

The R_K Puzzle and Analysis

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Abstract

Recent measurements of R_K ($\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-)/\mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)[1 - 6 \text{ GeV}^2]$) shows substantial deviation from its standard model prediction. This deviation could be due to new physics at a high-energy scale, that cause deviations in Wilson Coefficients of low-energy operators. This article seeks to constrain and analyze the Wilson Coefficients that are present in the branching ratios of decays.

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1 Introduction

The Standard Model (SM) of particle physics works extremely well when calculating decay rates of subatomic particle and explaining different types of physical phenomena that occur at the subatomic level. Included in the SM are lists of rules that govern interactions and different conserved quantities that have aligned well with the observed experimental results. The SM spectrum includes 4 types of particles: gauge bosons, quarks, leptons, and the Higgs boson. The gauge bosons are particles with spin 1 that mediate the different forces. For instance, the W and Z bosons mediate the weak force. In Table 1 we summarize the physical properties of this type of particles.

Gauge Bosons			
Boson	Mass	Charge	Force
γ	0 MeV	0	Electromagnetic
Z	91.1876 ± 0.00214 GeV	0	Weak
$W^{\pm 1}$	80.385 ± 0.01596 GeV	± 1	Weak
Gluon	0 MeV	0	Strong

Table 1: Table of Gauge Bosons in the SM [2]

In addition to the gauge bosons, the SM contains other particles known as fermions. Fermions have half-integer spin and are comprised of quarks and leptons. There are 3 types of leptons (electron, muon and tau), each with its corresponding neutrino. Each fermion (f) has an antiparticle (\bar{f}), which has the same mass but opposite charge. These leptons can be seen in Table 2.

Leptons		
Type	Mass	Charge
e	0.5109989461(31) MeV	-1
μ	105.6583745(24) MeV	-1
τ	1776.86 ± 0.12 MeV	-1

Table 2: Table of Leptons in the SM [2]

The other types of fermions are quarks. Quarks differ from leptons because quarks participate in the strong force, while leptons do not. Quarks also have either a $\frac{2}{3}$ or $-\frac{1}{3}$ charge and can be seen below in Table 3. Finally, there is the recently discovered Higgs boson, a spinless scalar particle responsible for generating gauge boson and fermion masses in the SM.

In spite of its remarkable success in explaining subatomic phenomena, recent observations made by BaBar, Belle, and LHCb collaborations provide hints that there is new physics beyond the SM. In this article, we will study decays of the B^+ ($\bar{b}u$) and B_s ($\bar{b}s$) mesons. We will focus on a few interesting channels that have received quite a bit of attention in the literature.

Quarks		
Type	Mass	Charge
u	$2.2^{+0.6}_{-0.4}$ MeV	$\frac{2}{3}$
d	$4.7^{+0.5}_{-0.4}$ MeV	$-\frac{1}{3}$
s	96^{+8}_{-4} MeV	$-\frac{1}{3}$
c	1.28 ± 0.03 GeV	$\frac{2}{3}$
b	$4.18^{+0.04}_{-0.03}$ GeV	$-\frac{1}{3}$
t	173.1 ± 0.6 GeV	$\frac{2}{3}$

Table 3: Table of Quarks in the SM [2]

The R_K and $R_{D^{(*)}}$ are two ratios of these B meson decays that show some puzzling experimental results. The R_K ratio is defined as $\mathcal{B}(B^+ \rightarrow K^+ \mu^+ \mu^-) / \mathcal{B}(B^+ \rightarrow K^+ e^+ e^-)$. The experimental value found by the LHCb Collaboration is [6]

$$R_K^{expt} = 0.745^{+0.090}_{-0.074} \text{ (stat)} \pm 0.036 \text{ (syst)}$$

This differs from the SM prediction of $R_K^{expt} = 1 \pm 0.01$ by 2.6σ . [7] Another puzzle is the $R_{D^{(*)}}$ ratio, defined as $\mathcal{B}(\bar{B} \rightarrow D^{(*)} \tau^- \bar{\nu}_\tau) / \mathcal{B}(\bar{B} \rightarrow D^{(*)} l^- \bar{\nu}_l)$ where ($l = \mu$ or e) We will focus on analyzing the possible NP contributions to the Wilson Coefficients (WC) arising from the effective Hamiltonian of the $b \rightarrow s \mu^+ \mu^-$ transition. The complete Hamiltonian is as follows: [5].

$$H = -\frac{\alpha G_f}{\sqrt{2}\pi} V_{tb} V_{ts}^* \sum_{a=9,10} (C_a O_a + C'_a O'_a) \quad (1)$$

This article will take the Hamiltonian and use the WC found in the branching ratio of the $B_s \rightarrow \mu^+ \mu^-$ decay to constrain the effects of NP parameters. The article begins by first exploring and computing different observables of the $\pi^+ \rightarrow l^+ \nu_l$ decay. (Where $l = \mu$ or e) This will provide us with a background in manipulating and understanding the theoretical expressions for branching ratios and decays. It will also serve as a guide to the format for the rest of the paper. In section 3 we will constrain the WC from the branching ratio of the $B_s \rightarrow \mu^+ \mu^-$ decay. We will use the Python package Flavio [4] to generate our data and construct our plots. Flavio's packages focus on flavor physics and allows the user to find the contributions of different WC for varying observable. Finally in Section 4 plots of the Branching ratio based upon the WC will be shown and fits to the data will be provided. We conclude the article in Section 5.

2 The branching Ratio of a Charged Pion decay

In order to calculate the Branching ratio of a charged pion, we will use the Feynman Rules of calculating amplitudes and the trace identities. We start by recognizing that the pion decay

is a charged current interaction since pion is made of quarks, and the decay is mediated by a massive W boson. A Feynman diagram for the decay may be seen in Figure 1:

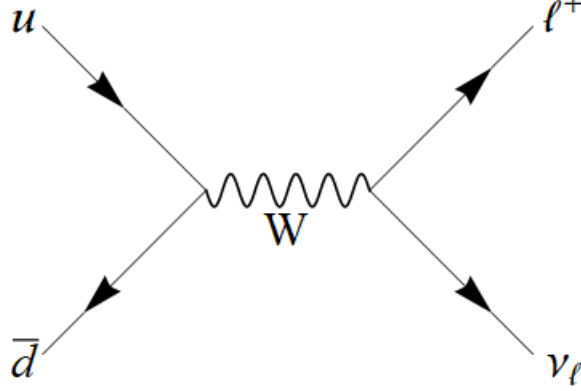


Figure 1: Pion Decay (where ℓ is μ or e)

Where the up and anti-down quark and the lepton and corresponding lepton neutrino are on the right.

