Search for New Physics in B decays

Zaineb Calcuttawala

Department of Physics
University of Calcutta

December 9, 2019

WHEPP XVI

Plan of the talk

- Introduction
- Study of some important B meson decay channels
  - $b \to s + invisible(s)$: $B \to K^{(*)} + invisibles$ and $B \to X_s + invisibles$
  - lepton flavor violating decay $\tau \to 3\mu$
- Conclusion

INTRODUCTION

- There are dedicated B physics experiments ex: BaBar, Belle, LHCb which provides a plethora of precise measurements of flavour observables in the B meson sector.
- Some of these results show consistent deviations from Standard Model predictions which hints towards New Physics.
- B decay anomalies are found in particular related to lepton flavour universality tests and angular observables in Flavour-Changing-Neutral-Current transitions.

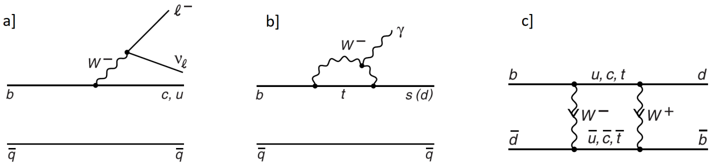


FIGURE: Some examples of B hadron decays

$b \to s \; + invisible(s)$

- We analyse the NP sensitivities of the observables in the decays $b \to s \; + invisible(s)$ using the Optimal Observables technique.
- We consider a NP model with only neutrinos as the carrier of missing energy but with a new operator involving right-handed quark current.
- The analysis takes into account all the new effective operators and their effects on the observables.

Only neutrinos as invisible

- The effective Hamiltonian for $b \to s\nu_i\bar{\nu}_i$ can be written as

$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[C_{SM} O_{SM} + C_{V_1} O_{V_1} + C_{V_2} O_{V_2} \right]$$

where

$$\begin{aligned} O_{SM} = O_{V_1} &= \left(\bar{s}_L \gamma^\mu b_L\right) \left(\bar{\nu}_{iL} \gamma_\mu \nu_{iL}\right) \\ O_{V_2} &= \left(\bar{s}_R \gamma^\mu b_R\right) \left(\bar{\nu}_{iL} \gamma_\mu \nu_{iL}\right) \end{aligned}$$

- We have assumed lepton flavor universality (LFU) and no lepton flavor violation (LFV)
- Under our simplifying assumption, we can write

$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* C_{SM} \left[(1 + C_1') O_{V_1} + C_2' O_{V_2} \right]$$

in terms of the scaled Wilson coefficients defined as $C'_{1,2} \equiv C_{V_{1,2}}/C_{SM}$, with

$$C_{SM} = \frac{\alpha}{2\pi \sin^2\theta_W} X_t(x_t)$$

where, the Inami-Lim function X_t at the leading order is given by

$$X_t^{LO} = \frac{x_t}{8}\left[\frac{x_t+2}{x_t-1} - 3\frac{x_t-2}{(x_t-1)^2}\ln x_t\right]$$

with $x_t = m_t^2/m_W^2$

Optimal Observable analysis

When the number of nonzero NP parameters is small, the analysis can be done by defining a quantity analogous to χ^2, such as

$$\chi^2 = \sum_{i,j} (c_i - c_i^0)(c_j - c_j^0) V_{ij}^{-1}$$

The c_i^0s are called the seed values, which can be considered as model inputs and V_{ij} is the covariance matrix.

