PHYSICS PROSPECTS FOR LHCB UPGRADE II

FRANCESCA DORDEI
INFN CAGLIARI
ON BEHALF OF LHCB
LHCP 2021, 7 JUNE 2021
WHAT IS LHCb UPGRADE II?

• Currently Upgrade I is under installation
• Upgrade II will come online in 2032
• Goal > 30 times the current integrated luminosity (inst. Lumi. $\mathcal{L} \sim (1-2) \times 10^{34}$ sec$^{-1}$cm$^{-2}$)
• pile-up $\sim 40$, from $\sim 5$ for Run 3/4 (today’s challenge)
WHAT IS LHCb UPGRADE II?

Upgrade II will involve changes to nearly all parts of experiment

- Vertexing: Pixel detector with timing
- Hadron PID: RICH with timing and improved resolution + TORCH for low-p
- Tracking: Magnet Side stations + (pixel) inner tracker
- Calorimeter: Timing + improved resolution
- Muon system: alternative technologies for high-rate regions

Timing information will be crucial

See the talks of S. Gambetta on Wednesday and T. Szumlak on Friday
WHY UPGRADE?

- Flavour Physics is a powerful tool to access NP beyond the reach of direct production at accelerators.
- Upgrade II aims to make full use of the capabilities of a forward acceptance detector during the High Luminosity LHC (HL-LHC) operational period.
- Some hints of New Physics in LHC Runs 1 & 2.
  - Lepton flavour (non-)universality?
  - No “discovery” but coherent set of discrepancies w.r.t. Standard Model. More data needed.
- More data to further challenge theoretical predictions.
  - Most of the measurements will be still statistically limited after Run 4.
- LHCb will upgrade to continue improving our knowledge of Flavour Physics.
RICH PHYSICS PROGRAMME

- CP Violation
- \( \gamma, \beta, \varphi \)
- Lepton Universality tests
- Charm Physics
- Unitarity triangle sides
- Rare decays
- Hadron spectroscopy
- Forward and high-\( p_T \) physics

arXiv:1808.08865
The SM works so remarkably well that we have to make more and more precise measurements. NP allowed at O(20%) in $b \rightarrow d$ and $b \rightarrow s$ transitions.
If we assume NP enters mainly at loop level, it is interesting to compare the determination of the parameters $(\rho, \eta)$ from processes dominated by tree diagrams ($V_{ub}, V_{cb}, \gamma,...$) with the ones from loop diagrams ($\Delta M_d$, $\Delta M_s$, $\Phi_s, \varepsilon_K, ...$).
**CKM ANGLE** $\gamma$

- $\gamma \equiv [-(V_{ub}^* V_{ud})/(V_{cb}^* V_{cd})]$; it does not depend on a top-quark coupling, measured via interference $b \to u$ and $b \to c$ transitions.

- Very well known within SM: $|\delta \gamma| \leq 10^{-7}$

**LHCb combination**

$\gamma = (67 \pm 4)^\circ$

- LHCb is nicely closing the sensitivity gap between direct measurements and global fits $\gamma = (65.7^{+0.9}_{-2.5})^\circ$

- Expected stat. sensitivity down to the degree level for individual modes. Expect a $0.35^\circ$ combined sensitivity.

- Comparison of measurements made in single decay modes interesting after Upgrade II → NP in tree level different for different final states.
**$B_S^0$ MIXING PHASE, $\Phi_S$**

- CP-violating phase arising from interference between mixing and decay, precisely predicted.
- Golden channel exploited by LHCb, ATLAS, CMS: $B_S^0 \rightarrow J/\psi\phi$
  
  **HFLAV combination**
  \[
  \phi_S = -0.041 \pm 0.025 \text{ rad}
  \]

- Statistically limited.

