Lepton-Flavour Violating Muon Decays and the Mu3e Experiment

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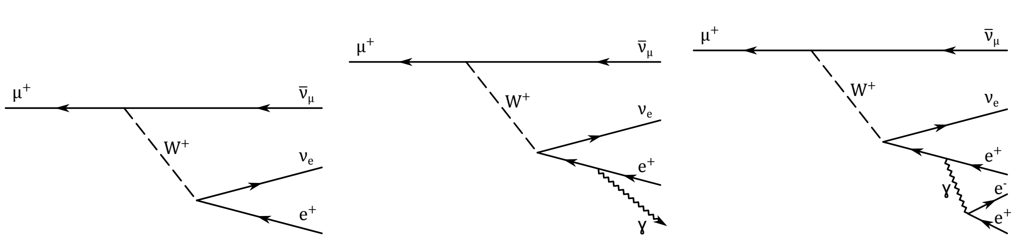
1 Muons in the Standard Model

The muon is the charged lepton of the second generation. It is about 200 times heavier than the electron with a mass of $105.658\,374\,5(24)\,\mathrm{MeV}$ [1] and decays via the weak interaction into electrons and neutrinos with a lifetime of $2.196\,981\,1(22)\,\mu\mathrm{s}$. The most dominant decay mode with a branching fraction of almost 100% is the so-called Michel decay $\mu \to e\nu\overline{\nu}$. With a branching fraction of about $1.4(4)\,\%$ an additional photon is emitted $\mu \to e\gamma\nu\overline{\nu}$, and with a branching fraction of $3.4(4) \cdot 10^{-5}$ this photon converts internally to an $e^+ e^-$ pair $\mu \to eee\nu\overline{\nu}$. The corresponding Feynman diagrams are shown in figure 1.

Muons can easily be produced in large quantities. Measurements of the Michel decay parameters of the decay $\mu \to e\nu\overline{\nu}$ are precision tests of the electro-weak theory. The latest measurements have been performed by the TWIST collaboration [2]. No deviation from the Standard Model has been found.
In the case of the anomalous magnetic moment of the muon, a discrepancy of about 3.6σ is observed between theoretical calculations and the latest measurements [3, 4]. This could hint at contributions from physics beyond the Standard Model. Nevertheless, the difference is not yet conclusive so that huge efforts are undertaken both on the experimental and theoretical side to solve this mystery.

In addition, muons are often investigated in intensity frontier experiments searching for New Physics phenomena at high mass scales showing up in loops and/or with small coupling strengths.



(a) $\mu \to e\nu\overline{\nu}$ (b) $\mu \to e\gamma\nu\overline{\nu}$ (c) $\mu \to eee\nu\overline{\nu}$

Figure 1: Decays of the muon in the Standard Model.

1.1 Muon Production

For the production of muons, usually a high rate proton beam hits a target producing amongst others a lot of pions. The charged pions preferentially decay into muons and neutrinos. The decay into electrons is helicity-suppressed. The muons are polarized, with μ^- from π^- decay having the spin pointing in the direction of the momentum and vice versa for μ^+ from π^+ decay.
Of particular interest are often the so-called surface and sub-surface muons (only μ^+). These muons stem from pions that decay at rest close to the surface of the production target. Their momentum is about 29.8 MeV in the case of surface muons and about 28 MeV for sub-surface muons.
Sub-surface muons beams are used in $\mu \to e\gamma$ and $\mu \to eee$ searches. Current and future experiments of this kind are located at the Paul-Scherrer Institute (PSI) which houses an intense proton beam accelerator. Muon rates of up to $10^8\,\mu/s$ of continuous beam are available at secondary beamlines. Options for rates of $10^{10}\,\mu/s$ are currently under study.

For the muon conversion experiments COMET at J-Parc [5] and Mu2e [6] at Fermilab pulsed muon beam in excess of $10^{10}\,\mu/s$ are envisaged.

