

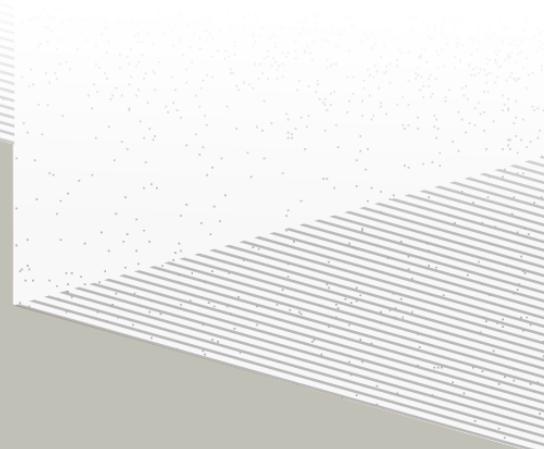
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THÈSE DE DOCTORAT DE

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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**

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³ List of Abbreviations

ACU	Automatic Calibration Unit
BDT	Boosted Decision Tree
CD	Central Detector
CLS	Cable Loop System
CNN	Convolutional NN
DNN	Deep NN
GNN	Graph NN
GT	Guiding Tube
IBD	Inverse Beta Decay
IO	Inverse Ordering
JUNO	Jiangmen Underground Neutrino Observatory
LPMT	Large PMT
LS	Liquid Scintillator
MC	Monte Carlo simulation
ML	Machine Learning
NMO	Neutrino Mass Ordering
NN	Neural Network
NO	Normal Ordering
OSIRIS	Online Scintillator Internal Radioactivity Investigation System
PE	Photo Electron
PMT	Photo-Multipliers Tubes
ROV	Remotely Operated under-LS Vehicle
SPMT	Small PMT
TAO	Taishan Antineutrino Observatory
TR Area	Total Reflexion Area
TTS	Time Transit Spread
TT	Top Tracker
WCD	Water Cherenkov Detector

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Remerciements

⁵²

53 Introduction

⁵⁴ **Chapter 1**

⁵⁵ **Neutrino physics**

⁵⁶

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.

⁵⁷ **1.1 Standard model**

⁵⁸ **1.1.1 Limits of the standard model**

⁵⁹ **1.2 Historic of the neutrino**

⁶⁰ **First theories**

⁶¹ **Discovery**

⁶² **Milestones and anomalies**

⁶³ **1.3 Oscillation**

⁶⁴ **1.3.1 Phenomologies**

⁶⁵ **1.4 Open questions**

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⁶⁶ **Chapter 2**

⁶⁷ **The JUNO experiment**

⁶⁸ “*Ave Juno, rosae rosam, et spiritus rex*”. It means nothing but I found it in tone.

⁶⁹ The first idea of a medium baseline (~ 52 km) experiment, was explored in 2008 [1] 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 the requirements of accurate knowledge of the reactor antineutrino spectra and the value of Δm_{32}^2 . From this idea is born the Jiangmen Underground Neutrino Observatory (JUNO) experiment.

⁷⁰ JUNO is a neutrino detection experiment under construction located in China, in Guangdong proving, near the city of Kaiping. Its main objectives are the determination of the mass ordering at the $3-4\sigma$ level in 6 years of data taking and the measurement at the sub-percent precision of the oscillation parameters Δm_{21}^2 , $\sin^2 \theta_{12}$, Δm_{32}^2 and with less precision $\sin^2 \theta_{13}$ [2].



FIGURE 2.1 – On the left: Location of the JUNO experiment and its reactor sources in southern China. On the right: Aerial view of the experimental site

⁷¹ For this JUNO will measure the electronic anti-neutrinos ($\bar{\nu}_e$) flux coming from the nuclear reactors of Taishan, Yangjiang, for a total power of 26.6 GW_{th} , and the Daya Bay power plant to a lesser extent. All of those cores are the second-generation pressurized water reactors CPR1000, which is a derivative of Framatome M310. Details about the power plants characteristics and their expected flux of $\bar{\nu}_e$ can be found in the table 2.1. The distance of 53 km has been specifically chosen to maximize the disappearance probability of the $\bar{\nu}_e$. The data taking is scheduled to start early 2025.

⁸⁴ **2.1 Neutrinos physics in JUNO**

⁸⁵ Even if the JUNO design detailed in section 2.2 was optimized for the measurement of the NMO, its large detection volume, excellent energy resolution and background level and understanding make it also an excellent detector to measure the flux coming from other neutrino sources. Thus

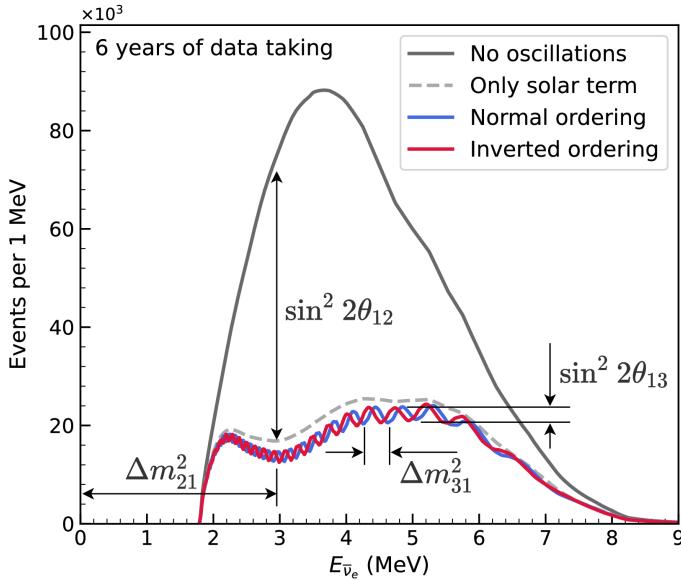


FIGURE 2.2 – Expected number of neutrinos event per MeV in JUNO after 6 years of data taking. The black curve shows the flux if there was no oscillation. The light gray curve shows the oscillation if only the solar terms are taken in account (θ_{12} , Δm_{21}^2). The blue and red curve shows the spectrum 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.

88 the scientific program of JUNO extends way over reactor antineutrinos. The following section is an
89 overview of the different physics topic JUNO will contribute in the coming years.

90 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 energy spectrum coming from medium baseline nuclear reactor. This disappearance probability can be expressed as [2] :

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} c_{13}^4 \sin^2 \frac{\Delta m_{21}^2 L}{4E} - \sin^2 2\theta_{13} \left[c_{12}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} + s_{12}^2 \sin^2 \frac{\Delta m_{32}^2 L}{4E} \right]$$

91 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
92 to the NMO in the dependency to Δm_{32}^2 and Δm_{31}^2 causing a phase shift of the spectrum as we can
93 see in the figure 2.2. By carefully adjusting a theoretical spectrum to the data, one can extract the
94 NMO and the oscillation parameters. The statistic procedure used to adjust the theoretical spectrum
95 is reviewed in more details in the section 2.7. To reach the desired sensitivity, JUNO must meet
96 multiple requirements but most notably:

- 97 1. An energy resolution of $3\% / \sqrt{E(\text{MeV})}$ to be able to distinguish the fine structure of the fast
98 oscillation.
- 99 2. An energy precision of 1% in order to not err on the location of the oscillation pattern.
- 100 3. A baseline of 53 ± 0.5 km to maximise the $\bar{\nu}_e$ oscillation probability.
- 101 4. At least $\approx 100,000$ events to limit the spectrum distortion due to statistical uncertainties.

102 **$\bar{\nu}_e$ flux coming from nuclear power plants**

103 To get such high measurements precision, it is necessary to have a very good understanding of
 104 the sources characteristics. For its NMO and precise measurement studies, JUNO will observe the
 105 energy spectrum of neutrinos coming from the nuclear power plants Taishan and Yangjiang's cores,
 106 located at 53 km of the detector to maximise the disappearance probability of the $\bar{\nu}_e$.

Reactor	Power (GW _{th})	Baseline (km)	IBD Rate (day ⁻¹)	Relative Flux (%)
Taishan	9.2	52.71	15.1	32.1
Core 1	4.6	52.77	7.5	16.0
Core 2	4.6	52.64	7.6	16.1
Yangjiang	17.4	52.46	29.0	61.5
Core 1	2.9	52.74	4.8	10.1
Core 2	2.9	52.82	4.7	10.1
Core 3	2.9	52.41	4.8	10.3
Core 4	2.9	52.49	4.8	10.2
Core 5	2.9	52.11	4.9	10.4
Core 6	2.9	52.19	4.9	10.4
Daya Bay	17.4	215	3.0	6.4

TABLE 2.1 – Characteristics of the nuclear power plants observed by JUNO. The IBD rate are estimated from the baselines, the reactors full thermal power, selection efficiency and the current knowledge of the oscillation parameters

107 The $\bar{\nu}_e$ coming from reactors are emitted from β -decay of unstable fission fragments. The Taishan
 108 and Yangjiang reactors are Pressurised Water Reactor (PWR), the same type as Daya Bay. In those
 109 type of reactor more the 99.7 % and $\bar{\nu}_e$ are produced by the fissions of four fuel isotopes ²³⁵U, ²³⁸U,
 110 ²³⁹Pu and ²⁴¹Pu. The neutrino flux per fission of each isotope is determined by the inversion of the
 111 measured β spectra of fission product [4–8] or by calculation using the nuclear databases [9, 10].

112 The neutrino flux coming from a reactor at a time t can be predicted using

$$\phi(E_\nu, t)_r = \frac{W_{th}(t)}{\sum_i f_i(t) e_i} \sum_i f_i(t) S_i(E_\nu) \quad (2.1)$$

113 where $W_{th}(t)$ is the thermal power of the reactor, $f_i(t)$ is the fraction fission of the i th isotope, e_i its
 114 thermal energy released in each fission and $S_i(e_\nu)$ the neutrino flux per fission for this isotope. Using
 115 this method, the flux uncertainty is expected to be of an order of 2-3 % [11].

116 In addition to those prediction, a satellite experiment named TAO[12] will be setup near the
 117 reactor core Taishan-1 to measure with an energy resolution of 2% at 1 MeV the neutrino flux coming
 118 from the core, more details can be found in section 2.4.1. It will help identifying unknown fine
 119 structure and give more insight on the $\bar{\nu}_e$ flux coming from this reactor.

120 One the open issue about reactor anti-neutrinos flux is the so-called neutrino anomaly [13], an
 121 unexpected surplus of neutrino emission in the spectra around 5 MeV. Multiples scientists are trying
 122 to explain this surplus by advanced recalculation of the nuclei model during beta decay [14, 15] but
 123 no consensus on this issue has been reached yet.

124 **Background in the neutrinos reactor spectrum**

125 Considering the close reactor neutrinos flux as the main signal, the signals that are considered as
 126 background are:

- 127 — The geoneutrinos producing background in the 0.511 ~ 2.7 MeV region.
- 128 — The neutrinos coming from the other nuclear reactors around Earth.

129 In addition to all those physics signal, non-neutrinos signal that would mimic an IBD will also be
 130 present. It is composed of:

- The signal coming from radioactive decay (α , γ , β) from natural radioactive isotopes in the material of the detector.
- Cosmogenic event such as fast neutrons and activated isotopes induced by muons passing through the detector, most notably the spallation on ^{12}C .
- All those events represent a non-negligible part of the spectrum as shown in figure 2.3.

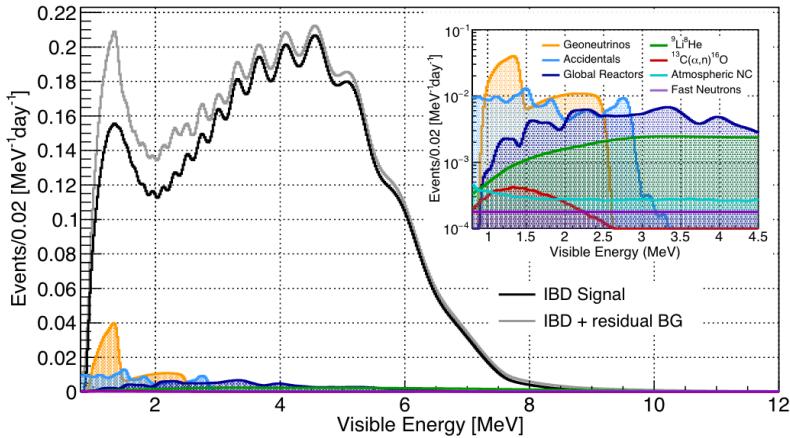


FIGURE 2.3 – Expected visible energy spectrum measured with the LPMT system with (grey) and without (black) backgrounds. The background amount for about 7% of the IBD candidate and are mostly localized below 3 MeV [11]

136 Identification of the mass ordering

137 To identify the mass ordering, we adjust the theoretical neutrino energy spectrum under the
 138 two hypothesis of NO and IO. Those give us two χ^2 , respectively χ^2_{NO} and χ^2_{IO} . By computing the
 139 difference $\Delta\chi^2 = \chi^2_{NO} - \chi^2_{IO}$ we can determine the most probable mass ordering and the confidence
 140 interval: NO if $\Delta\chi^2 > 0$ and IO if $\Delta\chi^2 < 0$. Current studies shows that the expected sensitivity
 141 the mass ordering would be of 3.4σ after 6 years of data taking in nominal setup[2]. More detailed
 142 explanations about the procedure can be found in the section 2.7.

