MODELING NEUTRINO-NUCLEUS SCATTERING FOR ACCELERATOR-BASED EXPERIMENTS

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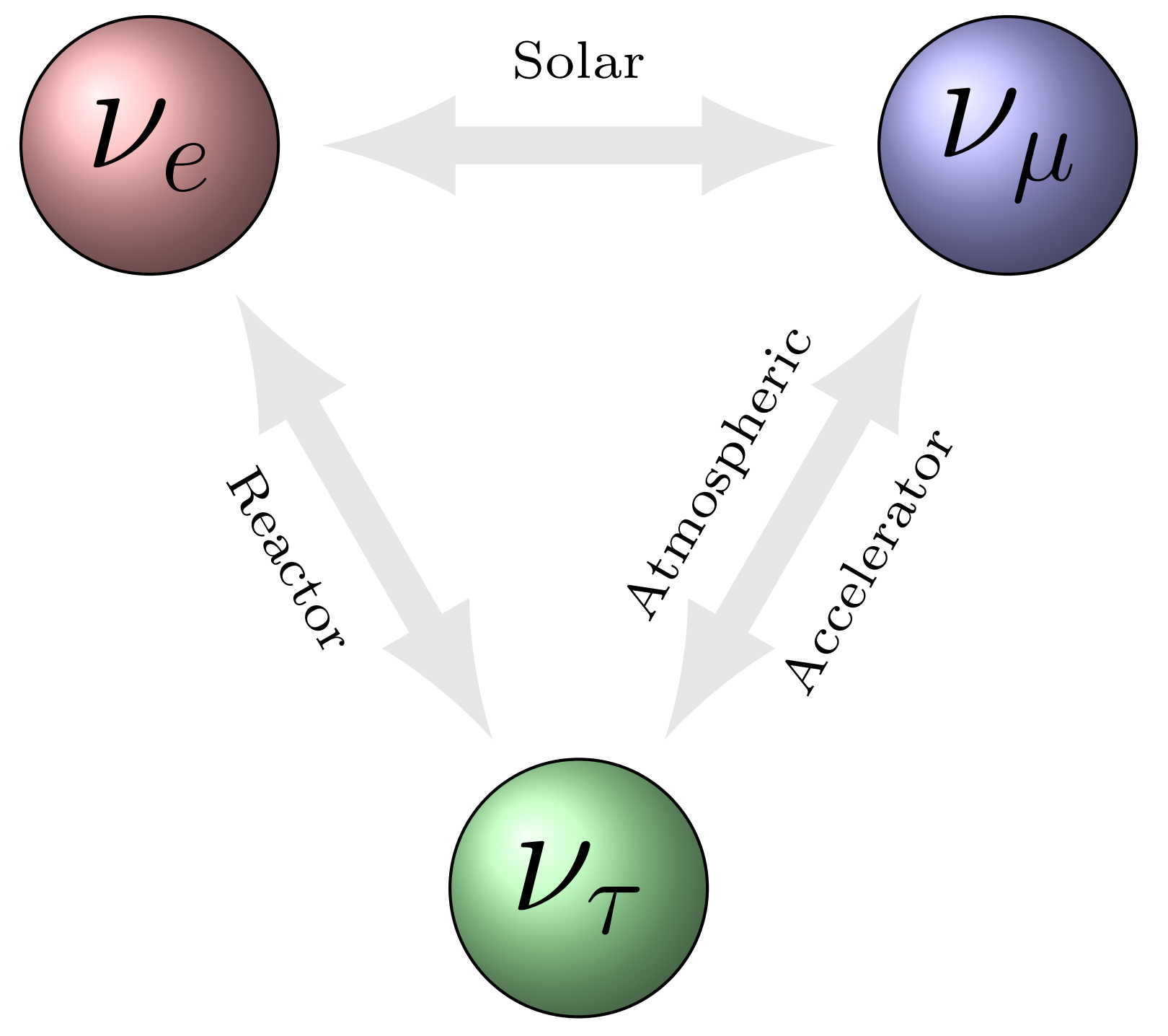
Neutrino oscillations & experiments

