Probing LNU with (semi)leptonic B decays

Gilberto Tetlalmatzi

Nikhef Theory Division

The 15th International Workshop on Tau Lepton Physics

September 25, 2018

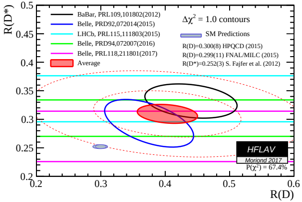
NP in Semileptonic B decays

$B \to D^{(*)}\ell\bar{\nu}_\ell$: $b \to c\ell\bar{\nu}_\ell$

There observable

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(B \to D^{(*)}\ell'\bar{\nu}_\ell)}, \quad \text{with} \qquad \ell' = e, \mu$$

has caused a lot of excitement.



BABAR + LHCb + Belle combination show a 3.9 σ deviation with respect to the SM.

Amhis et al. (2016), arXiv:1612.07233 [hep-ex]

What about potential NP in the $b \to u\ell\bar{\nu}_\ell$ transitions?

$$\begin{array}{lcl} B \to \pi\ell\bar{\nu}_\ell & \text{counterpart of} & B \to D\ell\bar{\nu}_\ell \\ B \to \rho\ell\bar{\nu}_\ell & \text{counterpart of} & B \to D^{*}\ell\bar{\nu}_\ell \end{array}$$

$$\ell = e, \mu, \tau$$

Recent study in: arXiv:1809.09051
developed in collaboration with Robert Fleischer, Ruben Jaarsma and Giovanni Banelli.

Investigating NP in $b \to u\ell\bar{\nu}_\ell$

To constrain NP in $b \to u\ell\bar{\nu}_\ell$ decays consider:

- Leptonic processes:

$$B^- \to \ell^- \bar{\nu}_\ell.$$

- Semileptonic processes:

$$B^- \to \rho^0 \ell^- \bar{\nu}_\ell, \qquad \bar{B}^0 \to \rho^+ \ell^- \bar{\nu}_\ell,$$
$$B^- \to \pi^0 \ell^- \bar{\nu}_\ell, \qquad \bar{B}^0 \to \pi^+ \ell^- \bar{\nu}_\ell.$$

Effective theory description

$$\mathcal{H}_{\rm eff} = \frac{4G_{\rm F}}{\sqrt{2}} V_{qb} \left[C_{V_L} \mathcal{O}^\ell_{V_L} + C^\ell_S \mathcal{O}^\ell_S + C^\ell_P \mathcal{O}^\ell_P \right] + h.c.$$

$$\mathcal{O}^\ell_{V_L} = (\bar{q}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu P_L \nu_\ell) \qquad \mathcal{O}^\ell_S = (\bar{q}b)(\bar{\ell}P_L\nu_\ell), \qquad \mathcal{O}^\ell_P = (\bar{q}\gamma_5 b)(\bar{\ell}P_L\nu_\ell).$$

In the SM: $C_{V_L} = 1,\ C_S = 0$ and $C_P = 0$.

The strongest NP constraints are derived from <u>(Pseudo)-Scalar</u> interactions.

Investigating NP in $b \to u\ell\bar{\nu}_\ell$

To constrain NP in $b \to u\ell\bar{\nu}_\ell$ decays consider:

- Leptonic processes:

$$B^- \to \ell^- \bar{\nu}_\ell .$$

- Semileptonic processes:

$$B^- \to \rho^0 \ell^- \bar{\nu}_\ell , \qquad \bar{B}^0 \to \rho^+ \ell^- \bar{\nu}_\ell ,$$
$$B^- \to \pi^0 \ell^- \bar{\nu}_\ell , \qquad \bar{B}^0 \to \pi^+ \ell^- \bar{\nu}_\ell .$$

Effective theory description

$$\mathcal{H}_{\rm eff} = \frac{4 G_{\rm F}}{\sqrt{2}} V_{qb} \left[C_{V_L} \mathcal{O}^\ell_{V_L} + C^\ell_S \mathcal{O}^\ell_S + C^\ell_P \mathcal{O}^\ell_P \right] + h.c.$$

$$\mathcal{O}^\ell_{V_L} = (\bar{q}\gamma^\mu P_L b)(\bar{\ell}\gamma_\mu P_L \nu_\ell) \qquad \mathcal{O}^\ell_S = (\bar{q}b)(\bar{\ell}P_L\nu_\ell), \qquad \mathcal{O}^\ell_P = (\bar{q}\gamma_5 b)(\bar{\ell}P_L\nu_\ell).$$

In the SM: $C_{V_L} = 1$, $C_S = 0$ and $C_P = 0$.

