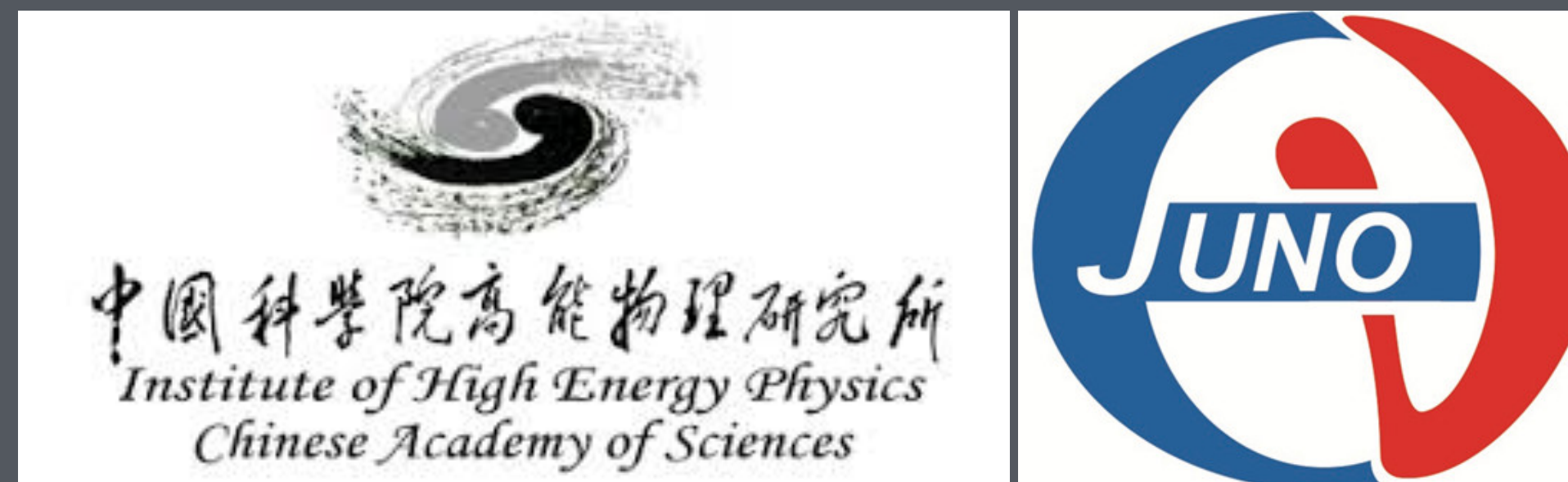


CRIME SCENE INVESTATION AT JUNO

W U M I N G L U O



OUTLINE

- ❖ Introduction: what/why/how...
- ❖ Reconstruction of reactor anti-neutrinos
 - ❖ Energy reco
 - ❖ Vertex reco
- ❖ Reconstruction of atmospheric neutrinos
 - ❖ Directionality
 - ❖ Particle Identification
- ❖ Summary

