UNIVERSITÉ DE NANTES

Precise measurement of neutrino solar oscillation parameters θ_{12} and Δm^2_{21} with the JUNO experiment

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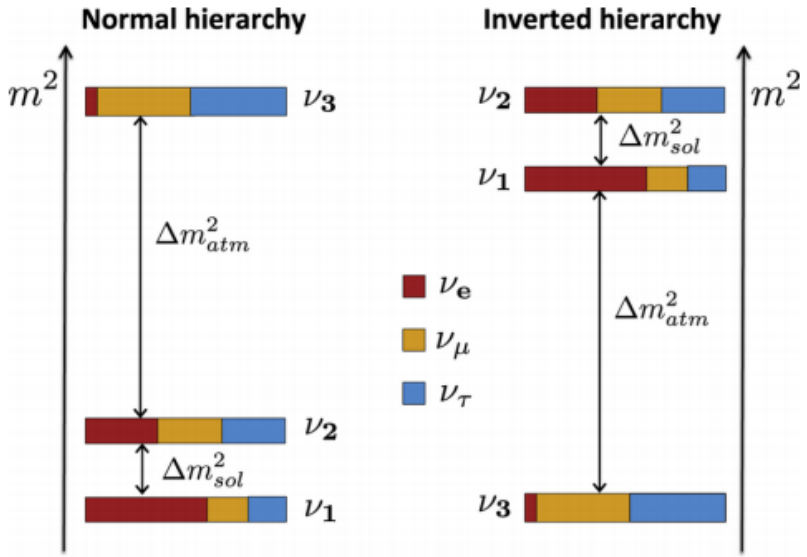
Mixing of neutrinos

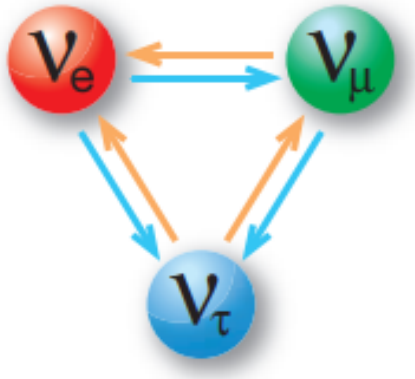
- The mass eigenstates $|\nu_{1,2,3}\rangle$ are linear combinations of flavor eigenstates $|\nu_{e,\mu,\tau}\rangle$
- Mixing of neutrinos with 3 masses m_1, m_2, m_3, 3 angles θ_{12}, θ_{13} and θ_{23} and a phase δ accounting for CP violation



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}\,e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}\,e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}\,e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}\,e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}\,e^{i\delta} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

With $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$

Oscillation of neutrinos



- Since the flavor eigenstates are linear combinations of mass eigenstates, there are oscillations :
  - We study the example of reactor $\overline{\nu_e}$ with their survival probability :

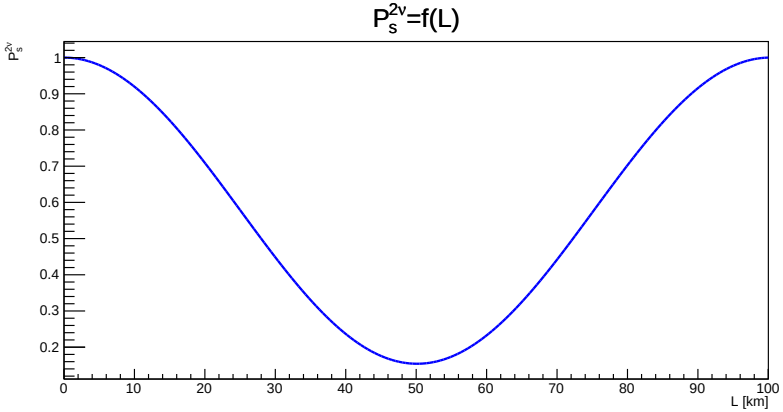
$$P^{2\nu}(\overline{\nu_e} \to \overline{\nu_e}) = 1 - \sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

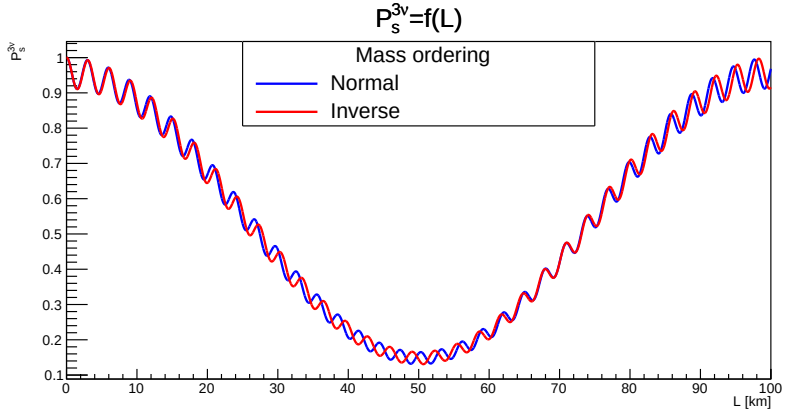
$$P^{3\nu}(\overline{\nu_e} \to \overline{\nu_e}) = 1 - \sin^2 2\theta_{13} \left(cos^2\theta_{12} \sin^2 \Delta_{31} + sin^2\theta_{12} sin^2 \Delta_{32}\right) - \cos^4 \theta_{13} sin^2 2\theta_{12} \sin^2 \Delta_{21}$$

  Avec $\Delta_{ij} = \frac{(m_i^2 - m_j^2) \times L}{4E}$.
- The solar parameters (in red) were the ones of interest during my internship

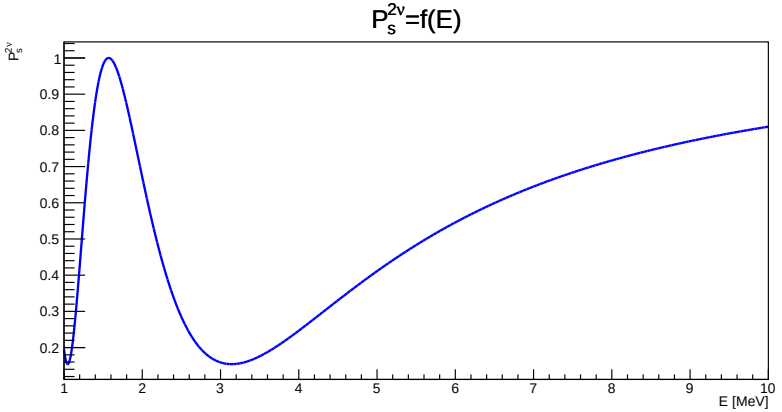
Probabilities of oscillations

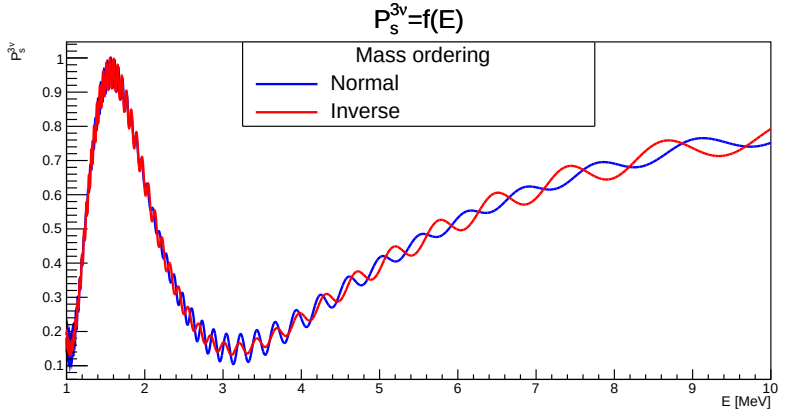
- The 2 and 3 flavors survival probabilities are studied as a function of the distance travelled L and the energy E of the neutrino
  - Energy fixed at 3 MeV :





