Probing New Physics with Leptonic Rare B Decays

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Setting the Stage

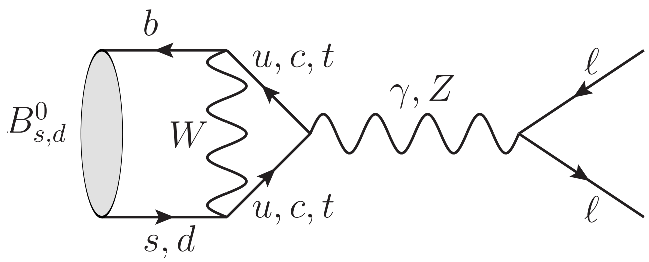
- Neutral leptonic rare decays: $B^0_{s,d} \to \ell^+\ell^-$
  - R.F., Ruben Jaarsma and Gilberto Tetlalmatzi-Xolocotzi:
    In Pursuit of New Physics with $B^0_{s,d} \to \ell^+\ell^-$
    JHEP **1705** (2017) 156 [arXiv:1703.10160 [hep-ph]].
  - R.F., Daniela Galárraga Espinosa, R. Jaarsma and G. Tetlalmatzi-Xolocotzi:
    CP Violation in Leptonic Rare B^0_s Decays as a Probe of New Physics
    Eur. Phys. J. C **78** (2018) 1 [arXiv:1709.04735 [hep-ph]].

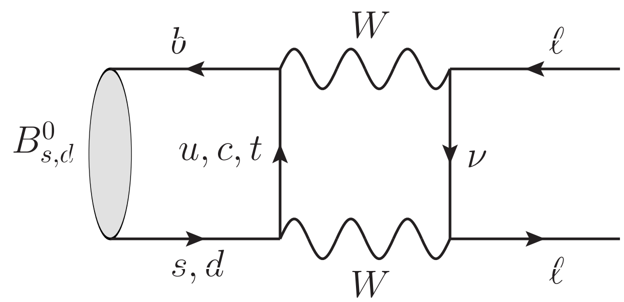
- Charged leptonic decays: $B^- \to \ell^-\bar{\nu}_\ell$
  - G. Banelli, R.F., R. Jaarsma and G. Tetlalmatzi-Xolocotzi:
    Decoding (Pseudo)-Scalar Operators in Leptonic and Semileptonic B Decays
    Eur. Phys. J. C **78** (2018) 911 [arXiv:1809.09051 [hep-ph]]

    Probing Lepton Universality with (Semi)-Leptonic B decays
    SciPost Phys. Proc. **1** (2019) 013 [arXiv:1812.05200 [hep-ph]].

General Features of $B^0_{s,d} \to \ell^+\ell^-$ Decays

- Situation in the Standard Model (SM): $\to$ only loop contributions:





  – Moreover: helicity suppression $\to$ branching ratio $\propto m_\ell^2$

$$\Rightarrow \boxed{\text{strongly suppressed decays}}$$

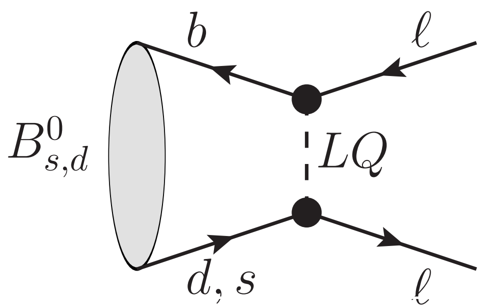
- Hadronic sector: $\to$ very simple, only the B_q decay constant F_{B_q} enters:

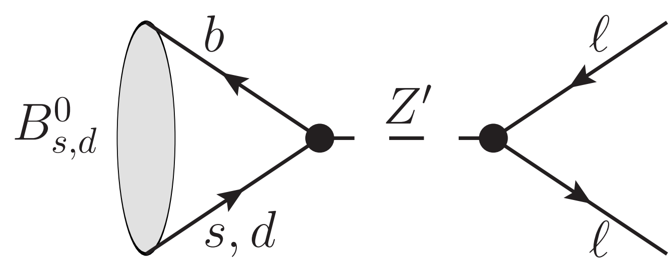
$$\langle 0|\bar{b}\gamma_5\gamma_\mu q|B^0_q(p)\rangle = iF_{B_q}p_\mu$$

$$\Rightarrow \boxed{B^0_{s,d} \to \ell^+\ell^- \text{ belong to the cleanest rare } B\text{-meson decays}}$$

- High sensitivity to physics from beyond the Standard Model:

$\rightarrow$ such as in NP models with leptoquarks, Z' bosons ...



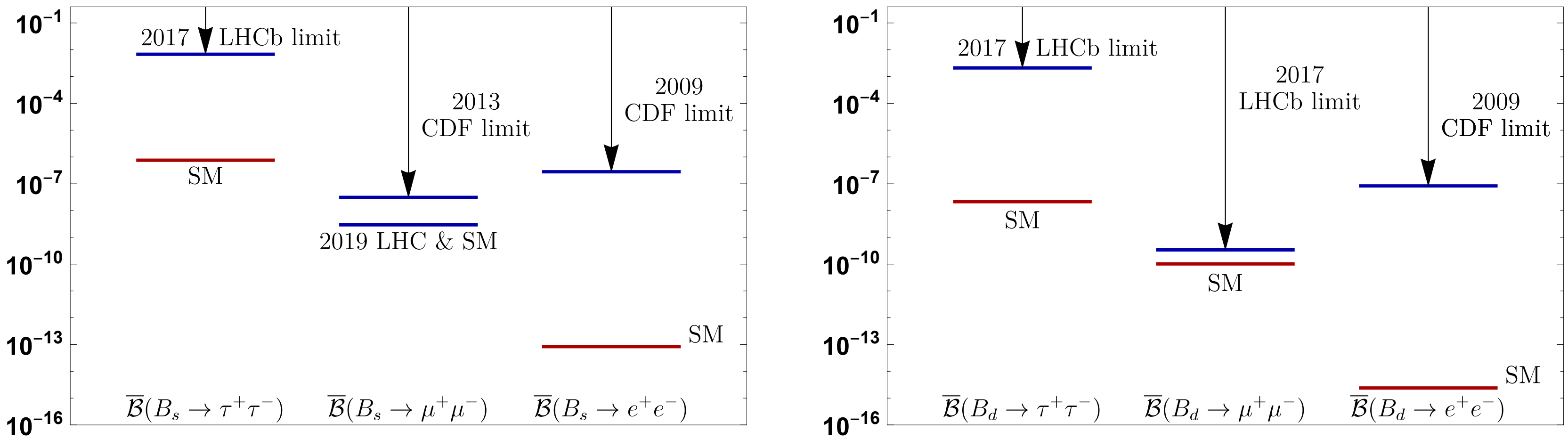


... also in SUSY + ... ???

$\rightarrow$ *particularly interesting:* new (pseudo)-scalars: lift helicity suppression!?

Status of $B^0_{s,d} \to \ell^+\ell^-$ Decays

- Overview of branching ratio measurements:



[$\to$ Talk by Monica Pepe-Altarelli]

- Comments:
  - Only $B^0_s \to \mu^+\mu^-$ has been observed at the LHC $\to$ *highlight!*
  - First limits on $B^0_{s,d} \to \tau^+\tau^-$: helicity suppression not very effective due to large τ mass but experimentally challenging due to τ reconstruction.
  - $B_{s,d} \to e^+e^-$ no attention (!?): *huge helicity suppression in the SM!*

Questions:

- Using the experimental $B_s^0 \to \mu^+\mu^-$ data obtained @ LHC as a guideline:
  - What are the constraints on New Physics, utilising new observables?
  - How large could be the $B_{s,d}^0 \to \tau^+\tau^-$, $B_{s,d}^0 \to e^+e^-$ branching ratios?
  - What is the impact of new sources of CP violation?

$\to$ *exploring* $B_{s,d}^0 \to \ell^+\ell^-$ *at the high-precision frontier ...*

[Thanks to Ruben Jaarsma for updating the plots and numerics (Moriond 2019)]

Theoretical Framework

- Low-energy effective Hamiltonian for $\bar{B}^0_s \to \ell^+\ell^-$: $\boxed{\text{SM} \oplus \text{NP}}$

$$\mathcal{H}_{\rm eff} = -\frac{G_{\rm F}}{\sqrt{2}\pi} V^*_{ts} V_{tb} \alpha \left[C^{\ell\ell}_{10} O_{10} + C^{\ell\ell}_S O_S + C^{\ell\ell}_P O_P + C^{\ell\ell'}_{10} O'_{10} + C^{\ell\ell'}_S O'_S + C^{\ell\ell'}_P O'_P \right]$$

[$G_{\rm F}$: Fermi's constant, V_{tq}: CKM matrix elements, α: QED fine structure constant]

- Four-fermion operators, with $P_{L,R} \equiv (1 \mp \gamma_5)/2$ and b-quark mass m_b:

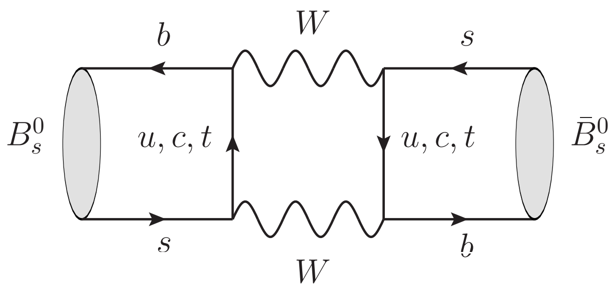
$$\begin{array}{lcllcl} O_{10} & = & (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell), & O'_{10} & = & (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell) \\ O_S & = & m_b(\bar{s} P_R b)(\bar{\ell}\ell), & O'_S & = & m_b(\bar{s} P_L b)(\bar{\ell}\ell) \\ O_P & = & m_b(\bar{s} P_R b)(\bar{\ell}\gamma_5\ell), & O'_P & = & m_b(\bar{s} P_L b)(\bar{\ell}\gamma_5\ell) \end{array}$$

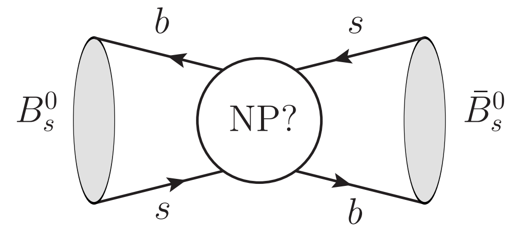
[Only operators with non-vanishing $\bar{B}^0_s \to \mu^+\mu^-$ matrix elements are included]

- The Wilson coefficients $C^{\ell\ell}_k$, $C^{\ell\ell'}_k$ encode the short-distance physics:
  - SM case: only $C^{\ell\ell}_{10} \neq 0$, and is given by the *real* coefficient $C^{\rm SM}_{10}$.
  - *Outstanding feature of* $\bar{B}^0_s \to \mu^+\mu^-$: sensitivity to (pseudo)-scalar lepton densities $\to O_{(P)S}$, $O'_{(P)S}$; WCs are still largely unconstrained.

[..., Altmannshofer, Niehoff and Straub (2017); Beneke, Bobeth and Szafron (2018-2019); ...]