See the talk of B. Khanji on Thursday.
\( B_s^0 \) MIXING PHASE, \( \Phi_s \)

- CP-violating phase arising from interference between mixing and decay, precisely predicted
- Golden channel exploited by LHCb, ATLAS, CMS: \( B_s^0 \rightarrow J/\psi \phi \)

**HFLAV combination**

\[ \phi_s = -0.041 \pm 0.025 \text{ rad} \]

- Statistically limited also @300 fb\(^{-1}\). LHCb precision <3mrad.
- Same performances as in Run 2 (tagging power, i.e. flavour identification of the \( B_s^0 \) at production, ~4%)
- Exp precision of the penguin pollution will scale similarly

See the talk of B. Khanji on Thursday
RARE DECAYS
RARE DECAYS AS PROBE FOR NP

- Rare FCNC decays are loop-suppressed in the SM ($\mathcal{B} \sim 10^{-6} - 10^{-7}$ but also much smaller)
- New heavy particles can significantly contribute, affecting decay rates and angular distributions
- Model independent description using effective, four-fermion point interactions

\[
\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i \mathcal{O}_i + \frac{k}{\Lambda_{\text{NP}}^2} \mathcal{O}_{\text{NP}}
\]

Wilson Coefficient (effective coupling)

NP coupling

NP scale

New Physics

Standard Model

\(i = 1, 2\) Tree

\(i = 3, 6, 8\) Gluon Penguin

\(i = 7\) Photon penguin

\(i = 9, 10\) EW penguin

\(i = S, P\) (Pseudo)scalar penguin
Golden modes in NP searches: precisely predicted in the SM.

With 2011–2018 LHCb data (9 fb⁻¹):

- \( \mathcal{B}(B_s^0 \to \mu^+\mu^-) = 3.09^{+0.46+0.15}_{-0.43-0.11} \times 10^{-9} \)
- \( \mathcal{B}(B^0 \to \mu^+\mu^-) = 1.2^{+0.8}_{-0.7} \pm 0.1 \times 10^{-10} \)

The SM point is near the 2σ band.

- \( \mathcal{B}(B_s^0 \to \mu^+\mu^-) \) has now 15% precision. Stat will be 1.8% with 300 fb⁻¹.
- The systematics are now 4-5%, dominated by \( f_s/f_d \). Hard to predict how this will evolve.
- New \( f_s/f_d \) 2021 measurement

- \( \mathcal{B}(B^0 \to \mu^+\mu^-) \) The statistical precision will be 10% with 300 fb⁻¹.
- \( \mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-) \) suffers from the same \( f_s/f_d \) limitation but will be still statistics-dominated (10% uncertainty).
- Yields will allow effective lifetime (2%) and TD CP asymmetries (10-20%).
$B^0 \rightarrow K^{*0} \mu\mu$

- $B^0 \rightarrow K^{*0} (\rightarrow K^+ \pi^-) \mu^+ \mu^-$ exhibits rich angular structure
- Measure optimised angular observables with reduced hadronic uncertainty, like $P_5^\prime$
- Most precise measurement from LHCb is above the SM
- However, non trivial charm-loop contribution close to the resonant regions

- Expect $\sim 440,000$ $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ candidates in Upgrade II
- Allows for determination of angular observables with unprecedented precision
- Different NP scenarios can be cleanly separated

---

### Table: ReC$_9^{(a)}$ Values for Different Scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>$C_9^{NP}$</th>
<th>$C_{10}^{NP}$</th>
<th>$C'_9$</th>
<th>$C'_{10}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>-1.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>II</td>
<td>-0.7</td>
<td>0.7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>III</td>
<td>0</td>
<td>0.3</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>0</td>
<td>0.3</td>
<td>0.3</td>
<td>-0.3</td>
</tr>
</tbody>
</table>

---

**Graph**

- $P_5^\prime$ distribution
- LHCb data
- Combined
- SM from DHMV

---

**Legend**

- $b \rightarrow sll$ data
- $b \rightarrow sll \& b \rightarrow clv$ data
- III. and IV. small right-handed currents

