SMEFT analysis of charged lepton flavor violating B-meson decays

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with

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Outline

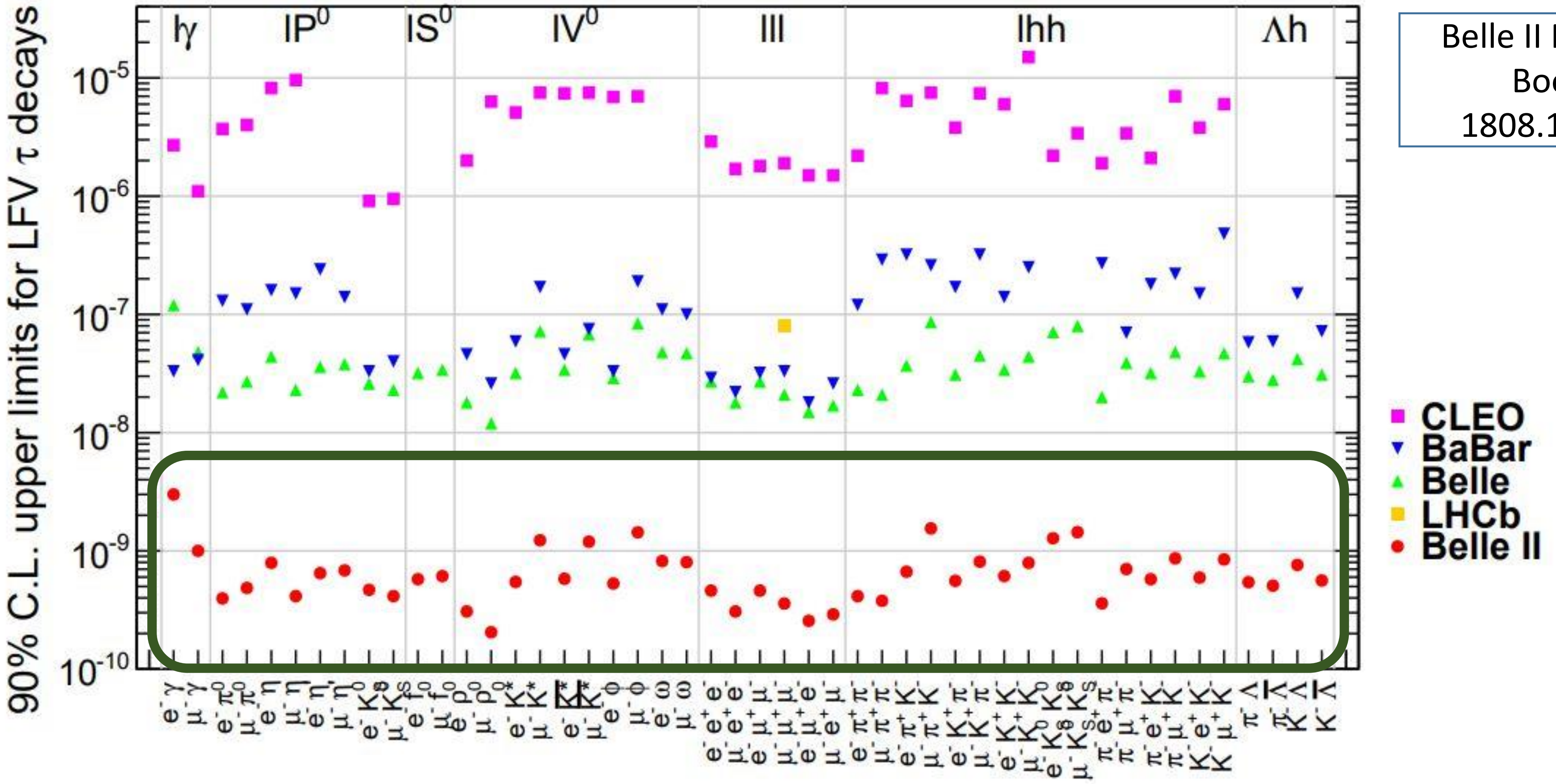
- Motivation
- Procedure
- Results
- Conclusion

Motivation I

- It is well known that the neutral part of the lepton family, neutrinos, mix among themselves giving rise to lepton flavor violation (LFV).

- Similar phenomena in the charged lepton sector, known as charged Lepton Flavor Violation (cLFV) has not been observed.

Motivation I



Belle II Physics Book 1808.10567

Motivation I

- We focused on LFV processes from B meson decays (LFVBD)

Observables of cLFV modes.	Present bounds		Expected future limits	
$BR(\mu \to e\gamma)$	4.2×10^{-13}	MEG(2016) [12]	6×10^{-14}	MEGII[13]
$BR(\mu \to eee)$	1.0×10^{-12}	SINDRUM(1988) [14]	10^{-16}	Mu3e[94]
$CR(\mu - e, Au)$	7.0×10^{-13}	SINDRUMII(2006) [15]	–	–
$CR(\mu - e, Al)$	-	-	6×10^{-17}	COMET/Mu2e[17], [95]
	-	-	10^{-15} (Phase I) & 10^{-17} (Phase II)	J-PARK[18]
$BR(\tau \to e\gamma)$	3.3×10^{-8}	BaBar(2010) [22]	3×10^{-9}	Belle-II[24]
$BR(\tau \to eee)$	2.7×10^{-8}	BaBar(2010) [96]	5×10^{-10}	Belle[97]
$BR(\tau \to e\mu\mu)$	2.7×10^{-8}	BaBar(2010) [96]	5×10^{-10}	Belle-II[24]
$BR(\tau \to \mu\gamma)$	4.2×10^{-8}	Belle(2021) [23]	10^{-9}	Belle-II[24]
$BR(\tau \to \mu\mu\mu)$	2.1×10^{-8}	BaBar(2010) [96]	4×10^{-10}	Belle-II[24]
$BR(\tau \to \mu ee)$	1.8×10^{-8}	BaBar(2010) [96]	3×10^{-10}	Belle-II[24]
$BR(\tau \to \pi\mu)$	1.1×10^{-7}	BaBar(2006) [98]	5×10^{-10}	Belle-II[24]
$BR(\tau \to \rho\mu)$	1.2×10^{-8}	BaBar(2011) [99]	2×10^{-10}	Belle-II[24]
$BR(Z \to \mu e)$	1.7×10^{-6} LEP (95% CL) [100]	7.5×10^{-7} LHC (95% CL)[101]	$10^{-8} - 10^{-10}$	CEPC/FCC-ee
$BR(Z \to \tau e)$	9.8×10^{-6} [100]	5.0×10^{-6} [101], [102]	10^{-9}	CEPC/FCC-ee
$BR(Z \to \tau\mu)$	1.2×10^{-5} [103]	6.5×10^{-6} [101], [102]	10^{-9}	CEPC/FCC-ee
$BR(B^+ \to K^+\mu^-e^+)$	$7.0(9.5) \times 10^{-9}$	LHCb(2019) [33]	–	-
$BR(B^+ \to K^+\mu^+e^-)$	$6.4(8.8) \times 10^{-9}$	LHCb(2019) [33]	–	-
$BR(B^0 \to K^{*0}\mu^+e^-)$	$5.7(6.9) \times 10^{-9}$	LHCb(2022) [34]	–	-
$BR(B^0 \to K^{*0}\mu^-e^+)$	$6.8(7.9) \times 10^{-9}$	LHCb(2022) [34]	–	-
$BR(B^0 \to K^{*0}\mu^\pm e^\mp)$	$10.1(11.7) \times 10^{-9}$	LHCb(2022) [34]	–	-
$BR(B_s^0 \to \phi\mu^\pm e^\mp)$	$16(19.8) \times 10^{-9}$	LHCb(2022) [34]	–	-
$BR(B^+ \to K^+\mu^-\tau^+)$	3.9×10^{-5}	LHCb(2020) [104]	–	-
$BR(B^+ \to K^+\tau^\pm e^\mp)$	3.0×10^{-5}	(2022)	2.1×10^{-6}	Belle-II [24]
$BR(B^+ \to K^+\tau^\pm\mu^\mp)$	4.8×10^{-5}	(2022)	3.3×10^{-6}	Belle-II [24]
$BR(B^0 \to K^{*0}\tau^+\mu^-)$	$1.0(1.2) \times 10^{-5}$	LHCb(2022) [105]	–	-
$BR(B^0 \to K^{*0}\tau^-\mu^+)$	$8.2(9.8) \times 10^{-6}$	LHCb(2022) [105]	–	-
$BR(B_s^0 \to \mu^\mp e^\pm)$	$5.4(6.3) \times 10^{-9}$	LHCb(2018) [31]	3×10^{-10}	LHCb-II [35]
$BR(B^0 \to \mu^\pm e^\mp)$	$1.0(1.3) \times 10^{-9}$	LHCb(2018) [31]	–	–
$BR(B_s^0 \to \tau^\pm e^\mp)$	7.3×10^{-4}(95%)	LHCb(2019) [32]	–	–
$BR(B^0 \to \tau^\pm e^\mp)$	2.1×10^{-5}(95%)	LHCb(2019) [32]	–	–
$BR(B_s^0 \to \tau^\pm\mu^\mp)$	4.2×10^{-5}(95%)	LHCb(2019) [32]	–	–
$BR(B^0 \to \tau^\pm\mu^\mp)$	1.4×10^{-5}(95%)	LHCb(2019) [32]	1.3×10^{-6}	Belle-II [24]

Motivation II

- To identify the most relevant operators responsible for Lepton Flavor Violating B-meson Decays (LFVBDs).

- To analyze their effect on other LFV processes in a model-independent way.

- We want to comment on the constraints on such operators coefficients.

- Also, in view of several proposed experiments to study charged LFV processes, we want to comment on the indirect constraints on such LFVBD processes.

