Experimental status of ϕ_s

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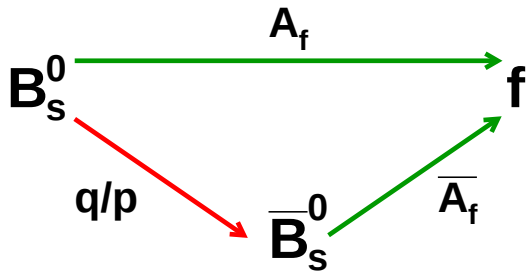
Workshop on ϕ_s and $A_{\rm SL}$ in B-"mesogenesis" • 19 Apr 2021

Introduction to ϕ_s

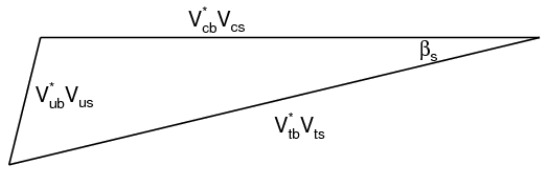
- ϕ_s is the mixing-induced CPV phase in B_s^0 decays via $b \to c\bar{c}s$ transitions such as $B_s^0 \to J/\psi K^+K^-$ and $B_s^0 \to J/\psi \pi^+\pi^-$

$$\lambda_f = \frac{q}{p}\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f}$$

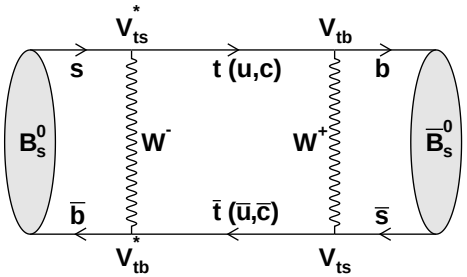


- Assuming only a SM tree contribution

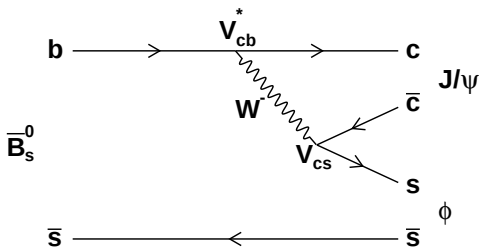
$$\phi_s^{SM} = -\arg(\lambda_f) = \phi_M^{SM} - 2\phi_D$$
$$= -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$



$\phi_M^{SM} = 2\arg(V_{ts}V_{tb}^*)$



$\phi_D = \arg(V_{cs}V_{cb}^*)$



$\phi_s^{SM} = -36.8\,^{+1.0}_{-0.8}$ mrad

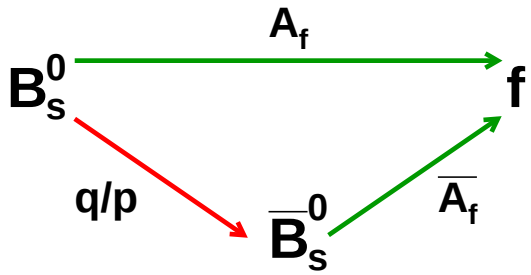
no penguins CKMFitter

$\phi_s^{SM} = -37.0\,^{+0.8}_{-0.7}$ mrad

no penguins UTFit

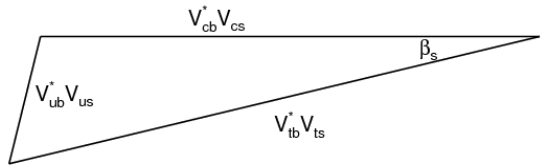
Introduction to ϕ_s

- Phase ϕ_s sensitive to BSM physics, even at energy scales unaccessible in direct searches

