Mixing and CP Violation at the LHC

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The following results will be presented:

beauty

- Measurement of the CKM angle ϕ_s using
  - $B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$ ⟹ ATLAS, CMS, and LHCb
  - $B_s^0 \to J/\psi(\to e^+e^-)\,\phi$ ⟹ LHCb
- Measurement of the CKM angle γ using
  - $B^\pm \to Dh^\pm, h \in \{K,\pi\}$, $D \to hh$ and $D \to K_s hh$
  - $B_s^0 \to D_s^\mp K^\pm \pi^\pm \pi^\mp$
  - $B_s^0 \to D_s^\mp h^\pm \pi^\pm \pi^\mp$
- Combined measurement for γ using all channels

charm

- Measurement of the time-integrated *CP* asymmetry in $D^0 \to K^+K^-$
- Direct *CP* violation in $D^0 \to \pi^+\pi^-$

LHCb

CP Violation in the Standard Model

- The CKM matrix is a 3×3 complex, unitary matrix whose elements represent the strength of flavor-changing weak interactions.

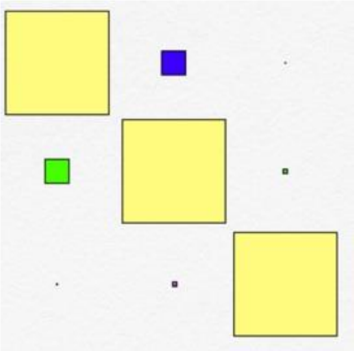
$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = V_{\text{CKM}} \begin{bmatrix} d \\ s \\ b \end{bmatrix}, \text{ where } V_{\text{CKM}} = \begin{bmatrix} V_{\text{ud}} & V_{\text{us}} & V_{\text{ub}} \\ V_{\text{cd}} & V_{\text{cs}} & V_{\text{cb}} \\ V_{\text{td}} & V_{\text{ts}} & V_{\text{tb}} \end{bmatrix}$$

An $N \times N$ matrix will have $N(N-1)/2$ real parameters (Euler Angles) and $(N-1)(N-2)/2$ nontrivial phase angles.

$V_{\text{CKM}} \longrightarrow$ 3 real parameters and **1 complex phase – origin of *CP* violation in SM**

- Using Wolfenstein's parametrization [PRL 51 (1983) 1945]

$$\begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4) \Rightarrow$$

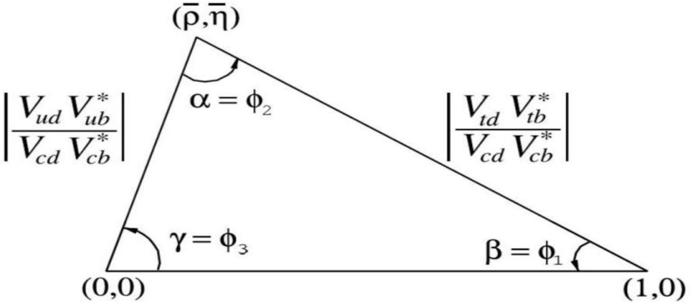


Relative quark coupling strengths

Exploiting the unitarity of the CKM matrix, we get 9 conditions from which 3 triangles could be created.

$$V_{\text{ud}}V_{\text{ub}}^* + V_{\text{cd}}V_{\text{cb}}^* + V_{\text{td}}V_{\text{tb}}^* = 0$$

most commonly used, obtained by multiplying 1st and 3rd column of CKM matrix



where

$$\alpha = \arg\left(-\frac{V_{\text{td}}V_{\text{tb}}^*}{V_{\text{ud}}V_{\text{ub}}^*}\right);$$

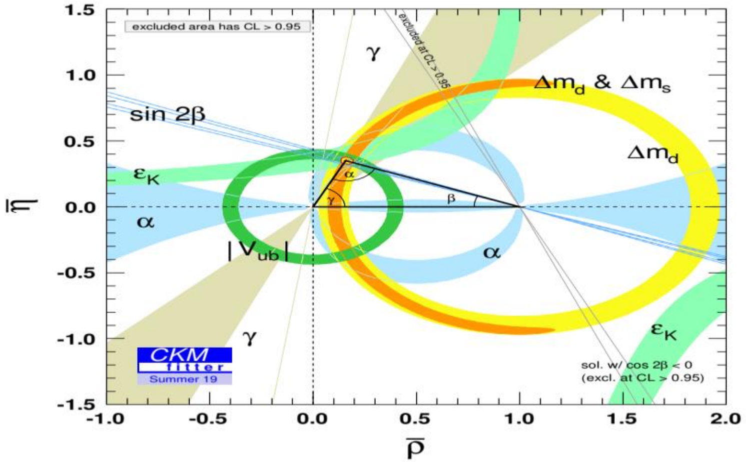
$$\beta = \arg\left(-\frac{V_{\text{cd}}V_{\text{cb}}^*}{V_{\text{td}}V_{\text{tb}}^*}\right); \text{ and}$$

$$\gamma = \arg\left(-\frac{V_{\text{ud}}V_{\text{ub}}^*}{V_{\text{cd}}V_{\text{cb}}^*}\right).$$

Area gives a measure of *CP* violation in the Standard Model.

The aim of experimental study of *CP* violation is to measure the angles α, β and γ precisely for each unitarity triangle by studying the decays involving quark transitions corresponding to the matrix elements V_{ij}. If the Standard Model is the correct description of our universe, then the unitarity of the CKM matrix should hold.

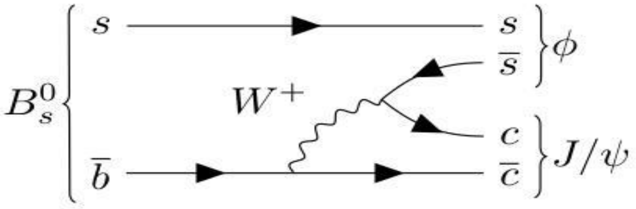
Unitarity triangle formed by the constraints from various measurements [CKMFitter]



Neutral B_s^0 mesons can oscillate into their counterparts via quantum loop processes opening additional mechanisms for *CP* symmetry breaking.