Procedure

- Effective Hamiltonian for $b \rightarrow s l_i l_j$ transitions process is given by

$$H_{Eff}^{l_i l_j} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* + \sum_{n=9,10,S,P} [C_n(\mu)\mathcal{O}_n(\mu) + C_n'(\mu)\mathcal{O}_n'(\mu)]$$

G_F	=	Fermi Constant
$V_{tb}V_{ts}^*$	=	Cabbibo-Kobayashi-Maskwa(CKM) matrix elements
n = 9,10	⟹	"Semi-leptonic" operators
n = S,P	⟹	Scalar and Pseudo-scalar operators
C_n' , $\mathcal{O}_n'$	⟹	Chiral Counterparts

Procedure

Operator Structures

$\mathcal{O}_{7-10}$

$$\mathcal{O}_7 = \frac{e}{g^2}\overline{m}_b[\bar{s}_{Li}\sigma^{\mu\nu}b_{Ri}]F_{\mu\nu}, \qquad \mathcal{O}_8 = \frac{1}{g}\overline{m}_b[\bar{s}_{Li}\sigma^{\mu\nu}T^a_{ij}b_{Ri}]G^a_{\mu\nu},$$

$$\mathcal{O}_9 = \frac{e^2}{g^2}[\bar{s}_L\gamma_\mu b_L][\bar{\ell}_i\gamma^\mu\ell_j], \qquad \mathcal{O}_{10} = \frac{e^2}{g^2}[\bar{s}_L\gamma_\mu b_L][\bar{\ell}_i\gamma^\mu\gamma_5\ell_j]$$

$\mathcal{O}'_{7-10}$

$$\mathcal{O}'_7 = \frac{e}{g^2}\overline{m}_b[\bar{s}_{Ri}\sigma^{\mu\nu}b_{Li}]F_{\mu\nu}, \qquad \mathcal{O}'_8 = \frac{1}{g}\overline{m}_b[\bar{s}_{Ri}\sigma^{\mu\nu}T^a_{ij}b_{Li}]G^a_{\mu\nu},$$

$$\mathcal{O}'_9 = \frac{e^2}{g^2}[\bar{s}_R\gamma_\mu b_R][\bar{\ell}_i\gamma^\mu\ell_j], \qquad \mathcal{O}'_{10} = \frac{e^2}{g^2}[\bar{s}_R\gamma_\mu b_R][\bar{\ell}_i\gamma^\mu\gamma_5\ell_j]$$

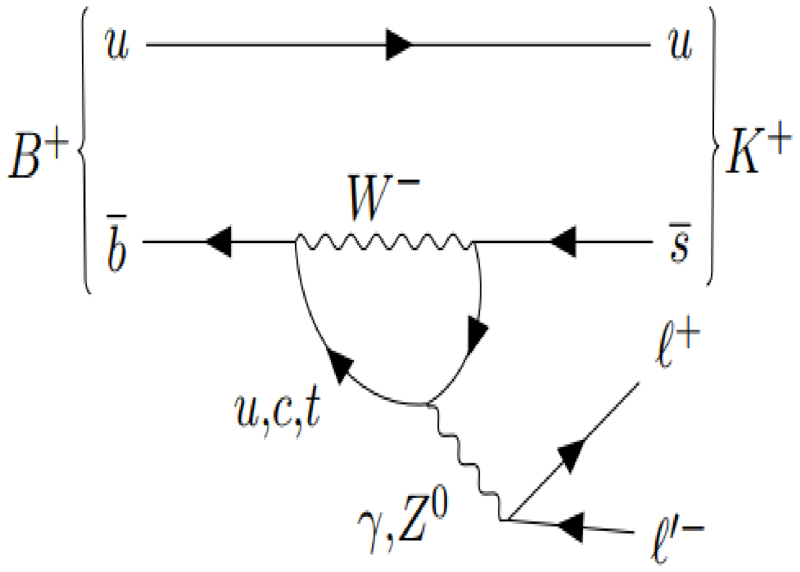
$\mathcal{O}^{(\prime)}_{S,P}$

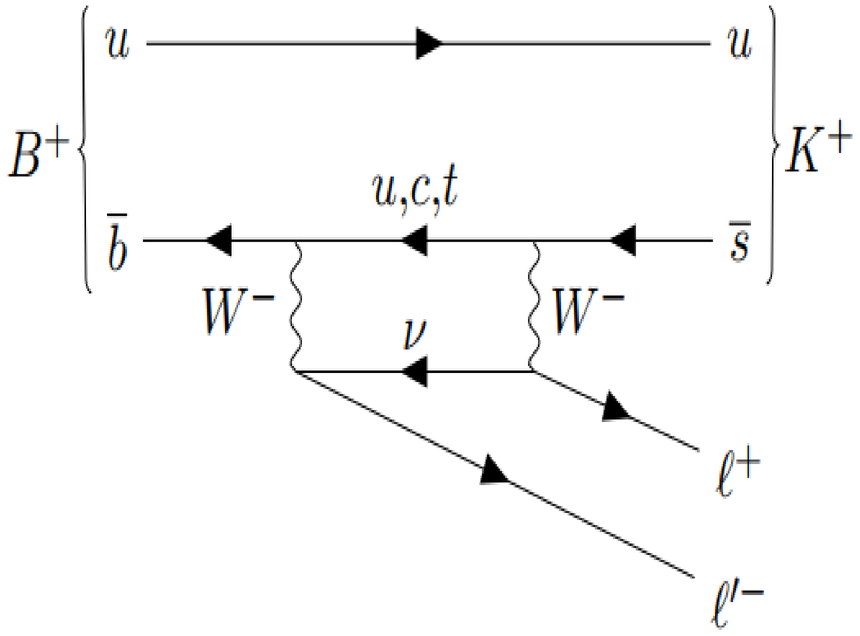
$$\mathcal{O}_S = \frac{e^2}{(4\pi)^2}[\bar{s}_L b_R][\bar{\ell}_i\ell_j], \qquad \mathcal{O}^{(\prime)}_S = \frac{e^2}{(4\pi)^2}[\bar{s}_R b_L][\bar{\ell}_i\ell_j],$$

$$\mathcal{O}_P = \frac{e^2}{(4\pi)^2}[\bar{s}_L b_R][\bar{\ell}_i\gamma_5\ell_j], \qquad \mathcal{O}^{(\prime)}_P = \frac{e^2}{(4\pi)^2}[\bar{s}_R b_L][\bar{\ell}_i\gamma_5\ell_j]$$

Procedure

Feynman Diagrams





Procedure

THEORY

$$\mathrm{Br}[B_s \to \ell_i^- \ell_j^+] = \frac{\tau_{B_s}}{64\pi^3}\frac{\alpha^2 G_F^2}{m_{B_s}^3} f_{B_s}^2 |V_{tb}V_{ts}^*|^2 \lambda^{1/2}(m_{B_s}, m_i, m_j)$$
$$\times\Bigg\{[m_{B_s}^2 - (m_i+m_j)^2]\cdot\left|(C_9^{\ell_i\ell_j} - C_9'^{\ell_i\ell_j})(m_i - m_j) + (C_S^{\ell_i\ell_j} - C_S'^{\ell_i\ell_j})\frac{m_{B_s}^2}{m_b+m_s}\right|^2$$
$$+[m_{B_s}^2 - (m_i-m_j)^2]\cdot\left|(C_{10}^{\ell_i\ell_j} - C_{10}'^{\ell_i\ell_j})(m_i + m_j) + (C_P^{\ell_i\ell_j} - C_P'^{\ell_i\ell_j})\frac{m_{B_s}^2}{m_b+m_s}\right|^2\Bigg\}$$

$$\mathrm{Br}[B \to K^{(*)}\ell_i^+\ell_j^-] = 10^{-9}\Big\{a_{K^{(*)}\ell_i\ell_j}\left|C_9^{\ell_i\ell_j} + C_9'^{\ell_i\ell_j}\right|^2 + b_{K^{(*)}\ell_i\ell_j}\left|C_{10}^{\ell_i\ell_j} + C_{10}'^{\ell_i\ell_j}\right|^2$$
$$+c_{K^*\ell_i\ell_j}\left|C_9^{\ell_i\ell_j} - C_9'^{\ell_i\ell_j}\right|^2 + d_{K^*\ell_i\ell_j}\left|C_{10}^{\ell_i\ell_j} - C_{10}'^{\ell_i\ell_j}\right|^2$$
$$+e_{K^{(*)}\ell_i\ell_j}\left|C_S^{\ell_i\ell_j} + C_S'^{\ell_i\ell_j}\right|^2 + f_{K^{(*)}\ell_i\ell_j}\left|C_P^{\ell_i\ell_j} + C_P'^{\ell_i\ell_j}\right|^2$$
$$+g_{K^{(*)}\ell_i\ell_j}\left|C_S^{\ell_i\ell_j} - C_S'^{\ell_i\ell_j}\right|^2 + h_{K^{(*)}\ell_i\ell_j}\left|C_P^{\ell_i\ell_j} - C_P'^{\ell_i\ell_j}\right|^2\Big\}.$$

Procedure

THEORY

$$C_9^{\ell_i\ell_j} = \frac{(4\pi)^2}{e^2\lambda_{bs}}\frac{v^2}{\Lambda^2}\left(C_{qe}^{\ell_i\ell_j} + C_{\ell q}^{(1)\ell_i\ell_j} + C_{\ell q}^{(3)\ell_i\ell_j}\right),$$

$$C_9^{\prime\ell_i\ell_j} = \frac{(4\pi)^2}{e^2\lambda_{bs}}\frac{v^2}{\Lambda^2}\left(C_{ed}^{\ell_i\ell_j} + C_{\ell d}^{\ell_i\ell_j}\right),$$

$$C_{10}^{\ell_i\ell_j} = \frac{(4\pi)^2}{e^2\lambda_{bs}}\frac{v^2}{\Lambda^2}\left(C_{qe}^{\ell_i\ell_j} - C_{\ell q}^{(1)\ell_i\ell_j} - C_{\ell q}^{(3)\ell_i\ell_j}\right),$$

$$C_{10}^{\prime\ell_i\ell_j} = \frac{(4\pi)^2}{e^2\lambda_{bs}}\frac{v^2}{\Lambda^2}\left(C_{ed}^{\ell_i\ell_j} - C_{\ell d}^{\ell_i\ell_j}\right)$$

$$C_S^{\ell_i\ell_j} = -C_P^{\ell_i\ell_j} = \frac{(4\pi)^2}{e^2\lambda_{bs}}\frac{v^2}{\Lambda^2}C_{\ell edq}^{\ell_i\ell_j},$$

$$C_S^{\prime\ell_i\ell_j} = C_P^{\prime\ell_i\ell_j} = \frac{(4\pi)^2}{e^2\lambda_{bs}}\frac{v^2}{\Lambda^2}C_{\ell edq}^{\prime\ell_i\ell_j},$$

Procedure

THEORY

- The decay rates (tree-level) of such LFVBD processes depend on

4-fermion Operator		Chirality
$Q_{\ell q}^{(1)}$	$(\bar{\ell}_i \gamma_\mu \ell_j)(\bar{q}_k \gamma^\mu q_l)$	$(\overline{L}L)(\overline{L}L)$
$Q_{\ell q}^{(3)}$	$(\bar{\ell}_i \gamma_\mu \tau^I \ell_j)(\bar{q}_k \gamma^\mu \tau^I q_l)$	$(\overline{L}L)(\overline{L}L)$
Q_{qe}	$(\bar{q}_i \gamma_\mu q_j)(\bar{e}_k \gamma^\mu e_l)$	$(\overline{L}L)(\overline{R}R)$
$Q_{\ell d}$	$(\bar{\ell}_i \gamma_\mu \ell_j)(\bar{d}_k \gamma^\mu d_l)$	$(\overline{L}L)(\overline{R}R)$
Q_{ed}	$(\bar{e}_i \gamma_\mu e_j)(\bar{d}_k \gamma^\mu d_l)$	$(\overline{R}R)(\overline{R}R)$
$Q_{\ell edq}$	$(\bar{\ell}_i^a e_j)(\bar{d}_k q_l^a)$	$(\overline{L}R)(\overline{R}L)$

Procedure

ANALYSIS

- In order to impose experimental constraints on the coefficients of higher dimensional operators, one needs to evaluate the Renormalization Group (RG) running from the scale Λ to the energy scale relevant for a given experiment.

