NMO sensitivity studies with MASFit

Milano Anti-neutrinos Spectrum Fitter

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What is MASFit?

I've developed a code to generate and fit the antineutrino spectrum for JUNO

It is based on an analytical approach

I've produced some results that have been crosschecked with IHEP, Dubna and SYSU Tech Notes (DocDB: 7494, 7489, 7491)

How does MASFit work?

Input

- Non oscillated reactor spectrum
- Core distances and power
- Oscillation and mass parameters

$\sin^2(\theta_{12}), \sin^2(\theta_{13}), \Delta m^2_{21}, \Delta m^2_{3l}$

Production of anti-neutrino flux

Using an analytical model it produces an Asimov spectrum of anti-neutrinos

$\Downarrow$

- Energy resolution (a,b,c)
- Systematic uncertainties

Accounting for detector response

It modifies the spectrum accounting for energy resolution of the detector

$\Downarrow$

Fit on the produced data-set

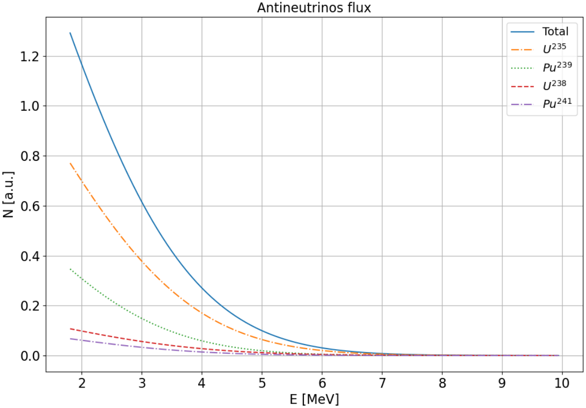
Output is $\Delta\chi^2 = \chi^2_{IO} - \chi^2_{NO}$

Anti-neutrinos reactor spectrum

The spectrum is produced using an analytical form (PhysRevD.78.111103):

$$\Phi_\nu = f_{235_U} \cdot \exp(0.870 - 0.160\, E_\nu - 0.091\, E_\nu^2) + f_{239_{Pu}} \cdot \exp(0.896 - 0.239\, E_\nu - 0.0981\, E_\nu^2)$$
$$+ f_{238_U} \cdot \exp(0.976 - 0.162\, E_\nu - 0.0790\, E_\nu^2) + f_{241_{Pu}} \cdot \exp(0.793 - 0.080\, E_\nu - 0.1085\, E_\nu^2)$$

where $f_{235_U} = 0.58$, $f_{239_{Pu}} = 0.30$, $f_{238_U} = 0.07$, $f_{241_P} = 0.05$ are the fission fraction of the isotopes in the reactor fuel.



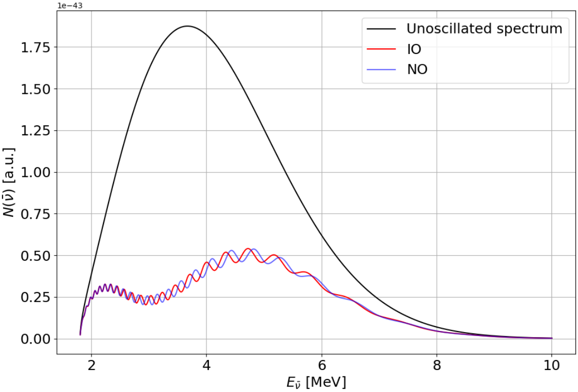
Oscillation probability

The total flux will be $N(\bar{\nu}) = \Phi_\nu \cdot \sigma_{IBD} \cdot P(\bar{\nu_e} \to \bar{\nu_e})$

