New physics in B meson mixing: future sensitivity and limitations

Luiz VALE SILVA (IFIC, UV - CSIC)


CKM 2021, Melbourne (virtual), 22-26 November 2021
• **Flavour physics** played a central role in the formulation of the SM (new fermion generations, manifestation of CP Violation, etc.)

• Many **flavour observables** enjoy the status of *precision physics*, thanks to progress in different fronts (e.g. QCD inputs)

• **Flavour physics** can play a *leading role* in addressing the questions left open by the SM, and reveal New Physics sectors

Hierarchies in the spectrum of particles and CKM matrix:
Reach to New Physics (NP)

- **Low-energy observables** → **probe energy scales much beyond the reach of direct searches**
- The bounds derived **shape NP candidates**
- If deviation seen, possible **NP manifestation**!

Different sectors:
Current status of flavour

- Overall agreement w/ the SM, but some exciting tensions (e.g. “B-anomalies”)
  
[CKMfitter update as of Spring ‘21: see talk later today by Wenbin Qian]

- Flavour is one of the main physics cases for future experiments

- Future data will guide the field, testing present anomalies and possibly revealing new ones
New era of flavour ahead

<table>
<thead>
<tr>
<th></th>
<th>LHC era</th>
<th>HL-LHC era</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS, CMS</td>
<td>25 fb(^{-1})</td>
<td>150 fb(^{-1})</td>
</tr>
</tbody>
</table>
| LHCb          | 3 fb\(^{-1}\)     | 9 fb\(^{-1}\)    | 23 fb\(^{-1}\)  | 50 fb\(^{-1}\)  | *300 fb\(^{-1}\) *

* assumes a future LHCb upgrade to raise the instantaneous luminosity to 2\(\times\)10\(^{34}\) cm\(^{-2}\)s\(^{-1}\)

[↑ See arXiv:1808.08865] [From arXiv:1808.10567 →]

- Expression of interest for an LHCb Upgrade II
- Belle II: 50x the Belle and nearly 100x the BaBar data sets; ongoing discussions about upgrade

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NP in B meson mixing

- **HERE** we address present and future bounds on NP in |ΔB|=2, and discuss future limitations.

- |ΔB|=2: NP competes with suppressions in the SM (GIM/loop), and enjoy the status of precision physics.

- Not discussing K, nor D meson mixing.


- Combine projections for future data: need global fit including "tree" and "loop" observables.

  [see e.g. CKMfitter]
NP in B meson mixing

• **NP in** $|\Delta B|=2$: 
  - $h_d$ and $h_s$ set sizes

• **Assumptions:**
  - No NP in $|\Delta F|=1$:
    - tree level in SM ($\gamma$, $|V_{ub}|$, $|V_{cb}|$, ...) free of NP
  - NP is short-distance
  - Unitarity of the CKM 3x3 matrix
  - Unrelated NP in $B_d$ and $B_s$ systems

• **SMEFT:** four-quark operators of different chiral structures

\[ M_{12} = M_{12}^{SM} \times (1 + h e^{2i\sigma}) \]

Bag parameters, ↓ decay constants

NP parameters

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Present status of NP in B meson mixing

- Agreement with the SM ($h_d=0$) at $\sim 1\sigma$
- Allowed size for NP at the level of $O(20\%)$!
- Extractions of $\rho$ and $\eta$ (Wolfenstein parm.) degrade by factor $\sim 3$

Black dot: best fit point; $\sigma_d$ and $\sigma_s$ are unconstrained
Benchmarks for the future

- **Phase I**: LHCb-upgrade I 50/ fb, & Belle II 50/ ab (late 2020s)
- **Phase II**: LHCb-upgrade II 300/ fb, & Belle II upgrade 250/ ab (late 2030s)
- **Phase III**: Phase II + FCC-ee

**FCC-ee**: initial phase of FCC; operates at different EW thresholds: $5 \times 10^{12}$ Z bosons, $10^8$ WW pairs, $>10^6$ Higgses, $>10^6$ tt pairs

<table>
<thead>
<tr>
<th>Particle production ($10^9$)</th>
<th>$B^0/\bar{B}^0$</th>
<th>$B^+/B^-$</th>
<th>$B^0_s/\bar{B}^0_s$</th>
<th>$\Lambda_b/\bar{\Lambda}_b$</th>
<th>$c\bar{c}$</th>
<th>$\tau^+\tau^-$</th>
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</thead>
<tbody>
<tr>
<td>Belle II</td>
<td>27.5</td>
<td>27.5</td>
<td>n/a</td>
<td>n/a</td>
<td>65</td>
<td>45</td>
</tr>
<tr>
<td>FCC-ee</td>
<td>1000</td>
<td>1000</td>
<td>250</td>
<td>250</td>
<td>550</td>
<td>170</td>
</tr>
</tbody>
</table>

