Atmospheric neutrino oscillations at JUNO

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On behalf of the JUNO collaboration

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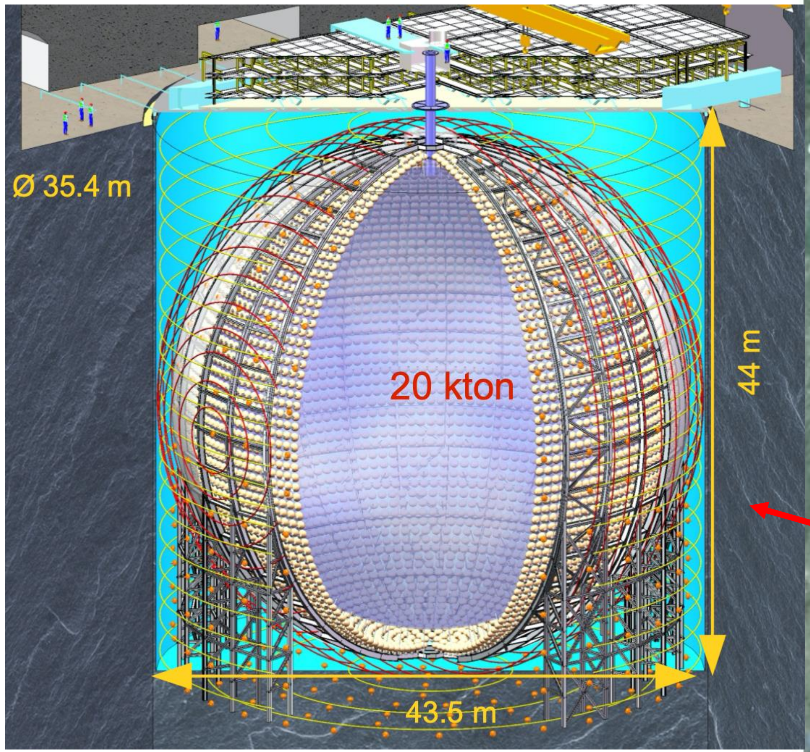
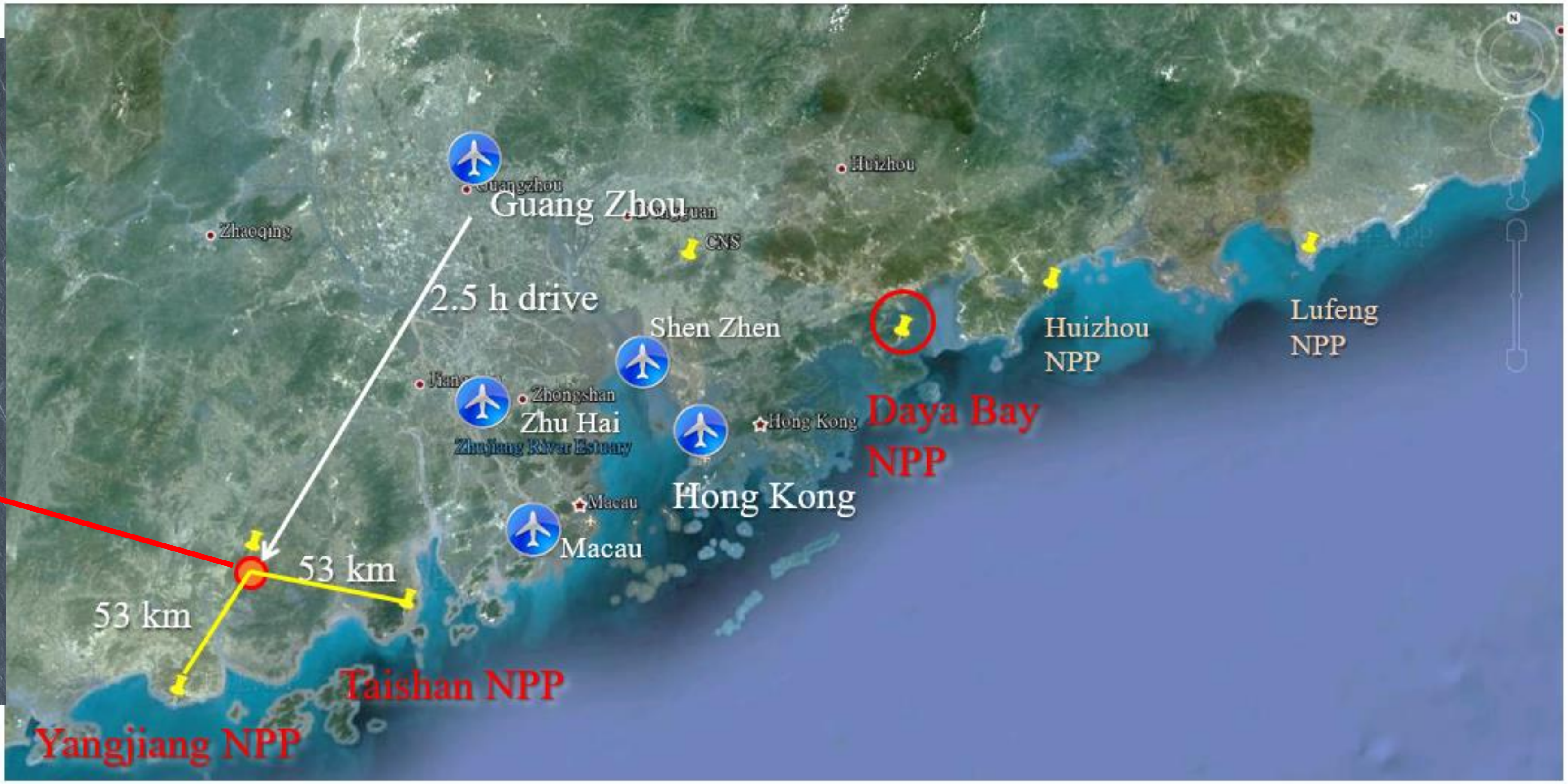
XX International Workshop on Neutrino Telescopes

JUNO Overview

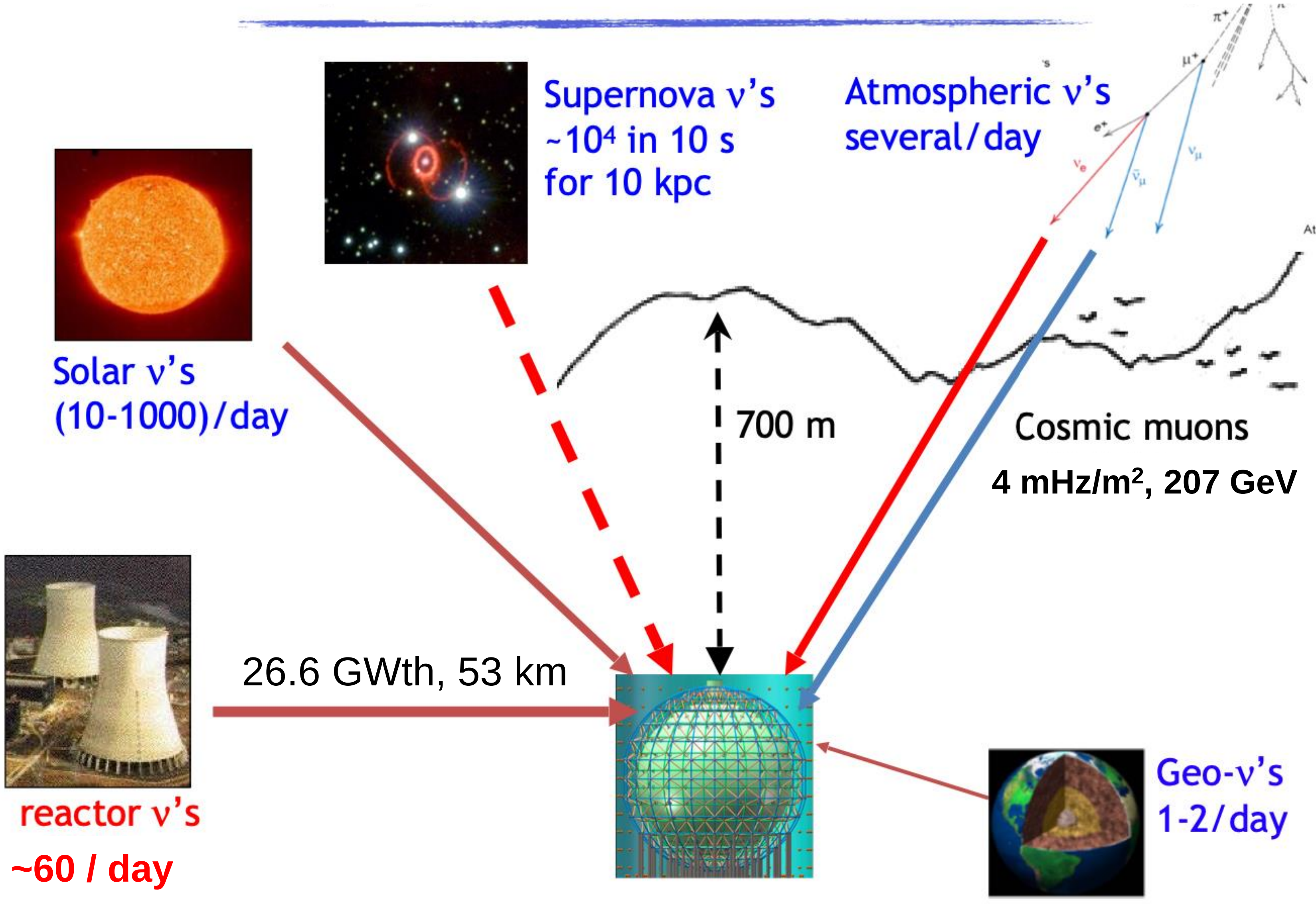




Largest ever LS detector
- 20 kton LS
- 78% photo-coverage
- Designed for low radioactivity background

Jiangmen Underground Neutrino Observatory (JUNO)
- Location optimized for neutrino mass ordering with reactor-ν
- 700m rock overburden to suppress muon flux
- Expected to finish detector construction in 2023

