Future prospects in Kaon Physics @ ECN3

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- Introduction
- NP models inspired by the LFU anomalies
- The role of Kaons
- Conclusions
Introduction

These days we are celebrating the 10\textsuperscript{th} anniversary of the Higgs discovery (or the completion of the SM spectrum).
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However, as for any QFT, we believe the SM is only an Effective Field Theory, i.e. the low energy limit of a more complete theory with more degrees of freedom.

\[ \mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \ldots \]

We identified the long-range properties of this EFT, but we struggle to understand

- the nature of short-distance dynamics
- why such peculiar structure emerges at low-energies


Introduction

Ideally, we would like to probe the UV directly, via high-energy experiments.

However, for > 30 years this will not be possible....

For the time being, we can only extract indirect UV infos exploring the low-energy limit of the EFT.

Many infos, with 2 clear messages:

- several tuned (SM) couplings
- several accidental (approximate) symmetries
**Introduction**

\[ \mathcal{L}_{\text{SM-EFT}} = \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \sum_{d,i} \frac{c_i^{[d]}}{\Lambda^{d-4}} O_i^{d\geq 5} \]

(long-distance interactions) (local contact interact.)

“Accidental symmetries” are symmetries which are not fundamental properties of the theory, but emerge accidentally at low energies / large distances → not enough “variables” to describe the violation of the symmetry [ ~ multipole expansion ]
Introduction

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“Accidental symmetries” are symmetries which are not fundamental properties of the theory, but emerge accidentally at low energies / large distances \(\rightarrow\) not enough “variables” to describe the violation of the symmetry \(\sim\) multipole expansion

If a symmetry arises accidentally in the low-energy theory, we expect it to be violated by higher dim. ops

Well-known past examples... but also the hints of Lepton Flavor Universality violations recently reported in B physics \([\rightarrow \text{more later}]\) belong to this category
Introduction

In this context Kaon physics plays a unique role:

Unique probe of flavor-symmetry breaking involving light families

The SM (approximate) accidental symmetries imply an extremely strong suppression of $A(s_L \rightarrow d_L)_{\text{FCNC}}$ [probed precisely only by $B(K^+ \rightarrow \pi^+ \nu\nu)$] & helicity-suppressed amplitudes such as $A(s_R \rightarrow u_L e_R \nu_L)$ [probed precisely by $R_{e/\mu}(K)$]

\[
A_{\text{SM}} \sim \frac{y_t^2 V_{ts}^* V_{td}}{16\pi^2 V_{us}} \quad A(K \rightarrow \pi e\nu) \\
(\sim 10^{-4})
\]

\[
A_{\text{SM}} \sim \frac{y_e}{y_\mu} \quad A(K \rightarrow \mu \nu) \\
(\sim 10^{-2})
\]
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- Unique probe of possible light, weakly coupled, new dynamics

- Unique probe of some of the fundamental SM parameters

- Ideal set-up for the “R&D” of theory tools about non pert. dynamics
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Unique probe of possible light, weakly coupled, new dynamics

Unique probe of some of the fundamental SM parameters

Ideal set-up for the “R&D” of theory tools about non pert. dynamics

Not covered in this talk, despite very interesting
NP models inspired by the recent LFU anomalies
Since 2013 results in semi-leptonic B decays started to exhibit tensions with the SM predictions connected to a possible violation of Lepton Flavor Universality.

More precisely, we seem to observe a different behavior (beside pure kinematical effects) of different lepton species in the following processes:

- $b \rightarrow s \, l^+l^-$ (neutral currents): $\mu$ vs. $e$
- $b \rightarrow c \, l\nu$ (charged currents): $\tau$ vs. light leptons ($\mu$, $e$)
The “anomalous” data

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N.B: LFU is an accidental symmetry of the SM Lagrangian in the limit where we neglect the lepton Yukawa couplings.

LFU is badly broken in the Yukawa sector: $y_e \sim 3 \times 10^{-6}$, $y_\mu \sim 3 \times 10^{-4}$, $y_\tau \sim 10^{-2}$

but all the lepton Yukawa couplings are small compared to SM gauge couplings, giving rise to the (approximate) universality of decay amplitudes which differ only by the different lepton species involved
The "anomalous" data

- \( b \to s \ell^+\ell^- \) (neutral currents): \( \mu \) vs. \( e \)

High significance: several observables pointing to the same coherent picture

- \( B \to K^*\mu\mu \) angular distribution

- \( B \to H \mu\mu \) branching ratios

\[ \Gamma(H_b \to H_s \mu\mu)/\Gamma(H_b \to H_s ee) \]