The strongest NP constraints are derived from (Pseudo)-Scalar interactions.

Currently $|V_{ub}|$ is extracted using branching fractions of $B \to \pi\ell\bar{\nu}_\ell$ processes.

Is this correct if these processes are affected by NP?

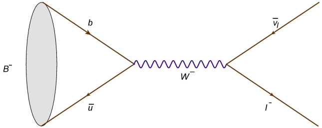
To avoid potential issues determine NP in the Wilson coefficients

in a $|V_{ub}|$ independent way using ratios of branching fractions.

Leptonic $B^- \to \ell\nu_\ell$ decays

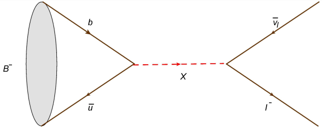
In the SM The branching ratio for B^- is given by

$$\mathcal{B}(B^- \to \ell^- \bar{\nu}_\ell)|_{\rm SM} = \frac{G_{\rm F}^2}{8\pi}|V_{ub}|^2 M_{B^-} m_\ell^2 \left(1 - \frac{m_\ell^2}{M_{B^-}^2}\right)^2 f_{B^-}^2 \tau_{B^-}.$$



In the presence of a NP pseudoscalar particle the branching ratio is modified according to

$$\mathcal{B}(B^- \to \ell^- \bar{\nu}_\ell) = \mathcal{B}(B^- \to \ell^- \bar{\nu}_\ell)|_{\rm SM} \left|1 + \frac{M_{B^-}^2}{m_\ell(m_b + m_u)} C_P^\ell\right|^2.$$



Example: In the THDM C_P^ℓ is given by: $C_P^\ell = -\tan^2\beta\left(\frac{m_b m_l}{M_{H^\pm}^2}\right)$

Leptonic $B^- \to \ell\nu_\ell$ decays

We evaluate the NP contributions considering ratios of branching fractions

For the leptonic study we use the ratio

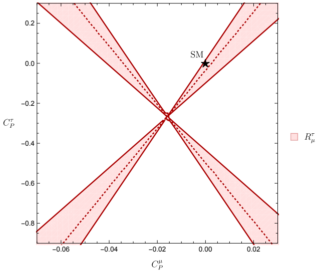
$$R^{\ell_1}_{\ell_2} \equiv \frac{m^2_{\ell_2}}{m^2_{\ell_1}} \left(\frac{M^2_{B^-} - m^2_{\ell_2}}{M^2_{B^-} - m^2_{\ell_1}} \right)^2 \frac{\mathcal{B}(B^- \to \ell_1^- \bar{\nu}_{\ell_1})}{\mathcal{B}(B^- \to \ell_2^- \bar{\nu}_{\ell_2})} = \left| \frac{1 + \mathcal{C}_{\ell_1;P}}{1 + \mathcal{C}_{\ell_2;P}} \right|^2 .$$

$$\mathcal{C}_{\ell;P} \equiv |\mathcal{C}_{\ell;P}| e^{i\phi_\ell} = \left[\frac{M^2_{B^-}}{m_\ell(m_b + m_q)} \right] C^\ell_P .$$

Key features of $R^{\ell_1}_{\ell_2}$ are:

- It does not depend on $|V_{ub}|$.
- It is theoretically clean because the decay constants cancel.
- In the SM: $R^{\ell_1}_{\ell_2}|_{\mathrm{SM}} = 1$.

