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Par
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Precision measurement of solar neutrino oscillation parameters with the JUNO small PMTs system and test of the unitarity of the PMNS matrix

Thèse présentée et soutenue à Nantes, le Too soon and too early at the same time
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List of Abbreviations

NMO	**N**eutrino **M**ass **O**rdering
JUNO	**J**iangmen **U**nderground **N**eutrino **O**bservatory
NO	**N**ormal **O**rdering
IO	**I**nverse **O**rdering
IBD	**I**nverse **B**eta **D**ecay

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Remerciements

Introduction

Chapter 1

Neutrino physics

The neutrino, or ν for the close friends, a fascinating and invisible particle. Some will say that dark matter also have those property but at least we are pretty confident that neutrinos exists.

1.1 Standard model

Decrire le
standard
Regarder
LHC / O
Kochebin

1.1.1 Limits of the standard model

Limite du
standard
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neutrinos
violation
? Pb des
?

1.2 Historic of the neutrino

First theories

Discovery

Milestones and anomalies

1.3 Oscillation

1.3.1 Phenomologies

1.4 Open questions

Chapter 2

The JUNO experiment

The first idea of a medium baseline (60 km) experiment, was explored in 2008 where it was demonstrated that the Neutrino Mass Ordering (NMO) could be determined by a medium baseline experiment if $\sin^2(2\theta_{13}) > 0.005$ without requirements on accurate information of reactor antineutrino spectra and the value of Δm^2_{32}. [1] It was shown that for value of

Stopped now. See JUNO ch before ge back here

The JUNO (Jiangmen Underground Neutrino Observatory) is a neutrino detection experiment located in China. Its main objective is the determination of the mass ordering at the 3-4σ level in 6 years of data taking [2].

2.1 Neutrinos physics in JUNO

As said before, the main goals of JUNO are the determination of the NMO and the precise measurements of the oscillation parameters Δm^2_{21}, $\sin^2 2\theta_{12}$, Δm^2_{32} and, with less precision, $\sin^2\theta_{13}$.

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2.1.1 Reactor neutrino oscillation for NMO and precise measurements

Previous works [1, 3] shows that oscillation parameters and the NMO can be observed by looking at the $\bar{\nu}_e$ disappearance spectrum coming from medium baseline nuclear reactor. This disappearance probability can be expressed as [2] :

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} c^4_{13} sin^2 \frac{\Delta m^2_{21} L}{4E} - \sin^2 2\theta_{13} \left[c^2_{12} \sin^2 \frac{\Delta m^2_{31} L}{4E} + s^2_{12} \sin^2 \frac{\Delta m^2_{32} L}{4E} \right]$$

Where $s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$, E is the $\bar{\nu}_e$ energy and L is the baseline. We can see the sensitivity to the NMO in the dependency to Δm^2_{32} and Δm^2_{31} causing a phase shift of the spectrum (Figure 2.1). By carefully fitting this spectrum, one can extract the NMO and the oscillation parameters.

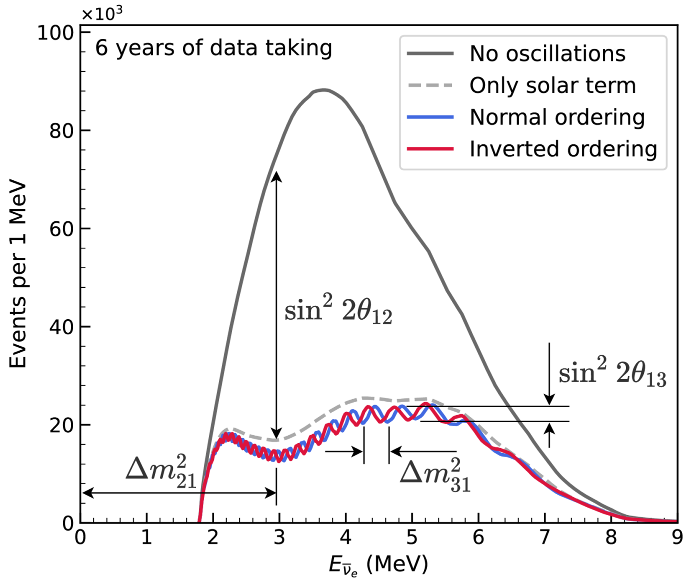

FIGURE 2.1 – Expected number of neutrinos event per MeV in JUNO after 6 years of data taking. The black curve shows the flux if there was no oscillation. The light gray curve shows the oscillation if only the solar terms are taken in account (θ_{12}, Δm^2_{21}). The blue and red curve shows the spectrum in the case of, respectively, NO and IO. The dependency of the oscillation to the different parameters are schematized by the double sided arrows. We can see the NMO sensitivity by looking at the fine phase shift between the red and the blue curve.