Impact of B_s^0–$\bar{B}_s^0$ Mixing:

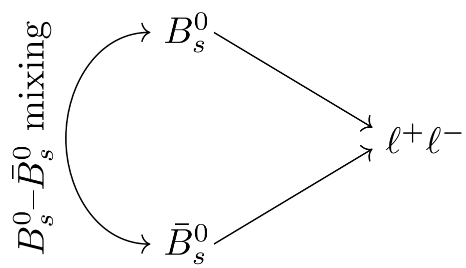




- Quantum mechanics: $\Rightarrow$ *time-dependent B_s^0–$\bar{B}_s^0$ oscillations:*
  - Mass eigenstates $B_{\mathrm{H,L}}^{(s)}$: $\Delta M_s \equiv M_{\mathrm{H}}^{(s)} - M_{\mathrm{L}}^{(s)}$, $\Delta\Gamma_s \equiv \Gamma_{\mathrm{L}}^{(s)} - \Gamma_{\mathrm{H}}^{(s)}$
  - CP-violating phase: $\phi_s = -2\delta\gamma + \phi_s^{\mathrm{NP}} \sim -2^\circ + \phi_s^{\mathrm{NP}}$

    $\rightarrow$ *determined (in particular) from analyses of $B_s^0 \rightarrow J/\psi\phi$*

- Interference effects (as in non-leptonic B_s decays [$\rightarrow$ talk E. Malami]):



[De Bruyn, R.F., Knegjens, Koppenburg, Merk, Pellegrino & Tuning (2012)]

$\rightarrow$ *convenient to go to the rest frame of the decaying $\bar{B}^0_s$ meson:*

- Distinguish between the $\ell^+_{\mathrm{L}}\ell^-_{\mathrm{L}}$ and $\ell^+_{\mathrm{R}}\ell^-_{\mathrm{R}}$ helicity configurations:

$$|(\ell^+_{\mathrm{L}}\ell^-_{\mathrm{L}})_{\mathrm{CP}}\rangle \equiv (\mathcal{CP})|\ell^+_{\mathrm{L}}\ell^-_{\mathrm{L}}\rangle = e^{i\phi_{\mathrm{CP}(\mu\mu)}}|\ell^+_{\mathrm{R}}\ell^-_{\mathrm{R}}\rangle$$

[$e^{i\phi_{\mathrm{CP}(\ell\ell)}}$ is a convention-dependent phase factor $\rightarrow$ cancels in observables]

- General expression for the decay amplitude [$\eta_{\mathrm{L}} = +1$, $\eta_{\mathrm{R}} = -1$]:

$$A(\bar{B}^0_s \to \ell^+_\lambda \ell^-_\lambda) = \langle \ell^-_\lambda \ell^+_\lambda | \mathcal{H}_{\mathrm{eff}} | \bar{B}^0_s\rangle = -\frac{G_{\mathrm{F}}}{\sqrt{2}\pi} V^*_{ts} V_{tb} \alpha$$

$$\times F_{B_s} M_{B_s} m_\ell \, C_{10}^{\mathrm{SM}} e^{i\phi_{\mathrm{CP}(\ell\ell)}(1-\eta_\lambda)/2} \left[\eta_\lambda P_{\ell\ell} + S_{\ell\ell}\right]$$

- Combination of Wilson coefficient functions [CP-violating phases $\varphi^{\ell\ell}_{P,S}$]:

$$P_{\ell\ell} \equiv \frac{C_{10}^{\ell\ell} - C_{10}^{\ell\ell\prime}}{C_{10}^{\mathrm{SM}}} + \frac{M^2_{B_s}}{2\, m_\ell}\left(\frac{m_b}{m_b + m_s}\right)\left[\frac{C_P^{\ell\ell} - C_P^{\ell\ell\prime}}{C_{10}^{\mathrm{SM}}}\right] \xrightarrow{\mathrm{SM}} 1$$

$$S_{\ell\ell} \equiv \sqrt{1 - 4\frac{m^2_\ell}{M^2_{B_s}}}\frac{M^2_{B_s}}{2\, m_\ell}\left(\frac{m_b}{m_b + m_s}\right)\left[\frac{C_S^{\ell\ell} - C_S^{\ell\ell\prime}}{C_{10}^{\mathrm{SM}}}\right] \xrightarrow{\mathrm{SM}} 0$$

[F_{B_s}: B_s decay constant, M_{B_s}: B_s mass, m_ℓ: ℓ mass, m_s: strange-quark mass]

- Key observable to calculate time-dependent decay rates:

$$\xi_\lambda^{\ell\ell} \equiv -e^{-i\phi_s}\left[e^{i\phi_{\rm CP}(B_s)}\frac{A(\bar{B}_s^0\to\ell_\lambda^+\ell_\lambda^-)}{A(B_s^0\to\ell_\lambda^+\ell_\lambda^-)}\right]$$

$$\Rightarrow A(B_s^0\to\ell_\lambda^+\ell_\lambda^-) = \langle\ell_\lambda^-\ell_\lambda^+|\mathcal{H}_{\rm eff}^\dagger|B_s^0\rangle \text{ is also needed ...}$$

- Using $(\mathcal{CP})^\dagger(\mathcal{CP})=\hat{1}$ and $(\mathcal{CP})|B_s^0\rangle = e^{i\phi_{\rm CP}(B_s)}|\bar{B}_s^0\rangle$ yields:

$$A(B_s^0\to\ell_\lambda^+\ell_\lambda^-) = -\frac{G_{\rm F}}{\sqrt{2}\pi}V_{ts}V_{tb}^*\alpha f_{B_s}M_{B_s}m_\ell C_{10}^{\rm SM}$$

$$\times\, e^{i[\phi_{\rm CP}(B_s)+\phi_{\rm CP}(\ell\ell)(1-\eta_\lambda)/2]}\left[-\eta_\lambda P_{\ell\ell}^* + S_{\ell\ell}^*\right]$$

- The convention-dependent phases cancel in $\xi_\lambda^{\ell\ell}$ $[\eta_{\rm L}=+1,\ \eta_{\rm R}=-1]$:

$$\xi_\lambda^{\ell\ell} = -e^{-i\phi_s^{\rm NP}}\left[\frac{+\eta_\lambda P_{\ell\ell}+S_{\ell\ell}}{-\eta_\lambda P_{\ell\ell}^*+S_{\ell\ell}^*}\right] \quad\Rightarrow\quad \boxed{\xi_{\rm L}^{\ell\ell}\left(\xi_{\rm R}^{\ell\ell}\right)^* = \xi_{\rm R}^{\ell\ell}\left(\xi_{\rm L}^{\ell\ell}\right)^* = 1}$$

[Note: analogous formalism for $B_d\to\ell^+\ell^-$ decays; $\Delta\Gamma_d/\Gamma_d$ is negligible.]

$$Application$$

$$to$$

$$B_s^0 \to \mu^+\mu^-$$

Untagged $B_s^0 \to \mu^+\mu^-$ Rate

- Interesting observable (well-known from studies of non-leptonic B_s^0 decays):

$$\mathcal{A}_{\Delta\Gamma_s}^{\mu\mu,\lambda} \equiv \frac{2\,\Re(\xi_\lambda^{\mu\mu})}{1+|\xi_\lambda^{\mu\mu}|^2} = \frac{|P_{\mu\mu}|^2\cos(2\varphi_P^{\mu\mu}-\phi_s^{\rm NP}) - |S_{\mu\mu}|^2\cos(2\varphi_S^{\mu\mu}-\phi_s^{\rm NP})}{|P_{\mu\mu}|^2+|S_{\mu\mu}|^2}$$

$\to$ *independent of the muon helicity* λ*:* $\mathcal{A}_{\Delta\Gamma_s}^{\mu\mu} \equiv \mathcal{A}_{\Delta\Gamma_s}^{\mu\mu,\lambda}$

- Challenge to measure the muon helicity: $\to$ *helicity-averaged rates:*

$$\Gamma(\overset{(-)}{B}{}_s^0(t)\to\mu^+\mu^-) \equiv \sum_{\lambda={\rm L,R}} \Gamma(\overset{(-)}{B}{}_s^0(t)\to\mu_\lambda^+\mu_\lambda^-)$$

- B_s^0 decay width difference $\Delta\Gamma_s$: $\quad y_s \equiv \Delta\Gamma_s\tau_{B_s}/2 = 0.0645 \pm 0.0045$

$\Rightarrow$ access to $\mathcal{A}_{\Delta\Gamma_s}^{\mu\mu}$ through the following *untagged decay rate:*

$$\langle\Gamma(B_s(t)\to\mu^+\mu^-)\rangle \equiv \Gamma(B_s^0(t)\to\mu^+\mu^-) + \Gamma(\bar{B}_s^0(t)\to\mu^+\mu^-)$$

$$\propto e^{-t/\tau_{B_s}}\left[\cosh(y_s t/\tau_{B_s}) + \mathcal{A}_{\Delta\Gamma_s}^{\mu\mu}\sinh(y_s t/\tau_{B_s})\right]$$

$B_s^0 \to \mu^+\mu^-$ Branching Ratio(s)

- LHC measurements concern the "experimental" branching ratio:

$$\to \textit{time-integrated untagged rate:}$$

$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-) \equiv \frac{1}{2}\int_0^\infty \langle \Gamma(B_s(t) \to \mu^+\mu^-)\rangle \, dt \stackrel{\rm LHC}{=} \boxed{(2.9 \pm 0.4) \times 10^{-9}}$$

- Relation to the "theoretical" branching ratio (referring to $t = 0$):

$$\underbrace{\mathcal{B}(B_s \to \mu^+\mu^-)}_{\text{calculated by theorists}} = \left[\frac{1 - y_s^2}{1 + \mathcal{A}_{\Delta\Gamma_s}^{\mu\mu}\, y_s}\right] \underbrace{\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)}_{\text{measured @ LHC}}$$

- $\mathcal{A}_{\Delta\Gamma_s}^{\mu\mu}|_{\rm SM} = +1$ gives a *SM reference value* for the comparison with the time-integrated experimental branching ratio $\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)$:

$$\boxed{\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)_{\rm SM} = (3.57 \pm 0.16) \times 10^{-9}}$$ [arXiv:1703.10160 [hep-ph]]

[De Bruyn, R.F., Knegjens, Koppenburg, Merk, Pellegrino & Tuning (2012)]

Effective $B_s^0 \to \mu^+\mu^-$ Lifetime

◇ *Collecting more and more data* $\oplus$ *include decay time information* $\Rightarrow$

- The effective $B_s \to \mu^+\mu^-$ lifetime can be measured:

$$\tau_{\mu\mu} \equiv \frac{\int_0^\infty t\,\langle\Gamma(B_s(t)\to\mu^+\mu^-)\rangle\,dt}{\int_0^\infty \langle\Gamma(B_s(t)\to\mu^+\mu^-)\rangle\,dt}$$

- Pioneering experimental results:

LHCb (2017): $\tau^s_{\mu\mu} = [2.04 \pm 0.44(\mathrm{stat}) \pm 0.05(\mathrm{syst})]$ ps

CMS (2019): $\tau^s_{\mu\mu} = \left(1.70^{+0.61}_{-0.44}\right)$ ps

[$\to$ Talk by Monica Pepe-Altarelli]

- $\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s}$ can be extracted from the effective lifetime $\tau^s_{\mu\mu}$:

$$\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s} = \frac{1}{y_s}\left[\frac{(1-y_s^2)\tau_{\mu\mu} - (1+y_s^2)\tau_{B_s}}{2\tau_{B_s} - (1-y_s^2)\tau_{\mu\mu}}\right] \xrightarrow{\mathrm{LHCb}} 8.24 \pm 10.72$$

$\Rightarrow$ $\boxed{\textit{LHC upgrade era and beyond...}}$

Probing New Physics through $B_s^0 \to \mu^+\mu^-$

- Useful to introduce the following ratio:

$$\overline{R}^s_{\mu\mu} \equiv \frac{\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)}{\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)_{\rm SM}} \quad \xrightarrow{\rm SM} \quad \boxed{1}$$

$$= \left[\frac{1 + y_s \cos(2\varphi_P^{\mu\mu} - \phi_s^{\rm NP})}{1 + y_s}\right] |P_{\mu\mu}|^2 + \left[\frac{1 - y_s \cos(2\varphi_S^{\mu\mu} - \phi_s^{\rm NP})}{1 + y_s}\right] |S_{\mu\mu}|^2$$

- Result following from current LHC data: $\boxed{\overline{R}^s_{\mu\mu} = 0.82 \pm 0.13}$

- $\overline{R}^s_{\mu\mu}$ *does not* allow a separation of the $P_{\mu\mu}$ and $S_{\mu\mu}$ contributions:

$\Rightarrow$ sizeable NP could still be present ...