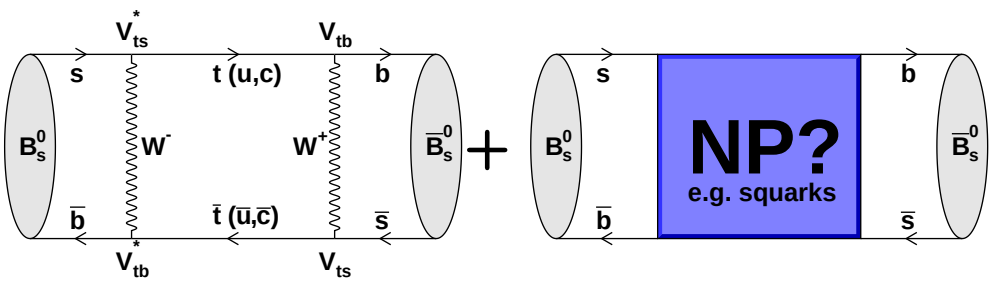


- Physics BSM could enter in the B_s^0-$\bar{B}_s^0$ mixing

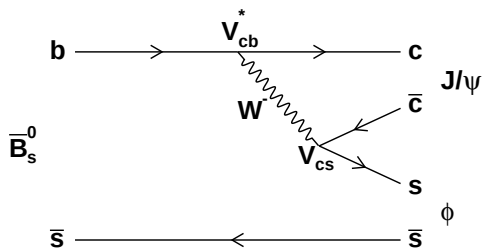
$$\phi_s = -\arg(\lambda_f) = \phi_M - 2\phi_D = -2\beta_s + \Delta\phi_{NP}$$



$\phi_M = \phi_M^{SM} + \Delta\phi_{NP}$

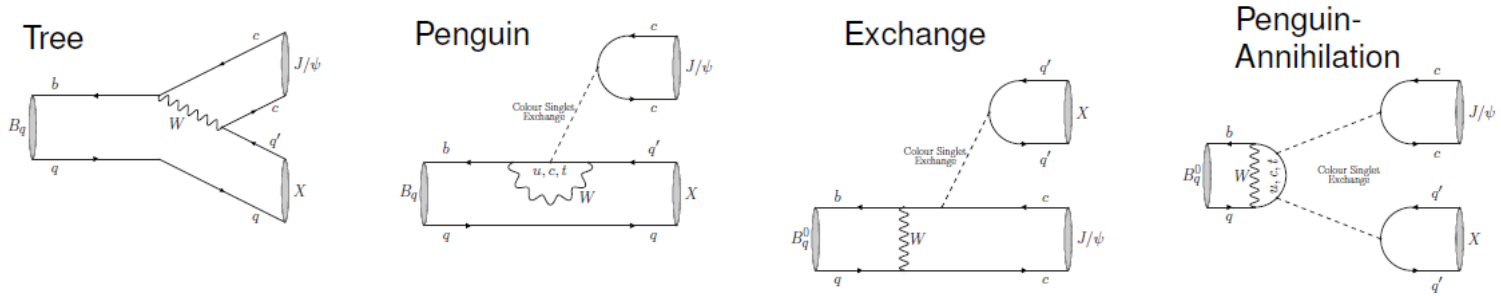


$\phi_D = \arg(V_{cs}V_{cb}^*)$



ϕ_s in $B_s^0 \to J/\psi KK$ and $B_s^0 \to J/\psi\pi\pi$

- Phase ϕ_s measured most precisely in processes dominated by $b \to c\bar{c}s$, where (SM) penguin pollution is small
- Decays admixture of *CP*-even and *CP*-odd final states



Golden mode

$B_s^0 \to J/\psi[\mu^+\mu^-]K^+K^-$

- Relatively large BF, $\mathcal{O}(10^{-3})$
- Also measurement of $\Gamma_s = \frac{\Gamma_H+\Gamma_L}{2}$, $\Delta\Gamma_s = \Gamma_L - \Gamma_H$, $\Delta m_s = m_H - m_L$