The formula given to describe the branching ratio of this decay is given by [1]:

$$\Gamma = \frac{S|\mathbf{p}|}{8\pi\hbar m_1^2 c} |\mathcal{M}|^2 \quad (2)$$

Where $|\mathbf{p}|$ is the outgoing momentum, S is the product of statistical factors (in our case it will be equal to 1), m_1 is the mass of the pion, and \mathcal{M} is the Feynman amplitude. In our notation, we will use $\hbar = c = 1$ and so our expression becomes:

$$\Gamma = \frac{S|\mathbf{p}|}{8\pi m_1^2} |\mathcal{M}|^2 \quad (3)$$

The next step is to determine \mathcal{M} . In the charged current decay, we have a certain notation for the vertices and propagators. The Feynman rules are:

1. For each vertex add a factor of $\frac{-ig_w}{2\sqrt{2}}(\gamma^\nu(1 - \gamma^5))$ where $g_w = \sqrt{4\pi\alpha_w}$
2. For each propagator we add a factor of $\frac{-ig_{\mu\nu} - \frac{q_\mu q_\nu}{m^2}}{q^2 - m^2}$ where m is the mass of the boson.
In our case, $m_w \gg q$ so the expression simplifies to $\frac{ig_{\mu\nu}}{m_w^2}$

From these rules and Figure 1 we are able to calculate the value of \mathcal{M}

$$-i\mathcal{M} = \left[\bar{u}(3) \left(\frac{-ig_w}{2\sqrt{2}}(\gamma^\nu(1 - \gamma^5)) \right) v(2) \right] \left[\frac{ig_{\mu\nu}}{m_w^2} \right] \left[\frac{-ig_w}{2\sqrt{2}} F^\mu \right] \quad (4)$$

Where F^μ is the form factor of the coupling of the pion to the W boson. F^μ has the form of $f_\pi p^\mu$.

$$\mathcal{M} = \frac{g_w^2}{8m_w^2} [\bar{u}(3)(\gamma^\mu(1 - \gamma^5))v(2)] F^\mu \quad (5)$$

In order to square the amplitude we do the following:

$$|\mathcal{M}^2| = \left(\frac{g_w^2}{8m_w^2} f_\pi \right)^2 \text{Tr}[(\bar{u}(3)(\gamma^\mu(1 - \gamma^5))v(2)p_\mu(\bar{v}(2)(\gamma^\nu(1 - \gamma^5))u(3))]p_\nu \quad (6)$$

$$|\mathcal{M}^2| = \left(\frac{g_w^2}{8m_w^2} f_\pi \right)^2 p_\mu p_\nu (8[p_3^\mu p_2^\nu + p_2^\mu p_3^\nu - (p_3 \cdot p_2)g^{\mu\nu}] + 8i\epsilon^{\mu\lambda\nu\sigma} p_{3\lambda} p_{2\sigma}) \quad (7)$$

Summing over the spins gives us:

$$|\mathcal{M}^2| = 8 \left(\frac{g_w^2}{8m_w^2} f_\pi \right)^2 [2(p_1 \cdot p_2)(p_1 \cdot p_3) - p^2(p_2 \cdot p_3)] \quad (8)$$

Since $p_1 = p_2 + p_3$, we can simplify the equation further. For simplicity and consistency we will use the following notation: $p_1 = p_\pi$, $p_2 = p_l$, $p_3 = p_{\nu_l}$. The value of the 4-momentum squared is:

$$p_1 = (E, \vec{p}_1) \quad (9)$$

$$(p_1)^2 = E^2 - (\vec{p}_1)^2$$

$$(p_1)^2 = m^2 \quad (10)$$

Similarly: $(p_\pi)^2 = m_\pi^2$, $(p_l)^2 = m_l^2$, $(p_{\nu_l})^2 = (m_{\nu_l})^2 = 0$. Using this we can further simplify Equation 8:

$$\frac{1}{2}[(m_\pi)^2 - (m_l)^2] = (p_2 \cdot p_3) \quad (11)$$

$$\frac{1}{2}[(m_\pi)^2 - (m_l)^2] = (p_1 \cdot p_3) \quad (12)$$

$$\frac{1}{2}[(m_\pi)^2 + (m_l)^2] = (p_1 \cdot p_2) \quad (13)$$

Returning to Equation 8 we now have

$$|\mathcal{M}^2| = 8 \left(\frac{g_w^2}{8m_w^2} f_\pi \right)^2 \left[\frac{1}{2}(m_l)^2((m_\pi)^2 - (m_l)^2) \right] \quad (14)$$

With the Feynman amplitude, we are able to complete the expression for the branching ratio of a pion. Returning to equation (3)

$$\Gamma = \frac{S|\mathbf{p}|}{8\pi m_1^2} |\mathcal{M}|^2 \quad (15)$$

$$\Rightarrow \Gamma = \frac{S|\mathbf{p}|}{\pi m_\pi^2} \left(\frac{g_w^2}{8m_w^2} f_\pi \right)^2 \left[\frac{1}{2}(m_l)^2((m_\pi)^2 - (m_l)^2) \right] \quad (16)$$

We then need to find the value of $|\mathbf{p}|$ which is simply the momentum of each outgoing particle.

$$|\mathbf{p}| = \frac{\sqrt{m_1^4 + m_2^4 - m_1^2 m_2^2}}{2m_1} \quad (17)$$

Because the neutrino is massless,

$$|\mathbf{p}| = \frac{(m_\pi^2 - m_l^2)}{2m_\pi} \quad (18)$$

Combining with Equation 14:

$$\Gamma = \frac{|\mathbf{p}|}{2\pi m_1^2} \left(\frac{g_w^2}{8m_w^2} f_\pi \right)^2 [(m_l)^2((m_\pi)^2 - (m_l)^2)] \quad (19)$$

$$\Rightarrow \Gamma = \frac{1}{4\pi} \left(\frac{g_w^2 f_\pi}{8m_w^2} \right)^2 \left(\frac{1}{m_\pi^3} \right) m_l^2 (m_\pi^2 - m_l^2)^2 \quad (20)$$

