Atmospheric Neutrino Oscillation at JUNO

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Outline

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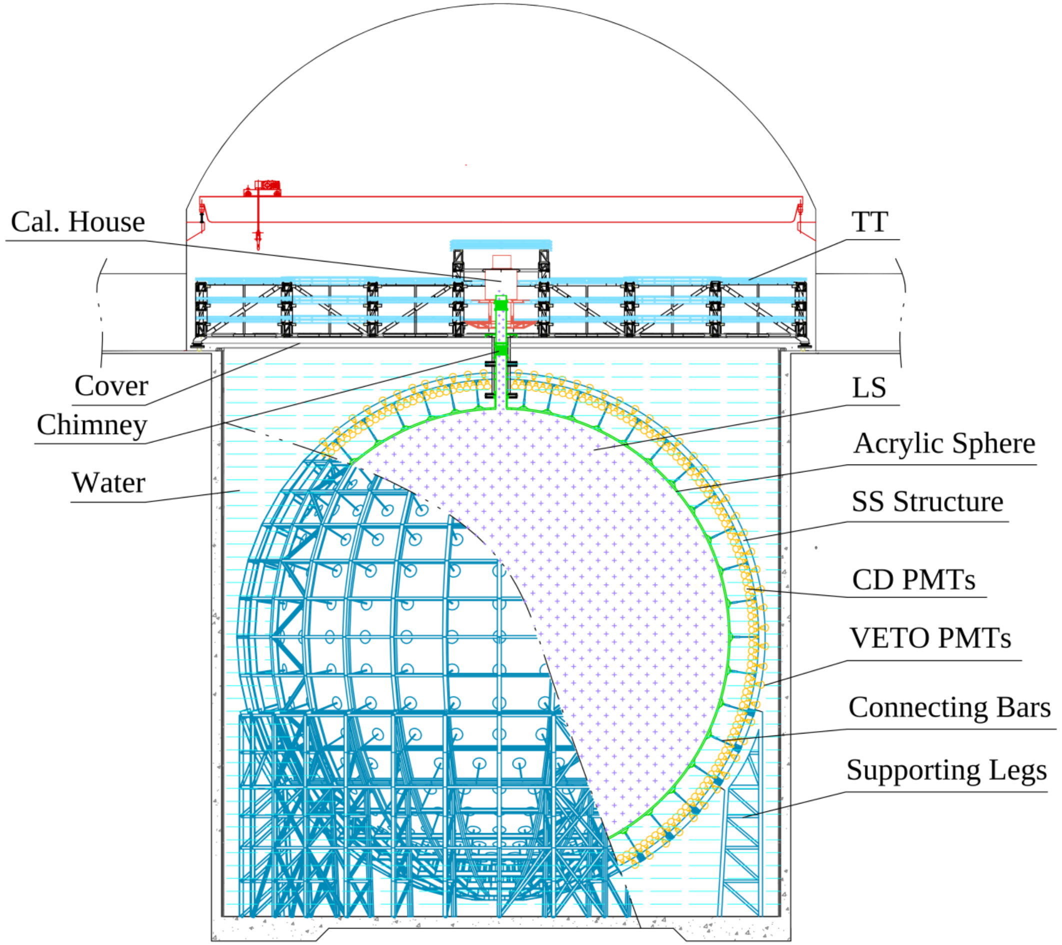
2. Earth Model
3. Matter Effect
4. Flux Comparison
5. Analyses with VALOR
6. Summary and Future Works

1. Introduction

JUNO Experiment



1. Jiangmen Underground Neutrino Observatory (JUNO) is a multi-purpose neutrino experiment located in Jiangmen, Guangdong Province, China. With capacity of 20 ktons of Liquid Scintillator (LS), the experiment is nearing the completion of its LS filling phase.
2. To make precise measurements of neutrino oscillation parameters and determining the Neutrino Mass Ordering (NMO)
3. Atmospheric neutrino provides a complementary detection channel to reactor:

   0.1-10 GeV energy range

   exploit matter effects

Atmo Nu in a Nutshell

$$n_\beta\left(\vec{x};\vec{\Theta},\vec{s}\right) = \sum\!\!\!\!\!\!\int_{\alpha,\vec{p}_\nu,\vec{x}_0} \Phi_\alpha\left(\vec{p}_\nu;\vec{s}_\Phi\right) P_{\alpha\beta}\left(\vec{p}_\nu;\vec{\Theta}\right) \sigma_\beta\left(E_\nu,\vec{x}_0;\vec{s}_\sigma\right) R\left(\vec{x}_0,\vec{x};\vec{s}_R\right)$$

3D flux for flavor α with systematic parameters s_Φ

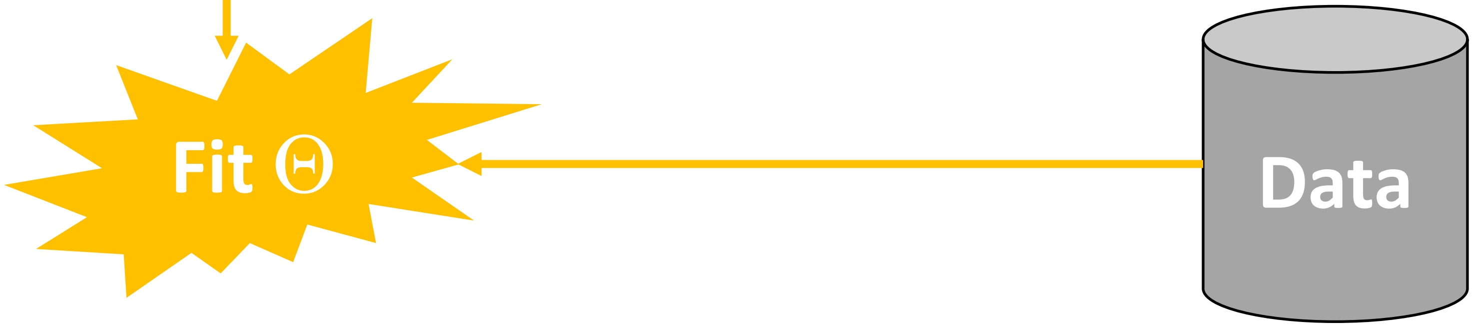
Oscillation probability from α to β with oscillation parameters Θ

