PRECISION MEASUREMENT OF THE CP-VIOLATING PHASE $\phi_s$ AT LHCb

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On behalf of the LHCb Collaboration

CERN SEMINAR
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Sakharov Conditions

1. Baryon Number Violation
2. C and CP violation
3. Interactions out of thermal equilibrium

[Rev. Mod. Phys. 88, 015004 (2016)]

- Baryon asymmetry of the Universe: $n_b/n_\gamma \sim 10^{-10}$
- CP violation in the SM does not account for it
- There must be New Physics and new sources of CP violation

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How to find New Physics at the LHC

- **High energy frontier**: require $E > mc^2$ for direct production $\rightarrow$ few TeV

- **Direct observation**: require $E > mc^2$ for direct production $\rightarrow$ few TeV

- **Precision frontier**: new particle effect loop processes $\rightarrow$ up to O(100 TeV)

  - $W^+ \rightarrow \bar{s} \bar{b}
  - $W^- \rightarrow s b$
  - $\bar{B}_s^0 \rightarrow u, c, t$
  - $B_s^0 \rightarrow \bar{u}, \bar{c}, \bar{t}$

  - **Indirect effects**: new particle effect loop processes $\rightarrow$ up to O(100 TeV)

Most HEP direct discoveries have been preceded by indirect evidence first!

- If we don’t see New Physics directly at the LHC can indirect evidence guide us where to look (or what to build) next?

See e.g. [L. Silvestrini: arXiv.1905.00798]
Flavour physics: a history of success

- **Parity violation**
  - 1956: T. D. Lee
  - 1964: C. N. Yang and C. S. Wu et al.

- **Strange particles: CP violation in K meson decays**

- **The CKM matrix**
  - 1970: M. Kobayashi and T. Maskawa

- **First observation of direct CP violation**
  - 1987: NA48 and KTeV collaborations

- **Observation of the $B_s^0 - \bar{B}_s^0$ oscillations**
  - 1999: CDF collaboration

- **Branching ratio of $K^0 \to \mu \mu$ and prediction of the charm quark**
  - 1973: N. Cabibbo

- **Observation of the $B^0 - \bar{B}^0$ oscillations and extrapolation of the top mass**
  - 1973: Argus collaboration

- **Observation of CP violation in the $B^0$ system**
  - 2001: Babar and Belle collaborations

- **Observation of CP violation in $D^0$ meson decays**
  - 2006: LHCb collaboration

- **Observation of CP violation in $K^0_\ell$ decays**
  - 2019: LHCb collaboration

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Quark transitions

In the SM quarks can change flavour by emission of a $W^\pm$ boson
- So must also change charge
  (i.e. from up-type to down-type or vice-versa)

\[ \begin{align*}
\text{Up-type:} & \quad u & c & t \\
\text{Down-type:} & \quad d & s & b
\end{align*} \]

- The probability for such a transition is governed by the elements of the $3 \times 3$ unitary CKM matrix

\[ \begin{align*}
q & \sim V_{qq'} q'  \\
\bar{q} & \sim V^*_{\bar{q}q'} \bar{q}'
\end{align*} \]

$W^+$

$W^-$

$CP$

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Quark transitions II

In the SM quarks can change flavour by emission of a $W^\pm$ boson
• So must also change charge
  (i.e. from up-type to down-type or vice-versa)

- The probability for such a transition is governed by the elements of the $3\times3$ unitary CKM matrix
- It exhibits a clear hierarchy

![Diagram of quark transitions](image)

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CP violation in the Standard Model

- **Wolfenstein parameterisation**: CKM matrix described by 4 parameters $\lambda, A, \rho, \eta$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{i\beta_s} & |V_{tb}| \end{pmatrix}$$

$$= \begin{pmatrix} 1 - \lambda^2/2 - \lambda^4/8 \\ -\lambda + A^2 \lambda^5 [1 - 2(\rho + i\eta)]/2 \\ A\lambda^3 [1 - (\rho + i\eta)(1 - \lambda^2/2)] \end{pmatrix} \begin{pmatrix} \lambda & A\lambda^3(\rho - i\eta) \\ 1 - \lambda^2/2 - \lambda^4(1 + 4A^2)/8 & A\lambda^2 \\ -A\lambda^2 + A\lambda^4 [1 - 2(\rho + i\eta)]/2 & 1 - A^2\lambda^4/2 \end{pmatrix} + \mathcal{O}(\lambda^6)$$

**Wolfenstein parametrisation**

$$\lambda = \sin (\theta_C) \approx 0.22, \ \eta \approx 0.3$$

- 3 quark generations allow for a CP violating phase: $\eta$ is the **only CPV source in the SM**
- But $\eta$ is small $\rightarrow$ where did the anti-matter go?
- Test the consistency of CKM picture within SM experimentally
Unitarity $V_{\text{CKM}} \cdot V_{\text{CKM}}^\dagger = I$ imposes several conditions which give rise to “unitarity” triangles.

