Updated ϕ_s measurements @ LHCb

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The 5th China LHC Physics Workshop

Outline

- CPV phase ϕ_s in neutral B_s^0 system

- ϕ_s measurements @ LHCb
  - ✓ $B_s^0 \to J/\psi\phi$ and $B_s^0 \to J/\psi\pi^+\pi^-$
  - ✓ $B_s^0 \to \phi\phi$ and $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$

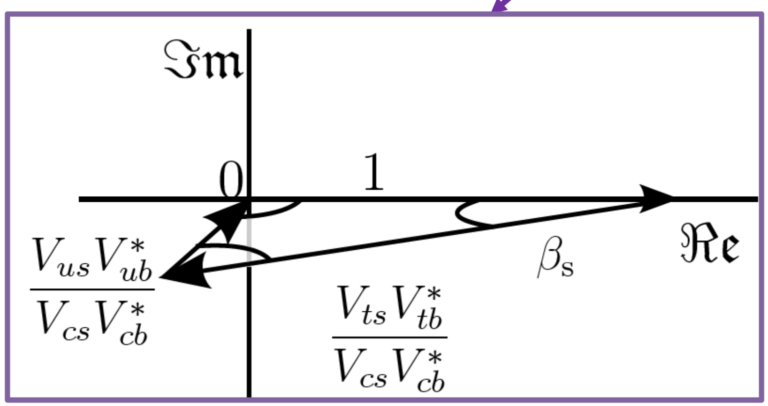
- Summary

CKM matrix in SM

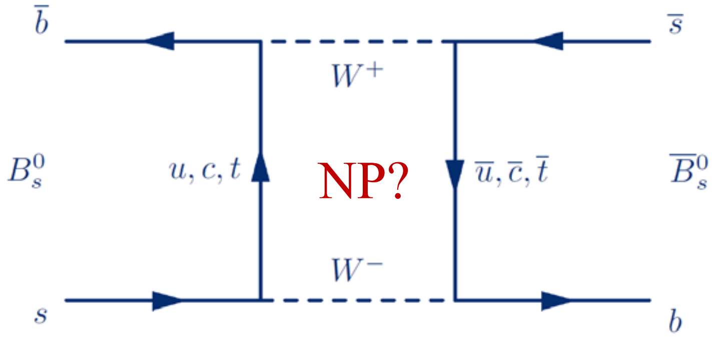
- CKM matrix governs the quark mixing and gives information on the strength of the flavour-changing weak interaction

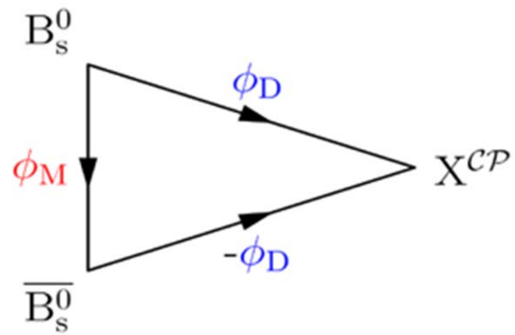
$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & \lambda^3 e^{-i\gamma} \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ \lambda^3 e^{-i\beta} & -\lambda^2 e^{-i\beta_s} & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Wolfenstein parametrization $\lambda \approx 0.22$



- CP violation of interference between mixing and decay





Weak phase $\phi_s = \phi_M - 2\phi_D$

Δm_s and $\Delta\Gamma_s$ can also be measured

- Why is this interesting ?
  - ✓ Excellent test for SM prediction on ϕ_s

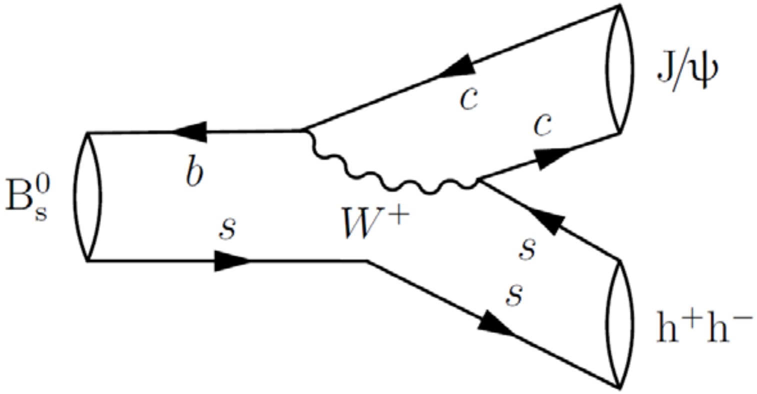
$$\phi_s^{SM} = -2arg\left(\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) = -2\beta_s = -0.0370 \pm 0.0006 \text{ rad}$$

[CKM Fitter]

  - ✓ Sensitive probe of NP in $B_s^0 - \bar{B}_s^0$ mixing

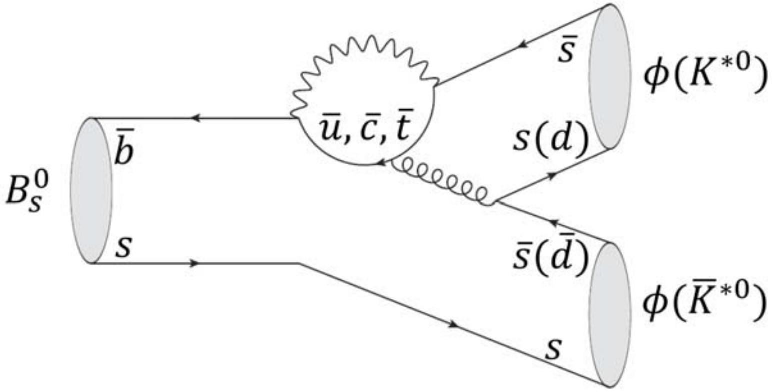
Decays used for measurement

- $B_s^0 \rightarrow J/\psi K^+K^-$ and $B_s^0 \rightarrow J/\psi \pi^+\pi^-$



✓ Relatively high branch ratio $\mathcal{O}(10^{-3})$ and $\mathcal{O}(10^{-4})$
✓ Small penguin pollution
✓ Clean signal peak

