Neutron detection to improve the neutrino energy resolution in oscillation experiments

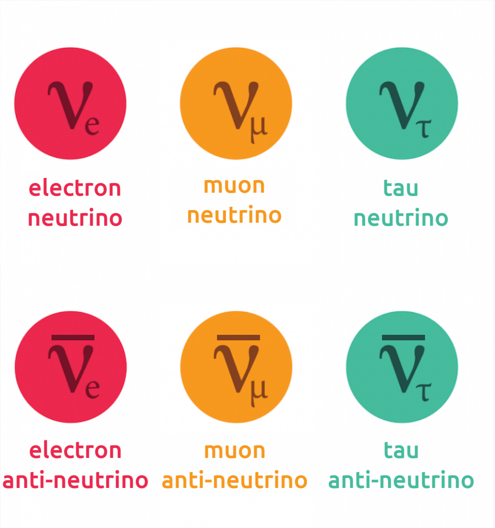
Pierre Granger
Neutrino group APC

Novenber 2, 2022

APC - CNRS

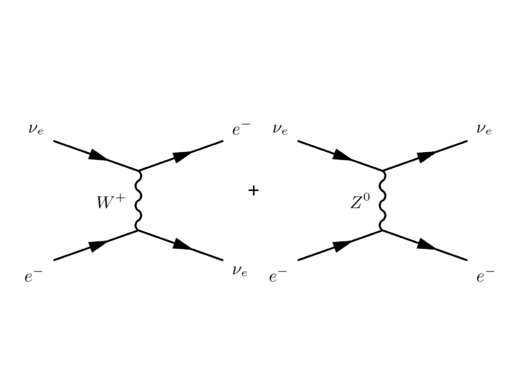
The neutrino:

- exists in 3 **flavours** (+ 3 associated antineutrinos)



The neutrino:

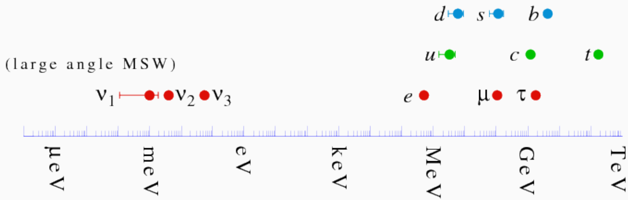
- exists in 3 **flavours** (+ 3 associated antineutrinos)
- interacts via **weak interaction**



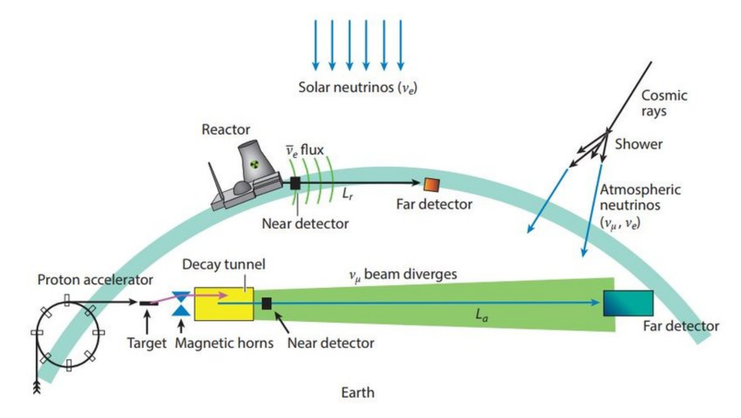
The neutrino

The neutrino:

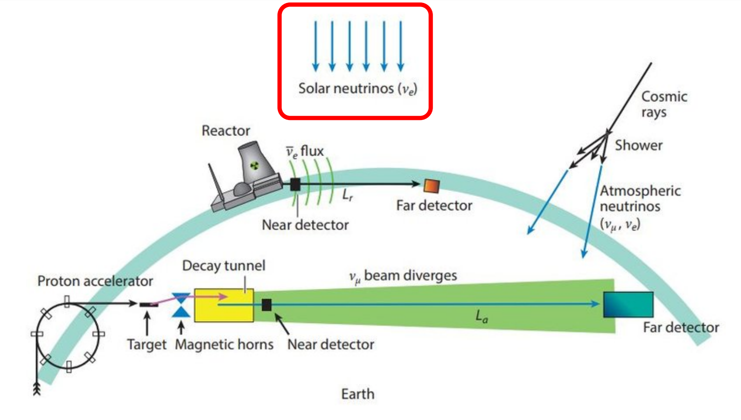
- exists in 3 **flavours** (+ 3 associated antineutrinos)
- interacts via **weak interaction**
- is **extremely light**

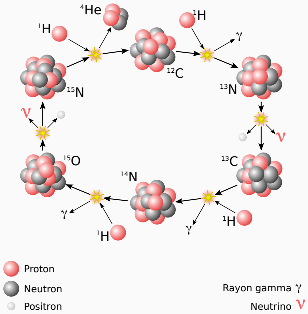


Neutrino sources

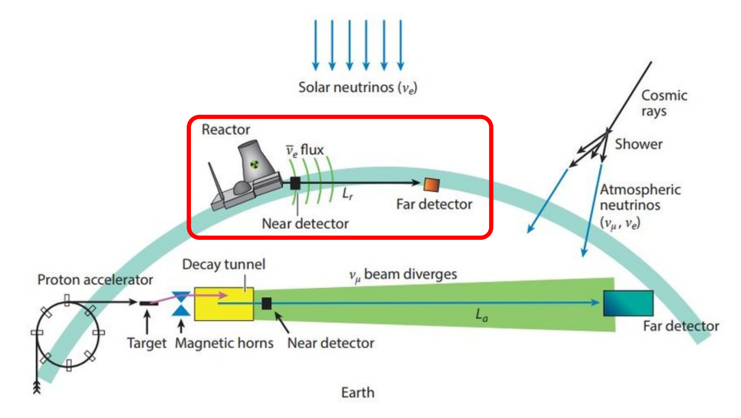


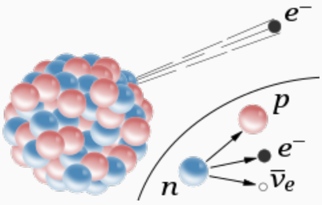
Neutrino sources



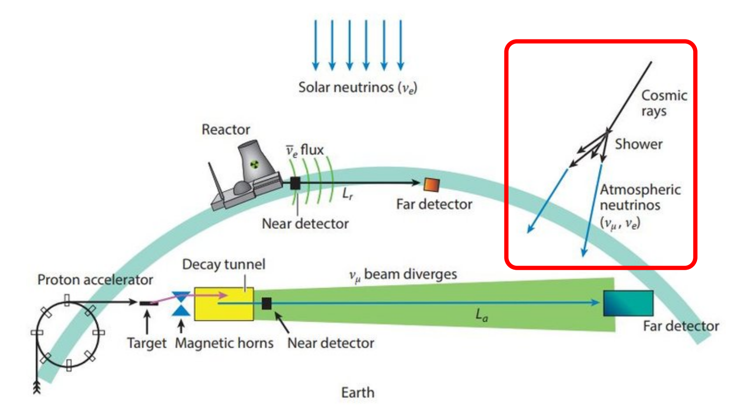


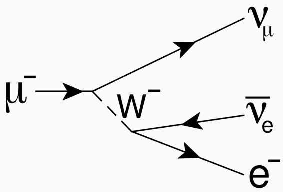
Neutrino sources



