Decoding Leptonic and Semileptonic $B_{(c)}$ Decays

Giovanni Banelli[1], Robert Fleischer[1,2], Ruben Jaarsma[1] and Gilberto Tetlalmatzi-Xolocotzi[1]

[1]Nikhef, Amsterdam, Netherlands
[2]Department of Physics and Astronomy, Vrije Universiteit Amsterdam, Netherlands

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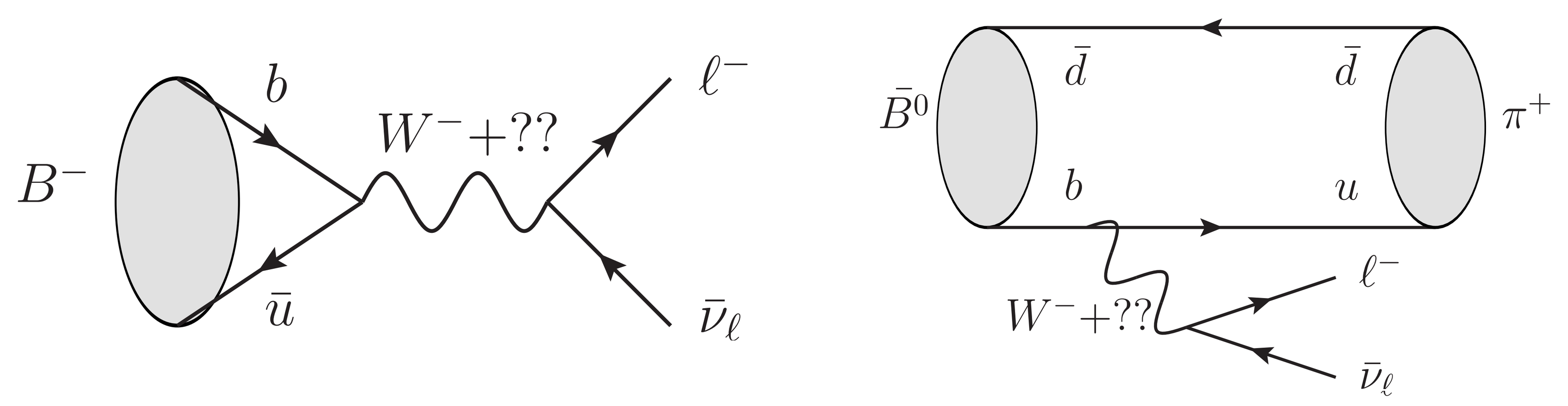
Introduction

$B^- \to \ell^- \bar{\nu}_\ell$ and $\bar{B} \to \pi \ell^- \bar{\nu}_\ell$ decays interesting to explore $b \to u$ 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:

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

and upper bounds:

- $\mathcal{B}(B^- \to e^- \bar{\nu}_e) < 9.8 \times 10^{-7}$ (90% C.L.)

Scalar New Physics

Look at NP effects using a simple EFT framework

$$\mathcal{H}_{\rm eff} = \frac{4G_{\rm F}}{\sqrt{2}} V_{ub} \left[\mathcal{O}_V^\ell + C_S^\ell \mathcal{O}_S^\ell + \ldots\right]$$

- SM operator: $\mathcal{O}_V = (\bar{u}_L \gamma^\mu b_L)(\bar{\tau}_R \gamma_\mu \nu_{\ell L})$
- NP contributions: we consider the scalar operator $\mathcal{O}_S = (\bar{u}_L b_R)(\bar{\ell}_R \nu_{\tau L})$ parametrised by the Wilson Coefficient C_S^ℓ.

We get the following NP-enhanced branching ratios:

$$\mathcal{B}(B^- \to \ell^- \bar{\nu}_\ell) = \frac{G_{\rm F}^2}{8\pi} |V_{ub}|^2 f_{B^-}^2 \tau_{B^-} M_{B^-}^3 \left(1 - \frac{m_\ell^2}{M_{B^-}^2}\right)$$
$$\times \left[\left(\frac{m_\ell}{M_{B^-}}\right)^2 + 2\frac{m_\ell}{M_{B^-}} \frac{M_{B^-}}{m_b + m_u} \Re(C_S^\ell) + \frac{M_{B^-}^2}{(m_b + m_u)^2} |C_S^\ell|^2\right]$$

and (after introducing $s \equiv \sqrt{q^2}$ and $\xi_\ell \equiv \frac{m_\ell}{s}$)