Procedure

$\mathbb{C}\ (\mu)$

ANALYSIS

$\Lambda\ (TeV)$

↓

m_Z (91 GeV)

↓

m_b(5-6 GeV)

↓

m_τ (1.78 GeV)

↓

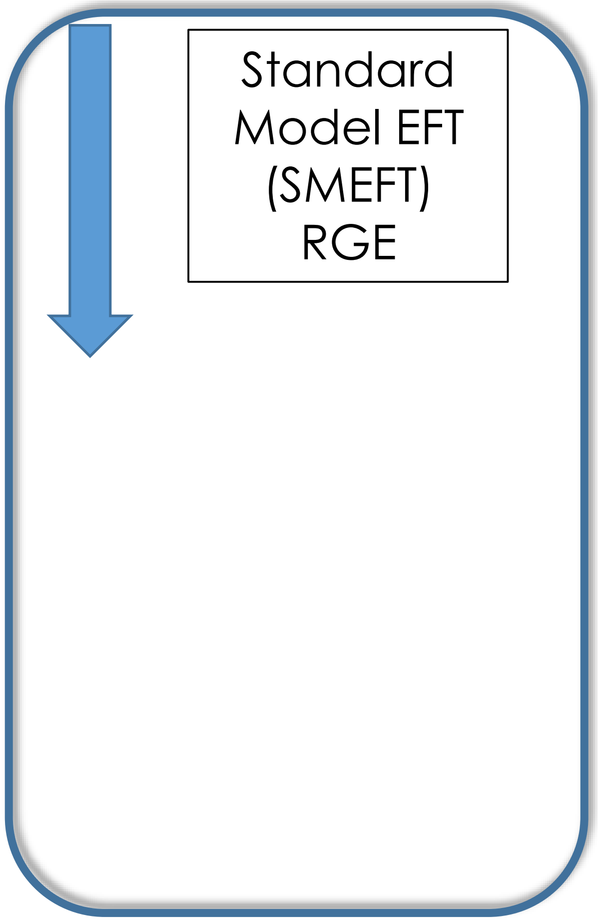
m_μ (0.1 GeV)

Procedure

C (μ)