143 Precise measurement of the oscillations parameters

144 The oscillations parameters θ_{12} , θ_{13} , Δm_{21}^2 , Δm_{31}^2 are free parameters in the fit of the oscillation
 145 spectrum. The precision on those parameters have been estimated and are shown in table 2.2. Wee
 146 see that for θ_{12} , Δm_{21}^2 , Δm_{31}^2 , precision at 6 years is better than the reference precision by an order of
 147 magnitude [11]

	Central Value	PDG 2020	100 days	6 years	20 years
$\Delta m_{31}^2 (\times 10^{-3} \text{ eV}^2)$	2.5283	± 0.034 (1.3%)	± 0.021 (0.8%)	± 0.0047 (0.2%)	± 0.0029 (0.1%)
$\Delta m_{21}^2 (\times 10^{-3} \text{ eV}^2)$	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%)

TABLE 2.2 – A summary of precision levels fir the oscillation parameters. The reference value (PDG 2020 [16]) is compared with 100 days, 6 years and 20 years of JUNO data taking.

2.1.2 Other physics

While the design of JUNO is tailored to measure $\bar{\nu}_e$ coming from nuclear reactor, JUNO will be able to detect neutrinos coming from other sources thus allowing for a wide range of physics studies as detailed in the table 2.3 and in the following sub-sections.

Research	Expected signal	Energy region	Major backgrounds
Reactor antineutrino	60 IBDs/day	0–12 MeV	Radioactivity, cosmic muon
Supernova burst	5000 IBDs at 10 kpc	0–80 MeV	Negligible
DSNB (w/o PSD)	2300 elastic scattering		
Solar neutrino	2–4 IBDs/year	10–40 MeV	Atmospheric ν
Atmospheric neutrino	hundreds per year for 8B	0–16 MeV	Radioactivity
Geoneutrino	hundreds per year	0.1–100 GeV	Negligible
	≈ 400 per year	0–3 MeV	Reactor ν

TABLE 2.3 – Detectable neutrino signal in JUNO and the expected signal rates and major background sources

152 Geoneutrinos

153 Geoneutrinos designate the antineutrinos coming from the decay of long-lived radioactive
 154 elements inside the Earth. The 1.8 MeV threshold necessary for the IBD makes it possible to measure
 155 geoneutrinos from ${}^{238}U$ and ${}^{232}Th$ decay chains. The studies of geoneutrinos can help refine the Earth
 156 crust models but is also necessary to characterise their signal, as they are a background to the mass
 157 ordering and oscillations parameters studies.

158 Atmospheric neutrinos

159 Atmospheric neutrinos are neutrinos originating from the decay of π and K particles that are
 160 produced in extensive air showers initiated by the interactions of cosmic rays with the Earth atmos-
 161 phere. Earth is mostly transparent to neutrinos below the PeV energy, thus JUNO will be able to
 162 see neutrinos coming from all directions. Their baseline range is large (15km \sim 13000km), they can
 163 have energy between 0.1 GeV and 10 TeV and will contain all neutrino and antineutrinos flavour.
 164 Their studies is complementary to the reactor antineutrinos and can help refine the constraints on
 165 the NMO [2].

166 Supernovae burst neutrinos

167 Neutrinos are crucial component during all stages of stellar collapse and explosion. Detection
 168 of neutrinos coming for core collapse supernovae will provide us important informations on the
 169 mechanisms at play in those events. Thanks to its 20 kt sensible volume, JUNO has excellent capa-
 170 bilities to detect all flavour of the $\mathcal{O}(10 \text{ MeV})$ postshock neutrinos, and using neutrinos of the $\mathcal{O}(1$
 171 MeV) will give informations about the pre-supernovae neutrinos. All those informations will allow
 172 to disentangle between the multiple hydro-dynamic models that are currently used to describe the
 173 different stage of core-collapse supernovae.

174 Diffuse supernovae neutrinos background

175 Core-collapse supernovae in our galaxy are rare events, but they frequently occur throughout the
 176 visible Universe sending burst of neutrinos in direction of the Earth. All those events contributes to
 177 a low background flux of low-energy neutrinos called the Diffuse Supernovae Neutrino Background
 178 (DSNB). Its flux and spectrum contains informations about the red-shift dependent supernovae rate,

179 the average supernovae neutrino energy and the fraction of black-hole formation in core-collapse supernovae.
 180 Depending of the DSNB model, we can expect 2-4 IBD events per year in the energy range
 181 above the reactor $\bar{\nu}_e$ signal, which is competitive with the current Super-Kamiokande+Gadolinium
 182 phase [17].

183 Beyond standard model neutrinos interactions

184 JUNO will also be able to probe for beyond standard model neutrinos interactions. After the
 185 main physics topics have been accomplished, JUNO could be upgraded to probe for neutrinoless
 186 beta decay ($0\nu\beta\beta$). The detection of such event would give critical informations about the nature
 187 of neutrinos, is it a majorana or a dirac particle. JUNO will also be able to probe for neutrinos that
 188 would come for the decay or annihilation of Dark Matter inside the sun and neutrinos from putative
 189 primordial black hole. Through the unitary test of the mixing matrix, JUNO will be able to search
 190 for light sterile neutrinos. Thanks to JUNO sensitivity, multiple other exotic can be performed on
 191 neutrino related beyond standard model interactions.

192 2.2 The JUNO detector

193 The JUNO detector is a scintillator detector buried 693.35 meters under the ground (1800 meters
 194 water equivalent). It consist of Central Detector (CD), a water pool and a Top Tracker (TT) as showed
 195 in figure 2.4a. The CD is an acrylic vessel containing the 20 ktons of Liquid Scintillator (LS). It is
 196 supported by a stainless steel structure and is immersed in that water pool that is used as shielding
 197 from external radiation and as a cherenkov detector for the background. The top of the experiment
 198 is partially covered by the Top Tracker (TT), a plastic scintillator detector which is use to detect the
 199 atmospheric muons background and is acting as a veto detector.

200 The top of the experiment also host the LS purification system, a water purification system, a
 201 ventilation system to get rid of the potential radon in the air. The CD is observed by two system of
 202 Photo-Multipliers Tubes (PMT). They are attached to the steel structure and their electronic readout
 203 is submersed near them. A third system of PMT is also installed on the structure but are facing
 204 outward of the CD, instrumenting the water to be cherenkov detector. The CD and the cherenkov
 205 detector are optically separated by Tyvek sheet. A chimney for LS filling and purification and for
 206 calibration operations connects the CD to the experimental hall from the top.

207 The CD has been dimensioned to meet the requirements presented in section 2.1.1:

- 208 — Its 20 ktons monolithic LS provide a volume sizeable enough, in combination with the ex-
 209 pected $\bar{\nu}_e$ flux, to reach the desired statistic in 6 years. Its monolithic nature also allow for a
 210 full containment of most of the events, preventing the energy loss in non-instrumented parts
 211 that would arise from a segmented detector.
- 212 — Its large overburden shield it from most of the atmospheric background that would pollute
 213 the signal.
- 214 — The localization of the experiment, chosen to maximize the disappearance with a 53km base-
 215 line and in a region that allow two nuclear power plant to be used as sources.

216 This section cover in details the different components of the detector and the detection systems.

217 2.2.1 Detection principle

The CD will detect the neutrino and measure their energy mainly via an Inverse Beta Decay (IBD) interaction with proton mainly from the ^{12}C and H nucleus in the LS:

$$\bar{\nu}_e + p \rightarrow n + e^+$$

218 Kinematics calculation shows that this interaction has an energy threshold for the $\bar{\nu}_e$ of $(m_n + m_e -$
 219 $m_p) \approx 1.806 \text{ MeV}$ [18] where m_λ is the mass of the λ particle. This threshold make the experiment

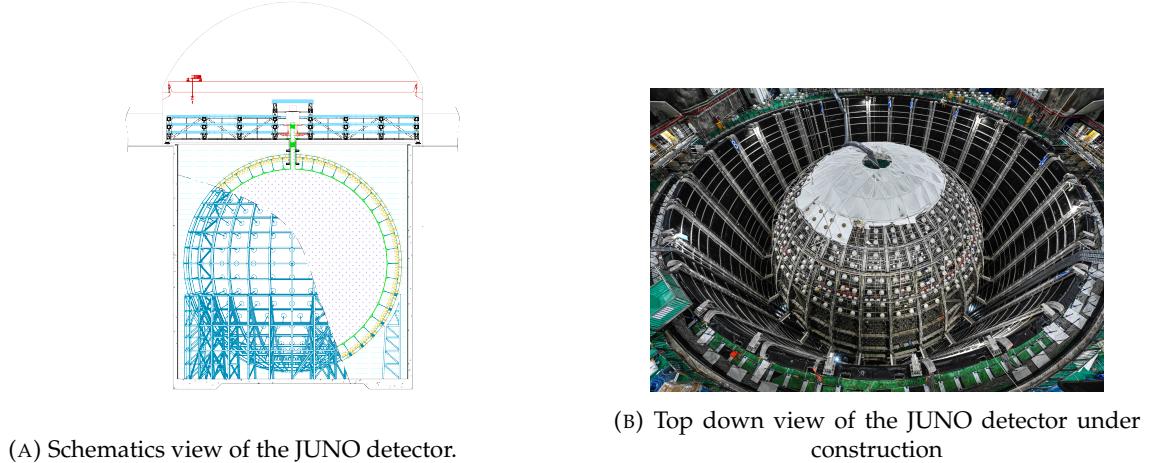


FIGURE 2.4

blind to very low energy neutrinos. The residual energy $E_\nu - 1.806$ MeV is be distributed as kinetic energy between the positron and the neutron. The energy of the emitted positron E_e is given by [18]

$$E_e = \frac{(E_\nu - \delta)(1 + \epsilon_\nu) + \epsilon_\nu \cos \theta \sqrt{(E_\nu - \delta)^2 + \kappa m_e^2}}{\kappa} \quad (2.2)$$

where $\kappa = (1 + \epsilon_\nu)^2 - \epsilon_\nu^2 \cos^2 \theta \approx 1$, $\epsilon_\nu = \frac{E_\nu}{m_p} \ll 1$ and $\delta = \frac{m_n^2 - m_p^2 - m_e^2}{2m_p} \ll 1$. We can see from this equation that the positron energy is strongly correlated to the neutrino energy.

The positron and the neutron will then propagate in the detection medium, the Liquid Scintillator (LS), loosing their kinetic energy by exciting the molecule of the LS (more details in section 2.2.2). Once stopped, the positron will annihilate with an electron from the medium producing two 511 KeV gamma. Those gamma will themselves interact with the LS, exciting it before being absorbed by photoelectrical effect. The neutron will be captured by an hydrogen, emitting a 2.2 MeV gamma in the process. This gamma will also deposit its energy before being absorbed by the LS.

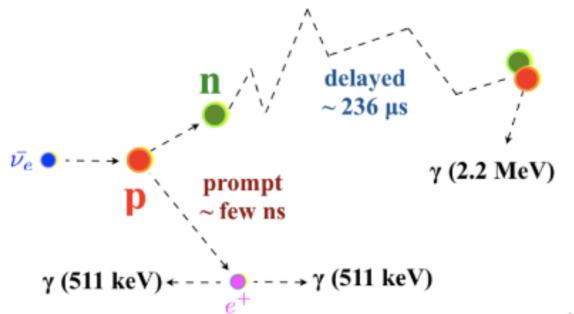


FIGURE 2.5 – Schematics of an IBD interaction in the central detector of JUNO

The scintillation photons have frequency in the UV and will propagate in the LS, being re-absorbed and re-emitted by compton effect before finally be captured by PMTs instrumenting the acrylic sphere. The analog signal of the PMTs digitized by the electronic is the signal of our experiment. The signal produced by the positron is subsequently called the prompt signal, and the signal coming from the neutron the delayed signal. This naming convention come from the fact that the positron will deposit its energy rather quickly (few ns) where the neutron will take a bit more time ($\sim 236 \mu\text{s}$).