$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Unitarity condition from 2nd and 3rd columns:

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

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The CKM fit: a lot of room for NP

- The SM works so remarkably well that we have to make more and more precise measurements

- $O(20\%)$ NP contributions to most loop-level processes (FCNC) are still allowed
  - See e.g. J. Charles at al arXiv:1309.2293 [hep-ph]

- Interesting comparison of tree-level vs higher-order observables. In the latter, unknown particles could contribute.
B flavour mixing

- Neutral $B^0_s$ mesons can oscillate between their particle and anti-particle states

The physical mass eigenstates ($L, H$) are admixtures of the weak eigenstates:

$$|B_L > = p |B^0_s > + q |\bar{B}^0_s >$$
$$|B_H > = p |B^0_s > - q |\bar{B}^0_s >$$

- with mass difference $\Delta m = m_H - m_L$ and decay-width difference $\Delta \Gamma = \Gamma_L - \Gamma_H$
- flavor at production ($t=0$) could be different from flavour at decay time $t$
CP violation

- Must have **two interfering amplitudes** with different strong ($\delta$) and weak ($\varphi$) phases
- For a $B_s^0$ decay to a CP eigenstate $f$, CP-violating effects depend on $\lambda_f = \frac{q \bar{A}_f}{p A_f}$

**CPV in decay**
- $P(B_s^0 \to f) \neq P(\bar{B}_s^0 \to f)$
- $|q/p| \neq 1$

**CPV in mixing**
- $P(B_s^0 \to \bar{B}_s^0) \neq P(\bar{B}_s^0 \to B_s^0)$
- $|q/p| \neq 1$

**CPV in the interference between decay and mixing**
- $P(B_s^0 \to f) \neq P(B_s^0 \to \bar{B}_s^0 \to f)$
- $\arg(\lambda_f) \neq 0$
CP violation

- Must have **two interfering amplitudes** with different strong ($\delta$) and weak ($\varphi$) phases
- For a $B_{s}^{0}$ decay to a CP eigenstate $f$, CP-violating effects depend on $\lambda_{f} = \frac{q \bar{A}_{f}}{p A_{f}}$

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CPV in $B_s^0$ mixing and decays

$B_{H,L} = pB_s^0 \pm q\bar{B}_s^0$

Golden mode: $B_s^0 \to J/\psi(\to \mu\mu)\phi(\to KK)$

MEASURABLE PHASE
CPV due to mixing-decay interference

$\varphi_s = \arg(\lambda_f(c\bar{c}s)) = \varphi_{s,SM}^S + \Delta\varphi_s^{peng} + \Delta\varphi_s^{NP} - 2\beta_s$

GLOBAL FIT PREDICTION
$\varphi_{s,SM}^S = -0.03686^{+0.00096}_{-0.00068}$ rad

[CKMfitter]
$\phi_s$ before Winter 2019

- Golden channel exploited by LHCb, ATLAS, CMS: $B_s^0 \rightarrow J/\psi \phi$
- LHCb also measured many other channels

- World average (dominated by LHCb) consistent with predictions;
- Exp. uncertainty (31 mrad) almost a factor of 30 larger than uncert. of indirect determination when penguin pollution is ignored.

GLOBAL FIT PREDICTION

$\phi_s^{SM} = -0.03686^{+0.00096}_{-0.00068}$ rad

$\Delta \Gamma_s = 0.090 \pm 0.005$ ps$^{-1}$

[HFLAV 2018]
The LHCb detector

- Single arm spectrometer designed for high precision flavour physics measurements
- Pseudorapidity range $\eta \in [2,5]$
The tracker upstream the magnet

The VErtext LOcator
- 42 silicon micro-strip stations with R-Φ sensors
- 2 retractable halves, 7 mm from beam.
Decay time res ~45 fs
IP res ~20 μm

Tracker Turicensis (TT)
- Four planes (0°,+5°,-5°, 0°) of silicon micro-strip sensor
- Total silicon area of 8 m²
- Already sensitive to the magnetic field
The tracker downstream the magnet

The Inner Tracker (IT)

Three stations each with four planes of silicon micro-strip sensors around the beam pipe
- Total silicon area of 4.2 m²

Outer Tracker (OT)

Three stations each with four planes (0°, +5°, -5°, 0°) of straw tubes
- Gas Mixture Ar/CO₂/O₂ (70/28.5/1.5)

Tracking performances
- $\Delta p/p = 0.4-0.6\%$ @ 5-100 GeV/c
- Tracking eff. > 96%
- Mass res. ~8 MeV/c² for $B \rightarrow J/\psi X$ decays with constraint on $J/\psi$ mass
Particle identification

**RICH 1**
- Upstream of the magnet
- $C_4F_{10}$ radiator
- $2<p<40$ GeV/c

**RICH 2**
- Downstream of the magnet
- CF10 radiator
- $15<p<100$ GeV/c
- 15-120 mrad
Particle identification

Electromagnetic CAL and Hadronic CAL
Scintillator planes + absorber material planes
• Used in the hardware trigger (L0) selection

Muon Chambers
5 stations, each equipped with 276 multi-wire proportional chambers
• Inner part of the first station equipped with 12 GEM detectors
• Used heavily in trigger

LHCb Detector Performance

Performance of the Muon Identification system
JINST 8 (2013) P10020

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Particle identification

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PID performance
• Kaon ID eff. ~95%
• Pion mis-ID fraction of ~5%
• Muon ID eff. ~97%

Performance of the Muon Identification system
JINST 8 (2013) P10020
Trigger principles

**BEAUTY SIGNATURES**

- Mass $m(B^+) = 5.28$ GeV/$c^2$
- Daughter $p_T \theta (1$ GeV/$c$)
- Lifetime $\tau(B) \sim 1.5$ ps
- Flight distance $\sim 1$ cm
- Detached secondary vertex

Since Run II the detector is calibrated and aligned online:
- Same reconstruction online and offline
- No need of offline data processing

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The full LHCb data set is about 9 fb⁻¹

Large number of beauty hadrons:

\[ \sigma_{b\bar{b}}(7 \text{ TeV}) = 72.0 \pm 0.3 \pm 6.8 \mu \text{b} \]
\[ \sigma_{b\bar{b}}(13 \text{ TeV}) = 154.3 \pm 1.5 \pm 14.3 \mu \text{b} \]

[PRL 118 (2017) 052002]
Decay channels discussed today

In $B_s^0 \rightarrow J/\psi(\rightarrow \mu^+ \mu^-)K^+K^-$ the final state is a mixture of CP-even ($L = 0, 2$) and CP-odd ($L = 1 + S$-wave) components:

- $|B_L| = p |B_s^0 > + q |\bar{B}_s^0 > \approx \text{CP – even}$
- $|B_H| = p |B_s^0 > - q |\bar{B}_s^0 > \approx \text{CP – odd}$

Rich resonant and non-resonant structure in the $\pi^+\pi^-$ mass spectrum.

