STATUS AND PROSPECTS WITH CP VIOLATION IN BEAUTY AT LHCb

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On behalf of the LHCb Collaboration

Upgrade-2 workshop
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The CKM fit: a lot of room for NP

- It is safe to say that the era of HL-LHC (together with Belle II) will produce a much more precise picture of the physics of flavour.
- O(20%) NP contributions to most loop-level processes (FCNC) are still allowed.
  - See e.g. arXiv:1309.2293 [hep-ph]
- Interesting comparison of tree-level vs higher-order observables. In the latter, unknown particles could contribute.
- The SM works so remarkably well that we have to make more and more precise measurements.
The experimental scenario

In this talk I will:

◦ Summarise current status of art of $\gamma$, $\varphi_s$ and $\beta$
◦ Give some perspectives for the evolution of these measurements for the LHCb Upgrade II
◦ Refer to the milestones indicated below

LHCb may be the only large-scale flavour physics experiment operating in the HL-LHC era.

End Run 3 → End Run 5: **ATLAS/CMS**: 300/fb → 3000/fb, **LHCb**: 23/fb → 300/fb
Status of $\gamma$

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

- $\gamma$ is still the least well-known angle of the Unitarity Triangle.
- Measurements of $\gamma$ from $B$ decays mediated only by tree-level transitions provide a “standard candle” for the SM (assuming no new physics in tree-level decays) \[\Rightarrow\text{Theoretically clean }\frac{\delta\gamma}{\gamma} \lesssim O\left(10^{-7}\right)\] \[\text{[JHEP 1401 (2014) 051]}\]
- This can be compared with $\gamma$ values from $B$ decays involving loop-level transitions, such as $B_{d,s}^0 \rightarrow hh'$ decays ($h = K, \pi$), to get signs of NP.

If the assumption is dropped, Upgrade 2 will allow to search for NP.

Can be measured in the interference between $b \rightarrow c$ (favoured) and $b \rightarrow u$ (suppressed) transitions, e.g.:

\[\frac{A_{sup}}{A_{fav}} = r_B^D h e^{i\delta_B^{Dh} \pm \gamma}\]

Ratio of magnitudes

Strong phase difference

Small signal yields ($\text{BR} \ 10^{-7}$), small interference effects ($\ 10\%$). Combining a plethora of independent decay modes is the key to achieve the ultimate precision.
State of art of $\gamma$

- Strategy similar to previous combinations: frequentist treatment.
- This combination includes new and updated measurements.

<table>
<thead>
<tr>
<th>$B$ decay</th>
<th>$D$ decay</th>
<th>Method</th>
<th>Ref.</th>
<th>Dataset</th>
<th>Status since last combination</th>
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<td>$B^+ \to DK^+$</td>
<td>$D \to h^+h^-$</td>
<td>GLW</td>
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<td>Run 1 &amp; 2</td>
<td>Minor update</td>
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<td>[26]</td>
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LHCb combination

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

In agreement with world averages
Supersedes the previous LHCb measurement.
Most precise determination of $\gamma$ from a single experiment to date.
Some thoughts on Upgrade 2

◦ Since the bulk of the sensitivity to $\gamma$ comes from the difference in rates of the $B - \bar{B}$ processes, a precise control of asymmetries in charged-particle identification and detection is crucial → these systematic uncertainties are considered to scale with integrated luminosity

◦ Upgrade of the calorimeter will greatly expand LHCb’s capabilities for modes with neutrals in the final state.

◦ Upgrade 2 will also make it interesting to measure $\gamma$ using baryonic decays → TORCH system particularly helpful in allowing for low-momentum separation of protons and kaons

◦ Addition of magnet-side stations may lead to important signal-yield improvements, particularly for high-multiplicity final states.

