CP violation & semileptonic decays in beauty and charm

LHCP June 8, 2018
Laurent Dufour, on behalf of the ATLAS, CMS and LHCb collaborations
CP violation

In the Standard Model: CP violation is only there in the weak interaction. The charged-current interaction for quarks is described by the CKM matrix

\[
V = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix} = \begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + O(\lambda^4)
\]

**Complex**: source of CP violation!
CP violation

Wolfenstein parametrisation

\[ V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4) \]

Unitarity

\[ V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \]

B^0 meson

Test the consistency of this triangle
Example of CP violation

\[ B^0 \]

\[ B^0_s \]
\[ B_S \rightarrow K^- \pi^+, \ B^0 \rightarrow K^+ \pi^- \]

\[
A_{CP} = \frac{|\bar{A}_{\bar{f}}|^2 - |A_f|^2}{|\bar{A}_{\bar{f}}|^2 + |A_f|^2}
\]

\( \bar{A}_{\bar{f}} \) Amplitude of \( \bar{B}^0 \) to \( K^-\pi^+ \)

\( A_f \) Amplitude of \( B^0 \) to \( K^+\pi^- \)
\[ B_S \rightarrow K^- \pi^+, \ B^0 \rightarrow K^+ \pi^- \]

\[ A_{CP} = \frac{\left| \bar{A}_{\bar{f}} \right|^2 - \left| A_f \right|^2}{\left| \bar{A}_{\bar{f}} \right|^2 + \left| A_f \right|^2} \]

- \( \bar{A}_{\bar{f}} \) Amplitude of \( \bar{B}^0 \) to \( K^-\pi^+ \)
- \( A_f \) Amplitude of \( B^0 \) to \( K^+\pi^- \)

**Figure 1:** Tree and penguin topologies contributing to the \( U \)-spin-related \( B_0 \) decays (\( q, q' \in \{ d, s \} \)).
CP violation in decay

\[ B_s^0 \rightarrow A_1 \xrightarrow{\phi_{\text{decay}}} K^- \pi^+ \]

\[ B_s^0 \rightarrow A_2 \xrightarrow{\phi_{\text{decay}}} K^- \pi^+ \]

\[ B_s^0 \rightarrow \bar{A}_1 \xrightarrow{\bar{\phi}_{\text{decay}}} K^+ \pi^- \]

\[ B_s^0 \rightarrow \bar{A}_2 \xrightarrow{\bar{\phi}_{\text{decay}}} K^+ \pi^- \]
$\mathcal{B}_s \rightarrow K^- \pi^+, \ B^0 \rightarrow K^+ \pi^-$

Count the number of decays + correct for the production and instrumental asymmetry.

\[
A_{CP}^{B^0} = -0.084 \pm 0.004 \pm 0.003 \\
A_{CP}^{B^0_s} = 0.213 \pm 0.015 \pm 0.007 \\
\Delta = -0.11 \pm 0.04 \pm 0.03
\]

\[
\Delta = \frac{A_{CP}^{B^0}}{A_{CP}^{B^0_s}} + \frac{\mathcal{B}(B^0_s \rightarrow \pi^+K^-)}{\mathcal{B}(B^0 \rightarrow K^+\pi^-)} \frac{\tau_d}{\tau_s} = 0.
\]

b baryons: $\Lambda_b$
\[ \Lambda_b \rightarrow pK, \quad \Lambda_b \rightarrow p\pi \]

Similar diagrams to \( B_s \rightarrow K^- \pi^+ \), \( B^0 \rightarrow K^+ \pi^- \)!
\[ \Lambda_b \rightarrow pK, \ \Lambda_b \rightarrow p\pi \]

**Result**

\[
A_{CP}^{pK} = -0.020 \pm 0.013 \pm 0.019 \\
A_{CP}^{p\pi} = -0.035 \pm 0.017 \pm 0.020
\]

Production + instr. asymmetries, correlated!
$\Lambda_b \rightarrow pK, \ \Lambda_b \rightarrow p\pi$

**Result**

$$A_{CP}^{pK} = -0.020 \pm 0.013 \pm 0.019$$

$$A_{CP}^{p\pi} = -0.035 \pm 0.017 \pm 0.020$$

production + instr. asymmetries, correlated!

