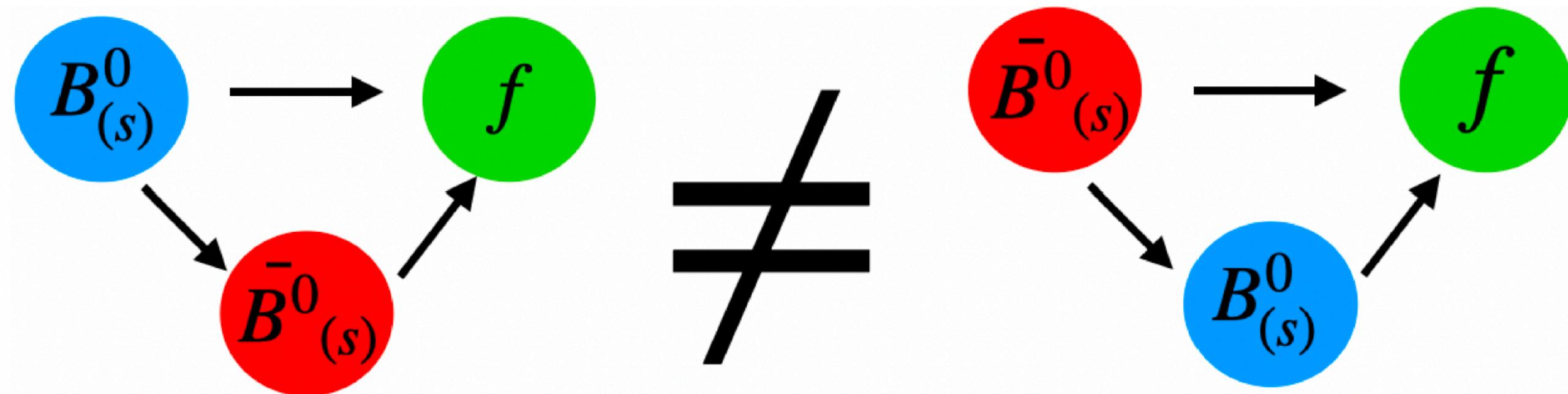


Measurements of B^0 and B_s^0 mixing phases at LHCb

Ramón Ángel Ruiz Fernandez on behalf of LHCb collaboration
21st Conference on Flavor Physics and CP violation | May 30, Lyon, France



CPV in B mesons



Direct CPV

CPV in mixing

CPV in the interference

⇒ Time-dependent CPV

3 Run2 Updates!

$B^0 \rightarrow \psi(\rightarrow l^+l^-)K_s^0(\rightarrow \pi^+\pi^-)$
LHCb-PAPER-2023-013

- ♦ Access to S ($\sin 2\beta$) and C
- ♦ Small penguin pollution
- ♦ $\Delta\Gamma_d = 0$

$B_s^0 \rightarrow \phi(\rightarrow K^+K^-)\phi(\rightarrow K^+K^-)$
arXiv:2304.06198v2

- ♦ Access to $\phi_s^{s\bar{s}s}$, $|\lambda|$
- ♦ $b \rightarrow s\bar{s}s$ penguin process
- ♦ Expected close to 0.

$B_s^0 \rightarrow J\psi(\rightarrow \mu^+\mu^-)\phi(\rightarrow K^+K^-)$
LHCb-PAPER-2023-016

- ♦ Access to $\phi_s^{c\bar{c}s}$, $|\lambda|$, $\Delta\Gamma_s$,
 $\Gamma_s - \Gamma_d$, Δm_s → **Golden channel**
- ♦ Small penguin pollution
- ♦ SM $\approx -2\beta_s$

Mass Fit and Selection

$B^0 \rightarrow \psi(\rightarrow l^+l^-)K_s^0(\rightarrow \pi^+\pi^-)$
LHCb-PAPER-2023-013

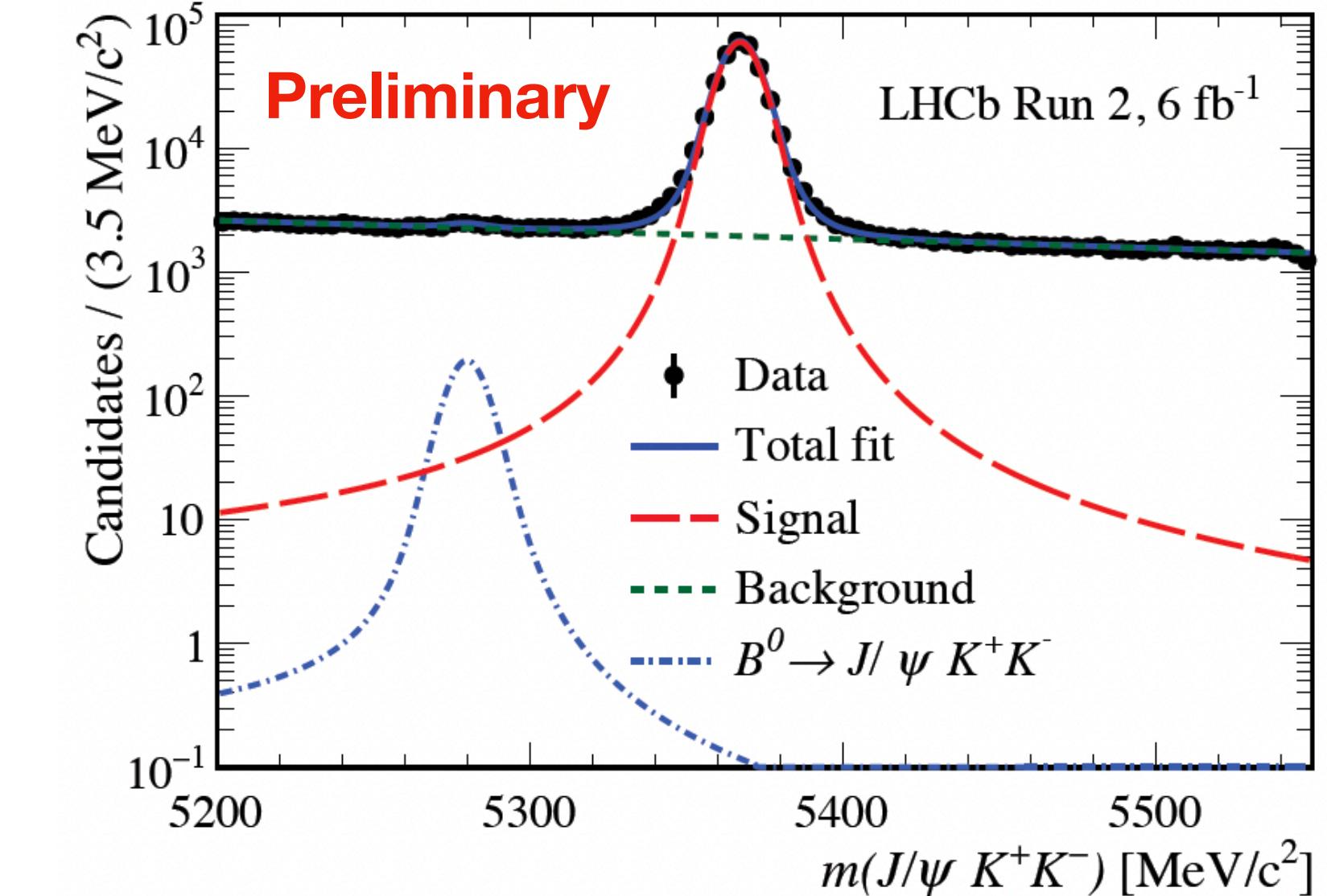
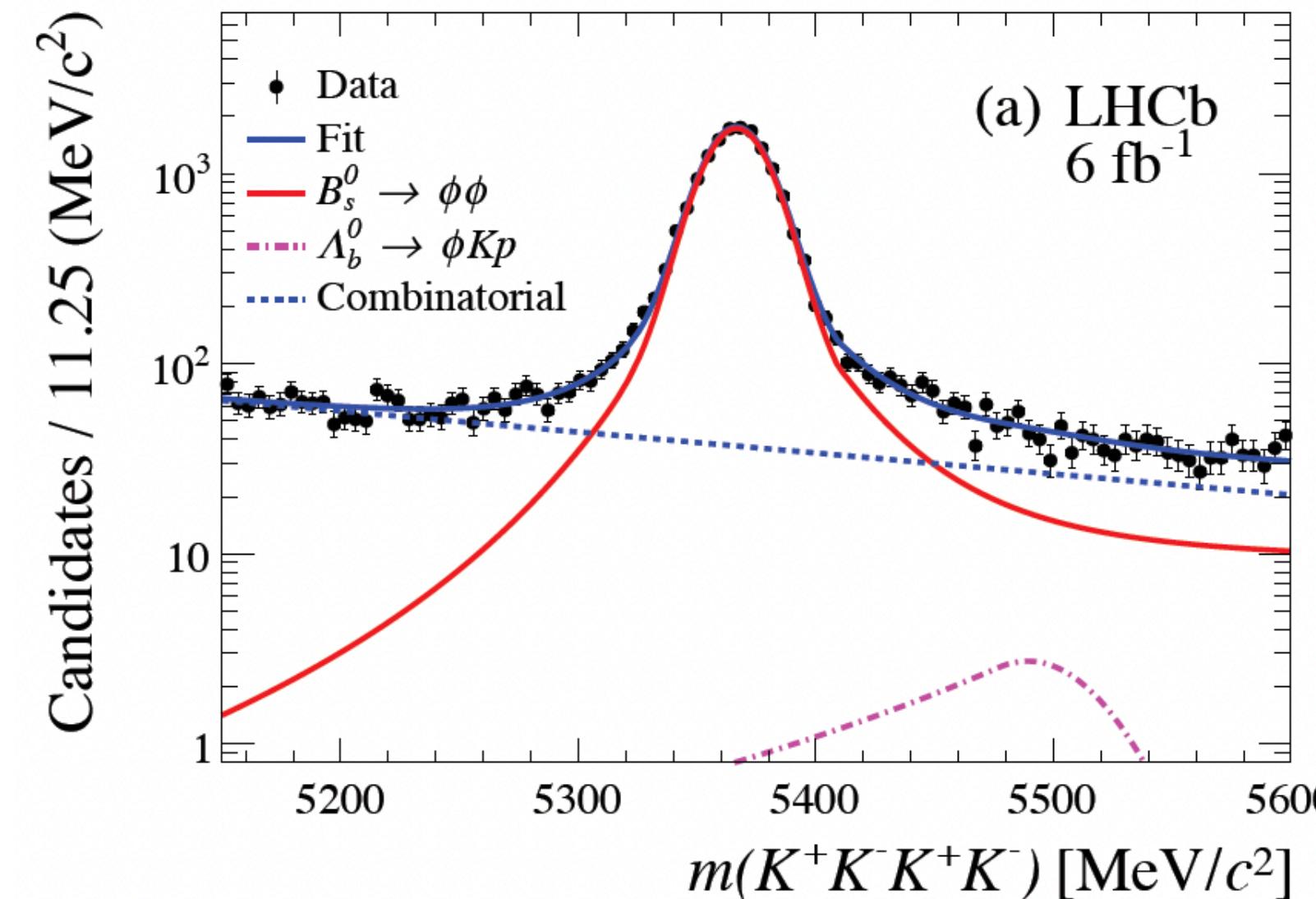
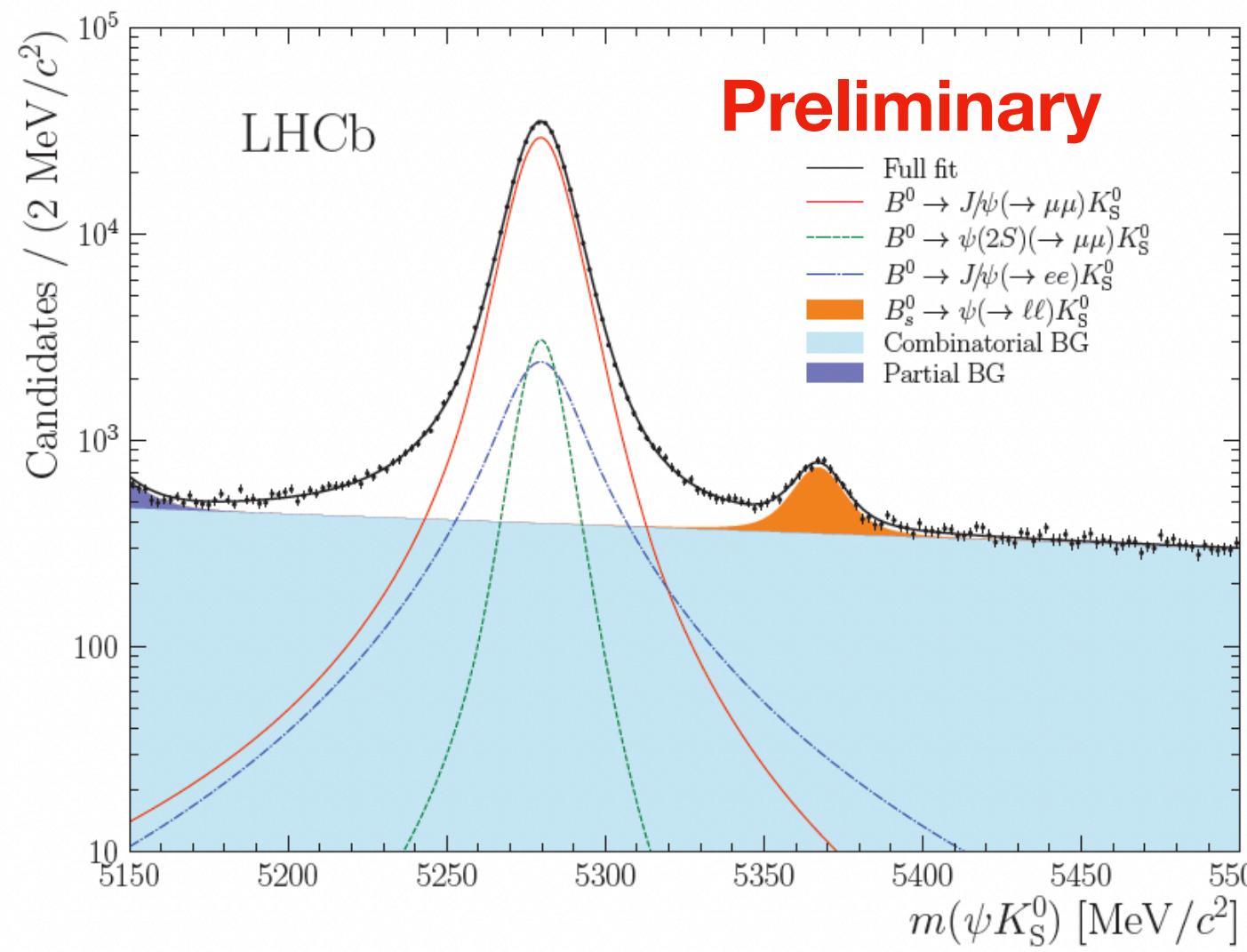
- ♦ BDT to suppress combinatorial.
- ♦ Partial reconstructed background on left tail

$B_s^0 \rightarrow \phi(\rightarrow K^+K^-)\phi(\rightarrow K^+K^-)$
[arXiv:2304.06198v2](https://arxiv.org/abs/2304.06198v2)

- ♦ Multilayer Perception (MLP) to suppress combinatorial.
- ♦ $\Lambda_b^0 \rightarrow \phi K p$.