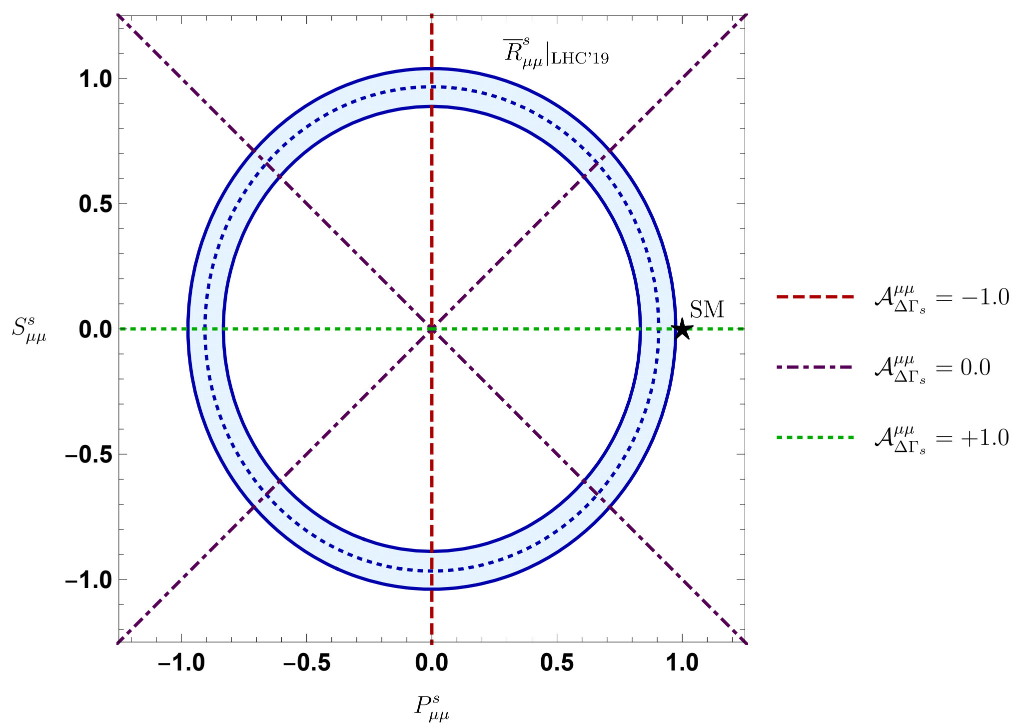
[See also Buras, R.F., Girrbach & Knegjens (2013)]

- Further information comes from the measurement of $\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s}$:

$$|S_{\mu\mu}| = |P_{\mu\mu}|\sqrt{\frac{\cos(2\varphi_P^{\mu\mu} - \phi_s^{\rm NP}) - \mathcal{A}^{\mu\mu}_{\Delta\Gamma_s}}{\cos(2\varphi_S^{\mu\mu} - \phi_s^{\rm NP}) + \mathcal{A}^{\mu\mu}_{\Delta\Gamma_s}}}$$

- Constraints in the $P_{\mu\mu}$–$S_{\mu\mu}$ plane following from current data:

$\rightarrow$ *assume real coefficients (e.g. MFV without flavour-blind phases):*



[CP-violating phases $\varphi_P^{\mu\mu}$, $\varphi_S^{\mu\mu} \neq 0^\circ, 180^\circ$ are discussed below]

Mapping Out

Further Decays:

$$B_d \to \mu^+\mu^-$$

$$B_{s,d} \to \tau^+\tau^-$$

$$B_{s,d} \to e^+e^-$$

[Detailed discussion: arXiv:1703.10160 [hep-ph]]

New Physics Scenario

- We assume *flavour-universal New Physics* contributions:

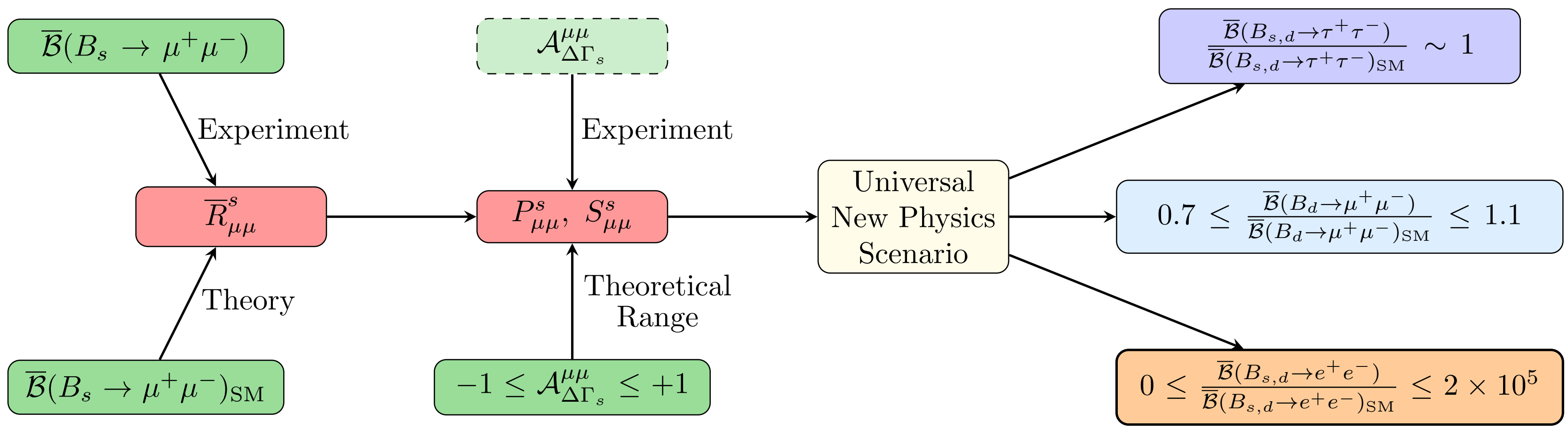
$$\Rightarrow \boxed{C_{10}^{\ell\ell(')},\ C_{P}^{\ell\ell(')},\ C_{S}^{\ell\ell(')}\ \textit{do not depend on flavour labels:}}$$

$$P_{\ell\ell}^{q} = \frac{C_{10} - C_{10}'}{C_{10}^{\rm SM}} + \frac{M_{B_q}^2}{2m_\ell}\left(\frac{m_b}{m_b + m_q}\right)\left[\frac{C_P - C_P'}{C_{10}^{\rm SM}}\right]$$

$$S_{\ell\ell}^{q} \equiv \sqrt{1 - 4\frac{m_\ell^2}{M_{B_q}^2}}\,\frac{M_{B_q}^2}{2m_\ell}\left(\frac{m_b}{m_b + m_q}\right)\left[\frac{C_S - C_S'}{C_{10}^{\rm SM}}\right]$$

- Data for $B \to K^{(*)}\ell^+\ell^-$ decays: $\Rightarrow$ $\mathcal{C}_{10} \equiv \dfrac{C_{10} - C_{10}'}{C_{10}^{\rm SM}}$
  - Use $\mathcal{C}_{10} = 1$ as the working assumption $\Rightarrow$ *NP in (pseudo)-scalars.*
- No new sources of CP violation: $\to$ real Wilson coefficients.

Linking $B_s^0 \to \mu^+\mu^-$ with $B_q^0 \to \ell^+\ell^-$ Decays

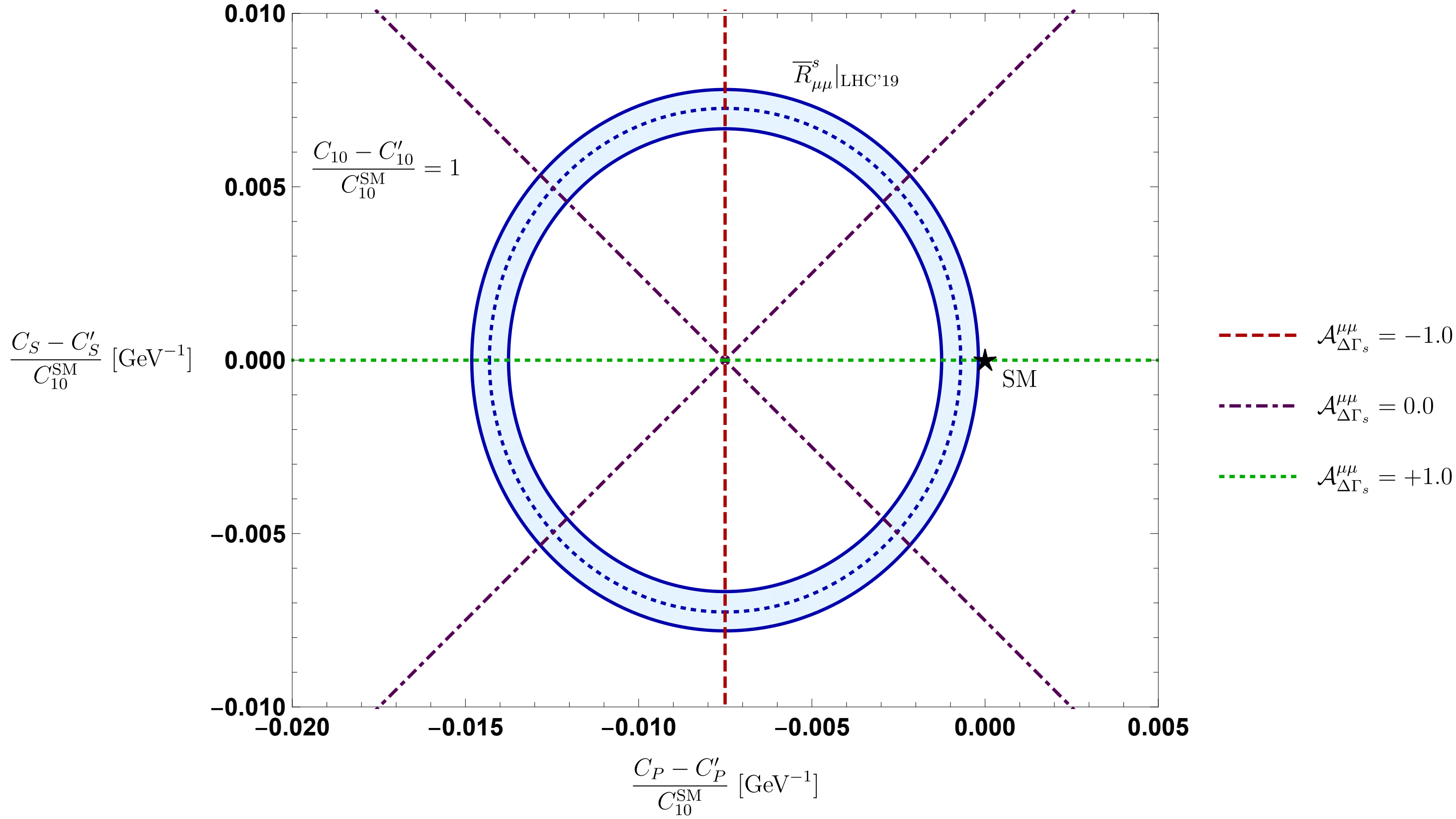


- Conversion of $\overline{R}^s_{\mu\mu}$ and $\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s}$ into Wilson coefficients:

$$|P^s_{\mu\mu}| = \sqrt{\frac{1}{2}(1+y_s)\left[\frac{1+\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s}}{1+y_s\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s}}\right]\overline{R}^s_{\mu\mu}} \quad \Rightarrow \quad \left|\frac{C_P - C_P'}{C_{10}^{\rm SM}}\right|$$

$$|S^s_{\mu\mu}| = \sqrt{\frac{1}{2}(1+y_s)\left[\frac{1-\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s}}{1+y_s\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s}}\right]\overline{R}^s_{\mu\mu}} \quad \Rightarrow \quad \left|\frac{C_S - C_S'}{C_{10}^{\rm SM}}\right|$$

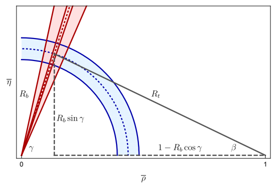
- Constraints for the Wilson coefficients from $B_s^0 \to \mu^+\mu^-$:



