Measurement of the CP violating phase ϕ_s and $\phi_s^{sq\bar{q}}$ at LHCb

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Introduction

- The measurement of the mixing-induced *CP*-violating phase ϕ_s in the $B_s^0 - \bar{B}_s^0$ system is one of the key goals of the LHCb experiment → Probe to physics beyond the Standard Model (SM).

- ϕ_s is related to the interference of B_s^0 mixing and decay amplitudes

$$\phi_s^{SM} \equiv -2\beta_s = -2arg(\frac{-V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}),$$

Predicted to be very precise

Neglecting penguin diagram contributions, PhysRevD.91.073007

Experimentally, can be accessed via the time-dependent asymmetries

$$\mathscr{A}_{CP}(t) = \frac{\Gamma_{\overline{B}_s^0}(t) - \Gamma_{B_s^0}(t)}{\Gamma_{\overline{B}_s^0}(t) + \Gamma_{B_s^0}(t)} = \frac{S_f \sin(\Delta m_s t) - C_f \cos(\Delta m_s t)}{\cosh(\frac{\Delta\Gamma_s t}{2}) + A^{\Delta\Gamma}\sinh(\frac{\Delta\Gamma_s t}{2})},$$

Parameters

C_f : Direct CP asymmetry

S_f and $A^{\Delta\Gamma}$: Mixing induced CP asymmetries

$\Gamma_{B_s^0(\bar{B}_s^0)}$: Time-dependent decay rate

$\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H$: Difference in the decay width between two mass eigenstates, B_L and B_H

$\Delta m_s \equiv m_H - m_L$: Mass difference

Introduction

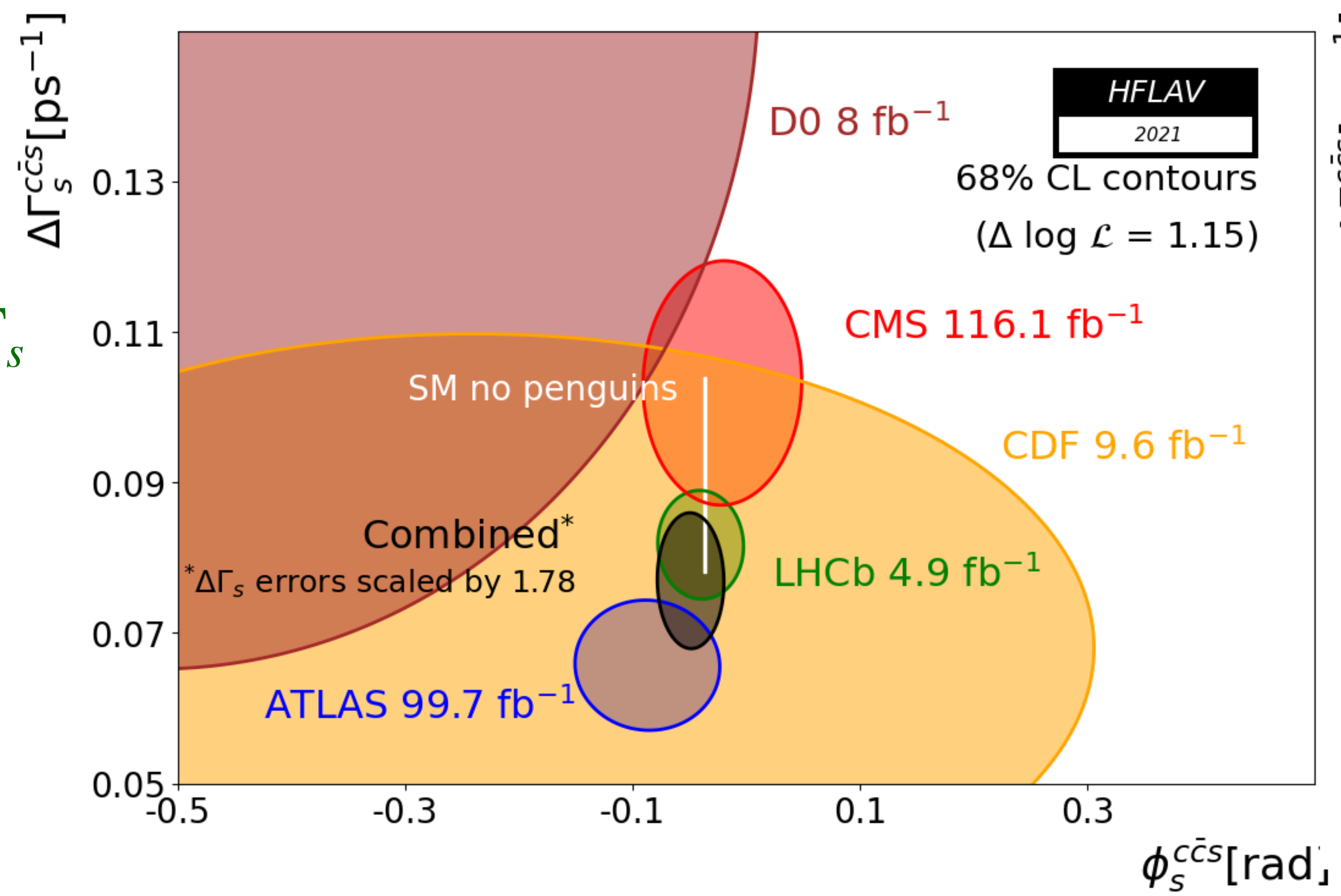
- These parameters are related to ϕ_s by

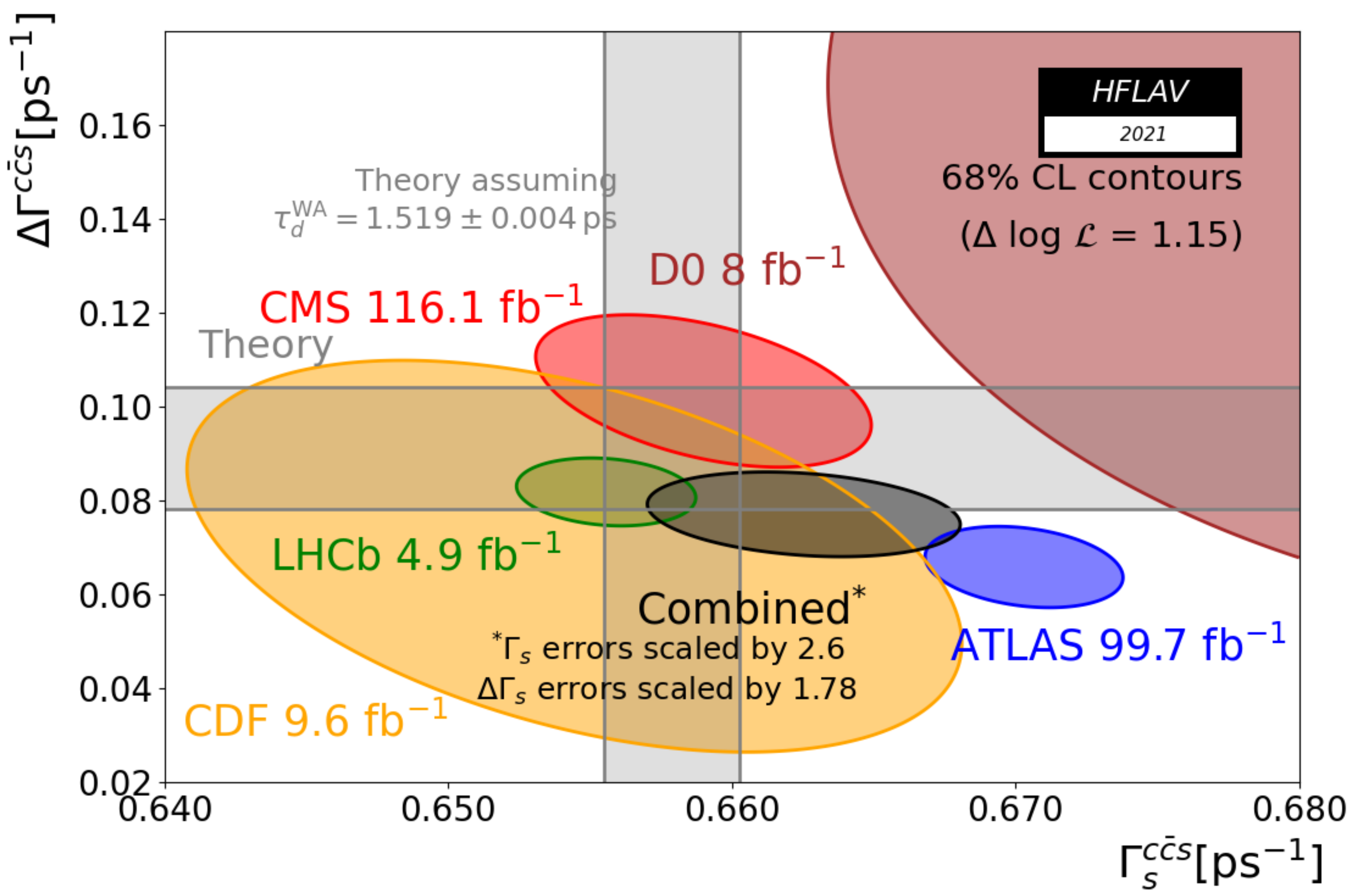
$$S_f = \eta_f \sin\phi_s, \text{ and } A^{\Delta\Gamma} = -\eta_f \cos\phi_s$$

t: Decay time
η_f: CP eigenvalue of the final state
Γ_s: Average width of B_s^0

The parameters of *CP*-violation are obtained experimentally through a flavor-tagger time-dependent angular analysis

Overview of current world averages of ϕ_s, $\Delta\Gamma_s$ and Γ_s





HFLAV group

Outline

- **Measurement of ϕ_s in $B_s^0 \to J/\psi K^+ K^-$ decays**
  - $\mathcal{L}$ = 6 fb^{-1} , Run 2 data from 2015 to 2018, (arXiv: 2308.01468)
- CP **violation measurements in the penguin-mediated decay** $B_s^0 \to \phi\phi$
  - $\mathcal{L}$ = 6 fb^{-1} , Run 2 data from 2015 to 2018, arXiv:2304.06198
- **A measurement of $\Delta\Gamma_s$ from $B_s^0 \to J/\psi\eta'$ and $B_s^0 \to J/\psi\pi^+\pi^-$ decays**
  - $\mathcal{L}$ = 9 fb^{-1} , Run 1 2011 + 2012 and Run 2 2015 to 2018 data, LHCb-PAPER-2023-025

- **Measurement of ϕ_s in $B_s^0 \to J/\psi K^+ K^-$ decays**
  - $\mathscr{L}$ = 6 fb^{-1} , Run 2 data from 2015 to 2018, arXiv: 2308.01468

Measurement of ϕ_s in $B_s^0 \to J/\psi K^+K^-$ (arXiv: 2308.01468)

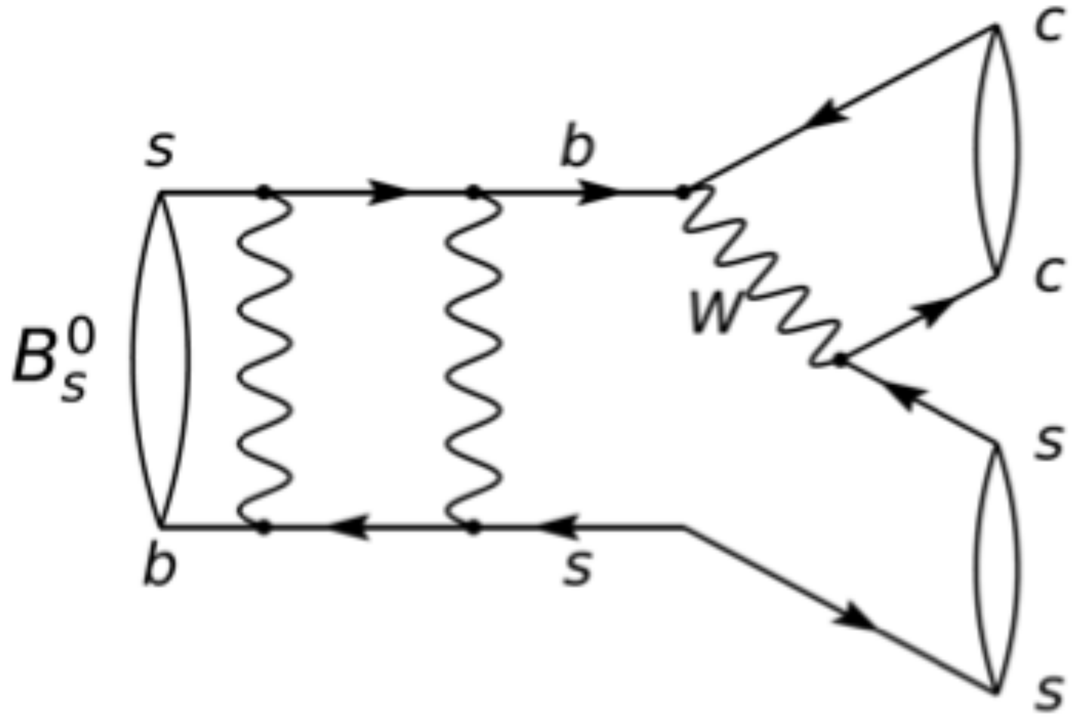
The LHCb collaboration has previously measured ϕ_s in the golden channel $B_s^0 \to J/\psi(\mu^+\mu^-)K^+K^-$ in the region of $\phi(1020)$ resonance, which gives the best sensitivity in ϕ_s [arXiv:1906.08356]

