Atmospheric Neutrino Oscillations at JUNO

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on behalf of JUNO

31st International Symposium on Lepton Photon Interactions at High Energies@Melbourne

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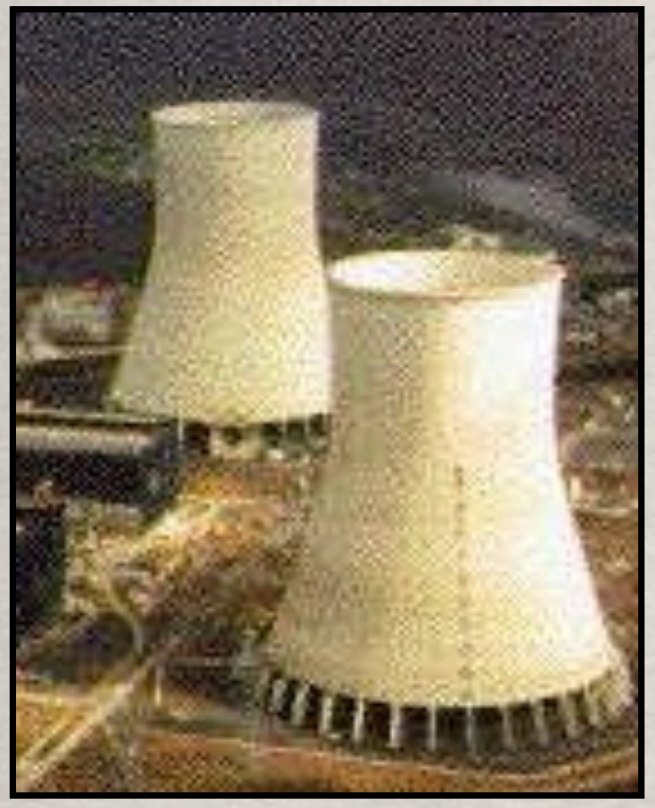
JUNO

OUTLINE

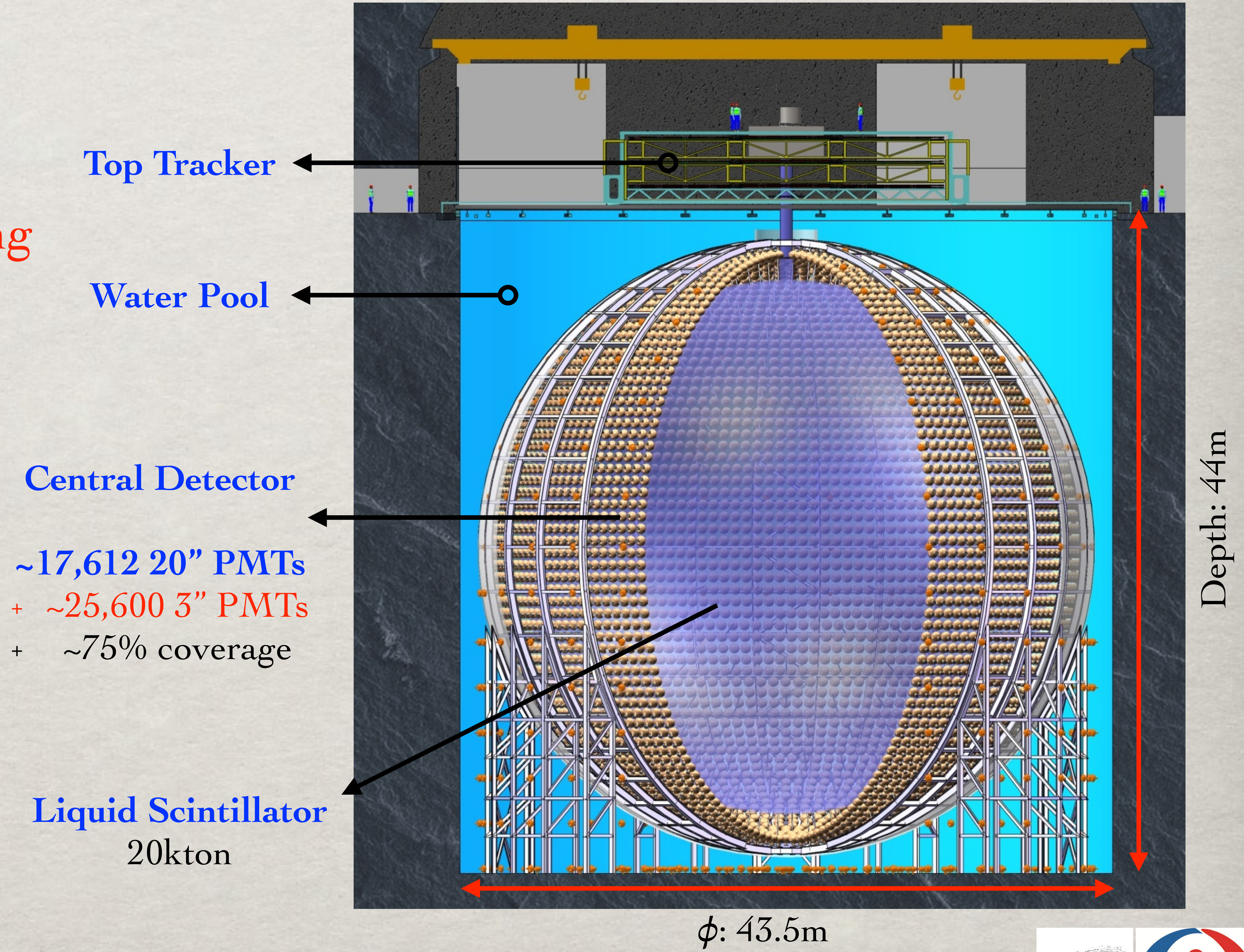
- Introduction to JUNO and atm. Neutrinos
- Updates w.r.t. JUNO Yellow Book
  - Neutrino flux and interactions
  - Directionality and PID
  - Event selection
- Summary and outlook

JUNO

- Jiangmen Underground Neutrino Observatory(JUNO):
  - Determine the neutrino mass ordering
  - Measure neutrino oscillation parameters to sub-percent level
  - SuperNova, Solar, Atm. Geo. etc



	DETECTOR TARGET MASS	ENERGY RESOLUTION
KamLAND	1000 t	6%@1MeV
D. Chooz	8+22 t	
RENO	16 t	8%@1MeV
Daya Bay	20 t	
Borexino	300 t	5%@1MeV
JUNO	**20000 t**	3%@1MeV



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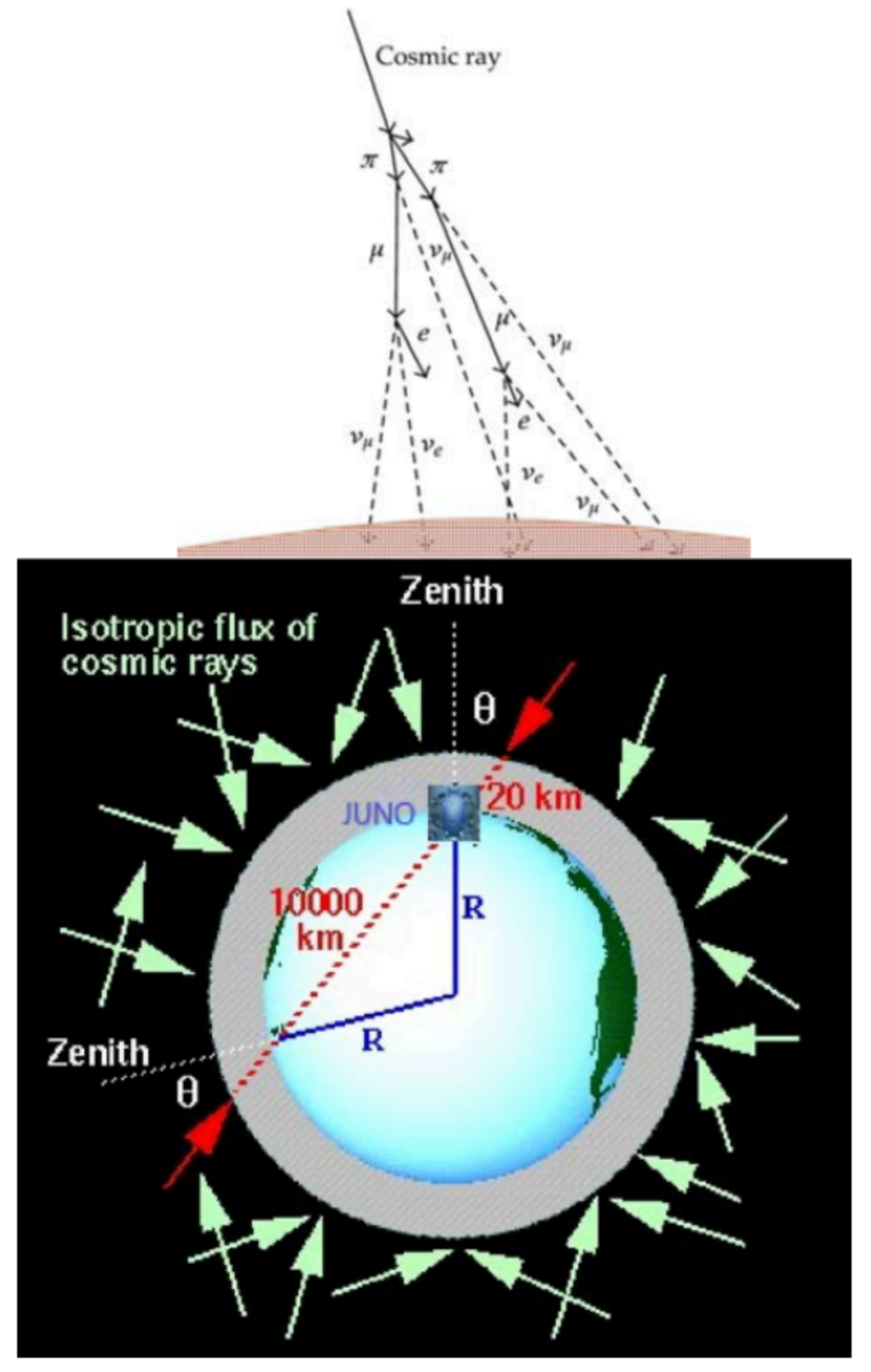
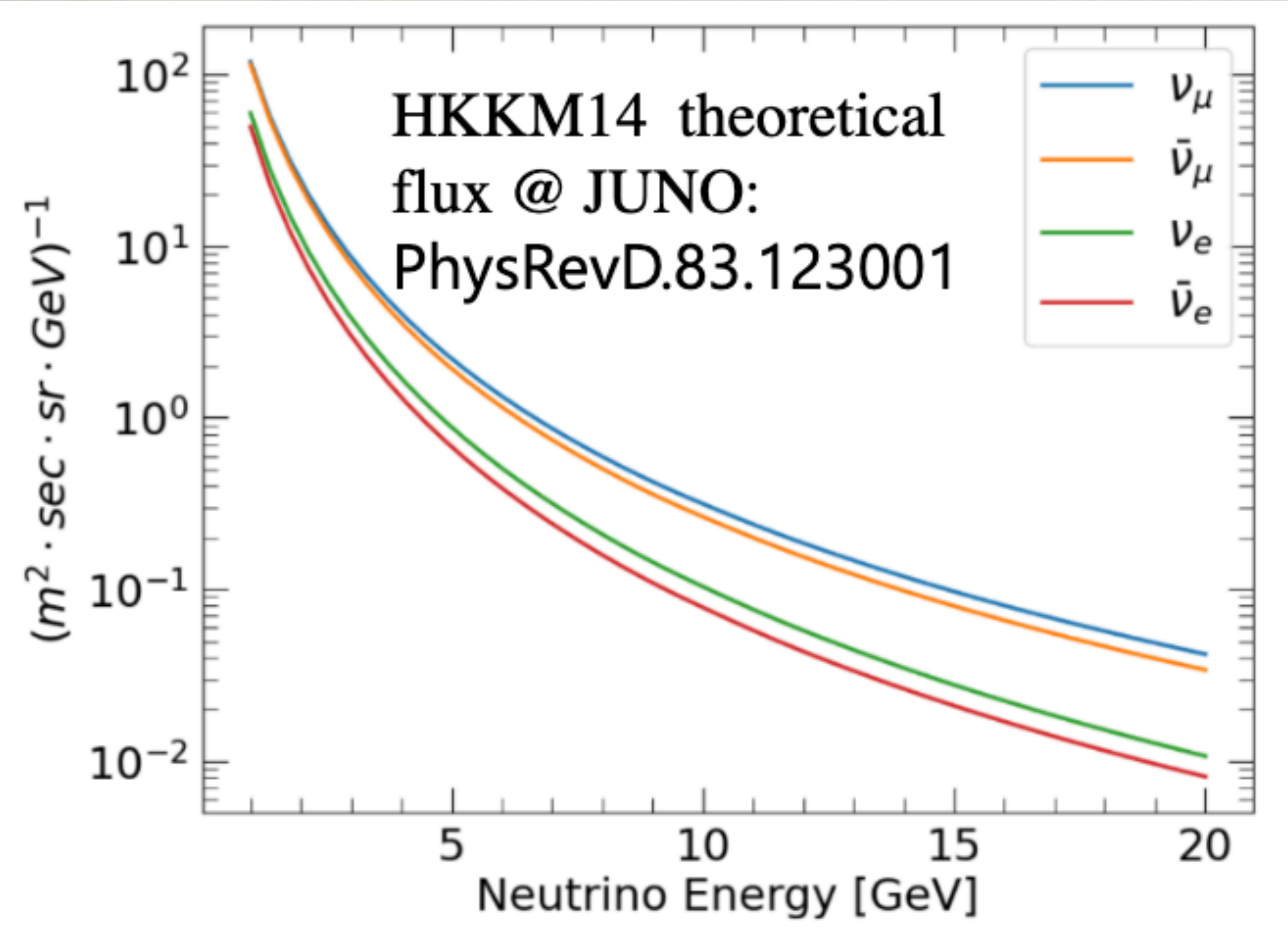
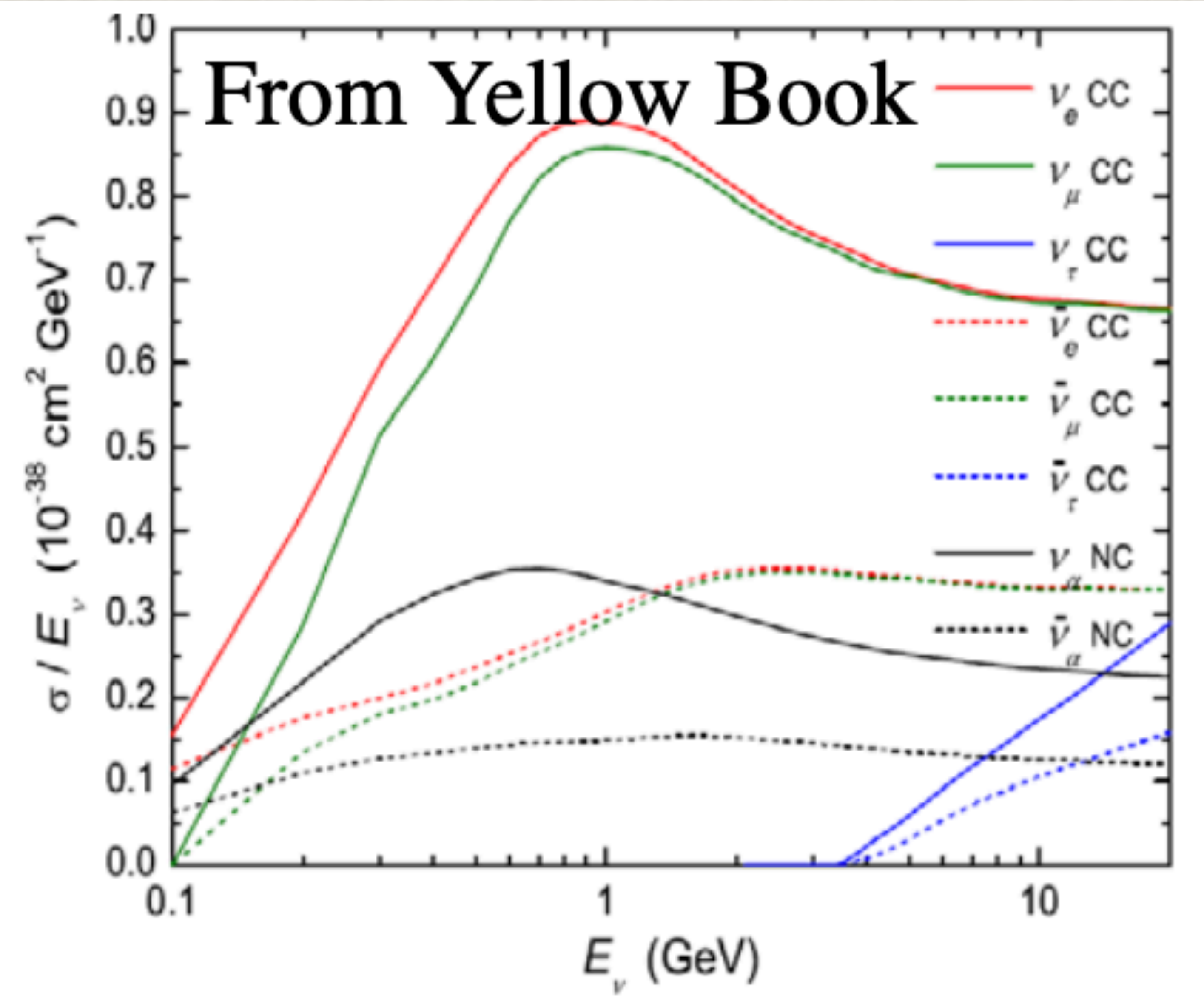


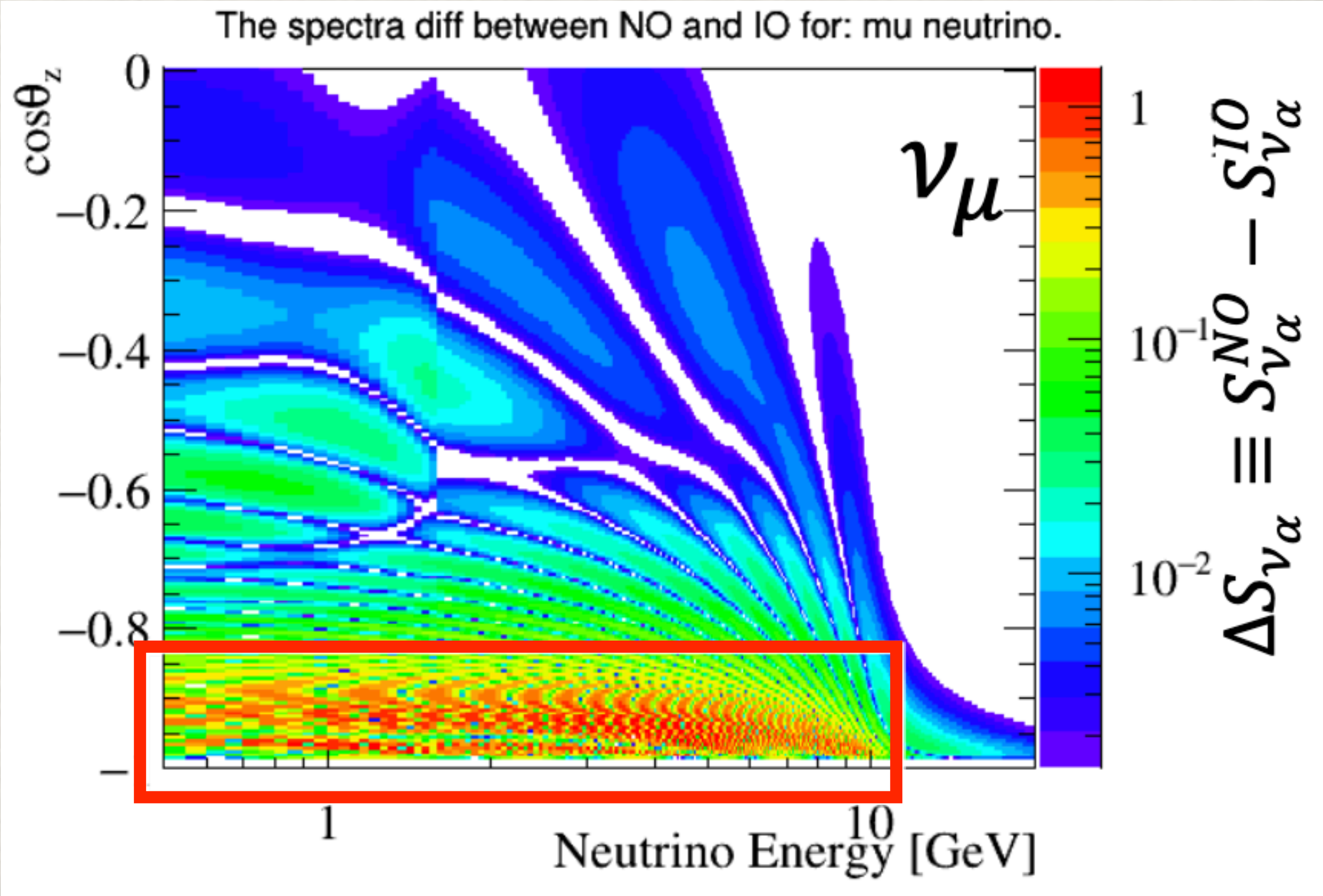
ATM. ν OSCILLATION

- **Production**: Cosmic Rays interact with Earth's atmosphere, decay of secondary mesons
- **Propagation**: oscillation in matter, sensitive to NMO
- **Detection**: interact with nuclei via Charge Current (CC) or Neutral Current (NC)

