Functional methods in an extension of the Standard Model with Leptoquarks

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Motivation

Some probes of physics beyond the Standard Model (SM) are:

- Low-energy physics.
- Rare semileptonic decays: Flavor-changing neutral currents (FCNCs)

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The colaborations BaBaR, Belle and LHCb have found some anomalies in[1]:

$$R_K = \frac{\Gamma\left(\bar{B} \to \bar{K}\mu^+\mu^-\right)}{\Gamma\left(\bar{B} \to \bar{K}e^+e^-\right)} = 0.745^{+0.090}_{-0.074} \pm 0.036 \qquad \overset{\text{differs}}{2.6\sigma} \qquad R_K = 1 \pm O\left(10^{-4}\right)$$

$$R_{D^{(*)}} = \frac{\Gamma\left(\bar{B} \to D^{(*)}\tau\bar{\nu}\right)}{\Gamma\left(\bar{B} \to D^{(*)}\ell\bar{\nu}\right)}, \qquad \ell = e, \mu \qquad \overset{\text{differs}}{3.5\sigma}$$

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Some models can explain this excess by adding new particles with masses near the TeV scale.

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Leptoquarks

Properties

- Electric and color charges.
- Baryonic and leptonic numbers.
- Scalar Leptoquark and vector Leptoquark.

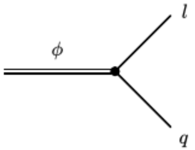

Figure: Leptoquark (B. Diaz *et al.*, 2017)

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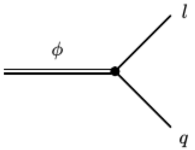

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- Grand Unification based on SU(5) and SU(10).
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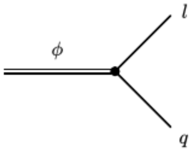

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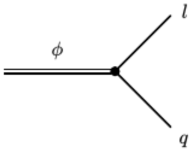

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This difference of scales lead us to work with Effective Field Theories.

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This method uses the technique *Expansion by Regions* in which we obtain the contribution of each region of the integrand.

How does this method work?[2]

1. Split the fields η of the Lagrangian in: $\eta = (\eta_H \;\; \eta_L)$ and make the change: $\eta \to \hat{\eta} + \eta$. The Lagrangian is equal to:

$$\mathcal{L} = \mathcal{L}^{tree}(\hat{\eta}) + \mathcal{L}^{(\eta^2)} + \mathcal{O}(\eta^3), \tag{1}$$

where $\mathcal{L}^{(\eta^2)} = \frac{1}{2}\eta^\dagger \mathcal{O} \eta$

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2. The contributions of the hard region are obtained from:

$$\widetilde{\Delta}_H = -\hat{D}^2 - m_H^2 - U \qquad \textit{and} \qquad \tilde{\Delta}_H = \Delta_H - X_{LH}\Delta_L^{-1}X_{LH} \tag{2}$$

where you must expand in Neuman series

$$\Delta_L^{-1} = \sum_{n=0}^{\infty}(-1)^n\left(\tilde{\Delta}_L^{-1}X_L\right)^n\tilde{\Delta}_L^{-1} \longrightarrow \Delta_L = \tilde{\Delta}_L + X_L \tag{3}$$

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3. Finally, the effective action is calculated as

$$S_H = \frac{i}{2} tr \int d^d x \int \frac{d^d p}{(2\pi)^d} \left(p^2 - m_H^2 - 2ip\hat{D} - \hat{D}^2 - U(x, \partial_x + ip)\right) \tag{4}$$

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Extension with a scalar Leptoquark

The general Lagrangian with a Leptoquark that transforms $(\mathbf{3},\mathbf{1})_{-\frac{1}{3}}$ under the SM gauge group is [3]:

$$\begin{aligned}\mathcal{L} =& \mathcal{L}_{SM} + (D_\mu\phi)^\dagger D_\mu\phi - M^2|\phi|^2 - g_{h\phi}|\Phi|^2|\phi|^2 - \frac{\kappa}{2}|\phi|^4 \\ &+ \lambda^L_{ps}\,\overline{Q^\alpha_p}^c i\tau_2 L_s\phi^*_\alpha + \lambda^R_{ps}\,\overline{u^\alpha_p}^c e_s\phi^*_\alpha + h.c\end{aligned} \tag{5}$$

where the covariant derivative is

$$(D_\mu\phi)^\alpha = \left(\delta_{\alpha\beta}\,\partial_\mu + \delta_{\alpha\beta}\,\frac{1}{3}ig' B_\mu - ig_c\, G^A_\mu T^A_{\alpha\beta}\right)\phi^\beta. \tag{6}$$

The EOM for the Leptoquark is:

$$\phi = \frac{1}{M^2}\left(\lambda^L_{ps}\overline{Q^\alpha_p}^c i\tau_2 L_s + \lambda^R_{ps}\,\overline{u^\alpha_p}^c e_s\right). \tag{7}$$

[3] Bauer *et al.*, 2016.

