The strange side of LHCb

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We provide a general effective-theory argument relating present-day discrepancies in semi-leptonic $B$-meson decays to signals in kaon physics, in particular lepton-flavour violating ones of the kind $K \rightarrow (\pi)e^{\pm}\mu^{\mp}$. We show that $K$-decay rates of around $10^{-12} - 10^{-13}$ are possible, for effective-theory cutoffs around $5 - 15$ TeV compatible with discrepancies in $B \rightarrow K^{(*)}\mu\mu$ decays. We perform a proof-of-principle study of the reach for such decays at LHCb, taking $K^{+} \rightarrow \pi^{+}\mu^{\pm}e^{\mp}$ as a benchmark. In spite of the long lifetime of the $K^{+}$ compared to the detector size, the huge statistics anticipated as well as the overall detector performance translate into encouraging results. These include the possibility to reach the $10^{-12}$ rate ballpark, and thereby significantly improve current limits. We substantiate these conclusions with a range of realistic assumptions on the particle identification performance as well as on the kinematic reconstruction thresholds for the signal candidates.

Introduction – Data on $b \rightarrow s\ell\ell$ and $b \rightarrow c\ell\nu$ transitions display persistent deviations with respect to Standard-Model (SM) expectations [1–7]. Deviations are seen in both individual decay modes and in the relative rates of $B$-meson decays to different lepton species. These latter deviations in particular hint at a sizeable violation of Lepton Universality (LUV). The pattern of observed departures from the SM finds a straightforward interpretation within an effective-field-theory (EFT) framework [2–7]. Interestingly, among the preferred operators to explain the anomalies is the product of two left-handed currents [8,9]. This can naturally be expressed in terms of the $SU(2)_L$-invariant fields $Q_L$ and $L_L$ [10,11], which is what one would expect of new effects generated above the electroweak (EW) symmetry-breaking (EWSB) scale. Furthermore, the fact that effects seem larger for heavier leptons is suggestive of new physics coupled dominantly to third-generation fermions [12] – in the ‘gauge’ basis, that in general is misaligned with the mass-eigenstate basis.\textsuperscript{1} Therefore, without further assumptions, observable LUV is accompanied by Lepton-Flavor Violation (LFV), whose expected size is related to the measured amount of LUV.

LFV may be expected in any $d \rightarrow d'$ transition, not only $b \rightarrow s$. In this work we present general arguments to relate LFV in $K$ decays to the existing LUV hints in $B$ decays, and

\textsuperscript{1} Starting from this zeroth-order hypothesis, a neat framework to explain all anomalies at one stroke is then to postulate a broken flavour symmetry distinguishing the third from the light generations, so that effects in $b \rightarrow c\tau\nu$ and respectively $b \rightarrow s\mu\mu$ are automatically of first and respectively third order in the breaking parameter [13] (see also [14–16], and, for the original formulation of the symmetry in a context other than the LUV anomalies, Ref. [17]).
produce predictions for the rates to expect. We then present a proof-of-principle study on the reach for such $K$ decays at the upgraded LHCb experiment.

**$K \to (\pi)e\mu$ decays as a probe of new physics** – Among kaon decays, the most straightforward manifestation of LFV would be in $K \to (\pi)e\mu$ modes. In order to relate predictions for these modes to the present theory understanding of $B$-decay discrepancies as model-independently as possible, we focus on an effective-theory picture, forgoing the introduction of new degrees of freedom. Our line of argument starts from observing that the kaon decays we are after are mediated by the current $s \to d$; we then relate this current to the analogous effective current advocated to explain discrepancies in $b \to s$. To first approximation, such approach does not require any discussion whatsoever of $b \to c$ discrepancies instead.