---

*See the talk of Yanting Fan on Tuesday*
LEPTON UNIVERSALITY: \( R(K^{(*)}) \)

\[
R_{K^{(*)}} = \frac{\Gamma(B \to K^{(*)} \mu^+ \mu^-)}{\Gamma(B \to K^{(*)} J/\psi \mu^+ \mu^-)} / \frac{\Gamma(B \to K^{(*)} e^+ e^-)}{\Gamma(B \to K^{(*)} J/\psi e^+ e^-)}
\]

- LHCb results are consistently lower than 1
- Results from B-factories are compatible (with less precision)

Upgrade 2: All 4 NP scenarios could be distinguished at >5σ:

<table>
<thead>
<tr>
<th>Nominal NP scenario</th>
<th>( R_K )</th>
<th>( \Delta C_9 = -1.4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb Upgrade II Scenario-I</td>
<td>( R_{K^{(*)}} )</td>
<td>( \Delta C_9 = -0.7 )</td>
</tr>
<tr>
<td>LHCb Upgrade II Scenario-II</td>
<td>( R_{K^{(*)}} )</td>
<td>( \Delta C_9 = +0.3 )</td>
</tr>
<tr>
<td>LHCb Upgrade II Scenario-III</td>
<td>( R_{\phi} )</td>
<td>( \Delta C_9 = +0.3 )</td>
</tr>
<tr>
<td>LHCb Upgrade II Scenario-IV</td>
<td>( R_{\phi} )</td>
<td>( \Delta C_9 = +0.3 )</td>
</tr>
<tr>
<td>LHCb Run 1</td>
<td>( R_{\phi} )</td>
<td>( \Delta C_9 = +0.3 )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Yield</th>
<th>Run 1 result</th>
<th>9 fb(^{-1})</th>
<th>23 fb(^{-1})</th>
<th>50 fb(^{-1})</th>
<th>300 fb(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B^0 \to K^0 \phi e^+ e^- )</td>
<td>111 ± 14 [122]</td>
<td>490 ± 160 [510]</td>
<td>1400 ± 300 [1500]</td>
<td>3300 ± 600 [3500]</td>
<td>20000 ± 4000 [22000]</td>
</tr>
<tr>
<td>( B^0 \to \phi e^+ e^- )</td>
<td>28 ± 6 [31]</td>
<td>80 ± 16 [85]</td>
<td>230 ± 40 [240]</td>
<td>530 ± 100 [550]</td>
<td>2300 ± 430 [2500]</td>
</tr>
<tr>
<td>( R_K ) precision</td>
<td>Run 1 result</td>
<td>9 fb(^{-1})</td>
<td>23 fb(^{-1})</td>
<td>50 fb(^{-1})</td>
<td>300 fb(^{-1})</td>
</tr>
<tr>
<td>( R_K )</td>
<td>0.745 ± 0.009 ± 0.036 [272]</td>
<td>0.043 ± 0.005 [0.047]</td>
<td>0.025 ± 0.005 [0.028]</td>
<td>0.017 ± 0.005 [0.019]</td>
<td>0.007 ± 0.005 [0.008]</td>
</tr>
<tr>
<td>( R_{K^{(*)}} )</td>
<td>0.69 ± 0.11 ± 0.05 [272]</td>
<td>0.052 ± 0.005 [0.055]</td>
<td>0.031 ± 0.005 [0.034]</td>
<td>0.020 ± 0.005 [0.022]</td>
<td>0.008 ± 0.005 [0.009]</td>
</tr>
<tr>
<td>( \phi )</td>
<td>0.130 ± 0.076 [0.140]</td>
<td>0.050 ± 0.050 [0.055]</td>
<td>0.020 ± 0.020 [0.024]</td>
<td>0.020 ± 0.020 [0.024]</td>
<td>0.008 ± 0.008 [0.010]</td>
</tr>
<tr>
<td>( R_K )</td>
<td>0.105 ± 0.061 [0.110]</td>
<td>0.041 ± 0.041 [0.045]</td>
<td>0.016 ± 0.016 [0.019]</td>
<td>0.016 ± 0.016 [0.019]</td>
<td>0.007 ± 0.007 [0.009]</td>
</tr>
<tr>
<td>( \tau )</td>
<td>0.302 ± 0.176 [0.310]</td>
<td>0.117 ± 0.117 [0.120]</td>
<td>0.047 ± 0.047 [0.050]</td>
<td>0.047 ± 0.047 [0.050]</td>
<td>0.023 ± 0.023 [0.025]</td>
</tr>
</tbody>
</table>

