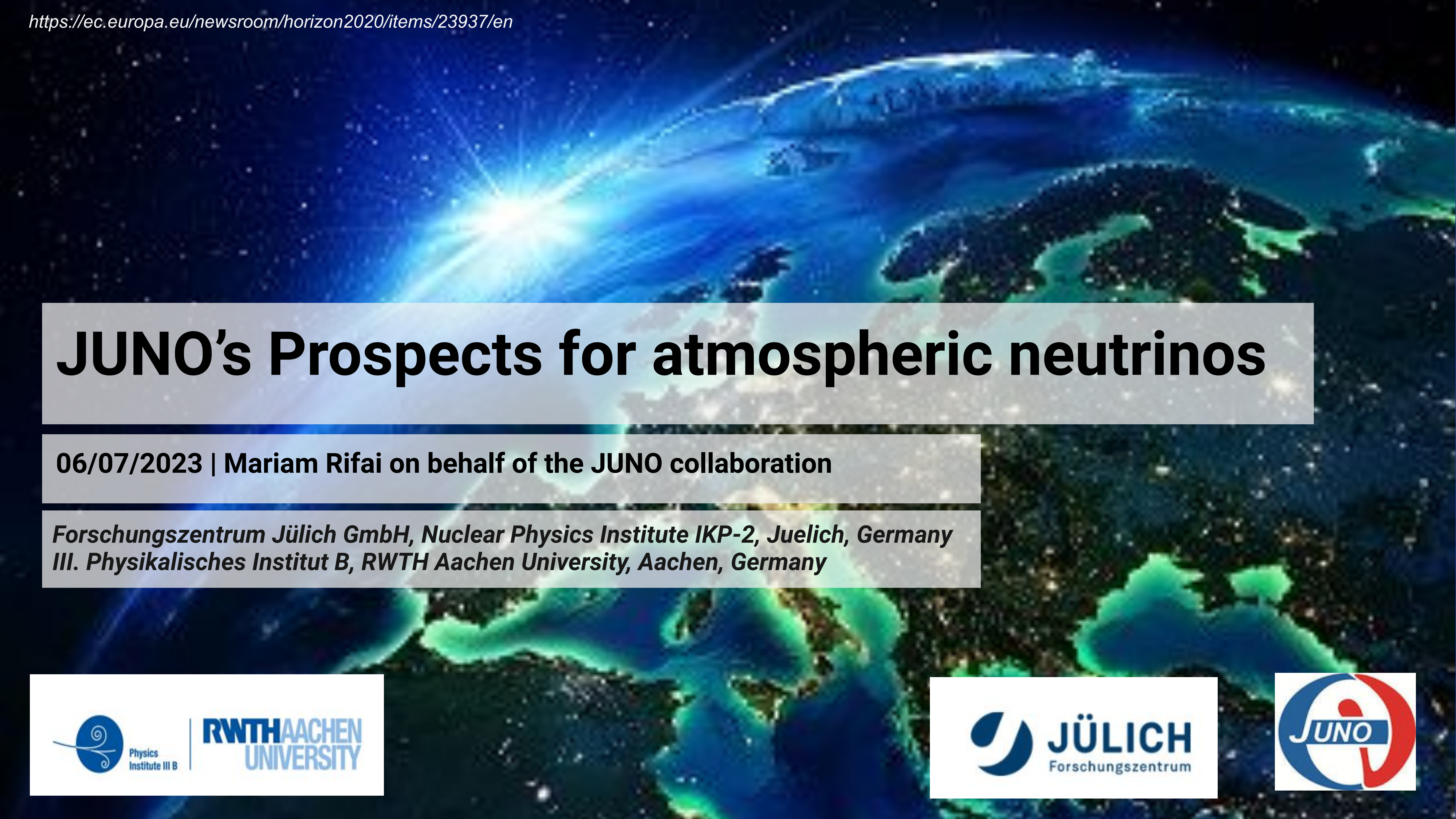

https://ec.europa.eu/newsroom/horizon2020/items/23937/en

JUNO’s Prospects for atmospheric neutrinos

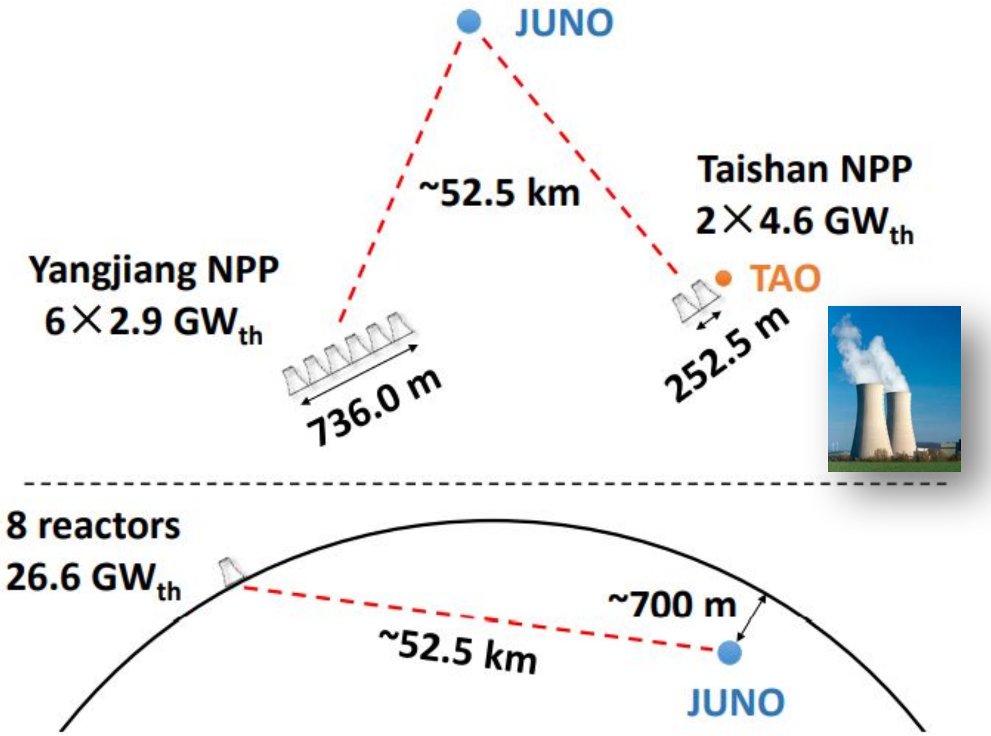
06/07/2023 | Mariam Rifai on behalf of the JUNO collaboration

Forschungszentrum Jülich GmbH, Nuclear Physics Institute IKP-2, Juelich, Germany
III. Physikalisches Institut B, RWTH Aachen University, Aachen, Germany

Jiangmen Underground Neutrino Observatory:

JUNO is the first multi-kton liquid scintillator (LS) detector ever built, located in China.

Main goal: determination of the Neutrino Mass Ordering (NMO), 3σ in 6 years with reactor neutrinos



47 anti-ν_e /day after suppressing the cosmogenic backgrounds

vacuum oscillation pattern independent of δcp and θ_{23}

(matter effect contributes maximal ~4% correction at around 3 MeV, *arXiv:1605.00900, arXiv:1910.12900*)

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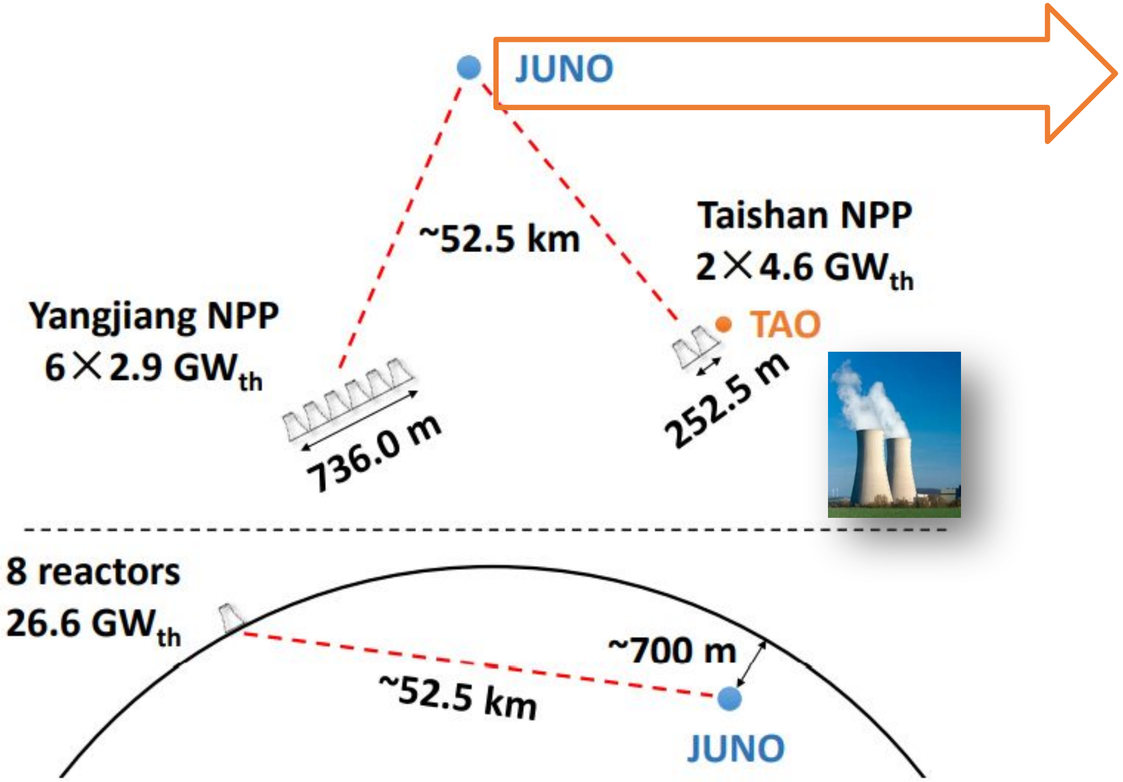