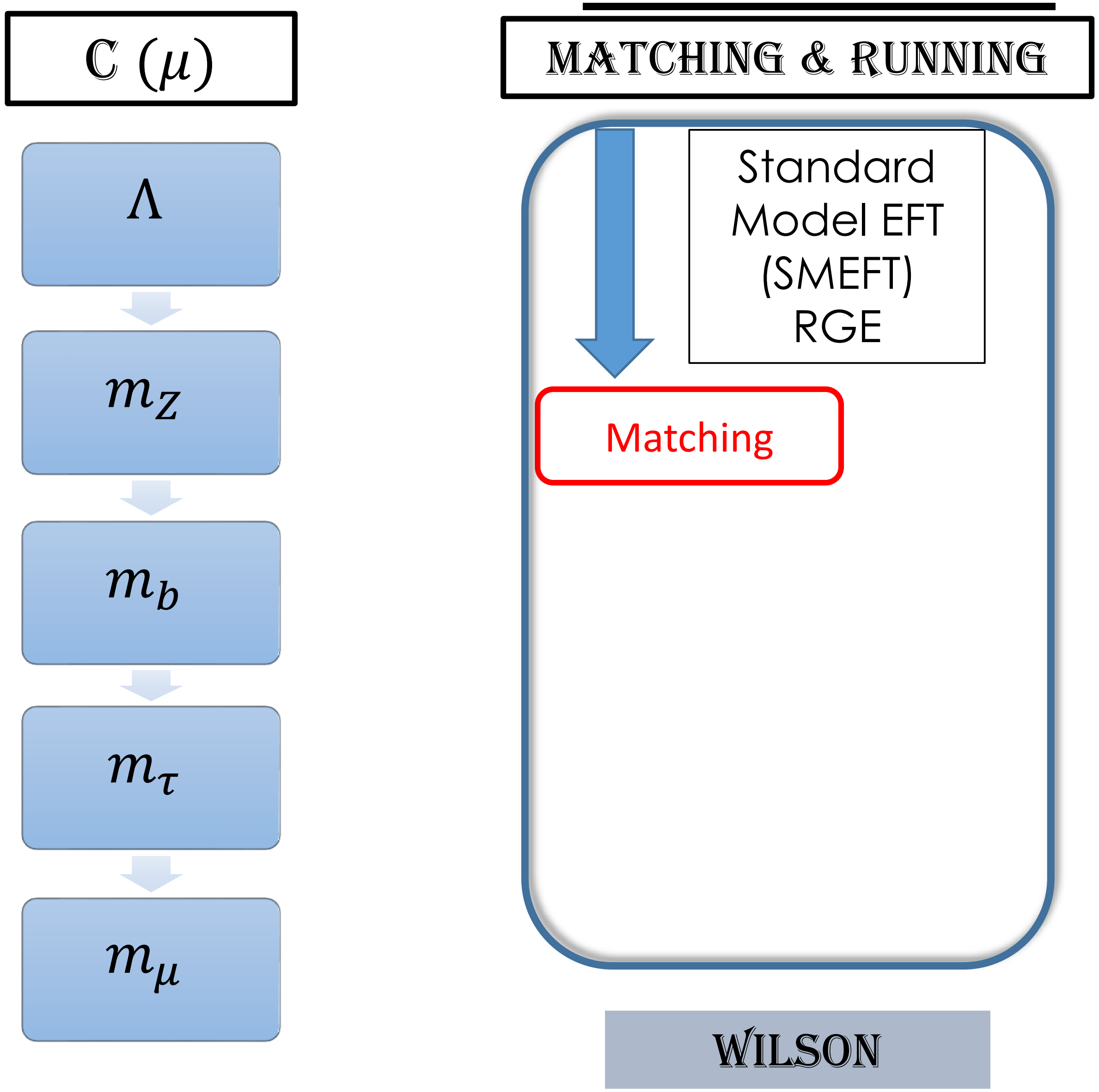
- Λ
- m_Z
- m_b
- m_τ
- m_μ

MATCHING & RUNNING

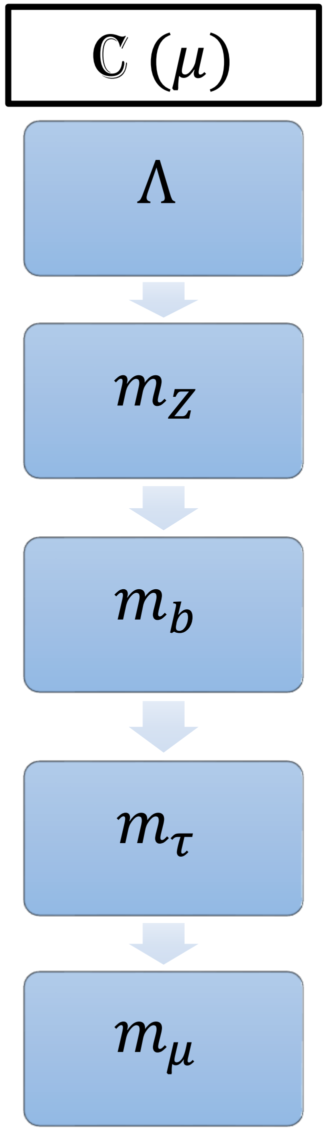


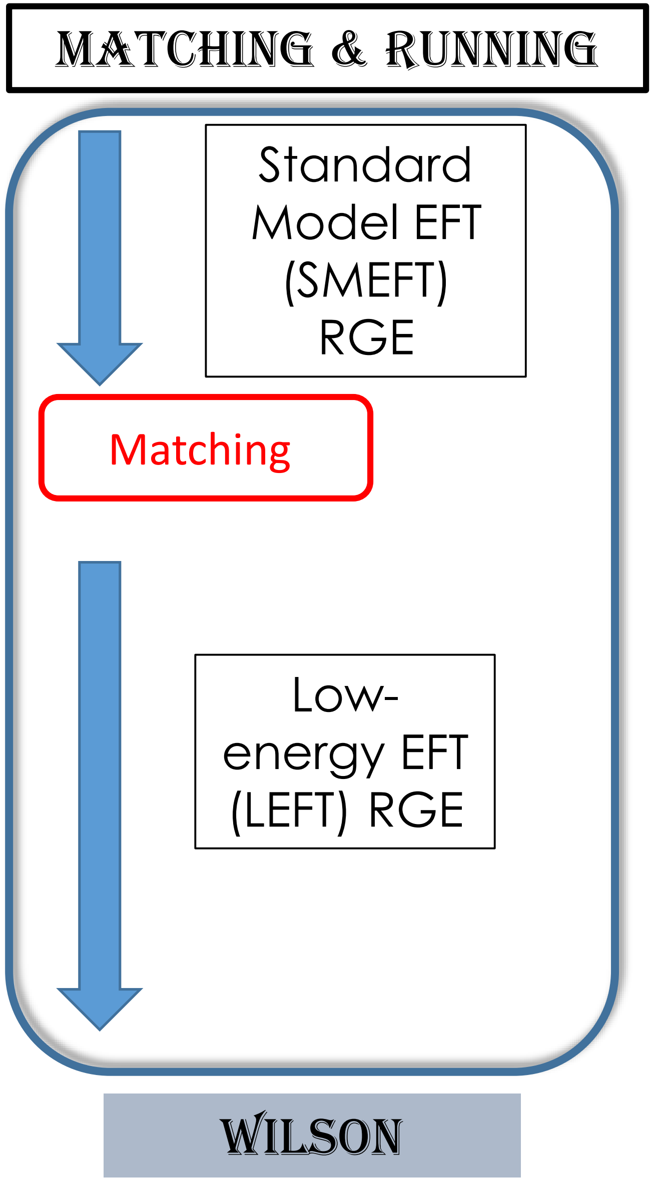
WILSON

Procedure

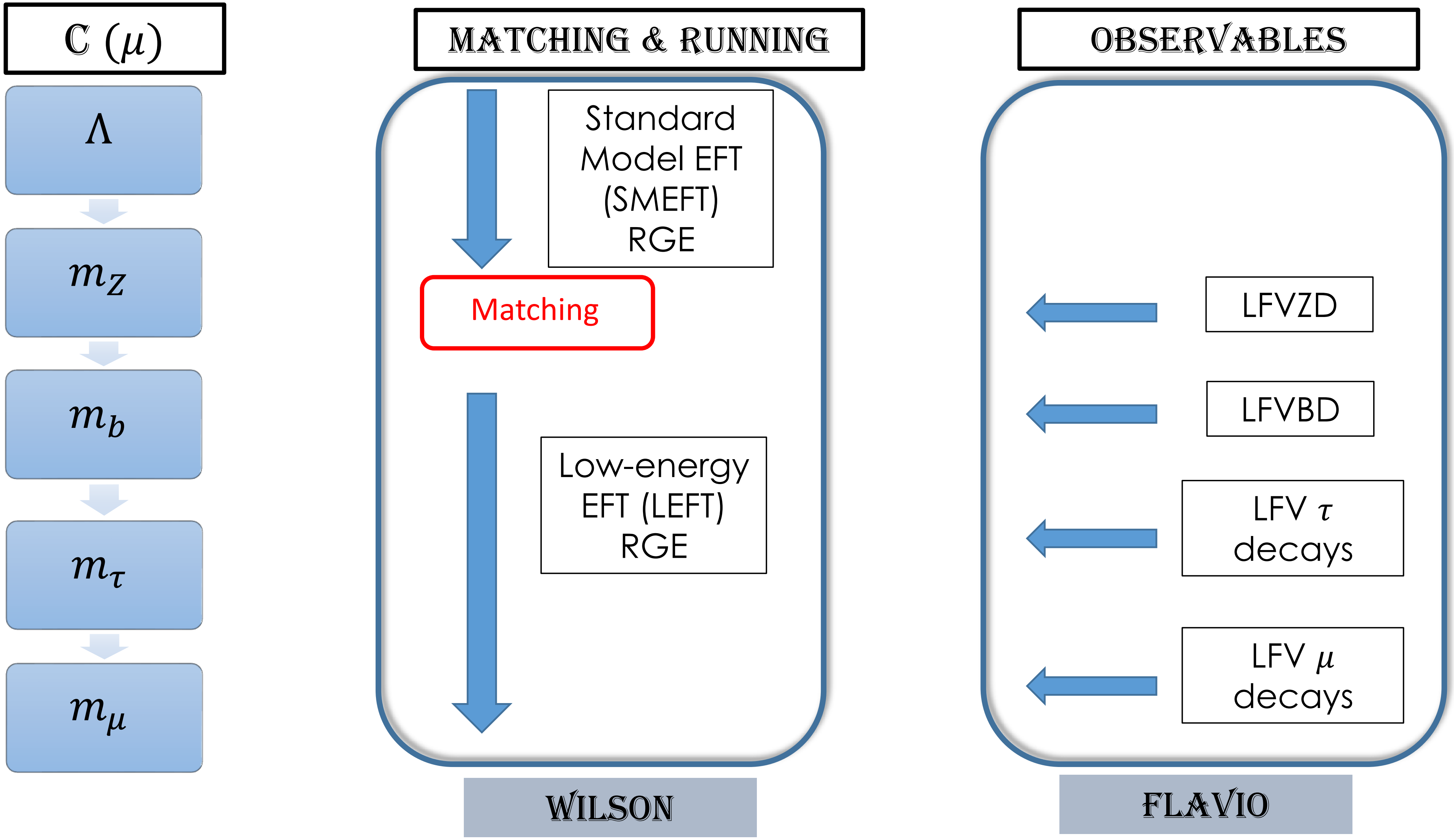

C (μ)
Λ
m_Z
m_b
m_τ
m_μ
MATCHING & RUNNING
Standard Model EFT (SMEFT) RGE
Matching
WILSON

Procedure


C (μ)
Λ
m_Z
m_b
m_τ
m_μ


MATCHING & RUNNING
Standard Model EFT (SMEFT) RGE
Matching
Low-energy EFT (LEFT) RGE
WILSON

Procedure


C (μ)
Λ
m_Z
m_b
m_τ
m_μ
MATCHING & RUNNING
Standard Model EFT (SMEFT) RGE
Matching
Low-energy EFT (LEFT) RGE
WILSON
OBSERVABLES
LFVZD
LFVBD
LFV τ decays
LFV μ decays
FLAVIO

Results (1-D Analysis)

RGE Effects

Processes	Most relevant operators
$B \to K \ell_i \ell_j$	$Q_{\ell q}^{(1)}, Q_{\ell q}^{(3)}, Q_{qe}, Q_{\ell d}, Q_{ed}, Q_{\ell edq}$
$B \to K^* \ell_i \ell_j$	$Q_{\ell q}^{(1)}, Q_{\ell q}^{(3)}, Q_{qe}, Q_{\ell d}, Q_{ed}, Q_{\ell edq}$
$B_s \to \mu e$	$Q_{\ell q}^{(1)}, Q_{\ell q}^{(3)}, Q_{qe}, Q_{\ell d}, Q_{ed}, Q_{\ell edq}$
$\ell_i \to \ell_j \gamma$	Q_{eB}, Q_{eW}
$\ell_i \to \ell_j \ell_j \bar{\ell}_j$	$Q_{\varphi\ell}^{(1)}, Q_{\varphi\ell}^{(3)}, Q_{\varphi e}, Q_{\ell\ell}, Q_{\ell e}, Q_{ee}$
$\ell_i \to \ell_j \ell_k \bar{\ell}_k$	$Q_{\varphi\ell}^{(1)}, Q_{\varphi\ell}^{(3)}, Q_{\varphi e}, Q_{\ell\ell}, Q_{\ell e}, Q_{ee}$
CR($\mu \to e$)	$Q_{\varphi\ell}^{(1)}, Q_{\varphi\ell}^{(3)}, Q_{\varphi e}, Q_{eu}, Q_{\ell u}, Q_{\ell q}^{(1)}, Q_{\ell q}^{(3)}, Q_{qe}, Q_{\ell d}, Q_{ed}, Q_{\ell edq}, Q_{\ell equ}$
$Z \to \ell_i \ell_j$	$Q_{\varphi\ell}^{(1)}, Q_{\varphi\ell}^{(3)}, Q_{\varphi e}, Q_{eB}, Q_{eW}$
$\tau \to \mathcal{V}\ell\ (\mathcal{V} = \rho, \phi)$	$Q_{\varphi\ell}^{(1)}, Q_{\varphi\ell}^{(3)}, Q_{\varphi e}, Q_{\ell u}, Q_{eu}, Q_{\ell equ}, Q_{eB}, Q_{eW}, Q_{\ell q}^{(1)}, Q_{\ell q}^{(3)}, Q_{qe}, Q_{\ell d}, Q_{ed}$
$\tau \to \mathcal{P}\ell\ (\mathcal{P} = \pi^0, K^0)$	$Q_{\varphi\ell}^{(1)}, Q_{\varphi\ell}^{(3)}, Q_{\varphi e}, Q_{\ell u}, Q_{eu}, Q_{\ell equ}, Q_{eB}, Q_{eW}, Q_{\ell q}^{(1)}, Q_{\ell q}^{(3)}, Q_{qe}, Q_{\ell d}, Q_{ed}, Q_{\ell edq}$

Results (1-D Analysis)
RGE Effects

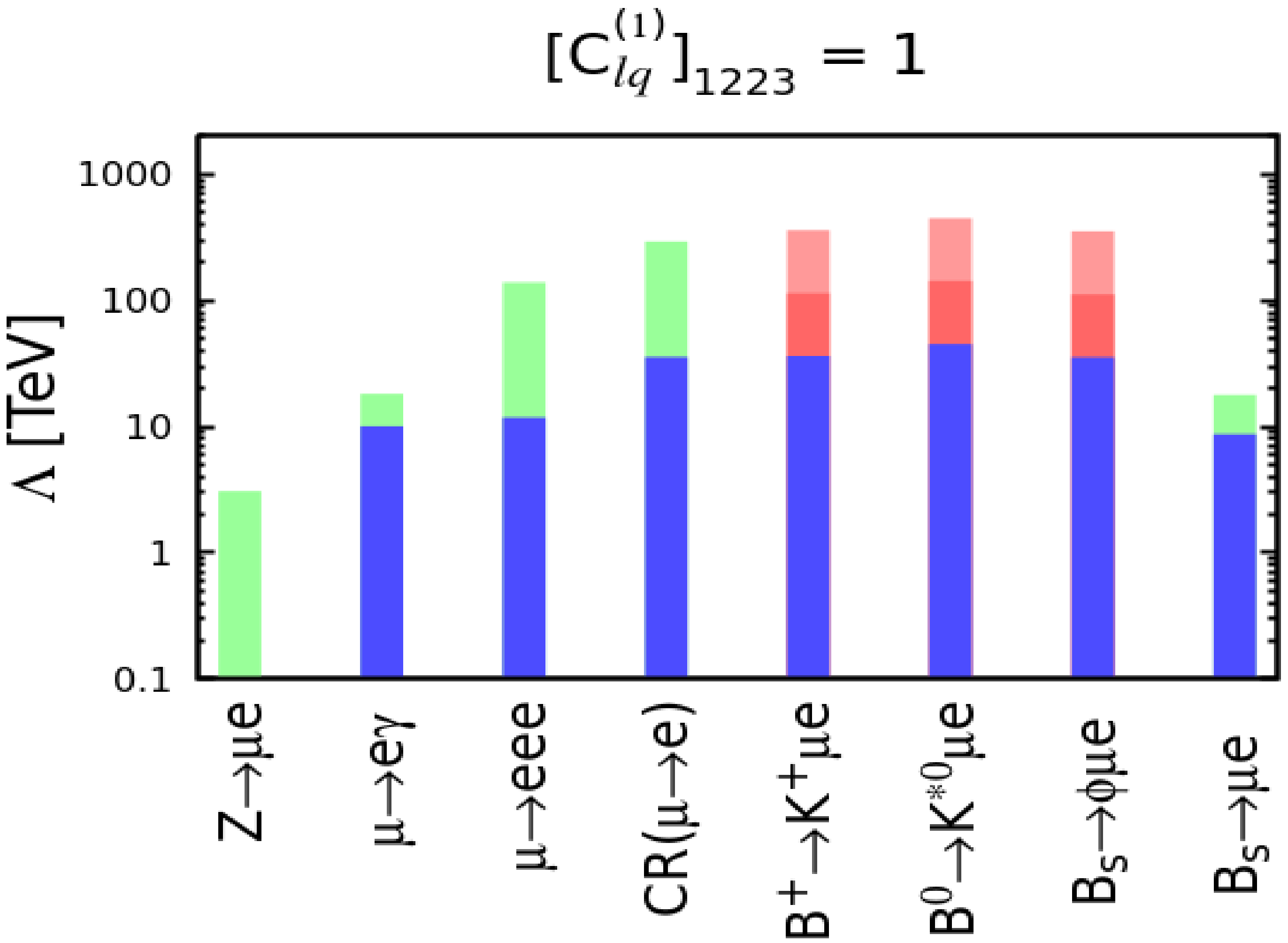
WCs	$[C_{\ell q}^{(1)}]_{1223}$	$[C_{\ell q}^{(3)}]_{1223}$	$[C_{qe}]_{2312}$	$[C_{ed}]_{1223}$	$[C_{\ell d}]_{1223}$	$[C_{\ell edq}]_{1223}$	$[C_{\varphi\ell}^{(1)}]_{12}$	$[C_{\varphi\ell}^{(3)}]_{12}$	$[C_{\varphi e}]_{12}$
$[C_{\ell q}^{(1)}]_{1223}$	10^{-6}	10^{-8}	10^{-17}	10^{-24}	10^{-14}	10^{-16}	10^{-10}	10^{-11}	10^{-20}
$[C_{\ell q}^{(3)}]_{1223}$	10^{-8}	10^{-6}	10^{-19}	10^{-25}	10^{-16}	10^{-16}	10^{-12}	10^{-9}	10^{-23}
$[C_{qe}]_{2312}$	10^{-17}	10^{-18}	10^{-6}	10^{-14}	10^{-24}	10^{-18}	10^{-20}	10^{-22}	10^{-10}
$[C_{ed}]_{1223}$	10^{-23}	10^{-23}	10^{-13}	10^{-6}	10^{-17}	10^{-16}	10^{-27}	10^{-27}	10^{-17}
$[C_{\ell d}]_{1223}$	10^{-13}	10^{-15}	10^{-24}	10^{-17}	10^{-6}	10^{-14}	10^{-17}	10^{-19}	10^{-27}
$[C_{\ell edq}]_{1223}$	10^{-15}	10^{-14}	10^{-17}	10^{-15}	10^{-13}	10^{-6}	10^{-18}	10^{-18}	10^{-21}
$[C_{\varphi\ell}^{(1)}]_{12}$	10^{-9}	10^{-11}	10^{-20}	10^{-26}	10^{-16}	10^{-18}	10^{-6}	10^{-12}	10^{-17}
$[C_{\varphi\ell}^{(3)}]_{12}$	10^{-11}	10^{-9}	10^{-22}	10^{-27}	10^{-19}	10^{-18}	10^{-12}	10^{-6}	10^{-23}
$[C_{\varphi e}]_{12}$	10^{-19}	10^{-21}	10^{-9}	10^{-16}	10^{-26}	10^{-20}	10^{-17}	10^{-22}	10^{-6}
$[C_{\ell\ell}]_{1112}$	10^{-14}	10^{-15}	10^{-22}	10^{-30}	10^{-22}	10^{-21}	10^{-10}	10^{-9}	10^{-20}
$[C_{\ell e}]_{1112}$	10^{-20}	10^{-19}	10^{-15}	10^{-24}	10^{-27}	10^{-20}	10^{-20}	10^{-20}	10^{-10}
$[C_{\ell e}]_{1211}$	10^{-15}	10^{-14}	10^{-20}	10^{-27}	10^{-24}	10^{-21}	10^{-9}	10^{-12}	10^{-20}
$[C_{ee}]_{1112}$	10^{-22}	10^{-22}	10^{-14}	10^{-23}	10^{-30}	10^{-23}	10^{-20}	10^{-22}	10^{-9}
$[C_{eu}]_{1211}$	10^{-22}	10^{-22}	10^{-15}	10^{-24}	10^{-31}	10^{-24}	10^{-20}	10^{-22}	10^{-10}
$[C_{\ell u}]_{1211}$	10^{-15}	10^{-15}	10^{-22}	10^{-30}	10^{-24}	10^{-21}	10^{-10}	10^{-12}	10^{-20}
$[C_{\ell q}^{(1)}]_{1211}$	10^{-15}	10^{-15}	10^{-23}	10^{-30}	10^{-22}	10^{-21}	10^{-10}	10^{-11}	10^{-21}
$[C_{\ell q}^{(3)}]_{1211}$	10^{-14}	10^{-15}	10^{-23}	10^{-30}	10^{-22}	10^{-21}	10^{-13}	10^{-9}	10^{-23}
$[C_{qe}]_{1112}$	10^{-23}	10^{-23}	10^{-15}	10^{-22}	10^{-31}	10^{-24}	10^{-20}	10^{-21}	10^{-10}
$[C_{ed}]_{1211}$	10^{-23}	10^{-22}	10^{-15}	10^{-19}	10^{-29}	10^{-24}	10^{-20}	10^{-23}	10^{-10}
$[C_{\ell d}]_{1211}$	10^{-15}	10^{-15}	10^{-23}	10^{-29}	10^{-19}	10^{-21}	10^{-10}	10^{-12}	10^{-20}
$[C_{\ell edq}]_{1211}$	10^{-19}	10^{-18}	10^{-21}	10^{-25}	10^{-23}	10^{-16}	10^{-19}	10^{-18}	10^{-22}
$[C_{\ell edq}]_{1222}$	10^{-19}	10^{-17}	10^{-23}	10^{-19}	10^{-16}	10^{-9}	10^{-17}	10^{-17}	10^{-21}
$[C_{\ell equ}^{(1)}]_{1211}$	10^{-19}	10^{-19}	10^{-21}	10^{-28}	10^{-26}	10^{-19}	10^{-19}	10^{-19}	10^{-22}
$[C_{eB}]_{12}$	10^{-15}	10^{-14}	10^{-17}	10^{-25}	10^{-23}	10^{-17}	10^{-16}	10^{-15}	10^{-18}
$[C_{eB}]_{21}$	10^{-17}	10^{-17}	10^{-15}	10^{-23}	10^{-25}	10^{-26}	10^{-18}	10^{-18}	10^{-16}
$[C_{eW}]_{12}$	10^{-15}	10^{-14}	10^{-17}	10^{-25}	10^{-22}	10^{-17}	10^{-16}	10^{-15}	10^{-18}
$[C_{eW}]_{21}$	10^{-17}	10^{-17}	10^{-15}	10^{-22}	10^{-25}	10^{-26}	10^{-18}	10^{-18}	10^{-16}