2 Lepton-Flavour-Violating Muon Decays

In the Standard Model, lepton flavour is expected to be conserved. The observation of neutrino oscillations [1] has however taught us that lepton flavour is violated in nature — at least in the case of neutral leptons — and that the Standard Model is incomplete. The Standard Model extended to include neutrino masses will be referred to as νSM in the following. As neutrino flavour is violated, also the flavour of charged leptons will be violated in some order in perturbation theory.
The lepton flavour violating muon decays are as follows: $\mu \to e\gamma$, $\mu \to eee$ and muon to electron conversion on nuclei $\mu N \to eN$. The first two will be presented in this lecture. In addition, lepton flavour violation can be investigated in muonium-antimuonium oscillations. For taus, there are more possible lepton flavour violating decays with leptons and/or hadrons in the final state.

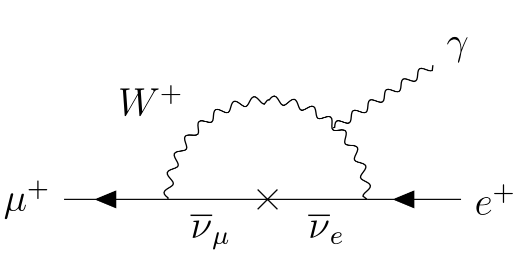
2.1 The Decays $\mu \to e\gamma$ and $\mu \to eee$ in the νSM

The contribution to the branching ratios for $\mu \to e\gamma$ that stem from the neutrino masses and mixing alone is extremely small and by far not accessible with experiments [7–9]:

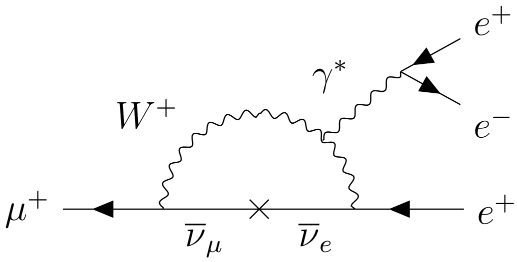
$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W}\right|^2 < 10^{-54}\,. \tag{1}$$

Herein, α denotes the fine structure constant, $U_{\alpha i}$ the elements of the neutrino mixing matrix, Δm^2_{ij} the differences of the squared neutrino masses, and M_W the mass of the W boson. The corresponding Feynman diagrams with neutrino mixing in a loop are shown in figure 2. The branching ratio for $\mu \to eee$ is even smaller because of the additional vertex of the photon conversion.

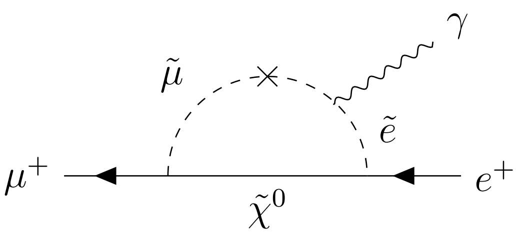
As the νSM contribution is negligible, $\mu \to e\gamma$ and $\mu \to eee$ are ideal probes to search for New Physics. Any observation would be an unambiguous signal for physics beyond the Standard Model (BSM). This is why over the past decades many experiments have been performed — so far with no signal found – and also for the future more experiments are planned pushing the sensitivity level further down (see figure 3).



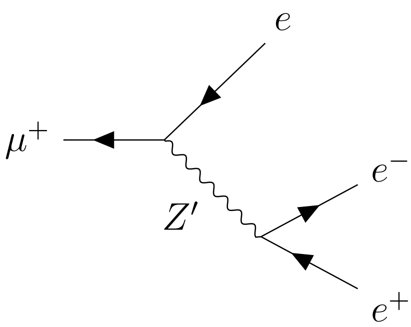
(a) μ → eγ via neutrino mixing.



(b) μ → eee via neutrino mixing.



(c) μ → eγ in SUSY.



(d) μ → eee with a Z′.

