Theory of leptonic rare B decays: $B_{s,d} \to \ell^+\ell^-$

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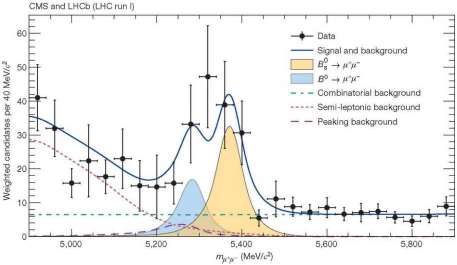
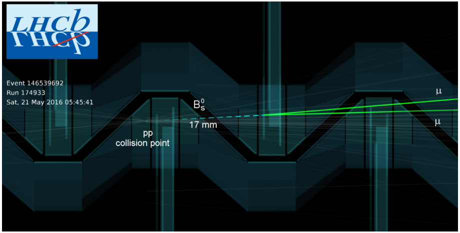
$B_{s,d} \to \mu^+\mu^-,\ B_{s,d} \to \tau^+\tau^-,\ B_{s,d} \to e^+e^-$

Very rare according to the SM:Loop induced, helicity suppressed.

Sensitive to the presence of New Physics (NP) scalars and pseudo-scalar particles.

Challenging to be measured.





$B_s \to \mu^+\mu^-$ has been observed: LHCb + CMS

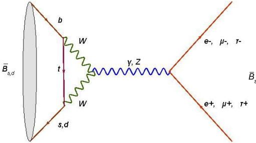
$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)_{CMS'13} = \left(3.0^{+1.0}_{-0.9}\right) \times 10^{-9}$ $\qquad$ $\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)_{LHCb'17} = \left(3.0 \pm 0.6^{+0.3}_{-0.2}\right) \times 10^{-9}$

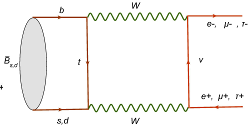
Nature 522, 68 –72 (04 June 2015),
Phys. Rev. Lett. 111, (2013) 101804, arXiv:1307.5025 [hep-ex],
Phys. Rev. Lett. 118, (2017) 191801, arXiv:1703.05747 [hep-ex].

*The "measurable" branching ratio is denoted as $\bar{\mathcal{B}}$ rather than $\mathcal{B}$, see explanation ahead.

Key Features of $B_q \to \ell^+\ell^-$ in the SM

- Tiny decay probabilities due to loop (FCNC) and helicity suppression(m_ℓ^2).





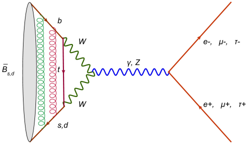
$$A(B_q \to \ell^+\ell^-) \propto m_\ell V_{tq}^* V_{tb} f_{B_q} M_{B_q} C_{10}^{\rm SM} \quad \Longrightarrow \quad \overline{\mathcal{B}}(B_q \to \ell^+\ell^-) \propto m_\ell^2$$

EW loop contributions contained in C_{10}^{SM} (Real in the SM, non CP violation).

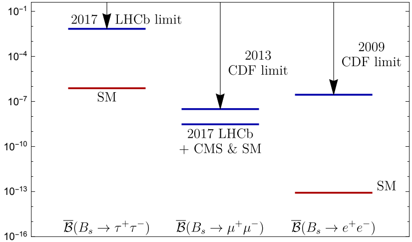
- Non hadronic final states lead to very clean and precise calculations.

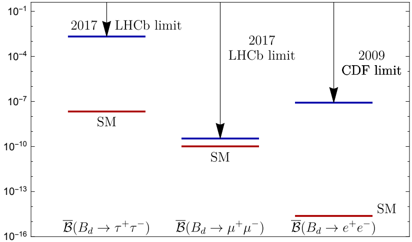
Hadronic information is contained only in the decay constant f_{B_q} (lattice precision $\mathcal{O}(2\%)$).

See lattice QCD Theory Session by C. Bouchard.



Experimental and theoretical status





Only $\bar{\mathcal{B}}(B_s \to \mu^+\mu^-)$ has been measured at the moment.

$\bar{\mathcal{B}}(B_s \to \tau^+\tau^-)$ challenging to measure due to difficult τ reconstruction.

Any measurement of $\bar{\mathcal{B}}(B_{s(d)} \to e^+e^-) \Longrightarrow$ strong evidence of NP.
(within the capabilities of current or foreseeable experiments)

Theoretical formalism

The theoretical formalism will be discussed using $B_s \to \ell^+\ell^-$ as an example.

To describe $B_d \to \ell^+\ell^-$ replace: $V_{ts} \to V_{td}, \quad m_s \to m_d, \quad f_{B_s} \to f_{B_d}$

(Also mixing parameters although they are tiny, see later).

The decay processes $B_s \to \ell^+\ell^-$ are described using an Effective Theory approach

The effective Hamiltonian used is:

$$\mathcal{H}_{\rm eff} = -\frac{G_{\rm F}}{\sqrt{2}\pi} V_{ts}^* V_{tb} \alpha \left[C_{10}^{\ell\ell} O_{10} + C_P^{\ell\ell} O_P + C_S^{\ell\ell} O_S + C_{10}^{\ell\ell'} O_{10}' + C_S^{\ell\ell'} O_S' + C_P^{\ell\ell'} O_P' \right] + h.c..$$

$$O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5\ell) \quad : \quad \text{vector operator,}$$

$$O_P = m_b(\bar{s}P_R b)(\bar{\ell}\gamma_5\ell) \quad : \quad \text{pseudo-scalar operator,}$$

$$O_S = m_b(\bar{s}P_R b)(\bar{\ell}\ell) \quad : \quad \text{scalar operator.}$$

$$\ell = \mu,\ e,\ \tau \quad P_{L/R} \equiv \frac{1}{2}(1 \mp \gamma_5)\,.$$

Operators O_{10}', O_P', O_S' obtained under the replacement $P_L \Longleftrightarrow P_R$

Theoretical formalism

Useful parameters

$$P_{\ell\ell}^s \equiv \frac{C_{10}^{\ell\ell} - C_{10}^{\ell\ell'}}{C_{10}^{\rm SM}} + \frac{M_{B_s}^2}{2m_\ell}\left(\frac{m_b}{m_b+m_s}\right)\left[\frac{C_P^{\ell\ell} - C_P^{\ell\ell'}}{C_{10}^{\rm SM}}\right] = |P_{\ell\ell}^s| e^{i\varphi_P}$$

$$S_{\ell\ell}^s \equiv \sqrt{1 - 4\frac{m_\ell^2}{M_{B_s}^2}}\frac{M_{B_s}^2}{2m_\ell}\left(\frac{m_b}{m_b+m_s}\right)\left[\frac{C_S^{\ell\ell} - C_S^{\ell\ell'}}{C_{10}^{\rm SM}}\right] = |S_{\ell\ell}^s| e^{i\varphi_S}$$

