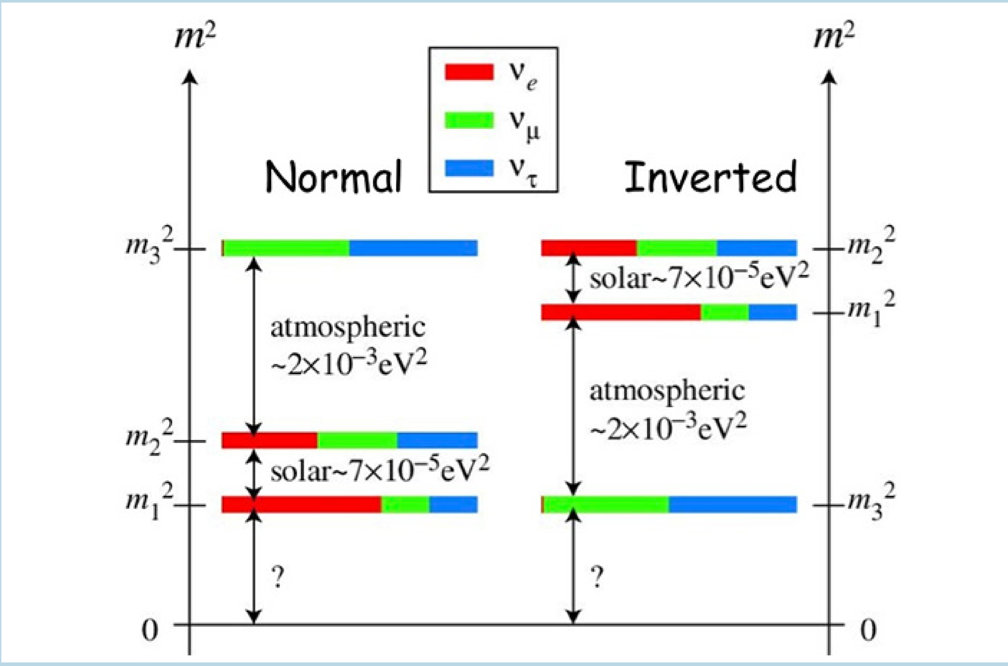
Determination of the NMO using atmospheric neutrinos in the JUNO experiment