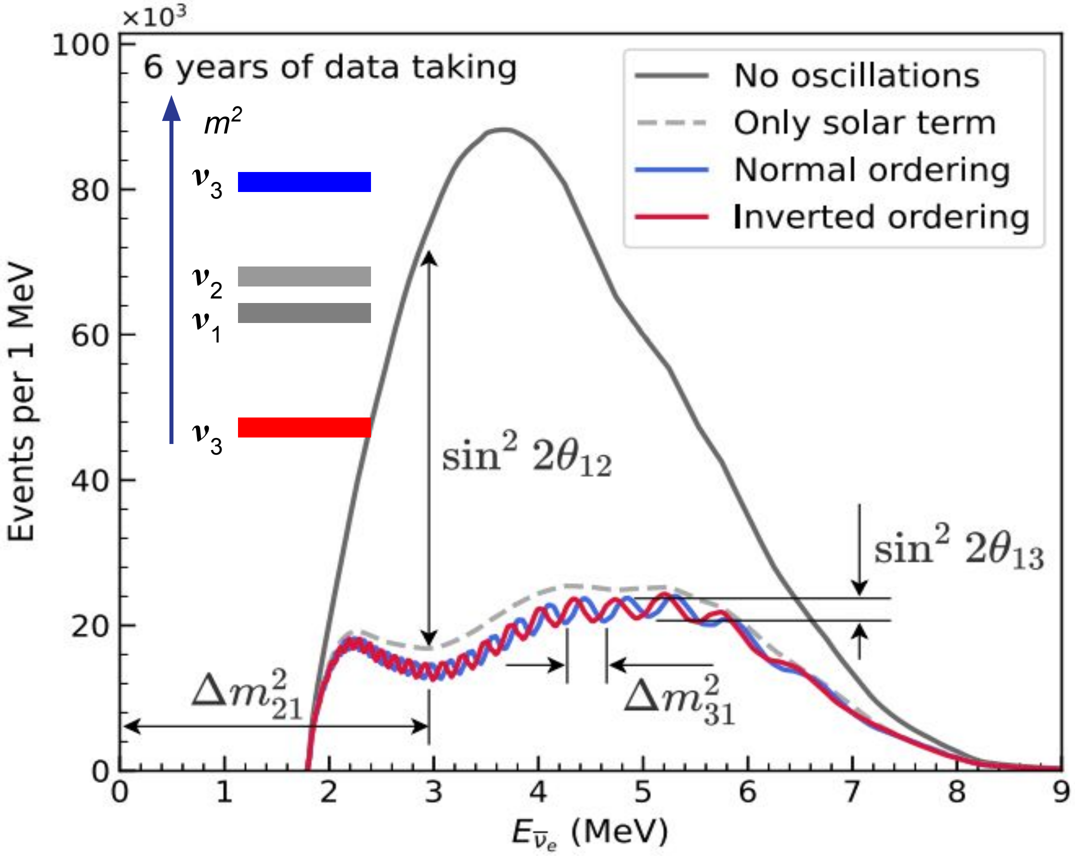

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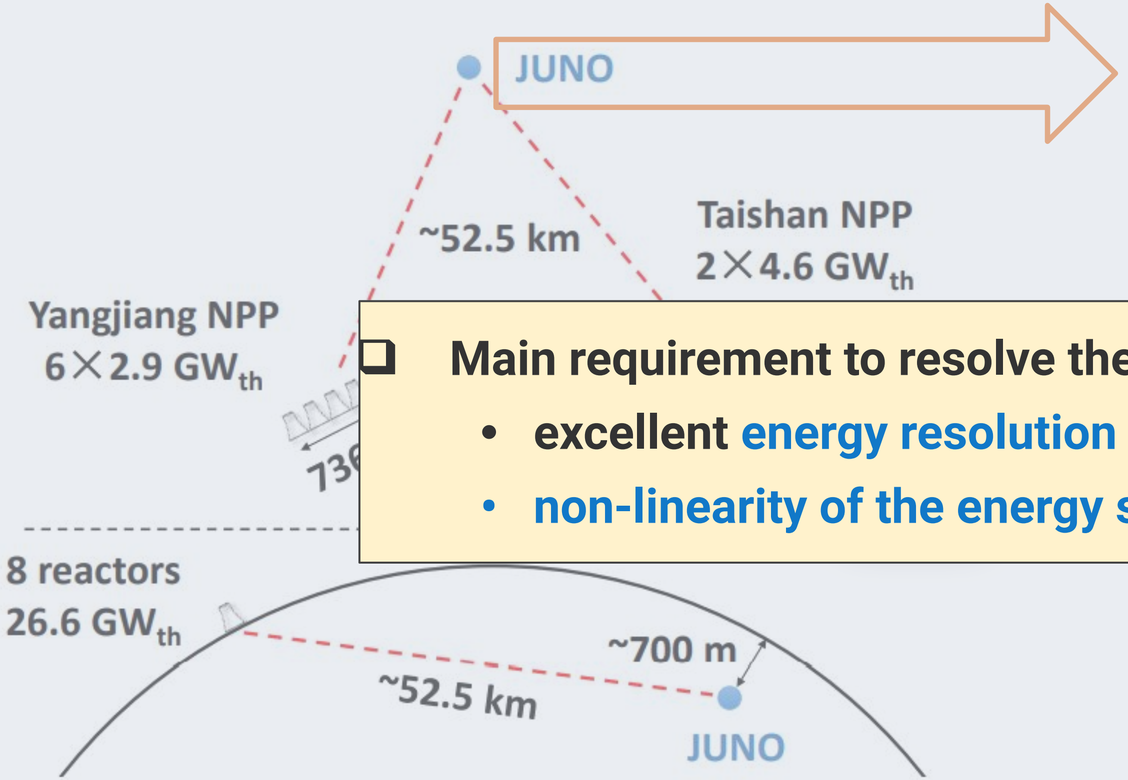
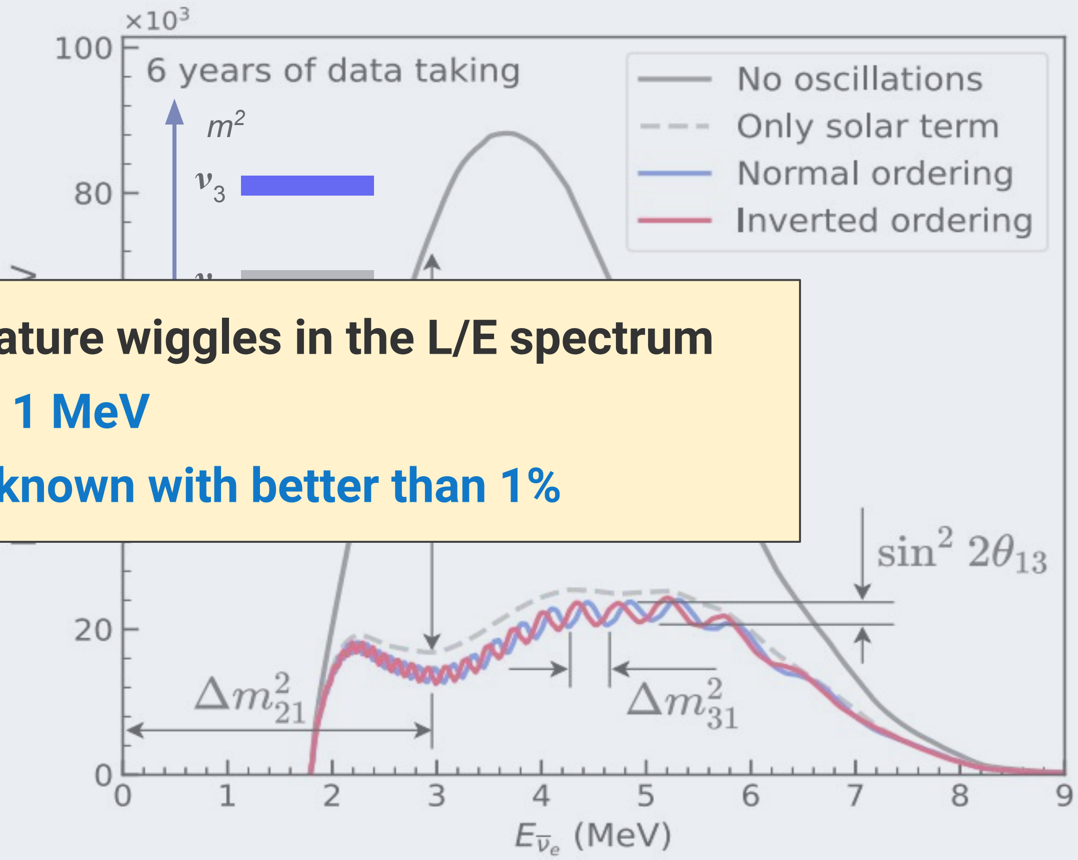


- ❑ **Main requirement to resolve the signature wiggles in the L/E spectrum**
  - **excellent energy resolution 3% @ 1 MeV**
  - **non-linearity of the energy scale known with better than 1%**



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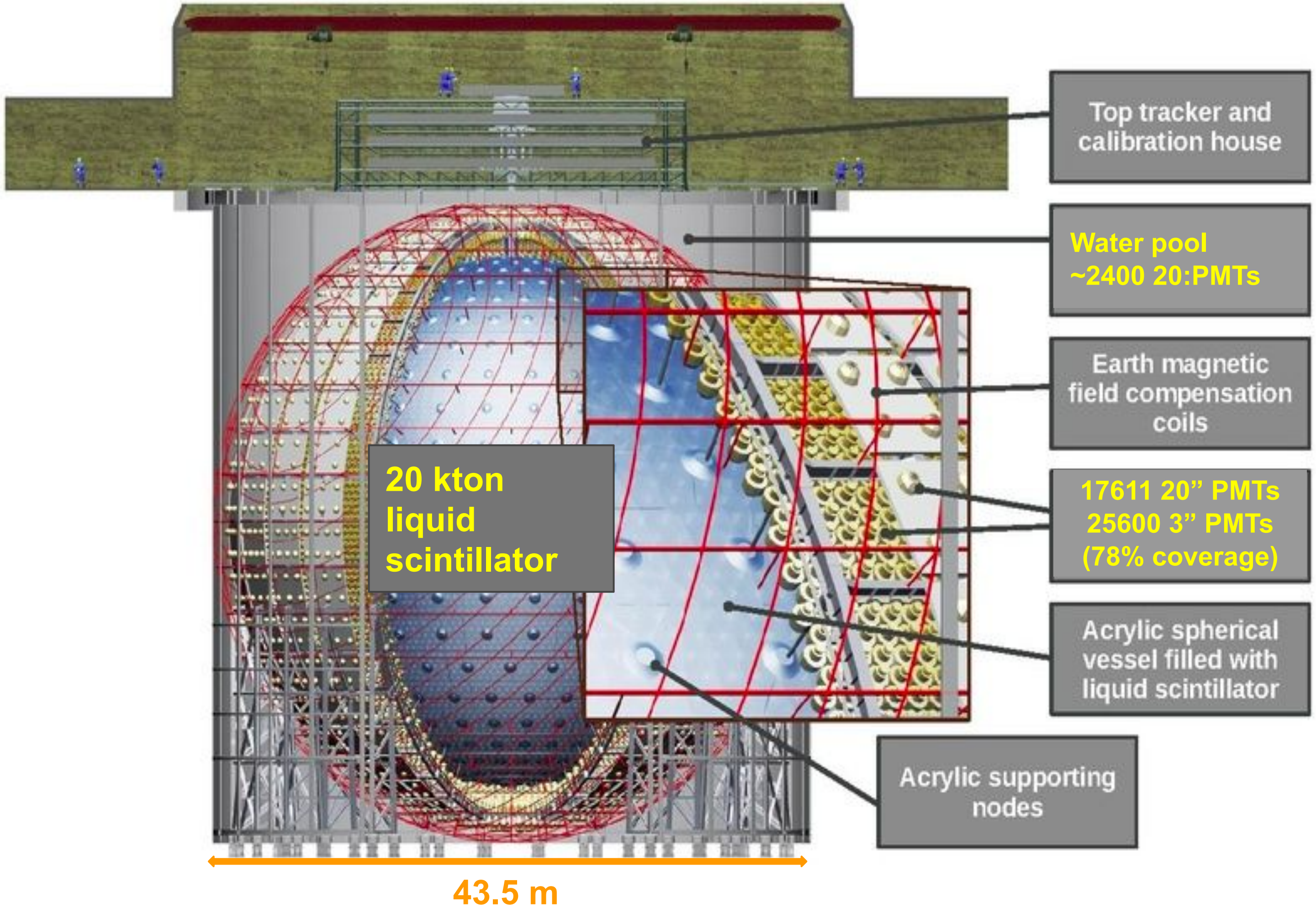
JUNO Detector



Top tracker and calibration house

Water pool
~2400 20:PMTs

Earth magnetic field compensation coils

17611 20” PMTs
25600 3” PMTs
(78% coverage)

Acrylic spherical vessel filled with liquid scintillator

Acrylic supporting nodes

20 kton liquid scintillator

43.5 m

20-inch and 3-inch PMTs interleaving

Large 20-inch PMTs

- large coverage (75%)
- high dark rate
- non-linearity at higher energies
- waveforms -> multiple hits with charge

Small 3-inch PMTs

- small coverage (3%)
- small dark rate, smaller non-linearity
- photon counting (no waveform)
- higher effective dynamic range

Reduce systematics using the 2 independent PMT systems

Physics Potential of JUNO

See Yury Malyshkin's talk

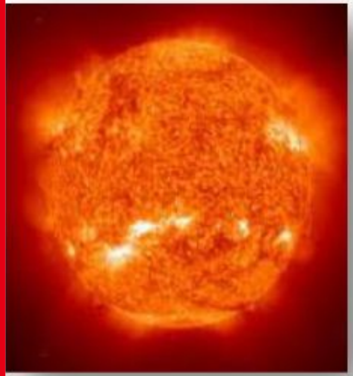
Reactor anti-ν

~47/day

Atmospheric ν

Several / day

Solar ν



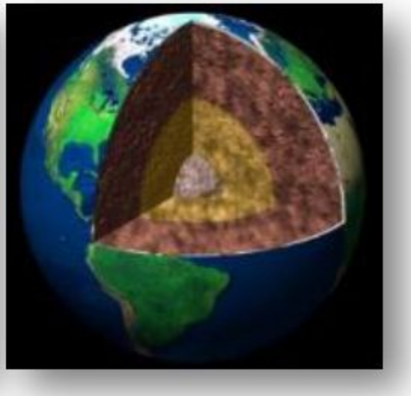
^{8}B: ~50/day
CNO: ~1000/day
^{7}Be: ~10000/day

Supernovae (SN) ν

Core Collapse SN
@ 10 kpc:
thousands in few sec.

Diffuse SN signal:
few / year

Geoneutrinos



~400 / year

\+

New physics

Proton decay

Neutrino magnetic moment

Sterile neutrinos

Non standard interactions

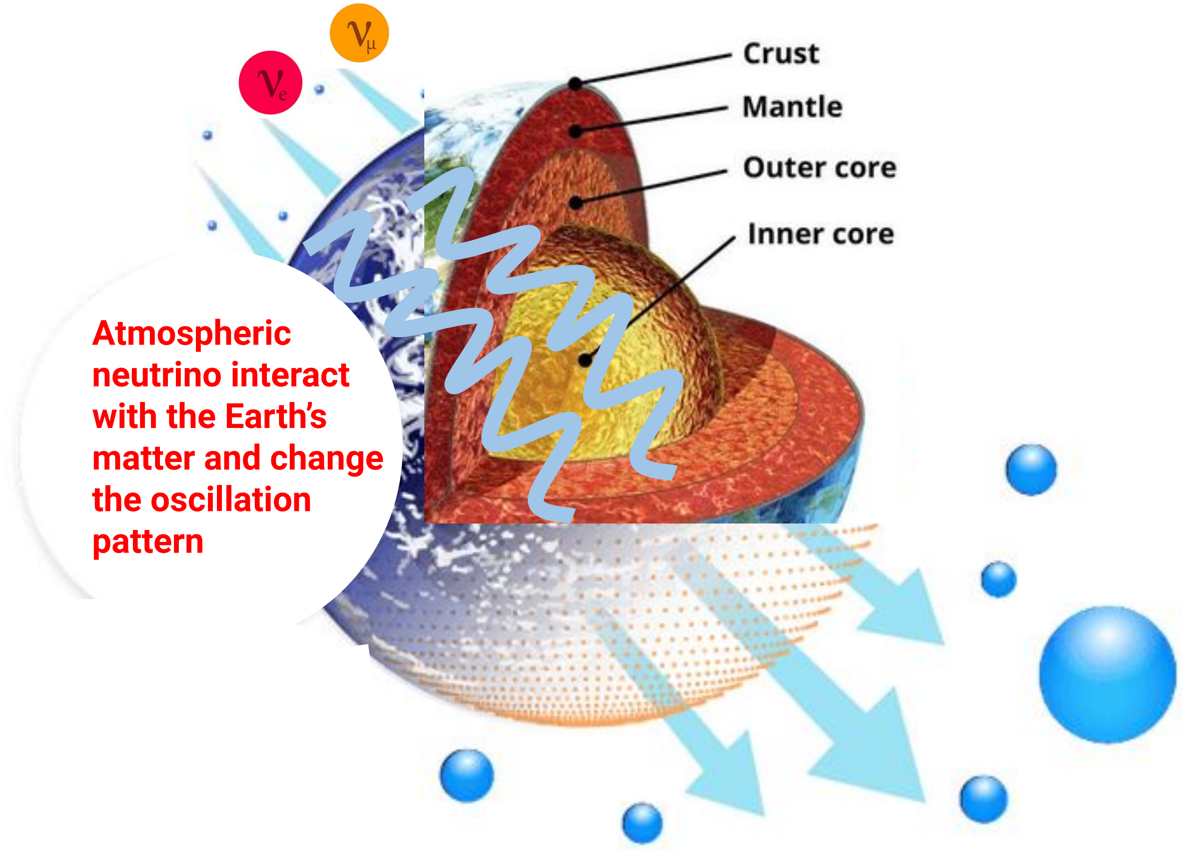
Lorentz invariance

Others

- *A. Abusleme et al., JUNO physics and detector, Progr. Part. Nucl. Ph. 123 (2022) 103927*
- *A. Abusleme et al., JUNO sensitivity to 7Be, pep, and CNO solar neutrinos, submitted to Journal of Cosmology and Astroparticle Physics*
- *A. Abusleme et al., JUNO Sensitivity on Proton Decay* $p\to\bar{\nu}K^+$ *Searches, submitted to Chin. Phys. C.*
- *J. Zhao et al., Model Independent Approach of the JUNO B8 Solar Neutrino Program, submitted to APJ.*
- *A. Abusleme et al., Prospects for Detecting the Diffuse Supernova Neutrino Background with JUNO, J. Cos. Astro. Phys. 10 (2022) 033.*
- *A. Abusleme et al., JUNO sensitivity to low energy atmospheric neutrino spectra, Eur. Phys. J. C 81 (2021) 887.*
- *Fengpeng An et al, Neutrino physics with JUNO ,2016 J. Phys. G: Nucl. Part. Phys. 43 030401*