In the Standard Model:

$$C_{10}^{\ell\ell} = C_{10}^{\rm SM} \neq 0 \quad C_{10}' = C_S^{(\prime)} = C_P^{(\prime)} = 0$$

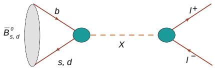
$$P_{\ell\ell}^s|_{\rm SM} = 1 \quad S_{\ell\ell}^s|_{\rm SM} = 0$$

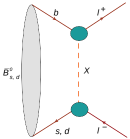
The presence of NP scalar and pseudoscalar particles can lift the helicity suppression,
$\Longrightarrow$ this will enhance $\overline{B}(B_s \to \ell^+\ell^-)$, important case $\ell = e$.

(possible scenarios: leptoquarks, SUSY, ...)

A. J. Buras, R. Fleischer et al., JHEP 1307 (2013) 77, arXiv:1303.3820[hep-ph]

W. Altmannshofer, et al., JHEP 05, (2017), arXiv 1702.05498 [hep-ph].





Theoretical formalism

$$A(\bar{B}_s^0 \to \ell_\lambda^+ \ell_\lambda^-) = \langle \ell_\lambda^- \ell_\lambda^+ | \mathcal{H}_{\rm eff} | \bar{B}_s^0 \rangle, \qquad A(B_s^0 \to \ell_\lambda^+ \ell_\lambda^-) = \langle \ell_\lambda^- \ell_\lambda^+ | \mathcal{H}_{\rm eff}^\dagger | B_s^0 \rangle$$

$\lambda =$ L, R: helicity of the final state lepton.

Since measuring helicities is challenging, consider:

$$\Gamma(B_s^0(t) \to \ell^+ \ell^-) \equiv \sum_{\lambda = \rm L,R} \Gamma(B_s^0(t) \to \ell_\lambda^+ \ell_\lambda^-),$$

time evolution accounts for mixing effects $B_s^0 \Leftrightarrow \bar{B}_s^0$.

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

Experimentally measurable quantity:

$$\overline{\mathcal{B}}\left(B_s \to \ell^+ \ell^-\right) \equiv \frac{1}{2} \int_0^\infty \langle \Gamma(B_s(t) \to \ell^+ \ell^-) \rangle \, dt$$

K. De Bruyn, R. Fleischer et al., Phys. Rev. Lett. 109, 041801 (2012), arXiv:1204.1737 [hep-ph]

Theoretical formalism

Theorists calculate the following branching ratio in the SM:

$$\mathcal{B}(B_s \to \ell^+\ell^-)|_{\rm SM} = m_\ell^2 \frac{\tau_{B_s} G_F^4 M_W^4 \sin^4\theta_W}{8\pi^5} \left| V_{ts} V_{tb}^* \right|^2 f_{B_s}^2 M_{B_s} \sqrt{1 - \frac{m_\ell^2}{M_{B_s}^2}} \left| C_{10}^{SM} \right|^2 .$$

The physically measurable quantity includes NP and mixing effects:

$$\overline{\mathcal{B}}(B_s \to \ell^+\ell^-) = \mathcal{B}(B_s \to \ell^+\ell^-)|_{\rm SM} \times \left\{ \left[\frac{1 + y_s \cos(2\varphi_P - \phi_s^{NP})}{1 - y_s^2} \right] |P_{\ell\ell}^s|^2 + \left[\frac{1 - y_s \cos(2\varphi_S - \phi_s^{NP})}{1 - y_s^2} \right] |S_{\ell\ell}^s|^2 \right\}.$$

m_ℓ^2	:	Lepton mass (helicity suppression factor).
f_{B_s}	:	B_s meson decay constant.
C_{10}^{SM}	:	EW loop functions.
$y_s = \Delta\Gamma_s/\Gamma_s$	:	Neutral B_s meson mixing factor.
$\phi_s^{\rm NP}$	:	NP effects in mixing $\approx 0.4^\circ$ (HFAG)
$P_{\ell\ell}^s = \lvert P_{\ell\ell}^s\rvert e^{i\varphi_P}, \quad S_{\ell\ell}^s = \lvert S_{\ell\ell}^s\rvert e^{i\varphi_S}$	:	Scalar and pseudoscalar New Physics functions.

In the SM $\quad \overline{\mathcal{B}}(B_s \to \ell^+\ell^-) = \frac{1}{1-y_s} \times \mathcal{B}(B_s \to \ell^+\ell^-)$

Mismatch between theoretical and experimental determination given by $1/(1-y_s)$

Theoretical formalism

To extract NP information out of $\mathcal{B}(B_s \to \ell^+\ell^-)$ introduce the ratio:

$$\overline{R}^s_{\ell\ell} \equiv \frac{\overline{\mathcal{B}}(B_s \to \ell^+\ell^-)}{\overline{\mathcal{B}}(B_s \to \ell^+\ell^-)|_{\rm SM}}$$

$$\overline{R}^s_{\ell\ell} = \left[\frac{1 + y_s \cos(2\varphi^{\ell\ell}_{P_s} - \phi^{\rm NP}_s)}{1 + y_s}\right] |P_{\ell\ell}|^2 + \left[\frac{1 - y_s \cos(2\varphi^{\ell\ell}_{S_s} - \phi^{\rm NP}_s)}{1 + y_s}\right] |S_{\ell\ell}|^2$$

If the scalar and pseudoscalar phases are trivial $(\varphi^{\ell\ell}_P, \varphi^{\ell\ell}_S \in \{0, \pi\})$

$$\overline{R}^s_{\ell\ell} \approx |P_{\ell\ell}|^2 + |S_{\ell\ell}|^2$$

$|P_{\ell\ell}|$ is correlated with $|S_{\ell\ell}|$ through a circumference of radious $\sqrt{\overline{R}^s_{\ell\ell}}$,

tiny corrections from y_s.

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

Current experimental and theoretical status for the branching ratio

$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)|_{\mathrm{LHCb'17+CMS'13}} = (3.00 \pm 0.5) \times 10^{-9}$$
$$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)|_{\mathrm{SM}} = (3.57 \pm 0.16) \times 10^{-9}$$

Electromagnetic corrections below m_b lead to effects of about 1% to the SM value.