Silver mode

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

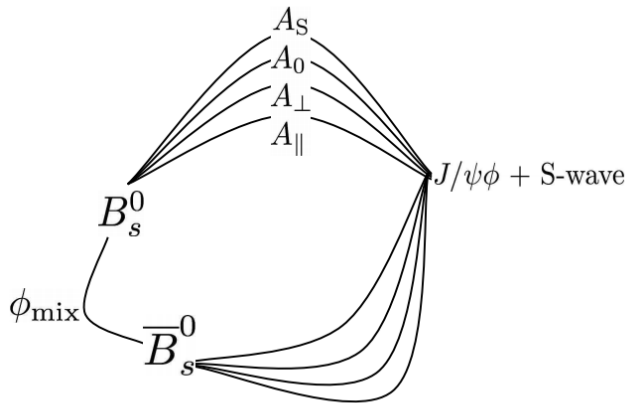
- BF $\mathcal{O}(10^{-4})$
- Mainly *CP*-odd, (almost) direct access to Γ_H

ϕ_s in $B_s^0 \to J/\psi KK$

- ϕ_s measured in the B_s^0 decay-time distribution
- $B_s^0 \to J/\psi KK$ in $\phi(1020)$ region admixture of

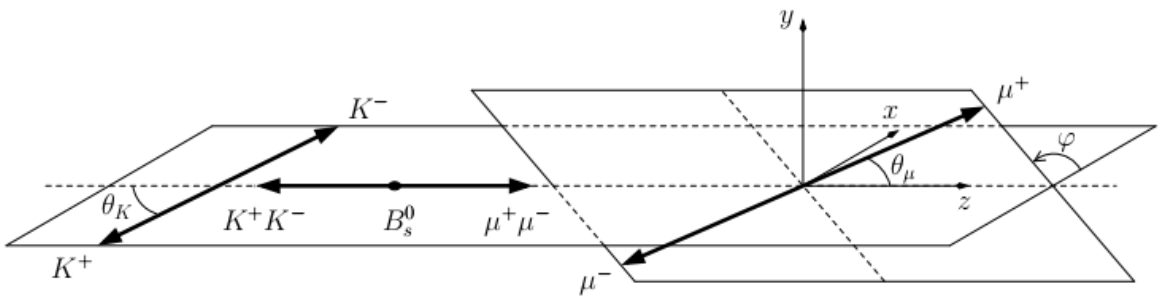
  $\phi(1020)$: CP-even($\mathcal{A}_0$+$\mathcal{A}_\parallel$)+CP-odd($\mathcal{A}_\perp$)

  S wave: CP-odd ($\mathcal{A}_S$)



$\to$ Use angular distribution (helicity angles) to disentangle *CP*-even and *CP*-odd components

$$\frac{d^4\Gamma(B_s^0 \to J/\psi\phi)}{dt\ d\Omega} \propto \sum_{i=1}^{10} h_k(t) f_k(\Omega)$$