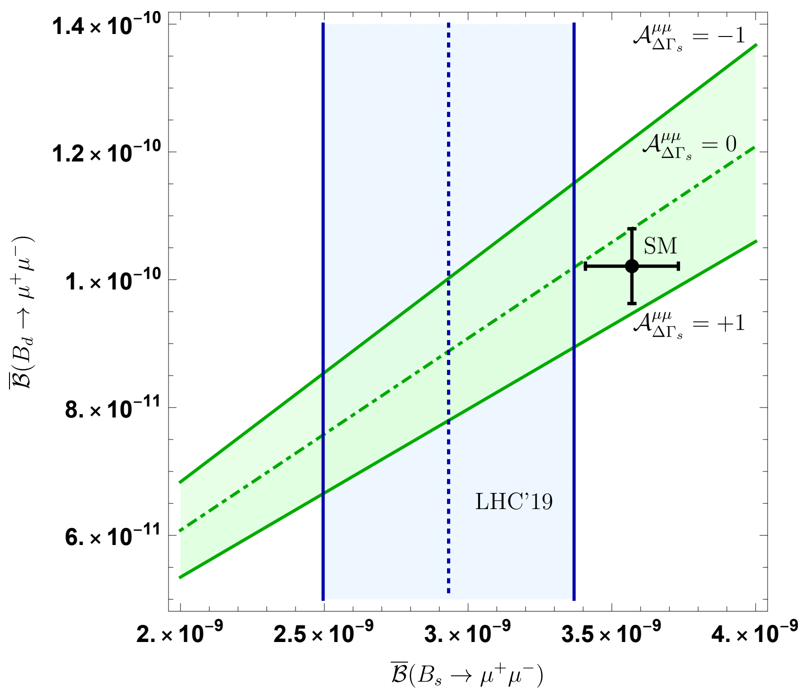
Predictions for $B_d^0 \to \mu^+\mu^-$

$$\frac{\overline{\mathcal{B}}(B_d \to \mu^+\mu^-)}{\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)} \propto \left[\frac{|P^d_{\mu\mu}|^2 + |S^d_{\mu\mu}|^2}{|P^s_{\mu\mu}|^2 + |S^s_{\mu\mu}|^2}\right]\left(\frac{f_{B_d}}{f_{B_s}}\right)^2 \left|\frac{V_{td}}{V_{ts}}\right|^2$$

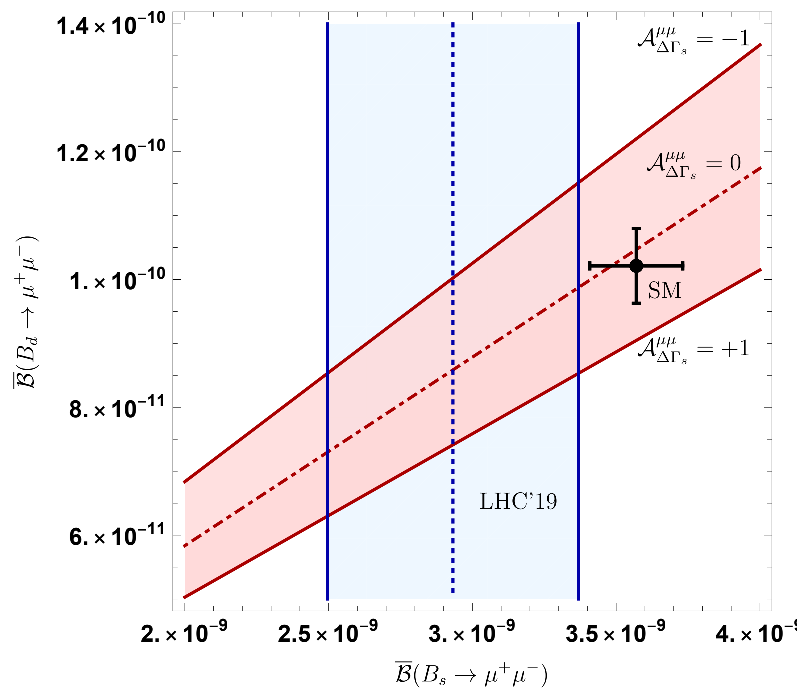
- Unitarity Triangle analysis: $\Rightarrow |V_{td}/V_{ts}| = 0.220 \pm 0.010$



- Flavour Universal New Physics Scenario:



$[P^s_{\mu\mu} > 0]$



$[P^s_{\mu\mu} < 0]$

Predictions for $B_s^0 \to \tau^+\tau^-$ and $B_d^0 \to \tau^+\tau^-$

- Standard Model predictions and experimental LHCb upper bounds (2017):

$$\overline{\mathcal{B}}(B_s \to \tau^+\tau^-)_{\rm SM} = (7.56 \pm 0.35) \times 10^{-7} < 6.8 \times 10^{-3} \text{ (95\% C.L.)}$$

$$\overline{\mathcal{B}}(B_d \to \tau^+\tau^-)_{\rm SM} = (2.14 \pm 0.12) \times 10^{-8} < 2.1 \times 10^{-3} \text{ (95\% C.L.)}$$

$$\overline{R}^s_{\tau\tau} \equiv \frac{\overline{\mathcal{B}}(B_s \to \tau^+\tau^-)}{\overline{\mathcal{B}}(B_s \to \tau^+\tau^-)_{\rm SM}} \quad \xrightarrow{\rm SM} \quad \boxed{1}$$

- Flavour Universal New Physics Scenario:

$$P^s_{\tau\tau} = \left(1 - \frac{m_\mu}{m_\tau}\right)\mathcal{C}_{10} + \frac{m_\mu}{m_\tau} P^s_{\mu\mu}, \qquad S^s_{\tau\tau} = \frac{m_\mu}{m_\tau}\sqrt{\frac{1 - 4\frac{m_\tau^2}{M_{B_s}^2}}{1 - 4\frac{m_\mu^2}{M_{B_s}^2}}}\, S^s_{\mu\mu}$$

$\Rightarrow$ *NP effects strongly suppressed by* $m_\mu/m_\tau \sim 0.06$*:*

$$\boxed{0.8 \leq \overline{R}^s_{\tau\tau} \leq 1.0, \qquad 0.995 \leq \mathcal{A}^{\tau\tau}_{\Delta\Gamma_s} \leq 1.000}$$

Predictions for $B_s^0 \to e^+e^-$ and $B_d^0 \to e^+e^-$

- SM predictions and experimental CDF upper bounds (2009):

$$\overline{\mathcal{B}}(B_s \to e^+e^-)_{\rm SM} = (8.35 \pm 0.39) \times 10^{-14} < 2.8 \times 10^{-7} \text{ (90\% C.L.)}$$

$$\overline{\mathcal{B}}(B_d \to e^+e^-)_{\rm SM} = (2.39 \pm 0.14) \times 10^{-15} < 8.3 \times 10^{-8} \text{ (90\% C.L.)}$$

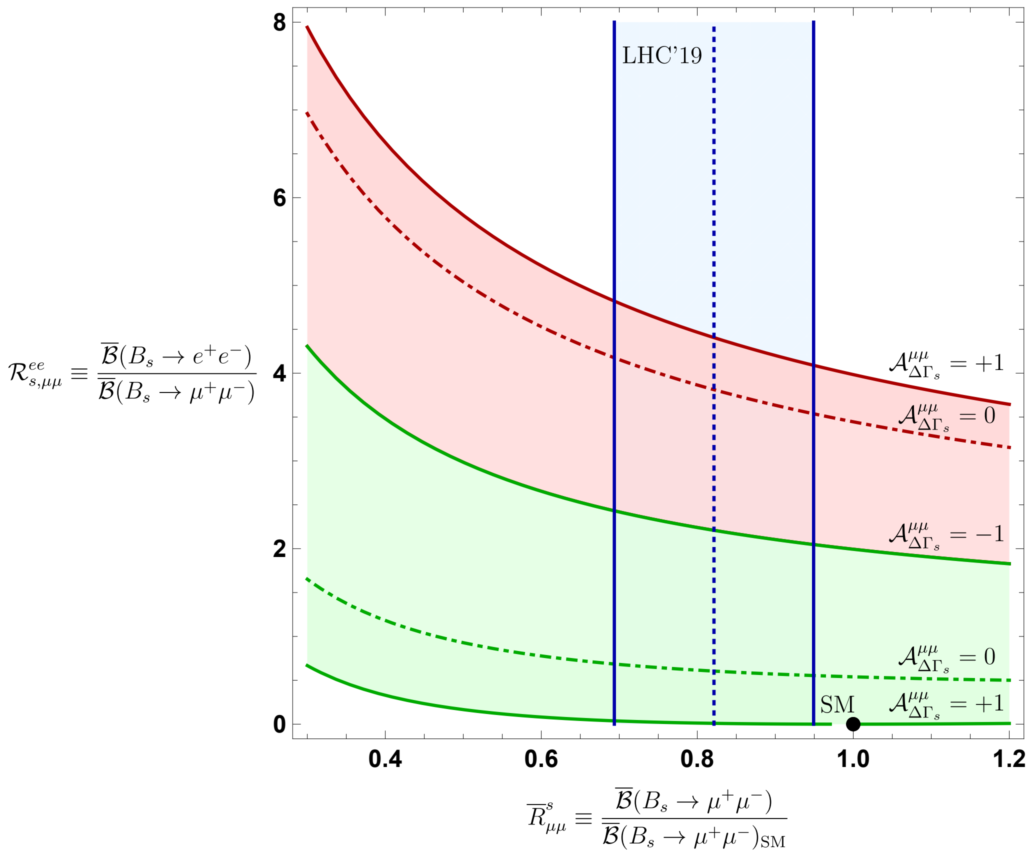
- Flavour Universal New Physics Scenario:

$$P_{ee}^s = \left(1 - \frac{m_\mu}{m_e}\right) \mathcal{C}_{10} + \frac{m_\mu}{m_e} P_{\mu\mu}^s, \qquad S_{ee}^s = \frac{m_\mu}{m_e} \sqrt{\frac{1 - 4\frac{m_\tau^2}{M_{B_s}^2}}{1 - 4\frac{m_\mu^2}{M_{B_s}^2}}} S_{\mu\mu}^s$$

$\Rightarrow$ *NP effects hugely amplified by* $m_\mu/m_e \sim 207$*:*

$$\mathcal{R}_{s,\mu\mu}^{ee} \equiv \frac{\overline{\mathcal{B}}(B_s \to e^+e^-)}{\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)} \approx \frac{\left(\mathcal{C}_{10} - P_{\mu\mu}^s\right)^2 + (S_{\mu\mu}^s)^2}{(P_{\mu\mu}^s)^2 + (S_{\mu\mu}^s)^2}$$

