From photo-multipliers to the matter anti-matter asymmetry

Interns’ seminar

Nicolas Lemaire

Supervisor : P. Paganini

Laboratoire Leprince-Ringuet

ÉCOLE POLYTECHNIQUE
UNIVERSITÉ PARIS-SACLAY

Summary

I. Hyper-Kamiokande test bench contributions

- Context of the test bench
- Choice of the generator

I. On low scale thermal leptogenesis

- Dirac and Majorana
- See-saw mechanism
- Leptogenesis

I. HK test bench contributions

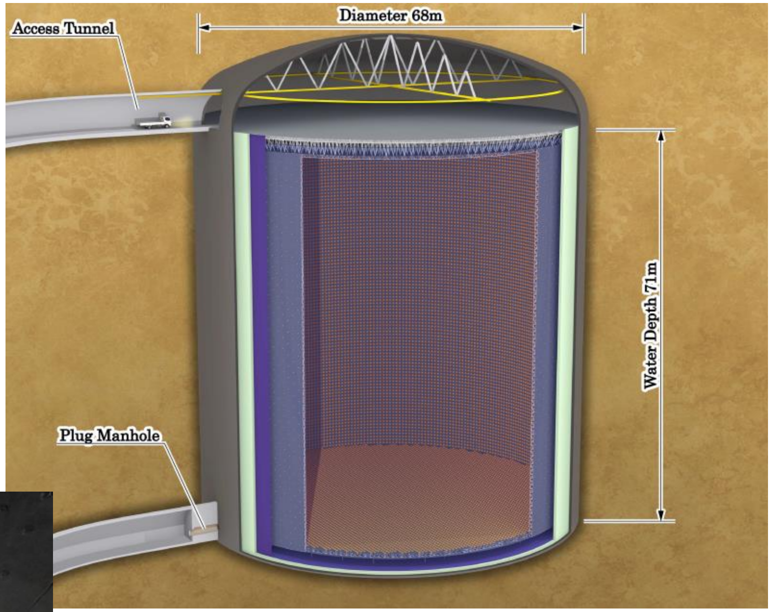
Context of the test bench

Hyper-Kamiokande

Water-Cherenkov detector for neutrinos

Around **8 times** the fiducial volume of Super-Kamiokande

Data taking starting **2027** with ~**20 000 PMTs**



Design of the detector

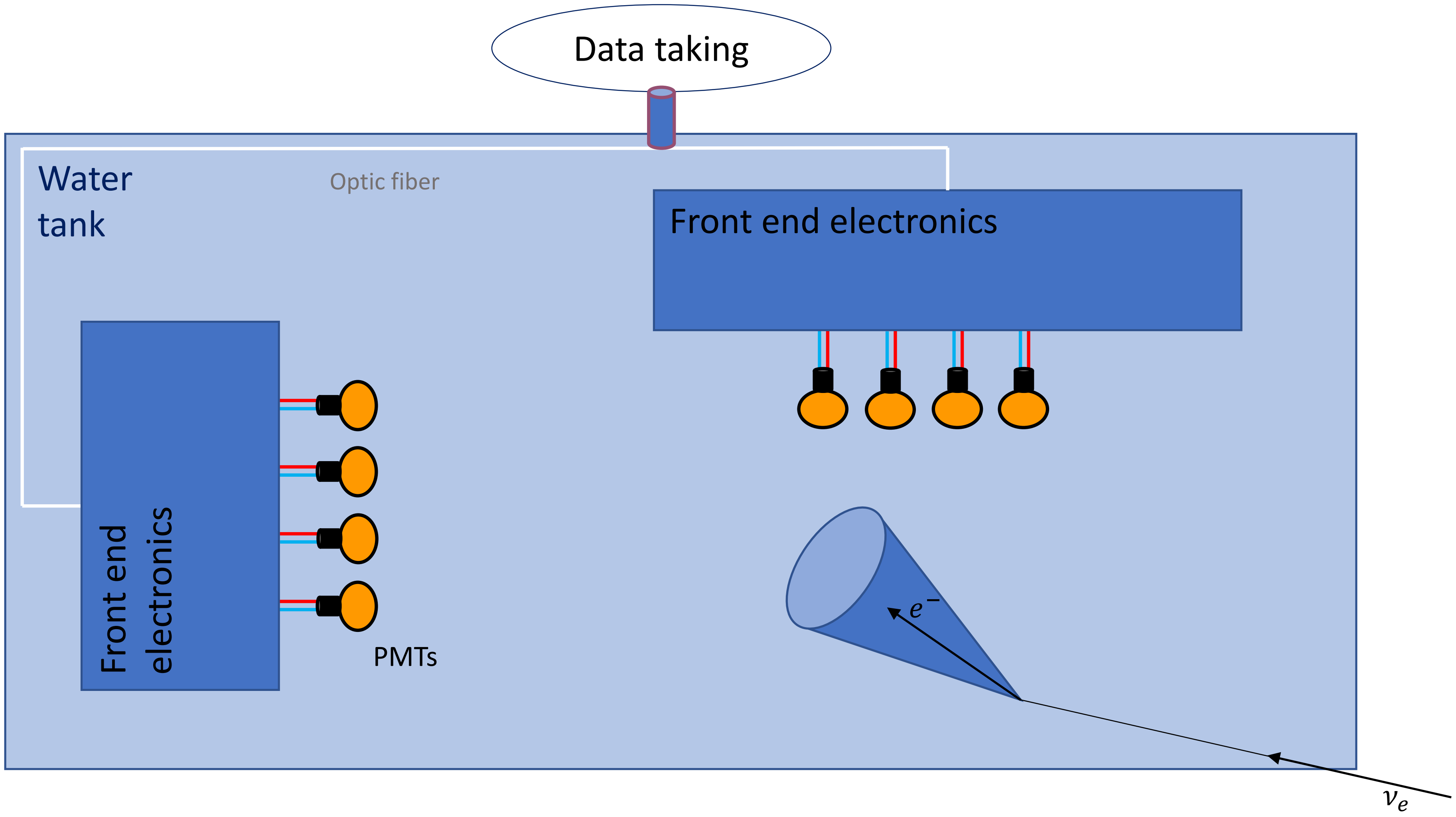
Photomultiplier tubes (PMT)