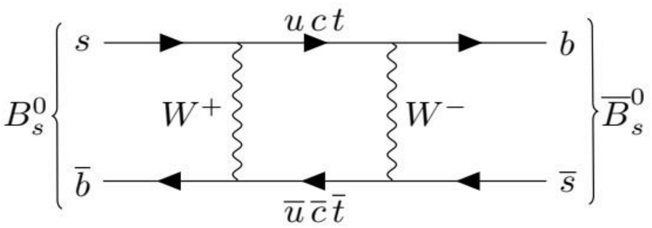
Decay Channel - B_s^0 decays to charmonium - $B_s^0 \to J/\psi\phi$

$B_s^0 \to J/\psi\phi$ decay proceeds via the $\bar{b} \to \bar{c}cs$ transition.

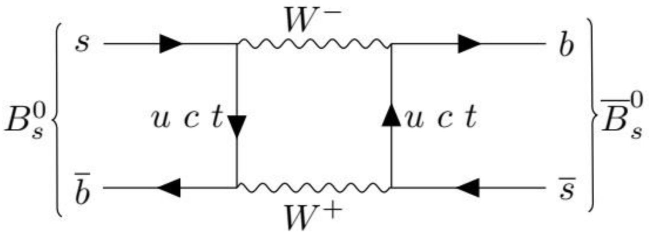


Two competing processes – a direct decay of B_s^0 and a decay from $B_s^0 - \overline{B}_s^0$ mixing to a common final state. Mixing occurs about 3×10^{12} Hz, making it a major experimental challenge.

$B_s^0 - \bar{B}_s^0$ oscillation ⇨



⇔



Measuring *CP* Violation Parameters in $B_s^0 \to J/\psi\phi$ Decays

SM parameters in $B_s^0 \to J/\psi\phi$ decay

$\boldsymbol{\phi_s}$

- A weak phase difference between mixing amplitude and decay amplitude
- Related to the CKM matrix via $\phi_s \approx -2\beta_s$, with $\beta_s = \arg[-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*]$.
- Assuming no New Physics is involved, a value of $-2\beta_s = -0.03696^{+0.00072}_{-0.00082}$ was predicted by the CKMFitter group [CKMFitter] and $-2\beta_s = 0.03700 \pm 0.00104$ by the UTfit Collaboration [JHEP **10** (2006) 081]
- Highly sensitive to New Physics

$\boldsymbol{\Gamma_s}$

- The average of the decay widths of light and heavy mass eigenstates
- Not sensitive to New Physics

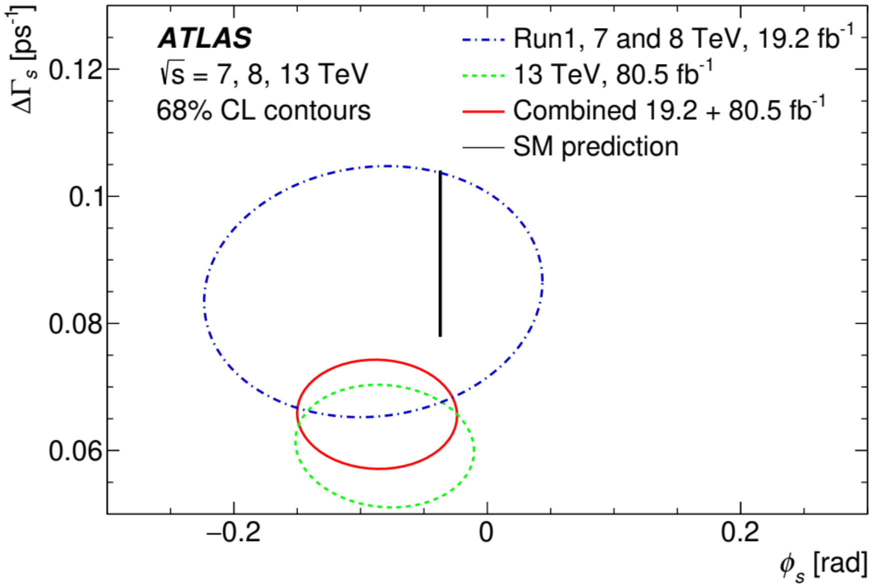
$\boldsymbol{\Delta\Gamma_s}$

- Difference between the decay widths of light and heavy mass eigenstates
- In the Standard Model, the value for $\Delta\Gamma_s$ is predicted to be (0.085 ± 0.015) ps^{-1} [RMP 88 (2016) 045002, arXiv:1511.09466v2]
- Moderately sensitive to New Physics.

If New Physics is involved, we expect different values of $\boldsymbol{\phi_s}$ and $\boldsymbol{\Delta\Gamma_s}$ compared to Standard Model prediction. Further, the oscillation frequency Δm_s provides a powerful constraint in global CKM fits.

