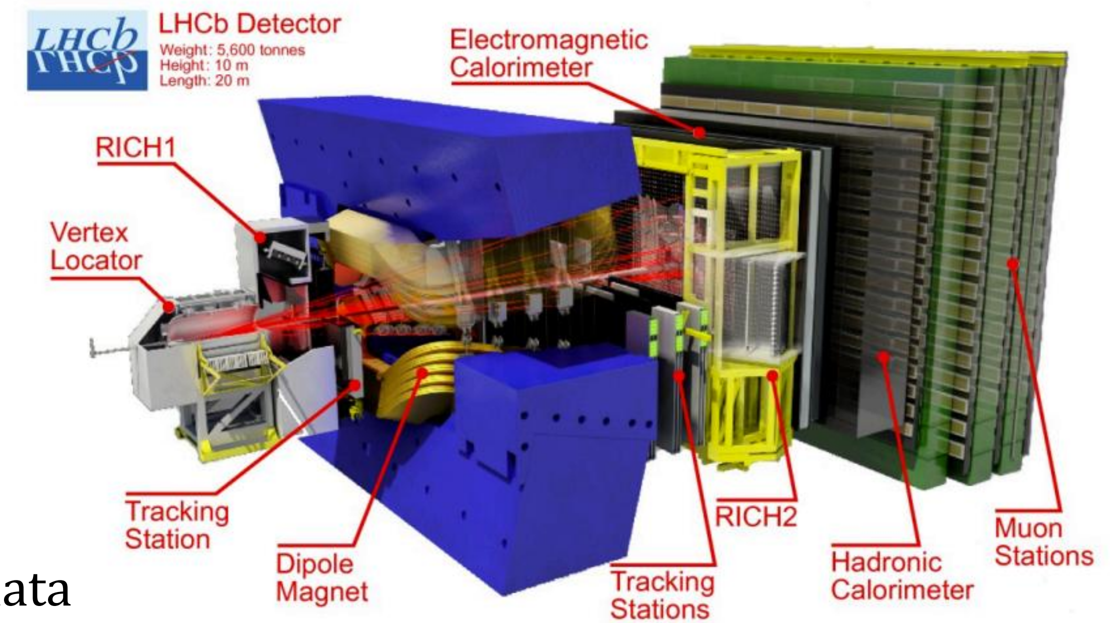
LHCb detector

➢ Single-arm spectrometer with high-precision of tracking, particle identification and decay vertex locater system



➢ Presentation based on RUN II data of LHCb:

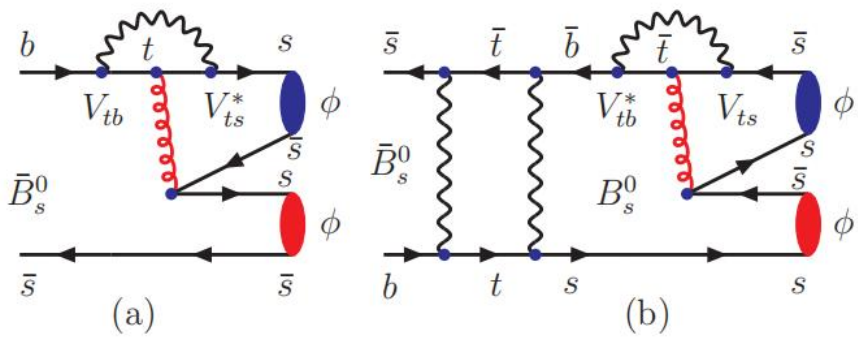
$L = 5.9\ fb^{-1}$ using $p-p$ collisions and center-of-mass energy of 13 TeV (2015-2018)

➢ Papers correlated with the presentation

CPV measurement in $B_s \to \phi\phi$[*PRL.* 131.171802]   CPV measurement in $B_s \to J/\psi\phi$ [arxiv.2308.01468]

Motivation

- $B_s^0 \to \phi\phi$ is a golden channel to study CP violation in $b \to s$ decays
  - ➢ Tiny CP violation expected in the SM
  - ➢ Sensitive to NP in B_s^0 mixing and $b \to s$ decay