Progress of the excavation (end 2023)

Main objective :
Precise measurement of the Dirac **CP-violating phase**

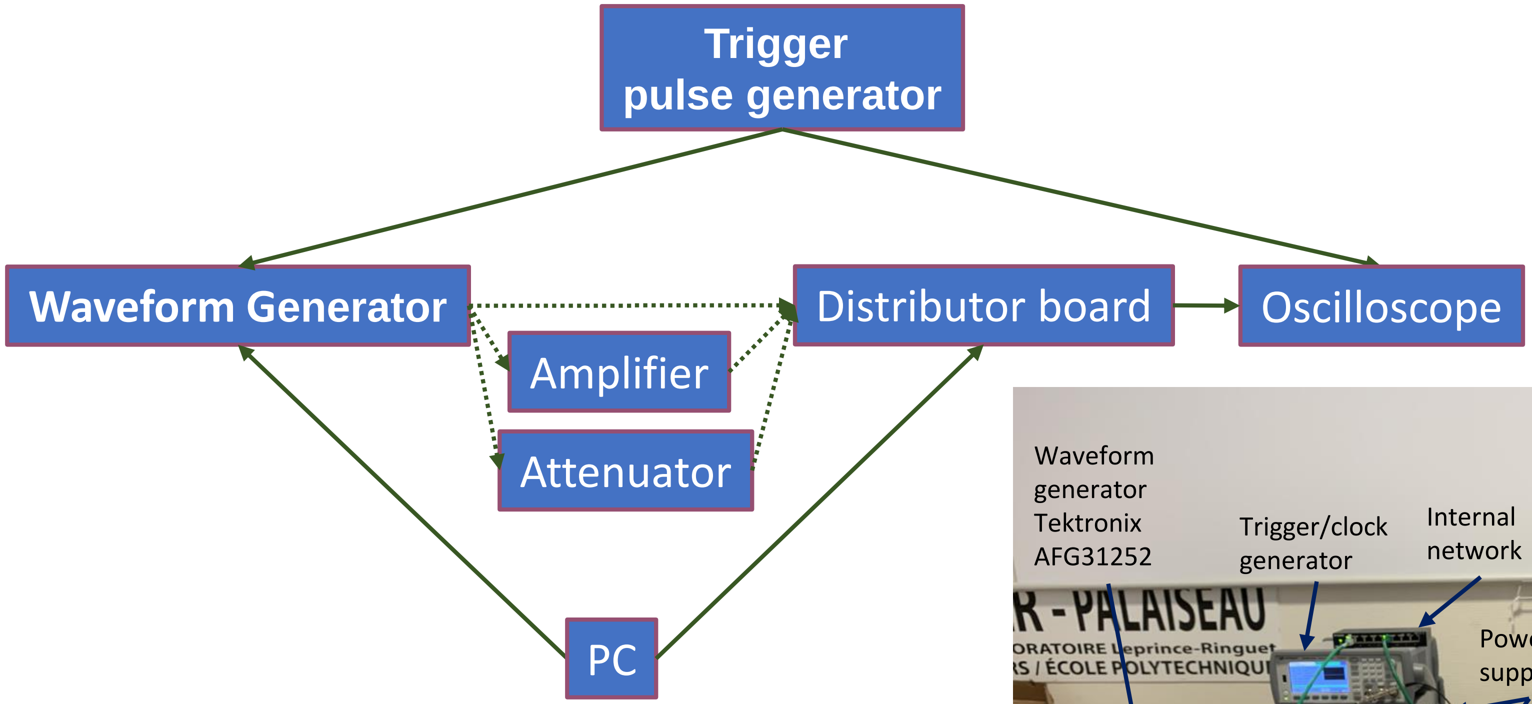
Context of the test bench

Huge volume and number of PMTs ⇨ Need to **limit the mass** of cables



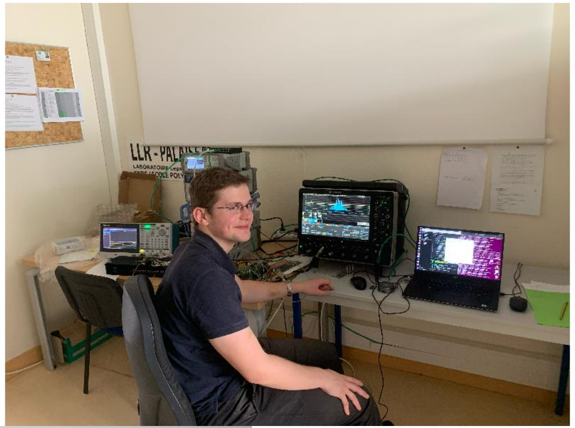
Objective :
test the electronics by **emulating PMTs**