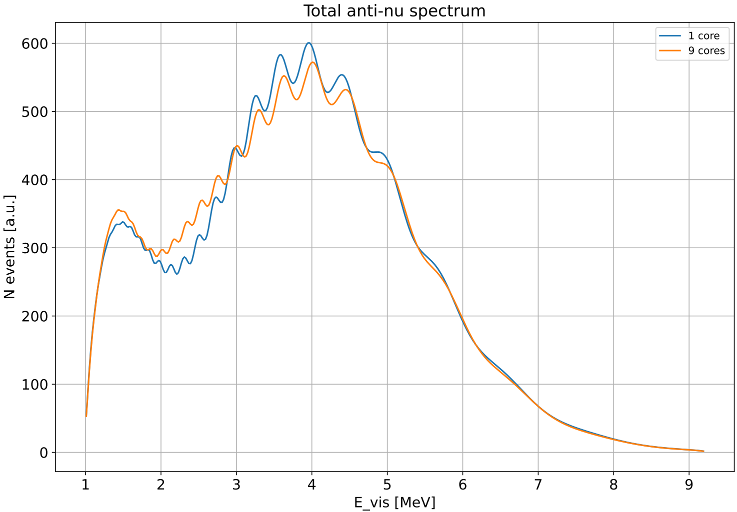
$$P(\bar{\nu_e} \to \bar{\nu_e}) = 1 - \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) - \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) - \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})$$

where $\Delta_{ij} = (m_i^2 - m_j^2)\frac{L}{4E_\nu}$

The spectrum with finite energy resolution is obtained through a convolution with the detector response.

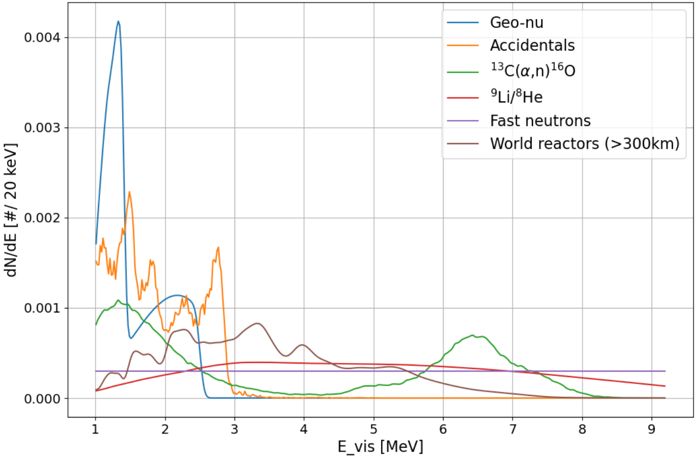


Real baseline distribution

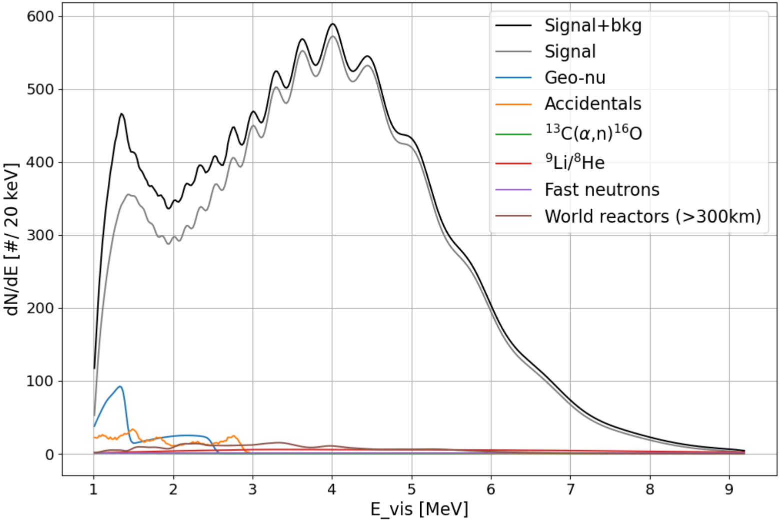


Backgrounds (from Common Inputs)

	IBD	Geo neutrinos	Accidentals	$^{13}C(\alpha, n), ^{16}O$	$^{9}Li/^{8}He$	Fast neutrons	World reactors
Rate [evt/day]	47	1.2	0.8	0.8	0.1	0.05	1



Total spectrum



Chi squared test

I test JUNO sensitivity to NMO with this procedure:

Assuming one ordering true

I produce a spectrum with this ordering (e.g. Normal Order)
It can be an Asimov spectrum or not.

$\Downarrow$

Fit with NO and IO

I compute $\chi^2 = \sum_i^{n_{bin}} \frac{(M_i - T_i)^2}{M_i}$ for both NO and IO theoretical spectrum.