BRIEF HISTORY OF ν

1930年

提出中微子假说

为解决原子核贝塔衰变的能量不守恒问题，奥地利物理学家泡利首次提出中微子存在的假说

1962年

发现第二种中微子

莱德曼、施瓦茨和斯坦博格利用美国布鲁克海文的加速器证明存在第二种中微子



获1988年度
诺贝尔奖

1987年

首次探测到超新星中微子

日本科学家小柴昌俊领导的神冈实验，首次观测到超新星SN1987A产生的中微子



获2002年度
诺贝尔奖

2001年

发现太阳中微子振荡

加拿大科学家麦克唐纳领导的SNO实验发现太阳中微子振荡



获2015年度
诺贝尔奖

1956年

首次探测中微子

美国物理学家莱因斯和柯温在核反应堆附近开展实验，首次直接证实中微子的存在



获1995年度
诺贝尔奖

1968年

首次探测到太阳中微子

戴维斯等人首次观测到太阳核聚变产生的中微子，并发现它远少于预期，引发了持续40余年的“太阳中微子丢失之谜”的研究



获2002年度
诺贝尔奖

1998年

发现大气中微子振荡

梶田隆章代表超级神冈实验宣布发现大气中微子振荡，表明中微子具有非零质量



获2015年度
诺贝尔奖

2012年

发现第三种中微子振荡模式

中国大亚湾反应堆中微子实验发现一种新的中微子振荡模式，并测量了其混合角 θ_{13}

UNKNOWNNS ABOUT ν

中微子振荡

1个半未知参数：

质量顺序、CP破坏、 θ_{13} 正性

是否为自身反粒子？

中微子质量大小？

反常磁矩？

是否存在惰性中微子？

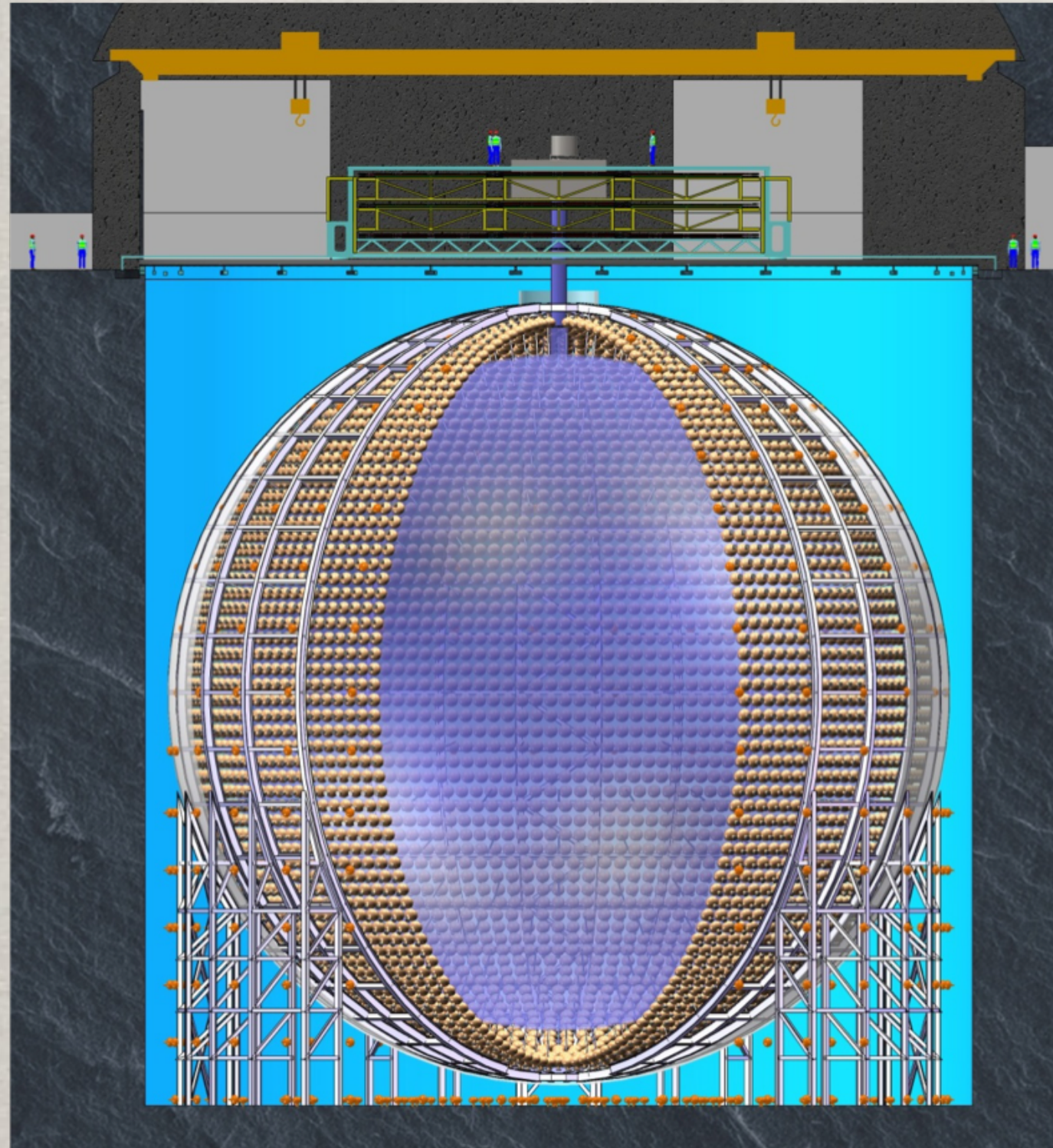
核心问题：中微子质量问题

做为一种新探测工具

超新星、宇宙大尺度结构、太阳物理、
超高能宇宙线起源、地球物理、核物理

宇宙大爆炸中微子？

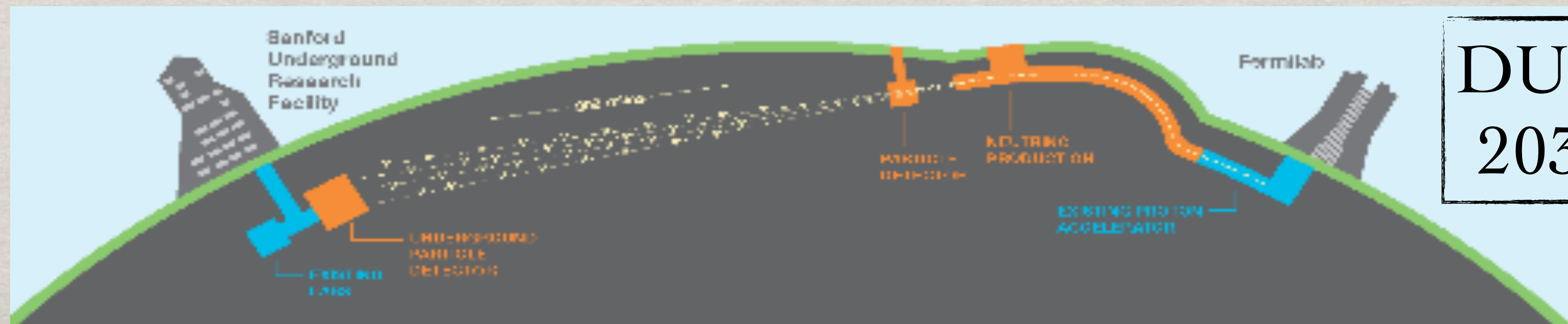
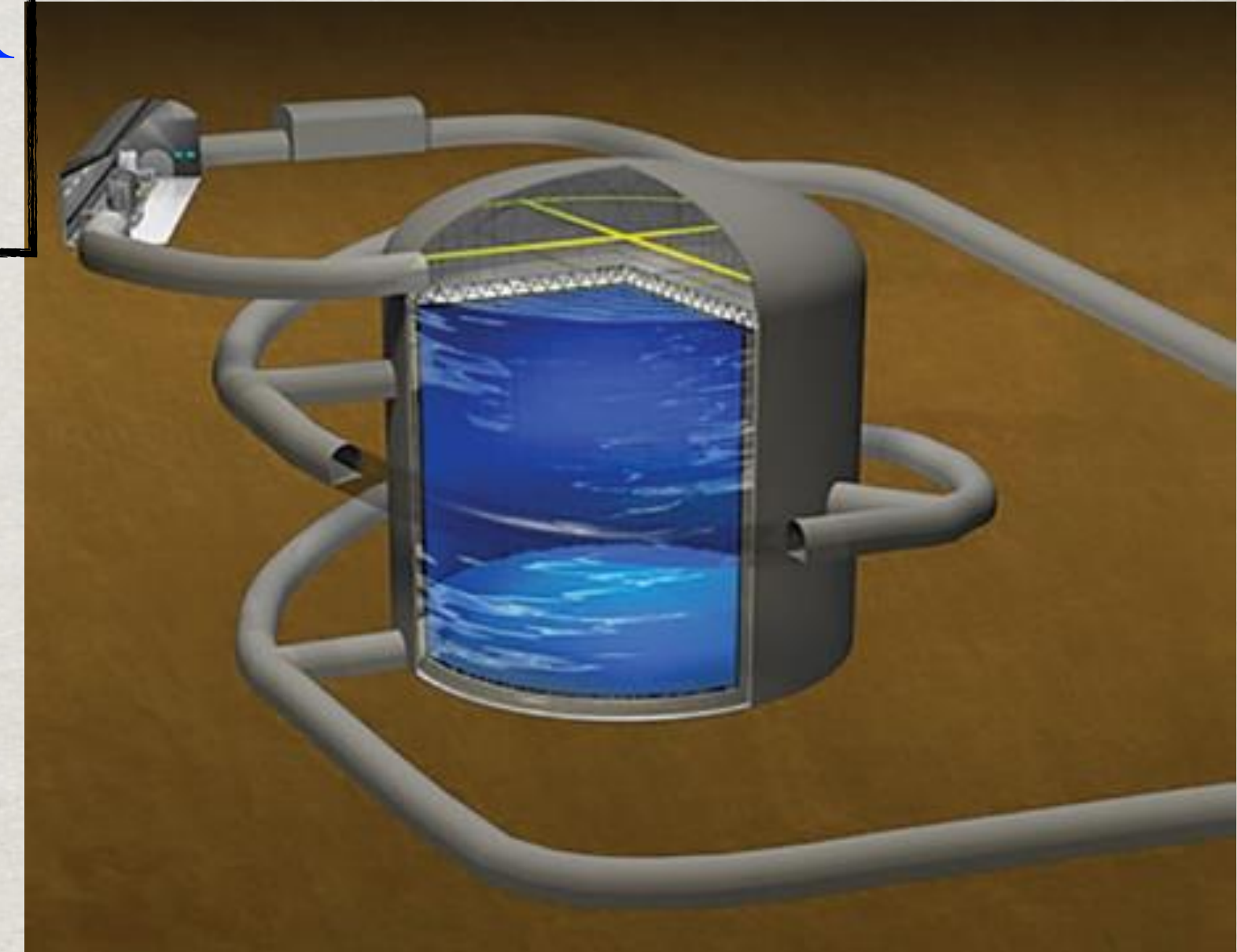
ROMANCE OF THREE “KINGDOMS”