Figure 2: Feynman diagrams for μ → eγ and μ → eee mediated via neutrino mixing and in BSM.

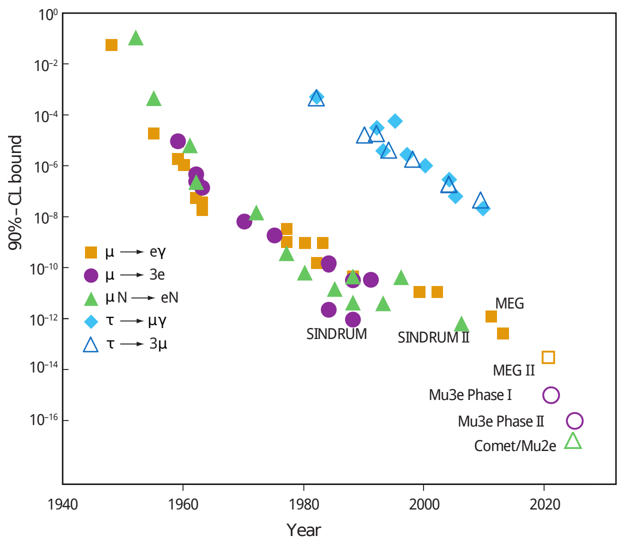


Figure 3: Past and future experiments searching for charged lepton flavour violating decays. Adapted from [10].

2.2 The Decays $\mu \to e\gamma$ and $\mu \to eee$ in BSM

Many models of New Physics predict charged lepton flavour violation at significantly enhanced rates compared to the νSM prediction of equation 1. One possibility is supersymmetric theories, but charged lepton flavour violation can also be mediated via e. g. a doubly-charged Higgs or a Z′ (see figure 2) [7, 11].

Effective field theories offer the possibility for model-independent studies. Charged lepton flavour violation is mediated by operators of dimension five or higher. The following effective Lagrangian illustrates with two exemplary operators how $\mu \to e\gamma$ and $\mu \to eee$ can be mediated [7]. More detailed considerations can be found in [11] and [12].

$$\begin{aligned}\mathscr{L}_{\mathrm{cLFV}} =& \frac{1}{(\kappa+1)}\frac{m_\mu}{\Lambda^2}\overline{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + h.c. \\ &+ \frac{\kappa}{(\kappa+1)}\frac{1}{\Lambda^2}\overline{\mu}_L\gamma_\mu e_L(\overline{e}\gamma^\mu e) + h.c.\end{aligned} \tag{2}$$

μ and e are the fermion fields with chiralities L and R, and $F^{\mu\nu}$ the photon field strength. The parameter Λ is the effective mass scale of the new degrees of freedom. And κ defines the relative size of the two operators.

The first term in equation 2 is a dipole-type operator. $\mu \to e\gamma$ is directly mediated via this operator, while $\mu \to eee$ is mediated at order α. The second term is an operator of four-fermion interaction. It mediates $\mu \to eee$ at tree level and $\mu \to e\gamma$ at one-loop level.

Figure 4 shows the sensitivity to the effective mass scale Λ as a function of κ for various limits on the branching ratio of $\mu \to e\gamma$ and $\mu \to eee$. In general, the expected branching ratio for decay experiments scales with Λ^{-4} meaning in order to investigate one more order in magnitude in mass scale, the sensitivity has to be improved by four orders of magnitude.

In the case of dominating dipole-like interaction (small κ), measurements of $\mu \to e\gamma$ excluded already effective mass scales up to more than 2000 TeV and future experiments will probe up to 4000 TeV. $\mu \to eee$ searches have to be about two orders of magnitude more sensitive to be competitive with $\mu \to e\gamma$ searches in the case of dipole-like operators. On the other hand, $\mu \to eee$ searches dominate the limits on Λ in the case of four-fermion interactions (large κ). Current results exclude mass scales up to a few hundred TeV, and future experiments are sensitive to mass scales of more than 1000 TeV.