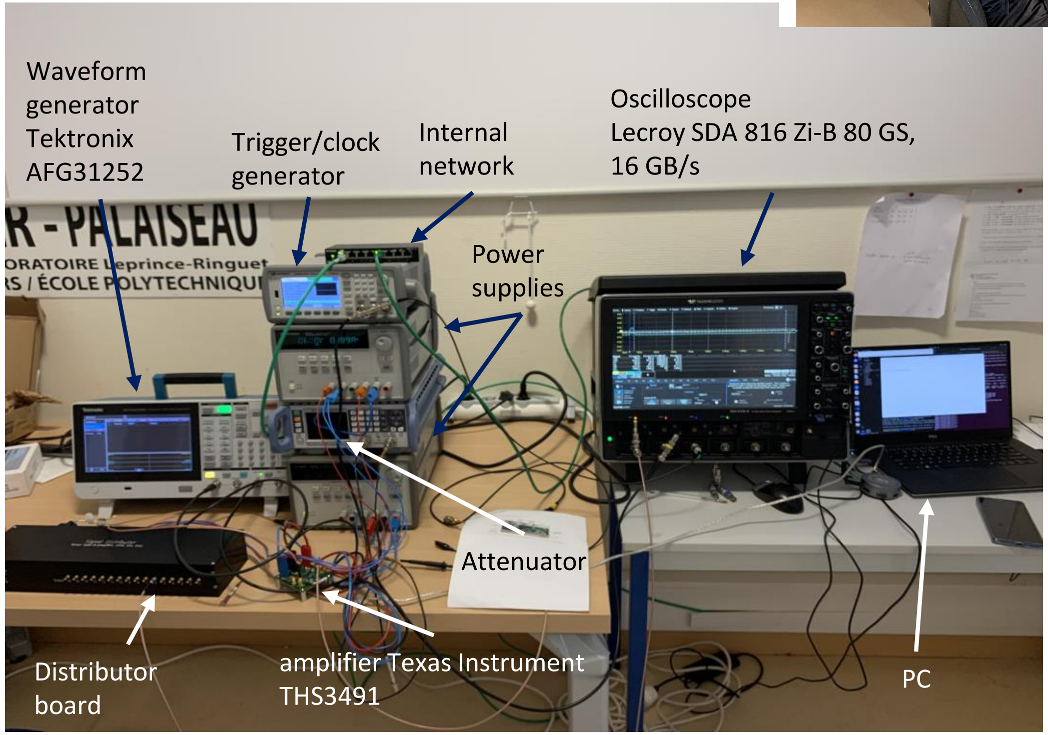
The test bench



Purpose :
Precisely generate signals corresponding to any number of **photo-electrons** (p.e.)