Atmospheric Neutrinos … Matter effects

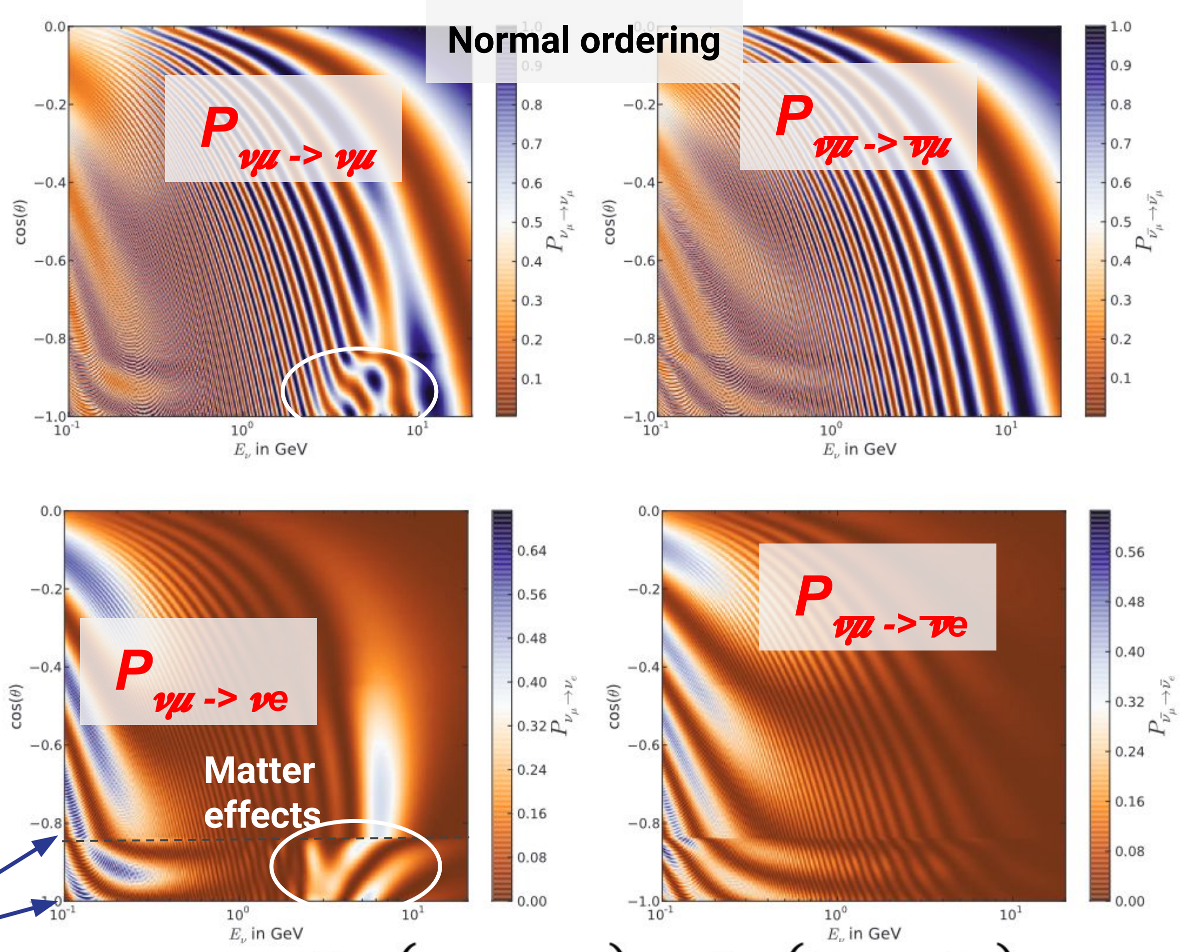
Oscillation probabilities in matter depends on **neutrino energy *E*** and **electron density *N*$_e$ in matter**



Atmospheric neutrino interact with the Earth's matter and change the oscillation pattern

https://www-sk.icrr.u-tokyo.ac.jp/en/sk/neutrino/about/

Neutrino physics with JUNO,J. Phys. G43:030401 (2016)



Sensitivity region to NMO:

- E~ [3, 10] GeV
- cos θ [-1, -0.8]

$$P_{NO}(\nu_\alpha \to \nu_\beta) \approx P_{IO}(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

Atmospheric Neutrinos analysis in JUNO

- Key Features:
    - 15 events/day [100 MeV - 15 GeV]
    - Large JUNO detector mass: 20 kton with 43.5 central detector diameter
        - Detect fully contained atmospheric events up to 15 GeV
    - Effective light yield: ~10^4 photons per MeV of electron energy scale equivalent
    - Attenuation length: >20 m @ 430 nm
    - Excellent energy resolution
    - Reduction of systematics thanks to the dual PMTs system.
- Precise measurements towards the low energy region which is still not covered by water Cherenkov experiments
    - Data for improvement of the current theoretical model
- JUNO detector will allow to investigate the neutrino neutrino mass ordering and the θ_{23} octant.

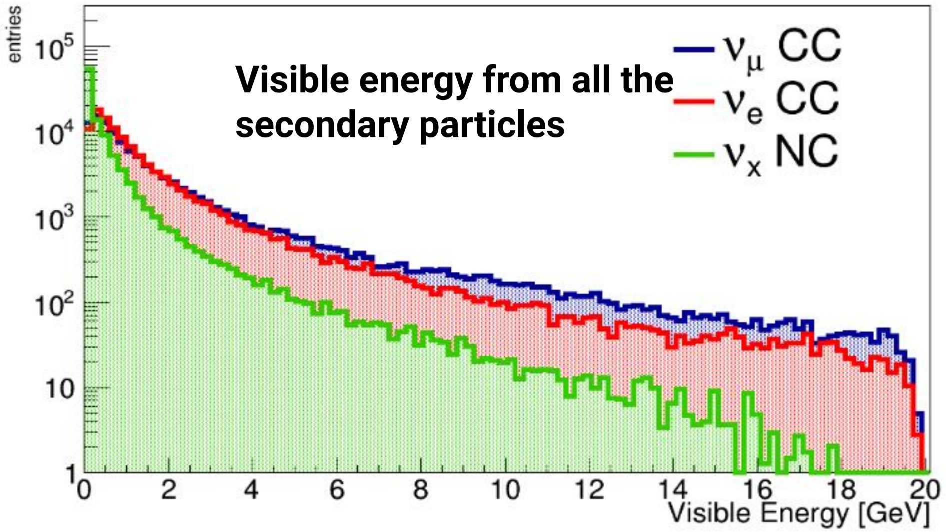
Published results

- Measurement of energy spectra and flavor identification based on MC simulation
    - *A. Abusleme et al., JUNO sensitivity to low energy atmospheric neutrino spectra, Eur. Phys. J. C 81 (2021) 887.*
- Sensitivity to neutrino mass ordering based on toy MC analysis
    - *Fengpeng An et al, Neutrino physics with JUNO ,2016 J. Phys. G: Nucl. Part. Phys. 43 030401*

A. Abusleme et al., JUNO sensitivity to low energy atmospheric neutrino spectra, Eur. Phys. J. C 81 (2021) 887.

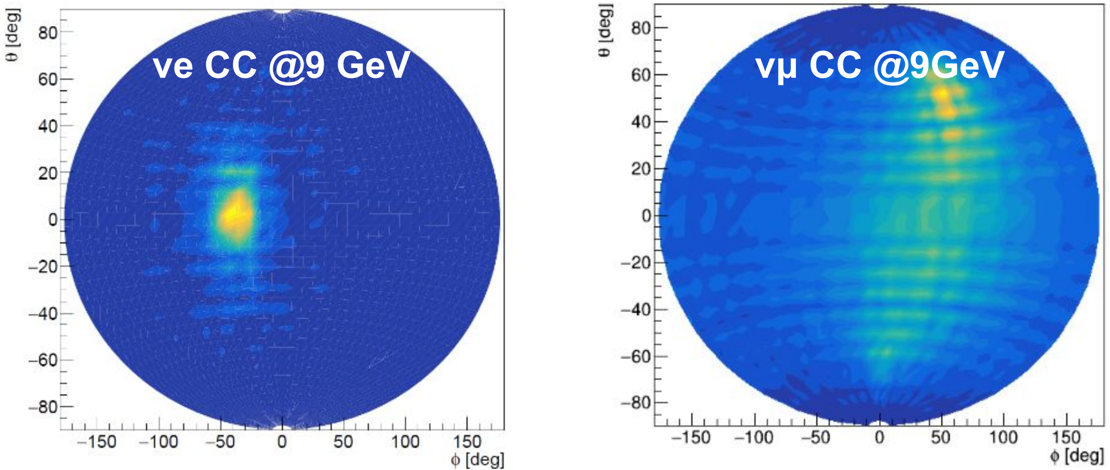
Geant4 detector simulation for energy spectra and flavor identification (e/mu)

1. **Neutrino interaction generation inside the detector:**
   - Energy range: 100MeV - 20 GeV
   - Statistics: ~ 5y ve + vμ (and antineutrinos)
   - Flux model: Honda Model (HKKM14)
   - Software: GENIE Neutrino Monte Carlo Generator
1. **Propagation of secondary particles**
   - **GEANT4 detector simulation**
2. **Oscillation effects included (vacuum + matter)**



Visible energy from all the secondary particles

Atmospheric neutrinos interacting inside JUNO can produce different final states.



Hitmap on 3″ PMT system

A. Abusleme et al., JUNO sensitivity to low energy atmospheric neutrino spectra, Eur. Phys. J. C 81 (2021) 887.

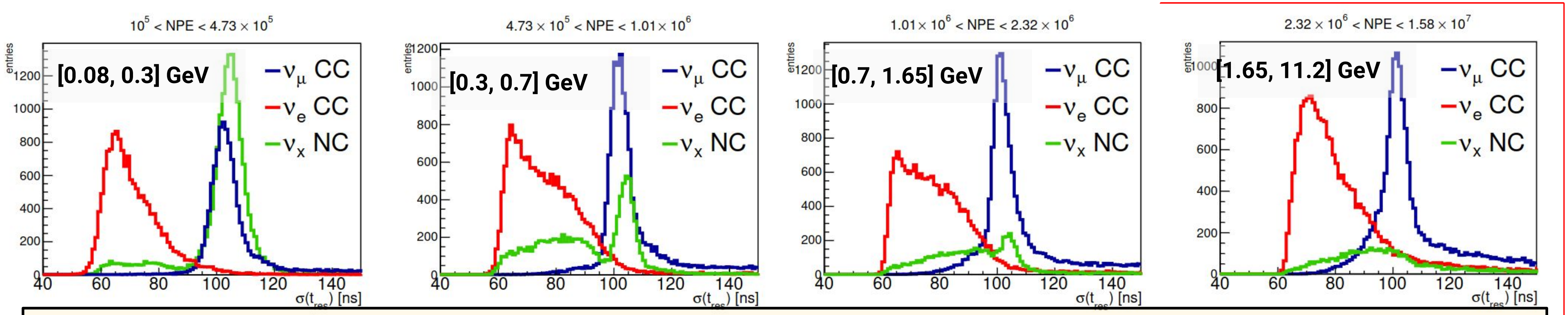
Flavor Identification: $\nu\mu$ and νe

- **$\nu\mu$ CC interaction: event elongated in time** because of μ ability to travel long distances and its late decay
- **νe CC interaction:** point-like event because of the **short e track**
- **NC interaction:** geometry of event depends on the particles produced

the time residual t_{res}, defined for each photo-electron (PE) on 3” PMT system, is a strongly flavor-dependent.

Flavor Identification based on t_{res} calculation, performed for different charge cut selection (NPE).

Relevant for the sensitivity region

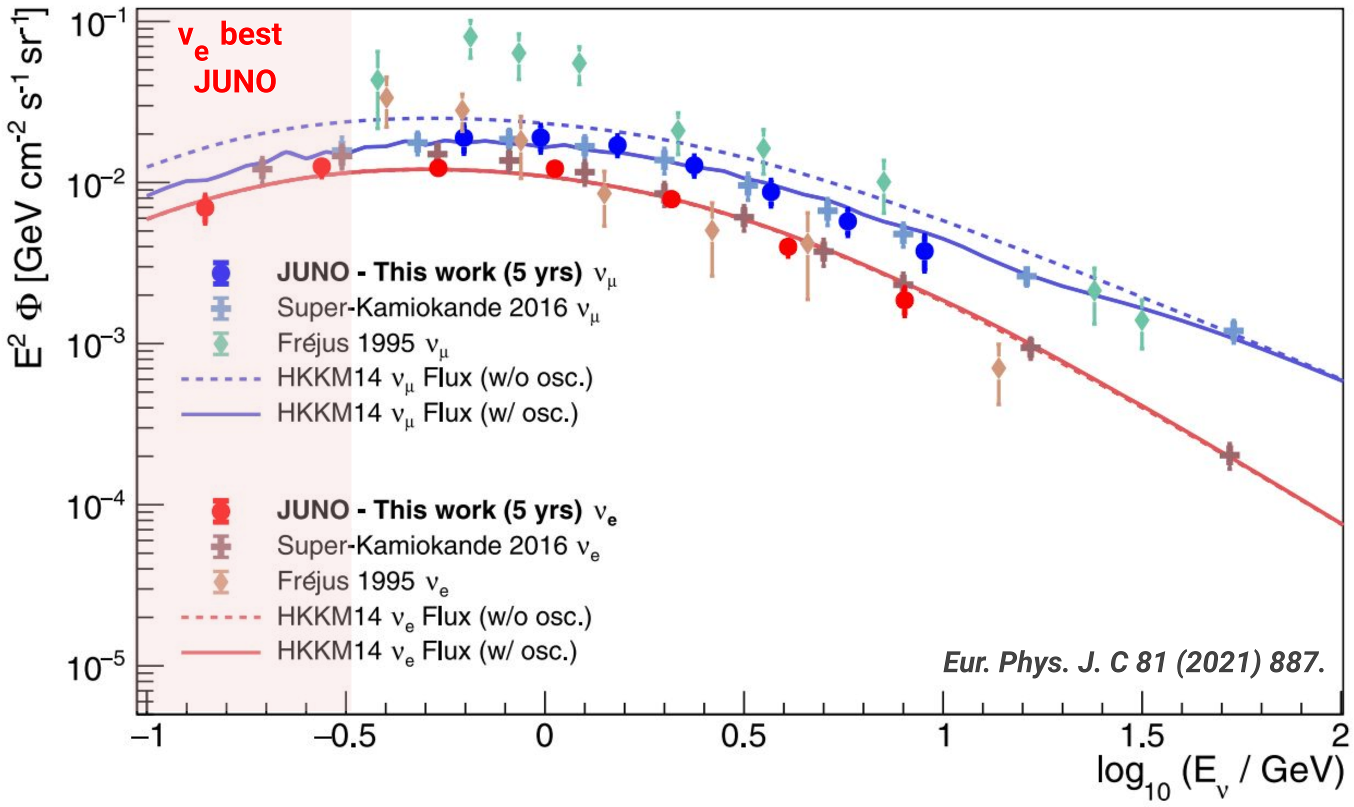


JUNO is able to distinguish between the different neutrino flavors (νe from 0.1 GeV $\nu\mu$ from 0.3 GeV up 11.2 GeV) and interaction types (CC and NC).