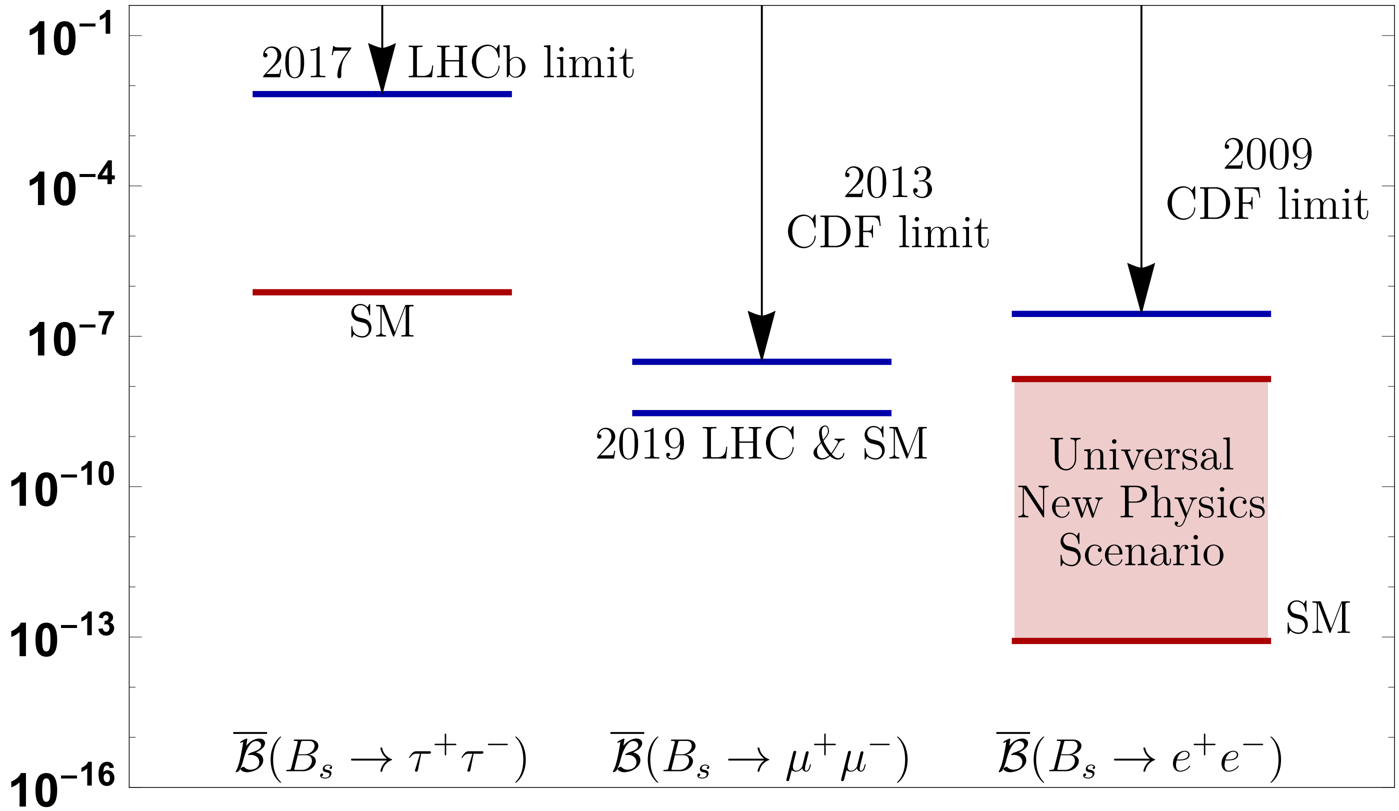
- (Pseudo)-scalar New Physics contributions lift in this scenario the helicity suppression of the extremely small Standard Model branching ratio:



[red: $P^s_{\mu\mu} < 0$, green: $P^s_{\mu\mu} > 0$]

$$\Rightarrow \quad \boxed{0 \leq \overline{R}^s_{ee} \leq 1.7 \times 10^5, \quad 0 \leq \overline{\mathcal{B}}(B_s \to e^+e^-) \leq 1.4 \times 10^{-8}}$$

- Similar situation for $B_d \to e^+e^-$: $\quad 0 \leq \overline{\mathcal{B}}(B_d \to e^+e^-) \leq 3.9 \times 10^{-10}$



$\Rightarrow$ $\boxed{\text{search for } B_{s(d)} \to e^+e^-\text{: } \textit{may give an unambiguous NP signal!}}$

$\diamond$ looking forward to the first LHC result for $\overline{\mathcal{B}}(B_{s(d)} \to e^+e^-)$ ...

Comment on the MSSM with Minimal Flavour Violation:

- Pattern different from flavour-universal NP scenario:

$$C_S = m_\ell \tilde{C}_S, \quad C_P = m_\ell \tilde{C}_P \quad \Rightarrow$$

$$P_{\ell\ell}^q|_{\rm MSSM}^{\rm MFV} = 1 - \frac{M_{B_q}^2}{2}\left(\frac{m_b}{m_b+m_q}\right)\left[\frac{\tilde{C}_S}{C_{10}^{\rm SM}}\right] \equiv 1 - A_q$$

$$S_{\ell\ell}^q|_{\rm MSSM}^{\rm MFV} = \sqrt{1-4\frac{m_\ell^2}{M_{B_q}^2}}\frac{M_{B_q}^2}{2}\left(\frac{m_b}{m_b+m_q}\right)\left[\frac{\tilde{C}_S}{C_{10}^{\rm SM}}\right] = \sqrt{1-4\frac{m_\ell^2}{M_{B_q}^2}}A_q$$

$\rightarrow$ A_q does not depend on the lepton flavour

[Bobeth, Hiller and Piranishvili (2007); Buras, R.F., Girrbach and Knegjens (2013)]

- Implication: $\mathcal{B}(B_{s,d}^0 \to \ell^+\ell^-)$ up to $\mathcal{O}(m_\ell^2/M_{B_q}^2)$ as in the SM.

- Similar pattern in an MFV scenario with heavy new degrees of freedom linearly realized in the electroweak symmetry in the Higgs sector.

[Altmannshofer, Niehoff and Straub (2017)]

Impact

of

CP-violating Phases

$\rightarrow$ *focus on* $B_s \rightarrow \mu^+\mu^-$*:*

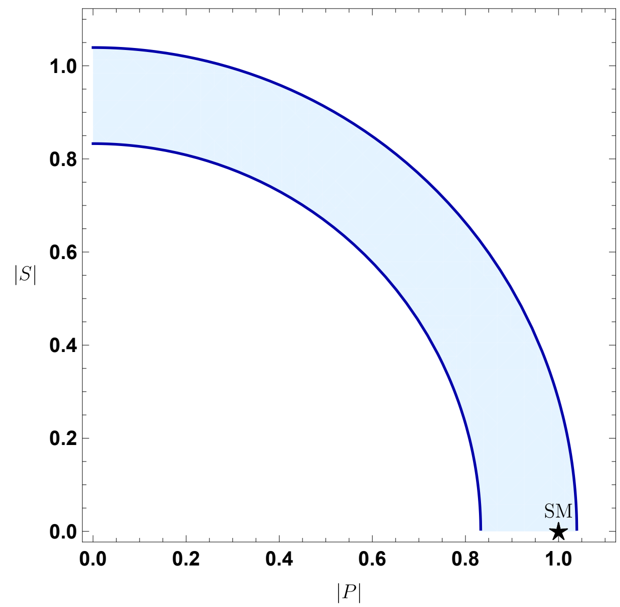
[Detailed discussion: arXiv:1709.04735 [hep-ph]]

General $B_s \to \mu^+\mu^-$ Branching Ratio Constraints

- Observable: $\overline{R}^s_{\mu\mu} \equiv \overline{R} = 0.82 \pm 0.13 \quad \to \quad$ *useful quantity:*

$$r \equiv \left[\frac{1+y_s}{1+\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s}\, y_s}\right]\overline{R} = |P_{\mu\mu}|^2 + |S_{\mu\mu}|^2$$

- Constraints on $|P| \equiv |P_{\mu\mu}|$, $|S| \equiv |S_{\mu\mu}|$ in the presence of unconstrained CP-violating phases $\varphi_P \equiv \varphi_P^{\mu\mu}$, $\varphi_S \equiv \varphi_S^{\mu\mu}$ yielding $-1 \leq \mathcal{A}^{\mu\mu}_{\Delta\Gamma_s} \leq +1$:



$\Rightarrow$ $\boxed{\textit{how to narrow down (pseudo)-scalar NP contributions?}}$

CP Asymmetries of $B_s \to \mu^+\mu^-$ Decays

- Time-dependent rate asymmetry: $\to$ *requires tagging of B_s^0 and $\bar{B}_s^0$:*

$$\frac{\Gamma(B_s^0(t)\to\mu_\lambda^+\mu_\lambda^-)-\Gamma(\bar{B}_s^0(t)\to\mu_\lambda^+\mu_\lambda^-)}{\Gamma(B_s^0(t)\to\mu_\lambda^+\mu_\lambda^-)+\Gamma(\bar{B}_s^0(t)\to\mu_\lambda^+\mu_\lambda^-)}=\frac{\mathcal{C}_{\mu\mu}^{\lambda}\cos(\Delta M_s t)+\mathcal{S}_\lambda\sin(\Delta M_s t)}{\cosh(y_s t/\tau_{B_s})+\mathcal{A}_{\Delta\Gamma_s}^{\mu\mu,\lambda}\sinh(y_s t/\tau_{B_s})}$$

- Observables: $\to$ *theoretically clean (no dependence on F_{B_s}):* $\boxed{\xrightarrow{\text{SM}} 0}$

$$\mathcal{C}_{\mu\mu}^{\lambda}\equiv\frac{1-|\xi_\lambda|^2}{1+|\xi_\lambda|^2}=-\eta_\lambda\left[\frac{2|PS|\cos(\varphi_P-\varphi_S)}{|P|^2+|S|^2}\right]\equiv-\eta_\lambda\mathcal{C}_{\mu\mu}$$

$$\mathcal{S}_{\mu\mu}^{\lambda}\equiv\frac{2\,\Im(\xi_\lambda)}{1+|\xi_\lambda|^2}=\frac{|P|^2\sin(2\varphi_P-\phi_s^{\rm NP})-|S|^2\sin(2\varphi_S-\phi_s^{\rm NP})}{|P|^2+|S|^2}\equiv\mathcal{S}_{\mu\mu}$$

$$\mathcal{A}_{\Delta\Gamma_s}^{\mu\mu,\lambda}\equiv\frac{2\,\Re(\xi_\lambda)}{1+|\xi_\lambda|^2}=\frac{|P_{\mu\mu}|^2\cos(2\varphi_P^{\mu\mu}-\phi_s^{\rm NP})-|S_{\mu\mu}|^2\cos(2\varphi_S^{\mu\mu}-\phi_s^{\rm NP})}{|P_{\mu\mu}|^2+|S_{\mu\mu}|^2}$$

- Note: $\mathcal{C}_{\mu\mu}$, $\mathcal{S}_{\mu\mu}\equiv S_\lambda^{\mu\mu}$, $\mathcal{A}_{\Delta\Gamma_s}^{\mu\mu}\equiv\mathcal{A}_{\Delta\Gamma_s}^{\mu\mu,\lambda}$ are *independent* of muon helicity λ.

- Helicity-averaged decay rates, as for the branching ratio discussion:

$$\Gamma(\overset{(-)}{B}{}^0_s(t) \to \mu^+\mu^-) \equiv \sum_{\lambda=\mathrm{L,R}} \Gamma(\overset{(-)}{B}{}^0_s(t) \to \mu^+_\lambda \mu^-_\lambda)$$

$\Rightarrow$ $\boxed{C^{\mu\mu}_\lambda \propto \eta^{\mu\mu}_\lambda \text{ terms cancel in the following } CP \textit{ asymmetry:}}$

$$\frac{\Gamma(B^0_s(t) \to \mu^+\mu^-) - \Gamma(\bar{B}^0_s(t) \to \mu^+\mu^-)}{\Gamma(B^0_s(t) \to \mu^+\mu^-) + \Gamma(\bar{B}^0_s(t) \to \mu^+\mu^-)} = \frac{\mathcal{S}_{\mu\mu}\sin(\Delta M_s t)}{\cosh(y_s t/\tau_{B_s}) + \mathcal{A}^{\mu\mu}_{\Delta\Gamma_s}\sinh(y_s t/\tau_{B_s})}$$

- Observables are not independent from one another:

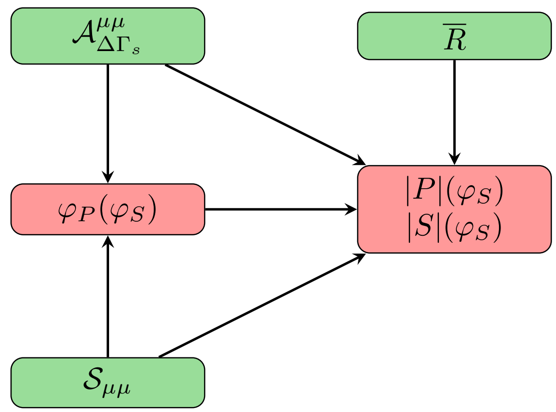
$$\boxed{(\mathcal{C}_{\mu\mu})^2 + (\mathcal{S}_{\mu\mu})^2 + (\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s})^2 = 1} \quad \oplus \quad \boxed{\overline{R}}$$

