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Testing universality of lepton couplings

Author: Andraž Lipanje

Mentor: prof. dr. Svjetlana Fajfer

Co-Mentor: asist. dr. Nejc Košnik

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Abstract

The universality of lepton couplings is a prediction of the Standard model. First of all we introduce the Fermi interaction. Because Fermi interaction does not explain the lepton universality, we needed to include electroweak interaction where lepton universality can be explained. Then we focus on different decays where some of them confirmed lepton universality while some show interesting hints of lepton universality breaking. At the end we mention some theories that explain the phenomenon where the lepton universality does not hold.

Contents

1 Introduction

In the last decades there has been a lot of different experimental studies that were observing weak decays. Because of those experiments a lot has been learned about lepton universality, which is the main topic of this seminar.

Standard model does not separate between the three leptons, electron, muon and tau, but it only takes into account the difference in their masses. The phenomenon is called lepton universality. Up until now all the experimental measurements are consistent with lepton universality. There are a lot of different decays, such as $\pi^- \to l^-\bar{\nu}_l$ or $Z \to l^+l^-$, that shows us matching experimental and theoretical values of their branching fractions. However, new data from B meson decays in BaBar experiment tells us otherwise. The measurements in this experiment do not match at 3.4σ [1] with theoretical calculations in Standard model, which means either that the measurements are wrong or that we need the expansion of Standard model, which would explain the measured values.

This seminar is organized as follows. In Section 2 we introduce the basic aspects of weak interaction. In Section 3 we briefly introduce lepton universality in $Z \to ll$ decay. Then in Section 4 we test lepton universality in pion and kaon leptonic decays. In Section 5 we give an example of semileptonic B decay where lepton universality does not hold. We finally conclude in Section 6.

2 Weak interaction

The experimental studies of pion decay show that there is a difference between the neutral and charged pion. The difference is in their lifetimes. For example, the neutral pion decays via electromagnetic interaction $\pi^0 \rightarrow \gamma\gamma$, with the lifetime of [2]: $\tau = 8.4 \cdot 10^{-17}$s, while charged pion decays via weak interaction $\pi^- \rightarrow \mu^-\bar{\nu_\mu}$, with the lifetime of [2]: $\tau = 2.6 \cdot 10^{-8}$s. As we see the weak interaction is much slower than electromagnetic and is also slower than strong interaction, where typical lifetimes are about 10^{-23}s. Because the lifetimes are inversely related to the coupling strength, we can see that the weak interaction is the weakest in Standard model and because of this we call it weak interaction. Due to their long lifetime, weak decays can be easily hidden by the more rapid strong or electromagnetic decay.

The weak interaction is responsible for radioactive β decay. Radioactive β decay can be separated in two different types of decays. First of them is beta minus (β^-) decay where neutron decay to proton, electron and electron anti-neutrino [2]:

$$n^0 \rightarrow p^+e^-\bar{\nu_e}. \tag{1}$$

The other possibility is beta plus (β^+) decay, where proton decays to neutron, positron and electron neutrino [2]:

$$p^+ \rightarrow n^0e^+\nu_e. \tag{2}$$

While the beta minus decay can occur for free neutrons, due to lower mass of proton, the beta plus decay can occur only inside the nuclei, where the final state has lower binding energy then the initial state.

Beta decay was theoretically explained by an Italian physicist Enrico Fermi in 1933 [3]. The theoretical explanation, that was Fermi inspired by, is based on electromagnetic electron-proton scattering. Decay amplitude of the $e^-p^+ \rightarrow e^-p^+$ scatering is proportional to the matrix element $\mathcal{M}$ [2]:

$$\mathcal{M} = (e\bar{u}_p\gamma^\mu u_p)(\frac{-1}{q^2})(-e\bar{u}_e\gamma_\mu u_e). \tag{3}$$

where u_p and u_e are Dirac spinors of proton and electron. What Fermi concluded was that the weak interaction must be similar to the electromagnetic and so is the matrix element. Because of these Fermi proposed the following form of the decay amplitude for beta decay [2]:

$$\mathcal{M} = \frac{G_F}{\sqrt{2}}(\bar{u_n}\gamma^\mu u_p)(\bar{u_{\nu_e}}\gamma_\mu u_e). \tag{4}$$