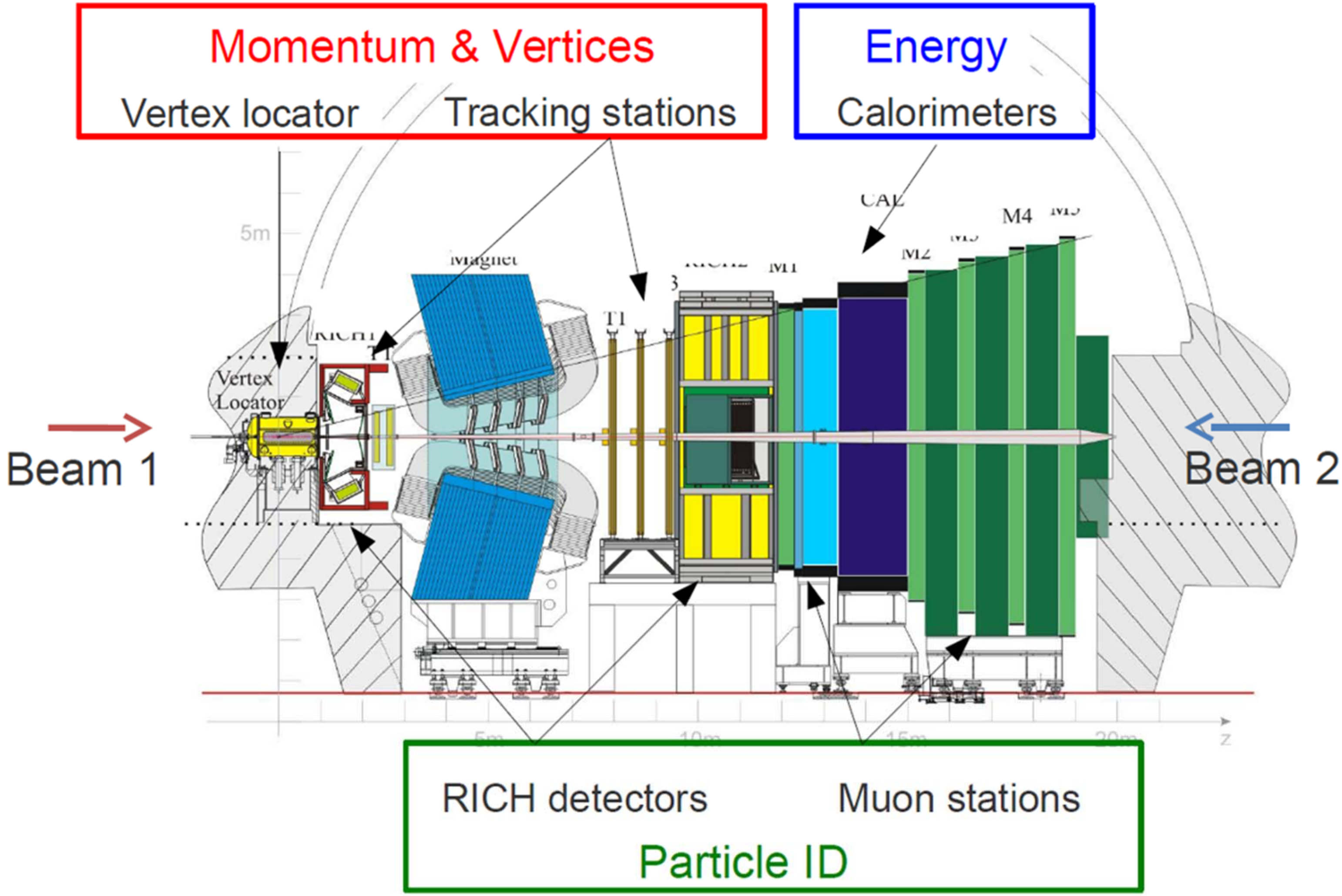
- $B_s^0 \rightarrow \phi\phi$ and $B_s^0 \rightarrow (K^+\pi^-)(K^-\pi^+)$



✓ Penguin dominated decay
✓ Sensitivity to NP in decay

LHCb detector

- Designed for beauty and charm physics, $2.0 < \eta < 5.0$



What measured experimentally ?

- Theoretical time-dependent CPV

$$A_{CP}(t) = \frac{\Gamma_{\bar{B}_s^0 \to f}(t) - \Gamma_{B_s^0 \to f}(t)}{\Gamma_{\bar{B}_s^0 \to f}(t) + \Gamma_{B_s^0 \to f}(t)} = \eta \sin(\phi_s) \sin(\Delta m_s t)$$

- Experimental challenge

ω , mistag ratio ⇒ good flavor tagging

σ_t, time resolution ⇒ good resolution

$$(1-2\omega) e^{-\frac{1}{2}\Delta m_s^2 \sigma_t^2} \eta \sin(\phi_s) \sin(\Delta m_s t)$$

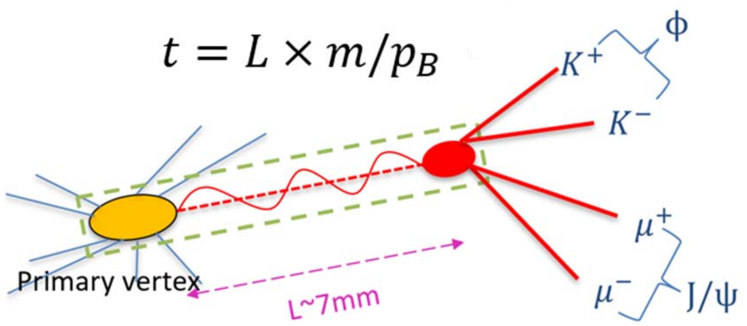
η, CP eigenvalue ⇒ angular analysis disentangles mixture of different final states