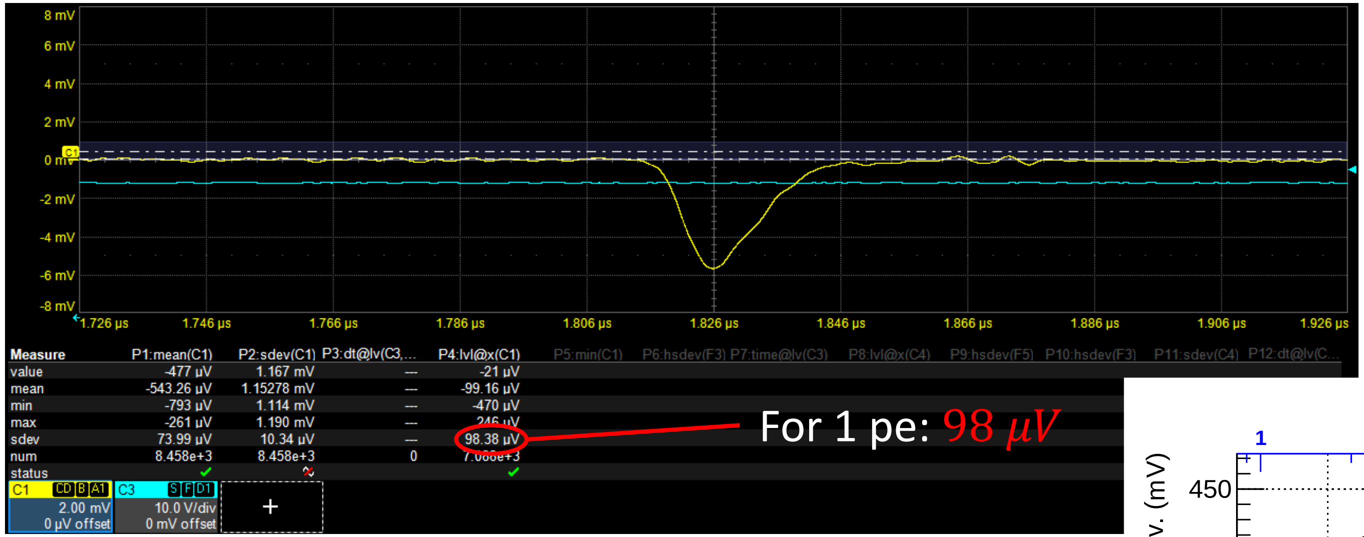
$1\ \mathrm{pe} \sim 6\ mV$





Choice of the generator

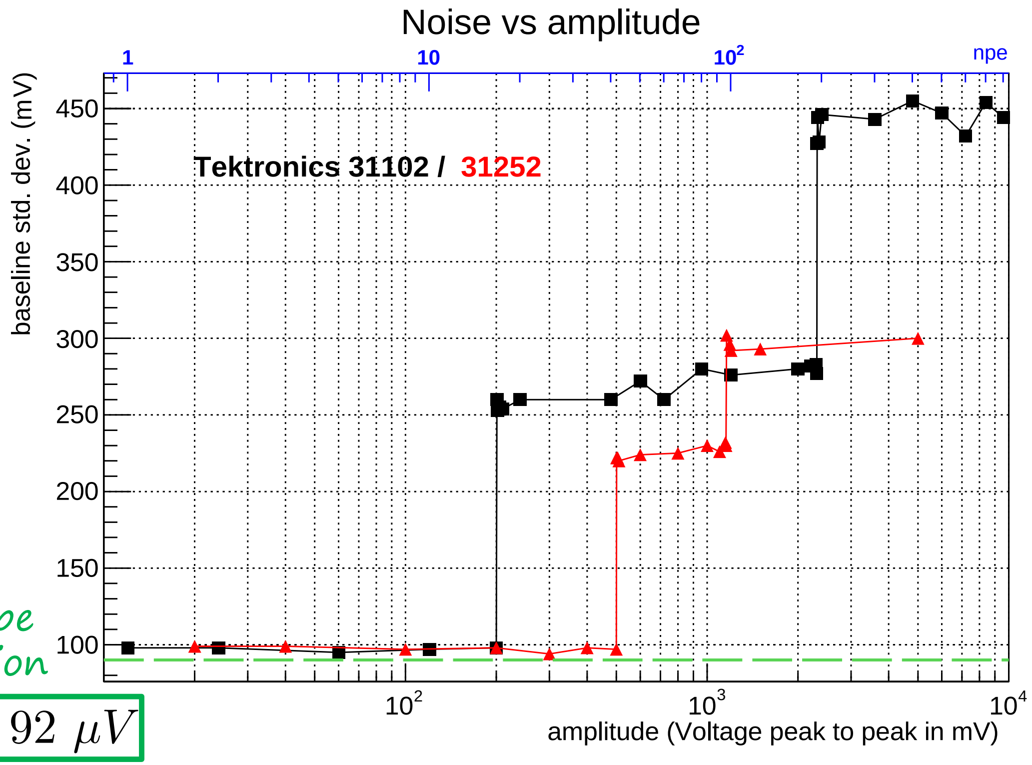
Noise



For 1 pe: $98\ \mu V$

One generator **significantly noisier**

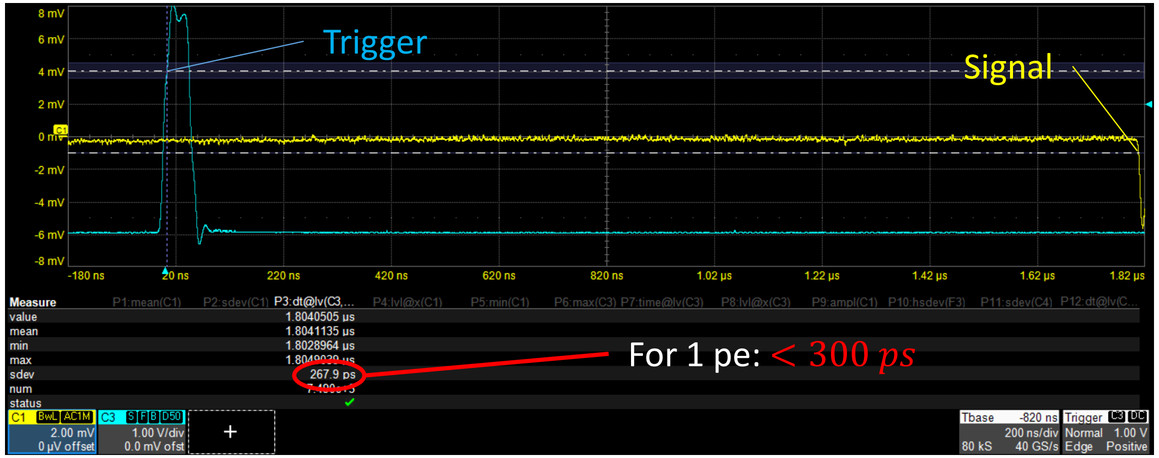
Three regions of same noise



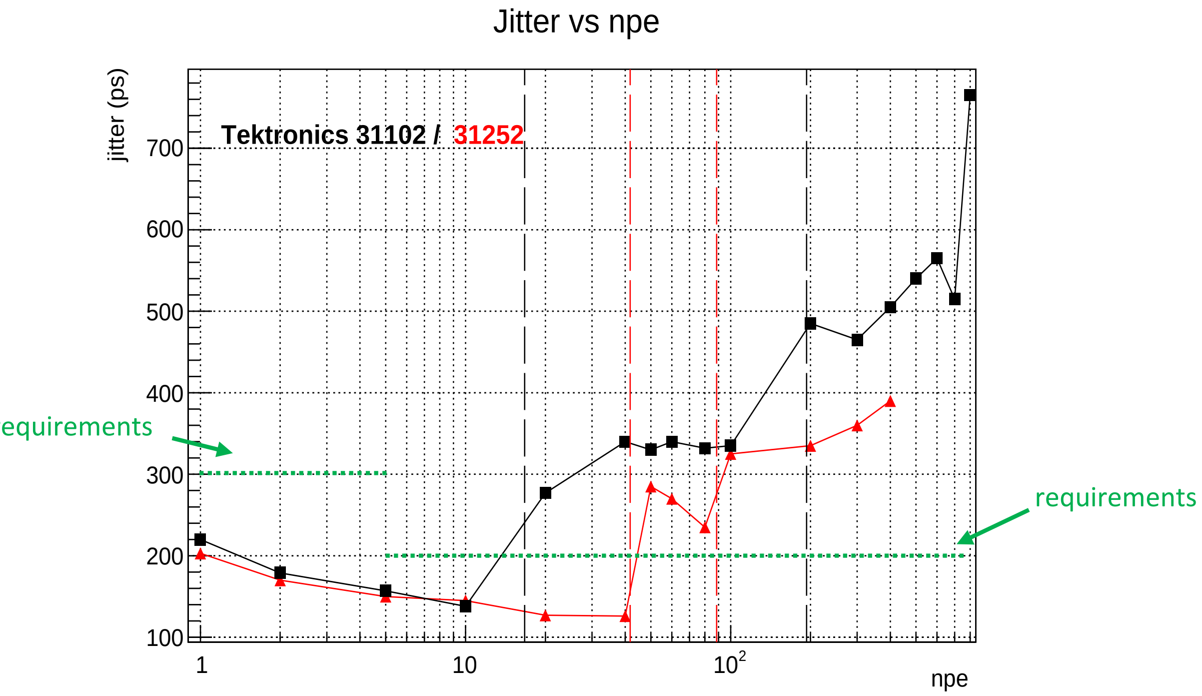
Oscilloscope contribution