**Mainly CP-odd:** requires an amplitude analysis to check the effect of the small CP-even component and it allows to measure $\Gamma_H$.
Measuring $\phi_s$

**Definition of time-dependent CP asymmetry:**

\[ A_{CP}(t) = \frac{\Gamma(B_s^0 \rightarrow f) - \Gamma(B_s^0 \rightarrow \bar{f})}{\Gamma(B_s^0 \rightarrow f) + \Gamma(B_s^0 \rightarrow \bar{f})} = \eta_f \sin \phi_s \sin(\Delta m_s t) \]

**Experimentally** it becomes:

\[ A_{CP}(t) = \eta_f \cdot e^{-\frac{1}{2} \Delta m^2 s t^2} \cdot (1 - 2\nu) \cdot \sin \phi_s \cdot \sin(\Delta m_s t) \]

Critical requirements:

- CP eigenvalue of the final state $\eta_f \rightarrow$ angular analysis
- Excellent decay-time resolution $\sigma_t \sim 45$ fs
- Tagging of meson flavour @ production: probability of getting the wrong tag $\omega$
- In the fit need to model decay-time efficiency $\epsilon(t)$ (due to selection and reconstruction) and angular efficiency $\epsilon(\Omega)$
First harvest of LHCb Run 2 data

- New results obtained analysing 2015 (0.3 fb\(^{-1}\)) and 2016 (1.6 fb\(^{-1}\)) data presented at Moriond EW ‘19
- \(B_s^0 \to J/\psi K^+K^-\) [LHCb-PAPER-2019-013] and \(B_s^0 \to J/\psi \pi^+\pi^-\) [arXiv:1903.05530]
- Not just an update: Run I strategy duly rediscussed and various methods carefully scrutinized and validated
- Simultaneous fit to the signal decay time and 3 helicity angles in 6 bins in \(m(K^+K^-)\) and \(m(\pi^+\pi^-)\)
Selection and mass fit

New: Boosted decision tree is trained to select signal candidates

- Injected negative weighted MC to subtract $\Lambda_b^0 \rightarrow J/\psi p K$
- Signal width is a function of per-candidate mass error to account for correlation with $\cos(\theta_H)$
- Use the wrong sign (WS) combination ($\pi^\pm \pi^\mp$) to determine the shape of the combinatorial background

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Fundamental to resolve fast $B_s^0 - \bar{B}_s^0$ oscillations:

How to determine $\sigma_t$ in data?

- Since the resolution of the secondary vertex is dominating, we reconstruct fake $B_s^0 \rightarrow \mu\mu hh$ with all tracks coming from the PV (prompt $J/\psi + 2$ random PV kaons or pions) and without using selections on decay time
- By definition for these candidates $t = 0 \pm \sigma_t$
- Method validated in MC comparing prompt and signal resolutions

The first contribution is $\approx 20$ times larger than the second, they become comparable only at several $B$ lifetimes
Decay-time resolution

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Decay-time resolution

Fitting $\sigma_{eff}$ in diff. bin of the event-by-event decay-by-event decay-time uncertainty $\delta_t$

$$\sigma_{eff} = \sqrt{\frac{-2}{\Delta m^2_s}} \ln D,$$

with

$$D = \sum_{i=1}^{3} f_i e^{-\sigma_i^2 \Delta m^2_s/2}$$

$\sigma_{eff} = 45.5$ fs

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

$\sigma_{eff} = 41.5$ fs

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

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Decay-time efficiency

Use \( \sim 550k \ B^0 \rightarrow J/\psi K^*(892)^0 \) as a data control channel (thanks to its well known lifetime \( \tau_{B^0} = \frac{1}{\Gamma_d} = 1.520 \pm 0.004 \ \text{ps} \)).

Efficiency obtained fitting simultaneously \( B^0 \) data and \( B^0 - B_s^0 \) data-corrected simulations fixing known lifetimes and resolutions:

\[
\varepsilon_{B_s^0}^{\text{data}}(t) = \varepsilon_{B^0}^{\text{data}}(t) \times \frac{\varepsilon_{B_s^0}^{\text{MC}}(t)}{\varepsilon_{B^0}^{\text{MC}}(t)}
\]

Small correction to account for differences between signal and control channels

**By product:** measure directly \( \Gamma_s - \Gamma_d \) in \( B_s^0 \rightarrow J/\psi K^+ K^- \) and \( \Gamma_H - \Gamma_d \) in \( B_s^0 \rightarrow J/\psi \pi^+ \pi^- \) being independent on the value and uncertainty of \( \Gamma_d \)

Interesting for comparisons with HQE where \( \Gamma_s / \Gamma_d \) is precisely predicted.
Decay-time efficiency II

Strategy validated using $B^0 \to J/\psi K^*(892)^0$ and $B^+ \to J/\psi K^+$ data control channels

E.g. $B^+ \to J/\psi K^+$

- Determine the $B^+$ lifetime using $B^0 \to J/\psi K^*0$ as control channel
- Replace the $B_s^0$ MC in the efficiency determination with $B^+$ MC and determine the efficiency
- Fit $B^+$ decay time distribution in data with this efficiency

$\Gamma_u - \Gamma_d = -0.0478 \pm 0.0013 \text{ ps}^{-1}$ (stat only) vs $(\Gamma_u - \Gamma_d)^{PDG} = -0.0474 \pm 0.0023 \text{ ps}^{-1}$
Angular efficiency