A Multipurpose Neutrino Observatory

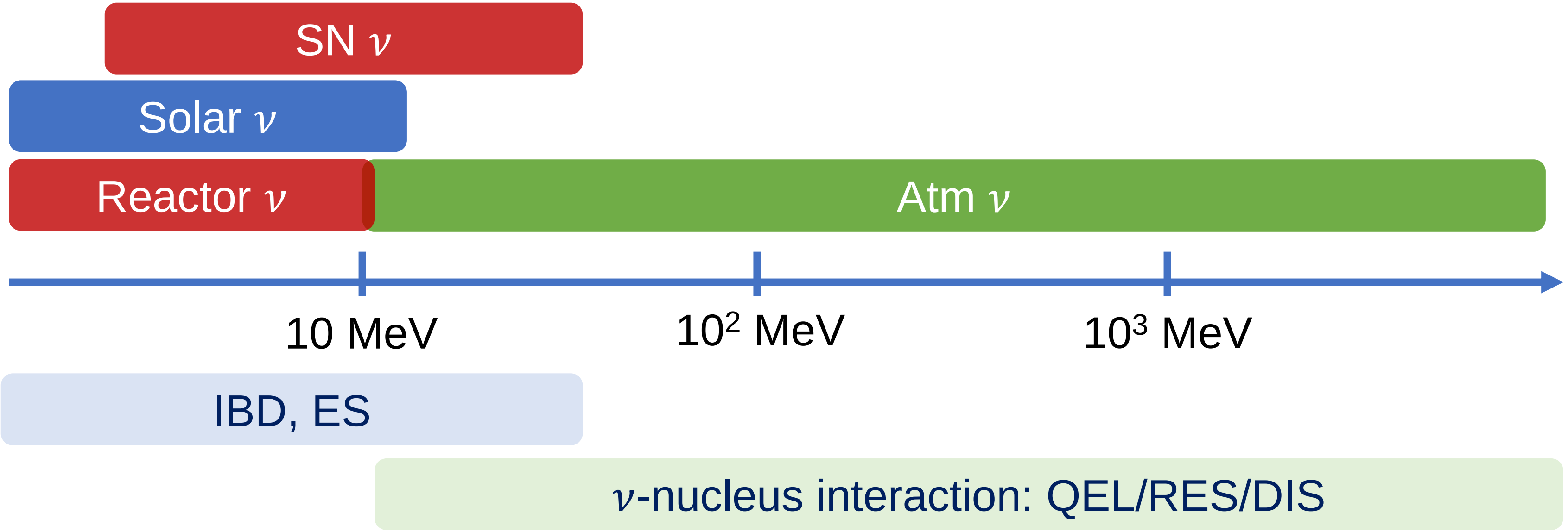


Primary physics goal
- NMO with reactor ν
- Precision meas. of osc. parameters

Rich program of non-oscillation physics:
- Solar ν
- Supernova ν
- Atmospheric ν
- Geo-ν
- Nucleon decays
- Indirect DM search
- …

From J. Pedro Ochoa-Ricoux

Atmospheric neutrino program at JUNO



- Greatly expanding JUNO's physics potential beyond MeV energies
  - Unexplored energy regime for LS

Opportunities

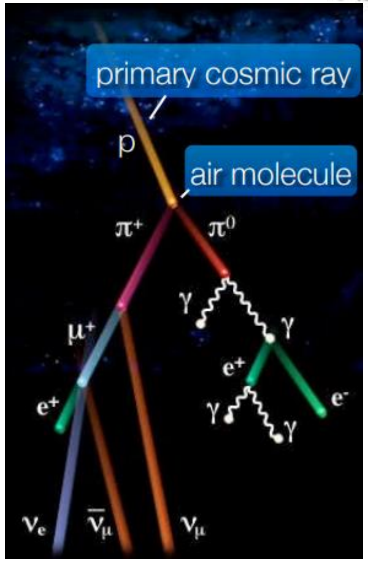
- **Oscillation physics (NMO)**
- Atm-ν flux
- Understanding of NC → bkgs for DSNB, PD …
- Constraints for νN interaction model
- …

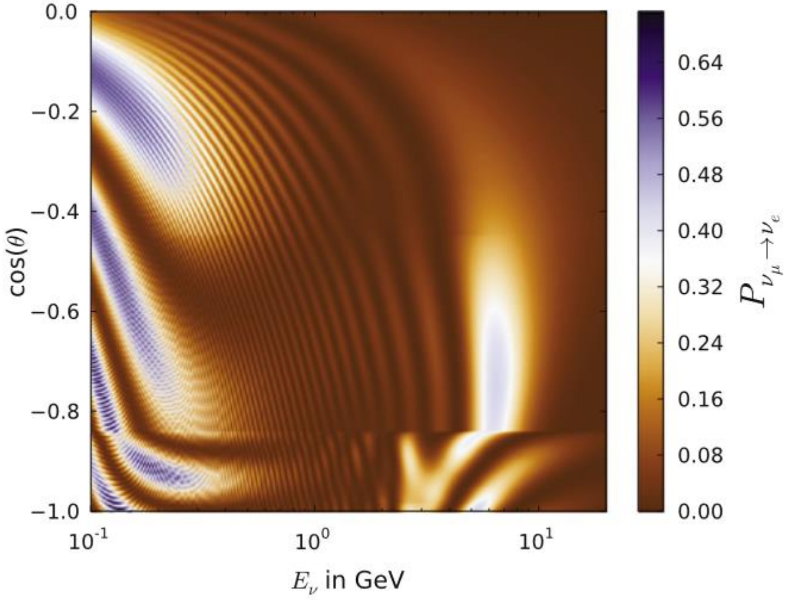
Challenges

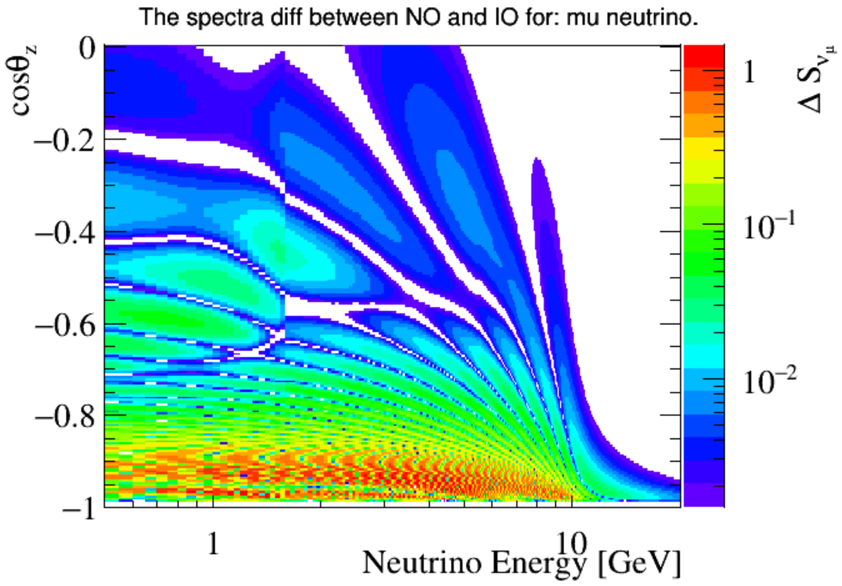
- GeV event reconstruction
- νN interaction uncertainties

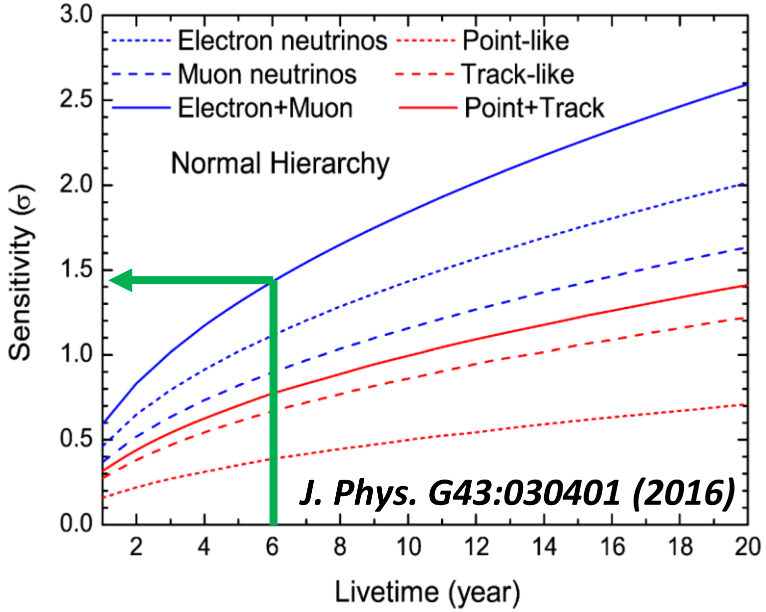
Atmospheric neutrino oscillations

- Produced by cosmic ray interaction with atmosphere
- Propagation in matter
  - **MSW** effect sensitive to NMO
- Potential to enhance overall NMO sensitivity at JUNO together with reactor neutrinos → *Talk by Andrea Serafini*
  - 0.8~1.4σ @ 6 years with atm ν only, ***J. Phys. G43:030401 (2016)***
  - **Significant analysis improvements towards a more realistic estimation** → *This talk!*