Identification of the mass ordering

To identify the mass ordering, we fit the neutrino energy spectrum under the two hypothesis of NO and IO. Those two fit give us two χ^2, respectively χ^2_{NO} and χ^2_{IO}. By computing the difference $\Delta\chi^2 = \chi^2_{NO} - \chi^2_{IO}$ we can determine the most probable mass ordering: NO if $\Delta\chi^2 > 0$ and IO if $\Delta\chi^2 < 0$. Current studies shows that the expected sensitivity the mass ordering would be of 3.4σ after 6 years of data taking in nominal setup[2].

Precise measurement of the oscillations parameters

The oscillations parameters θ_{12}, θ_{13}, Δm^2_{21}, Δm^2_{31} are free parameters in the fit of the oscillation spectrum. The precision on those parameters have been estimated and are shown in figure 2.2. Wee see that for θ_{12}, Δm^2_{21}, Δm^2_{31}, precision at 6 years is better than the reference precision by an order of magnitude [4]

	Central Value	PDG2020	100 days	6 years	20 years
Δm^2_{31} ($\times 10^{-3}$ eV^2)	2.5283	± 0.034 (1.3%)	± 0.021 (0.8%)	± 0.0047 (0.2%)	± 0.0029 (0.1%)
Δm^2_{21} ($\times 10^{-5}$ eV^2)	7.53	± 0.18 (2.4%)	± 0.074 (1.0%)	± 0.024 (0.3%)	± 0.017 (0.2%)
$\sin^2\theta_{12}$	0.307	± 0.013 (4.2%)	± 0.0058 (1.9%)	± 0.0016 (0.5%)	± 0.0010 (0.3%)
$\sin^2\theta_{13}$	0.0218	± 0.0007 (3.2%)	± 0.010 (47.9%)	± 0.0026 (12.1%)	± 0.0016 (7.3%)

FIGURE 2.2 – A summary of precision levels fir the oscillation parameters. The reference value (PDG 2020 [5]) is compared with 100 days, 6 years and 20 years of JUNO data taking.

2.1.2 Other physics

While reactor neutrinos are the main signal, JUNO will of course be sensitive to every neutrinos energetic enough to allow an IBD, and even some other more exotic channels.

Geoneutrinos

Geoneutrinos designate the antineutrinos coming from the decay of long-lived radioactive elements inside the Earth. The 1.8 MeV threshold necessary for the IBD makes it possible to measure geoneutrinos from ^{2}38U and ^{2}32Th decay chains. The studies of geoneutrinos can help refine the Earth crust models but is also necessary to characterise their signal, as they are a background to the mass ordering and oscillations parameters studies.

Atmospheric neutrinos

Atmospheric neutrinos are neutrinos originating from the decay of π and K particles that are produced in extensive air showers initiated by the interactions of cosmic rays with the Earth atmosphere. Earth is mostly transparent to neutrinos below the PeV energy, thus JUNO will be able to see neutrinos coming from all directions. Their baseline range is large

(15km $\sim$ 13000km), they can have energy between 0.1 GeV and 10 TeV and will contain all neutrino and antineutrinos flavour.

Beyond standard model neutrinos interactions

Supernovae burst neutrinos

Diffuse supernovae neutrinos background

Background in the neutrinos reactor spectrum

2.2 The JUNO detector

2.2.1 Central Detector (CD)

Acrylic containment sphere

Liquid scintillator

Large photo-multipliers (LPMTs)

Small photo-multipliers (SPMTs)

Data Acquisition System (DAQ)

Simulation

Software

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ne

2.2.2 Veto detector

Cherenkov in water pool

Top tracker

2.3 Calibration strategy

2.3.1 Energy scale calibration

2.3.2 Calibration system

2.3.3 Calibration program

2.4 Event selection and background rejection

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2.5.1 Interaction vertex reconstruction

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2.5.3 Particle identification

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Vertex reconstruction

Energy reconstruction

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Chapter 3

Machine learning and Artificial Neural Network

3.1 History of the Machine learning

3.2 Boosted Decision Tree (BDT)

3.3 Artificial Neural Network (NN)

3.3.1 Fully Connected Deep Neural Network (FCDNN)

3.3.2 Convolutional Neural Network (CNN)

3.3.3 Graph Neural Network (GNN)

3.3.4 Adversorial Neural Network (ANN)

Generative Adversorial Network (GAN)

Reinformcement Learning (RL)

Random Search (RS)

Bayesian Optimization

Chapter 4

Image recognition for IBD reconstruction with the SPMT system

Chapter 5

Graph representation of JUNO for IBD reconstruction with the LPMT system

Chapter 6

Reliability of machine learning methods

Chapter 7

Discrimination of e+/e- events in JUNO

Chapter 8

Conclusion

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