Here G_F is called Fermi constant and must be determined by experimental data. The form of the matrix element, that Fermi has written for the beta decay is the so-called contact interaction, because he did not consider any mediator for the interaction. That kind of interaction is shown in Figure 1 on the left-hand side. What Fermi considered in the weak interaction was only probability for the process and did not include carriers of the weak interaction.

Because weak interaction violates charge conjugation, $\hat{C}$, and parity, $\hat{P}$, a change in equation was needed. From the parity violation experiments it was learned that it is required to replace γ^μ with $\gamma^\mu(1-\gamma^5)$. And matrix element then becomes [2, 4, 5]:

$$\mathcal{M} = \frac{G_F}{\sqrt{2}}(\bar{u}_n\gamma^\mu(1-\gamma^5)u_p)(\bar{u}_{\nu_e}\gamma_\mu(1-\gamma^5)u_e). \tag{5}$$

If we define leptonic weak current as $J^\mu = \sum_i \bar{u}_{\nu_i}\gamma^\mu\frac{1-\gamma^5}{2}u_{l_i}$ where $i = 1, 2, 3$ denote generations, then we could write the amplitude for weak interaction among leptons as [2]:

$$\mathcal{M} = \frac{4G_F}{\sqrt{2}}J^\mu {J_\mu}^\dagger. \tag{6}$$

The theory that Fermi proposed was in the beginning very accurate, in comparison to the experimental data. But we need to know that the Fermi theory is an effective theory and it works only at energies much below the so-called weak scale, defined as $m_W c^2$. The success of Fermi theory was due to the very high mass of W and Z particles, whereas the early experiments were all done at low energies, where the Fermi theory is accurate.

2.1 Electroweak interaction

The Fermi theory, which has been introduced in previous Section, does not explain the universality of lepton couplings. In principle G_F could be lepton flavour dependent, G_F^e, G_F^μ, G_F^τ, but they are all measured to be equal. If we want to explain this observation we need to look at electroweak interaction. Inspired by electromagnetic and weak interaction Fermi wrote the effective interaction shown in eq. (5). But we could write it in a different way. If we use propagator for the carrier of interaction, we could use the quantum electrodynamics procedure, but instead of massless propagator $\frac{1}{q^2}$ we employ propagator for a massive particle: $\frac{1}{m^2-q^2}$. Then we get amplitude for charged weak interaction among leptons [2]:

$$\begin{aligned}\mathcal{M} &= \left(\frac{g}{\sqrt{2}}J_\mu\right)\left(\frac{1}{M_W^2-q^2}\right)\left(\frac{g}{\sqrt{2}}J^{\mu\dagger}\right)\\ &\approx \left(\frac{g}{\sqrt{2}}J_\mu\right)\left(\frac{1}{M_W^2}\right)\left(\frac{g}{\sqrt{2}}J^{\mu\dagger}\right).\end{aligned} \tag{7}$$

Here g is dimensionless weak coupling and we used approximation $q^2 \ll {M_W}^2$. Because of this approximation for weak interaction, that is shown in Figure 1 on the right-hand side, we got the effective coupling: $\frac{g^2}{8M_W^2}$. From the comparison of eq. (5) and eq. (7) we can calculate Fermi constant [2]:

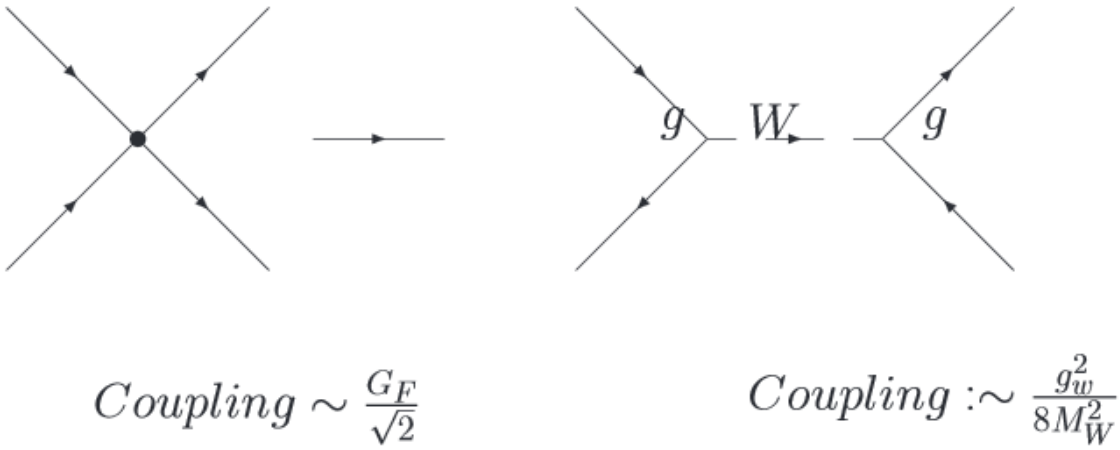

Figure 1: The picture on the left represents the contact interaction that Fermi proposed for weak interaction, and is due to the high mass of weak carriers true in a certain area of energy. On the right side is a picture of weak interaction with carrier W. Under the pictures is also written the propagator for each interaction. The weak constant g_W written in picture is the same as g used in the text [6].

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}. \tag{8}$$

In comparison to the charged weak current, which is proportional to the weak constant g, the neutral weak current is proportional to the $\frac{g}{\cos\theta_W}$. Because of that the amplitude for neutral weak interaction via Z boson is [2]:

$$\mathcal{M} = \left(\frac{g}{\cos\theta_W} J_\mu^{NC}\right)\left(\frac{1}{M_Z^2}\right)\left(\frac{g}{\cos\theta_W} J^{NC\mu}\right), \tag{9}$$

where we have written neutral current as [2] $J_\mu^{NC} = \sum_i \left[\bar{u}_{l_i}\gamma_\mu \frac{C_V^f - C_A^f\gamma^5}{2} u_{l_i} + \bar{\nu}_i\gamma_\mu \frac{C_V^f - C_A^f\gamma^5}{2}\nu_i\right]$ and Weinberg angle as θ_W. The Weinberg angle can be also called weak mixing angle and is a parameter in the Weinberg-Salam theory of the electroweak interaction, where it represents the mixing angle between photon and Z boson. This is also the reason for the difference between neutral and charged coupling constant. The Weinberg angle can be calculated from comparison between charged and neutral weak interaction [2]:

$$\frac{G_F}{\sqrt{2}} \approx \frac{g^2}{8\cos^2\theta_W M_Z^2} = \frac{g^2}{8M_W^2} \implies \cos^2\theta_W = \frac{M_W^2}{M_Z^2}. \tag{10}$$

The above correlation between the mixing angle and the weak boson masses has been verified experimentally.

Current for the charged weak interaction J_μ is proportional to the vertex factor of interaction. Let us say that we got meson W, carrier for weak interaction, which decay to electron and electron anti-neutrino and amplitude for the decay is proportional to the vertex factor [2]:

$$\mathcal{M}_{Wl\nu} \propto -i\frac{g}{\sqrt{2}}\gamma^{\mu}\frac{1}{2}(1-\gamma^{5}). \tag{11}$$

What is very important is that this vertex factor will be the same for any lepton flavour in the Standard model. However we are interested only in leptons, so if we look at doublets (ν_e, e^-), (ν_μ, μ^-) and (ν_τ, τ^-), decays with the same initial state and these three final states would have the same vertex factor. Because of that, the difference in the decay rate to these final states is only due to the difference in mass of leptons.