Reliable modeling of time & angular acceptance

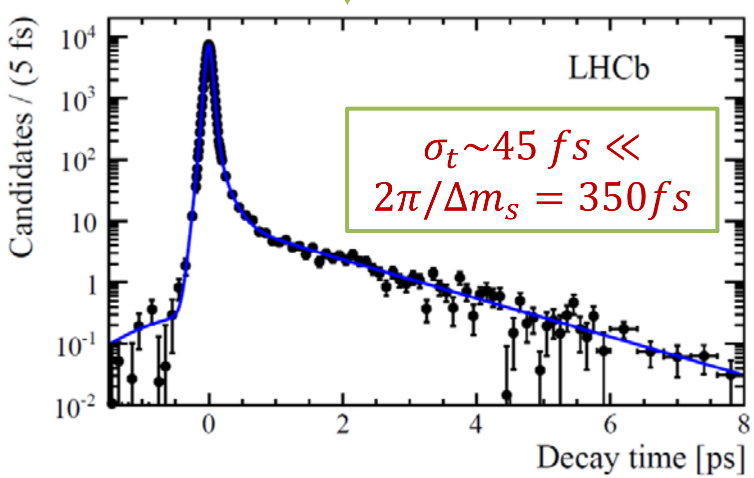
Time resolution and flavor tagging

Time resolution

$t = L \times m/p_B$

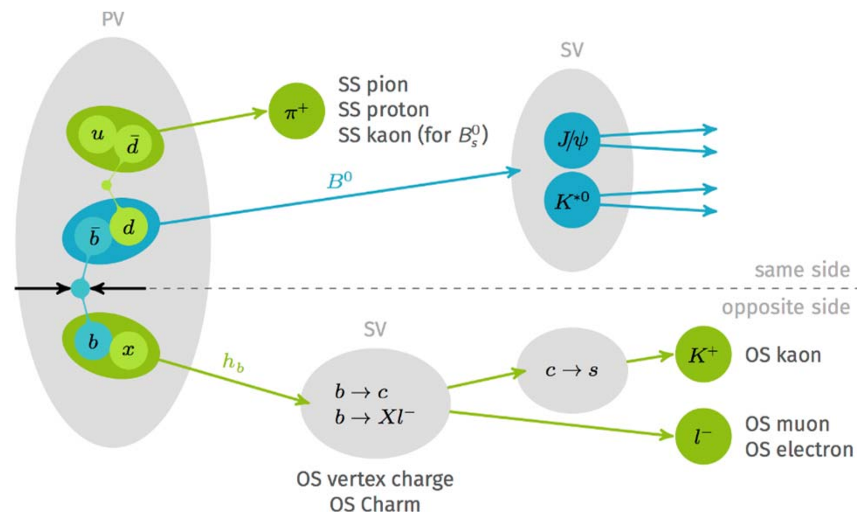


Calibrated with prompt sample



$\sigma_t \sim 45\ fs \ll 2\pi/\Delta m_s = 350 fs$

Flavor tagging



imperfect taggers

↓

tagging efficiency ε, mistag ratio ω

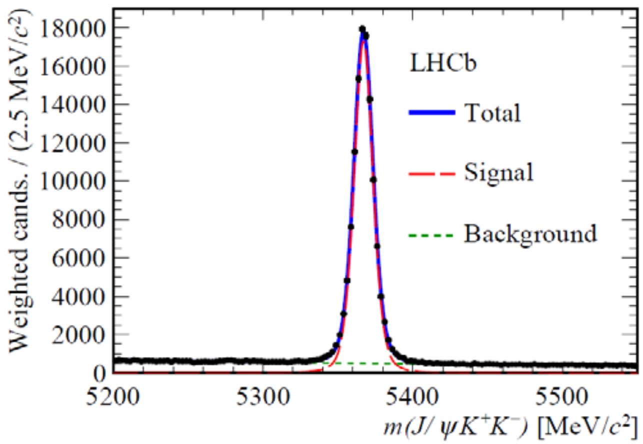
↓

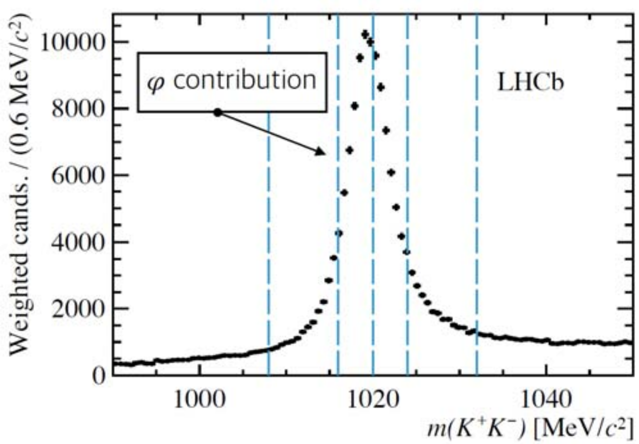
tagging power $\varepsilon(1-2\omega)^2$
effective tagged fraction

Signal yields in $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi\pi^+\pi^-$

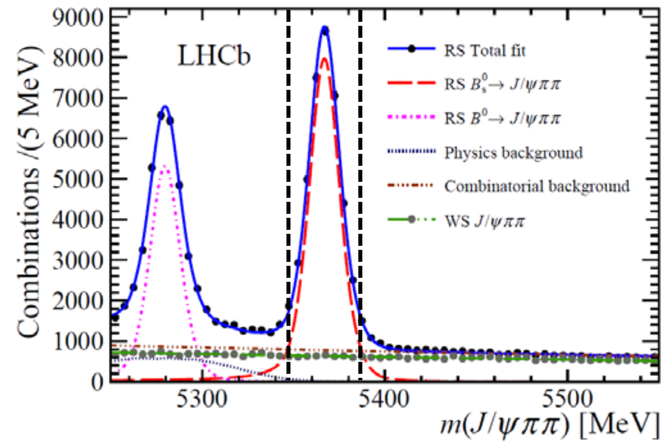
- Yields in 1.9 fb^{-1}(15+16) data

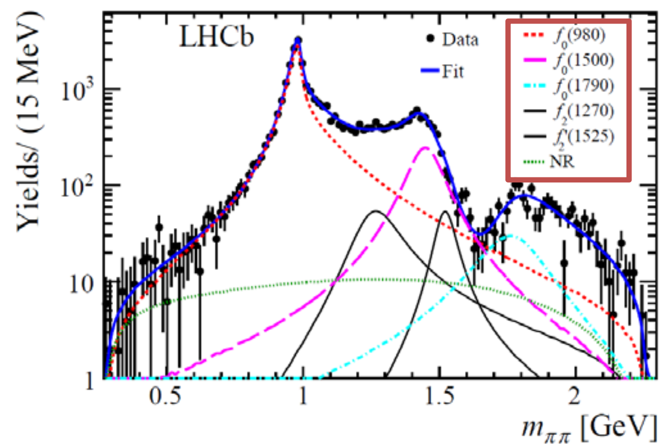
N_{sig}~117K
ϵD^2~$4.7 \pm 0.3\%$, σ_t~$45.5\ fs$