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[LHCB-PAPER-2018-025 in prep]
Direct CPV in charm

- Complicated calculations.
- Expectation: little CP violation.
- Enormous production at the LHC

(\begin{align*}
V_{ub}^* V_{cb} \\
V_{ud}^* V_{cd} \\
V_{us}^* V_{cs}
\end{align*})

(not to scale)
The $\Lambda_c^+$ invariant mass is used as a discriminating variable between signal and combinatorial background. Fits to the mass spectrum, shown in Fig. 2, are used to measure the $\Lambda_c^+$ signal yields in order to compute $A_{CP}$, as defined in Eq. (2). The sPlot procedure [22] is employed to statistically subtract the combinatorial background component in the data, as required for the kinematic weighting procedure, and takes the fitted model as input.

The chosen fit model is the sum of a signal component and a background component, each weighted by a corresponding yield parameter. The signal is modelled as the sum of two Gaussian distributions which share a common mean but have separate width parameters, and the combinatorial background is modelled as a first-order polynomial. A cost function is defined as Neyman's $\chi^2$

$$\chi^2 = \sum_{i=1}^{B} \left( \frac{N_i - N f_{Tot}(m_i; \vec{\alpha})}{N_i} \right)^2$$

where $i$ is the bin index over the number of bins $B$ in the mass spectrum, $N_i$ is the observed number of entries in the $i$th bin, $N$ is the expected number of entries in the dataset as the sum of the fitted signal and background yield parameters, and $f_{Tot}(m_i; \vec{\alpha})$ represents the integral of the total model in the $m_i$ bin with parameter vector $\vec{\alpha}$. The binning is set as 120 bins of width $1\text{MeV}/c^2$ in the range $2230 < m(pK^-K^+) < 2350 \text{MeV}/c^2$.

Fits to the $pK^+K^-$ and $p\pi^+\pi^-$ data, summed over all conditions, are shown in Fig. 2. A good description of the data by the model is seen in all fits to the data subsamples. The $pK^+K^-$ and $p\pi^+\pi^-$ signal yields, separated by data-taking conditions, are given in Table 1.

To measure $A_{CP}$ as in Eq. (2), each data subsample is split by proton charge into $\Lambda_c^+$ and $\Lambda_c^-$ subsets. The model used in the previously described fit is used to define charge-weighting procedure.
Details: Talk by A. Pearce, this afternoon

\[ \Delta A_{CP}^{\text{wgt}} = (0.30 \pm 0.91 \pm 0.61)\% , \]
The B's flagship

Willem van de Velde the Elder
The $B_s$ flagship

Time-dependent CP analyses

mixing
The mass eigenstates are mixtures of the flavour eigenstates

\[ \langle B^0_{s \, L, H} \rangle = p \langle B^0_s \rangle \mp q \langle \bar{B}^0_s \rangle \]

- Mass difference, $\Delta m_s$
- Oscillation frequency
- Decay width difference $\Delta \Gamma_s$
- Phase

Experimental evidence (~0.3%) + theoretical predictions: CP eigenstates $\sim$ mass eigenstates
CP violation in decay

\[ B_s^0 \xrightarrow{A_1, A_2} \phi_{\text{decay}} \xrightarrow{\text{CPV in decay}} K^- \pi^+ \]

\[ \bar{B}_s^0 \xrightarrow{\bar{A}_1, \bar{A}_2} \bar{\phi}_{\text{decay}} \xrightarrow{\text{CPV in decay}} K^+ \pi^- \]
CP violation in decay + mixing

\[ B_s^0 \rightarrow A_1, A_2 \]

\[ \bar{B}_s^0 \rightarrow \bar{A}_1, \bar{A}_2 \]

\[ \Phi_{\text{decay}} \]

\[ K^- K^+ \]