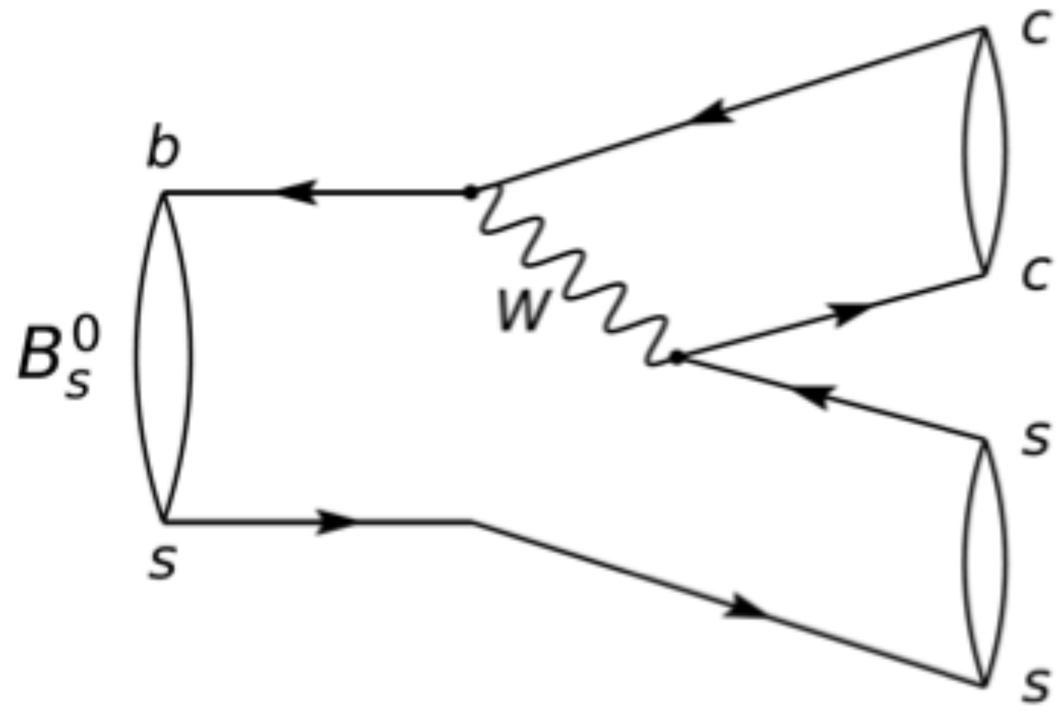
- Global fits to experimental data, gives $-2\beta_s = -36.9^{+0.9}_{-0.6}$ mrad (CKMFitter arXiv:1501.05013),
  $-2\beta_s = -37.0 \pm 1.0$ mrad (UTFit arXiv:hep-ph/0606167)

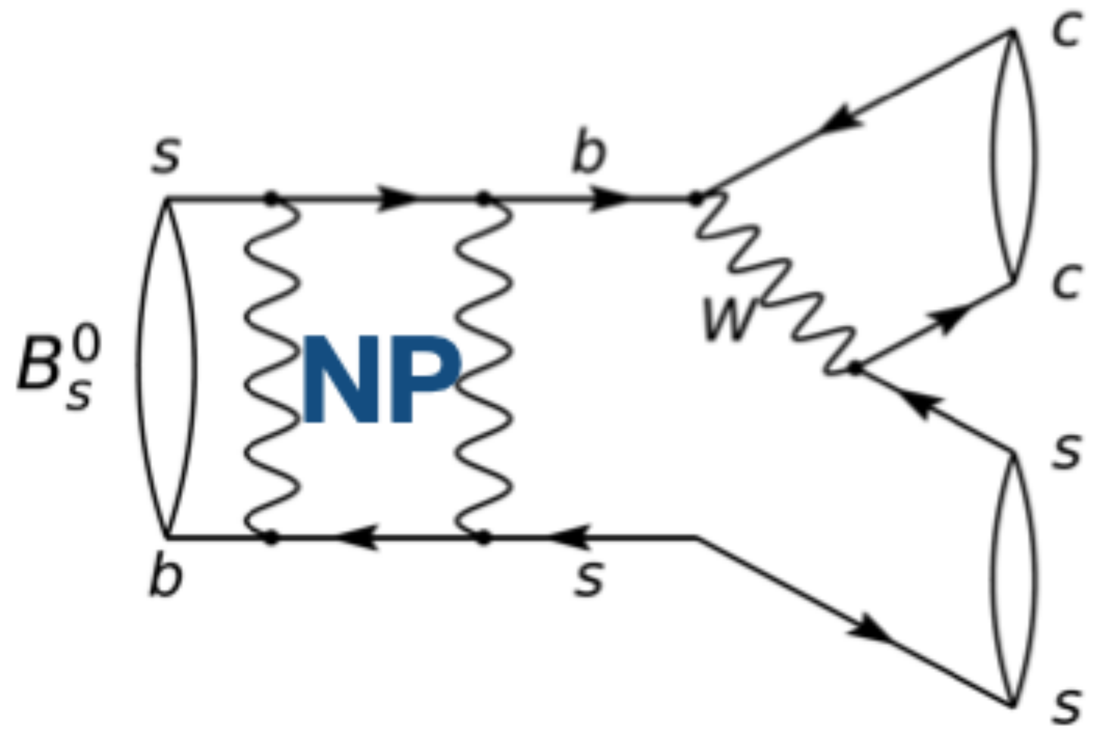
$$\phi_s = -2\beta_s + \Delta\phi_s^{NP}$$

Penguin pollution is small

$B_s^0 \to J/\psi K^+K^-$, via $b \to c\bar{c}s$ transition





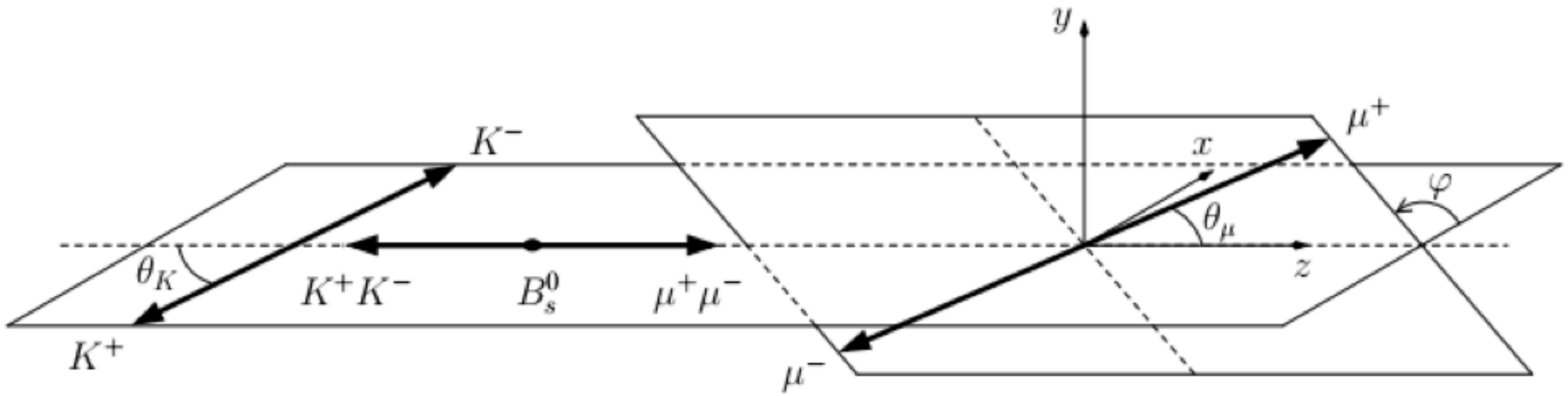


Measurement of ϕ_s in $B_s^0 \to J/\psi K^+K^-$ (arXiv: 2308.01468)

- The current World Average value for $\phi_s^{c\bar{c}s} = -0.049 \pm 0.019$ rad, dominated by LHCb result in $B_s^0 \to J/\psi h^+h^-$, with $h = K, \pi$ using 5 fb^{-1} [PDG2022]

- In this analysis an update of the CP-violating phase $\phi_s^{c\bar{c}s}$ is performed as well of the physics parameter $|\lambda|, \Delta\Gamma_s, \Gamma_s - \Gamma_d$ and the B_s^0 mass difference Δm_s, using the $B_s^0 \to J/\psi K^+K^-$ channel, in the vicinity of $\phi(1020)$ resonance with the full Run 2 dataset.

- The polarization amplitudes $\underbrace{A_0, A_{||}, A_\perp}_{\text{P-wave}} + \underbrace{A_s}_{\text{S-wave}}$ regarding to the polarization states of the K^+K^- system and *CP*-odd KK S-wave component are also determined.



Measurement of ϕ_s in $B_s^0 \to J/\psi K^+K^-$ (arXiv: 2308.01468)

Analysis Strategy

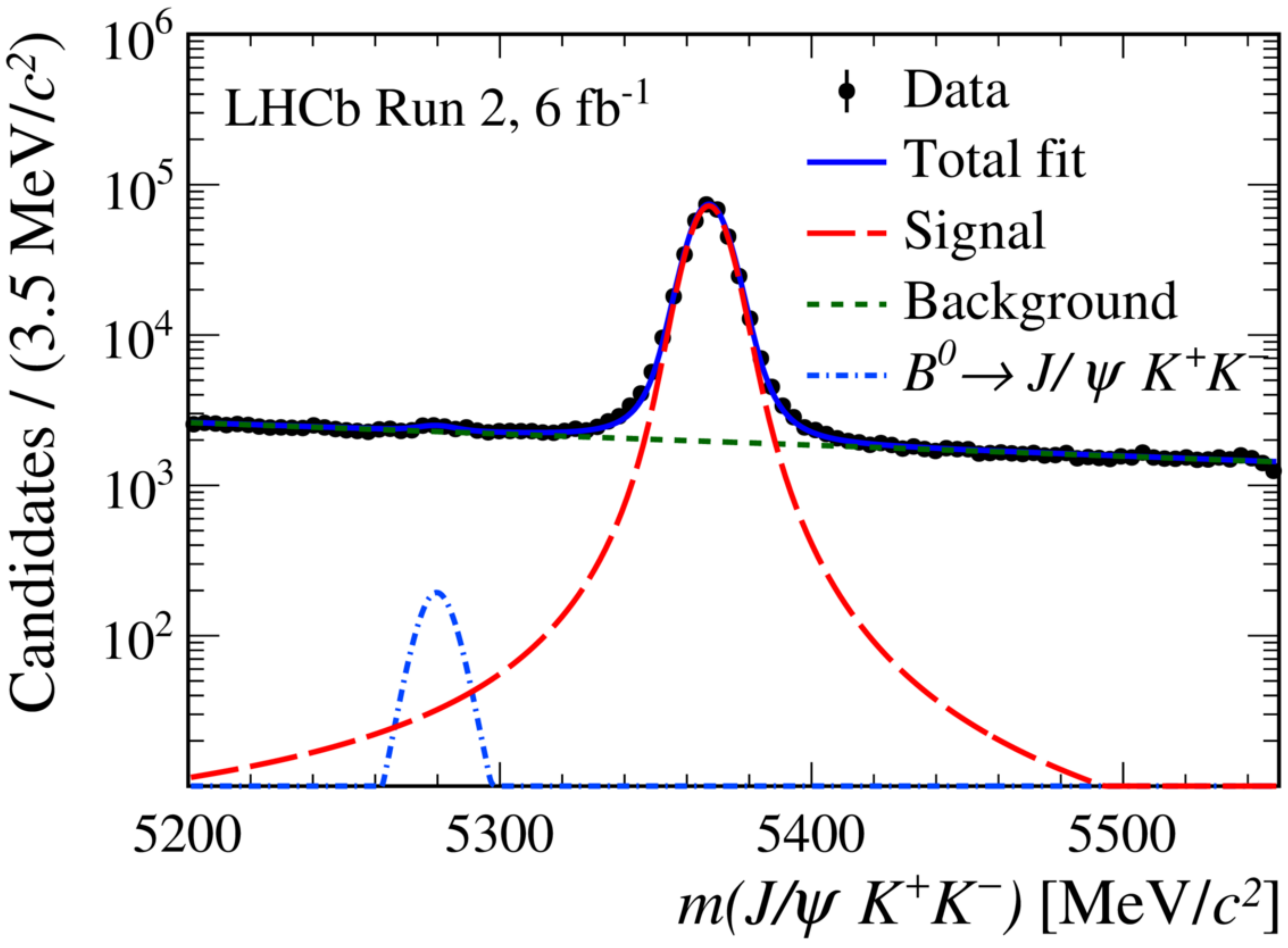
- Very similar to previous analysis [arXiv:1906.08356]

- A selection criteria considering the K^+K^- invariant mass region [990, 1050] MeV/c^2.

- The data sample is divided in 48 independent subsamples: 6 bins in the $\phi(1020)$ regions; two trigger categories, and four years of data taking

- **A yield of about 349 000 signal decays**

- **Extended maximum likelihood fit to extract $B_s^0 \to J/\psi K^+K^-$ signal yields.**



(arXiv: 2308.01468)

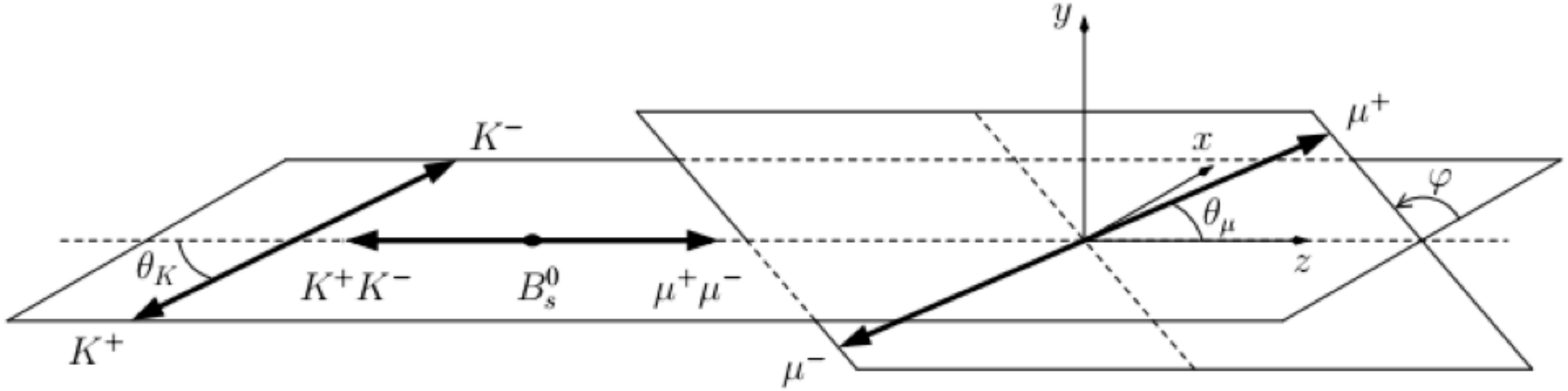
Measurement of ϕ_s in $B_s^0 \to J/\psi K^+ K^-$ (arXiv: 2308.01468)

- **To extract ϕ_s, CP-even and CP-odd decay-amplitudes need to be disentangled.**

  - A weighted simultaneous fit to decay time distribution and decays angles ($cos\theta_K, cos\theta_\mu, \phi_h$) in the helicity basis is performed.