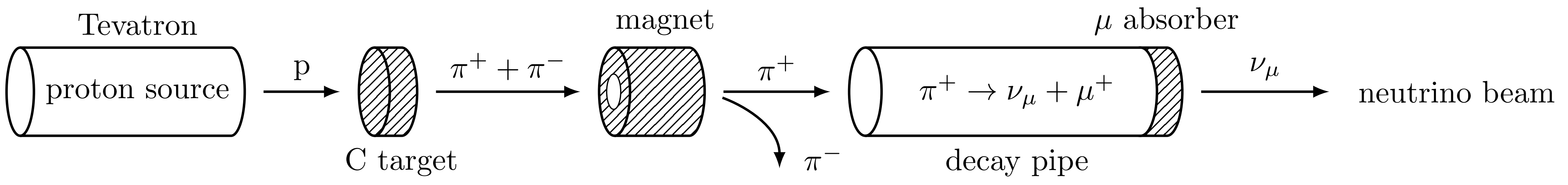
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita (of the *Super–Kamiokande* experiment) and Arthur B. McDonald (*Sudbury Neutrino Observatory*) for the discovery of *neutrino oscillations*, which show that neutrinos have mass.



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

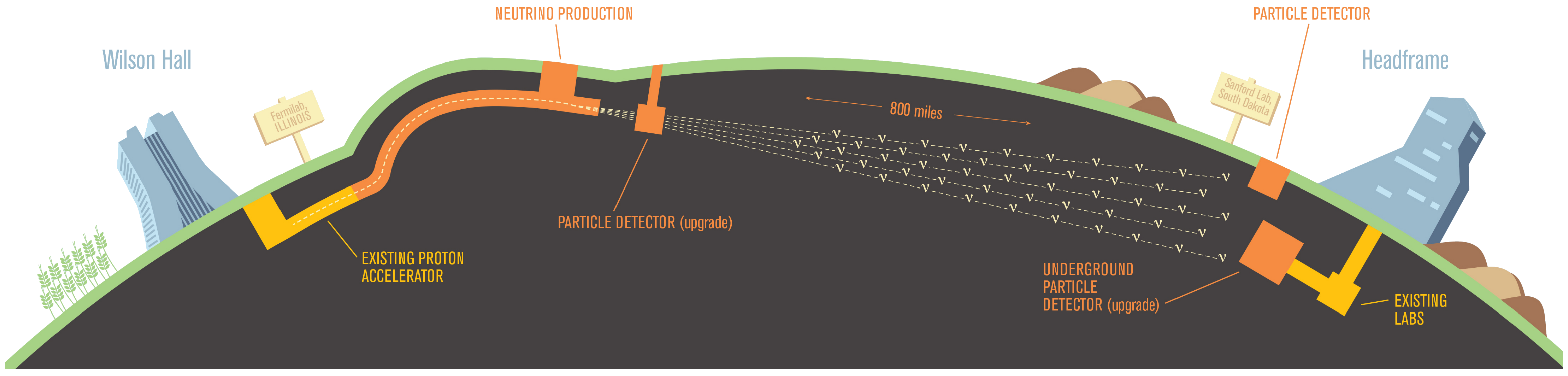
The determination of the parameters that describe the oscillations requires a *precise theoretical model* of the interaction between neutrinos and *atomic nuclei*. Neutrino-nucleus collisions are the primary way to detect neutrinos.

For the 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:



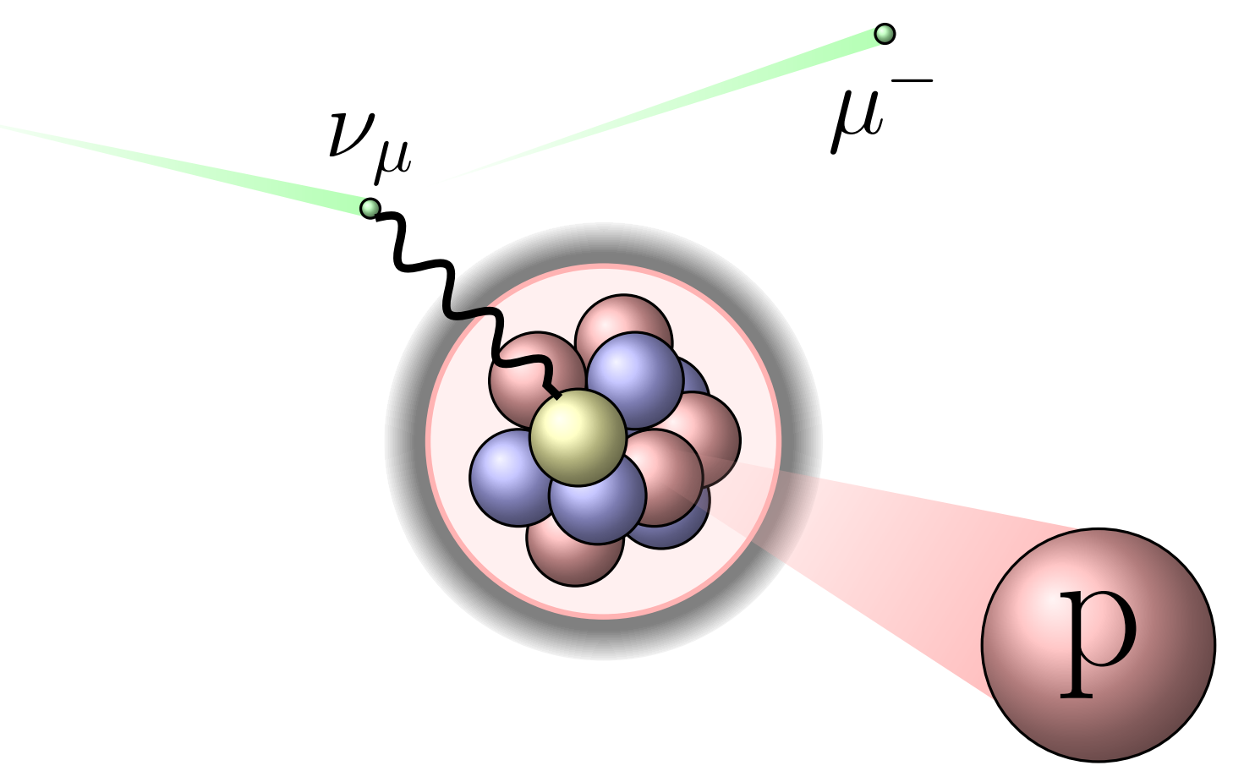
Colliding *high energy protons* (p) into a carbon target produces *pions* (π), which are subsequently separated according to their electrical charge using a magnet. These pions then decay, creating *neutrinos* (ν) and *muons* (μ). The latter are filtered out.

Neutrino oscillations are examined by *counting* the neutrinos at both the source (*near-detector)* and the *far-detector*. The difference gives 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. This is done with huge detectors, because the interaction rate is extremely low.