- \( R_{K^0}^{[0.05-1.1]} \)
- \( R_{K^0}^{[1.1-6]} \)
- \( R_{K^+}^{[1.1-6]} \)
- \( R_{pK}^{[0.1-6]} \)
- \( R_{K^*}^{[0.05-6]} \)
- \( R_{K0}^{[1.1-6]} \)

\[ \text{BR}(B_s \to \mu\mu) \]

\[ \text{BR}_{\text{exp}} = (2.85 \pm 0.32) \times 10^{-9} \quad \text{ATLAS+CMS+LHCb '21} \]

\[ \text{BR}_{\text{SM}} = (3.66 \pm 0.14) \times 10^{-9} \quad 2.3\sigma \]
**The “anomalous” data**

- $b \rightarrow s \ell^+\ell^- \text{ (neutral currents): } \mu \text{ vs. } e$

- $b \rightarrow c \ell\nu \text{ (charged currents): } \tau \text{ vs. light leptons (} \mu, e \text{)}$

![Graph showing R(X) = \frac{\Gamma(B \rightarrow X \tau\nu)}{\Gamma(B \rightarrow X \ell\nu)} \text{ for } X = D \text{ or } D^*$]

- Clean SM predictions (*uncertainties cancel in the ratios*)

- Consistent results by 3 different exp.ts: 3.1σ excess over SM

- Slower progress
**EFT considerations**

- Anomalies are seen only in semi-leptonic (quark×lepton) operators
- We definitely need non-vanishing **left-handed** current-current operators although other contributions are also possible

\[
C_{ij\alpha\beta} = \text{large for } 3^{rd} \text{ generation fields} + \text{ small terms for } 2^{nd} \text{ (and } 1^{st}) \text{ generations}
\]

- Large coupl. *compete with SM tree-level* in \( b(3^{rd}) \ c(2^{nd}) \rightarrow \tau(3^{rd}) \ \nu_{\tau}(3^{rd}) \)
- Small coupl. *compete with SM loop-level* in \( b(3^{rd}) \ s(2^{nd}) \rightarrow \mu(2^{rd}) \ \mu(2^{rd}) \)

Link to pattern of the Yukawa couplings!
EFT considerations

\[ \frac{10^{-3}}{\Lambda^2} \]

\( \mu_L \)
\( \tau_L \)

\( \frac{1}{\Lambda^2} \)

\( \Lambda \approx 1.5 \text{ TeV} \)

LFU in \( b \rightarrow s l^+l^- \) \([R_K, ...]\) \( \sim 4\sigma \)

LFU in \( b \rightarrow c \tau \nu \) \([R_D, ...]\)

CKM rotation

“natural” flavor connection
**EFT considerations**

\[ \frac{10^{-3}}{\Lambda^2} \]

\[ \Lambda \approx 1.5 \text{ TeV} \]

\[ \frac{10^{-2}}{\Lambda^2} \]

\[ \frac{10^{-1}}{\Lambda^2} \]

\[ \frac{1}{\Lambda^2} \]

\[ \text{not seen yet} \]

\[ \text{not seen yet} \]

\[ \text{not seen yet} \]

\[ \Lambda \approx 1.5 \text{ TeV} \]
**EFT considerations**

\[ \frac{\Lambda}{\Lambda^2} \]

- \(10^{-3}\)
- \(10^{-2}\)
- \(10^{-1}\)
- \(1\)

\[ \Lambda \approx 1.5 \text{ TeV} \]

\[ \not\text{seen yet} \]

\[ \not\text{not seen yet} \]

\[ \mu_L \]

\[ \gamma\text{-loop} \]

\[ \text{CKM rotation} \]

\[ \text{LFU in } b \to s l^+ l^- [\Delta C_9^{\text{Univ}}] \]

\[ \sim 2\sigma \]

\[ \text{LFU in } b \to c \]

\[ \not\text{seen yet} \]

\[ \not\text{seen yet} \]

\[ \text{pp} \to \tau \tau \]

**An exciting consistent path connecting old problems and recent anomalies**

- LFU in \( b \to s l^+ l^- \) [\( R_K, ... \)] \( \sim 4\sigma \)

- NP stabilizing the Higgs sector

- Higgs = pNGB of the new dynamics (\( \leftrightarrow \) LQ mass)
Model-building attempts

From a model-building perspective, these EFT results 
*challenge the “old” paradigm of flavour-universal BSM physics*

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The old MFV paradigm:

- Concentrate on the Higgs hierarchy problem
- Postpone (*ignore*) the flavor problem

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3 gen. = “identical copies”
up to high energies
**Model-building attempts**

From a model-building perspective, these EFT results fit well with the idea of a multi-scale construction related to flavor hierarchies:

**Main idea:**

- Flavor non-universal interactions already at the TeV scale:
- 1\textsuperscript{st} & 2\textsuperscript{nd} gen. have small masses because they are coupled to NP at heavier scales

3 gen. = “identical copies” up to high energies
Model-building attempts

From a model-building perspective, these EFT results fit well with the idea of a multi-scale construction related to flavor hierarchies:
**Model-building attempts**

From a model-building perspective, these EFT results fit well with the idea of a multi-scale construction related to flavor hierarchies:

Very interesting explicit class of models based on 4321 gauge symmetry @ TeV scale:

- Very good fit of all low and high-energy data (*precise predictions*)
- Can be embedded in more complete models explaining
  - Charge quantization
  - Flavor hierarchies
  - Higgs mass stabilization
  - Neutrino masses

Di Luzio, Greljo, Nardecchia, '17
Bordone, Cornella, Fuentes-Martin, GI '17
Fuentes-Martin *et al.* '20 & '22
Model-building attempts

From a model-building perspective, these EFT results fit well with the idea of a multi-scale construction related to flavor hierarchies:

- Very good fit of all low and high-energy data (precise predictions)
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LQ search in $pp \rightarrow \tau\tau$

Very interesting explicit class of models based on 4321 gauge symmetry @ TeV scale:

Di Luzio, Greljo, Nardecchia, '17
Bordone, Cornella, Fuentes-Martin, GI '17
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The role of Kaons
**The role of Kaons**

Already from the EFT considerations...

\[ C_{ij\alpha\beta} = \text{large for 3rd gen.} + \text{small terms for 2nd (& 1st) gen.} \]

… it is clear that small but non-negligible effects are naturally expected also in the 2nd generation → **Kaon Physics**

Strong renewed interest in **LFU tests** and **clean FCNC processes** both in **charged** & in **neutral** currents
The role of Kaons

Example-I: charged currents

From $R(D^*)$ & $R(D)$:

\[
\frac{\Gamma(b \rightarrow c\tau\nu)}{\Gamma(b \rightarrow c\mu\nu)} \sim 10\%
\]

The key observable for LFU tests is

\[
R_K = \frac{\Gamma(K^+ \rightarrow e^+\nu)}{\Gamma(K^+ \rightarrow \mu^+\nu)}
\]

Using simple EFT considerations, we can expect violations from SM in $R_K(K)$ up to $\sim 10^{-3}$

- Highly Precise SM value
  \[
  R_K = (2.477 \pm 0.001) \times 10^{-5}
  \]
  [V. Cirigliano, I. Rosell, Phys. Rev. Lett. 99, 231801]

- World Average (2013)
  \[
  R_K = (2.488 \pm 0.01) \times 10^{-5}
  \]
  $\Delta R_K / R_K \approx 0.4\%$

Maybe not impossible to reach this NP benchmark with future $K^+$ program @ ECN3
The role of Kaons

**Example-II:** neutral currents, $\mu^+\mu^-$ vs. $e^+e^-$

\[
V_+(z) = a_+ + b_+ z + V_+^{\pi\pi}(z)
\]

<table>
<thead>
<tr>
<th>Channel</th>
<th>$a_+$</th>
<th>$b_+$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ee$</td>
<td>$-0.587 \pm 0.010$</td>
<td>$-0.655 \pm 0.044$</td>
<td>E865 [78]</td>
</tr>
<tr>
<td>$ee$</td>
<td>$-0.578 \pm 0.016$</td>
<td>$-0.779 \pm 0.066$</td>
<td>NA48/2 [79]</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>$-0.575 \pm 0.039$</td>
<td>$-0.813 \pm 0.145$</td>
<td>NA48/2 [80]</td>
</tr>
</tbody>
</table>

Starting from $R_K(B) \sim 10\%$ using simple EFT considerations, we can expect LFU violations up to $\sim 10^{-3}$ in the coefficients (slopes) of the $K^+ \rightarrow \pi^+ ll$ form factors.

Probably impossible to reach this NP benchmark, but one order of magnitude improvement doable $\rightarrow$ definitely worth trying
The role of Kaons

Example-III: neutral currents, $\mu^+\mu^-$ vs. $\nu_\tau\nu_\tau$

The most interesting, and less ambiguous effects, are expected in $K \rightarrow \pi\nu\nu$
\[ K \rightarrow \pi \nu \nu \]

\[
B(K^+ \rightarrow \pi^+ \nu \nu)_{\text{SM}} = (8.4 \pm 1.0) \times 10^{-11}
\]

Th. error with sizable parametric component
[Lattice, CKM, m_c] \rightarrow will go down to \( \lesssim 5\% \)