See the talk of Yanting Fan on Tuesday
LEPTON FLAVOUR UNIVERSALITY AT TREE LEVEL

“I suppose I’ll be the one to mention the elephant in the room.”
LEPTON UNIVERSALITY TEST IN TREE-LEVEL DECAYS

Tests of LFU in semitaunonic decays are obtained measuring the following ratios

\[ R_X = \frac{\Gamma(B \rightarrow X_c \tau^+\nu_\tau)}{\Gamma(B \rightarrow X_c \mu^+\nu_\mu)} \]

with \( X_c = D^* \) or \( J/\psi \)

LHCb has performed analysis of

- \( R_{D^*} = 0.336 \pm 0.027 \pm 0.030 \) with \( \tau^- \rightarrow \mu^-\nu_\tau\bar{\nu}_\mu \)
  compatible with the SM at 2.1 \( \sigma \) [PRL 115 (2015) 111803]
- \( R_{D^*} = 0.291 \pm 0.019 \pm 0.026 \pm 0.013 \) with \( \tau^- \rightarrow \pi^-\pi^+\pi^- (\pi^0)\nu_\tau \)
  compatible with the SM at 1 \( \sigma \) [PRL 120 (2018) 171802]
- \( R_{J/\psi} = 0.71 \pm 0.17 \pm 0.18 \) using \( B_{c}^{+} \) decays
  compatible with the SM at \( \sim 2 \sigma \) [PRL 120 (2018) 121801]

See the talk of Alessandra Gioventu on Tuesday
FUTURE PROSPECTS

For an irreducible systematic uncertainty of 3% on \( R(D^*) \) and 5% on the other ratios.

- Expect \( 0(10 \text{ M}) \) \( \bar{B} \to D^{(*)\tau\bar{\nu}} \) candidates

- Sensitivity Upgrade II: \( \alpha(R_{D^*}) / R_{D^*} \sim 1\% \)

For an irreducible systematic uncertainty of 0.5% on \( R(D^*) \) and 2% on the other ratios.

Upgrade II: exploit other \( b \)-hadron species
- \( B_s^0 \to D_s^{(*)+} \tau^- \bar{\nu} \): 2.5% relative unc. After Upgrade II
- Semitauonic decays of \( b \)-baryons and of \( B_c^+ \) mesons
  - \( R(\Lambda_c^+) \): 2.5% relative unc. after Upgrade II
CONCLUSIONS

• 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;
• LHCb Upgrade has a far-reaching Flavour Physics program – see more in LHCB-PUB-2018-009
• We must push forward to use as efficiently the unique opportunity of a High-Luminosity Hadronic Collider
  • FTDR in preparation: coming by the end of summer!
• The Phase-II upgrade would collect a thirty times bigger data sample than LHCb currently has
• Improvements in detector will open up many little-explored modes
BACKUP
What we think is the main physics right now might not be what we use the detector for. Important that the detector is versatile.

