Relating $B_s$ Mixing and $B_s \rightarrow \mu^+ \mu^-$ with New Physics

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1. Introduction/Motivation

The Standard Model of electromagnetic, weak and strong interactions:

- is a consistent theory that describes all the experimental phenomena in particle physics up to a 100 GeV scale.

plus Higgs doublet $H$

or a physical Higgs state $h$
1. Introduction/Motivation

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- or a physical Higgs state $h$

there are several reasons to believe that the SM should be replaced by a more fundamental theory at energies ~ 100 GeV or larger
$\text{B}_s \rightarrow \mu^+ \mu^-$ - represents the possibility of low-energy indirect search for new physics (NP) beyond the SM.

$\text{B}_s (s \bar{b}), \mu^-, \mu^+$ - are the SM states, $M_{\text{B}_s} = 5.366$ GeV, $m_u = 0.113$ GeV, where should NP come from?
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\( B_s (s \bar{b}), \mu^-, \mu^+ \) - are the SM states, \( M_{B_s} = 5.366 \text{ GeV} \), \( m_\mu = 0.113 \text{ GeV} \), where should NP come from?

SM diagrams for \( B_s \rightarrow \mu^+ \mu^- \) to the leading order: occur due to exchange of heavy W and Z bosons (\( M_W = 80 \text{ GeV} \), \( M_Z = 91 \text{ GeV} \))

NP contribution: diagrams with other heavy (hypothetical) particles
In principle, NP contribution to $B_s \rightarrow \mu^+ \mu^-$ may be greater than that of the SM by orders of magnitude, because:

- The SM contribution occurs at one-loop (subleading order in perturbation theory), suppressed by a loop factor, $\alpha/(4 \pi \sin^2 \theta_W) = 2.5 \times 10^{-3}$

- Mixing between 2-nd and 3-rd quark generations is suppressed as $\lambda^2$ where $\lambda = \sin \theta_C = 0.2259$. 
Also, the helicity flip suppression:
• By conservation of spin, muon and antimuon spins must be oppositely directed, or helicity flip operator is needed. Within the SM that would be the muon mass insertion operator, leads to a suppression factor $m_\mu/M_B \sim 0.02$ in the transition amplitude.

\[ \mu^+ \hspace{1cm} \mu^- \]

\[ p \hspace{1cm} p \]

\[ spin \hspace{1cm} spin \]

Needs $\bar{\mu}_L \ldots \mu_R$ field operator product
The consequence:

\[ B_{B_s \to \mu^+ \mu^-}^{(SM)} \simeq 3.3 \times 10^{-9} \]

Compare to experimental data:

\[ B_{B_s \to \mu^+ \mu^-}^{(expt)} < 4.7 \times 10^{-8} \]

Room for new physics?....

May it happen that due to NP contribution

\[ B(B_s \to \mu^+ \mu^-) >> B^{SM}(B_s \to \mu^+ \mu^-) \]?
Beyond the SM:
• Many SM extensions allow quark Flavor Changing Neutral Currents (FCNC), $B_s \rightarrow \mu^+ \mu^-$ may occur at the tree level.

- Within many SM extensions mixing between quark generations is not suppressed.
- Within many SM extensions we get scalar or pseudoscalar operators with helicity flip.

In other words, NP contribution to $B_s \rightarrow \mu^+ \mu^-$ may exceed the SM contribution by orders of magnitude. Detecting $B_s \rightarrow \mu^+ \mu^-$ at a rate exceeding the SM one would manifest a signal for New Physics!
There is however a process with similar features but a slight (and essential) difference: $B_s - B_s$ oscillations (mixing) – one of the manifestations of mater-to-antimatter oscillations in the Nature.

Within the SM occurs via the “box” diagrams
Brief description of the oscillation formalism:

\[
\mathbf{i} \frac{\partial}{\partial t} \begin{pmatrix} \mathcal{B}_s(t) \\ \overline{\mathcal{B}}_s(t) \end{pmatrix} = \begin{pmatrix} \mathbf{M} - \frac{i}{2} \mathbf{\Gamma} \end{pmatrix} \begin{pmatrix} \mathcal{B}_s(t) \\ \overline{\mathcal{B}}_s(t) \end{pmatrix}
\]

The oscillation is parameterized by off-diagonal elements: \( M_{12} = M_{21}^* \) and \( \Gamma_{12} = \Gamma_{21}^* \) that are related to the transition amplitude.

