GNA fitter and detector response impact on JUNO mass hierarchy sensitivity

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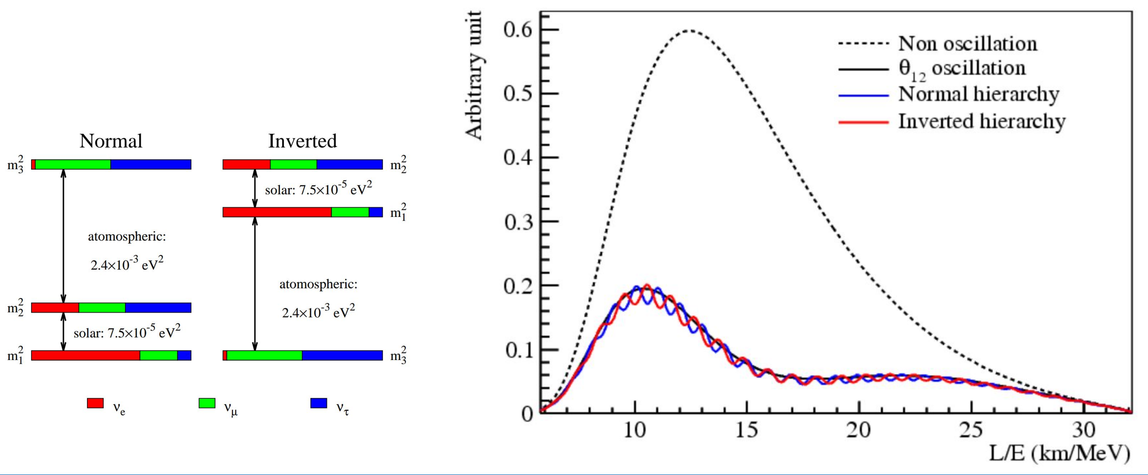
Introduction

The Jiangmen Underground Neutrino Observatory (JUNO) is a 20 kt liquid scintillator detector that will be located at Kaiping, Jiangmen city in South China. An energy resolution of 3% at 1 MeV is required to determine the neutrino mass hierarchy (MH) by spectral analysis. In this world largest liquid scintillator detector, a good understanding of the energy response is essential for MH determination.