$$\vec{s} \equiv \{\vec{s}_\Phi, \vec{s}_\sigma, \vec{s}_R\}$$

Cross section for final-state kinematics x_0 with systematic parameters s_σ

Predicted event counts for flavor β in observables x with oscillation parameter Θ and systematic parameters *s*

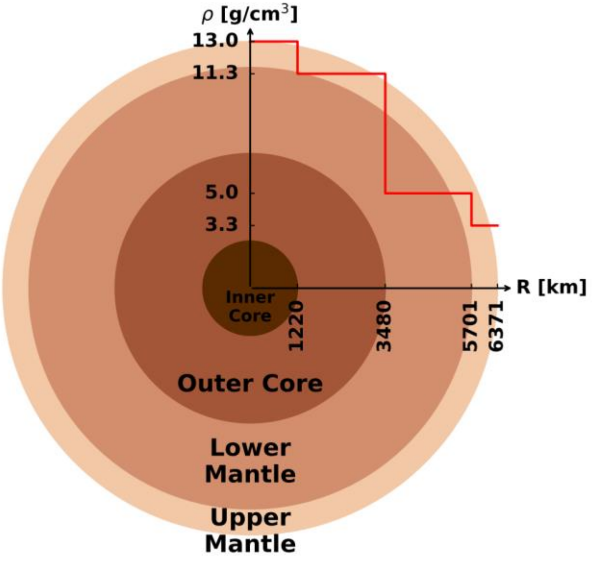
Detector response for x_0 to x with systematic parameters s_R



2. Earth Model

Simplified Earth

$$\rho(r) = \begin{cases} 13.0\,\mathrm{g/cm^3} & \text{if } 0\,\mathrm{km} \le r < 1220\,\mathrm{km} \\ 11.3\,\mathrm{g/cm^3} & \text{if } 1220\,\mathrm{km} \le r < 3480\,\mathrm{km} \\ 5.0\,\mathrm{g/cm^3} & \text{if } 3480\,\mathrm{km} \le r < 5701\,\mathrm{km} \\ 3.3\,\mathrm{g/cm^3} & \text{if } 5701\,\mathrm{km} \le r < 6371\,\mathrm{km} \\ 0\,\mathrm{g/cm^3} & \text{if } r \ge 6371\,\mathrm{km} \end{cases}$$

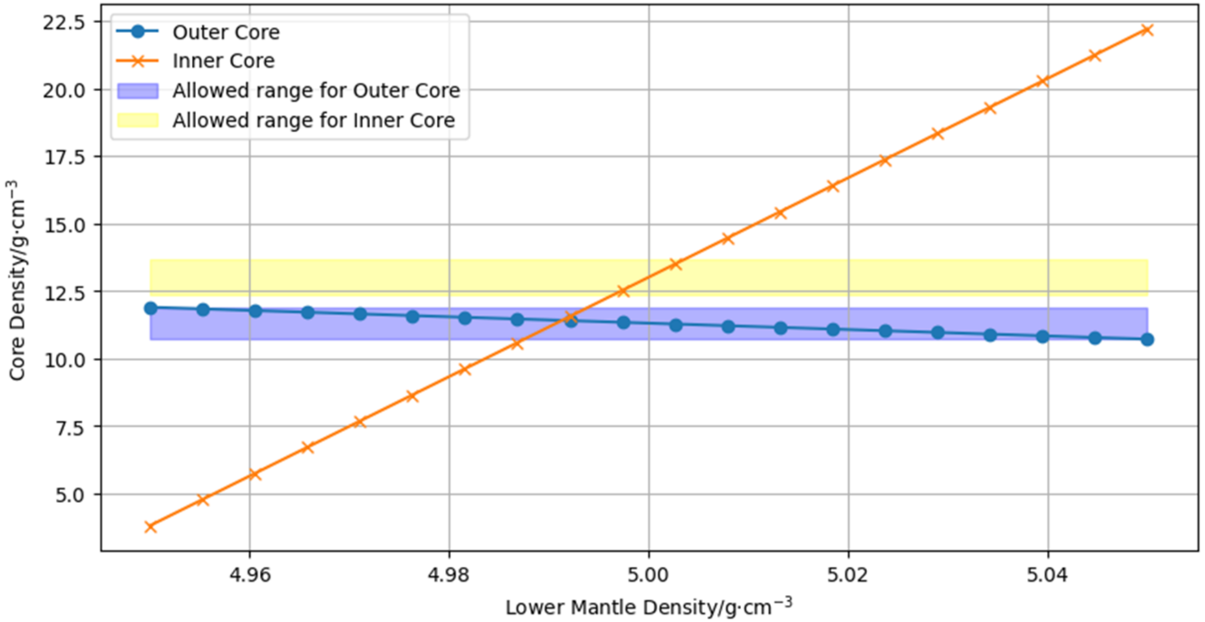


$$\frac{n_e}{n_p + n_n} = 0.497/0.468$$

for electron ratio in Mantle/Core*
(no distinction made inside mantle and core here)