N_{sig}~34K, $\pm$20 MeV of B_s^0
ϵD^2~$5.1 \pm 0.4\%$,σ_t~$42\ fs$

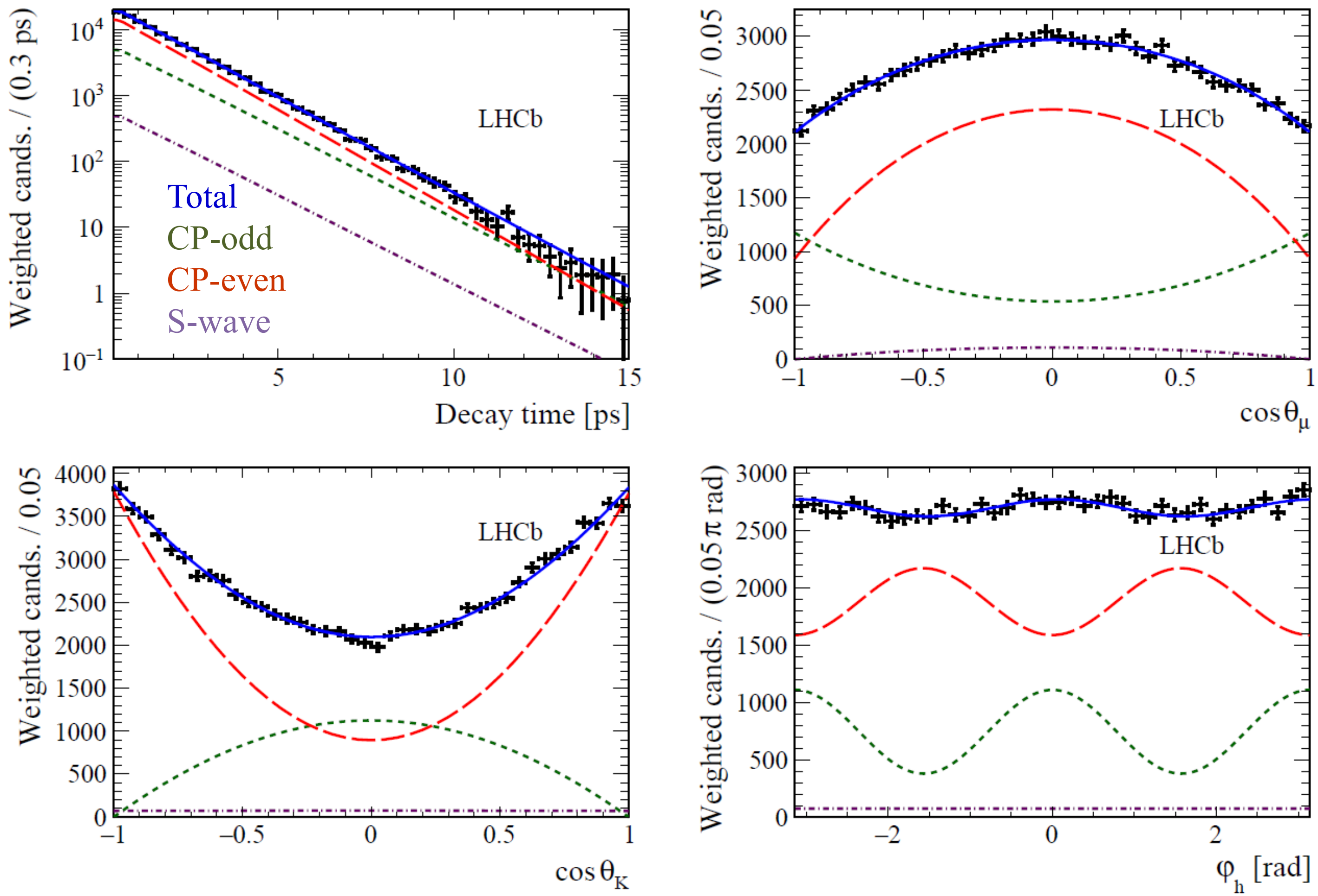




Fit results in $B_s^0 \to J/\psi K^+K^-$ EPJC 79 (2019) 706

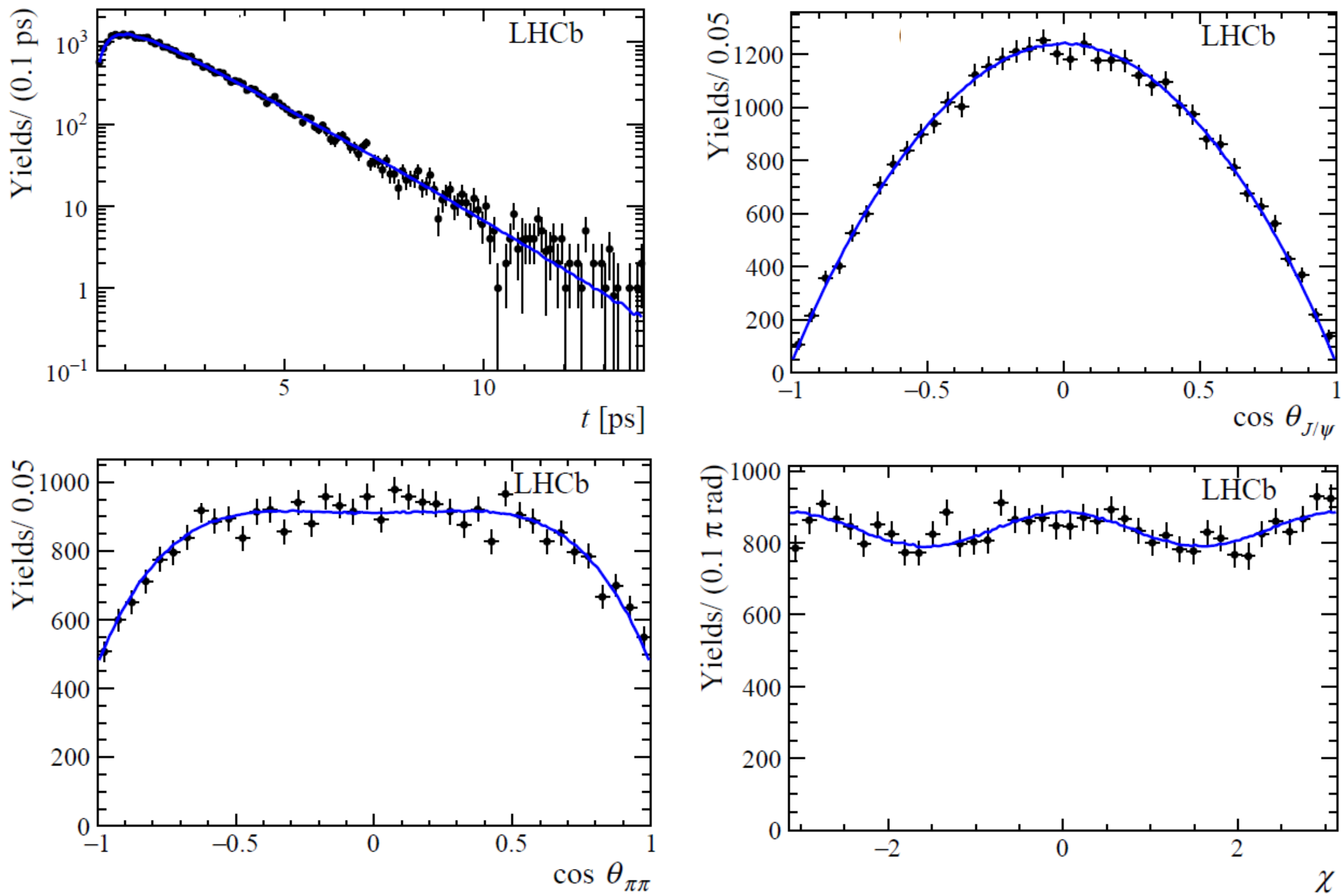
➢ Simultaneous fit to decay time and three helicity angles

$$\text{Run 2}: \phi_s = -0.080 \pm 0.041 \pm 0.006 \text{ rad}$$
$$\text{Run 1}: \phi_s = -0.058 \pm 0.049 \pm 0.006 \text{ rad}$$



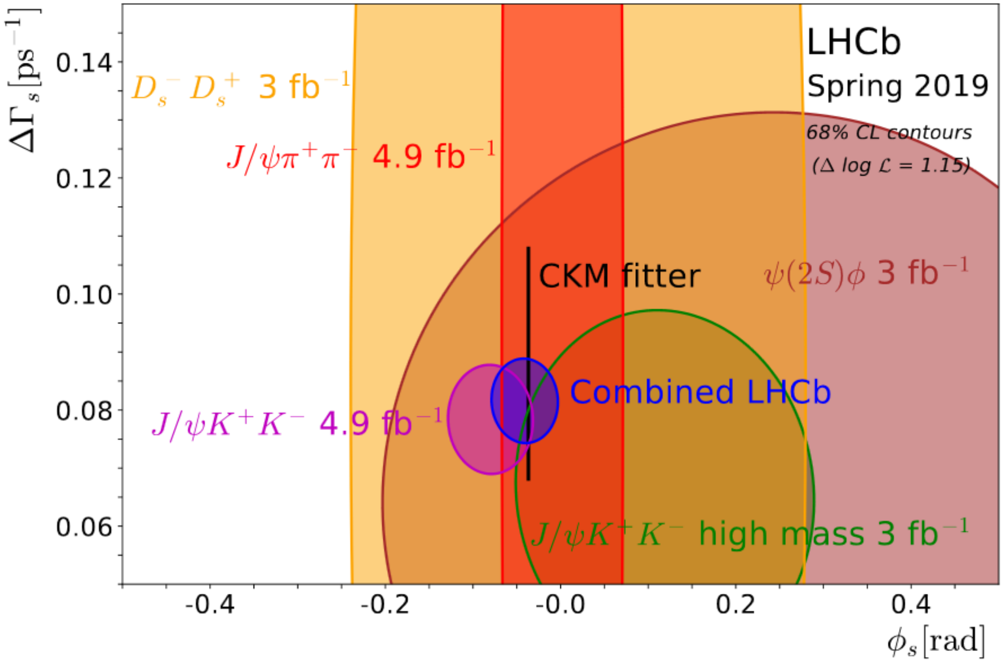
- Simultaneous fit to decay time and three helicity angles

$$\text{Run 2}: \phi_s = -0.057 \pm 0.060 \pm 0.011 \text{ rad}$$
$$\text{Run 1}: \phi_s = -0.075 \pm 0.065 \pm 0.014 \text{ rad}$$



Results

Combined Run1+2	$J/\psi\phi$	$J/\psi\pi^+\pi^-$	LHCb
ϕ_s(rad)	-0.078 ± 0.032	0.002 ± 0.046	-0.041 ± 0.025