The same universality is present in neutral current interacting with Z where amplitude is proportional to the vertex factor [2]:

$$\mathcal{M}_{Zll} \propto -i\frac{g}{\cos\theta_W}\gamma^{\mu}\frac{1}{2}(C_V^f - C_A^f\gamma^{5}). \tag{12}$$

Here C_V^f is vector coupling constant and C_A^f is axial-vector coupling constant. These two constants are equal -1 for neutrino. For charged leptons the constants are $C_V^f = -1$ and $C_A^f = -1 + 4\sin^2\theta_W$. Because the neutral carrier Z decays to fermion and anti-fermion the vertex factor is independent of the final state, it does not matter if Z decays into e^-e^+ or $\mu^-\mu^+$. The vertex factor is the same in both cases. The only difference is in mass of final state. This phenomenon of Standard model, where the coupling with leptons is the same in all three generation, is called universality of lepton couplings.

3 Lepton universality in $Z \to l^+l^-$

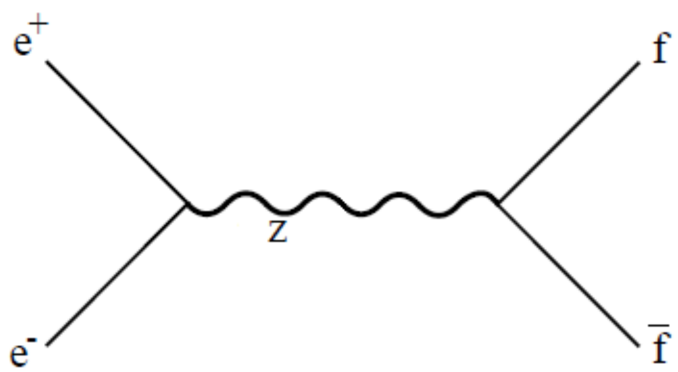

Figure 2: On the picture we represent the Feynman diagram for electron-positron annihilation into leptonic pair. This is neutral weak interaction with Z boson carrier [7].

Very good example to demonstrate lepton universality is the decay of Z boson, the carrier for the neutral weak interaction, into two leptons. This decay is observed in electron-positron annihilation: $e^+e^- \rightarrow l^+l^-$, where boson Z is carrier. The Feynman diagram can be seen in Figure 2.

The predicted partial width Γ_{ll} for the decay $Z \rightarrow l^-l^+$ in the limit $m_l \rightarrow 0$ is [7, 8]:

$$\Gamma_{ll}^{SM} = \frac{GM_Z^3}{6\sqrt{2}\pi}\left((C_V^f)^2 + (C_A^f)^2\right) = 83.42\text{MeV}. \tag{13}$$

The experimental measurements of the leptonic width for different leptons provides us following measurements [7]:

$$\begin{aligned} \Gamma_{ee} &= (83.94 \pm 0.14)\text{MeV}, \\ \Gamma_{\mu\mu} &= (83.84 \pm 0.20)\text{MeV}, \\ \Gamma_{\tau\tau} &= (83.68 \pm 0.24)\text{MeV}. \end{aligned} \tag{14}$$

We can see that the measurements give similar values for all three final states, which corresponds to the hypothesis of leptons universality described in previous Section.

4 Leptonic pion decay

Another good example, where we can test the lepton universality, is pion decay. To show the lepton universality, we will compare experimental data with theoretical calculations for the decay ratio between pion decay with electron in final state and muon in final state. If we now take pion decay, which is also shown in Figure 3:

$$\pi^-(q) \rightarrow \mu^-(p) + \bar{\nu}_\mu(k). \tag{15}$$

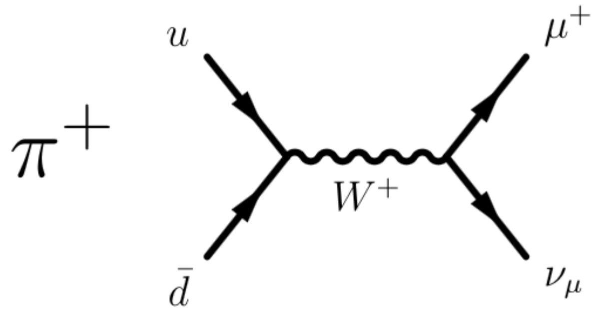

Figure 3: The picture shows the Feynman diagram for dominating leptonic pion decay. In the left side we have pion which decays weakly with weak carrier W to muon and muon-neutrino [9].