The mass eigenstates (heavy and light) are

\[
| \mathcal{B}_H \rangle = p | \mathcal{B}_s \rangle - q | \overline{\mathcal{B}}_s \rangle, \quad | \mathcal{B}_L \rangle = p | \mathcal{B}_s \rangle + q | \overline{\mathcal{B}}_s \rangle
\]

where

\[
\left( \frac{q}{p} \right)^2 = \frac{M_{12}^* - \frac{i}{2} \Gamma_{12}^*}{M_{12} - \frac{i}{2} \Gamma_{12}}
\]

The eigenstates mass and width difference are

\[
\Delta M \simeq 2 | M_{12} | \quad \Delta \Gamma \simeq 2 | \Gamma_{12} | \cos \Phi \quad \Phi = \text{arg}(-M_{12}/\Gamma_{12})
\]

Mass and width difference are the physical quantities used to describe meson-antimeson oscillations.
Similarly to $B_s \rightarrow \mu^+ \mu^-$:

- The SM contribution to $B_s$ mixing occurs at one-loop, is suppressed by a loop factor;

- is suppressed as $\lambda^4$, where $\lambda = \sin \theta_C = 0.2259$. 

[Diagram of $B_s$ mixing process with $W^\pm$ and $u, c, t$ quark lines]
Similarly to $B_s \rightarrow \mu^+ \mu^-$:

- Many SM extensions allow quark Flavor Changing Neutral Currents (FCNC), $B_s$ mixing may occur at the tree level.

- Within many SM extensions mixing between quark generations is not suppressed.

Having a large NP contribution to $B_s \rightarrow \mu^+ \mu^-$ we would in general also have a large NP contribution to $B_s$ mixing – these two processes are correlated!
Essential difference is the experimental data

\[ B^{(\text{expt})}_{B_s \to \mu^+ \mu^-} < 4.7 \times 10^{-8} \quad B^{(\text{SM})}_{B_s \to \mu^+ \mu^-} \simeq 3.3 \times 10^{-9} \]

Room for new physics?

The SM predictions for $B_s$ mixing is in agreement with the experiment, e.g. for the mass difference,

\[ \Delta M^{(\text{expt})}_{B_s} = (117.0 \pm 0.8) \times 10^{-13} \text{ GeV} \quad \Delta M^{(\text{SM})}_{B_s} = \left(117.1^{+17.2}_{-16.4}\right) \times 10^{-13} \text{ GeV} \]

The NP contribution to $\Delta M_{B_s}$ is constrained:

\[ |\Delta M^{(\text{NP})}_{B_s}| \leq 17.3 \times 10^{-13} \text{ GeV} \]

Leads to severe constraints on the relevant NP parameters

Because of the correlations between two processes, these constraints on the NP parameters imply also severe constraints on the $B_s \to \mu^+ \mu^-$ branching ratio.
2. Results

Within many SM extensions the NP contribution to $B_s \rightarrow \mu^+ \mu^-$ turns to be much less than the SM contribution, against what would be expected.

Models with $Z'$ boson (extra gauge boson in addition to those within the SM), FCNC’s are allowed with the exchange of $Z'$:

$$\frac{g_{Z's\bar{b}}^2}{M_{Z'}^2} = \frac{3|\Delta M_{B_s}^{(NP)}|}{M_{B_s} f_{B_s}^2 B_{B_s} r_1(m_b, M_{Z'})} \leq 2.47 \times 10^{-11} \text{ GeV}^{-2}$$

$$\mathcal{B}_{B_s \rightarrow \mu^+ \mu^-}^{(Z')} \leq 0.25 \times 10^{-9} \cdot \left(\frac{1 \text{ TeV}}{M_{Z'}}\right)^2$$
Family symmetry models: same charge quarks/leptons are gauge SU(3) triplets → SU(2) doublets – FCNC interactions with exchange of non-Abelian gauge bosons:

\[ B^{(FS)}_{B_s \rightarrow \mu^+ \mu^-} \leq 0.5 \times 10^{-12} \]
Of course, we are not always so successful, often the bounds are functions of some NP parameter, and in some corners of the parameter space, $\mathcal{B}^{NP}(B_s \rightarrow \mu^+ \mu^-)$ may be large enough, e.g. in 4 generation models.
In some models (e.g. RPV SUSY or FCNC Higgs models), $B_s$ mixing and $B_s \rightarrow \mu^+ \mu^-$ may depend on different combinations of NP couplings and masses, there may be no correlations between these two processes.

In these models bound on $B^\text{NP}(B_s \rightarrow \mu^+ \mu^-)$ is derived within simplified scenarios only.
Conclusions

• We studied possible correlations between the NP contribution to $B_s - \bar{B}_s$ mixing and $B_s \rightarrow \mu^+ \mu^-$ decay.

• The SM predictions for $B_s$ mixing are in a decent agreement with the experimental data – the NP contribution must be constrained and the relevant NP parameters must be constrained.

• In many SM extensions the constraints on the NP parameters lead to severe constraints on the $B^{\text{NP}}(B_s \rightarrow \mu^+ \mu^-)$ – no new physics can be seen in this decay.