Nikita Bessonov, Maxim Gonchar
bessonov@jinr.ru, gonchar@jinr.ru

LOMONOSOV MOSCOW STATE UNIVERSITY
JOINT INSTITUTE FOR NUCLEAR RESEARCH

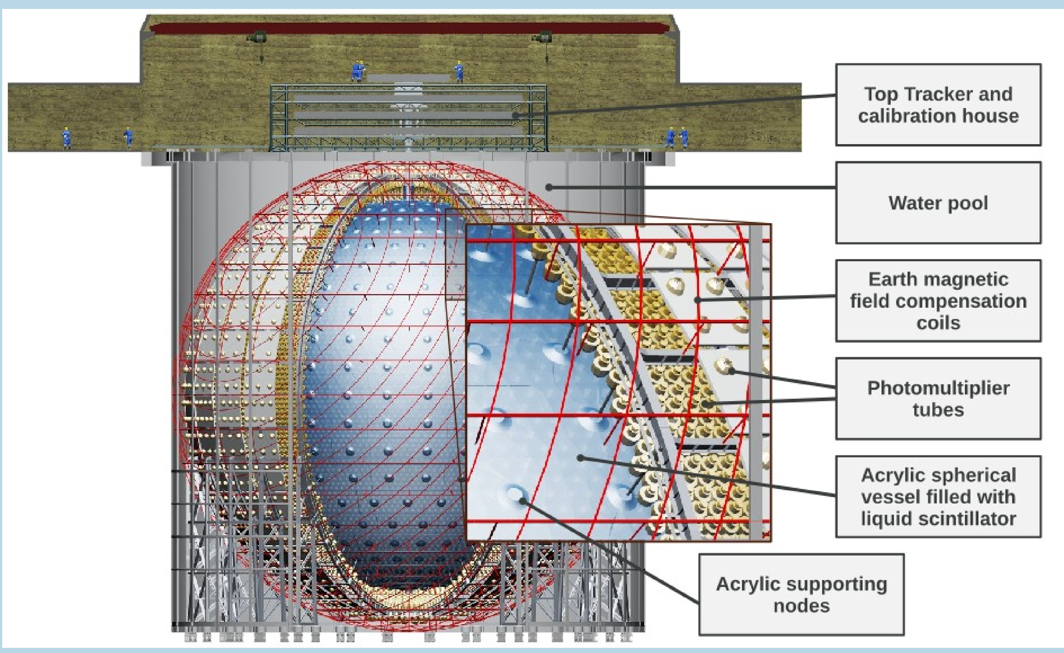
Problem

- The determination of the neutrino mass ordering (NMO) is one of the key unresolved problems in modern neutrino physics.
- Due to its large volume, high energy resolution, capability to reconstruct particle tracks, and the possibility to statistically identify the neutrino type, the JUNO experiment has the potential to determine the NMO using atmospheric and reactor neutrinos.
- The goal of this work is to study the experiment's sensitivity to neutrino oscillation parameters using atmospheric neutrinos with the GNA software framework.
- Global Neutrino Analysis (GNA) is a software package developed at DLNP JINR for high-performance analysis of neutrino experiments.



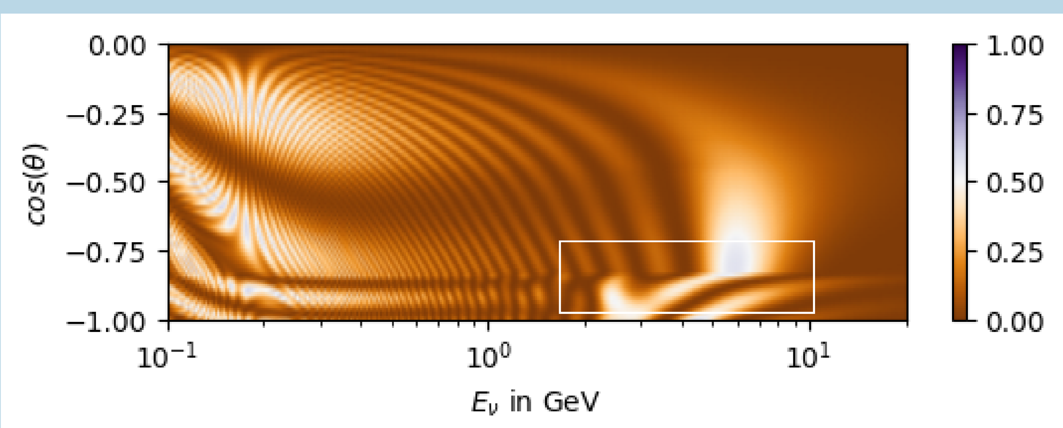
JUNO

- JUNO (Jiangmen Underground Neutrino Observatory) is a 20-kiloton liquid scintillator underground detector in China that is currently at the stage of filling and commissioning.
- The main goal of JUNO is to determine the NMO. Its unprecedented energy resolution and large active volume make it possible to solve many other problems in neutrino physics.



Oscillation probabilities

JUNO's sensitivity to the NMO is achieved due to its ability to resolve the resonant behavior of atmospheric neutrino oscillation probabilities at the Earth's core-mantle boundary, in the energy range of a few GeV. In the case of normal mass ordering (NO), this resonance occurs for neutrinos, and in the case of inverted ordering (IO), it is observed for antineutrinos. Therefore, particle identification (PID) plays the most significant role in the sensitivity to NMO.



$P(\nu_e \to \nu_\mu)$ (NO). The box highlights the region responsible for NMO sensitivity.