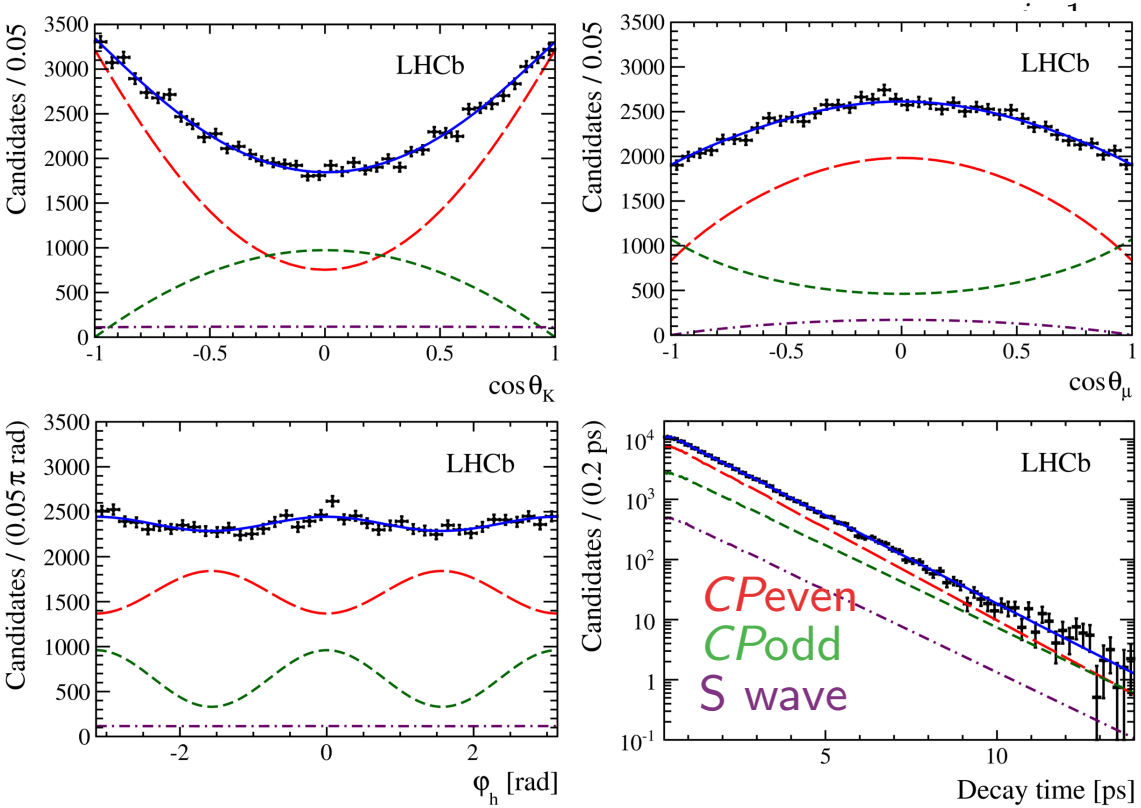


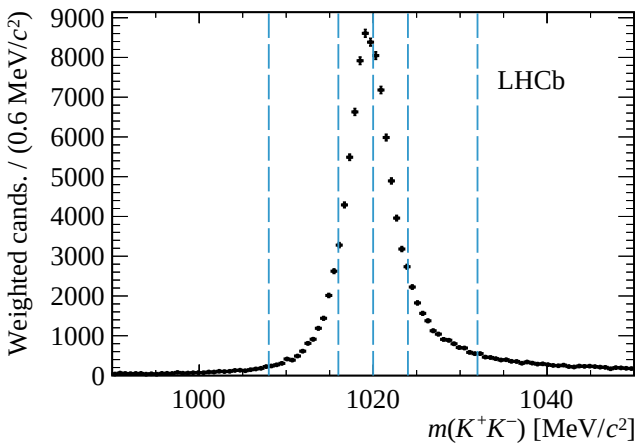
$$h_k(t) = N_k e^{-\Gamma_s t}\left[a_k \cosh\left(\frac{1}{2}\Delta\Gamma_s t\right) + b_k \sinh\left(\frac{1}{2}\Delta\Gamma_s t\right) + c_k \cos\left(\frac{1}{2}\Delta m_s t\right) + d_k \sin\left(\frac{1}{2}\Delta m_s t\right)\right]$$

LHCb ϕ_s in $B_s^0 \to J/\psi KK$

- LHCb: fit in six $m(KK)$ bins
- S-P-wave mass interference terms enter in $k = 8, 9, 10$, calculated per $m(KK)$ bin

$$\frac{d^4\Gamma(B_s^0 \to J/\psi\phi)}{dt\, d\Omega} \propto \sum^{10} h_k(t) f_k(\Omega)$$





LHCb ϕ_s combination [EPJC (2019) 79 706]