$B_s^0 \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\phi(\rightarrow K^+K^-)$
LHCb-PAPER-2023-016

- ♦ BDT to suppress combinatorial.
- ♦ $B^0 \rightarrow J/\psi KK$ on left tail.
- ♦ $\Lambda_b^0 \rightarrow \phi K p$ statistically subtracted



Decay time resolution

Accounted by convolving final pdf with a Gaussian.

Widths defined as linear calibrations of decay-time error

$B^0 \rightarrow \psi(\rightarrow l^+l^-)K_s^0(\rightarrow \pi^+\pi^-)$
LHCb-PAPER-2023-013

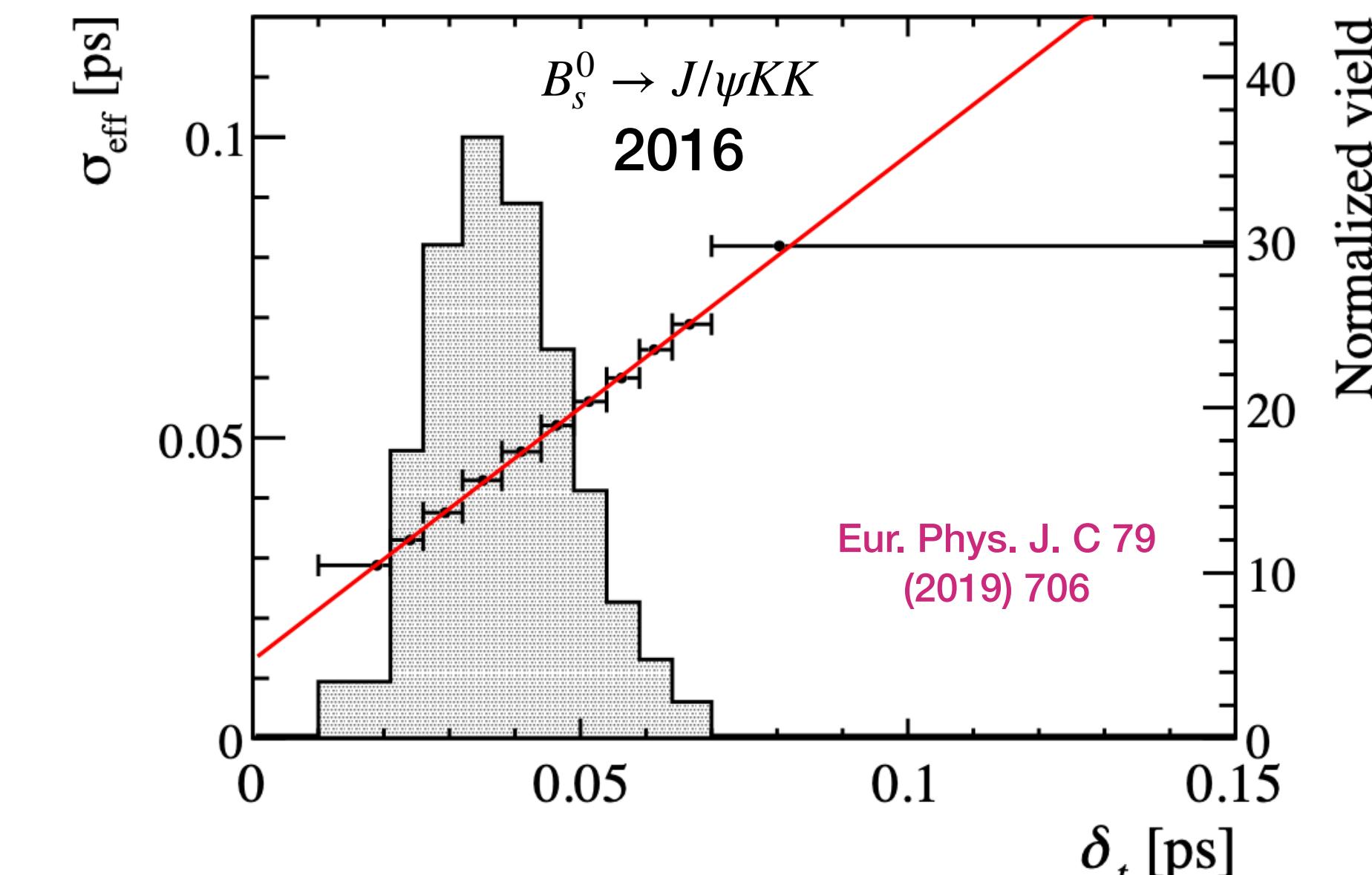
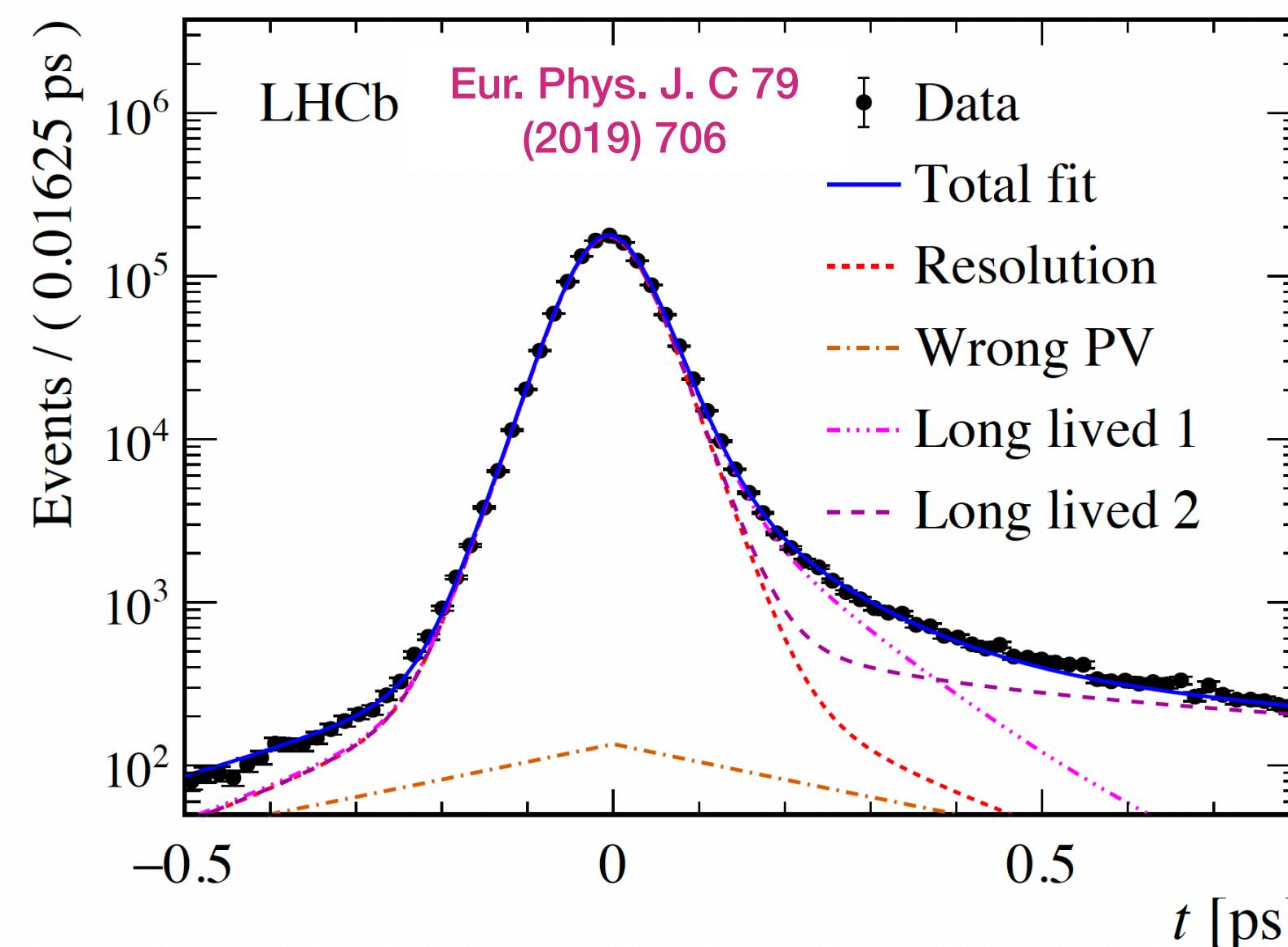
- ♦ Extracted from simulation.
- ♦ Effective resolution ≈ 60 fs

$B_s^0 \rightarrow \phi(\rightarrow K^+K^-)\phi(\rightarrow K^+K^-)$
arXiv:2304.06198v2

- ♦ Extracted from prompt data.
- ♦ Effective resolution ≈ 43 fs

$B_s^0 \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\phi(\rightarrow K^+K^-)$
LHCb-PAPER-2023-016

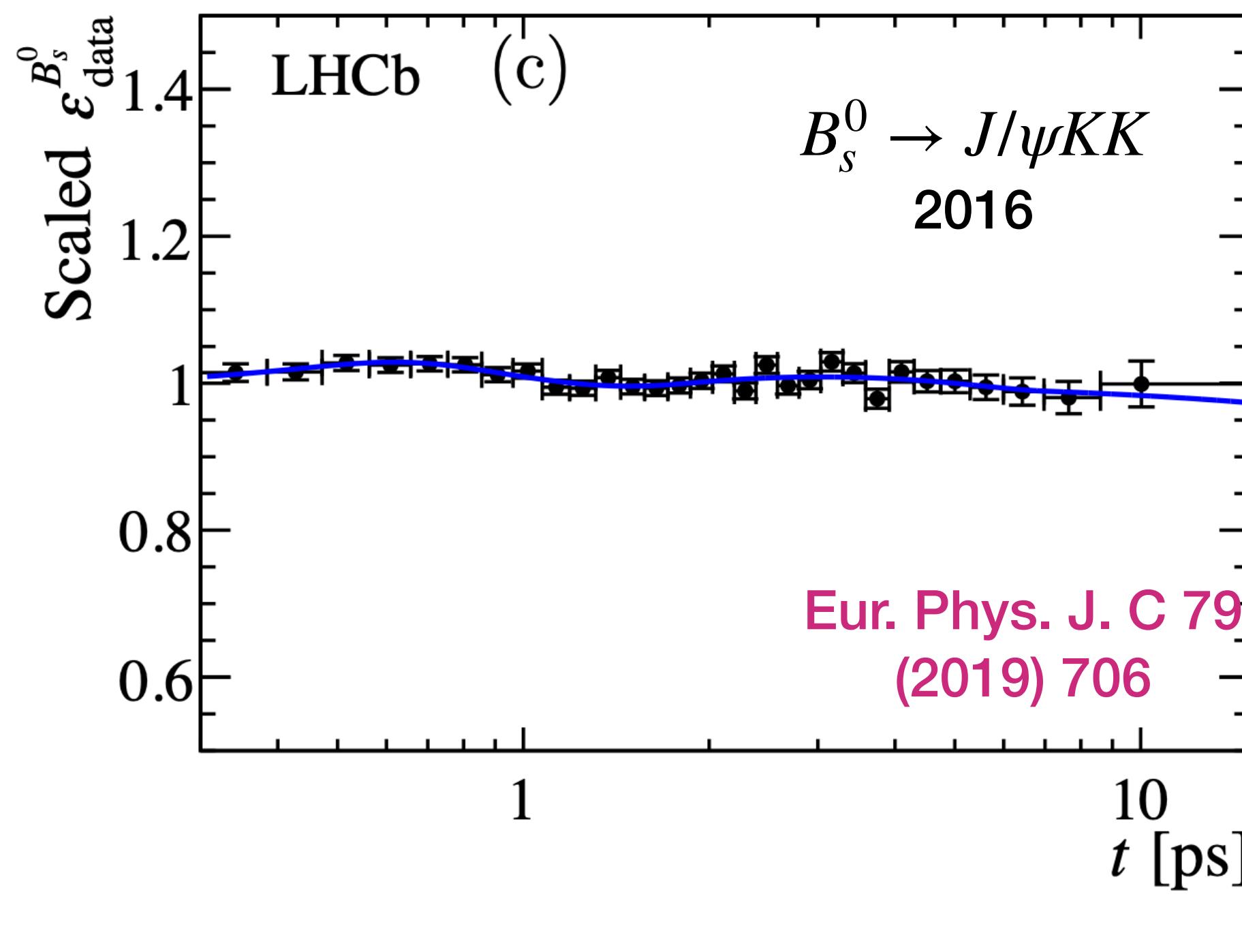
- ♦ Extracted from prompt data.
- ♦ Effective resolution ≈ 42 fs



Efficiencies

Decay-time Acceptance

- ♦ Needed for all the three measurements.
- ♦ $\epsilon(t) * (pdf \otimes G)$
- ♦ Model based on cubic splines.