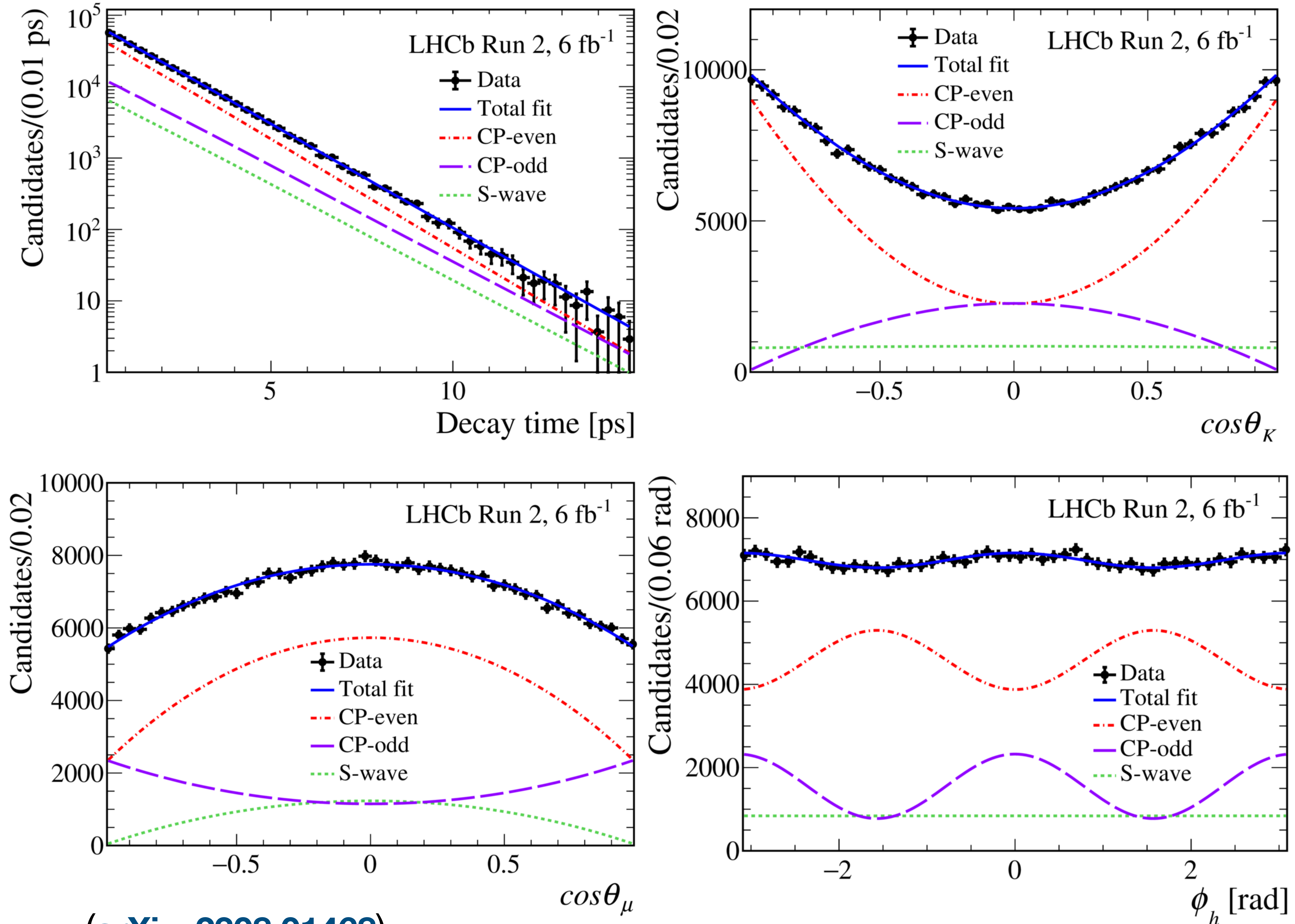
  - For each of the 48 sub-sample the fit function accounts for

    - **Decay-time resolution**
    - **The decay-time**
    - **Flavor tagging**
    - **Angular efficiencies**



Time dependent angular rate: $t, \theta_K, \theta_l, \phi$

Measurement of ϕ_s in $B_s^0 \to J/\psi K^+ K^-$ ([arXiv: 2308.01468](https://arxiv.org/abs/2308.01468))



([arXiv: 2308.01468](https://arxiv.org/abs/2308.01468))

Background-substracted data distribution with fit overlaid for Decay-time and decay-angles.

Parameter	Values		
ϕ_s [rad]	-0.039	± 0.022	± 0.006
$\lvert\lambda\rvert$	1.001	± 0.011	± 0.005
$\Gamma_s - \Gamma_d$ [ps^{-1}]	-0.0056	${}^{+0.0013}_{-0.0015}$	± 0.0014
$\Delta\Gamma_s$ [ps^{-1}]	0.0845	± 0.0044	± 0.0024
Δm_s [ps^{-1}]	17.743	± 0.033	± 0.009
$\lvert A_\perp\rvert^2$	0.2463	± 0.0023	± 0.0024
$\lvert A_0\rvert^2$	0.5179	± 0.0017	± 0.0032
$\delta_\perp - \delta_0$ [rad]	2.903	${}^{+0.075}_{-0.074}$	± 0.048
$\delta_\parallel - \delta_0$ [rad]	3.146	± 0.061	± 0.052

[arXiv: 2308.01468](https://arxiv.org/abs/2308.01468)

Results are in good agreement with LHCb Run 1 and 2015+2016 measurements

Measurement of ϕ_s in $B_s^0 \to J/\psi K^+ K^-$

In summary

Using the full Run 2 dataset collected by the LHCb experiment, it is measured

- $\phi_s = -0.039 \pm 0.022 \pm 0.006$ rad
- $\Gamma_s - \Gamma_d = -0.0056^{+0.0013}_{-0.0015} \pm 0.0014$
- $|\lambda| = 1.001 \pm 0.011 \pm 0.005$
- $\Delta\Gamma_s = 0.0845 \pm 0.0044 \pm 0.0024$

arXiv: 2308.01468

Superseding the previous Run 2 LHCb measurement in the same decay

No evidence for CP violation

Results consistent with previous measurements in $B_s^0 \to J/\psi(\mu^+\mu^-)K^+K^-$ and $B_s^0 \to J/\psi(e^+e^-)K^+K^-$ decays.
The combination results in

$$\phi_s = -0.044 \pm 0.020 \text{ rad}$$

$$|\lambda| = 0.990 \pm 0.010$$

- ϕ_s measurements independently for each polarization state of the K^+K^- system

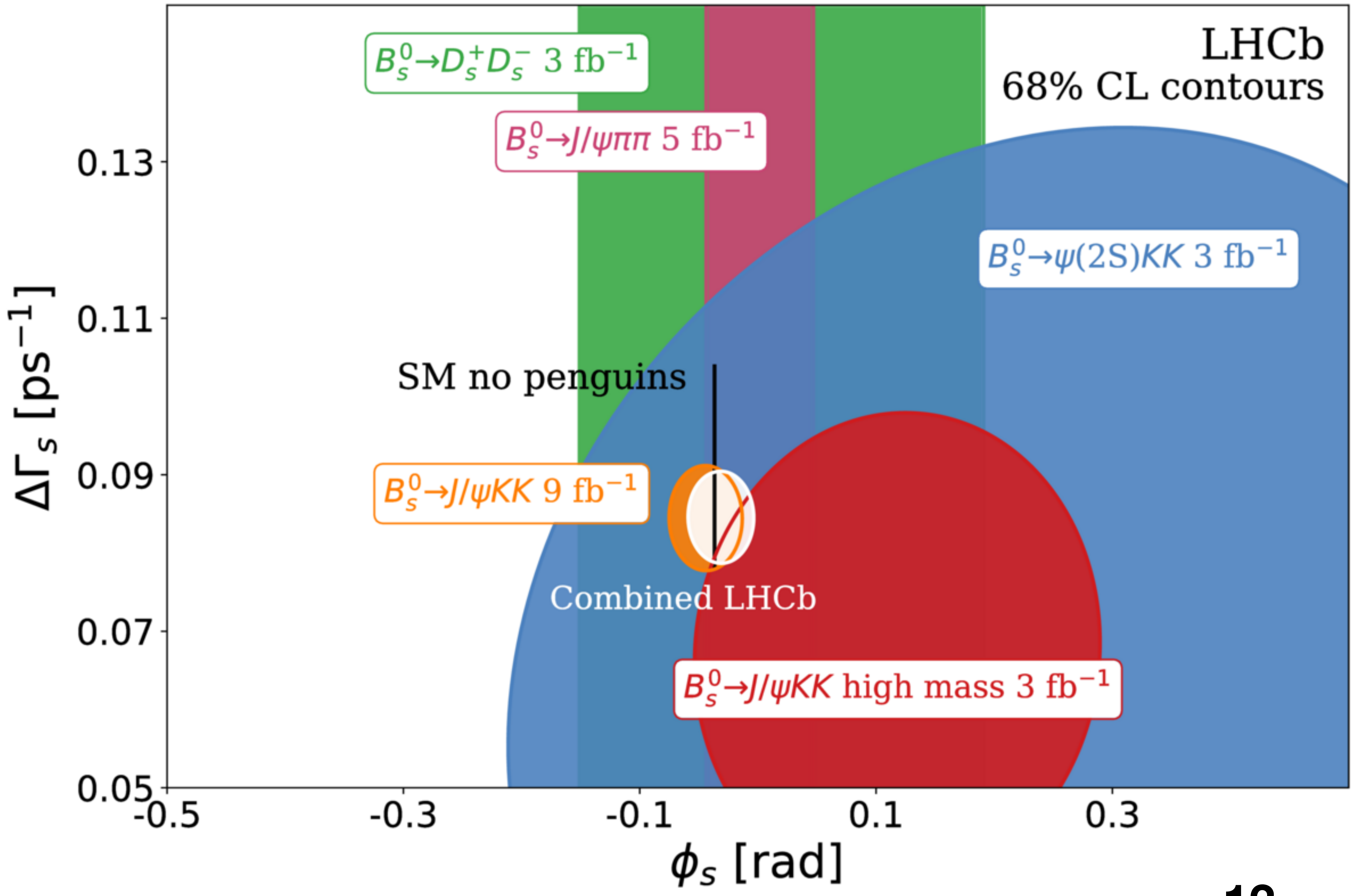
→ Shows no evidence for polarization dependence

arXiv: 2308.01468

Measurement of ϕ_s in $B_s^0 \to J/\psi K^+ K^-$ arXiv: 2308.01468

Combination of all LHCb ϕ_s measurements of B_s^0 decays via $b \to c\bar{c}s$: $B_s^0 \to J/\psi(\mu^+\mu^-)K^+K^-$, $B_s^0 \to D_s^+ D_s^-$, $B_s^0 \to J/\psi \pi^+\pi^-$, $B_s^0 \to J/\psi(2S)K^+K^-$ and $B_s^0 \to J/\psi K^+K^-$ gives

[PRL 114 (2015) 041801, EPJC 79 (2019) 706, EPJC81 (2021) 1026]
[PLB 736 (2014) 186, PLB 797 (2019) 134789, PLB 762 (2016) 253, PRL 113 (2014) 211801]



$$\boxed{\phi_s = -0.031 \pm 0.018 \text{ rad}}$$

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

- CP **violation measurements in the penguin-mediated decay** $B_s^0 \to \phi\phi$
    - $\mathcal{L}$ = 6 fb^{-1} , Run 2 data from 2015 to 2018, arXiv:2304.06198

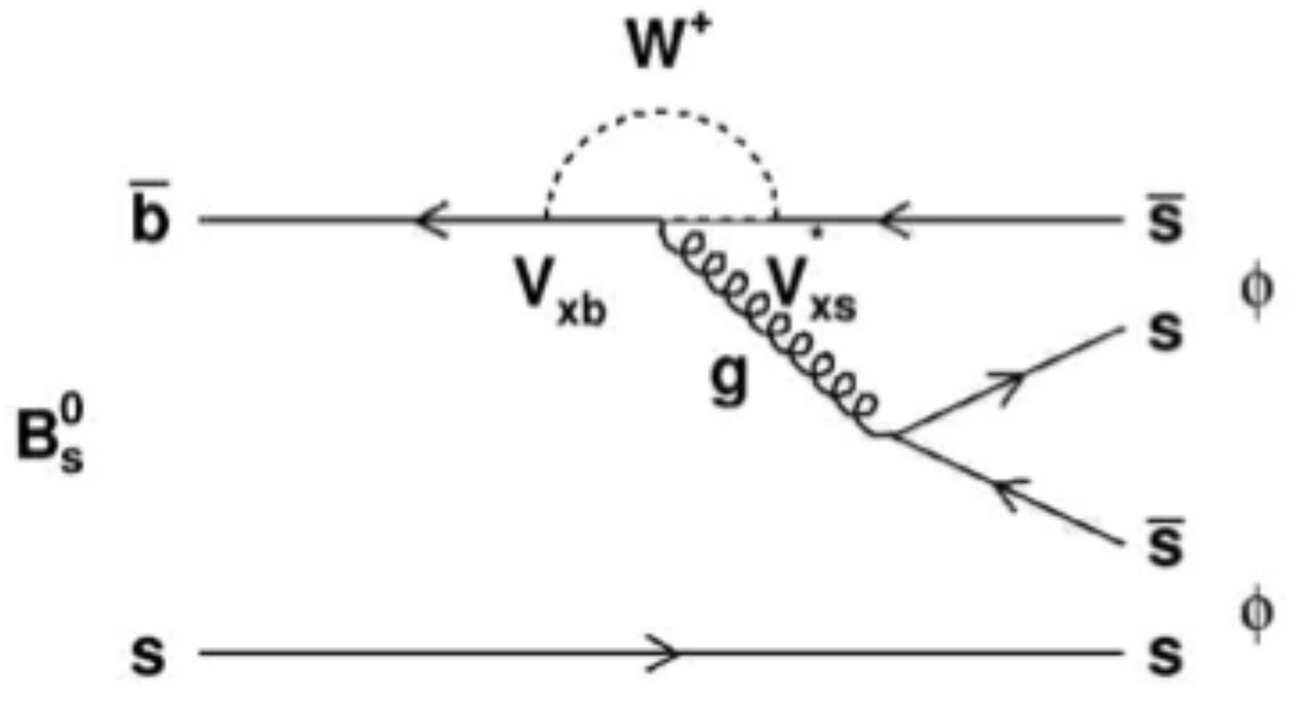
CP violation measurements in the penguin-mediated decay $B_s^0 \to \phi\phi$