2.2.2 Central Detector (CD)

The central detector, composed of 20 ktons of Liquid Scintillator (LS), is the main part of JUNO. The LS is contained in a spherical acrylic vessel supported by a stainless steel structure. The CD and its structural support are submerged in a cylindrical water pool of 43.5m diameter and 44m height. We're confident that the water pool provide sufficient buffer protection in every direction against the rock radioactivity.

Acrylic vessel

The acrylic vessel is a spherical vessel of inner diameter of 35.4 m and a thickness of 120 mm. It is assembled from 265 acrylic panels, thermo bonded together. The acrylic recipes has been carefully tuned with extensive R&D to ensure it does not include plasticizer and anti-UV material that would stop the scintillation photons. Those panels requires to be pure of radioactive materials to not cause background. Current setup where the acrylic panels are molded in cleanrooms of class 10000, let us reach a uranium and thorium contamination of <0.5 ppt. The molding and thermoforming processes is optimized to increase the assemblage transparency in water to >96%. The acrylic vessel is supported by a stainless steel structure via supporting node (fig 2.6). The structure and the nodes are designed to be resilient to natural catastrophic events such as earthquake and can support many times the effective load of the acrylic vessel.

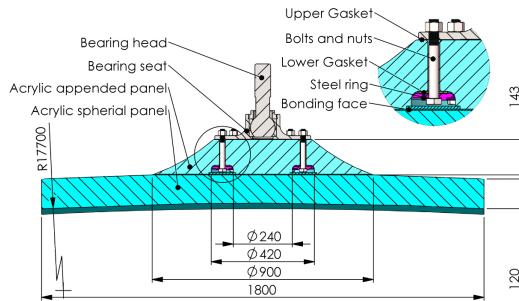


FIGURE 2.6 – Schematics of the supporting node for the acrylic vessel

Liquid scintillator

The Liquid Scintillator (LS) has a similar recipe as the one used in Daya Bay [19] but without gadolinium doping. It is made of three components, necessary to shift the wavelength of emitted photons to prevent their reabsorption:

1. The detection medium, the *linear alkylbenzene* (LAB). Selected because of its excellent transparency, high flash point, low chemical reactivity and good light yield. Accounting for $\sim 98\%$ of the LS, it is the main component with which ionizing particles and gamma interact. Charged particles will collide with its electronic cloud transferring energy to the molecules, gamma will interact via compton effect with the electronic cloud before finally be absorbed via photoelectric effect.
2. The second component of the LS is the *2,5-diphenyloxazole* (PPO). A fraction of the excitation energy of the LAB is transferred to the PPO, mainly via non radiative process [20]. The PPO molecules de-excites in the same way, transferring their energy to the bis-MSB. The PPO makes for 1.5 % of the LS.
3. The last component is the *p-bis(o-methylstyryl)-benzene* (bis-MSB). Once excited by the PPO, it will emit photon with an average wavelength of ~ 430 nm (full spectrum in figure 2.7) that can be detected by our photo-multipliers systems. It amount for $\sim 0.5\%$ of the LS.

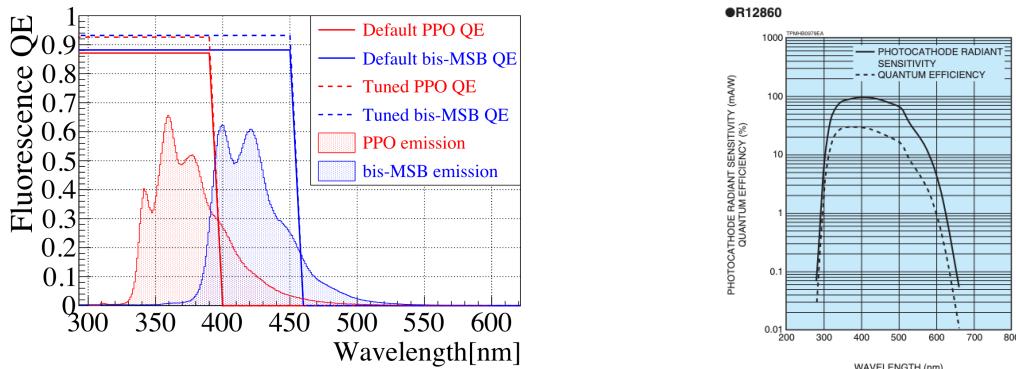


FIGURE 2.7 – On the left: Quantum efficiency (QE) and emission spectrum of the LAB and the bis-MSB [19]. On the right: Sensitivity of the Hamamatsu LPMT depending on the wavelength of the incident photons [21].

This formula has been optimized using dedicated studies with a Daya Bay detector [19, 22] to reach the requirements for the JUNO experiment:

- A light yield / MeV of the amount of 10^4 photons to maximize the statistic in the energy measurement.
- An attenuation length comparable to the size of the detector to prevent losing photons during their propagation in the LS. The final attenuation length is 25.8m [23] to compare with the CD diameter of 35.4m.
- Uranium/Thorium radiopurity to prevent background signal. The reactor neutrino program require a contamination fraction $F < 10^{-15}$ while the solar neutrino program require $F < 10^{-17}$.

The LS will frequently be purified and tested in the Online Scintillator Internal Radioactivity Investigation System (OSIRIS) [24] to ensure that the requirements are kept during the lifetime of the experiment, more details to be found in section 2.4.2.

Large Photo-Multipliers Tubes (PMTs)

The scintillation light produced by the LS is then collected by Photo-Multipliers Tubes (PMT) that transform the incoming photon into an electric signal. As described in figure 2.8, the incident photons interact with the photocathode via photoelectric effect producing an electron called a Photo-Electron (PE). This PE is then focused on the dynodes where the high voltage will allow it to be multiplied. After multiple amplification the resulting charge - in coulomb [C] - is collected by the anode and the resulting electric signal can be digitalized by the readout electronics from which the charge and timing can be extracted.

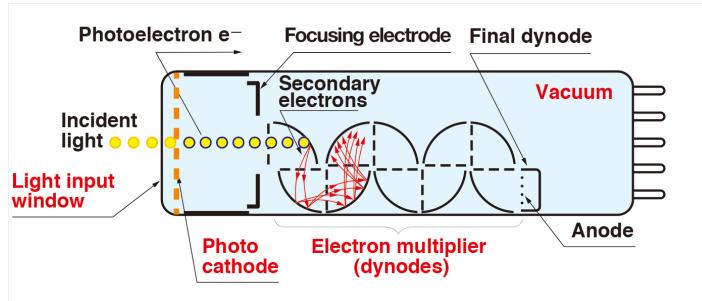


FIGURE 2.8 – Schematic of a PMT

The Large Photo-Multipliers Tubes (LPMT), used in the central detector and in the water pool, are 20-inch (50.8 cm) radius PMTs. ~ 5000 dynode-PMTs [21] were produced by the Hamamatsu[©] company and ~ 15000 Micro-Channel Plate (MCP) [25] by the NNVT[©] company. This system is the one responsible for the energy measurement with a energy resolution of $3\%/\sqrt{E}$, resolution necessary for the mass ordering measurement. To reach this precision, the system is composed of 17612 PMTs quasi uniformly distributed over the detector for a coverage of 75.2% reaching ~ 1800 PE/MeV or $\sim 2.3\%$ resolution due to statistic, leaving $\sim 0.7\%$ for the systematic uncertainties. They are located outside the acrylic sphere in the water pool facing the center of the detector. To maintain the resolution over the lifetime of the experiment, JUNO require a failure rate $< 1\%$ over 6 years.

The LPMTs electronic are divided in two parts. One "near", located underwater, in proximity of the LPMT to reduce the cable length between the PMT and early electronic. A second one, outside of the detector that is responsible for higher level analysis before sending the data to the DAQ.

The light yield per MeV induce that a LPMT can collect between 1 and 1000 PE per event, causing non linearity in the PMT response that need to be understood and calibrated, see section 2.3 for more details.

Small Photo-Multipliers Tubes (SPMTs)

The Small PMT (SPMTs) system is made of 3-inch (7.62 cm) PMTs. They will be used in the CD as a secondary detection system. Those 25600 SPMTs will observe the same events as the LPMTs, thus sharing the physics and detector systematics up until the photon conversion. With a detector coverage of 2.7%, this system will collect ~ 43 PE/MeV for a final energy resolution of $\sim 17\%$. This resolution is not enough to measure the NMO, θ_{13} , Δm_{31}^2 but will be sufficient to independently measure θ_{12} and Δm_{21}^2 .

Due to the low PE rate, SPMTs will be running in photo-counting mode in the reactor range and thus will be insensitive to non-linearity effect. Using this property, the intrinsic charge non linearity of the LPMTs can be measured by comparing the PE count in the SPMTs and LPMTs [26]. Also, due to their smaller size and electronics, SPMTs have a better timing resolutions than the LPMTs. At higher energy range, like supernovae events, LPMTs will saturate where SPMTs due to their lower PE collection will to produce a reliable measure of the energy spectrum.

The Data Acquisition System (DAQ) is designed to support the event rate of IBD, background, dark noise and supplementary storage buffers are present in the LPMT electronics to withstand the event rate during supernovae burst.

2.2.3 Veto detector

The CD will be bathed in constant background noise coming from numerous sources : the radioactivity from surrounding rock and its own components or from the flux of cosmic muons. This background needs to be rejected to ensure the purity of the IBD spectrum. To prevent a big part of them, JUNO use two veto detector that will tag events as background before CD analysis.

Cherenkov in water pool

The Water Cherenkov Detector (WCD) is the instrumentation of the water buffer around the CD. When high speed charged particles will pass through the water, they will produced cherenkov photons. The light will be collected by 2400 MCP LPMTs installed on the outer surface of the CD structure. The muons veto strategy is based on a PMT multiplicity condition. WCD PMTs are grouped in ten zones: 5 in the top, 5 in the bottom. A veto is raised either when more than 19 PMTs are triggered in one zone or when two adjacent zones simultaneously trigger more than 13 PMTs. Using this trigger, we expect to reach a muon detection efficiency of 99.5% while keeping the noise at reasonable level.

336 **Top tracker**

337 The JUNO Top Tracker (TT) is a plastic scintillator detector located on the top of the experiment
 338 (see figure 2.9). Made from plastic scintillator from OPERA [27] layered horizontally in 3 layers on
 339 the top of the detector, the TT will be able to detect incoming atmospheric muons. With its coverage,
 340 about 1/3 of the of all atmospheric muons that passing through the CD will also pass through the 3
 341 layer of the detector. While it does not cover the majority of the CD, the TT is particularly effective
 342 to detect muons coming through the filling chimney region which might present difficulties from the
 343 other subsystems in some classes of events.

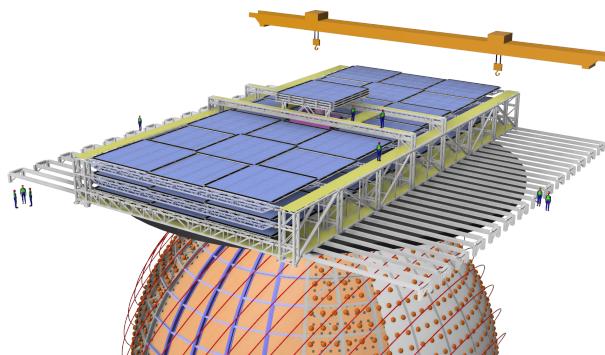


FIGURE 2.9 – The JUNO top tracker

343

344 **2.3 Calibration strategy**

345 The calibration is a crucial part of the JUNO experiment. Because we are looking at civil reactor
 346 neutrino it might be impossible to run measurement without signal, it would need to shut down
 347 every reactor from the Taishan and Yangjiang power plants which is realistically impossible. Because
 348 of this continuous rate, low frequency signal event, we need high frequency, recognisable sources in
 349 the energy range of interest : [0-12] MeV for the positron signal and 2.2 MeV for the neutron capture.
 350 It is expected that the CD response will be different depending on the type of particle, due to the
 351 interaction with LS, the position on the event and the optical response of the acrylic sphere (see
 352 section 2.6). We also expect a non-linear energy response of the CD due to the LS properties [19] but
 353 also due to the saturation of the LPMTs system when collecting a large amount of PE [26].