Because $\frac{g_w^2}{8m_w^2} = \frac{G_F}{\sqrt{2}}$ we are able to write:

$$\Gamma = \frac{1}{8\pi} (G_F f_\pi)^2 \left(\frac{1}{m_\pi^3} \right) m_l^2 (m_\pi^2 - m_l^2)^2 \quad (21)$$

Expanding on this idea, we are able to graph $\frac{\Gamma_l}{\Gamma_\pi}$ by:

$$\Gamma = \frac{1}{8\pi} (G_F f_\pi)^2 m_\pi^3 \left(\frac{m_l}{m_\pi} \right)^2 \left(1 - \left(\frac{m_l}{m_\pi} \right)^2 \right)^2 \quad (22)$$

In order to find $\frac{\Gamma_l}{\Gamma_\pi}$ we need to divide the above expression by $\frac{1}{\tau_\pi}$ but normalize it with $\hbar = 1$ using Natural Units so our final expression is:

$$\frac{\Gamma_l}{\Gamma_\pi} = \frac{1}{8\pi} (G_F f_\pi)^2 m_\pi^3 \left(\frac{\tau_\pi}{\hbar} \right) \left(\frac{m_l}{m_\pi} \right)^2 \left(1 - \left(\frac{m_l}{m_\pi} \right)^2 \right)^2 \quad (23)$$

The graph of the Equation 25 (with $m_l = m_e$) is found in Figure 2. and the graph of Equation 25 (with $m_l = m_\pi$) is found in Figure 3. These figures show the value of the branching ratio for certain values of m_l as well as the plot of $\frac{\Gamma_{m_l}}{\Gamma_\pi}$. Using the lifetime and mass values from PDG [2] we may compute ratios.

Observables	e	μ	π
τ (Lifetime)	6.6×10^{28} yr	$2.1969811(22) \times 10^{-6}$ s	$2.6033(5) \times 10^{-8}$ s
Mass(MeV)	0.5109989461(31)	105.6583745(24)	139.57061(24)

To calculate the ratio of the $\pi^- \rightarrow e^- + \nu_e$ and $\pi^- \rightarrow \mu^- + \nu_\mu$ we do the following:

$$\frac{\Gamma_e}{\Gamma_\mu} = \frac{m_e^2(m_\pi^2 - m_e^2)^2}{m_\mu^2(m_\pi^2 - m_\mu^2)^2} \quad (24)$$

$$\frac{\Gamma_e}{\Gamma_\mu} = 1.28334(73) \times 10^{-4} \quad (25)$$

This is an interesting observation because the value of $\frac{\Gamma_e}{\Gamma_\mu}$ suggests that the probability of $\pi^- \rightarrow \mu^- + \nu_\mu$ is higher than $\pi^- \rightarrow e^- + \nu_e$. This is somewhat striking because the mass of a muon is greater than the mass of an electron, indicating that the pion does not decay into the lightest particle most frequently.

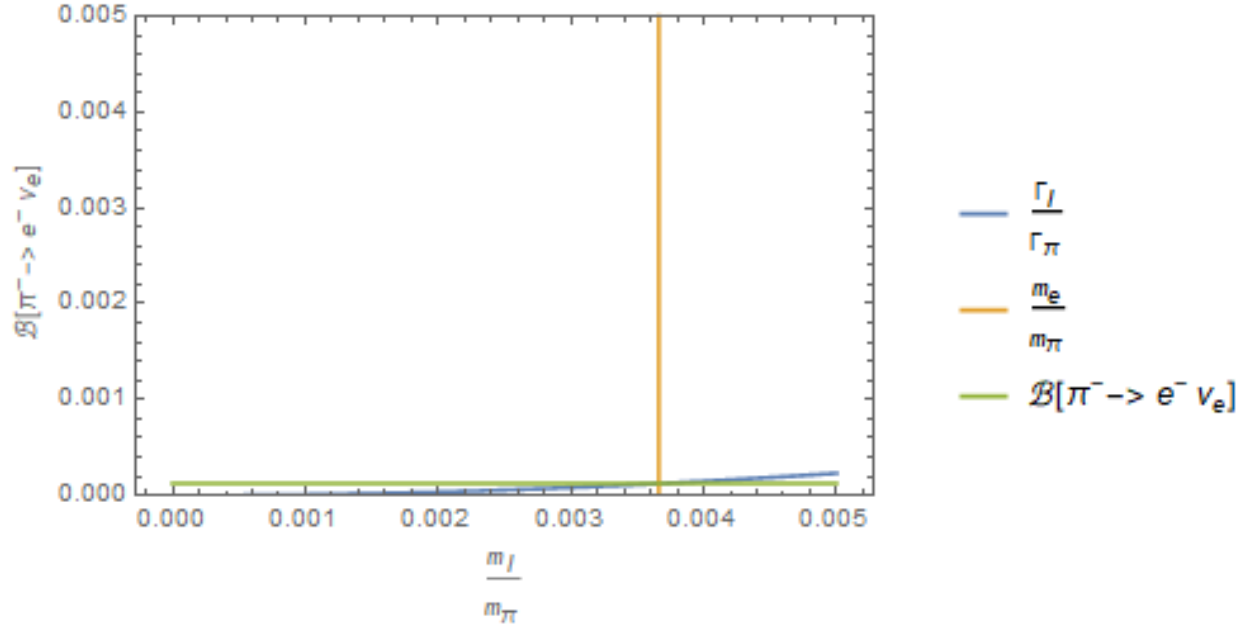


Figure 2: Graph of $\frac{\Gamma_{m_e}}{\Gamma_\pi}$ and the value of $\frac{m_e}{m_\pi}$ and the value of $\mathcal{B}(\pi^- \rightarrow e^- + \nu_e)$