- Four NP parameters: $|P_{\mu\mu}|$, $|S_{\mu\mu}|$, $\varphi^{\mu\mu}_P$, $\varphi^{\mu\mu}_S$

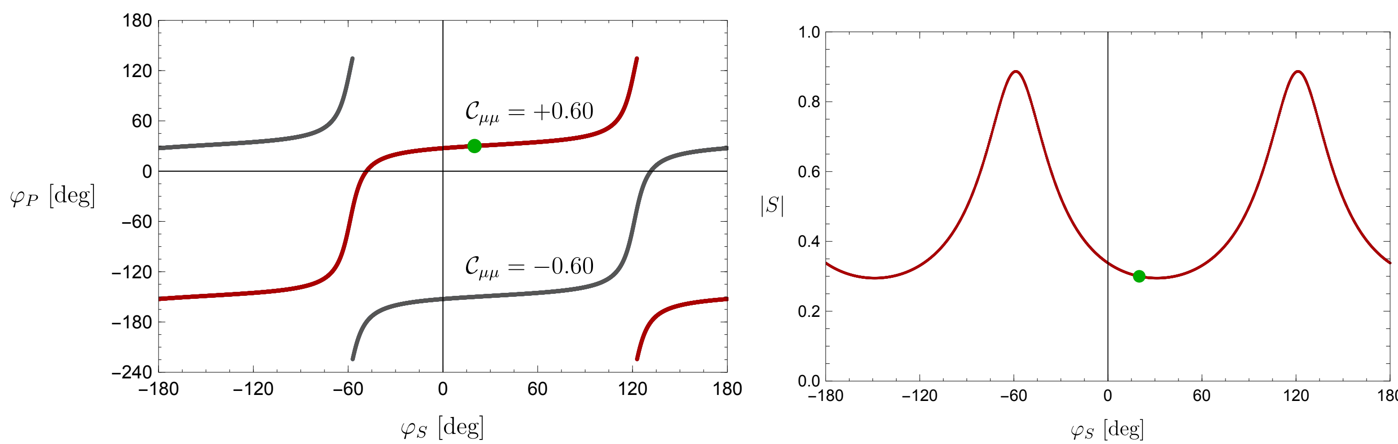
... while *three independent* observables ...

Probing $P_{\mu\mu}$ and $S_{\mu\mu}$: General Case

- <u>Determination of $|P| \equiv |P_{\mu\mu}|$, $|S| \equiv |S_{\mu\mu}|$ as functions of $\varphi_S \equiv \varphi_S^{\mu\mu}$:</u>



- <u>Illustration:</u> $\overline{R} = 0.84, \quad \mathcal{A}_{\Delta\Gamma_s}^{\mu\mu} = 0.37, \quad \mathcal{S}_{\mu\mu} = 0.71, \quad \mathcal{C}_{\mu\mu} = 0.60$



$\Rightarrow$ $\boxed{\textit{would establish non-vanishing (pseudo)-scalar NP contribution!}}$

Using More Information/Assumptions

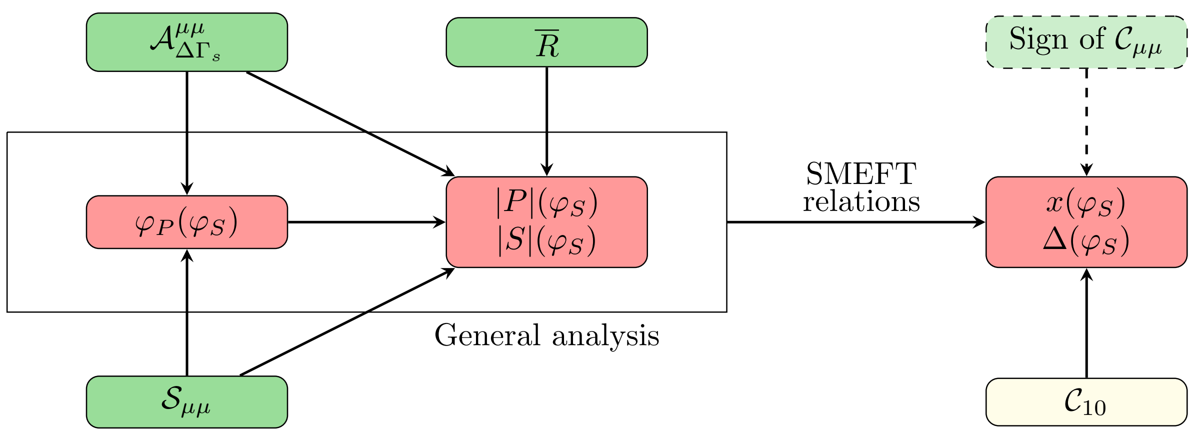
- Relations in "SM Effective Field Theory" (SMEFT): [arXiv:1407.7044 [hep-ph]]

$$C_P = -C_S, \quad C_P' = C_S'$$

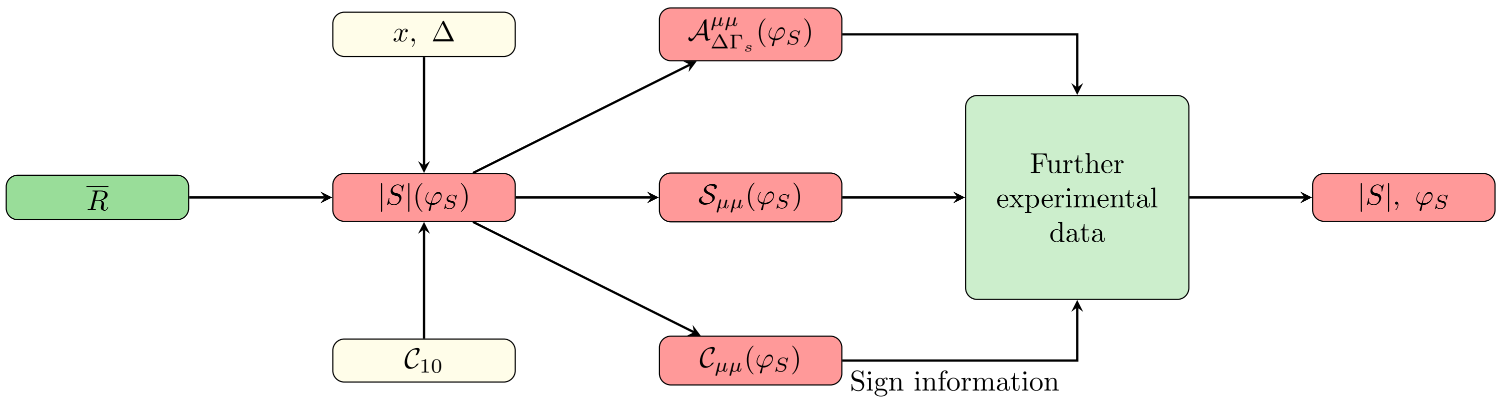
- New parametrisation:

$$x \equiv |x|e^{i\Delta} \equiv \left|\frac{C_S'}{C_S}\right| e^{i(\tilde{\varphi}_S' - \tilde{\varphi}_S)}, \quad P \equiv |P|e^{i\varphi_P} = \mathcal{C}_{10} - \left[\frac{1+|x|e^{i\Delta}}{1-|x|e^{i\Delta}}\right] |S|e^{i\varphi_S}$$

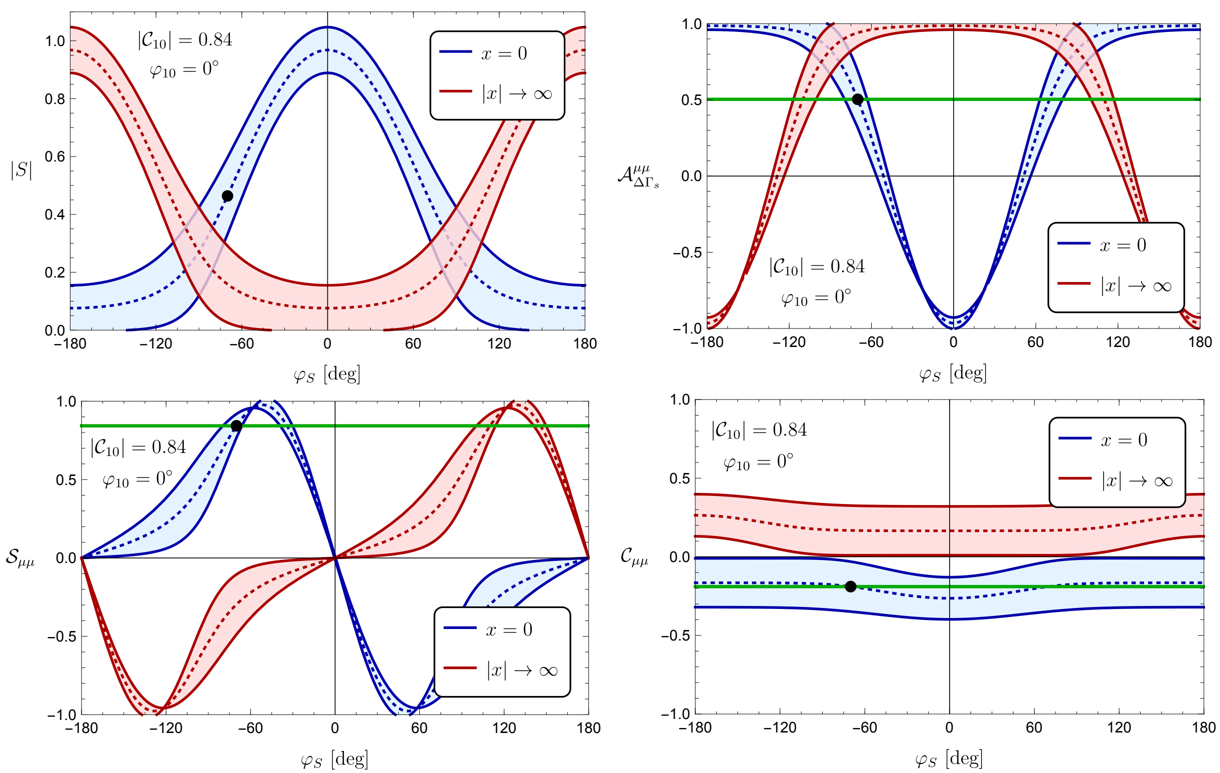
- Determination of NP parameters:



- <u>Various patterns of observables for different SMEFT assumptions:</u>

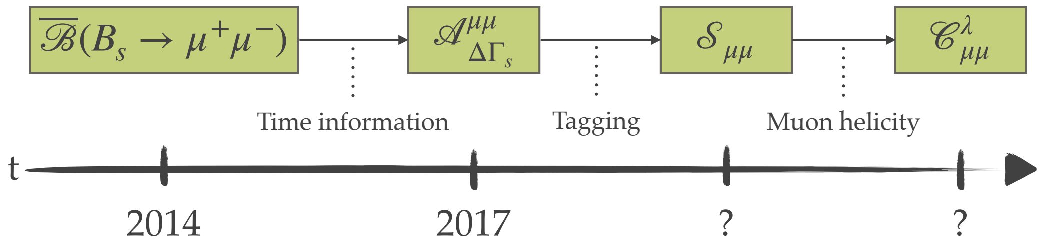


- <u>Studies of different scenarios:</u> $\rightarrow$ *interesting playground ...*