A. Abusleme et al., JUNO sensitivity to low energy atmospheric neutrino spectra, Eur. Phys. J. C 81 (2021) 887.

Atmospheric Neutrino Energy Spectra in JUNO

Energy range for: ν_e [0.1, 11.2] and ν_μ [0.3, 11.2] GeV divided in 7 bins.



Eur. Phys. J. C 81 (2021) 887.

Based on unfolding probabilistic method:

$$\boxed{P(E)^{\nu_\alpha}} = P(E|NPE)^{\nu_\alpha} \cdot \boxed{P(NPE)^{\nu_\alpha}} \qquad \alpha = e,\mu$$

Unfolded spectrum **Detector observable**

NPE: number of photo-electron detected by 20” PMTs

Atm. energy spectrum based on Geant4 detector simulation

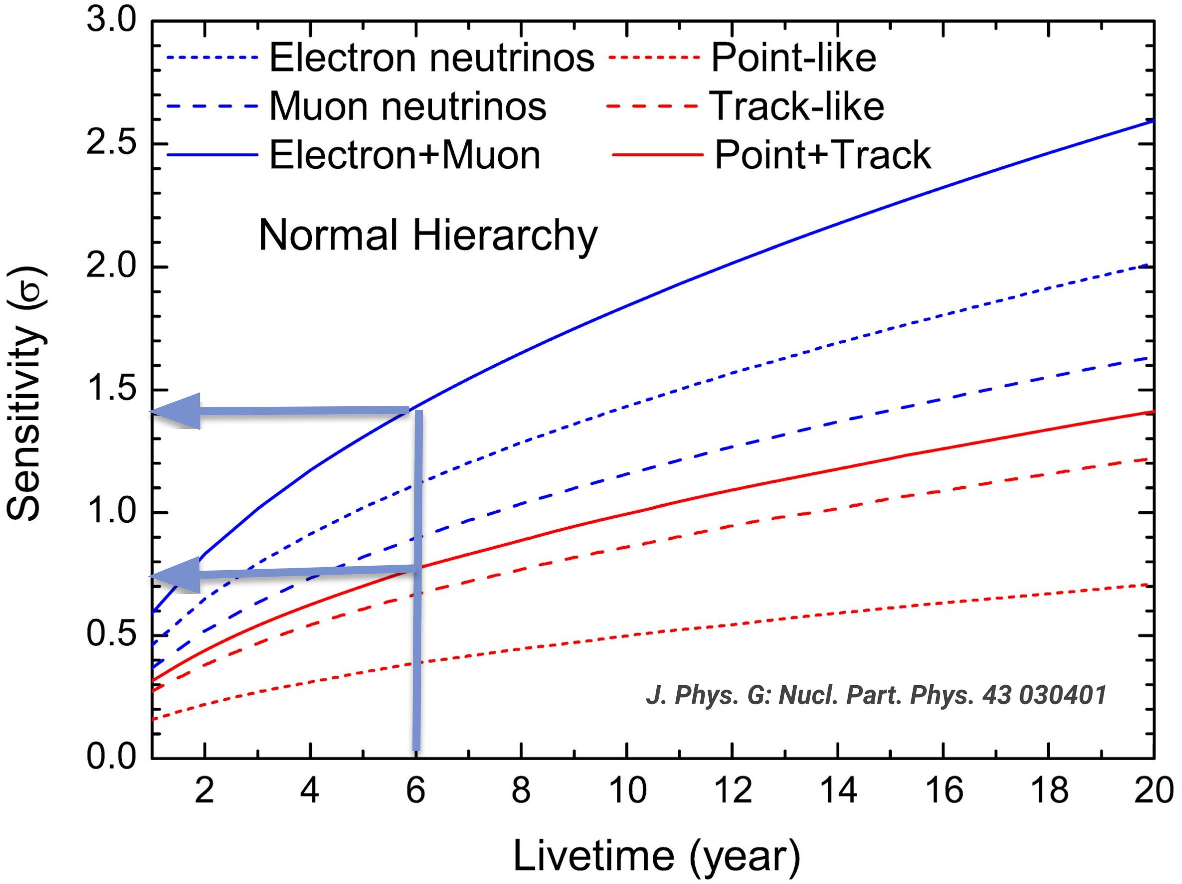
Energy spectrum can be measured within a 25% uncertainty in 5 yrs of detector lifetime.

Fengpeng An et al, Neutrino physics with JUNO ,2016 J. Phys. G: Nucl. Part. Phys. 43 030401

Sensitivity to neutrino mass ordering (NMO)

"statistical only"

“Toy MC analysis (work-in-progress)”



JUNO sensitivity on NMO:
0.75 ~1.4 σ (atmospheric only) @ ~6 yrs exposure, based on toy MC simulation.

- **To be combined with the 3σ in 6 yrs with reactor neutrinos**

Current Analysis!

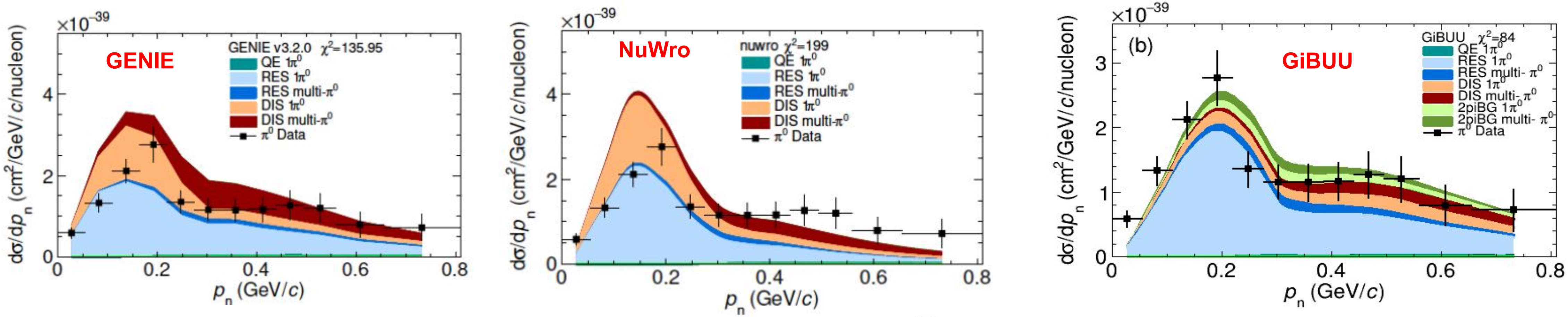
1. Considering different neutrino generator models: GENIE, NuWro, GiBUU
2. Developing further reconstruction techniques for energy and directionality
3. Flavor identification based on machine learning approach

Neutrino Interaction Model in LS

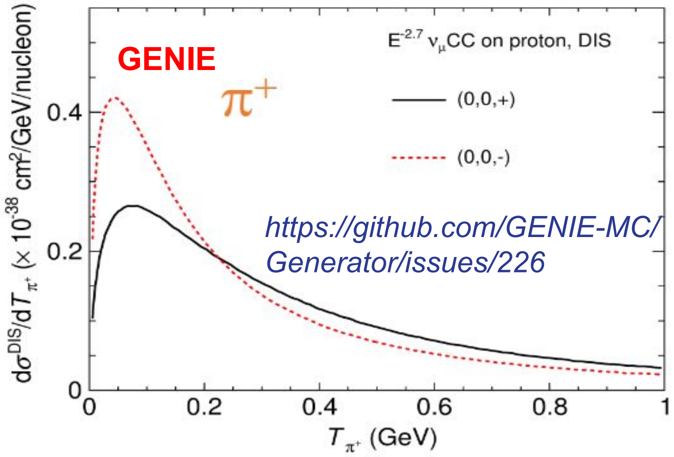
DOI: 10.5281/zenodo.6774990

To check reconstruction robustness and estimate systematic uncertainties, different generators (GENIE, NuWro, and GiBUU) is being implemented in JUNO.

1. **Validation physics** w.r.t to transverse Kinematic imbalance



Cross sections in p_n from previous MINERvA measurement compared to the different neutrino generator models.
Channel: Neutrino-Induced Charged-Current Neutral Pion CC$\boldsymbol{\pi}^0$



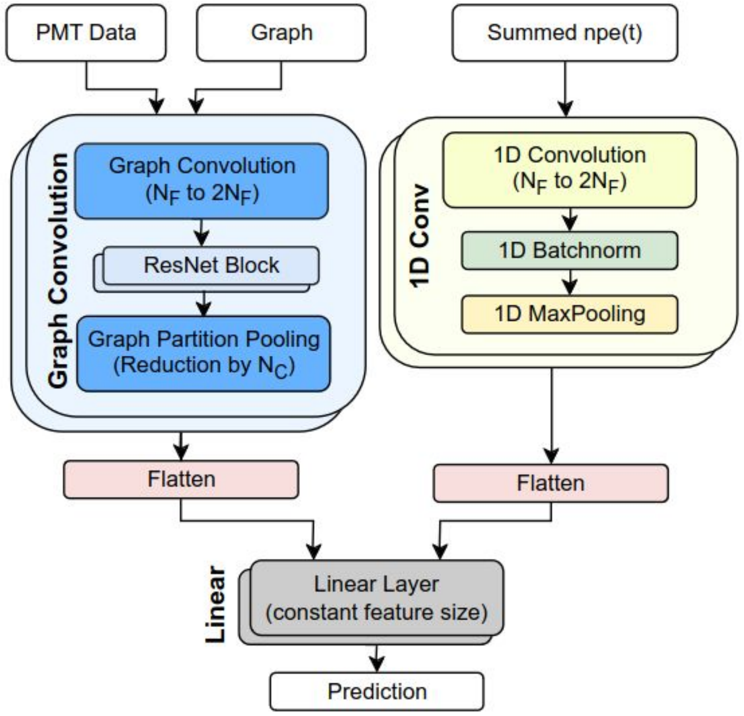
https://github.com/GENIE-MC/Generator/issues/226

2. **Improving generator:** fixing GENIE AGKYLowW (DIS) and aka directionality bug

Energy Reconstruction: Graph Convolutional Network

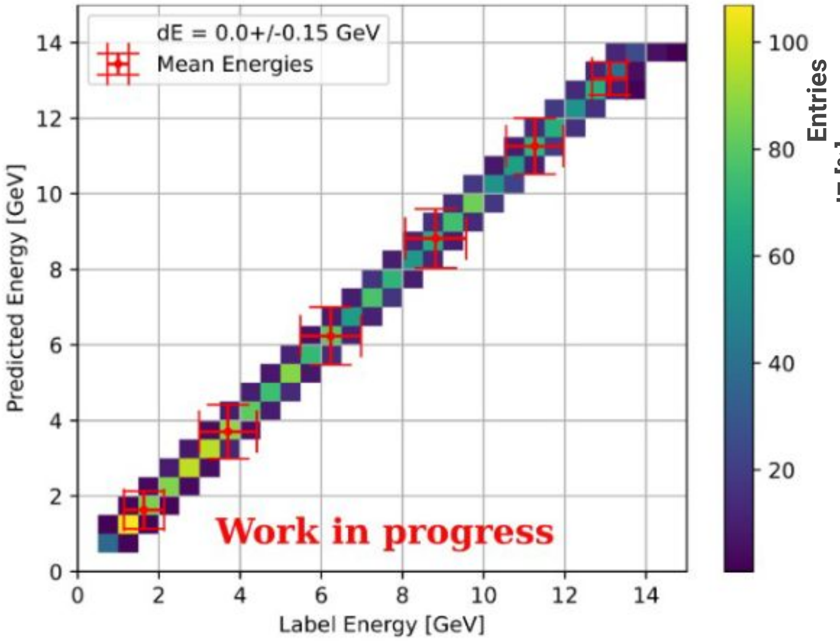
DOI: 10.5281/zenodo.6804861

Idea: Use convolution on charge (npe) detected by PMTs and on detector surface to reconstruct the energy of charged current atmospheric neutrino events.

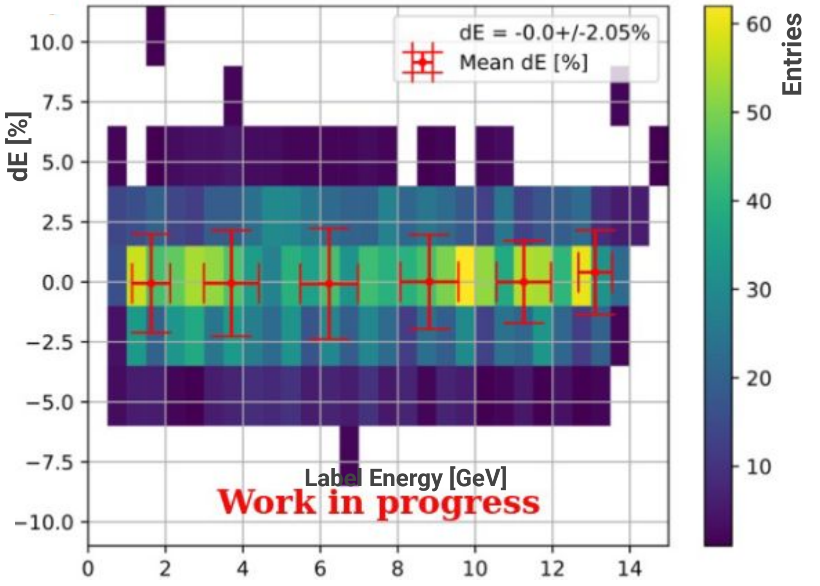


Inputs:

- "Graph": first hit time and total number of photo-electron detected per large PMT
- "test data": summed of number of photo-electron over time per Event



Reconstructed energy vs MC visible energy.