Relative strengths of LFV operators

Results (1-D Analysis)

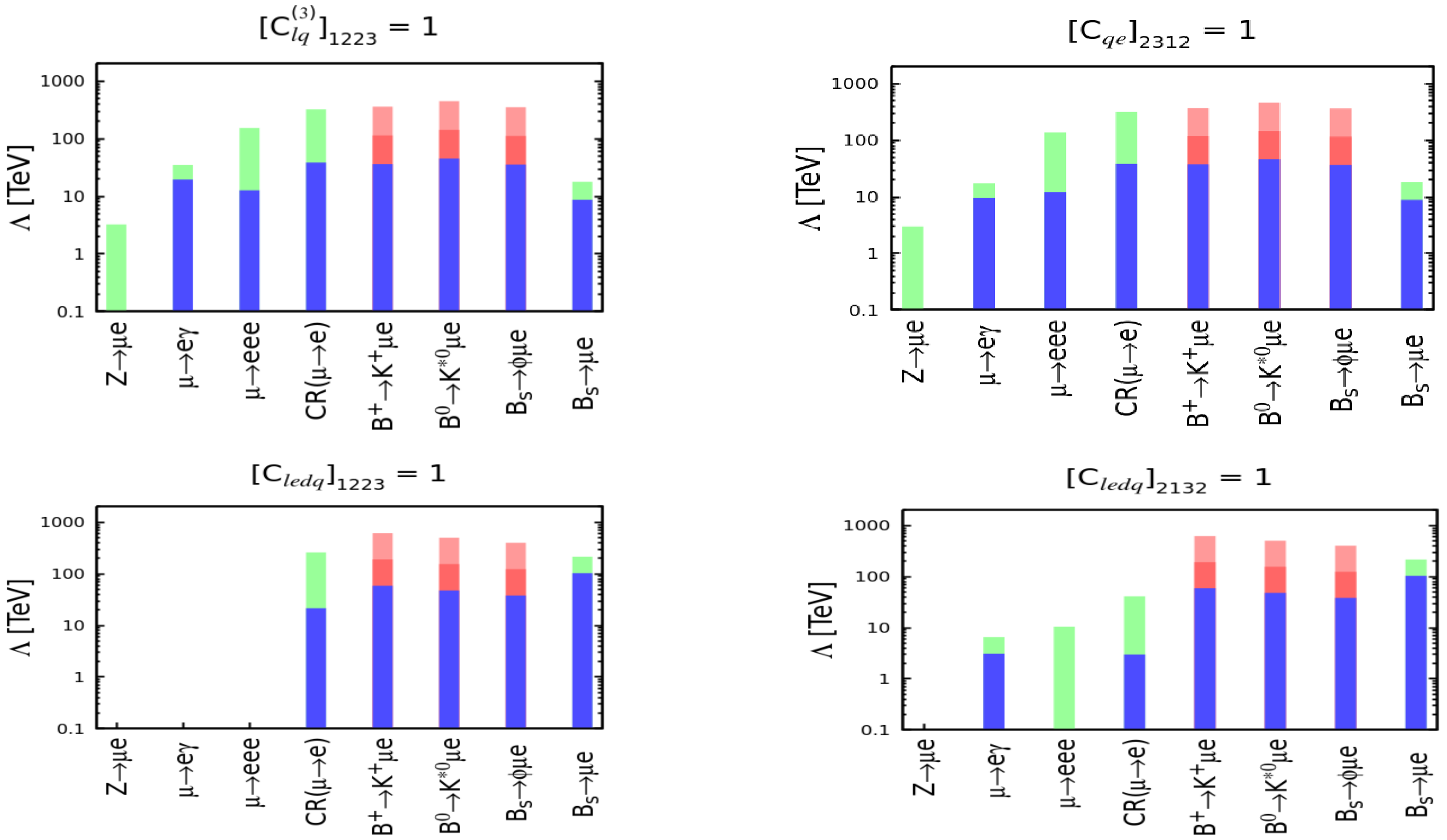
Color Codes

- Blue : Current Expt. Limits
- Green : Future Expt. Limits
- Red : 2-4 Orders (assumed) enhanced BR sensitivities



Single Operator Dominance at $\mu = m_b$

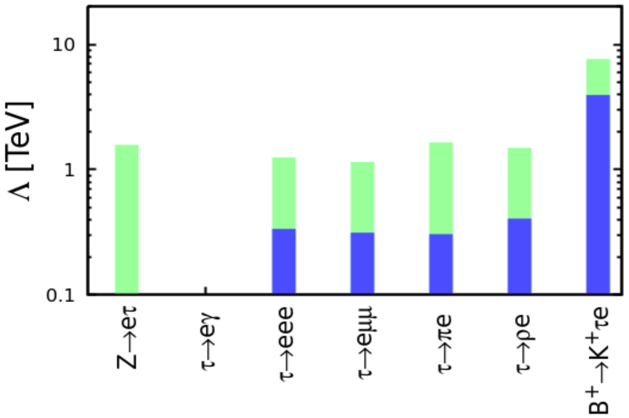
Results (1-D Analysis)



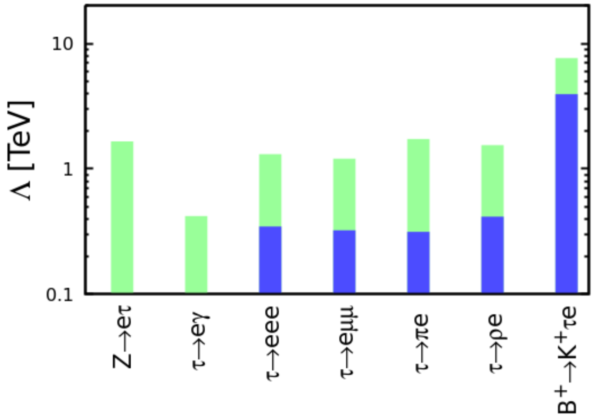
Single Operator Dominance at $\mu = m_b$

Results (1-D Analysis)