Experimental Aspects

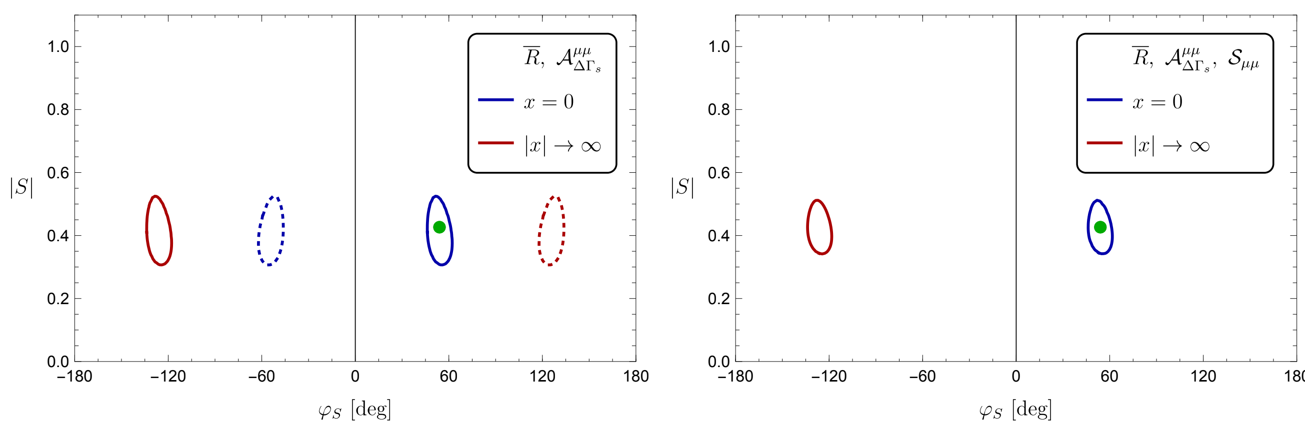
- Future timeline:



- NP scenario: $x = 0$ with the following "measured" observables:

$$\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s} = 0.58 \pm 0.20, \; \mathcal{S}_{\mu\mu} = -0.80 \pm 0.20, \; \mathcal{C}_{\mu\mu} = 0.16 \pm 0.20.$$

$\Rightarrow$ degeneracy with $|x| \to \infty$: $\to$ *could be resolved through sign of* $\mathcal{C}_{\mu\mu}$:



$$\to |S| = 0.43^{+0.07}_{-0.08}, \quad \varphi_S = (54^{+6}_{-7})^\circ$$

$\to$ $\boxed{\text{Perform detailed feasibility studies for LHCb upgrade and beyond!}}$

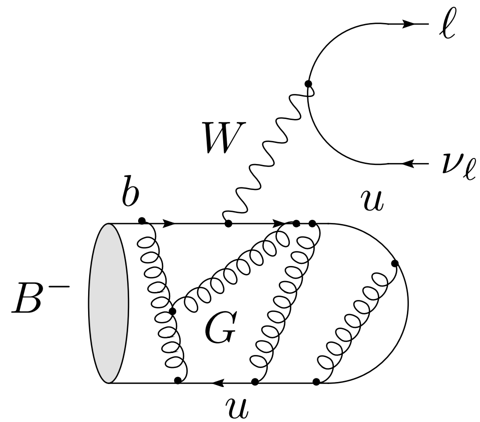
$$\boxed{\begin{array}{c}\textit{Charged}\\ \textit{Leptonic}\\ \textit{Decays:}\end{array}}$$

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

[Detailed discussions: arXiv:1809.09051, arXiv:1812.05200]

Theoretical Framework

- Standard Model:



$$\mathcal{O}^{\ell}_{V_L} = (\bar{q}\gamma^{\mu}P_L b)(\bar{\ell}\gamma_{\mu}P_L\nu_{\ell})$$

- Beyond the Standard Model:
  - Consider (pseudo)-scalar NP operators:

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

$$\mathcal{O}^{\ell}_{S} = (\bar{q}b)(\bar{\ell}P_L\nu_{\ell}), \quad \mathcal{O}^{\ell}_{P} = (\bar{q}\gamma_5 b)(\bar{\ell}P_L\nu_{\ell})$$

  - Further operators (not considered in the following)...:

$$\mathcal{O}^{\ell}_{V_R} = (\bar{q}\gamma^{\mu}P_R b)(\bar{\ell}\gamma_{\mu}P_L\nu_{\ell}), \quad \mathcal{O}^{\ell}_{T} = (\bar{q}\sigma^{\mu\nu}P_L b)(\bar{\ell}\sigma_{\mu\nu}P_L\nu_{\ell})$$

- Example of NP scenario: type II Two-Higgs-Doublet-Models (2HDM):

$$C^{\ell}_{P} = C^{\ell}_{S} = -\tan^2\beta\left(\frac{m_b m_{\ell}}{M^2_{H^{\pm}}}\right)$$

Branching Ratios & NP Constraints

- Branching ratio: $\rightarrow$ involves f_B as in $B_q^0 \rightarrow \ell^+\ell^-$
  - Helicity suppression in the SM:

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

  - Pseudoscalar operator can lift the helicity suppression:

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

- NP constraints from branching ratios: $\rightarrow$ $|V_{ub}|$ *cancels and clean:*

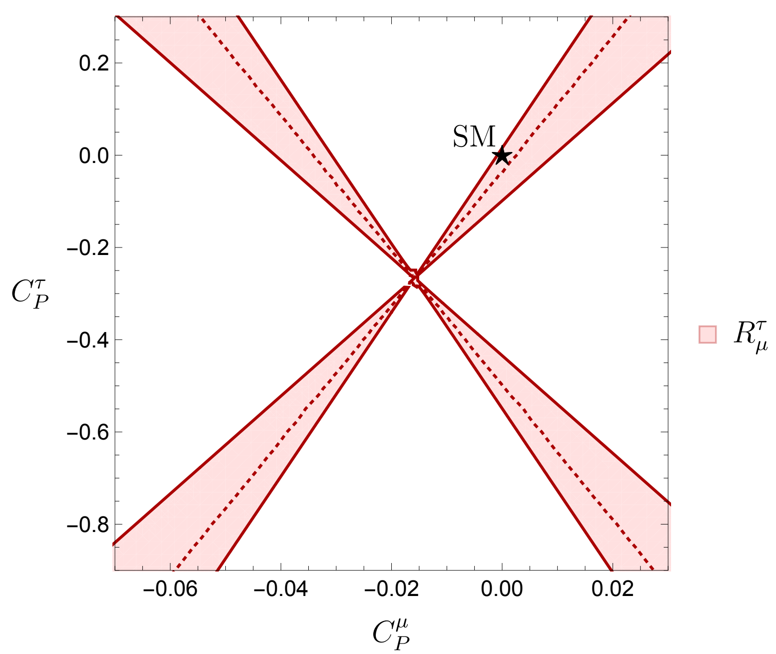
$$R_{\ell_2}^{\ell_1} \equiv \frac{m_{\ell_2}^2}{m_{\ell_1}^2}\left(\frac{M_{B^-}^2 - m_{\ell_2}^2}{M_{B^-}^2 - m_{\ell_1}^2}\right)^2 \frac{\mathcal{B}(B^- \rightarrow \ell_1^-\bar{\nu}_{\ell_1})}{\mathcal{B}(B^- \rightarrow \ell_2^-\bar{\nu}_{\ell_2})} = \left|\frac{1 + \mathcal{C}_{\ell_1;P}}{1 + \mathcal{C}_{\ell_2;P}}\right|^2$$

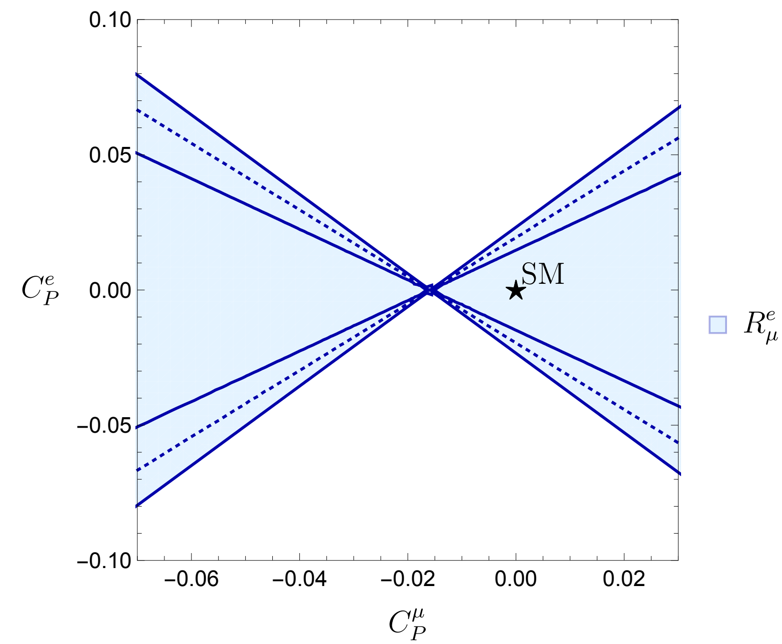
$$\mathcal{C}_{\ell;P} \equiv |\mathcal{C}_{\ell;P}| e^{i\phi_\ell} = \left[\frac{M_{B^-}^2}{m_\ell(m_b + m_q)}\right] C_P^\ell$$

- Currently available data:

$$
\begin{aligned}
\mathcal{B}(B^- \to e^-\bar{\nu}_e)|_{\text{Belle 07}} &< 9.8\times 10^{-7}\,\text{(90\% C.L.)}\\
\mathcal{B}(B^- \to \mu^-\bar{\nu}_\mu)|_{\text{Belle 18}} &= (6.46\pm 2.74)\times 10^{-7}\\
\mathcal{B}(B^- \to \tau^-\bar{\nu}_\tau)|_{\text{PDG}} &= (1.09\pm 0.24)\times 10^{-4}
\end{aligned}
$$

$$\Rightarrow \quad R_\mu^\tau = 0.76\pm 0.36, \quad R_\mu^e < 6.48\times 10^4 \quad \Rightarrow$$





[Leptonic B_c^- decays and lifetime: Alonso, Grinstein & J. Martin Camalich (2017), ...]

CP Violation in Leptonic Decays

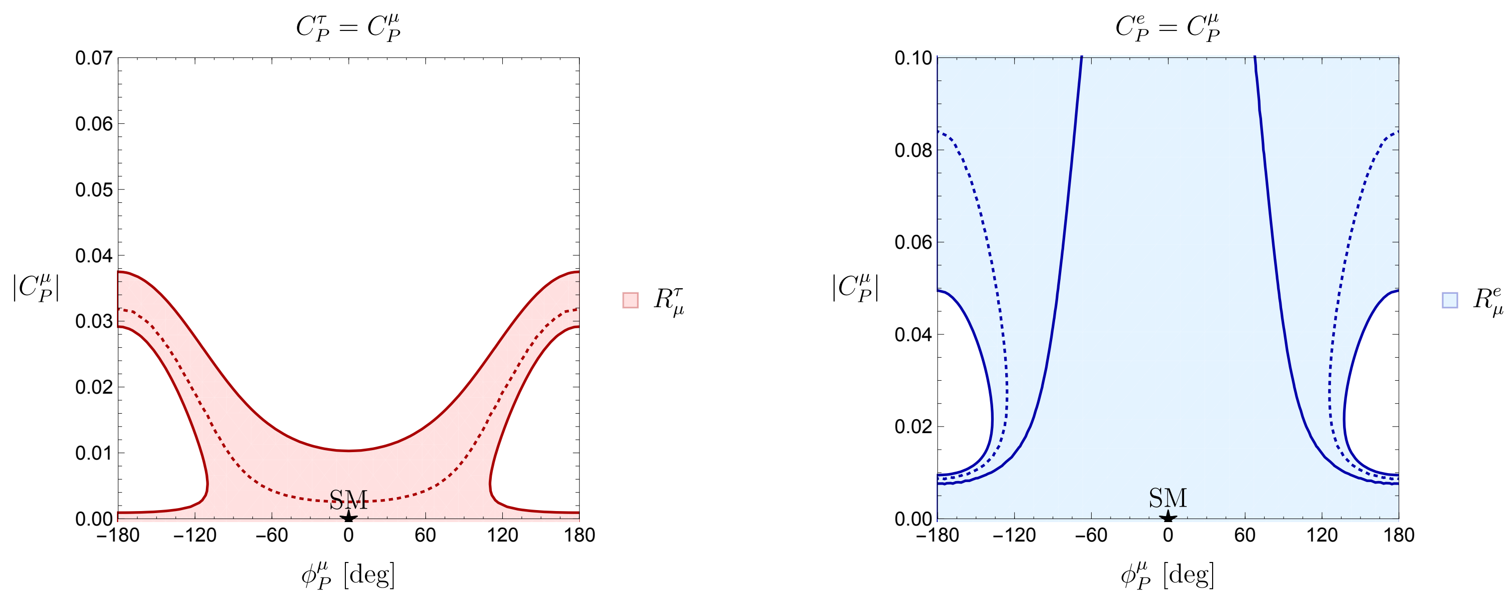
- CP asymmetries: $\rightarrow$ *only direct CP violation (charged decays)*

$$a_{\mathrm{CP}} \equiv \frac{\mathcal{B}(\bar{B} \to \bar{f}) - \mathcal{B}(B \to f)}{\mathcal{B}(\bar{B} \to \bar{f}) + \mathcal{B}(B \to f)}$$

vanish in leptonic decays at leading order in weak interactions while higher-order-effects can only generate negligible effects:

$\Rightarrow$ CP-violating NP phases would not be signalled!