Buras, Buttazzo, Girrbach-Noe, Knegjens '15

\[
\Gamma(K \rightarrow \pi \nu \nu) = \Gamma(K \rightarrow \pi \nu_e \bar{\nu}_e) + \Gamma(K \rightarrow \pi \nu_\mu \bar{\nu}_\mu) + \Gamma(K \rightarrow \pi \nu_\tau \bar{\nu}_\tau)
\]

SM like few % deviation as in \( b \rightarrow s \mu \mu \)

O(1) deviation from SM expected in models addressing B anomalies

Bordone, Buttazzo, GI, Monnard '16
Marzocca, Trifinopoulos, Venturini '21
$K \rightarrow \pi \nu \nu$

$$B(K^+ \rightarrow \pi^+ \nu \nu)_{SM} = (8.4 \pm 1.0) \times 10^{-11} \quad \text{Buras et al. '15}$$

$$B(K^+ \rightarrow \pi^+ \nu \nu)_{exp} = (10.6 \pm 4.0) \times 10^{-11} \quad \text{NA62 [2016+2017+2018]}$$

E.g.: Allowed range for the two $K \rightarrow \pi \nu \nu$ modes in a generic scalar-LQ model addressing the B anomalies

O(1) deviation from SM expected in models addressing B anomalies

Marzocca, Trifinopulos, Venturini '21
\[ K \rightarrow \pi \nu \nu \]

\[
B(K^+ \rightarrow \pi^+ \nu \nu)_{SM} = (8.4 \pm 1.0) \times 10^{-11} \quad \text{Buras et al. '15}
\]

\[
B(K^+ \rightarrow \pi^+ \nu \nu)_{\text{exp}} = (10.6 \pm 4.0) \times 10^{-11} \quad \text{NA62 [2016+2017+2018]}
\]

\[
\begin{align*}
B(K_L \rightarrow \pi^0 \nu \nu)_{SM} &= (3.0 \pm 0.3) \times 10^{-11} \quad \text{Buras et al. '15} \\
B(K_L \rightarrow \pi^0 \nu \nu)_{\text{exp}} &< 3.6 \times 10^{-9} \quad \text{KOTO '19}
\end{align*}
\]

More precise predictions can be derived in specific NP frameworks, such as the motivated 4321 gauge models:

- No tree-level contribution
- Interesting correlation with \( R_D \), high-pT, and \( B \rightarrow K \nu \nu \)
$K \rightarrow \pi \nu \nu$ in 4321

Ref. values for LQ mass and coupling ($\Lambda_U = \sqrt{2} M_U / g_U$)
from B anom. + high-energy searches ($\text{max} \ & \ \text{min values}$)

Present 2$\sigma$ range for $B(K^+ \rightarrow \pi^+ \nu \nu)$
$K \to \pi\nu\nu$ in 4321

Possible impact of future precision measurements.

$\Lambda_U = 1.8 \text{ TeV}$

$\Lambda_U = 1.3 \text{ TeV}$

$R_{D^*} @ 5\%$

$B(K^+ \to \pi^+\nu\nu)$ with 1000 events

Crosas, GI, Lizana, Selimovic Stefanek – to appear soon...
**K → πνν in 4321 & related processes**

Very similar observables (*loop-induced FCNC*) in this motivated class of models are

A) $B \rightarrow K\nu\nu$

![Diagram of $R_D \rightarrow$ enhancement of $B \rightarrow K\nu\nu$.](image1)

B) $B_s$ mixing [$\Delta F=2$]

![Diagram of $\delta(\Delta m_{B_s})$ vs $\delta R_D^*$.](image2)

Vector-like leptons need to be “light”

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Fuentes-Martin, GI, Konig, Selimovic, '20

Di Luzio et al. '18
Very similar observables (loop-induced FCNC) in this motivated class of models are

A) $B \rightarrow K\nu\nu$

- $R_D \rightarrow$ enhancement of $B \rightarrow K\nu\nu$

B) $B_s$ mixing [$\Delta F=2$]

- 2.8σ for signal $\sim 600$ GeV (not shown here)
Conclusions

• Flavor is an essential ingredient to understand the structure of physics beyond the SM. This statement, which we deduce already by the SM Yukawa structure, is reinforced by the recent anomalies in B physics.

• Measuring $\text{BR}(K^+ \rightarrow \pi^+ \nu \nu)$ @ 5% relative error is a milestone in this respect: unique probe of flavor mixing among light generations.

• This physics case is strongly reinforced by the recent B-anomalies, as illustrated by precise correlations in motivated NP models.

• The program of observing $\sim 1000$ events of $K^+ \rightarrow \pi^+ \nu \nu$ could be complemented with a series of additional interesting measurements (I mentioned here only a few examples...).