CP violation in decay
CP violation in decay+mixing

$B_s^0 \rightarrow \phi_{\text{decay}}$

$\phi_{\text{mix}}$

$M_{12}$

$\Gamma_{12}$

$\bar{B}_s^0 \rightarrow \bar{\phi}_{\text{decay}}$

$K^- K^+$

Illustration by Matthew Kenzie
CP violation in decay+mixing

\[ A_{CP}(t) = \frac{\Gamma_{B^0_{(s)}} \rightarrow f(t) - \Gamma_{\bar{B}^0_{(s)}} \rightarrow f(t)}{\Gamma_{B^0_{(s)}} \rightarrow f(t) + \Gamma_{\bar{B}^0_{(s)}} \rightarrow f(t)} \]
Time-dependent CP asymmetry

\[ A_{CP}(t) = \frac{\Gamma_{B_s^0 \rightarrow f}(t) - \Gamma_{B_s^0 \rightarrow f}(t)}{\Gamma_{B_s^0 \rightarrow f}(t) + \Gamma_{B_s^0 \rightarrow f}(t)} = -C_f \cos(\Delta m_{d,s} t) + S_f \sin(\Delta m_{d,s} t) \]

\[ \cosh \left( \frac{\Delta \Gamma_{d,s}}{2} t \right) + A^\Delta \Gamma_f \sinh \left( \frac{\Delta \Gamma_{d,s}}{2} t \right) \]

Observables

CPV decay \( C_f \)

CPV interference \( S_f \)

CPV in \( \Delta \Gamma \) \( A^\Delta \Gamma_f \)

(Assumed: \( |q/p| \sim 1 \))

1. Knowing the flavour at production.

2. Excellent proper-time resolution, \( O(50fs) \)

Requirements

Primary vertex

\( B_s \)

\( K^+ \)

\( K^- \)

\( b^{tag} \)

\( \mu^+ \)
The study of parameters entering the $B$ system

In this paper, measurements of the time-dependent $B$ meson decays $B^0 \rightarrow \pi^+ \pi^-$ are presented. Taking into account the sizes of statistical and systematic uncertainties, the presence of physics lying beyond the Standard Model has been shown that a combined analysis of the branching fractions and CP violation asymmetries, allows stringent bounds on the parameters $C_f$ and $S_f$.

The Asymmetry $A_{CP}(t)$ can be described by:

$$A_{CP}(t) = \frac{\Gamma_{B^0(\bar{B}^0)}^f(t) - \Gamma_{B^0(\bar{B}^0)}^i(t)}{\Gamma_{B^0(\bar{B}^0)}^f(t) + \Gamma_{B^0(\bar{B}^0)}^i(t)} = \frac{-C_f \cos(\Delta m_d t) + S_f \sin(\Delta m_d t)}{\cosh \left( \frac{\Delta \Gamma f}{2} \right) + A_\Delta \Gamma \sinh \left( \frac{\Delta \Gamma d s}{2} \right)}$$

Fitted observables

CPV decay $C_f$

CPV interference $S_f$

<table>
<thead>
<tr>
<th>$V_{ud}/V_{cb}$</th>
<th>$V_{td}/V_{cb}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha = \phi_s$</td>
<td>$\gamma = \phi_d$</td>
</tr>
</tbody>
</table>

LHCb

<table>
<thead>
<tr>
<th>Asymmetry</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS Tag</td>
</tr>
</tbody>
</table>

\begin{align*}
C_{\pi^+ \pi^-} &= -0.34 \pm 0.06 \pm 0.01, \\
S_{\pi^+ \pi^-} &= -0.63 \pm 0.05 \pm 0.01,
\end{align*}
The study of $B_s \rightarrow K^+K^-$ results

\[ A_{CP}(t) = \frac{\Gamma_{B^0_{(s)} \rightarrow f}(t) - \Gamma_{\bar{B}^0_{(s)} \rightarrow f}(t)}{\Gamma_{B^0_{(s)} \rightarrow f}(t) + \Gamma_{\bar{B}^0_{(s)} \rightarrow f}(t)} = \frac{-C_f \cos(\Delta m_{d,s}t) + S_f \sin(\Delta m_{d,s}t)}{\cosh\left(\frac{\Delta \Gamma_{d,s}}{2} t\right) + A_f^{\Delta \Gamma} \sinh\left(\frac{\Delta \Gamma_{d,s}}{2} t\right)} \]