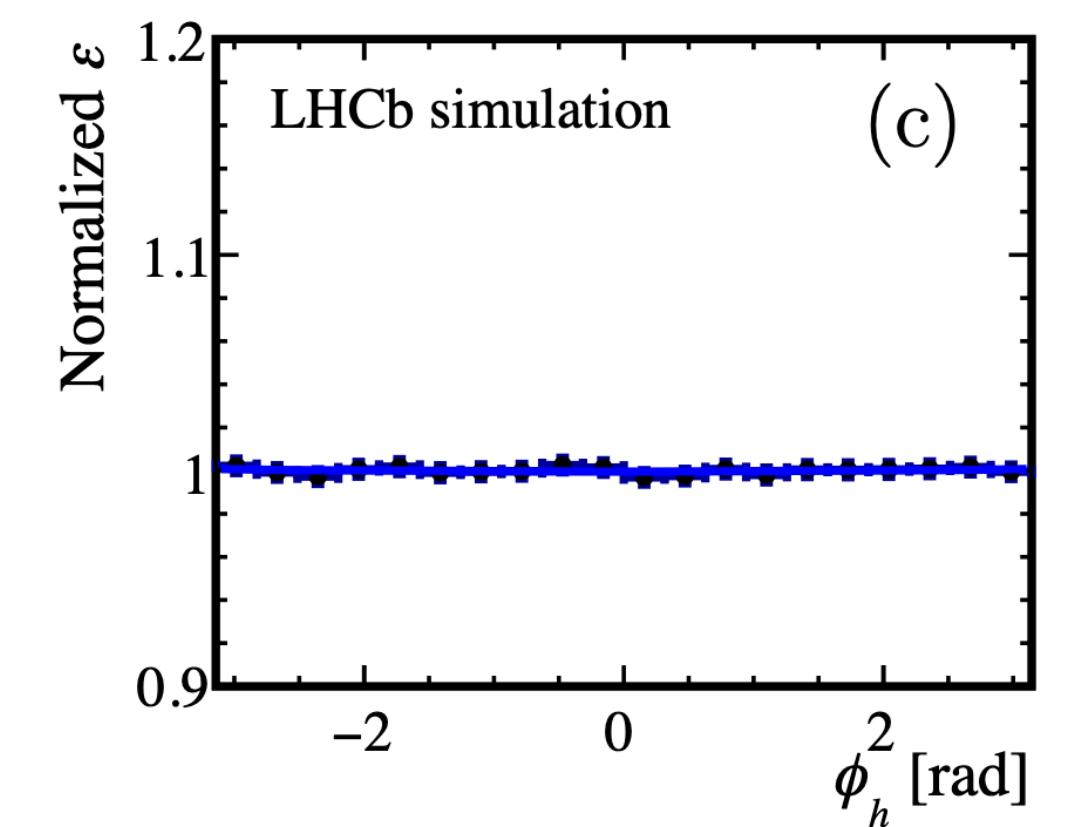
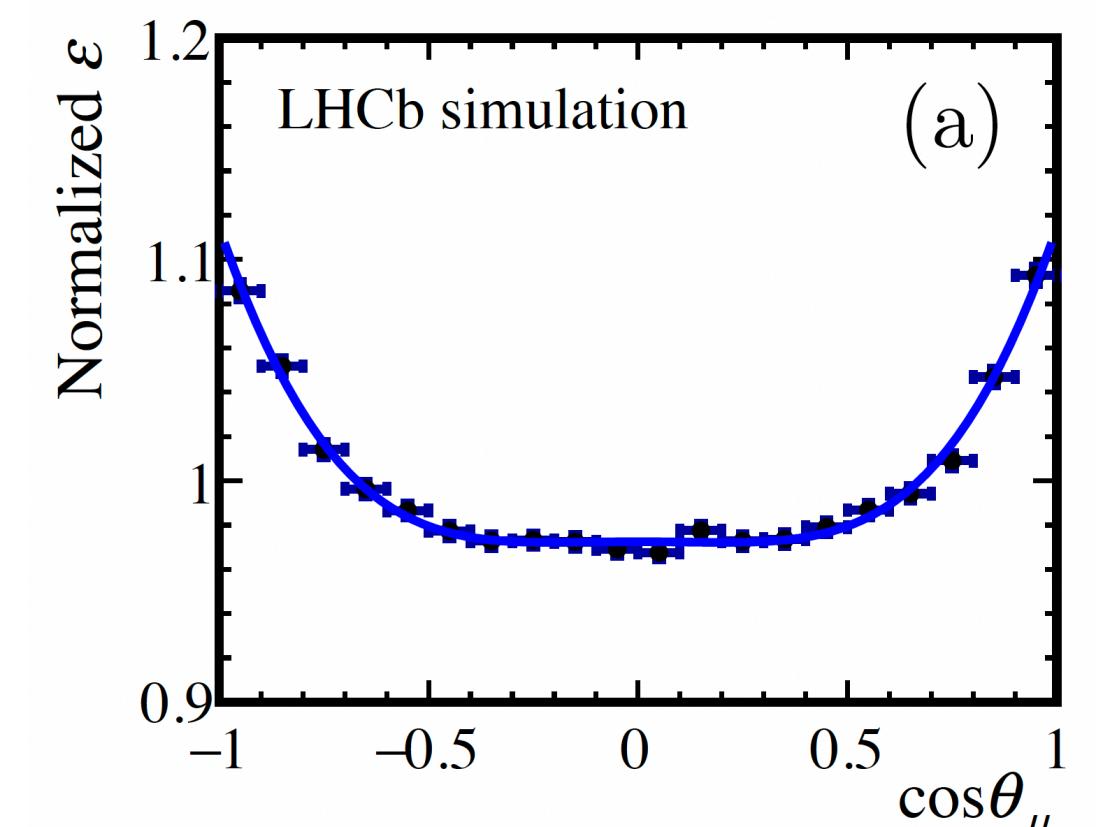
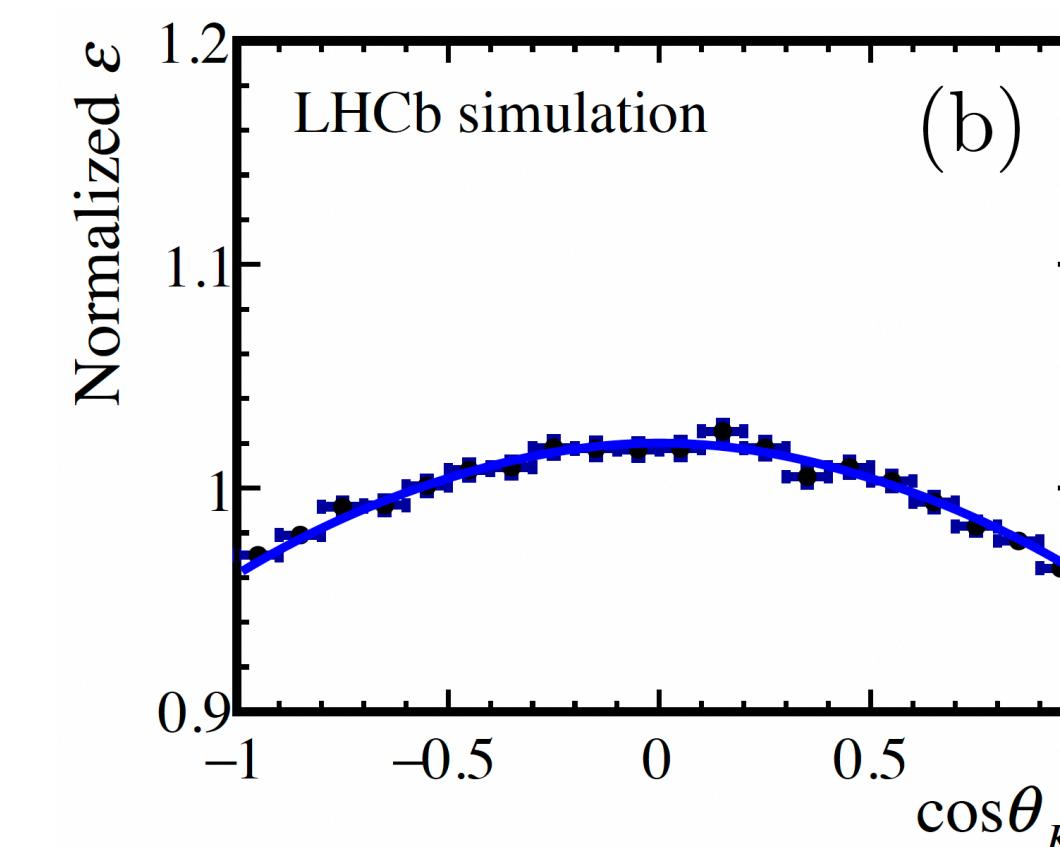


Angular Acceptance

- ♦ Only needed in $B_s^0 \rightarrow \phi\phi$ & $B_s^0 \rightarrow J/\psi KK$
- ♦ Normalization factors to each angular term
- ♦ Extracted from simulation iteratively corrected to data

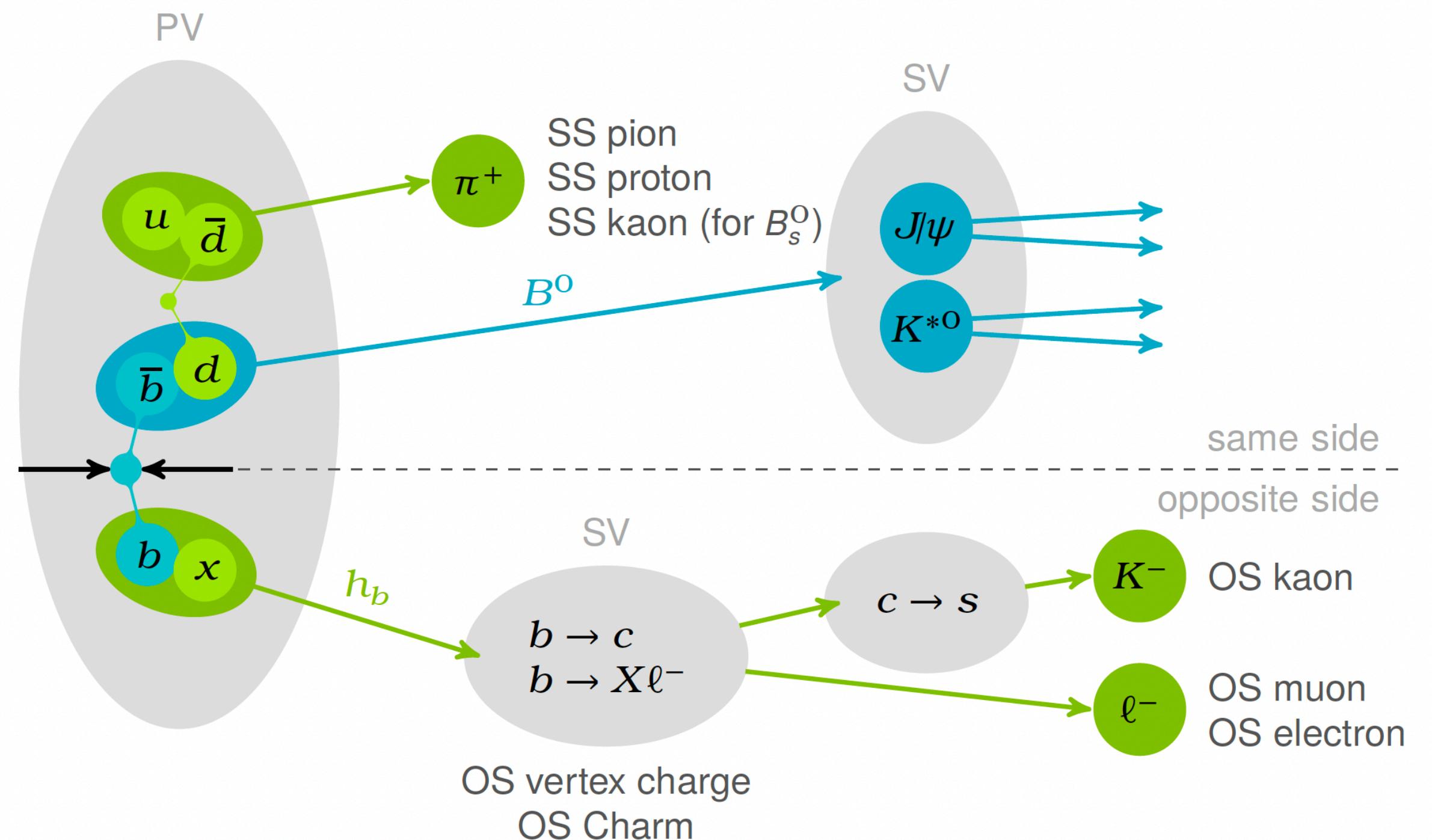
$B_s^0 \rightarrow J/\psi KK$
2016

Eur. Phys. J. C 79
(2019) 706



Flavor Tagging

- ❖ Flavor of the B meson at production is needed.
- ❖ Two methods:
 1. **OS tagging**: Information from the opposite b-hadron.
 2. **SS tagging**: Information from the fragmentation of the b-quark associated to the signal.
- ❖ Two informations: Decisions and Mistags (probability of a wrong decision).
- ❖ Mistags must be calibrated -> Data driven method.



Opposite Side (OS)

Calibrated in $B^+ \rightarrow J/\psi K^+$

Same-Side (SS)

1. SSK
Calibrated in $B_s^0 \rightarrow D_s \pi$
2. SS π /SS p ($\sin 2\beta$)
Calibrated in $B^0 \rightarrow J/\psi K^*$

$$\epsilon_{tag} = \epsilon_{eff}(1 - 2\omega)^2$$

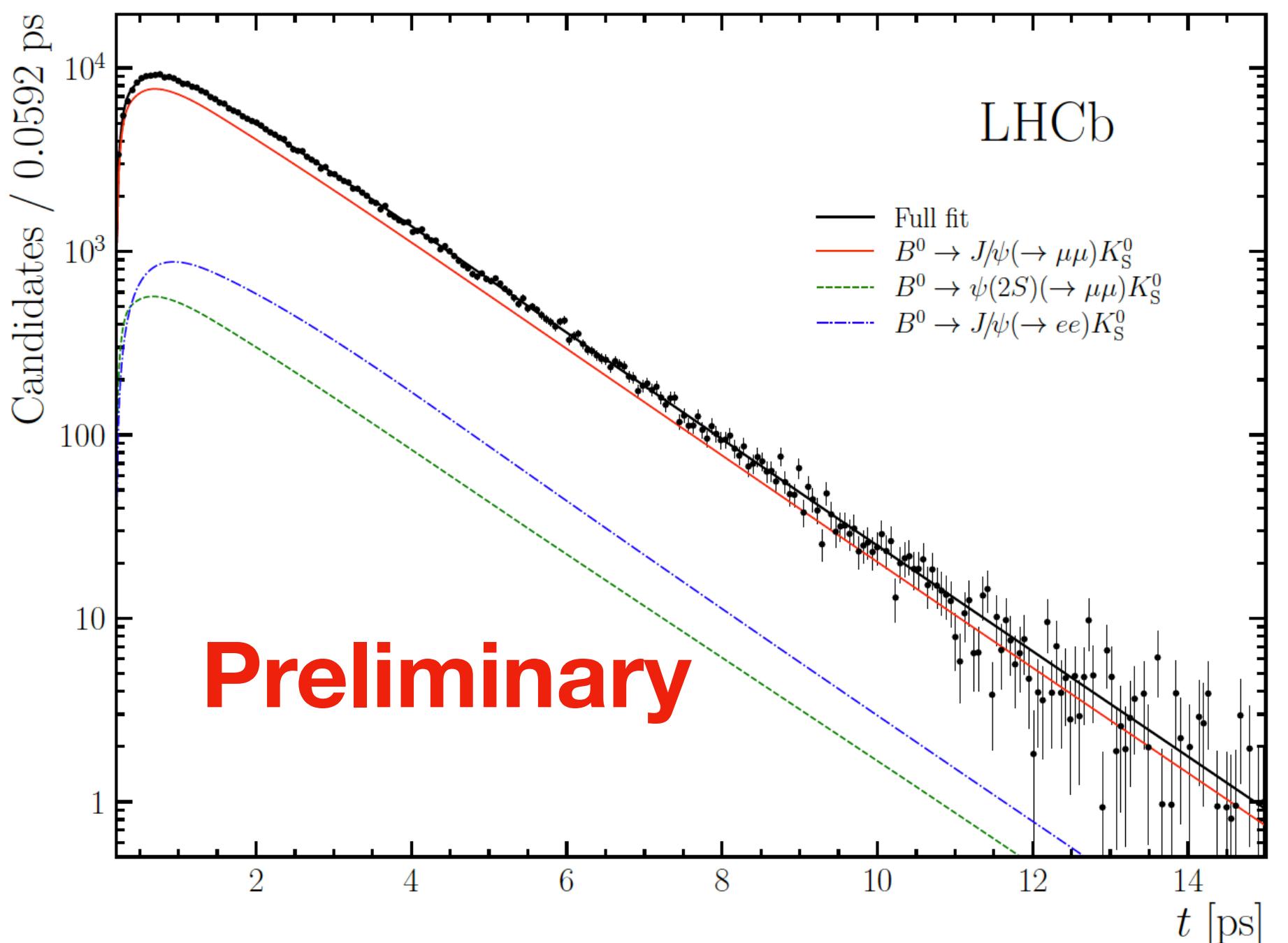
$$B^0 \rightarrow \psi K_s^0 \approx 4.8 \%$$

$$B_s^0 \rightarrow \phi \phi \approx 6 \%$$

$$B_s^0 \rightarrow J/\psi K^+ K^- \approx 4.3 \%$$

$B^0 \rightarrow \psi K_S^0$

- ❖ $\Gamma_d, \Delta m_d$ & Spline coefficients constrained to their known values.
- ❖ FT calibration parameters + \mathcal{A}_{prod} constrained to $B^0 \rightarrow J/\psi K^*$.