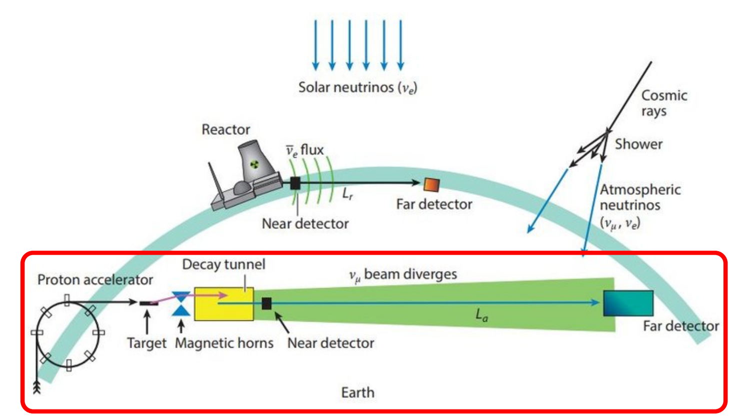


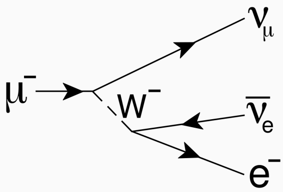
Neutrino sources



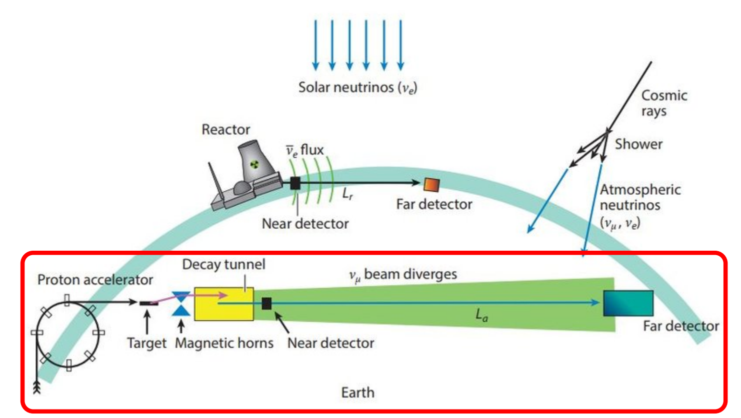


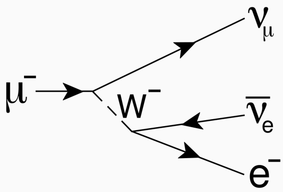
Neutrino sources





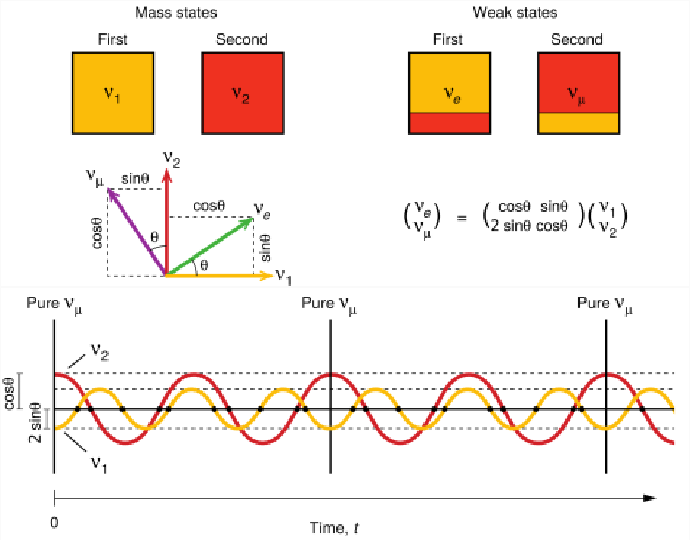
Neutrino sources



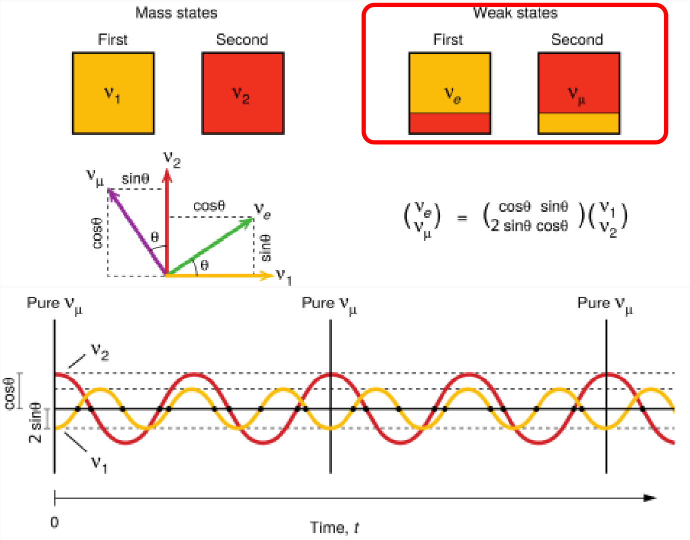


We observe changes in the neutrinos flavour as they travel
$\rightarrow$ **oscillations**

Neutrino oscillations