**Fitted observables**

- CPV decay: $C_f$
- CPV interference: $S_f$
- CPV in $\Delta \Gamma$: $A_f^{\Delta \Gamma}$

| $C_{K^+K^-}$ | $0.20 \pm 0.06 \pm 0.02$ |
| $S_{K^+K^-}$ | $0.18 \pm 0.06 \pm 0.02$ |
| $A_{K^+K^-}$ | $-0.79 \pm 0.07 \pm 0.10$ |

**LHCb Run-1 data set**

**First evidence Combined: 4σ**

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$\mathcal{B}_S \rightarrow K^+K^- : \gamma$

Can be used to constrain $\gamma$ (using U-spin symmetry) \cite{1,2}, anticipating update with new results

Theory very clean: $\delta\gamma/\gamma < O(10^{-7})$\cite{3}
Experimentally: least well known (just)

\begin{itemize}
  \item \cite{1}: R. Fleischer, Phys. Lett. B 459 (1999) 306 (concept)
  \item \cite{2}: LHCb-PAPER-2014-045 (application)
  \item \cite{3}: Brod, Zupan, JHEP 1401 (2014) 051
\end{itemize}
Direct $\gamma$ measurement: $B^0 \rightarrow D^+\pi^-$

The study of condition between mixing and decay, respectively. The quantities the terms and $U$-spin symmetry, parameters entering the picture \[1, 2\] of the quark-flavour mixing in the Standard Model (SM) and to investigate

1 Introduction

Assuming $B^0 \rightarrow \pi^+$ decays and of the time-integrated CPV interference $B^0 \rightarrow \pi^+$, where

- Direct measurement: $B^0 \rightarrow \pi^+$, when combined with other measurements from the isospin-related $f$ decays, allowing stringent

The analysis is based on a data sample of $B^0 \rightarrow \pi^+$ mesons to charged two-body decays and of the time-integrated CPV interference $B^0 \rightarrow \pi^+$, when combined with other measurements from the isospin-related $f$ decays, allowing stringent

The signal region, with a long tail towards the high-mass region; the shape of these backgrounds are determined from simulation. Cross-feed and to partially reconstructed decays, such as the known $B^0 \rightarrow \pi^+$ decays and of the time-integrated CPV interference $B^0 \rightarrow \pi^+$, when combined with other measurements from the isospin-related $f$ decays, allowing stringent

The simultaneous fit of the two distributions is described in the text and on the

The efficiency of the PID requirement on the companion $f$ component includes both $B^0 \rightarrow \pi^+$ cross-feed decays in the kaon-like $f$ system are

The fitted observables

CPV interference $B \rightarrow D^- \pi^+$ $S_f$

CPV interference $B \rightarrow D^+ \pi^-$ $S_{\bar{f}}$

LHCb Run-1 data set

(479000 ± 700) decays
Direct $\gamma$ measurement: $B^0 \to D^+\pi^-$

$B^0(t=0)$

$\delta+\gamma$

$\delta-\gamma$

$r \approx 2\%$

Fitted observables

CPV interference $B \to D^- \pi^+$ $S_f$

CPV interference $B \to D^+ \pi^-$ $S_{\bar{f}}$

Result
Status of gamma measurements

\[ \gamma = (74.0^{+5.0}_{-5.8})^\circ \]

LHCb

\[ \gamma = (73.5^{+4.2}_{-5.1})^\circ \]

HFLAV

Indirect: \( (65.3^{+1.0}_{-2.5})^\circ \) (~2σ)