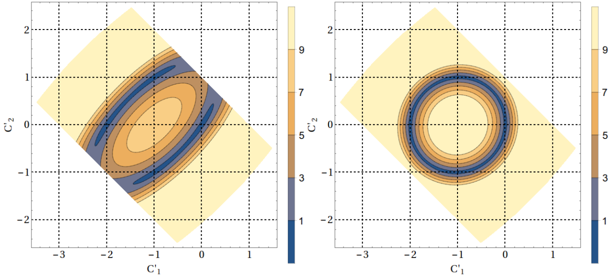
Only neutrinos as invisible

From the experimental bounds on the branching fractions, namely,

$$\mathrm{Br}(B \to K\nu\bar{\nu}) < 1.7 \times 10^{-5}$$
$$\mathrm{Br}(B \to K^*\nu\bar{\nu}) < 7.6 \times 10^{-5} \tag{1}$$

at 90% CL, we get the following approximate constraints on the scaled Wilson coefficients:

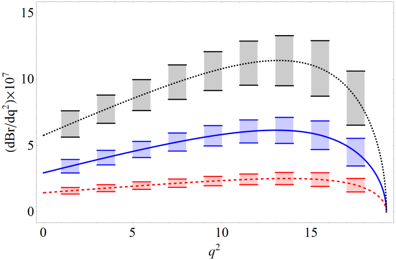
$$-3.0 \le C_1' + C_2' \le 1.0$$
$$\left(|1 + C_1'|^2 + |C_2'|^2\right) - 1.3\,(1 + C_1')\,C_2' \le 8.0 \tag{2}$$



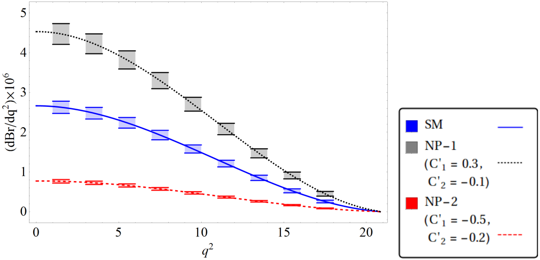
(A) $B \to K^*\nu\bar{\nu}$ (B) $B \to X_s\nu\bar{\nu}$

Figure: The SM-NP differentiating χ^2 contours for the observable dBR/dq^2 for $\mathcal{L}_{\rm int} = 50\ \mathrm{ab}^{-1}$.

Only neutrinos as invisible



(A) Decay rate distributions: $B \to K^* \nu \bar{\nu}$



(B) Decay rate distributions: $B \to X_s \nu \bar{\nu}$

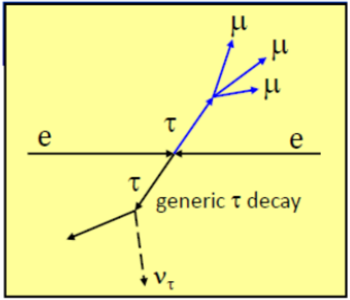
Figure: The q^2 (in GeV^2) distributions of the decay rates are shown in (A) and (B) respectively, with $\mathcal{L}_{\text{int}} = 50$ ab^{-1} for two benchmark scenarios of NP.

Lepton flavor violation

- Lepton flavor violating (LFV) processes are a smoking gun signal of New Physics.
- The LFV decay $\tau \to 3\mu$ is of crucial importance in the light of semileptonic B-decay anomalies, which hint at some new physics involving second and third generation leptons, probably a mixing among the charged leptons.
- In general four types of LFV processes have been looked for: (i) leptonic decays ($\tau \to 3e$, $\tau \to 3\mu$, $\mu \to 3e$, $\tau \to 1e + 2\mu$, $\tau \to 1\mu + 2e$), (ii) radiative decays ($\tau \to e\gamma$, $\tau \to \mu\gamma$, $\mu \to e\gamma$), (iii) semileptonic decays ($\ell_1 \to \ell_2 M$, where M is some meson) and (iv) conversion (like $\mu \to e$).
- We explore how far the nature of NP can be unravelled at the next generation B-factories like Belle-II, provided the decay $\tau \to 3\mu$ has been observed.
- We use four observables with which the differentiation among NP operators can be achieved.