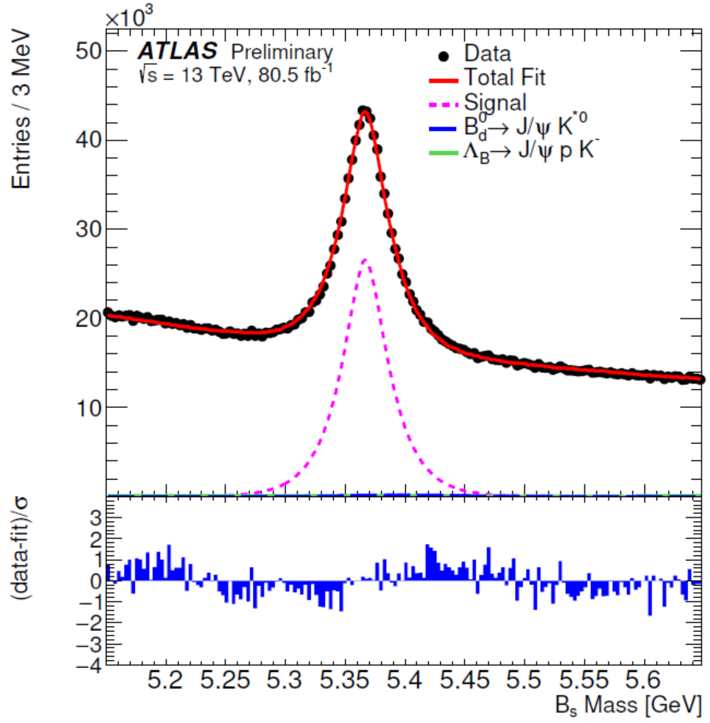
Full Run 2 data of $B_s^0 \to J/\psi\phi$ analysis is ongoing, statistical uncertainty can be decreased.

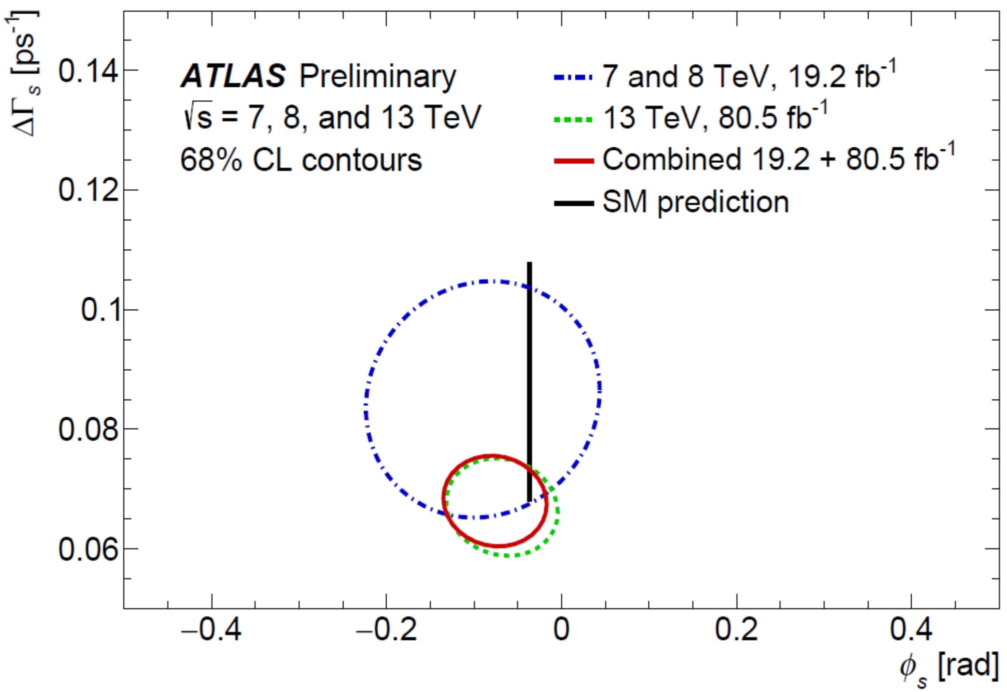
Results from ATLAS [ATLAS-CONF-2019-009]

➢ Use 80.5 fb^{-1}(15+16+17) $B_s^0 \to J/\psi\phi$ data

N_{sig}~477K, ϵD^2~1.65%
σ_t~97 → 69 fs
Benefited from IBL sub-detector

Run2 : $\phi_s = -0.068 \pm 0.038 \pm 0.018$ rad
Combined : $\phi_s = -0.076 \pm 0.034 \pm 0.019$ rad
Stats. is close to $B_s^0 \to J/\psi\phi$ results @ LHCb !