$$\frac{d\mathcal{B}}{ds^2}(\bar{B} \to \pi \ell^- \bar{\nu}_\ell) = \frac{G_F^2 |V_{ub}|^2 \tau_B}{24\pi^3 M_B^2} \left\{ \left(1 + \frac{1}{2}\xi_\ell^2\right) M_B^2 |\vec{p}_\pi|^2 |f_+(s^2)|^2 + \frac{3}{8}(M_B^2 - M_\pi^2)^2 \right.$$
$$\left. \times \left[\xi_\ell^2 + 2\xi_\ell \left(\frac{s}{m_b - m_u}\right) \Re(C_S^\ell) + \left(\frac{s}{m_b - m_u}\right)^2 |C_S^\ell|^2\right] |f_0(s^2)|^2 \right\} \left(1 - \xi_\ell^2\right)^2 |\vec{p}_\pi|$$

- 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

- $R_{\ell_2;u}^{\ell_1} \equiv \frac{m_{\ell_2}^2}{m_{\ell_1}^2} \left(\frac{M_{B^-}^2 - m_{\ell_2}^2}{M_{B^-}^2 - m_{\ell_1}^2}\right)^2 \frac{\mathcal{B}(B^- \to \ell_1^- \bar{\nu}_{\ell_1})}{\mathcal{B}(B^- \to \ell_2^- \bar{\nu}_{\ell_2})}$, where decay constant cancels, too
- $\mathcal{R}_{\ell_2;\pi}^{\ell_1} \equiv \frac{\mathcal{B}(B^- \to \ell_1^- \bar{\nu}_{\ell_1})}{\mathcal{B}(\bar{B} \to \pi \ell_2^- \bar{\nu}_{\ell_2})}$ and $\mathcal{R}_{\ell_2;\pi}^{\ell_1;\pi} \equiv \frac{\mathcal{B}(\bar{B} \to \pi \ell_1^- \bar{\nu}_{\ell_1})}{\mathcal{B}(\bar{B} \to \pi \ell_2^- \bar{\nu}_{\ell_2})}$

Unfortunately for $\mathcal{B}(\bar{B} \to \pi \ell^- \bar{\nu}_\ell)$ **available only average** over electrons and muons.

Hence the following observables are at our disposal:

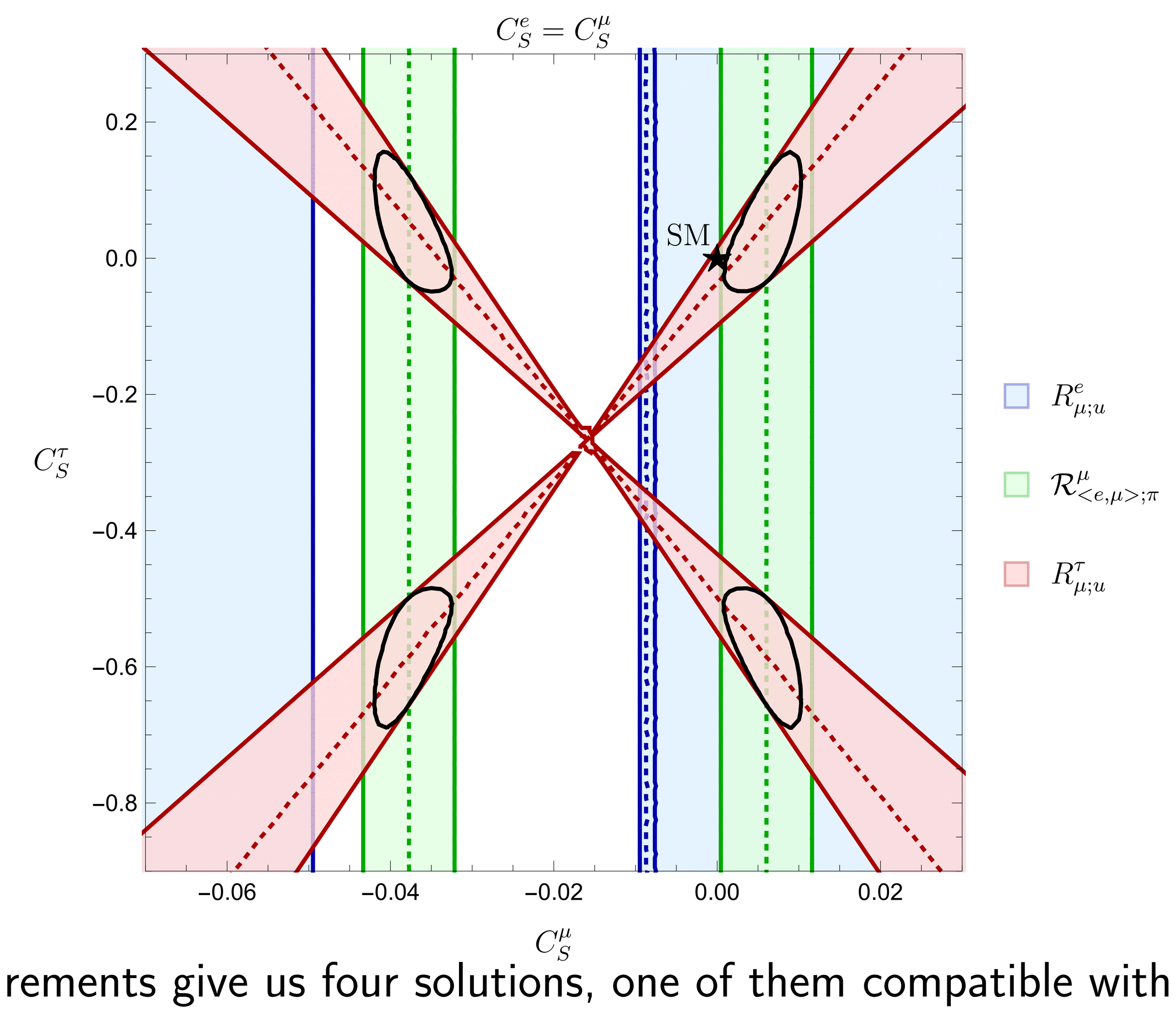
$$R_{\mu;u}^{\tau} \quad R_{\mu;u}^{e} \quad \mathcal{R}_{\langle e,\mu\rangle;\pi}^{\mu}$$