M. Beneke, C. Bobeth and R. Szafron, Phys. Rev. Lett. 120 (2018) 011801, arXiv:1708.09152 [hep-ph].

Combining theory and experiment for the branching ratio we extract:

$$\overline{R}^{s}_{\mu\mu}\Big|_{\text{LHCb'17+CMS}} = 0.84 \pm 0.16$$

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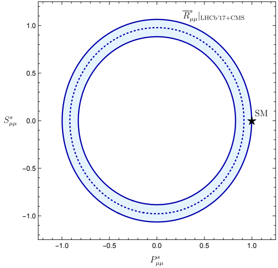

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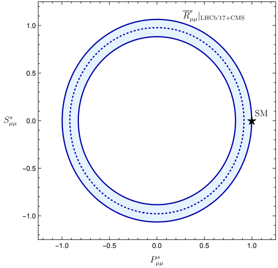

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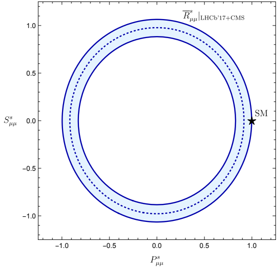

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$|P^s_{\ell\ell}|$ and $|S^s_{\ell\ell}|$ not uniquely determined.

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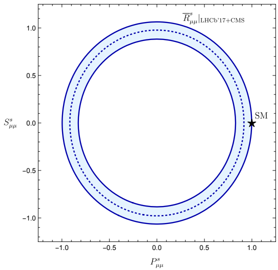

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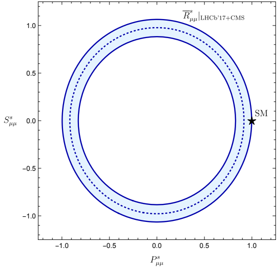

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Can we do better?.

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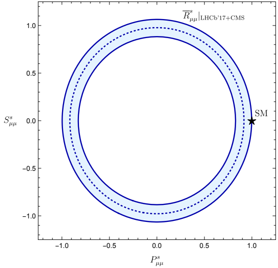

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Can we do better?.

potentially YES!.

The observable $\mathcal{A}^{\ell\ell}_{\Delta\Gamma_s}$

The untagged decay rate give us the observable $\mathcal{A}^{\ell\ell}_{\Delta\Gamma_s}$

$$
\begin{aligned}
\langle\Gamma(B_s(t)\to\ell^+\ell^-)\rangle &\equiv \Gamma(B^0_s(t)\to\ell^+\ell^-)+\Gamma(\bar{B}^0_s(t)\to\ell^+\ell^-) \\
&\propto e^{-t/\tau_{B_s}}\left[\cosh(y_s t/\tau_{B_s})+\mathcal{A}^{\ell\ell}_{\Delta\Gamma_s}\sinh(y_s t/\tau_{B_s})\right]
\end{aligned}
$$

$\mathcal{A}^{\ell\ell}_{\Delta\Gamma_s}$ is sensitive to $P^s_{\ell\ell}$ and $S^s_{\ell\ell}$

$$
\mathcal{A}^{\ell\ell}_{\Delta\Gamma_s}=\frac{|P^s_{\ell\ell}|^2\cos(2\varphi^{\ell\ell}_{P_s}-\phi^{\rm NP}_s)-|S^s_{\ell\ell}|^2\cos(2\varphi^{\ell\ell}_{S_s}-\phi^{\rm NP}_s)}{|P^s_{\ell\ell}|^2+|S^s_{\ell\ell}|^2}.
$$

Model independent relation $-1\le\mathcal{A}^{\ell\ell}_{\Delta\Gamma_s}\le+1$ in particular $\mathcal{A}^{\ell\ell}_{\Delta\Gamma_s}|_{\rm SM}=+1$.

Equivalently to $\mathcal{A}^{\ell\ell}_{\Delta\Gamma_s}$, the Effective Life-Time is given by

$$
\tau^s_{\ell\ell}\equiv\frac{\int_0^\infty t\,\langle\Gamma(B_s(t)\to\ell^+\ell^-)\rangle\,dt}{\int_0^\infty\langle\Gamma(B_s(t)\to\ell^+\ell^-)\rangle\,dt}\quad\Rightarrow\quad\mathcal{A}^{\ell\ell}_{\Delta\Gamma_s}=\frac{1}{y_s}\left[\frac{(1-y_s^2)\tau^s_{\ell\ell}-(1+y_s^2)\tau_{B_s}}{2\tau_{B_s}-(1-y_s^2)\tau^s_{\ell\ell}}\right].
$$

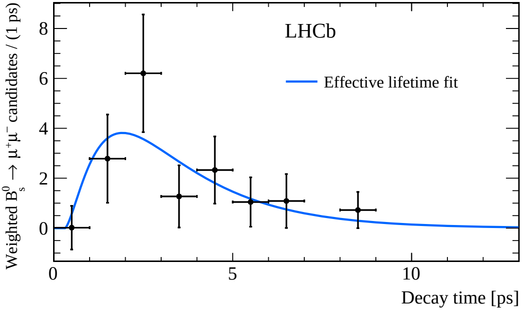
Experimental status of $\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s}$

For $B^0_s \to \mu^+\mu^-$ transitions

$$\tau^s_{\mu\mu}|_{\rm SM} = \frac{\tau_{B_s}}{1-y_s} = (1.61 \pm 0.01)\,\text{ps}.$$

First measurement: $\tau^s_{\mu\mu} = [2.04 \pm 0.44(\text{stat}) \pm 0.05(\text{syst})]\,\text{ps}. \Rightarrow \mathcal{A}^{\mu\mu}_{\Delta\Gamma_s} = 8.24 \pm 10.72$

LHCb Collaboration, Phys. Rev. Lett. 118, 191801 (2017), arXiv:1703.05747 [hep-ex].



