Modeling neutrino-nucleus scattering for accelerator-based experiments

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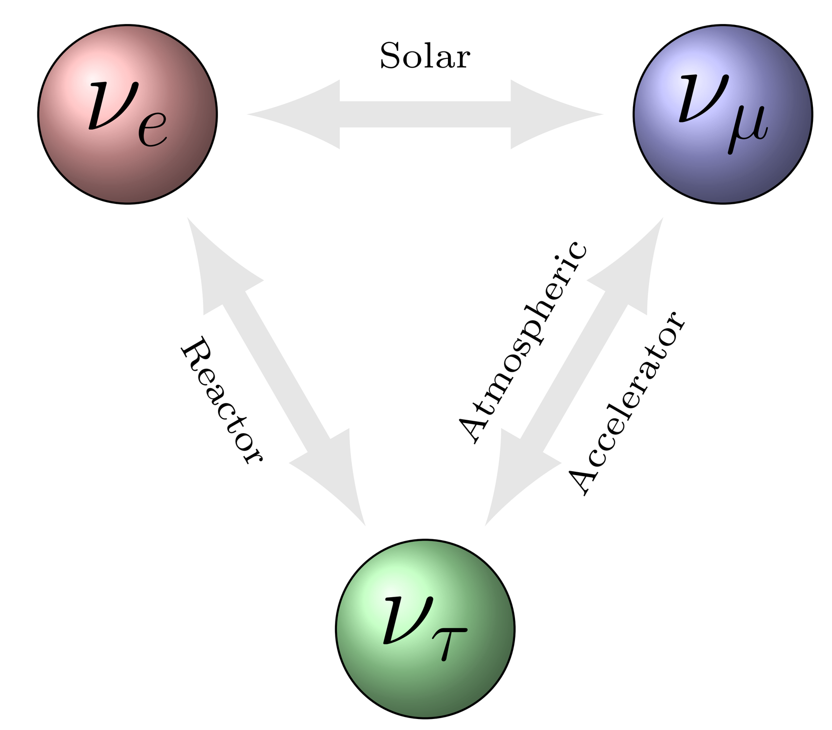
Neutrino oscillations & experiments

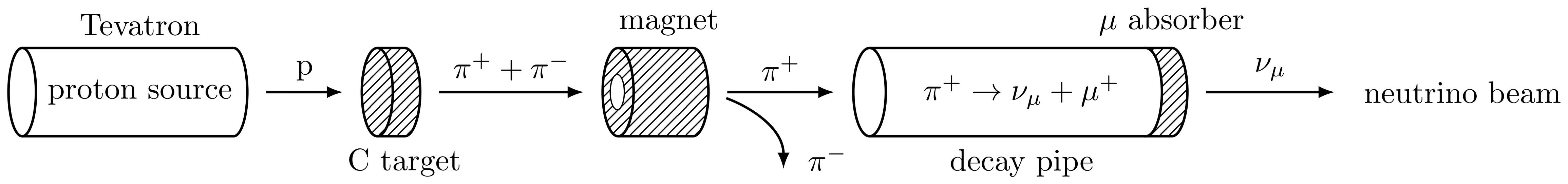
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita (of the *Super–Kamiokande* experiment) and Arthur B. McDonald (*Sudbury Neutrino Observatory*) for the discovery of *neutrino oscillations*, which show that neutrinos have mass.



Three types (or *flavors*) of neutrinos exist. They change into one another when they propagate: they *oscillate*.