Leptonic $B^- \to \ell\nu_\ell$ decays



From PDG 2018:

$$\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau)\Big|_{\mathrm{Exp}} = (1.09 \pm 0.24) \times 10^{-4}.$$

First measurement by Belle: $2.4\,\sigma$ excess over background:

$$\mathcal{B}(B^- \to \mu^- \bar{\nu}_\mu)\Big|_{\mathrm{Exp}} = (6.46 \pm 2.74) \times 10^{-7}.$$

$$R_\mu^\tau\Big|_{\mathrm{Exp}} = 0.76 \pm 0.36.$$

Belle Collaboration, Phys. Rev. Lett. 121, 031801 (2018), arXiv:1712.04123 [hep-ex]

Rather unconstrained regions $\Rightarrow$ Obtain stronger bounds using semileptonic B decays

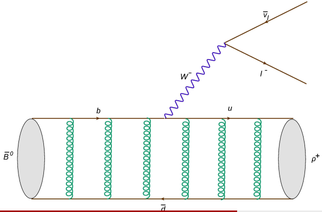
Semileptonic $\bar{B} \to \rho \ell^- \bar{\nu}_\ell$ decays

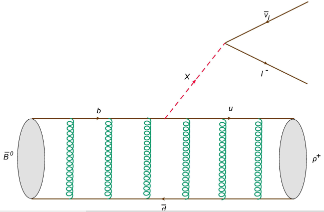
The process $\bar{B} \to \rho \ell^- \bar{\nu}_\ell$ is also sensitive to the presence of NP pseudoscalar particles

$$\frac{d\mathcal{B}(\bar{B} \to \rho \ell^- \bar{\nu}_\ell)}{dq^2} = \frac{G_F^2 \tau_B |V_{ub}|^2}{24\pi^3 m_B^2} \left\{ \left[\frac{1}{4}\left(1 + \frac{m_\ell^2}{2q^2}\right)\left(H_{V,+}^{\rho\ 2} + H_{V,-}^{\rho\ 2} + H_{V,0}^{\rho\ 2}\right) + \frac{3}{8}\frac{m_\ell^2}{q^2} H_{V,t}^{\rho\ 2} \right] \right.$$

$$\left. + \frac{3}{8}|C_P^\ell|^2 H_S^{\rho\ 2} + \frac{3}{4}\Re\left[C_P^{\ell *}\right] \frac{m_\ell}{\sqrt{q^2}} H_S^\rho H_{V,t}^\rho \right\} \frac{(q^2 - m_\ell^2)^2}{q^2} |\vec{p}_\rho|.$$

$$m_\ell^2 \le q^2 \le (M_B - M_\rho)^2 \qquad |\vec{p}_\rho| = \frac{\sqrt{\left[(M_B - M_\rho)^2 - q^2\right]\left[(M_B + M_\rho)^2 - q^2\right]}}{2M_B}.$$





Semileptonic $\bar{B} \to \rho \ell^- \bar{\nu}_\ell$ decays

- Semileptonic B decays are less clean than the leptonic B decays.
- The nonperturbative contributions are accounted for by the form factors:

$$H^{\rho}_{V,\pm},\ H^{\rho}_{V,0},\ H^{\rho}_{V,t} \text{ and } H^{\rho}_{S}.$$

Two approaches for the determination of the form factors depending on the value of q^2:

1. QCD Sum Rules, for the low q^2 regime:

$$0 \leq q^2 \leq q^2_{max}.$$

   Where typically $q^2_{\mathrm{max}} \in [12, 16]\mathrm{GeV}^2$.

2. Lattice QCD calculations, for q^2 close to the maximal leptonic momentum transfer:

$$q^2_{max} \leq q^2 \leq (M_{B^0} - M_\rho)^2.$$

Semileptonic $\bar{B} \to \rho \ell^- \bar{\nu}_\ell$ decays

The experimental results provided by Belle include contributions from e and μ leptons:

Belle Collaboration, Phys. Rev. D 88 (2013) 032005, arXiv:1306.2781 [hep-ex].

No independent determinations for e and μ for semileptonic decays.

$$\left\langle \mathcal{B}(\bar{B}^0 \to \rho^+ \ell^- \bar{\nu}_\ell) \right\rangle_{[\ell = e,\mu],\ q^2 \leq 12\ \mathrm{GeV}^2} \Bigg|_{\mathrm{Exp}} = (1.90 \pm 0.20) \times 10^{-4},$$

$$2 \left\langle \mathcal{B}(B^- \to \rho^0 \ell^- \bar{\nu}_\ell) \right\rangle_{[\ell = e,\mu],\ q^2 \leq 12\ \mathrm{GeV}^2} \Bigg|_{\mathrm{Exp}} = (2.03 \pm 0.16) \times 10^{-4}.$$