- Data collected at $\sqrt{s} = 13$ TeV corresponding to 80.5 fb^{-1} [EPJ C 81 (2021) 342]
- Results consistent with ATLAS Run 1 results using 7 and 8 TeV data [JHEP 08 (2016) 147]
- 9 physics parameters

Comparison of results using 7 and 8 TeV, 13 TeV and combined data using contours[1] of 68% confidence level in the $\boldsymbol{\phi_s}$- $\Delta\boldsymbol{\Gamma_s}$ plane [EPJ C 81 (2021) 342]



Statistically combined Run 1 and Run 2 results [EPJ C 81 (2021) 342]

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s[rad]	-0.087	0.036	0.021
$\Delta\Gamma_s$[ps^{-1}]	0.0657	0.0043	0.0037
Γ_s [ps^{-1}]	0.6703	0.0014	0.0018

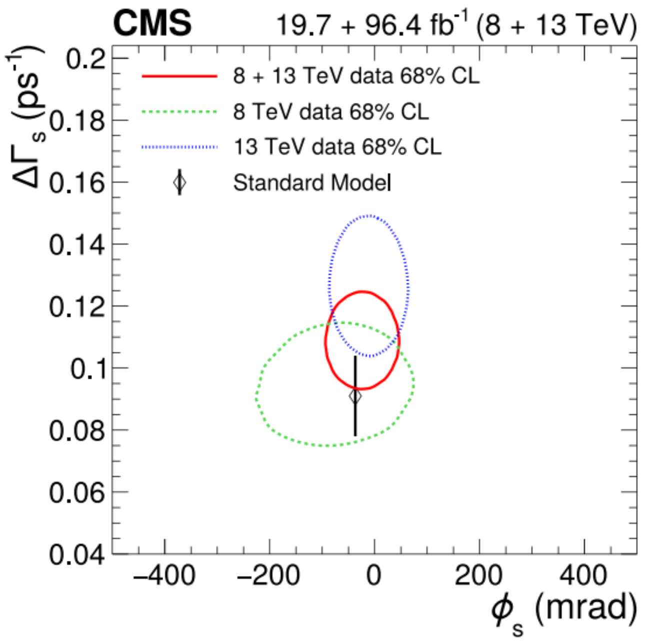
The measurement of the *CP* violating phase ϕ_s is consistent with the Standard Model prediction, and it improves on the precision of previous ATLAS measurements.

CMS Result - $B_s^0 \to J/\psi(\to \mu^+\mu^-)\,\phi$

- Measurement based on data corresponding to an integrated luminosity of 96.4 fb^{-1} collected at $\sqrt{s} =$ 13 TeV *pp* collisions [PLB 816 (2021) 136188]
- Significantly more precise than CMS Run 1 results using 8 TeV data [PLB 757 (2016) 97]
- In addition to 9 physics parameters, oscillation frequency, Δm_s, and direct CP violation parameter, $|\lambda|$, are estimated from the fit and consistent with the world average value [PRL D 98, 030001 (2018)] and with no *CP* violation, respectively.
- Statistically combined Run 1 and Run 2 measurements [PLB 816 (2021) 136188]

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s[rad]	-0.021	0.044	0.010
$\Delta\Gamma_s$[ps^{-1}]	0.1032	0.0095	0.0048

Comparison of results using 8 TeV and 13 TeV and combined data using contours[1] of 68% confidence level in the $\boldsymbol{\phi_s}$- $\Delta\boldsymbol{\Gamma_s}$ plane [PLB 816 (2021) 136188]



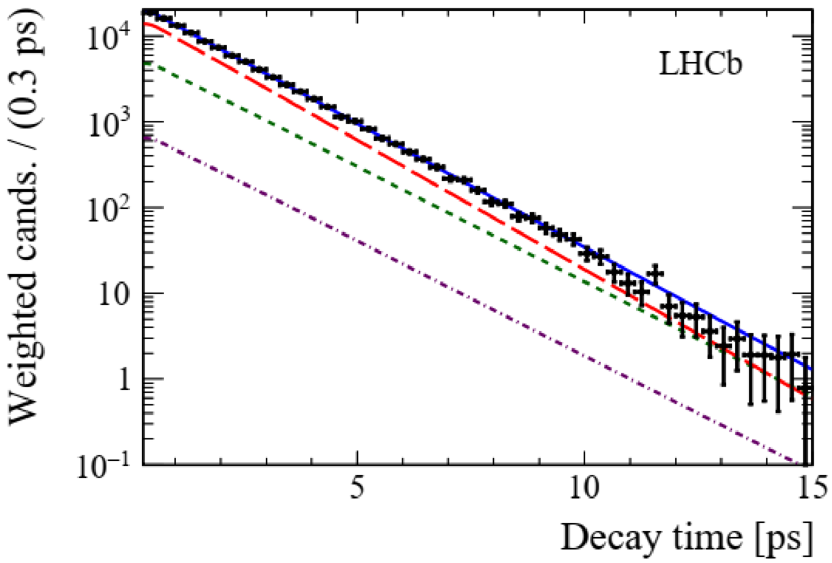
Significantly more precise than previous CMS measurement

- Data collected at 13 TeV corresponding to an integrated luminosity of 1.9 fb^{-1} [EPJ C 79 (2019) 706]
- 9 physics parameters
- Good agreement with LHCb Run 1 results using 7 and 8 TeV data [PRL 114, 041801 (2015)]
- Single most precise measurements of ϕ_s, $\Delta\Gamma_s$, and Γ_s to date
- Statistically combined Run 1 and Run 2 results [LHCb-PAPER-2019-013]

Parameter	Value	Uncertainty
ϕ_s[rad]	-0.081	0.032
$\Delta\Gamma_s$[ps^{-1}]	0.0777	0.0062
Γ_s [ps^{-1}]	0.6572	0.0023

- $\Delta m_s = 17.694 \pm 0.042$ ps^{-1} agrees well with the world average value [PRL D 98, 030001 (2018)]