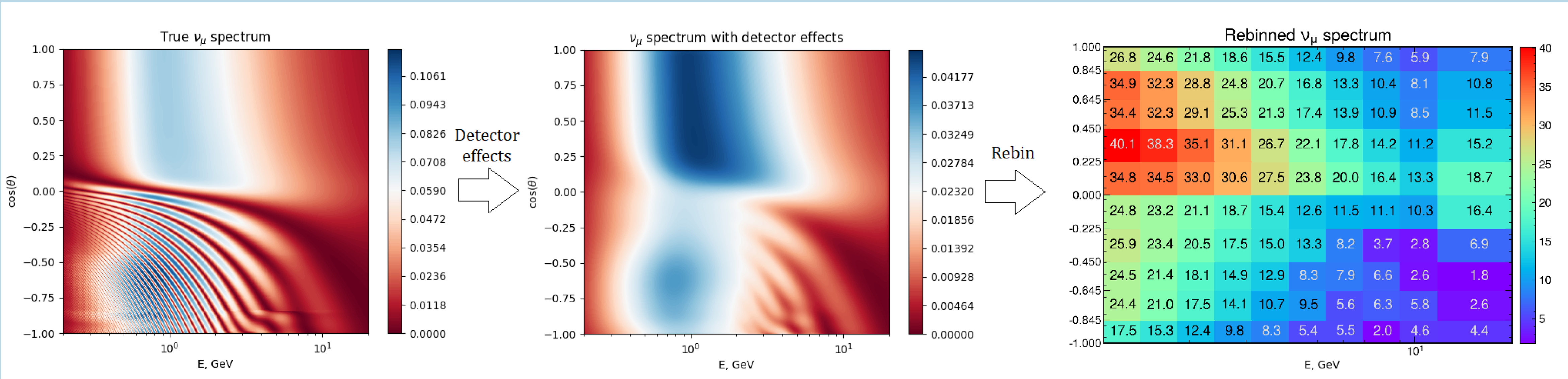
Calculation of spectra

$$N_{ij}^{fsc} = 2\pi MT \sum_{l=e,\mu} \int_{E_i}^{E_{i+1}} \mathrm{d}E \int_{\cos\theta_j}^{\cos\theta_{j+1}} \mathrm{d}\cos(\theta)\sigma_{fsc}(E)\Phi^0_{ls}(E,\cos\theta)P_{lfs}(E,\cos\theta)$$

- E: 400 bins $[E_i,\, E_{i+1}]$ in $[100\text{ MeV}, 20\text{ GeV}]$. $\cos\theta$: 400 bins $[\cos\theta_j,\, \cos\theta_{j+1}]$ in $[-1,1]$.
- Indices: l — flavor in initial state, f — flavor in final state, s — type (particle/antiparticle), c — current (NC/CC). Further, $\{fsc\} \to t$, where t in $\{\nu_e^{\mathrm{CC}}, \nu_\mu^{\mathrm{CC}}, \bar{\nu}_e^{\mathrm{CC}}, \bar{\nu}_\mu^{\mathrm{CC}}, \mathrm{NC}\}$.
- M — LS mass, T — exposure time, σ — cross section (Genie), Φ^0 — initial flux (HKKM14), P — oscillation probabilities (OscProb).

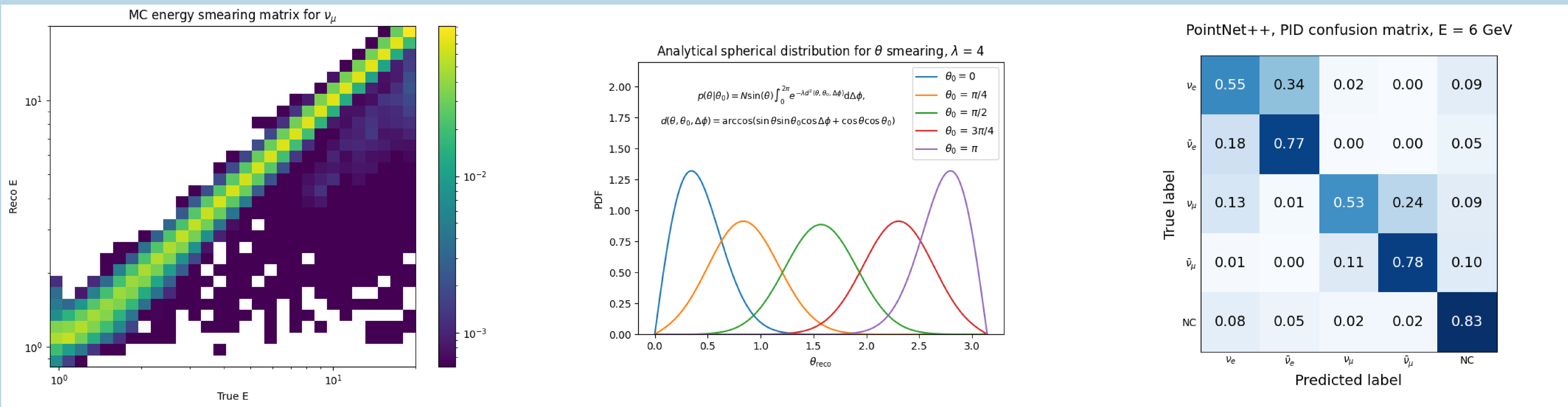
$$\widetilde{T}^p_{kl} = \sum_t \sum_j U^t_{jl} \sum_i V^t_{ijk}\epsilon^{tp}_j N^t_{ij}.$$

$\widetilde{T}$ — the final spectra. ϵ — confusion matrix (PID), U — energy smearing matrix, V — angle smearing E-dependent 3D array.
k: index of $\cos\theta_{rec}$, i: index of $\cos\theta$, t: true label,
i: index of E_{rec}, j: index of E_{true}, p: predicted label.
Binning optimized for NMO determination:
$\cos\theta$ — $[-1, -0.845, -0.645, -0.45, -0.225, 0., 0.225, 0.45, 0.645, 0.845, 1]$,
E — $[1.085, 1.414, 1.843, 2.402, 3.131, 4.081, 5.318, 6.931, 9.033, 11.774, 20]$ (GeV).