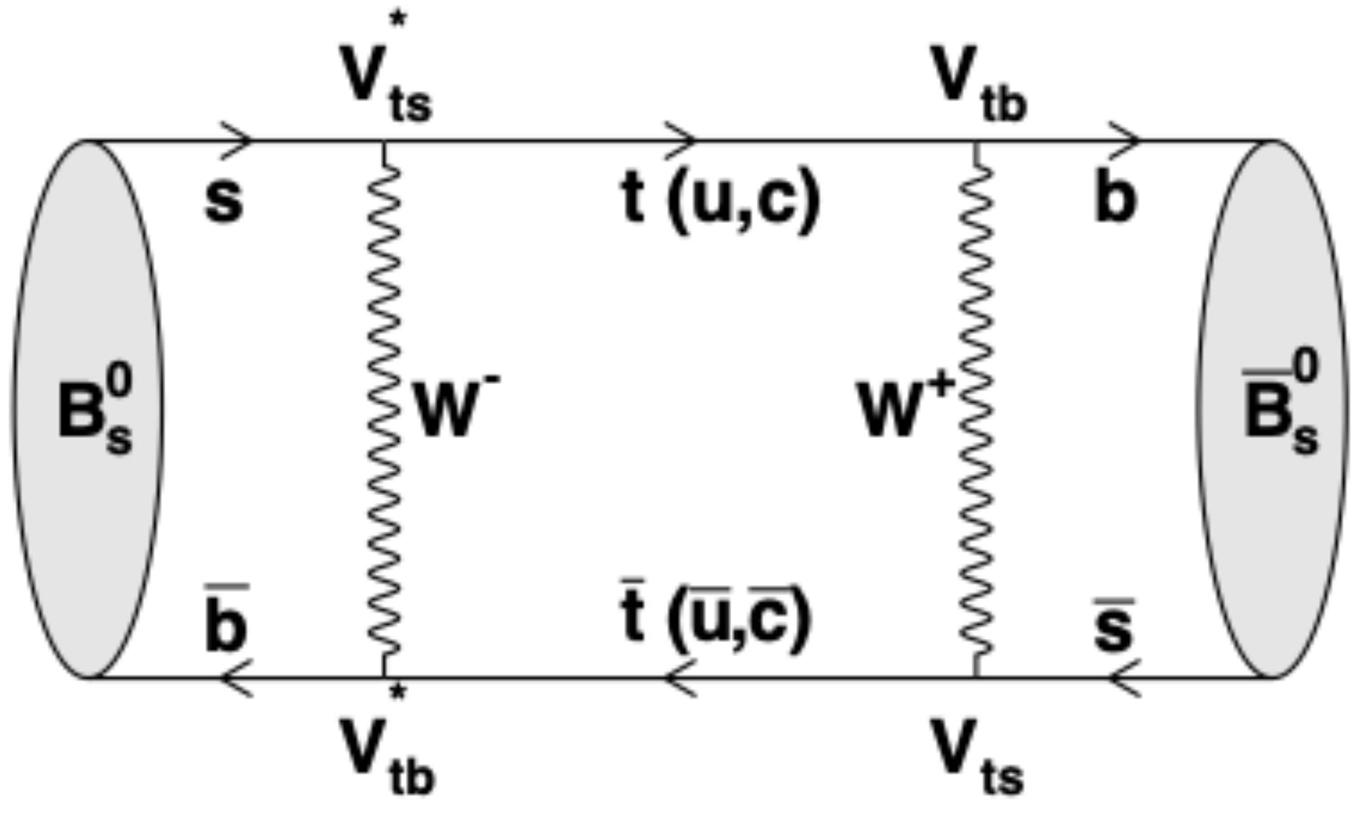
Flavour-changing neutral current (FCNC) decays of B mesons are highly sensitive to new physics contribution entering via loop processes

•arXiv:2304.06198

$B_s^0 \to \phi\phi$ ($b \to s\bar{s}s$ **transition)**

Benchmark channel at LHCb





- Measurements of the CP violation phase $\phi_s^{s\bar{s}s}$ and parameter $|\lambda|$ → New physics contributions entering in the penguin decay or mixing would be reflected in $\phi_s^{s\bar{s}s}$ and $|\lambda|$ values

- The $\phi\phi$ system produce three linear polarization states, new physics effects could be polarization dependent.

CP violation measurements in the penguin-mediated decay $B_s^0 \to \phi\phi$

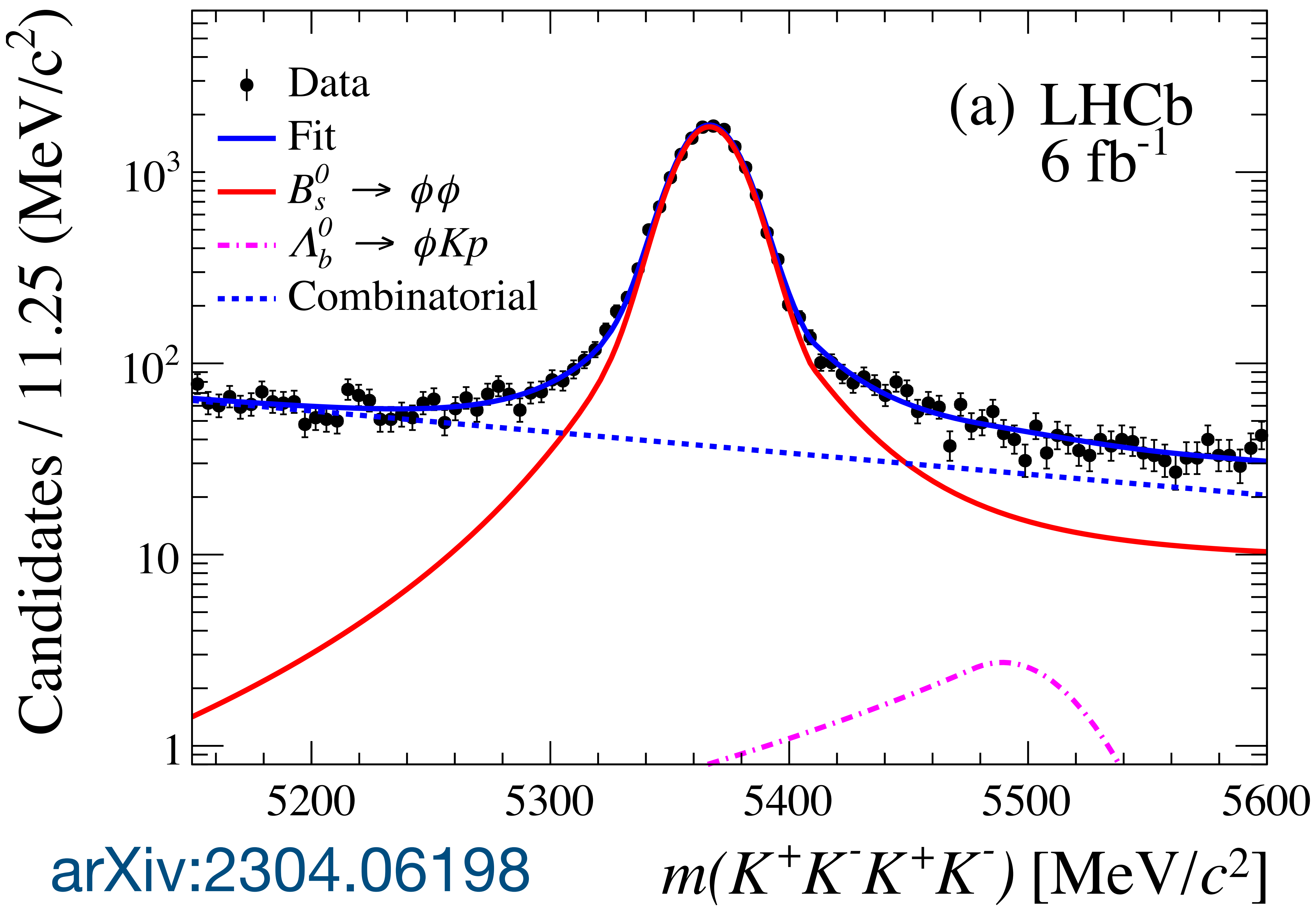
In this analysis the update measurements of the CP-violation parameters in $B_s^0 \to \phi\phi$ decays is reported with full Run 2 dataset (6 fb^{-1}), performing an angular analysis

Measurement of the CP-violation parameters independently for all polarization states for the first time

Analysis Strategy (same as ref JHEP 12 (2019) 155)

- $B_s^0 \to \phi\phi$ candidates selected in the mass region [5150, 5600] MeV/c^2
- Enhancing selection of four kaons in the final state ($K^+K^-K^+K^-$)
- Two sources of background: Combinatorial and from $\Lambda_b^0 \to \phi K^- p$ decays
- A maximum likelihood fit performed to $m(K^+K^-K^+K^-)$ invariant mass

15840 ± 140 **signal events extracted**

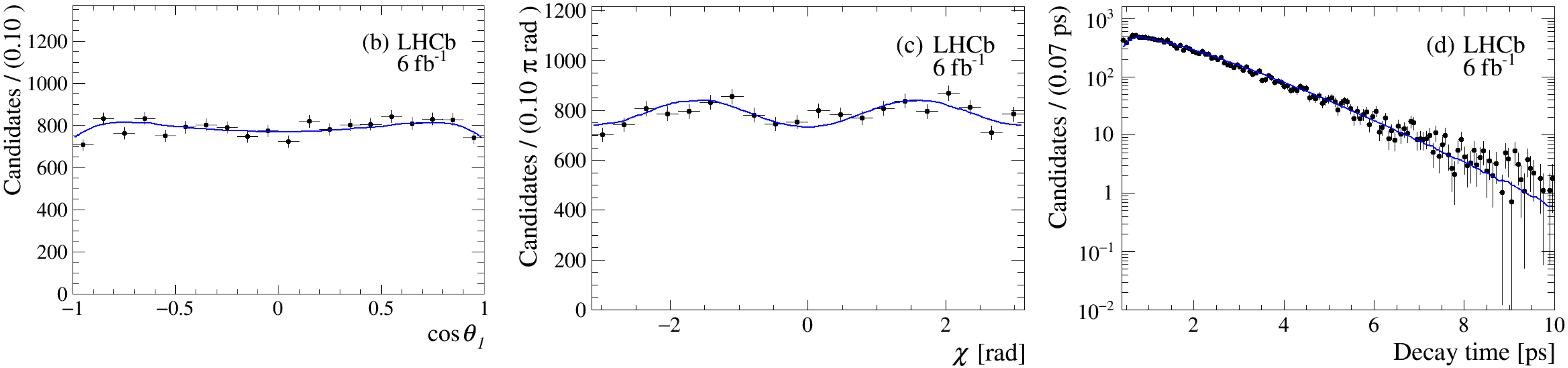


arXiv:2304.06198

CP violation measurements in the penguin-mediated decay $B_s^0 \to \phi\phi$

Fit projections onto background-subtracted distributions of angular variables and decay-time.

arXiv:2304.06198



where $\theta_l = \theta_1, \theta_2$ denotes the helicity angles of the K mesons in the corresponding ϕ rest frame.
χ is the angle between the two $\phi \to K^+K^-$ decay planes

CP violation measurements in the penguin-mediated decay $B_s^0 \to \phi\phi$

Measured observables in the polarization-independent fit

arXiv:2304.06198

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]	$2.769 \pm 0.105 \pm 0.011$

The following parameters have been constrained to the measurements by LHCb collaboration

$\Delta m_s = 17.766 \pm 0.006$ ps^{-1}

$\Gamma_s = 0.657 \pm 0.002$ ps^{-1}

$\Delta\Gamma_s = 0.078 \pm 0.006$ ps^{-1} with correlation coefficient of -0.35

In combination with LHCb Run 1 measurements

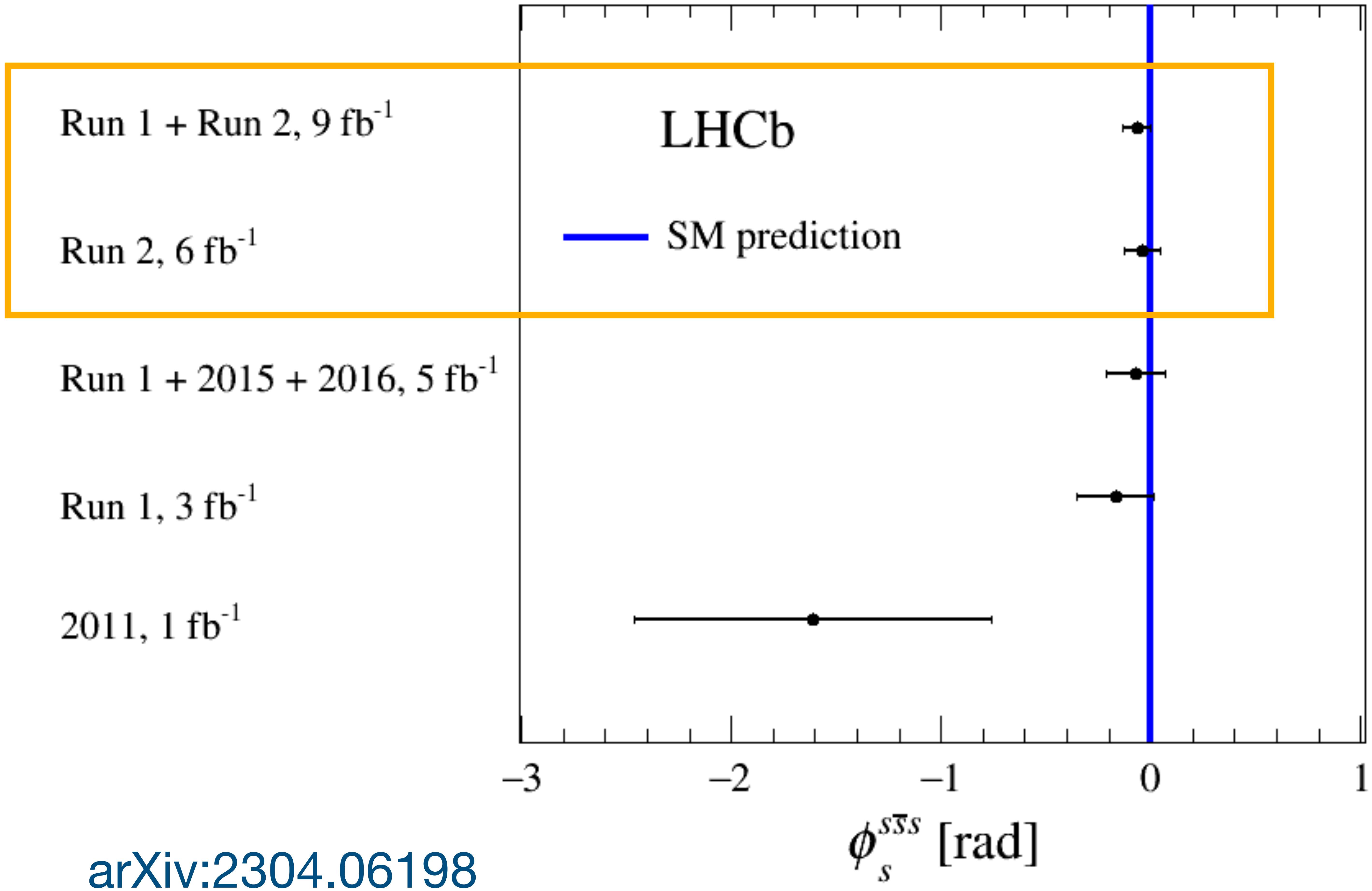
$\boxed{\phi^{s\bar{s}s} = -0.074 \pm 0.069 \text{ rad } \textbf{and } |\lambda| = 1.009 \pm 0.07 \pm 0.030}$

arXiv:2304.06198

This is the most precise measurement of *CP* violation in $B_s^0 \to \phi\phi$ to date