[**FCC Physics Opportunities, Conceptual Design Report**]
[Flavour cases: Monteil]

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### Experimental and Theoretical Inputs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Central Values</th>
<th>Current [28]</th>
<th>Phase I</th>
<th>Phase II</th>
<th>Phase III</th>
<th>Reference Phases I-III</th>
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</thead>
<tbody>
<tr>
<td>$</td>
<td>V_{cb}</td>
<td>$</td>
<td>0.97437</td>
<td>$\pm 0.00021$</td>
<td>id</td>
<td>id</td>
</tr>
<tr>
<td>$</td>
<td>V_{cd}</td>
<td>/</td>
<td>V_{td}</td>
<td>$</td>
<td>0.2177</td>
<td>$\pm 0.0004$</td>
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<td>$\Delta m_d$ [ps$^{-1}$]</td>
<td>0.5065</td>
<td>$\pm 0.0019$</td>
<td>id</td>
<td>id</td>
<td>id</td>
<td>[17]</td>
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<tr>
<td>$\Delta m_s$ [ps$^{-1}$]</td>
<td>17.757</td>
<td>$\pm 0.021$</td>
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<td>id</td>
<td>id</td>
<td>[17]</td>
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<tr>
<td>$</td>
<td>V_{cb}</td>
<td>_{SL} \times 10^3$</td>
<td>42.26</td>
<td>$\pm 0.58$</td>
<td>$\pm 0.60$</td>
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<td>$</td>
<td>V_{cb}</td>
<td>_{WB} \times 10^3$</td>
<td>3.56</td>
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<td>$\pm 0.042$</td>
<td>$\pm 0.032$</td>
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<tr>
<td>$</td>
<td>V_{ub}</td>
<td>_{SL} \times 10^3$</td>
<td>0.0842</td>
<td>$\pm 0.0050$</td>
<td>$\pm 0.0025$</td>
<td>$\pm 0.0008$</td>
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<tr>
<td>$B(B \rightarrow \tau \nu) \times 10^4$</td>
<td>0.83</td>
<td>$\pm 0.24$</td>
<td>$\pm 0.04$</td>
<td>$\pm 0.02$</td>
<td>$\pm 0.009$</td>
<td>[29, 34]</td>
</tr>
<tr>
<td>$B(B \rightarrow \mu \nu) \times 10^6$</td>
<td>0.37</td>
<td>...</td>
<td>$\pm 0.03$</td>
<td>$\pm 0.02$</td>
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<td>[29]</td>
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<tr>
<td>$\sin 2\beta$</td>
<td>0.680</td>
<td>$\pm 0.017$</td>
<td>$\pm 0.005$</td>
<td>$\pm 0.002$</td>
<td>$\pm 0.0008$</td>
<td>[29, 30, 34]</td>
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<tr>
<td>$\alpha^{(c)}$ (mod 180$^\circ$)</td>
<td>91.9</td>
<td>$\pm 4.4$</td>
<td>$\pm 0.6$</td>
<td>id</td>
<td>id</td>
<td>[29]</td>
</tr>
<tr>
<td>$\gamma^{(c)}$ (mod 180$^\circ$)</td>
<td>66.7</td>
<td>$\pm 5.6$</td>
<td>$\pm 1$</td>
<td>$\pm 0.25$</td>
<td>$\pm 0.20$</td>
<td>[29, 30, 34]</td>
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<tr>
<td>$\beta_1$ [rad]</td>
<td>$-0.035$</td>
<td>$\pm 0.021$</td>
<td>$\pm 0.014$</td>
<td>$\pm 0.004$</td>
<td>$\pm 0.002$</td>
<td>[30, 34]</td>
</tr>
<tr>
<td>$A_{SL} \times 10^4$</td>
<td>$-6$</td>
<td>$\pm 19$</td>
<td>$\pm 5$</td>
<td>$\pm 2$</td>
<td>$\pm 0.25$</td>
<td>[14, 17, 34, 37]</td>
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<td>$A_{SL} \times 10^5$</td>
<td>3</td>
<td>$\pm 300$</td>
<td>$\pm 70$</td>
<td>$\pm 30$</td>
<td>$\pm 2.5$</td>
<td>[14, 17, 34, 37]</td>
</tr>
<tr>
<td>$\bar{m}_1$ [GeV]</td>
<td>165.30</td>
<td>$\pm 0.32$</td>
<td>id</td>
<td>id</td>
<td>id</td>
<td>$\pm 0.020$</td>
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<tr>
<td>$\alpha_e (m_Z)$</td>
<td>0.1185</td>
<td>$\pm 0.0011$</td>
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<td>id</td>
<td>$\pm 0.00003$</td>
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<td>$f_+^{(c)}(0)$</td>
<td>0.9681</td>
<td>$\pm 0.0026$</td>
<td>$\pm 0.0012$</td>
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<td>id</td>
<td>id</td>
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<tr>
<td>$f_+^{(c)}$ [GeV]</td>
<td>0.1552</td>
<td>$\pm 0.0006$</td>
<td>$\pm 0.0005$</td>
<td>id</td>
<td>id</td>
<td>id</td>
</tr>
<tr>
<td>$f_B^{(c)}$ [GeV]</td>
<td>0.2315</td>
<td>$\pm 0.0020$</td>
<td>$\pm 0.0011$</td>
<td>id</td>
<td>id</td>
<td>id</td>
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<tr>
<td>$B_{Bs}$</td>
<td>1.219</td>
<td>$\pm 0.034$</td>
<td>$\pm 0.010$</td>
<td>$\pm 0.007$</td>
<td>id</td>
<td>id</td>
</tr>
<tr>
<td>$f_{Bs} / f_{B_d}$</td>
<td>1.204</td>
<td>$\pm 0.007$</td>
<td>$\pm 0.005$</td>
<td>id</td>
<td>id</td>
<td>id</td>
</tr>
<tr>
<td>$B_{Bs} / B_{B_d}$</td>
<td>1.054</td>
<td>$\pm 0.019$</td>
<td>$\pm 0.005$</td>
<td>$\pm 0.003$</td>
<td>id</td>
<td>id</td>
</tr>
<tr>
<td>$B_{Bs} / B_{B_d}$</td>
<td>1.02</td>
<td>$\pm 0.05$</td>
<td>$\pm 0.013$</td>
<td>id</td>
<td>id</td>
<td>id</td>
</tr>
<tr>
<td>$B_{Bs}$</td>
<td>0.98</td>
<td>$\pm 0.12$</td>
<td>$\pm 0.035$</td>
<td>id</td>
<td>id</td>
<td>id</td>
</tr>
<tr>
<td>$\eta_B$</td>
<td>0.5522</td>
<td>$\pm 0.0022$</td>
<td>id</td>
<td>id</td>
<td>id</td>
<td>id</td>
</tr>
</tbody>
</table>