- For each CP eigenstate f_i, determine CPV phase ϕ_i and direct CPV parameter $|\lambda_i|$ in the time-dependent CP asymmetry

$$A_{CP,i}(t) \equiv \frac{\Gamma_{(\bar{B} \to f_i)}(t) - \Gamma_{(B \to f_i)}(t)}{\Gamma_{(\bar{B} \to f_i)}(t) + \Gamma_{(B \to f_i)}(t)} = \frac{-C_i \cos \Delta m t + S_i \sin \Delta m t}{\cosh \frac{\Delta\Gamma t}{2} - D_i \sinh \frac{\Delta\Gamma t}{2}}$$

$$\lambda_f \equiv \eta_i \frac{q}{p} \frac{\bar{A}_{\bar{f}_i}}{A_{f_i}} = |\lambda_i| e^{-i\phi_i}$$

$$C_i = \frac{1-|\lambda_i|^2}{1+|\lambda_i|^2}, \; S_i = \frac{2\Im\lambda_i}{1+|\lambda_i|^2}, \; D_i = \frac{2\Re\lambda_i}{1+|\lambda_i|^2}$$

Phenomenon

- An angular analysis is needed to disentangle three polarization states of $B \to VV$ decays:
  - Longitudinal (0, CP even), parallel (∥, CP even) and perpendicular (⊥, CP odd)

Time dependent angular distribution

$$\frac{d^4\Gamma(t,\vec{\Omega})}{dt d\vec{\Omega}} \propto \sum_{i=1}^{15} K_i(t) f_i(\vec{\Omega})$$

i	K_i	f_i
1	$\lvert A_0(t)\rvert^2$	$4\cos^2\theta_1\cos^2\theta_2$
2	$\lvert A_\parallel(t)\rvert^2$	$\sin^2\theta_1\sin^2\theta_2(1+\cos 2\Phi)$
3	$\lvert A_\perp(t)\rvert^2$	$\sin^2\theta_1\sin^2\theta_2(1-\cos 2\Phi)$
4	$Im(A_\parallel^*(t)A_\perp(t))$	$-2\sin^2\theta_1\sin^2\theta_2\sin 2\Phi$
5	$Re(A_\parallel^*(t)A_0(t))$	$\sqrt{2}\sin 2\theta_1\sin 2\theta_2\cos\Phi$
6	$Im(A_0^*(t)A_\perp(t))$	$-\sqrt{2}\sin 2\theta_1\sin 2\theta_2\sin\Phi$
7	$\lvert A_{SS}(t)\rvert^2$	$\frac{4}{9}$
8	$\lvert A_S(t)\rvert^2$	$\frac{4}{3}(\cos\theta_1+\cos\theta_2)^2$
9	$Re(A_S^*(t)A_{SS}(t))$	$\frac{8}{3\sqrt{3}}(\cos\theta_1+\cos\theta_2)$
10	$Re(A_0(t)A_{SS}^*(t))$	$\frac{8}{3}\cos\theta_1\cos\theta_2$
11	$Re(A_\parallel(t)A_{SS}^*(t))$	$\frac{4\sqrt{2}}{3}\sin\theta_1\sin\theta_2\cos\Phi$
12	$Im(A_\perp(t)A_{SS}^*(t))$	$-\frac{4\sqrt{2}}{3}\sin\theta_1\sin\theta_2\sin\Phi$
13	$Re(A_0(t)A_S^*(t))$	$\frac{8}{\sqrt{3}}\cos\theta_1\cos\theta_2(\cos\theta_1+\cos\theta_2)$
14	$Re(A_\parallel(t)A_S^*(t))$	$\frac{4\sqrt{2}}{\sqrt{3}}\sin\theta_1\sin\theta_2(\cos\theta_1+\cos\theta_2)\cos\Phi$
15	$Im(A_\perp(t)A_S^*(t))$	$-\frac{4\sqrt{2}}{\sqrt{3}}\sin\theta_1\sin\theta_2(\cos\theta_1+\cos\theta_2)\sin\Phi$