•arXiv: 2308.01468

CP violation measurements in the penguin-mediated decay $B_s^0 \to \phi\phi$



arXiv:2304.06198

- ✤ The most precise measurement in $B_s^0 \to \phi\phi$ and in any penguin-dominated B meson decay
- ✤ Agrees with SM expectation
- ✤ The polarization-dependent measurements
  - ➡ Shows no dependence in the polarization states of $B_s^0 \to \phi\phi$

A measurement of $\Delta\Gamma_s$ from $B_s^0 \to J/\psi\eta^{'}$ and $B_s^0 \to J/\psi\pi^+\pi^-$ decays

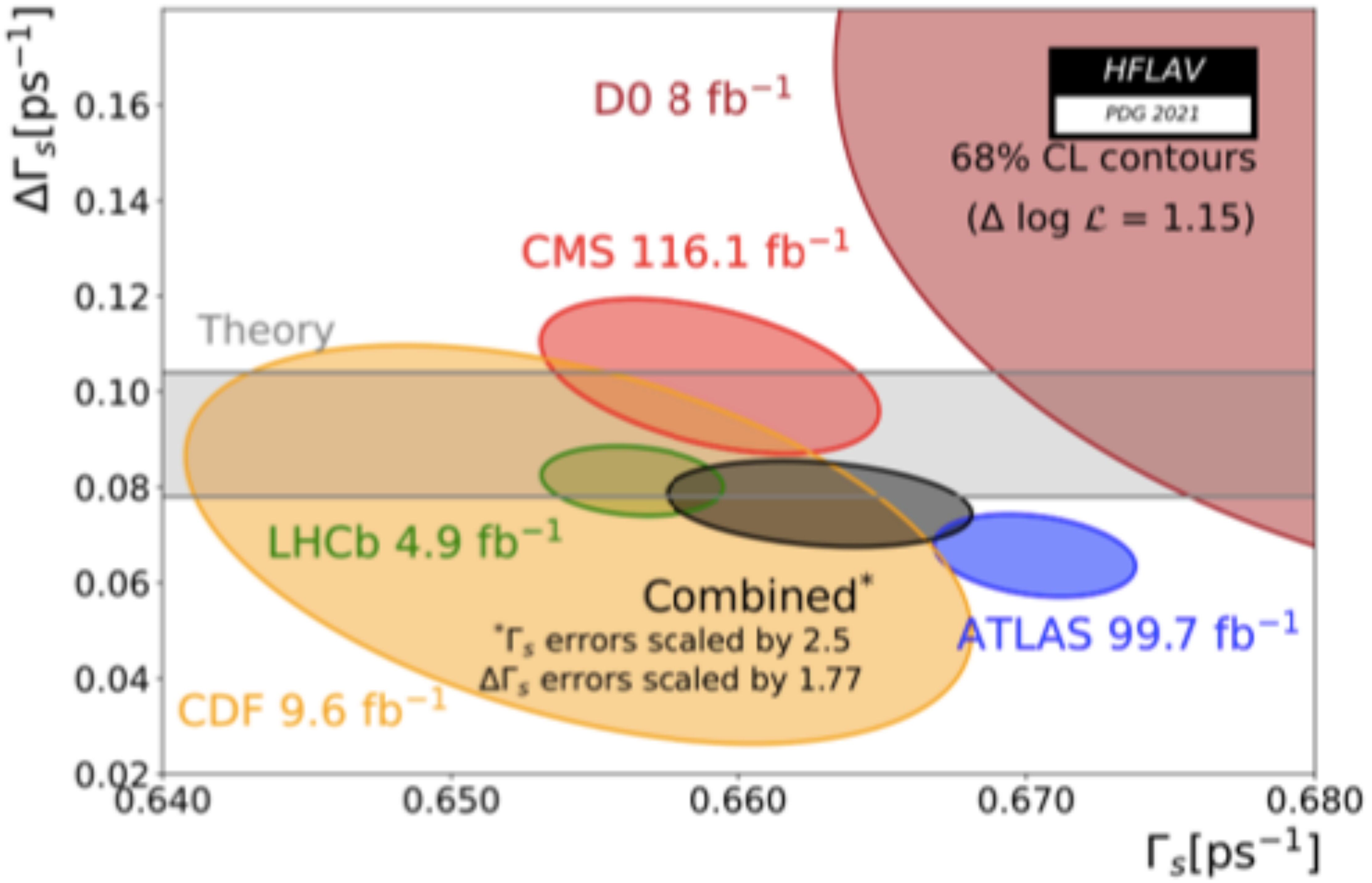
- $\mathscr{L}$ = 9 fb^{-1} , Run 1 2011 + 2012 and Run 2 2015 to 2018 data, LHCb-PAPER-2023-025

A measurement of $\Delta\Gamma_s$ from $B_s^0 \to J/\psi\eta'$ and $B_s^0 \to J/\psi\pi^+\pi^-$ decays

Motivation

- The measurements of the $B_s^0 - \bar{B}_s^0$ mixing parameters offer a powerful test of the Standard Model namely the **CP violating phase ϕ_s** and the **decay-width difference $\Delta\Gamma_s = \Gamma_L - \Gamma_H$**

- $\Delta\Gamma_s$ has been determined experimentally using the golden channel $B_s^0 \to J/\psi\phi$ by ATLAS, CMS and LHCb experiments



- Results precises but in tension with each other

This motivates independent measurements in other decays modes!

A measurement of $\Delta\Gamma_s$ from $B_s^0 \to J/\psi\eta'$ and $B_s^0 \to J/\psi\pi^+\pi^-$ decays

As ϕ_s is experimentally measured to be small

- CP-even modes measure the light mass eigenstates lifetime ($\tau_L = 1/\Gamma_L$)
- CP-odd modes measure the heavy mass eigenstates lifetime ($\tau_H = 1/\Gamma_H$)

- $\Delta\Gamma_s$ can be determined from the difference in decay-widths between a CP-odd and a CP-even B_s^0 mode.

In this analysis, $\Delta\Gamma_s$ is determined from decay-width difference between the CP-even decay $B_s^0 \to J/\psi\eta'$ and CP-odd $B_s^0 \to J/\psi f_0(980)$

- **Subsequent decays $J/\psi \to \mu^+\mu^-$, $\eta' \to \rho^0\gamma$ and $\rho^0 \to \pi^+\pi^-$ for signal and $f_0(980) \to \pi^+\pi^-$**
- **Requirement of the dipion mass to be around 90 MeV around the $f_0(980)$ mass**

A measurement of $\Delta\Gamma_s$ from $B_s^0 \to J/\psi\eta'$ and $B_s^0 \to J/\psi\pi^+\pi^-$ decays

Method

If CP violation is negligible, the time dependent rate can be expressed as

***CP*-even**

$$\Gamma(B_s^0(t) \to f) \propto e^{-\Gamma_s t}\left[\cosh(\frac{\Delta\Gamma_s t}{2}) - \sinh(\frac{\Delta\Gamma_s t}{2})\right]$$

and

***CP*-odd**

$$\Gamma(B_s^0(t) \to f) \propto e^{-\Gamma_s t}\left[\cosh(\frac{\Delta\Gamma_s t}{2}) + \sinh(\frac{\Delta\Gamma_s t}{2})\right]$$

Where $\Gamma_s = (\Gamma_H + \Gamma_L)/2$. Integrating both equations over a time bin $[t_1, t_2]$ and making the ratio, we obtain

$$R(t) = \frac{N_L}{N_H} \propto \frac{[e^{-\Gamma_s t(1+y)}]_{t1}^{t2}}{[e^{-\Gamma_s t(1-y)}]_{t1}^{t2}} \cdot \frac{1-y}{1+y}$$

$2y = \Delta\Gamma_s/\Gamma_s$

Needs to be corrected by a relative efficiency $A_r(t)$

$$R(t) = A_r(t) \cdot \frac{N_L^{RAW}}{N_H^{RAW}}$$

$N_{L,H}^{RAW}$ **are the observed yields!**

A measurement of $\Delta\Gamma_s$ from $B_s^0 \to J/\psi\eta'$ and $B_s^0 \to J/\psi\pi^+\pi^-$ decays

Then $\Delta\Gamma_s$ can be obtained from χ^2 minimization of the corrected $R(t)$, with $\Delta\Gamma_s$ as a free parameter and a arbitrary normalization factor

Analysis Strategy

- Using simulation studies, a time bin scheme of eight bins with similar number of events is defined
  - Lower Limit 0.5 ps → above this value time acceptance is relative flat
  - Upper limit 10 ps → above this value, contribution of $B_s^0 \to J/\psi\eta'$ is negligible

Binning Scheme LHCb-PAPER-2023-025 Preliminary

Bin number	Bin edges [ps]
1	0.5 - 0.7
2	0.7 - 0.9
3	0.9 - 1.2
4	1.2 - 1.5
5	1.5 - 2.0
6	2.0 - 2.5
7	2.5 - 3.5
8	3.5 - 10.0

- **$A_r(t)$ is evaluated at the barycentre of the bin**

A measurement of $\Delta\Gamma_s$ from $B_s^0 \to J/\psi\eta'$ and $B_s^0 \to J/\psi\pi^+\pi^-$ decays

Selection criteria is based on the topology and kinematics of the decays.

The mass fit to decays invariant mass is applied, in the eight time-bins, to extract the yields that are input to the fit the determines $\Delta\Gamma_s$