Cross section results

Neutrinos are detected by their interaction with a nucleus. When a ν_μ scatters off a nucleus, it can change 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.



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

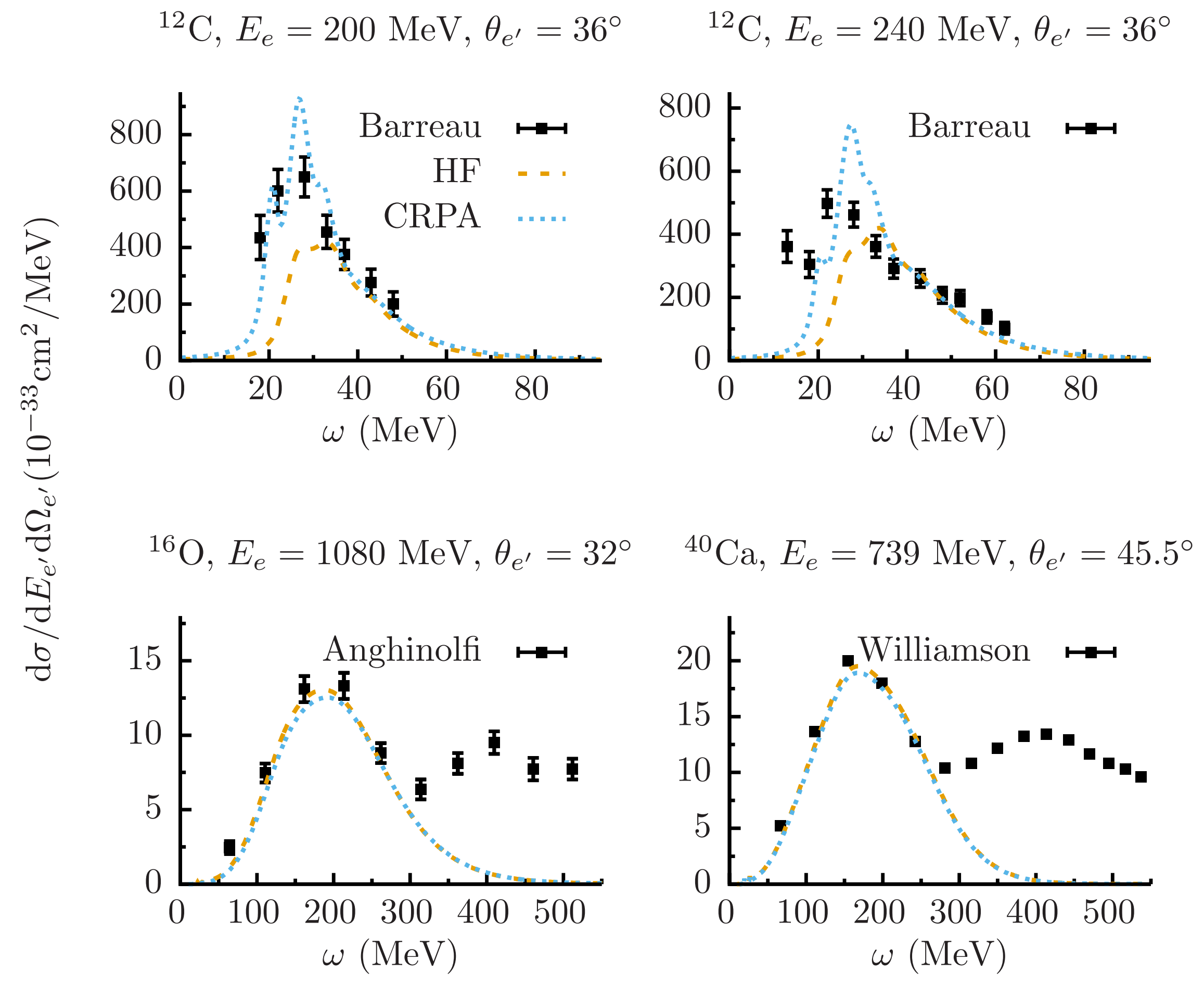
The theoretical description of the target nucleus is non–trivial. Each nucleus is constructed of protons and neutrons which are constantly interacting with each other through nuclear forces. This is considerably more difficult than a neutrino scattering off an individual nucleon.