JUNO
2025

Neutrino
Mass
Ordering

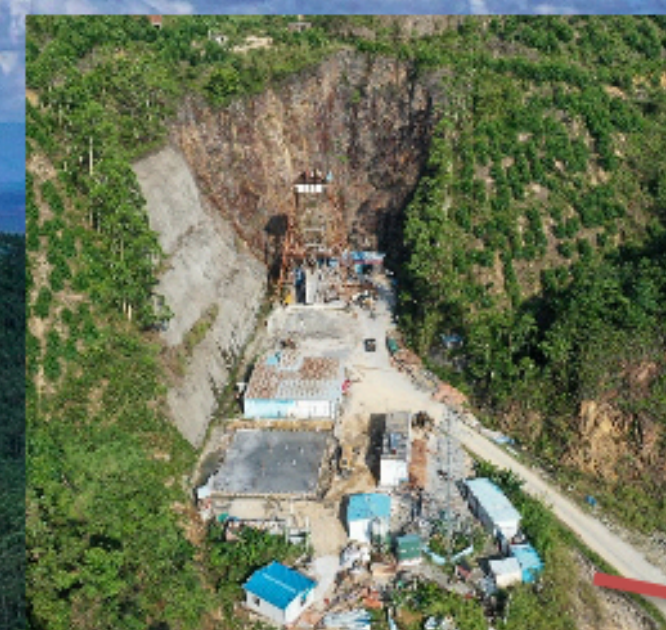
Hyper-K
2027



DUNE
2030?



Jiangmen **U**nderground **N**eutrino **O**bservatory



Vertical tunnel:
563 m

Overburden
~650 m (1800
m.w.e.)

Slope tunnel : 1265 m
@ slope of 42%

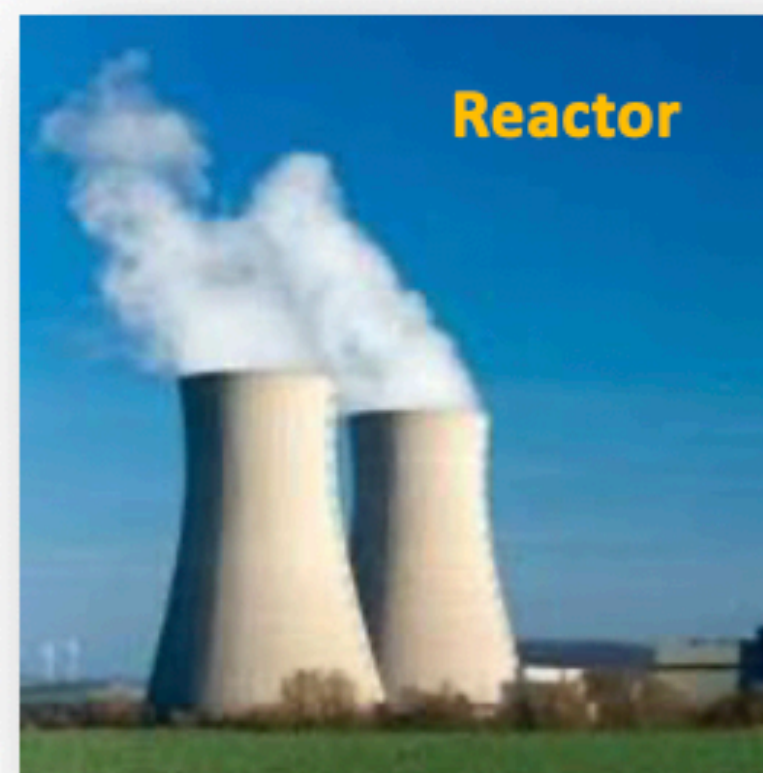


Civil construction finished in Dec, 2021

© 刘悦湘

MULTI-PURPOSE OBSERVATORY

- ❖ Physics goals: **neutrino mass ordering ($\sim 3\sigma$)**, precision measurement of neutrino mixing parameters ($\ll 1\%$), supernova ν , geo- ν , solar ν , nucleon decay,
- ❖ Future upgrade (2030s) : searching for $0\nu\beta\beta$