This simple comparison between $\mu \to e\gamma$ and $\mu \to eee$ also shows that a single channel can only provide limited information about the underlying New Physics. In the case of a positive signal in $\mu \to eee$, the distribution of the decay electrons could provide some information of the type and chirality of the operators [11]. But only the combination of various observables — not only from charged lepton flavour violation, but also for example from muon (g-2) measurements and neutrino experiments – can give a more complete picture.

2.3 The Decay $\mu \to e\gamma$

The latest results on lepton flavour violation searches of muons stem from the $\mu^+ \to e^+\gamma$ decay. As it is a two-body decay, it has a distinct signature. Ususally, muon decays at rest are observed. One searches for a positron and a photon with an energy of half the muon rest mass (about 52.83 MeV). Both particles are emitted in a back-to-back topology, have a common vertex, and appear coincidently.

One source of background is the Standard Model decay $\mu \to e\gamma\nu\overline{\nu}$. The neutrinos are not detected,

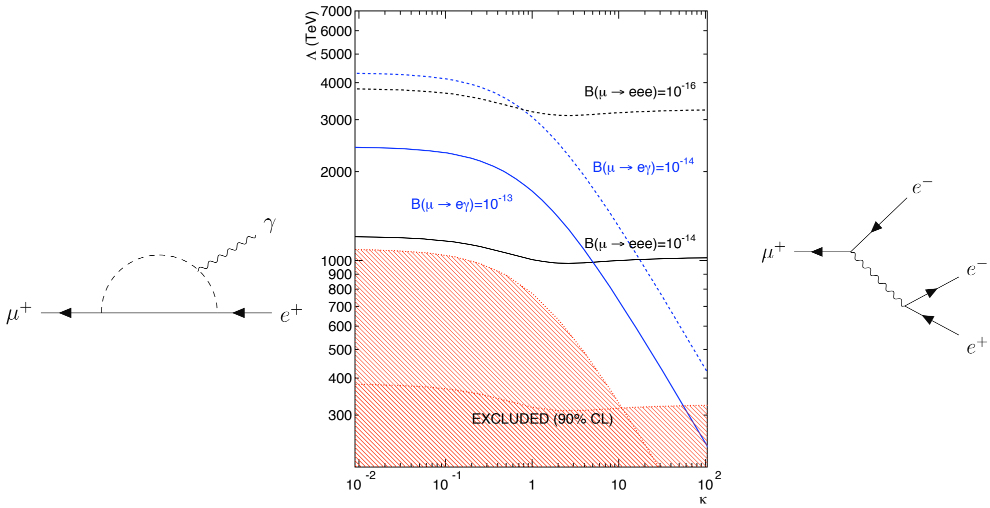


Figure 4: Comparison between $\mu \rightarrow e\gamma$ and $\mu \rightarrow eee$ in effective theories [7].

thus a positron and a photon from a common vertex are observed. Nevertheless, the two particles do not fully match the criteria on energy and the back-to-back topology. The energy and spatial resolution must be good enough to suppress this background.
In order to achieve competitve sensitivity levels with a reasonable measuring time, $\mu \rightarrow e\gamma$ experiments have to run a high muon rates. Thus, not single but multiple muon decays are observed at a time giving rise to accidental background, i. e. combinations of photons from $\mu \rightarrow e\gamma\nu\overline{\nu}$, Bremsstrahlung or positron annihilation with positrons for example from the dominant $\mu \rightarrow e\nu\overline{\nu}$ decay. Hence, in addition timing resolution becomes important to suppress accidental background.