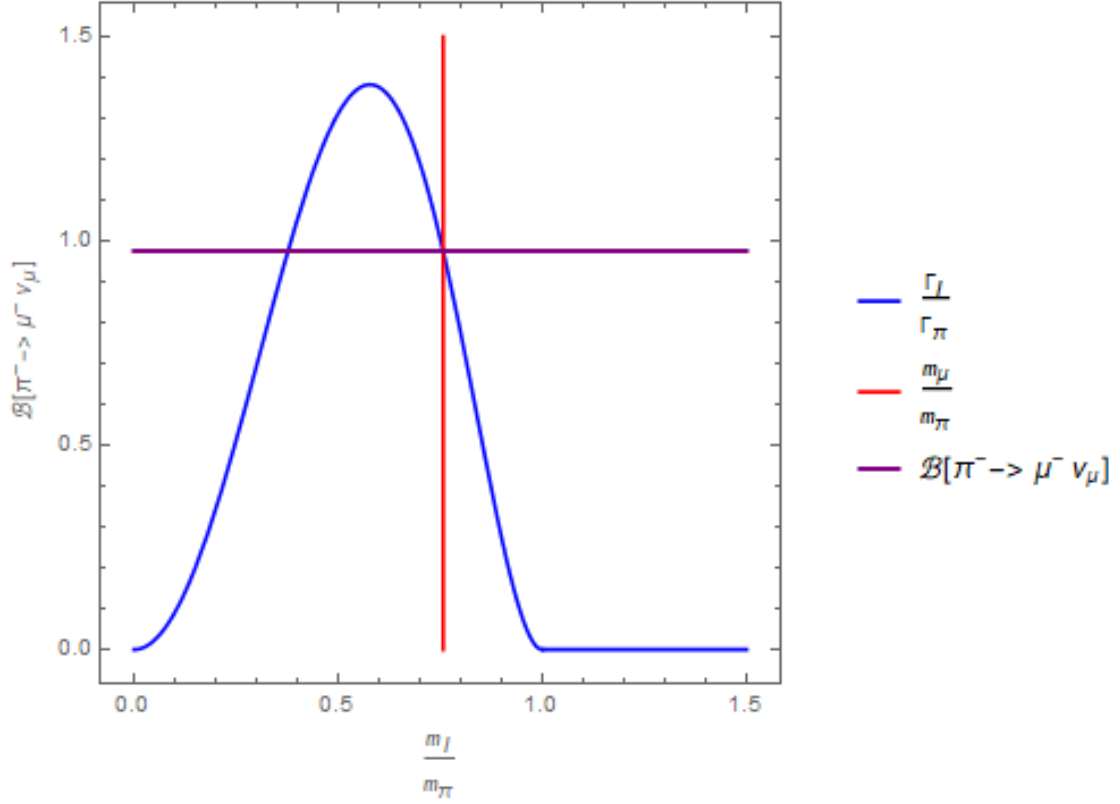


Figure 3: Graph of $\frac{\Gamma_{m_\mu}}{\Gamma_\pi}$ and the value of $\frac{m_\mu}{m_\pi}$ and the value of $\mathcal{B}(\pi^- \rightarrow \mu^- + \nu_\mu)$

3 The Branching Ratio of the $B_s \rightarrow \mu^+ \mu^-$ decay

From [12] the SM branching ratio value is $(3.66 \pm 0.23) \times 10^{-9}$. An expression for the branching ratio for $B_s \rightarrow \mu^+ \mu^-$ can be found in [3] including NP WC's. The expression for the branching ratio is seen below:

$$\mathcal{B}(B_s \rightarrow \mu^+ \mu^-) = \frac{G_F^2 \alpha_{em}^2 m_{B_s}^5 f_{B_s}^2 \tau_{B_s}}{64\pi^3} \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}} \left\{ \left(1 - \frac{4m_\mu^2}{m_{B_s}^2}\right) \left| \zeta \frac{C_S - C'_S}{m_b + m_s} \right|^2 + \left| \zeta \frac{C_P - C'_P}{m_b + m_s} + \frac{2m_\mu}{m_{B_s}^2} [|V_{tb} V_{ts}^*| C_{10} + \zeta(C_A - C'_A)] \right|^2 \right\} \quad (26)$$

Where $\zeta \equiv (\frac{g_{NP}^2}{\Lambda^2})(\frac{\sqrt{2}}{4G_F})(\frac{4\pi}{\alpha_{em}})$

The four-fermi operator diagram of the decay can be seen below: Since we seek to find

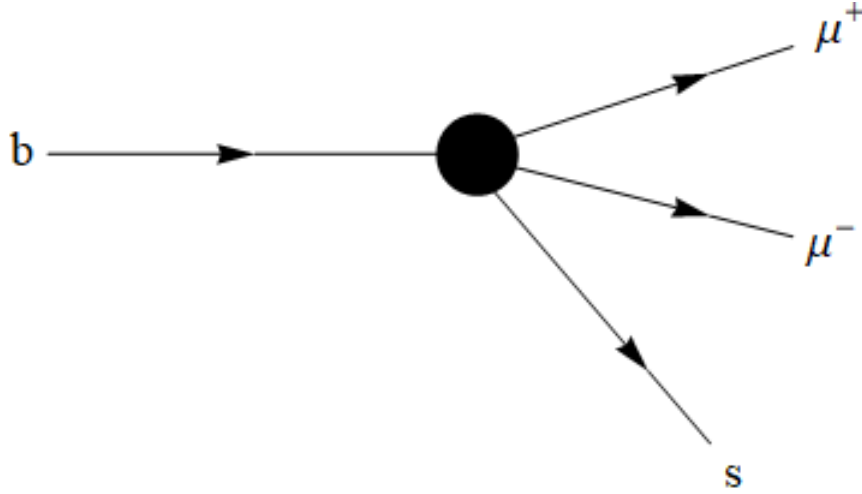


Figure 4: Diagram of $B_s \rightarrow \mu^+ \mu^-$ from four-fermi operators

the constraints on the parameters $C_S, C'_S, C_P, C'_P, C_A$, and C'_A we set the equation equal to the branching ratio given in [4]. We also use the values for $C_{10}, |V_{tb} V_{ts}^*|, g_{NP}$, and Λ given in [3]. Thus we are able to find the constraints on the parameters. In order to solve for one parameter, we allow the other two to be equal to 0, this will simplify our calculations. The experimental value for the branching ratio of $B_s \rightarrow \mu^+ \mu^-$ decay is equal to $2.4_{-0.7}^{+0.9} \times 10^{-9}$ [2]. We are able to find:

$$\begin{aligned} C_S &= \pm 1.6215i \times 10^{-4} \\ &= \pm 4.63981 \times 10^{-5} \end{aligned}$$

$$C_P = 6.3832 \times 10^{-5} \text{ or } 4.1125 \times 10^{-4}$$

$$= -4.482 \times 10^{-6} \text{ or } 4.7957 \times 10^{-4}$$

$$\begin{aligned} C_A &= 2.0348 \times 10^{-3} \text{ or } 1.31095 \times 10^{-2} \\ &= -1.48237 \times 10^{-4} \text{ or } 1.5287 \times 10^{-2} \end{aligned}$$

