

Phenomenological analysis of Charged Lepton Flavor Violation processes

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Outline

Introduction

- ▶ The Standard Model
- ▶ Charged Lepton Flavor Violation (CLFV) processes

Effective field theories (EFT)

- ▶ What is it?
- ▶ Why do we need EFT?
- ▶ Renormalization Group Equations

μ -e conversion in nuclei

- ▶ Motivation
- ▶ BSM model
- ▶ Prospects and conclusions

Introduction

Standard Model

- ▶ Particles of matter : quarks and leptons (3 generations)
- ▶ Force carriers : gauge bosons (and Higgs boson)



CLFV processes

- ▶ In the Standard model, the flavor is conserved.
- ▶ In CLFV processes, the initial and final number of flavors are different.
- ▶ CFLV forbidden in SM \rightarrow need BSM physics

Examples :

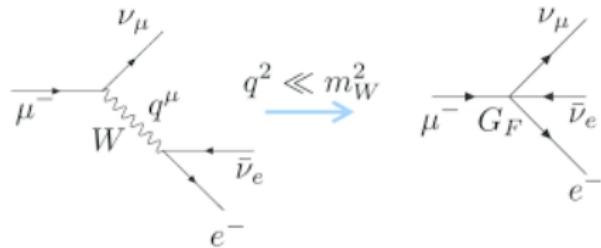
$\mu \rightarrow e$ conversion in nuclei , $\mu \rightarrow e\gamma$, $\mu \rightarrow ee\bar{e}$ and mesons decays such as $K \rightarrow \bar{\mu}e$

Flavor physics is sensitive to new physics at scales $\Lambda_{NP} \gg E_{Experiment}$

Effective fields theories (EFT)

What is EFT?

- ▶ Theoretical framework used to parametrize observables at a given **energy scale Λ** .
- ▶ Choose the relevant degrees of freedom to describe the dynamics
- ▶ Describe indirect effects of heavy **New Physics (NP)** on interactions between SM particles.
- ▶ Contact interactions



Why do we need EFT?

Assumption : new particles are too heavy to be produced

- ▶ Remove particles with $m > \Lambda$ from the theory → obtain an effective Lagrangian
- ▶ Operators and coefficients → parametrize the low energy EFT
- ▶ Compute observables at a specific scale $\Lambda < \Lambda_{NP}$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{SM} + \mathcal{L}_5 + \mathcal{L}_6 + \dots$$

where

$$\mathcal{L}_d = \sum_i \frac{C_i^d}{\Lambda_{NP}^{d-4}} \mathcal{O}_i^d$$

Example : $O^6 = (\bar{\mu}\gamma^\mu(1 - \gamma^5)\nu)(\bar{e}\gamma_\mu(1 - \gamma^5)\nu)$

Renormalization Group Equations (RGEs)

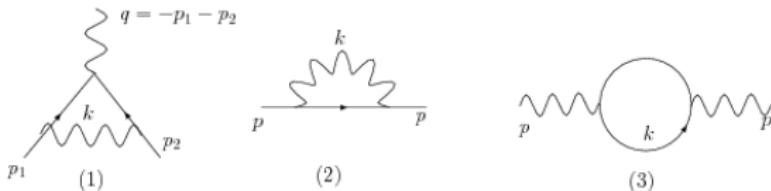
In an EFT, operator coefficients run with the energy scale and can mix to other operators!!

EFT \Rightarrow what is the scale of the physics we are interested in?
 $C_i^d(\Lambda_{NP})$ run down to the **scale of interest** (Λ_{exp})

\Rightarrow need a tool to relate the different scales

Solutions : RGEs

Every parameters of \mathcal{L} evolve with energy scale because of loops



- ▶ Counterterms δ obtained from loops
- ▶ Anomalous dimension γ encodes the running
- ▶ $\gamma = -2\alpha \frac{\partial \delta}{\partial \alpha}$

$$\Lambda \frac{\partial}{\partial \Lambda} (C_I, \dots C_J, \dots) = \frac{\alpha_e}{4\pi} \vec{C} \Gamma^e + \frac{\alpha_s}{4\pi} \vec{C} \Gamma^s$$