The amplitude for this decay can be written as [2]:

$$\mathcal{M} = \frac{G_F}{\sqrt{2}} \langle 0| \bar{d}\gamma^{\mu}(1-\gamma_5)u \, |\pi\rangle \, (\bar{u}(p)\gamma_{\mu}(1-\gamma^5)v(k))V_{ud}. \tag{16}$$

Because the vertex between quarks u and d is proportional to the matrix element V_{ud}, we also include matrix element from matrix in the equation. In equation we used $\langle 0| \bar{d}\gamma^{\mu}(1-\gamma_5)u \, |\pi\rangle$ which is a weak current matrix element for pion in initial state and free final state. We wrote it similarly as leptonic part of equation, but since the quarks in π meson are not in the free state but are bound, we can therefore use following equality [2]:

$$\langle 0| \bar{d}\gamma^{\mu}(1-\gamma_5)u \, |\pi\rangle \equiv iq^{\mu} f_{\pi}, \tag{17}$$

where f_{π} is pion decay constant and is calculated by the lattice simulations of quantum chromodynamics. It is important to know, that constant f_{π} has only limited precision [8]: $f_{\pi} = (130.41 \pm 0.03 \pm 0.20)$MeV. We can now put f_{π} in our equation and get [2]:

$$\mathcal{M} = \frac{G_F}{\sqrt{2}}(p^{\mu} + k^{\mu}) f_{\pi}[\bar{u}(p)\gamma_{\mu}(1-\gamma^5)v(k)]V_{ud}, \tag{18}$$

where $q^2 = (p^{\mu} + k^{\mu})^2 = m_{\mu}^2$. From this we can calculate the decay rate [2]:

$$d\Gamma = \frac{\overline{|\mathcal{M}|^2}}{2E} dQ. \tag{19}$$

where $\overline{|\mathcal{M}|^2}$ is the average of amplitude squared. Here dQ contains Lorentz invariant phase space factors and [2]:

$$dQ = \frac{d^3p}{(2\pi)^3 2E} \frac{d^3k}{(2\pi)^3 2\omega} (2\pi)^4 \delta(q-p-k). \tag{20}$$

After some calculation we get following decay width [2]:

$$\Gamma = \frac{{G_F}^2}{8\pi} {f_{\pi}}^2 m_{\pi} {m_{\mu}}^2 (1 - \frac{{m_{\mu}}^2}{{m_{\pi}}^2})^2 |V_{ud}|^2. \tag{21}$$

With the same calculation we can get decay rate for $\pi^- \to e^- \bar{\nu}_e$ [2]:

$$\Gamma = \frac{{G_F}^2}{8\pi} {f_{\pi}}^2 m_{\pi} {m_e}^2 (1 - \frac{{m_e}^2}{{m_{\pi}}^2})^2 |V_{ud}|^2. \tag{22}$$

We know that pion has spin 0 and if we want the conservation of angular momentum, the final state $(e^- \bar{\nu}_e)$ must have $J = 0$. Because anti-neutrino must always have positive helicity, the electron must also have positive helicity, as we can see in the Figure 4. But as we know, electron is left-handed in weak interaction which corresponds to negative helicity for massless particle. So in pion decay electrons or muons can be in positive helicity state only if they have mass. Either way that kind of decay in weak interaction is highly suppressed. But the difference between electron and muon is that muon is about 200 times