Notes about the Wilson Coefficients:

The first C_S coefficient is equal to $\pm 1.6215i \times 10^{-4}$ which indicates that the branching ratio will receive a negative contribution from this coefficient when the branching ratio is below the SM prediction. The C_P has two values, the first value is equal to 2.375×10^{-4} and the second value is equal to 2.375×10^{-4} as well (We are able to calculate a simple average due to the small number of measurements). The last coefficient C_A also has two values, the first value is equal to 7.572×10^{-3} and the second value is equal to 7.569×10^{-3} . Both C_P and C_A have two possible values because in the theoretical expression for the branching ratio, we take the absolute value of the WC added to another factor. After finding the Wilson Coefficients, we use the Python package Flavio [4] to compute the NP values of $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)$:

$$\begin{aligned} C_S &= \pm 1.6215i \times 10^{-4} \\ \text{Flavio Prediction: } \mathcal{B} &= 3.610 \times 10^{-9} \\ C_S &= \pm 4.63981 \times 10^{-4} \\ \text{Flavio Prediction: } \mathcal{B} &= 3.610 \times 10^{-9} \end{aligned}$$

$$\begin{aligned} C_P &= 2.375 \times 10^{-4} \\ \text{Flavio Prediction: } \mathcal{B} &= 3.555 \times 10^{-9} \end{aligned}$$

$$\begin{aligned} C_A &= 7.572 \times 10^{-3} \\ \text{Flavio Prediction: } \mathcal{B} &= 3.542 \times 10^{-9} \\ C_A &= 7.569 \times 10^{-3} \\ \text{Flavio Prediction: } \mathcal{B} &= 3.542 \times 10^{-9} \end{aligned}$$

4 Plots of $\mathcal{B}(WC)$

Figures 5, 6, 7, and 8 give an indication of how the variation of a Wilson Coefficient could change the value of the branching ratio. In figure 5 the value of $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)$ approaches 0 but has a minimum at the SM prediction which is on the order of 10^{-9} . The plot in Figure 6 also approaches 0 because the WC C_A could allow $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)$ to become 0. Figures 7 and 8 both share similar properties. Each has a minimum slightly below the SM predicted branching ratio for their respective channels. This is due to the contributions from certain WC's. C_A and C_9 allow for a lower branching ratio than the SM prediction, but C_S and C_P have minimums at the SM prediction. All of the plots follow a parabolic shape due to the branching ratio being dependent on the square of each WC.

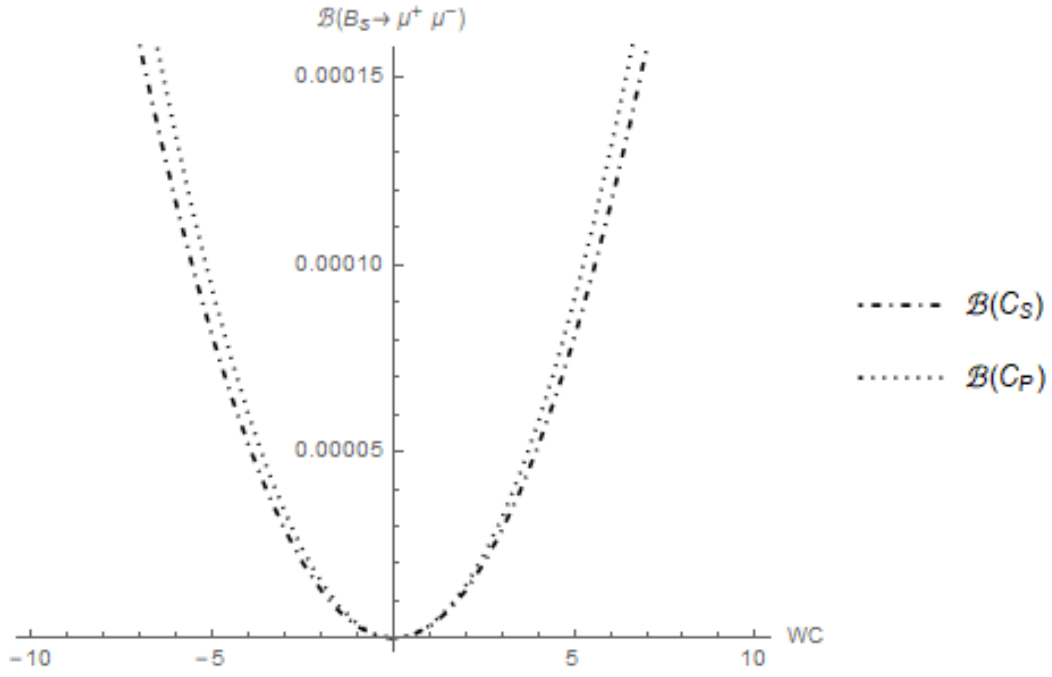


Figure 5: Graph of $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)$ as functions of the C_P and C_S Wilson Coefficients