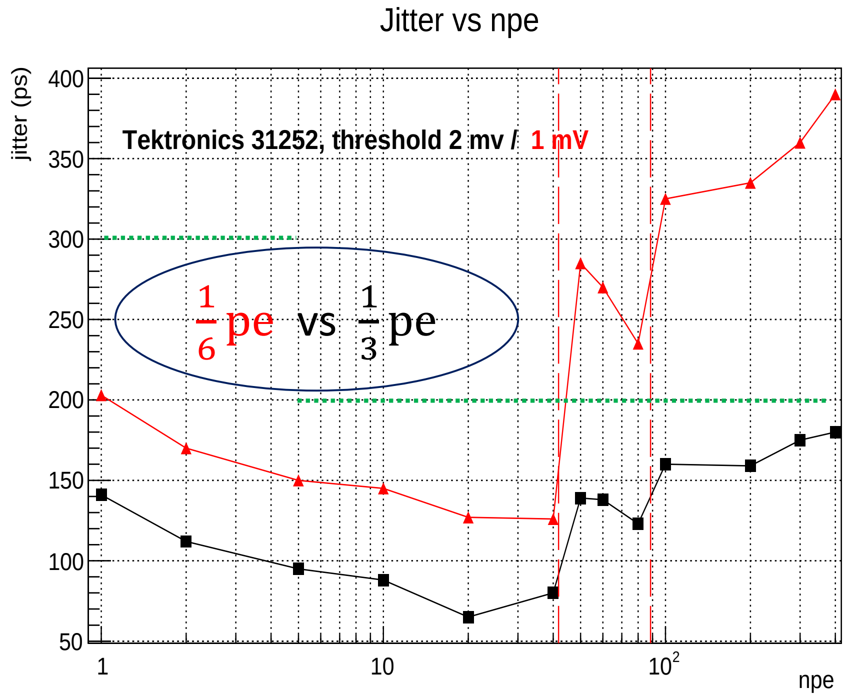
$$\sigma_V^{\text{oscil.}} = 92\ \mu V$$

Jitter



$$t_{signal}\left(\frac{1}{6}\text{pe} \approx 1\ mV\right) - t_{trigger}$$



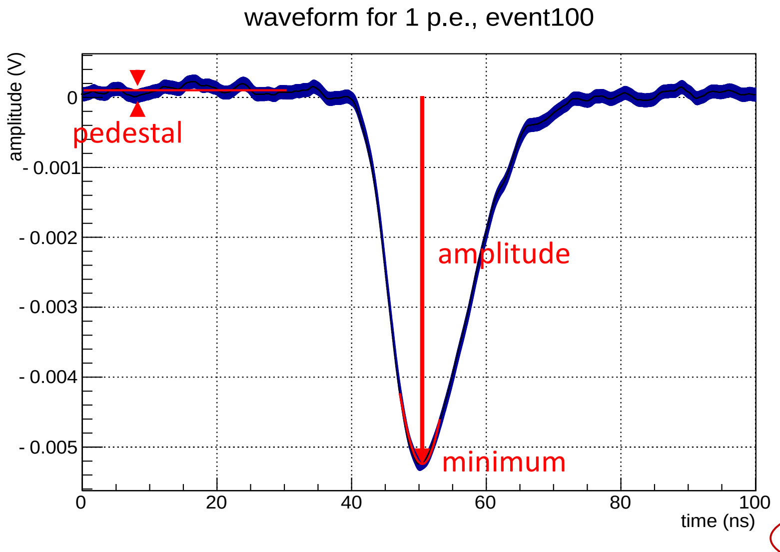


Less noise → better jitter

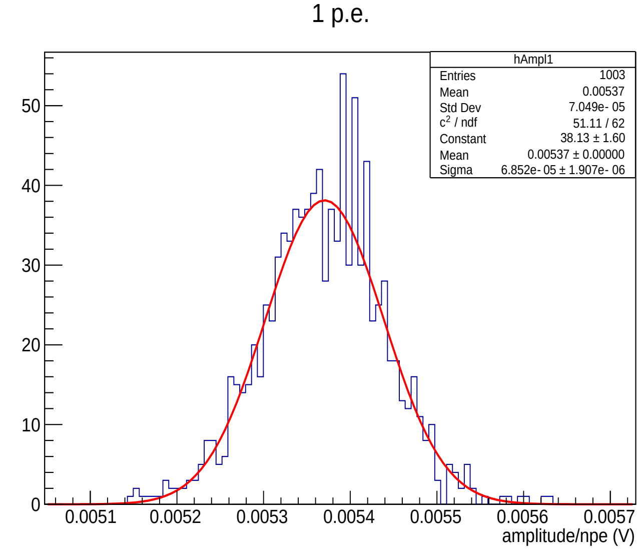
Adapt the threshold for high n_{pe}

Linearity

1)

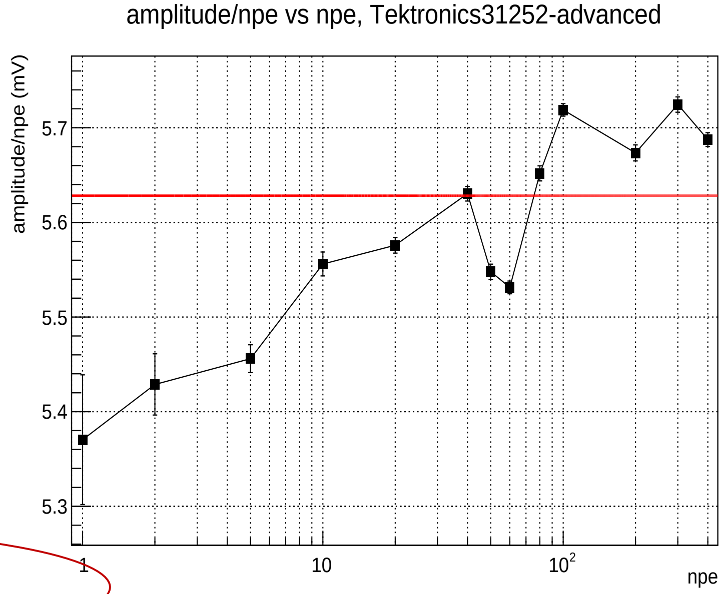


2)