Measured B_s^0 decay time



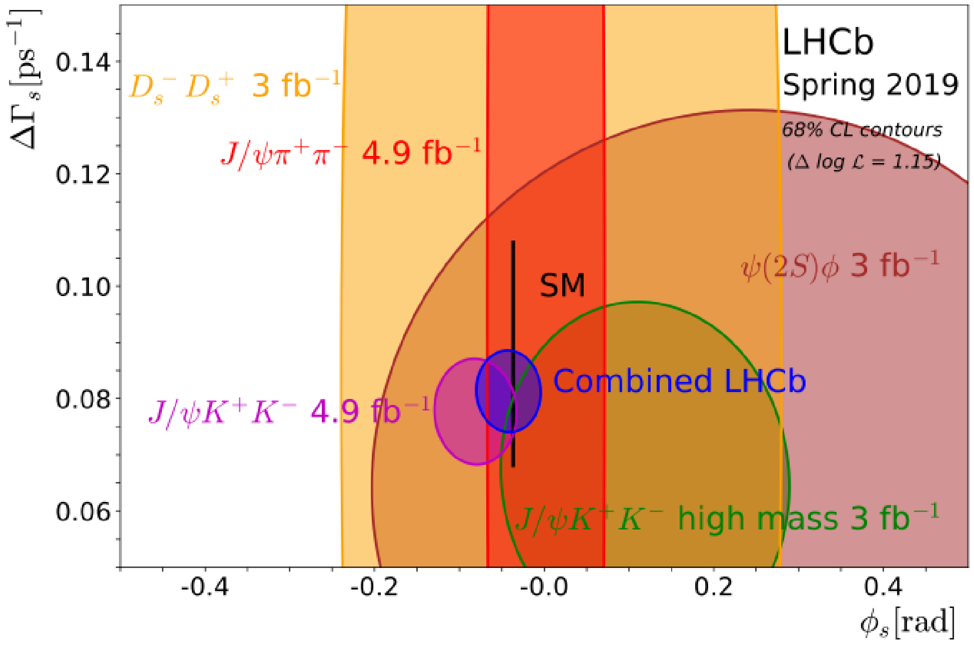
Most precise measurements of ϕ_s, $\Delta\Gamma_s$, and Γ_s using a single channel to date

Results using the following channels are combined [EPJ C 79 (2019) 706]:

- $B_s^0 \to J/\psi K^+ K^-$ [EPJ C 79 (2019) 706]
- $B_s^0 \to J/\psi \pi^+ \pi^-$ [PRL B797 (2019)]
- $B_s^0 \to D_s^+ D_s^-$ [PRL 113, 211801 (2014)]
- $B_s^0 \to \psi(2S)\phi$ [PRL B 762 (2016) 253-262]

Parameter	Value	Uncertainty
ϕ_s[rad]	-0.042	0.025
$\Delta\Gamma_s$[ps^{-1}]	0.0813	0.0048
Γ_s [ps^{-1}]	0.6563	0.0021

- Direct *CP* violation parameter
  $|\lambda| = 0.993 \pm 0.010$

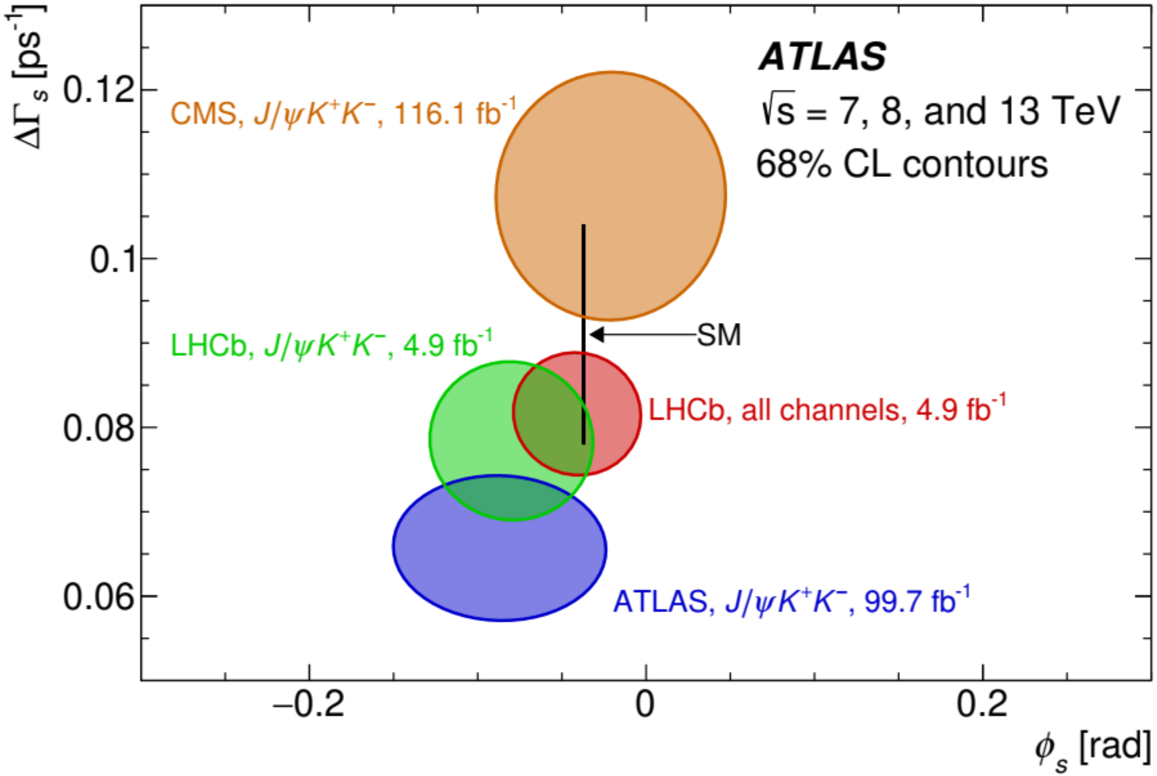


ϕ_s, $\Delta\Gamma_s$, Γ_s , and $|\lambda|$ are the most precise to date.

Value of $|\lambda|$ agrees well with the no direct *CP* violation in this decay and Γ_s and $\Delta\Gamma_s$ are consistent with the expectations of Heavy Quark Effective Theory (HQET) [JHEP 12 (2017) 068]

A comparison [EPJ C 81 (2021) 342] of measurements using $B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$ is shown at 68% confidence level in the ϕ_s- $\Delta\Gamma_s$ plane

Combined measurement from all channels by LHCb is shown.