The most recent result on $\mu \rightarrow e\gamma$ is set by the MEG experiment [13, 14] which was operated at the Paul-Scherrer Institute until 2013. The detector is shown in figure 5. A muon beam of about $3 \cdot 10^7\,\mu/s$ is stopped on a target in the centre of the experiment. For the momentum measurement of the positrons, a special magnetic gradient field is applied that ensures a nearly constant bending radius which only weakly depends on the emission angle. The positrons are tracked in a drift chamber system and their time is measured with a timing counter system made of scintillating bars. The photons are measured in a liquid Xenon calorimeter read out by photo-multiplier tubes.
A total of $7.5 \cdot 10^{14}$ muons has been stopped in the MEG experiment. The data set is analysed in a combined blind and maximum likelihood analysis (see figure 6). The sidebands are used to derive estimates for accidental background and background from $\mu \rightarrow e\gamma\nu\overline{\nu}$, before the analysis window is opened. No significant excess was found. The final result as published in 2016 excludes the decay $\mu^+ \rightarrow e^+\gamma$ to branching ratios of $BR < 4.2 \cdot 10^{-13}$ at 90% confidence level [14]. It is currently the most stringent bound in charged lepton flavour violating decays.
Figure 7 shows the distribution of events in the observables energy of photon and positron, time difference, and opening angle between photon and positron. No event lies in both of the signal regions.
At the moment, the MEG experiment undergoes an upgrade, called MEGII [15]. The positron tracker

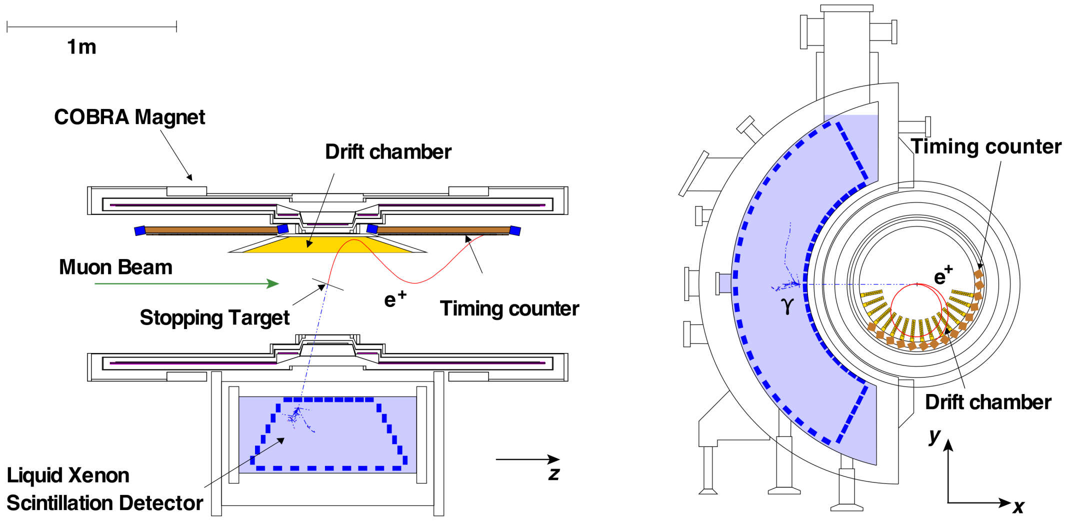


Figure 5: Sketch of the MEG detector [14].

and timing detector are replaced and the liquid Xenon calorimeter is upgraded. The thus improved energy, angular and timing resolution allows for running at higher muon rates. MEGII has a prospected sensitivity of $5 \cdot 10^{-14}$ in 3 years data taking, about one order in magnitude better than MEG.