Our research group has developed theoretical models for both electron and neutrino scattering off nuclei, which we now compare with experiment.

Step 1 - 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 $\approx 10^{-6}$

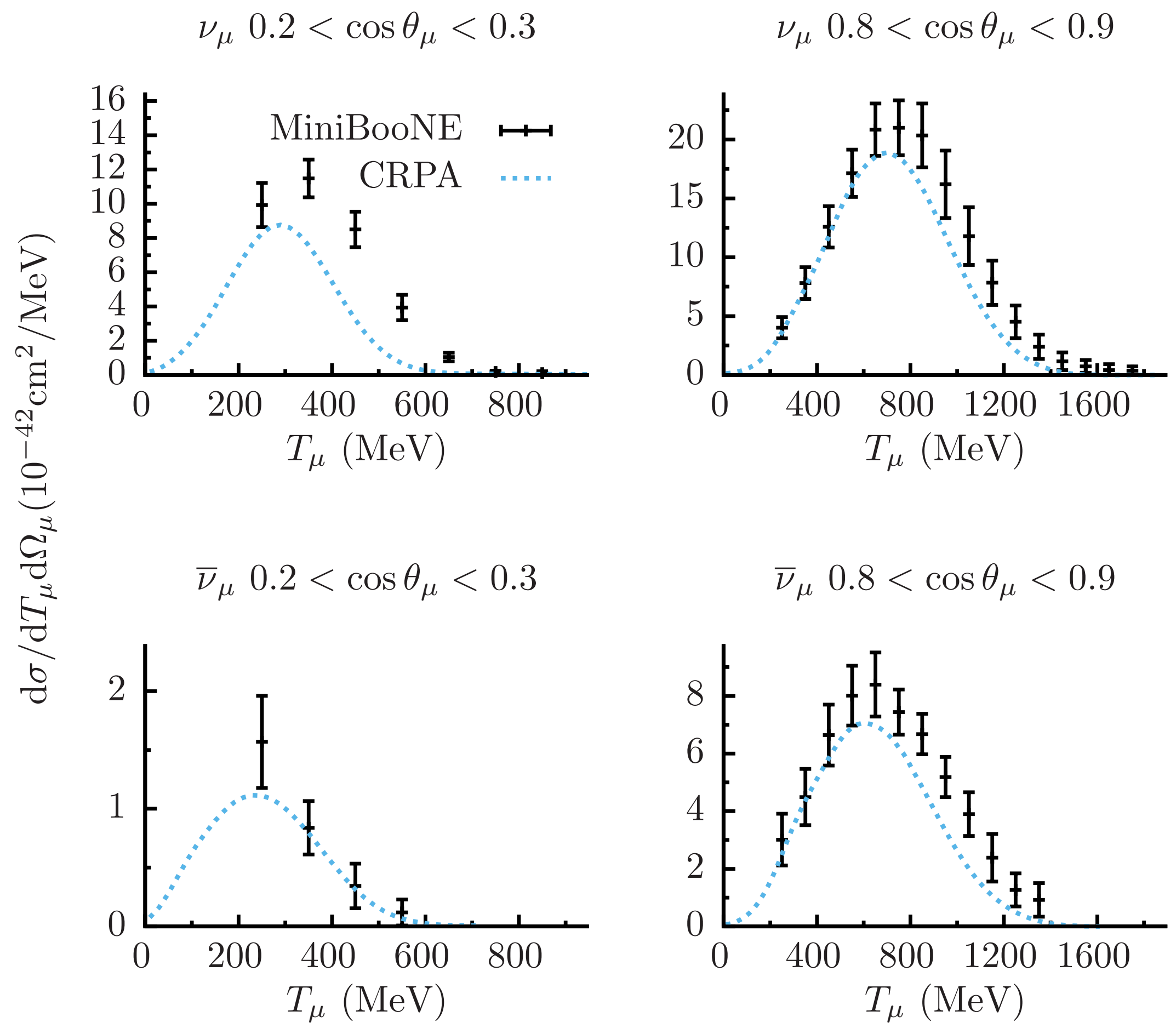


In these graphs, we compare experimental data with two theoretical models.

- **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.

Step 2 - Comparison with MiniBooNE data

MiniBooNE is one of the experiments that uses the neutrino beam at Fermilab, designed to observe neutrino oscillations (BooNE is an acronym for the Booster Neutrino Experiment).