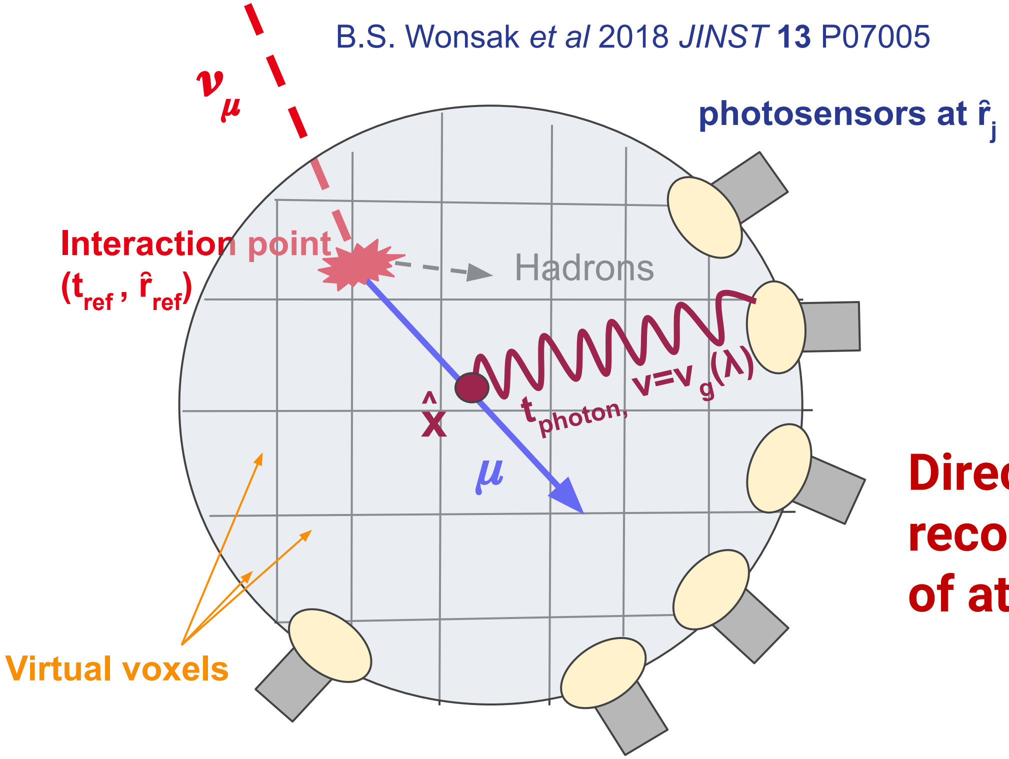


$$dE\,[\%] = \frac{(E_{label} - E_{prediction})}{E_{label}} \cdot 100$$

No bias and ~2% energy resolution.

Directionality: **topological reconstruction**

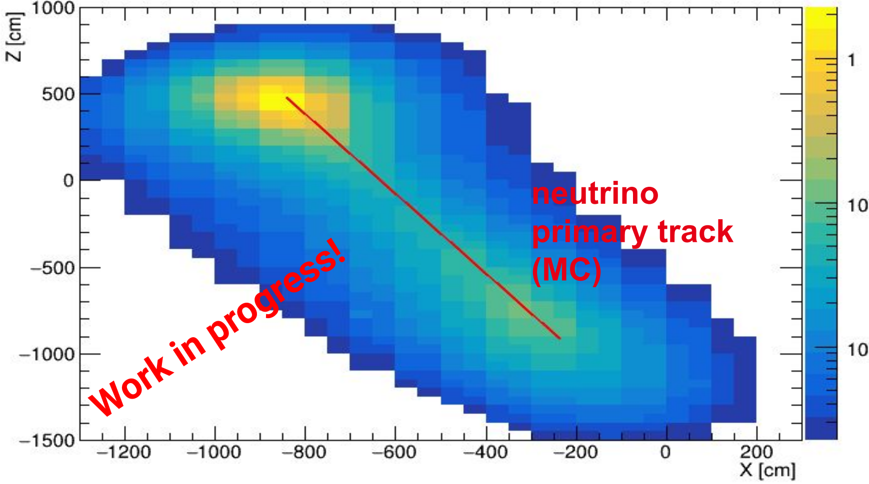
B.S. Wonsak *et al* 2018 *JINST* **13** P07005



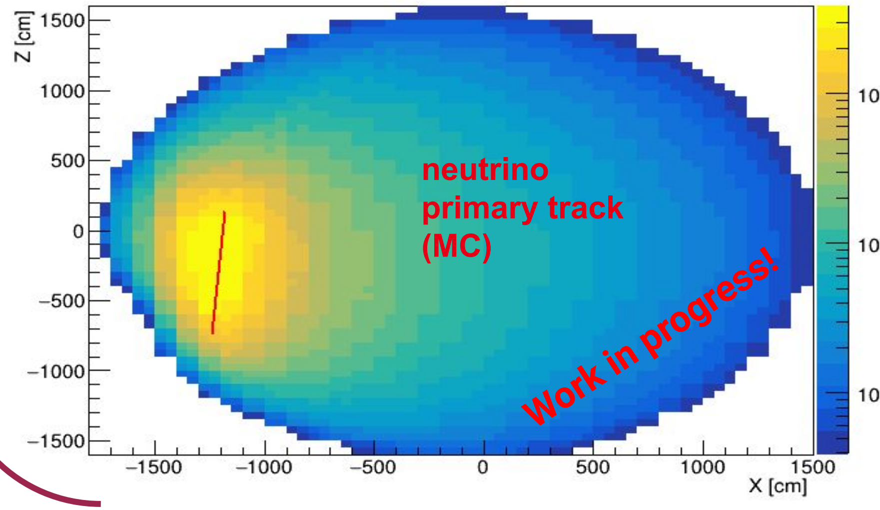
$$\hat{t}(x) = \boxed{t_{ref}} \pm \boxed{\underbrace{\frac{|\hat{x}-\hat{r}_{ref}|}{c_0}}_{t_{\substack{particle\\ \mu/e}}}} + \boxed{\underbrace{\frac{|\hat{r}_j-\hat{x}|}{v_g}}_{t_{photon}}}$$

Direction reconstruction of atmo events

Hadrons are negligible



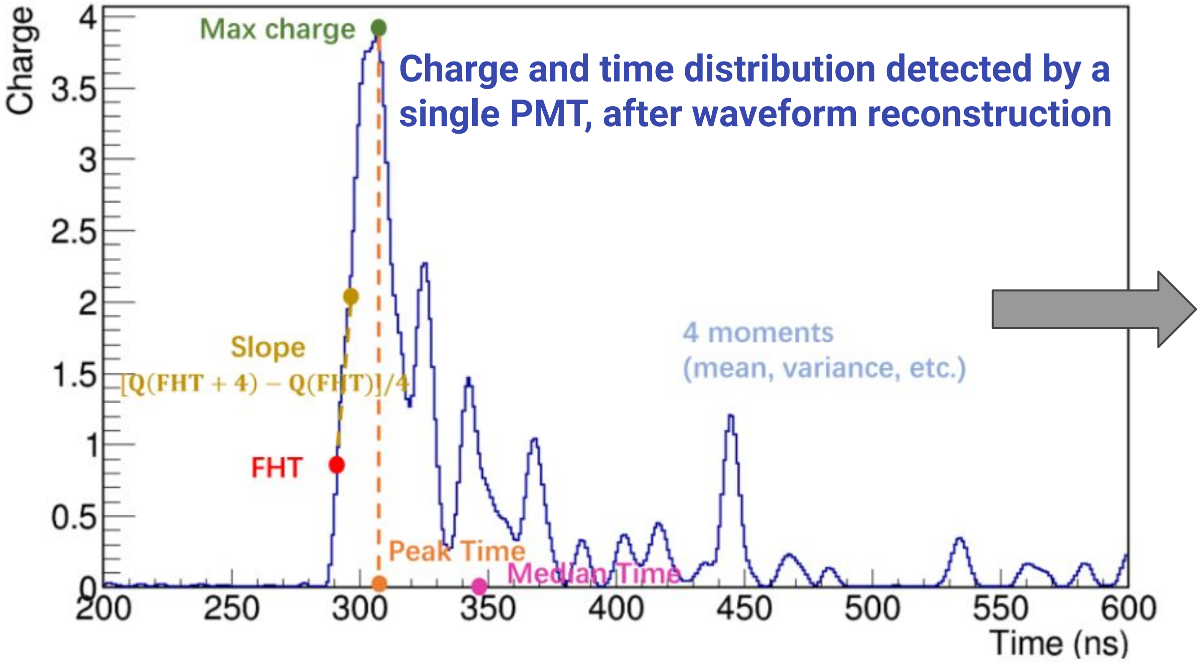
Hadrons are non negligible



Spatial probability of emitted light

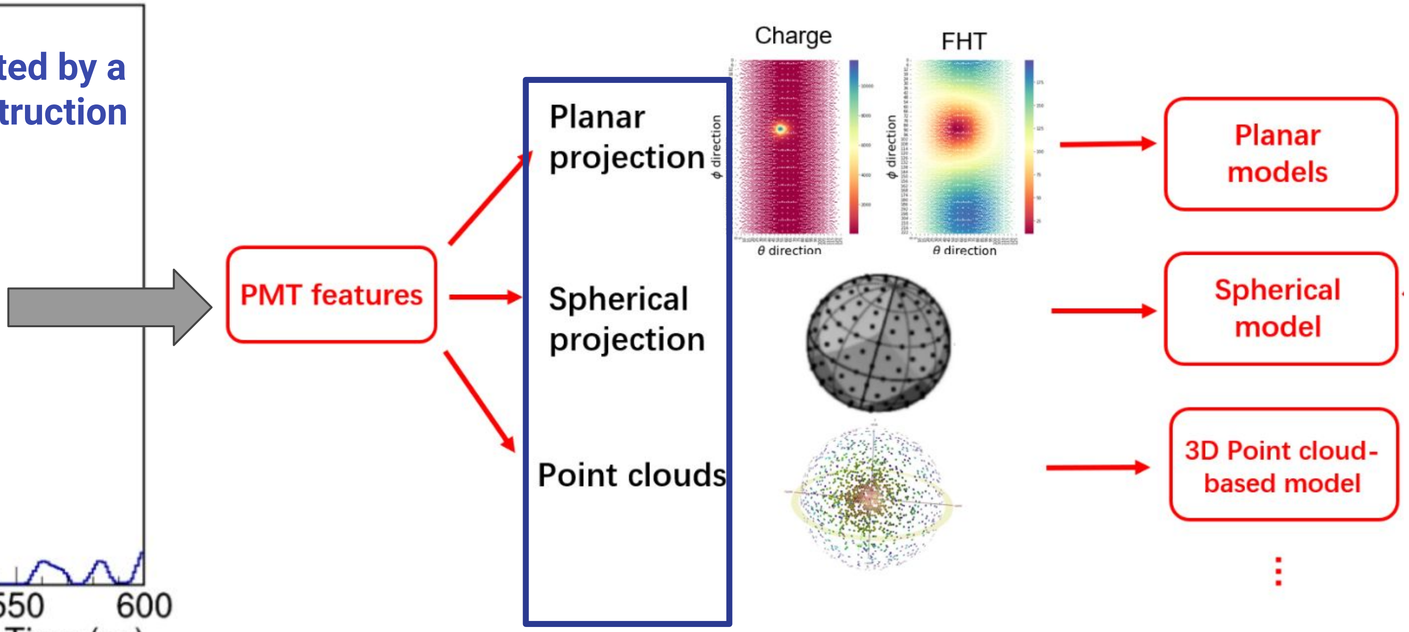
Directionality and flavor identification: machine learning based

Features extracted from each PMT's waveform reflect the event's topological structure and carry information about the event's direction, flavor types.



Charge and time distribution detected by a single PMT, after waveform reconstruction

waveform reconstruction based on deconvolution method



PMT features

Planar projection

Spherical projection

Point clouds

Planar models

Spherical model

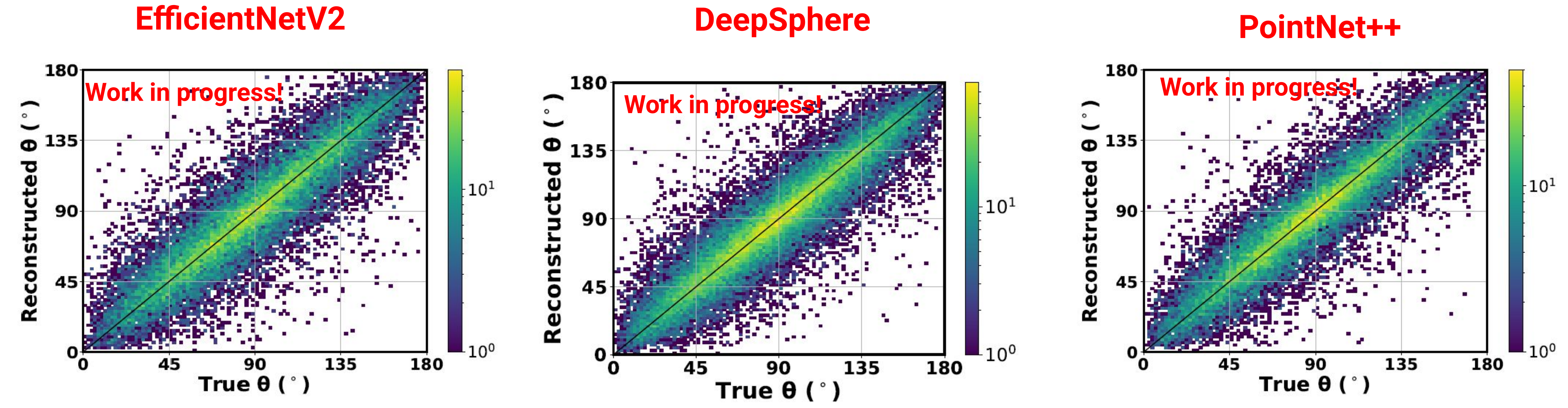
3D Point cloud-based model

⋮

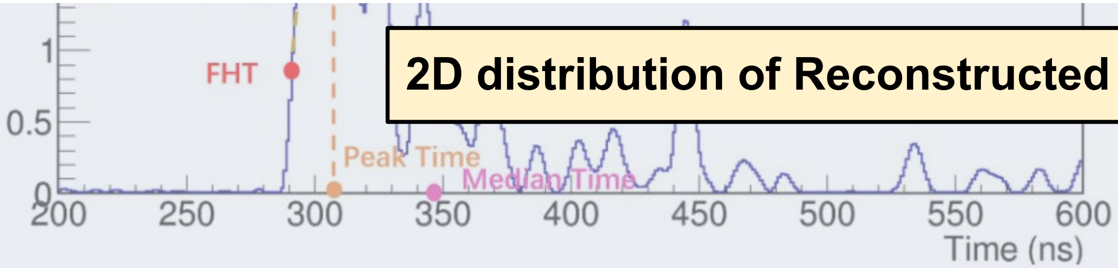
3 categories of machine learning methods have been evaluated.

https://indico.ihep.ac.cn/event/18269/contributions/135315/

Directionality and flavor identification: machine learning based



2D distribution of Reconstructed θ VS True θ in all energies.