- Kinematic selection and detector acceptance are causing non uniform efficiency as function of decay angles
- Efficiency taken from MC after iterative reweighting

Checks done in control data:
- Measurement of $B^0 \rightarrow J/\psi K^{*0}$ polarisation amplitudes in agreement with world average
- Correctly retrieved muon helicity distribution (expected $1 - \cos^2 \theta_\mu$ dependence) in $B^+ \rightarrow J/\psi K^+$ decays
Flavour tagging

- Two tagging algorithms are used: opposite side and same side. For each algorithm true mistag probability is calibrated assuming linear dependency with estimated one
  \[ \omega = p_0 + p_1(\eta - <\eta>) \]
- Tagging power is given as tagging efficiency times dilution squared \( \varepsilon_{tag}D^2 \) with \( D = (1 - 2\omega) \)

\[
\varepsilon_{tag}D^2 = 4.73 \pm 0.34 \%
\]
\[ B^0_S \rightarrow J/\psi K^+K^- \]

Run 1 was \( \approx 3.73 \% \)

\[
\varepsilon_{tag}D^2 = 5.06 \pm 0.38 \%
\]
\[ B^0_S \rightarrow J/\psi \pi^+\pi^- \]

Run 1 was \( \approx 3.89 \% \)

\~30\% relative improvement of tagging power

- More tagging power = better exploitation of data!
Flavour tagging

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

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

$\varphi_s$ mainly affected by Time res. & Ang. Acc., $\Delta \Gamma_s (|\lambda|)$ by Mass factorisation (& Ang. Acc.), $\Gamma_s - \Gamma_d$ by Time eff.

| Source                              | $|A_0|^2$ | $|A_1|^2$ | $\varphi_s$ [rad] | $|\lambda|$ | $\delta_s - \delta_0$ [rad] | $\delta_s - \delta_0$ [rad] | $\Gamma_s - \Gamma_d$ [ps$^{-1}$] | $\Delta \Gamma_s$ [ps$^{-1}$] | $\Delta m_s$ [ps$^{-1}$] |
|-------------------------------------|----------|----------|-------------------|------------|----------------------------|----------------------------|----------------------------|--------------------------|--------------------------|
| Mass width parametrisation          | 0.0006   | 0.0005   | -                 | - 0.05    | 0.009                      | -                          | 0.0002                    | 0.001                    |
| Mass factorisation                  | 0.0002   | 0.0004   | 0.004             | 0.0037    | 0.01                       | 0.004                      | 0.0007                    | 0.0022                   | 0.016                    |
| Multiple candidates                 | 0.0006   | 0.0001   | 0.0011            | 0.0011    | 0.01                       | 0.002                      | 0.0003                    | 0.0001                   | 0.001                    |
| Fit bias                            | 0.0001   | 0.0006   | 0.001             | - 0.02    | 0.033                      | -                          | 0.0003                    | 0.001                    | 0.002                    |
| $C_{2p}$ factors                    | -        | 0.0001   | 0.001             | 0.0010    | 0.01                       | 0.005                      | -                          | 0.0001                   | 0.001                    |
| Time res.: applicability of prompt  | -        | -        | -                 | -         | 0.001                      | -                          | -                          | 0.001                    |                          |
| Time res.: t bias                   | -        | -        | 0.0032            | 0.0010    | 0.08                       | 0.001                      | 0.0002                    | 0.0003                   | 0.005                    |
| Time res.: wrong PV                 | -        | -        | -                 | -         | 0.001                      | -                          | -                          | -                        | 0.001                    |
| Ang. acc.: MC sample size           | 0.0003   | 0.0004   | 0.0011            | 0.0018    | -                          | 0.004                      | -                          | 0.001                    |                          |
| Ang. acc.: BDT correction           | 0.0020   | 0.0011   | 0.0022            | 0.0043    | 0.01                       | 0.008                      | 0.0001                    | 0.0002                   | 0.001                    |
| Ang. acc.: low-quality tracks       | 0.0002   | 0.0001   | 0.0005            | 0.0014    | -                          | 0.002                      | 0.0002                    | 0.0001                   | -                        |
| Ang. acc.: t & $\sigma_t$ dependence| 0.0008   | 0.0012   | 0.0012            | 0.0007    | 0.03                       | 0.006                      | 0.0002                    | 0.0010                   | 0.003                    |
| Dec.-time eff.: statistical         | 0.0002   | 0.0003   | -                 | -         | -                          | -                          | 0.0012                    | 0.0008                   | -                        |
| Dec.-time eff.: kin. weighting      | -        | -        | -                 | -         | -                          | -                          | 0.0002                    | -                        | -                        |
| Dec.-time eff.: p.d.f. weighting    | -        | -        | -                 | -         | -                          | -                          | 0.0011                    | -                        | -                        |
| Dec.-time eff.: $\Delta \Gamma_s = 0$ sim. | 0.0001 | 0.0002 | - | - | - | - | 0.0003 | 0.0005 | - |
| Length scale                        | -        | -        | -                 | -         | -                          | -                          | -                          | -                        | 0.004                    |
| Quadratic sum of syst.             | 0.0024   | 0.0019   | 0.0061            | 0.0064    | 0.10                       | 0.037                      | 0.0015                    | 0.0026                   | 0.018                    |
### Systematics for $B_{s}^{0} \rightarrow J/\psi \pi^{+}\pi^{-}$

