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Bachelor Thesis in Physics
submitted by

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The comparison of the single QC and the ladder QC of silicon Pixel Sensors for the Mu3e Vertex Detector

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2 The Mu3e experiment at PSI

2.1 The Standard Model of Partice Physics and Beyond

2.1.1 The Standard Model of Particle Physics

- Summarizes current understanding of particle physics
- Describes fundamental particles and their interactions (fundamental forces)
- Consists of fermions and bosons (fermions: half-integer spins; bosons: integer spins)
- Three generations
- First generation: stable particles (up, down, electron, electron neutrino)
- Second and third generation: heavier, unstable particles
- Gauge bosons: force carriers
- Photon: carries electromagnetic force; gluon: carries strong force; W and Z bosons: carry weak force
- Electromagnetic und weak force → electroweak force
- Higgs boson: gives mass to particles via the Higgs mechanism
- Gravity is not included in the Standard Model

The Standard Model of Particle Physics summarizes our current understanding of the fundamental particles and their interactions. It describes the particles that make up matter and the forces through which they interact [6].
As can be seen in Figure 1 the particles described in the standard model are divided into fermions with half integer spins and bosons with integer spins. Furthermore the Standard Model consists of three generations. The particles described in the first generation (up, down, electron and electron neutrino) are stable and make up the ordinary matter. The particles in the other generations increase in mass and are unstable. They are produced in high-energy processes such as cosmic rays or particle accelerators.
The twelve fermions (up, down, electron, electron neutrino, charm, strange, muon, muon neutrino, top, bottom, tau, tau neutrino) are grouped into Quarks and Leptons. Quarks carry a charge of $+\frac{2}{3}e$ or $-\frac{1}{3}e$ aswell as a colour charge. This means they interact with the strong and weak force and also with the electormagnetic force. Leptons on the ohter hand carry an electric charge of $-e$ or 0 and no colour charge. Therefore they only interact with the weak and electromagnetioc force. In each generation there are two leptons, one carrying a charge and a Neutrino which is considered massless in the Standard Model. Until the discovery of neutrino oscillations it was believed that during decays the lepton flavour is conserved. According to this each generation of Leptons has it's own Lepton flavour.
The interactions between these particles are mediated by the gauge bosons. The photon γ carries the elctromagnetic force. The weak force is mediated by the $W^{\pm}$ and the Z boson. The $W^{\pm}$ bosons cary a charge of $\pm e$ and have a mass of 80.4GeV/c^2 while the Z boson is electrically neutral and has a mass of 91.3GeV/c^2 [4]. The weak and the electromagnetic force can be unified into the electroweak force. The strong force is mediated by the gluon g which

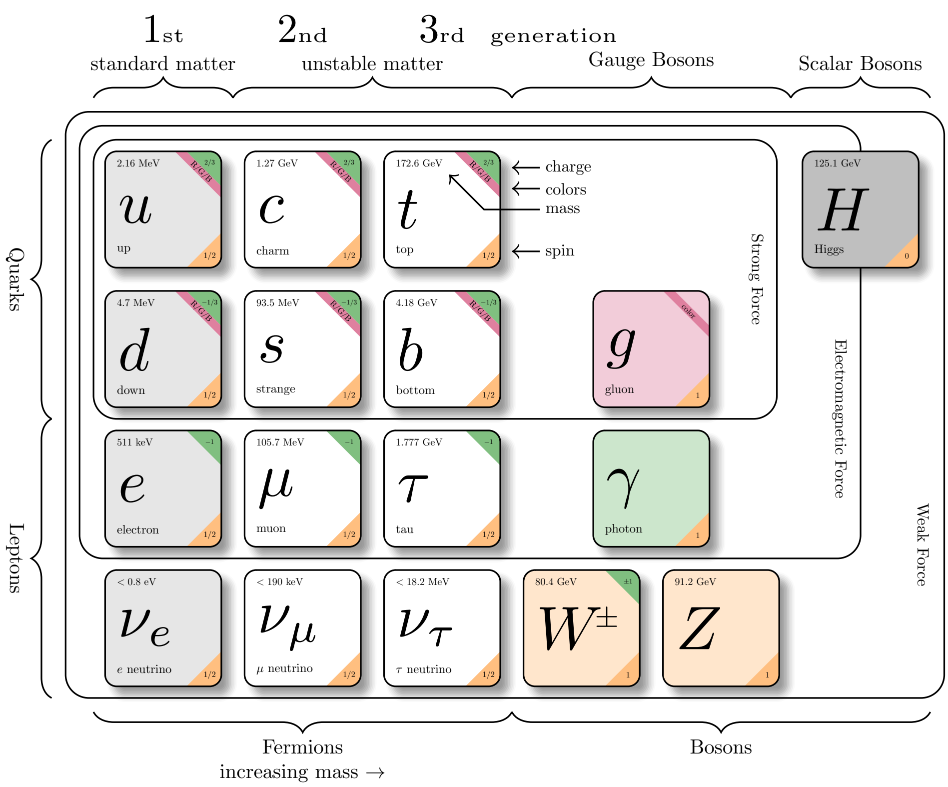

Figure 1: Visualisation of The Standard Model of Particle Physics taken from [5] and modified with values taken from [4]

itself carries a colour charge. This means that gluons can interact with themselves.