$B_s^0 \to J/\psi K^+K^-$ 4.9 fb^{-1}

$\phi_s = -81 \pm 32$ mrad

$|\lambda| = 0.994 \pm 0.013$

$\Gamma_s = 0.6572 \pm 0.0023$ ps^{-1}

$\Delta\Gamma_s = 0.0777 \pm 0.0062$ ps^{-1}

- LHCb Run1:
  $B_s^0 \to \psi(2S)KK$ PLB 762 (2016) 253
  $B_s^0 \to J/\psi KK$ above ϕ [JHEP 08 (2017) 037]
  $B_s^0 \to D_s^+ D_s^-$ [PRL 113 (2014) 211801]
- LHCb Run1+Run2 (2015-2016):
  $B_s^0 \to J/\psi KK$ [EPJC (2019) 79 706]
  $B_s^0 \to J/\psi \pi\pi$ [PLB 797 (2019) 134789]

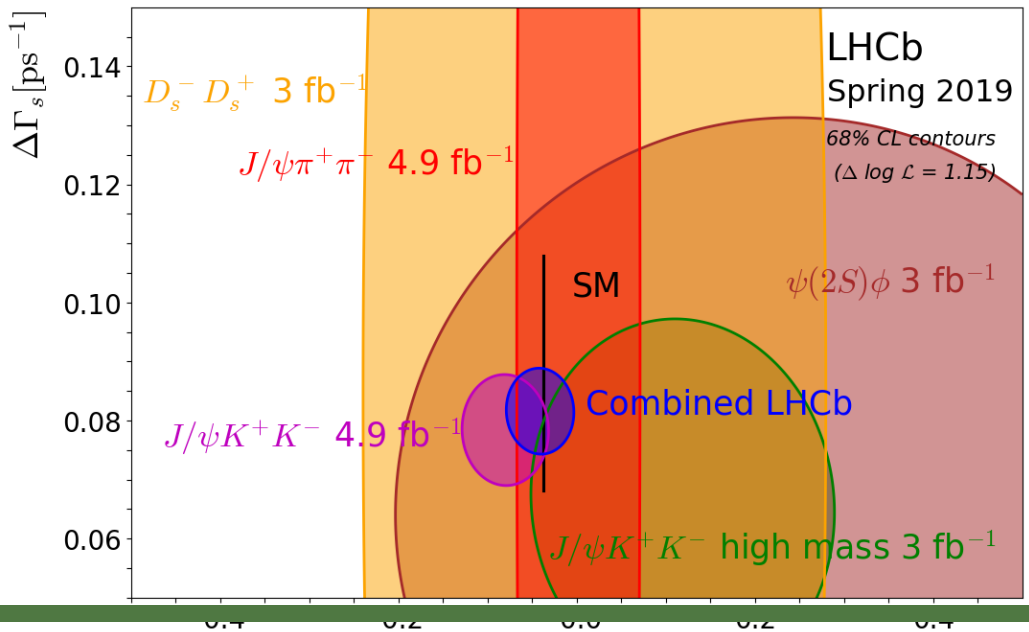
All LHCb

$\phi_s = -41 \pm 25$ mrad

$|\lambda| = 0.993 \pm 0.010$

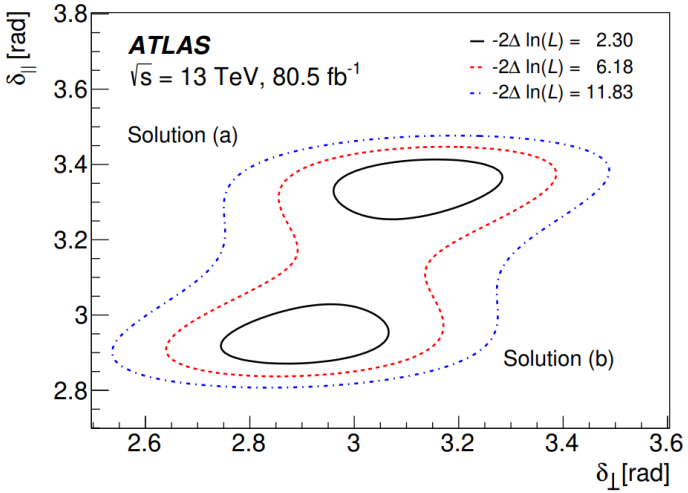
$\Gamma_s = 0.6562 \pm 0.0021$ ps^{-1}

$\Delta\Gamma_s = 0.0816 \pm 0.0048$ ps^{-1}



ϕ_s in $B_s^0 \to J/\psi KK$

- Also measurements of D0, CDF, ATLAS and CMS
- ATLAS [arXiv:2001.07115] and CMS [PLB 816 (2021) 136188] strategy somewhat different from LHCb
  - Study of a single-bin, narrower $m(KK)$ region, $\approx [1.009, 1.031]$ GeV/c^2 vs LHCb's $[0.990, 1.050]$ GeV/c^2
  - Background modelling vs LHCb's background-subtracted approach
- ATLAS saw two minima in their latest measurement – due to approximate symmetry in the PDF, inconsequential for main parameters