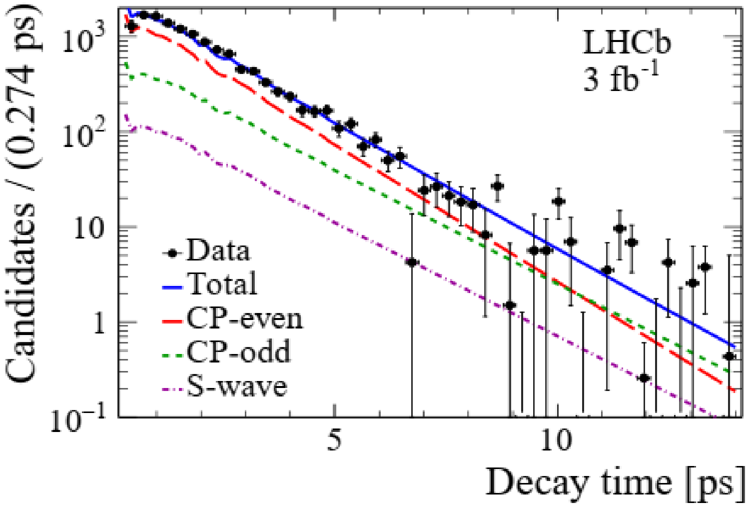


ϕ_s Measurement from $B_s^0 \to J/\psi(\to e^+e^-)\,\phi$ – LHCb Result

- First of its kind - J/ψ is reconstructed through its decay to an e^+e^- pair
- LHCb measured based on 7 and 8 TeV data corresponding to 3 fb^{-1} [EPJ C 81 (2021) 1026]
- 10 physics parameters
- Dominant sources of systematic uncertainty – imperfect mass and decay-time resolution models

Parameter	Value	Statistical uncertainty	Systematic uncertainty
ϕ_s[rad]	0.00	0.28	0.07
$\Delta\Gamma_s$[ps^{-1}]	0.115	0.045	0.011
Γ_s [ps^{-1}]	0.608	0.018	0.012

Measured B_s^0 decay time



These results constitute an important check on the results with muons in the final state.

Shows no evidence of *CP* violation

γ

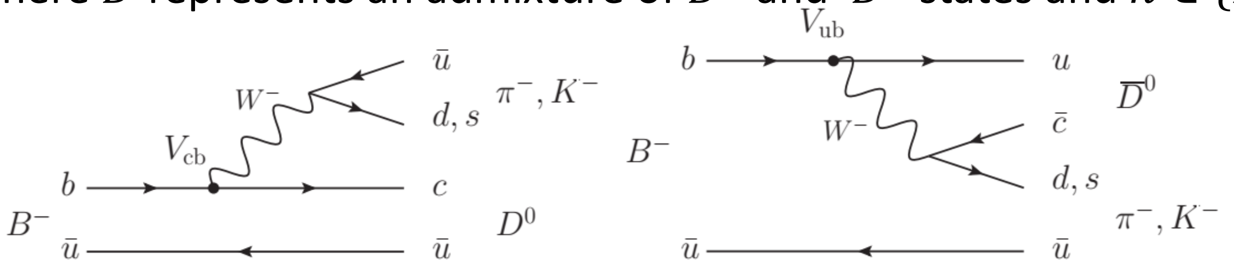
- Weak phase between $b \to u$ and $b \to c$
- Can be measured entirely from tree level decays
- World Average Value: $(66.2^{+3.4}_{-3.6})°$ [HFLAV20]
- Global CKM Fit: $(65.7^{+0.9}_{-2.7})°$ [CKMFitter]

LHCb Measurements

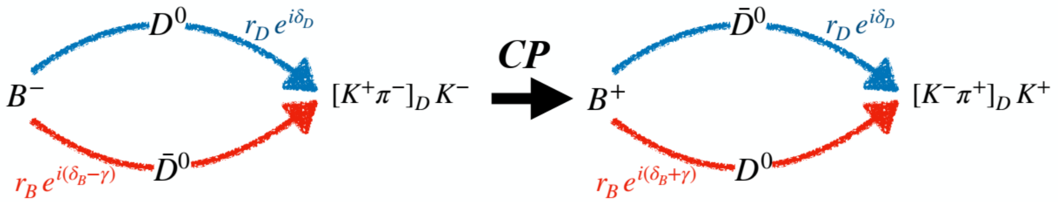
Tree level decays –

- *CP* Asymmetric rates in $B^{\pm} \to Dh^{\pm}, h \in \{K, \pi\}$ [JHEP 04 (2021) 081]
- Time dependent *CP* violation in $B_s^0 \to D_s^{\mp} K^{\pm} \pi^{\pm} \pi^{\mp}$ [JHEP 02 (2021) 169]

$B^{\pm} \to Dh^{\pm}$ where D represents an admixture of D^0 and $\bar{D}^0$ states and $h \in \{K, \pi\}$