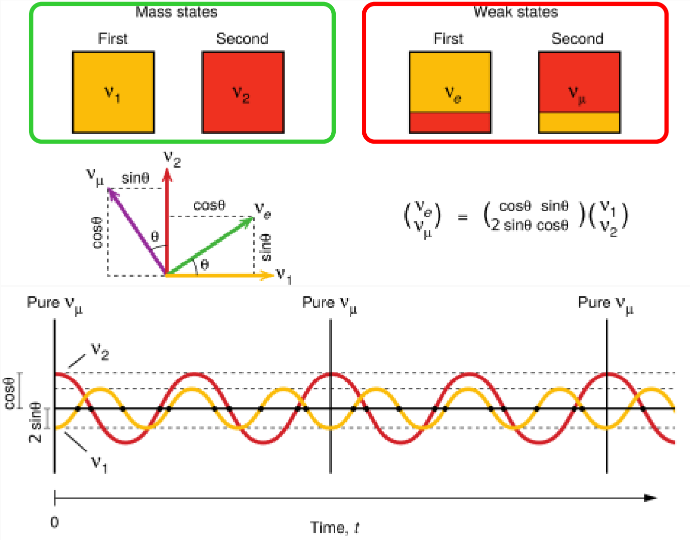


Neutrino oscillations



Weak states:

- States under which the neutrinos interact via weak interaction
- ν_e, ν_μ, ν_τ



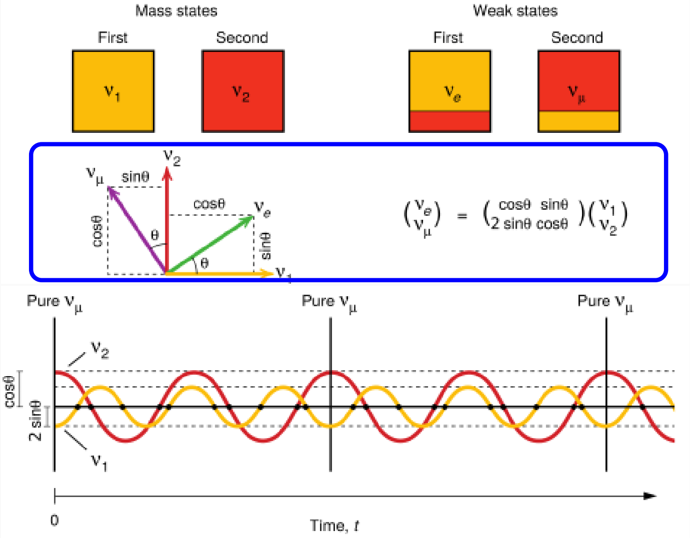
Weak states:

- States under which the neutrinos interact via weak interaction
- ν_e, ν_μ, ν_τ

Mass states:

- States under which the neutrinos propagate
- Eigenstates of the free Hamiltonian
- ν_1, ν_2, ν_3