$\Gamma_{H} - \Gamma_{d}$ mainly affected by Background, $\phi_{s}$ and $|\lambda|$ by Resonance modelling

| Source                        | $\Gamma_{H} - \Gamma_{B^{0}}$ [fs$^{-1}$] | $|\lambda|$ [$\times 10^{-3}$] | $\phi_{s}$ [mrad] |
|-------------------------------|------------------------------------------|----------------------------|-----------------|
| $t$ acceptance                | 2.0                                      | 0.0                        | 0.3             |
| $\tau_{B^{0}}$                | 0.2                                      | 0.5                        | 0.0             |
| Efficiency $(m_{\pi\pi}, \Omega)$ | 0.2                                      | 0.1                        | 0.0             |
| $t$ resolution width          | 0.0                                      | 4.3                        | 4.0             |
| $t$ resolution mean           | 0.3                                      | 1.2                        | 0.3             |
| Background                    | 3.0                                      | 2.7                        | 0.6             |
| Flavour tagging               | 0.0                                      | 2.2                        | 2.3             |
| $\Delta m_{s}$                | 0.3                                      | 4.6                        | 2.5             |
| $\Gamma_{L}$                  | 0.3                                      | 0.4                        | 0.4             |
| $B_{c}^{+}$                   | 0.5                                      | -                          | -               |
| Resonance parameters          | 0.6                                      | 1.9                        | 0.8             |
| Resonance modelling           | 0.5                                      | 28.9                       | 9.0             |
| Production asymmetry          | 0.3                                      | 0.6                        | 3.4             |
| **Total**                     | 3.8                                      | 29.9                       | 11.0            |

1) Using reweighted WS samples in the fit
2) Vary the background yields by $\pm 1\sigma$

1) Vary Barrier factor
2) Replace NR by $f_{0}(500)$
3) Solution II
4) Add $\rho(770)$
Results using 2015-2016 data

\( B_s^0 \to J/\psi K^+K^- \)

- \( \varphi_s = -0.083 \pm 0.041 \pm 0.006 \text{ rad} \)
- \( |\lambda| = 1.012 \pm 0.016 \pm 0.006 \)
- \( \Gamma_s - \Gamma_d = -0.0041 \pm 0.0024 \pm 0.0015 \text{ ps}^{-1} \)
- \( \Delta \Gamma_s = 0.0773 \pm 0.0077 \pm 0.0026 \text{ ps}^{-1} \)

\( \Gamma_s = 0.6538 \pm 0.0024 \pm 0.0015 \pm 0.0017 \) (input \( \Gamma_d \)) \text{ ps}^{-1}

Combining the above + Run 1: \( B_s^0 \to J/\psi KK, B_s^0 \to J/\psi\pi\pi, B_s^0 \to J/\psi KK \) high mass, \( B_s^0 \to D_sD_s, B_s^0 \to \psi(2S)\varphi \)

- \( \varphi_s = -0.041 \pm 0.025 \text{ rad} \)
- \( |\lambda| = 0.993 \pm 0.010 \)
- \( \Gamma_s = 0.6562 \pm 0.0021 \text{ ps}^{-1} \)
- \( \Delta \Gamma_s = 0.0816 \pm 0.0048 \text{ ps}^{-1} \)

\( B_s^0 \to J/\psi\pi^+\pi^- \)

- \( \varphi_s = -0.057 \pm 0.060 \pm 0.011 \text{ rad} \)
- \( |\lambda| = 1.01^{+0.08}_{-0.06} \pm 0.03 \)
- \( \Gamma_H - \Gamma_d = -0.050 \pm 0.004 \pm 0.004 \text{ ps}^{-1} \)

Correlations between the parameters and between the systematic uncertainties are taken into account.
Overview of LHCb combination

Combination of all LHCb (Run1 and 2) results

\[ \varphi_s = -0.041 \pm 0.025 \text{ rad} \]
\[ |\lambda| = 0.993 \pm 0.010 \]
\[ \Gamma_s = 0.6562 \pm 0.0021 \text{ ps}^{-1} \]
\[ \Delta \Gamma_s = 0.0816 \pm 0.0048 \text{ ps}^{-1} \]

\[ \varphi_s \text{ 0.1 } \sigma \text{ away from SM} \]
consistent with Standard Model

\[ \varphi_s \text{ 1.6 } \sigma \text{ away from 0} \]
consistent with no CPV in interference

\[ |\lambda| \text{ consistent with 1} \]
consistent with no direct CPV

\[ \Gamma_s - \Gamma_d \text{ consistent with HQE prediction} \]
New HFLAV combination

At Moriond EW ‘19 also ATLAS presented preliminary results exploiting 2015-2017 data using $B_s^0 \rightarrow J/\psi K^+K^-$. ATLAS combination with Run 1 results is:

$$\varphi_s = -0.076 \pm 0.034 \pm 0.019 \text{ rad}$$
$$\Gamma_s = 0.669 \pm 0.001 \pm 0.001 \text{ ps}^{-1}$$
$$\Delta\Gamma_s = 0.068 \pm 0.004 \pm 0.003 \text{ ps}^{-1}$$

[ATLAS-CONF-2019-009]

The preliminary HFLAV combination is:

$$\varphi_s = -0.055 \pm 0.021 \text{ rad}$$
$$\Delta\Gamma_s = 0.0764^{+0.0034}_{-0.0033} \text{ ps}^{-1}$$

[HFLAV PRELIMINARY]
Some considerations on the combination

- Combination among the experiments is getting more and more interesting
  - Entering in a regime where penguin pollution constraints are similar to the precision of the combination
  - Strength of LHCb: versatility and possibility to measure $\varphi_s$ also with many other channels, in particular $B_s^0 \rightarrow J/\psi\pi^+\pi^-$

The value of $\Gamma_s$ shows tension between LHCb and ATLAS:
- HFLAV (not including Run 2): $\Gamma_s^{HFLAV} = 0.6629 \pm 0.0018 \text{ ps}^{-1}$
- LHCb Run 2: $\Gamma_s^{LHCb} = 0.6538 \pm 0.0033 \text{ ps}^{-1} \rightarrow -2.4 \sigma$ from WA
- ATLAS Run 2: $\Gamma_s^{ATLAS} = 0.669 \pm 0.0014 \text{ ps}^{-1} \rightarrow +2.7 \sigma$ from WA