Our starting point to account for the LUV observed in $B \to K^{(*)}$ decays is the 3rd-generation effective interaction [12] mentioned in the introduction

$\mathcal{H}_{\text{NP}} = G \left( b_L^i \gamma^a b_L^j (\bar{\tau}_L^a \gamma_\alpha \tau_L^a) \right)$ ,

where $G \ll G_F$, $G_F$ being the Fermi constant, the subscript $L$ denotes left-handed fields, and primes identify the gauge basis. Below the EW scale, the rotation to the mass eigenbasis proceeds through the transformations

$$b_L^i \equiv (d_L^i)_3 = (U_L^d)_{3i}(d_L)_{i} \,,$$

$$\tau_L^i \equiv (\ell_L^i)_3 = (U_L^\ell)_{3i}(\ell_L)_{i} \,,$$

involving the unitary matrices $U_L^{d,\ell}$. Using the unitarity of these transformations and the measured amount of LUV, one can provide a general argument [12,18] for expecting LFV in $B \to K$ decays to be in the ballpark of $10^{-8}$.

The interaction (1) can be expected to also manifest itself in decays of the kind $K \to (\pi)\ell\ell^0$, although making this expectation quantitative requires a theory predicting the $U_L^{d,\ell}$ matrices. Before delving into this matter, the first observation to be made is of experimental nature: somewhat surprisingly, limits on such modes are decade-old

$$\mathcal{B}(K_L \to e^+\mu^-) < 4.7 \times 10^{-12} \, [21] \,,$$

$$\mathcal{B}(K_L \to \pi^0 e^+\mu^-) < 7.6 \times 10^{-11} \, [22] \,,$$

$$\mathcal{B}(K^+ \to \pi^+ e^-\mu^+) < 1.3 \times 10^{-11} \, [23] \,,$$

$$\mathcal{B}(K^+ \to \pi^+ e^+\mu^-) < 5.2 \times 10^{-10} \, [24] \,.$$  

In order to obtain corresponding theoretical expectations for these modes, let us first rewrite Eq. (1) after EWSB in a form akin to Ref. [14], i.e.

$$\mathcal{H}_{\text{NP}} = G \lambda_{ij} \lambda_{mn} (\bar{d}_i \gamma_\mu d_j)(\bar{\ell}_m \gamma_L \ell_n) \,,$$

where we have identified $\lambda_{ij} = (U_L^d)_{3i}(U_L^d)_{3j}$ and $\lambda_{mn} = (U_L^\ell)_{3m}(U_L^\ell)_{3n}$. Note that, in our setup, the $\lambda^{d,\ell}$ matrix couplings are hermitian by construction.\(^3\) Besides, we will use the SM interaction $\mathcal{H}_{\text{eff}}^{\text{SM}} = N_{\text{SM}}(\bar{s}_L \gamma_\mu u)(\bar{\nu}_L \gamma_\mu \mu) + \text{h.c.}$, with $N_{\text{SM}} = 4G_F/\sqrt{2} \cdot V^*_{ub}$. After suitably

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\(^2\) The first observable that comes to mind would be the $K$-physics analogue of $R_K$, namely the ratio $\mathcal{B}(K \to \pi\mu\mu)/\mathcal{B}(K \to \pi\nu\nu)$, which is, however, long-distance dominated [19,20].

\(^3\) This makes Eq. (1) not entirely general. For example, in leptoquark models not dominated by couplings with 3rd-generation fermions, the flavourful coupling multiplying the four-fermion structure is a four-index tensor, that cannot be factorized into two two-index tensors. Such notation would however unnecessarily clutter the discussion to follow, in particular Eqs. (6)-(8).
normalising the decay modes of interest in order to get rid of phase-space factors [25], and
after defining the abbreviations
\[ \kappa_\ell \equiv \left| \frac{2G_{\text{SM}}}{N_{\text{SM}}} \right|^2 |\lambda_{12}|^2, \quad \kappa_R^q \equiv (\text{Re}\lambda_{21}^q)^2, \quad \kappa_I^q \equiv (\text{Im}\lambda_{21}^q)^2, \]  
we find
\[ \frac{\Gamma(K_L \to e^\pm \mu^\mp)}{\Gamma(K^+ \to \mu^\pm \nu_\mu)} = \kappa_\ell \cdot \kappa_R^q \left( = \frac{\Gamma(K_S \to \pi^0 \mu^+e^-)}{\Gamma(K^+ \to \pi^0 \mu^+ \nu_\mu)} \right), \]  
\[ \frac{\Gamma(K_S \to e^\pm \mu^\mp)}{\Gamma(K^+ \to \mu^\pm \nu_\mu)} = \kappa_\ell \cdot \kappa_I^q \left( = \frac{\Gamma(K_L \to \pi^0 \mu^+e^-)}{\Gamma(K^+ \to \pi^0 \mu^+ \nu_\mu)} \right), \]  
\[ \frac{\Gamma(K^+ \to \pi^+ \mu^0e^-)}{\Gamma(K^+ \to \pi^0 \mu^+ \nu_\mu)} = \kappa_\ell \cdot (\kappa_R^q + \kappa_I^q). \]  
These formulas hold under the excellent approximations of neglecting the electron mass and the mass differences between charged and neutral mesons, as well as CP violation in mixing.