- To extract a bound on C_S^μ need **assumption on the relation between** C_S^e **and** C_S^μ.

Scanning $C_S^\mu - C_S^\tau$ parameter space

Simplest assumption: electron-muon universality $C_S^e = C_S^\mu$ and real coefficients $\Rightarrow$

Figure 1: Allowed regions for the Wilson coefficients C_S^μ and C_S^τ by the different observables.



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

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

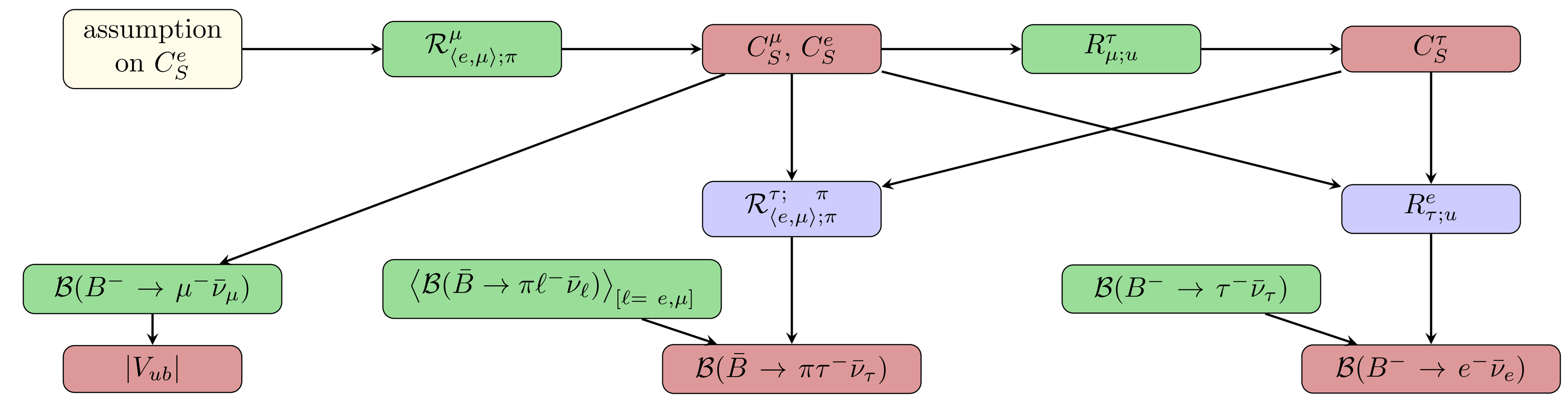


Figure 2: Flowchart describing the strategy used to give predictions for yet unmeasured branching ratios and to check $|V_{ub}|$ value stability in different models.