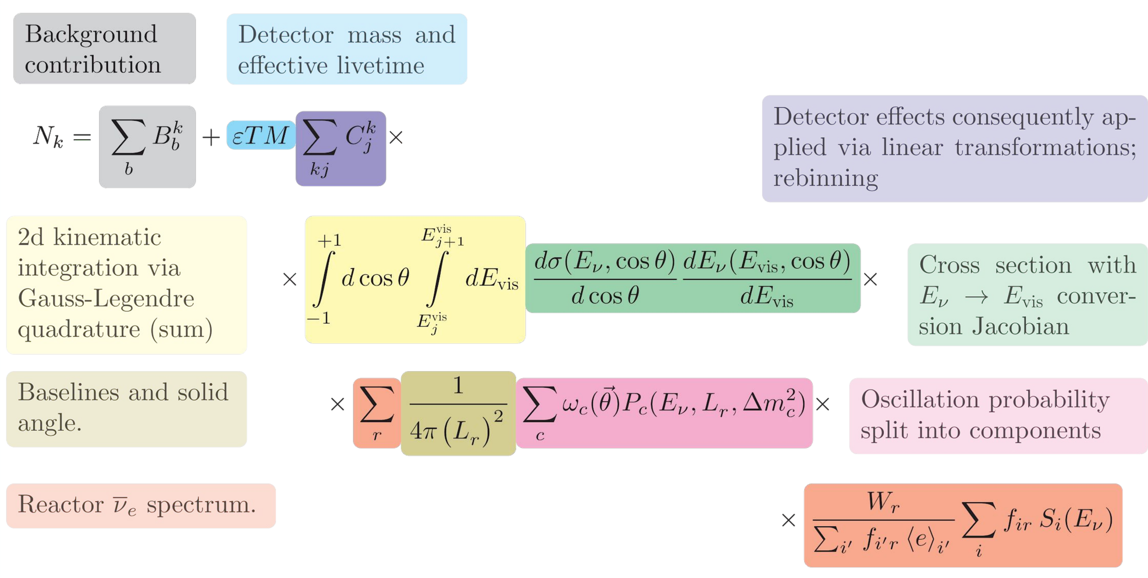


GNA features and JUNO calculation scheme

- GNA — a fitter for comprehensive physical models with large number of parameters.
- Design is based on the Daya Bay experience.
- Dataflow programming paradigm: model is built as directed lazily-evaluated graph that operates on vectors.
- Implementation: C++ (core), Python (interface).
- Built on top of: Eigen (linalg), ROOT (minimization), boost.
- Transparent multicore/GPGPU computations are on the way.
- Statistical approaches implemented:
  - χ^2 and Poisson test statistics.
  - Feldman-Cousins approach.
  - Likelihood profiling.
  - Propagation of systematics via pull term and covariance matrix.

http://astronu.jinr.ru/wiki/index.php/GNA

The energy spectra prediction is done in this way:



- Detector effects: energy scale nonlinearity, resolution.
- Huber-Muller antineutrino spectra for isotopes.
- SNF/off-equilibrium are not considered for sensitivity.

Statistical method

The χ^2 is constructed the following way:

$$\chi^2 = (x-\mu(\theta,\eta))^T V_{stat}^{-1}(x-\mu(\theta,\eta)) + (\eta-\eta_0)^T V_\eta^{-1}(\eta-\eta_0)$$

where:

- x, μ — vectors with data and model prediction.
- θ — vector with free parameters.
- η — vector with uncertainties, propagated via penalty terms.
- η_0 — default values of η.
- V_η — error matrix for η.

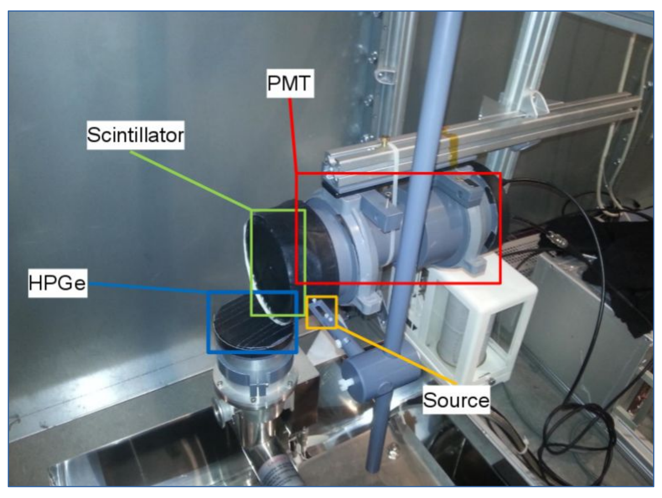
LS NL measurement

Several groups from Prague, TUM, Milan are working on LS non-linearity (NL) measurement now. The basic principle is compton coincidence technique.

$$E_{vis}^{e^+} = E_{vis}^{e^-} + 2 * E_{vis}^{\gamma(0.511MeV)}$$

$$E_{vis}^{\gamma} = \int E_{vis}^{e} * \frac{dN}{dE}(E_{true}^{e}) * dE_{true}^{e}$$

The method to propagate LS response from e^- to e^+ is based on the assumption that e^- and e^+ have identical behaviour while depositing kinetic energy in LS and then the gamma NL can be deduced from e^-/e^+.