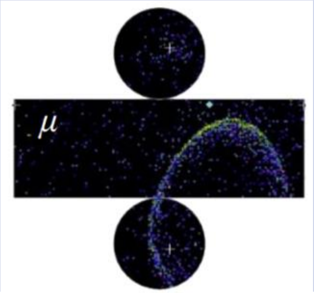






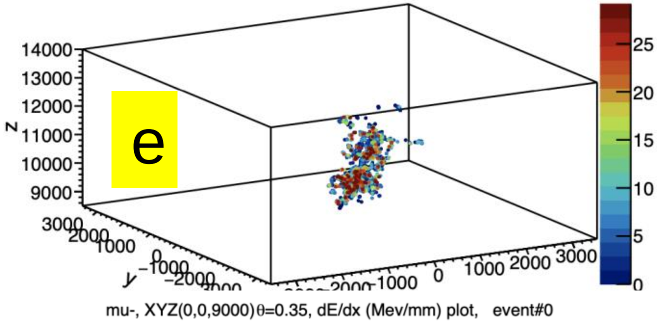


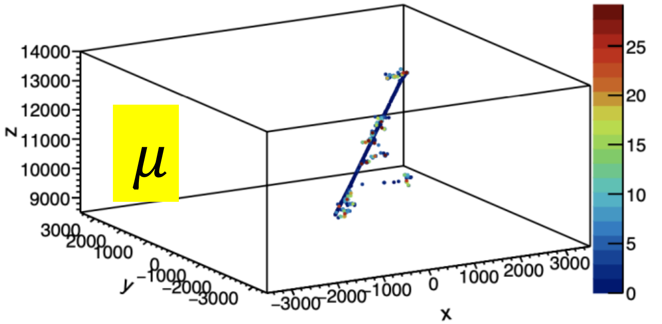
Atm-ν with large homogenous LS detector

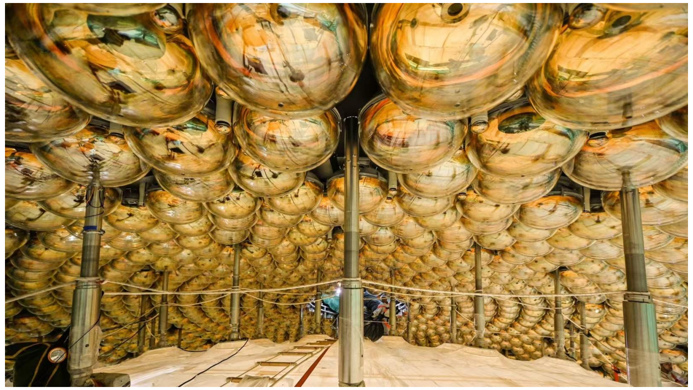
	Cherenkov detector	LS detector
Pros	Cherenkov ring 	Low E threshold High n-tagging efficiency

large homogenous LS detector like JUNO → good potential to reconstruct atm-ν

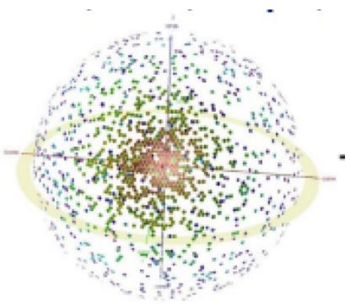
- ✓ Large photo-coverage → image for μ vs e, ν vs $\bar{\nu}$
- ✓ Hadronic information visible → better E/θ rec for ν (instead of $l^{\pm}$)
- ✓ Excellent neutron tagging → ν vs $\bar{\nu}$
- ✓ Final state isotopes identifiable → measure exclusive channels