354 **2.3.1 Energy scale calibration**

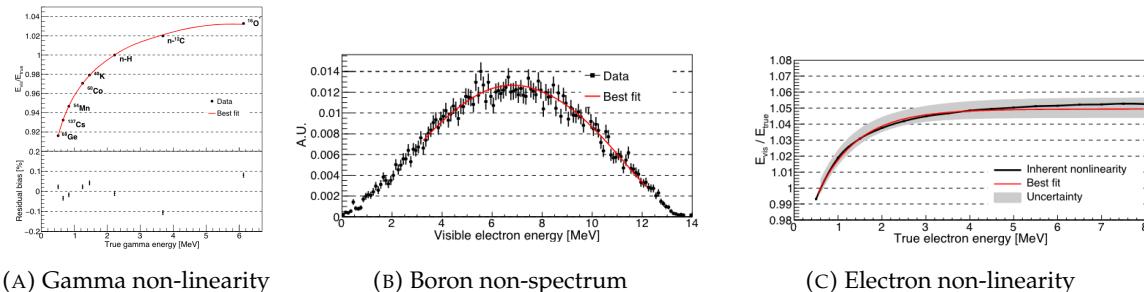
355 While electrons and positrons sources would be ideal, for a large LS detector thin-walled electrons
 356 or positrons sources could lead to leakage of radionucleides causing radioactive contamination.
 357 Instead, we consider gamma sources in the range of the prompt energy of IBDs. The sources are
 358 reported in table 2.4.

359 For the ^{68}Ge source, it will decay in ^{68}Ga via electron capture, which will itself β^+ decay into ^{68}Zn .
 360 The positrons will be absorbed by the enclosure so only the annihilation gamma will be released. In
 361 addition, (α, n) sources like $^{241}\text{Am-Be}$ and $^{241}\text{Am-}^{13}\text{C}$ are used to provide both high energy gamma
 362 and neutrons, which will later be captured in the LS producing the 2.2 MeV gamma.

363 From this calibration we call E_{vis} the "visible energy" that is reconstructed by our current algo-
 364 rithms and we compare it to the true energy deposited by the calibration source. The results shown
 365 in figure 2.10 show the expected response of the detector from calibration sources. The non-linearity
 366 is clearly visible from the $E_{\text{vis}}/E_{\text{true}}$ shape. See [28] for more details.

Sources / Processes	Type	Radiation
^{137}Cs	γ	0.0662 MeV
^{54}Mn	γ	0.835 MeV
^{60}Co	γ	$1.173 + 1.333$ MeV
^{40}K	γ	1.461 MeV
^{68}Ge	e^+	annihilation 0.511 + 0.511 MeV
$^{241}\text{Am-Be}$	n, γ	neutron + 4.43 MeV ($^{12}\text{C}^*$)
$^{241}\text{Am-}^{13}\text{C}$	n, γ	neutron + 6.13 MeV ($^{16}\text{O}^*$)
$(n, \gamma)p$	γ	2.22 MeV
$(n, \gamma)^{12}\text{C}$	γ	4.94 MeV or 3.68 + 1.26 MeV

TABLE 2.4 – List of sources and their process considered for the energy scale calibration

FIGURE 2.10 – Fitted and simulated non linearity of gamma, electron sources and from the ^{12}B spectrum. Black points are simulated data. Red curves are the best fits

2.3.2 Calibration system

The non-uniformity due to the event position in the detector (more details in section 2.6) will be studied using multiples systems that are schematized in figure 2.11. They allow to position sources at different location in the CD.

- For a one-dimension vertical calibration, the Automatic Calibration Unit (ACU) will be able to deploy multiple radioactive sources or a pulse laser diffuser ball along the central axis of the CD through the top chimney. The source position precision is less than 1cm.
- For off-axis calibration, a calibration source attached to a Cable Loop System (CLS) can be moved on a vertical half-plane by adjusting the length of two connection cable. Two set of CSL will be deployed to provide a 79% effective coverage of a vertical plane.
- A Guiding Tube (GT) will surround the CD to calibrate the non-uniformity of the response at the edge of the detector
- A Remotely Operated under-LS Vehicle (ROV) can be deployed to desired location inside LS for a more precise and comprehensive calibration. The ROV will also be equipped with a camera for inspection of the CD.

The preliminary calibration program is depicted in table 2.5.

2.4 Satellite detectors

As introduced in section 2.1.1 and section 2.2.2, the precise knowledge and understanding of the detector condition is crucial for the measurements of the NMO and oscillation parameters. Thus two satellite detectors will be setup to monitor the experiment condition. TAO to monitor and understand the $\bar{\nu}_e$ flux and spectrum coming from the nuclear reactor and OSIRIS to monitor the LS response.

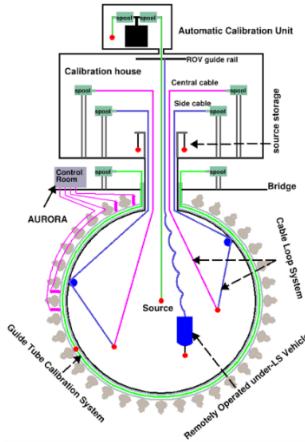


FIGURE 2.11 – Overview of the calibration system

Program	Purpose	System	Duration [min]
Weekly calibration	Neutron (Am-C)	ACU	63
	Laser	ACU	78
Monthly calibration	Neutron (Am-C)	ACU	120
	Laser	ACU	147
	Neutron (Am-C)	CLS	333
	Neutron (Am-C)	GT	73
Comprehensive calibration	Neutron (Am-C)	ACU, CLS and GT	1942
	Neutron (Am-Be)	ACU	75
	Laser	ACU	391
	^{68}Ge	ACU	75
	^{137}Cs	ACU	75
	^{54}Mn	ACU	75
	^{60}Co	ACU	75
	^{40}K	ACU	158

TABLE 2.5 – Calibration program of the JUNO experiment

2.4.1 TAO

The Taishan Antineutrino Observatory (TAO) [12, 29] is a ton-level gadolinium doped liquid scintillator detector that will be located near the Taishan-1 reactor. It aim to measure the $\bar{\nu}_e$ spectrum at very low distance ($< 30\text{m}$) from the reactor to measure a quasi-unoscillated spectrum. TAO also aim to provide a major contribution to the so-called reactor anomaly [13]. Its requirement are to the level of 2 % energy resolution at 1 MeV.

Detector

The TAO detector is close, in concept, to the CD of JUNO. It is composed of an acrylic vessel containing 2.8 tons of gadolinium-loaded LS instrumented by an array of silicon photomultipliers (SiPM) reaching a 95% coverage. To efficiently reduce the dark count of those sensors, the detector is cooled to $-50\text{ }^\circ\text{C}$. The $\bar{\nu}_e$ will interact with the LS via IBD, producing scintillation light, that will be detected by the SiPMs. From this signal the $\bar{\nu}_e$ energy and the full spectrum reconstructed. This spectrum will then be used by JUNO to calibrate the unoscillated spectrum, most notably the fission product fraction that impact the rate and shape of the spectrum. A schema of the detector is presented in figure 2.12a.

2.4.2 OSIRIS

The Online Scintillator Internal Radioactivity Investigation System (OSIRIS) [24] is an ultralow background, 20 m³ LS detector that will be located in JUNO cavern. It aim to monitor the radioactive contamination, purity and overall response of the LS before it is injected in JUNO. OSIRIS will be located at the end of the purification chain of JUNO, monitoring that the purified LS meet the JUNO requirements. The setup is optimized to detect the fast coincidences decay of ²¹⁴Bi – ²¹⁴Po and ²¹²Bi – ²¹²Po, indicators of the decay chains of U and Th respectively.

Detector

OSIRIS is composed of an acrylic vessel that will contains 17t of LS. The LS is instrumented by a PMT array of 64 20 inch PMTs on the top and the side of the vessel. To reach the necessary background level required by the LS purity measurements, in addition to being 700m underground in the experiment cavern, the acrylic vessel is immersed in a tank of ultra pure water. The water is itself instrumented by another array of 20 inch PMTs, acting as muon veto. A schema of the detector is presented in figure 2.12b.

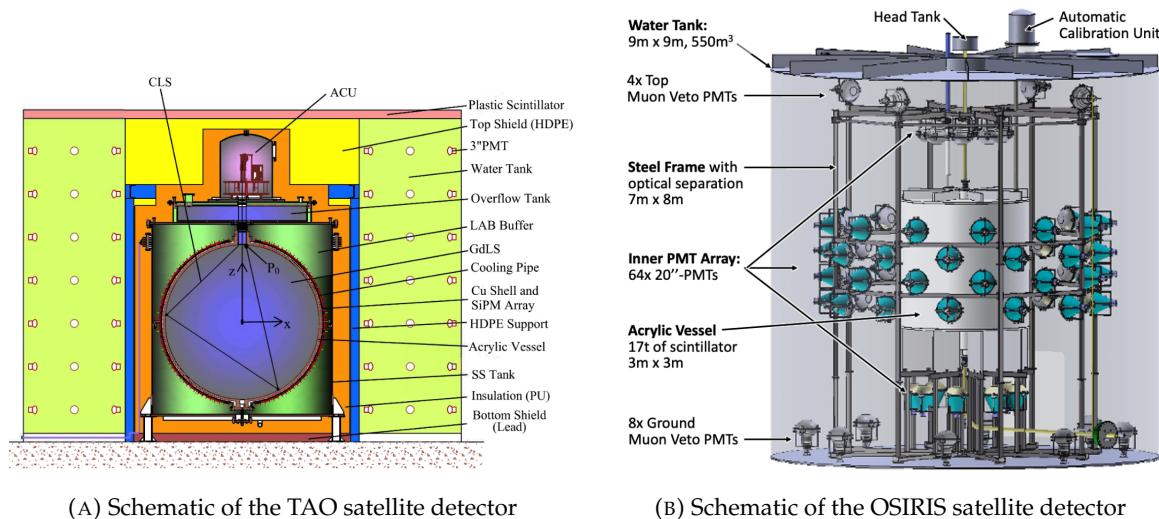


FIGURE 2.12

2.5 Software

The simulation, reconstruction and analysis algorithms are all packaged in the JUNO software, subsequently called the software. It is composed of multiple components integrated in the SNiPER [30] framework:

- Various primary particles simulators for the different kind of events, background and calibration sources.
- A Geant4 [31–33] Monte Carlo (MC) simulation containing the detectors geometries, a custom optical model for the LS and the supporting structures of the detectors. The Geant4 simulation integrate all relevant physics process for JUNO, validated by the collaboration. This step of the simulation is commonly called *Detsim* and compute up to the production of photo-electrons in the PMTs. The optics properties of the different materials and detector components have been measured beforehand to be used to define the material and surfaces in the simulation.

- An electronic simulation, simulating the response waveform of the PMTs, tracking it through the digitization process, accounting for effects such as non-linearity, dark noise, Time Transit Spread (TTS), pre-pulsing, after-pulsing and ringing if the waveform. It's also the step handling the event triggers and mixing. This step is commonly referenced as *Elecsim*.
- A waveform reconstruction where the digitized waveform are filtered to remove high-frequency white noise and then deconvoluted to yield time and charge informations of the photons hits on the PMTs. This step is commonly referenced as *Calib*.
- The charge and time informations are used by reconstruction algorithms to reconstruct the interaction vertex and the deposited energy. This step is commonly reported as *Reco*. See section 2.6 for more details on the reconstruction.
- Once the singular events are reconstructed, they go through event pairing and classification to select IBD events. This step is named Event Classification.
- The purified signal is then analysed by the analysis framework which depend of the physics topic of interest.

The steps Reco and Event Classification are divided into two category of algorithm. Fast but less accurate algorithms that are running during the data taking designated as the *Online* algorithms. Those algorithm are used to take the decision to save the event on tape or to throw it away. More accurate algorithms that run on batch of events designated *Offline* algorithms. They are used for the physics analysis. The Offline Reco will be one of the main topic of interest for this thesis.

2.6 State of the art of the Offline IBD reconstruction in JUNO

The main reconstruction method currently run in JUNO is a data-driven method based on a likelihood maximization [34, 35] using only the LPMTs. The first step is to reconstruct the interaction vertex from which the energy reconstruction is dependent. It is also necessary for event pairing and classification.

2.6.1 Interaction vertex reconstruction

To start the likelihood maximization, a rough estimation of the vertex and of the event timing is needed. We start by estimating the vertex position using a charge based algorithm.