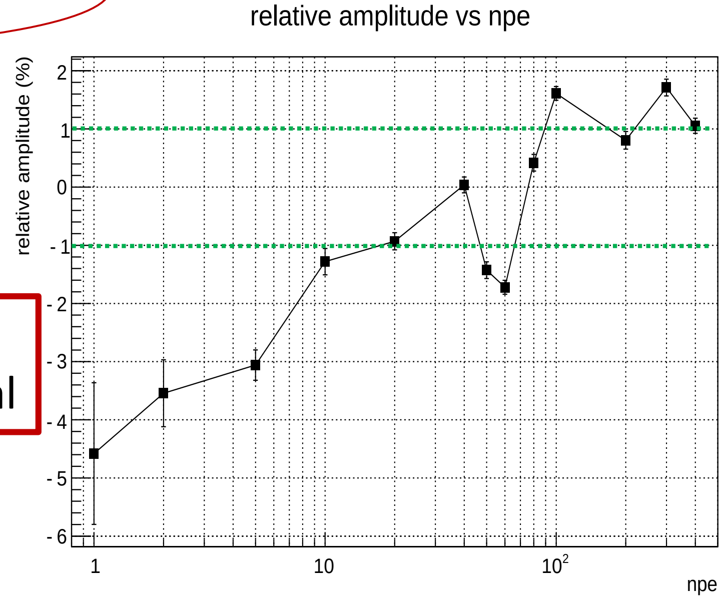


$$\text{Amplitude} \propto n_{pe} \text{ ?}$$

3)



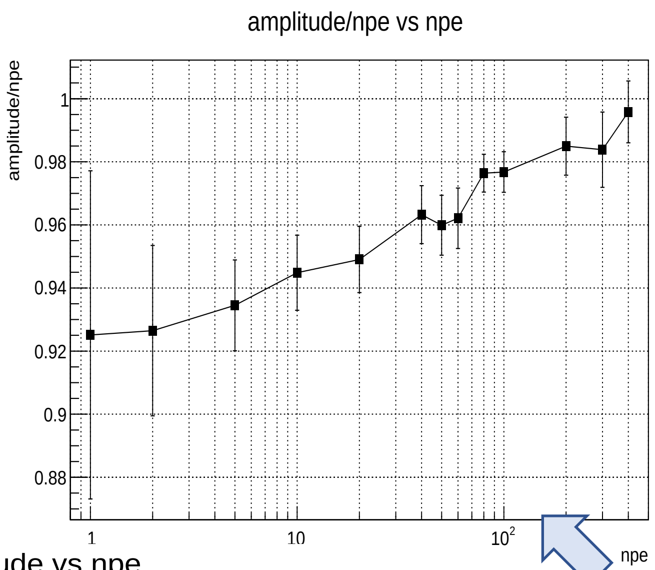
4)

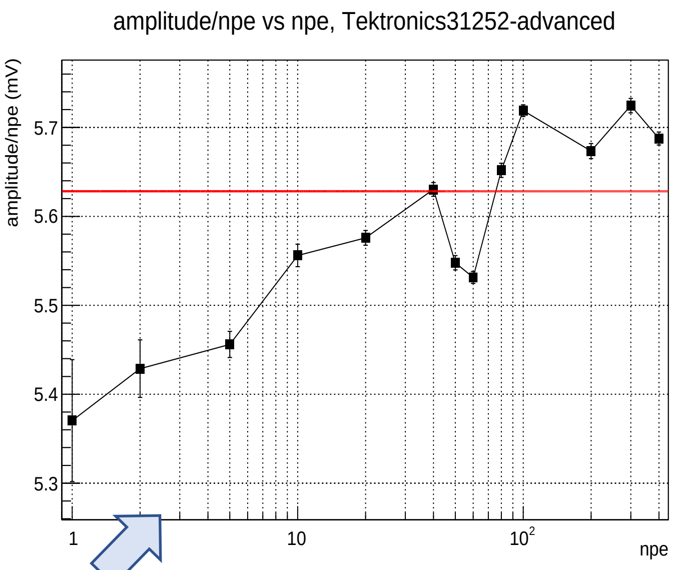


Not within the expected interval

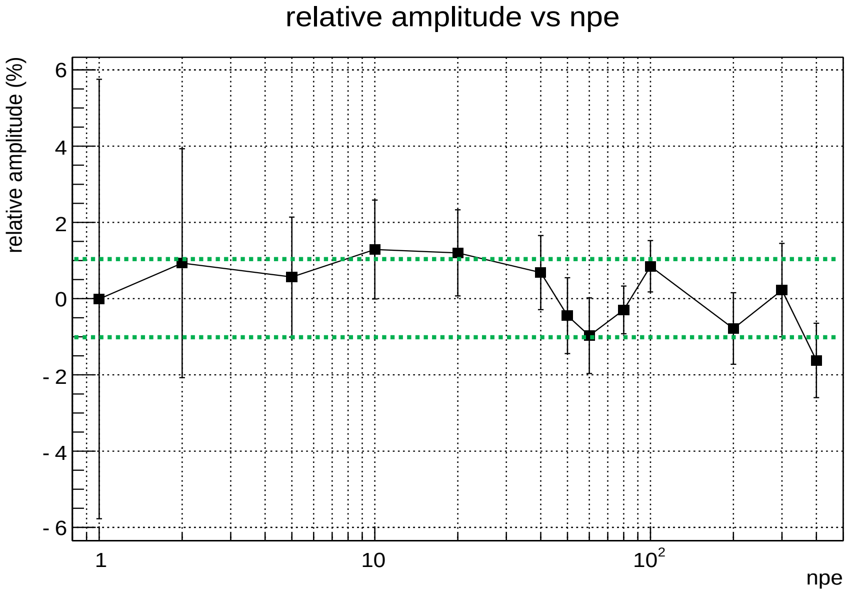
Imperfect oscilloscope

Realization after several weeks that the oscilloscope has a non linear behavior





Similar tendency



corrections → generator with reasonable specs

II. On low scale thermal leptogenesis

Dirac and Majorana

Majorana neutrinos

Paul Dirac
(1902-1984)

3 meanings of the term Majorana :

- Majorana representation
- Majorana mass term
- Majorana fermion

Ettore Majorana
(1906-?)