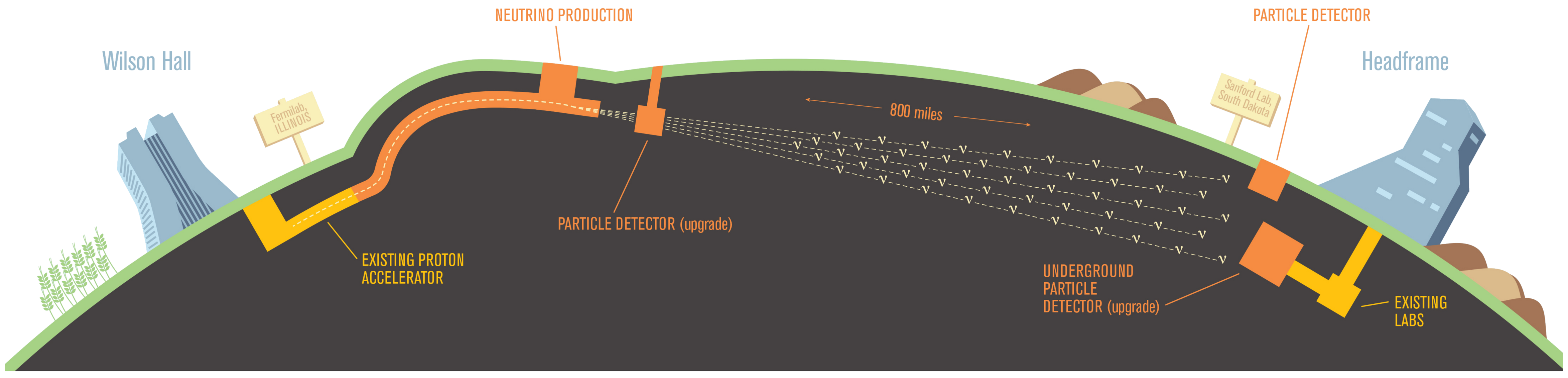
The determination of the parameters that describe the oscillations requires a *precise theoretical model* of the interaction between neutrinos and *atomic nuclei*. Neutrino-nucleus collisions are a method to detect neutrinos.

For accelerator-based experiments, we need an incoming *neutrino beam*. This is done e.g. at the *Tevatron* accelerator at Fermilab. The neutrino production process includes several steps:



Colliding *high energy protons* (p) into a carbon target produces *pions* (π), which are subsequently separated according to their electrical charge using a magnet. These pions then decay, creating *neutrinos* (ν) and *muons* (μ). The latter are filtered out.

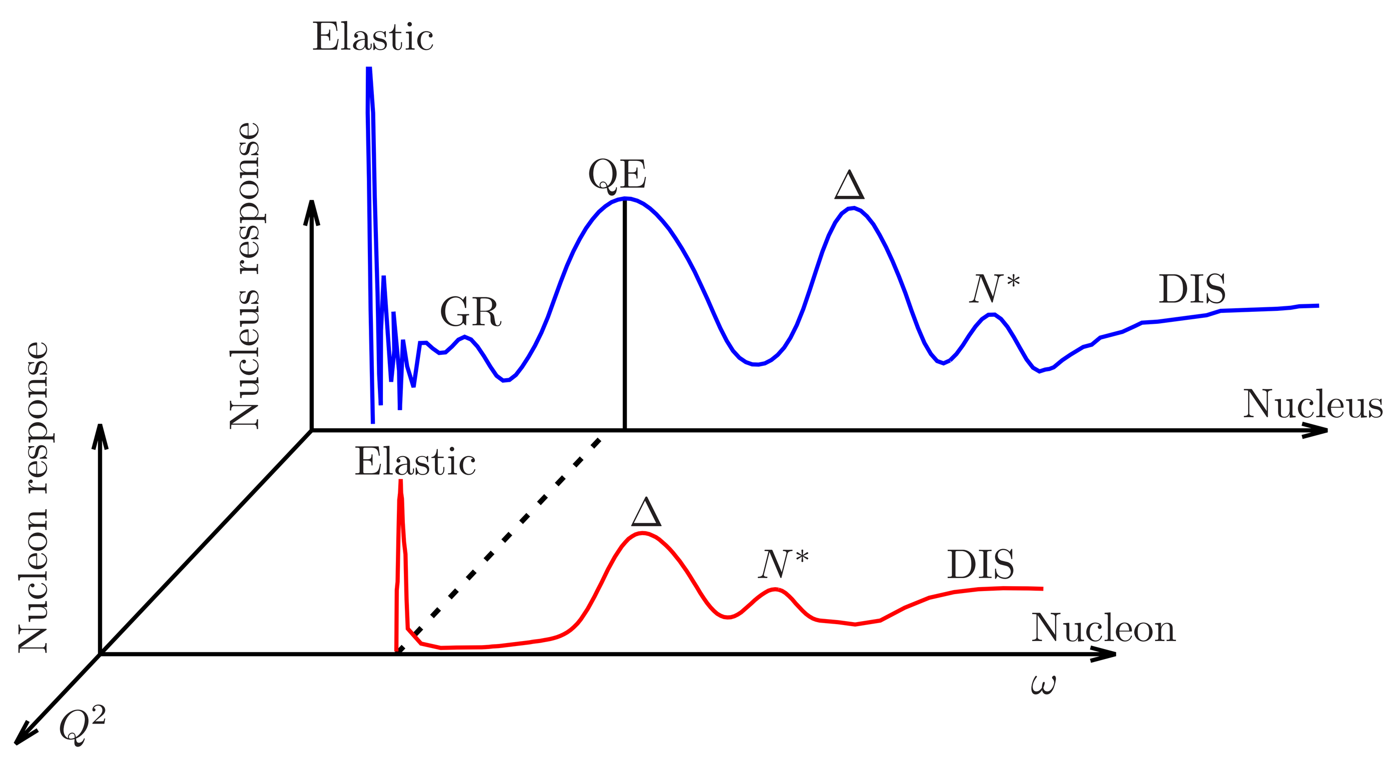
Neutrino oscillations are examined by *counting* and comparing the neutrinos at both the source (*near-detector)* and the *far-detector*. The different numbers give access to the oscillation parameters, as a lack of ν_μ at the far-detector means they have changed into ν_e or ν_τ. To actually *see* the neutrinos, we need to detect them in some way.