$\Downarrow$

Compute $\Delta\chi^2$

Output is $\Delta\chi^2 = \chi^2_{IO} - \chi^2_{NO}$

Chi squared test

The full minimizer used is:

$$\chi^2 = \sum_i^{n_{bin}} \left(\frac{\left(M_i - T_i \cdot (1 + \alpha_C + \sum_r w_r \cdot \alpha_r + \alpha_D) - \sum_B K_i^B \cdot (1 + \alpha_B)\right)^2}{M_i + (T_i \cdot \sigma_{b2b})^2 + \sum_B (\sigma_{shp}^B \cdot K_i^B)} \right) + \left(\frac{\alpha_C}{\sigma_C}\right)^2 + \left(\frac{\alpha_D}{\sigma_D}\right)^2 + \sum_r \left(\frac{\alpha_r}{\sigma_r}\right)^2 + \sum_B \left(\frac{\alpha_B}{\sigma_B}\right)^2 + \sum_{\zeta = a,b,c} \left(\frac{\zeta - \zeta_0}{\sigma_\zeta}\right)^2$$

- α_C represents a rate uncertainty related to reactors, with $\sigma_C = 2\%$, and it's correlated among all bins.
- α_r models another rate uncertainty related to reactors that is different from core to core, $\sigma_r = 0.8\%$ for each core.
- α_D represents a rate uncertainty related to detector, with $\sigma_D = 1\%$, and it's correlated among all bins.
- $\sigma_{b2b} = 1\%$ models a shape uncertainty that affects each bin separately.
- σ_{shp}^B represents a shape uncertainty on each background.
- σ_B represents a rate uncertainty on the background prediction.

What is in MASFit

This is what I've implemented until now in my code:

	MASFit
Real baseline	Antineutrino from 9 reactors weighted by distance and power
Backgrounds	Spectra from the 6 main sources with their predicted rate
Systematic uncertainties	On the predicted rate and shapes of spectra
Detector response	Energy resolution taken into account with a convolution
Statistical fluctuations	Simulated as Poisson fluctuations

Comparison with IHEP Tech Note

I've taken as reference the results shown in the IHEP Tech Note of July 2022 (DocDB:#7494-v8), but I'm still developing some features. Here I show the main differences from it:

	MASFit	**IHEP TN**
LSNL	Not considered	Computed as systematic and in the construction of events
Binning strategy	Fixed bin width of 20 keV: total 410 bins	Variable bin width: total 360 bins
Signal shape uncertainty (b2b)	Fixed at 1% for each energy	TAO_based (variable with energy)

Even though there are some differences the results are **comparable**.

$\Delta\chi^2$ (NO)	8.433	8.131
$\Delta\chi^2$ (IO)	9.401	8.621

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$\Delta\chi^2$ (NO)	8.433	8.131
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Input parameters for Asimov data-set

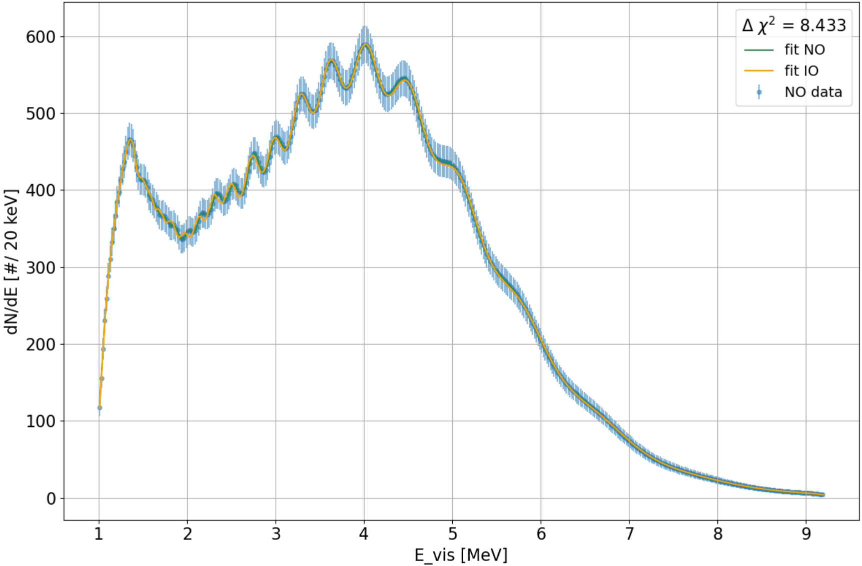
The simulation is run with energies from 1.8 MeV to 10 MeV, divided in 410 bins of 20 keV each. I've considered 6.7 years of data taking, with a duty cycle of 11/12: $\approx 105k$ evt.