P-wave (ϕϕ)

CP-even S-wave (f0f0)

CP-odd S-wave (ϕf0)

f0f0– ϕf0 interference

ϕϕ-f0f0 interference

ϕϕ-ϕf0 interference

Experimental dilution

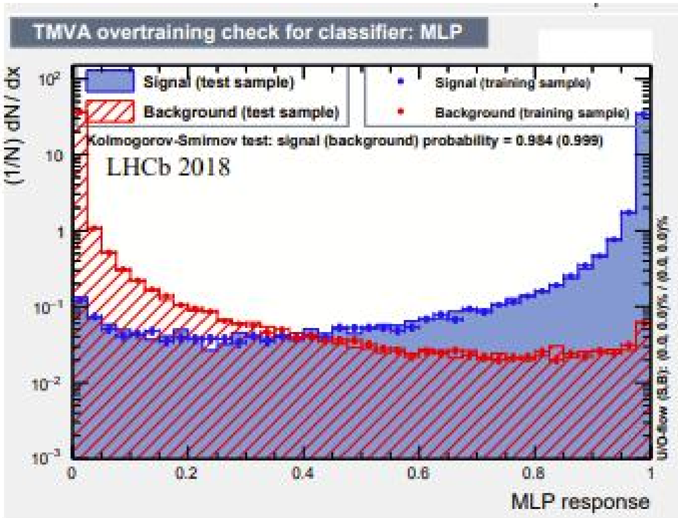
Considering experimental effect

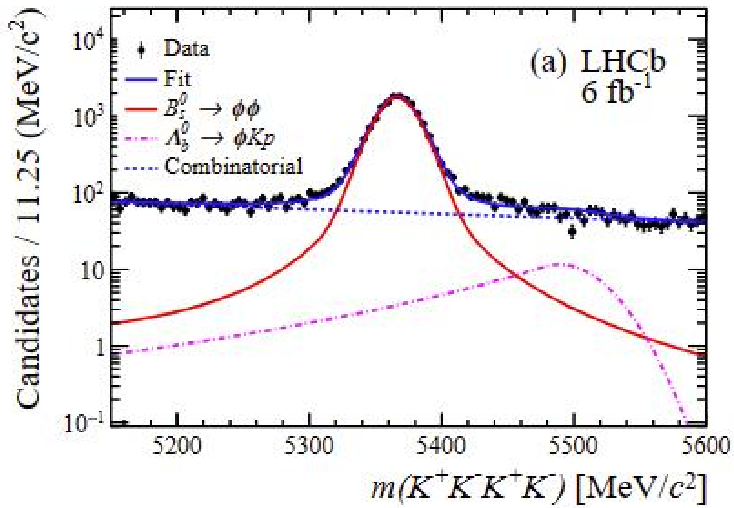
$$\mathcal{PDF}(\mathrm{t}) \propto \epsilon(t) \cdot \epsilon(\Omega) \cdot \mathrm{e}^{-\frac{1}{2}\Delta m_s^2 \sigma_t^2} \cdot (1-2\omega) \cdot \Gamma(t,\Omega)$$

parameters	definition
ε(t)	decay time efficiency
ε(Ω)	angular efficiency
w	mistag rate
σ_t	time resolution (42 fs in average)

- Key steps to extract Φ_s
  - Background substraction using MVA and splot
  - Modelling of angular acceptance and decay time acceptance
  - Flavour tagging and time resolution calibration