  - Distance fixed at 52.5 km :



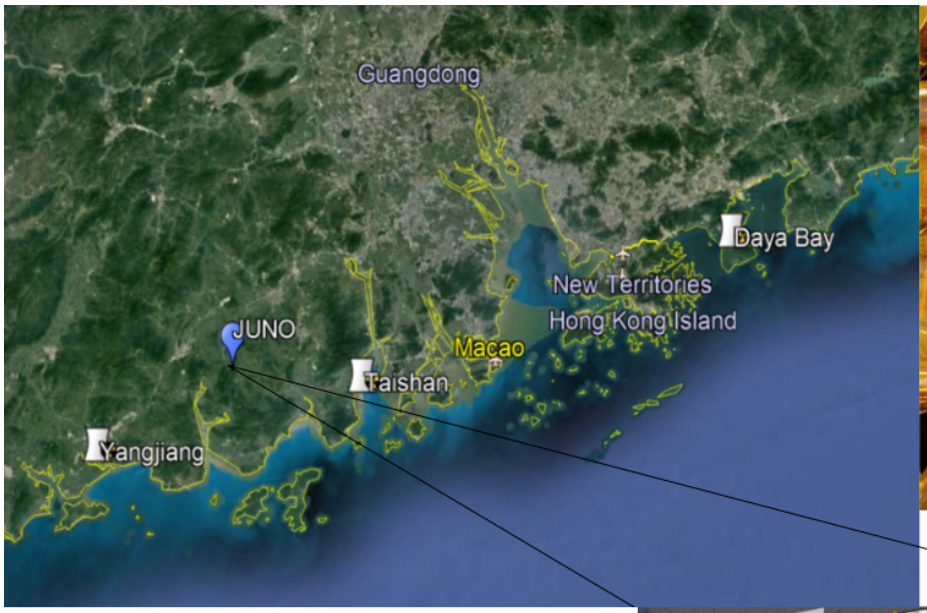


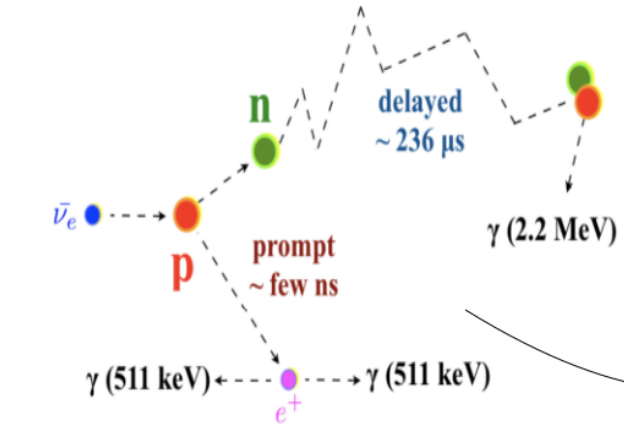
2 flavors

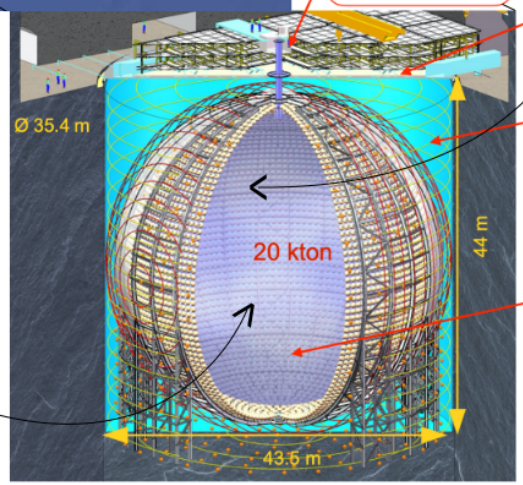
3 flavors

JUNO experiment and IBD

- JUNO, at 700 m of depth in the South-Eastern China







Calibration house
Multi-dimension calibration systems

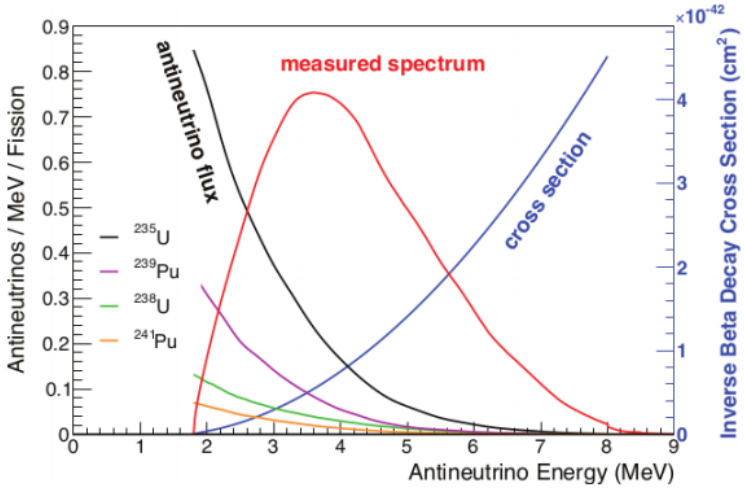
Top Tracker
- Precise muon tracker
- 3 layers of plastic scintillator
- ~ 60% of area above WCD

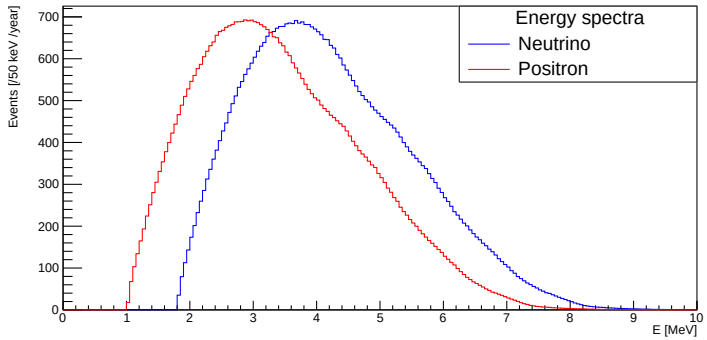
Water Cherenkov Detector (WCD)
- 35 kton ultra-pure water
- 2400 20-inch PMTs
- High muon detection efficiency
- Protects CD against external radioactivity

Central Detector (CD) - Neutrino target
- Acrylic sphere with 20 kton liquid scintillator (LAB)
- 18000 20-inch PMTs and 25600 3-inch PMTs
- 3% energy resolution at 1 MeV.