Input parameters

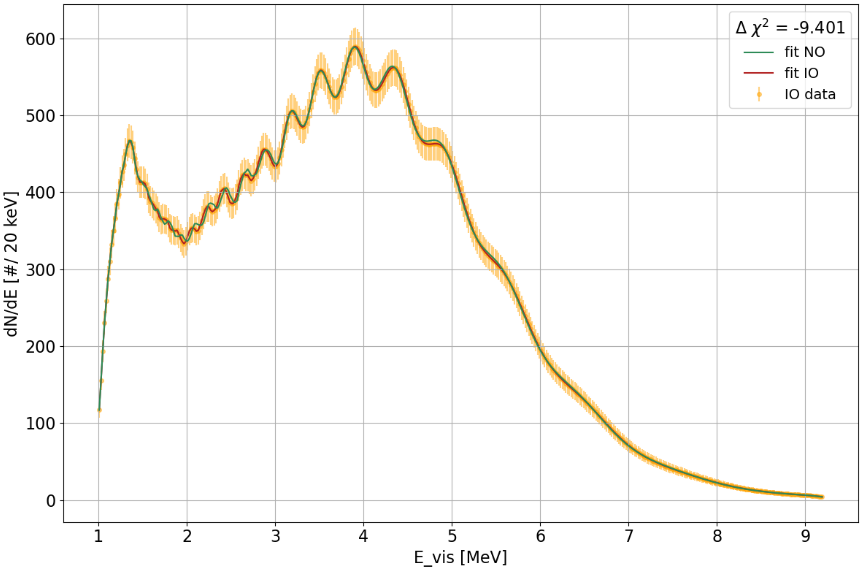
Parameter	Value	Free parameter?
$\sin^2(\theta_{12})$	0.304	✓
$\sin^2(\theta_{13,NO})$	0.0222	X
$\sin^2(\theta_{13,IO})$	0.02238	X
Δm^2_{21}	$7.42 \cdot 10^{-5}$	✓
$\Delta m^2_{31,NO}$	$2.515 \cdot 10^{-3}$	✓
$\Delta m^2_{32,IO}$	$-2.498 \cdot 10^{-3}$	✓
a(%)	2.614	Pulled
b(%)	0.640	Pulled
c(%)	1.20	Pulled
σ_a(%)	0.02	
σ_b(%)	0.01	
σ_c(%)	0.04	

Oscillation parameters from NuFit 5.1, and energy resolution from Tech Note July 2022 (DocDB:#7494-v8, juno.ihep.ac.cn/cgi-bin/Dev_DocDB/ShowDocument?docid=7494).