◦ Constrain $\beta(s)$ without penguin contaminations → $\sim 2^\circ$ sensitivity on $\gamma - 2\beta_s$ from $B_s^0 \rightarrow D_sK$
Prospects for $\gamma$

• D is reconstructed in a two charged-track final state
• All ADS/GLW asymm. currently statistically limited
• Dominant syst., due to knowledge of background contributions, expected to scale with statistics

◦ Belle-II targets a precision of $1.5^\circ$ at the end of data-taking (2025)
◦ Comparison of measurements made in single decay modes interesting after Upgrade II ($1^\circ$ sensitivity) $\rightarrow$ NP in tree level different for different final states

• D is reconstructed in a three-body self-conjugated final state
• Powerful input to the overall determination of $\gamma$
• Need good description of strong phase difference $\delta_D$
  • Current inputs taken from CLEO-c (current syst $\sim 2^\circ$)
  • Future BESIII and LHCb charm inputs are vital

[arXiv:1808.08865]
CP violation in B mixing and decay, $\phi_s$

CP-violating phase arising from interference between mixing and decay.

- Precisely predicted by the SM: $\phi_s^{SM} = 36.86^{+0.96}_{-0.68}$ mrad [CKMFitter]
- 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.
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
- $B_S^0 \rightarrow J/\psi KK$ [LHCb-PAPER-2019-013] and $B_S^0 \rightarrow J/\psi \pi\pi$ [arXiv:1903.05530]
- Both measure $\phi_s$ and $\lambda + \Delta \Gamma_s$ and $\Gamma_s - \Gamma_d$ (excellent test of HQE) and $\Gamma_H - \Gamma_d$ (final state mostly CP-odd)
- Simultaneous fit to the decay time and three helicity angles in 6 bins in $m(K^+K^-)$ and $m(\pi^+\pi^-)$
Overview of the results

Combination of all LHCb (Run1 and 2) results

\[ \phi_s = -0.040 \pm 0.025 \text{ rad} \]
\[ |\lambda| = 0.991 \pm 0.010 \]
\[ \Gamma_s = 0.6563 \pm 0.0021 \text{ ps}^{-1} \]
\[ \Delta \Gamma_s = 0.0812 \pm 0.0048 \text{ ps}^{-1} \]

\( \phi_s \) 0.1\( \sigma \) away from SM
consistent with Standard Model

\( \phi_s \) 1.6\( \sigma \) away from 0
consistent with no CPV in interference

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

\[ \Gamma_s - \Gamma_d \text{ consistent with HQE prediction} \]
News from ATLAS

- New since Run2: Insertable pixel B-Layer (IBL) + topological L1 trigger
  - $\sigma_{\text{eff}} = 69 \, \text{fs}$ (wrt 100 fs in Run 1)
- Integrated lumi of 80.5 fb$^{-1}$ (2015-2017) $\rightarrow$ Full Run 2 is 139 fb$^{-1}$
- $\epsilon_{\text{tag}} D^2 = 1.65\%$ (Run 1 was 1.49\%)

Very preliminary HFLAV combination

$\phi_s = -0.054 \pm 0.021 \, \text{rad}$
$\Delta \Gamma_s = 0.0762 \pm 0.0034 \, \text{ps}^{-1}$

Combining ATLAS Run 1 + Run 2:

$\phi_s = -0.076 \pm 0.034 \pm 0.019 \, \text{rad}$
$\Gamma_s = 0.669 \pm 0.001 \pm 0.001 \, \text{ps}^{-1}$
$\Delta \Gamma_s = 0.068 \pm 0.004 \pm 0.003 \, \text{ps}^{-1}$
Some considerations on the combination

- Combination among the experiments is getting more and more interesting
  - The largest correlation for the $\varphi_s$ LHCb result is with $\lambda$ (~15%), that ATLAS is not fitting for.
  - Interesting to see CMS results

- Strength of LHCb: versatility and possibility to measure $\varphi_s$ also with many other channels, in particular $B_s^0 \to J/\psi\pi\pi$
  - In Run 2 and beyond: time-dependent flavour-tagged analyses become possible for other channels (e.g., with 300/fb, we could have $4\% \times 300k = \sim 12k$ tagged $B_s^0 \to J/\psi\eta$, with $\eta \to \gamma\gamma$, candidates)

- Entering in a regime where penguin pollution constraints are similar to the precision of the combination