Seletion and mass fit





~15800 yields

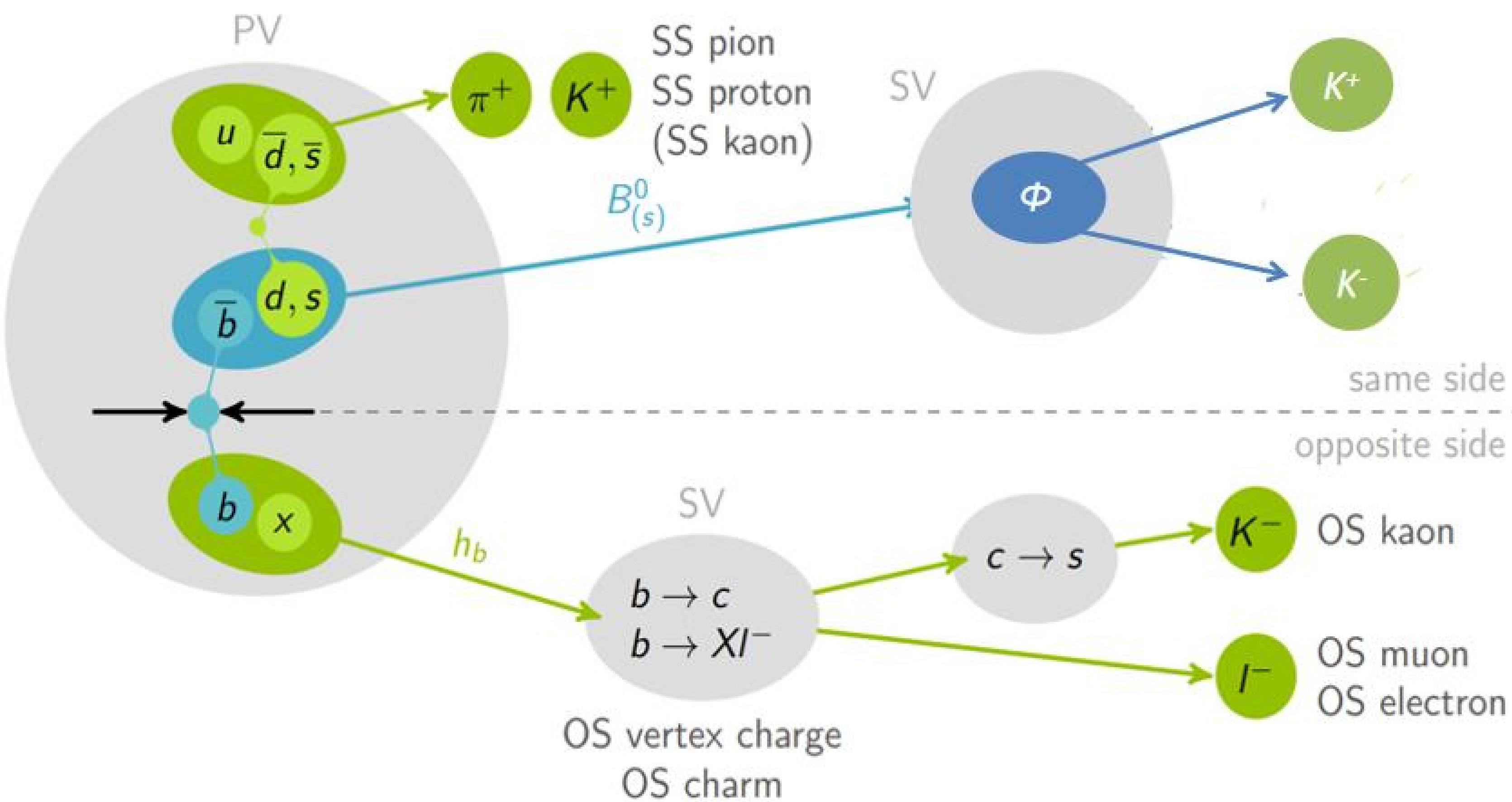
1.MLP network is trained using MC simulation and data sidebands.

2.Splot technique is used to further substrct the backgrounds

3.The Angular accpetance is parameterized and corrected using MC.