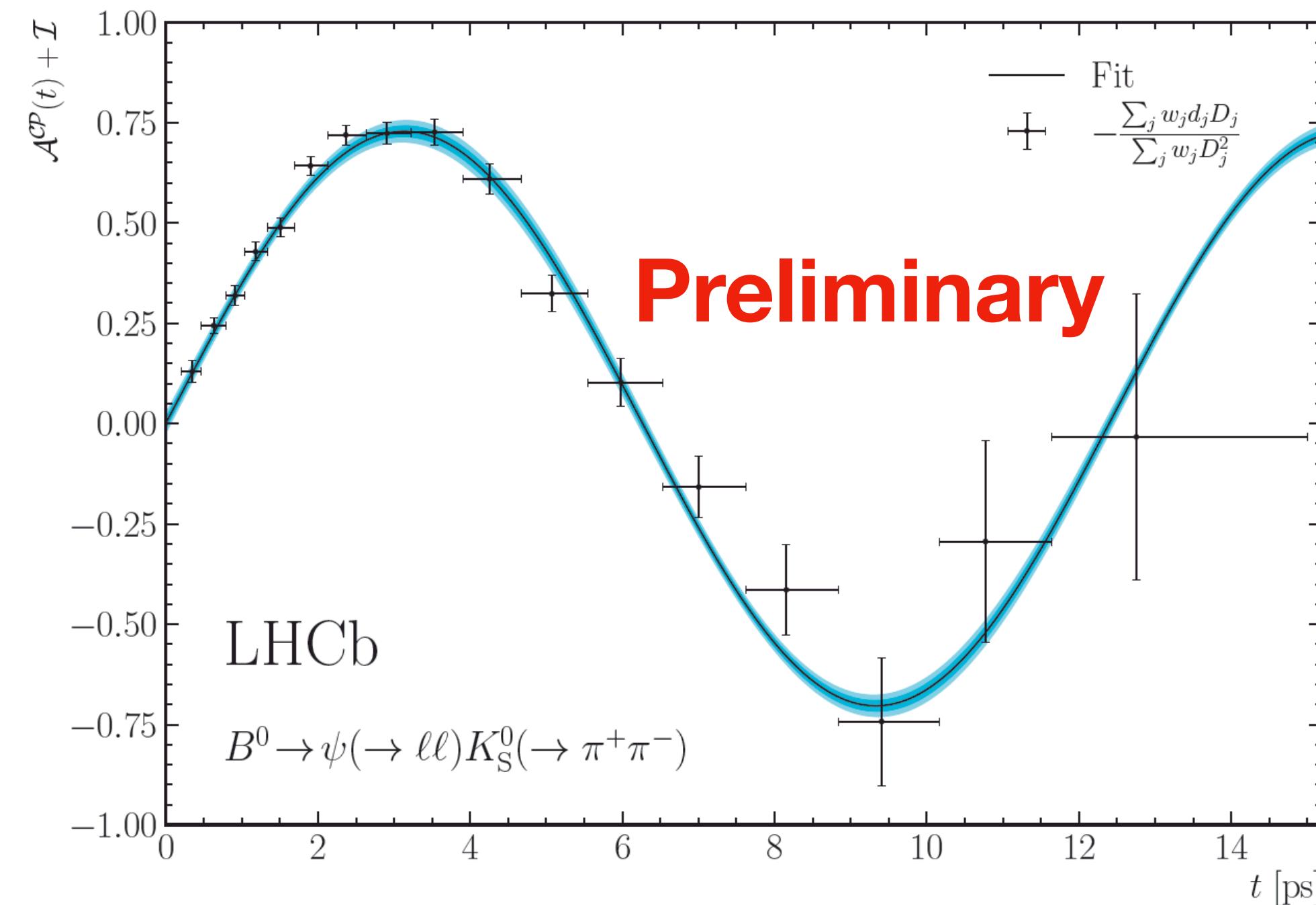


- Precision higher than current average
- In agreement with current average.

NEW!!

LHCb-PAPER-2023-013
HFLAV

\mathcal{I} : Small offset from 0, due to production and FT asymmetries



Full Run2 Results

$$S_{\psi K_S^0} = 0.716 \pm 0.013 \pm 0.008$$

$$C_{\psi K_S^0} = 0.012 \pm 0.012 \pm 0.003$$

Previous HFLAV

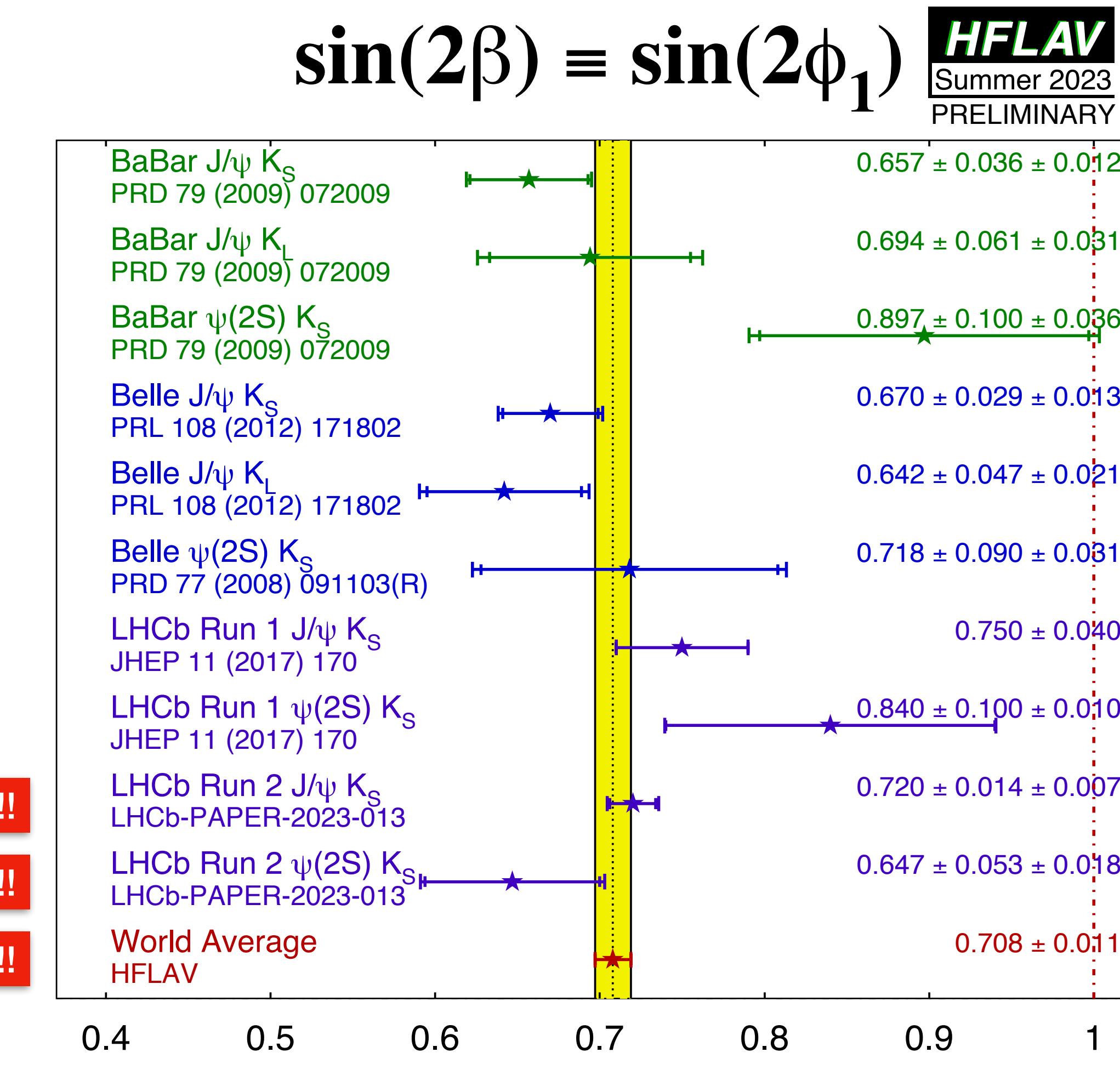
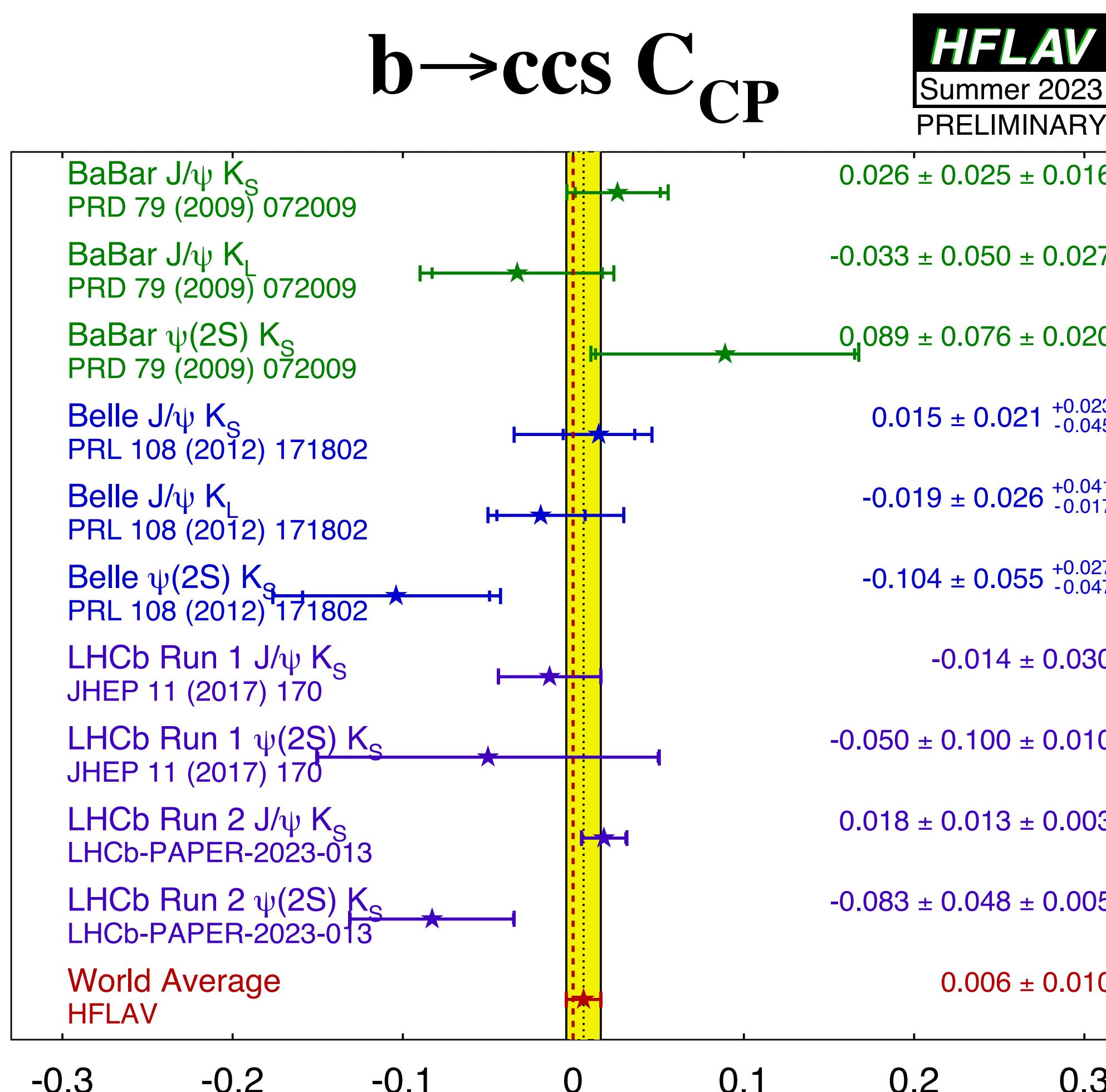
$$S = 0.699 \pm 0.017$$

$$C = -0.005 \pm 0.015$$

$B^0 \rightarrow \psi K_S^0$

Preliminary !!!

HFLAV



$B_S^0 \rightarrow \phi\phi$

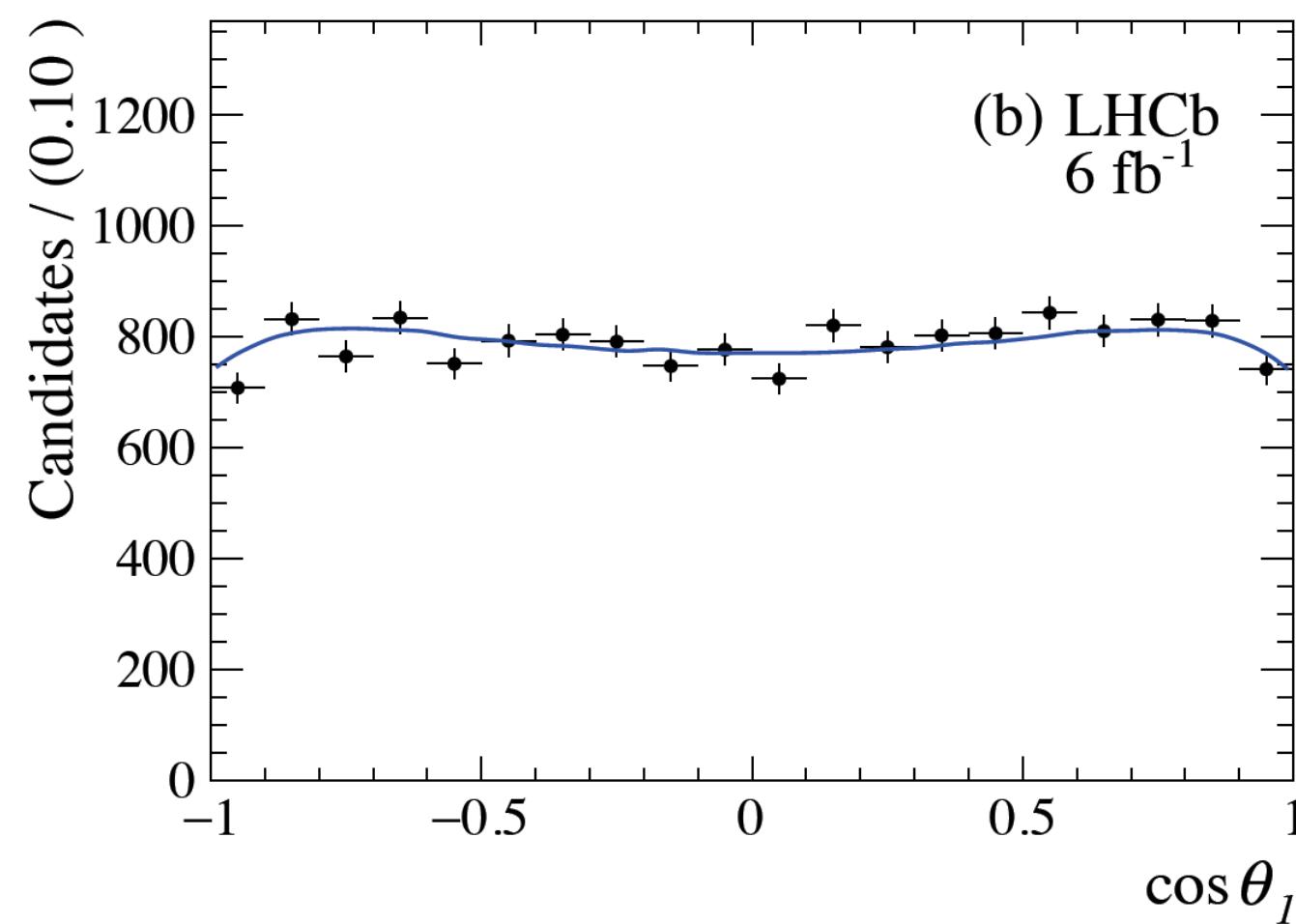
[arXiv:2304.06198v2](https://arxiv.org/abs/2304.06198v2)