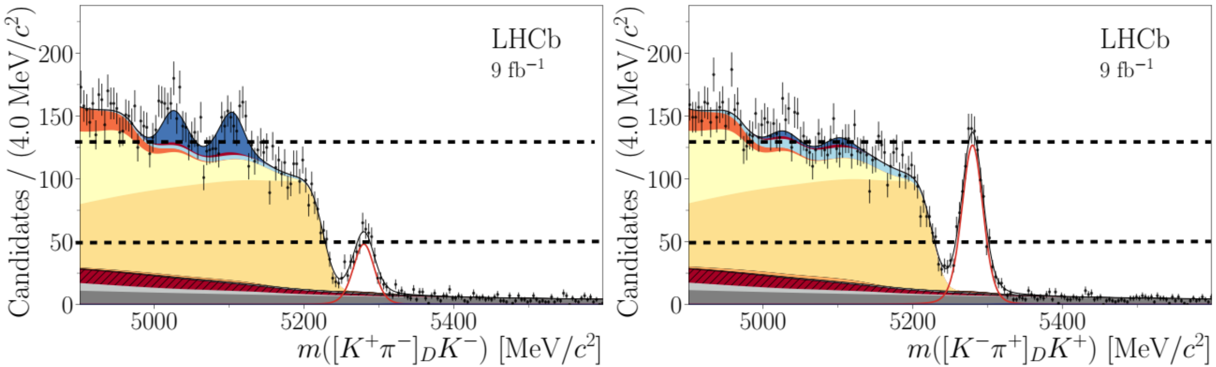


- If D^0 and $\bar{D}^0$ decay to a common final state *f*, interference effects sensitive to γ occur
- Parameters :
  - r_B – ratio of amplitude magnitudes of B^- and B^+ decays
  - δ_B – strong phase difference between B^- and B^+ decays
  - r_D – ratio of amplitude magnitudes of D^0 and $\bar{D}^0$ decays
  - δ_D – strong phase difference between D^0 and $\bar{D}^0$ decays

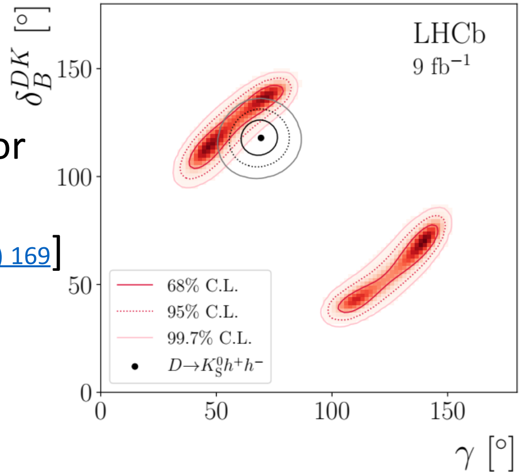


LHCb Result - $B^{\pm} \rightarrow Dh^{\pm}$ Decays

- Analyzed data - Run 1 + Run 2 (~9 fb^{-1})
- D decay channels (two body) - $D \rightarrow K^+K^-, D \rightarrow \pi^+\pi^-, D \rightarrow K^{\mp}\pi^{\pm}$ [JHEP 04 (2021) 081]
- 30 observables → tight constraints on r_B, δ_B, and γ
- Huge asymmetry between B^+ and B^- decays with *CP* Asymmetry $(A_{CP}) = (45 \pm 2.6)\%$



- Includes partially reconstructed $B^{\pm} \rightarrow D^*h^{\pm}$ decays where $D^* \rightarrow D\pi^0$ or $D^* \rightarrow D\gamma$
- D decay channels (self-conjugate three body) - $D \rightarrow K_s h^{\pm}h^{\mp}$ [JHEP 02 (2021) 169]
- Strong phase δ_D measured by CLEO-c/BES-III [PRD 101 112002 (2020)]



$$\gamma = (68.7^{+5.2}_{-5.1})^{\circ}$$

⇒ Most precise single measurement!

LHCb Result - CKM Angle γ From $B_s^0 \to D_s^{\mp} h^{\pm}\pi^{\pm}\pi^{\mp}$

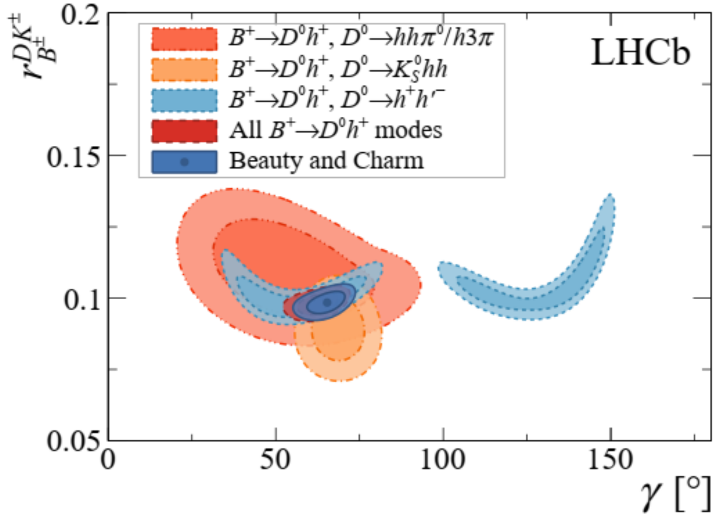
- Measurement using $B_s^0 \to D_s^{\mp} K^{\pm}\pi^{\pm}\pi^{\mp}$ and $\bar{B}_s^0 \to D_s^{\pm} K^{\mp}\pi^{\mp}\pi^{\pm}$ [JHEP 03 (2021) 137]
- Reconstructed using data corresponding to an integrated luminosity of 9 fb^{-1}
- Measured parameter: $\gamma - \phi_s = \gamma - 2\beta_s$ where β_s is well constrained from $B_s^0 \to J/\psi\phi$ decays and is taken as an external input [EPJ C 79 (2019) 706]
- Strong phase variations across phase space – time dependent amplitude analysis
- Calibration channel $B_s^0 \to D_s^{-}\pi^{+}\pi^{+}\pi^{-}$ can be used to measure Δm_s