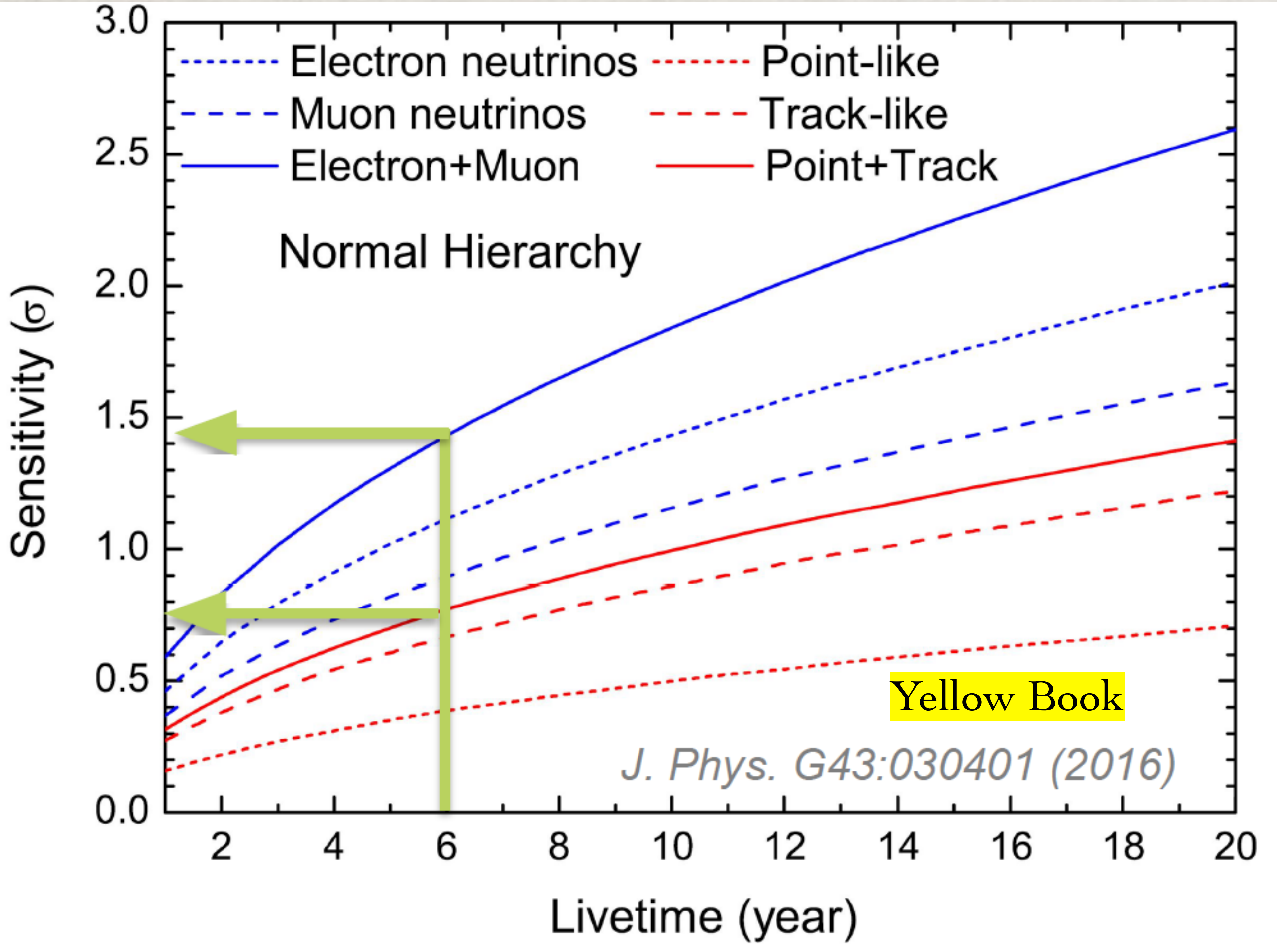
J. Phys. G: 43 (2016) 030401

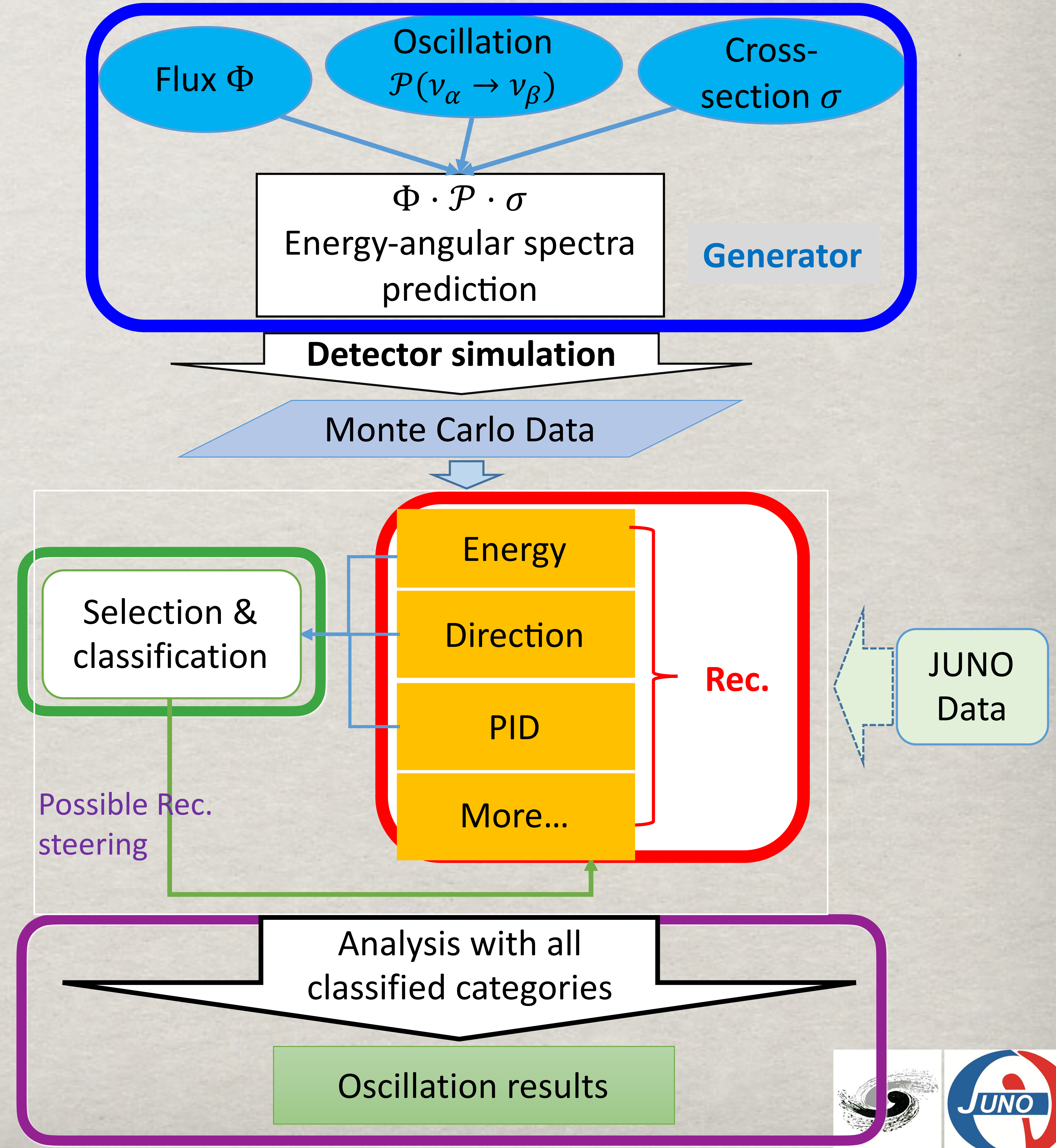






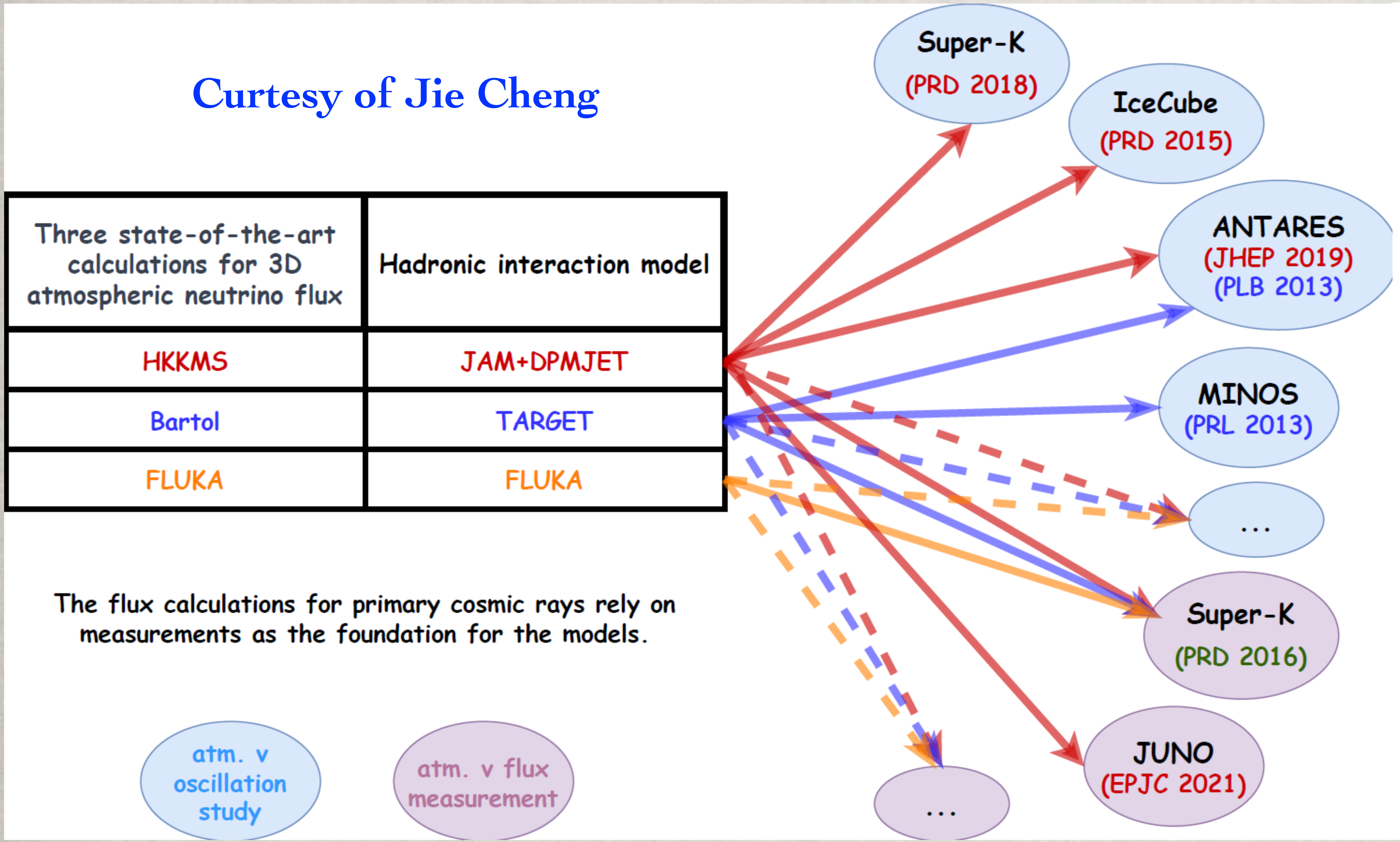
ATM. ν OSCILLATION@JUNO



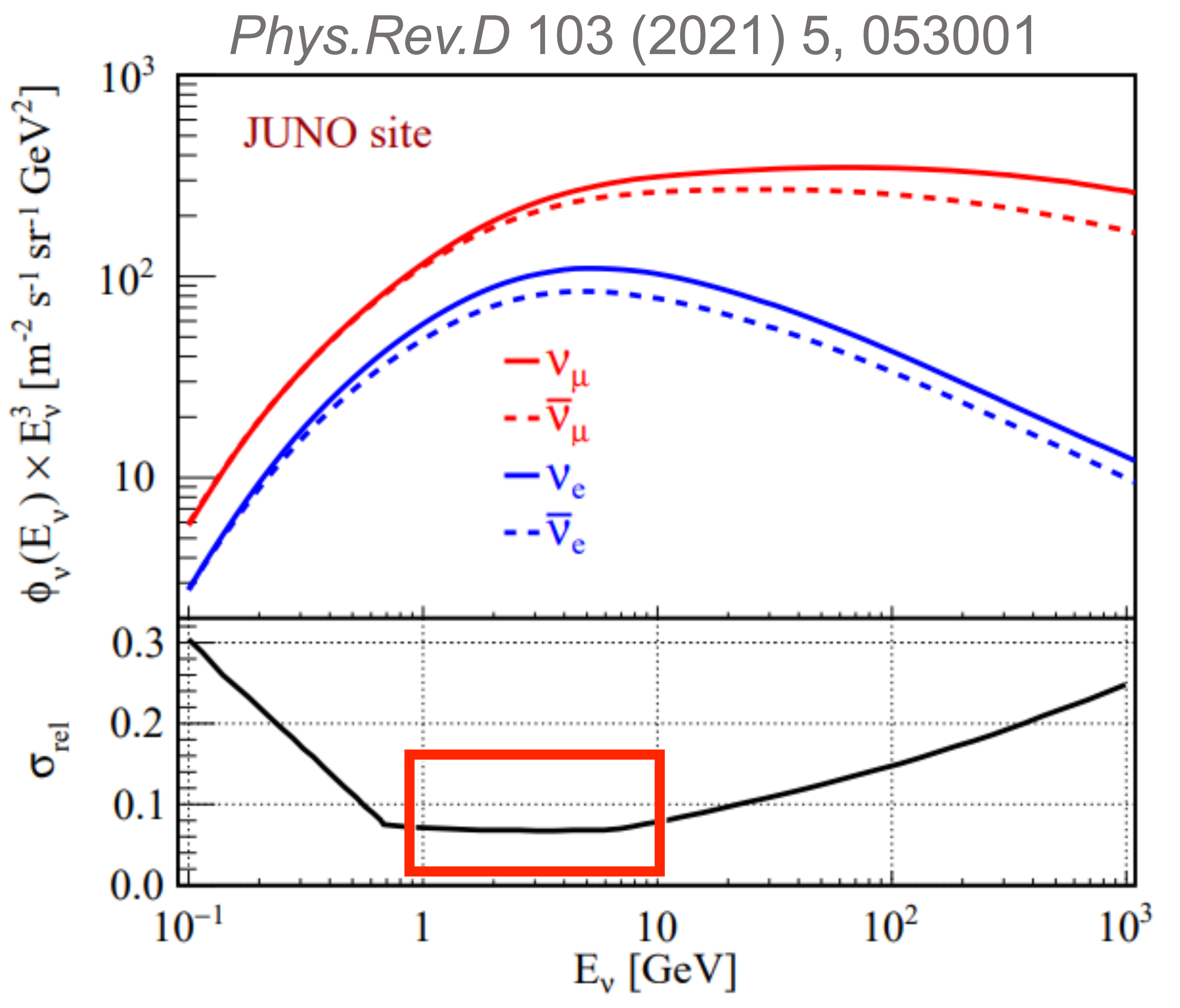


- Optimistic NMO sensitivity from JUNO Yellow Book: ~1.4σ@6years
- JUNO ensitivity to low energy atmospheric neutrino spectra (Eur.Phys.J.C 81 (2021) 10)
- Significant progress on the analysis components

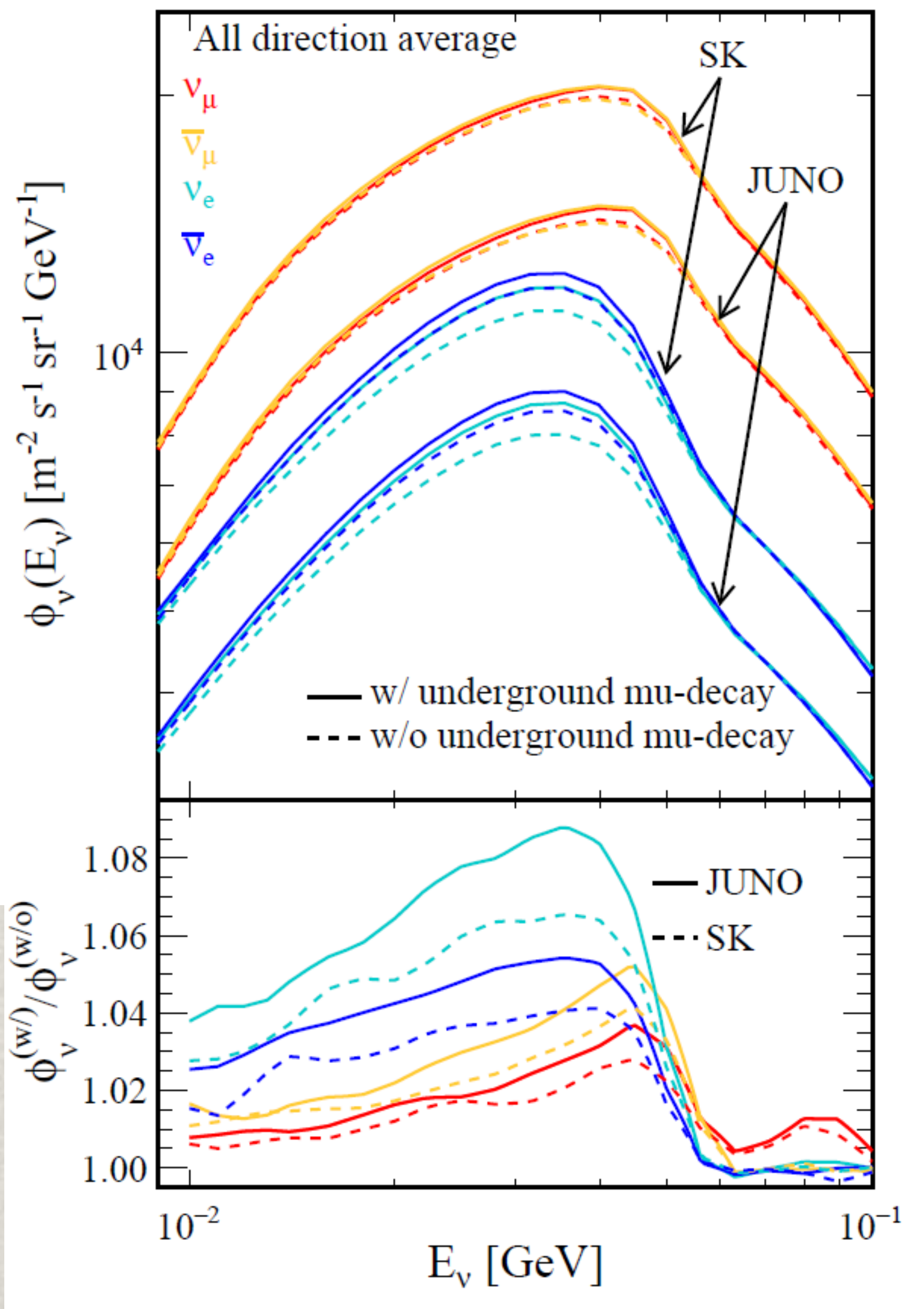
Flux



Three state-of-the-art calculations for 3D atmospheric neutrino flux	Hadronic interaction model
HKKMS	JAM+DPMJET
Bartol	TARGET
FLUKA	FLUKA