LHCb Run2 6 fb^{-1}

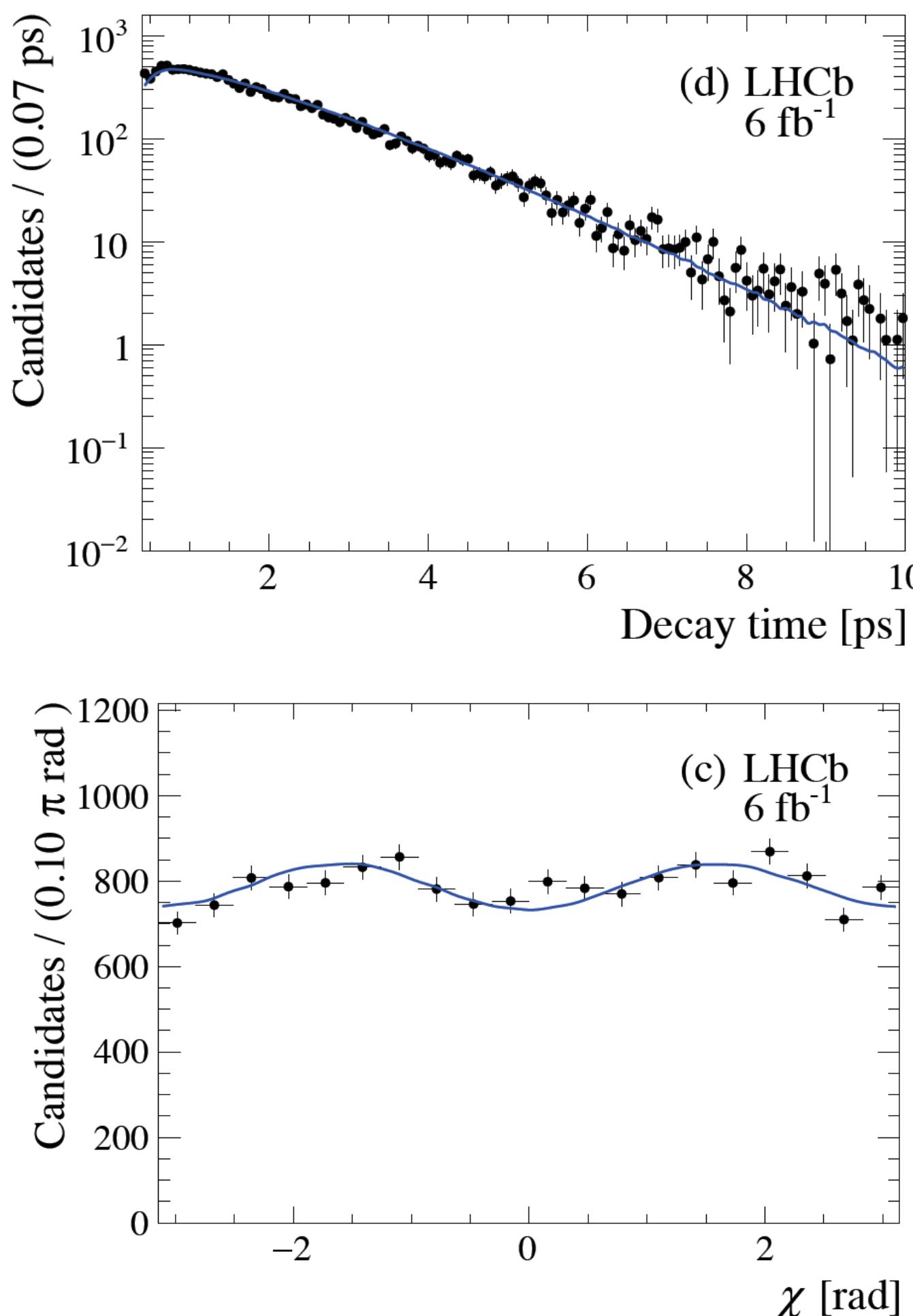
$$\phi_s^{s\bar{s}s} = -42 \pm 75 \pm 9 \text{ mrad}$$

$$|\lambda| = 1.004 \pm 0.030 \pm 0.009$$

Polarization dependence: No dependence observed



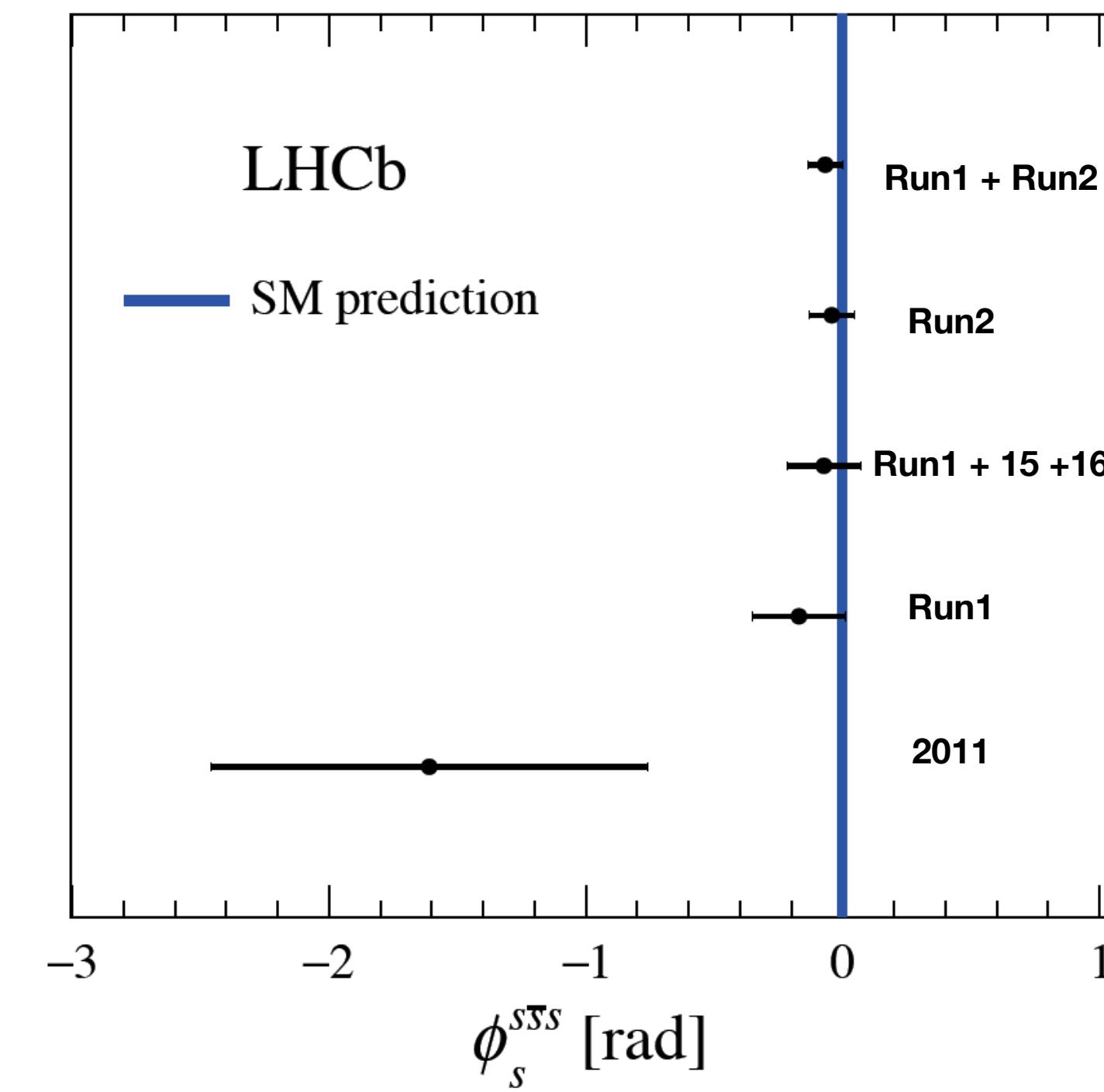
❖ Γ_s , $\Delta\Gamma_s$ and Δm_s gaussian constrained to LHCb measurements.



LHCb Combination 9 fb^{-1}

$$\phi_s^{s\bar{s}s} = -74 \pm 69 \text{ mrad}$$

$$|\lambda| = 1.009 \pm 0.030$$



Most precise measurement of CPV in penguin dominated decays.

In agreement with SM.

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

NEW!!