$$B_s^0 \to J/\psi\eta'$$

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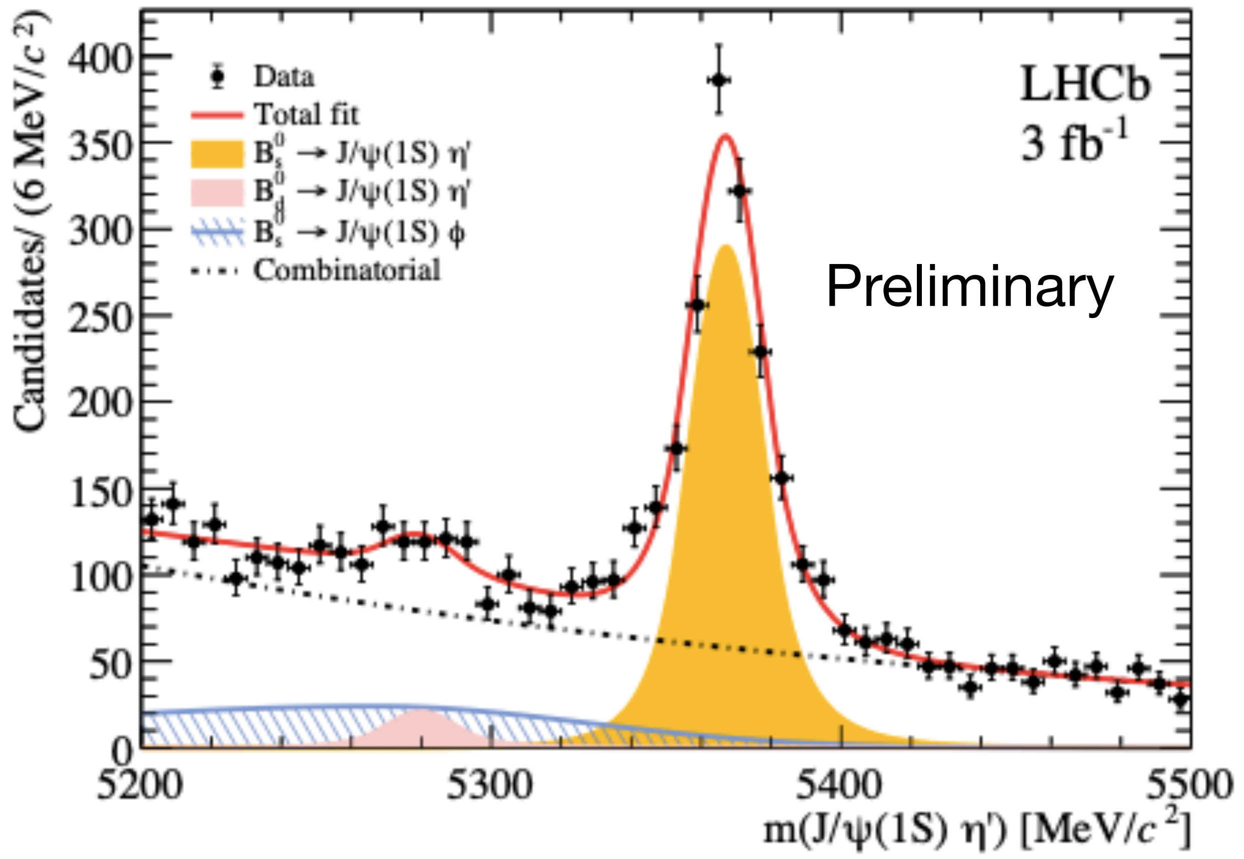
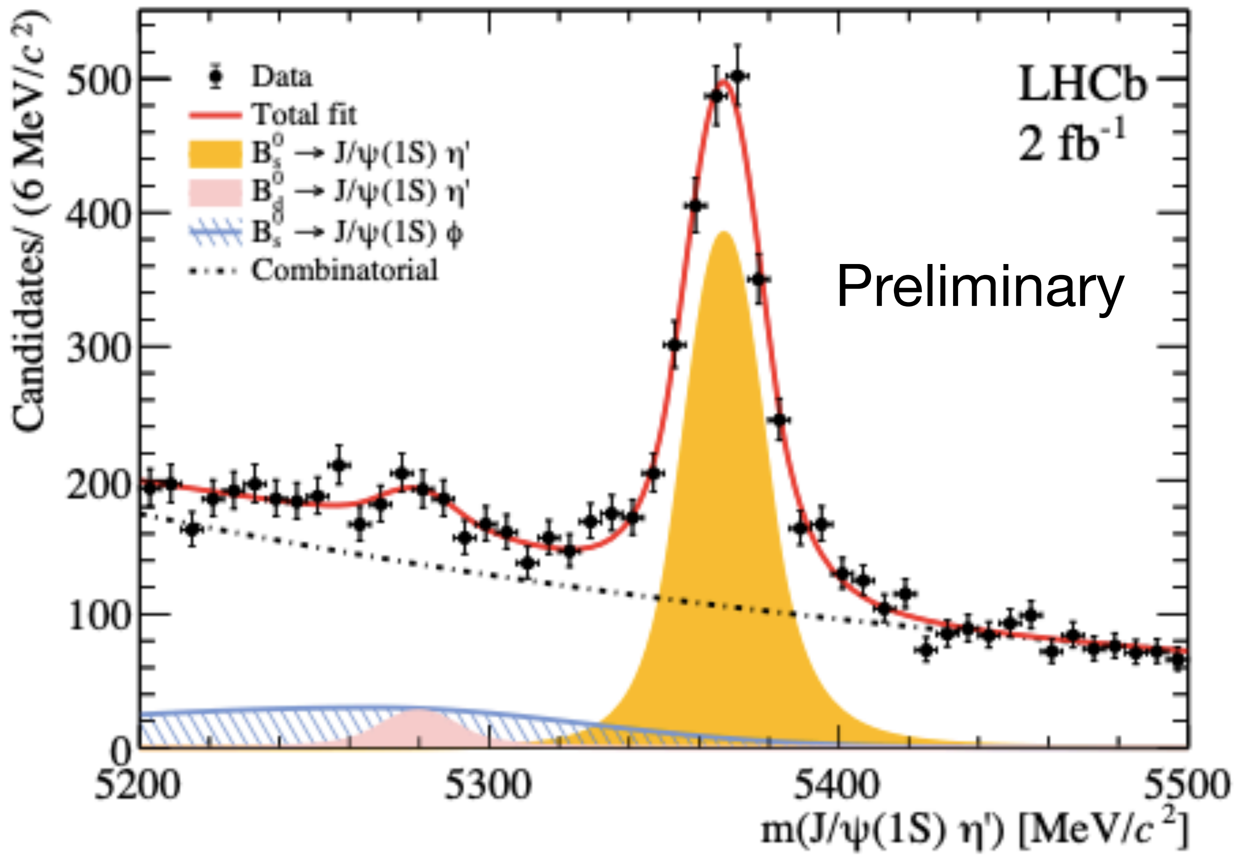
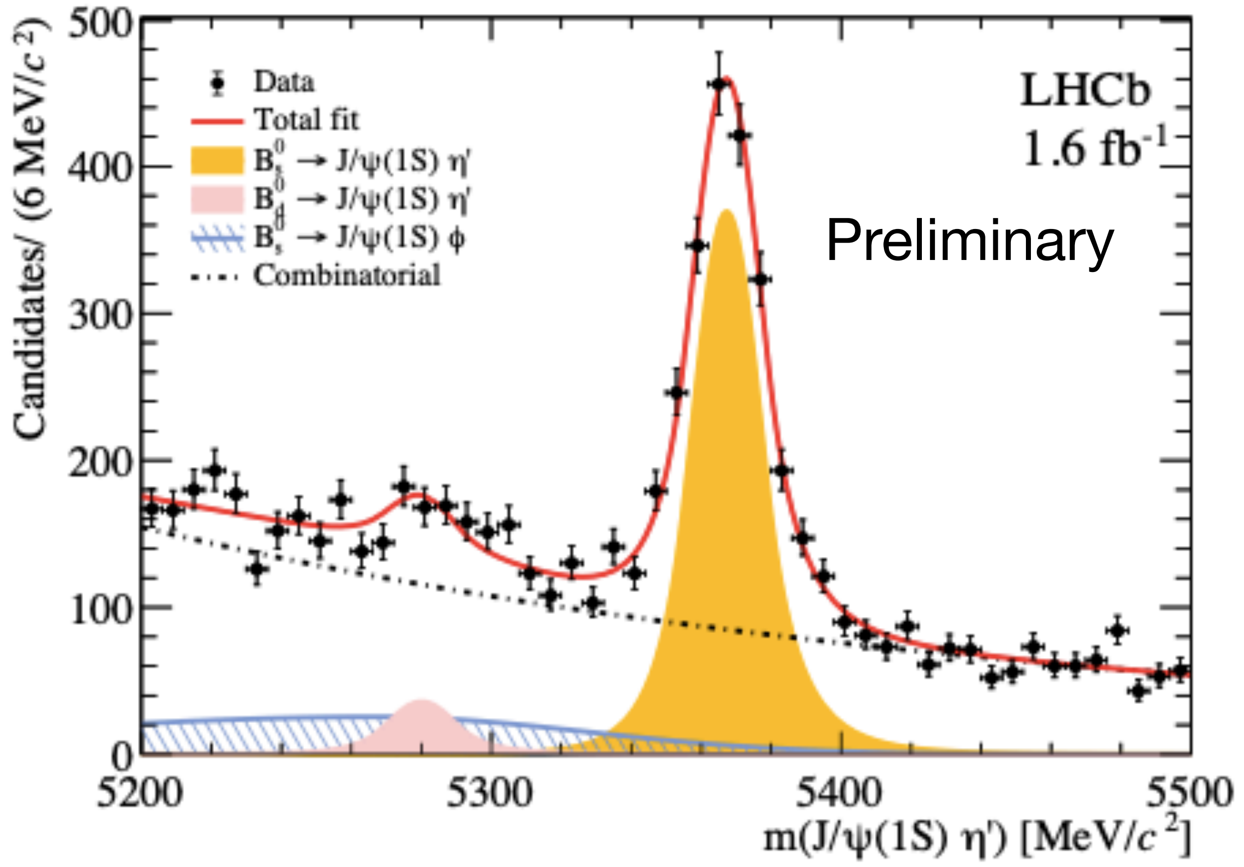
2011+2012

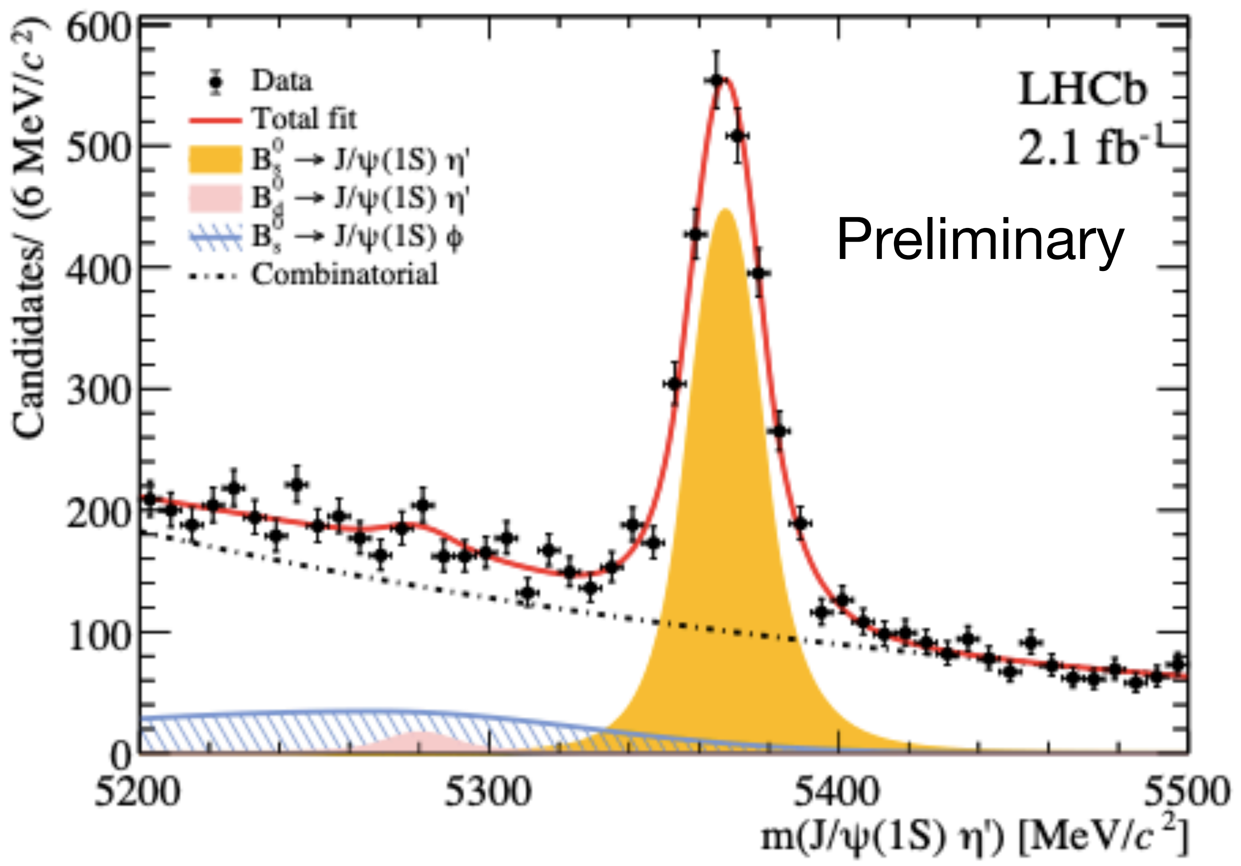




2015+2016

2017





2018

A measurement of $\Delta\Gamma_s$ from $B_s^0 \to J/\psi\eta'$ and $B_s^0 \to J/\psi\pi^+\pi^-$ decays