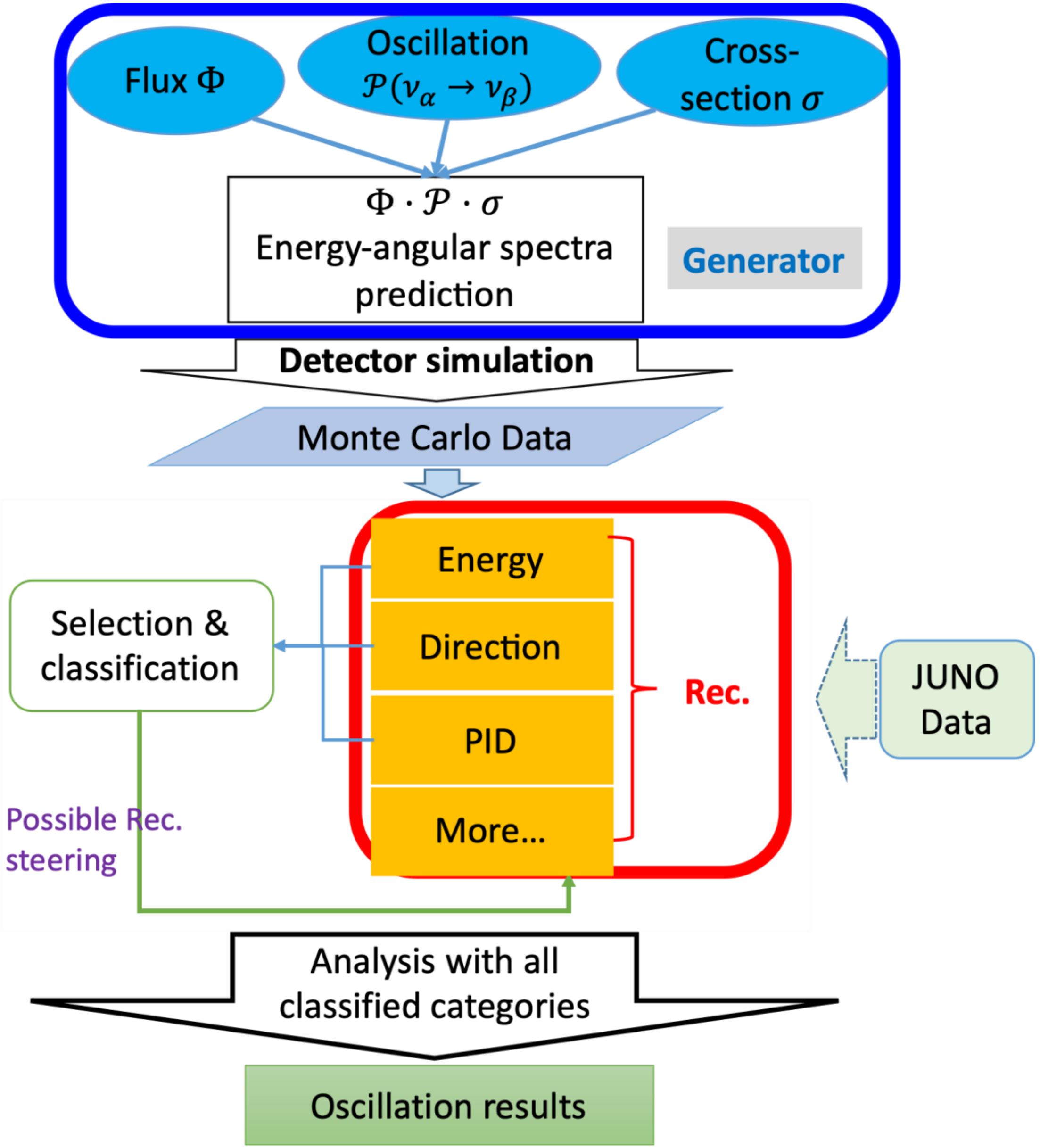




ML models

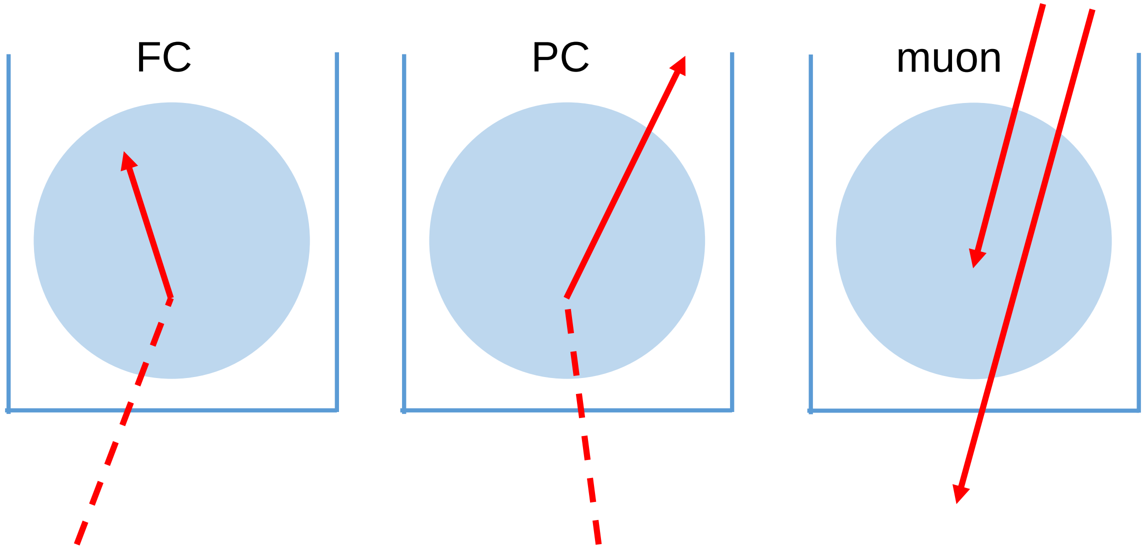


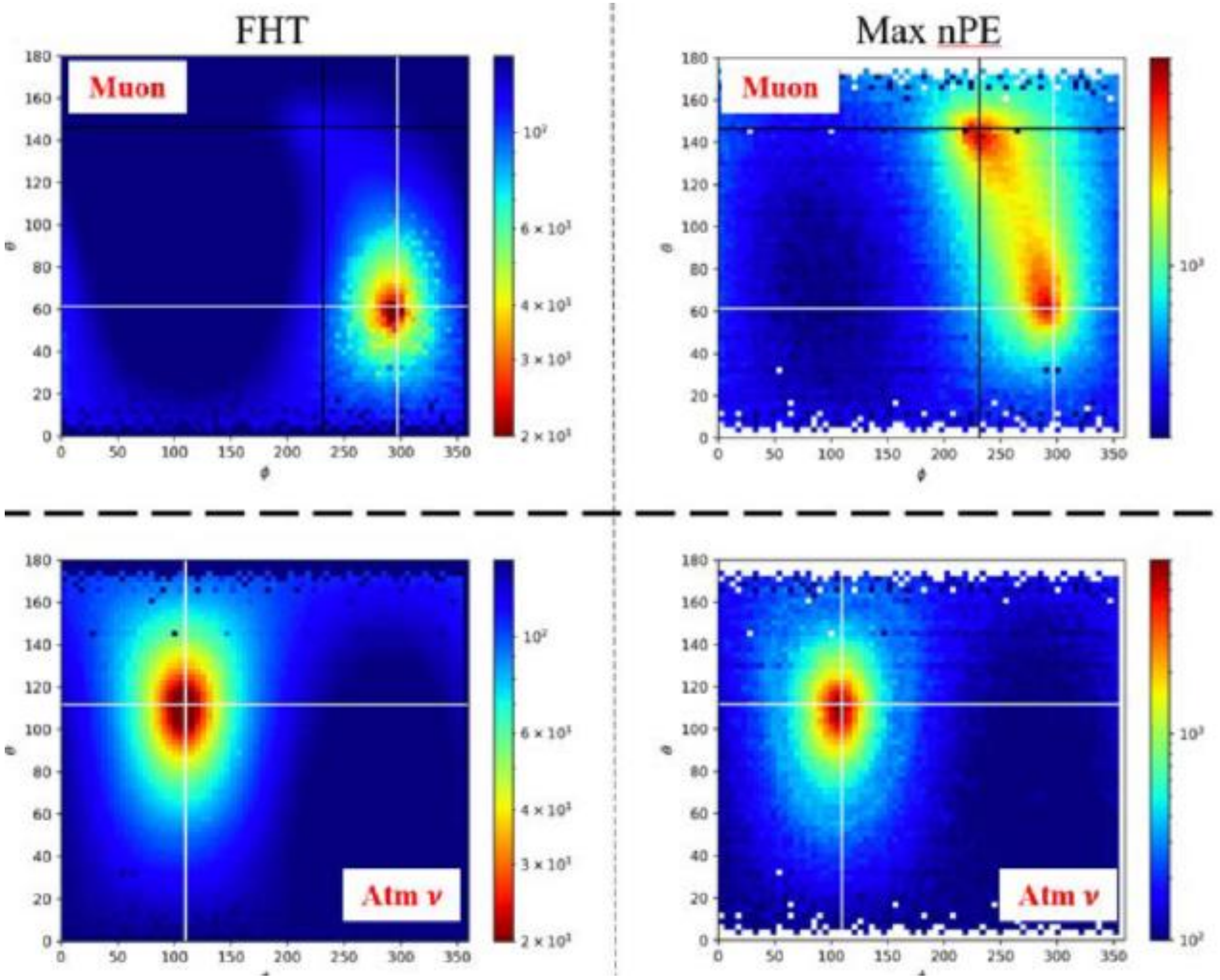
Oscillation Analysis overview



Event classification

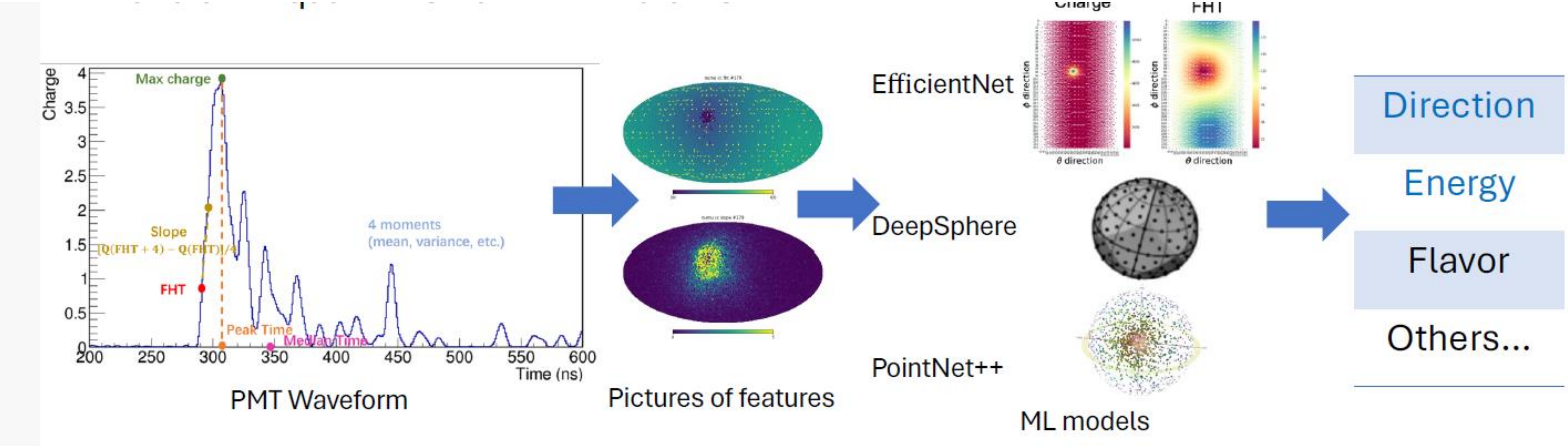
- FC/PC/muon classification
  - Timing info between CD and WP detectors
  - PMT hit charge/time patterns from both CD and WP





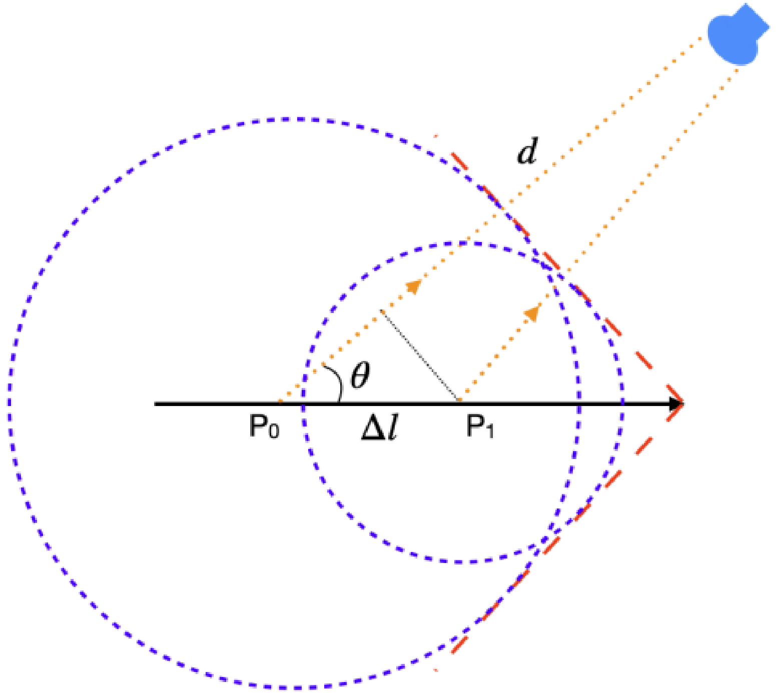
Event Reconstruction Method

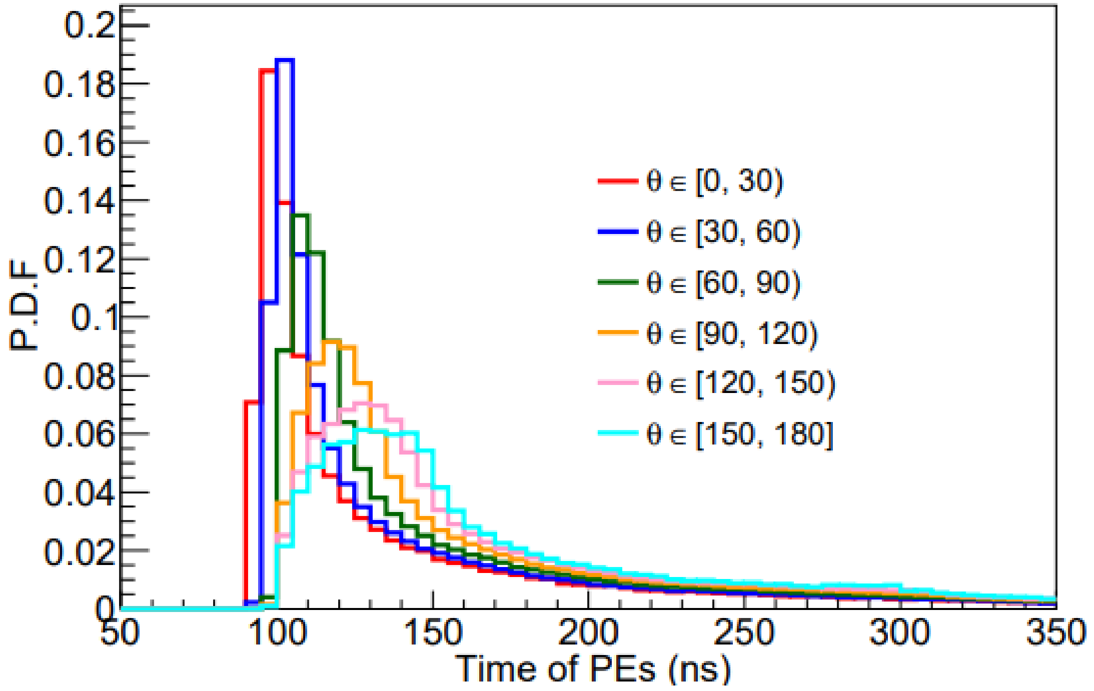
- General purpose machine learning framework for
  - Directionality, energy, PID …
- Waveform features extracted from each PMT for network input
  - First hit time, rising edge slope, NPE …



Methodology paper online, arxiv 2310.06281

How?