LHCb-PAPER-2023-016
HFLAV

LHCb Run2 6 fb $^{-1}$

$$\phi_s^{c\bar{c}s} = -39 \pm 22 \pm 6 \text{ mrad}$$

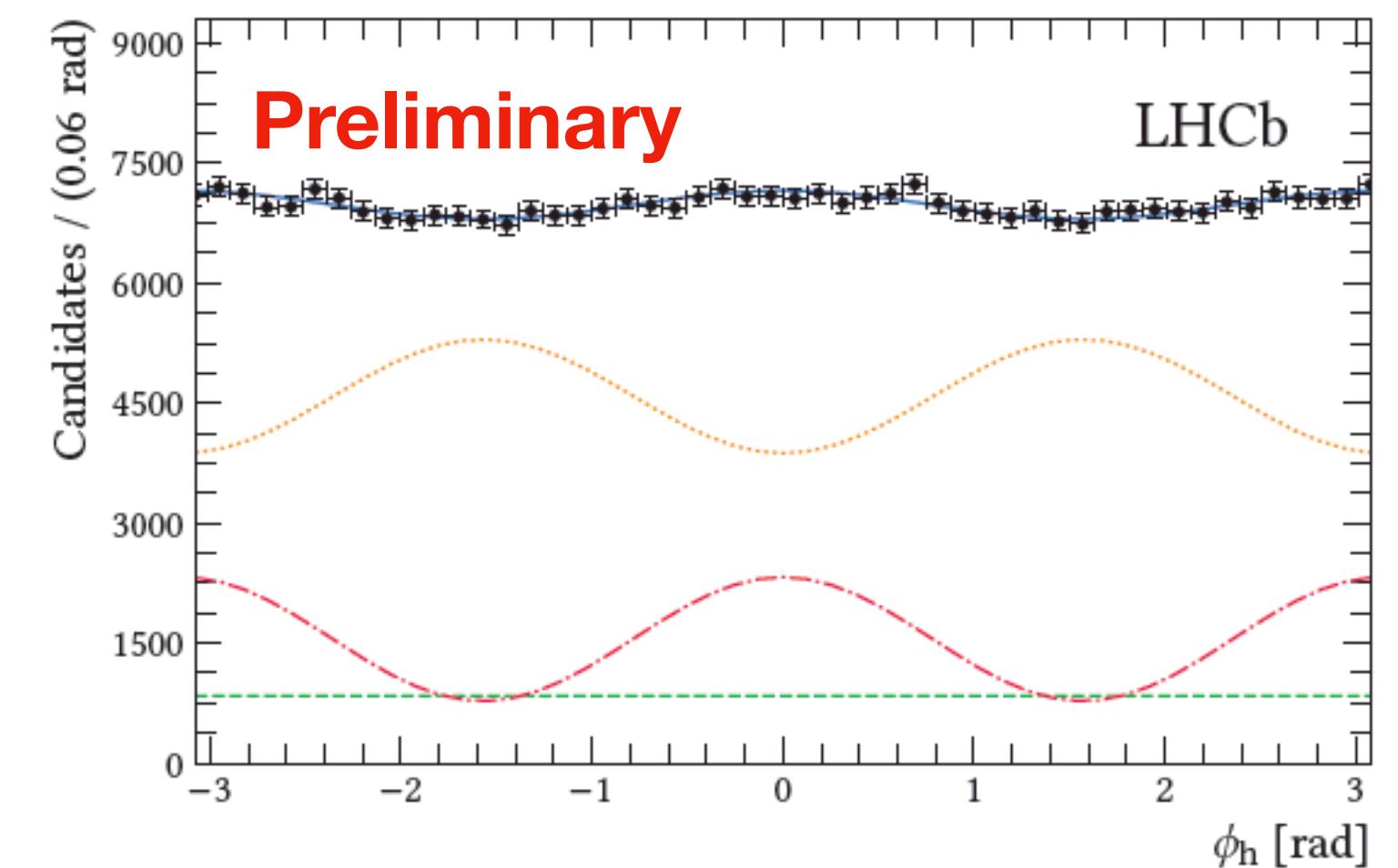
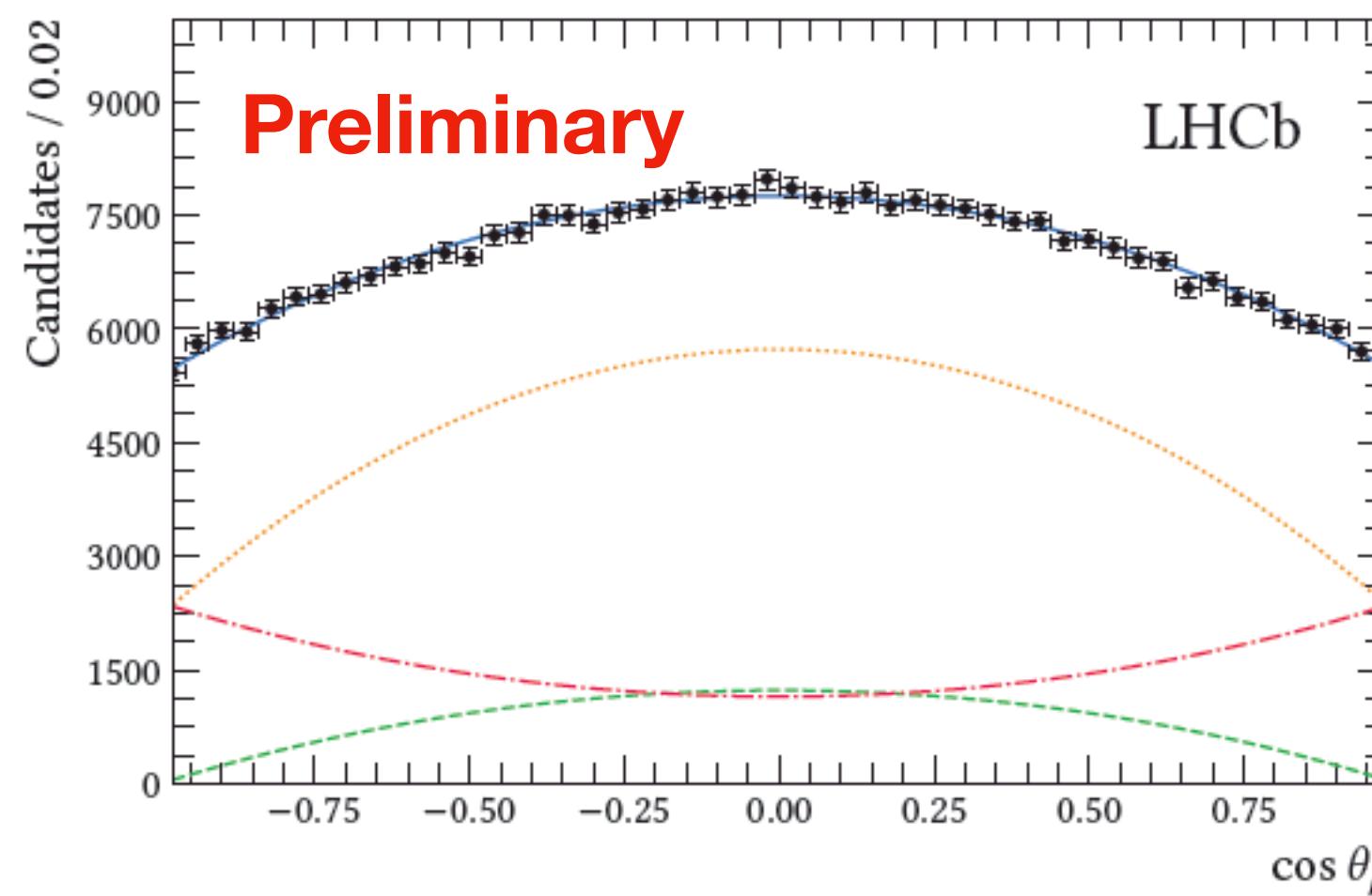
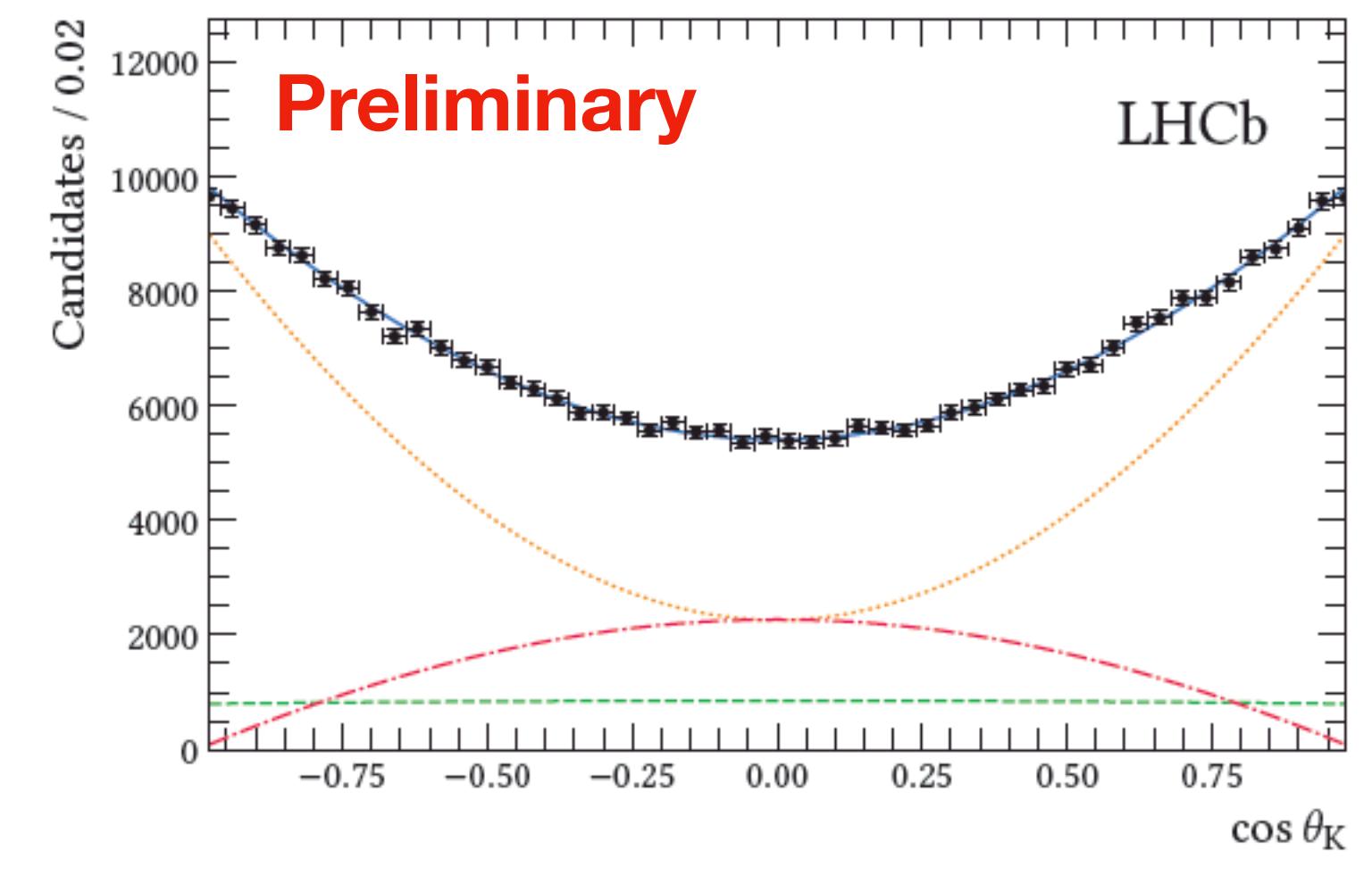
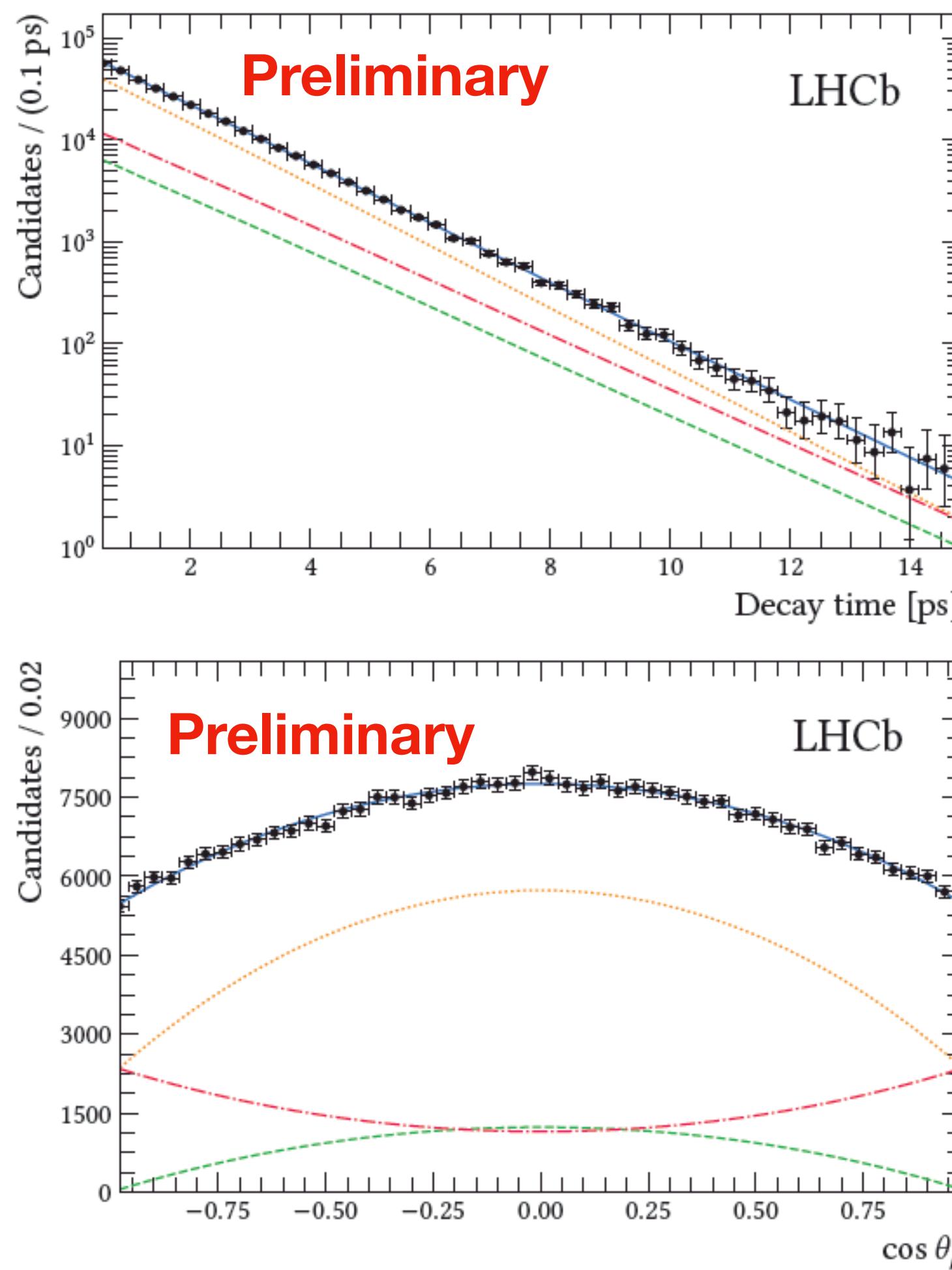
$$|\lambda| = 1.001 \pm 0.011 \pm 0.005$$

$$\Delta\Gamma_d^S = -0.0057^{+0.0013}_{-0.0015} \pm 0.0014 \text{ ps}^{-1}$$

$$\Delta\Gamma_s = 0.0846 \pm 0.0044 \pm 0.0024 \text{ ps}^{-1}$$

$$\Delta m_s = 17.743 \pm 0.033 \pm 0.009 \text{ ps}^{-1}$$

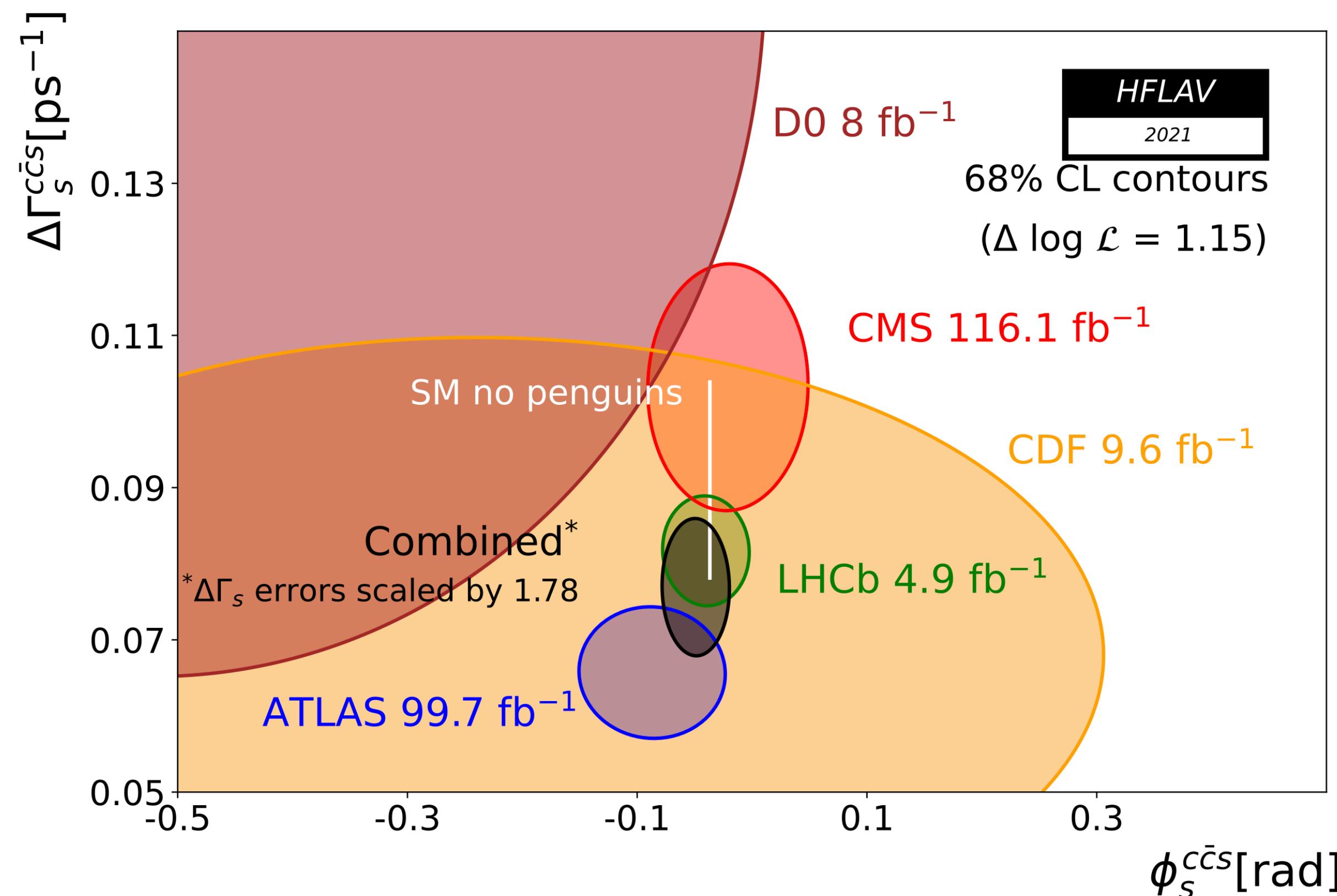
Polarization dependence: No dependence observed