Lepton flavor violation

- The Belle Collaboration has an upper bound on the branching ratio $\text{BR}(\tau \to 3\mu) < 2.1 \times 10^{-8}$ at 90% confidence level (CL).
- The existing bound on $\tau \to 3\mu$ comes from the analysis of 782 fb^{-1} data from the Belle collaboration and 468 fb^{-1} data from the BaBar collaboration.
- For 50 ab^{-1} of integrated luminosity at Belle-II, one expects $N_P = 4.6 \times 10^{10}$ $\tau^+\tau^-$ pairs. With a detection efficiency of 7.6% and using the present bound given, one expects a maximum number of such events to be about 73.



The New Physics Operators

- The most general LFV Lagrangian can be written as:

$$
\begin{aligned}
\mathcal{L} \quad = \quad & \frac{1}{\Lambda^2}\Big[g^S_{LL}(\bar\mu_L\mu_R)(\bar\mu_R\tau_L) + g^S_{LR}(\bar\mu_L\mu_R)(\bar\mu_L\tau_R) + g^S_{RL}(\bar\mu_R\mu_L)(\bar\mu_R\tau_L) + g^S_{RR}(\bar\mu_R\mu_L)(\bar\mu_L\tau_R) \\
& + g^V_{LL}(\bar\mu_R\gamma^\alpha\mu_R)(\bar\mu_L\gamma_\alpha\tau_L) + g^V_{LR}(\bar\mu_R\gamma^\alpha\mu_R)(\bar\mu_R\gamma_\alpha\tau_R) \\
& + g^V_{RL}(\bar\mu_L\gamma^\alpha\mu_L)(\bar\mu_L\gamma_\alpha\tau_L) + g^V_{RR}(\bar\mu_L\gamma^\alpha\mu_L)(\bar\mu_R\gamma_\alpha\tau_R) \\
& + \frac{1}{2}g^T_{LR}(\bar\mu_L\sigma^{\alpha\beta}\mu_R)(\bar\mu_L\sigma_{\alpha\beta}\tau_R) + \frac{1}{2}g^T_{RL}(\bar\mu_R\sigma^{\alpha\beta}\mu_L)(\bar\mu_R\sigma_{\alpha\beta}\tau_L)\Big],
\end{aligned}
$$

where, we denote the operator accompanying g^X_{IJ} ($X = S, V, T$, and $I, J = L, R$) as O^X_{IJ}. Λ is the cutoff scale, which we have set at 5 TeV for our analysis. We separate the operators into three major classes: S (operators of the form O^S_{IJ}), V (the O^V_{IJ} operators) and T (the tensor operators O^T_{IJ}). Thus, the effective Lagrangian is of the form

$$
\mathcal{L} = \frac{1}{\Lambda^2}\left[\sum_{I,J=L,R}\left(g^S_{IJ}O^S_{IJ} + g^V_{IJ}O^V_{IJ}\right) + \sum_{I\neq J} g^T_{IJ}O^T_{IJ}\right].
$$

Observables

- The differential branching ratio for the antimuon dB_τ/dx, where $x = 2E_{\bar{\mu}}/m_\tau$ is the reduced energy of the antimuon,
- The x-dependent asymmetry, normalized to the total number of events, defined as

$$\frac{dA_{FB}}{dx} \equiv A'_{FB}(x) = \sigma_{\rm Prod}\mathcal{L}_{\rm int}\epsilon \, \frac{\int_0^1 \, d(\cos\theta) \, \frac{dB_\tau}{dx \, d(\cos\theta)} - \int_{-1}^0 \, d(\cos\theta) \, \frac{dB_\tau}{dx \, d(\cos\theta)}}{N_B + N_F} \equiv \frac{N_F(x) - N_B(x)}{N} \, ,$$

- The differential branching ratio for the more energetic same-sign muon dB_τ/dy, where $y = 2E_\mu/m_\tau$ is the reduced energy of the more energetic same-sign muon,
- The y-dependent asymmetry, normalized to the total number of events, defined as

$$\mathcal{A}'_{FB}(y) = \frac{N_F(y) - N_B(y)}{N} = \sigma_{\rm Prod}\mathcal{L}_{\rm int}\epsilon \, \frac{\int_0^1 \, d(\cos\alpha) \, \frac{dB_\tau}{dy \, d(\cos\alpha)} - \int_{-1}^0 \, d(\cos\alpha) \, \frac{dB_\tau}{dy \, d(\cos\alpha)}}{N} .$$