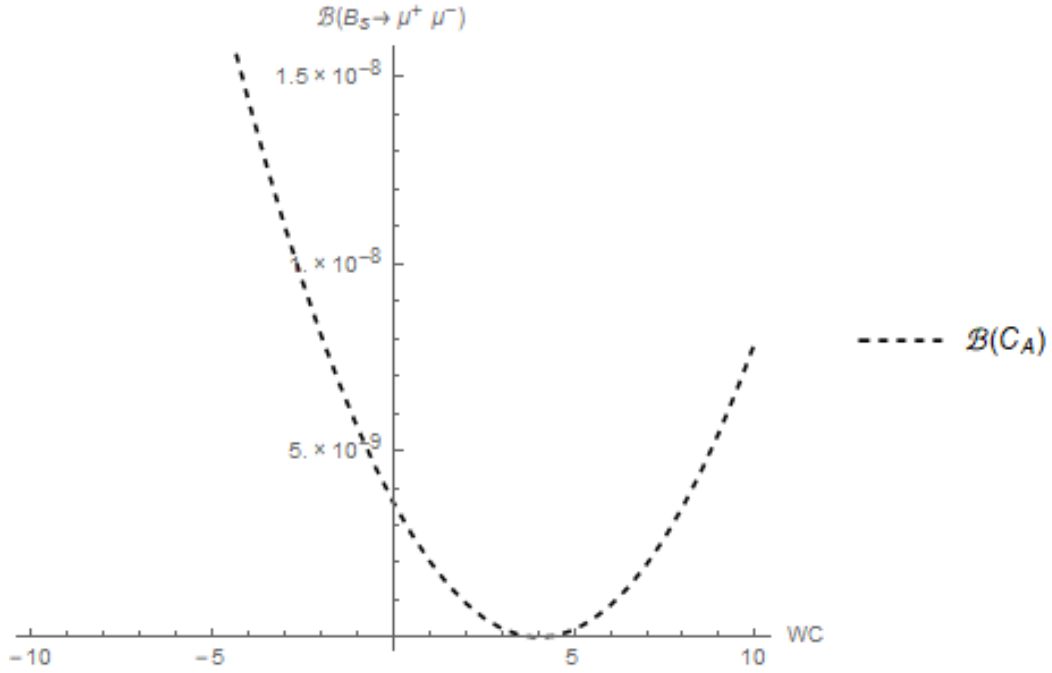


Figure 6: Graph of $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-)$ as functions of the C_A Wilson Coefficient

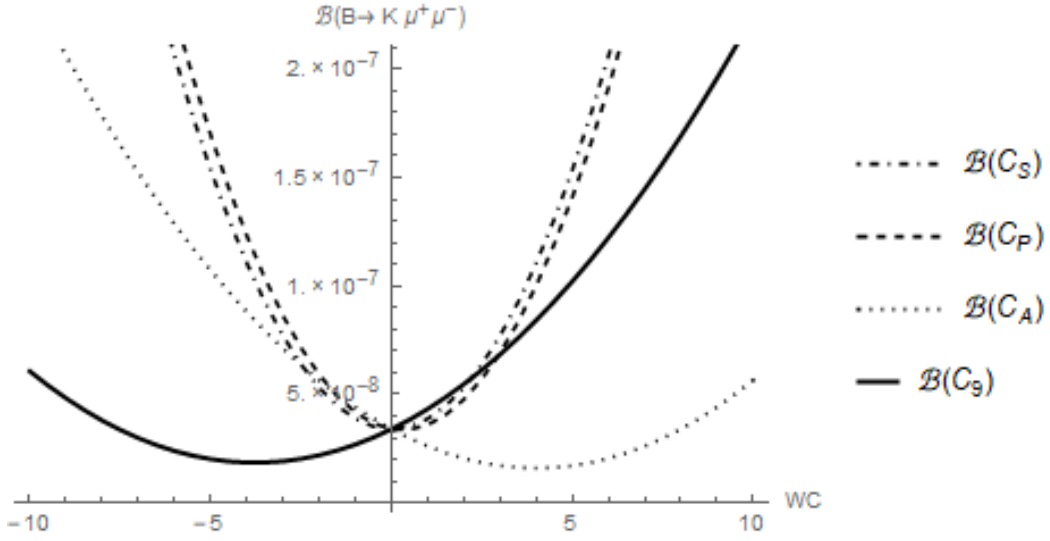


Figure 7: Graph of $\mathcal{B}(B \rightarrow K \mu^+ \mu^-)$ as functions of the Wilson Coefficients

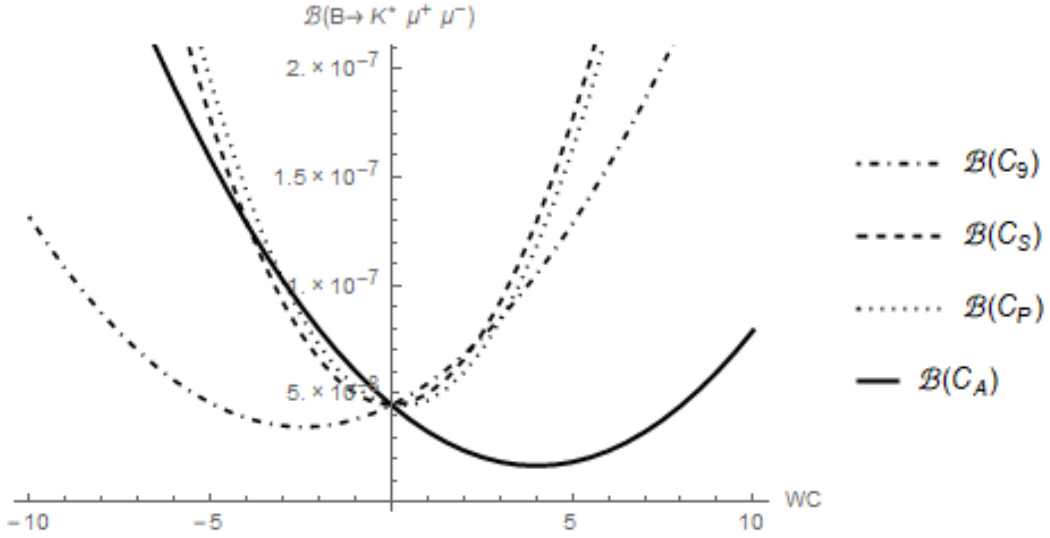


Figure 8: Graph of $\mathcal{B}(B \rightarrow K^* \mu^+ \mu^-)$ as functions of the Wilson Coefficients

5 Conclusion

The work done with the Wilson Coefficients indicates the sensitivity of potential NP contributions to B meson decay channels. These NP contributions are non-zero but are very modest. The WC have values of $10^{-4} - 10^{-5}$. As seen in Section 4, changing the WC by an order of magnitude will increase certain branching ratios by 3 orders of magnitude. The NP contributions from certain WC could also lower the branching ratio from the SM prediction. However, these are preliminary measurements and a more rigorous approach for this process will be taken at a later time.

The NP contributions also have large error bars. The expectation is that future work will be done using a chi squared minimization technique to help limit and constrain the WC. The chi squared technique would use the observables that have been measured experimentally from different experiments. In the future, we hope to provide a rigorous explanation that shows the existence of NP.

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7 Appendix

It was necessary to practice with spinor notation and different mathematical techniques before starting this project. This appendix summarizes what I was able to do in that regard.