❖ Spline coefficients & FT coefficients Gaussian constrained

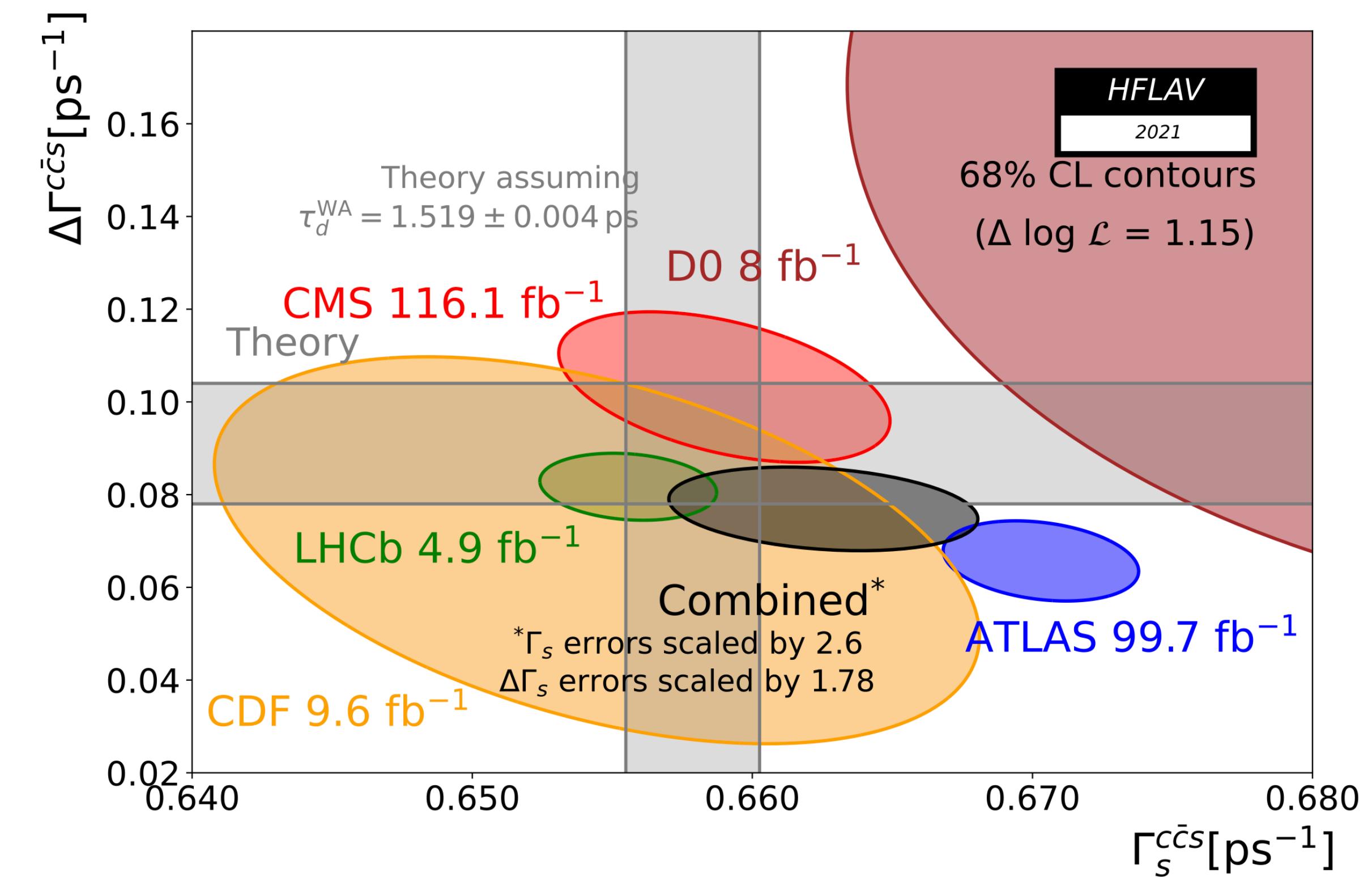
$\phi_s^{c\bar{c}s}$ Combination

HFLAV



SM no penguins
 $-2\beta_s = -36.8^{+0.6}_{-0.9}$ mrad

CKMFitter

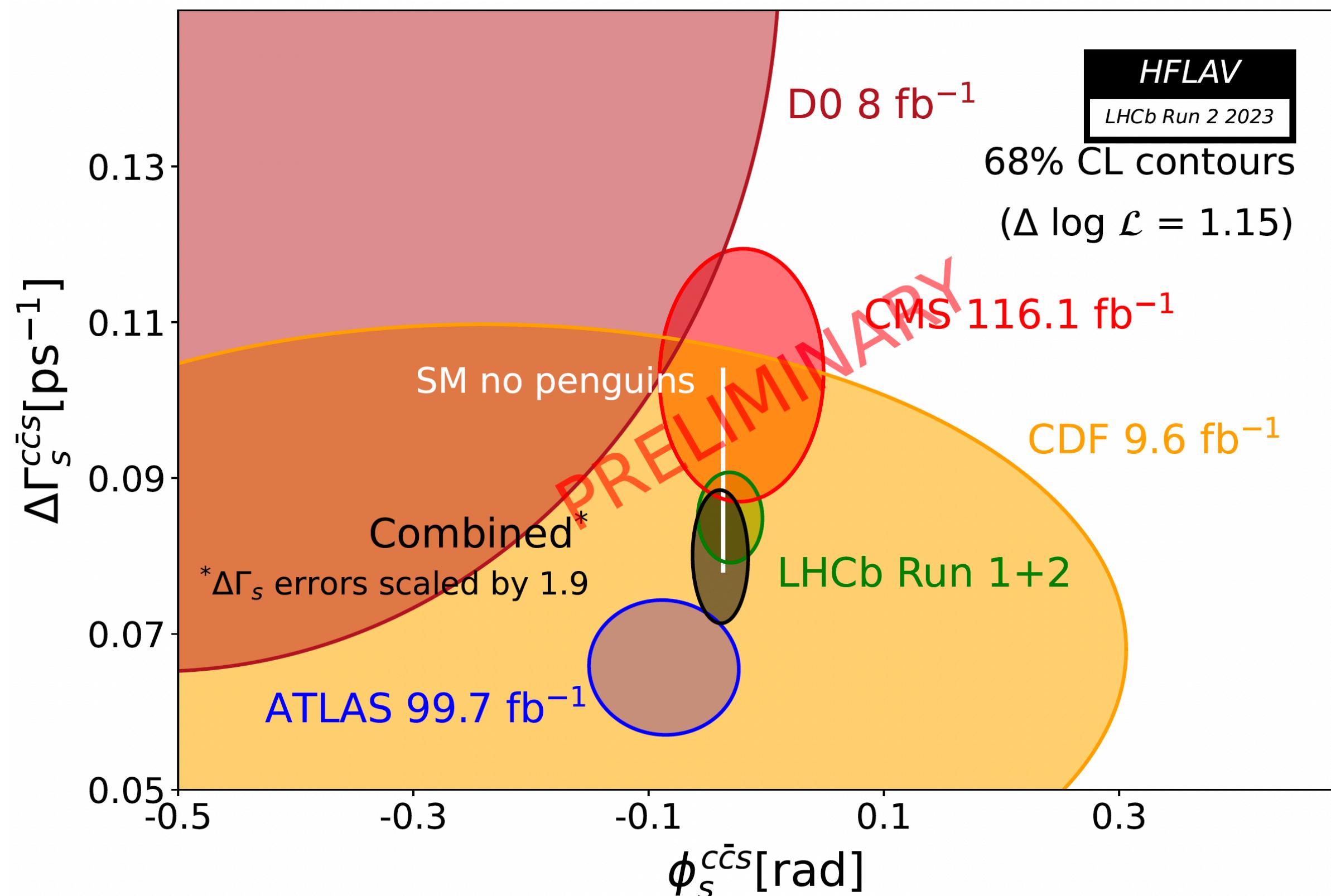


HFLAV old
 $\phi_s^{c\bar{c}s} = -0.049 \pm 0.019$ mrad

$\phi_s^{c\bar{c}s}$ Combination

Preliminary !!!

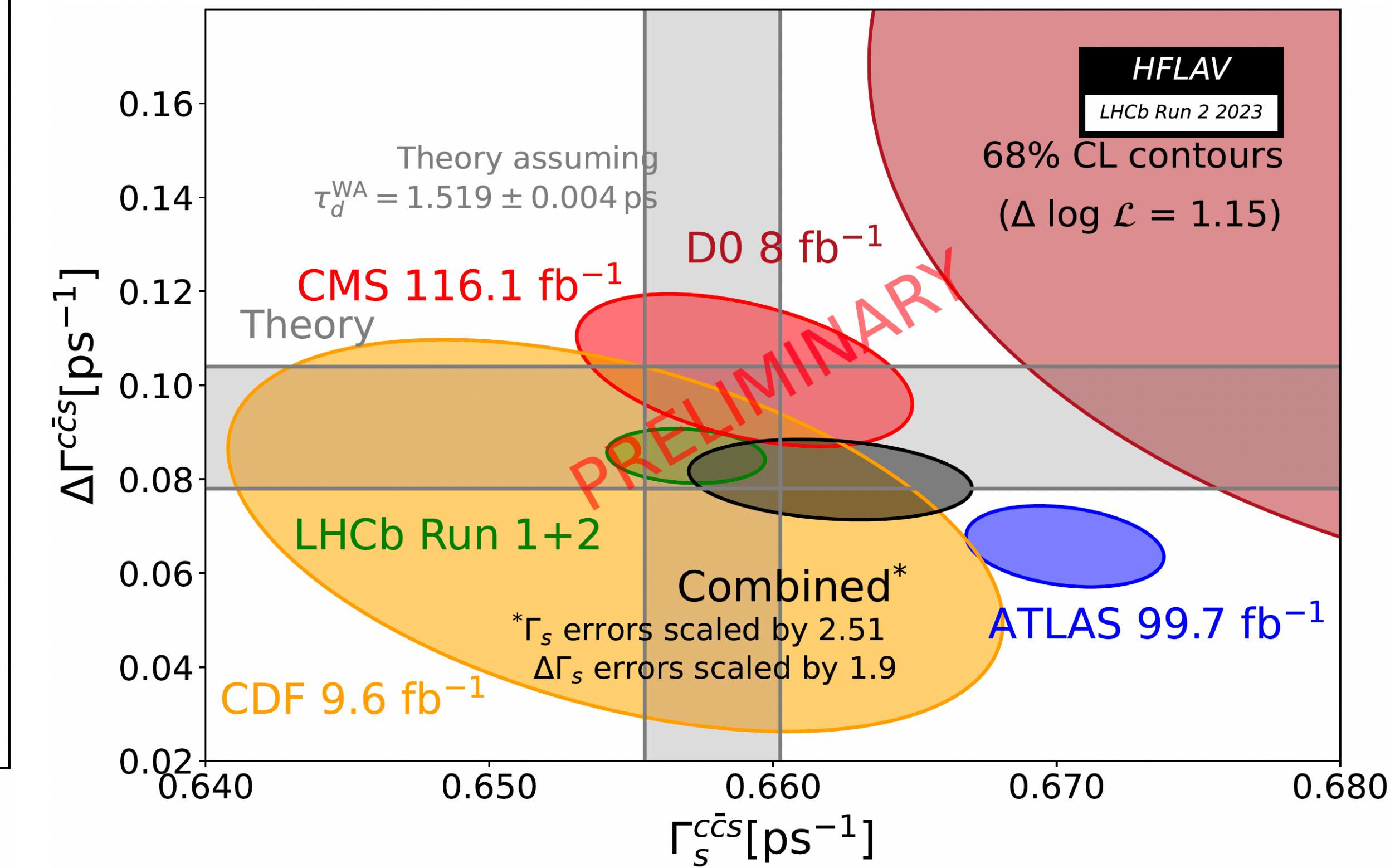
HFLAV



CKMFitter

SM no penguins

$-2\beta_s = -36.8^{+0.6}_{-0.9} \text{ mrad}$



HFLAV Preliminary

$\phi_{s,\text{Prelim.}}^{c\bar{c}s} = -0.039 \pm 0.016 \text{ mrad}$

Summary

- ✓ Measurement of $\sin 2\beta$ using full LHCb Run 2 data set, in agreement with the current world average. Precision from all channels is higher than the current average.
- ✓ Most precise measurement of time-dependent CP asymmetry in any penguin dominated B meson decay using $B_s^0 \rightarrow \phi\phi$. Result in agreement with SM prediction. No polarization dependence observed.
- ✓ Most precise measurement of the CP-violation phase ϕ_s , in agreement with SM prediction. No evidence of CP violation found. No polarization dependence observed. Most precise measurement of $|\lambda|$, $\Delta\Gamma_s$ and $\Gamma_s - \Gamma_d$.

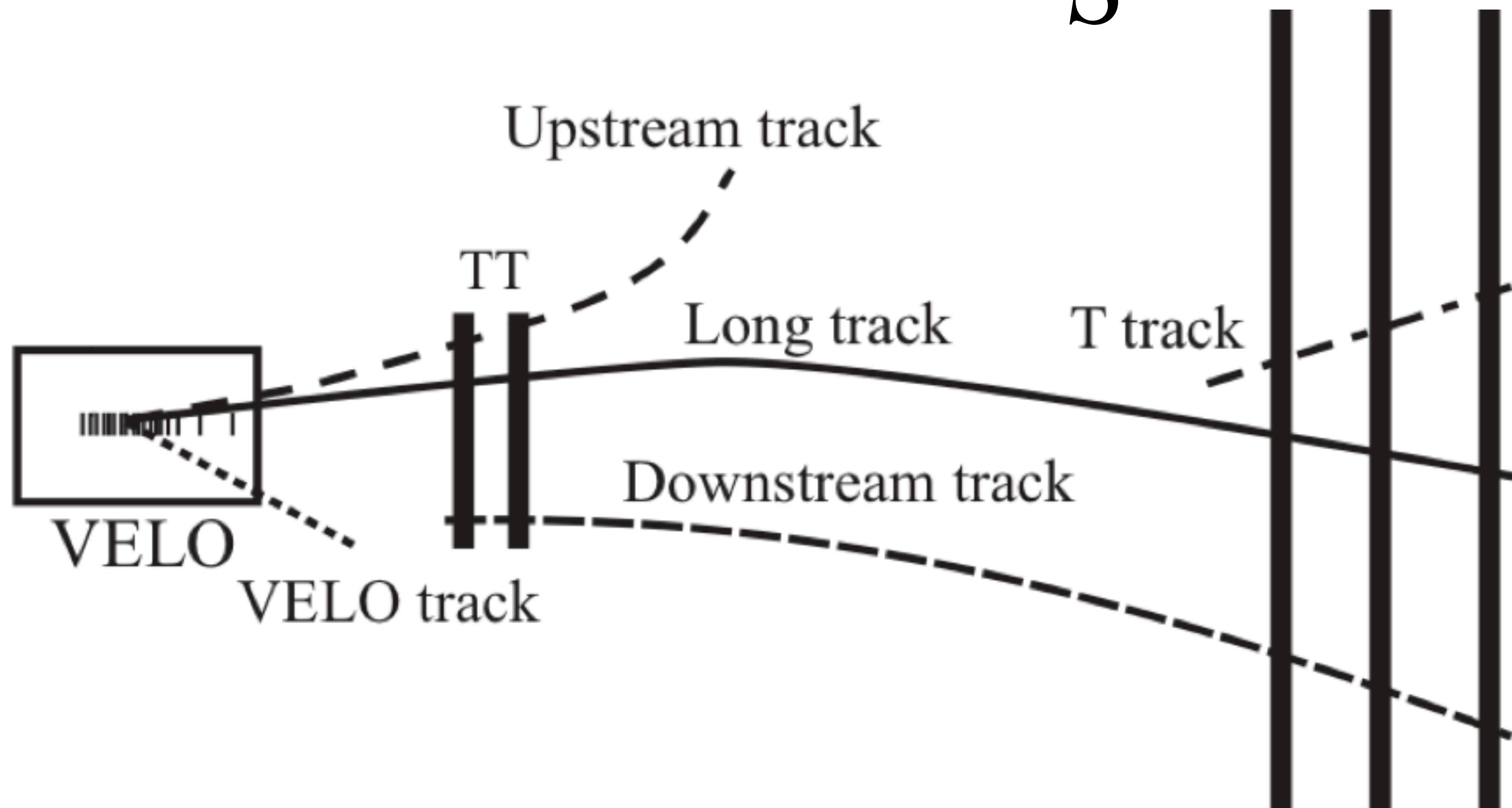
Summary

- ✓ Measurement of $\sin 2\beta$ using full LHCb Run 2 data set, in agreement with the current world average. Precision from all channels is higher than the current average.
- ✓ Most precise measurement of time-dependent CP asymmetry in any penguin dominated B meson decay using $B_s^0 \rightarrow \phi\phi$. Result in agreement with SM prediction. No polarization dependence observed.
- ✓ Most precise measurement of the CP-violation phase ϕ_s , in agreement with SM prediction. No evidence of CP violation found. No polarization dependence observed. Most precise measurement of $|\lambda|$, $\Delta\Gamma_s$ and $\Gamma_s - \Gamma_d$.