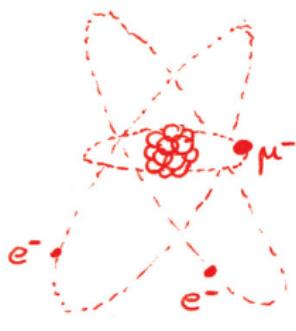
\Rightarrow all coefficients organized in the row vector \vec{C} , Γ is an anomalous dimension matrix

$\mu - e$ conversion in nuclei

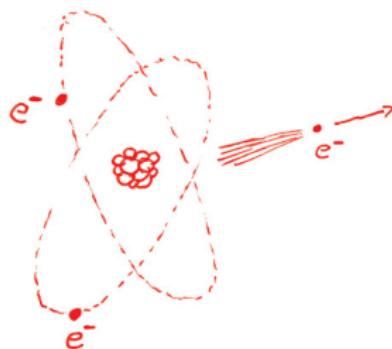
Why CLFV and muons?

- ▶ No SM contribution in CLFV \iff **Signal of BSM physics !!**
- ▶ μ^- are easy to produce : at least $\sim 10^8 \mu/\text{sec}$ at J-PARC
- ▶ Future experiments : $\sim 10^{12} \mu/\text{sec}$
- ▶ $\tau : 400 \tau/\text{sec}$ at super-KEKB

This is what we start with.



This is the process we are looking for.

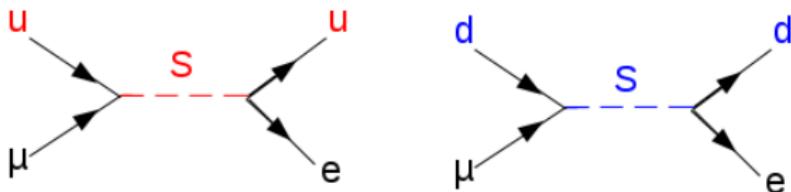


BSM scenario : Leptoquarks

- ▶ Bosons that allow leptons and quarks to interact
- ▶ Triplet of SU(3) and carry B and L numbers
- ▶ Could explain many similarities between quarks and leptons
- ▶ $m_{LQ} \sim TeV$

Extend the SM with two Leptoquarks S and \tilde{S}

$$\mathcal{L}_{BSM} = \mathcal{L}_{SM} + D^\mu S^\dagger D_\mu S + m^2 S^\dagger S + D^\mu \tilde{S}^\dagger D_\mu \tilde{S} + \tilde{m}^2 \tilde{S}^\dagger \tilde{S} + \\ [\lambda_L^*]_{\mu d} \bar{l}_\mu i\tau_2 q_{L,d}^c S + [\lambda_R^*]_{e u} \bar{e} u^c S + [\tilde{\lambda}^*]_{e d} \bar{e} d^c \tilde{S} + [\tilde{\lambda}^*]_{\mu d} \bar{\mu} d^c \tilde{S} + h.c$$



Operators and coefficients at $\Lambda_{NP} \sim m_{LQ}$

$$O_{T,X}^{uu} = (\bar{e}\sigma_{\alpha\beta}P_X\mu) \left(\bar{u}\sigma^{\alpha\beta}u \right), O_{S,X}^{uu} = (\bar{e}P_X\mu) (\bar{u}u)$$

$$O_{V,X}^{dd} = (\bar{e}\gamma_\alpha P_X\mu) (\bar{d}\gamma^\alpha d), O_{A,X}^{dd} = (\bar{e}\gamma_\alpha P_X\mu) (\bar{d}\gamma^\alpha\gamma_5 d)$$

$$\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu], P_X = P_{R,L} = \frac{1 \pm \gamma^5}{2}$$

For the Leptoquark S : $C_{S,X}^{uu} = \frac{[\lambda_L^*]_{\mu u} [\lambda_R]_{eu}}{4m^2}, C_{T,X}^{uu} = \frac{[\lambda_L^*]_{\mu u} [\lambda_R]_{eu}}{8m^2}$

For the Leptoquark \tilde{S} : $C_{V,X}^{dd} = C_{A,X}^{dd} = \frac{[\tilde{\lambda}^*]_{ed} [\tilde{\lambda}]_{\mu d}}{4\tilde{m}^2}$

But we need these coefficients at $\Lambda_{exp} \sim 2$ Gev (nucleon level)