Charge based algorithm

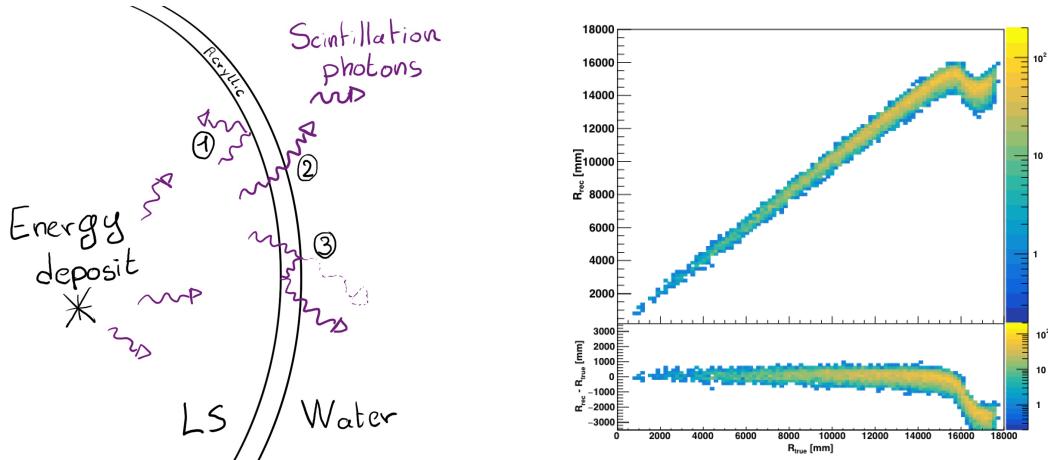
The charge-based algorithm is basically base on the charge-weighted average of the PMT position.

$$\vec{r}_{cb} = a \cdot \frac{\sum_i q_i \cdot \vec{r}_i}{\sum_i q_i} \quad (2.3)$$

Where q_i is the reconstructed charge of the pulse of the i th PMT and \vec{r}_i is its position. \vec{r}_0 is the reconstructed interaction position. a is a scale factor introduced because a weighted average over a 3D sphere is inherently biased. Using calibration we can estimate $a \approx 1.3$ [36]. The results in figure 2.13b shows that the reconstruction is biased from around 15m and further. This is due to the phenomena called “total reflection area” or TR Area.

As depicted in the figure 2.13a the optical photons, given that they have a sufficiently large incidence angle, can be deviated of their trajectories when passing through the interfaces LS-acrylic and water-acrylic due to the optical index difference. This cause photons to be lost or to be detected by PMT further than anticipated if we consider their rectilinear trajectories. This cause the charge barycenter the be located closer to the center than the event really is.

It is to be noted that charge based algorithm, in addition to be biased near the edge of the detector, does not provide any information about the timing of the event. Therefore, a time based algorithm needs to be introduced to provide initial values.



(A) Illustration of the different optical photons reflection scenarios. 1 is the reflection of the photon at the interface LS-acrylic or acrylic-water. 2 is the transmission of the photons through the interfaces. 3 is the conduction of the photon in the acrylic.

(B) Heatmap of R_{rec} and $R_{rec} - R_{true}$ as a function of R_{true} for 4MeV prompt signals uniformly distributed in the detector calculated by the charge based algorithm

FIGURE 2.13

471 Time based algorithm

472 The time based algorithm use the distribution of the time of flight corrections Δt (Eq 2.4) of an
473 event to reconstruct its vertex and t_0 . It follow the following iterations:

- 474 1. Use the charge based algorithm to get an initial vertex to start the iteration.
475 2. Calculate the time of flight correction for the i th PMT using

$$\Delta t_i(j) = t_i - \text{tof}_i(j) \quad (2.4)$$

476 where j is the iteration step, t_i is the timing of the i th PMT, and tof_i is the time-of-flight of the
477 photon considering an rectilinear trajectory and an effective velocity in the LS and water (see
478 [36] for detailed description of this effective velocity). Plot the Δt distribution and label the
479 peak position as Δt^{peak} (see fig 2.14a).

- 480 3. Calculate a correction vector $\vec{\delta}[\vec{r}(j)]$ as

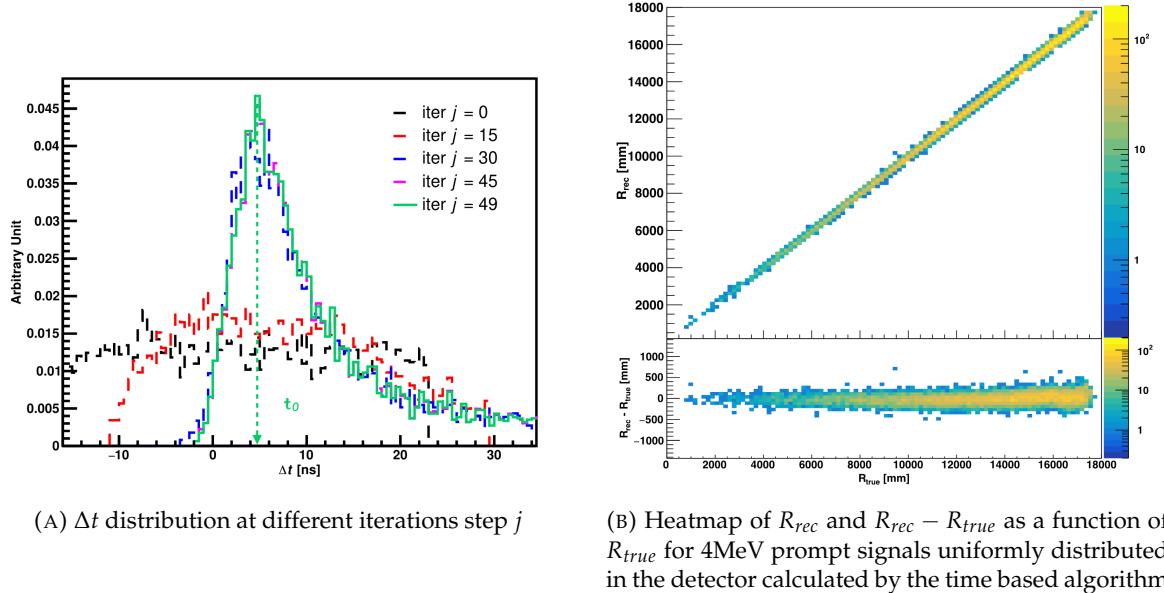
$$\vec{\delta}[\vec{r}(j)] = \frac{\sum_i \left(\frac{\Delta t_i(j) - \Delta t^{\text{peak}}(j)}{\text{tof}_i(j)} \right) \cdot (\vec{r}_0(j) - \vec{r}_i)}{N^{\text{peak}}(j)} \quad (2.5)$$

481 where \vec{r}_0 is the vertex position at the beginning of this iteration, \vec{r}_i is the position of the i th
482 PMT. To minimize the effect of scattering, dark noise and reflection, only the pulse happening
483 in a time window (-10 ns, +5 ns) around Δt^{peak} are considered. N^{peak} is the number of PE
484 collected in this time-window.

- 485 4. if $|\vec{\delta}[\vec{r}(j)]| < 1\text{mm}$ or $j \geq 100$, stop the iteration. Otherwise $\vec{r}_0(j+1) = \vec{r}_0(j) + \vec{\delta}[\vec{r}(j)]$ and go to
486 step 2.

487 However because the earliest arrival time is used, t_i is related to the number photoelectrons N_i^{pe}
488 detected by the PMT [37–39]. To reduce bias in the vertex reconstruction, the following equation is
489 used to correct t_i into t'_i :

$$t'_i = t_i - p_0 / \sqrt{N_i^{\text{pe}}} - p_1 - p_2 / N_i^{\text{pe}} \quad (2.6)$$

(A) Δt distribution at different iterations step j (B) Heatmap of R_{rec} and $R_{rec} - R_{true}$ as a function of R_{true} for 4MeV prompt signals uniformly distributed in the detector calculated by the time based algorithm

490 The parameters (p_0, p_1, p_2) were optimized to $(9.42, 0.74, -4.60)$ for Hamamatsu PMTs and $(41.31,$
 491 $-12.04, -20.02)$ for NNVT PMTs [36]. The results presented in figure 2.14b shows that the time based
 492 algorithm provide a more accurate vertex and is unbiased even in the TR area. This results (\vec{r}_0, t_0) is
 493 used as initial value for the likelihood algorithm.

494 Time likelihood algorithm

495 The time likelihood algorithm use the residual time expressed as follow

$$t_{\text{res}}^i(\vec{r}_0, t_0) = t_i - \text{tof}_i - t_0 \quad (2.7)$$

496 In a first order approximation, the scintillator time response Probability Density Function (PDF)
 497 can be described as the emission time profile of the scintillation photons, the Time Transit Spread
 498 (TTS) and the dark noise of the PMTs. The emission time profile $f(t_{\text{res}})$ is described like

$$f(t_{\text{res}}) = \sum_k \frac{\rho_k}{\tau_k} e^{-\frac{t_{\text{res}}}{\tau_k}}, \quad \sum_k \rho_k = 1 \quad (2.8)$$

499 as the sum of the k component that emit light in the LS each one characterised by it's decay time τ_k
 500 and intensity fraction ρ_k . The TTS component is expressed as a gaussian convolution

$$g(t_{\text{res}}) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(t_{\text{res}}-\nu)^2}{2\sigma^2}} \cdot f(t_{\text{res}}) \quad (2.9)$$

501 where σ is the TTS of PMTs and ν is the average transit time. The dark noise is not correlated with any
 502 physical events and considered as constant rate over the time window considered T . By normalizing
 503 the dark noise probability $\epsilon(t_{\text{res}})$ as $\int_T \epsilon(t_{\text{res}}) dt_{\text{res}} = \epsilon_{\text{dn}}$, it can be integrated in the PDF as

$$p(t_{\text{res}}) = (1 - \epsilon_{\text{dn}}) \cdot g(t_{\text{res}}) + \epsilon(t_{\text{res}}) \quad (2.10)$$

504 The distribution of the residual time t_{res} of an event can then be compared to $p(t_{\text{res}})$ and the best

505 fitting vertex \vec{r}_0 and t_0 can be chosen by minimizing

$$\mathcal{L}(\vec{r}_0, t_0) = -\ln \left(\prod_i p(t_{\text{res}}^i) \right) \quad (2.11)$$

506 The parameter of Eq. 2.10 can be measured experimentally. The results shown in figure 2.15
 507 used PDF from monte carlo simulation. The results shows that $R_{\text{rec}} - R_{\text{true}}$ is biased depending
 508 on the energy. While this could be corrected using calibration, another algorithm based on charge
 509 likelihood was developed to correct this problem.

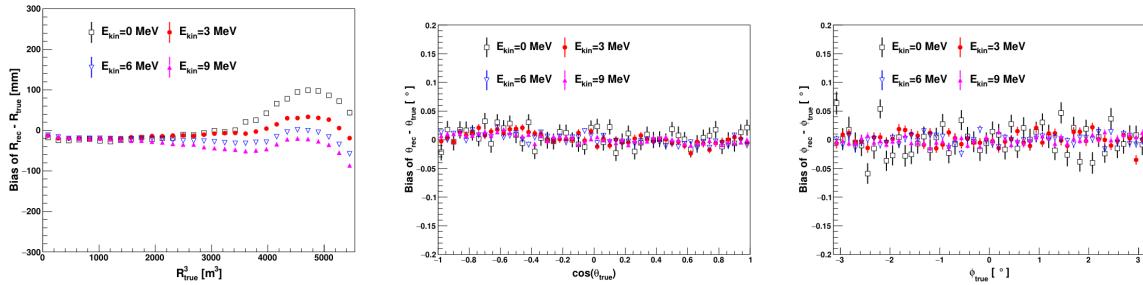


FIGURE 2.15 – Bias of the reconstructed radius R (left), θ (middle) and ϕ (right) for multiple energies by the time likelihood algorithm

510 Charge likelihood algorithm

511 Similarly to the time likelihood algorithms that use a timing PDF, the charge likelihood algorithm
 512 use a PE PDF for each PMT depending on the energy and position of the event. With $\mu(\vec{r}_0, E)$ the
 513 mean expected number of PE detected by each PMT, the probability to observe N_{pe} in a PMT follow
 514 a Poisson distribution. Thus

515 — The probability to observe no hit ($N_{\text{pe}} = 0$) in the j th PMT is $P_{\text{nohit}}^j(\vec{r}_0, E) = e^{-\mu_j}$

516 — The probability to observe $N_{\text{pe}} \neq 0$ in the i th PMT is $P_{\text{hit}}^i(\vec{r}_0, E) = \frac{\mu^{N_{\text{pe}}^i} e^{-\mu_i}}{N_{\text{pe}}^i!}$

517 Therefore, the probability to observe a specific hit pattern can be expressed as

$$P(\vec{r}_0, E) = \prod_j P_{\text{nohit}}^j(\vec{r}_0, E) \cdot \prod_i P_{\text{hit}}^i(\vec{r}_0, E) \quad (2.12)$$

518 The best fit values of \vec{R}_0 and E can then be calculated by minimizing the negative log-likelihood

$$\mathcal{L}(\vec{r}_0, E) = -\ln(P(\vec{r}_0, E)) \quad (2.13)$$

519 In principle, $\mu_i(\vec{r}_0, E)$ could be expressed

$$\mu_i(\vec{r}_0, E) = Y \cdot \frac{\Omega(\vec{r}_0, r_i)}{4\pi} \cdot \epsilon_i \cdot f(\theta_i) \cdot e^{-\sum_m \frac{d_m}{\zeta_m}} \cdot E + \delta_i \quad (2.14)$$

520 where Y is the energy scale factor, $\Omega(\vec{r}_0, r_i)$ is the solid angle of the i th PMT, ϵ_i is its detection
 521 efficiency, $f(\theta_i)$ its angular response, ζ_m is the attenuation length in the materials and δ_i the expected
 522 number of dark noise.