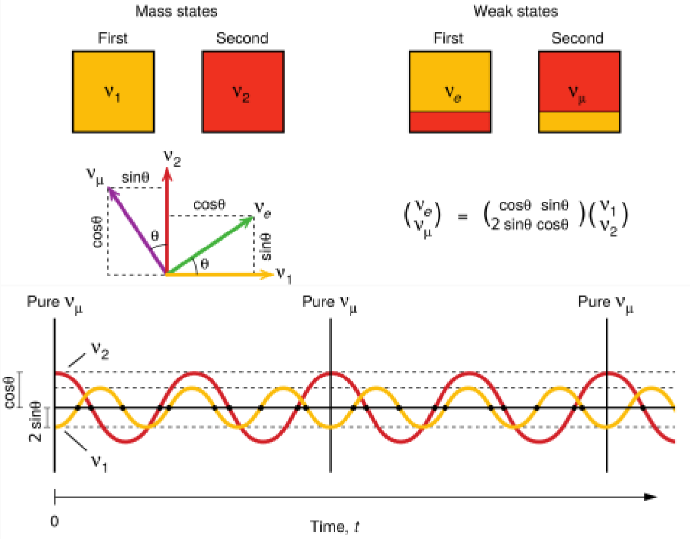
Neutrino oscillations



Relation:

- Each weak state is composed of a **linear superposition** of the mass states
- Parametrization with **mixing angles** $\theta_{i,j}$
- Oscillation inbetween the mass states during propagation (close masses) $\Longrightarrow$ **change in detected flavour**

Neutrino oscillations



2-flavour osc. prob.:

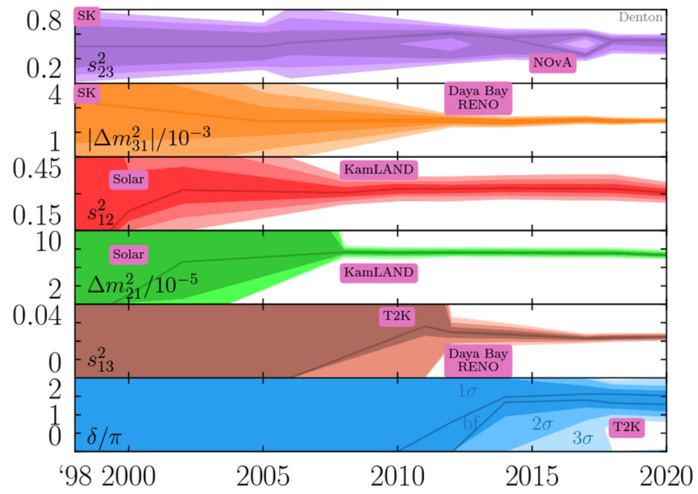
$\mathcal{P}(\nu_\alpha \to \nu_\beta) =$

$\sin^2(2\theta)\sin^2\left(\frac{\Delta m^2}{4}\frac{\mathbf{L}}{\mathbf{E}}\right)$

where $\Delta m^2 = m_2^2 - m_1^2$.

Oscillations are driven by the **L/E** ratio

Neutrino oscillations open questions



- What are the precise values of the oscillation parameters? → now entering an era of precision measurements
- Are oscillations the same for ν and $\bar{\nu}$ (driven by δ_{CP}) → could partly explain the matter-antimatter asymetry in the universe
- What is hierarchy of the neutrino masses (sign of Δm_{31}^2) → could help understand how neutrinos acquire mass

→ Necessity to improve number of events (larger detector masses) and E resolutions

Detecting neutrinos

Neutrinos interactions with matter:

$\nu_\ell + \mathbf{n} \rightarrow \ \ell^- + \mathbf{p}$ **(+ others)**

$\bar{\nu}_\ell + \mathbf{p} \rightarrow \ \ell^+ + \mathbf{n}$ **(+ others)**

Detecting neutrinos

Neutrinos interactions with matter:

$$\nu_\ell + \mathbf{n} \rightarrow \boxed{\ell^- + \mathbf{p}\ (+\ \mathbf{others})} \qquad \bar{\nu}_\ell + \mathbf{p} \rightarrow \boxed{\ell^+ + \mathbf{n}\ (+\ \mathbf{others})}$$