Curtesy of the Honda Group



Curtesy of Jie Cheng

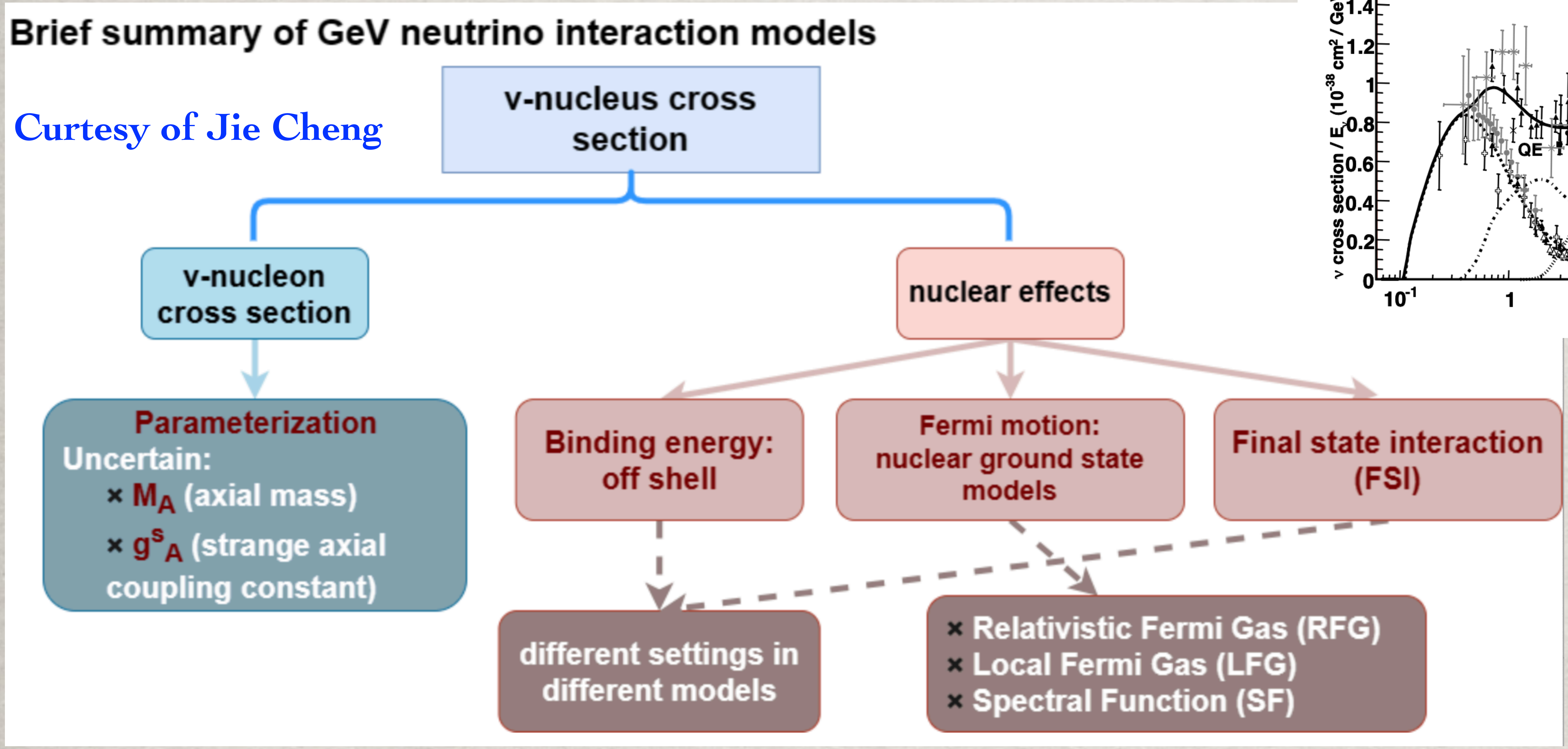
- HKKMS atmospheric neutrino flux model for JUNO
- Flux calculation developed from 10 MeV to 100GeV

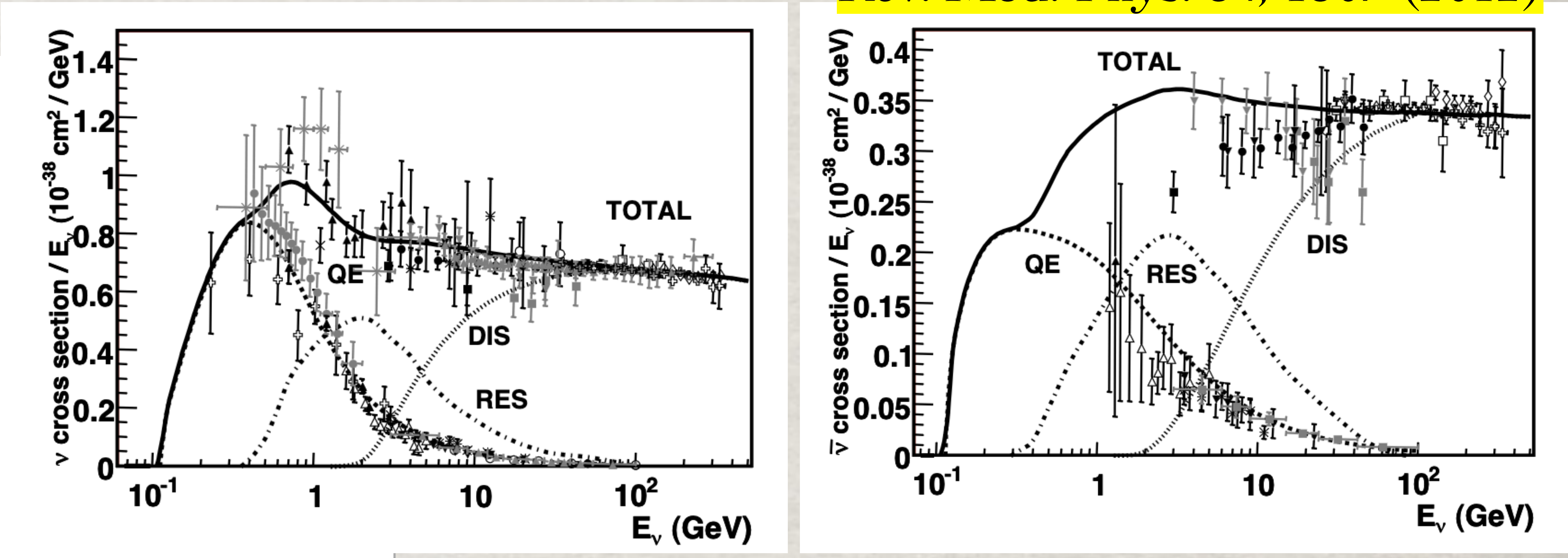
Jie Cheng@WANP2022

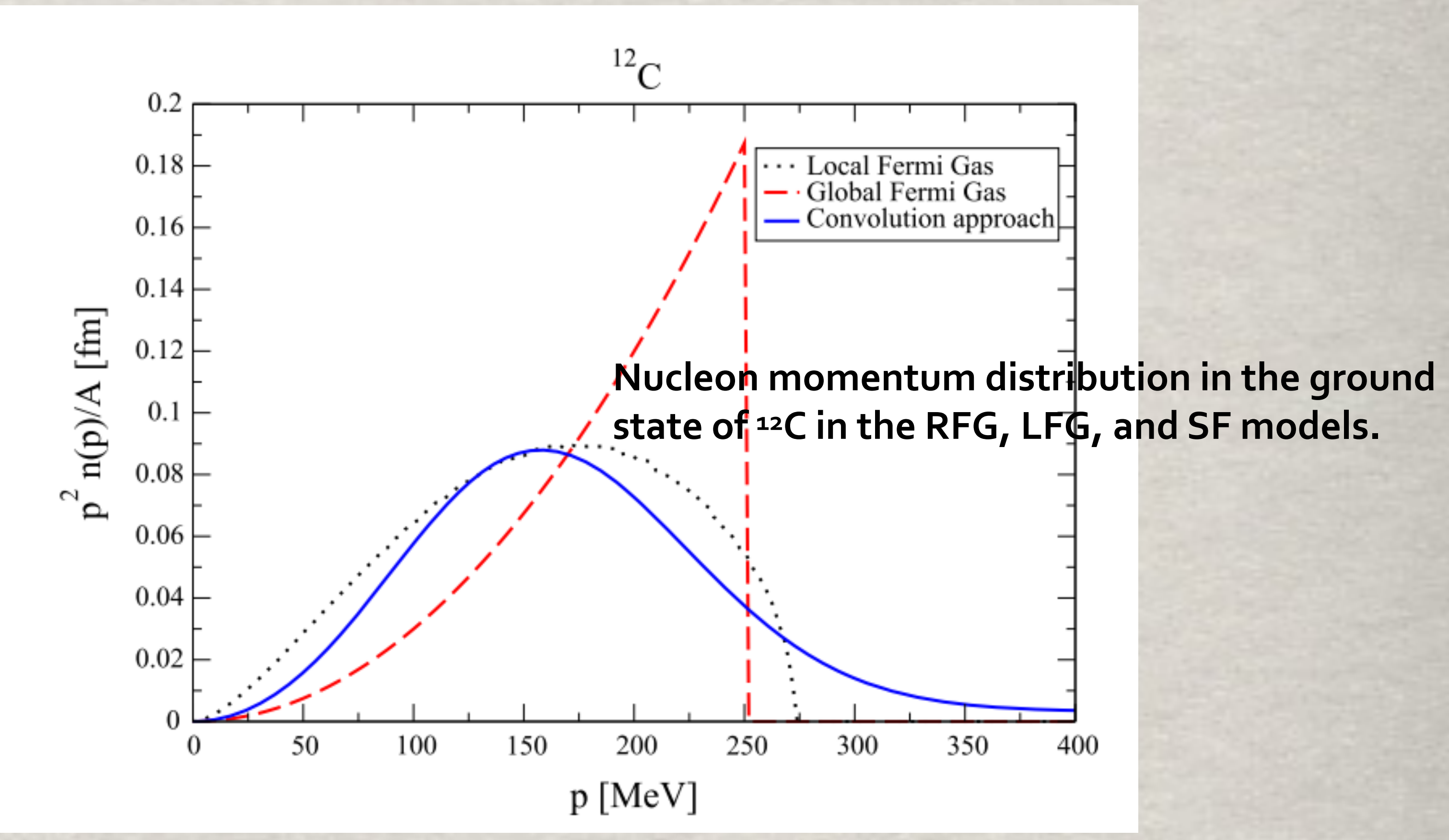
Sato Kazufumi@Neutrino2022

INTERACTION MODELS

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







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

Kaile Wen@Neutrino 2022

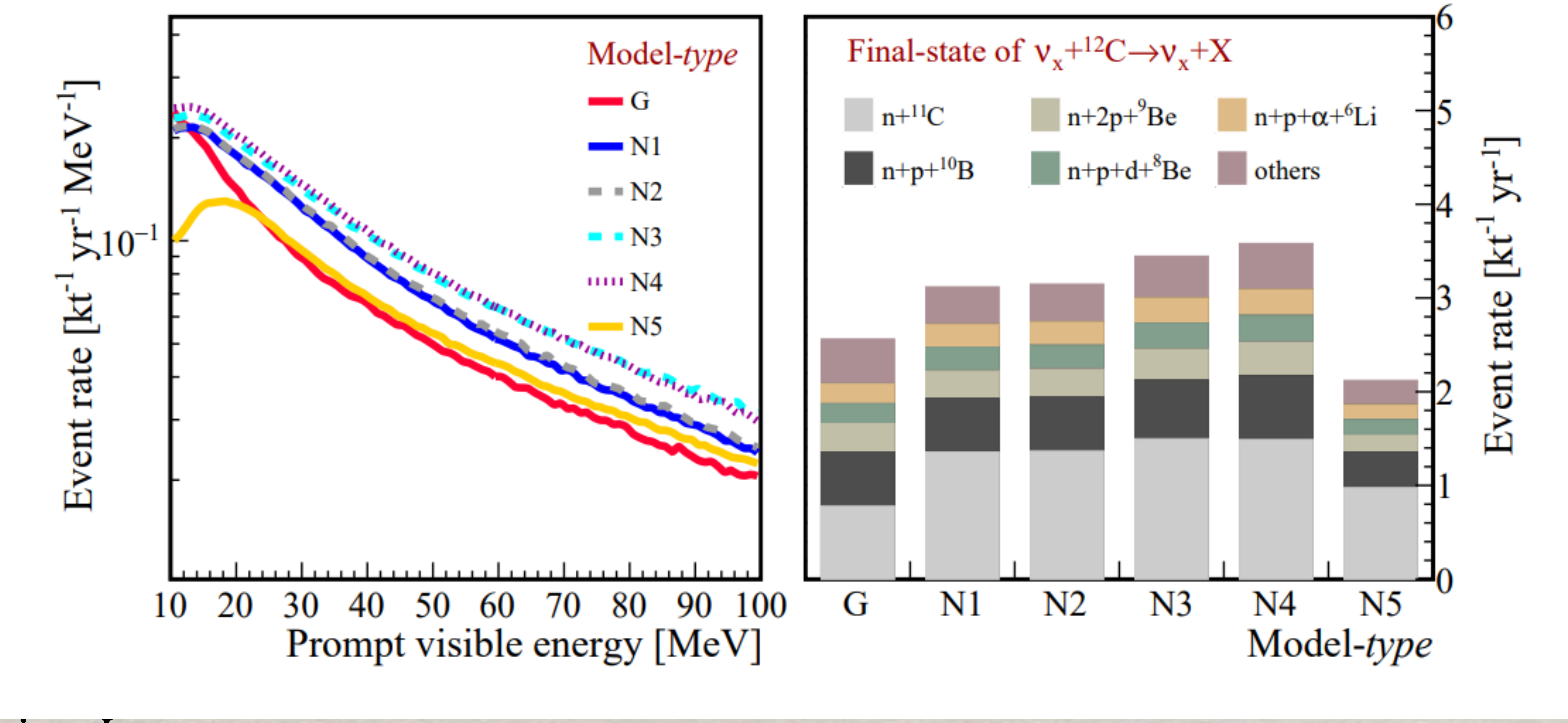
INTERACTION UNCERTAINTY

- Proposed methods of 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

Model variation:

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

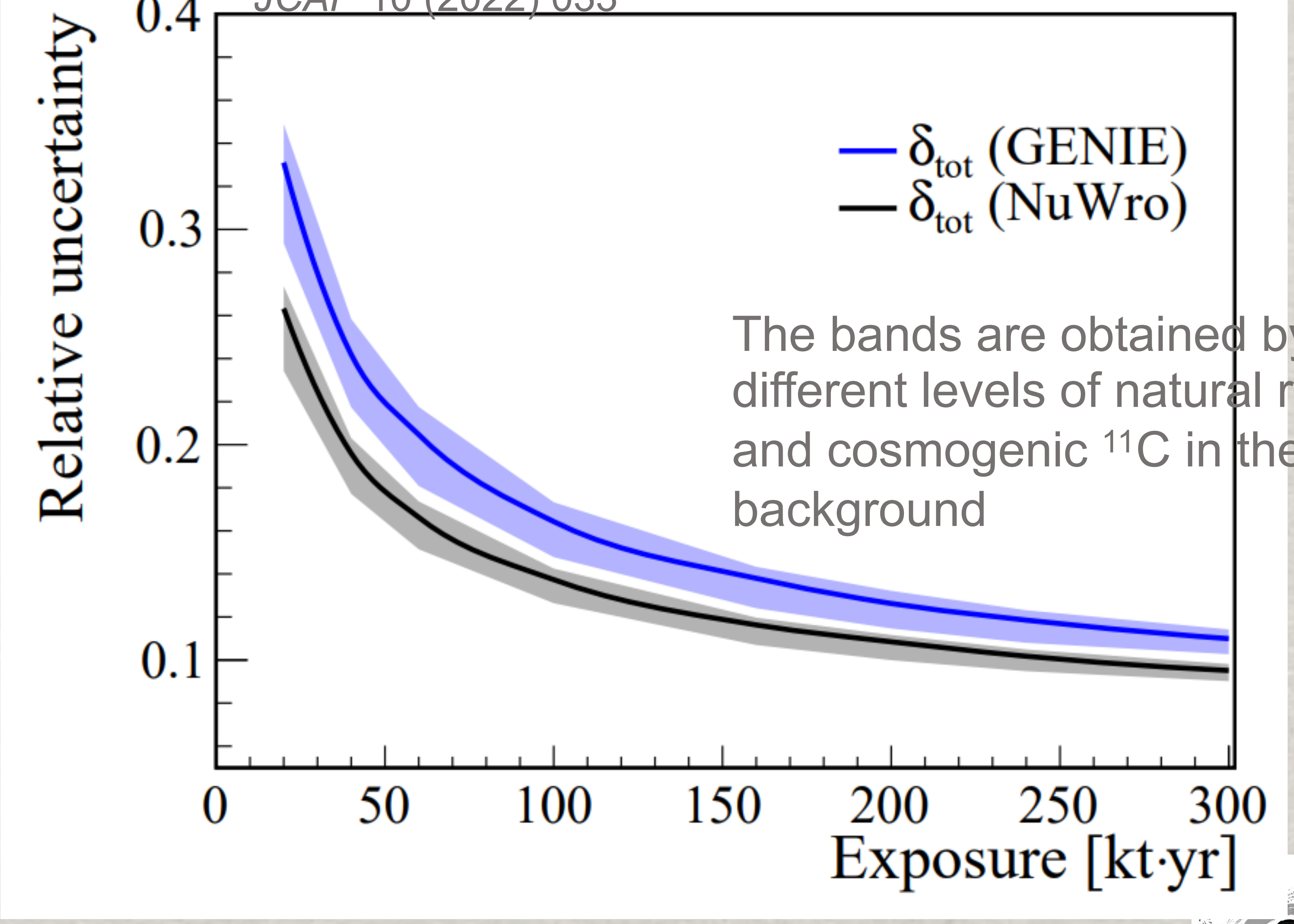
JCAP 10 (2022) 033



Methodology for In-situ measurement:

Phys.Rev.D 103 (2021) 5, 053002

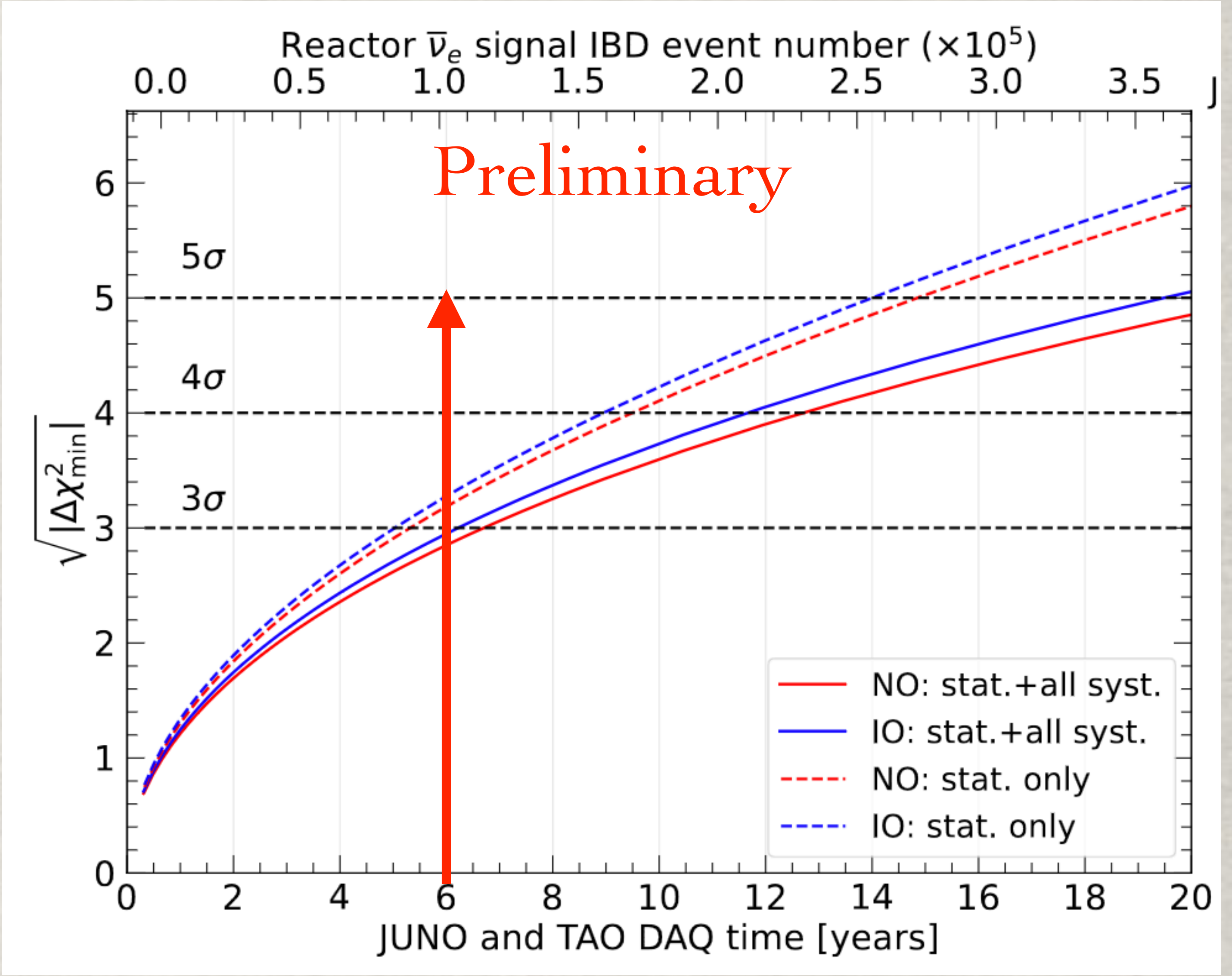
JCAP 10 (2022) 033



The bands are obtained by assuming different levels of natural radioactivity and cosmogenic ^{11}C in the accidental background

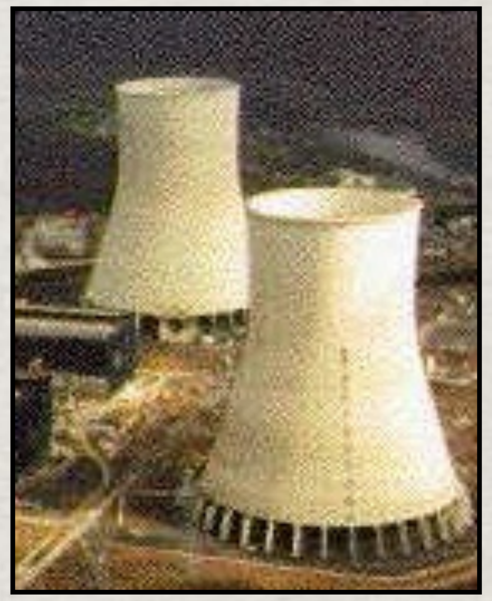
JUNO NMO SYNERGY

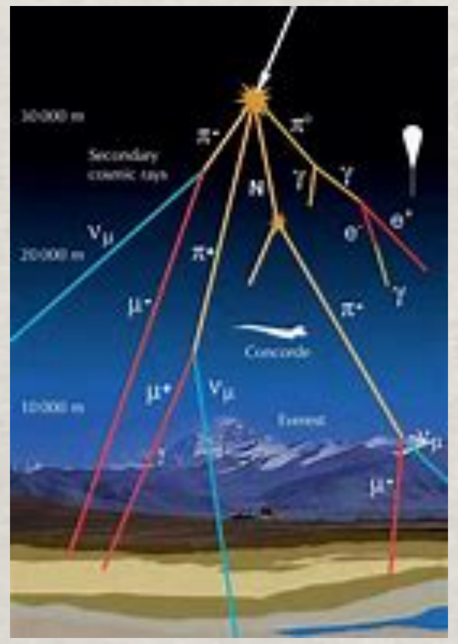
km baseline neutrino experiments by Liang Zhan



- NMO @ 6years $\Delta\chi^2$: Reactor(~ 9), atm.(~ 1.96), $|\Delta m^2_{ee}|$(4|1.5% or 9|1%)
- 1.96 of atm. was estimated with assumptions
- Can we do better than Yellow Book?

	Yellow Book assumptions
Event Selection $\nu_e/\overline{\nu}_e$	$E_{vis} > 1$GeV $Y_{vis}=E_h/E_{vis} < 0.5$
Directionality	$\sigma_{\theta\mu} = 1^\circ$ $\sigma_{\theta\nu} = 10^\circ$
Classification	CC-e vs CC-μ vs NC: 100% eff. ν vs $\overline{\nu}$: Ne, Y_{vis},
Energy	$\sigma_{Evis} = 1\%/\sqrt{E}$





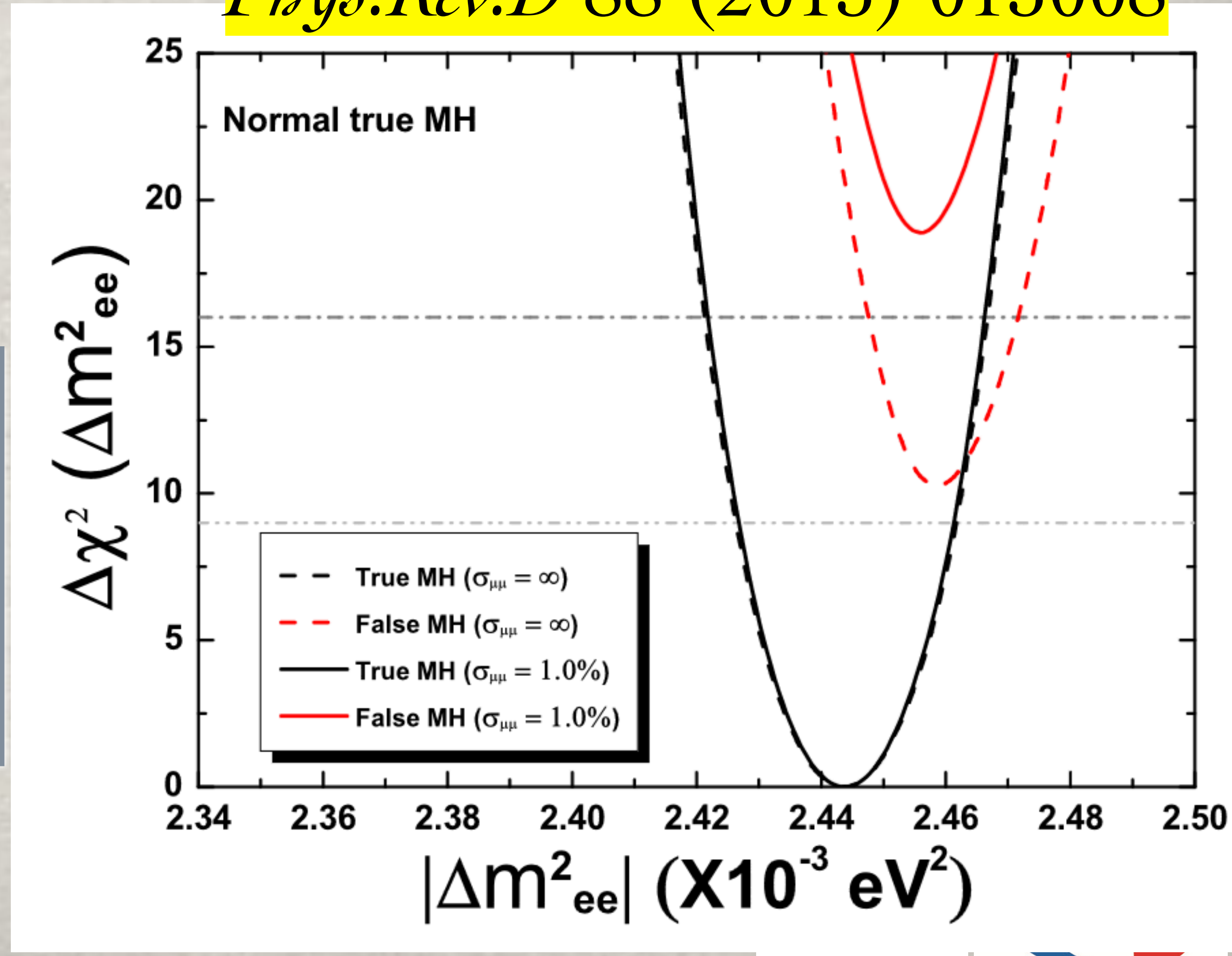
reactor ν
MeV

Neutrino Mass Ordering

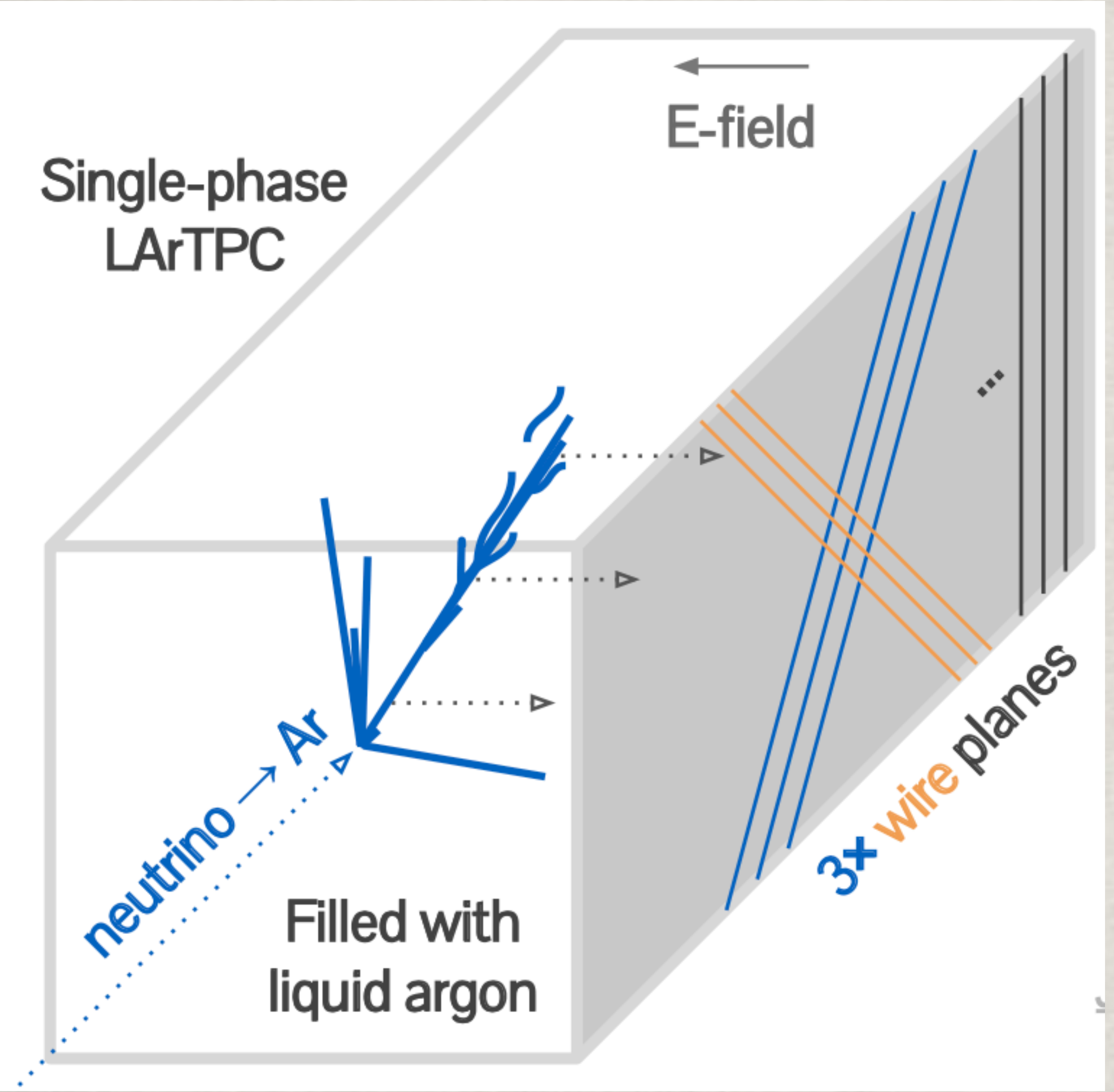
atm.ν
GeV

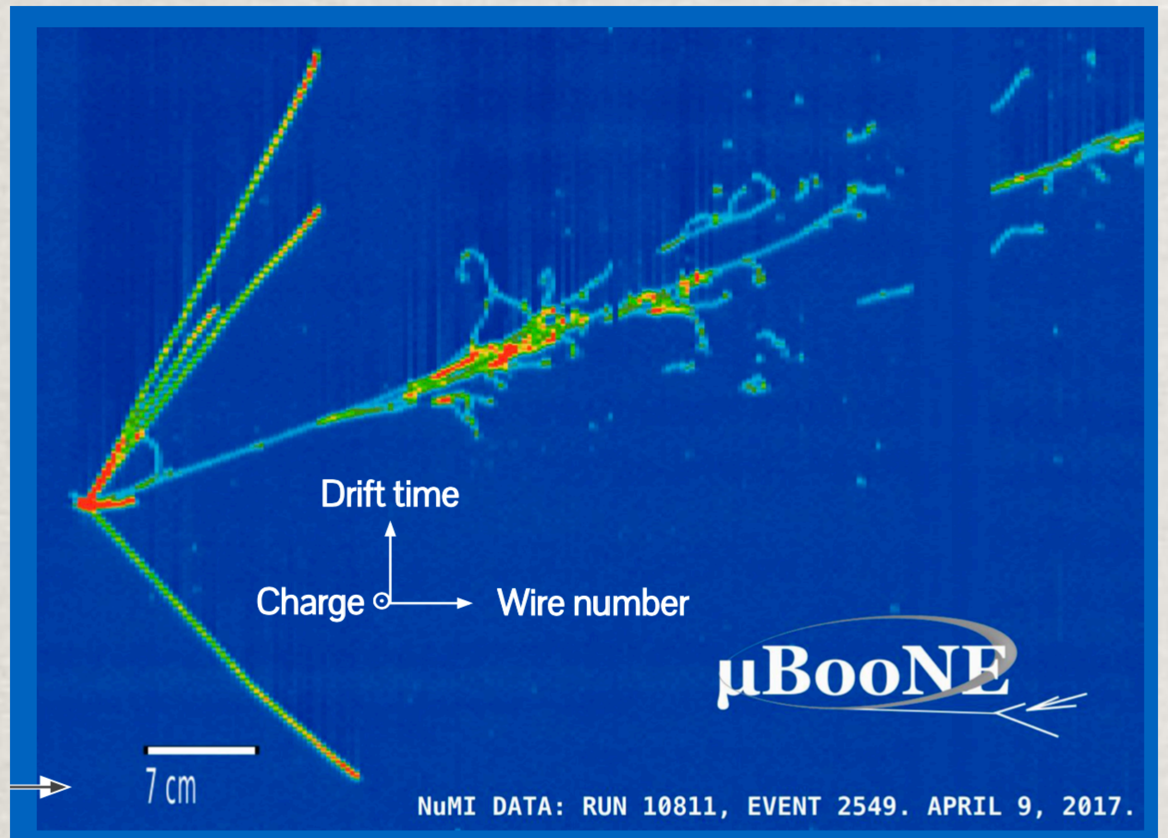
$|\Delta m^2_{\alpha\alpha}|$

Yufeng Li et al. *Phys.Rev.D* 88 (2013) 013008



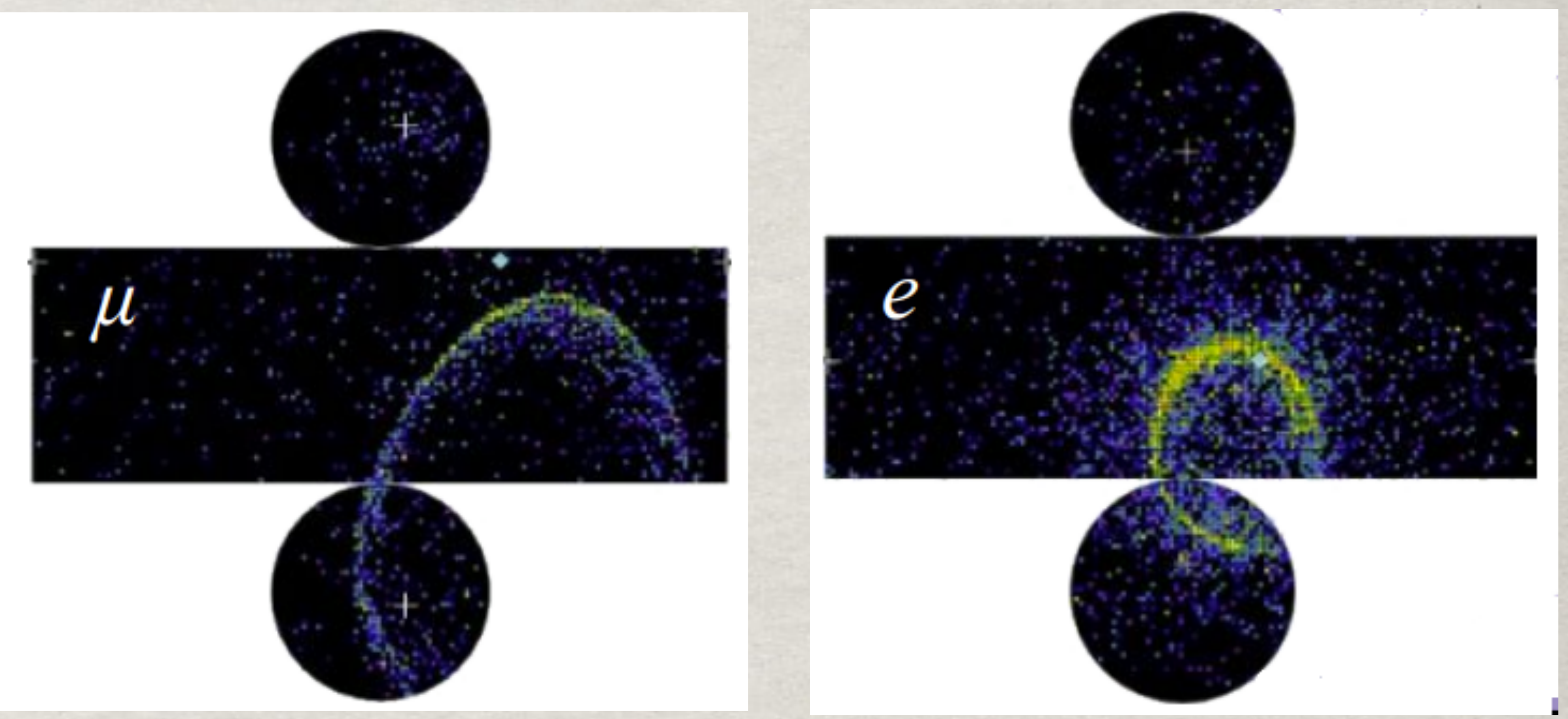
CHALLENGES AND OPPORTUNITIES





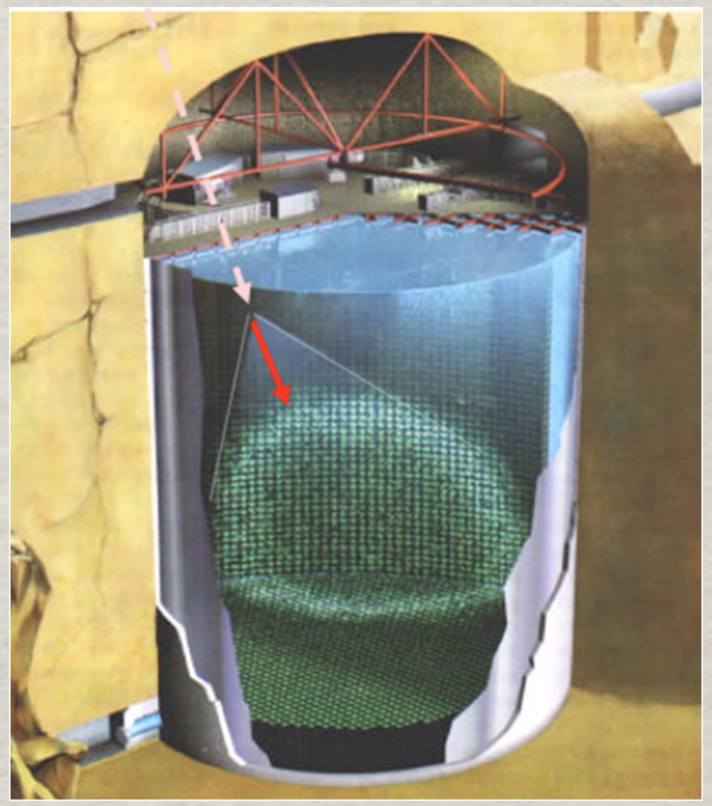
A neutrino interaction image from one wire plane in MicroBooNE