We also note that the interaction in Eq. (1) does not produce new tree-level contributions to the normalizing decays, and Eqs. (6)-(8) accordingly assume no new physics on these modes.

Finally, we quote formulas for the \( K_L \to \pi^0 \mu e \) modes (the last members of Eqs. (6)-(7), enclosed in parentheses) only for completeness with respect to Eqs. (3). At LHCb, these modes pose a substantial additional challenge because of the final-state \( \pi^0 \) and will not be discussed in the experimental section.

Clearly, in order to be able to make quantitative predictions, we need a model for (the relevant entries of) the flavour matrices \( \lambda^q \) and \( \lambda^\ell \), as well as for the overall strength, \( G \), of the new interaction. To this end, one can start from Eq. (4), properly generalised to be \( SU(2)_L \)-invariant above the EW scale [10], and discuss the parametric requirements on the \( \lambda^q, \lambda^\ell \) couplings and on \( G \) for an explanation of the \( B \)-physics anomalies [13,14]. Within our context, it will be useful to introduce explicitly the UV scale \( \Lambda \) via the identification
\[ G = \frac{C}{\Lambda^2}, \]  
so that the Wilson coefficient \( C \) is naturally of order unity.\(^4\) Departures from the limit \( \lambda_{ij}^{q,\ell} = \delta_{ij}^3 \delta_{33}^3 \) – that yields back the 3rd-generation-only interaction in Eq. (1) – are then parameterised by the spurions of a suitably chosen, global flavour symmetry [13]. \( B \)-physics anomalies can then be explained at one stroke by appropriate ranges for \( C/\Lambda^2 \) and for the relevant \( \lambda^q, \lambda^\ell \) couplings, expressed as functions of the chosen spurions [14].

We can exploit this framework to obtain a quantitative estimate of Eqs. (6)-(8) once the scale \( \Lambda \) and the relevant flavour couplings, in our case \( \lambda_{21}^q, \lambda_{12}^q \) and \( \lambda_{21}^\ell \), are specified. Fixing these couplings is the step that entails the largest degree of model dependence. One quite economical parameterization is that proposed in Ref. [26]. It applies to precisely the interaction introduced above, i.e. Eq. (1) and its \( SU(2)_L \)-invariant generalization. Another simple approach is to make, for the quark-sector couplings, a CKM-like ansatz, as e.g. in Ref. [14], namely
\[ \lambda_{ij}^{q,\ell} = b_q V_{ij}^q V_{ij}, \]  
with \( V \) the Cabibbo-Kobayashi-Maskawa (CKM) matrix and \( b_q \) a flavour-blind coupling, that in absence of further assumptions is expected to be of order unity. We will adhere to

\[^4\text{In the normalization of Ref. [14], flavour-blind Wilson coefficients are instead of } \mathcal{O}(v^2/\Lambda^2).\]
this ansatz, suggested in particular by the constraints imposed by data on Atomic Parity Violation [27,28] as well as $\mu \to e$ conversion in nuclei [29,30]. As a consequence, our coupling of interest is fixed as $\lambda_{12}^q = b_q V_{ts}^* V_{td}$, that per se entails a suppression mechanism for the effects we are seeking to predict.