Reconstruction of $\mathbf{E}_\nu$ **from final state**

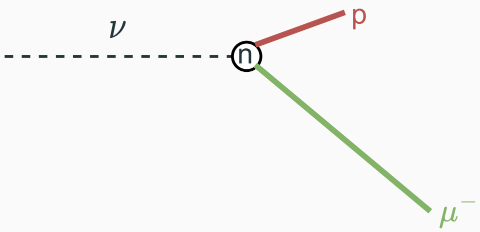
Detecting neutrinos

Neutrinos interactions with matter:

$$\nu_\ell + \mathbf{n} \rightarrow \boxed{\ell^- + \mathbf{p}\ (+\ \mathbf{others})} \qquad \bar{\nu}_\ell + \mathbf{p} \rightarrow \boxed{\ell^+ + \mathbf{n}\ (+\ \mathbf{others})}$$

Reconstruction of **$\mathbf{E}_\nu$ from final state**

- ℓ^- and p detected
- $\mathbf{E}_\nu = \mathbf{E_p} + \mathbf{E}_\ell$



Detecting neutrinos

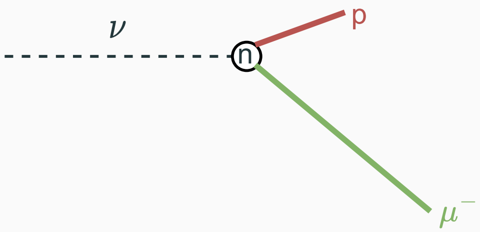
Neutrinos interactions with matter:

$\nu_\ell + \mathrm{n} \rightarrow \boxed{\ell^- + \mathrm{p}\ (+\ \text{others})}$

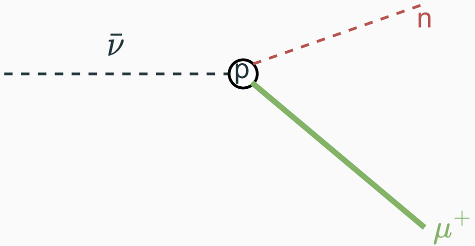
$\bar{\nu}_\ell + \mathrm{p} \rightarrow \boxed{\ell^+ + \mathrm{n}\ (+\ \text{others})}$

Reconstruction of $\mathbf{E}_\nu$ **from final state**

- ℓ^- and p detected
- $\mathbf{E}_\nu = \mathbf{E}_\mathrm{p} + \mathbf{E}_\ell$



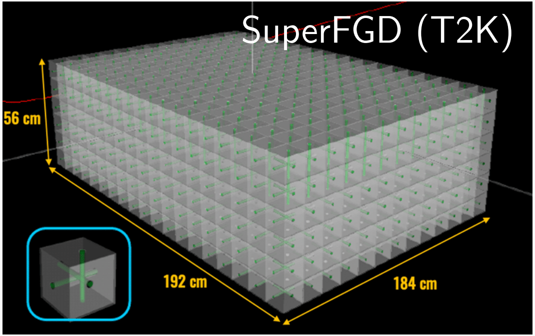
- ℓ^- only detected
- $\mathbf{E}_{\bar{\nu}} \simeq \dfrac{\mathbf{m}_\mathrm{n}^2 - \mathbf{m}_\mathrm{p}^2 - \mathbf{m}_\ell^2 + 2\mathbf{m}_\mathrm{p}\mathbf{E}_\ell}{2\left(\mathbf{m}_\mathrm{p} - \mathbf{E}_\ell + \mathbf{p}_\ell \cos\theta_\ell\right)}$



Detecting neutrinos with a fine grained scintillating detector

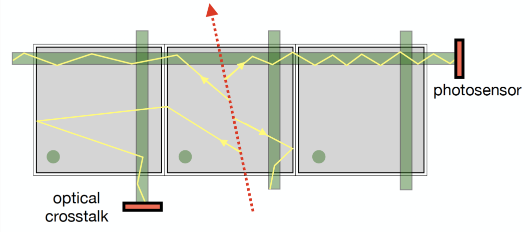
Detector design:

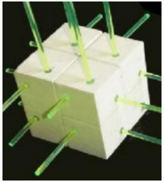
- High interaction rates → **large detector with fiber readout in 3 direction**
- High resolution events reconstruction → **High granularity** (1 cm size cubes) + **Good electronics time resolution** (< 1 ns)



FGD working principle:

Ionization by charged particles → Production of **scintillation light** → Light **collected by fibers** and read out



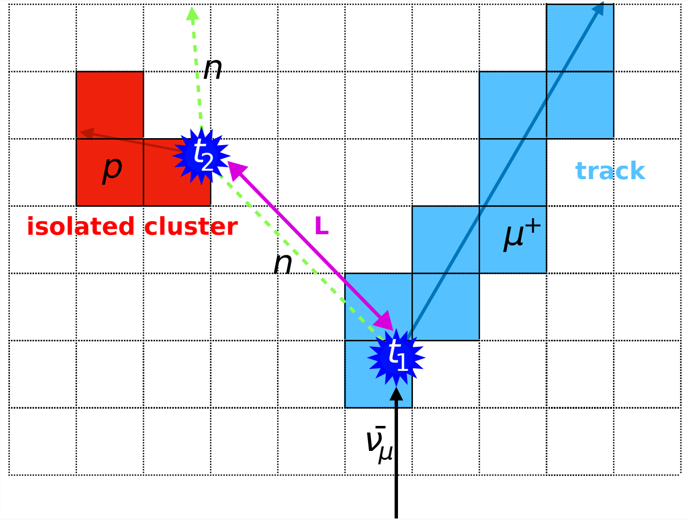


How to detect neutrons with the a fine grained scintillating detector

How to leverage the high granularity to measure neutrons energy:

How to detect neutrons with the a fine grained scintillating detector

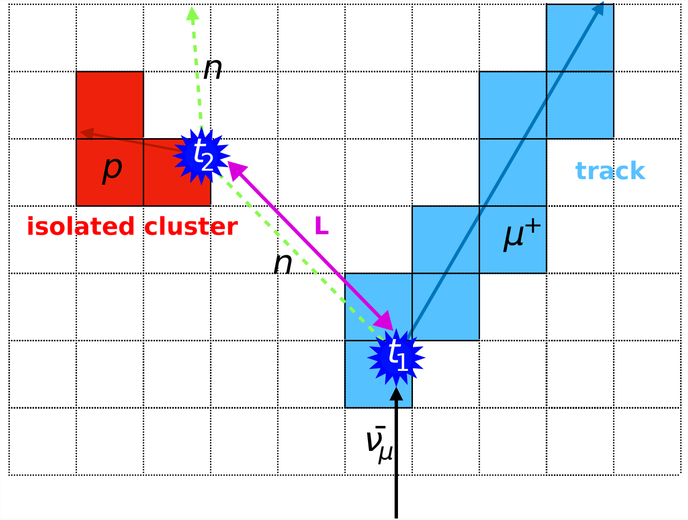
How to leverage the high granularity to measure neutrons energy:



- Neutrons **interact sporadically** (proton recoil) → **isolated clusters**

How to detect neutrons with the a fine grained scintillating detector

How to leverage the high granularity to measure neutrons energy:



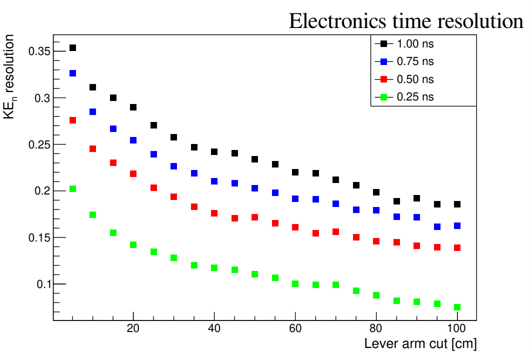
- Neutrons **interact sporadically** (proton recoil) → **isolated clusters**
- Their energy can be determined using the **time of flight** and **distance** to production vertex