Combining $\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)$ with $\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s}$

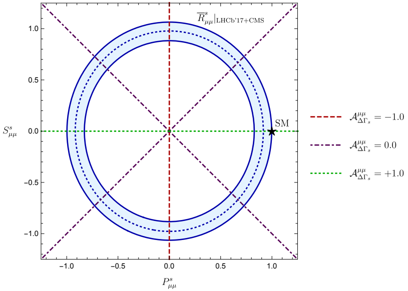
Summarizing our knowledge on $B_s^0 \to \mu^+\mu^-$

$$\overline{R}^s_{\mu^+\mu^-} = \frac{\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)\big|_{\rm LHC}}{\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)\big|_{\rm SM}} = 0.84 \pm 0.16$$

$\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s}|_{\rm LHC} = 8.24 \pm 10.72$ consistent with $-1 \leq \mathcal{A}^{\mu\mu}_{\Delta\Gamma_s} \leq 1$

Improving the measurement of $\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s}$ will provide a more precise determination of $P^s_{\mu\mu}$, $S^s_{\mu\mu}$

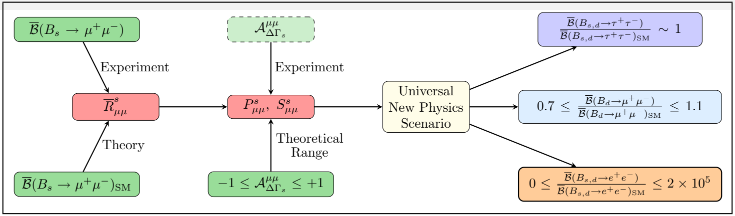
Our first results are derived considering $\varphi_P^{\ell\ell}, \varphi_S^{\ell\ell} \in \{0, \pi\}$. For a generalization see ahead...



Learning about:

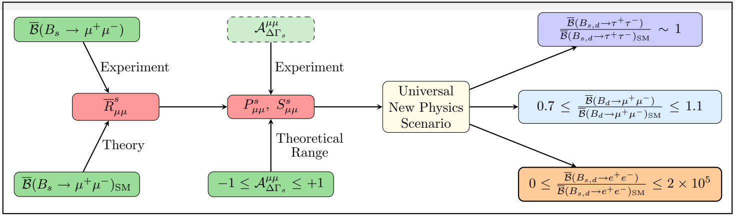
$$B_d \longrightarrow \mu^+\mu^-$$
$$B_{s,d} \longrightarrow e^+e^-$$
$$B_{s,d} \longrightarrow \tau^+\tau^-$$
from $B_s \longrightarrow \mu^+\mu^-$

Strategy



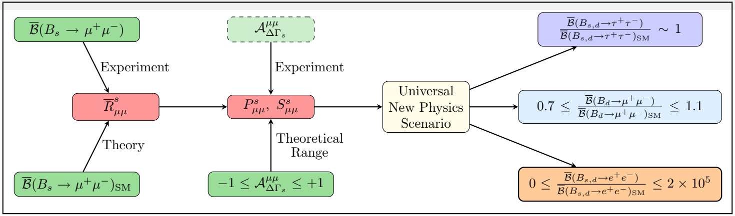
$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)$
$\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s}$
Experiment
Experiment
$\overline{R}^s_{\mu\mu}$
$P^s_{\mu\mu},\ S^s_{\mu\mu}$
Universal New Physics Scenario
Theory
Theoretical Range
$\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)_{\rm SM}$
$-1 \leq \mathcal{A}^{\mu\mu}_{\Delta\Gamma_s} \leq +1$
$\frac{\overline{\mathcal{B}}(B_{s,d}\to\tau^+\tau^-)}{\overline{\mathcal{B}}(B_{s,d}\to\tau^+\tau^-)_{\rm SM}} \sim 1$
$0.7 \leq \frac{\overline{\mathcal{B}}(B_d\to\mu^+\mu^-)}{\overline{\mathcal{B}}(B_d\to\mu^+\mu^-)_{\rm SM}} \leq 1.1$
$0 \leq \frac{\overline{\mathcal{B}}(B_{s,d}\to e^+e^-)}{\overline{\mathcal{B}}(B_{s,d}\to e^+e^-)_{\rm SM}} \leq 2 \times 10^5$

Strategy



- Based on the experimental and SM calculations of $\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)$ determine $\overline{R}^s_{\mu\mu}$.

Strategy



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- Allowing $-1 \leq \mathcal{A}^{\mu\mu}_{\Delta\Gamma_s} \leq +1$ estimate the range for $P^s_{\mu\mu},\ S^s_{\mu\mu}$.

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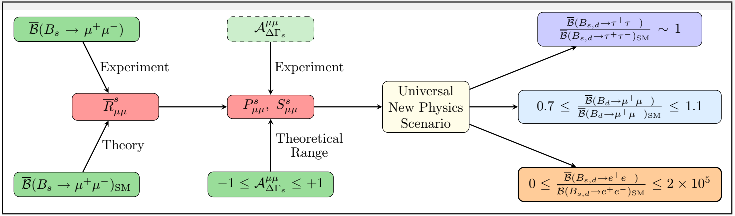

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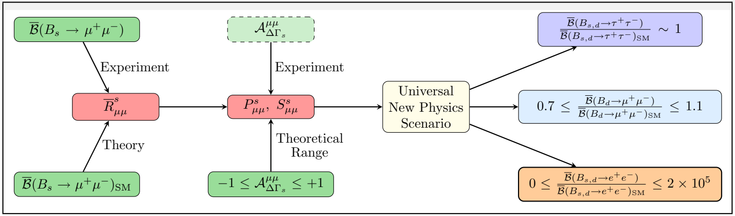
Strategy



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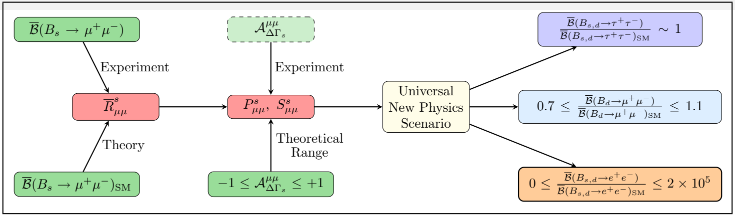
- Make an educated assumption on how $C_{S,P}^{(')\mu\mu}$ correlate with $C_{S,P}^{(')\tau\tau}$ and $C_{S,P}^{(')ee}$.

Strategy



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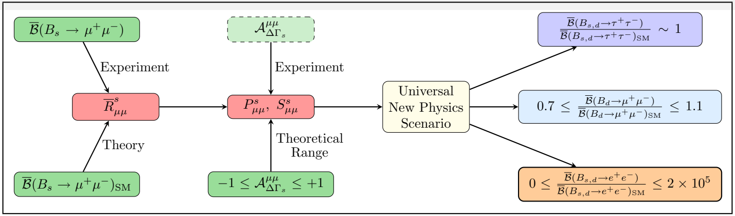
Strategy



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- Make an educated assumption on how $C^{(\prime)\mu\mu}_{S,P}$ correlate with $C^{(\prime)\tau\tau}_{S,P}$ and $C^{(\prime)ee}_{S,P}$.
- Evaluate the impact on: $B^0_d \to \mu^+\mu^-$, $B^0_{s,d} \to \tau^+\tau^-$ and $B^0_{s,d} \to e^+e^-$.