Thank you for your attention!

BACKUP

Tracks K_S^0



Using kaon track type combination: LL (1/3) , DD(2/3) + **LD + UL** $J/\psi(\mu^+\mu^-)$ (+13%)

Main systematics $B^0 \rightarrow J/\psi K_s^0$

Table 1: Sources of leading systematic uncertainties for the CP violation parameters S and C of the combined fit. Each contribution is a weighted average of the uncertainties of the individual fits.

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 $\Delta\epsilon_{tag}$ portability	0.0014	0.0017
Decay-time bias model	0.0007	0.0013

$\Delta\Gamma_d$ uncertainty: Pseudoexperiments generated with input values $\Delta\Gamma_d = \pm 1\sigma$

Portability: Differences between control channels and signal modes on FT calibration parameters, create pseudo experiments accounting for different calibration.

Different $\Delta\epsilon_{tag}$: in simulation, fit to data with different inputs.

Decay-time bias model: Pseudoexperiments where the parameters are varied within 1σ

B_s^0 system: Polarization dependence

$$B_s^0 \rightarrow \phi\phi$$

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

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

Parameters	Values
ϕ_s^0 [rad]	-0.034 ± 0.023
$\phi_s^\parallel - \phi_s^0$ [rad]	-0.0019 ± 0.021
$\phi_s^\perp - \phi_s^0$ [rad]	$-0.0008^{+0.020}_{-0.021}$
$\phi_s^S - \phi_s^0$ [rad]	$-0.0022^{+0.027}_{-0.026}$
$ \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 $	$1.121^{+0.085}_{-0.078}$

Systematics $B_s^0 \rightarrow \phi\phi$

Table 2: Systematic uncertainties for physics parameters in the polarization-independent fit, the values are given in units of 10^{-3} (10^{-3} rad for angles).

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

Time resolution: Statistical, Portability (signal and prompt), linear calibration, decay-time bias (from prompt).

Flavor tagging: statistical, Portability, Calibration model, Asymmetry from prompt D_s^+

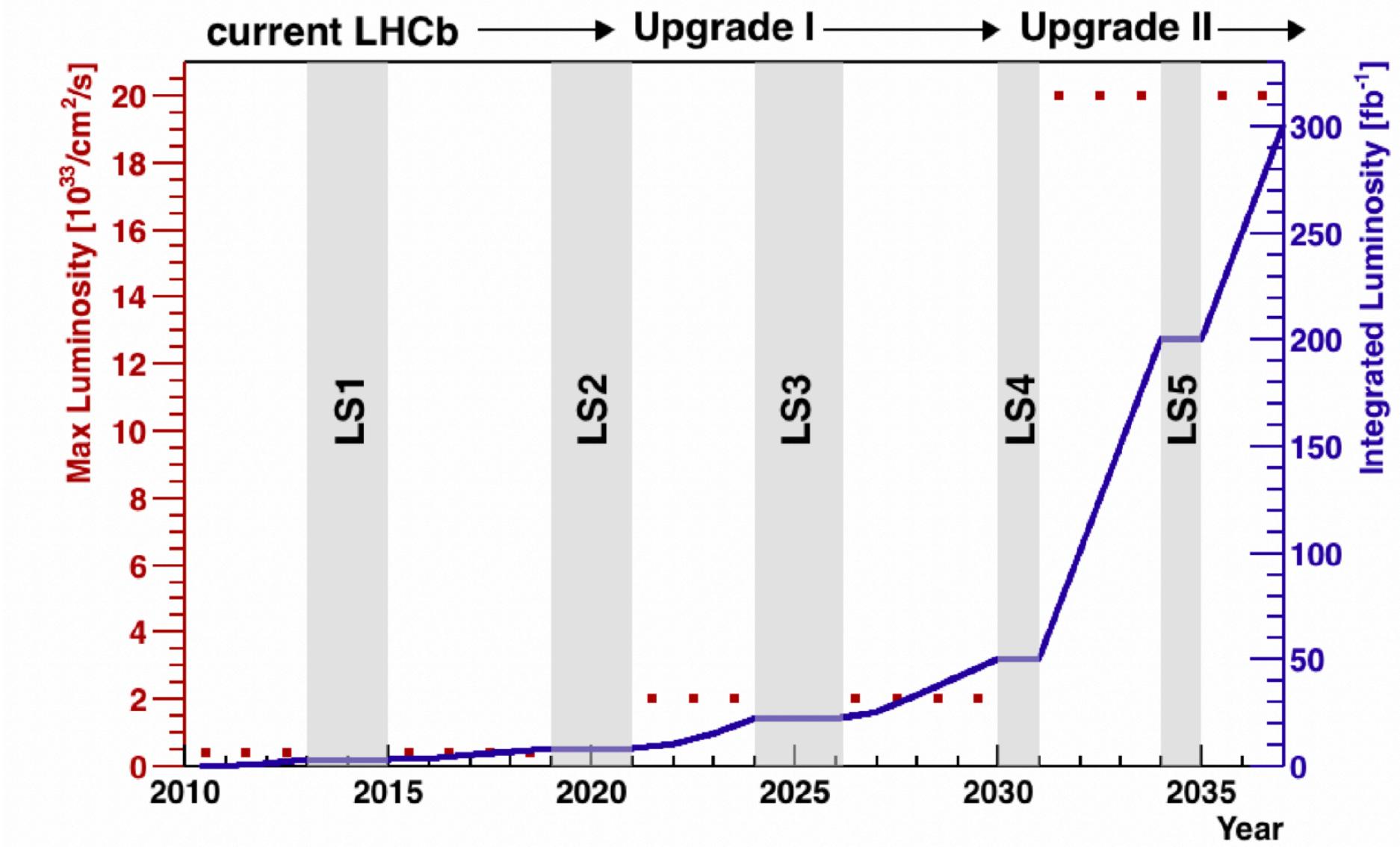
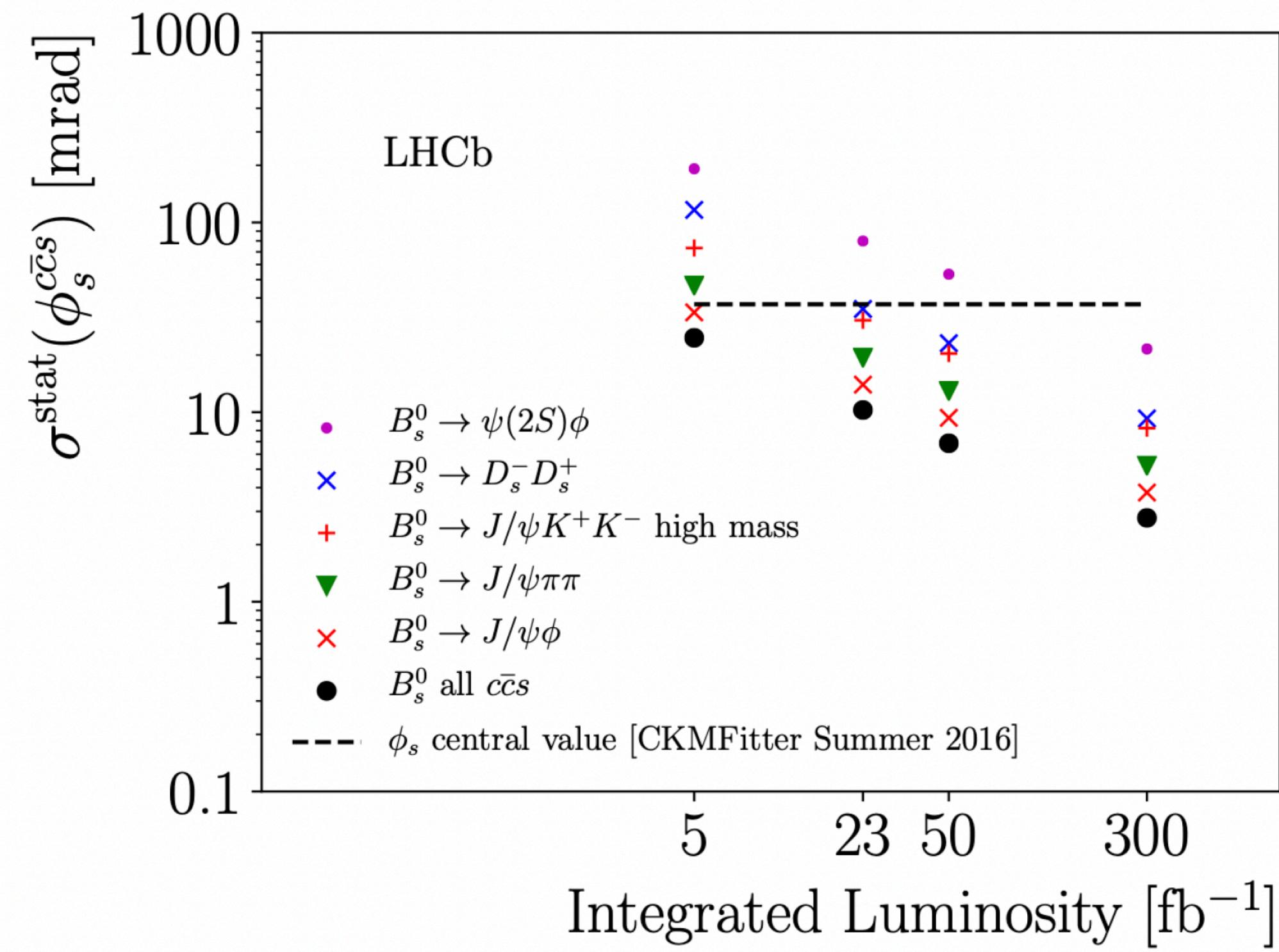
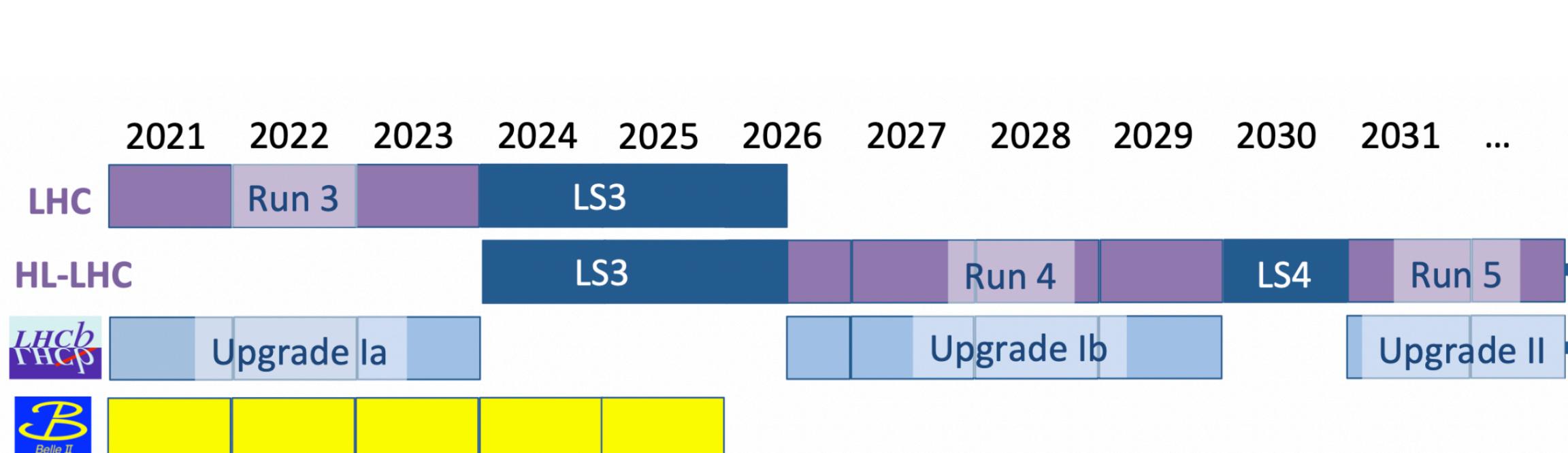
Angular Acceptance: Statistical and Iterative method (Differences between last 2 iterations).

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

Source	$ A_0 ^2$	$ A_{\perp} ^2$	ϕ_s [rad]	$ \lambda $	$\delta_{\perp} - \delta_0$ [rad]	$\delta_{\parallel} - \delta_0$ [rad]	$\Gamma_s - \Gamma_d$ [ps $^{-1}$]	$\Delta\Gamma_s$ [ps $^{-1}$]	Δm_s [ps $^{-1}$]	($\times 0.01$)
Mass parameterization	0.04	0.03	0.03	0.02	0.15	0.12	0.02	0.04	0.03	
Mass factorization	0.11	0.10	0.42	0.19	0.54	0.60	0.12	0.16	0.18	
Mass: shape statistical	0.04	0.04	0.05	0.09	0.62	0.33	0.02	0.01	0.11	
B_c^+ contamination ¹	0.04	0.05	—	0.02	—	0.17	(0.07)	(0.03)	—	
f_2 component	0.04	0.04	0.02	—	0.07	0.13	0.01	0.03	0.02	
Clone candidates	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_{SP} factors	—	0.01	0.01	0.03	0.73	0.41	—	0.01	0.04	
DTR ² calibration	—	—	0.03	0.02	0.11	0.07	—	—	0.05	
DTR model applicability	—	—	0.08	0.03	0.26	0.09	—	—	0.09	
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	
Position uncertainty	0.07	0.04	0.04	—	0.10	0.09	0.02	—	0.31	
Neglected correlations	—	—	—	—	4.20	4.96	—	—	—	
Total systematic uncertainty	0.31	0.24	0.64	0.54	4.82	5.17	0.14	0.24	0.86	
Statistical uncertainty	0.17	0.23	2.15	1.1	7.5	6.1	0.14	0.44	3.3	

Future Prospects

1808.08865



	Upgrade I	Upgrade II
$\sigma(\sin(2\beta))_{\text{stat}}$	0.011	0.003
$\sigma(\phi_s(J\psi KK))_{\text{stat}}$	14 mrad	4 mrad
$\sigma(\phi_s(\phi\phi))_{\text{stat}}$	39 mrad	11 mrad