Detector response

The following strategies of applying detector effects have been implemented in our GNA model:
1. Energy smearing: analytical method using a normal distribution, and a matrix MC method;
2. Zenith angle smearing: a matrix MC method and smearing using an analytical spherical distribution;
3. Particle identification (PID): both energy-independent and energy-dependent PID, based on DeepSphere and PointNet++.



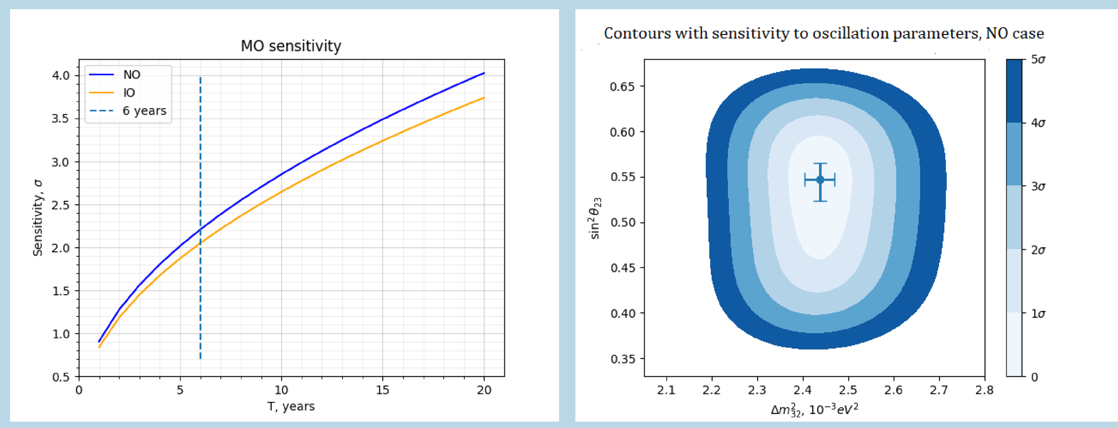
Likelihood

$$\chi^2 = 2\sum_{i=1}^{N_E}\sum_{j=1}^{N_{\cos\theta}}\left[N_{ij}\ln\left(\frac{N_{ij}}{\widetilde{T}_{ij}}\right) + \widetilde{T}_{ij} - N_{ij}\right] + \sum_{k=1}^{K}\xi_k^2$$

- ξ_k are penalty terms for systematics.
- PID systematics: 20 parameters due to the condition $\sum_p \epsilon^{tp} = 1$ (uncertainty is 10% for each parameter).
- Parameters of flux and cross section systematic uncertainties:

Flux	σ	π_{ij}
Overall normalization	20%	20%
Energy dependence	5%	$5\% \times \ln\frac{E_\nu}{E_0}$
Zenith angle dependence	5%	$5\% \times \langle\cos\theta\rangle$
$\nu_\mu + \bar{\nu}_\mu / \nu_e + \bar{\nu}_e$	2%	$\pm1\%$
$\nu_\mu / \bar{\nu}_\mu$	5%	$\pm2.5\%$
$\nu_e / \bar{\nu}_e$	5%	$\pm2.5\%$
Cross section	σ	π_{ij}
Overall normalization	10%	10%

Expected sensitivity results



- The maximum sensitivity to CP violation reaches about 1.2σ in the case of NO and 1σ in the case of IO for 10 years of data taking.
- The sensitivity to the θ_{23} octant varies in the range from 0.2σ to 1.2σ for θ_{23} values within $\pm1\sigma$ of the PDG value.
- The constraints on the parameters Δm^2_{32} and $\sin^2\theta_{23}$ are shown in the figure.
- The expected sensitivity to the NMO reaches about 2σ after 6 years of detector operation. A joint analysis of atmospheric neutrinos and reactor antineutrinos can significantly improve the sensitivity to the NMO.