Parameter	Solution (a) Value	Solution (a) Statistical uncertainty	Solution (a) Systematic uncertainty	Solution (b) Value	Solution (b) Statistical uncertainty	Solution (b) Systematic uncertainty
ϕ_s [rad]	−0.087	0.036	0.021	−0.087	0.036	0.021
$\Delta\Gamma_s$ [ps^{-1}]	0.0657	0.0043	0.0037	0.0657	0.0043	0.0037
Γ_s [ps^{-1}]	0.6703	0.0014	0.0018	0.6704	0.0014	0.0018
$\lvert A_\parallel(0)\rvert^2$	0.2220	0.0017	0.0021	0.2218	0.0017	0.0021
$\lvert A_0(0)\rvert^2$	0.5152	0.0012	0.0034	0.5152	0.0012	0.0034
$\lvert A_S\rvert^2$	0.0343	0.0031	0.0045	0.0348	0.0031	0.0045
$\delta_\perp$ [rad]	3.22	0.10	0.05	3.03	0.10	0.05
$\delta_\parallel$ [rad]	3.36	0.05	0.09	2.95	0.05	0.09
$\delta_\perp - \delta_S$ [rad]	−0.24	0.05	0.04	−0.24	0.05	0.04

HFLAV combination

- Latest combination just performed and sent to PDG
- Change in strategy (used to be a 2D fit in $\phi_s - \Delta\Gamma_s$)
- Now using full set of parameters V_{all}^{meas} and error matrices from all experiments to build a χ^2 to minimize

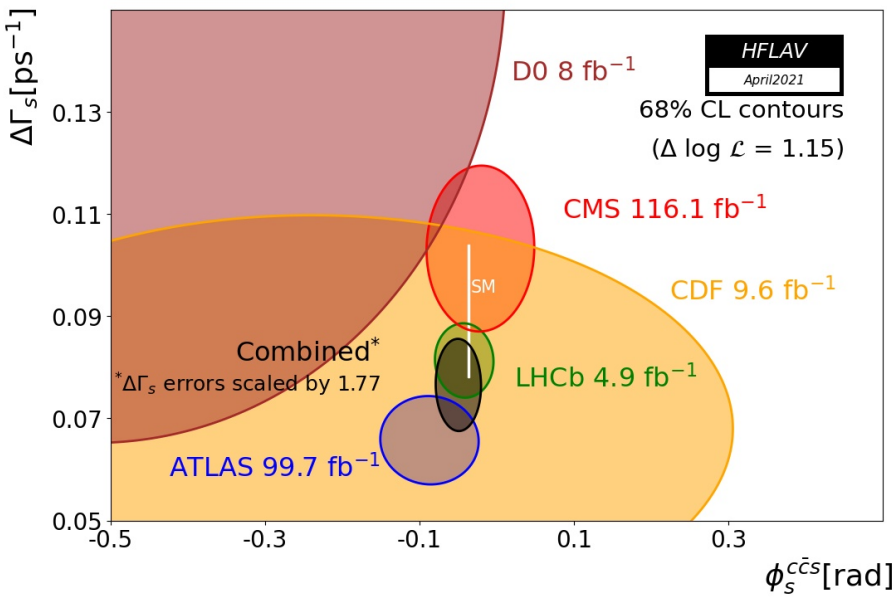
$$\chi^2 = \overline{\Delta}^T E_{all}^{-1} \overline{\Delta}$$