Tension between ATLAS and LHCb of $>4 \sigma$
Prospects for the future

- Include gain in trigger for $B_s^0 \to D_s^- D_s^+$ after Upgrade 1
- Same performances as in Run I
  - Assumed tagging power 4%
- Additional modes planned: $J/\psi \to e e$, $\eta' \to \rho^0 \gamma$ or, $\eta' \to \eta \pi \pi$ or $\gamma \gamma$ as cross checks

300/fb: $\sigma_{\text{STAT}}(\phi_s) \sim 4$ mrad from $B_s^0 \to J/\psi K K$ only

- Vital FT performance maintains or improves
- $\phi_s$ expected to be statistically limited

Impact of Upgrade I and II very important for $\phi_s$!
Control of penguin pollution

- U-spin or SU(3) flavour symmetry to constrain size of penguin with $b \rightarrow c\bar{c}d$ (related by s-d spectator exchange)
- Penguin pollution and/or CP violation could be different for each polarisation state, $f \in (0, \perp, \parallel, S)$
  
  
  → no sign yet of dependence in $B_s^0 \rightarrow J/\psi$ KK (also in Run 2) so penguins are small

- SU(3)$_F$: $B_s^0 \rightarrow J/\psi K^*$ and $B^0 \rightarrow J/\psi \rho^0$ are $b \rightarrow c\bar{c}d$ transitions.

\[
\begin{align*}
\Delta \phi_{s,0}^{J/\psi \phi} &= 0.000^{+0.009}_{-0.011} \text{ (stat) } ^{+0.004}_{-0.009} \text{ (syst) rad} \\
\Delta \phi_{s,\parallel}^{J/\psi \phi} &= 0.001^{+0.010}_{-0.014} \text{ (stat) } \pm 0.008 \text{ (syst) rad} \\
\Delta \phi_{s,\perp}^{J/\psi \phi} &= 0.003^{+0.010}_{-0.014} \text{ (stat) } \pm 0.008 \text{ (syst) rad}
\end{align*}
\]

**Precision of \(~10\) mrad**
To be compared with the current precision of HFLAV of \(21\) mrad

Fundamental to update these analyses, expected sensitivity at \(300/\)fb is \(1.5\) mrad (statistically limited)

+ adding $B_s^0 \rightarrow J/\psi \omega$ and $B^0 \rightarrow J/\psi \phi$ (E + PA diagrams only)
Conclusions and remarks

◦ Interest in precision flavour measurements is stronger than ever
  If no direct evidence of NP pops out of the LHC, flavour physics can play a key role.

◦ All results in this sector in good agreement with SM, need to go to even higher precision: x2 statistics already available in Run 2.

◦ Good prospects for the precision measurements in the Upgrade phase of LHCb. Considering all modes:

\[ 300/fb: \sigma^{\text{STAT}} (\phi_s) \sim 3 \text{ mrad} \]

statistically limited.
“And if someone dares to yawn during your presentation, this pointer easily transforms from a laser to a taser!”
Historical record of indirect discoveries

**GIM Mechanism**

Observed branching ratio $K^0 \rightarrow \mu\mu$

$$\frac{BR(K_L \rightarrow \mu^+\mu^-)}{BR(K_L \rightarrow \text{all})} = (7.2 \pm 0.5) \cdot 10^{-9}$$

In contradiction with theoretical expectation in the 3-Quark Model

**Glashow, Iliopoulos, Maiani (1970):**

Prediction of a 2nd up-type quark (1972), additional Feynman graph cancels the «u box graph»

But also e.g. CPV $K^0 \rightarrow \pi\pi$ that brought to CKM and 3rd generation, B mixing that brought to top mass extrapolation

Francesca Dordei - Precision measurement of the CP-violating phase $\phi_s$ at LHCb
Flavour tagging - references

Courtesy of S. Akar

Francesca Dordei - Precision measurement of the CP-violating phase $\phi_S$ at LHCb
Fit projections $B_s^0 \rightarrow J/\psi KK$
Table 4: Parameter estimates for the nominal fit. The first uncertainty is statistical and the second systematic.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_s$ [rad]</td>
<td>$-0.080 \pm 0.041 \pm 0.006$</td>
</tr>
<tr>
<td>$</td>
<td>\lambda</td>
</tr>
<tr>
<td>$\Gamma_s - \Gamma_d$ [ps$^{-1}$]</td>
<td>$-0.0044 \pm 0.0024 \pm 0.0015$</td>
</tr>
<tr>
<td>$\Delta \Gamma_s$ [ps$^{-1}$]</td>
<td>$0.0772 \pm 0.0077 \pm 0.0026$</td>
</tr>
<tr>
<td>$\Delta m_s$ [ps$^{-1}$]</td>
<td>$17.705 \pm 0.059 \pm 0.018$</td>
</tr>
<tr>
<td>$</td>
<td>A_1</td>
</tr>
<tr>
<td>$</td>
<td>A_0</td>
</tr>
<tr>
<td>$\delta_1 - \delta_0$</td>
<td>$2.64 \pm 0.19 \pm 0.10$</td>
</tr>
<tr>
<td>$\delta_{</td>
<td></td>
</tr>
</tbody>
</table>

Table 5: The correlation matrix including the statistical and systematic correlations between the parameters.