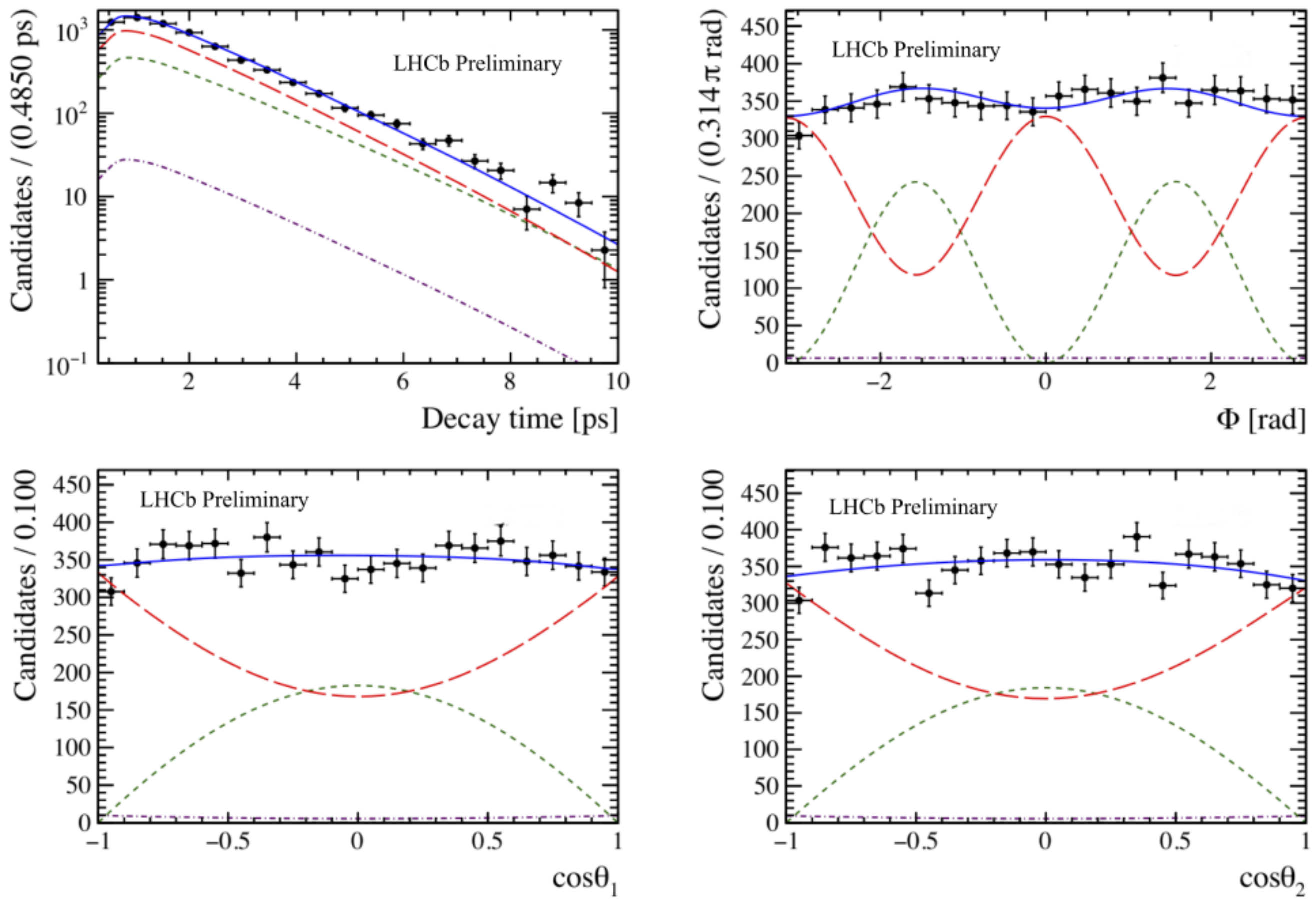


Fit results in $B_s^0 \to \phi\phi$ arXiv:1907.10003

- Use 3+1.9 fb^{-1} (Run 1+15+16) data

$$\phi_s^{s\bar{s}s} = -0.07 \pm 0.13 \pm 0.02 \text{ rad}$$

Consistent with SM prediction < 0.02 rad

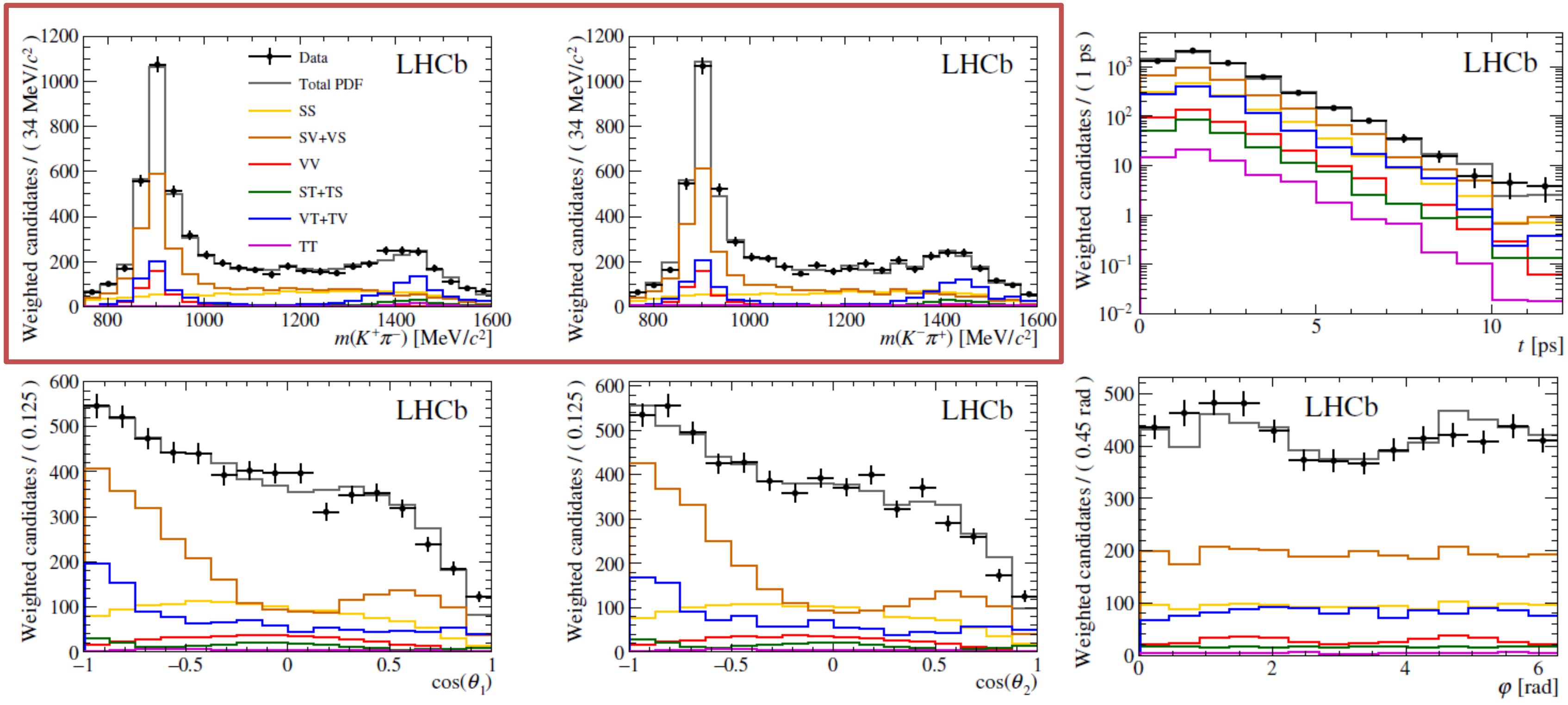


Fit results in $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$ JHEP 03 (2018) 140

➢ Use 3 fb^{-1}(Run 1) data

Simultaneous fit to different polarization amplitude component

$$\phi_s^{d\bar{d}s} = -0.10 \pm 0.13 \pm 0.14 \text{ rad}$$



Summary

- ϕ_s measurement is a good test for SM and sensitive probe to NP
- ϕ_s measurements @ LHCb

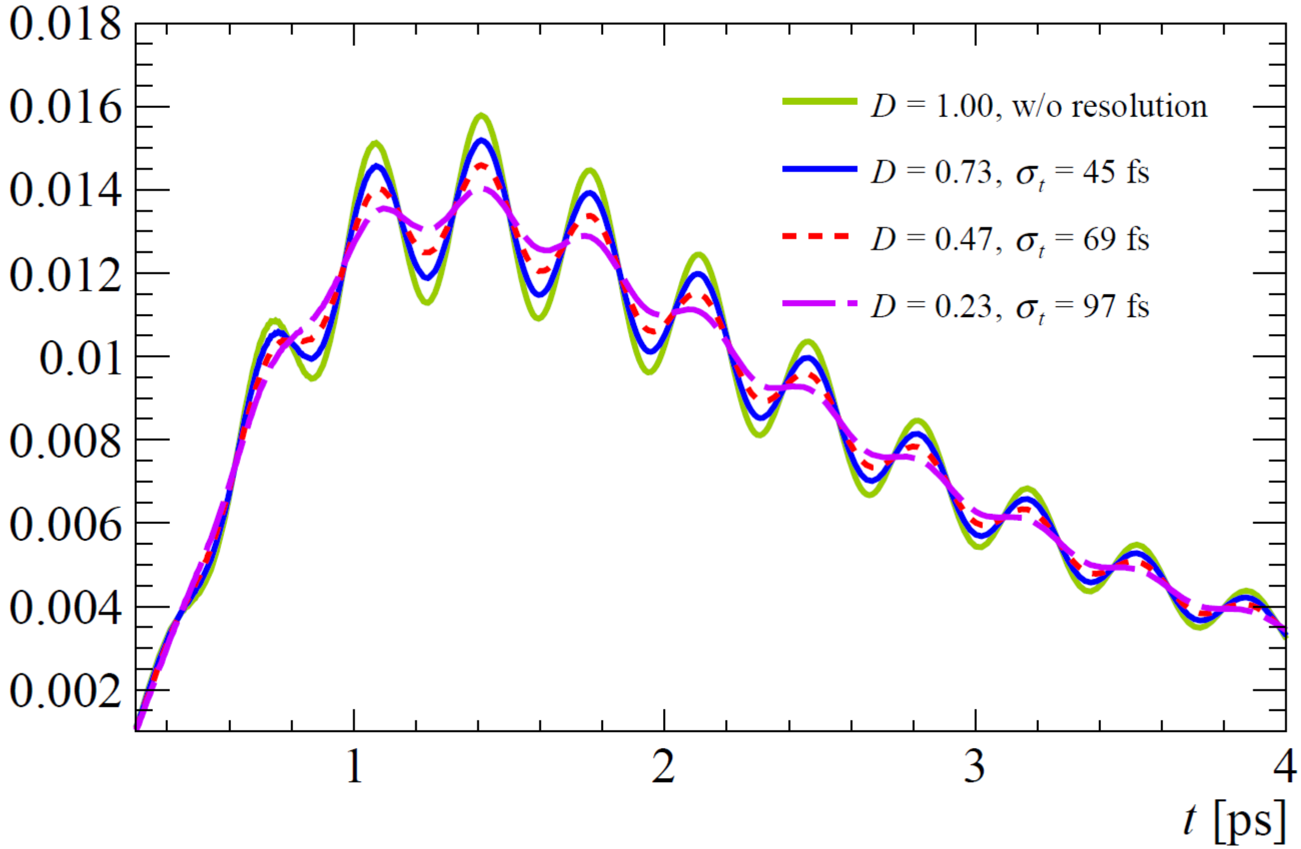
Channel	ϕ_s(rad)	SM(rad)
Tree dominated decays		
$B_s^0 \to J/\psi\phi$	$-0.080 \pm 0.041 \pm 0.006$	-0.0370 ± 0.0006
$B_s^0 \to J/\psi\pi^+\pi^-$	$-0.057 \pm 0.060 \pm 0.011$	
Combined LHCb	-0.041 ± 0.025	
Penguin dominated decays		
$B_s^0 \to \phi\phi$	$-0.07 \pm 0.13 \pm 0.02$	$\leq$0.02
$B_s^0 \to (K^+\pi^-)(K^-\pi^+)$	$-0.10 \pm 0.13 \pm 0.14$	-