These results can be combined using isospin symmetry to obtain

$$\left\langle \mathcal{B}(\bar{B} \to \rho \ell^- \bar{\nu}_\ell) \right\rangle_{[\ell = e,\mu],\ q^2 \leq 12\ \mathrm{GeV}^2} \Bigg|_{\mathrm{Exp}} = (1.98 \pm 0.12) \times 10^{-4}.$$

Semileptonic $\bar{B} \to \rho \ell^- \bar{\nu}_\ell$ decays

We introduce the $|V_{ub}|$ independent ratio

$$\mathcal{R}^{\mu}_{\langle e,\mu\rangle;\rho\ [q^2\leq 12]\ \mathrm{GeV}^2} \equiv \mathcal{B}(B^- \to \mu^- \bar{\nu}) / \left\langle \mathcal{B}(\bar{B} \to \rho \ell^- \bar{\nu}_\ell) \right\rangle_{[\ell=\ e,\mu],\ q^2\leq 12\ \mathrm{GeV}^2} .$$

$$\mathcal{R}^{\mu}_{\langle e,\mu\rangle;\rho\ [q^2\leq 12]\ \mathrm{GeV}^2}\Big|_{\mathrm{Exp}} = (3.3 \pm 1.4) \times 10^{-3}.$$

$$\mathcal{R}^{\mu}_{\langle e,\mu\rangle;\rho\ [q^2\leq 12]\ \mathrm{GeV}^2}\Big|_{\mathrm{SM}} = (1.52 \pm 0.29) \times 10^{-3}.$$

Independent measurements for the semileptonic ratios of electrons and muons are crucial to probe for Universality violations in light leptons

To test for NP we consider different correlations between C_P^e and C_P^μ.

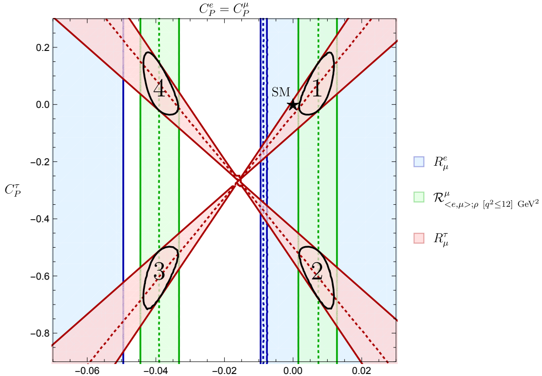
Semileptonic $\bar{B} \to \rho \ell^- \bar{\nu}_\ell$ decays

We have three independent Wilson coefficients: C_P^e, C_P^μ and C_P^τ

Assuming $C_P^e = C_P^\mu$ we can constraint C_P^μ and C_P^τ using

$$R_\mu^e \propto \frac{\mathcal{B}(B^- \to e^- \bar{\nu}_{\ell_1})}{\mathcal{B}(B^- \to \mu^- \bar{\nu}_{\ell_2})} \qquad R_\mu^\tau \propto \frac{\mathcal{B}(B^- \to \tau^- \bar{\nu}_{\ell_1})}{\mathcal{B}(B^- \to \mu^- \bar{\nu}_{\ell_2})}$$

$$\mathcal{R}^\mu_{\langle e,\mu\rangle;\rho\ [q^2 \leq 12]\ \mathrm{GeV}^2} = \mathcal{B}(B^- \to \mu^- \bar{\nu}) / \left\langle \mathcal{B}(\bar{B} \to \rho \ell^- \bar{\nu}_\ell) \right\rangle_{[\ell = e,\mu],\ q^2 \leq 12\ \mathrm{GeV}^2}$$