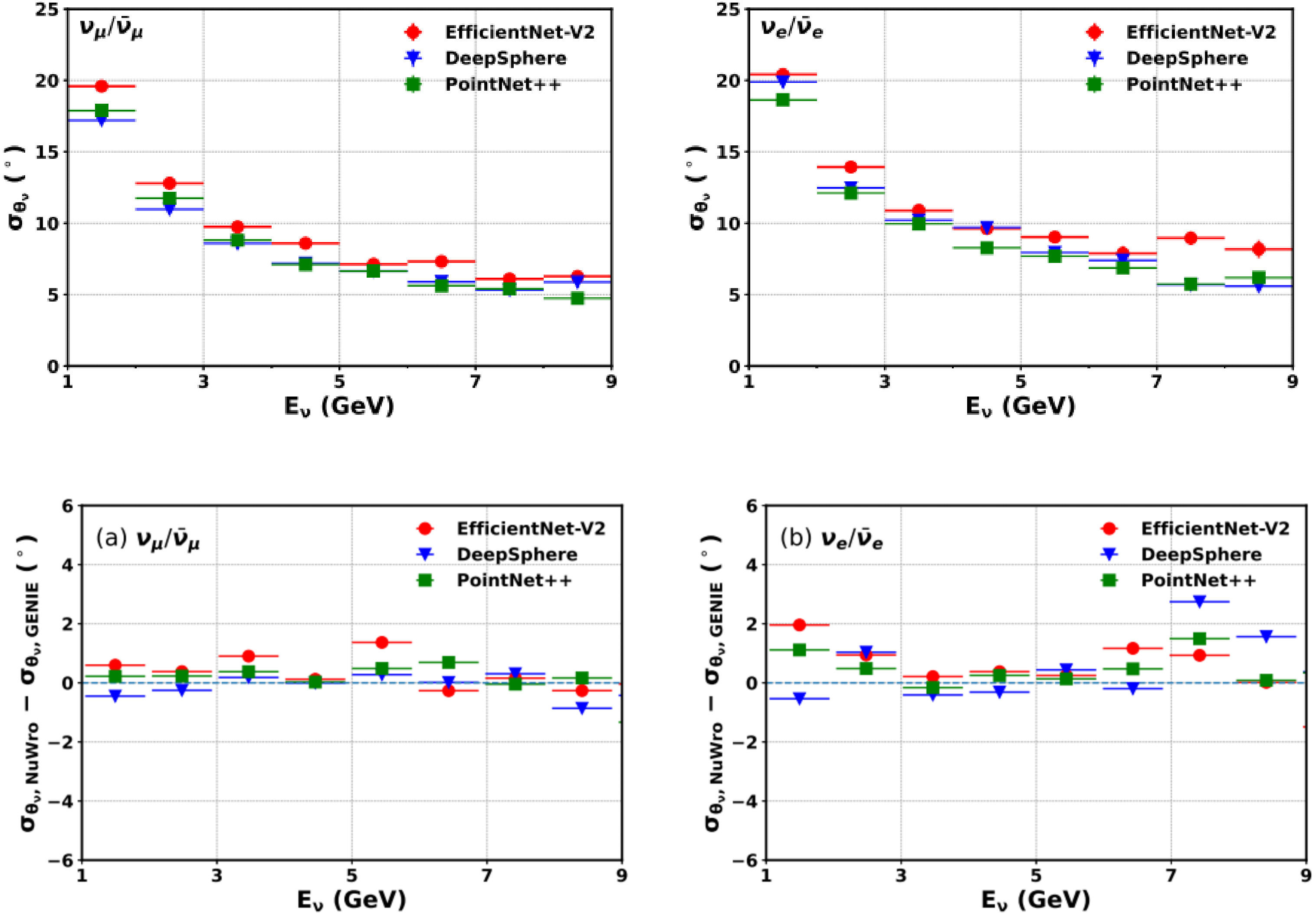


- Scintillation light is isotropic from point sources
- Light from a long track is not
- Hit time distribution is different for PMTs at different angles w.r.t. the track
  - Embedded information on direction, vertex, energy, PID …

Directionality

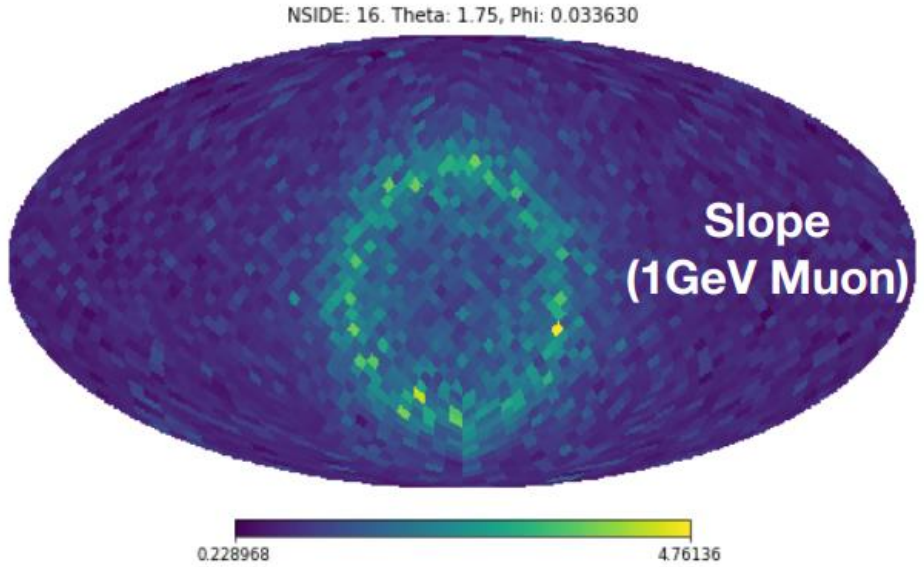
arxiv 2310.06281

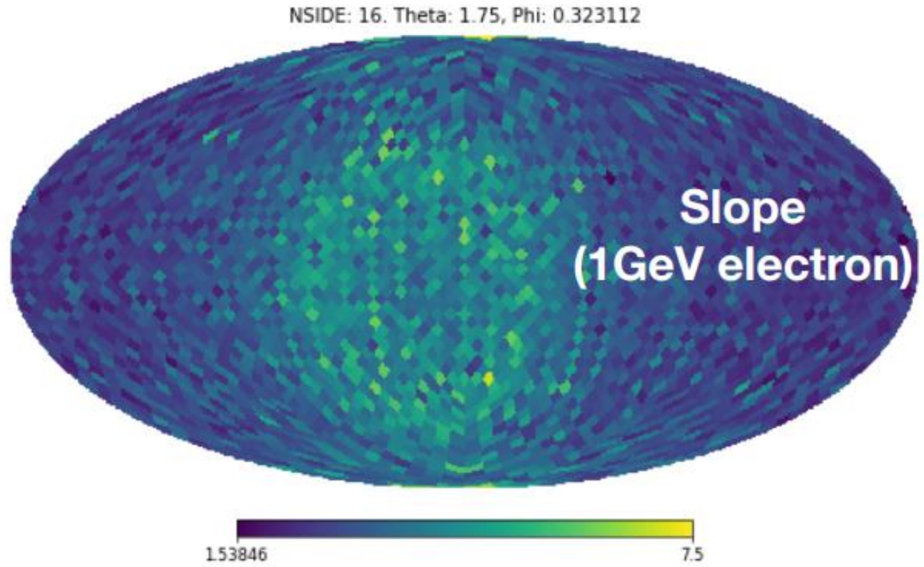
- Direction information embedded in the shape of hit time distribution
- ν Directionality better than 10° above 3 GeV
  - Hadronic information helps improve directionality
- Performance tested against different ν-generator models



More details in the talk by Z.K. Yang

Particle Identification μ vs e





- PMT pattern of slope feature show a ring like pattern for track event

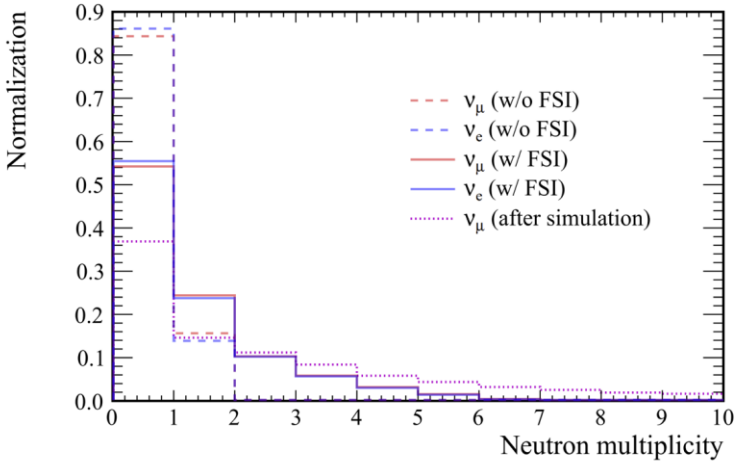
Particle Identification ν vs $\bar{\nu}$

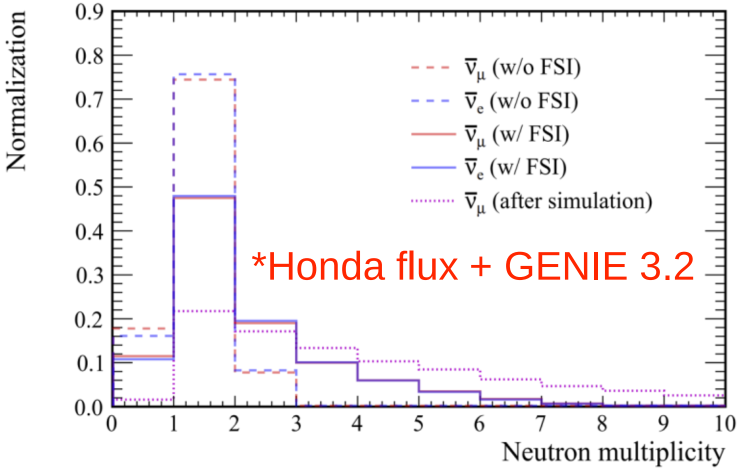
- More primary neutrons from interaction vertex for $\bar{\nu}$
  - $\bar{\nu}$ + p → n + l^+
  - ν + n → p + l^-

  → secondary event level info
- More energy transferred to hadrons for ν compared to $\bar{\nu}$
  - More hadronic components: different quenching and timing than leptons

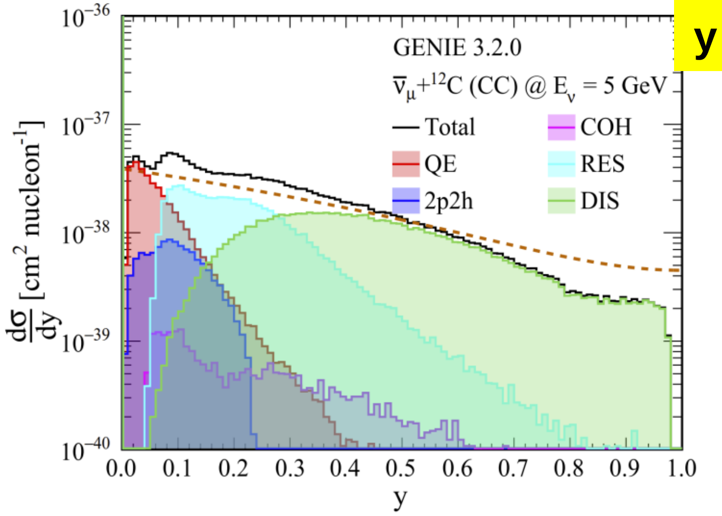
    → prompt event PMT pattern info
  - More hadronic interaction: more neutrons at higher energies