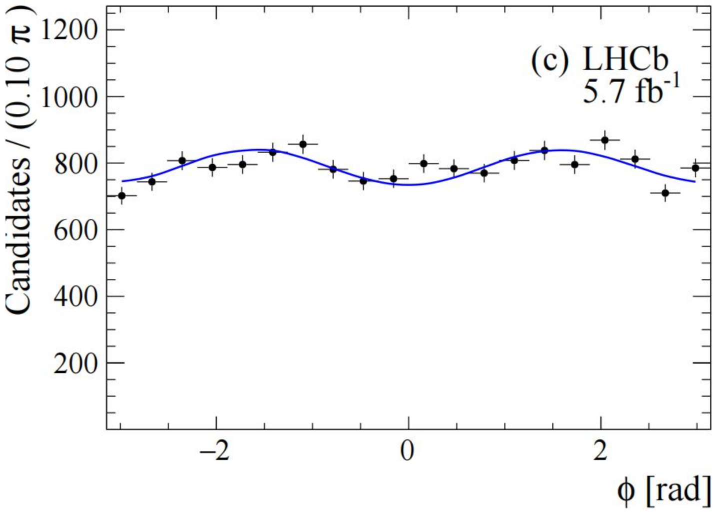
4.Leave time acceptance free in the fit.