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Status of gamma measurements

\[ \gamma = (74.0^{+5.0}_{-5.8})^\circ \]

\[ \gamma = (73.5^{+4.2}_{-5.1})^\circ \]

New results: talk by Susan Haines

LHCb-PAPER-2018-017 LHCb run 2 \( B^\pm \rightarrow D^0 K^\pm \)

LHCb-PAPER-2018-009 LHCb run 1 \( B^0 \rightarrow D^+ \pi^- \)
$B_s \rightarrow J/\psi \, K^- K^+$

$B^0_s \xrightarrow{A_1} \varphi_{\text{decay}} \xrightarrow{A_2} J/\psi K^+ K^-$

$B^0_s \rightarrow J/\psi \, K^- K^+$

Illustration by Matthew Kenzie

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Current averages

![Graph showing current averages with contributions from ATLAS, CMS, and LHCb.]

- ATLAS 19.2 fb\(^{-1}\)
- CDF 9.6 fb\(^{-1}\)
- CMS 19.7 fb\(^{-1}\)
- LHCb 3 fb\(^{-1}\)
- D0 8 fb\(^{-1}\)

68% CL contours
(Δ log L = 1.15)
Impact of mixing analyses

\[ M_{12}^{d,s} = (M_{12}^{d,s})_{SM} \times (1 + h_{d,s} e^{2i\sigma_{d,s}}). \]

Status in 2013

~ end of Run 2

Looking forward to Run-2 updates!
Semileptonic decays

- Large branching ratios
- Technically challenging: partially reconstructed
Lifetimes

measure momentum
+ decay length
Lifetimes

measure momentum
+ decay length
Measurement of $D_S$ & $B_S$ lifetimes

To use $B_S$ and $B^0$ semileptonic decays, to the same final state particles:

$$B_{(s)} \rightarrow D_{(s)}(\rightarrow KK\pi) \mu \nu$$

**Decay time acceptance:** Measure ratio of lifetimes for $B_S/B^0$ and $D_S/D^+$. Use world-average for the denominator.

Most precise single measurements

$$\tau(D^-_S) = 0.5064 \pm 0.0030 \pm 0.0017 \pm 0.0017 \text{ ps}$$

$$\tau(B^0_S) = 1.547 \pm 0.013 \pm 0.010 \pm 0.004 \text{ ps}$$

Measuring lifetimes with semileptonic decays is competitive!
Lifetime of $\Omega_c$

Try to do a similar procedure for $\Omega_c$ baryons: current relative uncertainty on $\Omega_c$ lifetime is 17%\textsuperscript{[1]}. Measure:

$$r'_{\Omega_c^0} \equiv \frac{\tau_{\Omega_c^0}}{\tau_{D^+}}$$

Using semileptonic decays:

$$B \rightarrow D^+ \mu \nu X \quad \Omega_b \rightarrow \Omega_{c0} \mu \nu X$$

$$D^+ \rightarrow K \pi \pi \quad \Omega_c^0 \rightarrow pKK\pi$$

$$\frac{\tau_{\Omega_c^0}}{\tau_{D^+}} = 0.258 \pm 0.023 \pm 0.010$$

$$\tau_{\Omega_c^0} = 268 \pm 24 \pm 10 \pm 2 \text{ fs},$$

Lifetime of $\Omega_c$
Lifetime of $\Omega_c$
Lifetime of $\Omega_C$

Expected hierarchy (Pauli interference)\footnote{Browder, Honscheid, Pedrini, \texttt{arXiv:hep-ph/9606354v2} (for example)}:

\[ \tau_{\Xi_c^+} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0} > \tau_{\Omega_c^0} \]

This measurement:

\[ \tau_{\Xi_c^+} > \tau_{\Omega_c^0} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0} \]
Conclusion

Seen that the domain of time-integrated CPV has been extended to $\Lambda_b$. Time-dependent CPV: closing in on the CKM angle $\gamma$ and shown the strongest evidence for time-dependent CPV in $B_s$ mesons ($B_s \rightarrow KK$).