523 However Eq. 2.14 assume that the scintillation light yield is linear with energy and describe
 524 poorly the contribution of indirect light, shadow effect due to the supporting structure and the
 525 total reflection effects. The solution is to use data driven methods to produce the pdf by using the
 526 calibrations sources and position described in section 2.3. In the results presented in figures 2.16, the
 527 PDF was produced using MC simulation and 29 specific calibrations position [36] along the Z-axis

of the detector. We see that the charge likelihood algorithm show little bias in the TR area and a

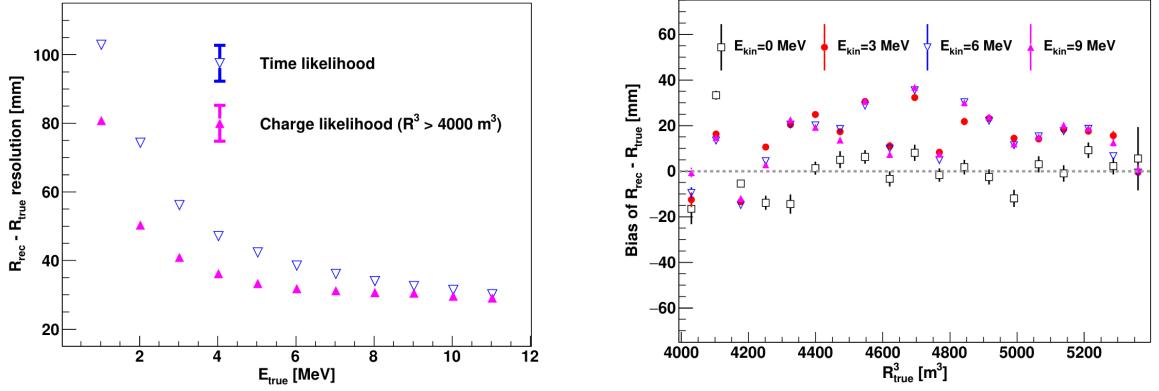


FIGURE 2.16 – On the left: Resolution of the reconstructed R as a function of the energy in the TR area ($R^3 > 4000 \text{ m}^3 \equiv R > 16 \text{ m}$) by the charge and time likelihood algorithms. On the right: Bias of the reconstructed R in the TR area for different energies by the charge likelihood algorithm

better resolution than the time likelihood. The figure 2.17 shows the radial resolution of the different algorithm presented for this section, we can see the refinement at each step and that the charge likelihood yield the best results.

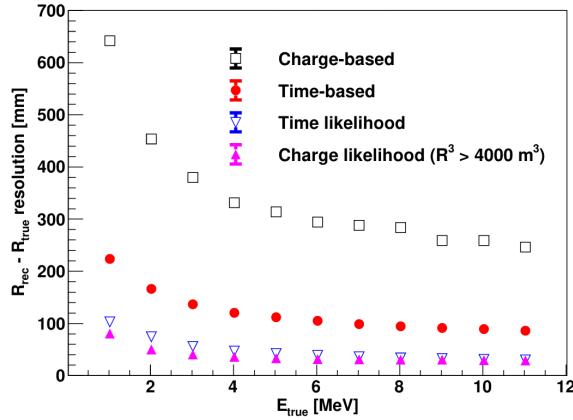


FIGURE 2.17 – Radial resolution of the different vertex reconstruction algorithms as a function of the energy

The charge based likelihood algorithms already give some information on the energy as Eq. 2.13 is minimized but the energy can be further refined as shown in the next section.

2.6.2 Energy reconstruction

As explained in section 2.1.1, energy resolution is crucial for the NMO and oscillation parameters measurements. Thus the energy reconstruction algorithm should take into consideration as much detector effect as possible. The following method is a data driven method based on calibration samples inspired by the charge likelihood algorithm described above [40].

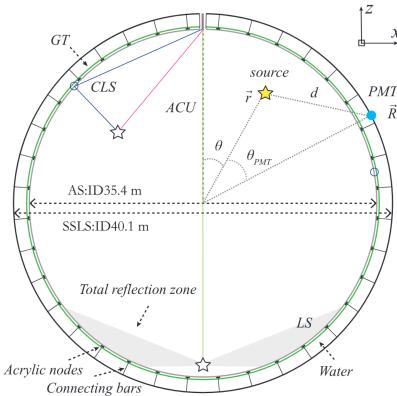


FIGURE 2.18 – Definition of the variables used in the energy reconstruction

539 Charge estimation

540 The most important element in the energy reconstruction is $\mu_i(\vec{r}_0, E)$ described in Eq. 2.14. For
 541 realistic cases, we also need to take into account the electronics effect that were omitted in the
 542 previous section. Those effect will cause a charge smearing due to the uncertainties in the N_{pe}
 543 reconstruction. Thus we define $\hat{\mu}^L(\vec{r}_0, E)$ which is the expected N_{pe}/E in the whole detector for an
 544 event with visible energy E_{vis} and position \vec{r}_0 . The position of the event and PMTs are now defined
 545 using $(r, \theta, \theta_{pmt})$ as defined in figure 2.18.

$$\hat{\mu}(r, \theta, \theta_{pmt}, E_{vis}) = \frac{1}{E_{vis}} \frac{1}{M} \sum_i^M \frac{\bar{q}_i - \mu_i^D}{DE_i}, \quad \mu_i^D = DNR_i \cdot L \quad (2.15)$$

546 where i runs over the PMTs with the same θ_{pmt} , DE_i is the detection efficiency of the i th PMT. μ_i^D
 547 is the expected number of dark noise photoelectrons in the time window L . The time window have
 548 been optimized to $L = 280$ ns [40]. \bar{q}_i is the average recorded photoelectrons in the time window
 549 and \bar{Q}_i is the expected average charge for 1 photoelectron. The N_{pe} map is constructed following the
 550 procedure described in [35].

551 Time estimation

552 The second important observable is the hit time of photons that was previously defined in Eq.
 553 2.7. It is here refined as

$$t_r = t_h - \text{tof} - t_0 = t_{LS} + t_{TT} \quad (2.16)$$

554 where t_h is the time of hit, t_{LS} is the scintillation time and t_{TT} the transit time of PMTs that is described
 555 by a gaussian

$$t_{TT} = \mathcal{N}(\mu_{TT} + t_d, \sigma_{TT}) \quad (2.17)$$

556 where μ_{TT} is the mean transit time in PMTs, σ_{TT} is the Transit Time Spread (TTS) of the PMTs and t_d
 557 is the delay time in the electronics. The effective refraction index of the LS is also corrected to take
 558 into account the propagation distance in the detector.

559 The timing PDF $P_T(t_r | r, d, \mu_l, \mu_d, k)$ can now be generated using calibration sources [40]. This PDF
 560 describe the probability that the residual time of the first photon hit is in $[t_r, t_r + \delta]$ with r the radius
 561 of the event vertex, $d = |\vec{r} - \vec{r}_{PMT}|$ the propagation distance, μ_l and μ_d the expected number of PE
 562 and dark noise in the electronic reading window and k is the detected number of PE.

563 Now let denote $f(t, r, d)$ the probability density function of "photoelectron hit a time t" for an

⁵⁶⁴ event happening at r where the photons traveled the distance d in the LS

$$F(t, r, d) = \int_t^L f(t', r, d) dt' \quad (2.18)$$

⁵⁶⁵ Based on the PDF for one photon $k = 1$, one can define

$$P_T^l(t|k = n) = I_n^l [f_l(t) F_l^{n-1}(t)] \quad (2.19)$$

⁵⁶⁶ where the indicator l means that the photons comes from the LS and I_n^l a normalisation factor. To this
⁵⁶⁷ pdf we add the probability to have photons coming from the dark noise indicated by the indicator d
⁵⁶⁸ using

$$f_d(t) = 1/L, F_d(t) = 1 - \frac{t}{L} \quad (2.20)$$

⁵⁶⁹ and so for the case where only one photon is detected by the PMT ($k = 1$)

$$P_T(t|\mu_l, \mu_d, k = 1) = I_1[P(1, \mu_l)P(0, \mu_d)f_l(t) + P(0, \mu_l)P(1, \mu_d)f_d(t)] \quad (2.21)$$

⁵⁷⁰ where $P(k_\alpha, \mu_\alpha)$ is the Poisson probability to detect k_α PE from $\alpha \in \{l, d\}$ with the condition $k_l + k_d = k$.

⁵⁷² Now that we have the individual timing and charge probability we can construct the charge
⁵⁷³ likelihood referred as QMLE:

$$\mathcal{L}(q_1, q_2, \dots, q_N | \vec{r}, E_{vis}) = \prod_{j \in \text{unfired}} e^{-\mu_j} \prod_{i \in \text{fired}} \left(\sum_{k=1}^K P_Q(q_i|k) \cdot P(k, \mu_i) \right) \quad (2.22)$$

⁵⁷⁴ where $\mu_i = E_{vis}\hat{\mu}_i^L + \mu_i^D$ and $P(k, \mu_i)$ is the Poisson probability of observing k PE. $P_Q(q_i|k)$ is the
⁵⁷⁵ charge pdf for k PE. And we can also construct the time likelihood referred as TMLE:

$$\mathcal{L}(t_{1,r}, t_{2,r}, \dots, t_{N,r} | \vec{r}, t_0) = \prod_{i \in \text{hit}} \frac{\sum_{k=1}^K P_T(t_{i,r}|r, d, \mu_i^l, \mu_i^d, k) \cdot P(k, \mu_i^l + \mu_i^d)}{\sum_{k=1}^K P(k, \mu_i^l + \mu_i^d)} \quad (2.23)$$

⁵⁷⁶ where K is cut to 20 PE and hit is the set of hits satisfying $-100 < t_{i,r} < 500$ ns.

⁵⁷⁷ Merging those two likelihood give the charge-time likelihood QTMLLE

$$\mathcal{L}(q_1, q_2, \dots, q_N; t_{1,r}, t_{2,r}, \dots, t_{N,r} | \vec{r}, t_0, E_{vis}) = \mathcal{L}(q_1, q_2, \dots, q_N | \vec{r}, E_{vis}) \cdot \mathcal{L}(t_{1,r}, t_{2,r}, \dots, t_{N,r} | \vec{r}, t_0) \quad (2.24)$$

⁵⁷⁸ The radial and energy resolutions of the different likelihood are presented in figure 2.19 (from
⁵⁷⁹ [40]). We can see the improvement of adding the time information to the vertex reconstruction and
⁵⁸⁰ that an increase in vertex precision can bring improvement in the energy resolution, especially at low
⁵⁸¹ energies.

⁵⁸² Data driven methods prove to be performant in the energy and vertex reconstruction given that
⁵⁸³ we have enough calibrations sources to produce the PDF. In the next section, we'll see another type
⁵⁸⁴ of data-driven method based on machine learning.

⁵⁸⁵ 2.6.3 Machine learning for reconstruction

⁵⁸⁶ Machine learning (ML) is family of data-driven algorithms that are inferring behavior and results
⁵⁸⁷ from a training dataset. A overview of methods and detailed explanation of the Neural Network
⁵⁸⁸ (NN) subfamily can be found in Chapter 3.