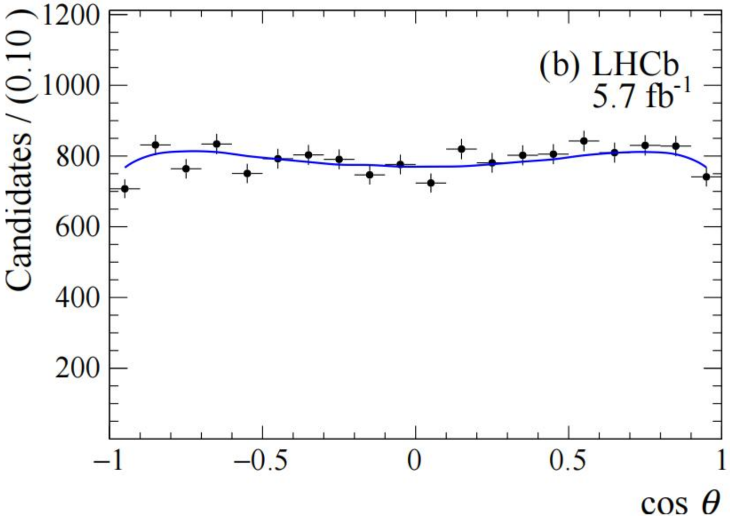
LHCb flavour tagging

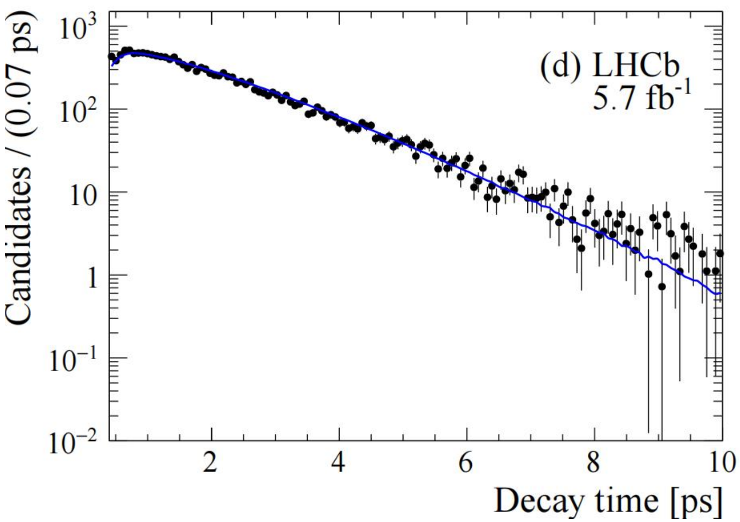


SS+OS ~ 6% effective tagging efficiency

Time dependent angular fit







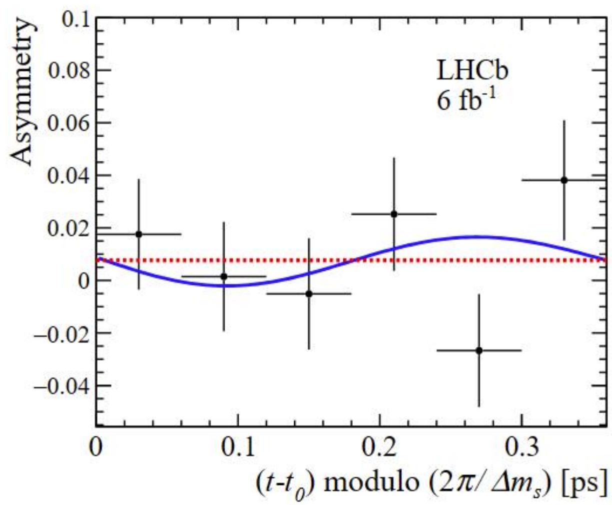
Results

Fit result and considered systematics

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]	$2.769 \pm 0.105 \pm 0.011$

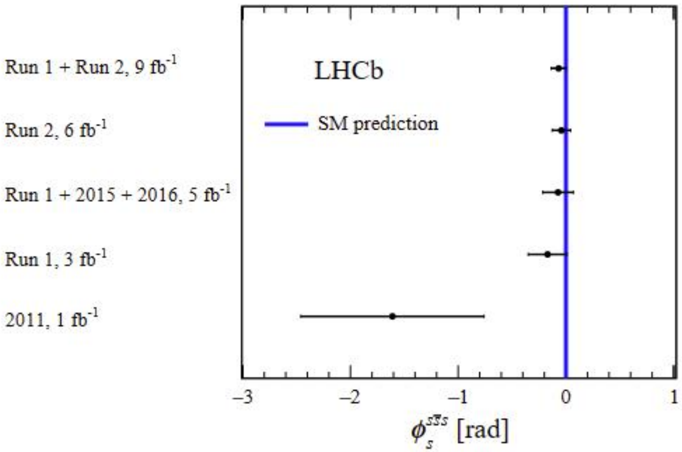
Source	$\phi_s^{s\bar{s}s}$	$\|\lambda\|$
Time resolution	4.9	2.6
Flavor tagging	4.8	4.7
Angular acceptance	3.9	4.9
Time acceptance	2.3	1.7
Mass fit & factorization	2.2	4.4
MC truth match	1.1	0.2
Fit bias	0.8	0.7
Candidate multiplicity	0.3	0.2
Total	8.8	8.6

Observed time dependent CP violation



Results

Combine Run2 results with Run1



✤The most precise measurement in and in any penguin-dominated B_s^0 decays

✤Agrees with SM expectation

- Use different ϕ_i and λ_i for different polarization states i $=$ 0, $\perp$, $\parallel$

$$\begin{aligned} \phi_{s,0} &= -0.18 \pm 0.09 \text{ rad} , & |\lambda_0| &= 1.02 \pm 0.17 , \\ \phi_{s,\parallel} - \phi_{s,0} &= 0.12 \pm 0.09 \text{ rad} , & |\lambda_\perp/\lambda_0| &= 0.97 \pm 0.22 , \\ \phi_{s,\perp} - \phi_{s,0} &= 0.17 \pm 0.09 \text{ rad} , & |\lambda_\parallel/\lambda_0| &= 0.78 \pm 0.21 . \end{aligned}$$