Scattering cross sections

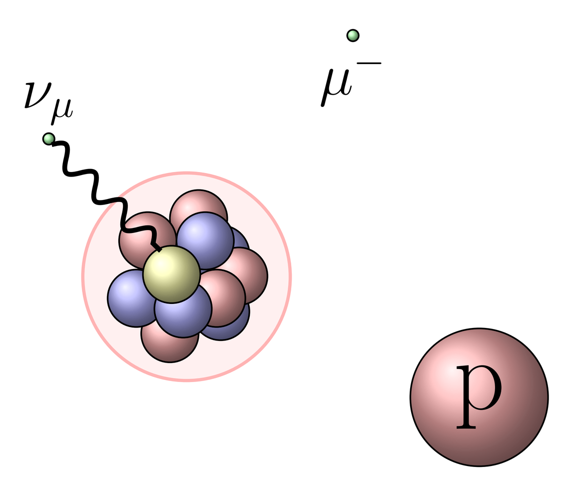
Depending on the energy transfer ω, different reaction mechanisms may occur

- **Elastic** scattering off a free nucleon or a nucleus as a whole
- **GR** - Giant resonance, collective excitation of the nucleus
- **QE** - Quasielastic - scattering off a bound nucleon, the nucleon remains intact
- **Δ or N^*** - Resonant scattering off a bound nucleon, the nucleon is excited
- **DIS** - Deep inelastic scattering, the nucleon breaks up