Observables

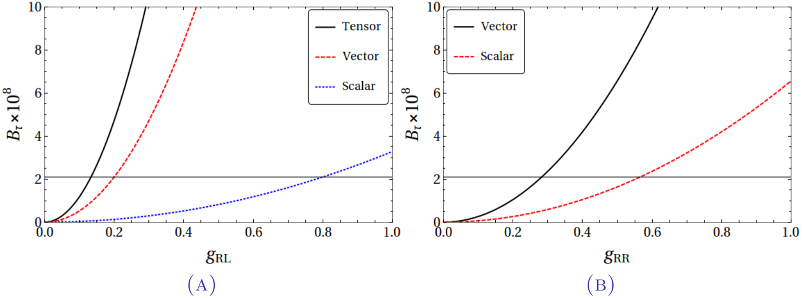


Figure: (a) Variation of $\mathrm{BR}(\tau \to 3\mu)$ with the WCs g_{RL}^I ($I = S, V, T$). (b) The same for g_{RR}^I ($I = S, V$). The horizontal line shows the present limit. The results for g_{LR}^I are identical to those for g_{RL}^I, and the results for g_{LL}^I are identical to those for g_{RR}^I.

One Operator Models

- In the single-coupling scheme, we consider four different models, depending upon which operator contributes

Model 1: O^S_{RL}	Model 2: O^S_{LL}
Model 3: O^S_{RR}	Model 4: O^S_{LR}

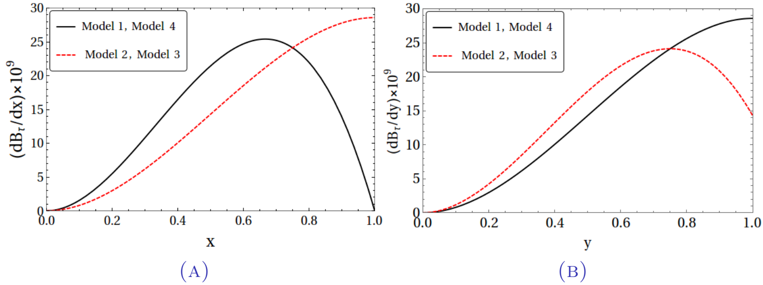


Figure: (a) dB_τ/dx and (b) dB_τ/dy for the four single coupling S class of models.

One Operator Models

$$A'_{FB}(x)_1 = -A'_{FB}(x)_4 = 6(x^2 - x^3)\,, \quad A'_{FB}(x)_2 = -A'_{FB}(x)_3 = x^2 - 2x^3\,.$$

$$A_{FB}(1) = -A_{FB}(4) = \frac{1}{2}\,, \quad A_{FB}(2) = -A_{FB}(3) = -\frac{1}{6}\,.$$

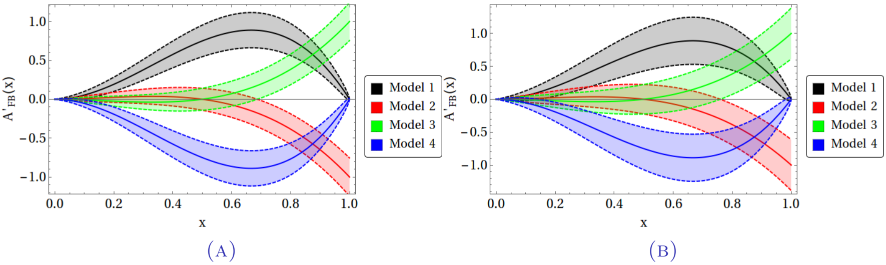


Figure: $A'_{FB}(x)$ for the antimuon with (a) 50 and (b) 20 events for the four single coupling S class of models.

