Particle Track reconstruction using a recurrent neural network at the $\mu - 3e$ experiment

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Abstract During the $\mu - 3e$ experiment we faced the challenge of reconstructing the paths of certain low momentum particles that curled back into the detector and cause additional hits. To face this, a recurrent neural network was used which found the right track for 87% of these particles.

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1 Standard Model

1.1 Elementary particles and forces

The Standard Model(SM) describes all known elementary particles as well as three of the four known forces[1].
The elementary particles that make up matter can be split into two categories, namely quarks and leptons. There are 6 types of quarks and six types of leptons. The type of a particle is conventionally called flavour. The six quark flavours and the six lepton flavours are separated over 3 generations (each which two quarks and two leptons in it). Experimental evidence suggests that there exist exactly three generations of particles. Each particle of the first generation has higher energy versions of itself with the same characteristics (e.g. $e^- \to \mu^- \to \tau^-$)as in other generations. Contrary, each following generation has a higher mass than the generation before.

Table 1: Quarks in the Standard Model

	Quarks			
	Particle		Q[e]	$\frac{mass}{GeV}$
1. Gen.	up	u	$-\frac{1}{3}$	0.003
	down	d	$\frac{2}{3}$	0.005
2. Gen.	strange	s	$-\frac{1}{3}$	0.1
	charm	c	$\frac{2}{3}$	1.3
3. Gen.	bottom	b	$-\frac{1}{3}$	4.5
	top	t	$\frac{2}{3}$	174

One category consists of quarks(q)(see Table 1). In this, we differentiate between up-type quarks, with charge $-\frac{1}{3}e$, and down-type, quarks with charge $\frac{2}{3}e$. Quarks interact with all fundamental forces.
Each quark carries a property called colour-charge. The possible color charges are red(r), green(gr), blue(bl) in which anti-quarks carry anti-colour. Quarks can only carry one colour, whilst every free particle has to be colorless[2]. In conclusion we cannot observe a single quark.
Free particles can achieve being colourless in two ways. Either by having all three colors present in the same amount (one quark of each color), which creates the characteristic group of baryons(qqq) and anti-baryons($\bar{q}\bar{q}\bar{q}$) or by having a color and its anticolor present, which creates the group of mesons($q\bar{q}$).

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[1] Strong, weak and electromagnetic forces

[2] Colour confinement

Table 2: Leptons in the standard model

Leptons				
	Particle		Q[e]	$\frac{mass}{GeV}$
1. Gen.	electron	e^-	-1	0.005
	neutrino	ν_e	0	$< 10^{-9}$
2. Gen.	muon	μ^-	-1	0.106
	neutrino	ν_μ	0	$< 10^{-9}$
3. Gen.	tau	τ^-	-1	1.78
	neutrino	ν_τ	0	$< 10^{-9}$

The other group consists of leptons(l)(see Table 2). They only interact through the weak and the electromagnetic force. Each generation consists of a lepton of charge -1 and a corresponding EM neutrally charged neutrino. The electron has the lowest energy of all charged leptons. This makes the electron stable while the higher generation particles decay to lower energy particles.

The leptons of one generation, namely the charged lepton and its corresponding neutrino are called a lepton family. A lepton of a family counts as 1 to its corresponding lepton family number whilst a anti-lepton counts as -1.

Table 3: Fundamental forces

Force	Strengh	Boson		Spin	Charge	$\frac{mass}{GeV}$
Strong	1	gluon	g	1	0	0
Electromagnetism	10^{-3}	photon	γ	1	0	0
Weak	10^{-8}	Z boson	Z	1	0	80.4
	10^{-8}	W boson	$W^\pm$	1	±1	91.2

The particles of the SM interact through the 3 fundamental forces of the SM. In these interactions, particles called bosons are being exchanged which are the carriers of their respective force (see Table 3).
As mentioned above, only quarks can interact through the strong force, in which they exchange gluons. Gluons are massless and EM neutrally charged. The strong force has the biggest coupling strengh of 1 (though it decreases with higher energies as a result of gluon-gluon self interaction loops, which interfere negatively in perturbation theory)[3]. A gluon carries colour charge and hence can change the colour of a quark but it conserves its flavour. The strong interaction has an underlying gauge symmetry of SU(3). Therefore, it can be derived that color charge is conserved through the strong interaction[4].
The electromagnetic(EM) force is propagated through the photon. It carries zero charge and no invariant mass. Exclusively charged particles can interact through the electromagnetic force. The coupling strength is $\alpha \approx \frac{1}{137}$, contrary to the strong force the coupling constant increases with higher energies[5]. This

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[3] Mark Thomson - Modern Particle physics - 10.5.2