Here we will explore the simplest possibility: $C^{(\prime)\mu\mu}_{S,P} = C^{(\prime)\tau\tau}_{S,P} = C^{(\prime)ee}_{S,P}$.

We will call to this model: Universal New Physics Scenario.

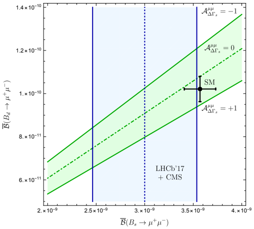
R. Fleischer, R. Jaarsma, G. Tetlalmatzi, JHEP 1705 (2017) 156, arXiv:1703.10160 [hep-ph]

$$U^{ds}_{\mu\mu} \equiv \sqrt{\frac{|P^d_{\mu\mu}|^2 + |S^d_{\mu\mu}|^2}{|P^s_{\mu\mu}|^2 + |S^s_{\mu\mu}|^2}} \propto \left(\frac{f_{B_s}}{f_{B_d}}\right)^2 \left|\frac{V_{ts}}{V_{td}}\right|^2 \frac{\overline{\mathcal{B}}(B^0_d \to \mu^+\mu^-)}{\overline{\mathcal{B}}(B^0_s \to \mu^+\mu^-)}$$

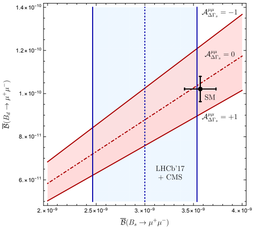
$U^{ds}_{\mu\mu}|_{\rm SM} = 1$ Useful to test consistency with Universality.

$$0.66 \times 10^{-10} \leq \overline{\mathcal{B}}(B_d \to \mu^+\mu^-) \leq 1.14 \times 10^{-10} \quad \Rightarrow \quad 0.65 \leq \overline{R}^d_{\mu\mu} \leq 1.11$$

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



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



Universal New Physics Scenario effects on $B^0_{s,d} \to \tau^+\tau^-$

Standard Model

$$\overline{\mathcal{B}}(B_s \to \tau^+\tau^-)\Big|_{\rm SM} = (7.56 \pm 0.35) \times 10^{-7}$$

$$\overline{\mathcal{B}}(B_d \to \tau^+\tau^-)\Big|_{\rm SM} = (2.14 \pm 0.12) \times 10^{-8}$$

Experiment (LHCb 2017)

$$\overline{\mathcal{B}}(B_s \to \tau^+\tau^-) < 6.8 \times 10^{-3} \text{ (95\% C.L.)}$$

$$\overline{\mathcal{B}}(B_d \to \tau^+\tau^-) < 2.1 \times 10^{-3} \text{ (95\% C.L.)}$$

The NP effects in the μ are mapped out to the τ through:

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

m_τ suppresses the NP contributions.

$$\frac{m_\mu}{m_\tau} = 0.059$$

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

Universal New Physics Scenario effects on $B^0_{s,d} \to e^+e^-$

Standard Model

$$\overline{\mathcal{B}}(B_s \to e^+e^-)\Big|_{\mathrm{SM}} = (8.35 \pm 0.39) \times 10^{-14}$$

Experiment (CDF 2009)

$$\overline{\mathcal{B}}(B_s \to e^+e^-) < 2.8 \times 10^{-7}$$

In the SM $\overline{\mathcal{B}}(B_s \to e^+e^-) \propto m_e^2 \Rightarrow$ helicity suppression

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Universal New Physics Scenario

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

$$\frac{m_\mu}{m_e} = 206.77$$

m_e amplifies the new physics contributions.

For the analogous case in leptonic B decays see G. Banelli's poster.

Universal New Physics Scenario effects on $B^0_{s,d} \to e^+e^-$

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$$\frac{m_\mu}{m_e} = 206.77$$

m_e amplifies the new physics contributions.

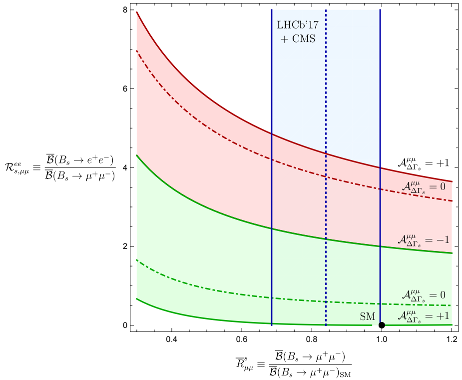
For the analogous case in leptonic B decays see G. Banelli's poster.

$$0 \leq \overline{\mathcal{B}}(B_s \to e^+e^-) \leq 1.4 \times 10^{-8} \quad 0 \leq \frac{\overline{\mathcal{B}}(B_s \to e^+e^-)}{\overline{\mathcal{B}}(B_s \to e^+e^-)\Big|_{SM}} \leq 1.7 \times 10^5$$

FACTOR OF 20 BELOW CDF BOUND

Universal New Physics Scenario effects on $B^0_{s,d} \to e^+e^-$

$$0 \leq \frac{\overline{\mathcal{B}}(B_s \to e^+e^-)}{\overline{\mathcal{B}}(B_s \to \mu^+\mu^-)} \leq 4.8$$



Standard Model

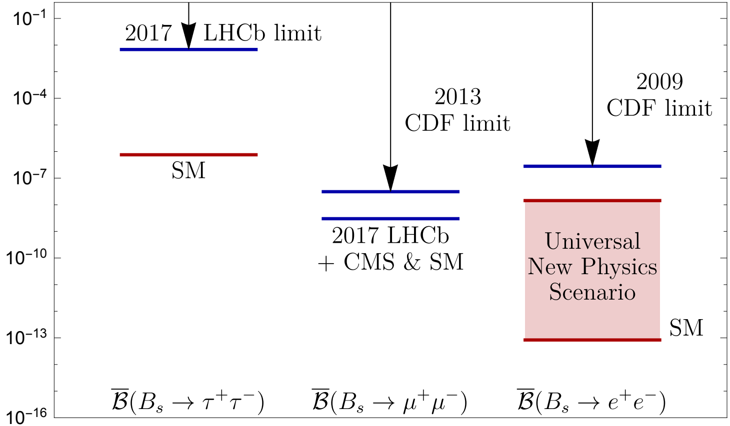
$$\overline{\mathcal{B}}(B_d \to e^+e^-)\Big|_{\rm SM} = (2.39 \pm 0.14) \times 10^{-15}$$

Experiment (CDF 2009)

$$\overline{\mathcal{B}}(B_d \to e^+e^-) < 8.3 \times 10^{-8}$$

Universal New Physics Scenario $0 \leq \overline{\mathcal{B}}(B_d \to e^+e^-) \leq 4.0 \times 10^{-10}$.