ONE OPERATOR MODELS

$$\mathcal{A}'_{FB}(y)_1 = -\mathcal{A}'_{FB}(y)_4 = y^2 - 2y^3\,, \quad \mathcal{A}'_{FB}(y)_2 = -\mathcal{A}'_{FB}(y)_3 = \frac{1}{2}(7y^2 - 8y^3)\,.$$

$$\mathcal{A}_{FB}(1) = \mathcal{A}_{FB}(3) = -\mathcal{A}_{FB}(2) = -\mathcal{A}_{FB}(4) = -\frac{1}{6}\,.$$

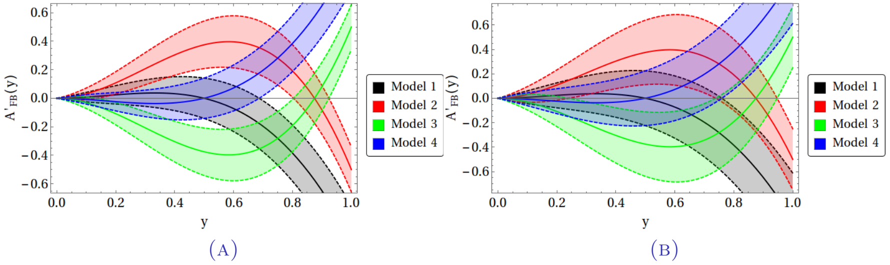


FIGURE: $A'_{FB}(y)$ for the more energetic of the two muons with (a) 50 and (b) 20 events for the four single coupling S class of models.

Two Operator Models

Model A: O^S_{RL} and O^S_{LL}

Model B: O^S_{RL} and O^S_{RR}

Model C: O^S_{RL} and O^S_{LR}

Model D: O^S_{RR} and O^S_{RL}

Model E: O^S_{RR} and O^S_{LL}

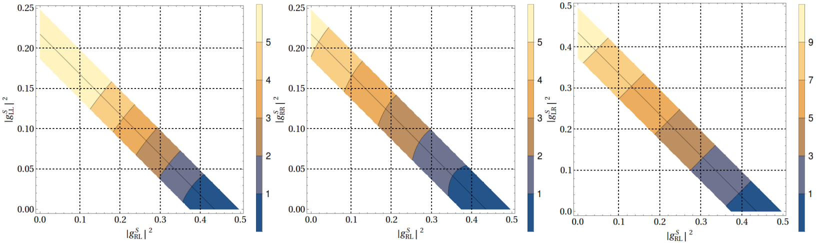
Model F: O^S_{RR} and O^S_{LR}

Inputs for the analysis

$$|g^S_{RL}|^2 = 0.44 \ (\mathrm{A, B, C}) , \quad |g^S_{RR}|^2 = 0.22 \ (\mathrm{D, E, F}) .$$

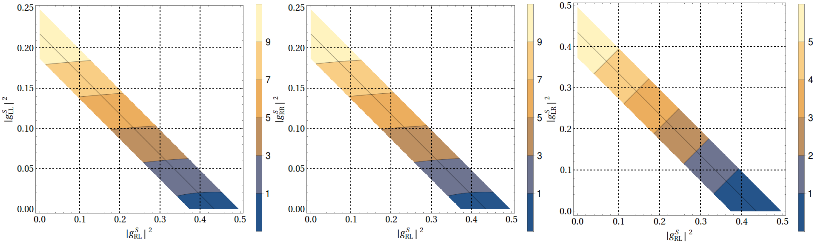
$$m_\tau = 1.78 \ \mathrm{GeV} , \quad T_\tau = 290.3 \ \mathrm{fs} , \quad \Lambda = 5 \ \mathrm{TeV} , \quad \mathcal{L}_{\rm int} = 50 \ \mathrm{ab}^{-1} .$$

Two Operator Models



(A) (B) (C)

Figure: The differentiability of the models A-C, shown in (A)-(C) respectively, from the 'seed' model, with $A'_{FB}(x)$ as the observable.