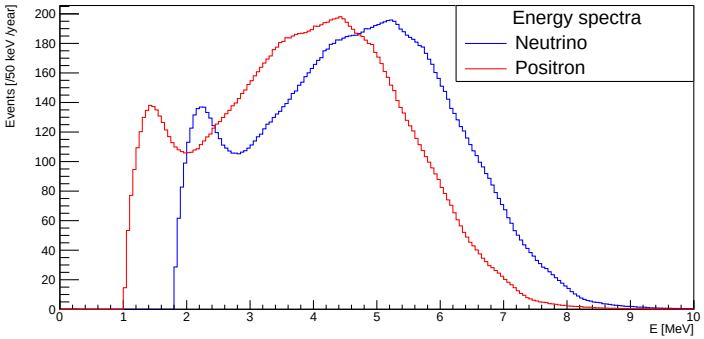
Energy spectra of neutrino and positron

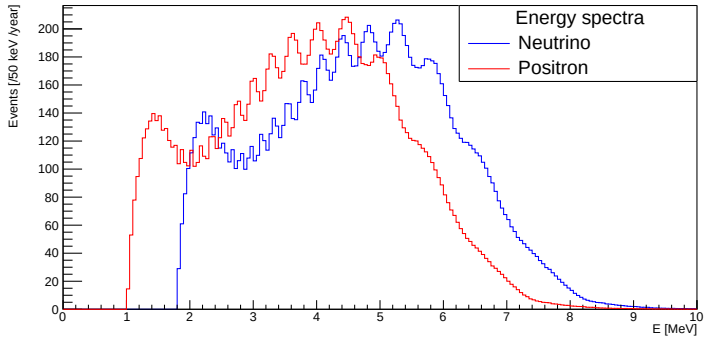
- Simulation of the energy spectrum near the nuclear plant :





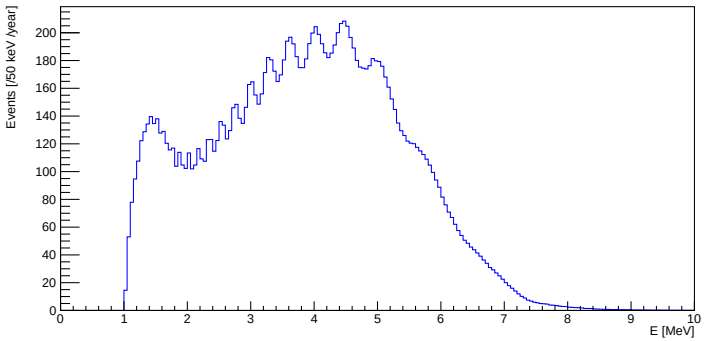
- Oscillation probability implementation : $P_s^{2\nu}$ then $P_s^{3\nu}$:





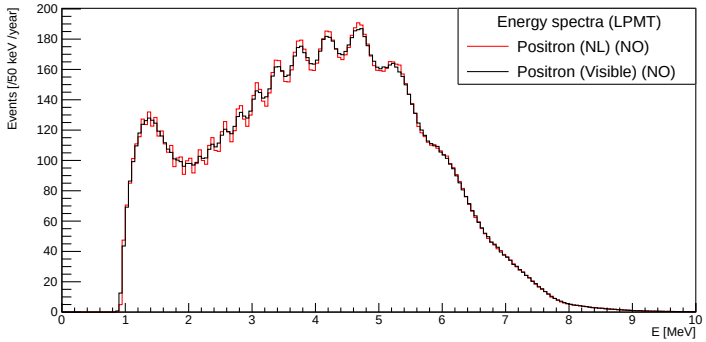
Detector effects

- e^+ energy spectrum :

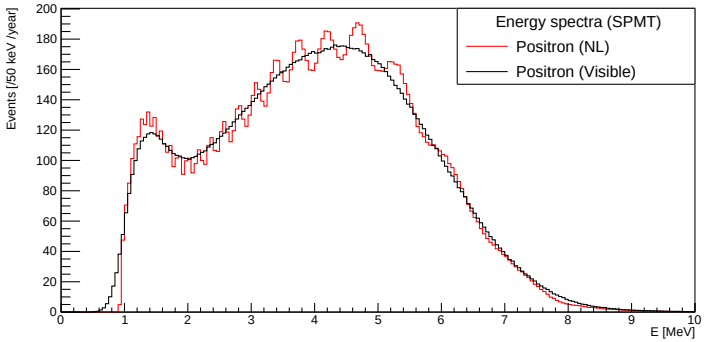


- Two main detector effects must be taken into account :
  - The liquid scintillator non-linearity ▸ 19
  - The energy resolution of PMTs ▸ 20

- Visible energy spectrum with the LPMTs *Res* $\simeq$ 3%@1 MeV

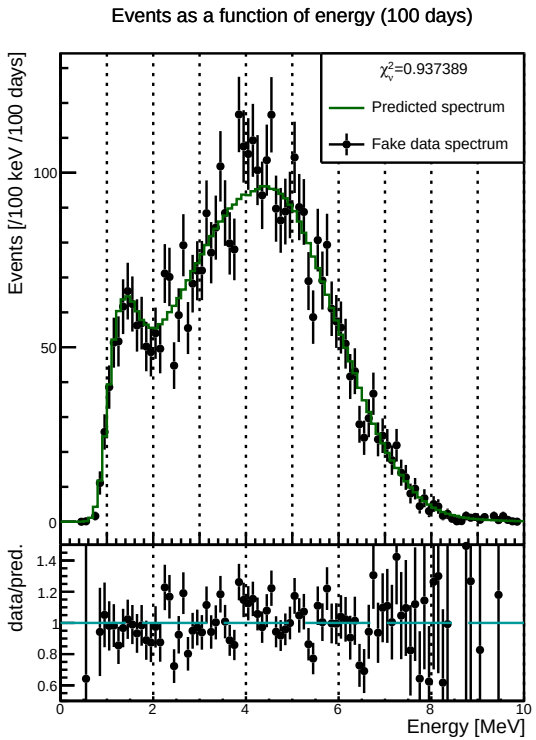


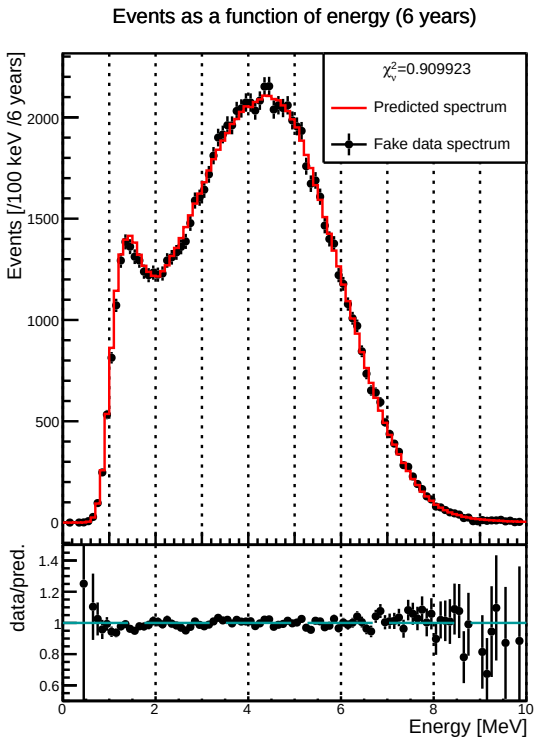
- Visible energy spectrum with the SPMTs *Res* $\simeq$ 15%@1 MeV