- Very high resolution calorimeter - millimeter-scale
- Can resolve individual particles down to low energies
- 3×2D views ⇒ 3D imaging



LArTPC

Water Cherenkov

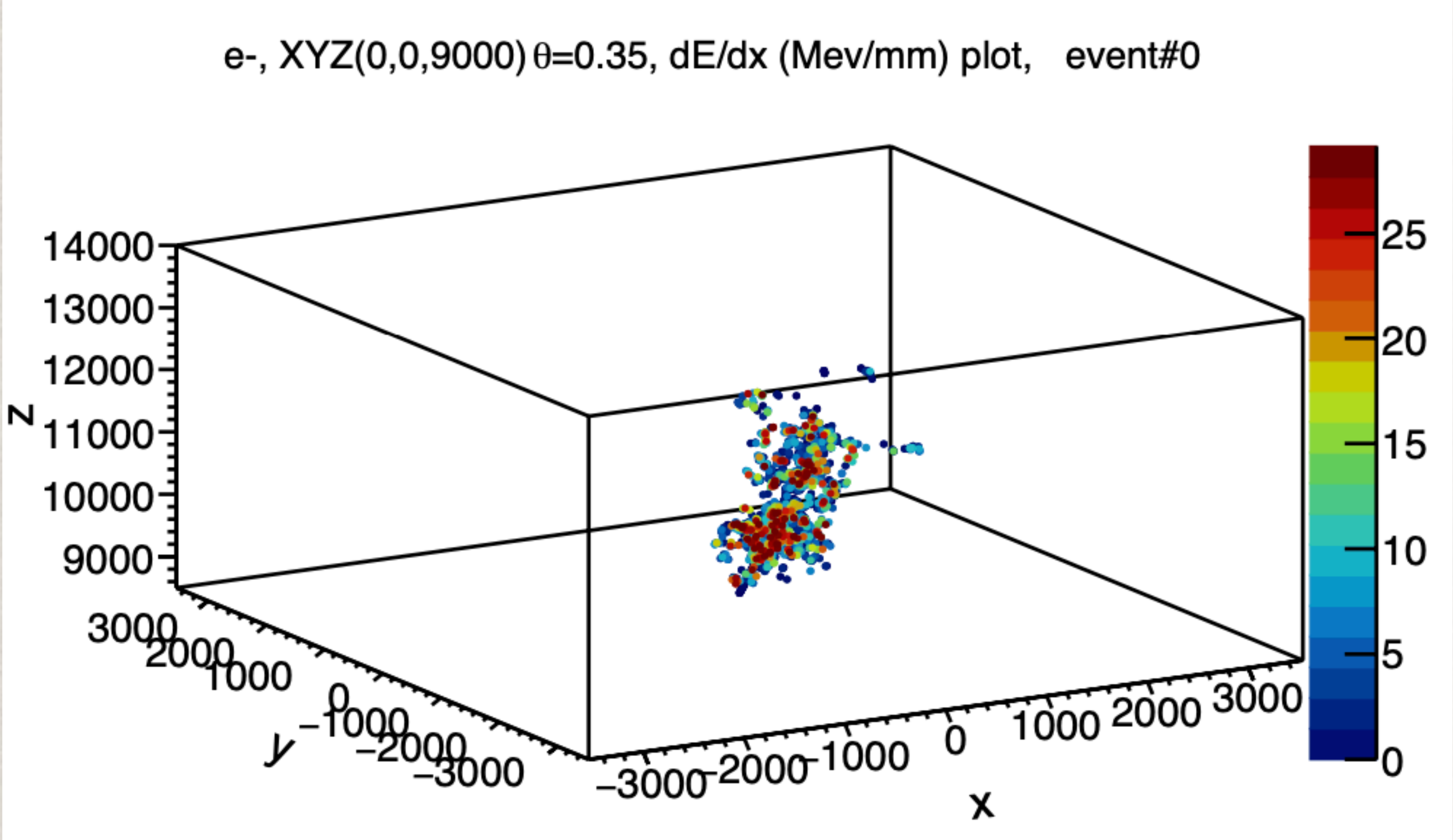


- Neither track information, nor Cherenkov rings for JUNO
- Can we still do <u>Direction reco and PID</u> for JUNO?
- Advantages of JUNO: 1. large PMT coverage(75%); 2. excellent neutron tagging; 3. hadronic component visible in LS; 4. can measure distinctive isotopes