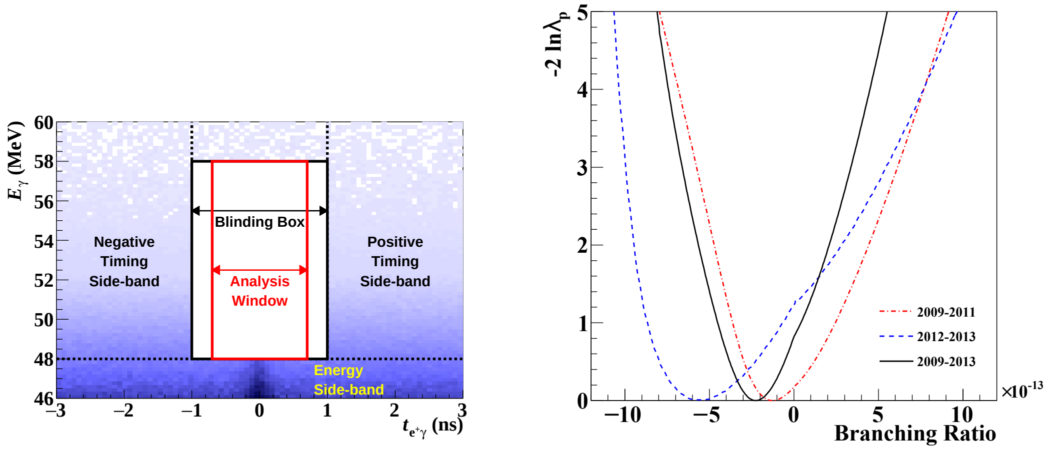
2.4 The Decay $\mu \to$ eee

In the case of $\mu \to$ eee, the signature is two positrons and one electron that appear coincidently from a common vertex. Studying muon decays at rest, the momenta of the electrons sum up to zero whereas the sum of the energies equals the muon rest mass. The maximum momentum of a single electron is about 53 MeV.

One source of background is $\mu \to \mathrm{eee}\nu\bar{\nu}$, as the neutrinos leave the detector unseen. It can be distinguished from the signal decay only because of the missing energy of the neutrinos. Therefore, a very good momentum resolution is crucial to suppress this background. This is illustrated in figure 8. Here, the branching ratio of $\mu \to \mathrm{eee}\nu\bar{\nu}$ is integrated with a cut on the missing energy $m_\mu - E_{\text{tot}} = m_\mu - \sum_{i=1}^{3} \vec{p}_i$. The missing energy needs to be known with better than 1 MeV precision in order to suppress this background below the aimed at sensitivity level.

Also $\mu \to$ eee searches have to cope with accidental background. These are usually coincidences of one or two positrons from the dominant Michel decay and an electron or electron-positron pair from Bhabha scattering or photon conversion. Also a positron track can look like an electron if the track is reconstructed in the opposite direction. Additionally to a good momentum resolution – in general these combinations do not necessarily fulfill the criteria on momentum and energy – accidental combinations can be suppressed by a good timing and vertex resolution.

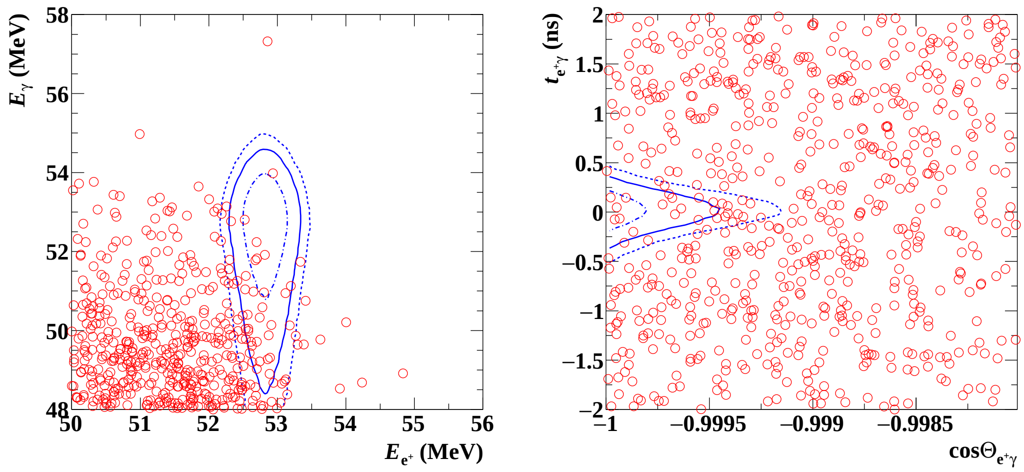
The decay $\mu \to$ eee has been last investigated by the SINDRUM experiment [16] in 1988. No signal event was found and an upper limit on the branching ratio was set at $\mathrm{BR} < 1.0 \cdot 10^{-12}$ at 90% confidence level.



