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Analysis of the $B_s^0 \to \mu^+\mu^-$ decay in the MSSM

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Abstract. The first observation of the $B_s^0 \to \mu^+\mu^-$ decay mode was reported by the CMS and LHCb collaboration. The small branching ratio inherent to this decay mode makes it highly sensitive for probing physics beyond the SM and we analyze this decay in the framework of the Minimal Supersymmetric Standard Model (MSSM). Complete analytical expressions for the decay amplitude at the one-loop order have been obtained with the aid of computational tools such as FeynArts and FeynCalc. The general recipe for utilising these computational tools to aid theoretical calculations in the MSSM is discussed. Working in the phenomenological MSSM with reduced parameter space, a simplification of the complete analytical expression was done to express the $B_s^0 \to \mu^+\mu^-$ branching ratio as a function of these parameters. Numerical studies of the parametric dependence of $B_s^0 \to \mu^+\mu^-$ branching ratio in the phenomenological MSSM can be easily performed with the obtained analytical expression.

1 Introduction

Direct searches for supersymmetric (SUSY) particles in collider experiments are limited in reach by the available center-of-mass energy. More accessible experiments such as electroweak precision tests are therefore crucial as a means to probe for new physics. Perturbative calculations can be carried out in SM extensions to address the contributions of the proposed new particles and viable SM extensions need to agree with experiments within errors. Such experiments thus place important constraints on the parameter landscapes of beyond the SM physics.

The rare dimuon decay of the strange B meson $B_s^0 \to \mu^+\mu^-$ was observed by the CMS and LHCb collaboration [1] with a measured branching ratio of $(2.8^{+0.7}_{-0.6}) \times 10^{-9}$. This particular decay mode is interesting in that its branching ratio predicted by the SM and the Minimal Supersymmetric Standard Model (MSSM) can be different up to a few orders of magnitudes due to new sources of flavour changing neutral currents (FCNC) at the one-loop level. This work describes how computer algebra systems can be used to facilitate perturbative calculations for obtaining an analytical expression of the $B_s^0 \to \mu^+\mu^-$ branching ratio in the phenomenological MSSM. We only focus on this single decay mode, but such a procedure can certainly be generalized to other high energy physics processes. It would be fruitful and fitting to incorporate other rare decay modes, thus addressing the experimental consequences raised by SUSY models and gain insights on their possible parameter landscapes.

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2 CAS for Computing the $B_s^0 \to \mu^+\mu^-$ Branching Ratio

Computer algebra systems (CAS) are indispensable tools in high energy physics; many precise predictions and calculations would be extremely tedious, if not impossible without the help of CAS. As illustrated in figure 1, they facilitate perturbative calculations by automating the procedures of generating contributing Feynman diagrams, performing Dirac algebra and contraction of indices and reduction of tensor loop integrals to the Passarino-Veltman basis.

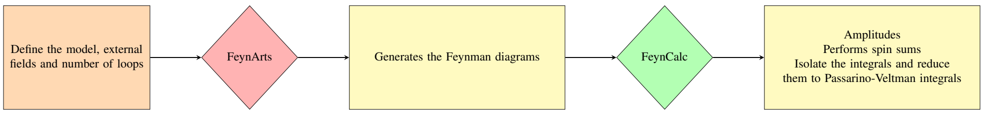


Figure 1: Semi-automated approach for computing scattering matrix amplitudes employing the Mathematica packages FeynArts [2] and FeynCalc [3]

Employing FeynArts and FeynCalc, we derive analytical expressions for the branching ratio of the $B_s^0 \to \mu^+\mu^-$ decay in the SM and the pMSSM. Due to space limitations, most technical details are omitted. The interested reader may refer to [4] for further details.

2.1 Numerical results within the SM

Within the SM, the only important diagrams are the box diagram consisting of two W bosons and a top quark as well as the $Z-$penguins consisting of the top quark and W / Goldstone boson. The divergent terms arising are eliminated upon taking into account the self energy diagrams.

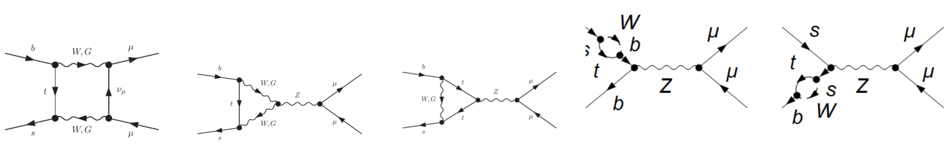


Figure 2: Major contributions to the $B_s^0 \to \mu^+\mu^-$ within the SM. From left to right: Box diagrams, Z-Penguin diagrams, Self-energy diagrams.

Upon calculating the combined amplitudes $\mathcal{M}$ of the diagrams, we obtain the branching ratio as

$$\begin{aligned}\mathcal{B}(B_s^0 \to \mu^+\mu^-) &= \tau_{B_s^0}\overline{|\mathcal{M}|^2}\frac{\sqrt{m_{B_s^0}^2-(2m_\mu)^2}}{8\pi m_{B_s^0}^2} \\ &= \tau_{B_s^0}\frac{\sqrt{m_{B_s^0}^2-(2m_\mu)^2}}{32\pi}|K^{33}K^{32\star}|^2 f_{B_s^0}^2 m_\mu^2\left(\frac{e^4}{16\pi^2 s_W^4}\right)^2 \\ &\quad \left[-\frac{m_t^2}{8m_W^2}\left(\frac{m_t^2-m_W^2}{m_t^2-4m_W^2}+\frac{3m_t^2m_W^2}{(m_t^2-m_W^2)^2}\ln\frac{m_t^2}{m_W^2}\right)\right]^2 .\end{aligned} \quad (1)$$

Plugging in the numerical values from [5], we obtain:

$$\mathcal{B}(B_s^0 \to \mu^+\mu) = (3.66 \pm 0.23)\times 10^{-9} \quad (2)$$

where the bulk of the theoretical uncertainty comes from the hadronic matrix elements such as $f_{B_s^0}$. This SM predictions fall within the experimental bounds of $(2.8^{+0.7}_{-0.6}) \times 10^{-9}$. However it is probable that with higher precision in the LHCb measurements, the SM predictions and the experimental results may not agree, signifying the presence of beyond SM physics.