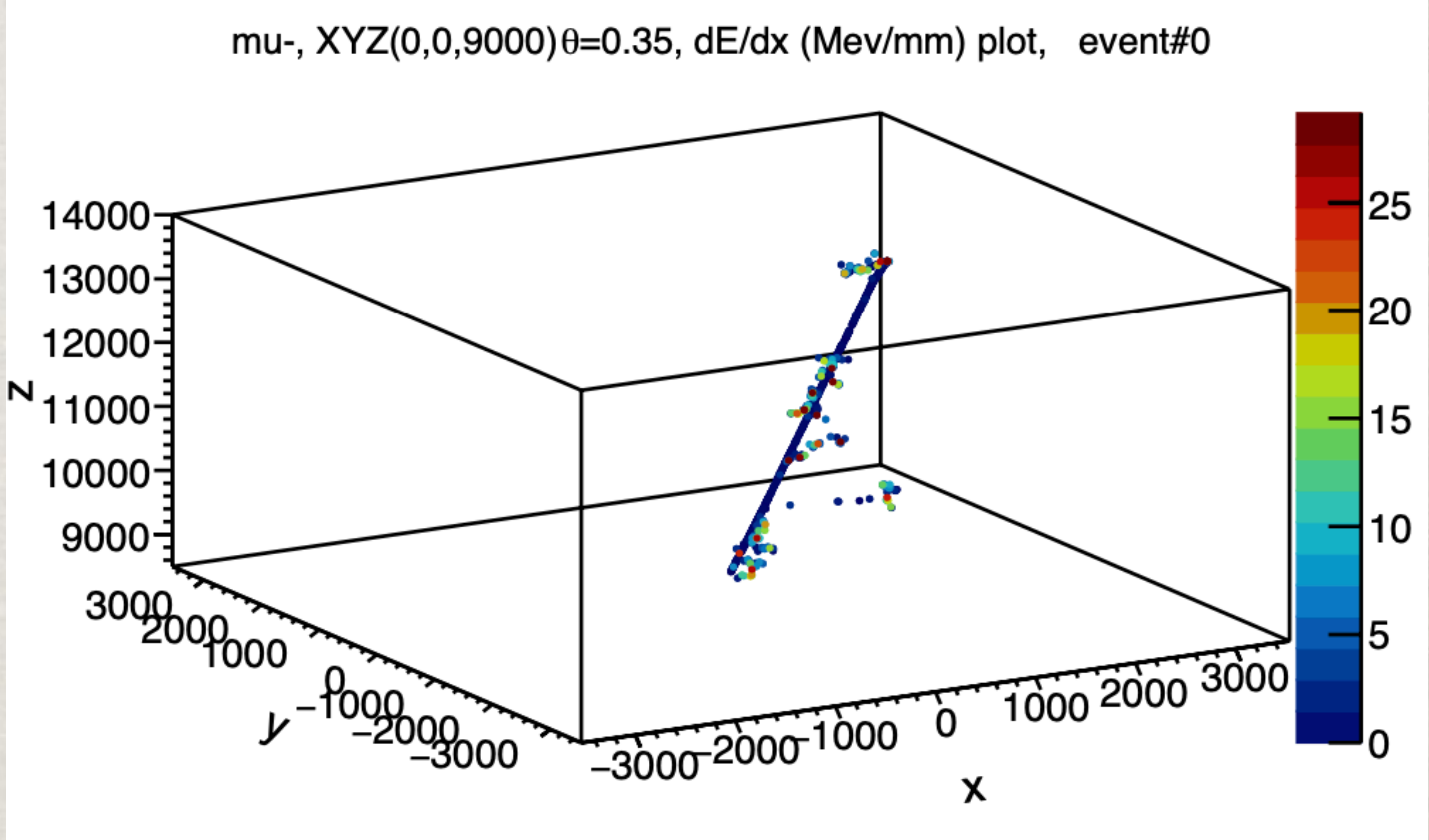
PARTICLE TOPOLOGY

Energy deposition topology in LS for different type of particles

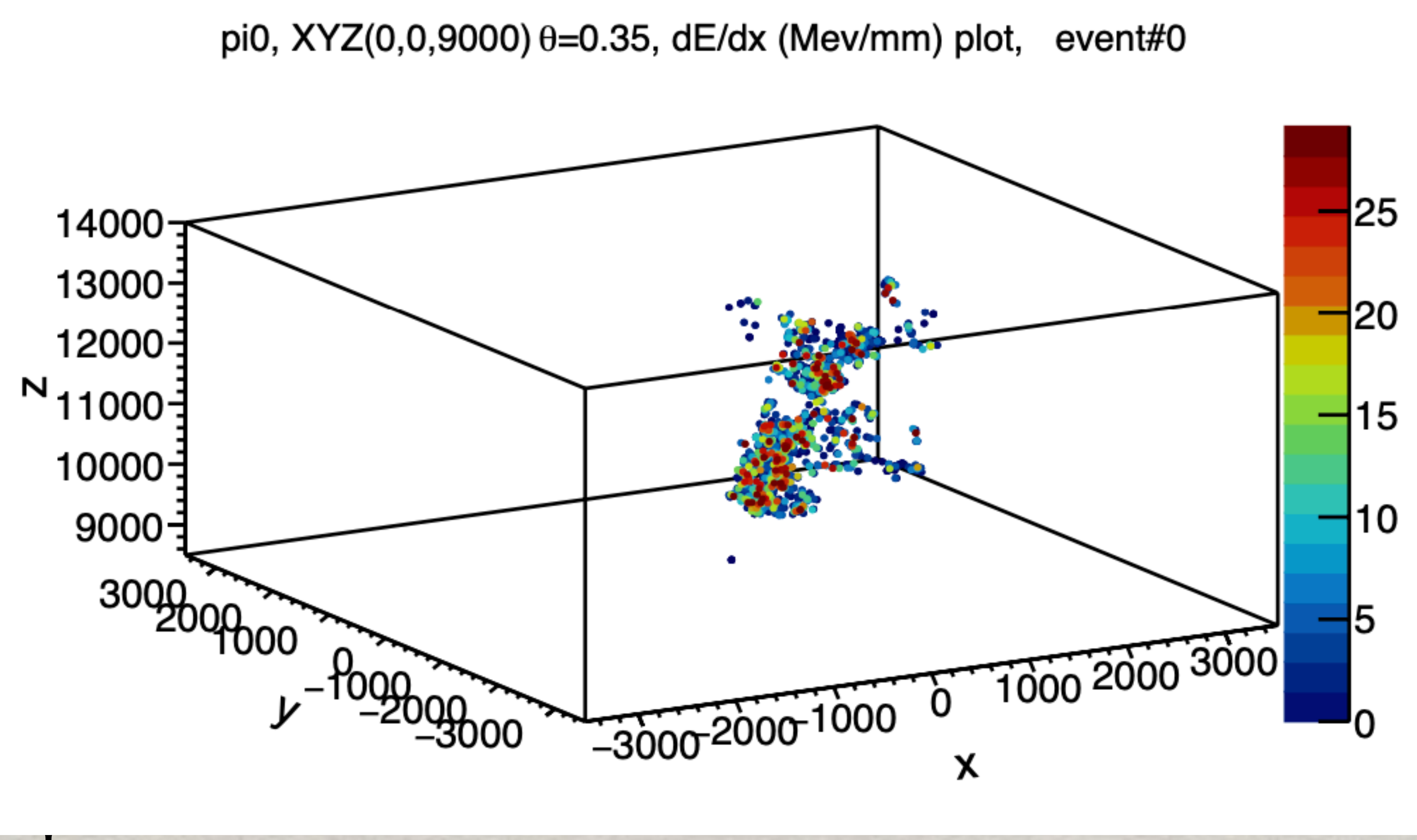
e



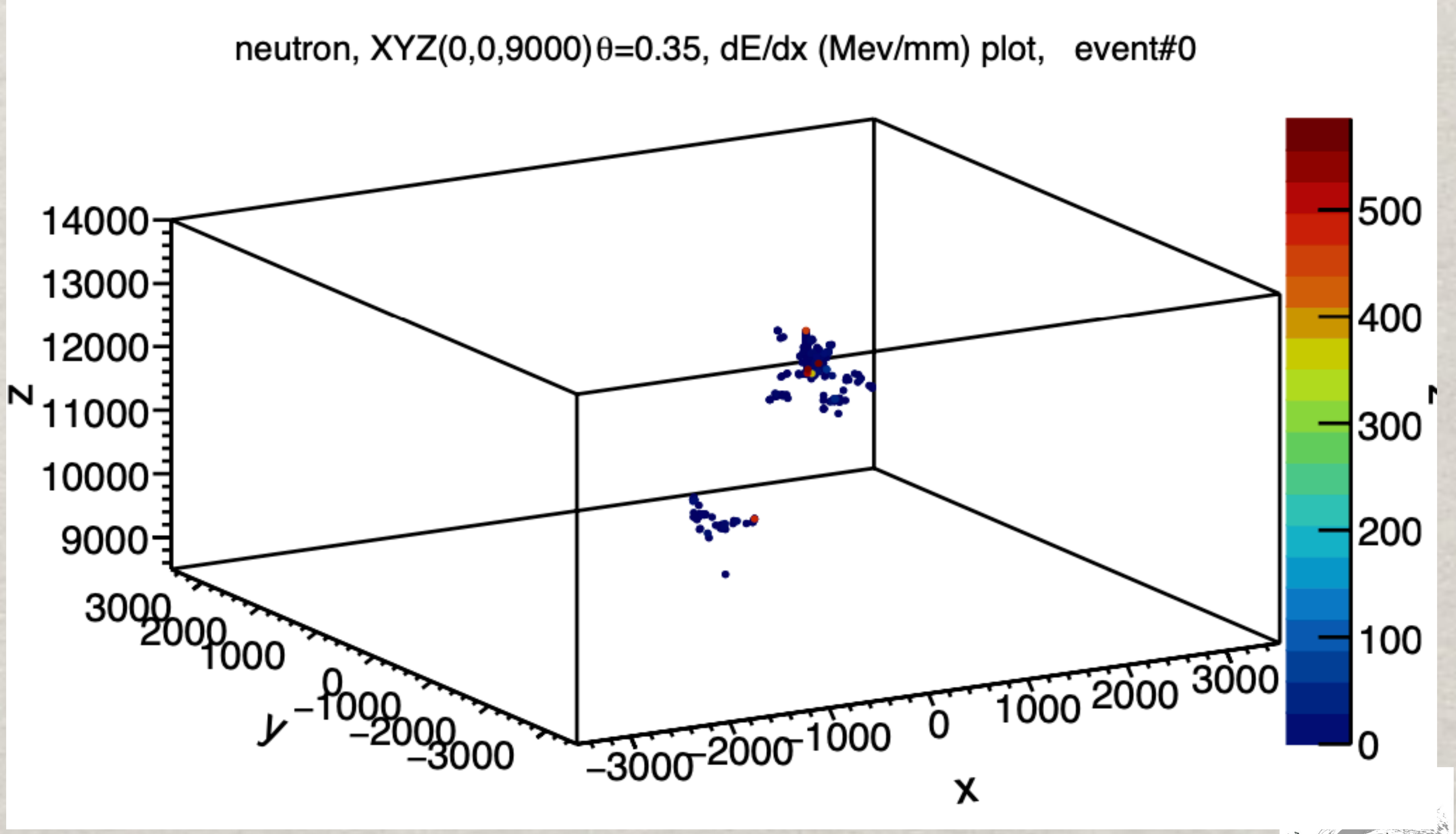
μ



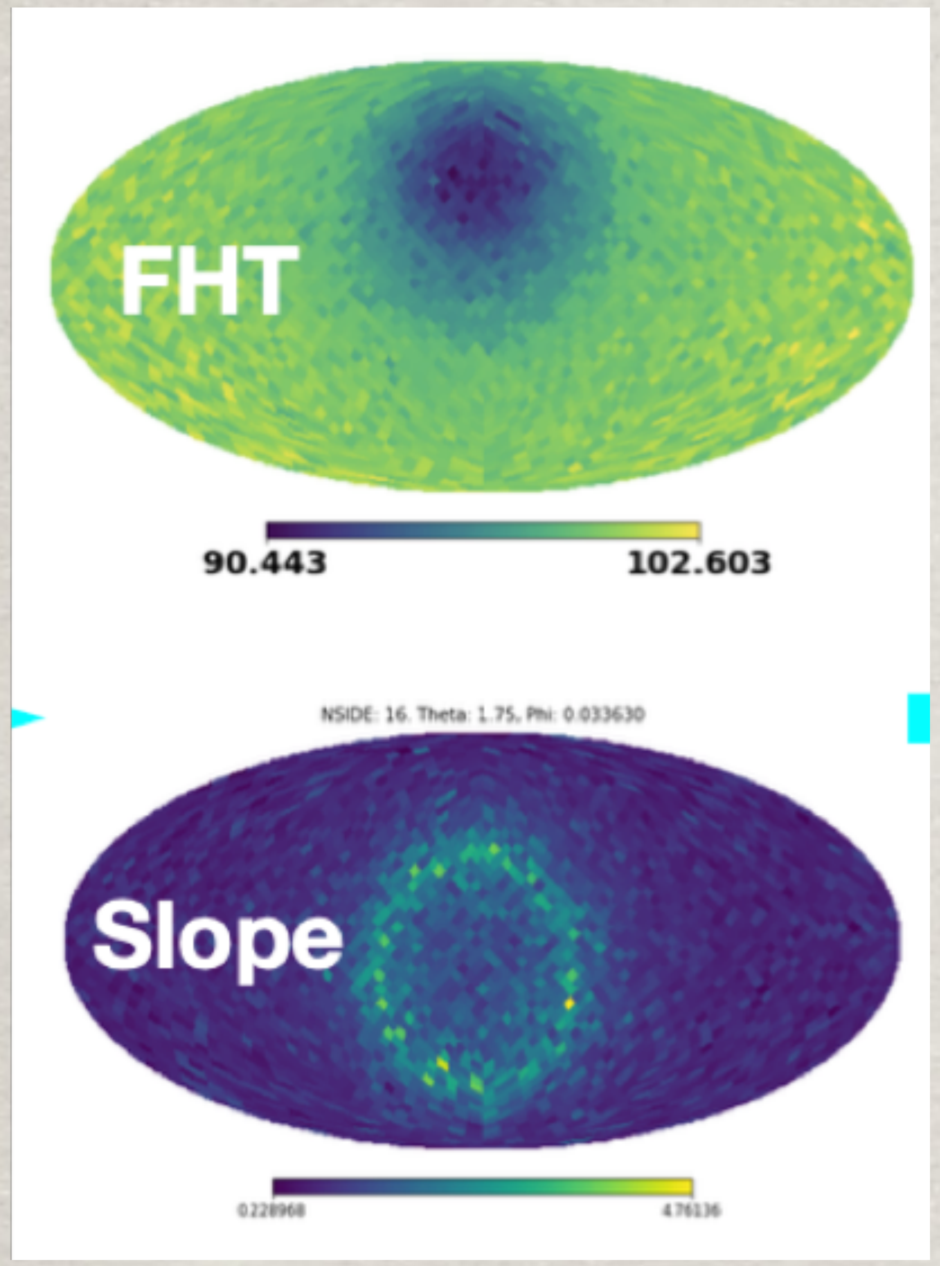
π^0



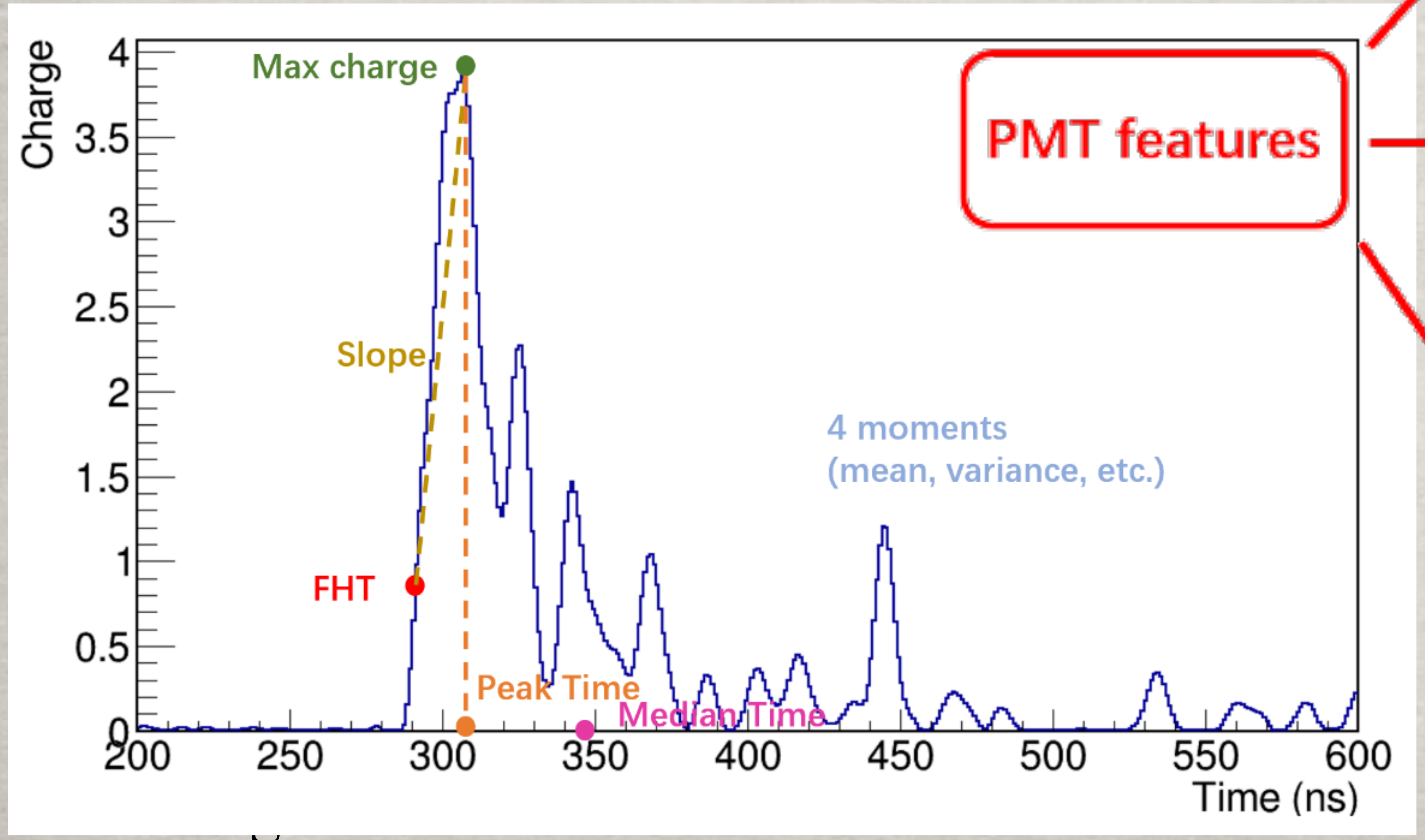
n

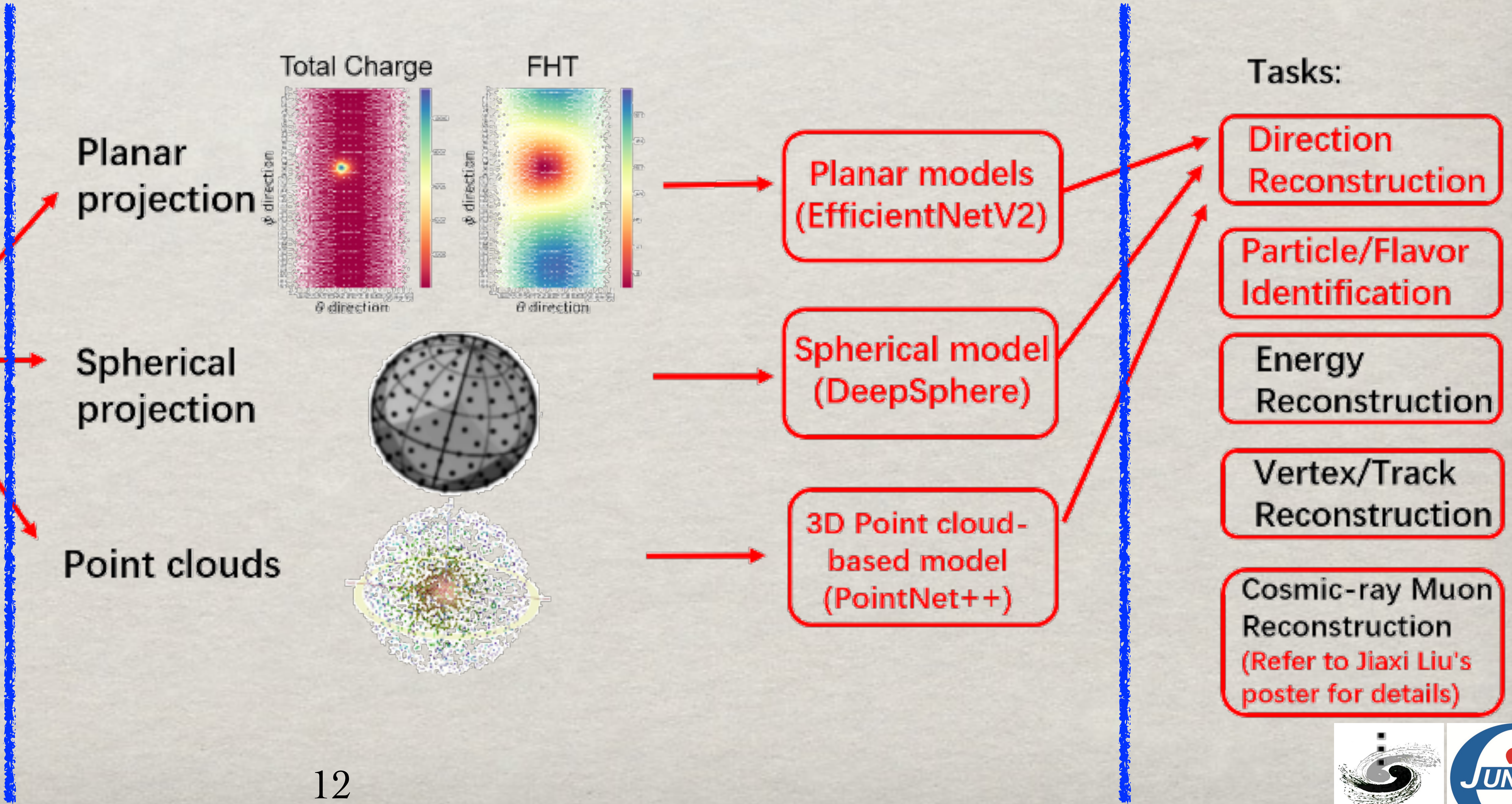


RECO/PID METHODOLOGY



- Step 1: feature extraction from PMT waveforms
- Step 2: model building
- Step 3: optimization and validation

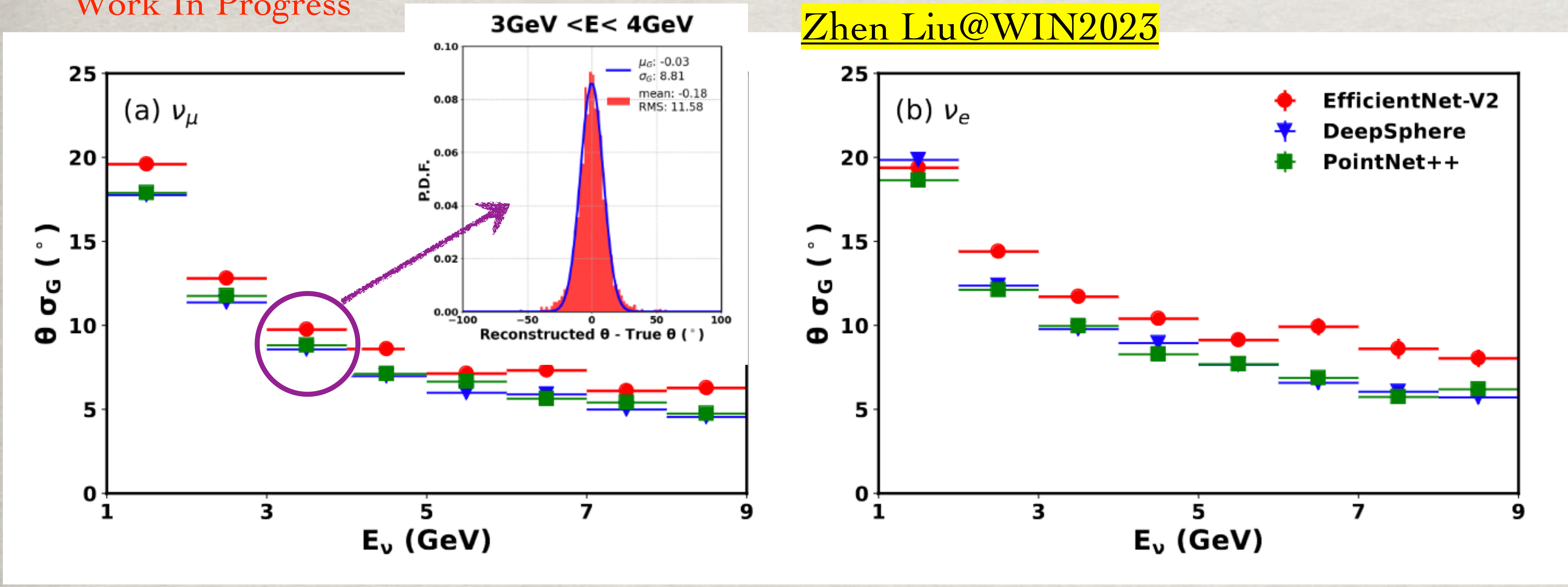


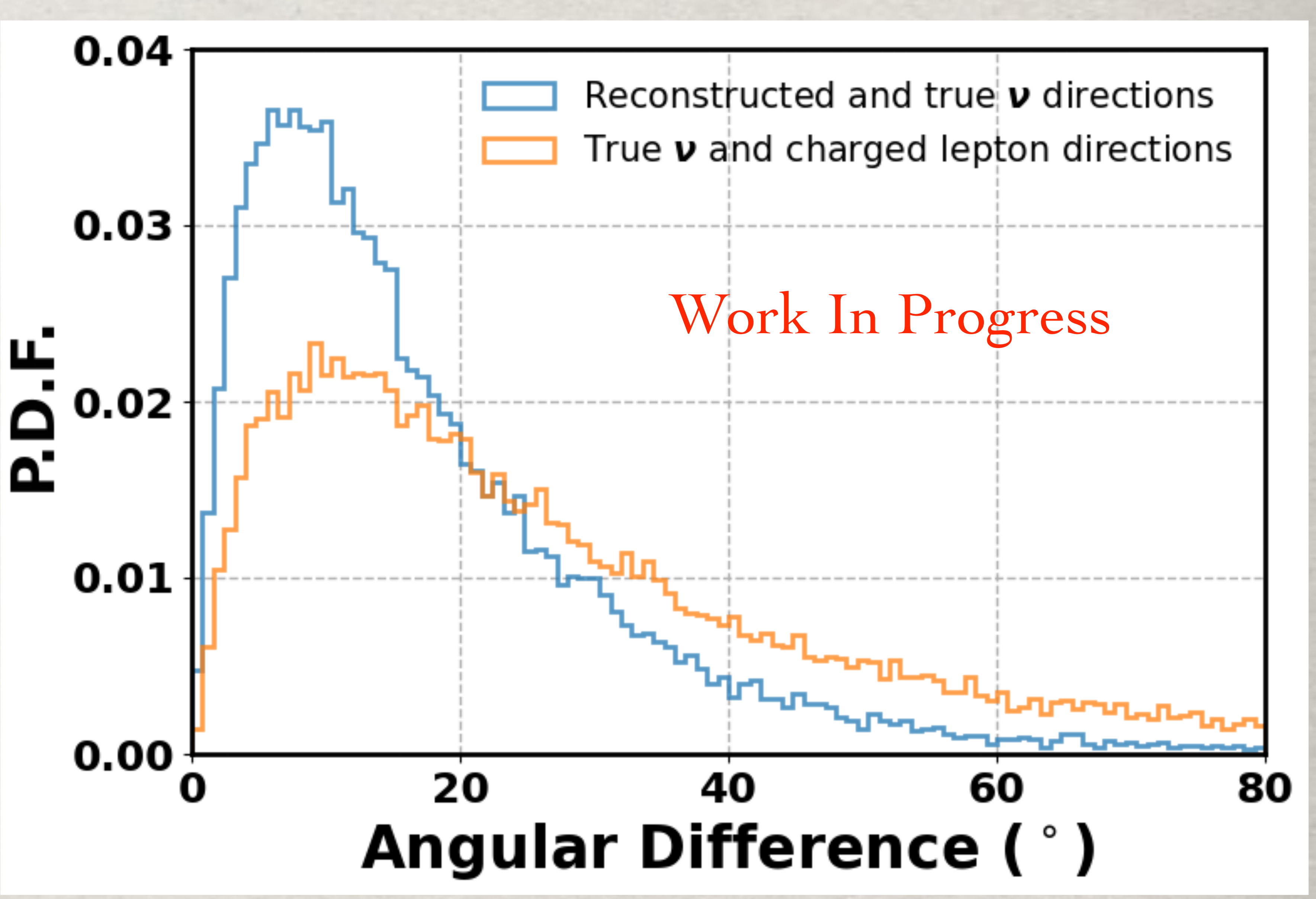


DIRECTIONALITY

Work In Progress

Zhen Liu@WIN2023





- Directly reconstruct the direction of ν instead of the charged lepton
  - mitigate the intrinsic large uncertainty between the two
  - hadronic component in LS also helps, advantageous w.r.t. Water Cerenkov
- Energy dependent Zenith Angle resolution, less than 10° for E>3GeV
- Methodology paper to be published soon