Semileptonic $\bar{B} \to \pi \ell^- \bar{\nu}_\ell$ decays

So far we have only constrained the pseudoscalar coefficient C_P^ℓ

The transition $\bar{B} \to \pi \ell^- \bar{\nu}_\ell$ gives us sensitivity to scalar NP interactions

$$\frac{d\mathcal{B}(\bar{B} \to \pi \ell^- \bar{\nu}_\ell)}{dq^2} = \frac{G_F^2 \tau_B |V_{ub}|^2}{24\pi^3 M_B^2} \left\{ \left[\left(1 + \frac{m_\ell^2}{2q^2}\right) \frac{H_{V,0}^{\pi\ 2}}{4} + \frac{3}{8} \frac{m_\ell^2}{q^2} H_{V,t}^{\pi\ 2} \right] + \frac{3}{8} |C_S^\ell|^2 H_S^{\pi\ 2} + \frac{3}{4} \Re\left[C_S^{\ell\ *} \right] \frac{m_\ell}{\sqrt{q^2}} H_S^\pi H_{V,t}^\pi \right\} \frac{(q^2 - m_\ell^2)^2}{q^2} |\vec{p}_\pi|.$$

$$m_\ell^2 \leq q^2 \leq (M_B - M_\pi)^2 \qquad |\vec{p}_\pi| = \frac{\sqrt{\left[(M_B - M_\pi)^2 - q^2\right]\left[(M_B + M_\pi)^2 - q^2\right]}}{2M_B}.$$

Combining the experimental information provided in the PDG we obtain

$$\left\langle \mathcal{B}(\bar{B} \to \pi \ell^- \bar{\nu}_\ell) \right\rangle_{[\ell = e,\mu]} \Big|_{\mathrm{Exp}} = (1.53 \pm 0.04) \times 10^{-4}.$$

Combining leptonic and semileptonic information

$$\mathcal{B}(B^- \to \ell^- \bar{\nu}_\ell), \quad \mathcal{B}(\bar{B} \to \rho \ell^- \bar{\nu}_\ell) \quad : \quad C_P^\ell$$
$$\mathcal{B}(\bar{B} \to \pi \ell^- \bar{\nu}_\ell) \quad : \quad C_S^\ell$$

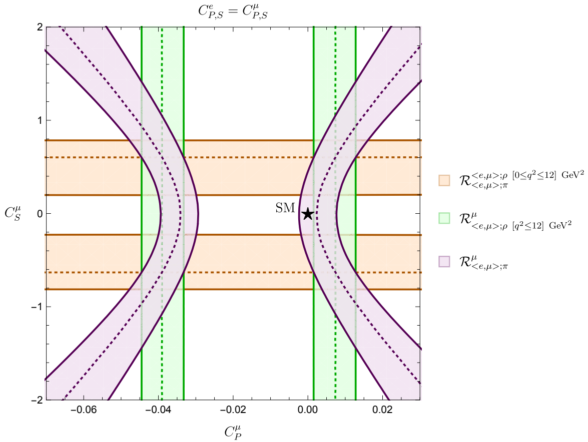
We consider the following ratios

$$\begin{aligned}
\mathcal{R}^{\mu}_{\langle e,\mu\rangle;\pi} &= \mathcal{B}(B^- \to \mu^- \bar{\nu}) / \left\langle \mathcal{B}(\bar{B} \to \pi \ell^- \bar{\nu}_\ell) \right\rangle , \\
\mathcal{R}^{\mu}_{\langle e,\mu\rangle;\rho\ [q^2 \leq 12]\ \mathrm{GeV}^2} &= \mathcal{B}(B^- \to \mu^- \bar{\nu}) / \left\langle \mathcal{B}(\bar{B} \to \rho \ell^- \bar{\nu}_\ell) \right\rangle_{[\ell = \ e,\mu],\ q^2 \leq 12\ \mathrm{GeV}^2} . \\
\mathcal{R}^{\langle e,\mu\rangle;\rho\ [0 \leq q^2 \leq 12]\ \mathrm{GeV}^2}_{\langle e,\mu\rangle;\pi} &= \left\langle \mathcal{B}(\bar{B} \to \rho \ell^- \bar{\nu}_\ell) \right\rangle_{[\ell = e,\mu]} \Big|_0^{12\ \mathrm{GeV}^2} / \left\langle \mathcal{B}(\bar{B} \to \pi \ell^- \bar{\nu}_\ell) \right\rangle_{[\ell = e,\mu]}
\end{aligned}$$

Under the assumptions $C_P^e = C_P^\mu$ and $C_S^e = C_S^\mu$

we can derive stronger constraints on these Wilson coefficients.