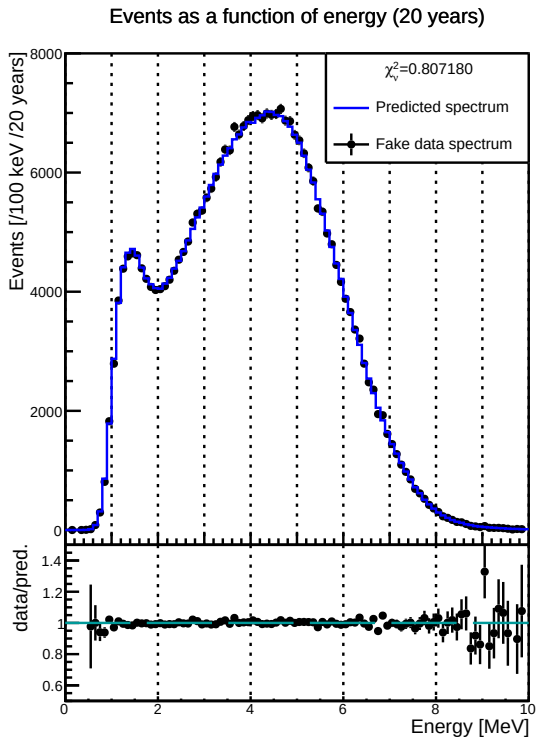


- θ_{13} et Δm^2_{31} have an effect on the spectrum
- Only θ_{12} and Δm^2_{21} seem to have an impact

- Fake data [1] were generated on the vivble energy thanks to a gaussian random generator $Gauss\left(N, \sqrt{N}\right)$ to simulate the data JUNO is supposed to obtain from 2023





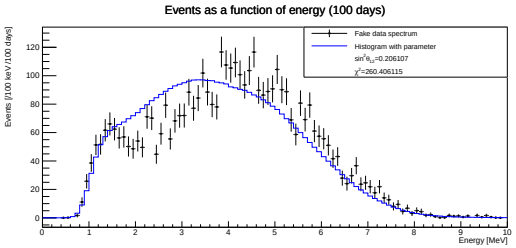


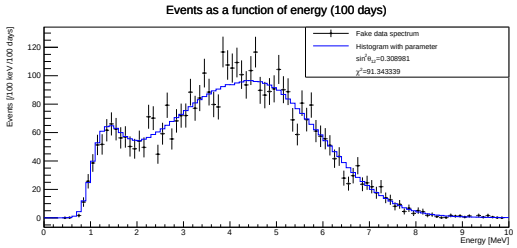
- χ^2_ν is decreasing and the "fake data/pred." ratio approaches 1 thanks to the statistical uncertainty decreasing with time

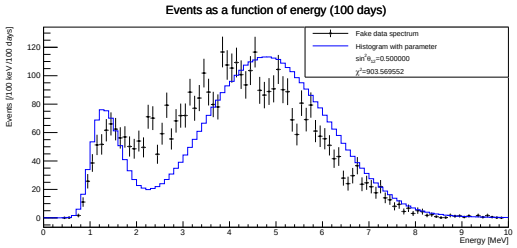
1. Using NuFit5.0 $\sin^2\theta_{12} = 0.304$, $\sin^2\theta_{13} = 0.02219$, $\Delta m^2_{21} = 7.42 \times 10^{-5}\text{eV}^2$ and $\Delta m^2_{31} = 2.517 \times 10^{-3}\text{eV}^2$

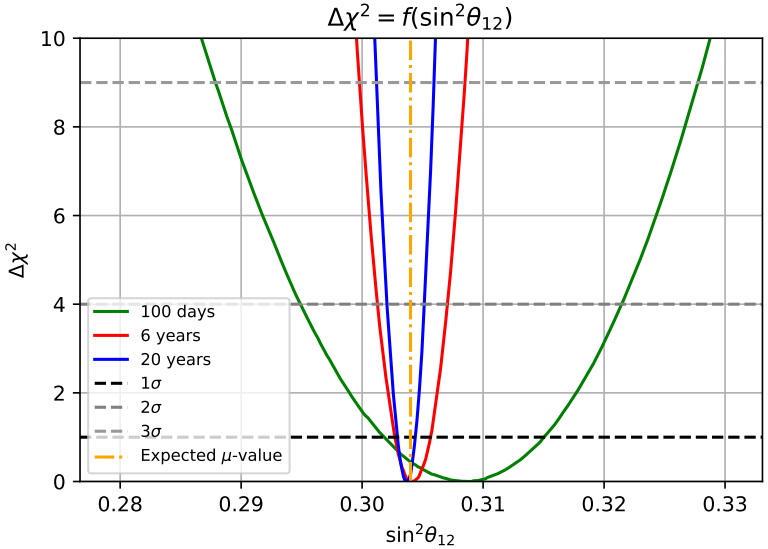
$\Delta\chi^2$ as a fuction of 1 parameter

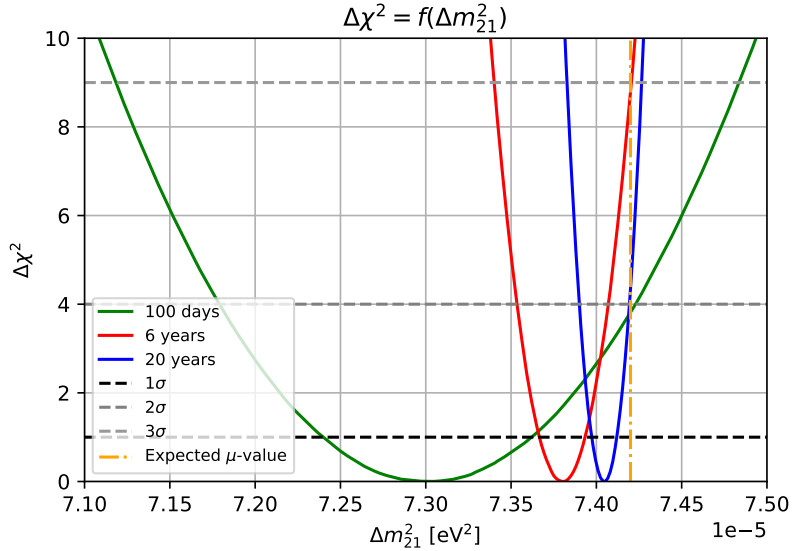
- A 1-parameter scan is made (here is an example with $\sin^2\theta_{12}$) ▸ Δm^2_{21} :







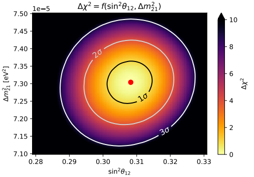


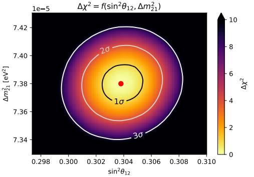


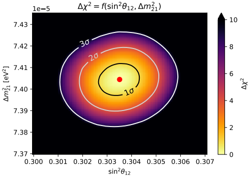
- The longer the experiment duration is, the better the accuracy will be
- A bias in the mean value is created by the choice of the seed