For the lepton-sector couplings $\lambda^\ell$ there is even larger freedom. A convenient assumption may be

$$\lambda^\ell_{mn} = b_{\ell} V_{3m}^* V_{3n}, \quad (11)$$

with $V$ the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix. Besides being consistent with the anarchic-looking pattern of flavour breaking in the leptonic sector, a PMNS-like ansatz amounts to $\lambda^\ell$ couplings of $O(1)$, namely as large as they can theoretically be. However, in truth this assumption is as arbitrary as any other one, because of the model-building uncertainties inherent in the lepton sector. We will therefore adopt a more agnostic approach, and discuss predictions for hierarchically different values of our relevant coupling $|\lambda_{12}^q|$ (see legend of Fig. 1).

Eqs. (9)-(11) imply that, even after fixing the flavourful couplings $\lambda^{q,\ell}$, our relevant amplitudes still depend on the choice of the product

$$C \equiv C \cdot b_q \cdot b_l, \quad (12)$$

of three flavour-blind numbers, namely the overall strength $C$ of the interaction (related to the choice of the UV scale $\Lambda$), as well as the normalizations $b_{q,\ell}$ of the $\lambda^{q,\ell}$ coupling matrices themselves. Rather than exploring the different directions of this parameter space, we will display predictions for one reference value: $C = 1$. We deem this value representative because: (i) $b_{q,\ell}$ are expectedly of $O(1)$ in the absence of further assumptions, as mentioned; (ii) the $C$ coupling can be expected to be at most unity or respectively $4\pi$ depending on the (unknown) UV theory being perturbatively coupled, or non-perturbative; (iii) branching-ratio predictions assuming, say, $C = 4\pi$ can be obtained by trivially multiplying by $(4\pi)^2$ those at $C = 1$.

One can then use Eqs. (6)-(8) to study predictions for each of the $K_{L,S} \to \mu^\pm e^\mp$ as well as the $K^+ \to \pi^0 \mu^+ e^-$ modes. In particular, recalling the definitions (5), along with $B(K^+ \to \mu^+ \nu_\mu) \approx 63.6\%$, $B(K^+ \to \pi^0 \mu^+ \nu_\mu) \approx 3.35\%$, $\Gamma(K^+)/\Gamma(K_L) \approx 4.13$ and $\Gamma(K_L)/\Gamma(K_S) \approx 1.75 \times 10^{-3}$ [35], one gets

$$B(K_L \to \mu^\pm e^\mp) \approx 2.6 \kappa^\ell \kappa_R^q, \quad B(K_S \to \mu^\pm e^\mp) \approx 4.6 \cdot 10^{-3} \kappa^\ell \kappa_I^q,$$

$$B(K^+ \to \pi^\pm \mu^\mp e^\pm) \approx 0.034 \kappa^\ell (\kappa_R^q + \kappa_I^q). \quad (13)$$

We note explicitly that, assuming the $\kappa^\ell_I$ coupling to be comparable to $\kappa_R^q$, the LFV mode of the $K_S$ is suppressed by a factor of about $\Gamma_{K_L}/\Gamma_{K_S} \approx 1.75 \times 10^{-3}$ with respect to the corresponding $K_L$ mode (cf. Eq. (13)). Notably, this physics suppression factor is, at LHCb, nearly compensated by the experimental acceptance enhancement, so that the product is invariant. We will comment further on these two modes at the end of the next Section.

In Fig. 1 we display predictions for $B(K_L \to \mu^\pm e^\mp)$ (left panel) and $B(K^+ \to \pi^\pm \mu^\mp e^\pm)$ (right panel) versus the new-physics scale $\Lambda$ as defined in Eq. (9). The color code refers to three possible choices for the leptonic coupling $\lambda^\ell_{12} = (\lambda^\ell_{12})^*$. Solid vs. dashed lines represent predictions in agreement with, and respectively outside, the $2\sigma$ range for $R_K^{(e)}$ [36]. As visible from the figure (end of solid lines), the $R_K^{(e)}$ constraints impose the upper bound $\Lambda \lesssim 8.6$ TeV. We note that these constraints depend on different $\lambda^q$ as well as $\lambda^\ell$ entries than our

5 For definiteness we took $|V_{us}| = 4.0 \times 10^{-2}$, $|V_{td}| = 8.6 \times 10^{-3}$ from a ‘tree-level’ CKM fit [31–33].