- Was written in 1995
- Observation of CP violation in $B$ mesons and $B_s^0$ oscillations the main selling points
- CP angle $\gamma$ would mainly be from time dependent analysis of $B_s^0 \rightarrow D_s^+ K^-$
- Charm physics only from $B \rightarrow D \ell \nu$ decays
- $B_s^0 \rightarrow \mu^+ \mu^-$only rare decay
- $\Lambda_b$ never mentioned
12 Physics Performance

12.1 LHC-B simulation programme .......... 96
12.2 Reconstruction of final states .......... 97
  12.2.1 The $B^0(\pi^+\pi^-)$ final state .... 97
  12.2.2 The $B^0(J/\psi K_S)$ final state .. 101
  12.2.3 The $B_s(J/\psi \phi)$ and $B_d(J/\psi K^{*0})$ final states .. 103
  12.2.4 The $B_s(D_s\pi)$ and $B_s(D_sK)$ final state ............... 104
  12.2.5 The $B^0(\bar{D}^0 K^{*0})$ Final State .. 106
12.3 Flavour Tagging ......................... 107
12.4 Control Channels and Systematics .... 109
12.5 The $B_s\bar{B}_s$ Oscillations ............. 110
  12.5.1 Introduction .......................... 110
  12.5.2 Determination of $x_s$, $\tau_s$ and $y_s$ .... 110
12.6 CP Sensitivities ......................... 111
  12.6.1 The angle $\alpha$ ....................... 111
  12.6.2 The angle $\beta$ ....................... 112
  12.6.3 The angle $\gamma$ Method-1 ............. 112
  12.6.4 The angle $\gamma$ Method-2 ............. 113
  12.6.5 CP violation in $B_s \rightarrow J/\psi \phi$ ... 114
12.7 $B_s \rightarrow \mu^+\mu^-$ ...................... 115
  12.7.1 Reconstruction Simulation ........... 116

LHCb LETTER
OF INTENT

What we think is the main physics right now might not be what we use the detector for.
Important that the detector is versatile.

- Was written in 1995
- Observation of CP violation in $B$ mesons and $B_s$ oscillations the main selling points
- CP angle $\gamma$ would mainly be from time-dependent analysis of $B^0 \rightarrow D_s^+ K^-$
- Charm physics only from $B_s \rightarrow D_s^+ K^-$ decays
- $B_s^0 \rightarrow \mu^+\mu^-$ decay only rare decay
- $\Lambda$ never mentioned