$\Delta\chi^2$ test as a function of 2 parameters

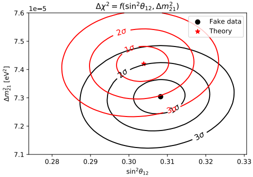
- A $\Delta\chi^2$ test as a function of 2 parameters was done in order to see if the bias is decreasing and if the accuracy is improving

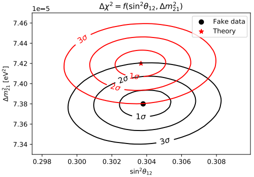


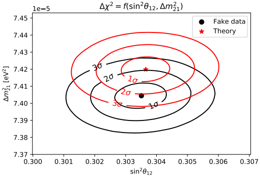




- Comparison with the theoretical values





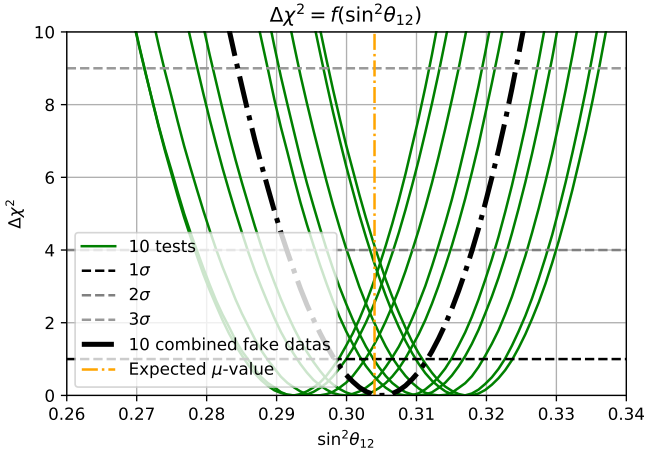


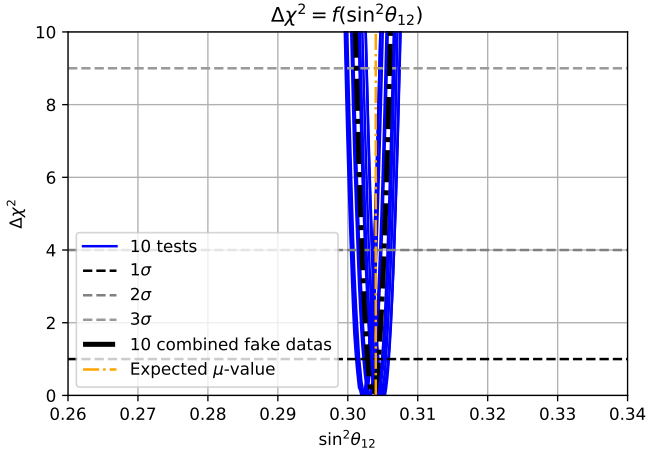
100 days | 6 years | 20 years

- The bias didn't decrease and the accuracy didn't improve

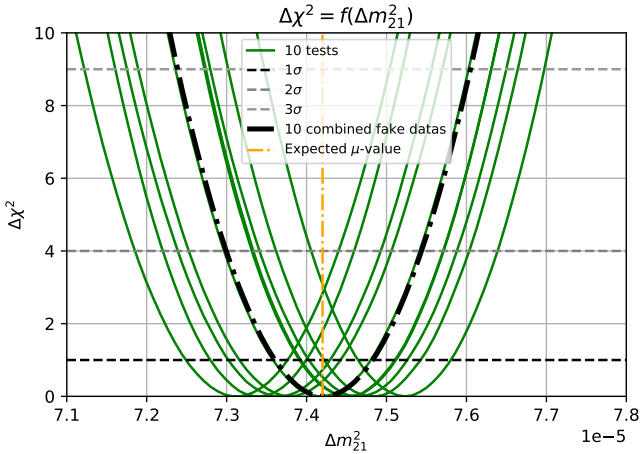
- 10 sets of fake data with 10 different seeds are generated and combined to avoid seed bias

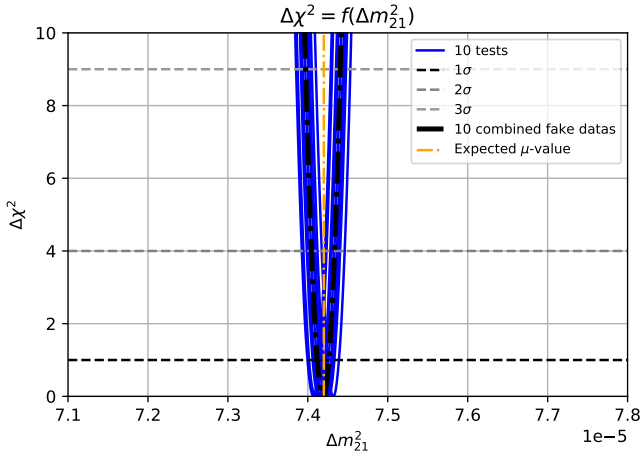
$\sin^2\theta_{12}$





Δm^2_{21}





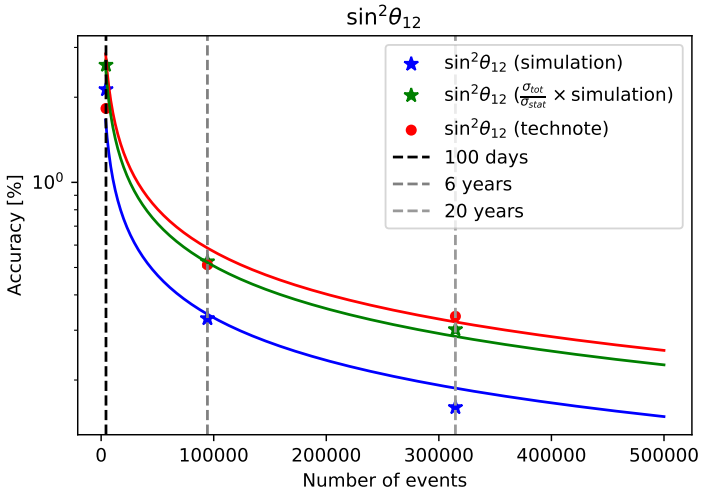
100 days 20 years

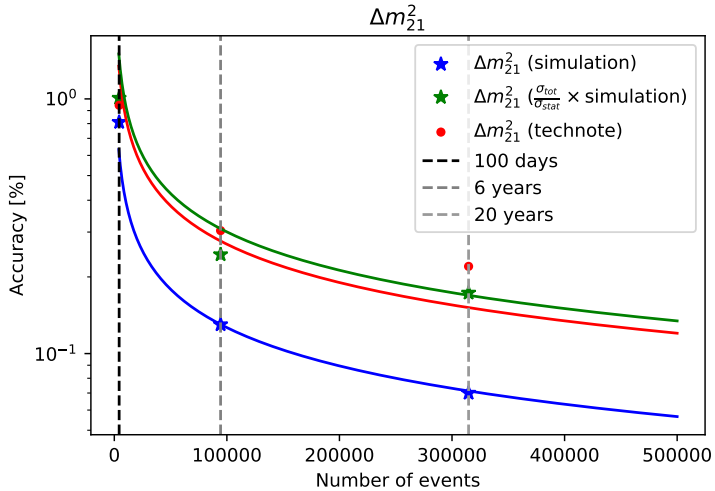
- The mean parabolas coincide with the theoretical mean values
- The bias is reduced with the duration of the experiment