* Bahcall, J. N. and Krastev, P. I. *Phys. Rev. C*, **56(5)** (1997) 2839-2857

Fixing total mass, moment of inertia and upper mantle density



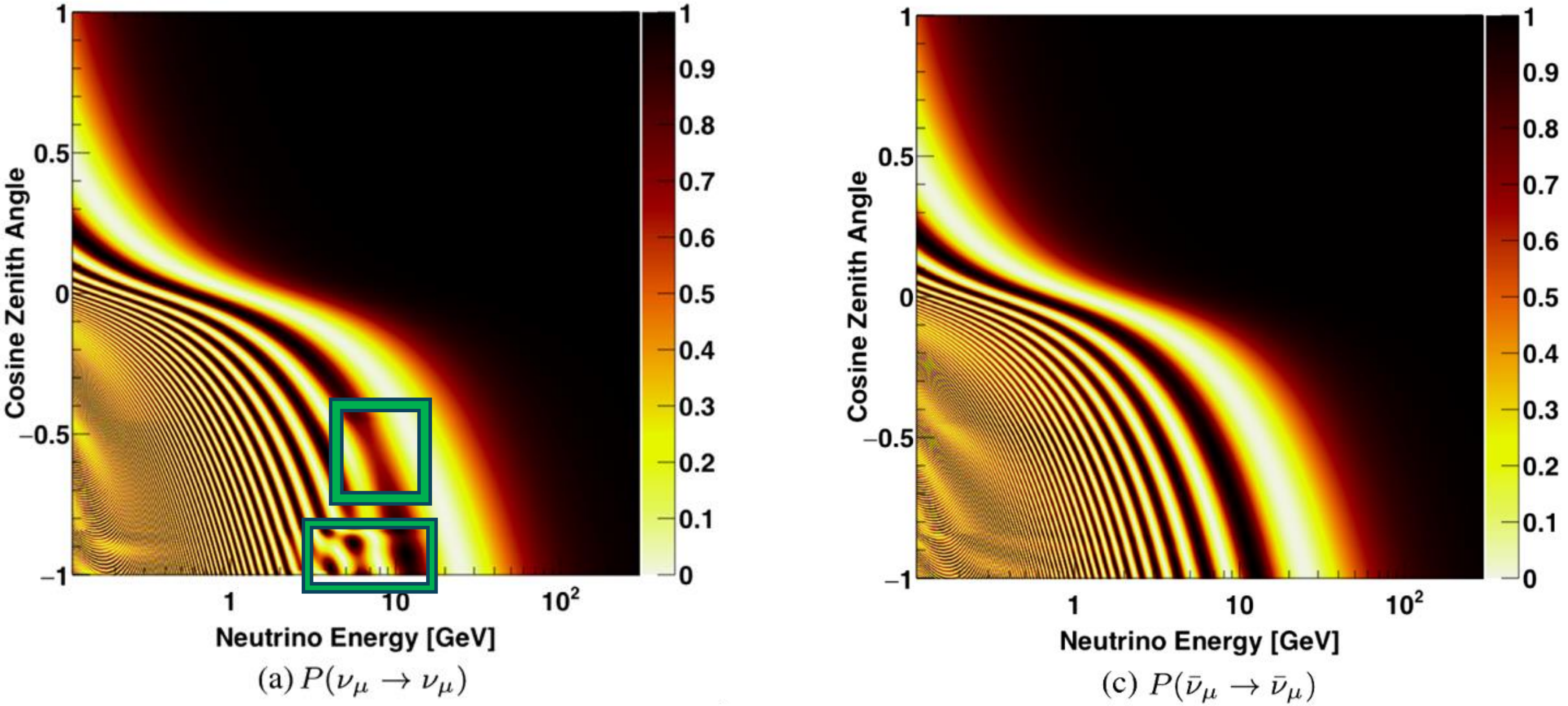
Inner Core density becomes the limiting factor.

Being the smallest mass fraction closest to the rotating axis.

3. Matter Effect

Changes in oscillation probabilities of atmospheric neutrinos as they pass through the Earth, enhancing or suppressing certain flavor transitions depending on the mass ordering. Key to NMO with atmo ν.

Assuming Normal Hierarchy



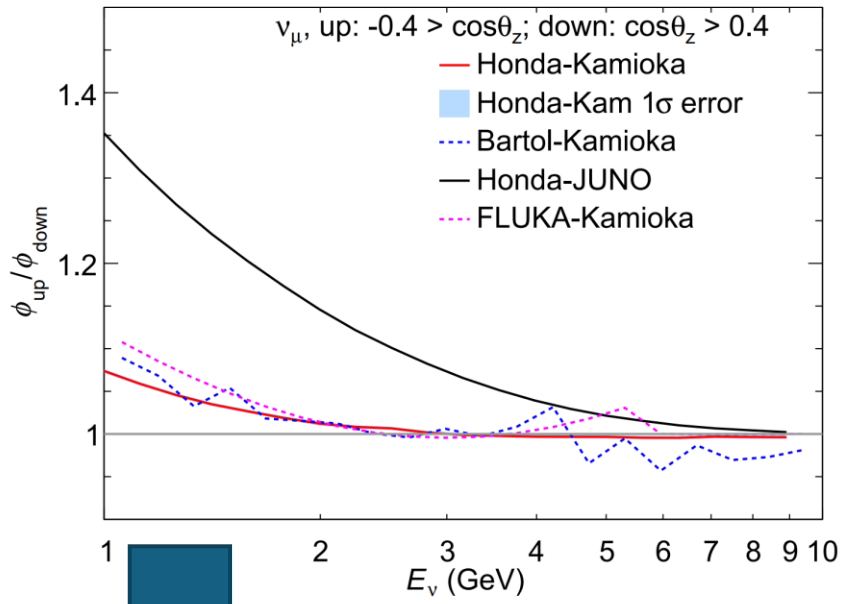
Between ν and $\bar{\nu}$ channels:

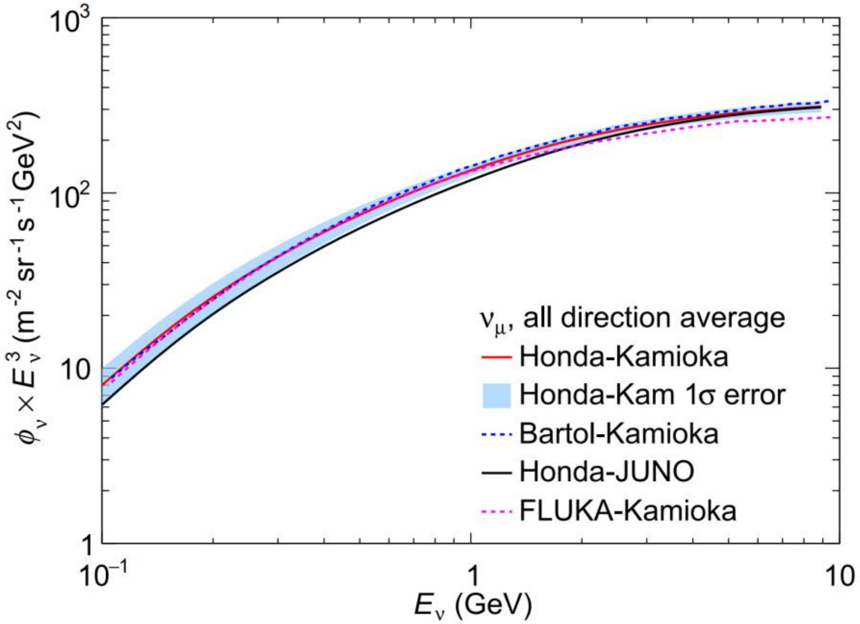
1. Enhancement of ν_e appearance

2. Discontiuity at Core/Mantle boundary

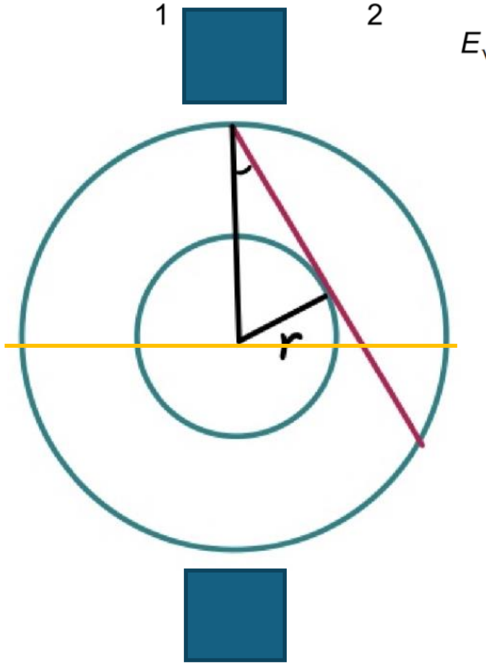
Abe, K., et al, *Phys. Rev. D* **97** (2018) 7, doi:https://doi.org/10.1103/physrevd.97.072001.

4. Flux Comparison





ν_μ shown here



1. Flux Comparison between different models at different sites. Honda, Bartol and FLUKA at Kamioka and Honda at JUNO

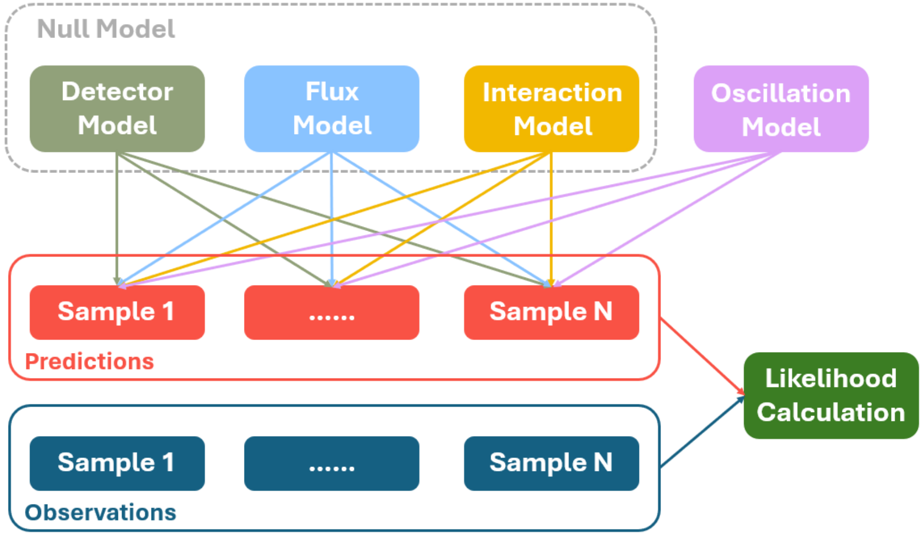
2. For each flavour's spectrum at different incoming directions (vertical, horizontal), flavour ratio (ν_μ/ν_e), Honda-JUNO are within the Super-Kamioka 1σ error range

3. JUNO has a much larger up/down ratio at few GeV range, due to a deficient in down-going flux, caused by geomagnetic effect

VALOR Framework Fitting Procedure

VALOR is a neutrino fitting group established within the T2K experiment in 2010.