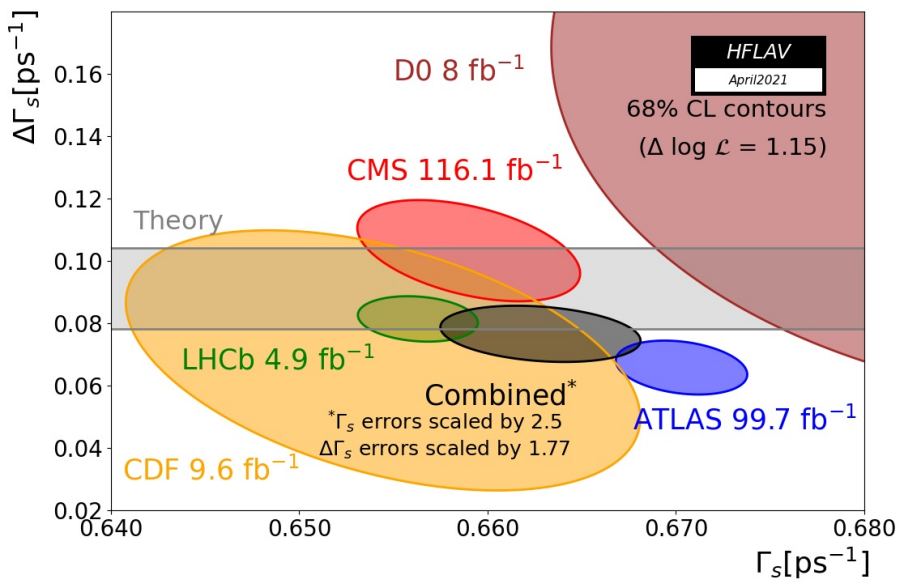
  where $\overline{\Delta} = V_{all}^{meas} - V_{all}^{fit}$ and overall error matrix E_{all}
- Parameters: ϕ_s, Γ_s, $\Delta\Gamma_s$, $\delta_\perp$, $\delta_\parallel$, $\delta_S - \delta_\perp$, $|A_0|^2$, $|A_\perp|^2$, Δm_s
- Fixed $|\lambda| = 1$
- Each experiment provides a pre-combined result which is then used in the HFLAV average
- Correlations between measurements of a given experiment taken into account
- No systematic correlations between experiments

HFLAV combination

- Due to tensions between experiments, errors of some parameters scaled
- Affects $\Delta\Gamma_s$, Γ_s, phases and amplitudes
- ϕ_s unaffected

$$\phi_s = -0.050 \pm 0.019 \text{ rad}$$





$$\Gamma_s = 0.6628 \pm 0.0035 \text{ ps}^{-1}$$

$$\Delta\Gamma_s = 0.0765 \pm 0.0059 \text{ ps}^{-1}$$

Outlook

Near future

- ATLAS to analyse remaining Run 2 data from 2018 ($\sim 40\,\text{fb}^{-1}$)
- CMS to add triggers and taggers to their full Run 2 data set
- LHCb to analyse remaining Run 2 data from 2017+2018 ($\sim 4\,\text{fb}^{-1}$)

  $\rightarrow$ Should get to $\sigma(\phi_s) \approx 22$ mrad from Run 1 + Run 2 from LHCb $B_s^0 \rightarrow J/\psi KK$ alone

Run 3 and beyond

- LHCb Run 1-3: $\sigma(\phi_s) \approx 14$ mrad from $B_s^0 \rightarrow J/\psi KK$
- LHCb Run 1-5: $\sigma(\phi_s) \approx 4$ mrad from $B_s^0 \rightarrow J/\psi KK$