Accuracy obtained

- Accuracy obtained as a function of experiment duration

Parameter	Duration	Accuracies (1σ) (stat)	Accuracies of the technote [2] (stat+sys)
$\sin^2\theta_{12}$	100 days	2.13%	1.83%
	6 years	0.33%	0.51%
	20 years	0.16%	0.34%
Δm^2_{21}	100 days	0.81%	0.94%
	6 years	0.13%	0.30%
	20 years	0.07%	0.22%





- The data are comparable when multiplied by the $\frac{\sigma_{tot}}{\sigma_{stat}}$ ratio

2. Work of 3 independant groups of the JUNO collaboration

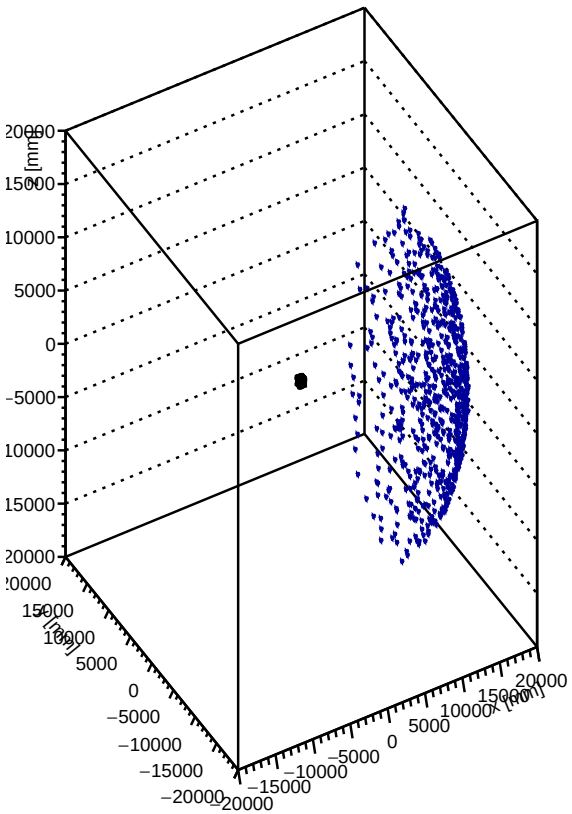
Conclusion

- A reconstruction of the $\overline{\nu_e}$ theoretical energy spectrum was performed
- Simulations of observable data from 2023 onwards were then generated
- $\sin^2\theta_{12}$ and Δm^2_{21} measurements thanks to $\Delta\chi^2$ showed a seed bias
- This bias is almost entirely solved when combining 10 sets of fake data
- The accuracies that were obtained are comparable with the ones obtained by 3 independant groups of the JUNO collaboration when multiplied by the $\frac{\sigma_{tot}}{\sigma_{stat}}$ ratio

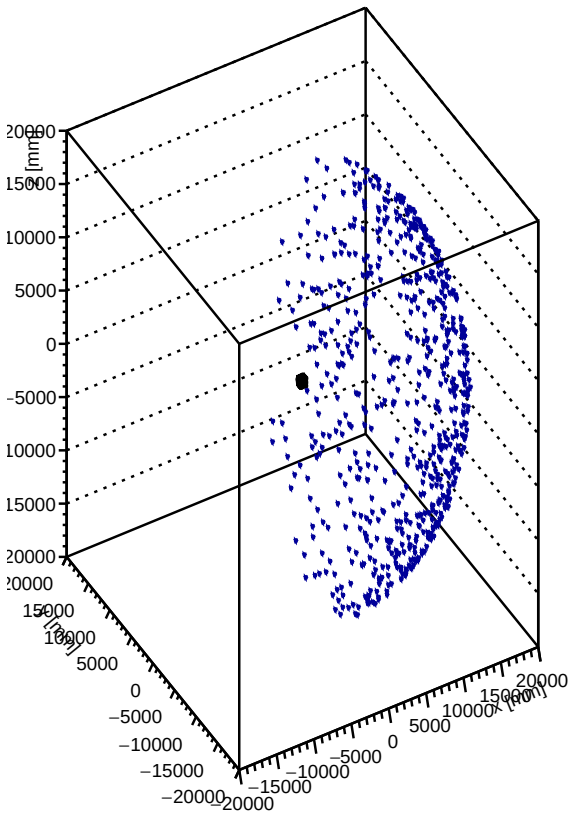
Perspectives

- Implementation of background and systematic uncertainties
- Combination of more sets of fake data
- Cross-referencing with LPMTs data