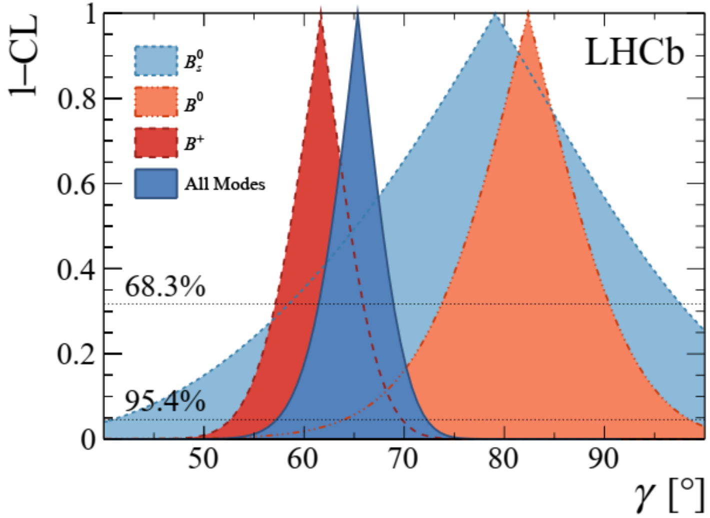
- Full time dependent amplitude fit: $\gamma - 2\beta_s = 42 \pm 10(\text{stat.}) \pm 4(\text{sys.}) \pm 5(\text{model})$
- Model independent fit: $\gamma - 2\beta_s = 42^{+19}_{-13}(\text{stat.})^{+6}_{-2}(\text{sys.})$

- Full time dependent amplitude fit: $\gamma = (44 \pm 12)^{\circ}$ modulo 180°
- Model independent fit: $\gamma = (44^{+20}_{-13})^{\circ}$ modulo 180°
- $\Delta m_s = (17.757 \pm 0.007 \pm 0.008)$ ps^{-1} – agrees well with world average value [PRL D 98, 030001 (2018)]

CKM Angle γ – Combination of all LHCb Measurements

- Last LHCb average: $\gamma = (74^{+5}_{-6})°$ [LHCb-CONF-2018-002]
- New LHCb average: $\gamma = (65.4^{+3.8}_{-4.2})°$ includes [JHEP 12 (2021) 141]
  - $B^{\pm} \to D^{*}h^{\pm}, h \in \{K, \pi\}$ and $D \to hh, K_S^0 hh$ [JHEP 04 (2021) 081, JHEP 02 (2021) 169]
  - $B_s^0 \to D_s^{\mp} K^{\pm}\pi^{\pm}\pi^{\mp}$ [JHEP 03 (2021) 137]





Getting closer to the precision of global fits: $\gamma = (65.6^{+0.9}_{-2.7})°$ [CKMFitter]

- New precise measurements of Δm_s and β_s are vital inputs for global CKM fits

- *CP* violation in *up* type quarks
- Expected to be tiny in the Standard Model, at the order of $10^{-4} - 10^{-3}$ [PRL D75, 036008 (2007)]

New Physics can alter this!

- Direct *CP* violation in decays of D^0
- *CP* violation in $D^0 - \overline{D}^0$ mixing
- Interference between mixing and decay amplitudes

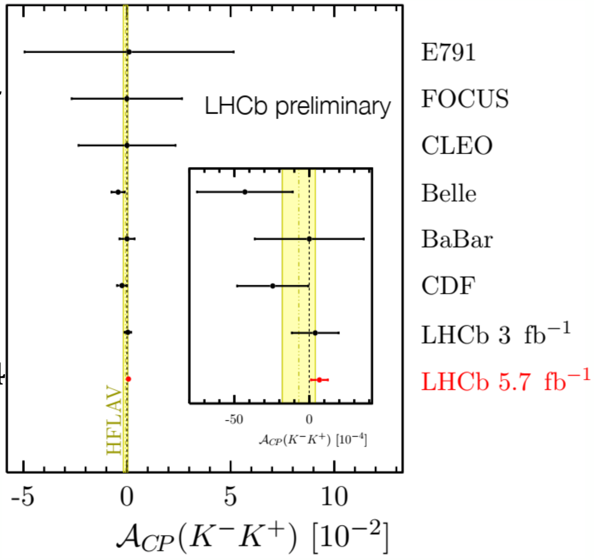
Ways to violate *CP* symmetry

- Difference of *CP* asymmetry parameters, ΔA_{CP}, for KK and $\pi\pi$ final states has been measured by LHCb [PRL 122 (2019) 211803]

$$\Delta A_{\mathrm{CP}} = A_{\mathrm{CP}}(K^+K^-) - A_{CP}(\pi^+\pi^-) = -(15.4 \pm 2.9) \times 10^{-4}$$

- New measurement of the *CP* asymmetry of the individual channel - $A_{\mathrm{CP}}(K^+K^-) = [6.8 \pm 5.4(\mathrm{stat.}) \pm 1.6(\mathrm{sys.})] \times 10^{-4}$

[LHCB-PAPER-2022-024]