Yellow Book

$\sigma_{\theta\mu} = 1^\circ$

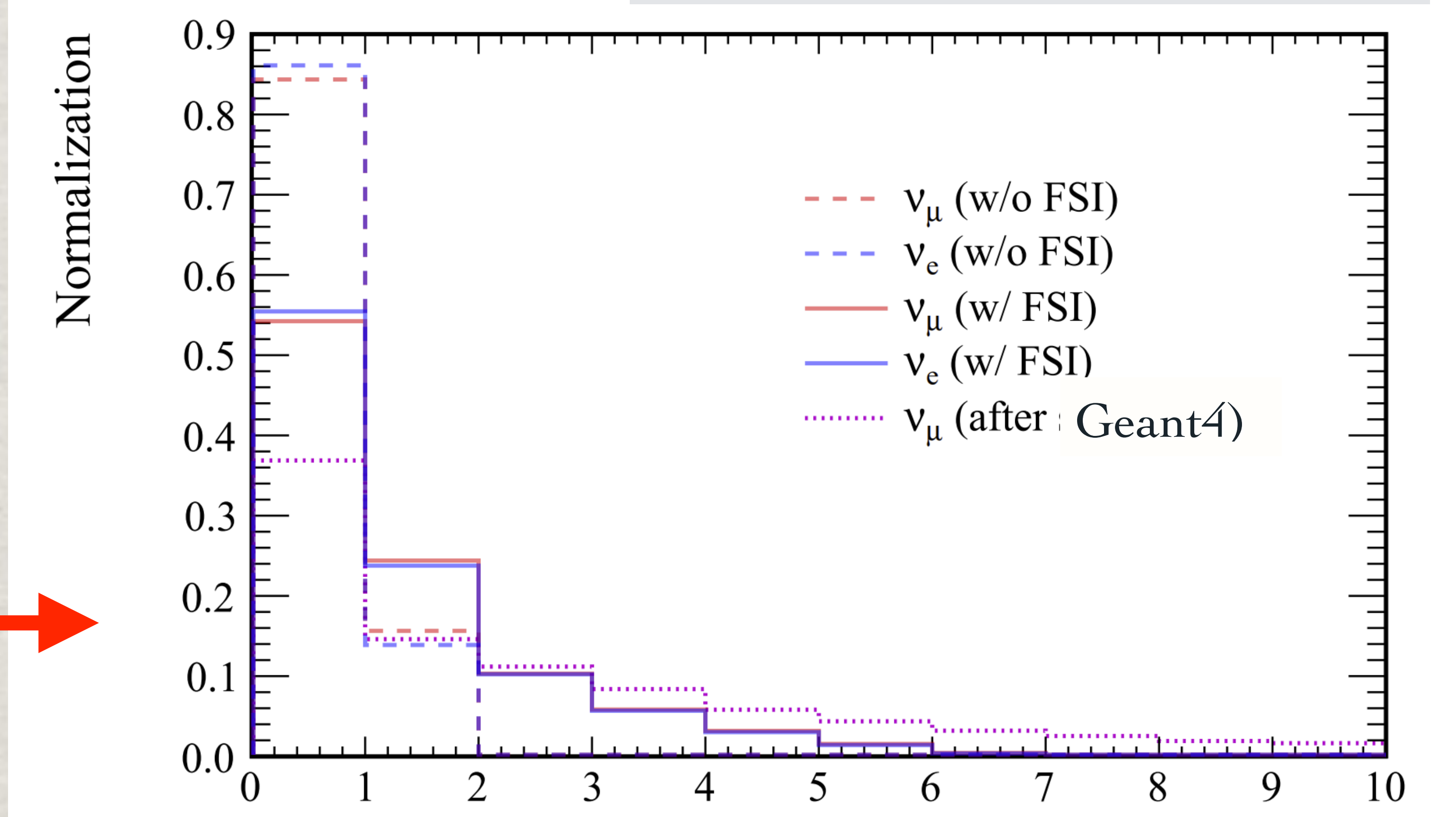
$\sigma_{\theta\nu} = 10^\circ$

PARTICAL IDENTIFICATION

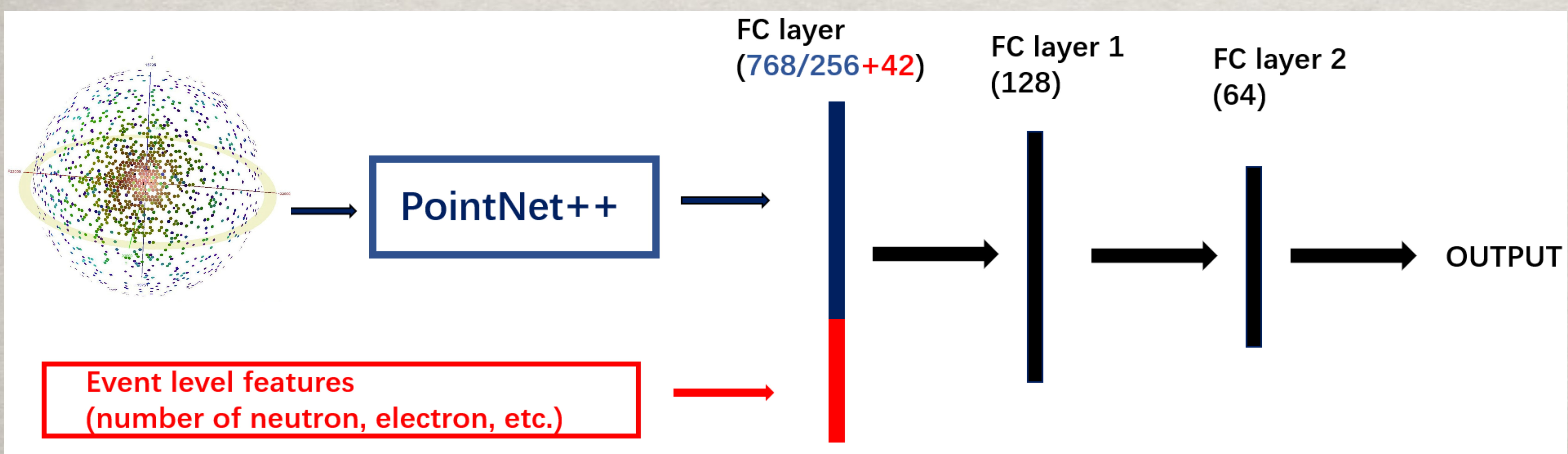
CC-e / CC-μ / NC: 100% eff. **Yellow Book**

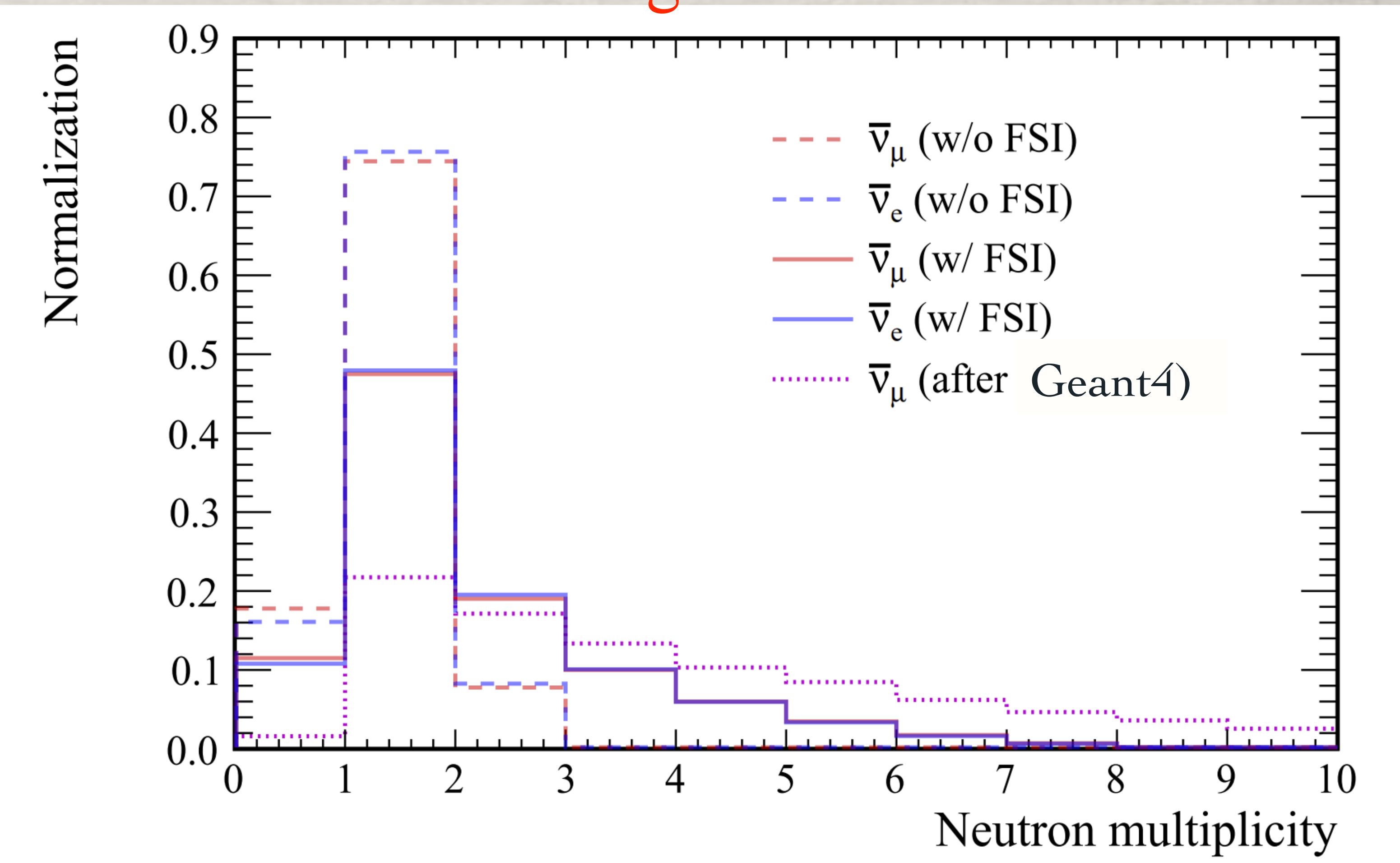
ν vs $\overline{\nu}$: simple classification with Ne, Y_{vis},

- Event classification: ν_μ vs $\overline{\nu}_\mu$ vs ν_e vs $\overline{\nu}_e$ vs NC
  - Case1: only using PMT features of prompt signal, comparable CC-e vs CC-μ vs NC eff. w.r.t. Yellow Book
  - Case2: PMT features + event level variables (neutron/micheal electron…), expecting better ν vs $\overline{\nu}$ separation w.r.t. Yellow Book
- Event level variables are crucial for ν vs $\overline{\nu}$
  - Analyses ongoing with full chain detector simulation&reconstruction