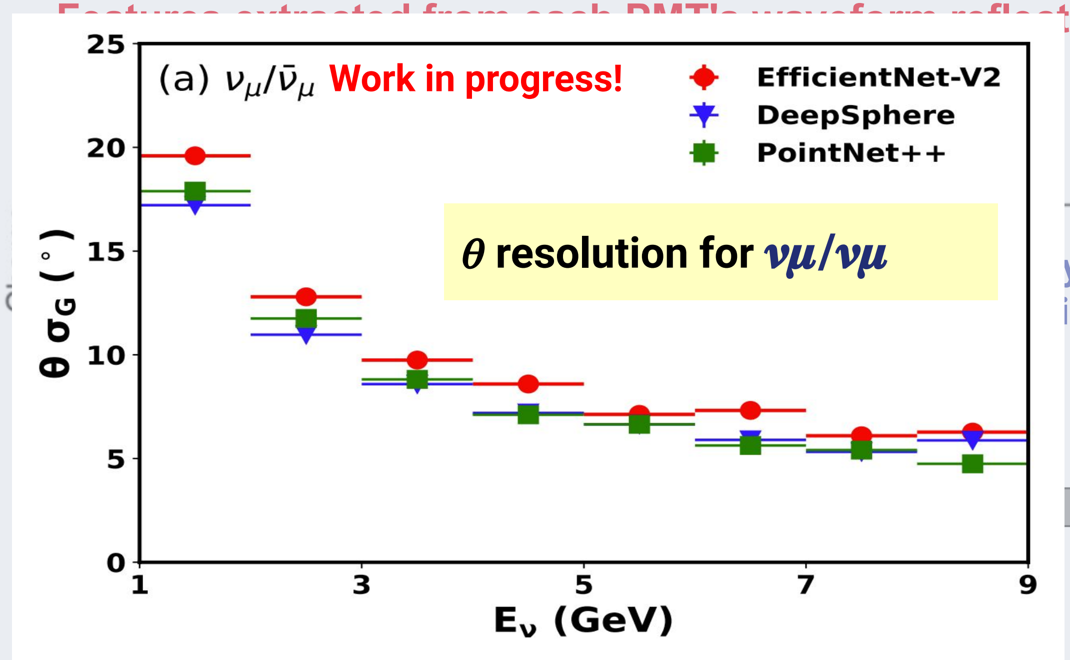
waveform reconstruction based on deconvolutional method

3 categories of machine learning methods have been evaluated

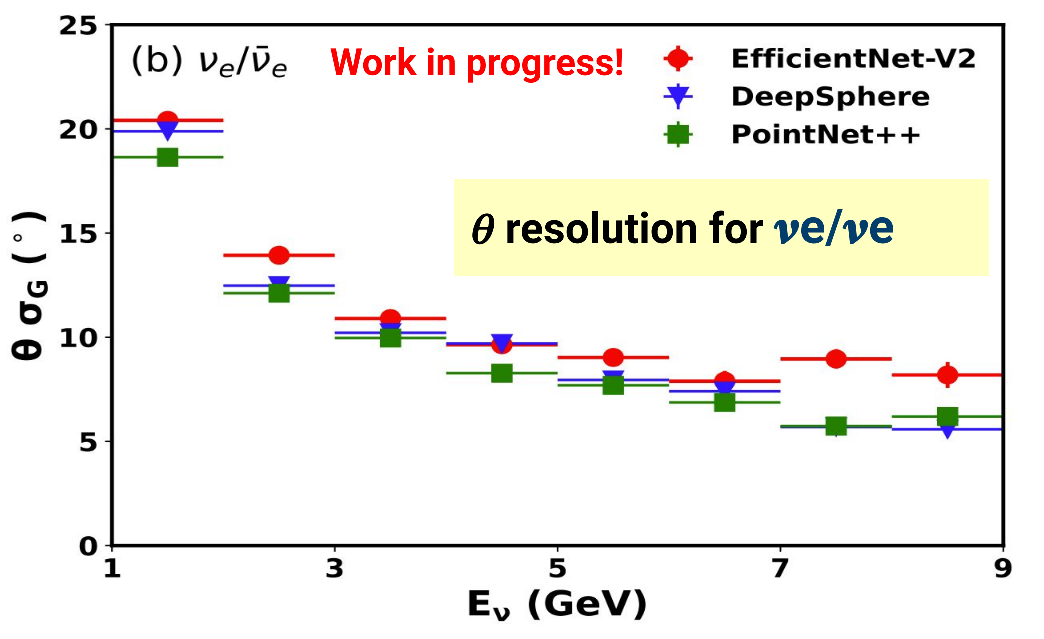
https://indico.ihep.ac.cn/event/18269/contributions/135315/

Directionality and flavor identification: machine learning based

Features extracted from each PMT's waveform reflect the event's topological structure and carry information



θ resolution for $\nu\mu/\nu\mu$



θ resolution for $\nu e/\nu e$

y a
ion

Planar models

Spherical model

Point clouds

Point cloud-based model

⋮

FHT

0.5

0

200

25

Time (ns)

The direction resolution is less than 10 deg in the sensitivity energy region [3, 10] GeV.

3 categories of machine learning methods have been evaluated

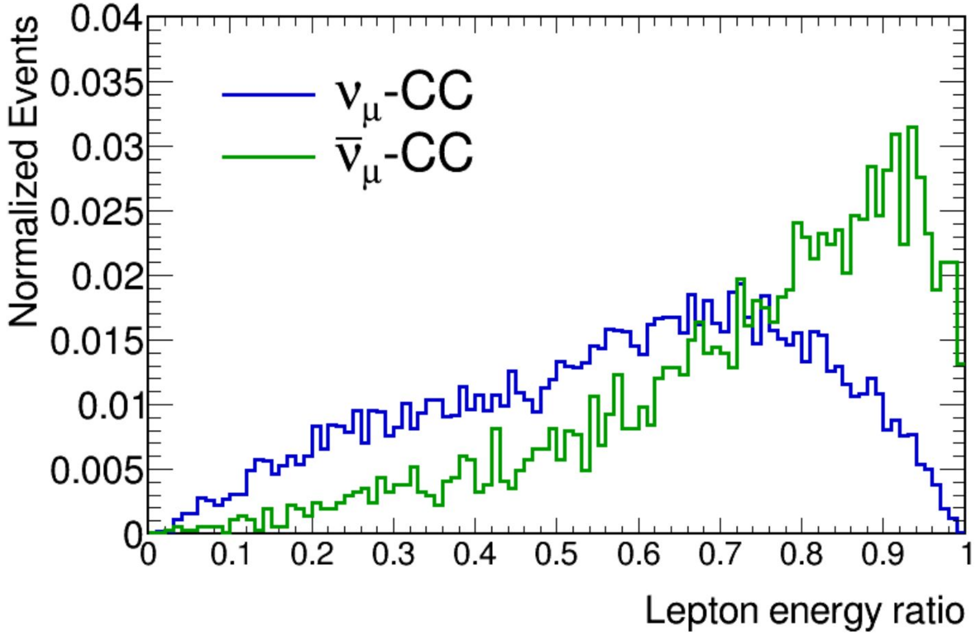
waveform reconstruction based on deconvolutional method

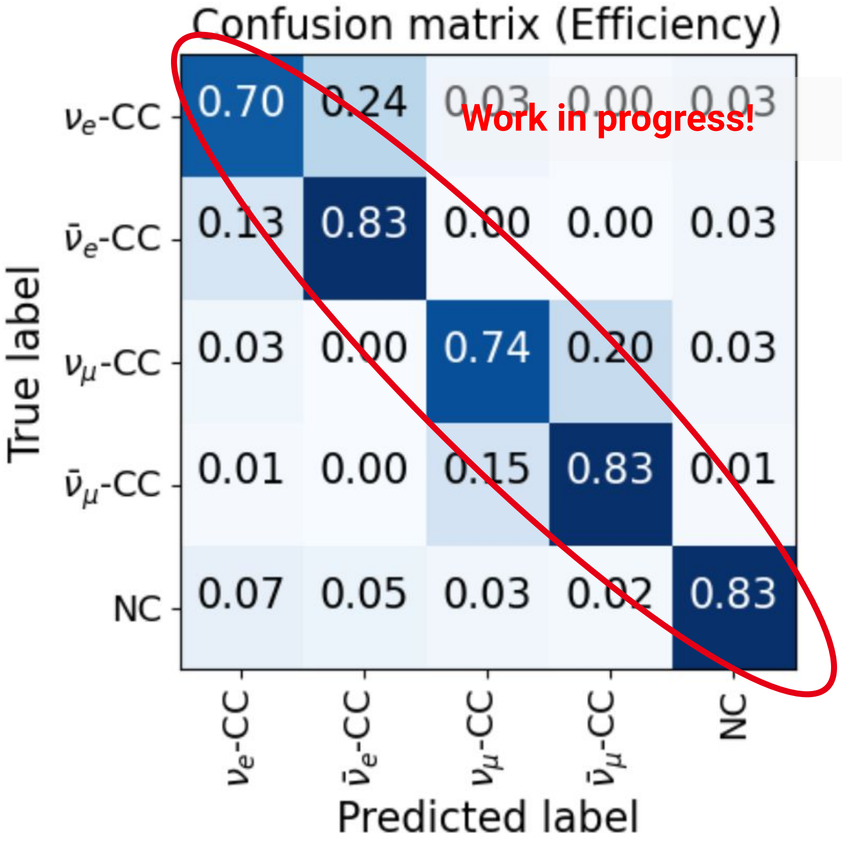
https://indico.ihep.ac.cn/event/18269/contributions/135315/

Directionality and flavor identification: machine learning based

Extra physics inputs has been added to the ML approach: lepton energy ratio, neutron multiplicity …

Results





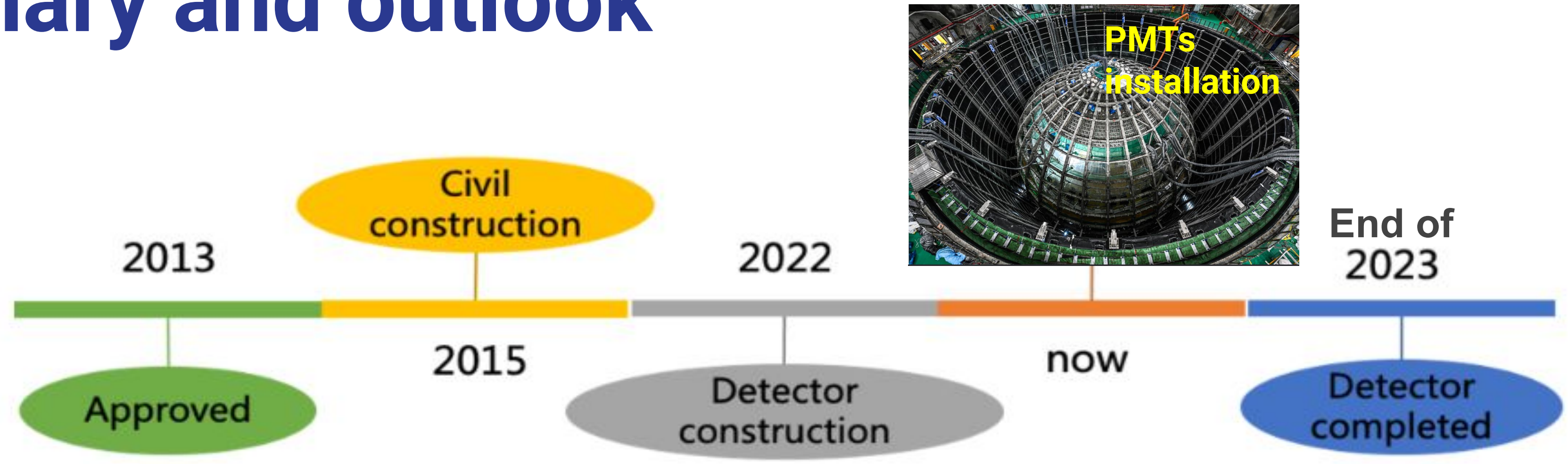
	ν_e-CC	$\bar{\nu}_e$-CC	ν_μ-CC	$\bar{\nu}_\mu$-CC	NC
ν_e-CC	0.70	0.24	0.03	0.00	0.03
$\bar{\nu}_e$-CC	0.13	0.83	0.00	0.00	0.03
ν_μ-CC	0.03	0.00	0.74	0.20	0.03
$\bar{\nu}_\mu$-CC	0.01	0.00	0.15	0.83	0.01
NC	0.07	0.05	0.03	0.02	0.83

$$\text{Efficiency} = \frac{N^i_{true}}{\sum_i N^i_{true}}$$

Result obtained without considering the electronic effect of the detector.

More than 70 % of the different neutrino flavors will be correctly classified in JUNO.