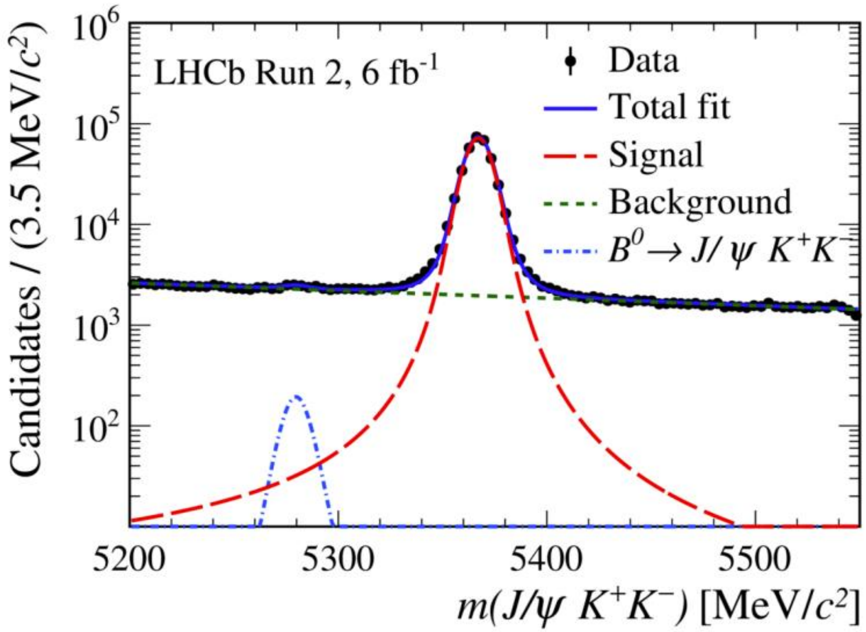
No significant difference between different polarization is seen.

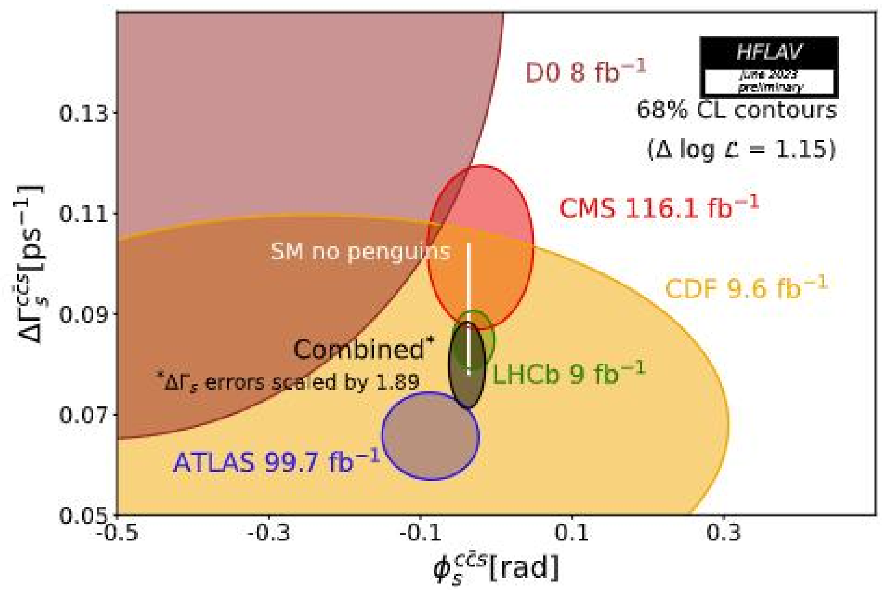
Measurements of $\sin 2\beta$ and ϕ_s with the full LHCb Run 1 & 2 data sample

Vukan Jevtic (TU Dortmund), Peilian Li (CERN)
On behalf of the LHCb collaboration