\[
\begin{array}{cccccccc}
& \phi_s & |\lambda| & \Gamma_s - \Gamma_d & \Delta \Gamma_s & \Delta m_s & |A_1|^2 & |A_0|^2 & \delta_1 & \delta_{||} \\
\phi_s & 1.00 & 0.16 & -0.05 & 0.02 & 0.01 & -0.03 & 0.00 & 0.04 & -0.01 \\
|\lambda| & 1.00 & 0.06 & -0.09 & 0.07 & 0.05 & -0.02 & 0.09 & 0.02 & \\
\Gamma_s - \Gamma_d & 1.00 & -0.46 & 0.07 & 0.35 & -0.24 & 0.04 & 0.05 & \\
\Delta \Gamma_s & 1.00 & -0.06 & -0.65 & 0.46 & -0.10 & -0.02 & \\
\Delta m_s & 1.00 & 0.01 & 0.01 & 0.61 & -0.00 & \\
|A_1|^2 & 1.00 & -0.64 & 0.07 & 0.09 & \\
|A_0|^2 & 1.00 & -0.03 & -0.02 & \\
\delta_1 & 1.00 & 0.24 & & \\
\delta_{||} & 1.00 & & & \\
\end{array}
\]
LHCb in the $\phi_s$ game

LHCb optimised with $\phi_s$ as a key goal. In particular it brings to the game:

High signal yields and high purity

Excellent decay-time resolution

And in addition new modes and analysis techniques:

Inclusion of $J/\psi KK$ decays above the $\phi$

Inclusion of $J/\psi \pi\pi$ decays:
Simpler analysis wrt $J/\psi \phi$

Francesca Dordei - Precision measurement of the CP-violating phase $\phi_s$ at LHCb
LHCb entered the game

LHCb optimised with $\phi_s$ as a key goal. In particular it brings to the game:

**Enormous signal yields**

**Excellent proper time resolution**

And in addition new modes and analysis techniques:

Inclusion of $J/\psi K K$ decays above the $\phi$

Inclusion of $J/\psi \pi \pi$ decays:

Overwhelmingly CP-odd and hence needs no angular analysis

---

**LHCb Run I results:**

<table>
<thead>
<tr>
<th>Decay Type</th>
<th>Phase [mrad]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi K^+ K^-$ in $\phi$ region</td>
<td>$-58 \pm 49 \pm 6$</td>
<td>[PRL 114 (2015) 041801]</td>
</tr>
<tr>
<td>$J/\psi K^+ K^-$ in high mass $K^+ K^-$ region</td>
<td>$119 \pm 107 \pm 34$</td>
<td>[JHEP 08 (2017) 037]</td>
</tr>
<tr>
<td>$J/\psi \pi^+ \pi^-$</td>
<td>$70 \pm 68 \pm 8$</td>
<td>[PLB 713 (2012) 378]</td>
</tr>
</tbody>
</table>

Overall: $1 \pm 37$ mrad

Other measurements:

<table>
<thead>
<tr>
<th>Decay Type</th>
<th>Phase [mrad]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\psi(2S)\phi$</td>
<td>$230^{+290}_{-280} \pm 20$</td>
<td>[PRL B762 (2016) 253]</td>
</tr>
<tr>
<td>$D_s^+ D_s^-$</td>
<td>$20 \pm 170 \pm 20$</td>
<td>[PRL 113 (2014) 211801]</td>
</tr>
</tbody>
</table>
### Table 5: Summary of systematic uncertainties assigned to the physical parameters of interest.