(a) Blinding box and side-bands.

(b) Negative log-likelihood ratio as a function of the branching ratio for $\mu \to e\gamma$.

Figure 6: Combination of blind and maximum likelihood analysis of the MEG data [14].



(a) Photon and positron energies.

(b) Time difference and opening angle.

Figure 7: Distibution of events in the MEG experiment. The signal PDF contours at 1σ, 1.64σ and 2σ signal regions are indicated [14].

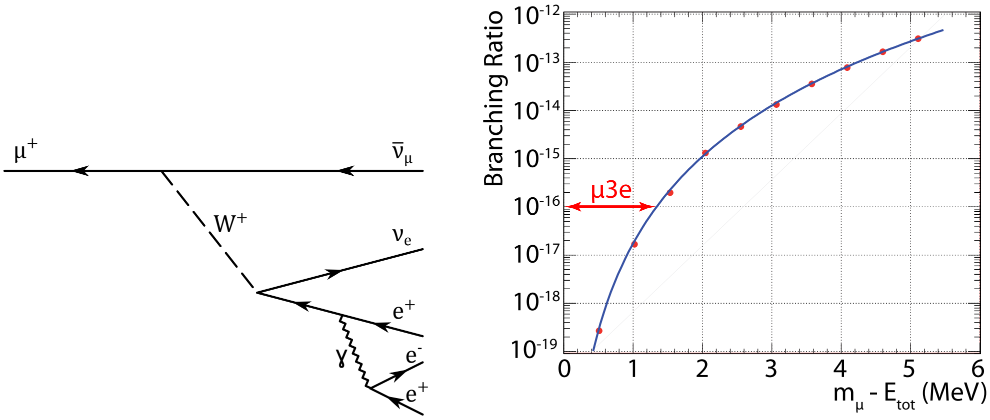
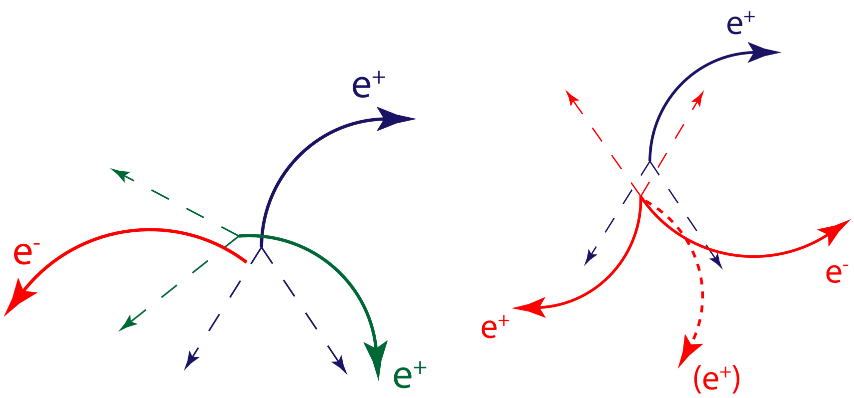


Figure 8: Integrated branching ratio for $\mu \to ee e\nu\overline{\nu}$ for various cuts on the missing energy [17].



(a) Combination of two e^+ from $\mu \to e\nu\overline{\nu}$ with an e^- for example from Bhabha scattering.

(b) Combination of a e^+ from $\mu \to e\nu\overline{\nu}$ and an e^+e^- pair from $\mu \to eee\nu\overline{\nu}$.

Figure 9: Accidental background for $\mu \to eee$.

3 References

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