2.2 Numerical results within the Phenomenological MSSM

The MSSM consists in its entirety 178 parameters which can be intractably large. In order to make meaningful phenomenological analyses, some reasonable simplifying assumptions motivated by experimental results are made, giving rise to the phenomenological MSSM with 7 additional parameters on top of the 19 SM parameters. These parameters are summarized in table 1.

Parameter	Description
$\tan\beta$	Ratio of the vev of the two Higgs doublet fields
m_{A^0}	Mass parameter of the pseudoscalar Higgs A^0
μ	Higgs-Higgsino mass parameter
$M_1 = M_2 = M_3$	Gauginos mass unification
$m_{\tilde{Q}^{1,2}} = m_{\tilde{Q}^3} = m_{\tilde{t}} = m_{\tilde{b}} = m_{\tilde{u}} = m_{\tilde{d}}$,	Squarks mass unification
$m_{\tilde{L}} = m_{\tilde{\tau}} = m_{\tilde{l}} = m_{\tilde{e}}$	Slepton mass unification
$A_t = A_b = A_\tau \equiv A_0$	3rd generation trilinear couplings unification

Table 1: Additional free parameters in the phenomenological MSSM.

Major qualitative features that may significantly alter the branching ratio consist in:

1. The two Higgs doublet feature of the MSSM introduces the parameters $\tan\beta$ and m_A. These parameters can enhance the contributions of diagrams involving Higgs bosons and such contributions can no longer be ignored.

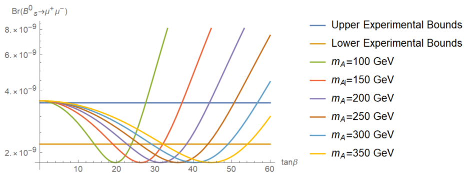
2. The charginos and squarks entering the MSSM introduce another source of amplification.

Incorporating these into consideration, we obtain the following:

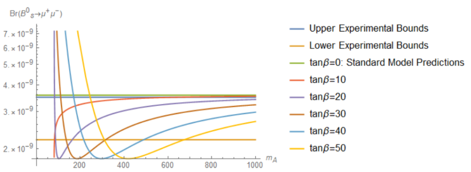
$$\begin{aligned}
\mathcal{B}(B_s^0 \to \mu^+\mu^-) \quad = \quad & \tau_{B_s^0} \frac{\sqrt{m_{B_s^0}^2 - (2m_\mu)^2}}{32\pi} |K^{33}K^{32\star}|^2 f_{B_s^0}^2 m_\mu^2 \left(\frac{e^4}{16\pi^2 s_W^4}\right)^2 \\
& \left\{\left[-\frac{m_t^2}{8m_W^2}\left(\frac{m_t^2 - m_W^2}{m_t^2 - 4m_W^2} + \frac{3m_t^2 m_W^2}{(m_t^2 - m_W^2)^2} \ln\frac{m_t^2}{m_W^2}\right)\right.\right. \\
& + \frac{m_{B_s^0}^2}{8m_W^2}\tan^2\beta \left.\left(\frac{m_t^2 \ln(\frac{m_A^2 - m_W^2}{m_t^2})}{m_A^2 - m_W^2 - m_t^2} + \frac{m_t^2 m_C}{m_A^2}(A_0\tan\beta + \mu)\frac{\mu^2 \ln\left(\frac{m_C^2}{m_Q^2}\right) - m_C + m_Q}{m_C^2 - m_Q^2}\right)\right]^2 \\
& + \left(1 - \frac{4m_\mu^2}{m_{B_s^0}^2}\right)^2 \frac{m_{B_s^0}^2}{8m_W^2}\tan^2\beta \left.\left(\frac{m_t^2 \ln(\frac{m_A^2 - m_W^2}{m_t^2})}{m_A^2 - m_W^2 - m_t^2} + \frac{m_t^2 m_C}{m_A^2}(A_0\tan\beta + \mu)\frac{\mu^2 \ln\left(\frac{m_C^2}{m_Q^2}\right) - m_C + m_Q}{m_C^2 - m_Q^2}\right)^2\right\}.
\end{aligned} \tag{3}$$

2.3 Parametric dependence of $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ in the pMSSM

Equation 3 gives the parametric dependence of $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ upon six (out of seven, excluding the unified sleptons mass parameter) of the parameters defined in table 1. Using equation 3, we plot some representative figures to illustrate how the MSSM parameters modify the branching ratio. The choice of values for the parameters are motivated by [6].



(a) $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ as a function of $\tan\beta$.



(b) $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ as a function of m_A.

Figure 3: Dependence of the branching ratio on the parameters $\tan\beta$ and m_A.

3 Conclusion

In this work we focused on the implications of a single decay mode on constraining the parameter space of the MSSM. Due to the large number of Feynman diagrams that enter the decay, the calculations are tedious and we have employed the use of Mathematica packages to perform them. The recipe for utilising these packages and our source codes can be found in [4]. It would be desirable to extend this study to performing numerical scans for multiple decay modes whose combined loci over the parameter space can provide more insight into the phenomenology of models beyond the SM.

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