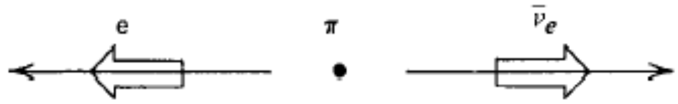

Figure 4: In the picture we can see positive helicity of outgoing leptons [2].

heavier than electron, and because of that the decay to a muon is much more likely to happen than decay to electron [8]:

$$\frac{\Gamma(\pi^- \to e^- + \bar{\nu}_e)}{\Gamma(\pi^- \to \mu^- + \bar{\nu}_\mu)} = \frac{{m_e}^2(1 - \frac{{m_e}^2}{{m_\pi}^2})^2}{{m_\mu}^2(1 - \frac{{m_\mu}^2}{{m_\pi}^2})^2}. \tag{23}$$

The numerical number is calculated by inserting masses. With consideration of the radiation corrections we get calculated ratio [10]: $(1.2351 \pm 0.0002) \cdot 10^{-4}$. We calculated the ratio of pion decay in different final states because f_π and V_{ud} are the same for both decays and ratio does not depend on them. This is beneficial because we do not know the precise values of f_π and V_{ud}. If we look for experimental data we see that there is good agreement. The experimental ratio is [8]: $(1.230 \pm 0.004) \cdot 10^{-4}$.

Similar can be seen with kaon decays: $K^- \to e^- + \bar{\nu}_e$ and $K^- \to \mu^- + \bar{\nu}_\mu$. With the same calculation that we used to calculate decay ratio for pion, we can calculate the same decay ratio for kaon [8]:

$$\frac{\Gamma(K^- \to e^- + \bar{\nu}_e)}{\Gamma(K^- \to \mu^- + \bar{\nu}_\mu)} = \frac{{m_e}^2(1 - \frac{{m_e}^2}{{m_K}^2})^2}{{m_\mu}^2(1 - \frac{{m_\mu}^2}{{m_K}^2})^2}. \tag{24}$$

If we now compare the Standard model prediction [11]: $(2.472 \pm 0.001) \cdot 10^{-5}$ with experimental value we see that it is well matched [8]: $(2.488 \pm 0.009) \cdot 10^{-5}$.

5 Semileptonic $B \to Dl\nu$ decay

Until now, all the decays that we looked into, show us the universality of lepton couplings. This means that all three leptons, electron, muon and tau, have the same coupling in weak interaction. However, the lepton universality can also be tested in semileptonic decays of B mesons. Because of high mass of the B mesons, semileptonic decays to final states with τ are accessible, which was not the case with π and K decays.

In this Section we will look at semileptonic B decays, which are mediated by W boson and have $Dl\nu$ in the final state. These semileptonic decays are in the Standard model well known, thanks to the development of heavy-quark effective theory and non-perturbative methods for treating matrix elements between bound states. Due to the experiments performed at B factories the decays of B mesons are well measured.

The B meson decay $\bar{B} \to D^* \tau^- \bar{\nu_\tau}$ was first discovered in 2007 by the Belle Collaboration in Japan. Until now both B factories, Belle and BaBar, have published strong evidence for $\bar{B} \to D\tau^- \bar{\nu_\tau}$ decay. Also LHCb collaboration plans to search for this decay[1, 12].

If we want to test the universality of lepton couplings we look at the ratio between the branching ratio for decay which has in final state tau and the branching ratio for decay which has in final state electron or muon [1]:

$$R(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)} \tau^- \bar{\nu_\tau})}{\mathcal{B}(\bar{B} \to D^{(*)} l^- \bar{\nu_l})}. \tag{25}$$

The amplitude for $B \to Dl\nu$ decay is written similar to the pion decay [13]:

$$\mathcal{M} = \frac{G_F}{\sqrt{2}} \langle D| \, \bar{c}\gamma^\mu b \, |\bar{B}\rangle \, (\bar{\nu_\tau}\gamma_\mu(1-\gamma_5)\tau) V_{cb}. \tag{26}$$