Done before start-up
Different method
Prompt production
Vastly expanded

See Ulrik Egede, ICHEP 2020
Figure 2.1: Luminosity projections for the original LHCb, Upgrade I, and Upgrade II experiments as a function of time. The red points and the left scale indicate the anticipated instantaneous luminosity during each period, with the blue line and right scale indicating the integrated luminosity accumulated.
| \( |V_{ud}| \) | Current | Phase I | Phase II | Ref. |
|---|---|---|---|---|
| | \( \pm 0.00021 \) | \( \pm 0.00021 \) | \( \pm 0.00021 \) | [4] |
| \( |V_{ub}|f_{\pi}^{K\rightarrow\pi}(0) \) | \( \pm 0.0004 \) | \( \pm 0.0004 \) | \( \pm 0.0004 \) | [4] |
| \( |\epsilon_K| \times 10^3 \) | \( \pm 0.011 \) | \( \pm 0.011 \) | \( \pm 0.011 \) | [4] |
| \( |V_{cd}| \) | \( \pm 0.005 \) | \( \pm 0.003 \) | \( \pm 0.003 \) | [2] |
| \( |V_{cs}| \) | \( \pm 0.016 \) | \( \pm 0.014 \) | \( \pm 0.014 \) | [2] |
| \( \Delta m_d \text{ [ps}^{-1}] \) | \( \pm 0.0019 \) | \( \pm 0.0019 \) | \( \pm 0.0019 \) | [5] |
| \( \Delta m_s \text{ [ps}^{-1}] \) | \( \pm 0.021 \) | \( \pm 0.021 \) | \( \pm 0.021 \) | [5] |
| \( |V_{ub}| \times 10^3 (b \rightarrow u\nu\bar{\nu}) \) | \( \pm 0.23 \) | \( \pm 0.04 \) | \( \pm 0.04 \) | [3] |
| \( |V_{cb}| \times 10^3 (b \rightarrow c\nu\bar{\nu}) \) | \( \pm 0.7 \) | \( \pm 0.5 \) | \( \pm 0.5 \) | [3] |
| \( |V_{ub}/V_{cb}| (A_b) \) | \( \pm 0.0050 \) | \( \pm 0.0025 \) | \( \pm 0.0008 \) | [1] |
| \( \sin 2\beta \) | \( \pm 0.017 \) | \( \pm 0.005 \) | \( \pm 0.003 \) | [1] and [3] |
| \( \alpha [^\circ] \) | \( \pm 4.4 \) | \( \pm 0.6 \) | \( \pm 0.6 \) | [3] |
| \( \gamma [^\circ] \) | \( \pm 5.6 \) | \( \pm 1 \) | \( \pm 0.35 \) | [1] and [3] |
| \( \beta_s \text{ [rad]} \) | \( \pm 0.031 \) | \( \pm 0.014 \) | \( \pm 0.004 \) | [1] |
| \( B(B \rightarrow \tau\nu) \times 10^4 \) | \( \pm 0.21 \) | \( \pm 0.04 \) | \( \pm 0.04 \) | [3] |
| \( B(B \rightarrow \mu\nu) \times 10^6 \) | – | \( \pm 0.03 \) | \( \pm 0.03 \) | [3] |
| \( B(B_s \rightarrow \mu\mu) \times 10^9 \) | \( \pm 0.66 \) | \( \pm 0.34 \) | \( \pm 0.17 \) | [1] |
| \( B(B_d \rightarrow \mu\mu) \times 10^{11} \) | – | \( \pm 3.5 \) | \( \pm 1.0 \) | [1] |
| \( \frac{B(B_s \rightarrow \mu\mu)}{B(B_d \rightarrow \mu\mu)} \) | – | \( \pm 0.010 \) | \( \pm 0.003 \) | [1] |
| \( m_c \text{ [GeV]} \) | \( \pm 0.012 \) \((0.9 \%)\) | \( \pm 0.005 \) \((0.4 \%)\) | \( \pm 0.005 \) \((0.4 \%)\) | [1] |
| \( m_b \text{ [GeV]} \) | \( \pm 0.73 \) \((0.4 \%)\) | \( \pm 0.35 \) \((0.2 \%)\) | \( \pm 0.35 \) \((0.2 \%)\) | [4] |
| \( \alpha_s(m_Z) \) | \( \pm 0.0011 \) \((0.9 \%)\) | \( \pm 0.0011 \) \((0.9 \%)\) | \( \pm 0.0011 \) \((0.9 \%)\) | [4] |
| \( f_{K}^{K\rightarrow\pi}(0) \) | \( \pm 0.0026 \) \((0.3 \%)\) | \( \pm 0.0012 \) \((0.12 \%)\) | \( \pm 0.0012 \) \((0.12 \%)\) | [1] |
| \( f_{\pi}^{K\rightarrow\pi}(0) \) | \( \pm 0.0006 \) \((0.5 \%)\) | \( \pm 0.0005 \) \((0.4 \%)\) | \( \pm 0.0005 \) \((0.4 \%)\) | [1] |
| \( B_K \) | \( \pm 0.012 \) \((1.6 \%)\) | \( \pm 0.005 \) \((0.7 \%)\) | \( \pm 0.004 \) \((0.5 \%)\) | [1] |
| \( B_{B_s} \text{ [GeV]} \) | \( \pm 0.0025 \) \((1.1 \%)\) | \( \pm 0.0011 \) \((0.5 \%)\) | \( \pm 0.0011 \) \((0.5 \%)\) | [1] |
| \( B_{B_d} \text{ [GeV]} \) | \( \pm 0.034 \) \((2.8 \%)\) | \( \pm 0.010 \) \((0.8 \%)\) | \( \pm 0.007 \) \((0.5 \%)\) | [1] |
| \( f_{B_d}/f_{B_s} \) | \( \pm 0.007 \) \((0.6 \%)\) | \( \pm 0.005 \) \((0.4 \%)\) | \( \pm 0.005 \) \((0.4 \%)\) | [1] |
| \( B_{B_d}/B_{B_s} \) | \( \pm 0.020 \) \((1.9 \%)\) | \( \pm 0.005 \) \((0.5 \%)\) | \( \pm 0.003 \) \((0.3 \%)\) | [1] |

