LHCb finds evidence for the violation of lepton universality in B meson decays

Experimental and theoretical discoveries by hundreds of physicists over the past century have brought about a remarkable insight into the fundamental structure and interaction of matter. The Standard Model (SM) of particle physics encapsulates our best understanding of the set of principles that describe matter and their interactions up to a very small length scale of about 10^{-18}–10^{-19} m. Developed in the early 1970s, it has triumphantly explained a whole slew of experimental results and accurately predicted a wide variety of phenomena. However, many experimental observations strongly suggest the existence of new matter and interactions beyond those of the SM. Incidentally, all the important hints of the existence of physics beyond the SM have come from astrophysical and cosmological observations. Thus a large effort is underway to find such hints in laboratory-based particle physics experiments. These experimental efforts can broadly be classified in two categories: (1) Experiments whose main goal is to discover new particles by colliding known particles with large kinetic energy; (2) Those that try to discover new interactions by finding deviations in properties of already known particles through increasingly accurate measurements. The ATLAS and CMS experiments at CERN primarily focus on the first aspect. Their principal aim is to discover new states of heavier masses than those of the SM. On the other hand, the LHCb experiment at CERN and the Belle II experiment in Japan are examples of the latter kind.

The LHCb collaboration has recently announced[1] an update of their previous measurements[2,3] of an observable called R_K which is a ratio of two branching fractions (Figure 1): one for the decay $B^+ \to K^+ \mu^+ \mu^-$ and the other for the decay $B^+ \to K^+ e^+ e^-$. The quantity branching fraction refers to the ratio of the number of B mesons decaying to a specific final state to the total number of B mesons produced. The SM predicts that the individual branching fractions are of the order 10^{-7}. This means that on the average only one B meson decays to this final state if 10^7 B mesons are produced! This makes the experimental study of such processes extremely challenging since a very large number of B mesons have to be produced.

Notice that the only difference between the two decay modes mentioned above is the identity of the leptons in the final state. The lepton in the numerator of R_K is a muon, but the lepton in the denominator is our well-known electron. An important property of the SM (and consistent with all other measurements till date) is that the only difference between muon and electron is their mass. Muon is about 200 times heavier than electron. Thus, according to the SM, the deviation of this ratio from unity should only be a function of their mass difference. The precise SM prediction taking this into account is $R_K = 1 \pm 0.01$. LHCb instead finds $R_K = 0.846 \pm 0.044$ which is 3.1 standard deviation away from the prediction of the SM, the edifice of particle physics.

One should also be informed that the LHCb collaboration, in their analysis, actually reconstructed 3850 $B^+ \to K^+ \mu^+ \mu^-$ decays as opposed to 1640 $B^+ \to K^+ e^+ e^-$ decays. So the conclusion that decay to muons is less probable than those to electrons was only reached after taking into account the different reconstruction efficiencies for muons and electrons. In fact, reliable estimate of these efficiencies is the most crucial (and difficult) ingredient of the analysis.

Now, deviation from the SM prediction could very well be due to statistical fluctuations. Indeed, 2–3 standard deviation fluctuations are not rare in particle physics experiments. So it is completely legitimate to doubt this result as evidence of physics beyond the SM. Nonetheless, there is a valid reason for the excitement among the practitioners: the LHCb collaboration first measured R_K in 2014. At that time, the measurement was only deviating from the SM by 2.6 standard deviation. Due to the smaller amount of data collected, LHCb reconstructed only approximately 1226 $B^+ \to K^+ \mu^+ \mu^-$ decays and 254 $B^+ \to K^+ e^+ e^-$ decays. In 2019, they updated the measurement with a larger dataset consisting of about 1943 reconstructed $B^+ \to K^+ \mu^+ \mu^-$ decays and 766 $B^+ \to K^+ e^+ e^-$ decays. However, the significance neither increased nor decreased. This was a cause of concern for the new physics proponents. However, the recent measurement (see Figure 2 for a summary of all the measurements) with the same central value and a smaller uncertainty compared to the 2019 measurement has given us hope that the signal is perhaps not a statistical fluke. It is definitely not close to the fabled number of 5 standard deviation, but it is still significant enough to be not tossed aside.

From the theoretical side, an explanation of this deviation requires a new interaction outside the ambit of the SM involving the b- and s-quarks and muons. In the SM, processes that convert a b-quark to s-quark are called Flavour Changing Neutral Current (FCNC) processes. The name arises from the fact that the final state quark has the same electric change as the initial state quark but they are of different flavour/from different fermion generations. A

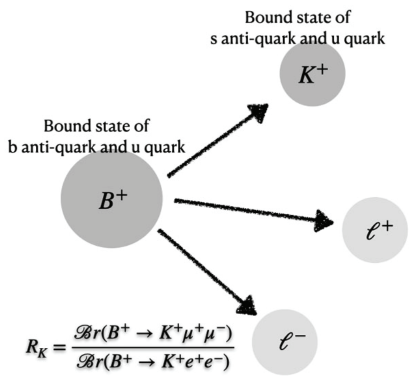

Figure 1. Schematic diagram of the decays relevant for R_K.