- All of results are consistent with SM prediction

Backup

Oscillation plot with different dilution

$$D = e^{-\frac{1}{2}\Delta m_s^2 \sigma_t^2}$$



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

2015+2016

Parameter	Value
ϕ_s [rad]	$-0.080 \pm 0.041 \pm 0.006$
$\lvert\lambda\rvert$	$1.006 \pm 0.016 \pm 0.006$
$\Gamma_s - \Gamma_d$ [ps^{-1}]	$-0.0041 \pm 0.0024 \pm 0.0015$
$\Delta\Gamma_s$ [ps^{-1}]	$0.0772 \pm 0.0077 \pm 0.0026$
Δm_s [ps^{-1}]	$17.705 \pm 0.059 \pm 0.018$
$\lvert A_\perp\rvert^2$	$0.2457 \pm 0.0040 \pm 0.0019$
$\lvert A_0\rvert^2$	$0.5186 \pm 0.0029 \pm 0.0024$
$\delta_\perp - \delta_0$	$2.64 \pm 0.13 \pm 0.10$
$\delta_\parallel - \delta_0$	$3.061^{+0.084}_{-0.073} \pm 0.037$

Run I+2015+2016

$$
\begin{aligned}
\phi_s &= -0.078 \pm 0.032\,\mathrm{rad}\,,\\
|\lambda| &= 0.991 \pm 0.013\,,\\
\Gamma_s - \Gamma_d &= -0.0013 \pm 0.0021\,\mathrm{ps}^{-1}\,,\\
\Delta\Gamma_s &= 0.0773 \pm 0.0062\,\mathrm{ps}^{-1}\,,\\
\Delta m_s &= 17.695 \pm 0.042\,\mathrm{ps}^{-1}\,,\\
|A_\perp|^2 &= 0.2491 \pm 0.0035\,,\\
|A_0|^2 &= 0.5195 \pm 0.0035\,,\\
\delta_\perp &= 2.88 \pm 0.11\,\mathrm{rad}\,,\\
\delta_\parallel &= 3.153 \pm 0.079\,\mathrm{rad}.
\end{aligned}
$$

1. Single most precise measurement of ϕ_s, $\Delta\Gamma_s$, $\Gamma_s - \Gamma_d$ and Γ_s/Γ_d
2. Combine results with that of Run I while considering correlations between them

$\phi_s = 0.078 \pm 0.032$ rad, see 2.4 StdDev from zero

2015+2016

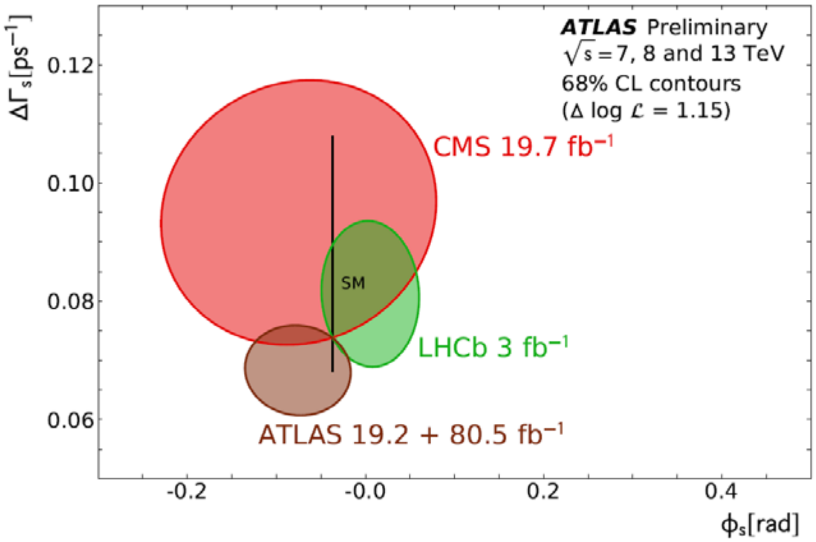
$\Gamma_H - \Gamma_{B^0}$ (ps^{-1})	$-0.050 \pm 0.004 \pm 0.004$
$\lvert\lambda\rvert$	$1.01^{+0.08}_{-0.06} \pm 0.03$
ϕ_s (rad)	$-0.057 \pm 0.060 \pm 0.011$

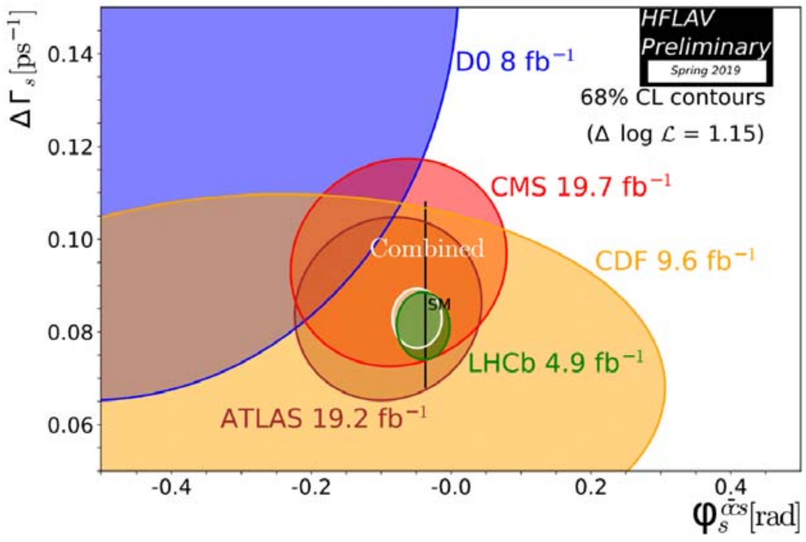
Run I+ 2015+2016

$$\Gamma_H - \Gamma_{B^0} = -0.050 \pm 0.004 \pm 0.004\ \text{ps}^{-1}$$
$$|\lambda| = 0.949 \pm 0.036 \pm 0.019$$
$$\phi_s = 0.002 \pm 0.044 \pm 0.012\ \text{rad}$$