Tree level

Integrating out the heavy fields, we obtain the Low-energy Lagrangian as:

$$\mathcal{L}_\phi = \frac{1}{2M^2}\left[\frac{1}{2}\lambda^L_{ps}\lambda^{L\,\dagger}_{rq}Q^{(3)}_{lq} - \frac{1}{2}\lambda^L_{ps}\lambda^{L\,\dagger}_{rq}Q^{(1)}_{lq} - \lambda^R_{ps}\lambda^{R\,\dagger}_{rq}Q_{eu} + \left(\lambda^R_{ps}\lambda^{L\,\dagger}_{rq}Q^{(1)}_{lequ} + h.c\right)\right],$$

where the six- dimension operators set is

$$Q_{eu} \equiv \left(\overline{u^\alpha_q}\gamma_\mu u^\alpha_{Lp}\right)\left(\bar{e}_r\gamma^\mu e_{Ls}\right), \qquad Q^{(1)}_{lequ} \equiv \left(\overline{Q^\alpha_{qm}}\; u^\alpha_{Lp}\right)\epsilon_{km}\left(\bar{L}_{r_k} e_{Rs}\right),$$

$$Q^{(3)}_{lq} \equiv \left(\overline{Q^\alpha_q}\,\gamma_\mu\tau^I\, Q^\alpha_{Rp}\right)\left(\bar{L}_r\gamma^\mu\tau^I L_{Rs}\right), \qquad Q^{(1)}_{lq} \equiv \left(\overline{Q^\alpha_{qi}}\,\gamma_\mu\, Q^\alpha_{Rpi}\right)\left(\bar{L}_{r_j}\gamma_\mu L_{Rsj}\right).$$

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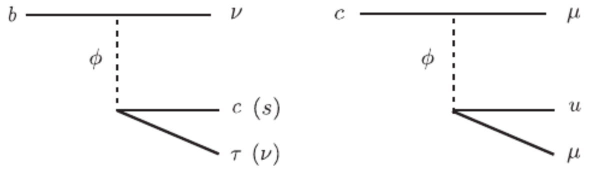

Figure: Tree level diagrams contributing to rare decays (Bauer, 2016)

$$\lambda^{L*}_{c\tau}\lambda^{L*}_{\nu\nu_\tau} \approx 0.35\hat{M}^2_\phi \qquad \lambda^{L*}_{c\tau}\lambda^{L*}_{\nu\nu_\tau} \approx 0.35\hat{M}^2_\phi$$

1-loop (Some results)

- Heavy fluctuations: $\Delta_H = \begin{pmatrix} \Delta_{\phi^*\phi} & X^\dagger_{\phi\phi} \\ X_{\phi\phi} & \Delta^\intercal_{\phi^*\phi} \end{pmatrix}$

- Light fluctuations

$$\Delta_L = \begin{pmatrix} \Delta_{\Phi^*\Phi} & X^\dagger_{\Phi\Phi} & (X^\nu_{A\Phi})^\dagger & \overline{X}_{\overline{\psi}\Phi} & -X^\intercal_{\overline{\psi}\Phi^*} \\ X_{\Phi\Phi} & \Delta^\intercal_{\Phi^*\Phi} & (X^\nu_{A\Phi})^\intercal & \overline{X}_{\overline{\psi}\Phi^*} & -X^\intercal_{\overline{\psi}\Phi} \\ X^\mu_{A\Phi} & (X^\mu_{A\Phi})^* & \Delta^{\mu\nu}_A & \overline{X}^\mu_{\overline{\psi}A} & -(X^\mu_{\overline{\psi}A})^\intercal \\ X_{\overline{\psi}\Phi} & X_{\overline{\psi}\Phi^*} & X^\nu_{\overline{\psi}A} & \Delta_{\overline{\psi}\psi} & 0 \\ -\overline{X}^\intercal_{\overline{\psi}\Phi^*} & -\overline{X}^\intercal_{\overline{\psi}\Phi} & -(\overline{X}^\nu_{\overline{\psi}A})^\intercal & 0 & -\Delta^\intercal_{\overline{\psi}\psi} \end{pmatrix}$$

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- Deriving the cuadratic term for the interaction Higgs-Higgs:

$$\Delta_{\Phi^*\Phi} = -\hat{D}^2 - M^2_\Phi - g_{h\phi}\left(\hat{\phi}^\dagger\hat{\phi}\right) - \lambda\hat{\Phi}\hat{\Phi}^\dagger - \lambda\left(\hat{\Phi}^\dagger\hat{\Phi}\right). \qquad (8)$$

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- Obtaining the inverse, expanding $p, M \sim \zeta$

$$\Delta_{\Phi^*\Phi}(x, \partial_x + ip)^{-1} = \frac{1}{p^2} + \frac{1}{p^4}\left(m^2_\Phi + \Omega\right) + 2i\frac{p_\mu}{p^4}\hat{D}^\mu - 4\frac{p_\mu p_\nu}{p^6}\hat{D}^\mu\hat{D}^\nu + \cdots$$

Finally...

We obtain relevant terms like:

$$\frac{1}{(p^2 - m_\phi^2)p^2}\left[\lambda_{rq}^{L*} y_u y_u^\intercal \lambda_{rq}^{L\dagger} C\bar{L}P_R u\gamma_0 P_L L^\dagger Q^c + \ldots\right] \tag{10}$$

where we can induce the FCNCs at the processes:

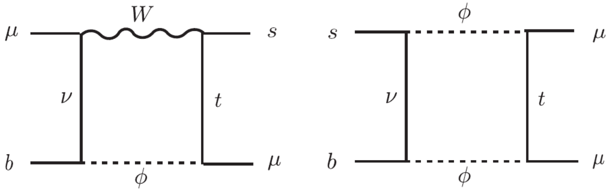

Figure: Loop contributions to $b \to s\mu^+\mu^-$ (Bauer, 2016).

Conclusions

1. The functional integration offers us a great simplification to calculate the EFTs couplings. Furthermore, this systematic procedure can help us to obtain contributions easier than the conventional methods.
2. The Leptoquarks can explain the observed desviations by the BaBaR, Belle and LHCb collaborations.

Obrigada!