⇒ Renormalization Group Equations

Running down to the experimental scale



$$C_I(\Lambda_{\text{exp}}) = C_J(\Lambda_{NP}) \lambda^{a_J} \left(\delta_{JI} - \frac{\alpha_e \tilde{\Gamma}_{JI}^e}{4\pi} \log \frac{\Lambda_{NP}}{\Lambda_{\text{exp}}} \right)$$

- ▶ $\lambda = \frac{\alpha_s(\Lambda_{NP})}{\alpha_s(\Lambda_{\text{exp}})} \rightarrow \text{QCD running}$
- ▶ $a_J = \frac{\Gamma_{JJ}^s}{2\beta_0} \rightarrow \text{QCD running}$
- ▶ $\tilde{\Gamma}_{JI}^e \rightarrow \text{QED/QCD running and mixing}$

Branching ratio

$$BR = BR_{SI} + BR_{SD} \quad (\text{SI} = \text{Spin Independent}, \text{SD} = \text{Spin Dependent})$$

$$\boxed{\begin{aligned} BR_{SI} &= 2B_0 \left| Z[C_{V,R}^{pp} + C_{S,L}^{pp} + \frac{m_\mu}{m_p} C_{T,L}^{pp}] F_p(m_\mu) + N[C_{V,R}^{nn} + C_{S,L}^{nn} + \frac{m_\mu}{m_n} C_{T,L}^{nn}] F_n(m_\mu) \right|^2 \\ BR_{SD} &= 8B_0 \frac{J+1}{J} \left| (S_p C_{A,R}^{pp} + S_n C_{A,R}^{nn})^2 + (2S_p C_{T,L}^{pp} + 2S_n C_{T,L}^{nn})^2 \right| \frac{S_A(m_\mu)}{S_A(0)} \end{aligned}}$$

- ▶ $B_0 = G_F^2 m_\mu^5 (\alpha Z)^3 / (\pi^2 \Gamma_{cap})$
- ▶ $S_{p,n}$, $F_{p,n}$ and $\frac{S_A(m_\mu)}{S_A(0)}$ are nuclear factors
- ▶ Different coefficients (\tilde{S} and S) in BR_{SI} and BR_{SD}
- ▶ BR_{SD} highly suppressed

What can we do to constrain coefficients?

Bounds on coefficients

Using experimental bounds on branching ratios :

- ▶ $BR_{SI}(\mu Al \rightarrow e Al) \leq 10^{-14}$, $BR_{SD}(\mu Al \rightarrow e Al) \leq 10^{-14}$
- ▶ $BR_{SI}(\mu Ti \rightarrow e Ti) \leq 10^{-14}$, $BR_{SD}(\mu^{47} Ti \rightarrow e^{47} Ti) \leq 10^{-14}$
- ▶ $BR_{SI}(\mu Pb \rightarrow e Pb) \leq 10^{-14}$

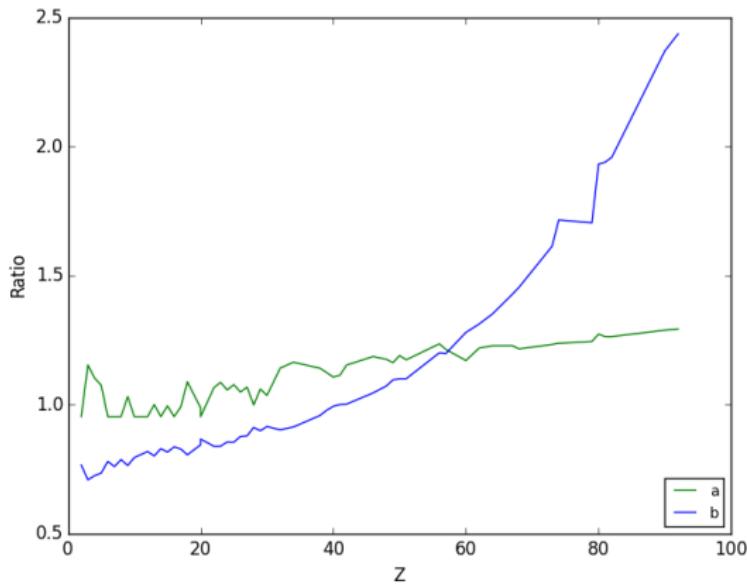
give the **bounds on the coefficients** : $C_{V,R}^{dd} \leq \sqrt{0.0103 \times BR}$,
 $C_{S,L}^{uu} \leq \sqrt{0.0011 \times BR} \dots$

How to distinguish operators?