- The value of $\Gamma_s$ shows tension between LHCb and ATLAS:
  - HFLAV (not including Run 2): $\Gamma_s^{HFLAV} = 0.6629 \pm 0.0018$ ps$^{-1}$
  - LHCb Run 2: $\Gamma_s^{LHCb} = 0.6538 \pm 0.0033$ ps$^{-1} \rightarrow -2.4 \sigma$ from WA
  - ATLAS Run 2: $\Gamma_s^{ATLAS} = 0.669 \pm 0.0014$ ps$^{-1} \rightarrow +2.7 \sigma$ from WA
  - Wrt $\Gamma_s / \Gamma_d(HQE)=1.0006 \pm 0.0025$, LHCb is @1.4 $\sigma$, ATLAS @3.1 $\sigma$

\[\text{Difference between ATLAS and LHCb of } \sim 5 \sigma\]
Prospects for the future

- Include gain in trigger for $B_s^0 \to D_s^- D_s^+$ after Upgr 1
- Same performances as in Run 2 (tagging power 4%)
- Planning new modes: $J/\psi \to ee, \eta' \to \rho^0 \gamma$ or, 
  $\eta' \to \eta\pi\pi$ or $\gamma\gamma$
  - To improve the precision
  - But also to allow independent tests of the SM

300/fb: $\sigma^{STAT}(\varphi_s) \sim 4$ mrad from $B_s^0 \to J/\psi\phi$ only

- Fundamental that FT keep the same performance
- $\varphi_s$ expected to be statistically limited
Control of penguin pollution

- U-spin or SU(3) flavour symmetry to constrain size of penguin with $b \rightarrow c\bar{c}d$
- Penguin pollution and/or CP violation could be different for each polarisation state, $f \in (0, \perp, \parallel, S)$
  \[ \rightarrow \text{no sign yet of dependence in } B_s^0 \rightarrow J/\psi \text{ KK (also in Run 2) so penguins are small} \]
- SU(3)$_F$: $B_s^0 \rightarrow J/\psi K^{*0}$ and $B^0 \rightarrow J/\psi \rho^0$ are $b \rightarrow c\bar{c}d$ transitions (related by s-d spectator exchange).
  
  $B^0 \rightarrow J/\psi \rho^0$ contains E + PA diagrams that are not present in $B_s^0 \rightarrow J/\psi K^{*0}$

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

**Precision of \( \sim 10 \text{ mrad} \)**
To be compared with the current precision of HFLAV of \( 21 \text{ mrad} \)

Fundamental to update these analyses, expected sensitivity **at 300/\( fb \) is 1.5 mrad** (statistically limited) [arXiv:1808.08865]

+ $B_s^0 \rightarrow J/\psi \omega$ and $B^0 \rightarrow J/\psi \phi$ (E + PA diagrams only)
\( \varphi_s \) from penguin decays

- Include gain in trigger after Upgrade 1

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

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

- \( B_s^0 \to \phi\phi \) will remain stat. limited
- Limiting syst for \( B_s^0 \to K\pi K\pi <30 \) mrad from MC (important to exploit rapid MC production) and modelling resonances.
State of art of $\sin(2\beta)$

Golden channel $B^0 \to J/\psi K^0_S$, averages including all charmonium:

LHCb:
- $S = 0.760 \pm 0.034$ [JHEP 11(2017) 170]

Belle:
- $S = 0.667 \pm 0.026$ [PRL 108(2012) 171802]

Babar:
- $S = 0.691 \pm 0.031$ [PRD 79(2009) 072009]

$LHCb$ has a similar precision to the B-factories
- Small tension of B-factories results with SM predictions to be clarified
Prospects for $\sin(2\beta)$

- @50/fb: $\sigma_{\text{stat}} = 0.006$ with $B^0 \to J/\psi K^0_s$
- @300/fb: $\sigma_{\text{stat}} = 0.003$ with $B^0 \to J/\psi K^0_s$

Belle II @50/ab: $\sigma_{\text{stat}} = 0.005$ with $B^0 \to J/\psi K^0_s$

Systematics:
- Mostly depends on size of control samples \( \rightarrow \) scale with statistics
- Important to understand how to take into account $K^0 - \bar{K}^0$ CP violation and nuclear cross-section asymmetry.