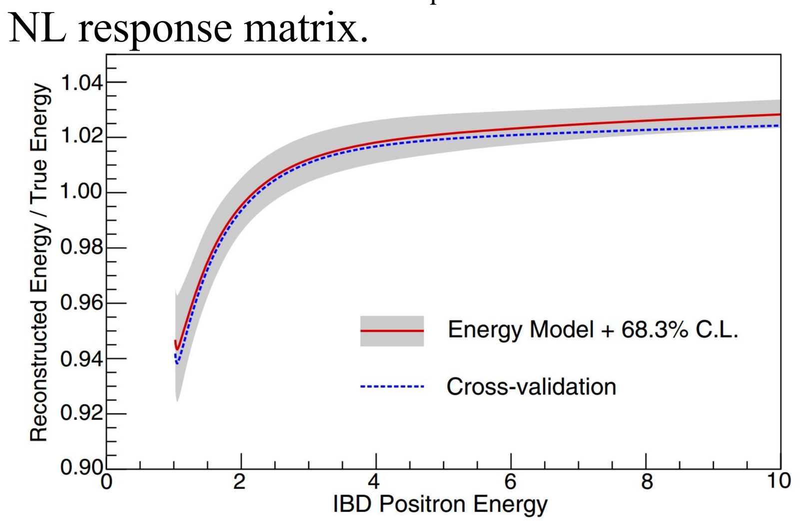


Non-linearity study based on DYB model

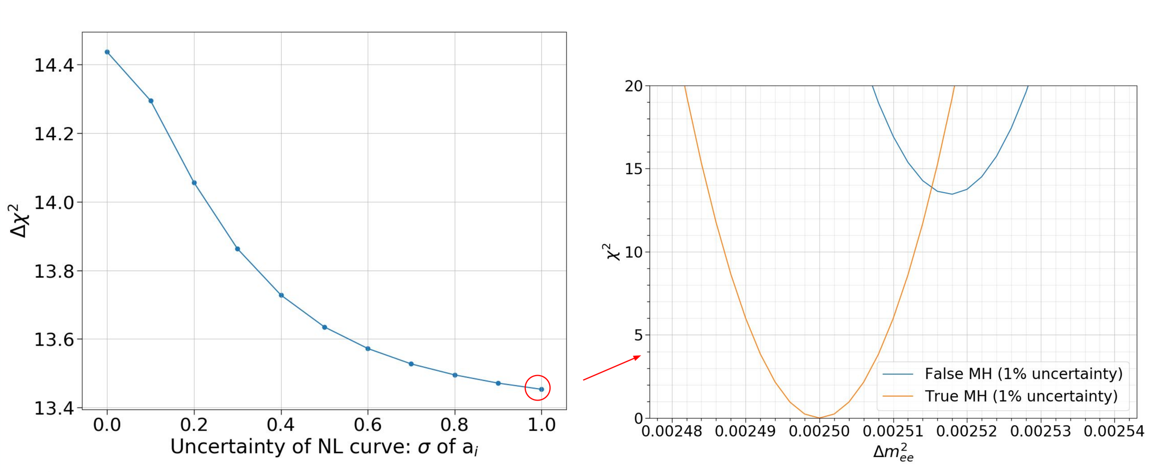
The Daya Bay (DYB) non-linearity (NL) curve is tuned based on various DYB gamma calibration sources and the continuous beta spectrum of ^{12}B is also used (Ref. [1]).
The Daya Bay energy nonlinearity is parametrized in this way:

$$\frac{E_{rec}}{E_{true}} = f_0(E) + \sum a_i(f_i(E) - f_0(E))$$

Function $f_0(E)$ is the nominal model. The functions $f_i(E)$ represent the alternative curves chosen in order to parametrize $f_0(E)$ uncertainty with parameters a_i=0±1. From the NL curve, we can get NL response matrix.



Change the uncertainty of NL curve by changing the sigma value of a_i. Adding pull terms for a_i, and use the measured spectrum itself to calibrate the NL model. Varying the uncertainty of the NL curve and studying its impact by inspecting the $\Delta\chi^2$ between False MH and true MH. **From the left plot, we can see the overall change in $\Delta\chi2$ is less than 1.** The right plot is the scan result for sigma(a_i)=1.