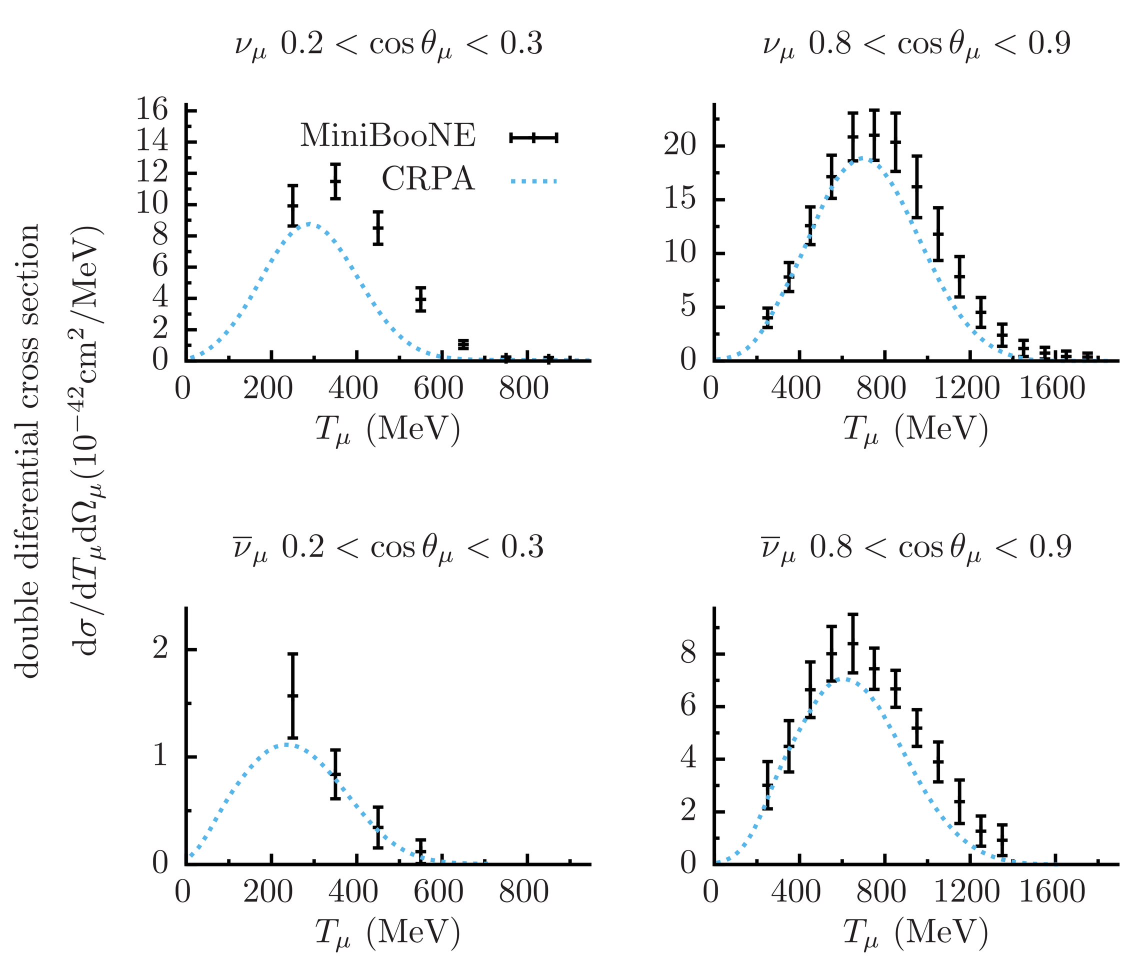


Quasielastic scattering

When a ν_μ scatters off a nucleus with a charged current, it changes into a μ^- which can easily be detected. In these reactions, a neutrino can knock one or multiple nucleons out of the target nucleus. Commonly used targets are ^{12}C, ^{16}O and ^{40}Ar.



$$\nu_\mu + {}^{12}\mathrm{C} \to \mu^- + {}^{11}\mathrm{C} + \mathrm{p}.$$

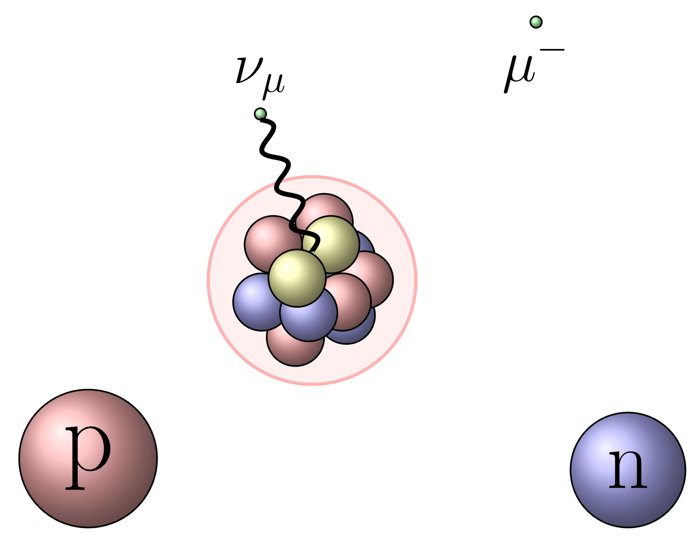


Two approaches are used to describe the quasielastic cross section

- **HF** – The so–called Hartree–Fock method models a nucleus such that the protons and neutrons do not interact: they move around independently, oblivious to the presence of other individual nucleons. They are only subject to an 'average' force: the *mean field*.
- **CRPA** – The Continuum Random-Phase Approximation, goes beyond this and *does* allow for interactions between nucleons. This turns out to be crucial in order to accurately describe situations where the energy transferred to the nucleus (ω) is low, but is less important at high energy transfers.