1. Combine results with that of Run I while considering correlations between them
2. Combined ϕ_s result is slightly more precise than the Run-I $B_s^0 \to J/\psi\phi$ result : $-0.058 \pm 0.049 \pm 0.006$

- Combined results





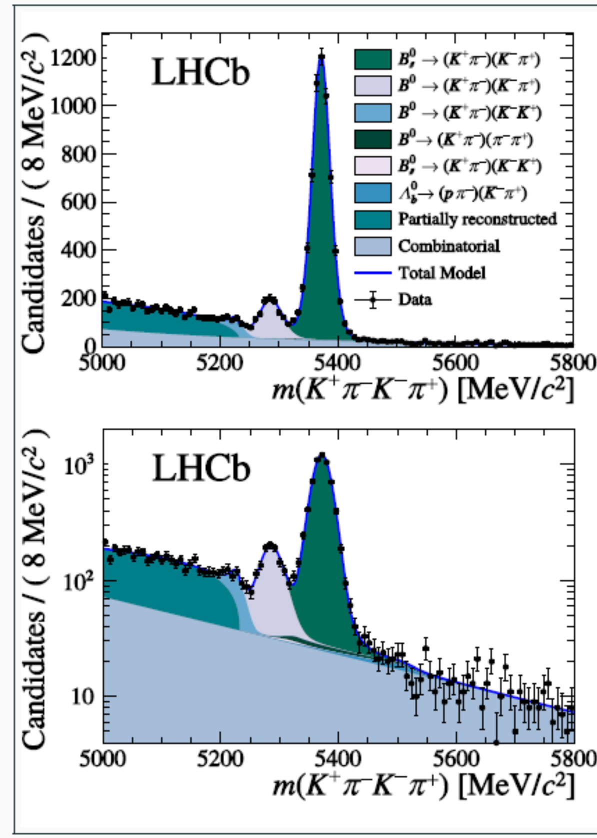
Components in $B_s^0 \to (K^+\pi^-)(K^-\pi^+)$

- Different polarization amplitude components of final states

Scalar (S), Vector (V) and Tensor (T) contributions:

Decay	Polarization amplitudes
$B_s^0 \to (K^+\pi^-)_0^*(K^+\pi^-)_0^*$	SS
$B_s^0 \to (K^+\pi^-)_0^*\overline{K}^*(892)^0$	SV
$B_s^0 \to K^*(892)^0(K^+\pi^-)_0^*$	VS
$B_s^0 \to (K^+\pi^-)_0^*\overline{K}_2^*(1430)^0$	ST
$B_s^0 \to K_2^*(1430)^0(K^-\pi^+)_0^*$	TS
$B_s^0 \to K^*(892)^0\overline{K}^*(892)^0$	VV0, VV$\parallel$, VV$\perp$
$B_s^0 \to K^*(892)^0\overline{K}_2^*(1430)^0$	VT0, VT$\parallel$, VT$\perp$
$B_s^0 \to K_2^*(1430)^0\overline{K}^*(892)^0$	TV0, TV$\parallel$, TV$\perp$
$B_s^0 \to K_2^*(1430)^0\overline{K}_2^*(1430)^0$	TT0, TT$\parallel_1$, TT$\perp_1$, TT$\parallel_2$, TT$\perp_2$

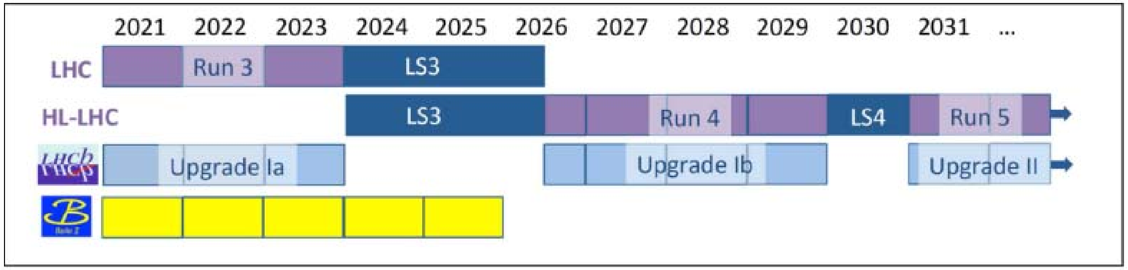
In total 19 different polarization amplitudes!



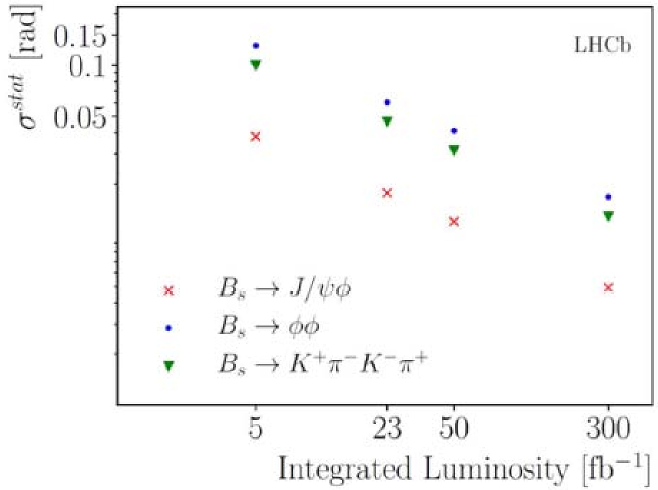
$N_{signal} = 6080 \pm 83$

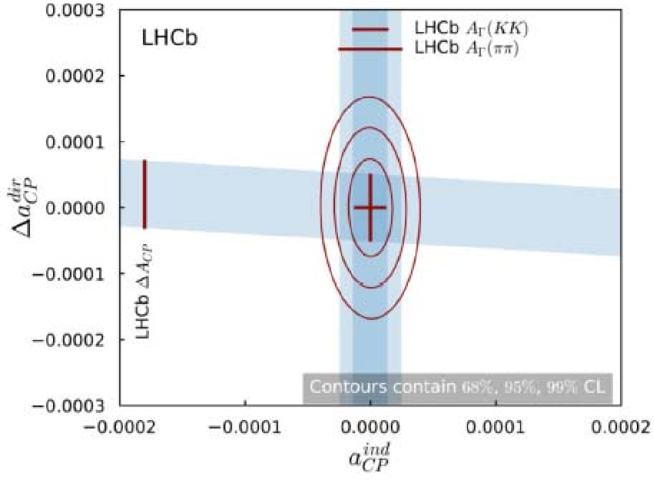
LHCb upgrade II

- **Two major upgrade at LS2 and LS4** [arXiv:1808.08865]



- **Aim to take 300 fb^{-1}, improve key measurements by 10X**
  - $\sigma_{\phi_s} \sim 4$ mrad, $\sigma_\gamma \sim 0.4^\circ$, $\sigma_{A_\Gamma} \sim 10^{-5}$, $\sigma_{\Delta A_{CP}} \sim 3\times10^{-5}$





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