Combining leptonic and semileptonic constraints



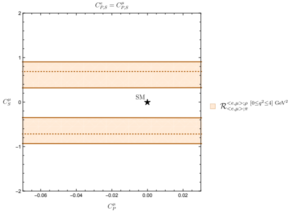
The SM point is excluded at the level of $(1-2)\ \sigma$.

The source of tension is $\mathcal{R}^{\langle e,\mu\rangle;\rho\ [0\leq q^2\leq 12]\ \mathrm{GeV}^2}_{\langle e,\mu\rangle;\pi}$.

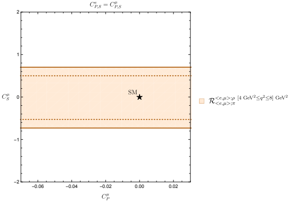
Combining leptonic and semileptonic constraints

Perform a bin by bin analysis for the contributions of $\mathcal{R}^{\langle e,\mu\rangle;\rho}_{\langle e,\mu\rangle;\pi}$

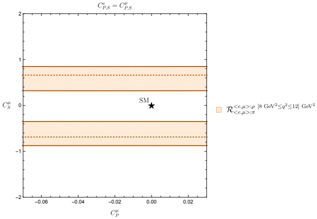
$0 \leq q^2 \leq 4\ \mathrm{GeV}^2$



$4\ \mathrm{GeV}^2 \leq \mathrm{q}^2 \leq 8\ \mathrm{GeV}^2$



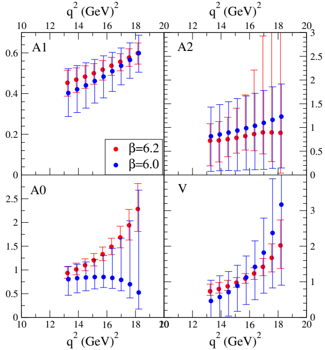
$8\ \mathrm{GeV}^2 \leq \mathrm{q}^2 \leq 12\ \mathrm{GeV}^2$



Combining leptonic and semileptonic information

Study the high q^2 regime

$$12.7\ \mathrm{GeV}^2 \leq q^2 \leq 18.2\ \mathrm{GeV}^2$$



K. C. Bowler et al. [UKQCD Collaboration], JHEP 0405 (2004) 035, arXiv:0402023[hep-lat]

These results are 14 years old. Large uncertainties.

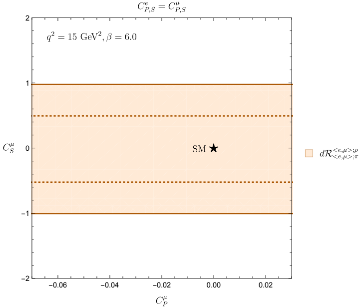
An update is required.!!

Combining leptonic and semileptonic information

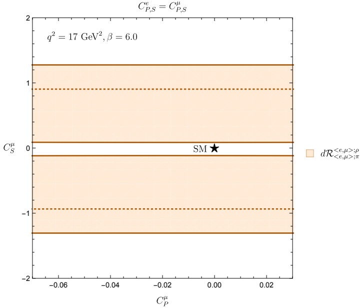
For the high q^2 study we consider the observable:

$$d\mathcal{R}^{\langle e,\mu\rangle;\rho}_{\langle e,\mu\rangle;\pi} = \frac{2\left\langle d\mathcal{B}(B^- \to \rho^0 \ell^- \bar{\nu}_\ell)/dq^2 \right\rangle_{[\ell=e,\mu]}}{\left\langle \mathcal{B}(\bar{B} \to \pi \ell^- \bar{\nu}_\ell) \right\rangle_{[\ell=e,\mu]}}.$$

$q^2 = 15\ \mathrm{GeV}^2$



$q^2 = 17\ \mathrm{GeV}^2$



Determination of $|V_{ub}|$ and predictions

We propose the following method to extract $|V_{ub}|$

- With the ratios of leptonic and semileptonic branching fractions perform a $|V_{ub}|$-independent extraction of C_P^ℓ
- Substitute C_P^ℓ in any of the leptonic or semileptonic branching ratios available, i.e. $\mathcal{B}(B^- \to \mu^- \bar{\nu}_\mu)$ or $\mathcal{B}(\bar{B} \to \rho \ell^- \bar{\nu}_\ell)$, and then solve for $|V_{ub}|$