June 12, 2023
CERN Seminar

Results

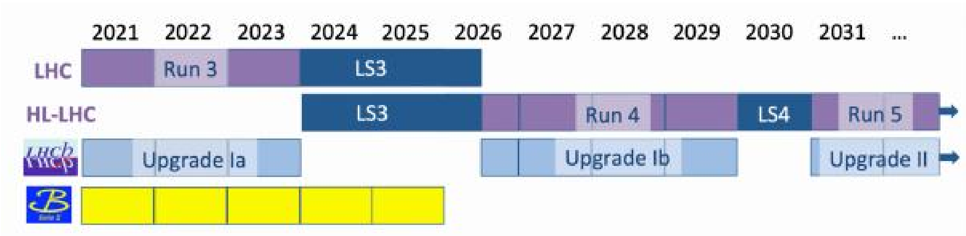


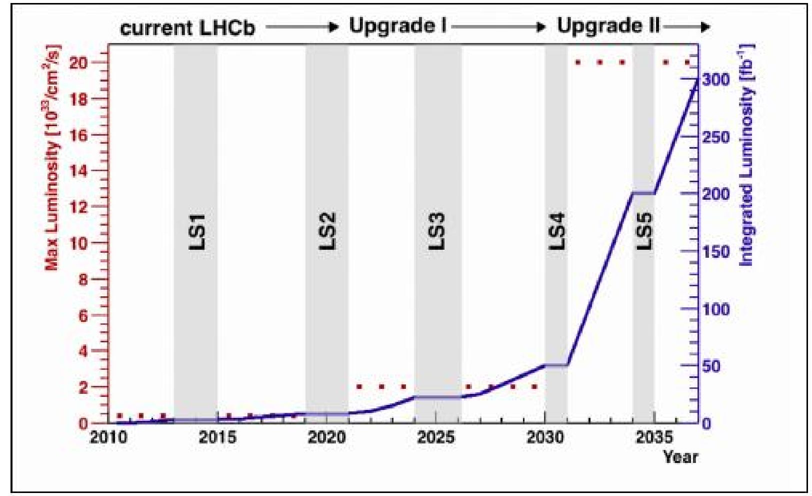


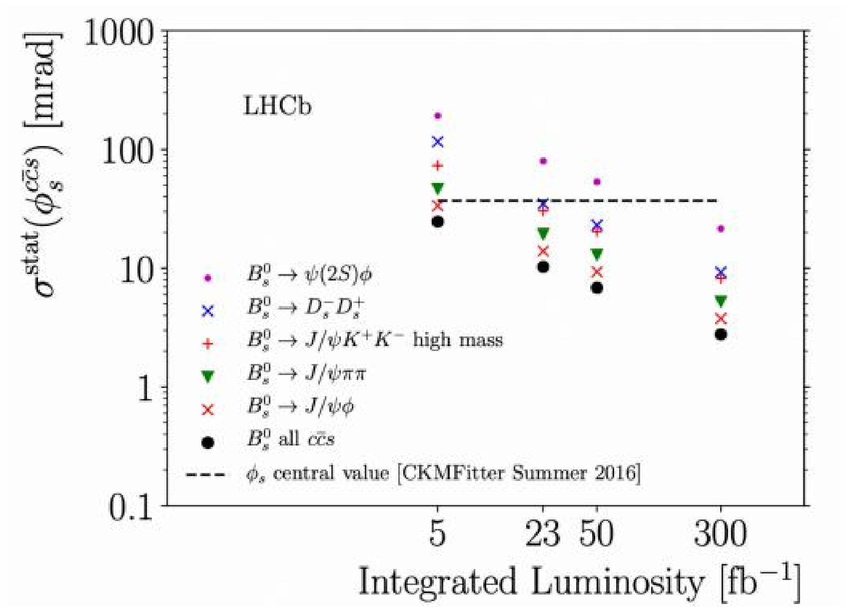
- Similar to analysis procedure of $B_s^0 \to \phi\phi$
- A yield of about 349 000 signal decays
- Extended maximum likelihood fit to extract B signal yields.

This is the most precise measurement to date and is consistent with SM predictions

Future Prospects







	Upgrade I	Upgrade II
$\sigma(\phi_s(J\psi KK))_{stat}$	14 mrad	4 mrad
$\sigma(\phi_s(\phi\phi))_{stat}$	39 mrad	11 mrad

Conclusion

- Flag-ship time-dependent measurements of CP violation in $B_s^0 \to \phi\phi$ with the full LHCb Run1+Run2 data sample, giving the most precise measurement:

$$\phi_s^{s\bar{s}s} = -0.074 \pm 0.069 \text{ rad}$$

$$\phi_s^{c\bar{c}s} = -0.044 \pm 0.020 \text{ rad}$$

- LHCb dominates the world average in Φ_s measurements

- Still statistic limited, Upgrade I and II needed to test the SM and search for NP indirectly

Thank you for listening!