Summary and outlook



JUNO has potential to measure the atmospheric neutrino spectra

- **Advantages: low energy threshold and fine energy resolution**
- **Sub – GeV to multi – GeV energy range**
- **First measurement with a LS – based detector, 15 events/day**
- **Low O(100 MeV) threshold - backgrounds for rare events searches and benchmark for theoretical models**
- **Energy spectrum can be measured within a 25% uncertainty in 5 yrs of detector lifetime**

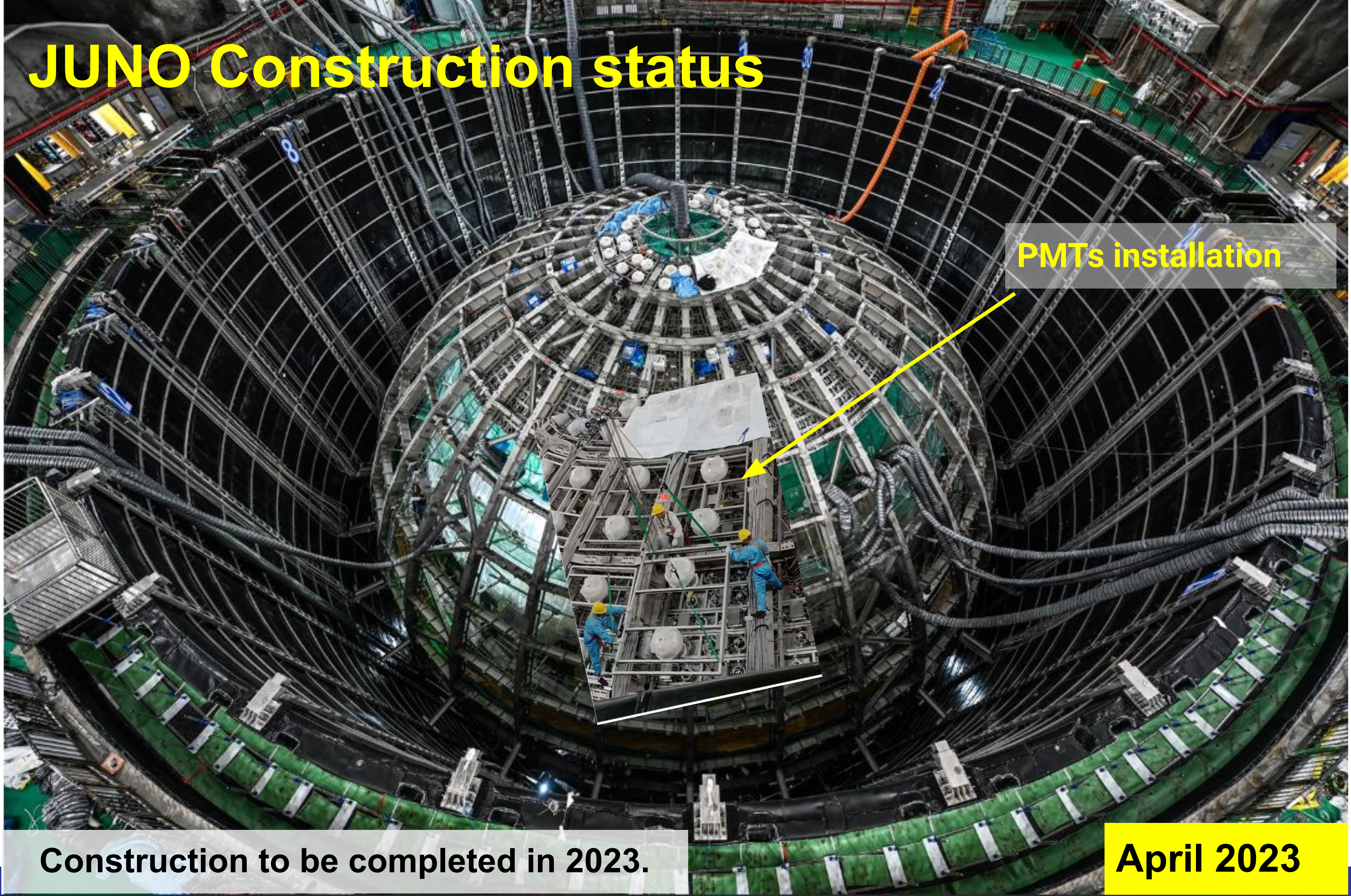
Ongoing!

Different machine learning and conventional reconstruction techniques under developpement.

More realistic sensitivity study to NMO via atmospheric neutrinos.

Joint analysis with atmospheric neutrinos in order to enhance the sensitivity of JUNO to NMO.

JUNO Construction status



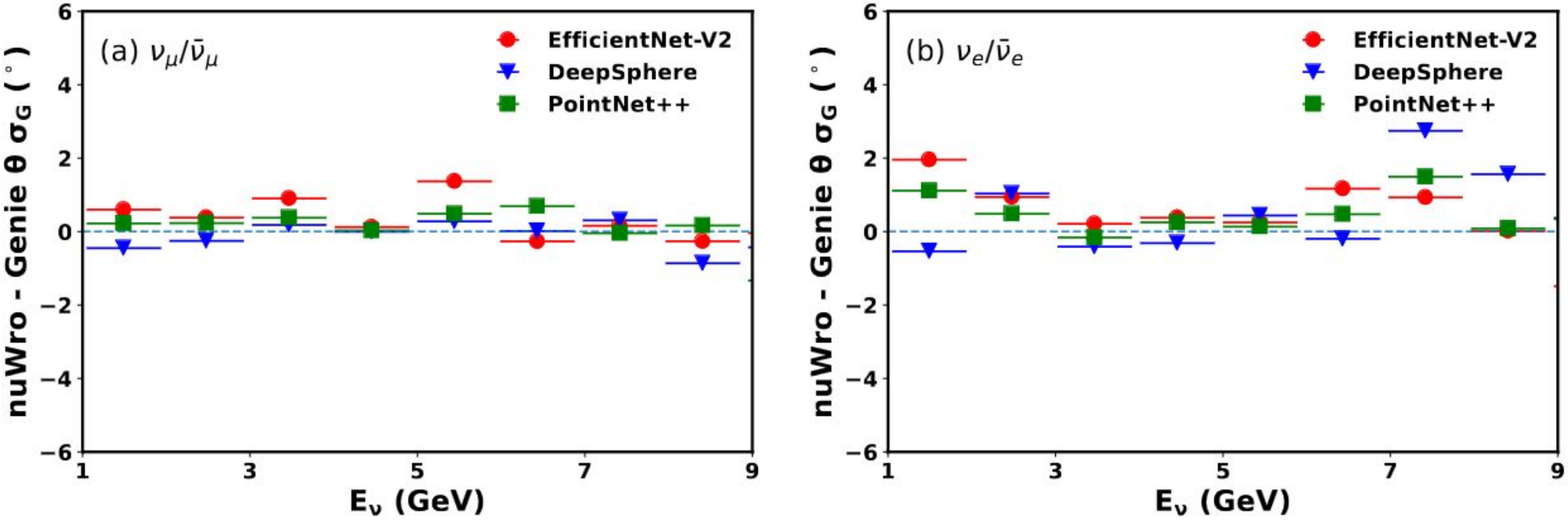
Construction to be completed in 2023.

April 2023

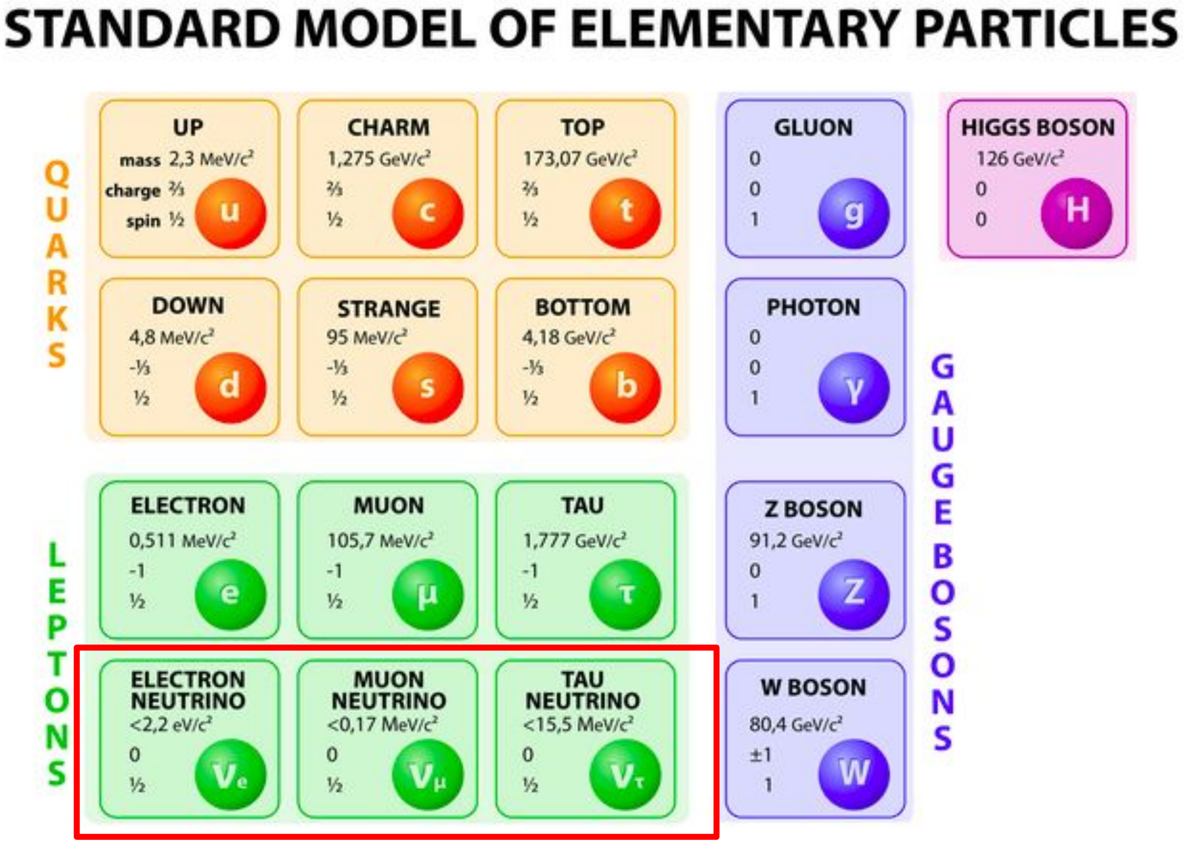
Back up

On going! Study the effects of different generator on the directionality reconstruction performance

- The difference in the θν resolutions obtained from νμ and νe CC samples simulated by NuWro and GENIE using different ML models as functions of incoming neutrino energy.



Neutrino Basics



STANDARD MODEL OF ELEMENTARY PARTICLES

QUARKS	UP mass 2,3 MeV/c^2 charge ⅔ spin ½ u	CHARM 1,275 GeV/c^2 ⅔ ½ c	TOP 173,07 GeV/c^2 ⅔ ½ t	GLUON 0 0 1 g	HIGGS BOSON 126 GeV/c^2 0 0 H
	DOWN 4,8 MeV/c^2 -⅓ ½ d	STRANGE 95 MeV/c^2 -⅓ ½ s	BOTTOM 4,18 GeV/c^2 -⅓ ½ b	PHOTON 0 0 1 γ	
LEPTONS	ELECTRON 0,511 MeV/c^2 -1 ½ e	MUON 105,7 MeV/c^2 -1 ½ μ	TAU 1,777 GeV/c^2 -1 ½ τ	Z BOSON 91,2 GeV/c^2 0 1 Z	
	ELECTRON NEUTRINO <2,2 eV/c^2 0 ½ ν_e	MUON NEUTRINO <0,17 MeV/c^2 0 ½ ν_μ	TAU NEUTRINO <15,5 MeV/c^2 0 ½ ν_τ	W BOSON 80,4 GeV/c^2 ±1 1 W	
				GAUGE BOSONS	

- Originally, **in the Standard Model neutrinos have exactly zero mass**, all neutrinos are left-handed and all antineutrinos are right handed
- **Discovery of neutrino oscillation** (from atmospheric and solar neutrino experiments) (Nobel Prize 2015) **leads to a non-zero neutrino mass.**
- Non-zero mass requires at least a minimal extension of the Standard Model;

- No electric charge = no elmag interactions
- No color = no strong interactions
- **Only weak interactions = very small cross sections of interactions with matter**
- Difficult to detect
  - Large detectors
  - Underground laboratories
  - Extreme radio-purity

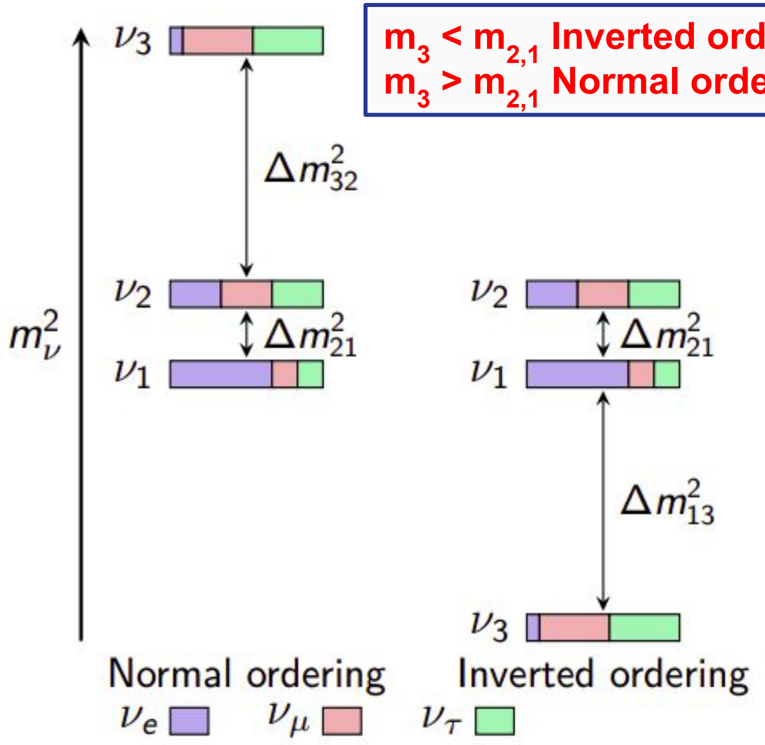
Neutrino Oscillation Physics

α = e, μ, τ
Flavour eigenstates
INTERACTIONS

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U_{\alpha i}\,|\nu_i\rangle$$

i = 1, 2, 3
Mass eigenstates
PROPAGATION

$m_3 < m_{2,1}$ Inverted ordering
$m_3 > m_{2,1}$ Normal ordering



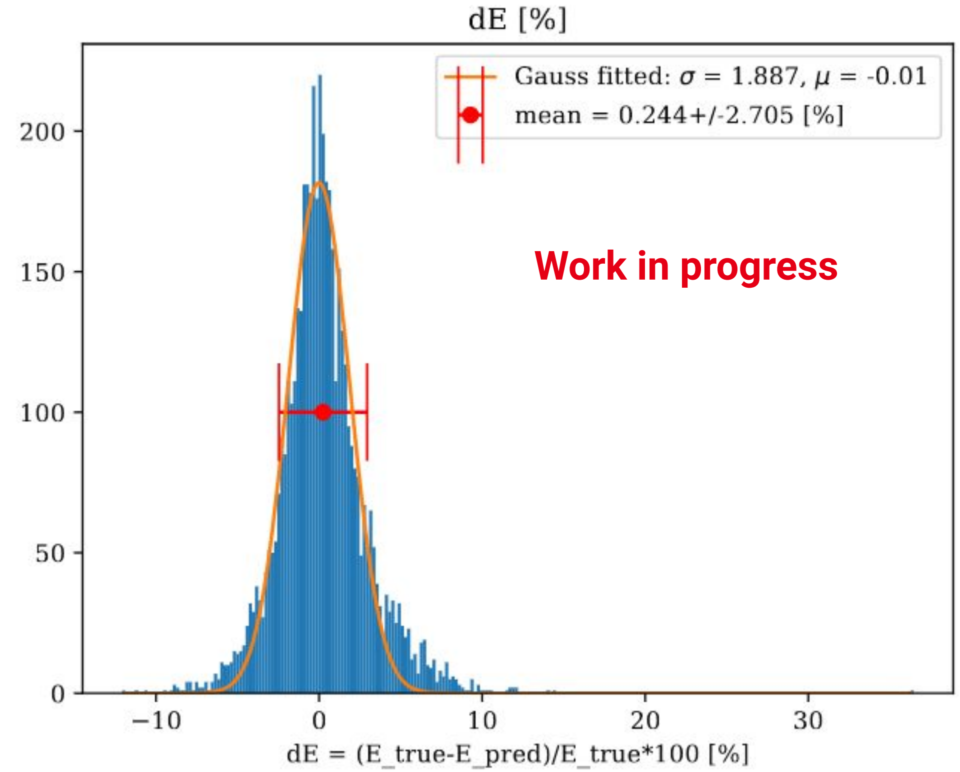
Primary Goals of Neutrino Physics: measure the oscillation parameters of the PMNS matrix