**Experimental and theoretical inputs**

- **Caveat**: many experimental sensitivity studies are simplistic or not yet available

- $|V_{ub}|_{SL}$ & $|V_{cb}|_{SL}$: dominance of stat. uncs. (Belle II)
  
  $|V_{cb}|$ accuracy $\sim 0.4\%$ @ FCC-ee: $W \rightarrow bc$  
  [Schune, Monteil]

- **Future accuracy in angles** $(\alpha, \beta, \beta_s, \gamma) \sim< 1^\circ$

- **Phases I and II uncs. for Lattice QCD** (form-factors, bag parameters) $< 1\%$

  Literature discusses Lattice QCD projections up to Phase II
Future improvements

- SM reference: shift the central values
- Compared to Current, improvement by factor $>3$ (5) at Phase I (II)

<table>
<thead>
<tr>
<th>Sensitivities</th>
<th>Summer 2019</th>
<th>Phase I</th>
<th>Phase II</th>
<th>Phase III</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_d$</td>
<td>0.26</td>
<td>0.073</td>
<td>0.049</td>
<td>0.038</td>
</tr>
<tr>
<td>$h_s$</td>
<td>0.12</td>
<td>0.065</td>
<td>0.044</td>
<td>0.031</td>
</tr>
</tbody>
</table>

Phase I
~late 202x: LHCb U. I + Belle II

Phase II
~203x: LHCb U. II + Belle II U.

Phase III
~204x: Phase II + FCC-ee
Future reach to NP in B meson mixing

\[ \frac{C_{ij}^2}{\Lambda^2} (\bar{q}_{i,L} \gamma_{\mu} q_{j,L})^2, \]

\[ h \approx 1.5 \frac{|C_{ij}|^2 (4\pi)^2}{|\lambda'_{ij}|^2 G_F \Lambda^2} \approx \frac{|C_{ij}|^2}{|\lambda'_{ij}|^2} \left( \frac{4.5 \text{ TeV}}{\Lambda} \right)^2, \]

\[ \sigma = \arg(C_{ij} \lambda'^{i*}_{ij}), \]

\[ \text{In the absence of suppression mechanisms: NP scale} \gg \text{TeV} \]

\[ \text{Possible flavour and loop suppressions: alleviate bounds on NP} \]