(A) (B) (C)

FIGURE: The differentiability of the models A-C, shown in (A)-(C) respectively, from the 'seed' model, with $A'_{FB}(y)$ as the observable.

Two Operator Models

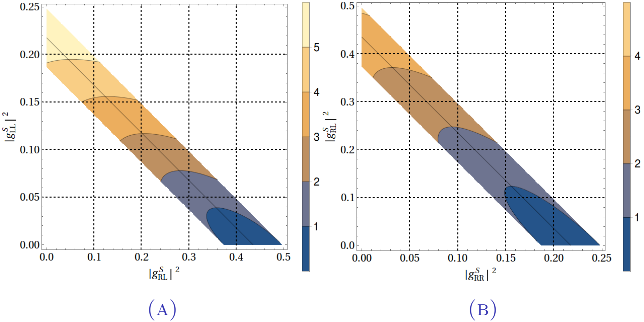
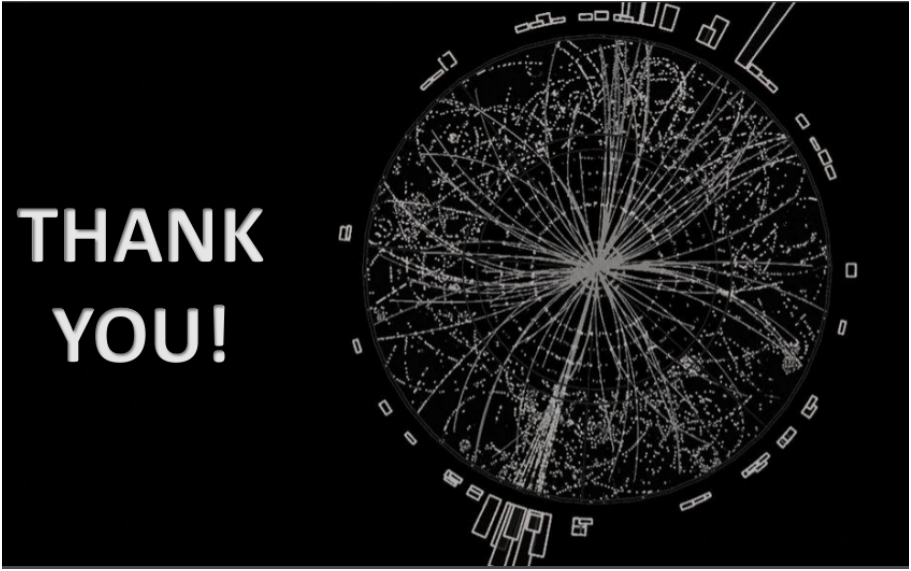


FIGURE: The differentiability of the Models A and D, shown in (a) and (b) respectively, from the 'seed' model, with dB_τ/dx as the observable. Model B is identical with Model A, and Model F is identical with Model D.

Conclusion

- From the results obtained for the $b \to s$ plus missing energy channels, we see that the observable that we have considered in our analysis is sensitive to NP effects, and even small NP effects might be detectable at future high-luminosity Belle-II. The exclusive distributions are different from the the inclusive distributions, so that may serve as a good discriminator.
- In the lepton flavor violating decay $\tau \to 3\mu$, even a single event will unequivocally indicate new physics. From our analysis, we try to study whether it is possible to say anything about the underlying operators using four observables. We see that asymmetries in different energy bins are the better observables to distinguish the operators from one another than the distribution of the number of events.
- If we have enough number of events (≈ 50), we should be able to say whether there is only one underlying operator or two. Asymmetries in different energy bins are the better observables, but the distribution of the number of events can also help and act as complementary ones


THANK
YOU!