$$\begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix}$$

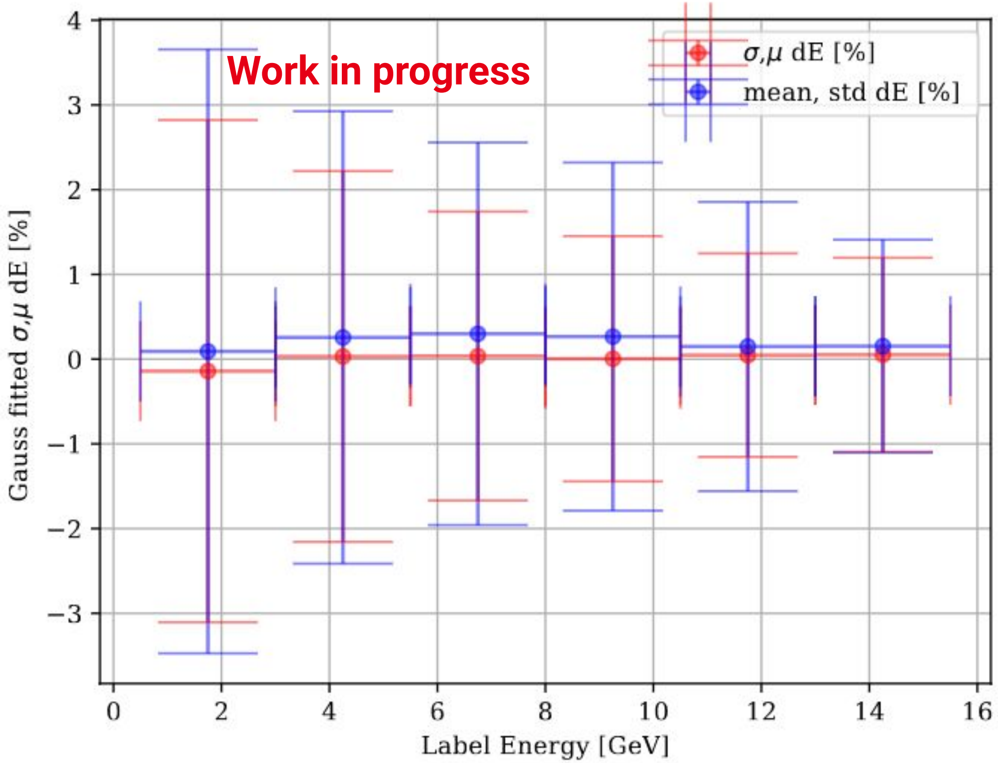
atmospheric Reactor Solar

Determination of the Mass Ordering is relevant to the neutrino oscillation tomography

Energy reconstruction



Work in progress



Work in progress

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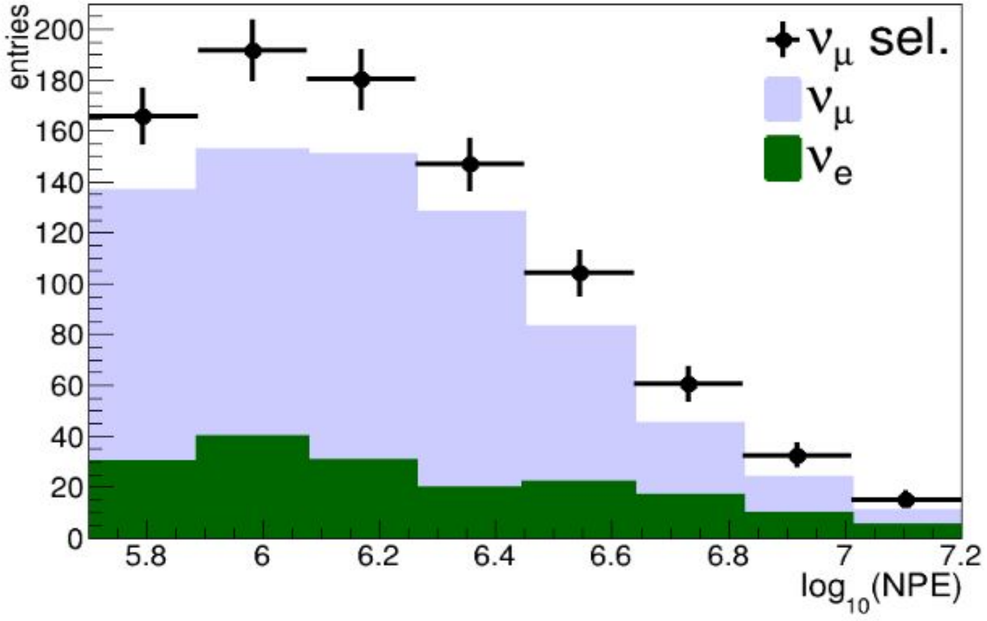
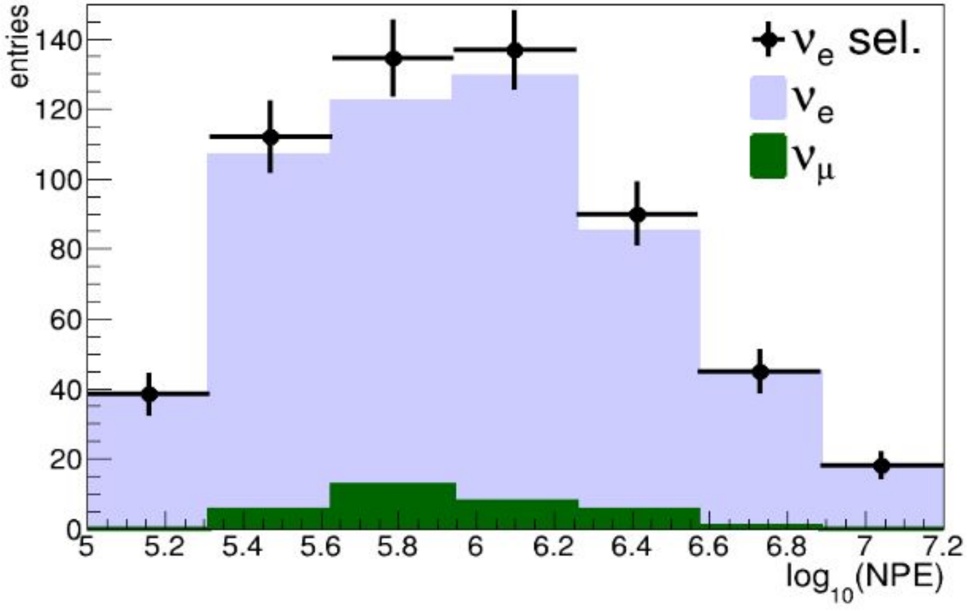
Energy Spectrum Reconstruction

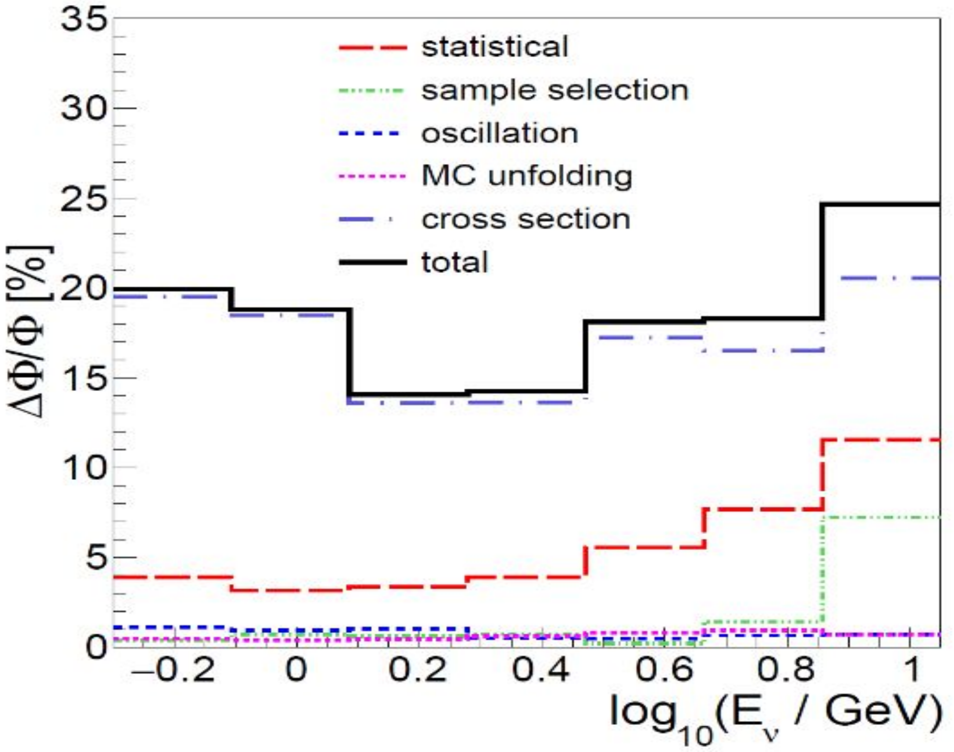
- Unfolding probabilistic method to extract the energy spectrum from detector observables
- Based on Iterative Bayesian Unfolding
  - G. D'Agostini, Nucl.Instrum.Meth.A 362 (1995) 487-498. arXiv:1010.0632

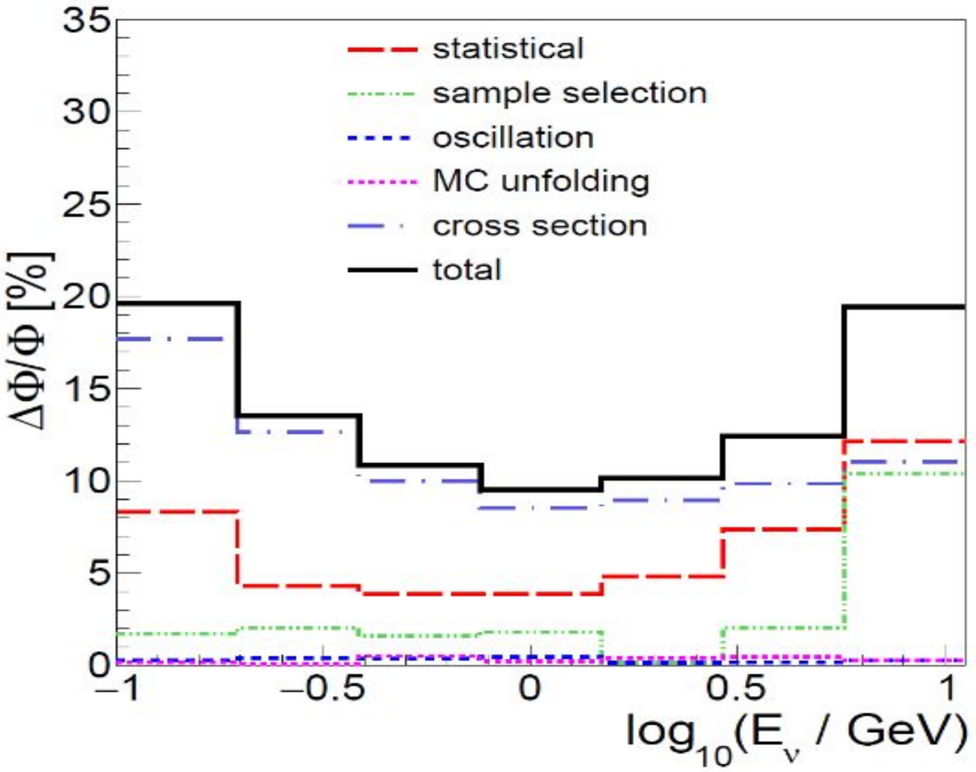
~5 yrs of detector lifetime MC events have been generated as real data





Systematic Uncertainty





Total uncertainty between 10 – 25%

- Dominant contribution from cross – section

A. Abusleme et al., JUNO sensitivity to low energy atmospheric neutrino spectra, Eur. Phys. J. C 81 (2021) 887.

Neutrino Oscillation … Matter effects

Schrodinger equation: $i\frac{d}{dt}\upsilon_f = (U\frac{M^2}{2E}U^T + V)\upsilon_f$

$$With\ldots M^2 = diag(m_1^2, m_2^2, m_3^2)$$

$$and\ldots V = diag(2^{1/2}G_f N_e, 0, 0)$$

Two flavor approximation: Matter effects is proportional to L

- **Vacuum:** $P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{31})\sin^2(2\theta_{23})\sin\frac{\Delta m^2_{atm}L}{4E}$
- **Matter effect**: $P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_M)\sin^2(2\theta_{23})\sin\frac{\Delta m^2_M L}{4E}$

$$\Delta m^2_M = \Delta m^2_{atm}\,.\xi$$

$$\sin 2\theta_M = \sin\frac{2\theta}{\xi}$$

$$\xi = \sqrt{\sin^2(2\theta_{31}) + \left(\cos(2\theta_{13}) - \frac{A_{cc}}{\Delta m^2_{atm}}\right)^2}$$

$$\boxed{A_{cc} = \pm 2\sqrt{2}\,.\,G_F E_\nu N_e}$$

+: **neutrino**
−: **antineutrino**

neutrino energy

Electron density

Resonance energy can be described as:

$$E_\nu = \frac{\Delta m^2_{31}\cos 2\theta_{13}}{2\sqrt{2}G_F N_e} = 32.1\text{GeV}\frac{g/\text{cm}^3}{\rho}\frac{0.5}{Y_e}\frac{\Delta m^2_{31}}{2.43\times10^{-3}\text{eV}^2}\cos 2\theta_{13}$$