⇒ Use different target nuclei

$$a = \frac{\frac{BR(A\mu \rightarrow Ale)}{BR(X\mu \rightarrow Xe)}}{\frac{BR(A\mu \rightarrow Ale)}{BR(X\mu \rightarrow Xe)}} \Bigg|_{\xi}$$

$$b = \frac{\frac{BR(Nb\mu \rightarrow Nbe)}{BR(X\mu \rightarrow Xe)}}{\frac{BR(Nb\mu \rightarrow Nbe)}{BR(X\mu \rightarrow Xe)}} \Bigg|_{\begin{array}{l} \text{scalar} \\ \text{vector} \end{array}}$$



Conclusions and prospects

- ▶ Charged Lepton Flavor Violation \Leftrightarrow signal of physics beyond the Standard Model
- ▶ Future experiments will improve their sensitivity
- ▶ Effective operators parametrization
- ▶ Coefficients run with the scale
- ▶ Different operators in SI and SD branching ratios
- ▶ Use various nuclei to distinguish operators and separate S and \tilde{S} contributions to the branching ratio

I'm a second year PhD student...



THANKS FOR YOUR
ATTENTION

BACKUP

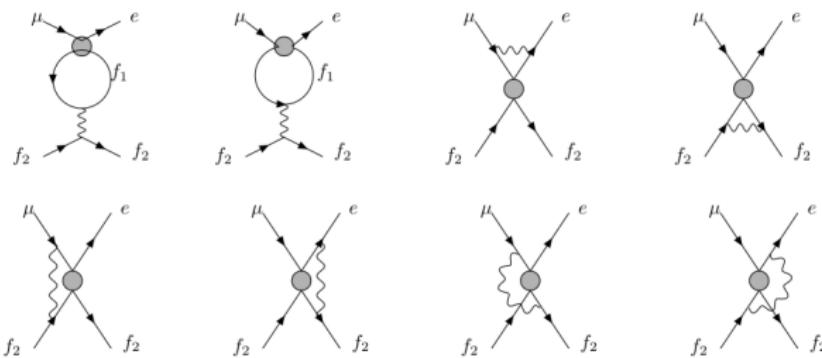
Anomalous dimension and mixing

The operators coefficients below the scale Λ_{NP} are organized in the vector \vec{C} as following :

$$\vec{C} = (\vec{C}_V^u, \vec{C}_V^d, \vec{C}_A^u, \vec{C}_A^d, \vec{C}_S^u, \vec{C}_S^d, \vec{C}_T^u, \vec{C}_T^d)$$

$$\vec{C}_V^f = (C_{VL}^{ff}, C_{VR}^{ff}) \quad \vec{C}_A^f = (C_{AL}^{ff}, C_{AR}^{ff})$$

$$\vec{C}_S^f = (C_{S,L}^{ff}, C_{S,R}^{ff}) \quad \vec{C}_T^f = (C_{T,L}^{ff}, C_{T,R}^{ff})$$



In the basis of \vec{C} , the QED anomalous dimension matrix can be written $\Gamma^e = \begin{bmatrix} \Gamma_{VA} & 0 \\ 0 & \Gamma_{ST} \end{bmatrix}$ with

$$\Gamma_{ST} = \begin{bmatrix} \gamma_{S,S}^{u,u} & 0 & \gamma_{S,T}^{u,u} & 0 \\ 0 & \gamma_{S,S}^{d,d} & 0 & \gamma_{S,T}^{d,d} \\ \gamma_{T,S}^{u,u} & 0 & \gamma_{T,T}^{u,u} & 0 \\ 0 & \gamma_{T,S}^{d,d} & 0 & \gamma_{T,T}^{d,d} \end{bmatrix} \quad \Gamma_{VA} = \begin{bmatrix} 0 & 0 & \gamma_{V,A}^{u,u} & 0 \\ 0 & 0 & 0 & \gamma_{V,A}^{d,d} \\ \gamma_{A,V}^{u,u} & 0 & 0 & 0 \\ 0 & \gamma_{A,V}^{d,d} & 0 & 0 \end{bmatrix}$$