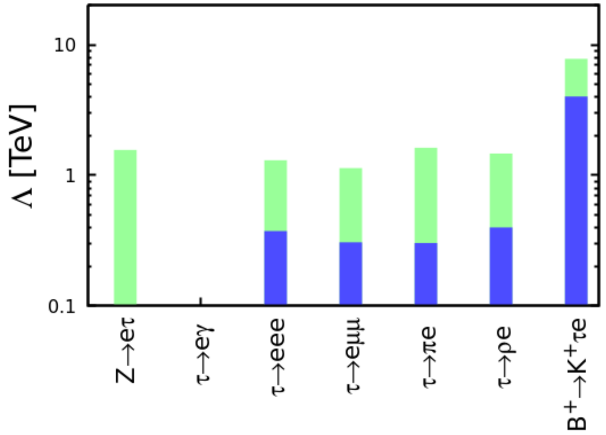
$[C_{lq}^{(1)}]_{1323} = 1$



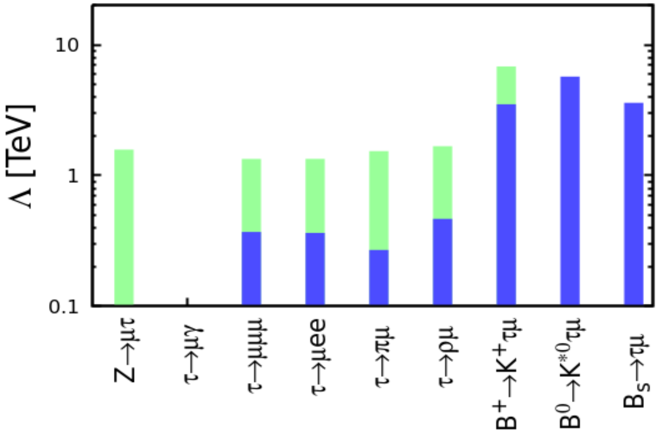
$[C_{lq}^{(3)}]_{1323} = 1$



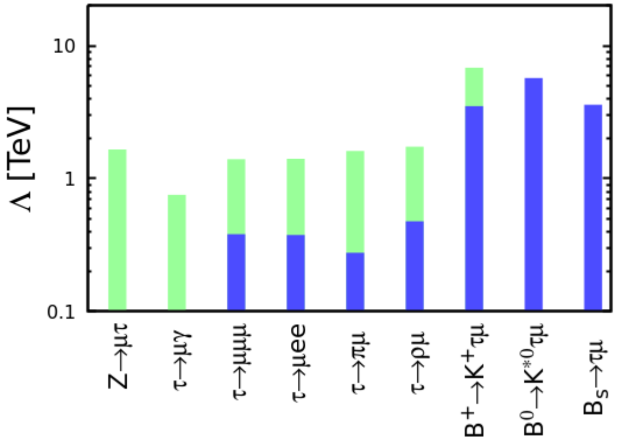
$[C_{qe}]_{2313} = 1$



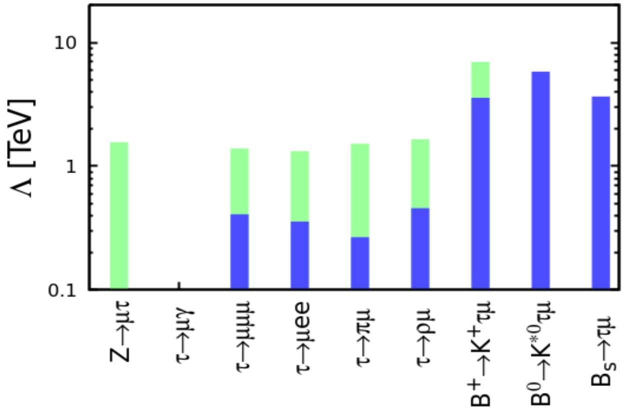
$[C_{lq}^{(1)}]_{2323} = 1$



$[C_{lq}^{(3)}]_{2323} = 1$



$[C_{qe}]_{2323} = 1$



Single Operator Dominance at $\mu = m_b$

Results (1-D Analysis)

Observable	WC	UL from BR($\mu \to eee$)	UL from CR($\mu \to e$, Al), Phase I	UL from CR($\mu \to e$, Al), Phase II
BR($B^+ \to K^+ \mu^- e^+$)	$[C_{\ell q}^{(1)}]_{1223}$	2.9×10^{-11}	2.2×10^{-10}	1.5×10^{-12}
	$[C_{\ell q}^{(3)}]_{1223}$	1.9×10^{-11}	1.5×10^{-10}	9.8×10^{-13}
	$[C_{qe}]_{2312}$	3.2×10^{-11}	1.8×10^{-10}	1.2×10^{-12}
	$[C_{ledq}]_{1223}$	-	-	1.9×10^{-11}
BR($B^0 \to K^{*0} \mu^- e^+$)	$[C_{\ell q}^{(1)}]_{1223}$	6.3×10^{-11}	4.7×10^{-10}	3.4×10^{-12}
	$[C_{\ell q}^{(3)}]_{1223}$	4.2×10^{-11}	3.3×10^{-10}	2.3×10^{-12}
	$[C_{qe}]_{2312}$	6.9×10^{-11}	3.8×10^{-10}	2.9×10^{-12}
	$[C_{ledq}]_{1223}$	-	-	7.9×10^{-12}
BR($B_s \to \phi \mu^- e^+$)	$[C_{\ell q}^{(1)}]_{1223}$	6.7×10^{-11}	4.9×10^{-10}	3.4×10^{-12}
	$[C_{\ell q}^{(3)}]_{1223}$	4.5×10^{-11}	3.5×10^{-10}	2.3×10^{-12}
	$[C_{qe}]_{2312}$	7.5×10^{-11}	4.1×10^{-10}	2.8×10^{-12}
	$[C_{ledq}]_{1223}$	-	-	8.6×10^{-12}
BR($B_s \to \mu^- e^+$)	$[C_{\ell q}^{(1)}]_{1223}$	8.0×10^{-14}	5.9×10^{-13}	4.0×10^{-15}
	$[C_{\ell q}^{(3)}]_{1223}$	5.3×10^{-14}	4.2×10^{-13}	2.7×10^{-15}
	$[C_{qe}]_{2312}$	8.9×10^{-14}	4.9×10^{-13}	3.4×10^{-15}
	$[C_{ledq}]_{1223}$	-	-	1.4×10^{-10}

Indirect upper limits on LFVBDs from other LFV processes in μ sector

Results (1-D Analysis)

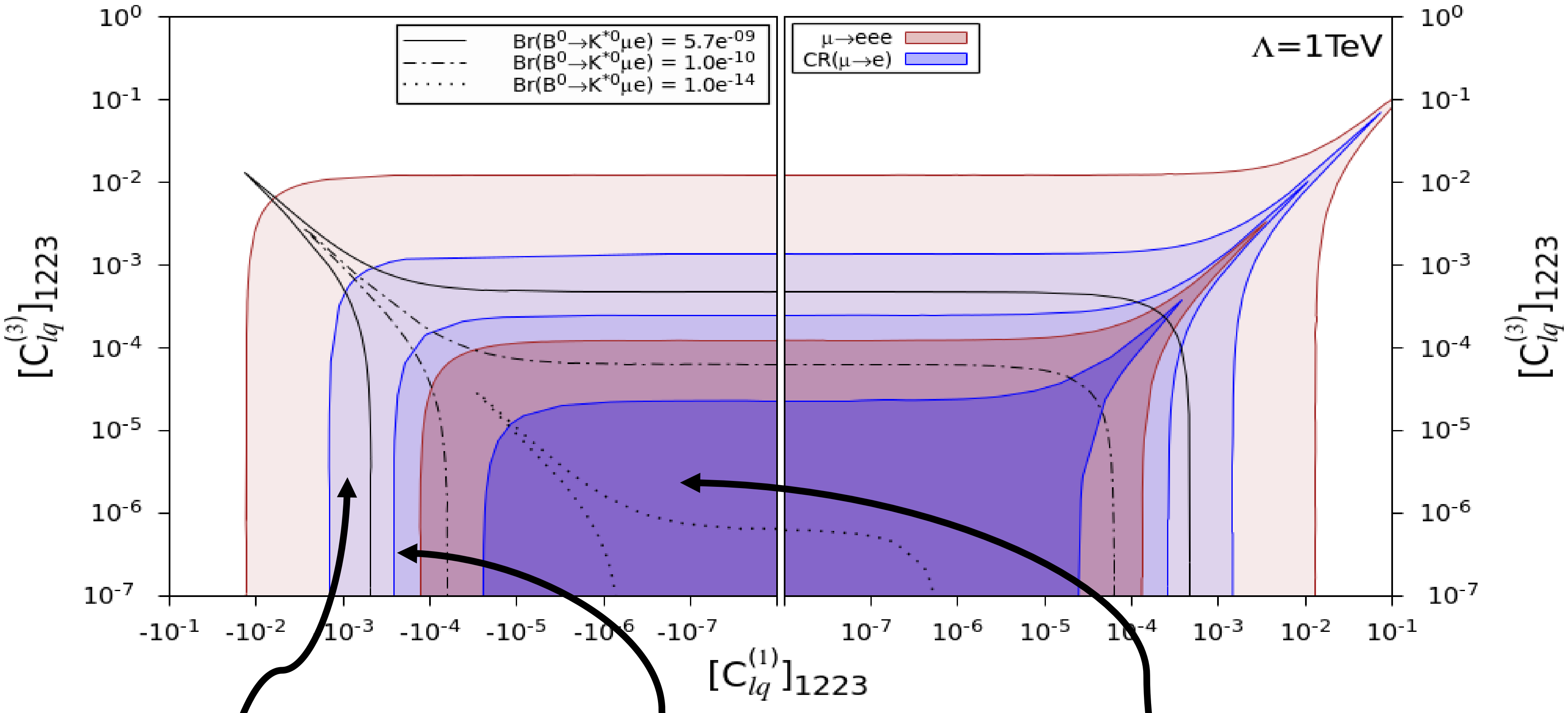
Operator	BR($Z \to \mu\tau$)	BR($\tau \to \mu\gamma$)	BR($\tau \to \mu\mu\mu$)	BR($\tau \to eee$)	BR($\tau \to \pi\mu$)	BR($\tau \to \rho\mu$)
$Q_{\ell q}^{(1)\mu\tau}$	5.668×10^{-12}	2.529×10^{-13}	1.327×10^{-12}	9.661×10^{-13}	2.570×10^{-12}	1.455×10^{-12}
$Q_{\ell q}^{(1)\mu\tau}$	7.179×10^{-12}	2.222×10^{-12}	1.664×10^{-12}	1.252×10^{-12}	3.258×10^{-12}	1.743×10^{-12}
$Q_{qe}^{\mu\tau}$	5.017×10^{-12}	2.128×10^{-13}	1.307×10^{-12}	8.489×10^{-13}	2.260×10^{-12}	1.264×10^{-12}

Indirect upper limits on other LFV processes in τ sector

Results(2-D Analysis)

Processes	Most relevant operators
$B \to K \ell_i \ell_j$	$Q_{\ell q}^{(1)}, Q_{\ell q}^{(3)}, Q_{qe}, Q_{\ell d}, Q_{ed}, Q_{\ell edq}$
$B \to K^* \ell_i \ell_j$	$Q_{\ell q}^{(1)}, Q_{\ell q}^{(3)}, Q_{qe}, Q_{\ell d}, Q_{ed}, Q_{\ell edq}$
$B_s \to \mu e$	$Q_{\ell q}^{(1)}, Q_{\ell q}^{(3)}, Q_{qe}, Q_{\ell d}, Q_{ed}, Q_{\ell edq}$
$\ell_i \to \ell_j \gamma$	Q_{eB}, Q_{eW}
$\ell_i \to \ell_j \ell_j \bar{\ell}_j$	$Q_{\varphi \ell}^{(1)}, Q_{\varphi \ell}^{(3)}, Q_{\varphi e}, Q_{\ell \ell}, Q_{\ell e}, Q_{ee}$
$\ell_i \to \ell_j \ell_k \bar{\ell}_k$	$Q_{\varphi \ell}^{(1)}, Q_{\varphi \ell}^{(3)}, Q_{\varphi e}, Q_{\ell \ell}, Q_{\ell e}, Q_{ee}$
CR($\mu \to e$)	$Q_{\varphi \ell}^{(1)}, Q_{\varphi \ell}^{(3)}, Q_{\varphi e}, Q_{eu}, Q_{\ell u}, Q_{\ell q}^{(1)}, Q_{\ell q}^{(3)}, Q_{qe}, Q_{\ell d}, Q_{ed}, Q_{\ell edq}, Q_{\ell equ}$
$Z \to \ell_i \ell_j$	$Q_{\varphi \ell}^{(1)}, Q_{\varphi \ell}^{(3)}, Q_{\varphi e}, Q_{eB}, Q_{eW}$
$\tau \to \mathcal{V} \ell$ ($\mathcal{V} = \rho, \phi$)	$Q_{\varphi \ell}^{(1)}, Q_{\varphi \ell}^{(3)}, Q_{\varphi e}, Q_{\ell u}, Q_{eu}, Q_{\ell equ}, Q_{eB}, Q_{eW}, Q_{\ell q}^{(1)}, Q_{\ell q}^{(3)}, Q_{qe}, Q_{\ell d}, Q_{ed}$
$\tau \to \mathcal{P} \ell$ ($\mathcal{P} = \pi^0, K^0$)	$Q_{\varphi \ell}^{(1)}, Q_{\varphi \ell}^{(3)}, Q_{\varphi e}, Q_{\ell u}, Q_{eu}, Q_{\ell equ}, Q_{eB}, Q_{eW}, Q_{\ell q}^{(1)}, Q_{\ell q}^{(3)}, Q_{qe}, Q_{\ell d}, Q_{ed}, Q_{\ell edq}$