6 E.g. $|V_{31}| = 0.4$ and $|V_{32}| = 0.6$ (see [34]).
We assume a CKM-like structure for the quark-sector flavourful coupling (Eq. (10)) and vary the lepton-sector one as in the legend. Dashed lines signify that the parameter space is outside the 2σ range for $R_K$ [36]. See text for further details.

$K \to (\pi)e\mu$ predictions, namely $\lambda_{12}^q$, that we fixed again as in Eq. (10), and $\lambda_{12}^t$, which we leave as a free parameter. The mentioned bound on $\Lambda$ arises from the requirement $|\lambda_{12}^t| < 1$.

Fig. 1 prompts a number of comments: (a) noteworthy, we generically obtain rates around $10^{-13}$, or even above, in quite a large part of the discussed parameter space, and for $\Lambda$ all the way up from 1 to about 15 TeV. Given the suppression mechanisms at play, such ‘large’ branching ratios are a non-trivial finding; (b) the mentioned bound $\Lambda \lesssim 8.6$ TeV from $R_K^{(s)}$’s 2σ ranges holds, as discussed, taking $C = 1$ (representative of a perturbatively coupled UV theory with natural choices of the flavour-blind couplings); taking instead a larger $C$, as in strongly-coupled new-physics scenarios, the corresponding upper bound on $\Lambda$ would increase accordingly. In short, since the $R_K^{(s)}$ constraints impose an upper bound on $\Lambda$, they tend to push signals in $K \to (\pi)\mu\mu$ decays towards larger values, as one may intuitively expect; (c) larger values of $|\lambda_{12}^t|$ tend to be in tension with the existing limits on $b \to s\mu\mu$ modes. In particular, we considered the limits

$$B(K_L \to \mu^\pm e^\mp) < 3.8 \times 10^{-8} \quad [37], \quad B(K^\pm \to \mu^\pm e^\mp) < 1.1 \times 10^{-7} \quad [39],$$

and found that the first mode is the most constraining. Relevant formulas are implemented following Ref. [40]. We note that these constraints depend on the flavour couplings $\lambda_{32}^q$ and $\lambda_{12}^t$, so they translate unambiguously into bounds on $|\lambda_{12}^t|$ or $|\kappa^t|$ (see eq. (5)). We obtain the limit $k^t \lesssim 0.028$, which would amount to the upper bounds $B(K_L \to \mu^\pm e^\mp) \lesssim 1.7 \times 10^{-11}$ and $B(K^\pm \to \pi^\pm \mu^\pm e^\mp) \lesssim 2.5 \times 10^{-13}$. Nonetheless, we stress that these bounds should not be taken at face value, because, for example, our CKM ansatz for $\lambda_y$ is expected to hold within factors of $O(1)$. This fact, however, implies that scenarios represented by the upper two curves (red or green) in both panels of Fig. 1 tend to predict a signal in $b \to s\mu\mu$ modes very close to the present limits of eq. (14).

To conclude, Fig. 1 illustrates the fact that within a motivated EFT setup, that accounts for the present $b \to s$ and $b \to c$ anomalies, one ends up with predictions for LFV $K$ decays potentially right beneath current limits. To get some perspective, one may start from a

![Figure 1: Predictions for $B(K_L \to \mu^\pm e^\mp)$ and $B(K^\pm \to \pi^\pm \mu^\pm e^\mp)$ as a function of the UV scale $\Lambda$. We assume a CKM-like structure for the quark-sector flavourful coupling (Eq. (10)) and vary the lepton-sector one as in the legend. Dashed lines signify that the parameter space is outside the 2σ range for $R_K$ [36]. See text for further details.](image)
completely different stance, and e.g. consider models for the mixing matrices in Eq. (2). Examples include [41], motivated by a solution to the strong-\(CP\) problem, or [42], which is an attempt to connect \(B\)-physics anomalies to neutrino physics. In both cases one obtains again rates for LFV \(K\) decays in the ballpark of \(10^{-13}\).