Results Asimov data-set NO

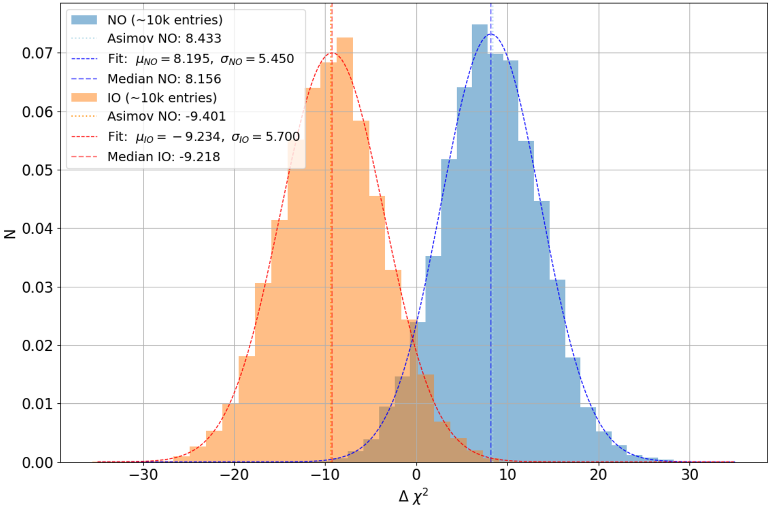


Results Asimov data-set IO



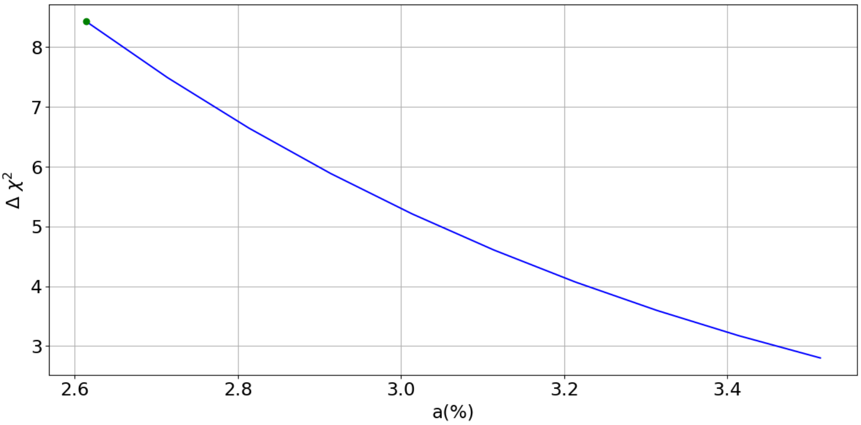
Results fluctuated data-set

Median sensitivity for NO hypothesis: 3.28 σ
Median sensitivity for IO hypothesis: 3.39 σ



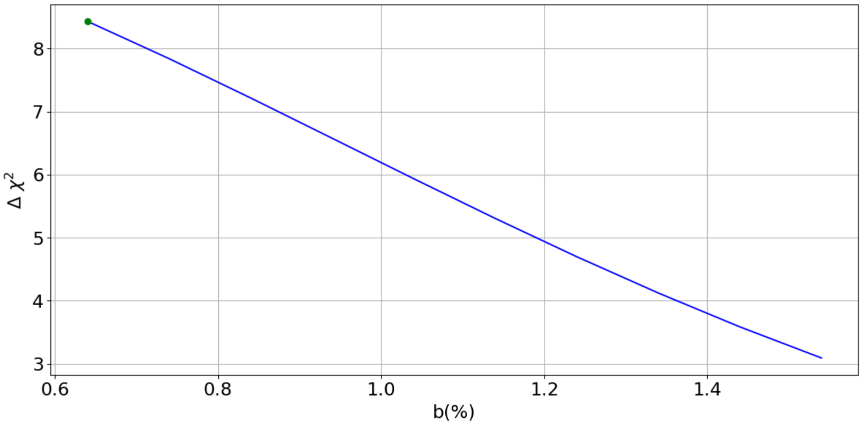
Other results: dependence from energy resolution

$\Delta\chi^2$ in function of the term a of energy resolution (reference value a=2.614 %)..



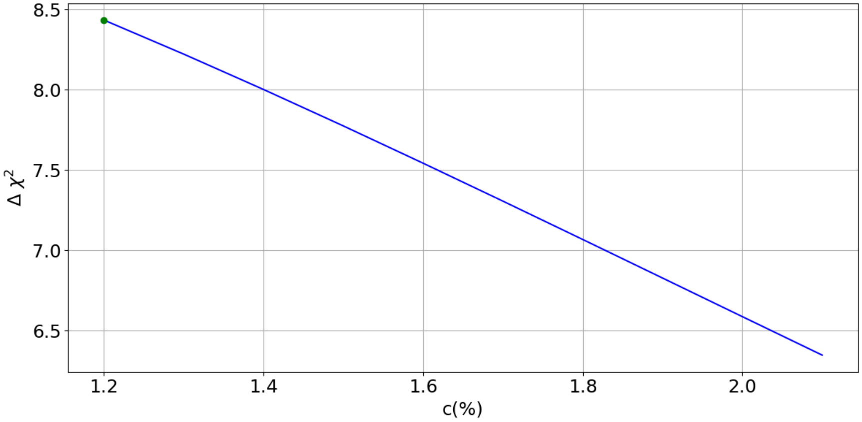
Other results: dependence from energy resolution

$\Delta\chi^2$ in function of the term b of energy resolution (reference value b=0.640 %).