It provides a generic, CPU-efficient, and highly flexible oscillation analysis framework. It has been used in the analyses of multiple experiments, including T2K, SBN, DUNE and Hyper-K.



Andreopoulos, C., et.al. "VALOR: Software for Oscillation Analysis." , https://valor-fit.github.io/.

Event Rate Prediction in VALOR

$$n^{pred}_{b;d;s}(r;\vec{\theta};\vec{f}) = \sum_m \sum_t P_{b;d;m}(t;\vec{\theta}) \cdot R_{b;d;s;m}(r,t;\vec{f}) \cdot T_{b;d;s;m}(r,t)$$

Predicted Number of Events

Oscillation Probabilities

Systematic Parameters Variations

Unoscillated Number of Events

- n is defined in reco parameter space
- Physics hypothesis in true space for each configuration, sample and mode
- Systematic response applied to each configuration, sample and mode, in (r, t)
- MC templates map between reco and true information, for each configuration, sample and mode

d: Detector (SBND, JUNO)
b: Beam configuration (FHC, RHC, JUNO Atmo)
s: Event sample (ν_μ CC 0π)
m: True reaction mode (ν_μ CCQE)
r: Multi-dim. Reco kinematic bin ({$E_{\nu,\ reco}$, θ_{reco}})
t: Multi-dim. True kinematic bin ({$E_{\nu,\ true}$, θ_{true}})
$\vec{\theta}$: Physics parameter set
$\vec{f}$: Systematics parameter set

6. Summary and Future Works

1. Earth model and flux systematics summed up in technotes and are being reviewed

2. VALOR-JUNO under development, adding atmospheric experiment functions and JUNO specific settings

3. To constrain flux and cross section with down-going neutrino data at JUNO

Thank You

Backups

Matter Effect

Time evolution of neutrino flavour state in vacuum, in natural units

$$i\frac{\partial\psi}{\partial t} = H_F\psi \quad \text{where} \quad H_F = \frac{1}{2E}UMU^\dagger$$

$$M = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix}$$

In matter, $UMU^\dagger$ modified as

$$UMU^\dagger \pm \begin{pmatrix} 2E\sqrt{2}G_F N_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

minus sign and h.c. for anti-neutrinos

G_F for Fermi constant, N_e for electron density

Diagnolised to find eigenvalues and eigenvectors.

The normalised eigenvectors of the modified $UMU^\dagger$ form the columns of the effective mixing matrix

For E in a few GeV range, assuming $|m_2^2 - m_1^2| \ll |m_3^2 - m_{1,2}^2|$

We have

$$\mathrm{P}(\nu_\mu \to \nu_e) = \mathrm{P}(\nu_e \to \nu_\mu) = \sin^2\theta_{23}\sin^2 2\theta_{13}^M \sin^2\left(\frac{1.27\Delta m_M^2 L}{E}\right)$$

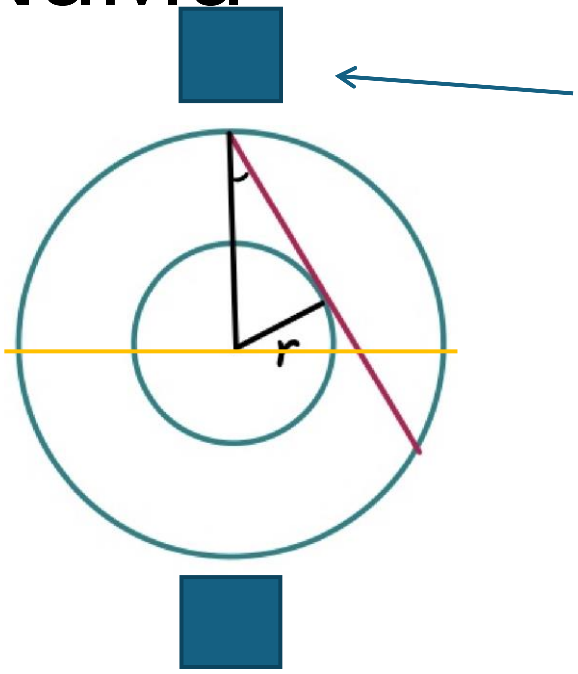
with modified values in matter

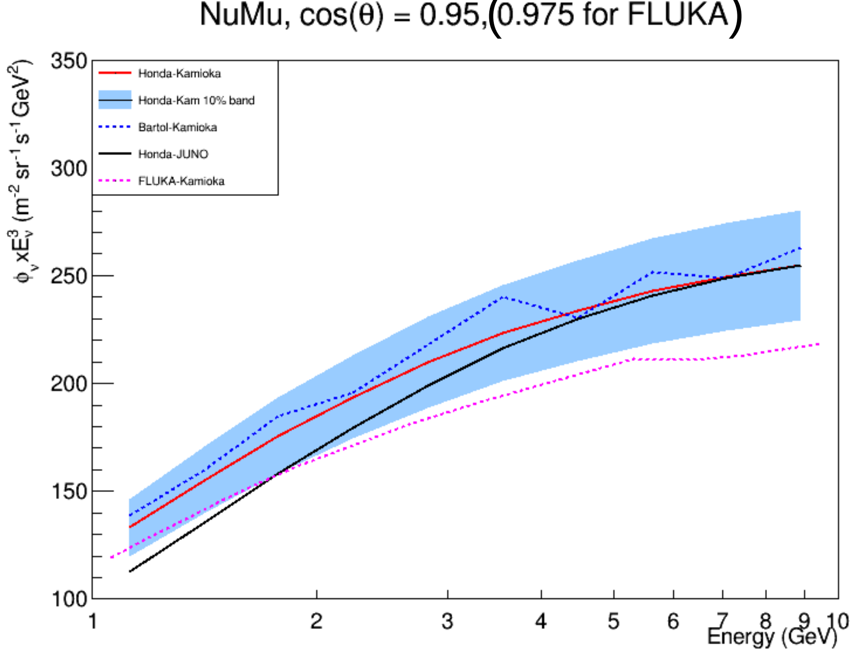
$$\sin^2 2\theta_{13}^M = \frac{\sin^2 2\theta_{13}}{\left(\cos 2\theta_{13} \mp \frac{2\sqrt{2}G_F N_e E}{\Delta m^2}\right)^2 + \sin^2 2\theta_{13}}$$