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

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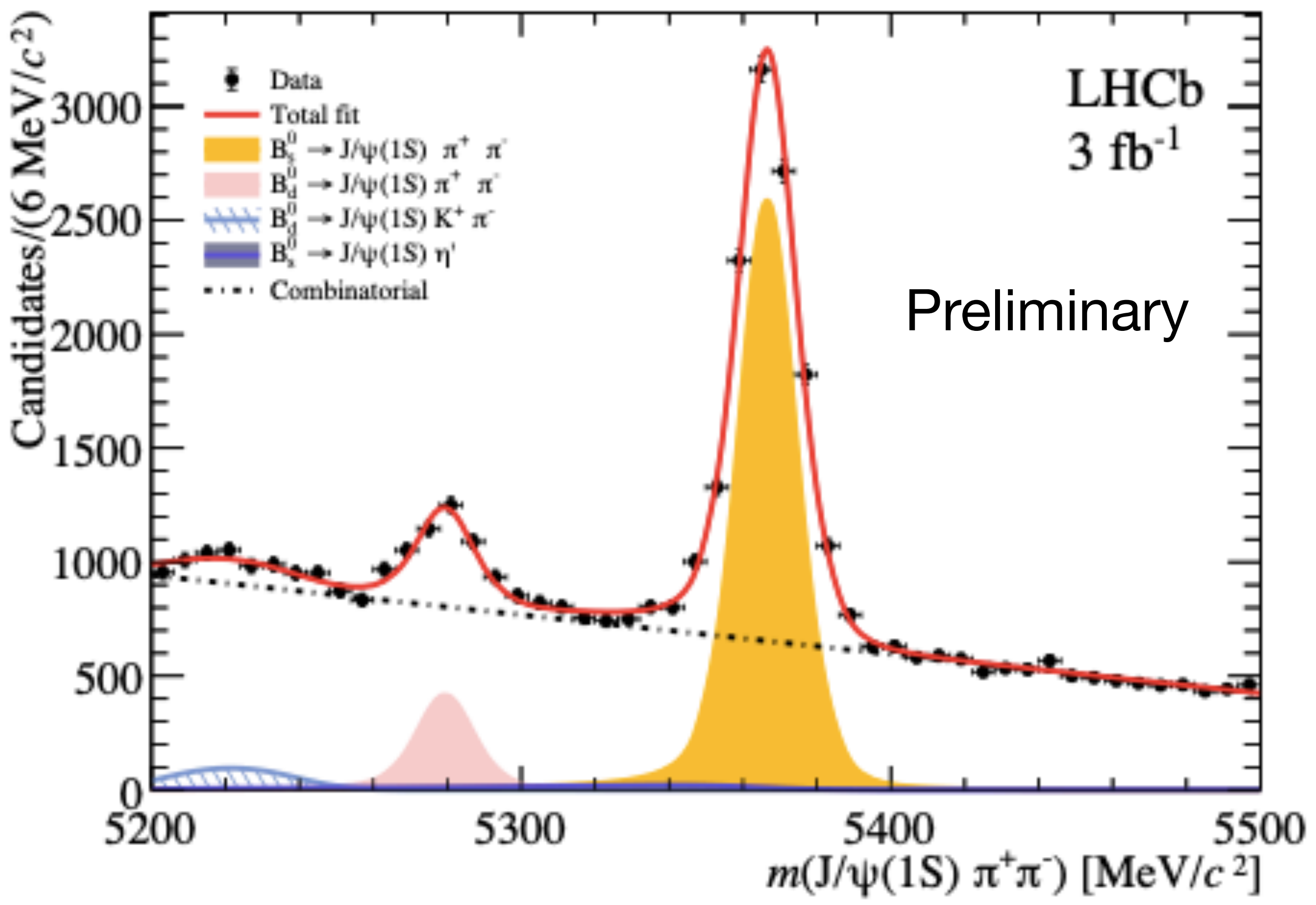
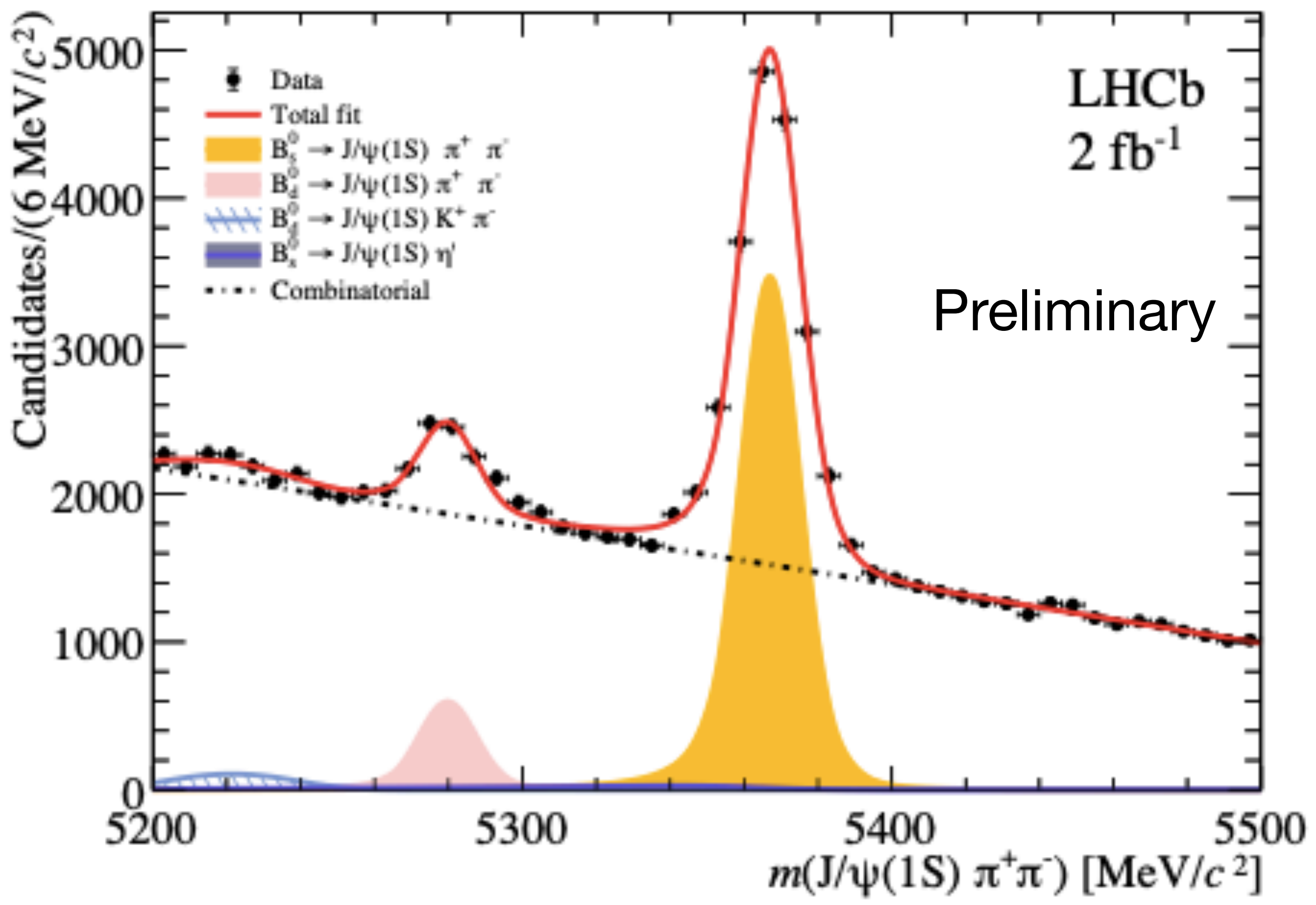
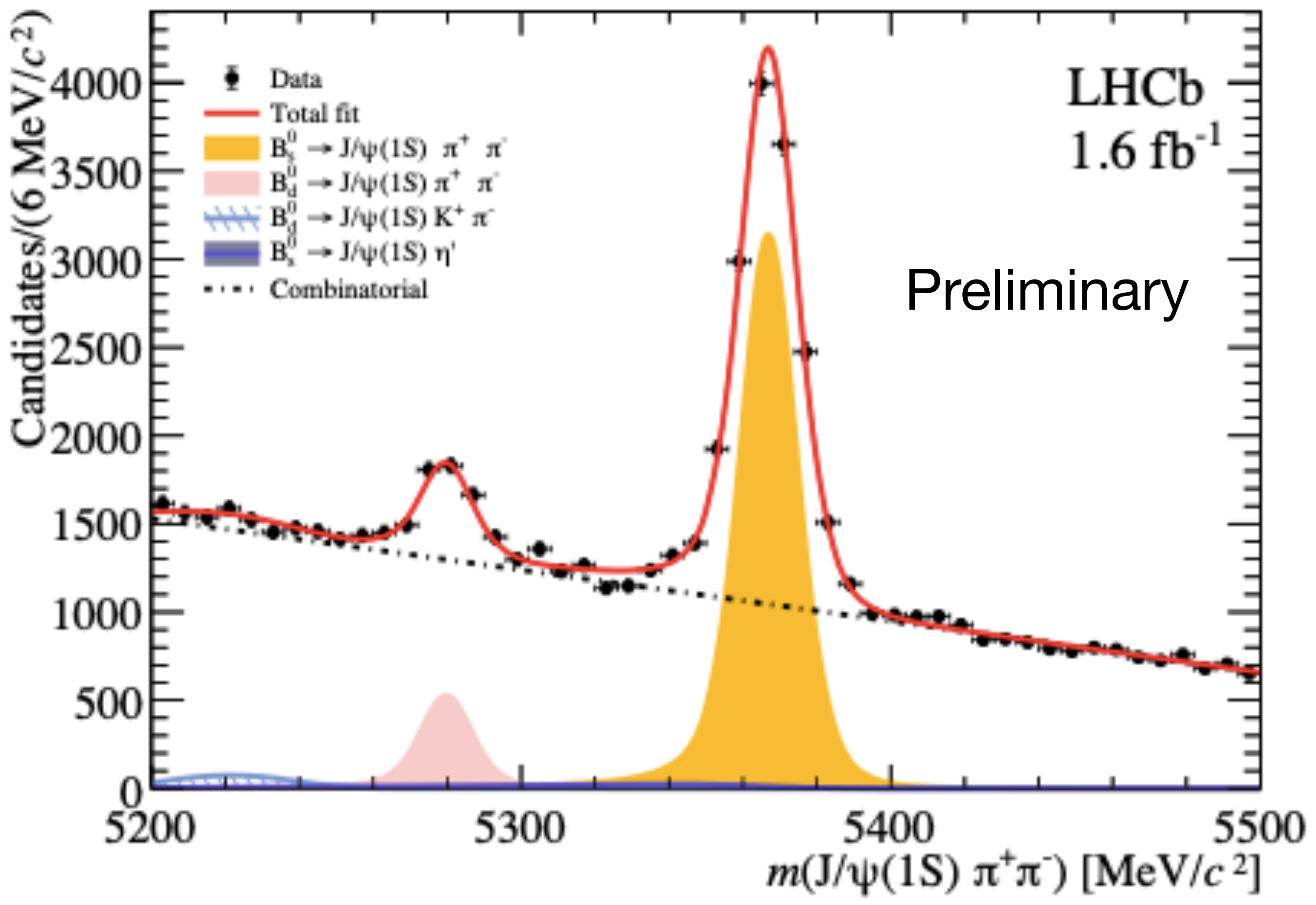
2011+2012



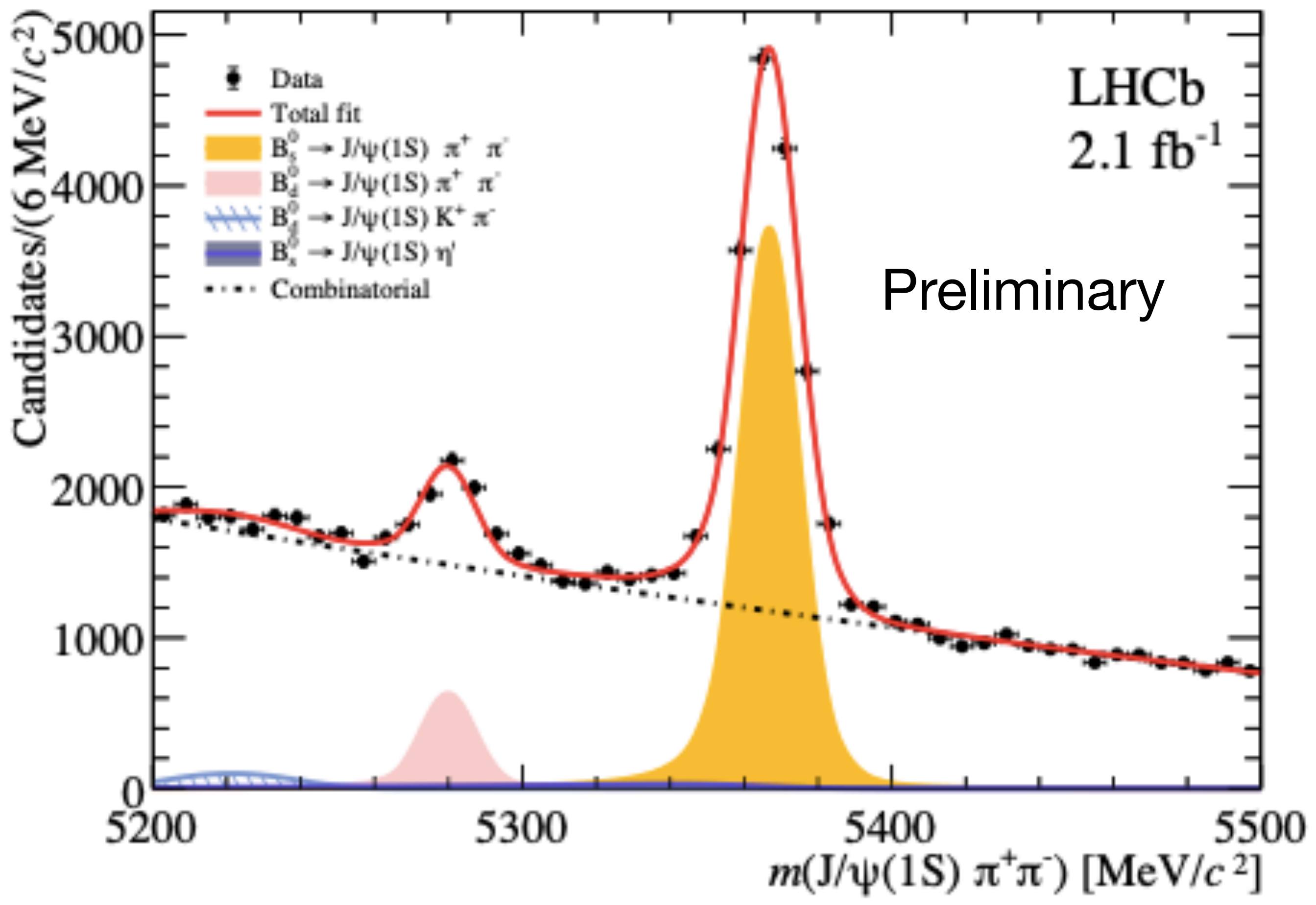
2015+2016



2017



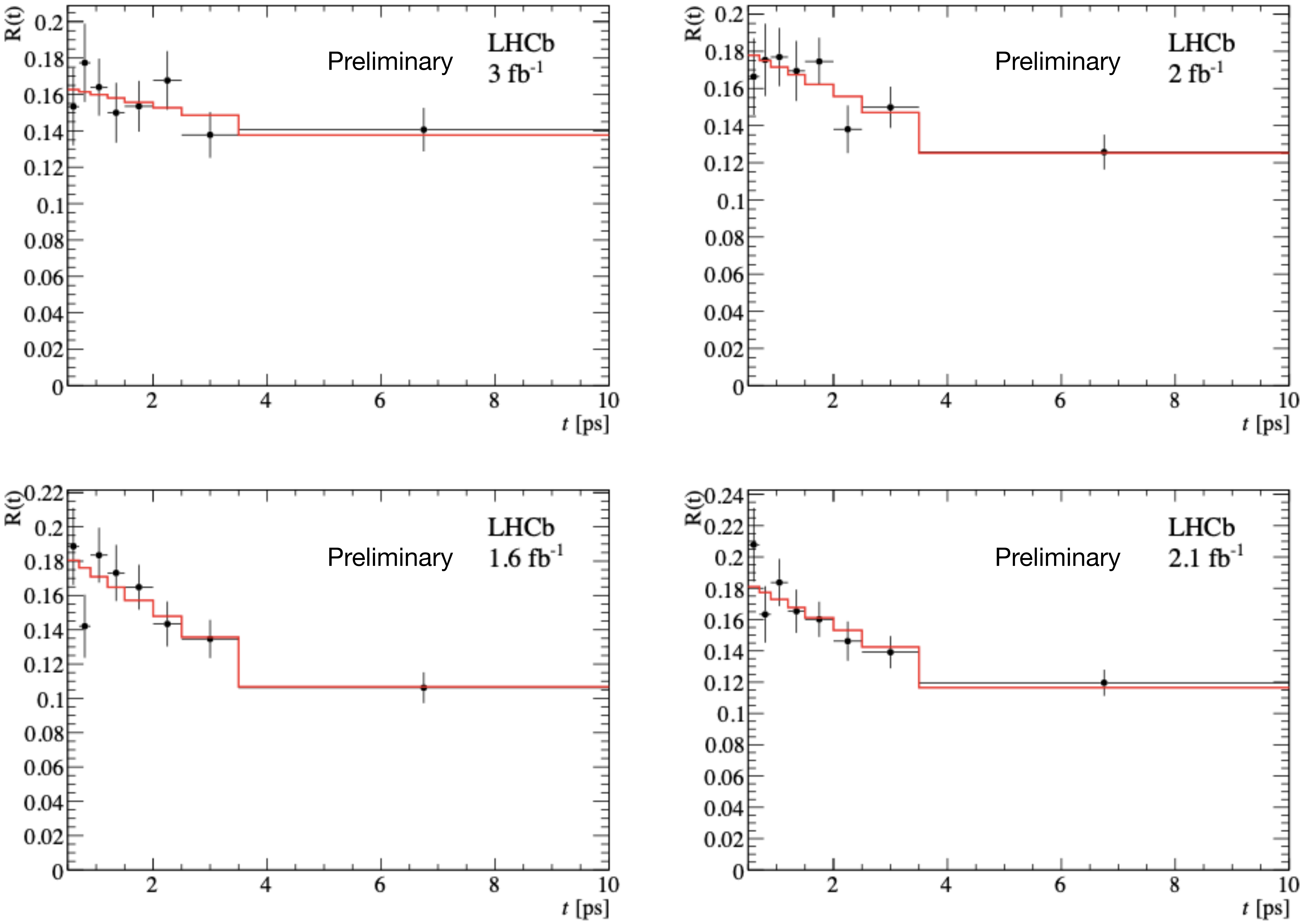
2018



A measurement of $\Delta\Gamma_s$ from $B_s^0 \to J/\psi\eta'$ and $B_s^0 \to J/\psi\pi^+\pi^-$ decays

Results

Ratio of yields in each decay-time bin, corrected by the corresponding relative time acceptance and the χ^2 fit is performed.