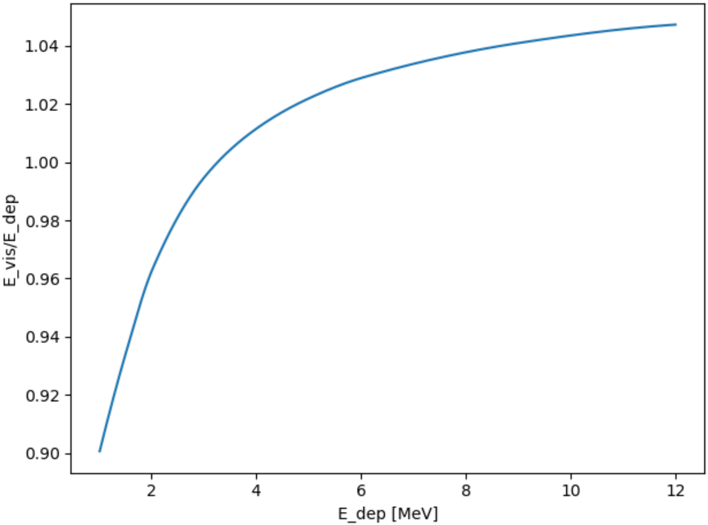
Other results: dependence from energy resolution

$\Delta\chi^2$ in function of the term c of energy resolution (reference value c=1.20 %).



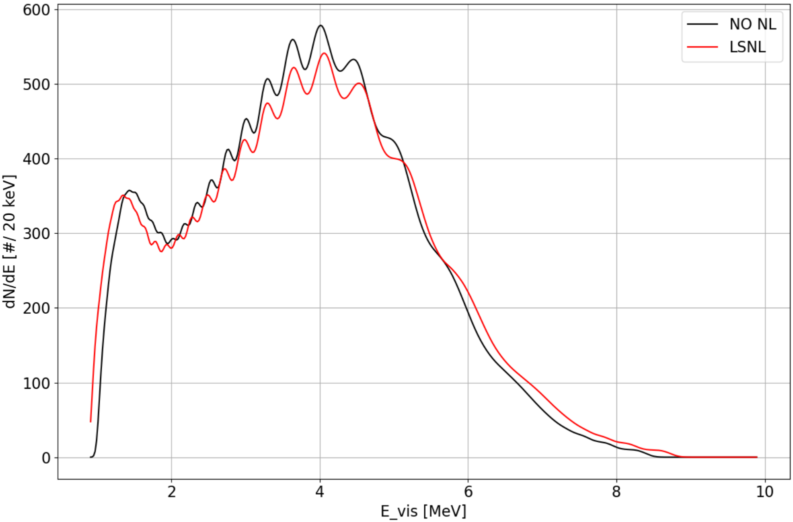
Work in progress: liquid scintillator non linearity

$$E_{vis} = f_{LSNL} \cdot E_{dep}$$



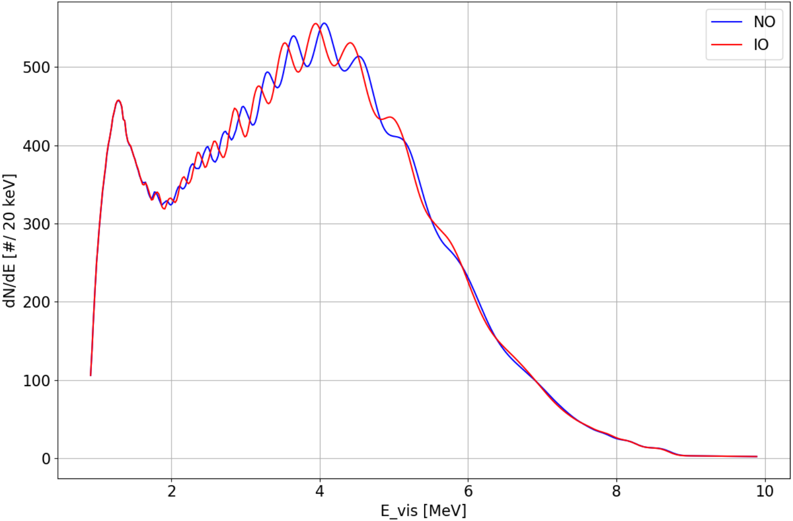
Work in progress: liquid scintillator non linearity

I'm adding the LSNL (liquid scintillator non linearity), both in the energy reconstruction and in the pull terms.