BACKUP SLIDES

Optimal Observable analysis

- Suppose there is an observable O which depends on the variable ϕ as

$$O(\phi) = \sum_i c_i f_i(\phi)\,,$$

where c_is are model-dependent coefficients, like the Wilson coefficients (WC), and $f_i(\phi)$ are known functions of ϕ. For our case, ϕ can be identified with the momentum transfer squared.

- To get c_i, one can fold with weighting functions $w_i(\phi)$ such that

$$\int w_i(\phi) O(\phi)\, d\phi = c_i\,.$$

- There happens to be a unique choice of $w_i(\phi)$ such that the statistical error in c_is are minimized. For this choice, the covariance matrix V, defined as

$$V_{ij} \propto \int w_i(\phi) w_j(\phi) O(\phi)\, d\phi$$

is at a stationary point with respect to the variation of ϕ: $\delta V_{ij} = 0$.

Optimal Observable analysis

- This happens if we choose

$$w_i(\phi) = \frac{\sum_j X_{ij} f_j(\phi)}{O(\phi)} ,$$

  where

$$X_{ij} = (M^{-1})_{ij} , \quad M_{ij} = \int \frac{f_i(\phi) f_j(\phi)}{O(\phi)} \, d\phi .$$

- For only this choice of weighting functions, the covariance matrix is

$$V_{ij} = \langle \Delta c_i \Delta c_j \rangle = \frac{(M^{-1})_{ij} \sigma_T}{N} ,$$

  where $\sigma_T = \int O(\phi)\, d\phi$. (If $O(q^2) = d\Gamma/dq^2$, $\sigma_T = \Gamma$.) N is the total number of events, given by the integrated cross-section times total luminosity times the efficiencies
- When the number of nonzero NP parameters is small, the analysis can also be done by defining a quantity analogous to χ^2, such as

$$\chi^2 = \sum_{i,j} (c_i - c_i^0)(c_j - c_j^0) V_{ij}^{-1} .$$

  The c_i^0s are called the seed values, which can be considered as model inputs.

Observables

$$\frac{dB_\tau}{dx\, d(\cos\theta)} = \frac{T_\tau\, m_\tau^5}{128 \times 48\pi^3\Lambda^4} \left[3x^2 g_1 - x^3 g_2 + x^2 \cos\theta\, g_3 - x^3 \cos\theta\, g_4\right] ,$$

where,

$$\begin{aligned}
g_1 &\equiv |g^S_{RL}|^2 + |g^S_{LL}|^2 + |g^S_{RR}|^2 + |g^S_{LR}|^2 , \\
g_2 &\equiv 3|g^S_{RL}|^2 + 2|g^S_{LL}|^2 + 2|g^S_{RR}|^2 + 3|g^S_{LR}|^2 , \\
g_3 &\equiv 3|g^S_{RL}|^2 + |g^S_{LL}|^2 - |g^S_{RR}|^2 - 3|g^S_{LR}|^2 , \\
g_4 &\equiv 3|g^S_{RL}|^2 + 2|g^S_{LL}|^2 - 2|g^S_{RR}|^2 - 3|g^S_{LR}|^2 .
\end{aligned}$$

Model	Seed	Second operator	C_1	C_2
A	RL	LL	$3\|g^S_{RL}\|^2 + \|g^S_{LL}\|^2$	$3\|g^S_{RL}\|^2 + 2\|g^S_{LL}\|^2$
B	RL	RR	$3\|g^S_{RL}\|^2 - \|g^S_{RR}\|^2$	$3\|g^S_{RL}\|^2 - 2\|g^S_{RR}\|^2$
C	RL	LR	$3\|g^S_{RL}\|^2 - 3\|g^S_{LR}\|^2$	$3\|g^S_{RL}\|^2 - 3\|g^S_{LR}\|^2$
D	RR	RL	$-\|g^S_{RR}\|^2 + 3\|g^S_{RL}\|^2$	$-2\|g^S_{RR}\|^2 + 3\|g^S_{RL}\|^2$
E	RR	LL	$-\|g^S_{RR}\|^2 + \|g^S_{LL}\|^2$	$-2\|g^S_{RR}\|^2 + 2\|g^S_{LL}\|^2$
F	RR	LR	$-\|g^S_{RR}\|^2 - 3\|g^S_{LR}\|^2$	$-2\|g^S_{RR}\|^2 - 3\|g^S_{LR}\|^2$

Table: C_1 and C_2 for different models. The observable is $A'_{FB}(x)$.