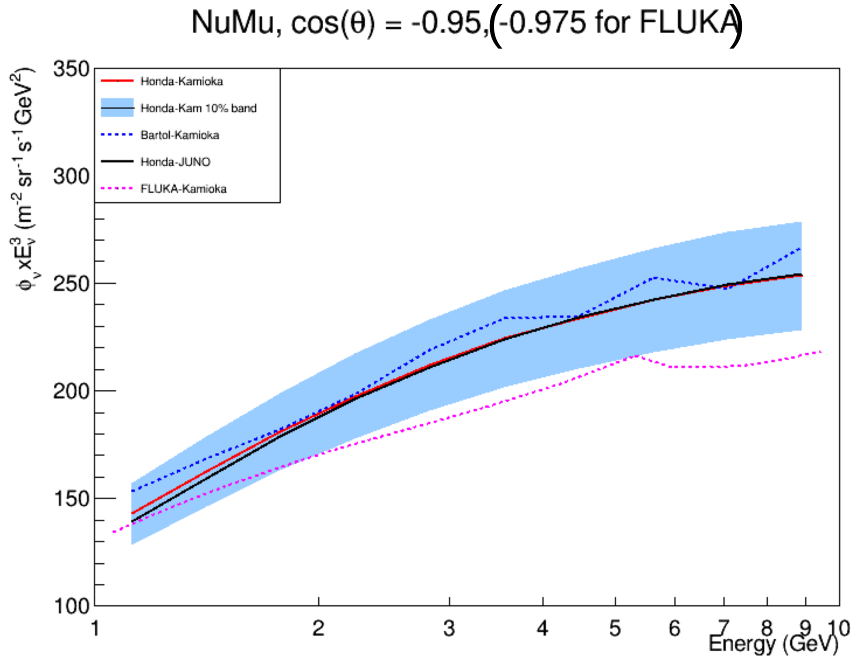
$$\frac{\Delta m_M^2}{\Delta m^2} = \sqrt{\left(1 \mp \frac{2\sqrt{2}G_F N_e E}{\Delta m^2 \cos 2\theta_{13}}\right)^2 \cos^2 2\theta_{13} + \sin^2 2\theta_{13}}$$

minus sign for NH, such that when θ_{13}^M is increased, ν_e appearance is enhanced