The technique of using semileptonic decays for lifetime proved useful, this time with striking results for the $\Omega_c^0$ baryon.

Eagerly awaiting the Run-2 results!
CP violation & semileptonic decays in beauty and charm

LHCb June 8, 2018
Laurent Dufour, on behalf of the ATLAS, CMS and LHCb collaborations
Backup slides
Systematics lifetime analysis $D_s/B_s$

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>$\sigma[\Delta(D)]$ [ps$^{-1}$]</th>
<th>$\sigma[\Delta(B)]$ [ps$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit bias</td>
<td>0.0004</td>
<td>0.0009</td>
</tr>
<tr>
<td>Decay model of $B_s^0 \rightarrow D_s^- \mu^+ \nu$</td>
<td>0.0005</td>
<td>0.0025</td>
</tr>
<tr>
<td>Sample composition</td>
<td>0.0007</td>
<td>0.0005</td>
</tr>
<tr>
<td>$f_s/f_d(p_T)$</td>
<td>0.0018</td>
<td>0.0028</td>
</tr>
<tr>
<td>Decay-time acceptance</td>
<td>0.0049</td>
<td>0.0004</td>
</tr>
<tr>
<td>Decay-time resolution</td>
<td>0.0039</td>
<td>0.0004</td>
</tr>
<tr>
<td>Feed-down from $B_c^+$ decays</td>
<td>-</td>
<td>0.0010</td>
</tr>
<tr>
<td>Total systematic</td>
<td>0.0065</td>
<td>0.0041</td>
</tr>
<tr>
<td>Statistical</td>
<td>0.0117</td>
<td>0.0053</td>
</tr>
</tbody>
</table>
Systematics lifetime analysis $\Omega_c$

Table 1: Summary of systematic uncertainties on the lifetime ratio, $r_{\Omega_c^0}$, in units of $10^{-4}$.

<table>
<thead>
<tr>
<th>Source</th>
<th>$r_{\Omega_c^0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decay time acceptance</td>
<td>13</td>
</tr>
<tr>
<td>$\Omega_b^-$ prod. spectrum</td>
<td>3</td>
</tr>
<tr>
<td>$\Omega_b^-$ lifetime</td>
<td>4</td>
</tr>
<tr>
<td>Decay time resolution</td>
<td>3</td>
</tr>
<tr>
<td>Background subtraction</td>
<td>18</td>
</tr>
<tr>
<td>$H_c(\tau^-, D)$, random $\mu^-$</td>
<td>8</td>
</tr>
<tr>
<td>Simulated sample size</td>
<td>98</td>
</tr>
<tr>
<td>Total systematic</td>
<td>101</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>230</td>
</tr>
</tbody>
</table>
Semileptonic decays

Are the mixing probabilities the same for $B$ and $\bar{B}$?

Are the mixing probabilities the same for $B_s$ and $\bar{B}_s$?
$B_s \rightarrow KK, \, B^0 \rightarrow \pi\pi$

1. Fit the decay time distribution (split by flavour tag), using all components: access to $\Gamma(B_s \rightarrow f)$

2. Use the mass resolution to select the correct decay.
All phis measurements

Table 1: Direct experimental measurements of $\phi_s^{c\bar{s}}$, $\Delta \Gamma_s$ and $\Gamma_s$ using $B^0_s \to J/\psi \phi$, $J/\psi K^+ K^-$, $\psi(2S)\phi$, $J/\psi \pi^+ \pi^-$ and $D^+_s D^-_s$ decays. Only the solution with $\Delta \Gamma_s > 0$ is shown, since the two-fold ambiguity has been resolved in Ref. [1]. The first error is due to statistics, the second one to systematics. The last line gives our average.