[4] E.g. through Gell-Mann matrices

[5] Mark Thomson - Modern Particle physics - 10.5.1

difference stems from the fact that photon-photon interaction loops are not allowed whereas gluon-gluon interaction loops are. In perturbation theory this results in only positive terms being added to the coupling strength. The underlying gauge symmetry is of SU(1). The electromagnetic force also conserves flavour.
The weak force has two types of bosons. The bosons of the weak force are the only bosons to have an inertial mass.
First we will discuss the EM neutrally charged Z boson[6]. Even though the Z boson belongs to the weak force it, it also has an electromagnetic part additionally to the weak force part[7]. It follows directly, that the Z boson couples weaker to uncharged particles.
The other boson of the weak force is the W boson[8]. In the classical SM, the only way particles can change flavour is through the weak force by emitting or absorbing W boson. It is important to notice that, besides of having an invariant mass, the W boson is the only boson with a non zero charge ($Q_{W^\pm} = \pm 1e$). In the gauge symmetry of the weak force the $W^\pm$ are actually the creation and annihilation operators of said symmetry[9].
An important characteristic of the weak force is that it exclusively couples to lefthanded(LH) particles and righthanded(RH) antiparticles (describing chirality states)[10].
The chirality operators for left- and righthandedness are:

LH: $\frac{1}{2}(1 - \gamma^5)$, RH: $\frac{1}{2}(1 + \gamma^5)$

As a consequence RH particles and LH anti-particles cant couple to the W boson at all. This also results in charged RH particles and LH anti-particles to couple to the Z boson only through the electromagnetic part of the itself, while uncharged RH particles and LH anti particles (e.g. RH ν, LH $\bar{\nu}$) don't couple with the EM force nor the weak force.

1.2 Interaction rules

Now we will establish the general rules for interactions in the SM.

Baryon number is conserved
As we already established before, the only interaction that can change flavour is the weak force through the W boson. We directly see that all other interactions baryon number has to be conserved. So any up-type quark can be changed to a down-type quark and backwards by emitting or absorbing a W boson. In the end however, there are still 3 quarks which form a baryon[11], even though it changed its type and charge. A well known example is the beta decay, where a down quark in a neutron decays into a an up quark to form now a proton(e.g. see Figure 1a). We easily see that the baryon number is conserved.

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[6] Discovered at Super Proton Synchrotron accelerator - Cern - 1983

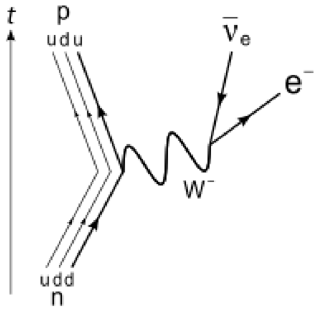
[7] $Z \to EM_{part} + W^3$, Modern Particle Physics - Blababla

[8] Discovered at Super Proton Synchrotron accelerator - Cern - 1983

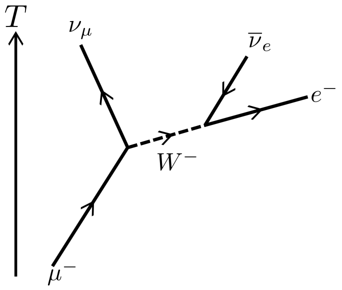
[9] $W^\pm = W_1 \pm iW_2$

[10] In the ultrarelativistic limit helicity and chirality eigenstates are the same

[11] I exclude $q\bar{q}$ pair-antipair production to form a pentaquark($qqqq\bar{q}$) and other exotic states



(a) Feynman diagram of the β-decay



(b) Feynman diagram of a μ-decay

Lepton family number is conserved
According to the SM lepton family number is conserved. As all interactions beside the W conserve particle flavour, it is easy to see that lepton family number is conserved.
Whenever a lepton interaction with a W boson, it just changes a lepton to its corresponding lepton neutrino and or the other way around (e.g. see Figure 1b).

2 Physics beyond the SM

2.1 Neutrino Oscillation

Classically the SM considers neutrinos to be massless. While this assumption works well for a lot of cases, we know nowadays that at least two of the three neutrinos have to have mass[12]. Neutrinos are known to oscillate between all three states of flavour, as the eigenstates of flavour are not eigenstates of mass. As a consequence ν_e, ν_μ and ν_τ are not fundamental particle states but a mixture of the mass eigenstates ν_1, ν_2 and ν_3. They are connected through the PMNS matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e_1} & U_{e_2} & U_{e_3} \\ U_{\mu_1} & U_{\mu_2} & U_{\mu_1} \\ U_{\tau_1} & U_{\tau_2} & U_{\tau_3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \tag{1}$$

As a result neutrinos propagate as a superposition of all mass eigenstates. Additionally we can describe the PMNS matrix through three mixing angles θ_{12}, θ_{13} and θ_{23} and a complex phase δ [13]. The electron superposition looks then like this:

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[12] The mass difference between neutrinos is non zero: $m_i - m_j = \Delta m_{i,j} \neq 0$, $\forall j \neq i$

[13] Measurements: $\theta_{12} \approx 35°$, $\theta_{13} \approx 10°$, $\theta_{23} \approx 45°$ - KamLAND, MINOS, ...

$$|\nu_e\rangle = U_{e_1}|\nu_1\rangle e^{-i\Phi_1} + U_{e_2}|\nu_2\rangle e^{-i\Phi_2} + U_{e_3}|\nu_3\rangle e^{-i\Phi_3} \text{ with } \Phi_i = E_i \times t$$

As a result lepton family number is not a conserved quantity anymore as neutrino flavour oscillates over time.
We can calculate the probability for a neutrino to transition from flavour α to β like:

$$\begin{aligned} P(\nu_\alpha \to \nu_\beta) = 2Re\left(U_{\alpha_1}U^*_{\beta_1}U^*_{\alpha_2}U_{\beta_2}e^{-i(\Phi_1-\Phi_2)}\right) \\ +2Re\left(U_{\alpha_1}U^*_{\beta_1}U^*_{\alpha_3}U_{\beta_3}e^{-i(\Phi_1-\Phi_3)}\right) \\ +2Re\left(U_{\alpha_2}U^*_{\beta_2}U^*_{\alpha_3}U_{\beta_3}e^{-i(\Phi_2-\Phi_3)}\right) \end{aligned} \tag{2}$$

An important thing to note is, that if any elements of the PMNS matrix are complex, this process is not invariant under time reversal $(t \to -t)$[14]
$P(\nu_\alpha \to \nu_\beta) \neq P(\nu_\beta \to \nu_\alpha)$.

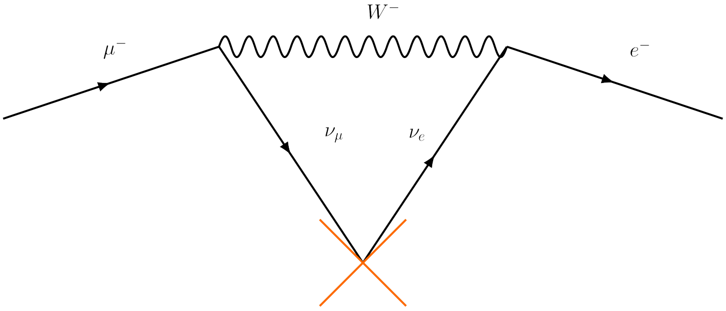

Figure 2: Process that violates lepton family number conservation through neutrino oscillation

Nowadays it's a well accepted fact that lepton family number gets violated through neutrino oscillation.
But why should flavour oscillation be exclusive to neutrinos?
Maybe there are ways for the EM charged leptons as well to directly transition to another lepton family[15]?

2.2 New physics

As a consequence of neutrino oscillation lepton flavour is a broken symmetry. The SM has to be adapted to include lepton flavour violation (LFV) and massive neutrinos. LFV is also expected for charged neutrinos.
Although it has yet to be determined how LFV violation exactly works to which scale it exists.

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[14] The probability does not change if we add a complex phase to the PMNS matrix, just if one of the elements has a phase different from the others

[15] Maybe also possible for quarks?

This may raise the question on why charged LFV has never been observed yet. This is especially surprising as the mixing angles of the neutrinos have been measured to be big.
There are two reasons why charged LFV is strongly surpressed: The first is that charged leptons are much heavier than neutrinos and the other that the mass differences between neutrino flavour are tiny compared to the W boson mass.

In the classical SM, charged LFV is already forbidden at tree level. Though it can be induced indirectly through higher order loop diagrams (using neutrino oscillation). By adding new particles beyond the SM, we generate new ways for LFV in the charged sector to happen. As LFV is naturally generated in many models beyond the SM, finding charged LFV is a strong hint for new physics.

Image LFV via neutrino, at tree level and directly involving supersymmetric particles

One way charged LFV can occur is through super symmetric particles (see Figure Bratenene). By observing charged LFV supersymmetry would gain new importance.
Together with supersymmetric models, other extensions of the SM such as left-right symmetric models, grand unified models, models with an extended Higgs sector and models where electroweak symmetry is broken dynamically are all good candidates to explain charged LFV and most importantly experimentally accessible in a large region of the parameter space.

3 Experimental setup of the $\mu \rightarrow eee$-experiment

4 Machine learning

Machine learning has already proven itself to be very successful in resolving many problems in numerous other areas of science and also in the private sector. Based on these promising results, scientists are eager to study the potential of machine learning in physics.