| Source                          | $\phi_s$  | $\Delta \Gamma_s$ $\Gamma_s$ | $|A_{||}(0)|^2$ | $|A_0(0)|^2$ | $|A_S(0)|^2$ | $\delta_\perp$ | $\delta_\parallel$ | $\delta_\perp - \delta_S$ |
|--------------------------------|-----------|-------------------------------|----------------|-------------|-------------|---------------|----------------|--------------------------|
| Tagging                        | $1.7 \times 10^{-2}$ | $0.4 \times 10^{-3}$ | $0.3 \times 10^{-3}$ | $0.2 \times 10^{-3}$ | $0.2 \times 10^{-3}$ | $2.3 \times 10^{-3}$ | $1.9 \times 10^{-2}$ | $2.2 \times 10^{-2}$ | $2.2 \times 10^{-3}$ |
| Acceptance                     | $0.7 \times 10^{-3}$ | $< 10^{-4}$ | $< 10^{-4}$ | $< 10^{-4}$ | $< 10^{-4}$ | $3.3 \times 10^{-2}$ | $1.4 \times 10^{-2}$ | $1.4 \times 10^{-2}$ | $2.6 \times 10^{-3}$ |
| ID alignment                   | $0.7 \times 10^{-3}$ | $0.1 \times 10^{-3}$ | $0.5 \times 10^{-3}$ | $< 10^{-4}$ | $< 10^{-4}$ | $1.0 \times 10^{-2}$ | $7.2 \times 10^{-3}$ | $< 10^{-4}$ | $< 10^{-4}$ |
| $S$–wave phase                 | $0.2 \times 10^{-3}$ | $< 10^{-4}$ | $< 10^{-4}$ | $< 10^{-4}$ | $0.3 \times 10^{-3}$ | $1.1 \times 10^{-2}$ | $2.1 \times 10^{-2}$ | $8.3 \times 10^{-3}$ | $8.3 \times 10^{-3}$ |
| Background angles model:       |                        |                             |               |             |             |               |                 |                           |
| Choice of fit function         | $1.8 \times 10^{-3}$ | $0.8 \times 10^{-3}$ | $< 10^{-4}$ | $1.4 \times 10^{-3}$ | $0.7 \times 10^{-3}$ | $0.2 \times 10^{-3}$ | $8.5 \times 10^{-2}$ | $1.9 \times 10^{-1}$ | $1.8 \times 10^{-3}$ |
| Choice of $p_T$ bins           | $1.3 \times 10^{-3}$ | $0.5 \times 10^{-3}$ | $< 10^{-4}$ | $0.4 \times 10^{-3}$ | $0.5 \times 10^{-3}$ | $1.2 \times 10^{-3}$ | $1.5 \times 10^{-3}$ | $7.2 \times 10^{-3}$ | $1.0 \times 10^{-3}$ |
| Choice of mass interval        | $0.4 \times 10^{-3}$ | $0.1 \times 10^{-3}$ | $0.1 \times 10^{-3}$ | $0.3 \times 10^{-3}$ | $0.3 \times 10^{-3}$ | $1.3 \times 10^{-3}$ | $4.4 \times 10^{-3}$ | $7.4 \times 10^{-3}$ | $2.3 \times 10^{-3}$ |
| Dedicated backgrounds:         |                        |                             |               |             |             |               |                 |                           |
| $B_d^0$                        | $2.3 \times 10^{-3}$ | $1.1 \times 10^{-3}$ | $< 10^{-4}$ | $0.2 \times 10^{-3}$ | $3.1 \times 10^{-3}$ | $1.4 \times 10^{-3}$ | $1.0 \times 10^{-2}$ | $2.3 \times 10^{-2}$ | $2.1 \times 10^{-3}$ |
| $\Lambda_b$                   | $1.6 \times 10^{-3}$ | $0.4 \times 10^{-3}$ | $0.2 \times 10^{-3}$ | $0.5 \times 10^{-3}$ | $1.2 \times 10^{-3}$ | $1.8 \times 10^{-3}$ | $1.4 \times 10^{-2}$ | $2.9 \times 10^{-2}$ | $0.8 \times 10^{-3}$ |
| Fit model:                     |                        |                             |               |             |             |               |                 |                           |
| Time res. sig frac             | $1.4 \times 10^{-3}$ | $1.1 \times 10^{-3}$ | $< 10^{-4}$ | $0.5 \times 10^{-3}$ | $0.6 \times 10^{-3}$ | $0.6 \times 10^{-3}$ | $1.2 \times 10^{-2}$ | $3.0 \times 10^{-2}$ | $0.4 \times 10^{-3}$ |
| Time res. $p_T$ bins           | $3.3 \times 10^{-3}$ | $1.4 \times 10^{-3}$ | $0.1 \times 10^{-2}$ | $< 10^{-4}$ | $< 10^{-4}$ | $0.5 \times 10^{-3}$ | $6.2 \times 10^{-3}$ | $5.2 \times 10^{-3}$ | $1.1 \times 10^{-3}$ |
| Total                          | $1.8 \times 10^{-2}$ | $0.2 \times 10^{-2}$ | $0.1 \times 10^{-2}$ | $0.2 \times 10^{-2}$ | $0.4 \times 10^{-2}$ | $0.4 \times 10^{-2}$ | $9.7 \times 10^{-2}$ | $2.0 \times 10^{-1}$ | $0.1 \times 10^{-1}$ |
**Penguin pollution roadmap**

- With increasing precision crucial to understand penguin pollution
- Can use U-spin and SU(3) related modes, where penguin not suppressed, to determine its size \([S. \text{ Faller, R. Fleischer, M. Jung, T. Mannel, arXiv:0809.0842]}\)

Golden modes: \(b \rightarrow c\bar{c}s\) amplitude \((i = 0, \|, \perp)\)

\[
A_i'(b \rightarrow c\bar{c}s) = \left(1 - \frac{\lambda^2}{2}\right) A_i \left[1 + \epsilon a_i' e^{i \theta'} e^{i \gamma}\right]
\]

Control modes: \(b \rightarrow c\bar{c}d\) amplitude

\[
A_i(b \rightarrow c\bar{c}d) = -\lambda A_i \left[1 + a_i e^{i \theta} e^{i \gamma}\right]
\]

Overall \(\lambda\) factor, BF is suppressed. Absence of \(\epsilon\), penguin effects are magnified.

**SU(3):** \(a_i' = a_i, \theta_i' = \theta_i\). Extract \(\Delta \phi_s^{peng}(a_i, \theta_i)\) and \(\Delta \beta^{peng}(a_i, \theta_i)\) from t to CP parameters and BF.
Penguin pollution roadmap $\phi_s$

Studied at LHCb with 3 fb$^{-1}$:
- $B^0 \rightarrow J/\psi \rho$ (BF, C and S) [JHEP11(2015)082]
- $B^0_S \rightarrow J/\psi K^{*0}$ (BF and C), has no PA and E [PLB742(2015)38-49]

Measure penguin phase shift for each polarisation state, $f \in (0, \perp, \parallel, S)$ [JHEP 11 (2015) 082]

Small penguin shift $\sim 0.06^\circ$ wrt experimental precision $\sigma(\phi_s) \sim 1.7^\circ$!!
Side note: $\varphi_s$ from penguin decays

- Include gain in trigger after Upgrade 1

$300/\text{fb}: \sigma^{\text{STAT}}(\varphi_s) \sim 11 \text{ mrad}$ from $B_s^0 \rightarrow \phi\phi$

$300/\text{fb}: \sigma^{\text{STAT}}(\varphi_s) \sim 9 \text{ mrad}$ from $B_s^0 \rightarrow K\pi K\pi$

- $B_s^0 \rightarrow \phi\phi$ will remain stat. limited
- Limiting syst for $B_s^0 \rightarrow K\pi K\pi < 30 \text{ mrad}$ from MC (important to exploit rapid MC production) and modelling resonances.

Francesca Dordei - Precision measurement of the CP-violating phase $\varphi_s$ at LHCb
Sakharov Conditions

1. Baryon Number Violation
2. C and CP violation
3. Interactions out of thermal equilibrium

[Rev. Mod. Phys. 88, 015004 (2016)]

- Baryon asymmetry of the Universe: $n_b/n_\gamma \sim 10^{-10}$
- CP violation in the SM does not account for it
- There must be New Physics and new sources of CP violation