Leading sources of systematic uncertainty are different between Belle II and LHCb

Penguins controlled using $B^0 \to J/\psi \pi^0$ and $B^0_s \to J/\psi K^0_s$ studied by LHCb [Phys. Rev. Lett. 115 (2015) 031601]

- $B^0_s \to J/\psi K^0_s$ studied by LHCb
- Belle II expects a good precision for $B^0 \to J/\psi \pi^0$
- Improving ECAL will allow also LHCb to contribute
- Upgrade II will also allow to study other $SU(3)$ related modes
Flavour tagging in the future

Almost everything will be new in Run3 (similar situation as in 2010)

- **Upgrade challenge**: increase in track multiplicity and pile-up (~6 for Upgrade-I and ~55 for Upgrade-II) that have negative effect on ω and $\varepsilon_{tag}$.
- FT performance directly linked to the ability to associate PV ↔ track. To improve/maintain tagging performance need:
  - **Hardware**: timing information (upgrade-II workshops)
  - **Software**: deep neural networks to learn correlations between all tracks and the signal B meson (inclusive taggers), need to reduce significantly persisted info.

- Better exploitation of data = more tagging power!
  - Run2 LHCb: ~30% relative improvement of tagging power
  - Belle 2 will do much better with their data for $B^0$
  - CMS/ATLAS do worse but with more data
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;
- Good prospects for the precision measurements in the Upgrade phase;
- Didn’t talk about CP violation in Baryons which is also a rich program for Upgrade 2.

- For LHCb upgrades we should improve/maintain the flavour-tagging performance, use high-yield control channels to control efficiencies and understand precisely vertex/time resolution.
“And if someone dares to yawn during your presentation, this pointer easily transforms from a laser to a taser!”
Results using 2015-2016 data

\[ B_s^0 \rightarrow J/\psi KK \]

\[ \varphi_s = -0.080 \pm 0.041 \pm 0.006 \text{ rad} \]
\[ |\lambda| = 1.006 \pm 0.016 \pm 0.006 \]
\[ \Gamma_s - \Gamma_d = -0.0041 \pm 0.0024 \pm 0.0015 \text{ ps}^{-1} \]
\[ \Delta \Gamma_s = 0.0772 \pm 0.0077 \pm 0.0026 \text{ ps}^{-1} \]
\[ \Gamma_s = 0.6538 \pm 0.0024 \pm 0.0015 \pm 0.0017 \text{ (input } \Gamma_d \text{) ps}^{-1} \]

Combining the above + Run 1: \( B_s^0 \rightarrow J/\psi KK, B_s^0 \rightarrow J/\psi \pi \pi, B_s^0 \rightarrow J/\psi KK \text{ high mass}, B_s^0 \rightarrow D_s D_s, B_s^0 \rightarrow \psi(2S)\phi \)

\[ \varphi_s = -0.040 \pm 0.025 \text{ rad} \]
\[ |\lambda| = 0.991 \pm 0.010 \]
\[ \Gamma_s = 0.6563 \pm 0.0021 \text{ ps}^{-1} \]
\[ \Delta \Gamma_s = 0.0812 \pm 0.0048 \text{ ps}^{-1} \]

\[ B_s^0 \rightarrow J/\psi \pi \pi \]

\[ \varphi_s = -0.057 \pm 0.060 \pm 0.011 \text{ rad} \]
\[ |\lambda| = 1.01^{+0.08}_{-0.06} \pm 0.03 \]
\[ \Gamma_H - \Gamma_d = -0.050 \pm 0.004 \pm 0.004 \text{ ps}^{-1} \]
Systematics for $B_s^0 \rightarrow J/\psi KK$