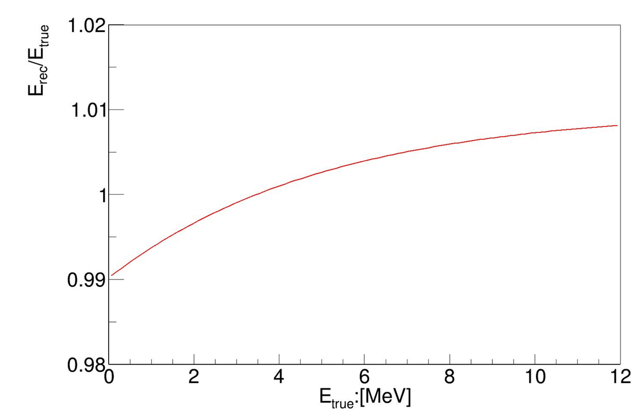
Ref. [1] PRD 95, 072006(2017)

Non-linearity study based on analytical model

Assume after the energy non-linearity correction, we have a residual nonlinearity with the form like this (Ref. [2]):

$$\frac{E_{rec}}{E_{true}} = \frac{1+p_0}{1+p_1 * exp(-p_2 E_{true})}$$

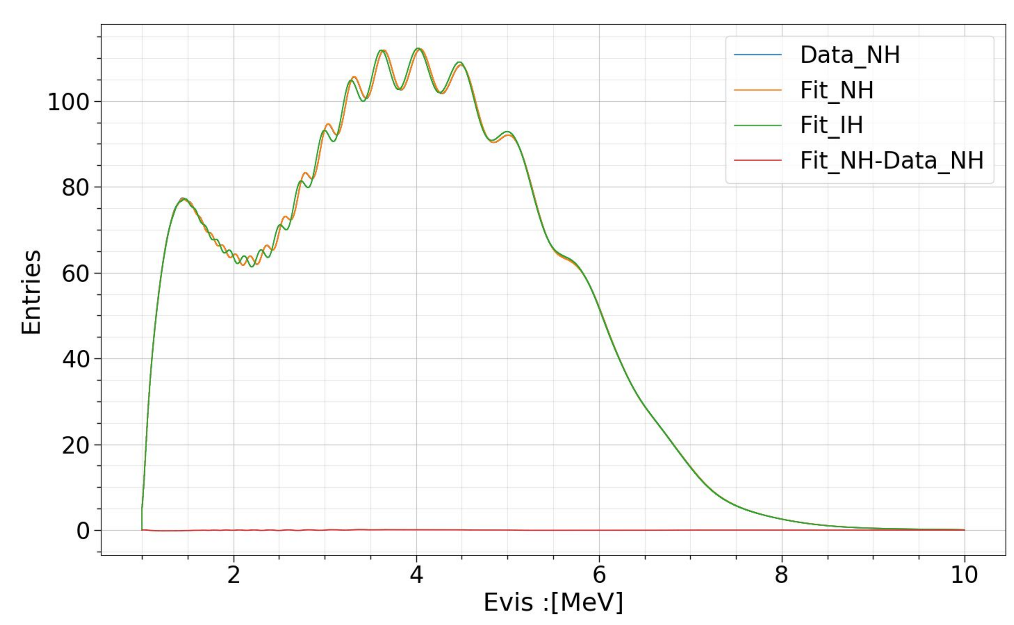
Here p2 = 0.2/MeV, we studied p0 and p1 with combinations like (p0, p1)=(0.5%, 1%) (1%, 2%) (1.5%, 3%)
If p0=1% and p1=2%, we will have a residual NL like this:



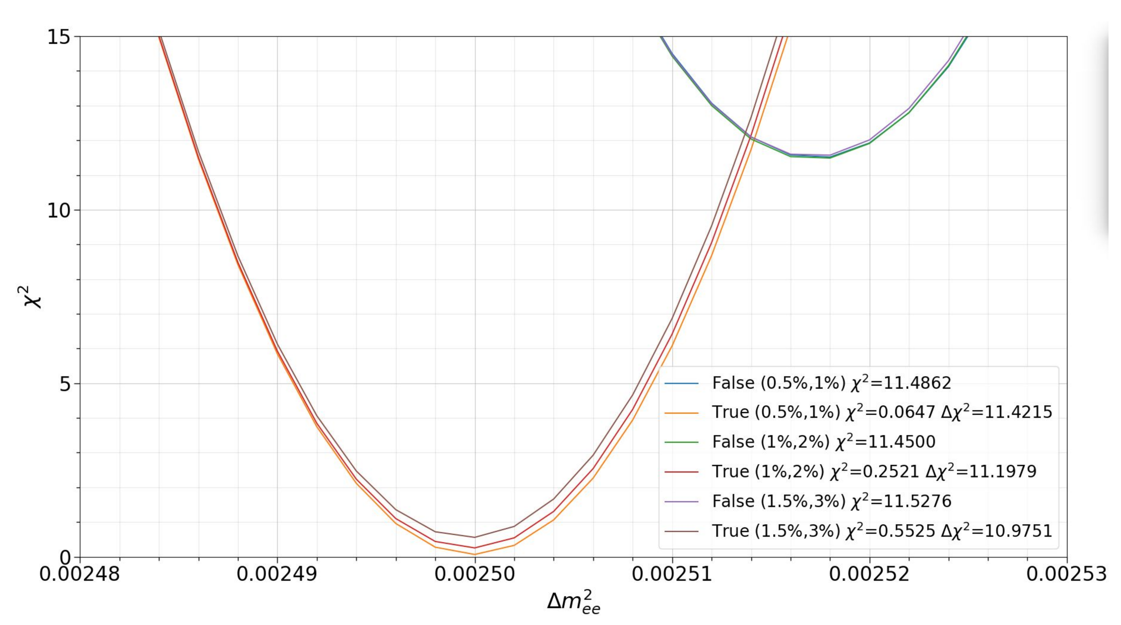
According to Ref. [2], we can measure this residual nonlinearity to some extent by the spectrum itself, based on the multiple peaks induced by Δm^2_{ee} oscillation.
A test quadratic nonlinear function can be used in the prediction, pull terms are added, here we consider the sigma of q1, q2, and q3 are 0.02.

$$E_{rec} = q_0 + (1+q_1) * E_{true} + q_2 * E_{true}^2$$

The best fit results for p0=1% , p1=2% is:



Assume that the true MH is normal, then with different intensities of residual NL (represented by p0 and p1), using the quadratic NL function in two prediction scenarios NH (true MH) and IH (false MH), the results are as follows, the $\Delta\chi2$ is quite stable inside this residual NL range



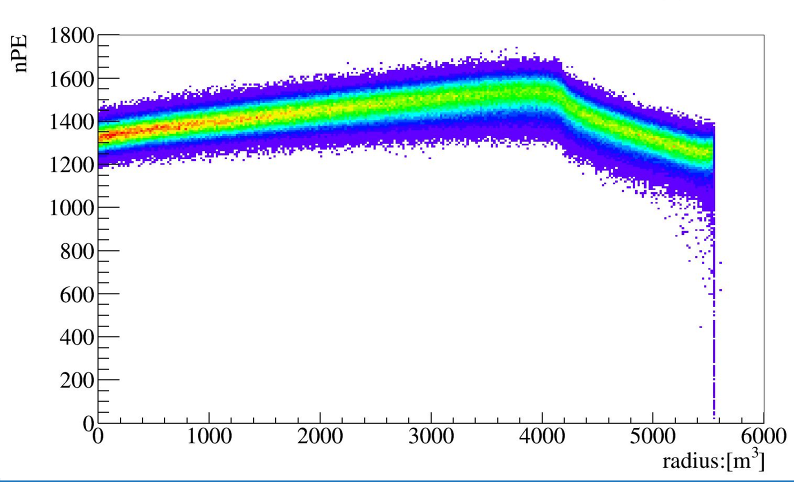
Ref. [2] PRD 88, 013008 (2013)

Non-Uniformity study

From detector center to edge, we can see clear change in the number of photoelectrons (nPE) per MeV wrt radius. Since b in the energy resolution parametrization

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

is related to photon fluctuation, we can use different energy resolution at different radius. Coefficient b can be updated as the reciprocal of the square root of mean nPE/MeV at the certain radius.



How many layers is enough to catch the structure in nPE/MeV curve? A scan results is shown below.
Divide the whole LS region into equal-volumed shells, apply different energy resolution in each shell.
From this plot, we can see that small improvements can be made, $\Delta\chi^2$ increase ~0.25. From 10 layers on, the $\Delta\chi^2$ is almost stable.