Results(2-D Analysis)



Two Operators Interference at $\mu = \Lambda$

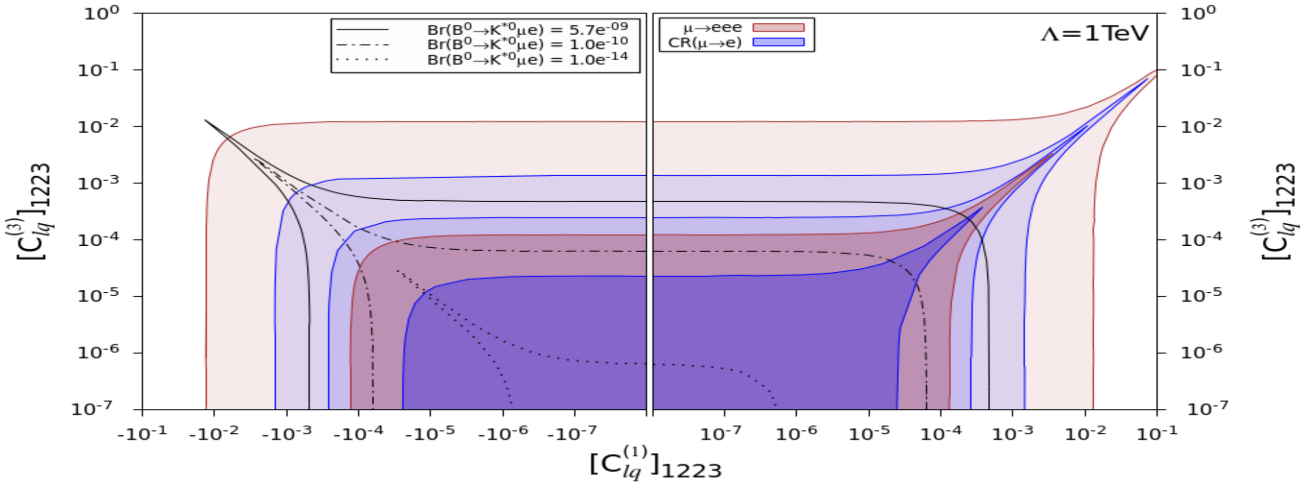
Phase I (~10^{-15})

Phase II (~10^{-17})

Currently allowed by CR ($\mu \to e$) experiments

Future possible reach by CR ($\mu \to e$) experiments

Results (2-D Analysis)

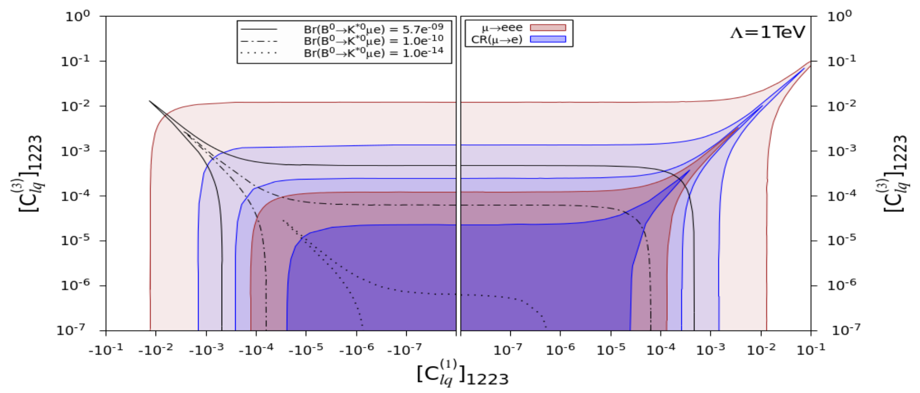


Two Operators Interference at $\mu = \Lambda$

- Flat directions between the pairs of LFVBD WCs are trivial

$$
\begin{aligned}
\mathrm{Br}\left[B_s \to \ell_i^+ \ell_j^-\right] &\sim k_1\left\{k_2\left(C_{\ell q}^{(1)} + C_{\ell q}^{(3)} + C_{qe}\right) + k_3\left(C_{\ell edq} - C'_{\ell edq}\right)\right\}^2 \\
&+ k_4\left\{k_5\left(C_{\ell q}^{(1)} + C_{\ell q}^{(3)} - C_{qe}\right) + k_6\left(C_{\ell edq} + C'_{\ell edq}\right)\right\}^2, \\
\mathrm{Br}\left[B^0 \to K^{(*)} \ell_i^+ \ell_j^-\right] &\sim k_7\left\{\left(C_{\ell q}^{(1)} + C_{\ell q}^{(3)}\right)^2 + \left(-C_{qe}\right)^2\right\} \\
&+ k_8\left\{\left(C_{\ell q}^{(1)} + C_{\ell q}^{(3)}\right)^2 + \left(C_{qe}\right)^2\right\} \\
&+ k_9\left(C_{\ell edq} - C'_{\ell edq}\right)^2,
\end{aligned}
$$

Results (2-D Analysis)



- Flat directions for other LFVs are non-trivial. These cancellations occur between $C_{\varphi\ell}^{(1)}$ and $C_{\varphi\ell}^{(3)}$ and is a direct consequence of the RGE effects

$$\Gamma_{\mu\to e\ \mathrm{conv}} = \frac{m_\mu^5}{\omega_{\mathrm{capt}}\Lambda^4}\left\{\left|\widetilde{C}_{DL}D + \widetilde{C}_{SL}^{(p)}S^{(p)} + \widetilde{C}_{SL}^{(n)}S^{(n)} + \widetilde{C}_{VL}^{(p)}V^{(p)} + \widetilde{C}_{VL}^{(n)}V^{(n)}\right|^2 + \left|L \leftrightarrow R\right|^2\right\}$$

$$\widetilde{C}_{VL}^{(p)} = 2g_{LV,RV}^{(u)} + g_{LV,RV}^{(d)}\,, \qquad \widetilde{C}_{VL}^{(n)} = g_{LV,RV}^{(u)} + 2g_{LV,RV}^{(d)}\,,$$

with

$$g_{VL}^{(u)} = \left(C_{\ell q}^{(1)} - C_{\ell q}^{(3)} + C_{\ell u}\right)^{e\mu uu} + (1 - \frac{8}{3}s_{\mathrm{w}}^2)\left(C_{\varphi l}^{(1)} + C_{\varphi l}^{(3)}\right)^{e\mu}\,,$$

$$g_{VL}^{(d)} = \left(C_{\ell q}^{(1)} + C_{\ell q}^{(3)} + C_{\ell d}\right)^{e\mu dd} - (1 - \frac{4}{3}s_{\mathrm{w}}^2)\left(C_{\varphi l}^{(1)} + C_{\varphi l}^{(3)}\right)^{e\mu}\,,$$

$$g_{VR}^{(u)} = C_{eu}^{e\mu uu} + C_{qe}^{uue\mu} + (1 - \frac{8}{3}s_{\mathrm{w}}^2)C_{\varphi e}^{e\mu}\,,$$

$$g_{VR}^{(d)} = C_{ed}^{e\mu dd} + C_{qe}^{dde\mu} - (1 - \frac{4}{3}s_{\mathrm{w}}^2)C_{\varphi e}^{e\mu}\,,$$

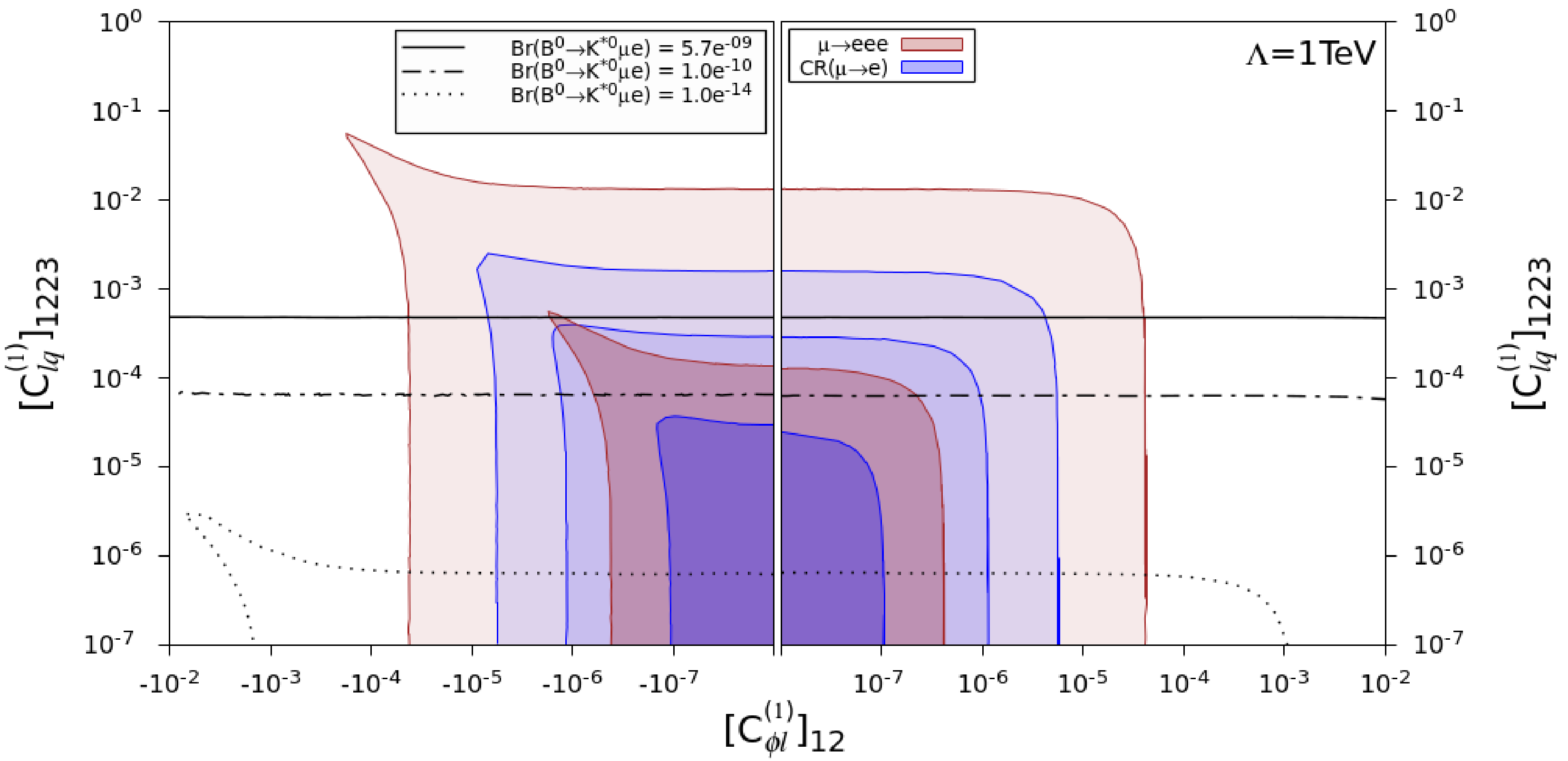
$$[C_{\phi\ell}^{(1)}(\mu) + C_{\phi\ell}^{(3)}(\mu)]_{12} \approx \frac{3Y_cY_t}{8\pi^2}\log(\frac{\mu}{\Lambda})[C_{\ell q}^{(1)}(\Lambda) - C_{\ell q}^{(3)}(\Lambda)]_{1223}.$$