⁵⁸⁹ The power of ML is the ability to model complex response to a specific problem. In JUNO
⁵⁹⁰ the reconstruction problematic can be expressed as follow: knowing that each PMT, large or small,
⁵⁹¹ detected a given number of PE Q at a given time t and their position is x, y, z where did the energy

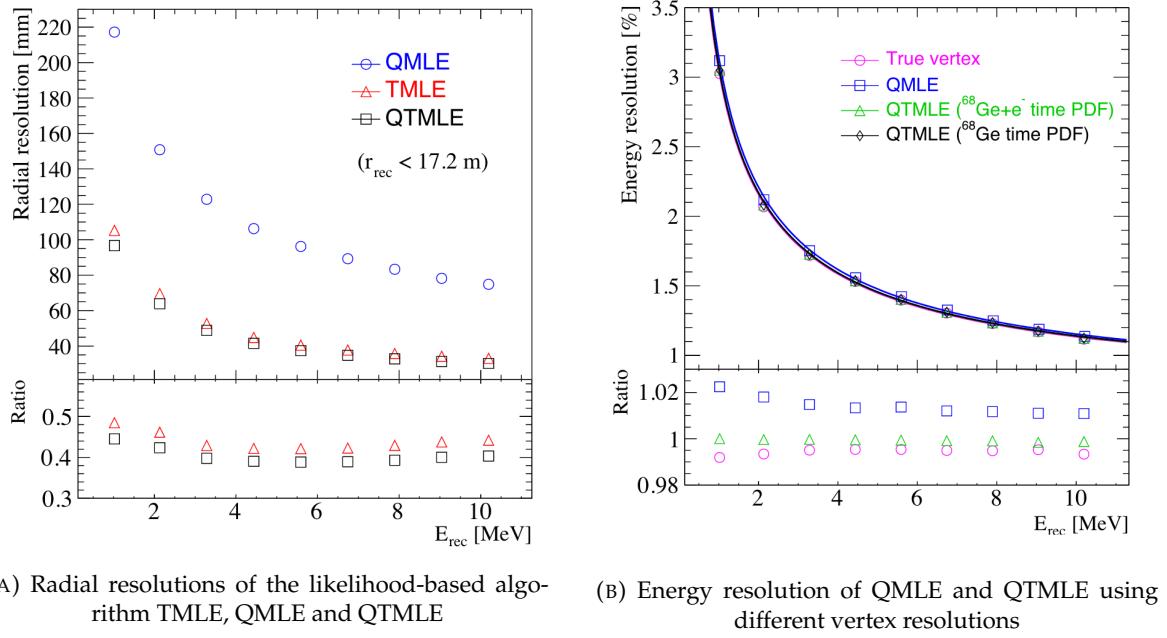


FIGURE 2.19

592 was deposited and how much energy was it, modeling a function that naively goes:

$$\mathbb{R}^{5 \times N_{\text{pmt}}} \mapsto \mathbb{R}^4 \quad (2.25)$$

593 It is worth pointing that while this is already a lot in informations, this is not the rawest representation
 594 of the experiment. We could indeed replace the charge and time by the waveform in the time
 595 window of the event but that would lead to an input representation size that would exceed our
 596 computational limits. Also, due to those computational limits, most of the ML algorithm reduce this
 597 input phase space either by structurally encoding the information (pictures, graph), by aggregating
 598 it (mean, variance, ...) or by exploiting invariance and equivariance of the experiment (rotational
 599 invariance due to the sphericity, ...).

600 For machine learning to converge to performant algorithm, a large dataset exploring all the phase
 601 space of interest is needed. For the following studies, data from the monte carlo simulation presented
 602 in section 2.5 are used for training. When the detector will be finished calibrations sources will be
 603 complementarily be used.

604 Boosted Decision Tree (BDT)

605 On of the most classic ML method used in physics in last years is the Boosted Decision Tree (see
 606 chapter 3.1). They have been explored for vertex reconstruction [41] et for energy reconstruction [41,
 607 42].

608 For vertex and energy reconstruction a BDT was developed using the aggregated informations
 609 presented in 2.6.

610 Its reconstruction performances are presented in figure 2.21.

611 A second and more advanced BDT, subsequently named BDTE, that only reconstruct energy use
 612 a different set of features [42]. They are presented in the table 2.7

Parameter	description
$nHits$	Total number of hits
$x_{cc}, y_{cc}, z_{cc}, R_{cc}$	Coordinates of the center of charge
ht_{mean}, ht_{std}	Hit time mean and standard deviation

TABLE 2.6 – Features used by the BDT for vertex reconstruction

AccumCharge	$ht_{5\% - 2\%}$
R_{cht}	pe_{mean}
z_{cc}	J_{cht}
pe_{std}	ϕ_{cc}
nPMTs	$ht_{35\% - 30\%}$
$ht_{kurtosis}$	$ht_{20\% - 15\%}$
$ht_{25\% - 20\%}$	$pe_{35\%}$
R_{cc}	$ht_{30\% - 25\%}$

TABLE 2.7 – Features used by the BDTE algorithm. pe and ht reference the charge and hit-time distribution respectively and the percentages are the quantiles of those distributions. cht and cc reference the barycenters of hit time and charge respectively

613 Neural Network (NN)

614 The physics have shown a rising for Neural Network (NN) in the past years for event reconstruction,
 615 notably in the neutrino community [43–46]. Three type of neural networks have explored for
 616 event reconstruction in JUNO Deep Neural Network (DNN), Convolutional Neural Network (CNN)
 617 and Graph Network (GNN). More explanation about those neural network can be found in chapter
 618 3.

619 The CNN are using 2D projection of the detector representing it as an image with two channel,
 620 one for the charge Q and one for the time t . The position of the PMTs is structurally encoded in the
 621 pixel containing the information of this PMT. In [41], the pixel is chosen based on a transformation
 622 of θ and ϕ coordinates to the 2D plane and rounded to the nearest pixel. A sufficiently large image
 623 has been chosen to prevent two PMT to be located in the same pixel. An example of this projection
 624 can be found in figure 2.20. The performances of the CNN can be found in figure 2.21.

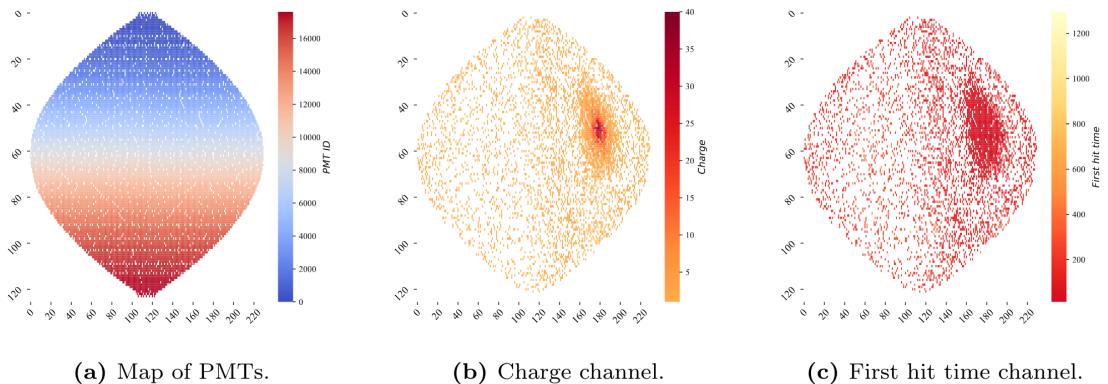


FIGURE 2.20 – Projection of the LPMTs in JUNO on a 2D plane. (a) Show the distribution of all PMTs and (b) and (c) are example of what the charge and time channel looks like respectively

625 Using 2D have the upside of encoding a large part of the informations structurally but loose
 626 the rotational invariance of the detector. It also give undefined information to the neural network

(what is a pixel without PMT ? What should be its charge and time ?), cause deformation in the representation of the detector (sides of projection) and loose topological informations.

One of the way to present structurally the sphericity of JUNO to a NN is to use a graph: A collection of objects V called nodes and relations E called edges, each relation associated to a couple v_1, v_2 forming the graph $G(E, V)$. Nodes and edges can hold informations or features. In [41] the nodes, are geometrical region of the detector as defined by the HealPix [47]. The features of the nodes are aggregated informations from the PMTs it contains. The edges contains geographic informations of the nodes relative positions.

This data representation has the advantages to keep the topology of the detector intact. It also permit the use of rotational invariant algorithms for the NN, thus taking advantage of the symmetries of the detector.

The neural network then process the graph using Chebyshev Convolutions [48]. The performances of the GNN are presented in figure 2.21.

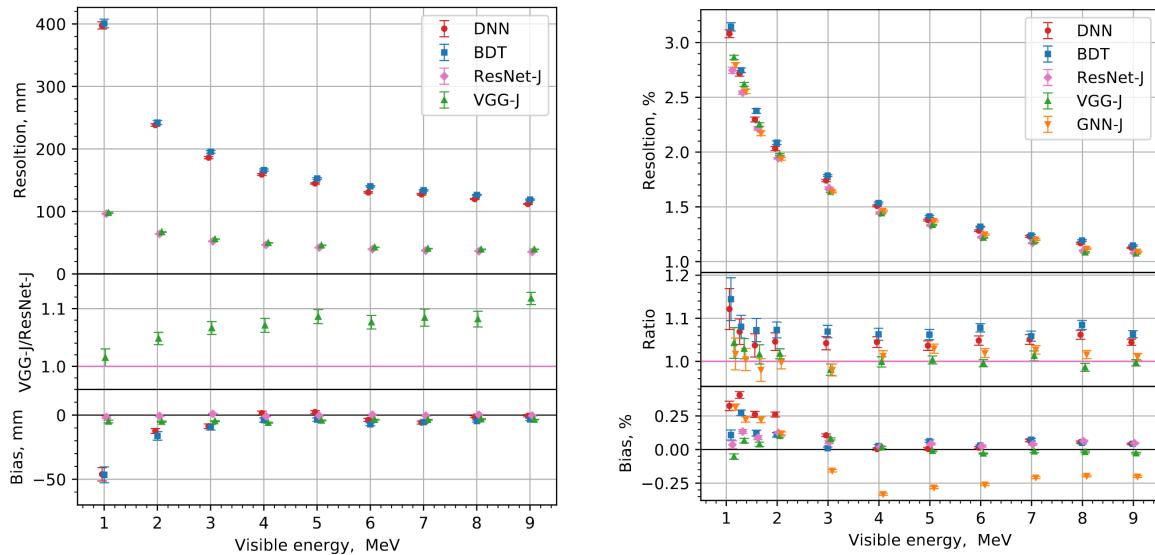


FIGURE 2.21 – Radial (left) and energy (right) resolutions of different ML algorithms. The results presented here are from [41]. DNN is a deep neural network, BDT is a BDT, ResNet-J and VGG-J are CNN and GNN-J is a GNN.

Overall ML algorithms show similar performances as classical algorithms in term of energy reconstructions with the more complex structure CNN and GNN showing better performances than BDT and DNN. For vertex reconstruction, the BDT and DNN show poor performance while CNN are on the level of the classical algorithms.

2.7 JUNO sensitivity to NMO and precise measurements

Now that the event have been reconstructed, selected and that the non-IBD background have been rejected, we have access to the measured energy flux from JUNO. We consider two spectra, the one measured by the LPMT system and the one measured by the SPMT system. This give rise to three possible analysis: A LPMT only analysis, a SPMT only analysis and a joint analysis. This joint analysis is the subject of the chapter 7 of this thesis.

The following details about JUNO measurement is common to the three analysis. The details and specific of the joint analysis are detailed in chapter 7.

2.7.1 Theoretical spectrum

To extract the oscillation parameters and the NMO from the measured spectrum, it is compared to a theoretical spectrum. This theoretical spectrum is produced based on the theory of the three flavour oscillation (see section 1.3), the measurements of the calibration and satellite experiments and Monte Carlo simulation:

- The absolute flux and the fission product fraction calibrated by TAO.
- The estimation of the neutrinos flux from other sources, such as the geoneutrinos, by theoretical model.
- The computed cross-section of $\bar{\nu}_e$ and the LS.
- The estimation of mislabelled event, such as fast neutron events from cosmic muons, using Monte Carlo simulation.
- The measured bias and resolution of the LPMT and SPMT system by the calibration.
- The time dependent reactor parameters (age of fuel, instantaneous power of the reactors, etc...)

These systematics parameters come with their uncertainties that need to be taken into account by the fitting framework. This theoretical spectrum will, in the end, depend of the oscillation parameters of interest $\theta_{13}, \theta_{12}, \Delta m_{21}^2, \Delta m_{31}^2$. Noise parameters can be included in the parameters spectrum such as the earth density ρ between the power plants and JUNO.

2.7.2 Fitting procedure

The theoretical and measured spectra are represented as two histograms depending on the energy. The theoretical spectrum is adjusted with the data using a χ^2 minimization where χ^2 is naively defined as

$$\chi^2 = \sum_i \frac{(N_{th}^i - N_{data}^i)^2}{\sigma_i^2} \quad (2.26)$$

where N_{th}^i is the number event in the i th bin of the theoretical spectrum, N_{data}^i is the number of event in the i th bin of the measured spectrum and σ_i is the uncertainty of this bin. Two classic statistic test exist Pearson and Neyman where the difference is the estimation of σ_i parameters.