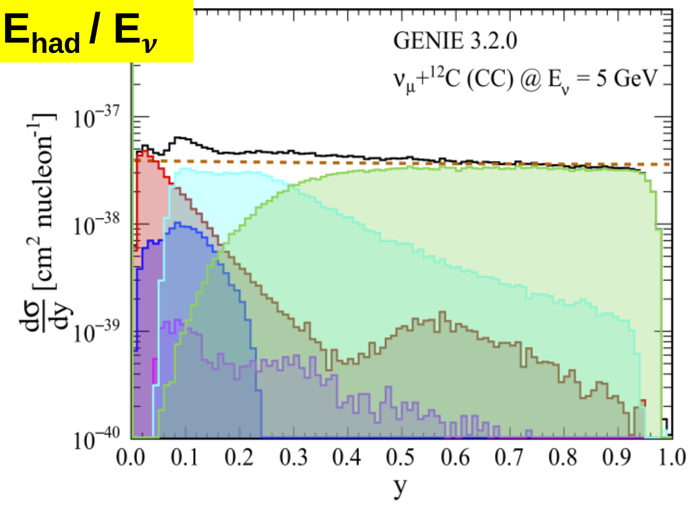
    → secondary event level info





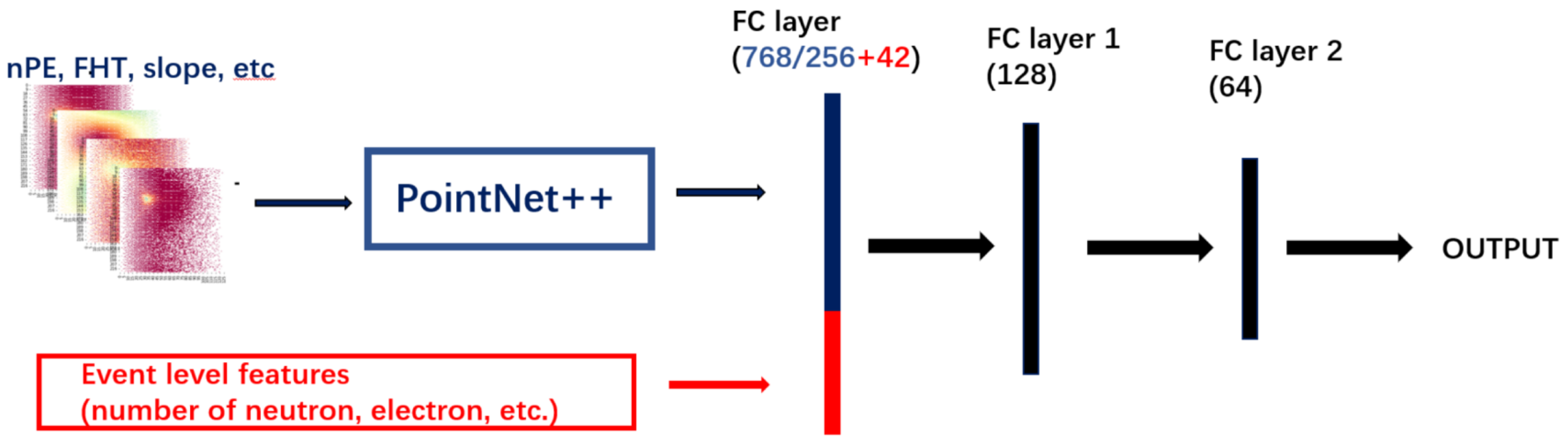
y = E_{had} / E_ν





Particle Identification

- ν_μ vs $\bar{\nu}_\mu$ vs ν_e vs $\bar{\nu}_e$ vs NC classification relies on
  - Event interaction topology, e.g. μ-type vs e-type
  - Hadronic information: energy fraction, neutrons …
- Extracted PMT features of the primary trigger is useful
- Adding event level info (n, e) is good for ν vs $\bar{\nu}$ separation
- Analysis ongoing with full detector simulation and reconstruction

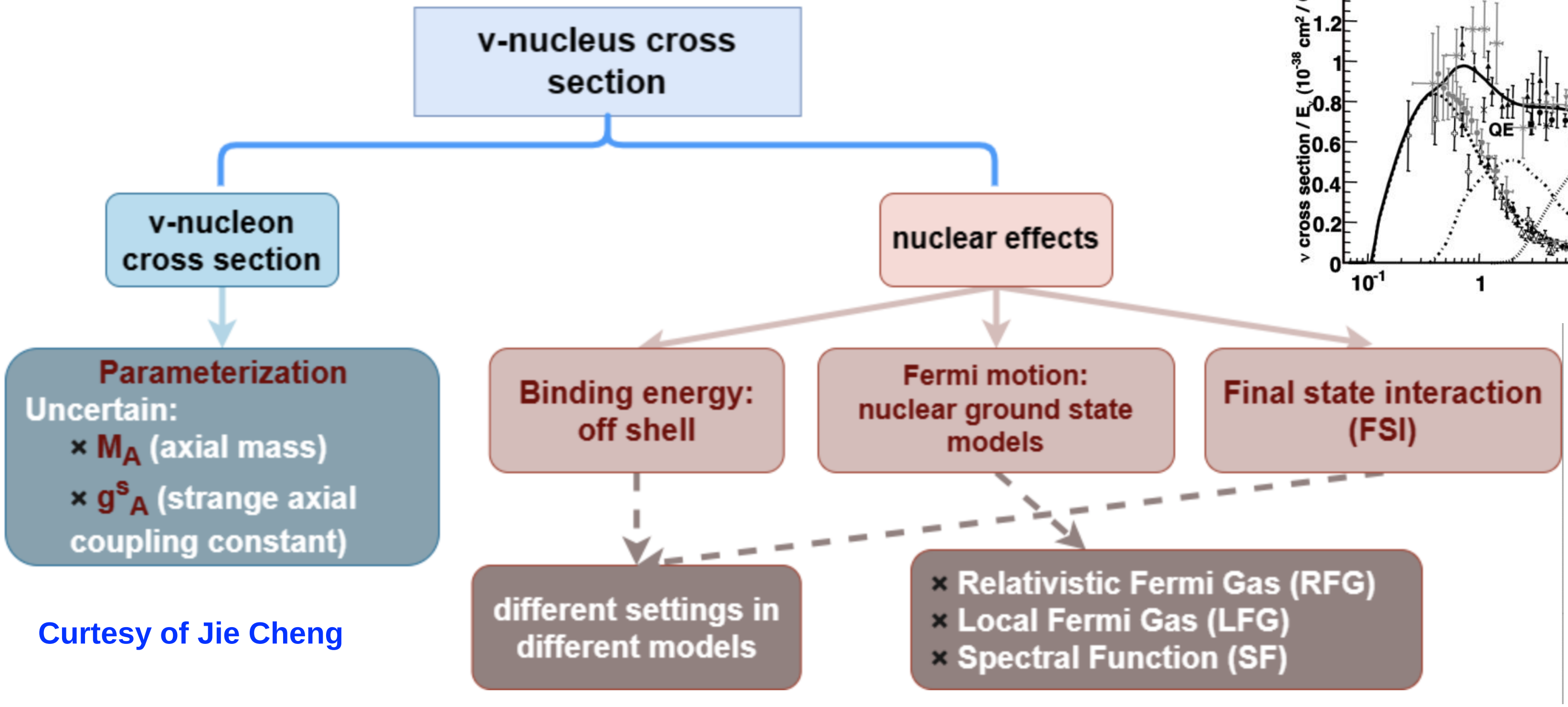


More details in the talk by R. Wirth

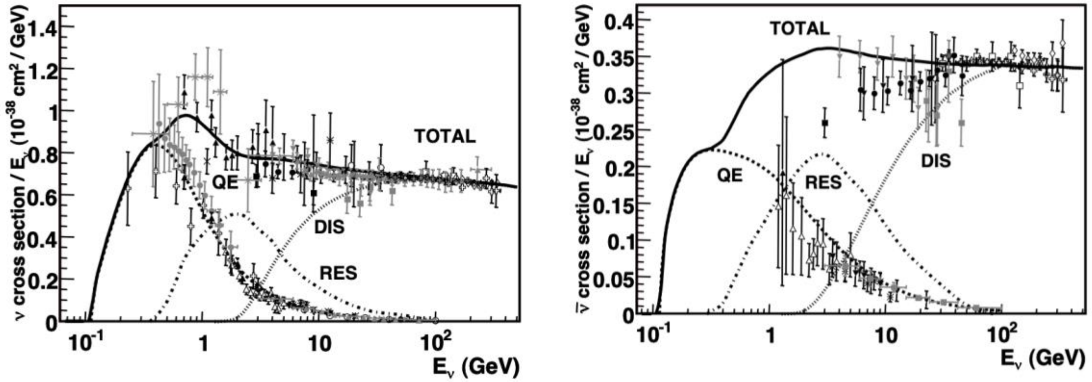
Interaction models

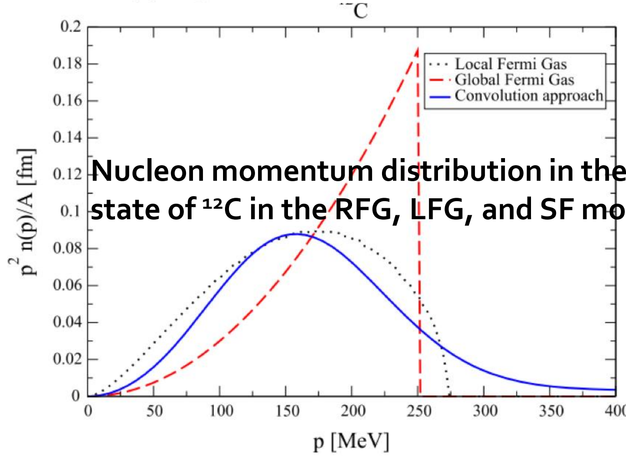
J.A. Formaggio, G.P. Zeller
Rev. Mod. Phys. 84, 1307 (2012)