\(K \rightarrow (\pi)e\mu\) decays at LHCb – We next discuss the LHCb reach for the above mentioned kaon decays as a function of the integrated luminosity to be collected by the LHCb experiment and its upgrades [43,44] over the next years.

We parameterise the differential cross section for kaon production in \(pp\) collisions at 13 TeV using Pythia 8.230 [45,46] with default tuned parameter set. We find that this parametrisation gives an average \(K^+\) rapidity density in the central rapidity region in agreement with CMS measurements at 0.9, 2.76, 7 and 13 TeV [47,48] at the 5\% level. We obtain a total \(K^\pm\) cross section of 0.63 barn. Taking into account the fraction of kaons in the pseudorapidity acceptance of LHCb, \(2 < \eta < 5\), we find that one can profit from a \(K^\pm\) cross section as large as \(0.14\) barn.

The benchmark case of \(K^+ \rightarrow \pi^+\mu^\pm e^\mp\) – In the following we study the reach of searches for charged kaon LFV decay of the type \(K^+ \rightarrow \pi^+\mu^\pm e^\mp\) at the LHCb upgrades. We estimate the LHCb detector response using the RapidSim package [49], which implements a parametric simulation of the LHCb detector acceptance, momentum, and vertex resolutions, including electron bremsstrahlung. The parametrizations are based on published performances of the current LHCb detector, but the LHCb upgrades are expected to have performances which are at least as good. As kaon mass resolutions critically depend on both the momentum and opening-angle resolution, the default RapidSim parametrization of momentum and vertex resolutions is tuned specifically for this analysis using public LHCb numbers for kaon decays from [50]. In addition, in order to get accurate estimates of the acceptance, we perform an approximate simulation of the LHCb-upgrade tracking system using the information in the Technical Design Reports [51,52] (see also [53] for the description of the magnetic-field modeling).

The \(K^+ \rightarrow \pi^+\mu^\pm e^\mp\) candidate is considered if all of its decay products lie within the LHCb tracker acceptance leaving hits in both the vertex detector and tracker stations, and if each of the daughter particles crosses at least three stations in the vertex detector. In practice this criterion imposes a roughly 0.5 m long decay volume for the kaons. By comparing the efficiencies we obtain for \(K_S \rightarrow \pi^+\pi^- e^+ e^-\) to LHCb public numbers in [54] we estimate that electrons from kaon decays are 50\% less likely than pions or muons to be reconstructed and we correct our simulation accordingly.

Kinematic selection – We implement a simple selection to separate the signal decays from backgrounds. Because of the long lifetime of charged kaons, selection criteria on the impact parameters of final-state tracks with respect to the \(pp\) collision allow to reduce the combinatorial background from tracks coming from the \(pp\) collision while keeping very high signal efficiency. However, this background has the potential to become dangerous for kaon decays with branching fractions as low as \(10^{-12}\). The rate of fake tracks due to random associations of hits in the trackers could also be a sizeable background at high multiplicity. At the moment it is difficult to estimate these background rates at the luminosity of the LHCb Upgrade II, \(O(10^{34})\) cm\(^{-2}\)s\(^{-1}\). In this paper we assume the dominant background is coming from misidentified kaon decays and leave the estimate of other backgrounds for future studies.