A measurement of $\Delta\Gamma_s$ from $B_s^0 \to J/\psi\eta'$ and $B_s^0 \to J/\psi\pi^+\pi^-$ decays

LHCb-PAPER-2023-025

$\Delta\Gamma_s$ results and probability of χ^2

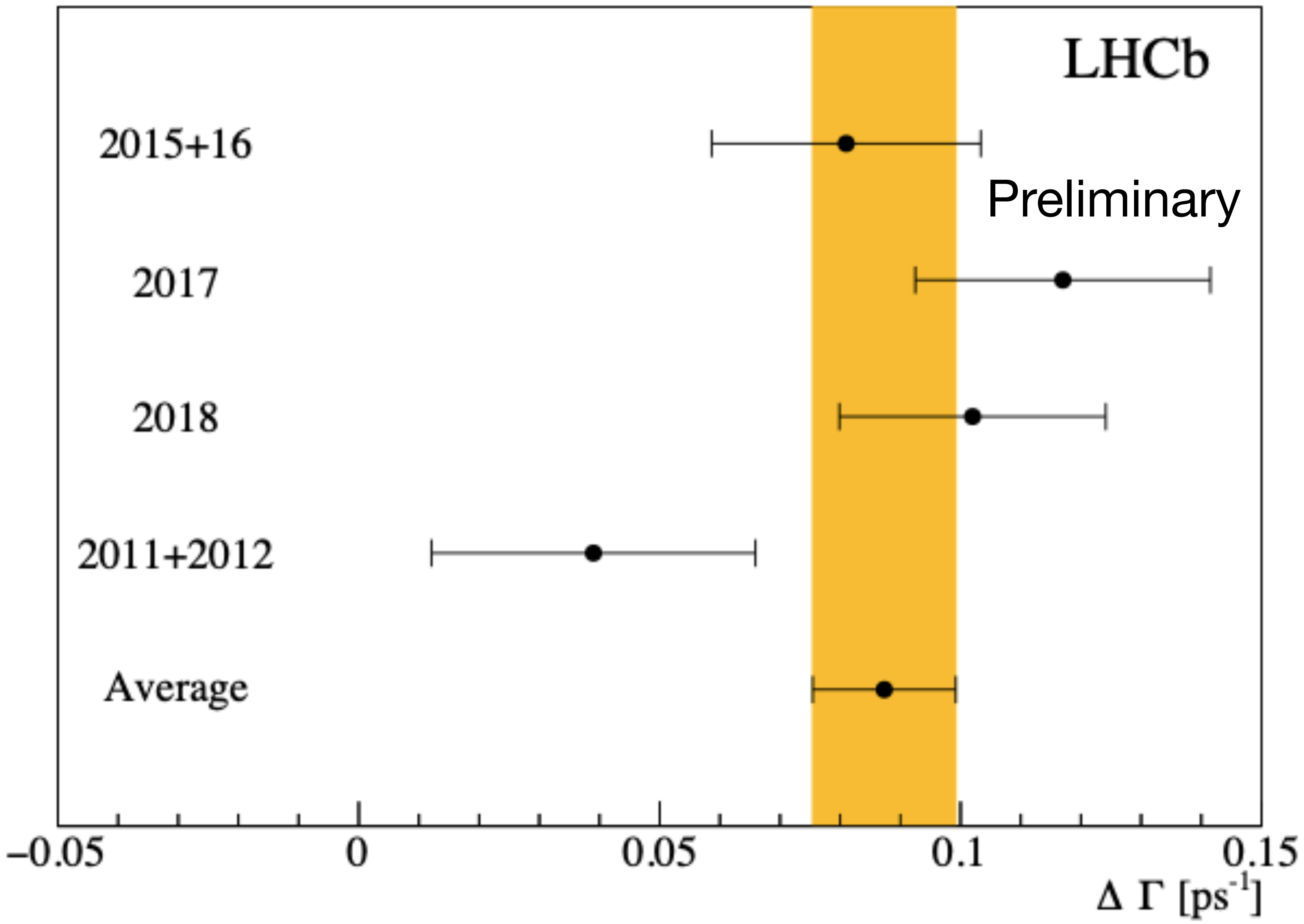
Dataset	$\Delta\Gamma_s$ [ps^{-1}]	P(χ^2)
2011+12	0.039 ± 0.026	0.83
2015+16	0.081 ± 0.022	0.77
2017	0.117 ± 0.024	0.57
2018	0.102 ± 0.021	0.78

Summary

Using full pp-collision dataset between 2011 and 2018, $B_s^0 \to J/\psi\eta'$ and $B_s^0 \to J/\psi\pi^+\pi^-$, $\Delta\Gamma_s$ is measured to be

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

Comparison between the four data sets



Orange band is 1σ error band

➡ This is the first $\Delta\Gamma_s$ measurement using the $B_s^0 \to J/\psi\eta'$

Summary

- A lot of work ongoing in the LHCb experiment, with a very broad program in the search for *CP*-asymmetries in b- and c-hadrons.

- *CP*-violation and decay-width parameters in the decay $B_s^0 \to J/\psi K^+K^-$ are measured using the full Run 2 dataset.
    - These results supersede previous LHCb measurement (2015+2016, [arXiv:1906.08356])
    - No evidence of *CP* violation is found.

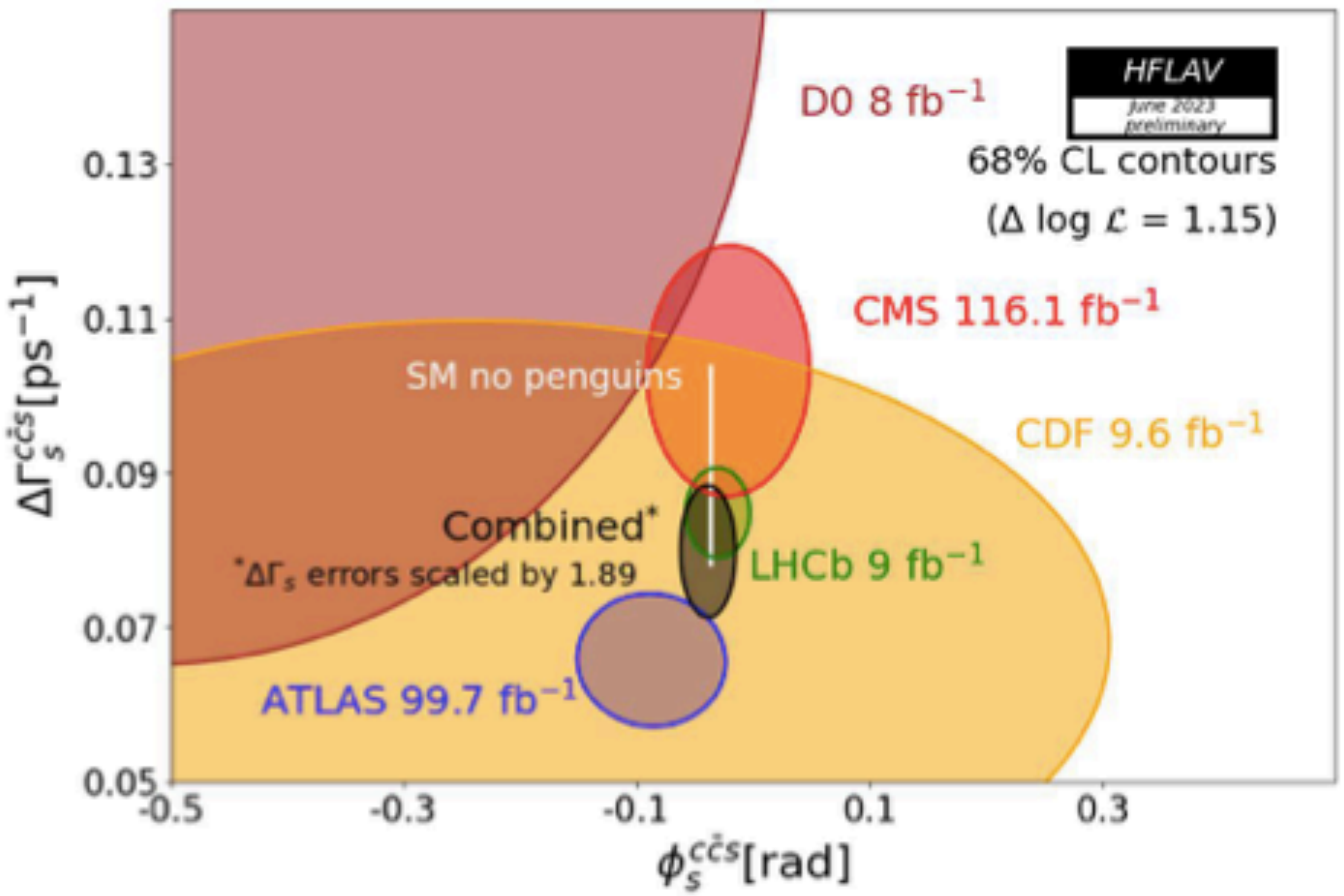
- Measurement of *CP*-observables in $B_s^0 \to \phi\phi$ decays
    - $\phi_s^{s\bar{s}s} = -0.074 \pm 0.069$ rad and $|\lambda| = 1.009 \pm 0.030$, most precise measurements in this decay and any penguin-dominated *B* meson decay
    - First time polarization-dependent *CP*-violation parameters measurement.

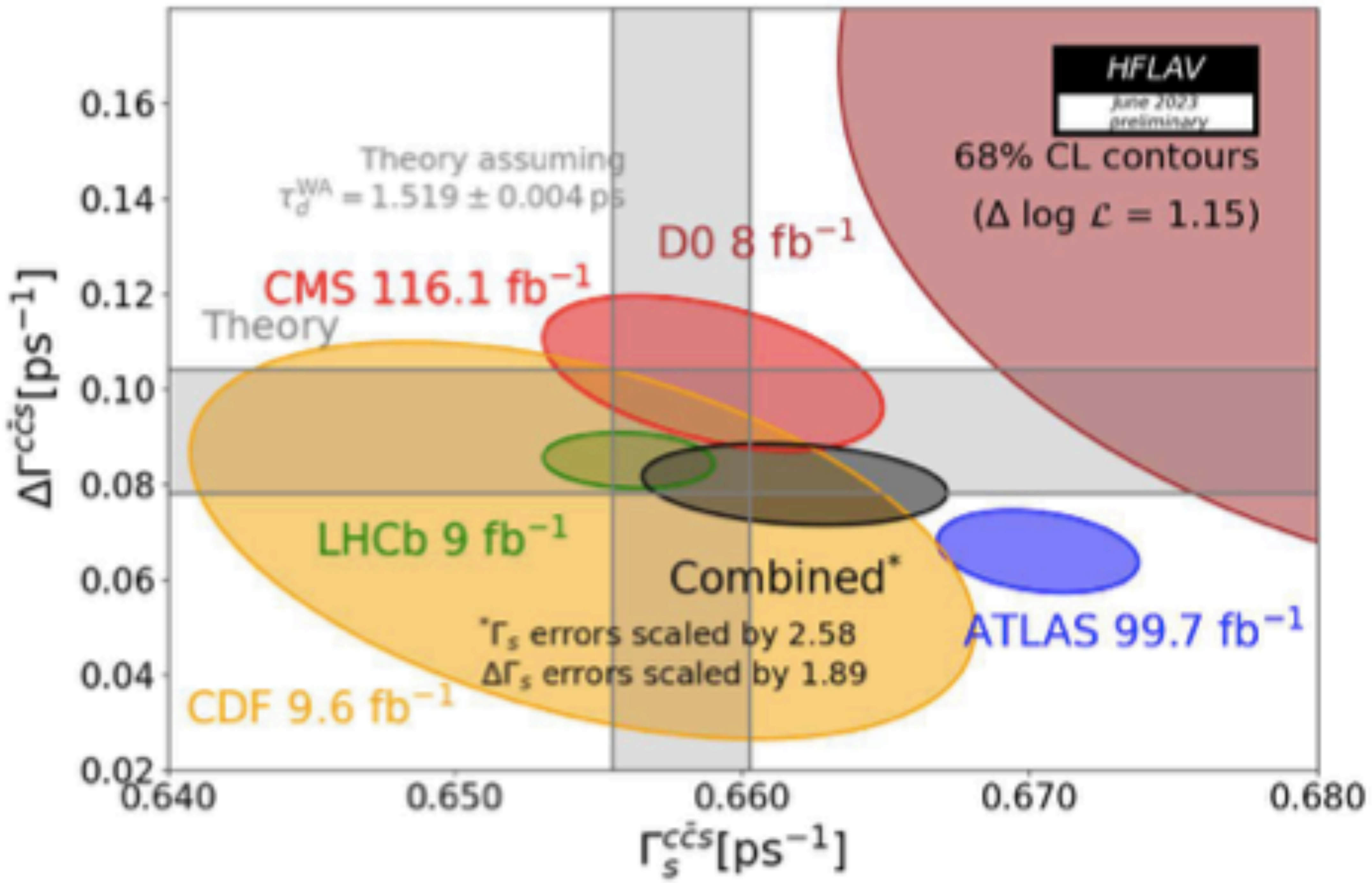
Summary

- Decay-width difference measurement, $\Delta\Gamma_s$, using the decay channels $B_s^0 \to J/\psi\eta'$ and $B_s^0 \to J/\psi\pi^+\pi^-$
  - $\Delta\Gamma_s = 0.087 \pm 0.012 \pm 0.009$ ps^{-1}
  - First time $\Delta\Gamma_s$ measurement using the $B_s^0 \to J/\psi\eta'$ decay model
  - Result in agreement with the average value for $\Delta\Gamma_s$ from $B_s^0 \to J/\psi\phi$

¡Gracias!

Measurement of ϕ_s in $B_s^0 \to J/\psi K^+ K^-$ arXiv: 2308.01468





ϕ_s world average:

$$\phi_s = -0.039 \pm 0.016 \text{ rad}$$
$$\phi_s(J/\psi KK) = -0.050 \pm 0.017 \text{ rad}$$