Universal New Physics Scenario effects on $B_{s,d}^0 \to e^+e^-$



Dramatic enhancement: motivation for experimental searches

A measurement of $\overline{\mathcal{B}}(B_{s,d} \to e^+e^-)$ would be a signal of new physics!

Assessing the effects of CP Violation phases in $B_s \to \mu^+\mu^-$

CP Violation in rare B decays

Previous assumption : $\varphi_{P_s}^{\mu\mu}, \varphi_{S_s}^{\mu\mu} \in \{0, \pi\}$

What would be the smoking gun of New CP violation phases in rare decays?

It is possible to develop a strategy sensitive to New Weak phases in rare decays!

CP violation effects in hadronic decays see K. Vos talk.

CP violation effects in leptonic and semileptonic decays see G. Banelli's poster.

Consider the time dependent asymmetries

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

λ: lepton helicity.

Non trivial φ_P and φ_S can be unveiled using $\mathcal{A}_{\Delta\Gamma_s}^\lambda$, $\mathcal{S}_{\mu\mu}^\lambda$, $\mathcal{C}_{\mu\mu}^\lambda$.

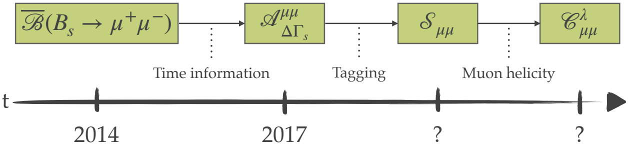
R. Fleischer, D. Galarraga, R. Jaarsma, G. Tetlalmatzi, Eur.Phys.J. C78 (2018) no.1, 1, arXiv:1709.04735 [hep-ph].

CP Violation in rare B decays

$$\mathcal{C}^{\lambda}_{\mu\mu} \equiv \frac{1-|\xi^{\mu\mu}_{\lambda}|^2}{1+|\xi^{\mu\mu}_{\lambda}|^2}, \quad \mathcal{S}^{\lambda}_{\mu\mu} \equiv \frac{2\,\mathrm{Im}\,\xi^{\mu\mu}_{\lambda}}{1+|\xi^{\mu\mu}_{\lambda}|^2}, \quad \mathcal{A}^{\lambda,\mu\mu}_{\Delta\Gamma} \equiv \frac{2\,\mathrm{Re}\,\xi^{\mu\mu}_{\lambda}}{1+|\xi^{\mu\mu}_{\lambda}|^2}$$

$$\xi^{\mu\mu}_{\lambda} \equiv -e^{-i\phi_s}\left[e^{i\phi_{\mathrm{CP}}(B_s)}\frac{A(\bar{B}^0_s \to \mu^+_{\lambda}\mu^-_{\lambda})}{A(B^0_s \to \mu^+_{\lambda}\mu^-_{\lambda})}\right], \quad \phi_s \equiv 2\mathrm{arg}(V^*_{ts}V_{tb}), \quad (\mathcal{CP})|B^0_s\rangle = e^{i\phi_{\mathrm{CP}}(B_s)}|\bar{B}^0_s\rangle$$

Time line for the determination of the CP asymmetries



Scalar and pseudoscalar contributions to CP Asymmetries

Sensitivity to scalar and pseudoscalar NP contributions.

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

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

$$\mathcal{A}_{\Delta\Gamma_s}^{\lambda,\mu\mu} = \frac{|P|^2 \cos(2\varphi_P - \phi_s^{\mathrm{NP}}) - |S|^2 \cos(2\varphi_S - \phi_s^{\mathrm{NP}})}{|P|^2 + |S|^2} \equiv \mathcal{A}_{\Delta\Gamma_s}^{\mu\mu}.$$

In the SM: $\mathcal{A}_{\Delta\Gamma_s}^{SM,\mu\mu} = 1 \quad \mathcal{C}_{\mu\mu} = \mathcal{S}_{\mu\mu} = 0$

CP-asymmetries are theoretically clean, free from the hadronic parameter f_B.

$\mathcal{C}_{\mu\mu}$, $\mathcal{S}_{\mu\mu}$, $\mathcal{A}_{\mu\mu}$ helicity independent.

The three observables are related through:

$$(\mathcal{A}_{\Delta\Gamma_s}^{\mu\mu})^2 + (\mathcal{S}_{\mu\mu})^2 + (\mathcal{C}_{\mu\mu})^2 = 1.$$

A. J. Buras, R. Fleischer et al., JHEP 1307 (2013) 77, arXiv:1303.3820[hep-ph]

CP violation in the SMEFT

Basic relations between Scalar and Pseudo-scalar Wilson coefficients

$$C_P^{\mu\mu} = -C_S^{\mu\mu} \qquad C_P^{'\mu\mu} = C_S^{'\mu\mu}$$

R. Alonso, B. Grinstein and J. Martin Camalich, Phys. Rev. Lett. 113 (2014) 241802, arXiv:1407.7044 [hep-ph].

Change of parameterization $x \equiv |x| e^{i\Delta} \equiv \left| \frac{C_S'}{C_S} \right| e^{i(\tilde{\varphi}'_S - \tilde{\varphi}_S)}$ $\quad \mathcal{C}_{10} \equiv \frac{C_{10} - C'_{10}}{C_{10}^{\mathrm{SM}}} = 1 + \mathcal{C}_{10}^{\mathrm{NP}}$

$$S = |S| e^{i\varphi_S} \qquad P = |P| \cos\varphi_P + i|P| \sin\varphi_P = \mathcal{C}_{10} - \frac{1}{w} \left[\frac{1 + |x| e^{i\Delta}}{1 - |x| e^{i\Delta}} \right] |S| e^{i\varphi_S}$$

The new parameterization makes obvious symmetries between different scenarios.

Example between the cases:

$C_S^{'\mu\mu} = 0$ $(x = 0)$ and $C_S^{\mu\mu} = 0$ $(x = \infty)$.