Table 1: Uncertainties for the CKMfitter projections.
DIRECT VS INDIRECT CKM
ANGLE $\gamma$
DIRECT CPV CHARM

- The observation of CPV in charm decays is a milestone that marks the start of a next era for charm physics.
- Significant theory interest in ACP(D^0 -> K_S K_S)
- Estimates vary from ~ 1% to O(3/2 ΔA_{CP}) (depending on SU(3) breaking)

<table>
<thead>
<tr>
<th></th>
<th>Uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle I</td>
<td>± 1.53 ± 0.17</td>
</tr>
<tr>
<td>LHCb '12-'16</td>
<td>± 2.8 ± 0.9</td>
</tr>
<tr>
<td>LHCb Run 2</td>
<td>± 1.5</td>
</tr>
<tr>
<td>Belle II</td>
<td>± 0.23</td>
</tr>
<tr>
<td>LHCb Upgrade-II</td>
<td>± 0.12 - 0.23*</td>
</tr>
</tbody>
</table>

[1]: Nierste, Schacht '15
[2]: Hiller, Jung, Schacht '13
[3]: Cheng, Chaing '12

Upgrade-II essential, event trigger main challenge
CPV IN MIXING

\[ D^0 \quad \rightarrow \quad \bar{D}^0 \]

Mixing phase

- HFLAV World Average 2017
- LHCb 300/fb

Contours hold 68%, 95% CL

CPV in mixing (similar to \( a_\phi \))
**LEPTON FLAVOUR VIOLATION**

- LFV branching fractions enhanced to $10^{-11}$ in certain models of leptoquarks, $Z'$ \[\text{[Medeiros Varzielas, Hiller, JHEP 06 (2015) 072]}\]
- LHCb was the first experiment to search for LFV $\tau$ decays in a hadron collider

<table>
<thead>
<tr>
<th></th>
<th>$B(B_s^0 \to e\mu)$</th>
<th>$B(B \to \tau\mu)$</th>
<th>$B(\tau \to \mu\mu\nu)$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Run I @ 90 C.L.</strong></td>
<td>$&lt; 1.0 \times 10^{-9}$</td>
<td>Soon</td>
<td>$&lt; 4.6 \times 10^{-8}$</td>
</tr>
<tr>
<td><strong>Upgrade II @ 90 C.L.</strong></td>
<td>$&lt; 3 \times 10^{-10(11)}$</td>
<td>$&lt; 3 \times 10^{-6}$</td>
<td>$&lt; \mathcal{O}(10^{-9})$</td>
</tr>
</tbody>
</table>

Similar to what is expected from Belle II

Searches for $B \to Ke\mu, B \to K^{*0}\tau(\to \pi\pi\nu)\mu, B \to K\tau(\to \pi\pi\nu)\mu$ and $\Lambda_b^0 \to \Lambda^0 e\mu$ are ongoing

- Using Run1 + Run2 data expects limits $\mathcal{O}(10^{-9})$ and $\mathcal{O}(10^{-6})$ for $B \to Ke\mu$ and $B \to K^{*0}\tau\mu$, respectively
- Complementary as charged lepton FV couplings among different families are expected to be different
- Multi-body final states: allow the measurement of more observables
Part of the success of the LHCb experiment was the unplanned:

- $\Lambda\bar{b}$ physics and baryon CPV;
- spectroscopy;
- top and electroweak physics;
- searches for dark photons;
- heavy ion physics;
- ...

With its flexible trigger, LHCb has proven itself as a general purpose detector in the forward region. Head room for innovative techniques was key for these developments. The phase-2 upgrade detector should preserve this
**WHY TIMING?**

Upgrade 2: ~40 visible interactions

Primary vertices are also spread in time