Thus all forces exept for gravity are included in the Standard Model. The graviton is a hypothetical boson which would mediate the gravitational force but has not been dicovered yet.

The last discovered particle of the Standard Model was the Higgs boson H reference added??.

The Higgs boson is the particle which gives other particles their mass.

2.1.2 Neutrino Oscillation and Lepton Flavour Violation

Neutrino Oscillation was first proposed in 1958 by B.Pontecorvo [1]. Inspired by the phenomenon of neutral kaon oscillation, he suggested that if neutrinos had a non-zero mass, they could change their flavour while propagating through space.

The existance of neutrino oscillation was experimentally confirmed in 1998 by the Super-Kamiokande experiment in Japan, which observed the oscillation of atmospheric neutrinos. This discovery provided strong evidence that neutrinos have mass and that flavour eigentstates are not identical to mass eigenstates.

Subsequent experiments, such as the Sudbury Neutrino Observatory (SNO) in Canada and the KamLAND experiment in Japan, further confirmed neutrino oscillations by studying solar and reactor neutrinos, respectively [6]. Both Super-Kamiokande and SNO measured the flux of

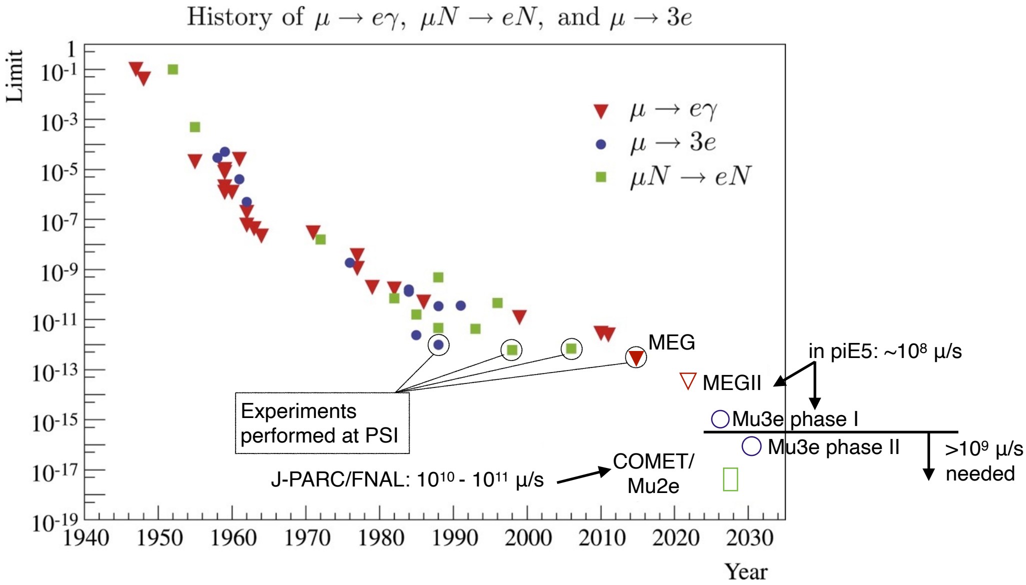

Figure 2: History of the upper limits on the branching ratios of different cLFV processes [3].

neutrinos originating from the Sun. They observed a significant deficit of electron-neutrinos compared to predictions from the Standard Solar Model (SSM), while the total flux of all neutrino flavours agreed with SSM calculations.

This procieded clear evidence that electron neutrinos produced through fusion in the Sun were oscillation into muon- and tau-neutrinos [1][2][6][7]. Neutrino oscillation thus demonstrates that lepton flavour is not conserved in the neutral lepton sector.

2.1.3 Charged Lepton Flavour Violation

The observation of neutrino oscillations [] has revealed limitations of the Standard Model. In particular, it demonstrated that lepton flavour is not a strictly conserved quantity in the neuttal lepton sector. Extending the Standard Model to include right-handed neutrinos naturally accommodated lepton flavour violation in the framework of quatum field theory. As a consequence, processes that violate lepton flavour in the charged lepton sector — known as charged lepton flavour violation (cLFV) — are also expected to occur at some level.

Examples of such processes include $\mu^+ \to e^+ + \gamma$ (searched for by the MEG experiment at PSI) and $\mu^+ \to e^+e^-e^+$ (target of the MU3e experiemnt). Although no cLFV process has yet been observed, decades of experimental searches habe significalty imporved the upper limit on their brachnich ratios, as illustraded in Figure 2. These increasingly stringent limits provide valuable constraints on pyhscs beyond the Standard Model.

2.2 The goal of the Mu3e experiment

2.3 The setup of the Mu3e experiment

2.4 The Mu3e vertex detector

3 The Detection and pyhsics behind the vertex detector

3.1 The silicon pixel sensors

3.2 PN-junctions

3.3 Pixel Sensors

Part II
Current status of the QC

4 single QC

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