Dirac equation : $i\gamma^{\mu}\partial_{\mu}\psi = m\psi$

Majorana equations : $i\gamma^{\mu}\partial_{\mu}\psi_{L/R} = m(\psi_{L/R})^{C}$
And $\psi = \psi^{C}$

L/R : **Chirality** (not helicity)

Opposite chirality

Generation of neutrino mass

Standard Model :
Massless neutrinos

Only **left handed** neutrino interacts

No **right handed** (**sterile**) neutrino

Oscillation experiments : neutrinos have **non vanishing mass**

Mechanism for generation of mass :
addition of **sterile** particles ?

Mass terms generated with **left**
and **right** handed fields

Dirac and Majorana mass terms

- **Dirac** : Yukawa coupling → same as charged fermions

$$\mathcal{L}_D = -\, m_D \overline{\nu_R} \nu_L + H.c.$$

- **Majorana** : lepton number violating term

$$\mathcal{L}_M^L = -\frac{1}{2}\, m_L \overline{\nu_L^C} \nu_L + H.c.$$
$$\mathcal{L}_M^R = -\frac{1}{2}\, m_R \overline{\nu_R^C} \nu_R + H.c.$$

Neutrino mass matrix
(single flavor)

$$M = \begin{pmatrix} m_L (= 0) & m_D \\ m_D & m_R \end{pmatrix}$$

$$\mathcal{L}_{D+M} = -\frac{1}{2} \left(\overline{\nu_L^C} \; \overline{\nu_R} \right) M \begin{pmatrix} \nu_L \\ \nu_R^C \end{pmatrix} + H.c.$$

No neutrino nature requirement !

See-saw mechanism

See-saw : Motivation and principle

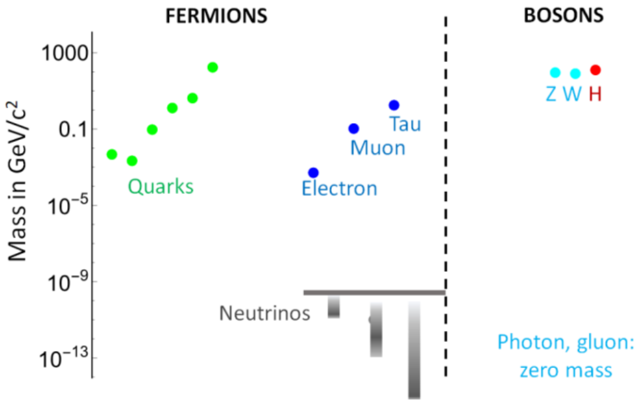
- Difference in order of mass neutrinos vs other fermions

  →« Compensation » with heavy neutrinos

$$\begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \xrightarrow{\text{diagonalization}} \begin{pmatrix} m_\nu & 0 \\ 0 & M_N \end{pmatrix}$$

Interaction basis
$\nu_R^C, \nu_L, \quad \nu_R, \nu_L^C$

Mass basis
ν, N



Neutrino (< 1 eV) vs fermion mass scale (MeV to ~100 GeV)

$$m_R \gg m_D \Rightarrow M_N \approx m_R \gg m_\nu \approx \frac{m_D^2}{m_R}$$

GUT scale : $m_R \sim 10^{16}$ GeV
Higgs scale : $m_D \sim 10^2$ GeV
⇒ $m_\nu \approx \frac{m_D^2}{m_R} \sim 10^{-12}\ \text{GeV} = 10^{-3}\ \text{eV}$

See-Saw mechanism (single flavor)

Active neutrino — **Sterile** neutrino

- Two Majorana neutrinos : $\boldsymbol{\nu_A = \nu_L + \nu_L^C}$ and $\boldsymbol{\nu_S = \nu_R^C + \nu_R}$

In detectors : Interpreted as the **neutrino** part (ν_L) — Interpreted as the **antineutrino** part (ν_L^C)

$$\begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix}$$ **Interacting** states $\neq$ **Mass** states $$\begin{pmatrix} m_\nu & 0 \\ 0 & M_N \end{pmatrix}$$

- **See-saw :** $\boldsymbol{m_R \gg m_D}$ $\Rightarrow$ mass states ν, N almost flavor states

N can be considered the « right sterile neutrino », but still a mixing of the active and sterile one.