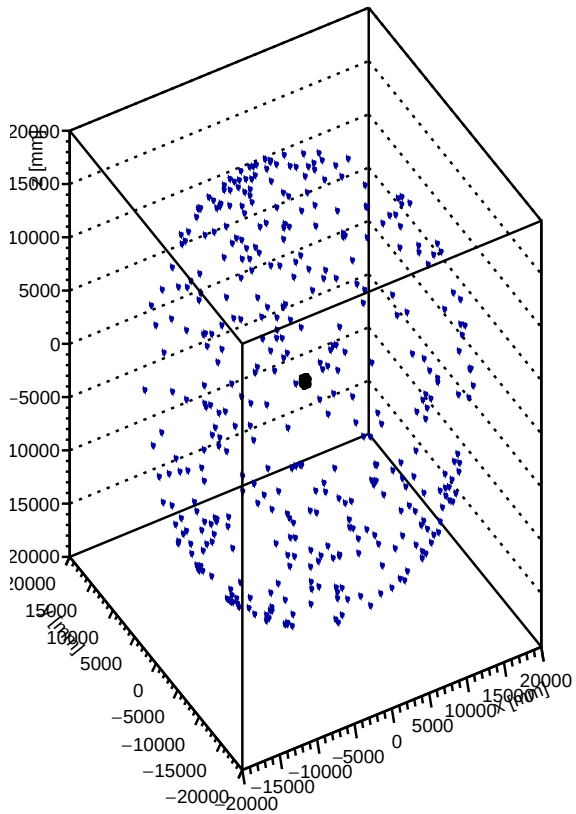
t∈[0,80] µs



t∈]80,100] µs



t∈]120,140] µs



— Thank you —

— Backup —

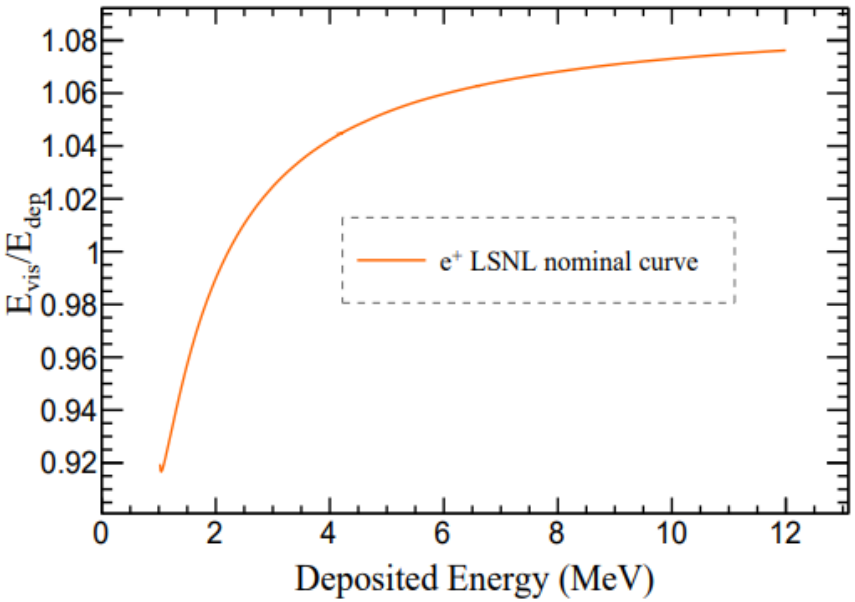
Results obtained

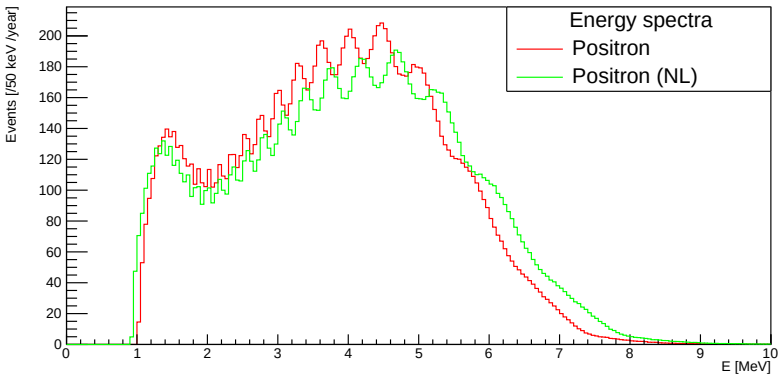
Parameter	Duration	Value$\pm 1\sigma$	2σ area	3σ area
$\sin^2\theta_{12}$	100 days	$0.309^{+0.006}_{-0.007}$	$0.295 - 0.321$	$0.288 - 0.328$
	6 years	$0.304^{+0.002}_{-0.001}$	$0.301 - 0.307$	$0.300 - 0.309$
(1 fake data)	20 years	$0.304^{+0.001}_{-0.001}$	$0.302 - 0.305$	$0.301 - 0.306$
$\sin^2\theta_{12}$	100 days	$0.305^{+0.007}_{-0.007}$	$0.291 - 0.318$	$0.284 - 0.324$
	6 years	$0.304^{+0.001}_{-0.002}$	$0.301 - 0.306$	$0.299 - 0.308$
(10 combined fake datas)	20 years	$0.304^{+0.000}_{-0.001}$	$0.302 - 0.305$	$0.301 - 0.306$
$\sin^2\theta_{12}$	100 days	$0.304^{+0.007}_{-0.007}$	$0.290 - 0.317$	$0.283 - 0.323$
	6 years	$0.304^{+0.001}_{-0.002}$	$0.301 - 0.306$	$0.299 - 0.308$
(theoretical spectra)	20 years	$0.304^{+0.000}_{-0.001}$	$0.302 - 0.305$	$0.301 - 0.306$
Δm^2_{21} $[\times 10^{-5}\text{eV}^2]$	100 days	$7.30^{+0.06}_{-0.06}$	$7.18 - 7.42$	$7.12 - 7.48$
	6 years	$7.38^{+0.01}_{-0.01}$	$7.35 - 7.41$	$7.34 - 7.42$
(1 fake data)	20 years	$7.41^{+0.00}_{-0.01}$	$7.39 - 7.42$	$7.38 - 7.43$
Δm^2_{21} $[\times 10^{-5}\text{eV}^2]$	100 days	$7.42^{+0.06}_{-0.06}$	$7.30 - 7.54$	$7.24 - 7.61$
	6 years	$7.42^{+0.01}_{-0.01}$	$7.39 - 7.44$	$7.38 - 7.46$
(10 combined fake datas)	20 years	$7.42^{+0.01}_{-0.01}$	$7.40 - 7.43$	$7.40 - 7.44$
Δm^2_{21} $[\times 10^{-5}\text{eV}^2]$	100 days	$7.42^{+0.06}_{-0.06}$	$7.30 - 7.54$	$7.24 - 7.61$
	6 years	$7.42^{+0.01}_{-0.01}$	$7.39 - 7.44$	$7.38 - 7.46$
(theoretical spectra)	20 years	$7.42^{+0.01}_{-0.01}$	$7.40 - 7.43$	$7.40 - 7.44$

The liquid scintillator non-linearity effects

Go Back

- The intensity of the light emitted is not perfectly proportional to the positron energy, so it has to be taken into account in the study :





- The normal mass ordering is considered here.

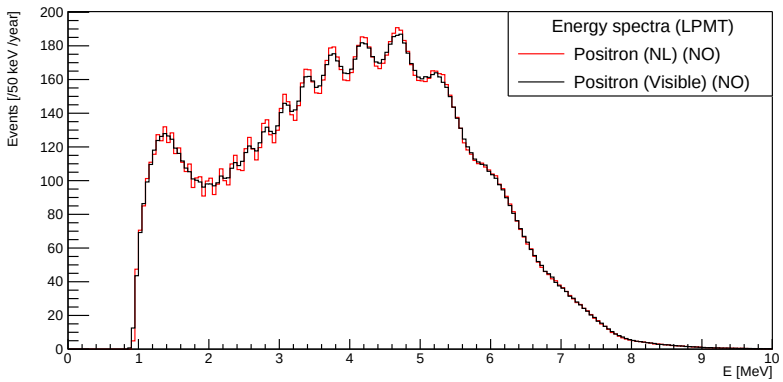
Comparison of the LPMT and SPMT energy resolutions

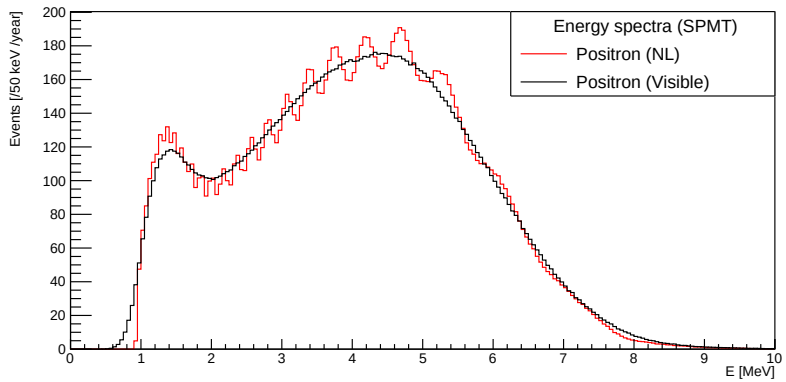
Go Back

- In order to take into account the energy resolution, a random gaussian generator $Gauss(E, \sigma_E)$ is applied on each of the bins of the data :

$$\frac{\sigma_E}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2}$$

- With $a_{LPMT} = 0.0261$, $a_{SPMT} = 0.1536$, $b = 0.0082$ and $c = 0.0123$.