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Mode</th>
<th>Dataset</th>
<th>$\phi_s^{c\bar{s}}$</th>
<th>$\Delta \Gamma_s$ (ps$^{-1}$)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF</td>
<td>$J/\psi \phi$</td>
<td>9.6 fb$^{-1}$</td>
<td>$[-0.60, +0.12]$, 68% CL</td>
<td>$+0.068 \pm 0.026 \pm 0.009$</td>
<td>[2]</td>
</tr>
<tr>
<td>D0</td>
<td>$J/\psi \phi$</td>
<td>8.0 fb$^{-1}$</td>
<td>$-0.55^{+0.38}_{-0.36}$</td>
<td>$+0.163^{+0.065}_{-0.064}$</td>
<td>[3]</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$J/\psi \phi$</td>
<td>4.9 fb$^{-1}$</td>
<td>$+0.12 \pm 0.25 \pm 0.05$</td>
<td>$+0.053 \pm 0.021 \pm 0.010$</td>
<td>[4]</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$J/\psi \phi$</td>
<td>14.3 fb$^{-1}$</td>
<td>$-0.110 \pm 0.082 \pm 0.042$</td>
<td>$+0.101 \pm 0.013 \pm 0.007$</td>
<td>[5]</td>
</tr>
<tr>
<td>ATLAS</td>
<td>above 2 combined</td>
<td></td>
<td>$-0.090 \pm 0.078 \pm 0.041$</td>
<td>$+0.085 \pm 0.011 \pm 0.007$</td>
<td>[5]</td>
</tr>
<tr>
<td>CMS</td>
<td>$J/\psi \phi$</td>
<td>19.7 fb$^{-1}$</td>
<td>$-0.075 \pm 0.097 \pm 0.031$</td>
<td>$+0.095 \pm 0.013 \pm 0.007$</td>
<td>[6]</td>
</tr>
<tr>
<td>LHCb</td>
<td>$J/\psi K^+ K^-$</td>
<td>3.0 fb$^{-1}$</td>
<td>$-0.058 \pm 0.049 \pm 0.006$</td>
<td>$+0.0805 \pm 0.0091 \pm 0.0032$</td>
<td>[7]</td>
</tr>
<tr>
<td>LHCb</td>
<td>$J/\psi \pi^+ \pi^-$</td>
<td>3.0 fb$^{-1}$</td>
<td>$+0.070 \pm 0.068 \pm 0.008$</td>
<td>---</td>
<td>[8]</td>
</tr>
<tr>
<td>LHCb</td>
<td>$J/\psi K^+ K^-a$</td>
<td>3.0 fb$^{-1}$</td>
<td>$+0.119 \pm 0.107 \pm 0.034$</td>
<td>$+0.066 \pm 0.018 \pm 0.010$</td>
<td>[9]</td>
</tr>
<tr>
<td>LHCb</td>
<td>above 3 combined</td>
<td></td>
<td>$+0.001 \pm 0.037$(tot)</td>
<td>$+0.0813 \pm 0.0073 \pm 0.0036$</td>
<td>[9]</td>
</tr>
<tr>
<td>LHCb</td>
<td>$\psi(2S)\phi$</td>
<td>3.0 fb$^{-1}$</td>
<td>$+0.23^{+0.29}_{-0.28} \pm 0.02$</td>
<td>$+0.066^{+0.41}_{-0.44} \pm 0.007$</td>
<td>[10]</td>
</tr>
<tr>
<td>LHCb</td>
<td>$D^+_s D^-_s$</td>
<td>3.0 fb$^{-1}$</td>
<td>$+0.02 \pm 0.17 \pm 0.02$</td>
<td>---</td>
<td>[11]</td>
</tr>
<tr>
<td>All combined</td>
<td></td>
<td></td>
<td>$-0.021 \pm 0.031$</td>
<td>$+0.085 \pm 0.006$</td>
<td></td>
</tr>
</tbody>
</table>

$^a m(K^+ K^-) > 1.05$ GeV/c$^2$. 

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References:

1. [Ref. 1]
2. [Ref. 2]
3. [Ref. 3]
4. [Ref. 4]
5. [Ref. 5]
6. [Ref. 6]
7. [Ref. 7]
8. [Ref. 8]
9. [Ref. 9]
10. [Ref. 10]
11. [Ref. 11]