Two-nucleon knockout

An experiment such as MiniBooNE is only able to detect muons. This means the data does not indicate whether one or more nucleons have been knocked out of the nucleus. Thus in order to improve our description of the data, we include two-nucleon knockout mechanisms

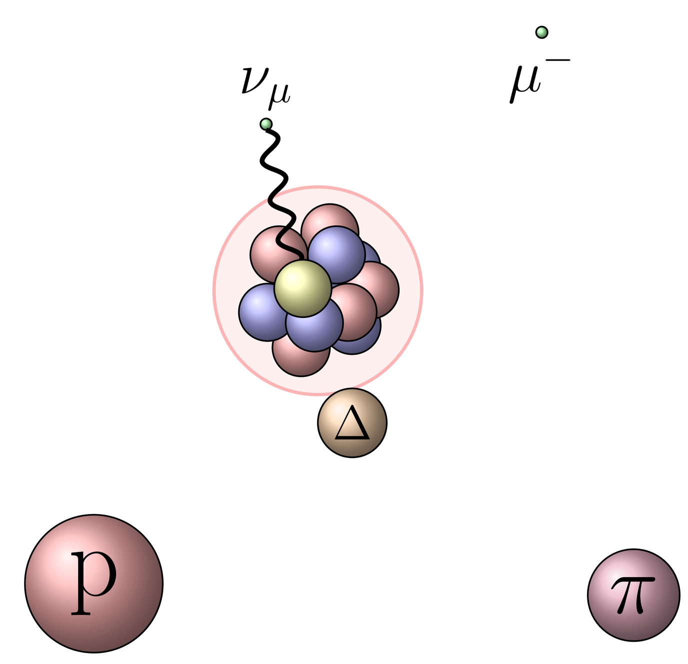


$$\nu_\mu + {}^{12}\mathrm{C} \to \mu^- + {}^{10}\mathrm{C} + \mathrm{p} + \mathrm{n},$$
$$\to \mu^- + {}^{10}\mathrm{B} + \mathrm{p} + \mathrm{p}.$$

- **SRC** – The Short-Range Correlations take into account that protons and neutrons inside the nucleus often occur in *pairs*. When a neutrino interacts with a pair of nucleons, they can both be knocked out of the nucleus.
- **MEC** – Nucleons in a nucleus interact with each other by exchanging virtual mesons, these are called Meson-Exchange Currents.

Pion production

When the incoming energy is sufficiently high, the target nucleon can be excited to a Δ (or any other nucleon resonance N^*) which subsequently decays into a π and a nucleon



$$\nu_\mu + {}^{12}\mathrm{C} \to \mu^- + {}^{10}\mathrm{C} + \Delta$$
$$\hookrightarrow \mathrm{p} + \pi$$

- **RMF** - A Relativistic Mean-Field model is used to describe the nucleus and Δ and other nuclear resonances N^* are taken into account

Comparison with precision electron data

Neutrinos are very similar to electrons, for which plenty of data is around. We can therefore test our model against electron scattering data. The two situations have several practical differences, which include the following:

electrons	neutrinos
produced easily	produced as secondary decay products
initial energy known precisely	come in a wide range of energies
determination type of interaction	different types of interactions at the same time
coupling strength 1/137	coupling strength $\approx 10^{-6}$

References

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[3] M. Martini, N. Jachowicz, M. Ericson, V. Pandey, *et al.*, (2016, submitted)
[4] T. Van Cuyck, N. Jachowicz, R. González-Jiménez, *et al.*, (2016, in preparation)