Additional considered models:

- Two Higgs Doublet Model (2HDM): $C_S^e = \frac{m_e}{m_\mu} C_S^\mu$, $\quad C_S^\tau = \frac{m_\tau}{m_\mu} C_S^\mu$
- 3rd generation-only NP: $C_S^e = C_S^\mu = 0$

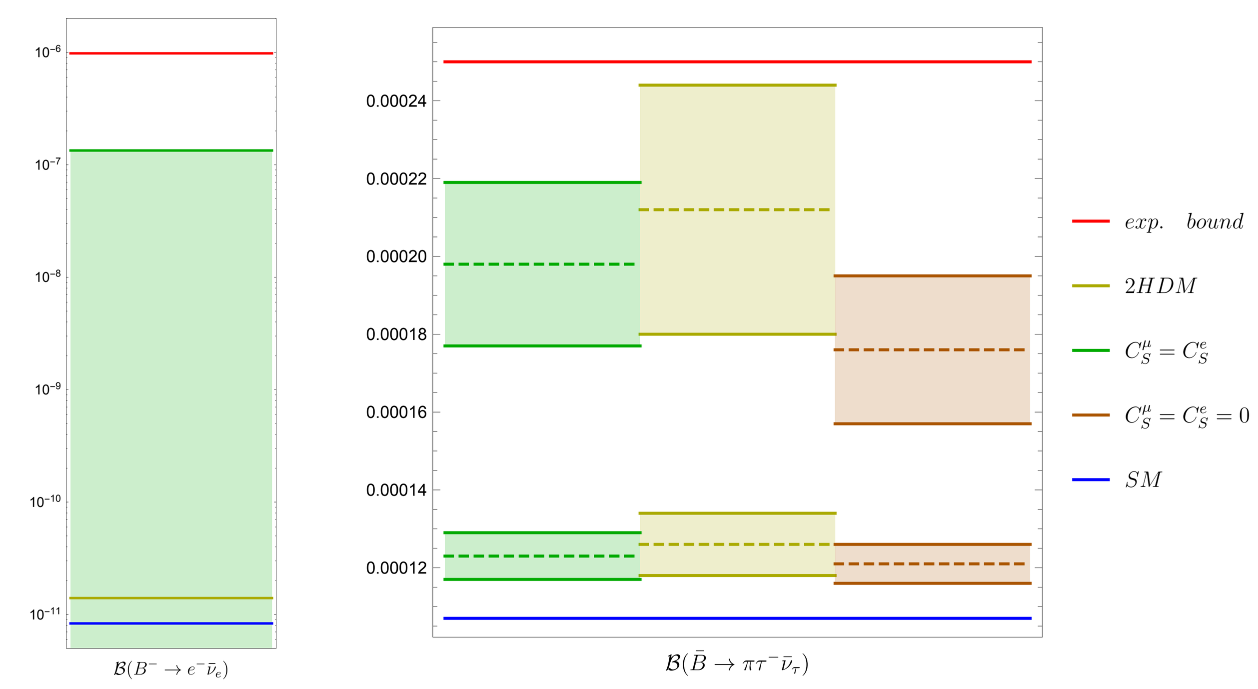


Figure 3: Compilation of different solutions and comparison with experimental bound.

New sources of CP violation

- Wilson coefficients get complex: $C_S^\ell = |C_S^\ell| e^{i\phi_S^\ell}$

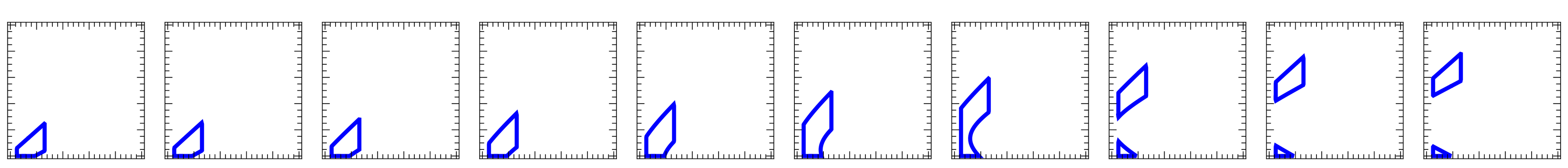


Figure 4: Allowed regions on $|C_S^\mu| - |C_S^\tau|$ quadrant as evolving while increasing ϕ_S^τ in steps of 20° from 0° to 180°, for $\phi_S^\mu = 0°$ (same assumptions on the coefficients as for Fig.??).

- 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 $b \to c$ transitions.