$$\gamma_{S,S}^{f,f} = \begin{array}{c|cc} C_{S,L}^{ff} & C_{S,R}^{ff} \\ \hline C_{S,L}^{ff} & 6(1+Q_f^2) & 0 \\ C_{S,R}^{ff} & 0 & 6(1+Q_f^2) \end{array} \quad \gamma_{T,S}^{f,f} = \begin{array}{c|cc} C_{S,L}^{ff} & C_{S,R}^{ff} \\ \hline C_{T,L}^{ff} & -96Q_f & 0 \\ C_{T,R}^{ff} & 0 & -96Q_f \end{array}$$

$$C_I(\Lambda_{exp}) = C_J(\Lambda_{NP}) \lambda^{a_J} \left(\delta_{JI} - \frac{\alpha_e \tilde{\Gamma}_{JI}^e}{4\pi} \log \frac{\Lambda_{NP}}{\Lambda_{exp}} \right)$$

$$C_{S,L}^{qq}(\Lambda_{exp}) = 24 \lambda^{a_T} f_{TS} Q_q \frac{\alpha_e}{\pi} \log \frac{\Lambda_{NP}}{\Lambda_{exp}} C_{T,L}^{qq}(\Lambda_{NP}) + \lambda^{a_S} \left[1 - \frac{3}{2} \frac{\alpha_e}{\pi} \log \frac{\Lambda_{NP}}{\Lambda_{exp}} (1 + Q_q^2) \right] C_{S,L}^{qq}(\Lambda_{NP})$$

Finally, the coefficients at the experimental scale Λ_{exp} are obtained via the matching condition :

$$C_{O,Y}^{NN}(\Lambda_{exp}) = \sum_{q=u,d} G_O^{N,q} C_{O,Y}^{qq}(\Lambda_{exp})$$

Covariance matrix

In the basis $(C_{V,R}^{dd}, C_{S,L}^{uu}, C_{T,L}^{uu}, C_{A,R}^{dd})$ the matrix is written :

$$M^{-1} = \begin{bmatrix} V^2 & SV & TV & 0 \\ SV & S^2 & ST & 0 \\ TV & ST & T^2 & AT \\ 0 & 0 & AT & A^2 \end{bmatrix}$$

$$\begin{aligned} T^2 &= 2B_0^{AI} |2Z^{AI} \frac{m_\mu}{m_p} G_T^{p,u} + 2N^{AI} \frac{m_\mu}{m_n} G_T^{n,u}|^2 F_{p,AI}^2 \\ &\quad + 2B_0^{Ti} |2Z^{Ti} \frac{m_\mu}{m_p} G_T^{p,u} + 2N^{Ti} \frac{m_\mu}{m_n} G_T^{n,u}|^2 F_{p,Ti}^2 \\ &\quad + 32B_0^{Pb} |2S_p^{Pb} \frac{m_\mu}{m_p} G_T^{p,u} + 2S_n^{Pb} \frac{m_\mu}{m_n} G_T^{n,u}|^2 \\ &\quad + 8B_0^{AI} \frac{J_{AI} + 1}{J_{AI}} \frac{S_{AI}(m_\mu)}{S_{AI}(0)} |2\tilde{S}_p^{AI} G_T^{p,u} + 2\tilde{S}_n^{AI} G_T^{n,u}|^2 \\ &\quad + 8B_0^{Ti} \frac{J_{Ti} + 1}{J_{Ti}} \frac{S_{Ti}(m_\mu)}{S_{AI}(0)} |2\tilde{S}_p^{Ti} G_T^{p,u} + 2\tilde{S}_n^{Ti} G_T^{n,u}|^2 \end{aligned}$$

$$\begin{aligned} AT &= 8B_0^{AI} \frac{J_{AI} + 1}{J_{AI}} \frac{S_{AI}(m_\mu)}{S_{AI}(0)} |\tilde{S}_p^{AI} G_A^{p,d} + \tilde{S}_n^{AI} G_A^{n,d}| |2\tilde{S}_p^{AI} G_T^{p,u} + 2\tilde{S}_n^{AI} G_T^{n,u}| \\ &\quad + 8B_0^{Ti} \frac{J_{Ti} + 1}{J_{Ti}} \frac{S_{Ti}(m_\mu)}{S_{Ti}(0)} |\tilde{S}_p^{Ti} G_A^{p,d} + \tilde{S}_n^{Ti} G_A^{n,d}| |2\tilde{S}_p^{Ti} G_T^{p,u} + 2\tilde{S}_n^{Ti} G_T^{n,u}| \end{aligned}$$