NuMu



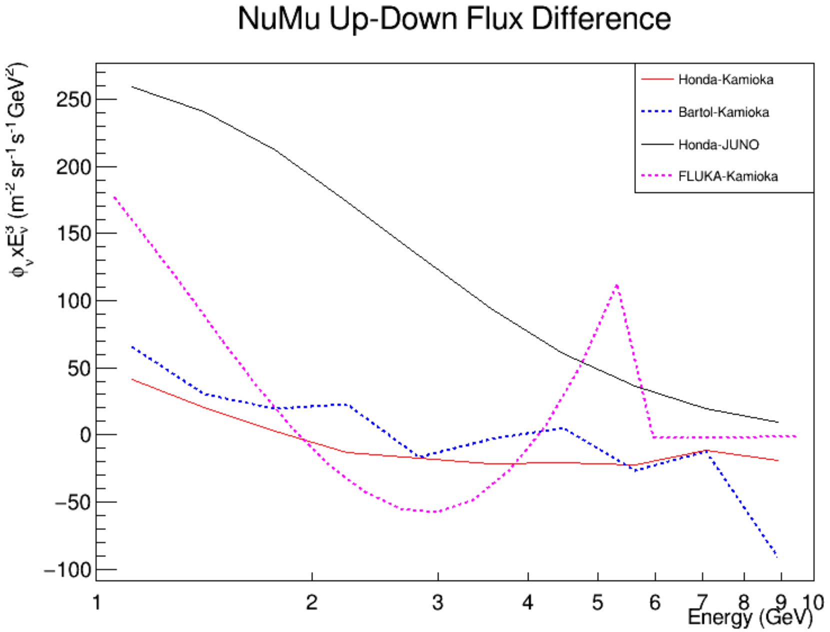


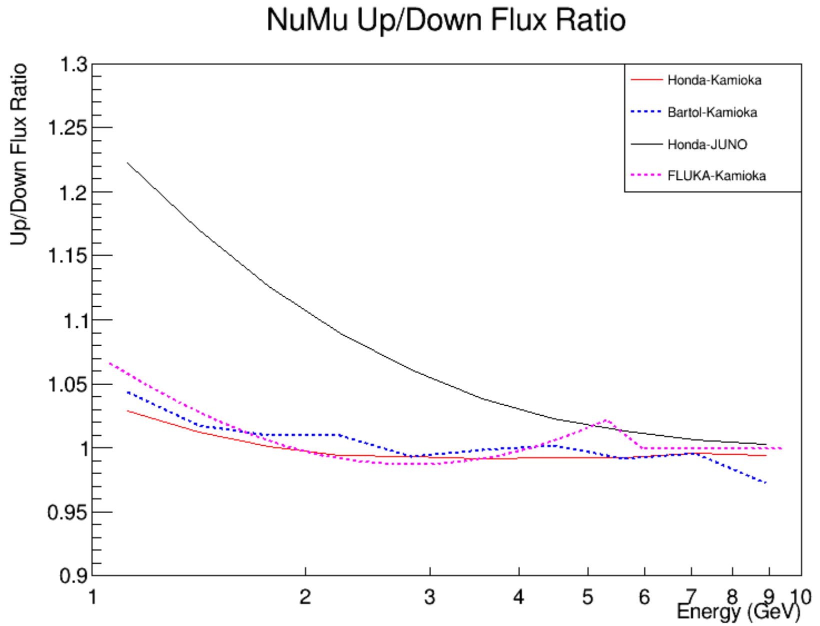


Up-going: sum of flux bins with cos(z)<0

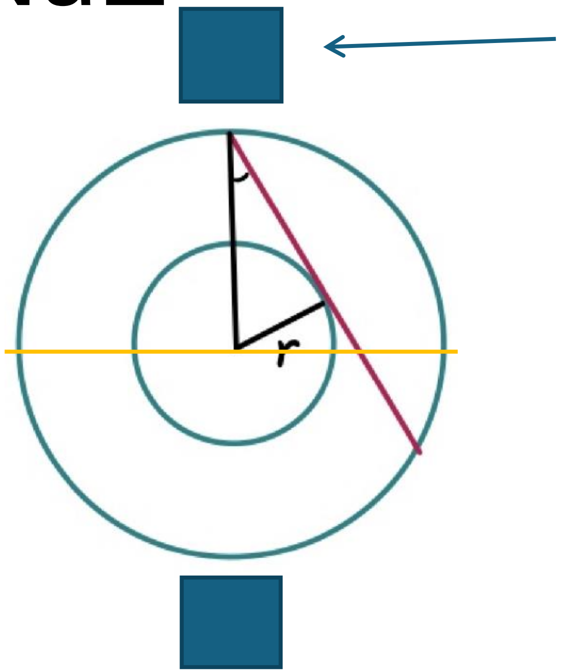
Down-going: sum of flux bins with cos(z)>0

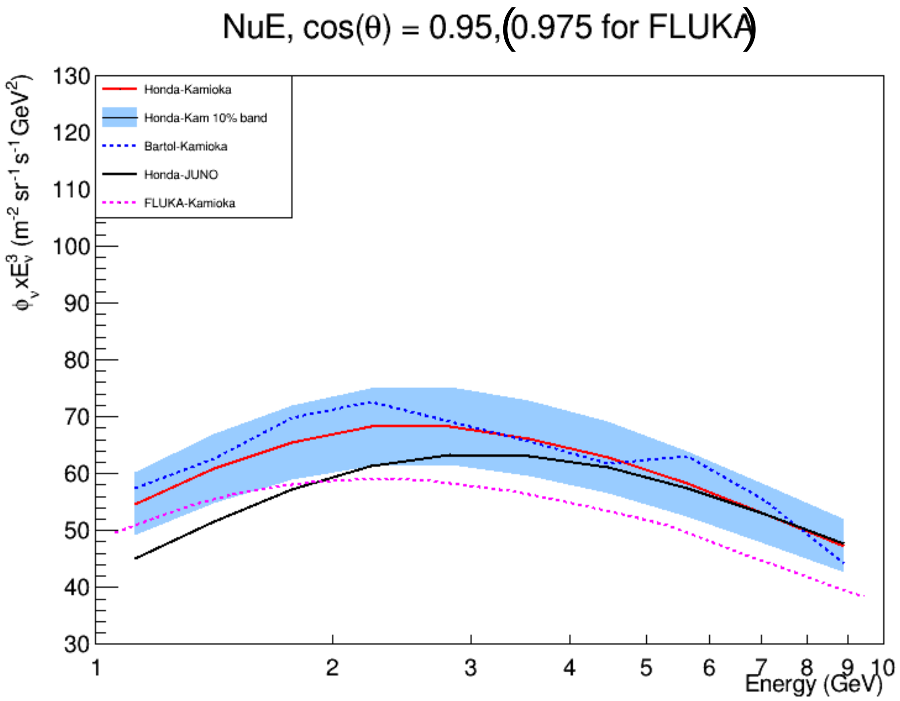
cos(θ)=0.95 for Honda and Bartol; =0.975 for FLUKA