Multiple flavors : the PMNS matrix

Pontecorvo-Maki-Nakagawa-Sakata matrix

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Three **CP-violating phases** : $\boldsymbol{\delta_{CP}}$(Dirac) and $\boldsymbol{\alpha_1, \alpha_2}$(Majorana)

- Apply the **see-saw** mechanism introducing several non interacting states, and new **heavy** mass states(N_1, N_2, N_3)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Becomes an **approximation** in the case of the **see-saw** model

Dirac phase – CP-violation in oscillations

- Asymmetry because of $\boldsymbol{\delta_{CP}}$ in oscillation experiments

$$A_{\alpha\beta} = P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

Not necessarily vanishing for **Majorana** neutrinos

Related to observation : neutrino/antineutrino associated to charged lepton/antilepton

Majorana interacting neutrino field

$$\boldsymbol{\nu_\alpha = \nu_{\alpha L} + \nu_{\alpha L}^{C} = \nu_\alpha^{C}}$$

Interpreted as the **neutrino** part ($\nu_{\alpha L}$)

Interpreted as the **antineutrino** part ($\nu_{\alpha L}^{C}$)

Dirac phase – CP-violation in oscillations

CP-asymmetry $$A_{e\mu} = 4\mathrm{J}_{\mathrm{CP}}\mathrm{F}_{\mathrm{osc}}^{\mathrm{vac}}$$

Dependance on the mass ordering

$$\mathrm{F}_{\mathrm{osc}}^{\mathrm{vac}} = \sin\left(\frac{\Delta m_{21}^2}{2E}L\right) + \sin\left(\frac{\Delta m_{32}^2}{2E}L\right) + \sin\left(\frac{\Delta m_{13}^2}{2E}L\right)$$

Jarlskog invariant

Non dependant on PMNS parametrization

$$\mathrm{J}_{\mathrm{CP}} = \frac{1}{4}\sin 2\theta_{12}\sin 2\theta_{23}\cos^2\theta_{13}\sin\theta_{13}\sin\delta$$

Determination of $\boldsymbol{A_{e\mu}}$ provides information on $\boldsymbol{\delta_{CP}}$

Leptogenesis

Basis of leptogenesis

- CP-violating phases create the observed **baryon asymetry of the universe** (BAU)

Cosmic Microwave Background →

$$\boldsymbol{\eta_{CMB} \approx 6,1 \cdot 10^{-10}}$$
$$\eta = (n_B - n_{\overline{B}})/n_\gamma$$

baryon asymetry

- Asymetry in leptonic sector → propagates in the baryon sector

Objective :

Recreate this value through fine tuning of the **neutrino masses** and **CP-phases**

Variables

Mass of the lightest **heavy neutrino** $\boldsymbol{N_1}$ $(10^6 < M_1 < 10^{15}\ \mathrm{GeV})$

Three ranges of interest (related to the number of independent lepton flavors)

→ not something that can be evaluated at the moment

Light neutrino **mass ordering** (and absolute mass scale)

→ KaTriN, SK/HK, beta decay experiments, etc.

CP phases (only δ_{CP} has an approximate experimental value)

→ oscillation (Dirac) and neutrinoless double beta decay experiments

Conclusion

Prospects for the last few weeks of my M1 internship:

- Arrival of a new **waveform generator**

  → Repeat the process to check the specs

- Understand the relation between the **PMNS CP-phases**, and the reactions involved in **leptogenesis**

Back up slides

Multiple flavor see-saw

- Diagonalize a 6 x 6 mass matrix

Still the same blocks

$$\begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix}$$

Active neutrino states dependant on light neutrino mass states (PMNS matrix), and also heavy neutrino mass states (heavily suppressed in see-saw)

$$\begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \\ \nu_{s_1 R}^C \\ \nu_{s_2 R}^C \\ \nu_{s_3 R}^C \end{pmatrix} = \begin{pmatrix} U_{PMNS} & A \approx 0 \\ B \approx 0 & C \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \mathrm{N}_1 \\ \mathrm{N}_2 \\ \mathrm{N}_3 \end{pmatrix}$$

Leptogenesis schematized

$0\nu\beta\beta$
experiments

Majorana
nature of
neutrinos

Prerequisites
of the theory

Type I See-saw
mechanism

Oscillation
experiments

δ_{CP}

Mass ordering
and absolute
scale

Variables that
can be tested

Other
parameters

Majorana
phases

Heavy neutrino
masses

Sphaleron processes

$$u_L + d_L + c_L + s_L + t_L + b_L + \nu_{eL} + \nu_{\mu L} + \nu_{\tau L} \rightarrow \overline{d_R} + \overline{b_R} + \overline{s_R}$$

- $\boldsymbol{B - L}$ **conserving** but $\boldsymbol{B + L}$ **violating** non perturbative processes
- Present in the standard model

$$\Delta \mathrm{B} = \Delta L = 3$$

$$\boldsymbol{\eta_B \approx \frac{a}{f} n_{B-L} \approx 10^{-2} n_{B-L}}$$

$\boldsymbol{a = 28/79}$, partial conversion of the asymetry

$\boldsymbol{f = \frac{n_\gamma^{rec}}{n_\gamma^*} = \frac{2387}{86}}$ dilution of the asymetry (change of photon density between leptogenesis and recombination)

Majorana phases – CP-violation experiments

- Oscillation experiments not dependant on $\boldsymbol{\alpha_1, \alpha_2}$

Mainly evaluation of **effective mass** in $0\nu\beta\beta$ experiments

Boltzmann equations

Lightest heavy neutrino density

Lepton asymmetry density

$$\frac{dn_{N_1}}{dz} = -D_i\left(n_{N_1} - n_{N_1}^{eq}\right), \qquad z = \frac{\mathrm{M}_1}{\mathrm{T}}$$

Strictly increasing with time

$$\frac{dn_{B-L}}{dz} = \sum_{i=1}^{3}\left(\epsilon^{(i)} D_i\left(n_{N_1} - n_{N_1}^{eq}\right) - W_i n_{B-L}\right)$$

Asymmetry generating term | Washout term

With $D_i \equiv \frac{\Gamma_i + \overline{\Gamma_i}}{Hz}, W_i \equiv \frac{1}{2}\frac{\Gamma_i^{ID} + \overline{\Gamma_i}^{ID}}{Hz}$, $\Gamma_i \equiv \Gamma(N_1 \to \phi^\dagger l_i)$ decay width of heavy neutrinos

And $\epsilon^{(i)} \equiv -\frac{\Gamma_i - \overline{\Gamma_i}}{\Gamma_i + \overline{\Gamma_i}}$ the CP-asymmetry parameter