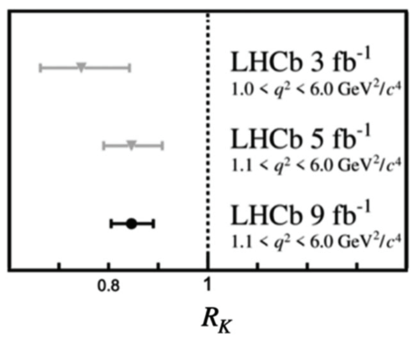

Figure 2. Summary of the LHCb measurements of R_k. The numbers 3, 5, 9 fb^{-1} indicate the amount of data collected and the dotted vertical line is the SM expectation. The quantity q^2 refers to the square of the Lorentz-invariant mass of the two leptons in the final state. The bottom-most experimental number is the most recent measurement.

remarkable property of the SM is that the FCNC processes take place only at higher orders in perturbation theory and thus their rates are suppressed. This way, the SM provides an explanation of the extremely small branching fractions ($\sim 10^{-7}$) of these processes.

There is of course no guarantee that the new physics that might be responsible for this deviation will also share the same property. In fact, in many models, such FCNC processes arise at lower orders of the couplings. However, in that case, in order to be consistent with the experimentally measured small branching fractions, either the new heavy particles associated to such new interactions have to be quite heavy (tens of TeV) or the new couplings associated to such new interactions must be unnaturally small. On the other hand, if the new physics is SM-like (in the sense that the FCNC processes still take place at higher order in the couplings), then the new particles can be rather light (close to a TeV) even when the new couplings are not too small. So the good news is that, if the R_K value is indeed due to new physics, the heavy particles responsible for it must have masses in the range between a TeV and tens of TeV. Hence, the LHC or the next high energy collider should be able to discover these new particles directly.

If one is too concerned about the possibility of an experimental oversight in the measurement of R_K, the encouraging facts are that (i) within a year or two there will be new measurements or updates of some other observables closely related to R_K, (ii) The BELLE II experiment will independently verify the LHCb result in 4–5 years and, finally, (iii) the LHC run 3 is also coming soon enabling LHCb to update their measurement with a lot more data.

It is noteworthy that the recent measurement[4] of the Landé *g*-factor of the muon at Fermilab has also amplified the exhilaration that physics associated with muons might indeed be hanging over the SM like a sword of Damocles.

Finally, although I have focused on R_K here, in recent years the LHCb collaboration has reported hints of new physics in a few other observables too. At the moment it is quite premature to firmly claim those as signals of new physics; but one should keep a close eye on them as experiments collect more data in the future and theorists reduce the uncertainties in their SM calculations.

So, while the recent LHCb update has raised questions about the redoubtable SM, the jury is still out, and we may be tantalizingly close for a special scientific treat in the near future.

1. Aaij, R. *et al*., e-Print: 2103.11769 [hep-ex].
2. Aaij, R. *et al*., *Phys. Rev. Lett*., 2014, **113**, 151601, e-Print: 1406.6482 [hep-ex].
3. Aaij, R. *et al*., *Phys. Rev. Lett*., 2019, **122**(19), 191801, e-Print: 1903.09252 [hep-ex].
4. Abi, B. *et al*., *Phys. Rev. Lett*., 2021, **126**(14), 141801, e-Print: 2104.03281 [hep-ex].

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Wobbling muons deepen fundamental mystery

Who has not been intrigued as a child by a bar magnet? For many among us, the innocuous magnet was our first foray as children into the fascinating world of science and its alluring mysteries. Even in the world of sub-atomic particles, the endowed intrinsic magnetic moments of particles continue to furnish important insights into the fundamental constituents and forces of our universe.

Elementary particles, such as electrons and their heavier cousins muons, as well as composite particles, such as protons and neutrons (which are bound states of elementary quarks), are all bestowed with intrinsic magnetic moments. The exact values of these intrinsic magnetic moments can serve as a test of the underlying theory – the Standard Model (SM) of particle physics, which gives a unified description of the electromagnetic, weak nuclear and strong nuclear interactions. Apart from this, they may also give us a peep into new physics beyond SM that we are currently ignorant about. The latter belief is driven by the incontrovertible observation of dark matter, dark energy, matter–antimatter asymmetry and other puzzles in the universe, to which we do not currently have a complete answer in any of the present frameworks.

We learn from basic electromagnetic theory that a loop of wire carrying a current generates a magnetic moment. Surprisingly, for elementary fermions, initial measurements of their intrinsic magnetic moments ($\vec{M}$) gave a value about twice that expected from a naive analogy with a current-carrying loop. In other words, the particle's gyromagnetic ratio or *g*-factor (*g*), defined via the relation $\vec{M} = g(q/2m)\vec{S}$ for a particle of charge *q*, mass *m* and carrying spin $\vec{S}$, was found to be $g = 2$, rather than $g = 1$. This was subsequently understood as a consequence of their spin-1/2 nature, in the quantum mechanical framework consistent with special theory of relativity, put forward by Paul Dirac.

The basic strategy in most of the experiments is to measure the magnetic moment from the precession – the wobbling of the spin axis – as the particle travels around a ring in the presence of a magnetic field. More precise experimental measurements later revealed that for electrons, the value, in fact, deviated slightly from $g = 2$ – hence the nomenclature *anomalous* magnetic moment for $(g-2)/2$ – with the actual value being closer to $g = 2.00232$. An explanation for this deviation was absent in the old Dirac theory and had to await further theoretical advances.

The advent of quantum field theories, more correctly interpreting and unifying the principles of quantum mechanics and special relativity, brought new physics insights along with it – such as the presence of virtual particle creation and annihilation, absent in the earlier Dirac framework. Importantly, it also enabled meticulous theoretical calculations. It was realized gradually that the quantum field theoretic corrections, involving virtual particles appearing and disappearing into the vacuum, would give corrections to intrinsic particle properties. The effect of these quantum fluctuations, in a very loose sense, is analogous to the effect of a dielectric material