This σ_i is composed of the systematics uncertainties discussed above but also from the statistic uncertainty of the spectrum. Considering a Poisson process, the statistic uncertainty is estimated as $\sigma_{stat}^i = \sqrt{N^i}$. In a Pearson test, $N^i \equiv N_{th}^i$ whereas in a Neyman test $N^i \equiv N_{data}^i$. Under the assumption that the content of each bin follow a Gaussian distribution (a Poisson with high enough statistic), the two test are equivalent. But studies on Monte Carlo spectrum showed that the Pearson and Neyman statistic are biased in opposite direction. It is easily visible where, for the same data, Pearson will prefer a higher N_{th}^i to reduce the ration $\frac{1}{N_{th}^i}$ whereas Neyman will prefer a lower N_{th}^i to reduce the $(N_{th}^i - N_{data}^i)$ term.

This problematic can be circumvented by summing the two test, yielding the CNP statistic test and/or by adding a term

$$\chi^2 = \sum_i \frac{(N_{th}^i - N_{data}^i)^2}{\sigma_i^2} - \ln |\mathbf{V}| \quad (2.27)$$

where V is the covariance matrix of the theoretical spectrum yielding the PearsonV and CNPV statistic test.

The χ^2 is minimized by exploring the parameter phase space via gradient descent.

2.7.3 Physics results

The oscillation parameters are directly extracted from the minimization procedure and the error can be estimated directly from the procedure. For the NMO, the data are fitted under the two assumption of NO and IO. The difference in χ^2 give us the preferred ordering and the significance of our test. Latest studies show that the precision on oscillation parameters after six year of data

⁶⁹⁴ taking will be of 0.2%, 0.3%, 0.5% and 12.1% for Δm_{31}^2 , Δm_{21}^2 , $\sin^2 \theta_{12}$ and $\sin^2 \theta_{13}$ respectively [11].
⁶⁹⁵ The expected sensitivity to mass ordering is 3σ after 6 years [49].

⁶⁹⁶ 2.8 Summary

⁶⁹⁷ JUNO is one the biggest new generation neutrino experiment. Its goal, the measurements of os-
⁶⁹⁸ cillation parameters with unprecedented precision and an NMO preference at the 3 sigma confidence
⁶⁹⁹ level, needs an in depth knowledge and understanding of the detector and the physics at hand. The
⁷⁰⁰ characterisation and calibration of the detector are of the utmost importance and the understanding
⁷⁰¹ of the detector response in its resolution and bias is capital to be able to correctly carry the high
⁷⁰² precision physics analysis of the neutrino oscillation.

⁷⁰³ In this thesis, I explore the usage of data-driven reconstruction methods to validate and optimize
⁷⁰⁴ the reconstruction of IBD events in JUNO in the chapters 4, 5 and 6 and the usage of the dual
⁷⁰⁵ calorimetry in the detection of possible mis-modelisation in the theoretical spectrum 7.

⁷⁰⁶ **Chapter 3**

⁷⁰⁷ **Machine learning and Artificial
Neural Network**

⁷⁰⁹ *"I have the shape of a human being and organs equivalent to those of a
human being. My organs, in fact, are identical to some of those in a
prosthetized human being. I have contributed artistically, literally, and
scientifically to human culture as much as any human being now
alive. What more can one ask?"*

Isaac Asimov, The Complete Robot

⁷¹⁰ Machine Learning (ML) and more specifically Neural Network (NN) are a family of data-driven
⁷¹¹ algorithm. They are used to model complex distribution from a finite dataset to extract a gener-
⁷¹² alist behavior where they learn, adapt their intrinsic parameters, interactively by computing the
⁷¹³ performance or *loss* on those dataset. They take advantage of simple microscopic operation such
⁷¹⁴ as *if condition*, non-continuous but differentiable function like *ReLU*. Through optimizer and the
⁷¹⁵ combination of those microscopic operation, they can yield complex and precise behavior.

⁷¹⁶ They are now widely used in a wide variety of domain including natural language processing,
⁷¹⁷ computer vision, speech recognition and, the subject of this thesis, scientific studies.

⁷¹⁸ They are now widely used in particle physics, either as the main algorithm or as secondary
⁷¹⁹ algorithm, for event reconstruction, event classification, waveform reconstruction, etc... Domains
⁷²⁰ where the underlying physic and detector process is complex and highly dimensional. Physicists
⁷²¹ have traditionally used algorithms where simplification or assumption were made (a good example
⁷²² is the algorithm presented in section 2.6) machine learning could refine and take into account those
⁷²³ effects, providing that they have enough data and computing power, thus the appeal for physicist.

⁷²⁴ **3.1 Boosted Decision Tree (BDT)**

⁷²⁵ One of the most classic machine learning algorithm used in particle physics is Boosted Decision
⁷²⁶ Tree [50] (or more recently Gradient Boosting Machine [51]). The principle of BDT is fairly simple
⁷²⁷ : Based on a set of observables, a serie of decisions, represented as node in a tree, are taken by the
⁷²⁸ algorithm. Each decision point, or node, takes its decision based on a set of trainable parameters
⁷²⁹ leading to a subtree of decision. The process is repeated until it reach the final node, yielding the
⁷³⁰ prediction. A simplistic example is given in figure 3.1.

⁷³¹ The training procedure follow a simple score reward procedure. During the training phase the
⁷³² prediction of the BDT is compared to a known truth about the data. The score is then used to
⁷³³ backpropagate corrections to the parameters of the tree. Modern BDT use gradient boosting where
⁷³⁴ the gradient of the loss is calculated for each of the BDT parameters. Following the gradient descent,
⁷³⁵ we can reach the, hopefully, global minima of the loss for our set of parameters.

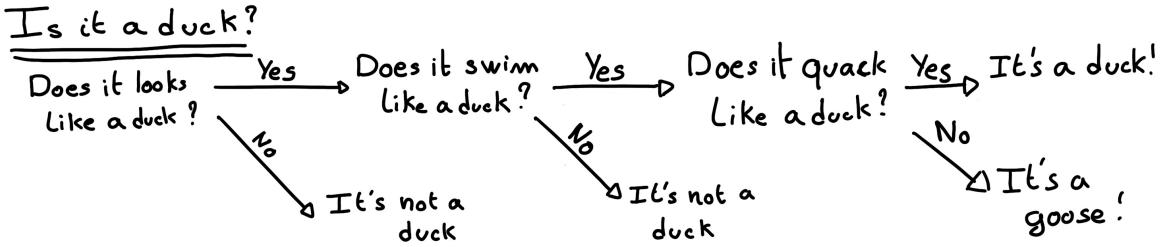


FIGURE 3.1 – Example of a BDT that determine if the given object is a duck

736 3.2 Artificial Neural Network (NN)

737 One other big family of machine learning algorithm is the Artificial Neural Networks (ANN)
 738 more commonly designated as Neural Networks (NN). The idea of developing automates which
 739 component mimic, in a simplistic way, the behavior of biological neurons emerge in 1959 with
 740 the paper “*What the Frog’s Eye Tells the Frog’s Brain*” [52]. They develop an automate where each
 741 component possess an *activation function*. Each one of those component then transmit it’s information
 742 to the other following a certain efficiency or *weight*. Those works influenced scientist and notably
 743 Frank Rosenblatt who published in 1958 what is considered the first neural network model the
 744 perceptron [53].

745 Modern neural network still nowadays use the neuron metaphor to represent neural network,
 746 but approach them as a graph where the nodes are neurons possessing an activation function and
 747 edges holding the weights between those nodes. Most of the modern neural network work with the
 748 principle of neurons layers. For example the most basic, fully connected set of layer is a set where
 749 each layers possessing the same activation function F and the connection between two layers as a
 750 tensor T_j^i where i is the index of the precedent layer and j the index of the next layer. The propagation
 751 from the layer I to J is then described as

$$J_j = F_j(T_j^i I_i + B_j) \quad (3.1)$$

752 where the learning parameters are the tensor T_j^i and the bias tensor B_j . This is the fundamental
 753 component of the Fully Connected Deep NN (FCDNN) family presented in section 3.2.1. Most of the
 754 modern neural network use gradient descent to optimize their parameters, i.e. the gradient of the
 755 parameter θ in respect of the loss function \mathcal{L} is subtracted to it

$$\theta_{i+1} = \theta_i - \frac{\partial \theta}{\partial \mathcal{L}} \quad (3.2)$$

756 i being the training iteration index. This needs the expression of \mathcal{L} dependent of θ to be differentiable,
 757 thus the layer and their activation function also need to be differentiable. This simple gradient
 758 descent, designated as Stochastic Gradient Descent (SGD), can be completed with first and second
 759 order momentum like with the Adam optimizer [54].

760 This description of neural networks as layer introduced the principle of *depth* and *width*, the
 761 number of layers in the NN and the number of neurons in each layer respectively.

762 3.2.1 Fully Connected Deep Neural Network (FCDNN)

763 Fully Connected Deep Neural Network (FCDNN) architecture is the natural evolution of the
 764 Perceptron. The input data is represented as a first order tensor I_j and then fed forward to multiple
 765 fully connected layers (Eq 3.1) as presented in the figure 3.2a. Most of the time, the classic ReLU

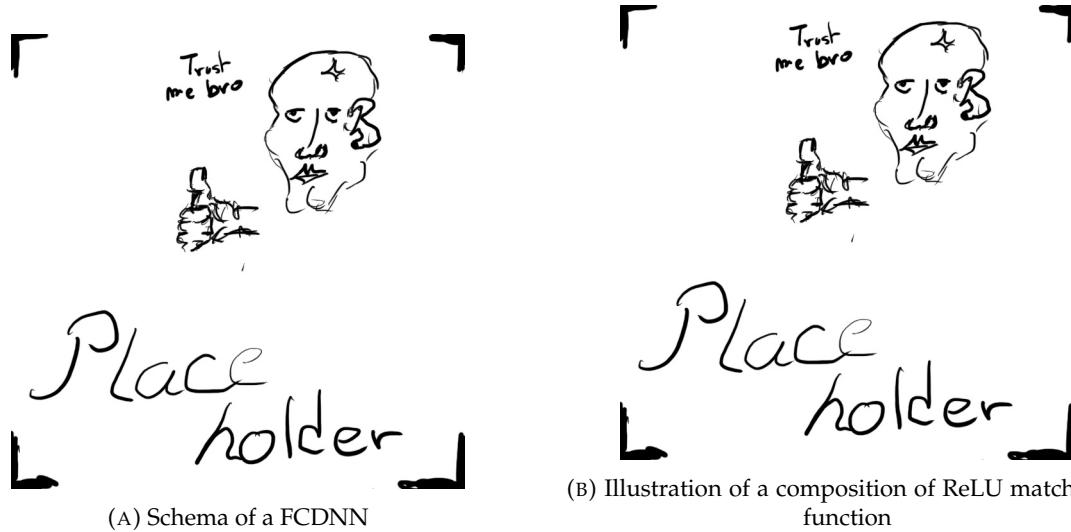
766 function

$$\text{ReLU}(x) = \begin{cases} x & \text{if } x \geq 0 \\ 0 & \text{otherwise} \end{cases} \quad (3.3)$$

767 as activation function. Prelu and Sigmoid are also popular choices

$$\text{Sigmoid}(x) = \frac{1}{1 + e^{-x}} \quad (3.4) \quad \text{PReLU}(x) = \begin{cases} x & \text{if } x \geq 0 \\ \alpha x & \text{otherwise} \end{cases} \quad (3.5)$$

769 The reasoning behind ReLU and PReLU is that with enough of them, you can mimic any continuous function as illustrated in figure 3.2b. Sigmoid is more used in case of classification, its behavior 770 going hand in hand with the Cross Entropy loss function used in classification problems.



772 Due to its simplicity, FCDNN are also used as basic pieces for more complex architecture such as
773 the CNN and GNN that will be presented in the next section.

774 **3.2.2 Convolutional Neural Network (CNN)**

775 **3.2.3 Graph Neural Network (GNN)**

776 **3.2.4 Adversarial Neural Network (ANN)**

777 **Generative Adversarial Network (GAN)**

778 **Reinforcement Learning (RL)**

779 **Random Search (RS)**

780 **Bayesian Optimization**

⁷⁸¹ **Chapter 4**

⁷⁸² **Image recognition for IBD
reconstruction with the SPMT system**

⁷⁸³

⁷⁸⁴ **Chapter 5**

⁷⁸⁵ **Graph representation of JUNO for IBD
reconstruction with the LPMT system**

⁷⁸⁶

⁷⁸⁷ **Chapter 6**

⁷⁸⁸ **Reliability of machine learning
methods**

⁷⁸⁹

⁷⁹⁰ Chapter 7

⁷⁹¹ Joint fit between the SPMT and LPMT
⁷⁹² spectra

⁷⁹³ **Chapter 8**

⁷⁹⁴ **Conclusion**

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