Decoding Leptonic and Semileptonic $B(c)$ Decays
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Introduction

$B^{-} \rightarrow \ell^{-} \bar{\nu}_{\ell}$ and $\bar{B} \rightarrow \ell^{+} \bar{\nu}_{\ell}$ decays interesting to explore $b \rightarrow u$ transitions:
- Leptons in final state, so interesting to search for NP.
- Leptonic decay is helicity suppressed in the SM, involves decay constant only.
- Semileptonic decays require hadronic form factors (lattice, QCD sum rules).

Available data

Currently available measurements:
- $B(B^{-} \rightarrow \mu^{-} \bar{\nu}_{\mu}) = (6.46 \pm 2.74) \times 10^{-7}$ [First measurement by Belle]
- $B(B^{-} \rightarrow \tau^{-} \bar{\nu}_{\tau}) = (1.09 \pm 0.24) \times 10^{-4}$
- $B(\bar{B} \rightarrow \pi^{-} \bar{\nu}_{\mu}) = (1.45 \pm 0.05) \times 10^{-4}$, $\ell \in (e, \mu)$

and upper bounds:
- $B(\bar{B} \rightarrow e^{-} \bar{\nu}_{e}) < 9.8 \times 10^{-7}$ (90% C.L.)

Scalar New Physics

Look at NP effects using a simple EFT framework

$$H_{\text{NP}} = \frac{4 G_F}{\sqrt{2}} V_{ub} [O'_{u} + C_{F}^{l} O_{S}^{l} + ...]$$

SM operator: $O_{u} = (\bar{u} \gamma^{\mu} b_{\mu}) (\bar{f}_{\nu} \gamma_{\nu} \mu_{a})$

NP contributions: we consider the scalar operator $O_{S} = (\bar{u} b_{\mu}) (\bar{f}_{\nu} \gamma_{\nu} \mu_{a})$ parametrised by the Wilson Coefficient $C_{F}^{l}$.

We get the following NP-enhanced branching ratios:

$$B(B^{-} \rightarrow \ell^{-} \bar{\nu}_{\ell}) = \frac{G_{F}^{2} |V_{ub}|^{2} \tau_{B} M_{B}^{2}}{24 \pi^{2} M_{W}^{2}} \left( 1 - \frac{m_{\ell}^{2}}{M_{B}^{2}} \right) \left[ \frac{s}{m_{\ell} - m_{B}} \right]^{2} \left[ \frac{C_{F}^{l}}{M_{B}^{2}} \right]^{2}$$

and (after introducing $s \equiv \sqrt{q^{2}}$ and $\xi = \frac{M_{B}}{M_{W}}$)

$$\frac{d B}{d s} (\bar{B} \rightarrow \pi^{-} \bar{\nu}_{\ell}) = \frac{G_{F}^{2} |V_{ub}|^{2} \tau_{B}}{24 \pi^{2} M_{W}^{2}} \left( 1 + \frac{1}{2} \xi^{2} \right) M_{B}^{2} \left[ \frac{1}{M_{B}^{2}} \right]^{2} \left( \frac{M_{B}^{2} - M_{W}^{2}}{M_{B}^{2}} \right)^{2} \left[ \frac{C_{F}^{l}}{M_{B}^{2}} \right]^{2}$$

- Helicity suppression is lifted for NP in the leptonic mode.
- Semileptonic mode has more complex structure, not helicity suppressed in SM.

The strategy

Starting point: quantities independent of $|V_{ub}|$, such as the ratios
- $R_{\text{vol}}^{l} = \frac{m_{\ell}^{2}}{m_{B}^{2}} \left( \frac{M_{B}^{2} - m_{\ell}^{2}}{M_{B}^{2} - m_{B}^{2}} \right)^{2} \frac{B(B^{-} \rightarrow \ell^{-} \bar{\nu}_{\ell})}{B(B^{-} \rightarrow \tau^{-} \bar{\nu}_{\ell})}$, where decay constant cancels, too
- $R_{\text{vol}}^{l} = \frac{B(\bar{B} \rightarrow \pi^{-} \bar{\nu}_{\mu})}{B(\bar{B} \rightarrow \pi^{-} \bar{\nu}_{\mu})}$ and $R_{\text{vol}}^{l} = \frac{B(\bar{B} \rightarrow \pi^{-} \bar{\nu}_{\mu})}{B(\bar{B} \rightarrow \pi^{-} \bar{\nu}_{\mu})}$

Unfortunately for $B(\bar{B} \rightarrow \pi^{-} \bar{\nu}_{\mu})$ available only average over electrons and muons.

Hence the following observables are at our disposal:

- $R_{\text{vol}}^{l} R_{\text{vol}}^{l} R_{\text{vol}}^{l}$
- $R_{\text{vol}}^{l} R_{\text{vol}}^{l} R_{\text{vol}}^{l}$

To extract a bound on $C_{F}^{l}$ need assumption on the relation between $C_{F}^{l}$ and $C_{F}^{l}$.

Scanning $C_{F}^{l} - C_{F}^{l}$ parameter space

Simplest assumption: electron-muon universality $C_{F}^{l} = C_{F}^{l}$ and real coefficients $\Rightarrow$

Figure 1: Allowed regions for the Wilson coefficients $C_{F}^{l}$ and $C_{F}^{l}$ by the different observables.

- Measurements give us four solutions, one of them compatible with the SM.
- The $B^{-} \rightarrow e^{-} \bar{\nu}_{e}$ upper bound is excluding two of them with this assumption.

Effects on SM values of $|V_{ub}|$, $B(B^{-} \rightarrow e^{-} \bar{\nu}_{e})$ and $B(\bar{B} \rightarrow \pi^{-} \bar{\nu}_{\mu})$

Figure 2: Flowchart describing the strategy used to give predictions for yet unmeasured branching ratios and to check $|V_{ub}|$ value stability in different models.

Additional considered models:
- Two Higgs Doublet Model (2HDM): $C_{F}^{l} = \frac{m_{\ell}}{m_{B}} C_{F}^{l}$, $C_{F}^{l} = \frac{m_{\ell}}{m_{B}} C_{F}^{l}$
- 3rd generation-only NP: $C_{F}^{l} = C_{F}^{l} = 0$

Figure 3: Compilation of different solutions and comparison with experimental bound.

New sources of CP violation

- Wilson coefficients get complex: $C_{F}^{l} = |C_{F}^{l}| e^{i \phi_{C}}$

Figure 4: Allowed regions on $|C_{F}^{l} | - |C_{F}^{l}|$ quadrant as evolving while increasing $\phi_{C}$ in steps of 20' from 0' to 180', for $\phi_{C} = 0'$ (same assumptions on the coefficients as for Fig. 2).
- Phases have a strong impact.

Conclusions

- We give a new strategy to probe scalar NP coefficients: consistency with SM.
- Specific measurements for different lepton flavours necessary to test models.
- Similar strategy can be applied for $B_{c}$ decays and related $b \rightarrow c$ transitions.