Notation:

1. $S = \bar{u}u$
2. $P = \bar{u}\gamma^5 u$
3. $V^\mu = \bar{u}\gamma^\mu u$
4. $A^\mu = \bar{u}\gamma^\mu\gamma^5 u$

1. $(\bar{u}_1\gamma^\mu u_2)^* = ?$

Note: $(\gamma^0)^\dagger = \gamma^0$ and $(\gamma^\mu)^\dagger = \gamma^0\gamma^\mu\gamma^0$

$(\bar{u}_1 \gamma^\mu u_2)$ is a 1×1 matrix. Therefore, its complex conjugate is the same as its Hermitian conjugate, i.e. if we call $V^\mu = (\bar{u}_1 \gamma^\mu u_2)$, then $(V^\mu)^* = (V^\mu)^\dagger$. We can then express this quantity as follows:

$$\begin{aligned}
V^\mu &= \bar{u}_1 \gamma^\mu u_2 \\
\Rightarrow (V^\mu)^* &= (V^\mu)^\dagger \\
&= (\bar{u}_1 \gamma^\mu u_2)^\dagger, \\
&= ((u_1)^\dagger \gamma^0 \gamma^\mu u_2)^\dagger \quad \text{using } (A \dots Z)^\dagger = Z^\dagger \dots A^\dagger, \\
&= (u_2^\dagger) (\gamma^\mu)^\dagger (\gamma^0)^\dagger (u_1) \\
&= (u_2^\dagger) \gamma^0 \gamma^\mu \gamma^0 \gamma^0 (u_1) \\
&= (u_2^\dagger) \gamma^0 \gamma^\mu (u_1) \\
&= \bar{u}_2 \gamma^\mu (u_1)
\end{aligned} \tag{27}$$

Therefore $(\bar{u}_1 \gamma^\mu u_2)^* = \bar{u}_2 \gamma^\mu u_1$. To solve for $|V^\mu|^2$ we simply use $|V^\mu|^2 = \text{Tr}[\bar{u}_1 \gamma^\mu u_2 \bar{u}_2 \gamma^\nu u_1]$. Note: $\text{Tr}[\gamma^\mu \gamma^\nu] = 4g^{\mu\nu}$, $\text{Tr}[\gamma^\mu \gamma^\nu \gamma^\lambda \gamma^\sigma] = 4(g^{\mu\nu} g^{\lambda\sigma} - g^{\mu\lambda} g^{\nu\sigma} + g^{\mu\sigma} g^{\nu\lambda})$, The trace over the product of an odd number of gamma matrices is zero.

$$\begin{aligned}
|V^\mu|^2 &= \text{Tr}[\bar{u}_1 \gamma^\mu u_2 \bar{u}_2 \gamma^\nu u_1] \\
&= \text{Tr}[\bar{u}_1 \gamma^\mu (\not{p}_2 + m) \gamma^\nu u_1] \\
&= \text{Tr}[u_1 \bar{u}_1 \gamma^\mu (\not{p}_2 + m) \gamma^\nu] \\
&= \text{Tr}[(\not{p}_1 + m) \gamma^\mu (\not{p}_2 + m) \gamma^\nu] \\
&= \text{Tr}[\not{p}_1 \gamma^\mu \not{p}_2 \gamma^\nu] + m[\text{Tr}(\gamma^\mu \not{p}_1 \gamma^\nu) + \text{Tr}(\gamma^\mu \gamma^\nu \not{p}_2)] + m^2 \text{Tr}[\gamma^\mu \gamma^\nu] \\
&= \text{Tr}[\not{p}_1 \gamma^\mu \not{p}_2 \gamma^\nu] + m^2 \text{Tr}[\gamma^\mu \gamma^\nu] \\
&= \text{Tr}[(p_1)_\lambda \gamma^\lambda \gamma^\mu (p_2)_\sigma \gamma^\sigma \gamma^\nu] + 4m^2 g^{\mu\nu} \\
&= (p_1)_\lambda (p_2)_\sigma \text{Tr}[\gamma^\lambda \gamma^\mu \gamma^\sigma \gamma^\nu] + 4m^2 g^{\mu\nu} \\
&= (p_1)_\lambda (p_2)_\sigma 4(g^{\mu\nu} g^{\lambda\sigma} - g^{\mu\lambda} g^{\nu\sigma} + g^{\mu\sigma} g^{\nu\lambda}) + 4m^2 g^{\mu\nu} \\
&= 4[p_1^\mu p_2^\nu - g^{\mu\nu} (p_1 \cdot p_2) + p_2^\mu p_1^\nu] + 4m^2 g^{\mu\nu}
\end{aligned} \tag{29}$$

2. $(\bar{u}_1 \gamma^\mu \gamma^5 u_2)^*$ is also a 1×1 Matrix so the same reasoning applies as above in 1. Note: $(\gamma^5)^\dagger = \gamma^5$ We define: A^μ as $\bar{u}_1 \gamma^\mu \gamma^5 u_2$ thus:

$$\begin{aligned}
(A^\mu)^* &= (A^\mu)^\dagger \\
&= (\bar{u}_1 \gamma^\mu \gamma^5 u_2)^\dagger \\
&= ((u_1)^\dagger \gamma^0 \gamma^\mu \gamma^5 u_2)^\dagger \\
&= (u_2^\dagger) (\gamma^5)^\dagger (\gamma^\mu)^\dagger (\gamma^0)^\dagger (u_1) \\
&= (u_2^\dagger) \gamma^5 \gamma^0 \gamma^\mu \gamma^0 \gamma^0 u_1 \\
&= (u_2^\dagger) \gamma^5 \gamma^0 \gamma^\mu (1) u_1 \\
&= -(u_2^\dagger) \gamma^0 \gamma^5 \gamma^\mu u_1 \\
&= -\bar{u}_2 \gamma^5 \gamma^\mu u_1
\end{aligned} \tag{31}$$

$$= \bar{u}_2 \gamma^\mu \gamma^5 u_1 \quad (32)$$

Therefore $(\bar{u}_1 \gamma^\mu \gamma^5 u_2)^* = \bar{u}_2 \gamma^\mu \gamma^5 u_1$