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

| Source                        | $|A_0|^2$ | $|A_1|^2$ | $\phi_s$ [rad] | $|\lambda|$ | $\delta_1 - \delta_0$ [rad] | $\delta_1 - \delta_0$ [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            | -               | 0.0033                 | -                   | 0.0003           |
| $C_{Sp}$ factors              | -        | 0.0001    | 0.001         | 0.0010     | 0.01            | -               | 0.005                  | -                   | 0.001            |
| Quadratic OS tagging         | -        | -        | -             | -          | -               | -               | -                      | -                   | -                |
| Time res.: statistical       | -        | -        | -             | -          | -               | -               | -                      | -                   | -                |
| Time res.: prompt            | -        | -        | -             | -          | -               | -               | -                      | -                   | -                |
| Time res.: mean offset       | -        | -        | **0.0032**    | 0.0010     | 0.08            | 0.001           | 0.0002                 | 0.0003              | 0.005            |
| Time res.: Wrong PV          | -        | -        | -             | -          | -               | -               | -                      | -                   | -                |
| Ang. acc.: statistical       | 0.0003   | 0.0004    | **0.0011**    | **0.0018** | -               | -               | 0.004                  | -                   | 0.001            |
| Ang. acc.: 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.: $t$ & $\sigma$ 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.: $\Delta \Gamma_s = 0$ sim. | 0.0001 | 0.0002    | -             | -          | -               | -               | 0.0003                 | 0.0005              | -                |
| Dec.-time eff.: knot pos.    | -        | -        | -             | -          | -               | -               | -                      | -                   | -                |
| Dec.-time eff.: p.d.f. weighting | -      | -        | -             | -          | -               | -               | 0.0001                 | 0.0001              | -                |
| Dec.-time eff.: kin. weighting | -      | -        | -             | -          | -               | -               | 0.0002                 | -                   | -                |
| Length scale                 | -        | -        | -             | -          | -               | -               | -                      | -                   | -                |
| Quadratic sum of syst.       | 0.0024   | 0.0019    | 0.0061        | 0.0064     | 0.10            | 0.037           | 0.0015                 | 0.0026              | 0.018            |

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Systematics for $B_S^0 \rightarrow J/\psi\pi\pi$

$\Gamma_H - \Gamma_d$ mainly affected by Background, $\varphi_s$ 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 $\rho(770)$
### Table 5: Summary of systematic uncertainties assigned to the physical parameters of interest.

|                     | $\phi_s$ [rad] | $\Delta \Gamma_s$ [ps$^{-1}$] | $\Gamma_s$ [ps$^{-1}$] | $|A_\parallel(0)|^2$ | $|A_0(0)|^2$ | $|A_\perp(0)|^2$ | $\delta_\perp$ [rad] | $\delta_\parallel$ [rad] | $\delta_\perp - \delta_\parallel$ [rad] |
|---------------------|----------------|-------------------------------|-------------------------|----------------------|-------------|------------------|-------------------|-------------------|------------------------|
| 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          | $0.7 \times 10^{-3}$ | $< 10^{-4}$ | $< 10^{-4}$ | $0.8 \times 10^{-3}$ | $0.7 \times 10^{-3}$ | $2.4 \times 10^{-3}$ | $3.3 \times 10^{-2}$ | $1.4 \times 10^{-2}$ | $2.6 \times 10^{-3}$ |
| ID alignment        | $0.7 \times 10^{-3}$ | $0.1 \times 10^{-3}$ | $0.5 \times 10^{-3}$ | $< 10^{-4}$ | $< 10^{-4}$ | $< 10^{-4}$ | $1.0 \times 10^{-2}$ | $7.2 \times 10^{-3}$ | $< 10^{-4}$ |
| $S$–wave phase      | $0.2 \times 10^{-3}$ | $< 10^{-4}$ | $0.3 \times 10^{-3}$ | $< 10^{-4}$ | $0.3 \times 10^{-3}$ | $1.1 \times 10^{-2}$ | $2.1 \times 10^{-2}$ | $8.3 \times 10^{-3}$ |                |
| 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: | | | | | | | | | |
| $B^0_d$             | $2.3 \times 10^{-3}$ | $1.1 \times 10^{-3}$ | $< 10^{-4}$ | $0.2 \times 10^{-3}$ | $3.1 \times 10^{-3}$ | $1.4 \times 10^{-3}$ | $1.0 \times 10^{-2}$ | $2.3 \times 10^{-2}$ | $2.1 \times 10^{-3}$ |
| $\Lambda_b$        | $1.6 \times 10^{-3}$ | $0.4 \times 10^{-3}$ | $0.2 \times 10^{-3}$ | $0.5 \times 10^{-3}$ | $1.2 \times 10^{-3}$ | $1.8 \times 10^{-3}$ | $1.4 \times 10^{-2}$ | $2.9 \times 10^{-2}$ | $0.8 \times 10^{-3}$ |
| 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**           | $1.8 \times 10^{-2}$ | $0.2 \times 10^{-2}$ | $0.1 \times 10^{-2}$ | $0.2 \times 10^{-2}$ | $0.4 \times 10^{-2}$ | $0.4 \times 10^{-2}$ | $9.7 \times 10^{-2}$ | $2.0 \times 10^{-1}$ | $0.1 \times 10^{-1}$ |