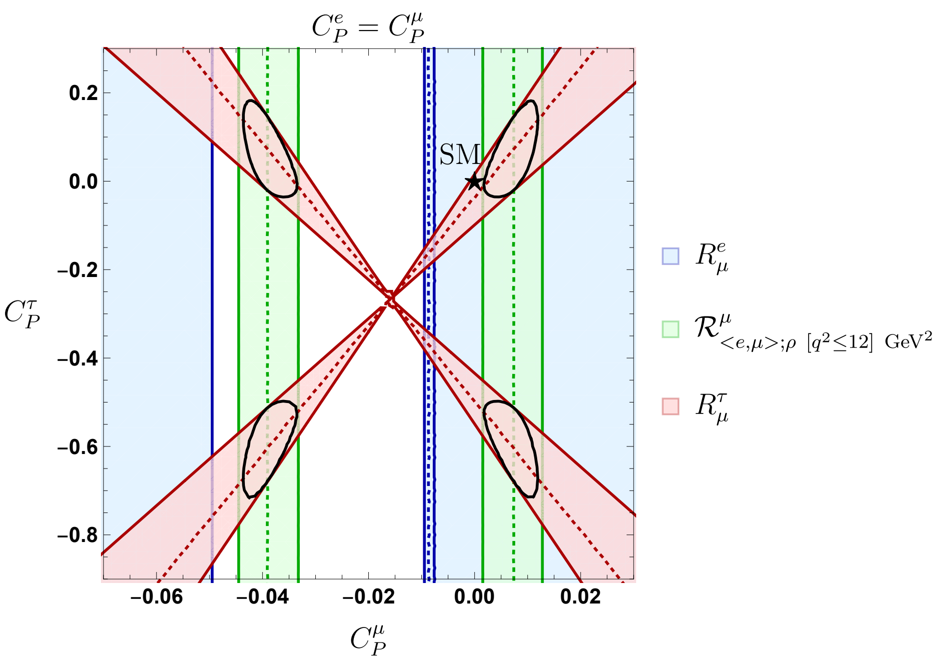
- New Physics regions in the ϕ_P^μ–$|C_P^\mu|$ plane, assuming flavour universality for the pseudoscalar Wilson coefficients of μ, τ and μ, e:

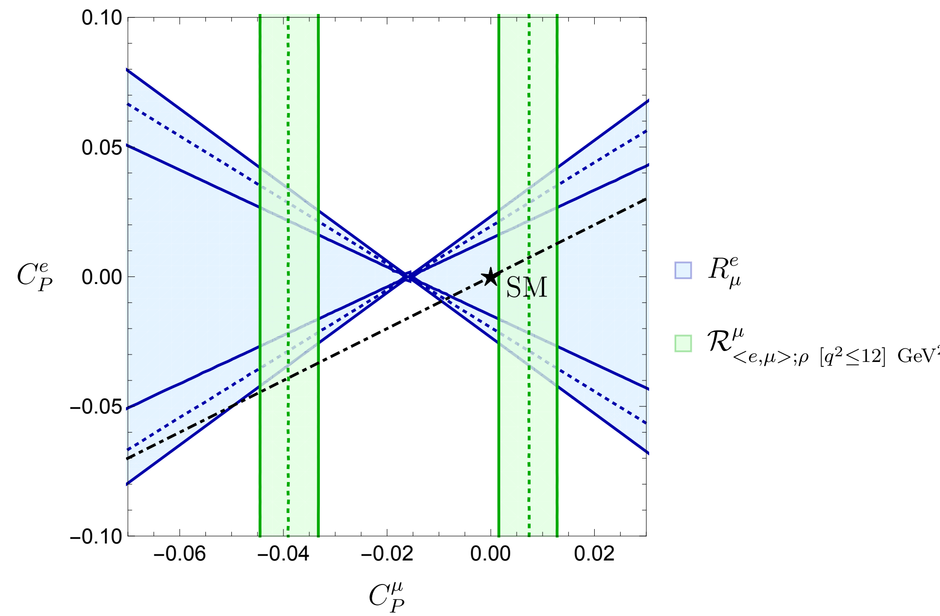


Further Constraints: Semi-Leptonic Decays

- Ratios of branching ratios: $\rightarrow$ *independent of* $|V_{ub}|$

$$\mathcal{R}^{e}_{e;\pi} \equiv \frac{\mathcal{B}(B^- \to e\bar{\nu}_e)}{\mathcal{B}(\bar{B} \to \pi e^- \bar{\nu}_e)},\ \mathcal{R}^{\mu}_{\mu;\pi} \equiv \frac{\mathcal{B}(B^- \to \mu^-\bar{\nu}_\mu)}{\mathcal{B}(\bar{B} \to \pi \mu^- \bar{\nu}_\mu)},\ \mathcal{R}^{\tau}_{\tau;\pi} \equiv \frac{\mathcal{B}(B^- \to \tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to \pi \tau^- \bar{\nu}_\tau)}$$

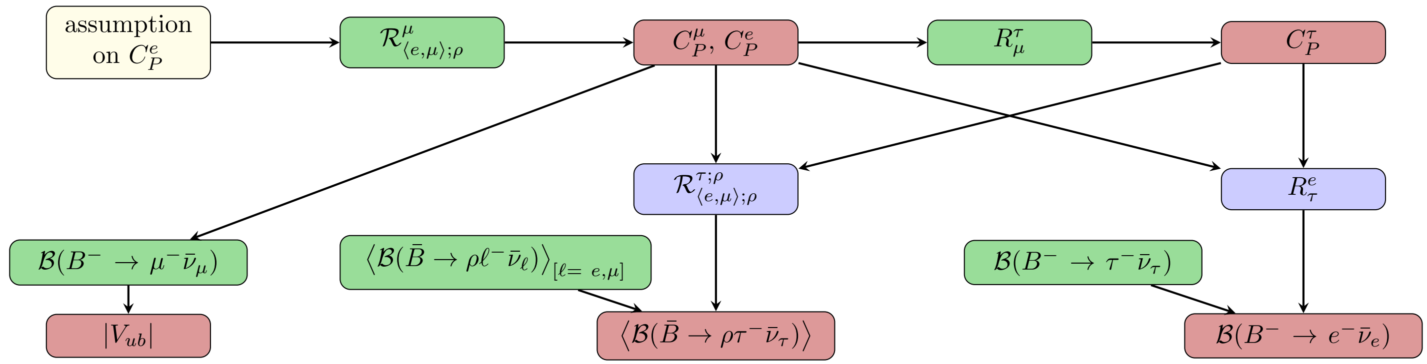




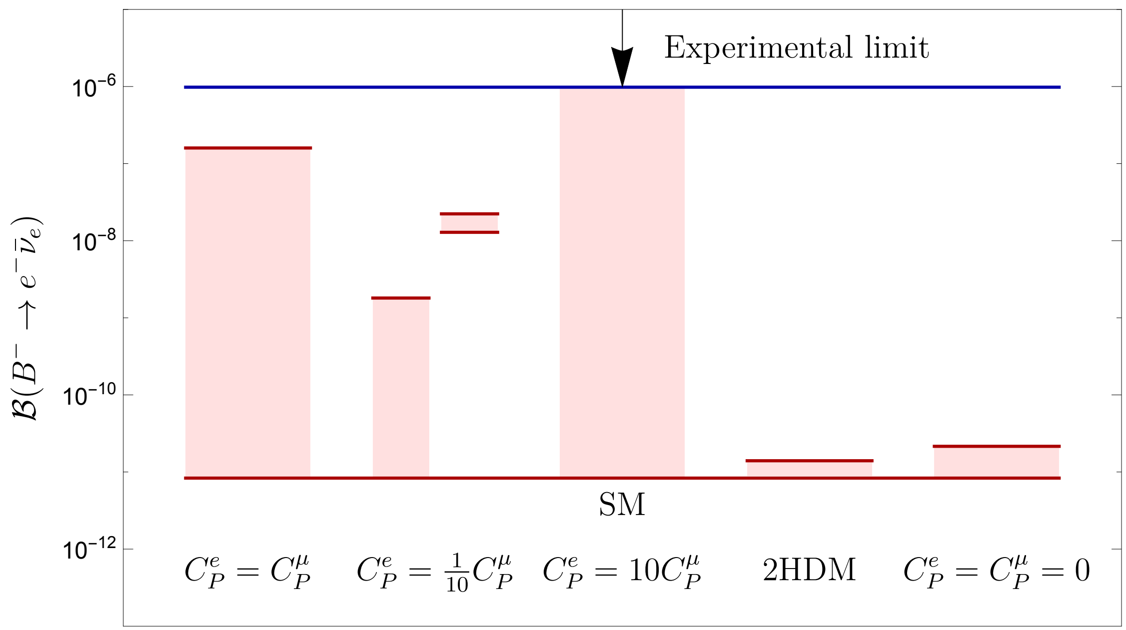
... interesting subtleties, etc., ...

$\Rightarrow$ various studies: $\rightarrow$ see our papers [arXiv:1809.09051, arXiv:1809.09051] ...

- New strategies for the determination of $|V_{ub}|$ and predictions of unmeasured observables in the presence of New Physics:



- May lift the helicity suppression for $B^- \to e^-\nu_e$: $\to$ *illustrations:*



$\Rightarrow$ $\boxed{\textit{search for it} \ldots}$

Conclusions

and

Outlook

Towards New Frontiers with Leptonic B Decays

- Neutral leptonic rare $B_{s,d} \to \ell^+\ell^-$ decays:
  - $\Delta\Gamma_s$ provides access to another (theoretically clean) observable $\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s}$:

    $\to$ *pioneering LHCb measurement* $\Rightarrow$ fully exploit in the future.
  - $\overline{\mathcal{B}}(B_s \to e^+e^-)$ could be as large as $\mathcal{O}(\overline{\mathcal{B}}(B_s \to \mu^+\mu^-))$:

    $\to$ *search for* $B_{s(d)} \to e^+e^-$ *at the LHC* $\to$ *would give clear NP signal!*
  - Interesting strategies for revealing new sources of CP violation.

- Charged leptonic $B^- \to \ell^-\bar{\nu}_\ell$ decays:
  - Offer interesting probes of lepton flavour universality in a clean setting.
  - Powerful interplay with semileptonic $B \to \rho\ell\bar{\nu}_\ell$, $B \to \pi\ell\bar{\nu}_\ell$, ... decays.
  - $\mathcal{B}(B^- \to e^-\bar{\nu}_e)$ could be hugely enhanced:

    $\to$ *search for this channel at Belle II* $\to$ *would give clear NP signal!*

$\Rightarrow$ $\boxed{\text{Exciting topics for the era of Belle II, LHC upgrade and beyond!}}$