We also are able to calculate $|A^\mu|^2$

$$\begin{aligned} |A^\mu|^2 &= \text{Tr}[(\bar{u}_1 \gamma^\mu \gamma^5 u_2)(\bar{u}_2 \gamma^\nu \gamma^5 u_1)] \\ &= \text{Tr}[\bar{u}_1 \gamma^\mu \gamma^5 (\not{p}_2 + m) \gamma^\nu \gamma^5 u_1] \\ &= \text{Tr}[u_1 \bar{u}_1 \gamma^\mu \gamma^5 (\not{p}_2 + m) \gamma^\nu \gamma^5] \\ &= \text{Tr}[(\not{p}_1 + m) \gamma^\mu \gamma^5 (\not{p}_2 + m) \gamma^\nu \gamma^5] \\ &= \text{Tr}[\not{p}_1 \gamma^\mu \gamma^5 \not{p}_2 \gamma^\nu \gamma^5 + m^2 (\gamma^\mu \gamma^5 \gamma^\nu \gamma^5)] \\ &= \text{Tr}[(p_1)_\lambda \gamma^\lambda \gamma^\mu \gamma^5 (p_2)_\sigma \gamma^\sigma \gamma^\nu \gamma^5] + m^2 \text{Tr}[\gamma^\mu \gamma^5 \gamma^\nu \gamma^5] \\ &= (p_1)_\lambda (p_2)_\sigma \text{Tr}[\gamma^\lambda \gamma^\mu \gamma^5 \gamma^\sigma \gamma^\nu \gamma^5] - m^2 \text{Tr}[\gamma^\mu \gamma^5 \gamma^5 \gamma^\nu] \\ &= (p_1)_\lambda (p_2)_\sigma \text{Tr}[\gamma^\lambda \gamma^\mu \gamma^5 \gamma^5 \gamma^\sigma \gamma^\nu] - m^2 \text{Tr}[\gamma^\mu \gamma^\nu] \\ &= (p_1)_\lambda (p_2)_\sigma \text{Tr}[\gamma^\lambda \gamma^\mu \gamma^\sigma \gamma^\nu] - m^2 (g^{\mu\nu}) \\ &= (p_1)_\lambda (p_2)_\sigma 4(g^{\mu\nu} g^{\lambda\sigma} - g^{\mu\lambda} g^{\nu\sigma} + g^{\mu\sigma} g^{\nu\lambda}) - 4m^2 g^{\mu\nu} \\ &= 4[p_1^\mu p_2^\nu - g^{\mu\nu} (p_1 \cdot p_2) + p_2^\mu p_1^\nu] - 4m^2 g^{\mu\nu} \end{aligned} \quad (34)$$

3. $(\bar{u}_1 u_2)^* = ?$ We let $S = \bar{u}_1 u_2$

$$\begin{aligned} (S)^* &= (S)^\dagger \\ &= (\bar{u}_1 u_2)^\dagger, \\ &= ((u_1)^\dagger \gamma^0 u_2)^\dagger \\ &= (u_2)^\dagger (\gamma^0)^\dagger (u_1) \\ &= (u_2)^\dagger \gamma^0 (u_1) \\ &= \bar{u}_2 (u_1) \end{aligned} \quad (35)$$

Therefore $(\bar{u}_1 u_2)^* = \bar{u}_2 u_1$. In order to find $|S|^2$ we simply do the following:

$$\begin{aligned} |S|^2 &= \text{Tr}[\bar{u}_1 u_2 \bar{u}_2 u_1] \\ &= \text{Tr}[(\not{p}_1 + m)(\not{p}_2 + m)] \\ &= \text{Tr}[\not{p}_1 \not{p}_2 + m(\not{p}_1 + \not{p}_2) + m^2] \\ &= \text{Tr}[\not{p}_1 \not{p}_2] + \text{Tr}[m(\not{p}_1 + \not{p}_2)] + \text{Tr}[m^2] \\ &= \text{Tr}[\not{p}_1 \not{p}_2] + m(\text{Tr}[\not{p}_1] + \text{Tr}[\not{p}_2]) + m^2 \text{Tr}[1] \\ &= \text{Tr}[\not{p}_1 \not{p}_2] + 4m^2 \\ &= 4(p_1 \cdot p_2) + 4m^2 \end{aligned} \quad (37)$$

4. By the same reasoning as shown above it can be shown that $(\bar{u}_1 \gamma^5 u_2)^* = \bar{u}_2 \gamma^5 u_1$

If we let $P = \bar{u}_1 \gamma^5 u_2$ then:

$$(P)^* = (P)^\dagger \quad (39)$$

$$\begin{aligned}
&= (\bar{u}_1 \gamma^5 u_2)^\dagger, \\
&= ((u_1)^\dagger \gamma^0 \gamma^5 u_2)^\dagger \\
&= (u_2)^\dagger (\gamma^5)^\dagger (\gamma^0)^\dagger (u_1) \\
&= (u_2)^\dagger (\gamma^5) \gamma^0 (u_1) \\
&= -(u_2)^\dagger \gamma^0 \gamma^5 (u_1) \\
&= -\bar{u}_2 \gamma^5 (u_1)
\end{aligned} \tag{40}$$

Therefore $(\bar{u}_1 \gamma^5 u_2)^* = -\bar{u}_2 \gamma^5 u_1$

In order to square P we do the following:

$$\begin{aligned}
|P|^2 &= \text{Tr}[\bar{u}_1 \gamma^5 u_2 (-\bar{u}_2 \gamma^5 u_1)] \\
&= \text{Tr}[u_1 \bar{u}_1 \gamma^5 (-\not{p}_2 - m) \gamma^5] \\
&= \text{Tr}[(\not{p}_1 + m) \gamma^5 (-\not{p}_2 - m) \gamma^5] \\
&= \text{Tr}[(p_1)_\mu \gamma^\mu + m) \gamma^5 ((-p_2)_\nu \gamma^\nu - m) \gamma^5] \\
&= \text{Tr}[(p_1)_\mu \gamma^\mu \gamma^5 + m \gamma^5] ((-p_2)_\nu \gamma^\nu \gamma^5 - m \gamma^5) \\
&= \text{Tr}[(p_1)_\mu \gamma^\mu \gamma^5 (-p_2)_\nu \gamma^\nu \gamma^5] - 4m^2 \\
&= (p_1)_\mu (-p_2)_\nu \text{Tr}[\gamma^\mu \gamma^5 \gamma^\nu \gamma^5] - 4m^2 \\
&= (p_1)_\mu (-p_2)_\nu \text{Tr}[\gamma^\mu \gamma^5 (-\gamma^5 \gamma^\nu)] - 4m^2 \\
&= (p_1)_\mu (-p_2)_\nu (-\text{Tr}[\gamma^\mu \gamma^\nu]) - 4m^2 \\
&= (p_1)_\mu (-p_2)_\nu (-4g^{\mu\nu}) - 4m^2 \\
&= 4(p_1)(p_2) - 4m^2
\end{aligned} \tag{42}$$

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