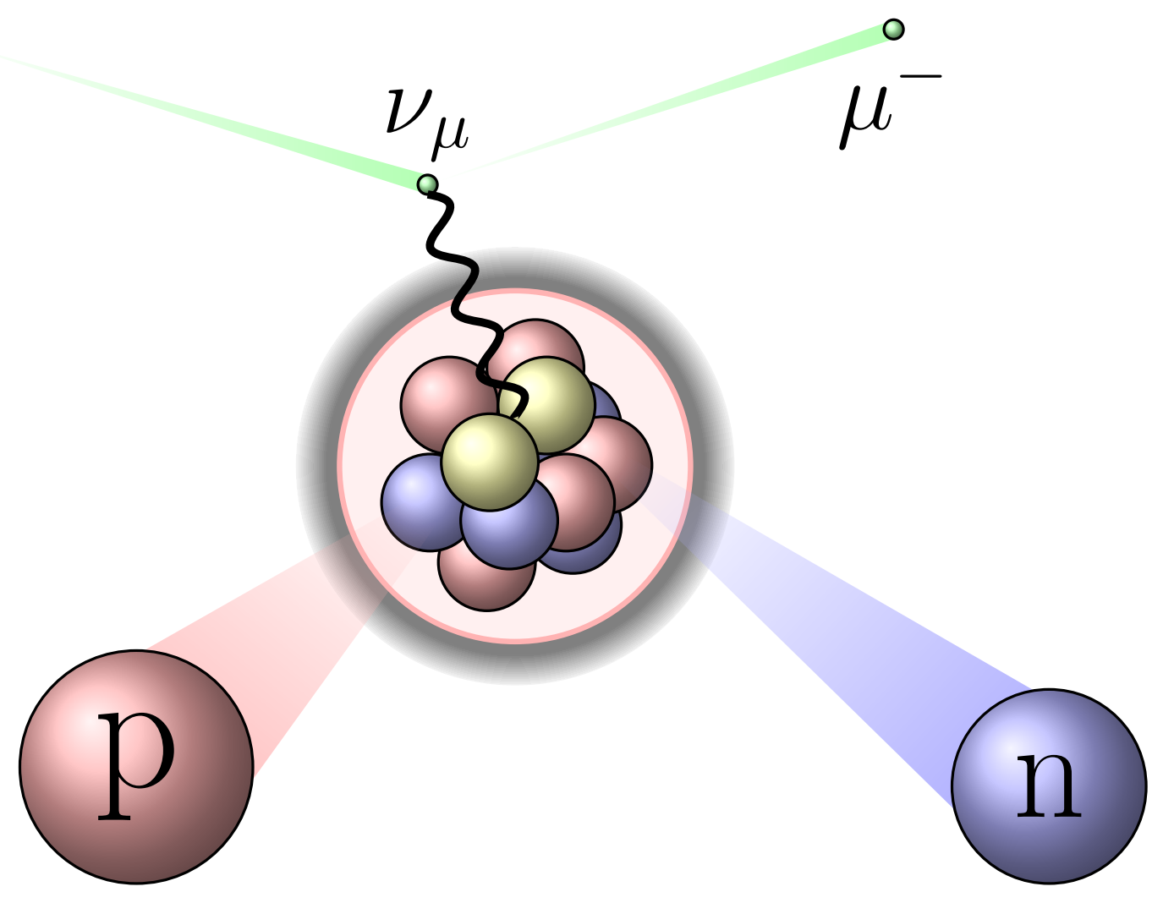


Our model is reasonably successful at reproducing experimental data. However, in comparing with MiniBooNE, we notice a systematic underestimation of the data. We need to improve our model to solve this.

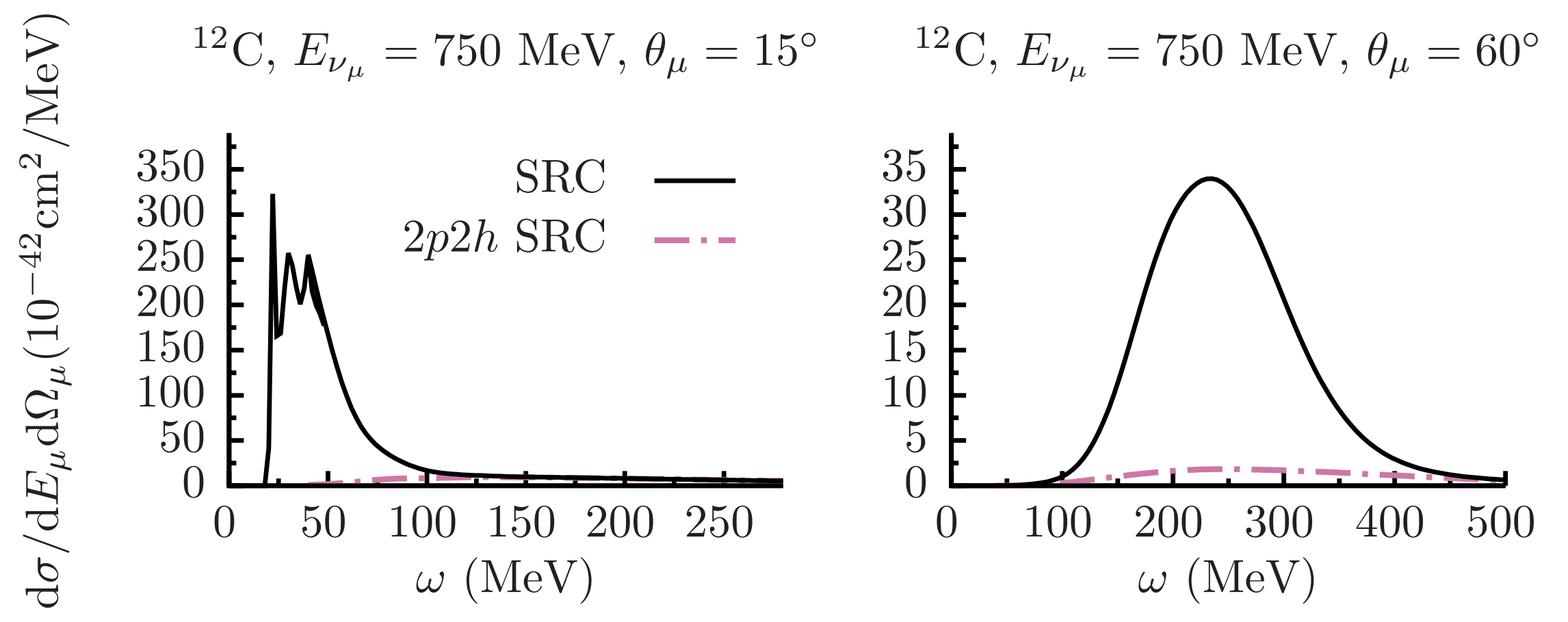
Step 3 - Inclusion of two-nucleon knockout

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

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



- **SRC** – The Short-Range Correlations take into account that protons and neutrons inside the nucleus often occur in *pairs*. When an electron or neutrino interacts with a pair of nucleons, they can both be knocked out of the nucleus.



The two-nucleon knockout of SRC pairs increases the cross section, but more two-nucleon effects have to be incorporated for a full description of the data.

References

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