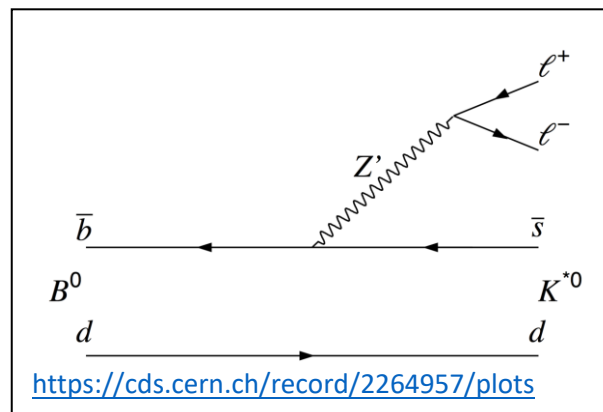


Growing hints of lepton-universality violation: progress and implications

To understand lepton-universality (LU) and its possible violation we must first understand what leptons are. Of half-integer spin and not undergoing strong interactions, leptons are elementary particles which are split into 3 generations and 2 classes. The 3 generations are electron (e), muon (μ) and tau (τ), which have a negative charge and increase in mass respectively. Each of these charged leptons have a neutrino equivalent with very little mass and no charge. The theory of lepton-universality states that - except for their masses - all SM interactions treat electrons, muons, and taus identically.¹

The quantity most often measured in experiments testing LU is the ratio of branching fractions of 2 different decays, usually of a B meson (subatomic particle composed of a bottom anti-quark and either an up, down, strange or charm quark). Mesons are used to study the interactions of quarks because they exist for enough time (a few billionths of a second) for particle detectors to observe them. The B meson then decays into a lighter meson and a pair of leptons. The reason this ratio is often measured is because it is predicted precisely by the SM.



In order for experimental results to disprove a theory, the results must be 5 standard deviations (σ) away from the SM prediction, which currently no experiment has achieved. Furthermore there are various experimental results confirming LU.

Lepton-universality violation occurs when the rate at which something decays into a lepton is different to that of another lepton. According to the SM this should not be possible, however various experiments have had results which are not consistent with lepton-universality. Interest grew when the BaBar collaboration (2012) and the Belle collaboration (2015) also found results consistently higher than the SM prediction. Another experiment in 2020 at LHCb using the decays of beauty baryons obtained a decay ratio of slightly below 1, with a significance of 1σ . One LHCb experiment² in March 2021 compared the rates at which B mesons decayed into muons and electrons. In the experiment, a beauty-meson transforms into a strange meson with the emission of either an electron and a positron, or a muon and an antimuon. Results showed muons were produced slower than predicted, with a statistical significance of 3.1σ away from the SM prediction. This suggests the existence of physics outside of the SM, such as a new fundamental reaction between quarks and leptons. A previous experiment in 2018 at LHCb also “hinted at potential deviations from LU”³, showing a difference in the decay rate of muons and electrons, and muons and taus. Overall, various experiments have shone some light onto the LU violation, however none have been significant enough to prove it.

On the other hand, various experiments have supported LU, such as one from the Large Electron–Positron (LEP) collider at CERN studying decays of W and Z bosons, the PIENU and NA62 experiments studying decays of pions and kaons, and in J/ψ decays by the BES-III, CLEO and KEDR collaborations.

¹ <https://home.cern/news/news/physics/lhcb-explores-beauty-lepton-universality>

² <https://arxiv.org/abs/2103.11769>

³ <https://cerncourier.com/a/beauty-quarks-test-lepton-universality/>

Most recently (Dec-22), new LHCb analysis presented at the LHC seminar⁴ based on the full data from Run 1 (2011-12) and data from Run 2 (2015-18) found “no direct evidence of Beyond Standard Model particles”. Furthermore the analysis is described as “the most sensitive lepton universality test in rare b-decays and the results obtained supersede the previous LHCb measurements of $R(K)$ and $R(K^{*0})$ ”. The experiment was the first time that muon-electron universality in 2 different decays were tested simultaneously. This was achieved through measurements in 2 different mass regions, yielding 4 different independent comparisons of the decays, all of which were in accordance with the SM. In addition, results from one LEP experiment that supposedly hinted at lepton-universality violation were then analysed by the ATLAS collaboration, whose precision was twice that of the original LEP result⁵. Initially the value of $R(\tau/\mu) = 1.070 \pm 0.026$, however the new analysis resulted in a value of $R(\tau/\mu) = 0.992 \pm 0.013$, which is in agreement with the SM. This proves that even when results seem to point towards LU violation, new analysis can overturn previous ones.

In conclusion, growing hints of LU violation are implying the existence of new physics and a change to the SM, however the results in themselves aren't concrete enough for the SM's immediate rejection. In addition, further experiments supporting LU cast doubt onto the reliability of the controversial results. If experimental results arrive with a deviation of over 5σ , then this would hint towards physics outside of the SM – perhaps some light may be shed on some of the many unanswered questions in particle physics (such as why the number of generations of both leptons and quarks is 3), or even the possibility of the existence of a new particle.

⁴ <https://cds.cern.ch/record/2845155>

⁵ <https://physicstoday.scitation.org/doi/10.1063/PT.6.1.20210709a/full/>