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<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(</td>
<td>C_{ij}</td>
<td>=</td>
<td>V_{ti} V_{ij}^{*}</td>
<td>)</td>
</tr>
<tr>
<td>( ) (CKM-like)</td>
<td>One loop</td>
<td>0.7</td>
<td>1.3</td>
<td>1.6</td>
</tr>
<tr>
<td>(</td>
<td>C_{ij}</td>
<td>= 1 )</td>
<td>Tree level</td>
<td>( 1 \times 10^3 )</td>
</tr>
<tr>
<td>( ) (No hierarchy)</td>
<td>One loop</td>
<td>80</td>
<td>2 \times 10^2</td>
<td>2 \times 10^2</td>
</tr>
</tbody>
</table>

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Sensitivity to SMEFT operators

- $|\Delta F| = 2$ dim.-6 operators: talk by J. Aebischer

- $(|\Delta F| = 1$ dim.-6$)^2$ => $|\Delta F| = 2$ dim.-8 operators

NP bag parameters: [ETM ’15, FNAL-MILC ’16] [LVS, work in preparation]

~ 6 TeV

~ 3 TeV

~ 50 TeV

NP in $(t\,t)\otimes(\psi\,\xi)$ & $(\psi\,t)\otimes(t\,\xi)$ contact interactions ($\psi, \xi = b, s, d$)

$|\Delta m_d|: |(C_{quqd})^2|$  
$|\Delta m_s|: |(C_{quqd})^2|$  
$|\epsilon_K|: |\text{Im}\{(C_{quqd})^2\}|$
Bottlenecks

Necessary improvements beyond current expectations for enhancing sensitivity to NP:

- **Lattice QCD** (also short-distance QCD corrections)
- $|V_{cb}|$, overall normalization (Wolfenstein parameter $A$)
- Individual impacts on $h_d$ and $h_s$: $O(20-30)\%$

Phase II

$\sim 203x$: LHCb U. II + Belle II U.

Phase II

Lattice QCD uncs. largely reduced

Phase II

LQCD and $|V_{cb}|$ uncs. largely reduced: $\sim 70\%$ effect
Discovery prospects

B meson mixing observables also provide potential discovery for NP

Phase I
~late 202x:
LHCb U. I + Belle II

Phase II
~203x:
LHCb U. II + Belle II U.
Conclusions

- Flavour physics: crucial in shaping the SM, but also in looking for candidates of NP
- $|\Delta B|=2$: only one flavour aspect of future experimental and theoretical progress
- Allowed NP in B meson mixing still large: bounds will largely improve
- Identified future limitations: LQCD and $|V_{cb}|$

Many thanks for your attention!
BACK UP!
Experimental quantities vs. theoretical ones

Observables considered in the fit that are modified by NP in $|\Delta B|=2$:

$$\Delta_q = |\Delta_q| e^{i2\Phi_q^{NP}}$$

<table>
<thead>
<tr>
<th>parameter</th>
<th>prediction in the presence of NP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_q$</td>
<td>$</td>
</tr>
<tr>
<td>$2\beta$</td>
<td>$2\beta^{SM} + \Phi_d^{NP}$</td>
</tr>
<tr>
<td>$2\beta_s$</td>
<td>$2\beta_s^{SM} - \Phi_s^{NP}$</td>
</tr>
<tr>
<td>$2\alpha$</td>
<td>$2(\pi - \beta^{SM} - \gamma) - \Phi_d^{NP}$</td>
</tr>
<tr>
<td>$\Phi_{12,q} = \text{Arg}\left[-\frac{M_{12,q}}{\Gamma_{12,q}}\right]$</td>
<td>$\Phi_{12,q}^{SM} + \Phi_q^{NP}$</td>
</tr>
<tr>
<td>$A_{SL}^q$</td>
<td>$\frac{\Gamma_{12,q}^{SM}}{M_{12,q}^{SM}} \times \frac{\sin(\Phi_{12,q}^{SM} + \Phi_q^{NP})}{</td>
</tr>
<tr>
<td>$\Delta \Gamma_q$</td>
<td>$2</td>
</tr>
</tbody>
</table>
\begin{equation}
\left\langle B_q \mid \mathcal{H}_{\Delta B=2}^{SM+NP} \mid \bar{B}_q \right\rangle \equiv \left\langle B_q \mid \mathcal{H}_{\Delta B=2}^{SM} \mid \bar{B}_q \right\rangle \times (\text{Re}(\Delta_q) + i\text{Im}(\Delta_q))
\end{equation}

\text{Re}(\Delta_q) + i\text{Im}(\Delta_q) = r_q^2 e^{i2\theta_q} = 1 + h_q e^{i\sigma_q}

Soares & Wolfenstein, PRD 47, 1021 (1993)
Deshpande, Dutta & Oh, PRL77, 4499 (1996)
Silva & Wolfenstein, PRD 55, 5331 (1997)
Cohen et al., PRL78, 2300 (1997)
Acknowledgements

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