$$\beta = \frac{L}{c(t_2 - t_1)} \qquad E_n = \frac{m_n}{\sqrt{1-\beta^2}}$$

Neutron detection performances

The neutrons kinetic energy can be measured

$$\beta = \frac{L}{c(t_2 - t_1)} \quad E_n = \frac{m_n}{\sqrt{1-\beta^2}}$$



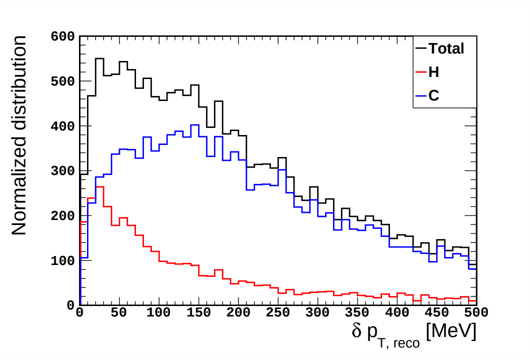
Energy resolution improves when:

- spatial resolution improves (increase granularity)
- time resolution improves (improve the electronics time response)
- the distance traveled by the neutron (lever arm) gets larger (apply a selection on the events)

The choices of the electronics and granularity impact the neutron energy resolution, and thus neutrino energy resolution: $E_\nu = E_\mu + E_n$

Using the neutron information

The momentum in the plane ⊥ neutrino beam (δp_T) can be measured



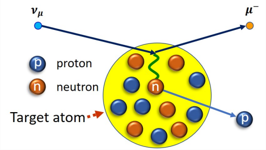
Allows to **select $\bar{\nu}$ + H interactions** that enable a **better neutrino energy reconstruction** w.r.t $\bar{\nu} + C$ (no nuclear effect)

$\bar{\nu}$ interaction on H:

- H nucleus = proton at rest
- $P_p + P_\nu = P_n + P_\mu \implies 0 = P_n^\perp + P_\mu^\perp$
  $\implies \delta P_T = 0$

$\bar{\nu}$ interaction on C:

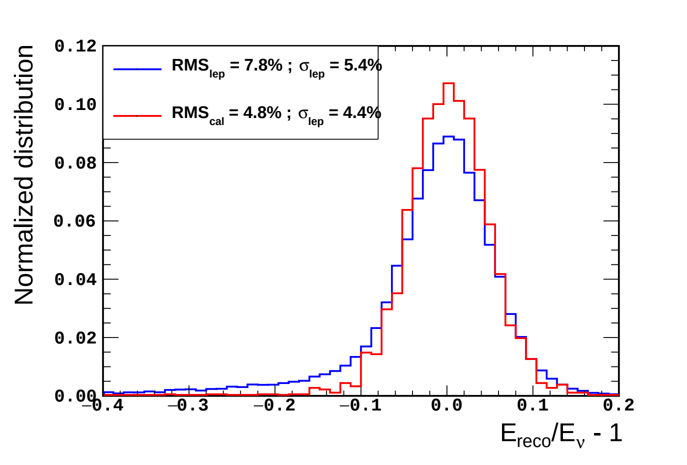
- C nucleus → interaction with a proton in interaction with other nucleons
- $P_p + P_\nu = P_n + P_\mu \implies P_p^\perp = P_n^\perp + P_\mu^\perp$
  $\implies \delta P_T \neq 0$



Improvement on the neutrino energy resolution

Comparing the resolution on the reconstructed neutrino energy:

- with the muon-only information: $E_{\bar{\nu}}^{lep} = \frac{m_n^2 - m_p^2 - m_\mu^2 + 2m_p E_\mu}{2(m_p - E_\mu + p_\mu \cos\theta_\mu)}$
- with the neutron information: $E_{\bar{\nu}}^{cal} = E_\mu + E_n - m_p$ with
  - Neutron distance to vertex $L > 10\,\text{cm}$
  - $\delta p_T < 40\,\text{MeV}$



Being able to detect the neutrons and measure their energy improves E_ν reconstruction!