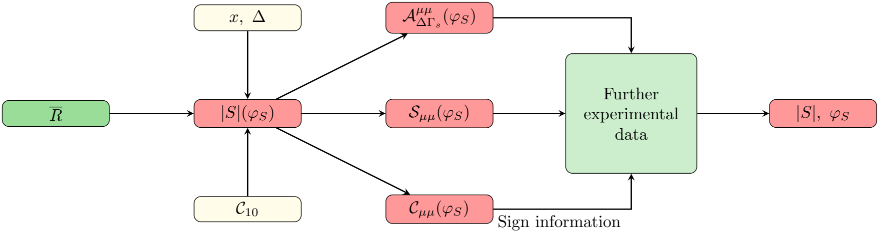
Using experimental data from $B \to K^{(*)}\ell^+\ell^-$ decays we may determine $\mathcal{C}_{10}$

This establishes an interesting bridge with the Flavour Anomalies:

$R_K^{(*)}$ (quark level transition $b \to s\ell^+\ell^-$)

CP Violation in leptonic rare B decays

Strategy for the determination of φ_S and $|S|$



CP Violation in leptonic rare B decays

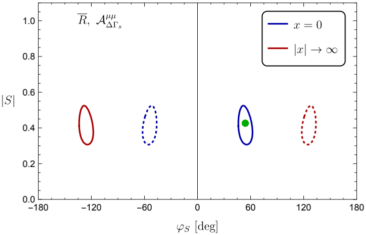
Experimental aspects

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

Deviations from the SM

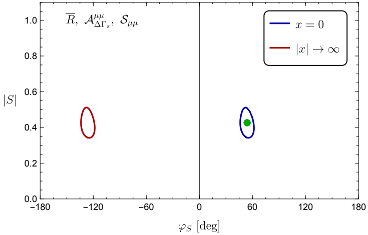
$\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s}$: 2σ, $\mathcal{S}_{\mu\mu}$: 4σ, $\mathcal{C}_{\mu\mu}$: 1σ

χ^2 fit to $\bar{R}$ and $\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s}$



Non-zero value for $|S|$ at 3 σ level

χ^2 fit to $\bar{R}$, $\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s}$ and $\mathcal{S}_{\mu\mu}$



Non-zero value for $|S|$ at 5 σ level

1 σ allowed regions

Exciting prospects for the ultimate precision era!

Conclusions and outlook I

- Rare decays $B_s^0 \to \ell^+\ell^-$ for $\ell = \mu, \tau, e$:

  Theoretically very clean, QCD information only in f_q with $\mathcal{O}(2\%)$ precision.

  Ideal to search for NP effects from scalar and pseudo-scalar particles.

  Also sensitive to vector-like particles Z', ...

- $\overline{\mathcal{B}}(B_s^0 \to e^+e^-)$ forgotten by the High Energy Physics community.

  In the SM $\overline{\mathcal{B}}(B_s^0 \to e^+e^-) \propto m_e^2$ extremely suppressed (helicity suppression).

  Helicity suppression can be lifted by NP scalar and pseudoscalar particles.

- $\overline{\mathcal{B}}(B_s^0 \to \mu^+\mu^-)$ has been measured by LHCb and CMS.

- $B_s^0 \Leftrightarrow \bar{B}_s^0$ mixing gives access to the observable $\mathcal{A}_{\Delta\Gamma_s}^{\mu\mu}$.

- First pioneering determination of $\mathcal{A}_{\Delta\Gamma_s}^{\mu\mu}$ by LHCb.

Conclusions and outlook II

- Using the Universal New Physics Scenario (lepton flavour independent) we have mapped out NP bounds from $\overline{\mathcal{B}}(B_s^0 \to \mu^+\mu^-)$ on

  $B_d \to \mu^+\mu^-$ $\Rightarrow$ small suppression in $\mathcal{B}(B_d \to \mu^+\mu^-)$ respect to the SM.

  $B_{s,d} \to \tau^+\tau^-$ $\Rightarrow$ NP effects are suppressed by m_μ/m_τ in $\mathcal{B}(B_{s,d} \to \tau^+\tau^-)$.

  $B_{s,d} \to e^+e^-$ $\Rightarrow$ potential enhancement of NP effects due to m_μ/m_e in $\mathcal{B}(B_{s,d} \to e^+e^-)$.

  $\Longrightarrow$ Search for $B_{s,d} \to e^+e^-$ at the LHC, a measurement would imply NP!

- Processes $B_{s,d} \to \ell^+\ell^-$ can unveil the presence of NP sources of CP violation.

  This entails the interplay of the CP asymmetries: $\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s}$, $\mathcal{S}_{\mu\mu}$ and $\mathcal{C}_{\mu\mu}$.

  $\Longrightarrow$ Improve the measurement of $\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s}$, paramount in the search for NP phases.

Conclusions and outlook II

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  $\Longrightarrow$ Improve the measurement of $\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s}$, paramount in the search for NP phases.

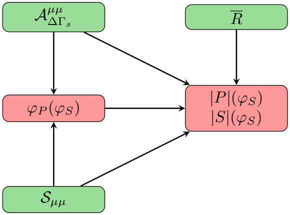
Rare B decays are an exciting subject of study (theory & experiment)!!

Rich an interesting physics structure, not only about branching ratios, also CP asymmetries...

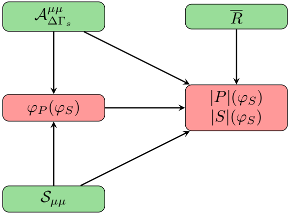
They have the potential to reveal interesting effects in our quest for NP.

Backup Slides

Generic Approach

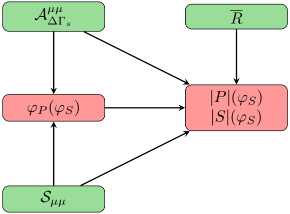


Generic Approach



- Using the expressions for $\mathcal{A}_{\Delta\Gamma_s}^{\mu\mu}$ and $\mathcal{S}_{\mu\mu}$ calculate $\varphi_P(\varphi_S)$.

Generic Approach



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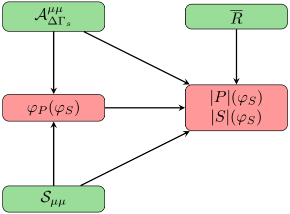
- Calculate $|P|$ and $|S|$ as a function of $\mathcal{A}^{\mu\mu}_{\Delta\Gamma_s}$ (or $\mathcal{S}_{\mu\mu}$), φ_S and $r(\bar{R})$.