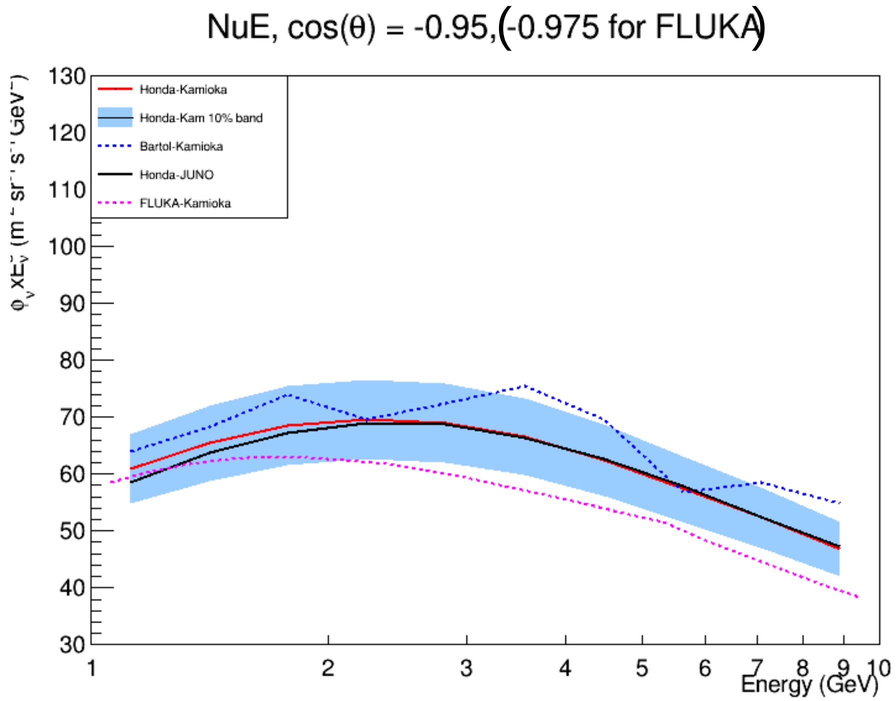




NuE







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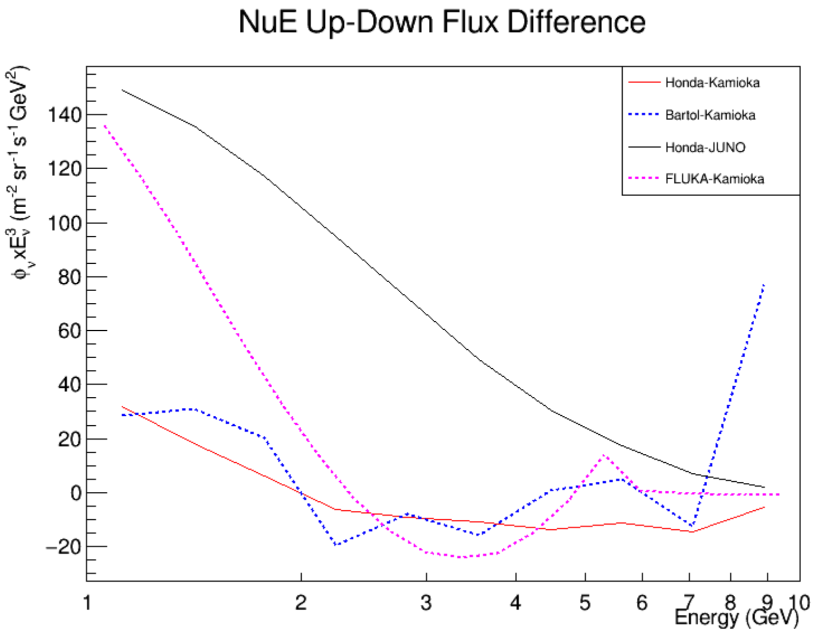

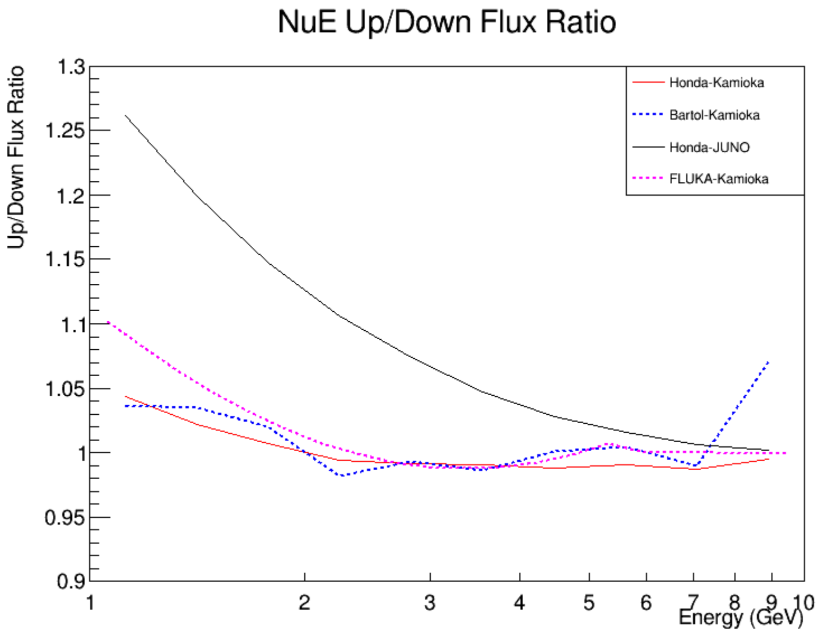

Binned Likelihood

$$\chi^2 = -2\ln\mathcal{L}(\vec{\theta};\vec{f}) = -2\ln\mathcal{L}_0(\vec{\theta};\vec{f}) - 2\ln\mathcal{L}_{phys}(\vec{\theta}) - 2\ln\mathcal{L}_{syst}(\vec{f})$$

$$\chi_0^2 = -2\ln\mathcal{L}_0(\vec{\theta};\vec{f}) = 2\sum_{b,d,s,r}\left(n_{b;d;s}^{\mathrm{data}}(r)\cdot\ln\frac{n_{\mathrm{b;d;s}}^{data}(r)}{n_{b;d;s}^{pred}(r;\vec{\theta};\vec{f})} + (n_{b;d;s}^{\mathrm{pred}}(r;\vec{\theta};\vec{f}) - n_{b;d;s}^{\mathrm{data}}(r))\right)$$

1. Poisson likelihood, n constructed in reco parameter space, for each beam, detector configuration and each sample

2. Penalty terms due to prior physics and systematics constraints

3. Pure statistical χ^2 results checked among analyzers within the collaboration, assuming perfect detector

d: Detector (SBND, JUNO)
b: Beam configuration (FHC, RHC, JUNO Atmo)
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$\vec{\theta}$: Physics parameter set
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