As with pion decay we also have Cabibbo-Kobayashi-Maskawa matrix element, but in this case it is V_{cb}. But there is a main difference between those two decays. The difference is in matrix element $\langle D| \, \bar{c}\gamma^\mu(1-\gamma_5)b \, |\bar{B}\rangle$, which represents weak current between initial state, B meson, and final state, D meson. This matrix element is much more complex than in the case of leptonic decay [13]:

$$\langle D(p')| \, \bar{c}\gamma^\mu b \, |\bar{B}(p)\rangle = (p_\mu + p'_\mu - \frac{m_B^2 - m_D^2}{q^2} q_\mu) F_+(q^2) + \frac{m_B^2 - m_D^2}{q^2} q_\mu F_0(q^2). \tag{27}$$

Considering this, we can calculate differential branching ratio [13]:

$$\frac{d\mathcal{B}(\bar{B} \to Dl^- \bar{\nu_l})}{dq^2} = |V_{cb}|^2 \mathcal{B}_0 |F_0(q^2)|^2 \left[c_+^l(q^2) + c_0^l(q^2) \left| \frac{F_0(q^2)}{F_+(q^2)} \right|^2 \right]. \tag{28}$$

Here are $c_{+,0}^l(q^2)$ functions of particle masses and q^2, where $q^\mu = (p - p')^\mu$ [13]. In eq. (28) we used constant $\mathcal{B}_0 = \tau_B^0 \frac{G_F^2}{192\pi^3 m_b^3}$. Eq. (28) is more complex because of form factors F_+ and F_0, that are difficult to calculate precisely. But if we want to know the ratio between two decays, we only need to calculate the bracket, because everything else is cancelled out in the calculation.

If we calculate these branching ratios we get the following Standard model prediction [1]:

$$\begin{aligned} R(D) &= 0.297 \pm 0.017 \\ R(D^*) &= 0.252 \pm 0.003. \end{aligned} \tag{29}$$

Comparison of these results with measurements by BaBar [1]:

$$\begin{aligned} R(D) &= 0.440 \pm 0.058 \pm 0.042, \\ R(D^*) &= 0.332 \pm 0.024 \pm 0.018, \end{aligned} \tag{30}$$

reveals a large mismatch with a significance 3.4σ. The result of this can be interpreted as a hint of some New Physics that we do not know about. On the other hand, we should also wait for experimental confirmation by Belle and LHCb collaboration.

One of the possibilities to explain, why in the $B \to D\tau\nu$ decay experimental and theoretical results do not match is existence of a leptoquark. Leptoquark is hypothetical particle which could mediate $B \to D\tau\nu$ decay. It is a boson particle that converts between leptons and quarks. In our case it would have a charge of 2/3 [14].

Another example of New Physics is Two Higgs Doublet Model type III (2HDM). 2HDM try to explain that next to the one Higgs doublet in Standard model, there exists another Higgs doublet. This theory would introduce another Higgs doublet and obtain four additional Higgs particles. Among these four particles would be charged Higgs that could mediate $B \to D\tau\nu$ decay and explain the difference between experimental and theoretical results [15].

6 Conclusion

As we have seen in this seminar, Standard model does not distinguish between different lepton couplings. Therefore decays with different leptons in final state vary only because of their masses and not because of their couplings. This can be seen in pion and kaon decays where experimental data match with the results of theoretical calculations. However this is not true for $B \to D\tau\nu$ decay, where experimental data and theoretical calculations differs with 3.4σ significance.

As we have seen this can be interpreted as a presence of New Physics. There are a lot of different theories that try to explain this phenomenon. The two possibilities are Leptoquark, with fractional electric charge and Two Higgs Doublet Model type III theory which introduces charged Higgs. However, before we can claim the discovery of New Physics, an independent experiment confirmation of the BaBar result will be needed, by Belle and LHCb experiments.

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