Brief summary of GeV neutrino interaction models



Curtesy of Jie Cheng



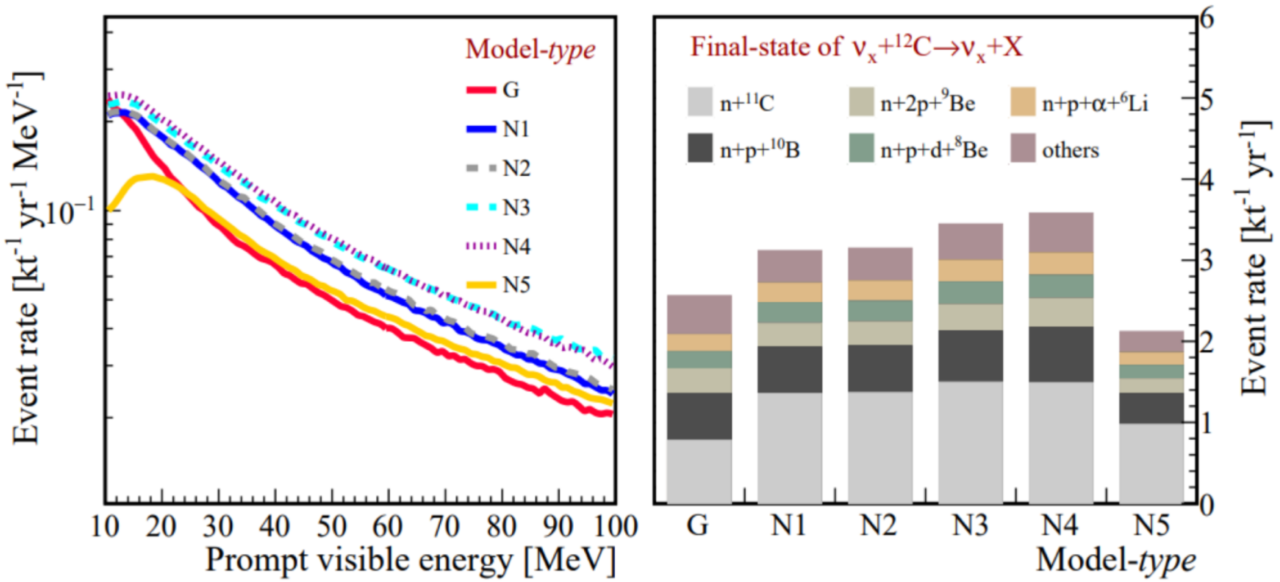


Nucleon momentum distribution in the ground state of ^{12}C in the RFG, LFG, and SF models.

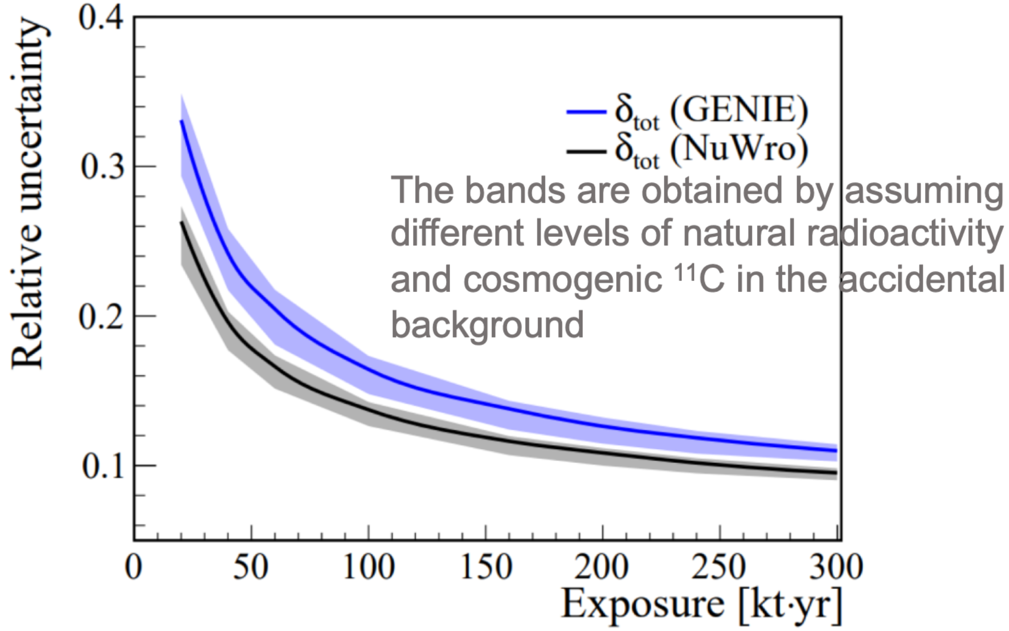
- GeV neutrino interaction is model dependent! Existing generators at JUNO:
  - GENIE/NuWro/GiBUU
  - NEUT incorporation in progress
- We are working on the latest versions of the generators, within the Gev ν-A high-eNergY MEDium Effect (GANYMEDE) working group

Interaction models

Model variation:
Phys.Rev.D 103 (2021) 5, 053001
JCAP 10 (2022) 033



Methodology for In-situ measurement:
Phys.Rev.D 103 (2021) 5, 053002
JCAP 10 (2022) 033

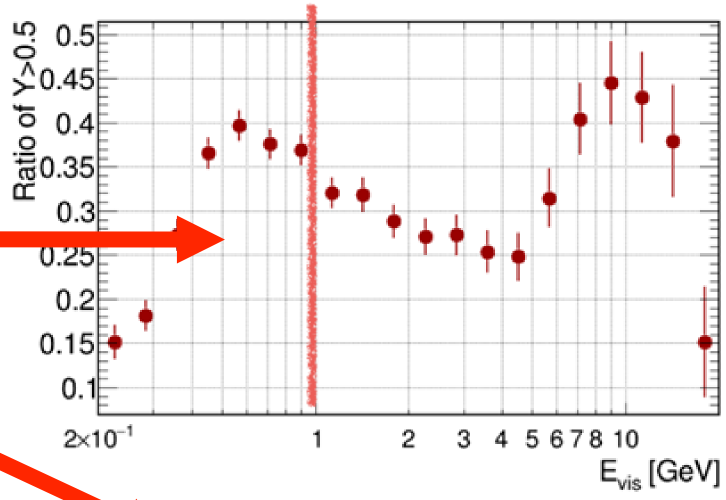


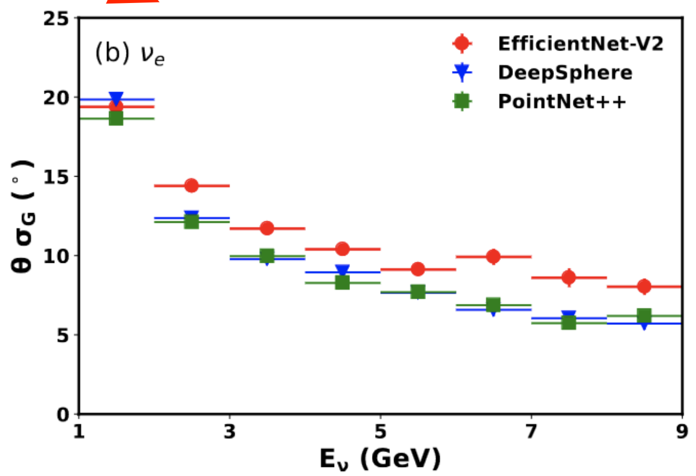
- Proposed methods for estimating interaction uncertainty for GeV neutrinos
  - Model variation: take the difference of the model predictions as one source of the uncertainties
  - *In-situ* measurements: seek unique features within the atm. ν events for *in-situ* measurements
- Developed for NC background prediction in Diffuse Supernova Neutrino Background (DSNB) study, also applicable for GeV CC events

JCAP 10 (2022) 033

NMO improvements

	JUNO Physics Book assumptions	NEW developments	Potential improvement
Event Selection ν_e/ν_e	E_{vis} > 1GeV **$Y_{vis}=E_h/E_{vis}$ < 0.5**	E_{vis} > 1GeV	~30% more stats
Directionality	$\sigma_{\theta\mu}=1^\circ$ **$\sigma_{\theta\nu}=10^\circ$**	**$\sigma_{\theta\nu}<10^\circ$** (E>3GeV)	Better resolution, E-dependent
Classification	CC-e / CC-μ / NC: **100% eff.**	CC-e / CC-μ / NC: **80%~95% eff.**	—
	ν vs $\bar{\nu}$: **simple classification with $N_{michel-e}$, Y_{vis}**	ν vs $\bar{\nu}$: **50%~80% eff.**	Better ν vs $\bar{\nu}$ separation
Energy	$\sigma_{E_{vis}}$ = 1%/√E	$\sigma_{E\nu}$	E_ν instead of E_{vis}





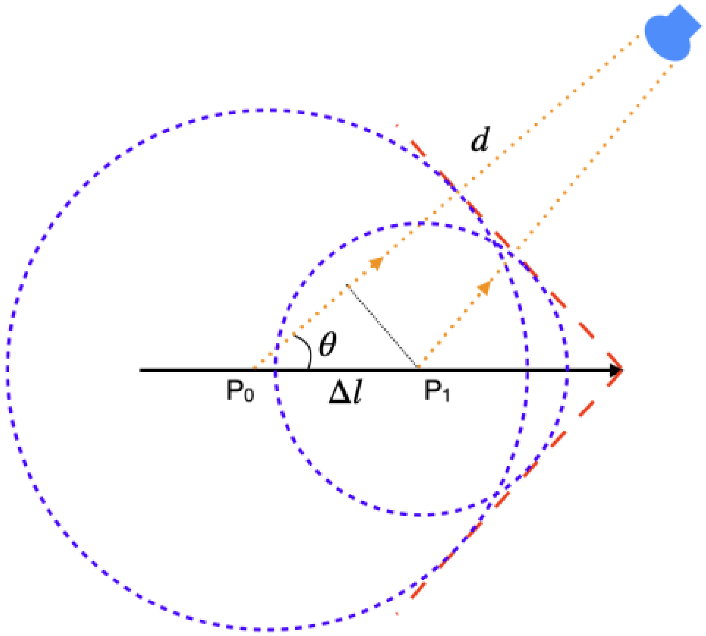
Overall improvement against JUNO Physics book evaluation expected