Because of the light kaon mass, the selection criteria which dominate the signal efficiency are the kinematic requirements on the final-state decay products. The most stringent of these is linked to the kinematic threshold to reconstruct charged particle tracks in LHCb’s
Decay

| Decay                        | BR       | mis-ID                      |
|------------------------------|----------|-----------------------------|
| $K^+ \rightarrow \pi^+\pi^+\pi^-$ | $5.6 \times 10^{-2}$ | $\pi^+ \rightarrow \mu^+$ and $\pi^- \rightarrow e^-$ |
| $K^+ \rightarrow \pi^+\mu^+\mu^-$ | $0.94 \times 10^{-7}$ | $\mu^- \rightarrow e^-$ |
| $K^+ \rightarrow \pi^+e^+e^-$     | $3.0 \times 10^{-7}$ | $e^+ \rightarrow \mu^+$ |

Table 1: Kaon decays simulated in RapidSim that can enter as background if some of the final state tracks are mis-identified. Branching ratios are taken from [55].

real-time processing (trigger). LHCb’s upgrade trigger will have access to all information from all of LHCb’s subdetectors at the full LHC collision rate, and the kinematic threshold above which it will be able to find tracks will be determined by how effectively LHCb is able to use the available computing resources and not any inherent detector limitation. While it is hard to make definitive predictions today, we try in what follows to give a feeling for what might be possible given some reasonable assumptions. First of all, we demand a momentum larger than 2 GeV for all charged tracks so that they are not swept out of the detector acceptance by the dipole magnet. Moreover, muon candidates are required to have a momentum in excess of 3 GeV in order to reach the muon stations. We foresee a trigger strategy involving the identification of a muon track in the muon stations which is subsequently matched to the vertex detector and upstream tracking stations and required to have a large impact parameter with respect to the collision vertex. We assume this will allow to reconstruct muons in real time down to 0.1 GeV in transverse momentum. The muon track could then be used to identify a region of interest in the tracker where two further displaced tracks are looked for to form a $K^+ \rightarrow \pi^+\mu^+e^-$ candidate. We assume that the $\pi^+$ and $e^\pm$ candidate tracks can be reconstructed in real time if their transverse momentum, $p_T$, exceeds a threshold value that we vary between 0.1 and 0.3 GeV.

Misidentified backgrounds – We estimate the abundance of misidentified (mis-ID) backgrounds from kaon decays leaking in the $m(\pi^+\mu^+e^\pm)$ signal region by simulating the processes reported in Table 1 with RapidSim. Double misidentification of $K^+ \rightarrow \pi^+\mu^+e^-\mu^-$ with the $e^+\mu^-$ mis-ID as $\pi^+$ and the $\pi^+\mu^-$ mis-ID as $\mu^+$ is considered to be negligible. We estimate their abundances in the signal region based on their known branching fractions, their mass spectra obtained from our parametrisation of tracking, and the particle identification performances explained in the following. The resulting mass spectra are shown in Fig. 2.

Since the particle-identification performance of LHCb’s upgrades may be significantly different than that of the current detector, we study a range of misidentification working points as reported in Table 2.

Pions can be misidentified as muons with up to 5% probability [56] (assuming 90% identification efficiency) in the relevant range of momentum around 6 GeV. However, significantly better performance could be possible thanks to the combination of all available information through machine-learning techniques (e.g. $10^{-3}$ rejection is reached in [57]).

Electrons are reconstructed with a median momentum between 5 and 10 GeV, depending on the trigger $p_T$ threshold. Pions in this kinematic range can be misidentified as electrons with up to 1% probability [56] for an identification efficiency of 50%. Much better performance could be obtained with future optimisations and the kind of higher granularity electromagnetic calorimeter being studied for future upgrades of LHCb [44]. It’s also worth noting that the RICH detectors provide high discriminating power for low momentum electrons, although this feature is largely not relevant to contemporary LHCb analyses in which electrons are produced in $B$ decays.

Electrons misidentified as muons are very rare thanks to the different signatures they have in the RICH detectors, calorimeters and muon chambers. We estimate their PID perfor-
Table 2: Ranges of misidentification probabilities assumed in this study for efficiencies of correct identification of 50% for electrons and 90% for muons and pions.

| mis-ID | optimistic | pessimistic |
|--------|------------|-------------|
| π± mis-ID as μ± | 0.1% | 5% |
| π± mis-ID as e± | 0.1% | 1% |
| e± mis-ID as π± | 0.1% | 1% |
| e± mis-ID as μ± | 0.01% | 0.05% |
| μ± mis-ID as e± | 0.01% | 0.1% |

Figure 2: Mass spectra expected at LHCb for an integrated luminosity of 300 fb⁻¹ of 13 TeV pp collisions. Four different scenarios in terms of PID performance and pT threshold are shown. The signal branching ratio shown for each scenario is the one of the corresponding expected limit.