Generic Approach



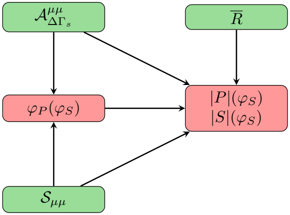
- Using the expressions for $\mathcal{A}_{\Delta\Gamma_s}^{\mu\mu}$ and $\mathcal{S}_{\mu\mu}$ calculate $\varphi_P(\varphi_S)$.
- Calculate $|P|$ and $|S|$ as a function of $\mathcal{A}_{\Delta\Gamma_s}^{\mu\mu}$ (or $\mathcal{S}_{\mu\mu}$), φ_S and $r(\bar{R})$.

$$|P| = \sqrt{\left(\frac{\cos\Phi_S + \mathcal{A}_{\Delta\Gamma_s}^{\mu\mu}}{\cos\Phi_S + \cos\Phi_P}\right) r}, \quad |S| = \sqrt{\left(\frac{\cos\Phi_P - \mathcal{A}_{\Delta\Gamma_s}^{\mu\mu}}{\cos\Phi_P + \cos\Phi_S}\right) r}$$

$$\Phi_P \equiv 2\varphi_P - \phi_s^{\mathrm{NP}}, \quad \Phi_S \equiv 2\varphi_S - \phi_s^{\mathrm{NP}}.$$

$$r \equiv \left[\frac{1+y_s}{1+\mathcal{A}_{\Delta\Gamma_s}^{\mu\mu}}\right]\bar{R} = |P|^2 + |S|^2$$

Generic Approach



- Using the expressions for $\mathcal{A}_{\Delta\Gamma_s}^{\mu\mu}$ and $\mathcal{S}_{\mu\mu}$ calculate $\varphi_P(\varphi_S)$.
- Calculate $|P|$ and $|S|$ as a function of $\mathcal{A}_{\Delta\Gamma_s}^{\mu\mu}$ (or $\mathcal{S}_{\mu\mu}$), φ_S and $r(\bar{R})$.

$$|P| = \sqrt{\left(\frac{\cos\Phi_S + \mathcal{A}_{\Delta\Gamma_s}^{\mu\mu}}{\cos\Phi_S + \cos\Phi_P}\right) r}, \quad |S| = \sqrt{\left(\frac{\cos\Phi_P - \mathcal{A}_{\Delta\Gamma_s}^{\mu\mu}}{\cos\Phi_P + \cos\Phi_S}\right) r}$$

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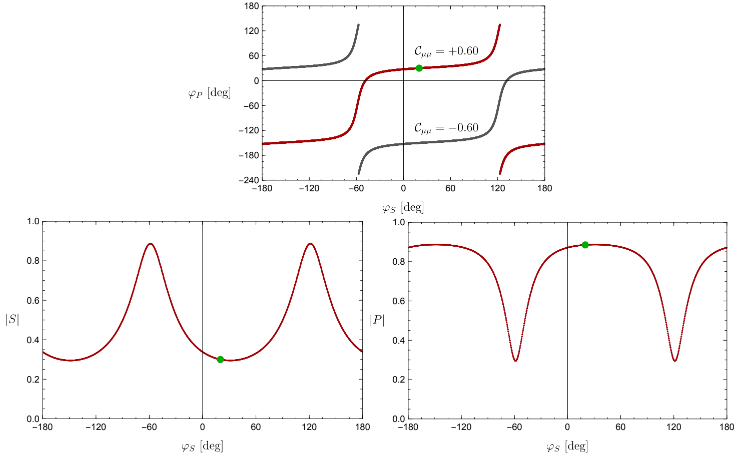
R. Fleischer, D. Galarraga, R. Jaarsma, G. Tetlalmatzi, Eur.Phys.J. C78 (2018) no.1, 1, arXiv:1709.04735 [hep-ph].

Generic Approach

Example

$$\overline{R} = 0.84, \quad \mathcal{A}^{\mu\mu}_{\Delta\Gamma_s} = 0.37, \quad \mathcal{S}_{\mu\mu} = 0.71, \quad \mathcal{C}_{\mu\mu} = 0.60,$$



Lower bounds for the Scalar and Pseudo-scalar contributions. Non trivial phases solutions.

CP Violation in leptonic rare B decays

Working example

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

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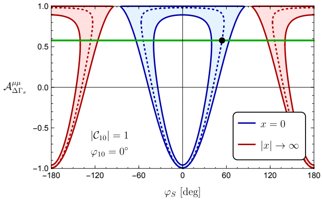
$\mathcal{A}_{\Delta\Gamma_s}^{\mu\mu} = 0.58$



$\varphi_S^{(1)} = -126°$, $\varphi_S^{(2)} = -54°$, $\varphi_S^{(3)} = 54°$, $\varphi_S^{(4)} = 126°$

CP Violation in leptonic rare B decays

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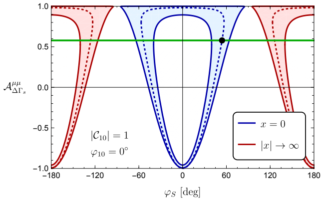

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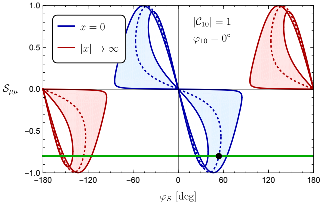

$\varphi_S^{(1)} = -126°$, $\varphi_S^{(3)} = 54°$

CP Violation in leptonic rare B decays

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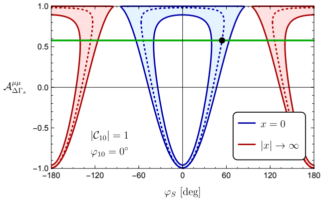

$\varphi_S^{(1)} = -126^\circ$, $\varphi_S^{(2)} = -54^\circ$, $\varphi_S^{(3)} = 54^\circ$, $\varphi_S^{(4)} = 126^\circ$

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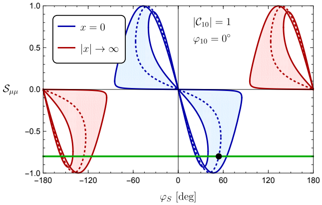
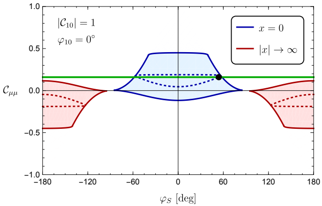


$\varphi_S^{(1)} = -126^\circ$, $\varphi_S^{(3)} = 54^\circ$

$\mathcal{C}_{\mu\mu} = 0.16$



$\varphi_S^{(3)} = 54^\circ$