Work in progress: liquid scintillator non linearity

Here is the comparison of the two spectra with LSNL and backgrounds.



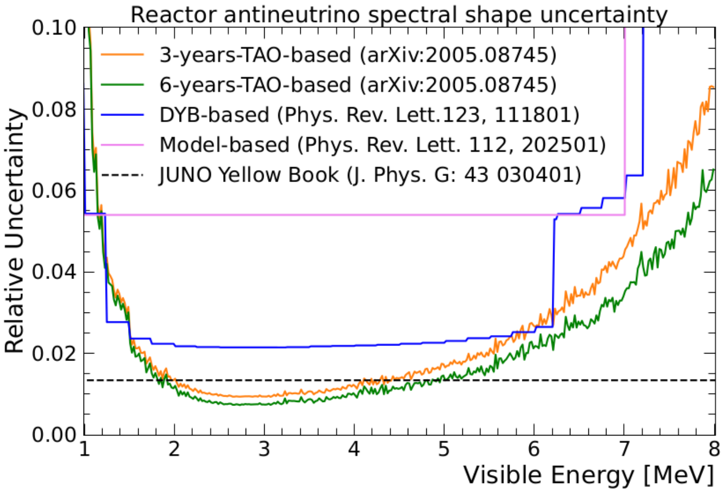
MASFit

- MASfit is a code that can generate and fit the antineutrinos spectrum in JUNO.
- It can be used as a fitter, but I've done also other analysis (correlation, energy resolution).
- It is a very flexible code (can be run easily with different parameters) and has been used by Marco Malabarba to study the dependence of the sensitivity from different characteristics of the liquid scintillator.
- It takes both the antineutrino and backgrounds spectra from input, so it easy to use with different models.
- The code is uploaded on GitHub with open access, if you want to try it. Every feedback is welcome. (*https://github.com/elisapercalli/MASFit_2*)

Thanks for your attention

Backup

Shape uncertainties (b2b)



Binning strategy IHEP

	Energy interval (MeV)	Bin width (keV)	Number of bins
	(0.8, 0.94)	140	1
	(0.94, 7.44)	20	325
	(7.44, 7.8)	40	9
	(7.8, 8.2)	100	4
	(8.2, 12)	2800	1
Total	(0.8, 12)	-	340

Chi squared definition

$$\chi^2_{\text{Poisson}} = 2\sum_{i=1}^{n}\left(\mu - M_i + M_i \ln\frac{M_i}{\mu}\right),$$

$$\chi^2_{\text{Neyman}} = \sum_{i}^{n}\frac{(\mu - M_i)^2}{M_i},$$

$$\chi^2_{\text{Pearson}} = \sum_{i}^{n}\frac{(\mu - M_i)^2}{\mu}.$$

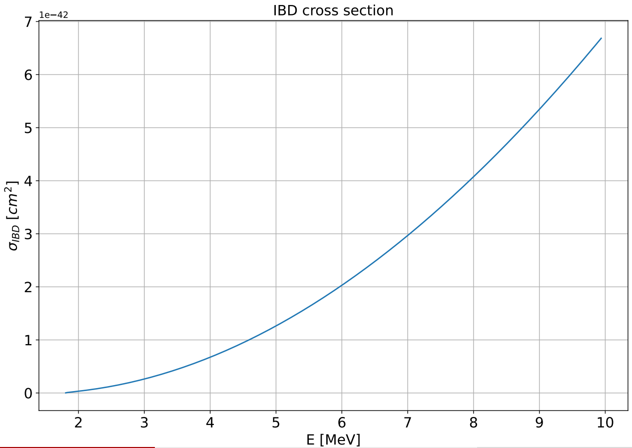
$$\chi^2_{\text{CNP}} \equiv \frac{1}{3}\left(\chi^2_{\text{Neyman}} + 2\chi^2_{\text{Pearson}}\right) = \sum_{i=1}^{n}\frac{(\mu - M_i)^2}{3/(\frac{1}{M_i} + \frac{2}{\mu})},$$

IBD cross section

The neutrino will interact in the liquid scintillator via the Inverse Beta Decay process: $\nu_e + p \rightarrow n + e^+$.
The IBD cross section is approximated, for $E_\nu < 300\ MeV$ with this formula:

$$\sigma_{IBD} = 10^{-43} p_e E_e E_\nu^{-0.07056+0.02018 \ln E_\nu - 0.001953 \ln^3 E_\nu}\ [cm^2]$$