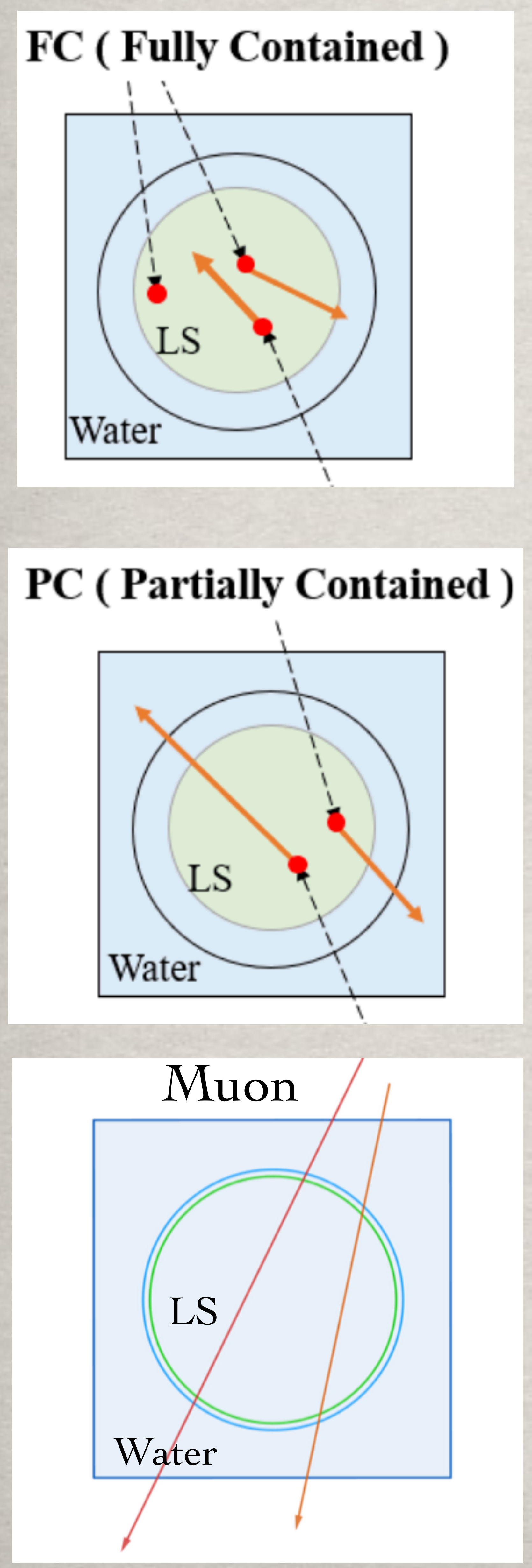


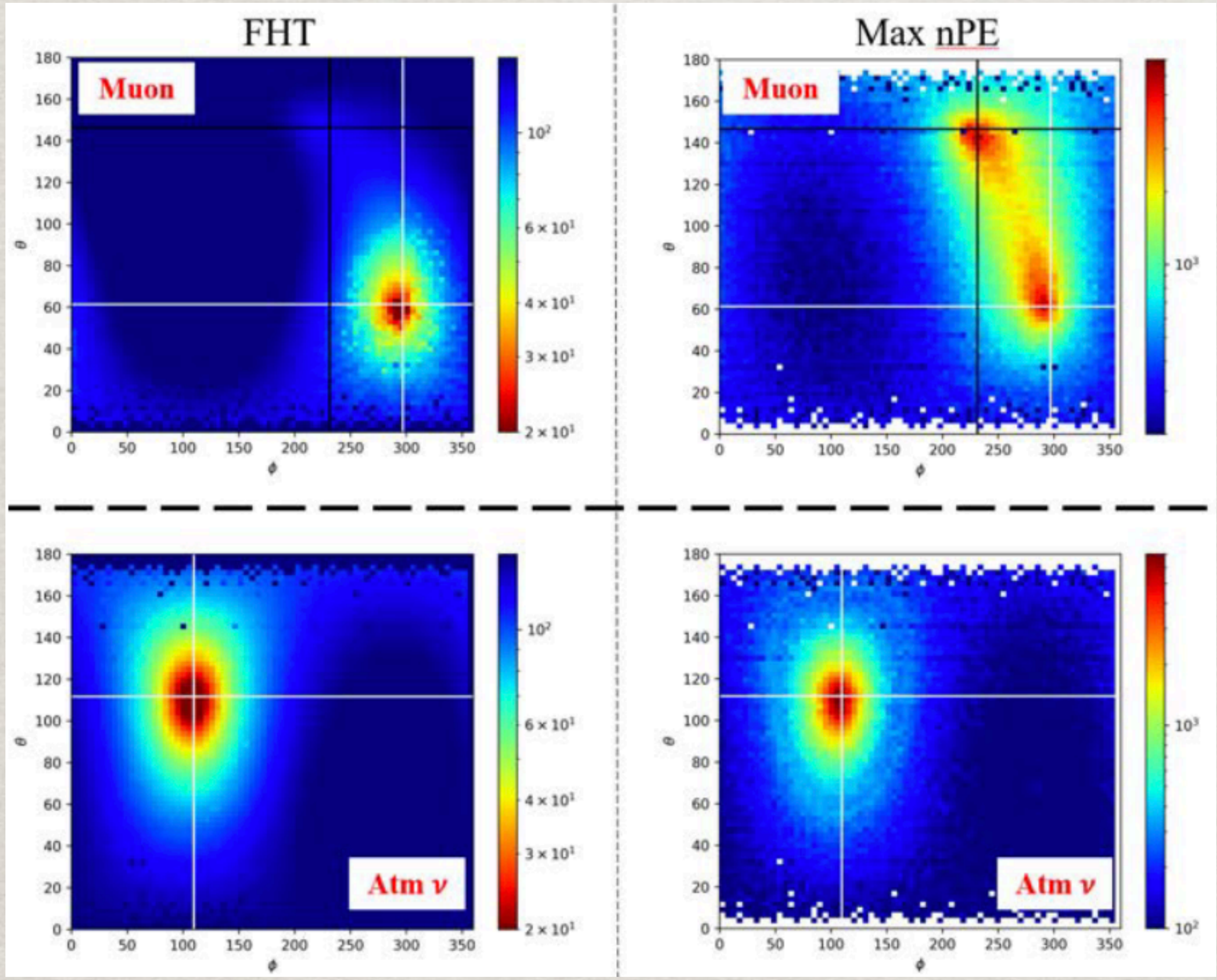
*honda flux + genie 3.2

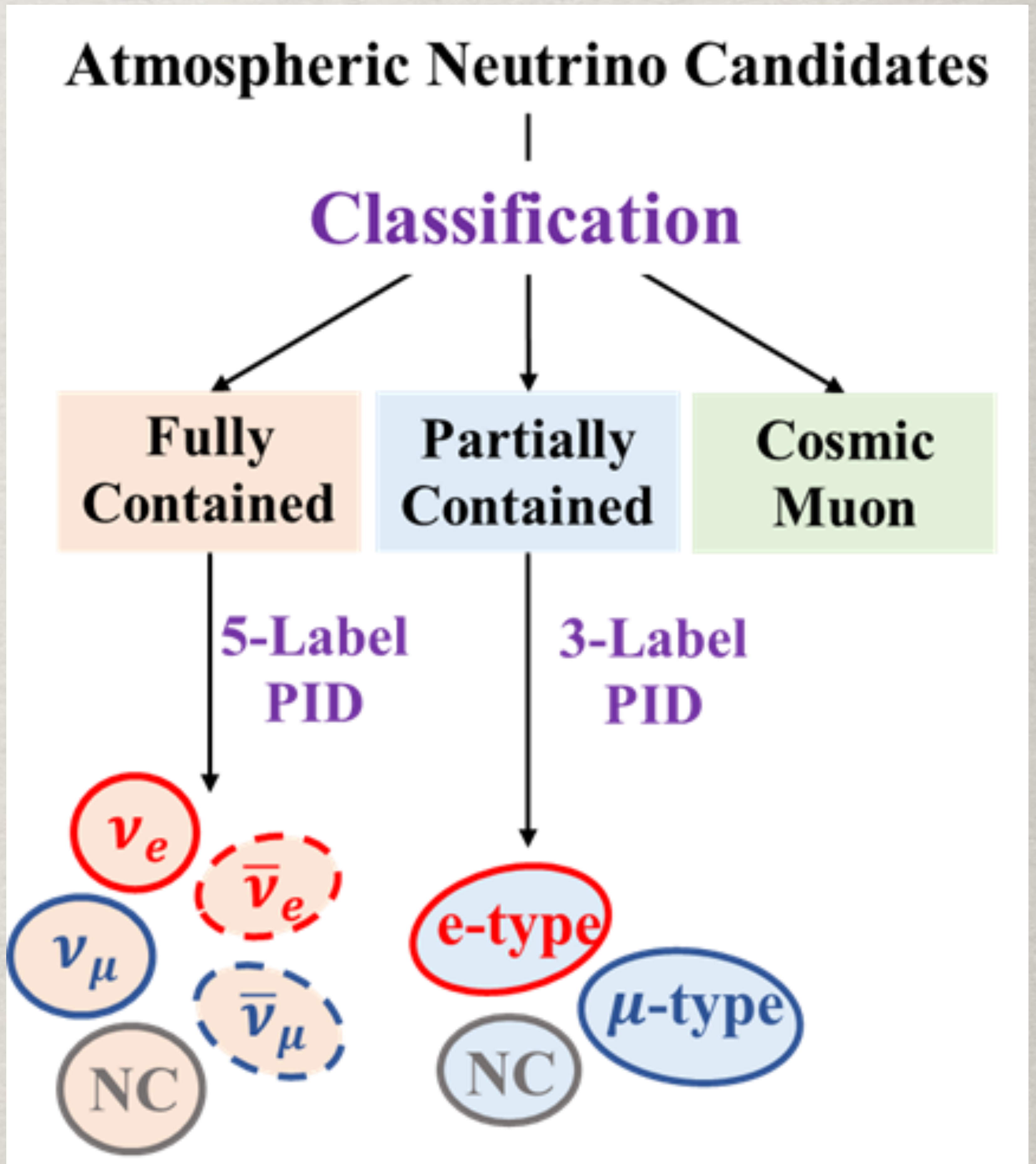




EVENT SELECTION FLOW



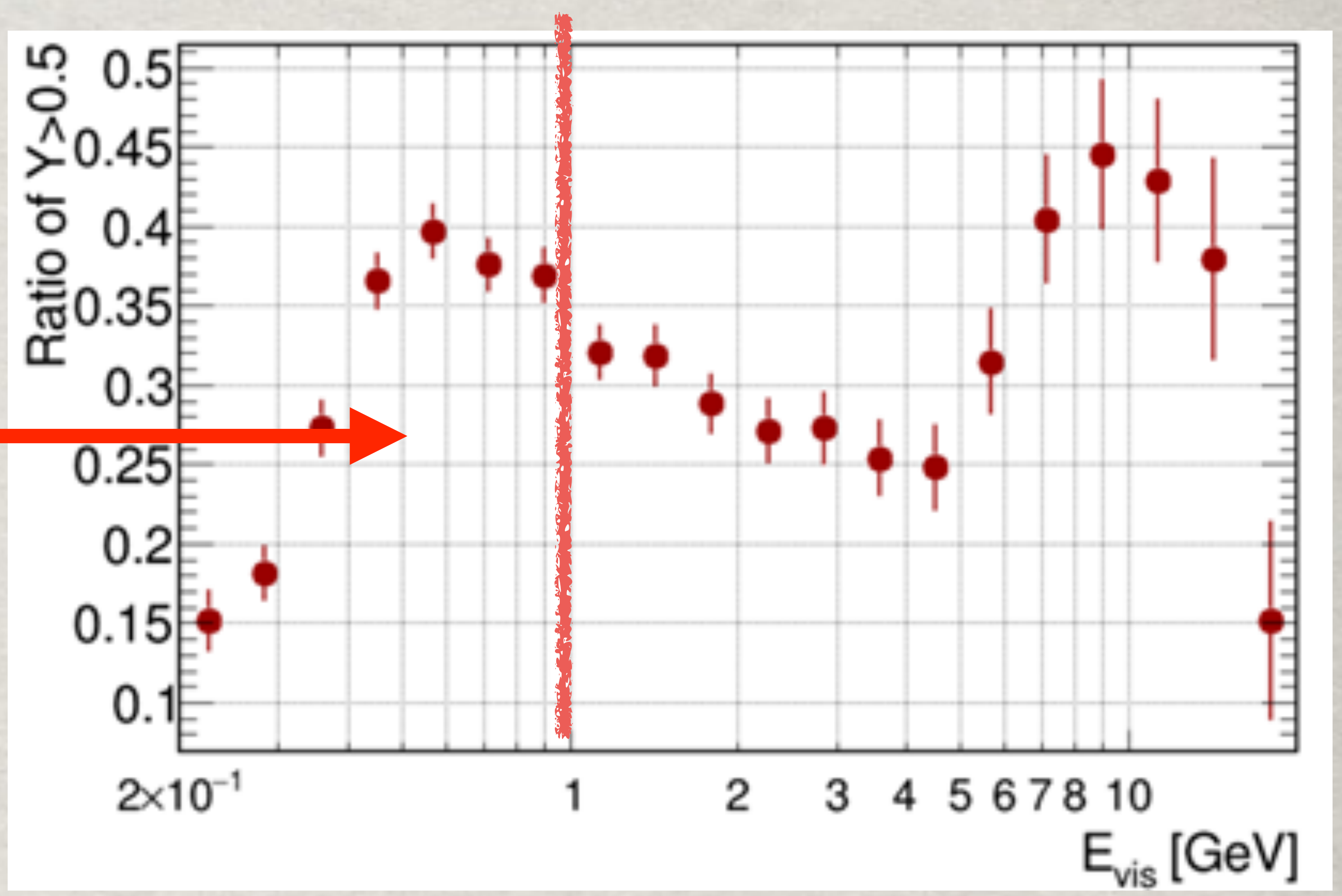


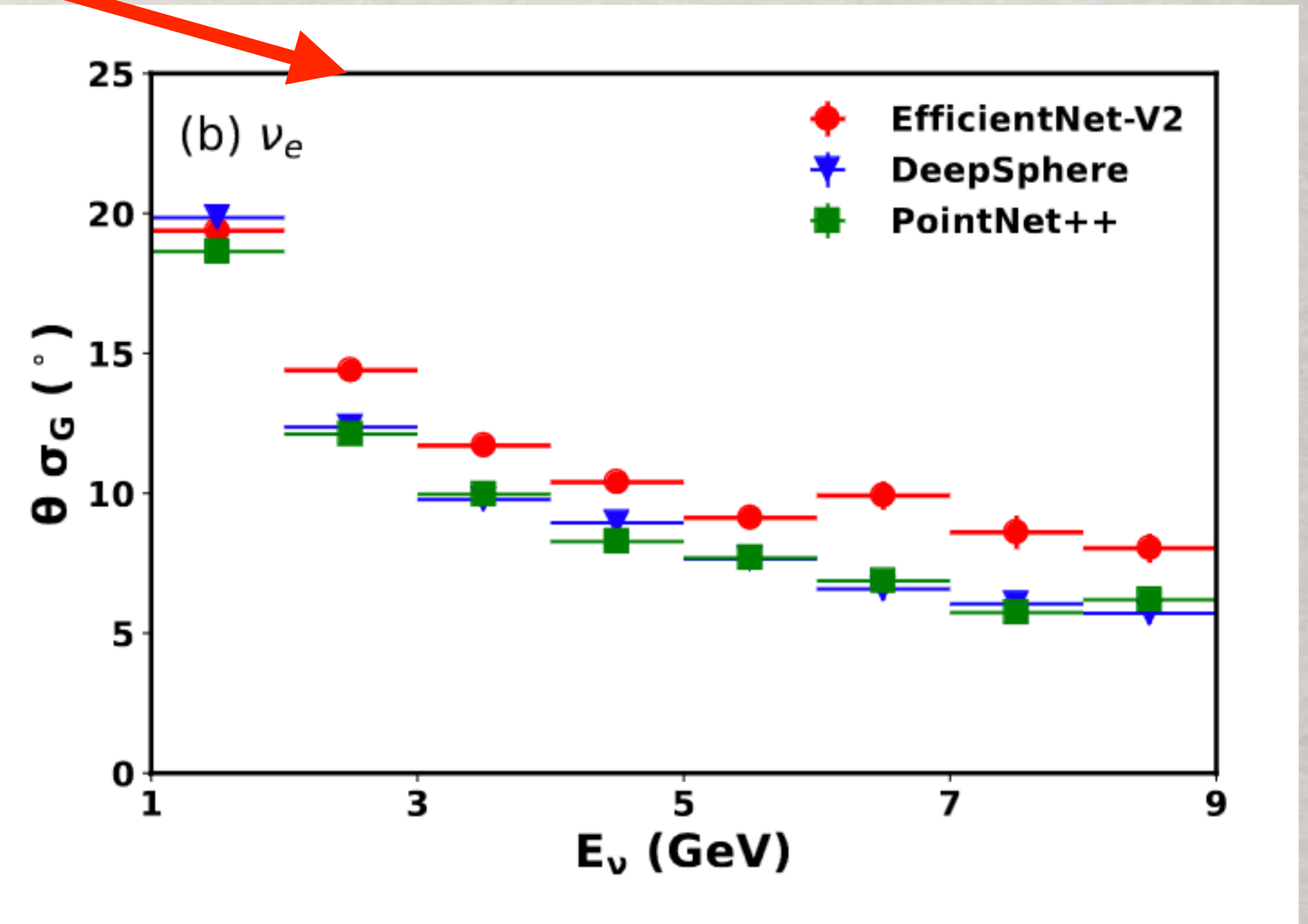


- Use Central Detector and Water Pool PMT features to classify FC/PC/Muon events
- Right plot: an exemplar event classification/selection strategy

Updates w.r.t. Yellow Book

	Yellow Book assumptions	NEW developments	Potential improvement
Event Selection $\nu_e/\bar{\nu}_e$	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)	Energy dependent
Classification	CC-e / CC-μ / NC: 100% eff.	CC-e / CC-μ / NC: 80%~95% eff.	—
	ν vs $\bar{\nu}$: simple classification with Ne, Y_{vis},	ν vs $\bar{\nu}$: 50%~80% eff.	Better ν vs $\bar{\nu}$ separation
Energy	σ_{Evis} = 1%/√E	$\sigma_{E\nu}$	E_ν instead of E_{vis}



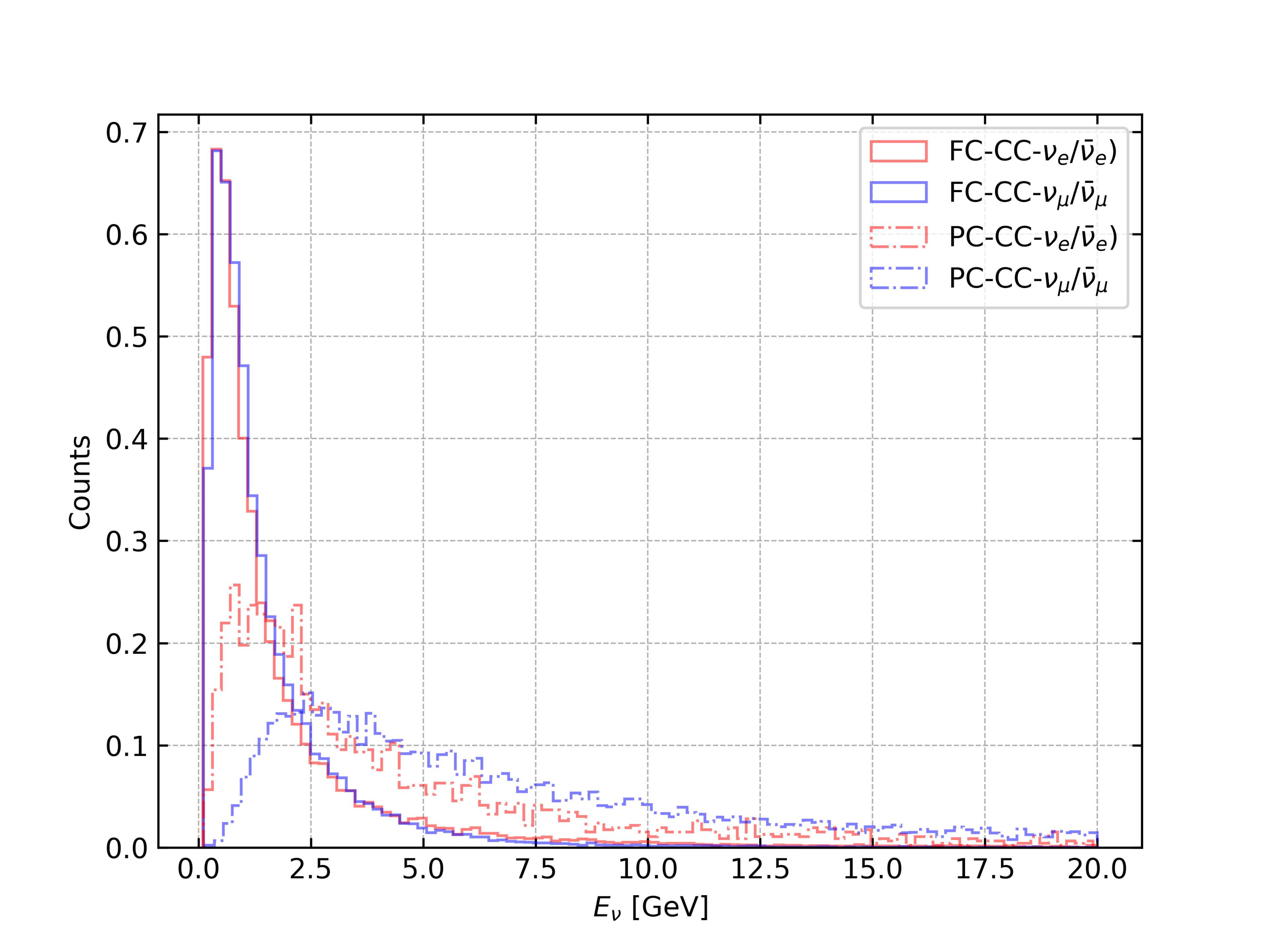


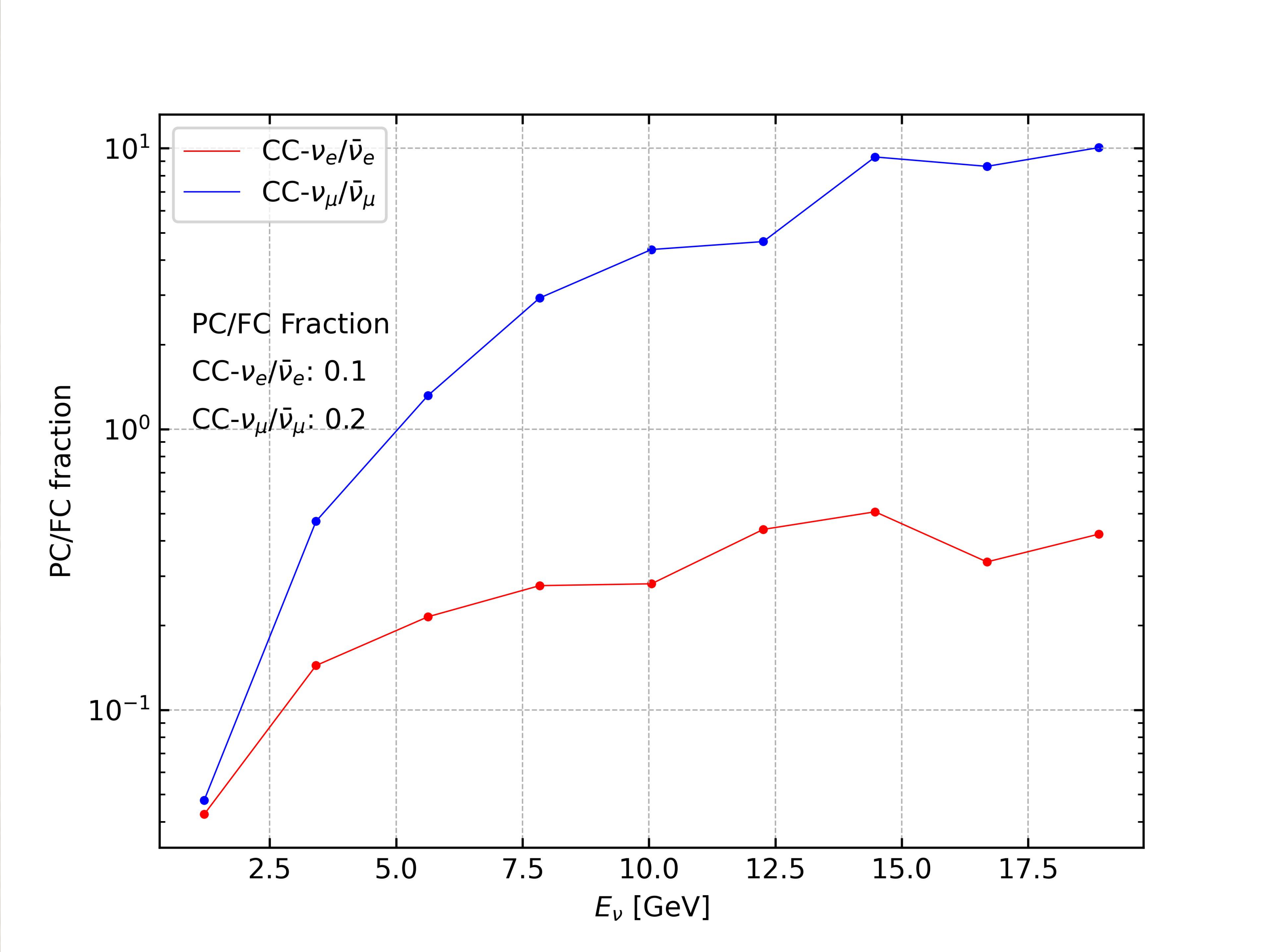
SUMMARY

- Combined with reactor ν, GeV atm. ν can further enhance the NMO sensitivity of JUNO
- Critical challenges for atm. ν are Directionality and PID
  - Developed a multi-purpose Machine-Learning method
  - Preliminary results show that JUNO has good potential in these aspects
- Many more progress on the Oscillation analysis (flux/interaction, event selection, systematics etc)
- Please stay tuned!

THANK YOU!

BACK UP

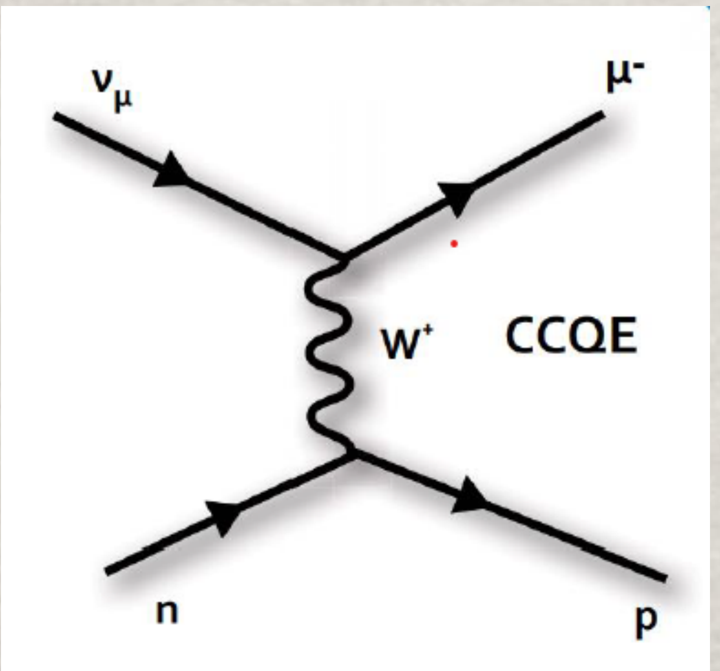


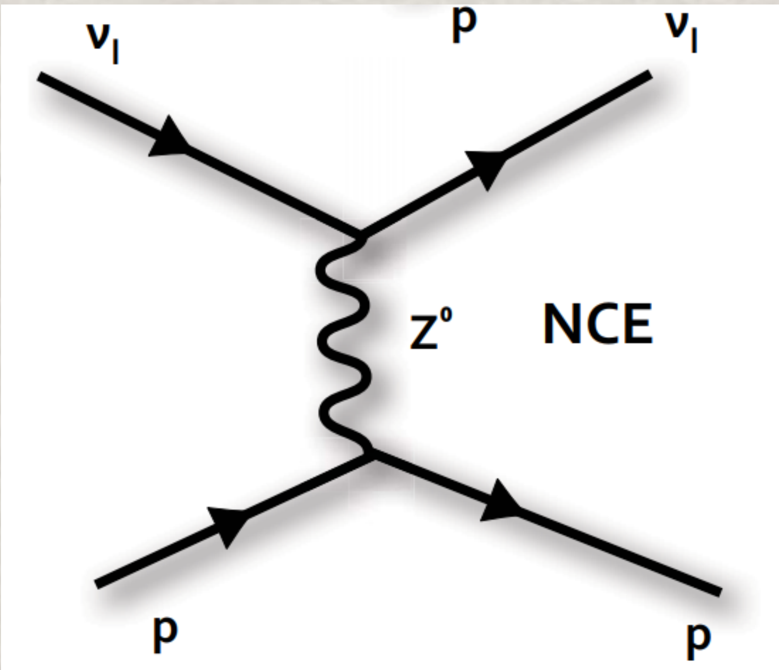


	Super-K
Direction	single-ring **e**-like: 3.0°
	single-ring **μ**-like: 1.8°
ν/ν̄ separation (purity)	ν_e/ν̄_e**:** 62.1%/54.6% for single-ring events; 47.1%/71.5% for multi-ring events.
	ν_μ/ ν̄_μ: N.A.

- Systematic Uncertainties:
- Normalization rate error:
  1. Cross section error: $\sigma_{Xsec} = 10\%$;
  2. Overall flux error: $\sigma_\phi = 20\%$.
- Flux energy E_ν and zenith angle $\cos\theta_z$ dependent error.
  1. Energy dependent uncertainty [1]:
     - $\sigma^\phi_{E_\nu} = 5\%,\ \pi_n^{E_\nu} = 5\% \cdot \ln\frac{E_\nu}{2\ \mathrm{GeV}}$.
  2. Angular dependent uncertainty [1] :
     - $\sigma^\phi_{\cos\theta_z} = 5\%,\ \pi_n^{zenith} = 5\% \cdot < \cos\theta_z >$.

samples. The track-like sample contains only $\nu_\mu/\bar{\nu}_\mu$ CC events with a $E_h/E_\nu < 0.65$ inelasticity and the point-like sample all other CC and NC events. Here we do not consider the statistical separation of neutrinos and antineutrinos, and do not discriminate the FC and PC events. In contrast to the optimistic case, we take the $5\%\sqrt{E_{\mathrm{vis}}}$ and $37.2°/\sqrt{E_\nu}$ for the visible energy and the neutrino direction resolutions, respectively. $37.2°/\sqrt{E_\nu}$ corresponds to the mean angle between the lepton and neutrino directions. In order to calculate the MH





Experiments	Flux uncertainty				Ref.
	Flux normalization	Spectral index	ν_μ/ν_e ratio	Others	
Super-K	25% (< 1GeV) 15% (>1 GeV)	5%	5%	ν/ν-bar ratio: 5%	*PRD* 97 (2018) 072001
Ice-Cube	20% (tens of GeV) 40% (TeV)	10% 3%	20% /	Meson production: π: 15%-30% K: 30-40%	*arXiv: 2304.12236,* *arXiv: 2201.03566,* *PRD* 91 (2015) 072004
ANTARES	Free	10%	20%	/	*JHEP* 06 (2019) 113
MINOS	15%	10%	5%	/	*PRD* 86 (2012) 052007