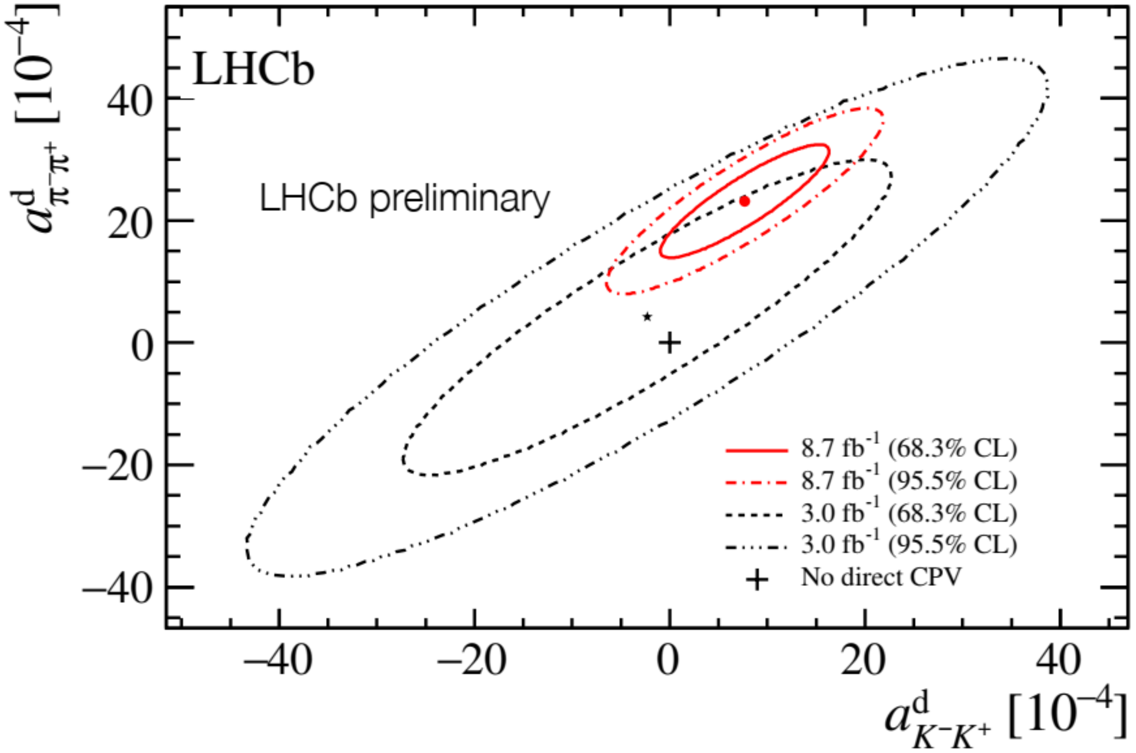


Direct *CP* violation parameters, a^d_{KK} and $a^d_{\pi\pi}$, are calculated from the combination of $A_{\rm CP}(K^+K^-)$ and $\Delta A_{\rm CP}$

$$a^d_{KK} = (7.7 \pm 5.7) \times 10^{-4}$$

$$a^d_{\pi\pi} = (23.2 \pm 6.1) \times 10^{-4}$$

[LHCB-PAPER-2022-024]



First evidence of direct *CP* violation in $D^0 \to \pi^+\pi^-$ at the level of 3.8σ !

Summary

- Single most precise measurement of the CKM angle γ using $B^{\pm} \rightarrow Dh^{\pm}, D \rightarrow K_s h^{\pm} h^{\mp}$ in the LHCb experiment

- Precision of ϕ_s, $\Delta\Gamma_s$, and Γ_s measurements using $B_s^0 \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\phi(\rightarrow K^+K^-)$ by ATLAS, CMS, and LHCb is greatly improved, and values agree with the Standard Model predictions

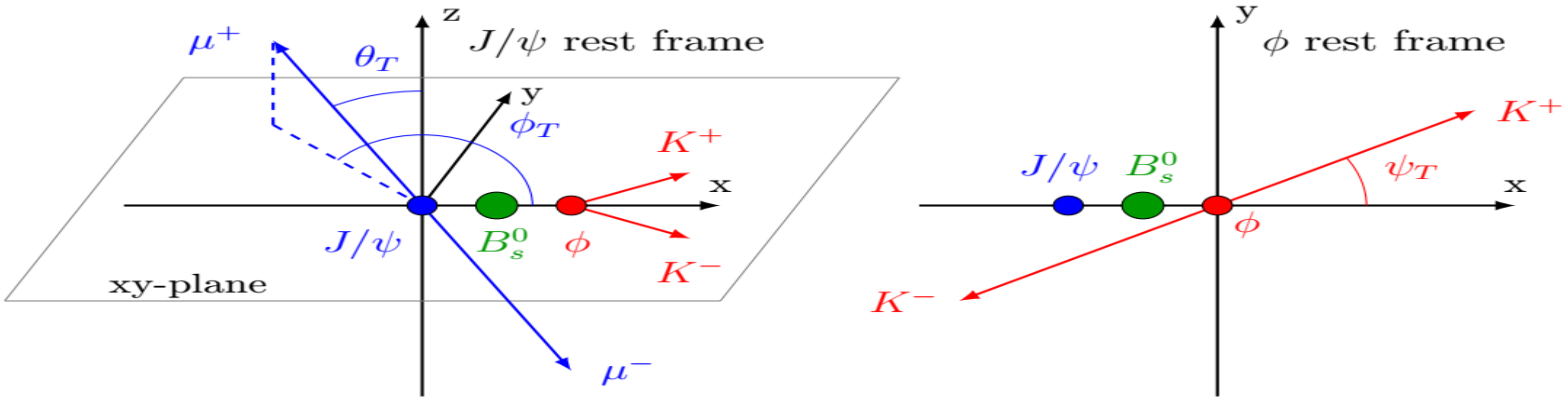
- Measurements of ϕ_s, $\Delta\Gamma_s$, and Γ_s using all channels in LHCb are the most precise to date

- Δm_s measured using $\bar{B}_s^0 \rightarrow D_s^{\pm} K^{\mp} \pi^{\mp} \pi^{\pm}$ in the LHCb experiment agrees well with the world average value

- First evidence of direct *CP* violation in $D^0 \rightarrow \pi^+\pi^-$ decays has been reported by LHCb

BACK UP

Final state of a $B_s^0 \rightarrow J/\psi\phi$ decay is an admixture of *CP* even and odd states. Time dependent angular analysis [PLB 369 (1996) 144-150] where the statistical contribution of *CP* even and odd states, is required for the extraction of SM parameters.



- In the transversity angle $\Omega(\theta_\mathrm{T}, \psi_\mathrm{T}, \phi_\mathrm{T})$ basis, four time dependent decay amplitudes - A_0 and $A_\parallel$ corresponding to *CP* even eigenstates and $A_\perp$ and A_S corresponding to *CP* odd eigenstates can be defined and their values at $t = 0$ are observables in this study.

- In addition, four relative strong phases $\delta_0, \delta_{||}, \delta_\perp$ and δ_S are also defined as observables with $\delta_0 = 0$ by convention.