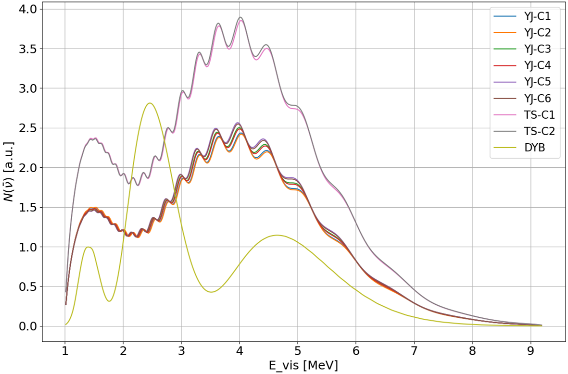
where $E_e = E_\nu - \Delta$ is the positron energy and $\Delta = m_n - m_p \approx 1.293\ MeV$.



Real baseline distribution

Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6	TS-C1	TS-C2	DYB
Baseline [km]	52.74	52.82	52.41	52.49	52.11	52.19	52.77	52.64	215
Power [GW]	2.9	2.9	2.9	2.9	2.9	2.9	4.6	4.6	17.4

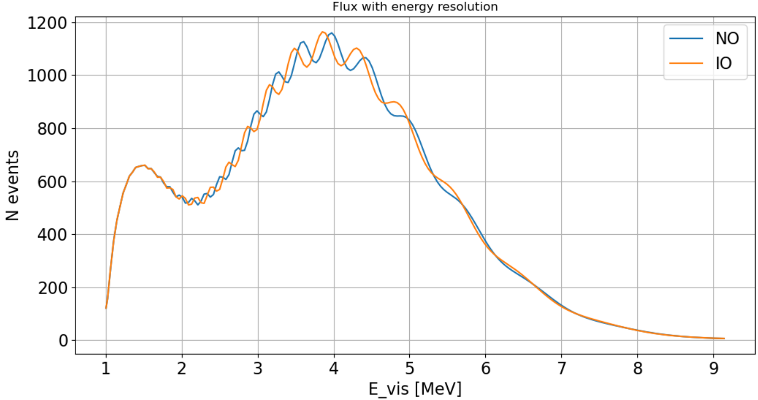
I compute then the total spectrum: $N_{tot} = \sum_{i=0}^{9} w_i N_i$, where $w_i = \frac{P_i}{L_i^2}$.



Energy resolution

The detector response is approximated as a Gaussian: $G(E_{dep} - E_{vis}, \delta E_{dep}) = \frac{1}{\sqrt{2\pi}\delta E_{dep}} \exp\left(-\frac{(E_{dep}-E_{vis})^2}{2(\delta E_{dep})^2}\right)$ where $E_{dep} = E_\nu - 0.8$ is the deposited energy, E_{vis} is the visible energy. The energy resolution on the deposited energy is: $\frac{\delta E_{dep}}{E_{dep}} = \sqrt{\left(\frac{a}{\sqrt{E_{dep}}}\right)^2 + b^2 + \left(\frac{c}{E_{dep}}\right)^2}$

The spectrum with finite energy resolution is obtained through a convolution of the previous spectrum with the detector response G.



Energy Resolution	a ($\times 10^{-2}\sqrt{\text{MeV}}$)	b ($\times 10^{-2}$)	c ($\times 10^{-2}$) MeV	$\tilde{a}$(%)	At 1 MeV
Calibration paper	2.61 ± 0.02	0.82 ± 0.01	1.23 ± 0.04	3.02	3.00%
J22.1.0-rc0	2.614 ± 0.005	0.640 ± 0.003	1.20 ± 0.01	2.91	2.95%

Real baseline distribution

Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Baseline [km]	52.74	52.82	52.41	52.49	52.11	52.19	52.77	52.64	52.33	52.23	215	265
Power [GW]	2.9	2.9	2.9	2.9	2.9	2.9	4.6	4.6	4.6	4.6	17.4	17.4

I compute then the total spectrum: $N_{tot} = \sum_{i=0}^{12} w_i N_i$, where $w_i = \frac{P_i}{L_i^2}$.