Figure 3: Expected confidence level upper limits on the branching ratios for different scenarios of detector performance in Fig. 2. There we can see that LHCb has the potential to probe branching fractions between 10⁻¹² and 5 × 10⁻¹¹ with 300 fb⁻¹ of integrated luminosity.

Sensitivity reach – The estimated background mass spectra are used to obtain background yields in a signal mass region between 0.480 and 0.505 GeV. From them, a counting-experiment approach is used to obtain the expected 90% confidence level upper limits on the $K^+ \rightarrow \pi^+ \mu^+ e^+$ branching ratio. The upper limits are shown as a function of the integrated luminosity and for different scenarios of detector performance in Fig. 3. There we can see that LHCb has the potential to probe branching fractions between 10⁻¹² and 5 × 10⁻¹¹ with 300 fb⁻¹ of integrated luminosity.
LHCb will also be able to probe $K^0 \rightarrow \mu^\pm e^\mp$, both if the initial state belongs to a $K_S$ or to a $K_L$. The LHCb acceptance is roughly 100 times better for $K^0_S$ than for $K^\pm$, and roughly 3 times worse for $K^0_L$ than for $K^\pm$. This implies a $K^0_S/K^0_L$ acceptance improvement compensating almost exactly the relative lifetime suppression, as already commented on below eq. (13). This compensation is not accidental. In fact, in the limit of a very small VELO, it can be shown that the acceptance ratio is indeed $\tau_L/\tau_S$. It is beyond any doubt that LHCb can produce a world-best measurement of $B(K^0_S \rightarrow \mu^\pm e^\mp)$ since it would be the first search. But, interestingly, assuming a similar performance and background level as we did for $K^+ \rightarrow \pi^+\mu^\pm e^\mp$, even a competitive measurement of $B(K^0_L \rightarrow \mu^\pm e^\mp)$ might be feasible. Keeping in mind that the $K^0_L$ and $K^0_S$ decay modes are sensitive to the real and respectively the imaginary part of $\lambda^q$ (see e.g. Eqs. (6)-(7)), a joint measurement of the two modes would serve as a model discriminator.

Conclusions – We presented general, effective-theory arguments that relate existing signals of LUV in $B$ decays to possible signatures in $K$ decays. These arguments rest on the main assumption of a $(V-A) \times (V-A)$ 4-fermion interaction coupled mainly to the 3rd generation (in the gauge basis) and on a CKM-like structure for the flavourful quark couplings, whereas we stay agnostic on the lepton couplings. We obtain predictions for $B(K_L \rightarrow \mu^\pm e^\mp)$ right beneath the existing limit of $4.7 \times 10^{-12}$, and for $B(K^+ \rightarrow \pi^+\mu^\pm e^\mp)$ in the range $10^{-12} - 10^{-13}$, if the new-physics scale is relatively light, $\lesssim 10$ TeV. We performed a sensitivity study of these modes at the LHCb in its upgrade phase, taking the $K^+ \rightarrow \pi^+\mu^\pm e^\mp$ mode as a benchmark. In particular, with a range of assumptions for all the known unknowns (including the kinematic thresholds to reconstruct charged particles in real time and the PID performance), LHCb may update all the existing limits, and probe part of the parameter space suggested by the $B$-physics discrepancies.

The perhaps most conspicuous message of our study is the conclusion that LHCb, a machine not designed for kaon decays, may well be very competitive even or rare such decays.
This conclusion in turn calls attention to other running and upcoming facilities including NA62 [58], which is a dedicated $K^+$ experiment with exquisite light-lepton identification capabilities, as well as the newly proposed TauFV [59] experiment, that may benefit from no less than $O(10^{19})$ kaons in a decay volume of a similar size to LHCb’s and with a similar detector layout. We hope that our results will encourage dedicated sensitivity studies for these facilities.

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