Two Operators Interference at $\mu = \Lambda$

Results(2-D Analysis)

Processes	Most relevant operators
$B \to K \ell_i \ell_j$	$Q_{\ell q}^{(1)}, Q_{\ell q}^{(3)}, Q_{qe}, Q_{\ell d}, Q_{ed}, Q_{\ell edq}$
$B \to K^* \ell_i \ell_j$	$Q_{\ell q}^{(1)}, Q_{\ell q}^{(3)}, Q_{qe}, Q_{\ell d}, Q_{ed}, Q_{\ell edq}$
$B_s \to \mu e$	$Q_{\ell q}^{(1)}, Q_{\ell q}^{(3)}, Q_{qe}, Q_{\ell d}, Q_{ed}, Q_{\ell edq}$
$\ell_i \to \ell_j \gamma$	Q_{eB}, Q_{eW}
$\ell_i \to \ell_j \ell_j \bar{\ell}_j$	$Q_{\varphi\ell}^{(1)}, Q_{\varphi\ell}^{(3)}, Q_{\varphi e}, Q_{\ell\ell}, Q_{\ell e}, Q_{ee}$
$\ell_i \to \ell_j \ell_k \bar{\ell}_k$	$Q_{\varphi\ell}^{(1)}, Q_{\varphi\ell}^{(3)}, Q_{\varphi e}, Q_{\ell\ell}, Q_{\ell e}, Q_{ee}$
CR($\mu \to e$)	$Q_{\varphi\ell}^{(1)}, Q_{\varphi\ell}^{(3)}, Q_{\varphi e}, Q_{eu}, Q_{\ell u}, Q_{\ell q}^{(1)}, Q_{\ell q}^{(3)}, Q_{qe}, Q_{\ell d}, Q_{ed}, Q_{\ell edq}, Q_{\ell equ}$
$Z \to \ell_i \ell_j$	$Q_{\varphi\ell}^{(1)}, Q_{\varphi\ell}^{(3)}, Q_{\varphi e}, Q_{eB}, Q_{eW}$
$\tau \to \mathcal{V}\ell$ ($\mathcal{V} = \rho, \phi$)	$Q_{\varphi\ell}^{(1)}, Q_{\varphi\ell}^{(3)}, Q_{\varphi e}, Q_{\ell u}, Q_{eu}, Q_{\ell equ}, Q_{eB}, Q_{eW}, Q_{\ell q}^{(1)}, Q_{\ell q}^{(3)}, Q_{qe}, Q_{\ell d}, Q_{ed}$
$\tau \to \mathcal{P}\ell$ ($\mathcal{P} = \pi^0, K^0$)	$Q_{\varphi\ell}^{(1)}, Q_{\varphi\ell}^{(3)}, Q_{\varphi e}, Q_{\ell u}, Q_{eu}, Q_{\ell equ}, Q_{eB}, Q_{eW}, Q_{\ell q}^{(1)}, Q_{\ell q}^{(3)}, Q_{qe}, Q_{\ell d}, Q_{ed}, Q_{\ell edq}$

Results(2-D Analysis)



Two Operators Interference at $\mu = \Lambda$

- $2q2\ell$ operators responsible for LFVBDs are best constrained by LFVDs only
- More similar plots in arXiv:2312.05071

Conclusion

- Out of six operators responsible for LFVBDs, operators with left-handed quark currents, such as $C_{\ell q}^{(1,3)}$ and C_{qe}, only contribute to other LFV processes significantly.

- If new physics primarily generates the LFVBD operators between the scales $100 - 1000\,TeV$, we expect that LFVBDs and CR($\mu \to e$) to be quite promising in regard to future experiments.

- In μ sector, two processes, $\mu \to eee$ and CR($\mu \to e$) can put indirect constraints on BRs of several B-decay processes ($\sim 10^{-10}$) which are within the future limits.

- The relevant operators of this analysis receives strongest constraints from LFVBDs only.

THANK YOU

Extra slides

Procedure

- Effective Hamiltonian for $b \to s l_i l_j$ transitions process is given by

$$H_{Eff}^{l_i l_j} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* + \sum_{n=1}^{10,S,P} [C_n(\mu) \mathcal{O}_n(\mu) + C'_n(\mu) \mathcal{O}'_n(\mu)]$$

G_F	=	Fermi Constant
$V_{tb} V_{ts}^*$	=	Cabbibo-Kobayashi-Maskwa(CKM) matrix elements
n= 1,2	⇨	"Current-Current" operators mediated by W boson or gluon
n = 3, 4, 5, 6	⇨	"QCD-Penguin" operators
n = 7,8	⇨	"Magnetic-Penguin" operators
n = 9,10	⇨	"Semi-leptonic" operators
n = S,P	⇨	Scalar and Pseudo-scalar operators

Analysis with Single operator

- For example, we consider the operator $Q_{\phi e}$ and the coefficient $C_{\phi e}^{fi}$.
- Modified branching ratio formula becomes

$$\mathrm{Br}[\ell_i \to \ell_j \ell_k \overline{\ell}_l]_{\phi e} = \frac{N_c M^5}{6144\pi^3 \Lambda^4 \Gamma_{l_i}} (|C'_{VRR}|^2 + |C'_{VRL}|^2 + |C'_{SLR}|^2)$$

with

$$C'_{VRR} = 2\left(2s_W^2 C_{\phi e}^{ji}\right)$$

$$C'_{VRL} = -\frac{1}{2} C'_{SLR} = (2s_W^2 - 1) C_{\phi e}^{ji}$$

Results (1-D Analysis)
RGE Effects

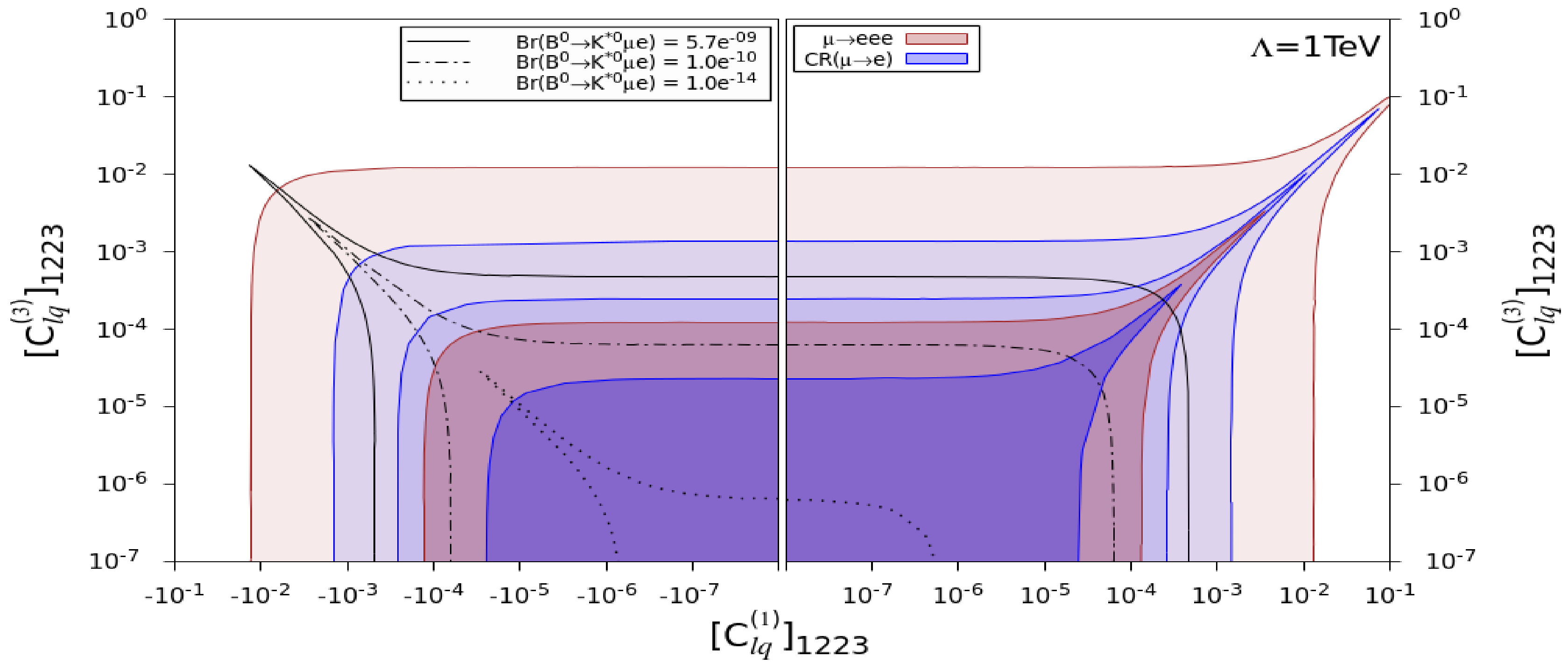
- $C_{q\ell}^{(1/3)ij}$ has significant RGE impacts on $C_{q\ell}^{(3/1)ij}$, $C_{\varphi\ell}^{(1)ij}$ and $C_{\varphi\ell}^{(3)ij}$.
- C_{qe}^{ij} has significant RGE impact on $C_{\varphi e}^{ij}$.
- C_{ledq}^{1223} has RGE impact on C_{ledq}^{1222}

Operators

- Contribution of different operators to different decay types

	Decay Types	
Operators	$\ell_i \to \ell_j \ell_k \ell_l$	$\ell_i \to \ell_j \gamma$
$\ell\ell X\Psi$ (Dipole)	Tree-level	Tree-level
$\ell\ell\ell\ell$ (4-lepton)	Tree-level	1-loop level
$\ell\ell qq$ (2-lepton-2-Higgs)	1-loop-level	1-loop level
$\ell\ell\Psi^2 D$ or $\ell\ell\Psi^3$ (lepton-Higgs)	Tree + loop level	Tree + loop level

Results (2-D Analysis)



Two Operators Interference at $\mu = \Lambda$

- Flat directions between the pairs of LFVBD WCs are trivial
- Flat directions for other LFVs are non-trivial. These cancellations occur between $C^{(1)}_{\varphi\ell}$ and $C^{(3)}_{\varphi\ell}$ and is a direct consequence of the RGE effects

$$[C^{(1)}_{\phi\ell}(\mu) + C^{(3)}_{\phi\ell}(\mu)]_{12} \approx \frac{3Y_cY_t}{8\pi^2}\log(\frac{\mu}{\Lambda})[C^{(1)}_{\ell q}(\Lambda) - C^{(3)}_{\ell q}(\Lambda)]_{1223}.$$