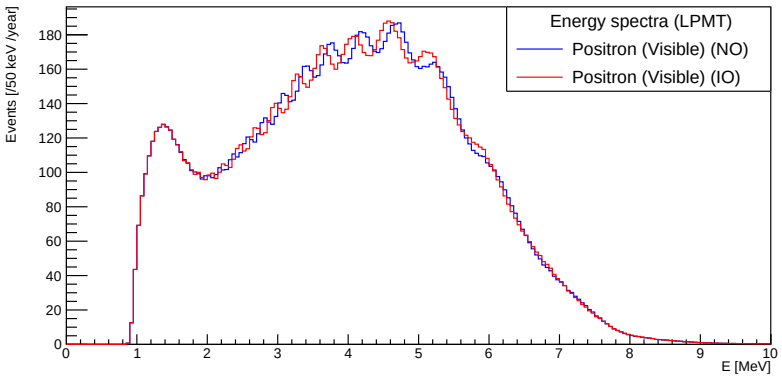




- The visible energy spectrum of SPMTs is only influenced by the solar terms θ_{12} and Δm^2_{21}

Mass ordering

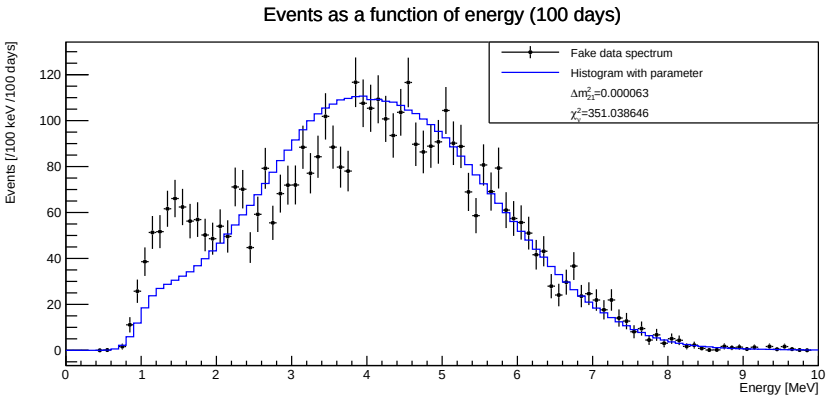
- One can study the mass ordering thanks to the energy resolution of the LPMTs :

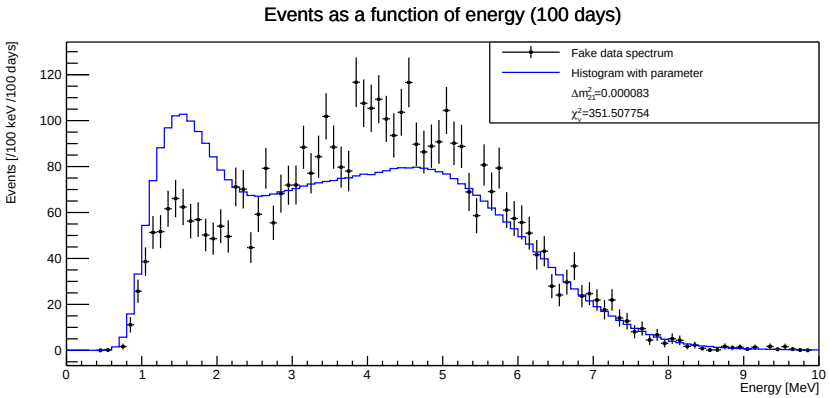


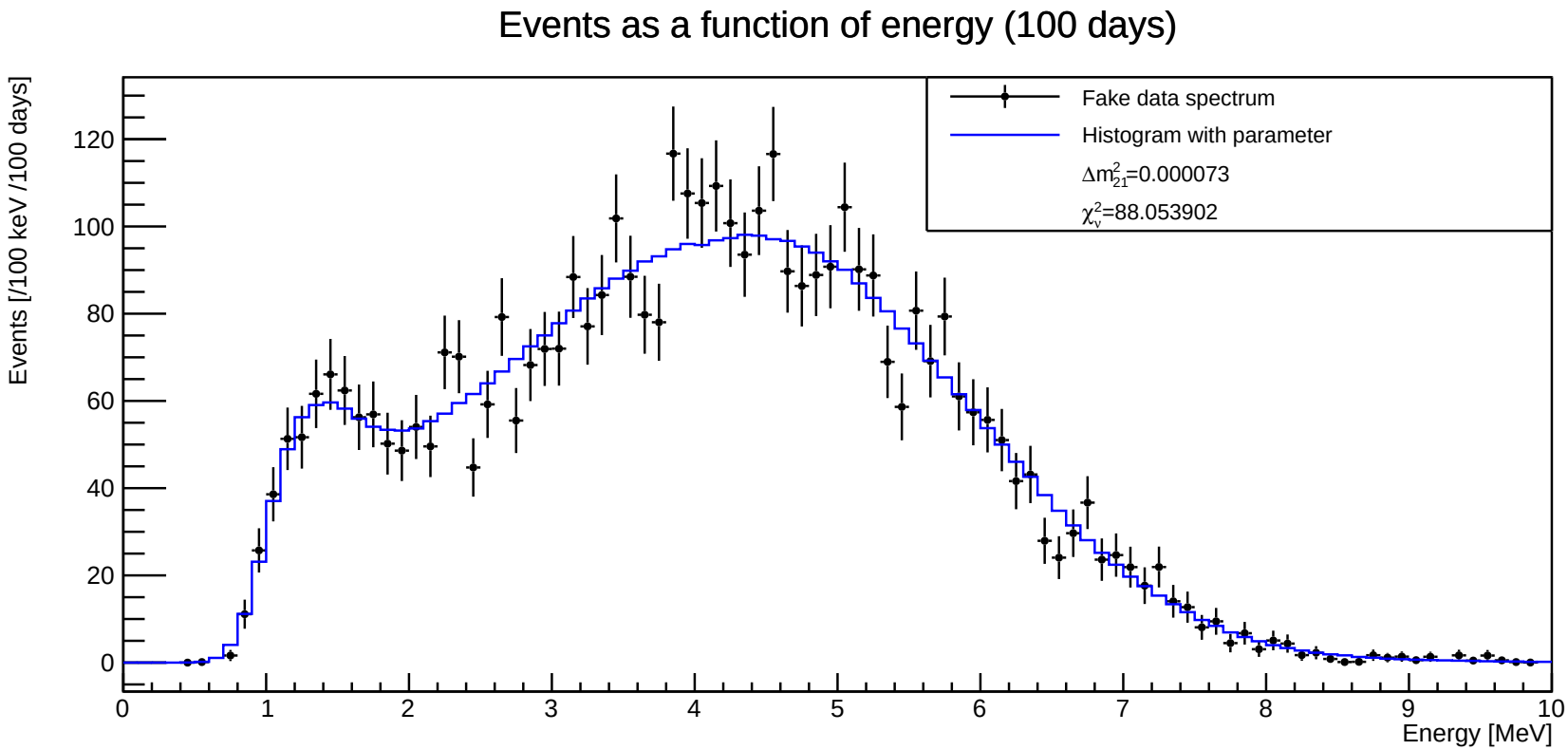
  - A phase shift can be observed for $E_{vis} \in [2.5; 5.5]$ MeV

Test for the Δm^2_{21} parameter

Go Back







Test for the $\sin^2\theta_{12}$ parameter