We can also make predictions for the not-yet measured:

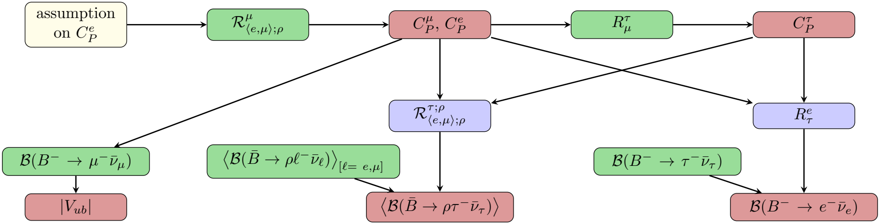
$$\mathcal{B}(B^- \to e^- \bar{\nu}_e), \quad \mathcal{B}(\bar{B} \to \rho \tau^- \bar{\nu}_\tau)$$

In the case of $B^- \to e^- \bar{\nu}_e$ the following bound is available

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

Belle Collaboration, Phys. Lett. B 647 (2007) 67, [hep-ex/0611045]

Determination of $|V_{ub}|$ and predictions

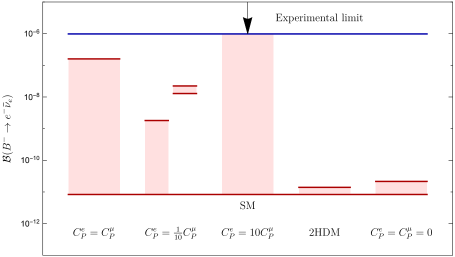


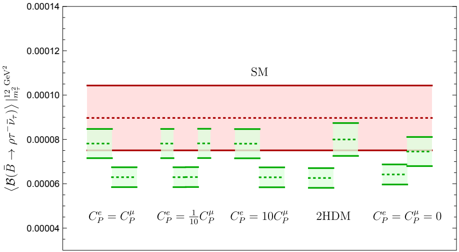
Determination of $|V_{ub}|$ and predictions

We consider the following scenarios:

1. $C_P^e \ll C_P^\mu$; in particular
$$C_P^e = (1/10)C_P^\mu.$$
2. $C_P^\mu \ll C_P^e$; we focus on
$$C_P^e = 10C_P^\mu.$$
3. The 2HDM,
$$C_P^e = \frac{m_e}{m_\mu}C_P^\mu, \qquad C_P^\tau = \frac{m_\tau}{m_\mu}C_P^\mu.$$
4. NP entering only through the 3rd generation:
$$C_P^\tau \neq 0, \qquad C_P^e = C_P^\mu = 0.$$

Determination of $|V_{ub}|$ and predictions





For the analogous effect in $B \to e^+ e^-$ see

R. Fleischer, R. Jaarsma and G. Tetlalmatzi-Xolocotzi, JHEP 1705 (2017) 156, arXiv:1703.10160 [hep-ph].

For all the scenarios: $|V_{ub}| = (3.31 \pm 0.32) \times 10^{-3}$.

The only exception is the 4th scenario where NP enters exclusively in the 3rd generation:

$$|V_{ub}| = (4.85 \pm 1.03) \times 10^{-3}$$

Relatively high as for the Inclusive determination.

Conclusions and Outlook

- Leptonic and semileptonic decays triggered by the $b \to u$ transitions are very intersting channels unveil NP.
- They are particularly sensitive to (pseudo)-scalar contributions.
- To avoid the usage of $|V_{ub}|$ the NP analysis should be done using ratios of leptonic and semileptonic branching fractions.
- To have a better assessment of potential NP effects independent determinations of $\left\langle \mathcal{B}(\bar{B} \to \pi \ell^- \bar{\nu}_\ell) \right\rangle$ and $\left\langle \mathcal{B}(\bar{B} \to \rho \ell^- \bar{\nu}_\ell) \right\rangle$ for electrons and muons are required.
- Tension with the SM for ratios including the branching fraction of $\bar{B} \to \rho \ell^- \bar{\nu}_\ell$ appears at low and high q^2.
- Improvements in the determination of the form factors for $\mathcal{B}(\bar{B} \to \rho \ell^- \bar{\nu}_\ell)$ are necessary.

THANKS!! :)