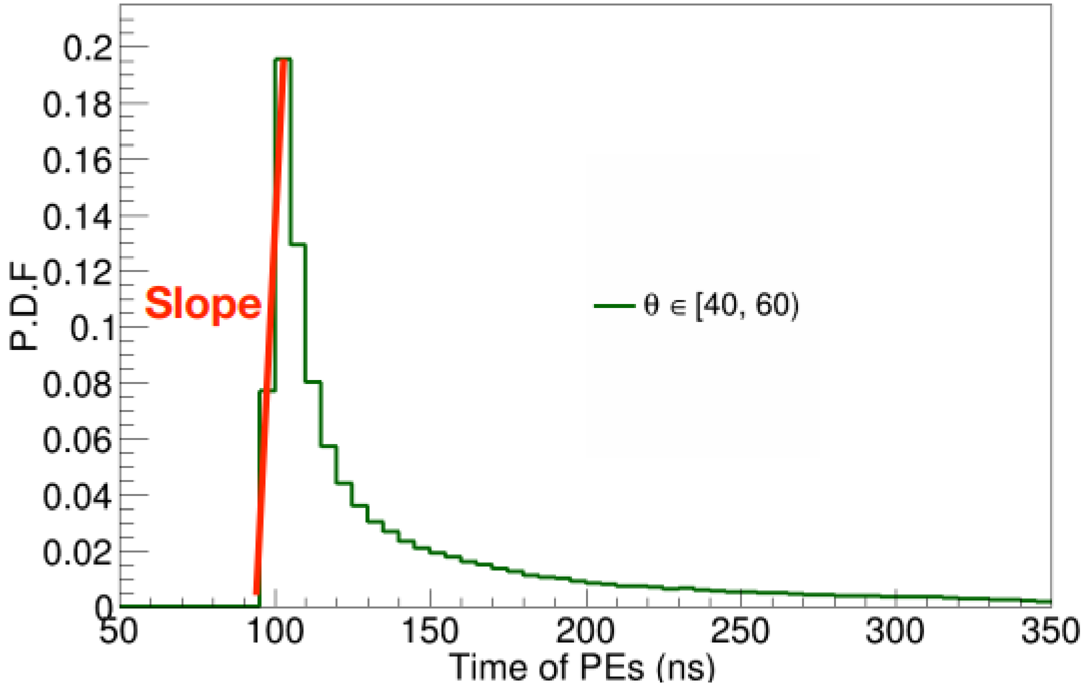
Summary

- Atmospheric neutrino oscillations through MSW can enhance the NMO sensitivity at JUNO
- Many analysis progresses has been made to fully explore its potential
- Techniques for GeV atmospheric neutrino reconstruction (directionality PID, energy) have been developed
  - Critical for oscillation analysis
  - Preliminary results are promising
- Efforts on interaction models
  - evaluation of systematics
  - *in-situ* measurements with JUNO data to constrain model
- Stay tuned

Backup

Directionality





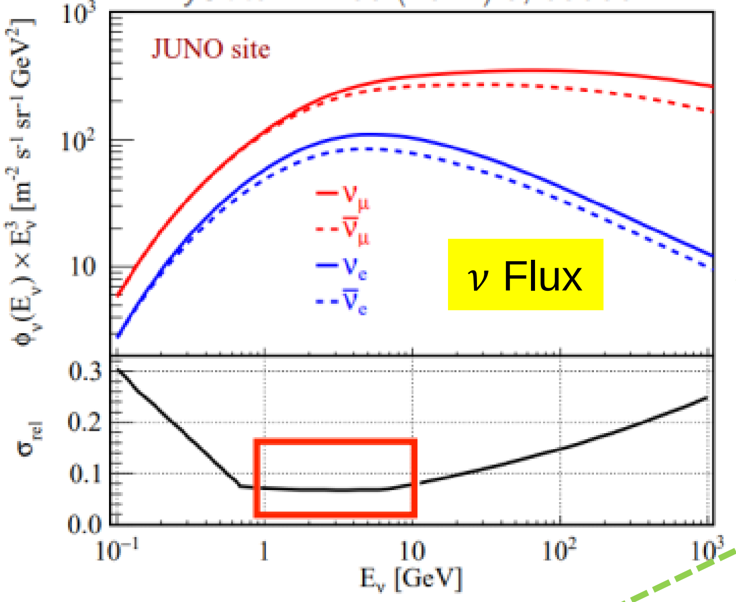
$$\Delta t = \left| \frac{\Delta l}{v} - \frac{\Delta l \cos\theta}{c/n} \right| = \Delta l \left| \frac{1 - n\beta\cos\theta}{v} \right|$$

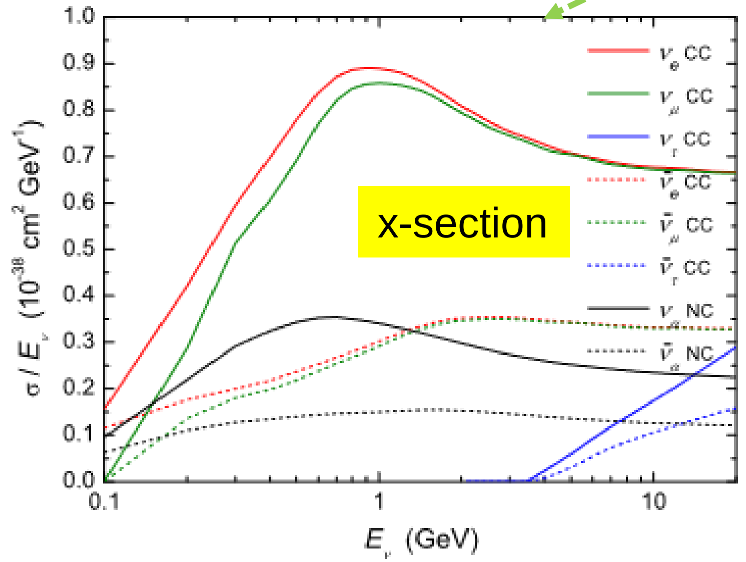
$$\frac{\mathrm{d}l}{\mathrm{d}t} = \frac{v}{|1 - n\beta\cos\theta|}$$

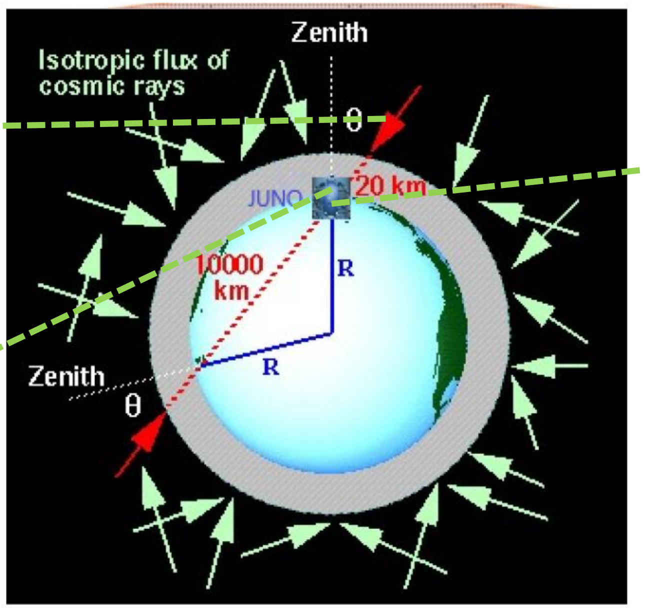
- Scintillation photon dl/dt reaches maximum at Cherenkov angle

Atmospheric neutrinos

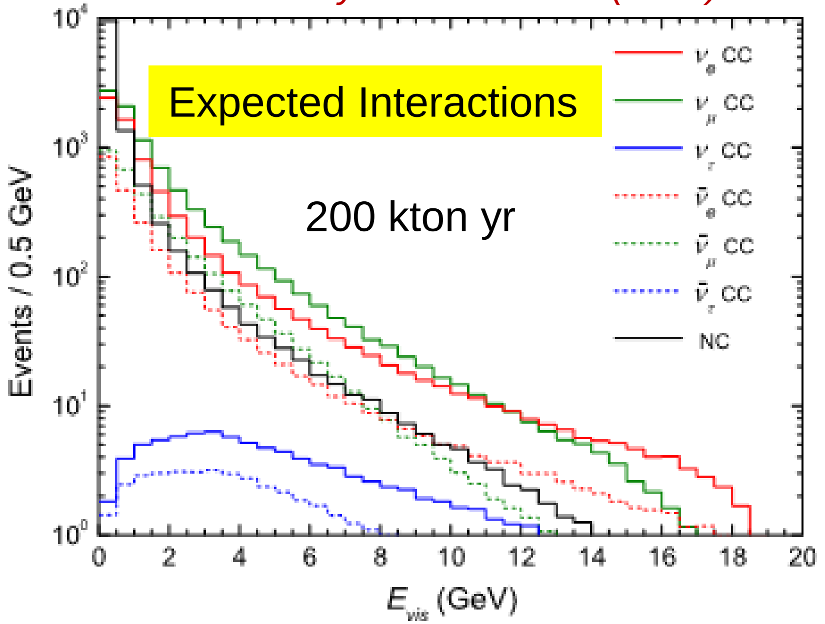
Phys.Rev.D 103 (2021) 5, 053001







J. Phys. G43:030401 (2016)



ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC	ν_τ CC	$\bar{\nu}_\tau$ CC	NC
8662	3136	6637	2221	90	40	12255