Observables

Model	Seed	Second operator	C_1	C_2
A	RL	LL	$\lvert g_{RL}^S\rvert^2 + \lvert g_{LL}^S\rvert^2$	$3\lvert g_{RL}^S\rvert^2 + 2\lvert g_{LL}^S\rvert^2$
B	RL	RR	$\lvert g_{RL}^S\rvert^2 + \lvert g_{RR}^S\rvert^2$	$3\lvert g_{RL}^S\rvert^2 + 2\lvert g_{RR}^S\rvert^2$
C	RL	LR	$\lvert g_{RL}^S\rvert^2 + \lvert g_{LR}^S\rvert^2$	$3\lvert g_{RL}^S\rvert^2 + 3\lvert g_{LR}^S\rvert^2$
D	RR	RL	$\lvert g_{RR}^S\rvert^2 + \lvert g_{RL}^S\rvert^2$	$2\lvert g_{RR}^S\rvert^2 + 3\lvert g_{RL}^S\rvert^2$
E	RR	LL	$\lvert g_{RR}^S\rvert^2 + \lvert g_{LL}^S\rvert^2$	$2\lvert g_{RR}^S\rvert^2 + 2\lvert g_{LL}^S\rvert^2$
F	RR	LR	$\lvert g_{RR}^S\rvert^2 + \lvert g_{LR}^S\rvert^2$	$2\lvert g_{RR}^S\rvert^2 + 3\lvert g_{LR}^S\rvert^2$

Table: C_1 and C_2 for different models. The observable is dB_τ/dx.

Reaction	Present limit	C.L.	Experiment	Year
$\mu^+ \to e^+\gamma$	$< 4.2 \times 10^{-13}$	90%	MEG at PSI	2016
$\mu^+ \to e^+e^-e^+$	$< 1.0 \times 10^{-12}$	90%	SINDRUM	1988
$\mu^-\mathrm{Ti} \to e^-\mathrm{Ti}^{\dagger}$	$< 6.1 \times 10^{-13}$	90%	SINDRUM II	1998
$\mu^-\mathrm{Pb} \to e^-\mathrm{Pb}^{\dagger}$	$< 4.6 \times 10^{-11}$	90%	SINDRUM II	1996
$\mu^-\mathrm{Au} \to e^-\mathrm{Au}^{\dagger}$	$< 7.0 \times 10^{-13}$	90%	SINDRUM II	2006
$\mu^-\mathrm{Ti} \to e^+\mathrm{Ca}^{*\,\dagger}$	$< 3.6 \times 10^{-11}$	90%	SINDRUM II	1998
$\mu^+e^- \to \mu^-e^+$	$< 8.3 \times 10^{-11}$	90%	SINDRUM	1999
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$	90%	BaBar	2010
$\tau \to \mu\gamma$	$< 4.4 \times 10^{-8}$	90%	BaBar	2010
$\tau \to eee$	$< 2.7 \times 10^{-8}$	90%	Belle	2010
$\tau \to \mu\mu\mu$	$< 2.1 \times 10^{-8}$	90%	Belle	2010
$\tau \to \pi^0 e$	$< 8.0 \times 10^{-8}$	90%	Belle	2007
$\tau \to \pi^0 \mu$	$< 1.1 \times 10^{-7}$	90%	BaBar	2007
$\tau \to \rho^0 e$	$< 1.8 \times 10^{-8}$	90%	Belle	2011
$\tau \to \rho^0 \mu$	$< 1.2 \times 10^{-8}$	90%	Belle	2011