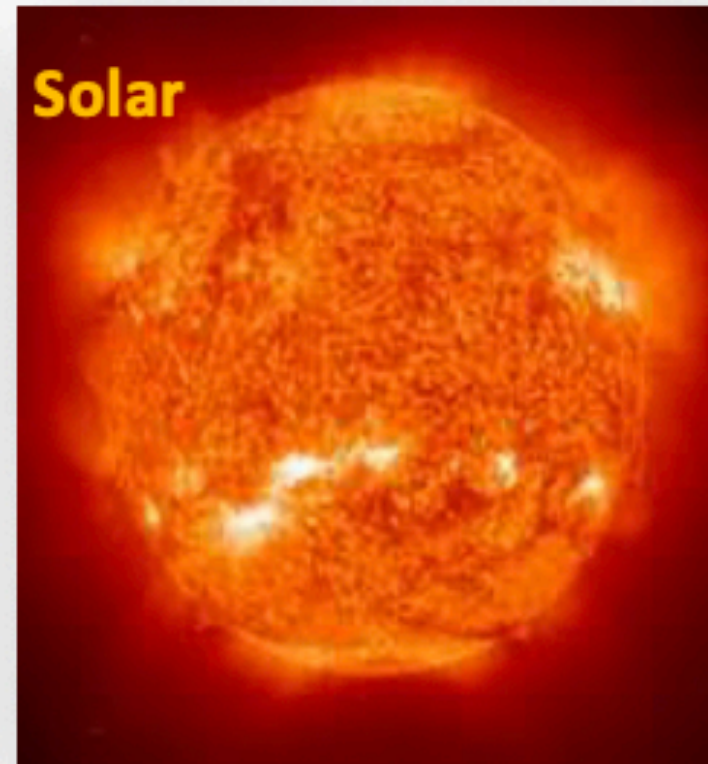
Reactor

~60 IBDs per day



Atmosphere

Several per day



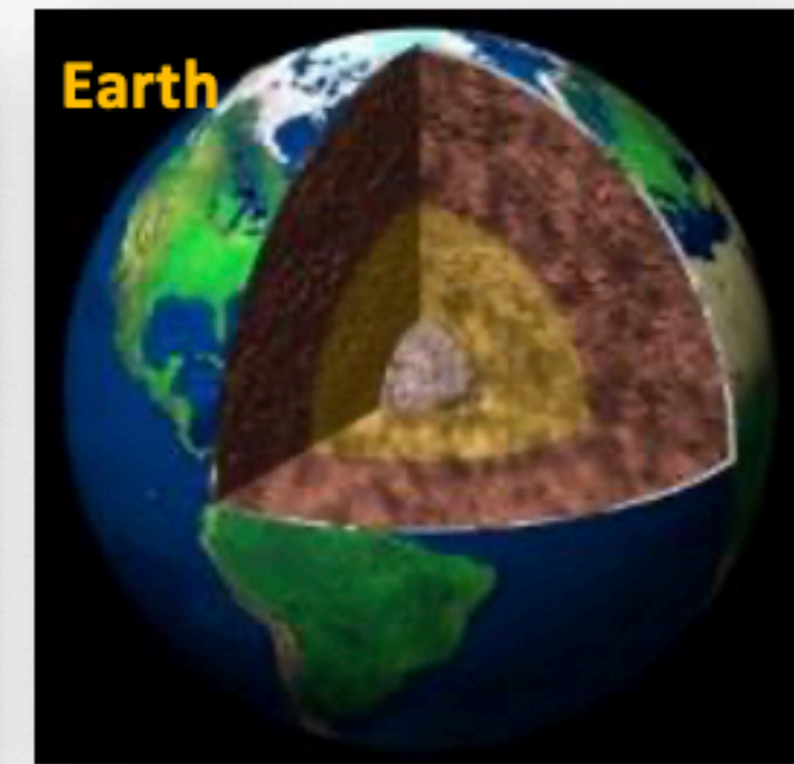
Solar

Hundreds per day



Supernova

~5000 IBDs for
CCSN @10 kpc



Earth

Several IBDs per day

+

New
physics

IBD: inverse beta decay
CCSN: core-collapse supernova

Neutrino oscillation & properties

Neutrinos as a probe

BALLISTICS TEST IN THE DARK KNIGHT

1



2



3

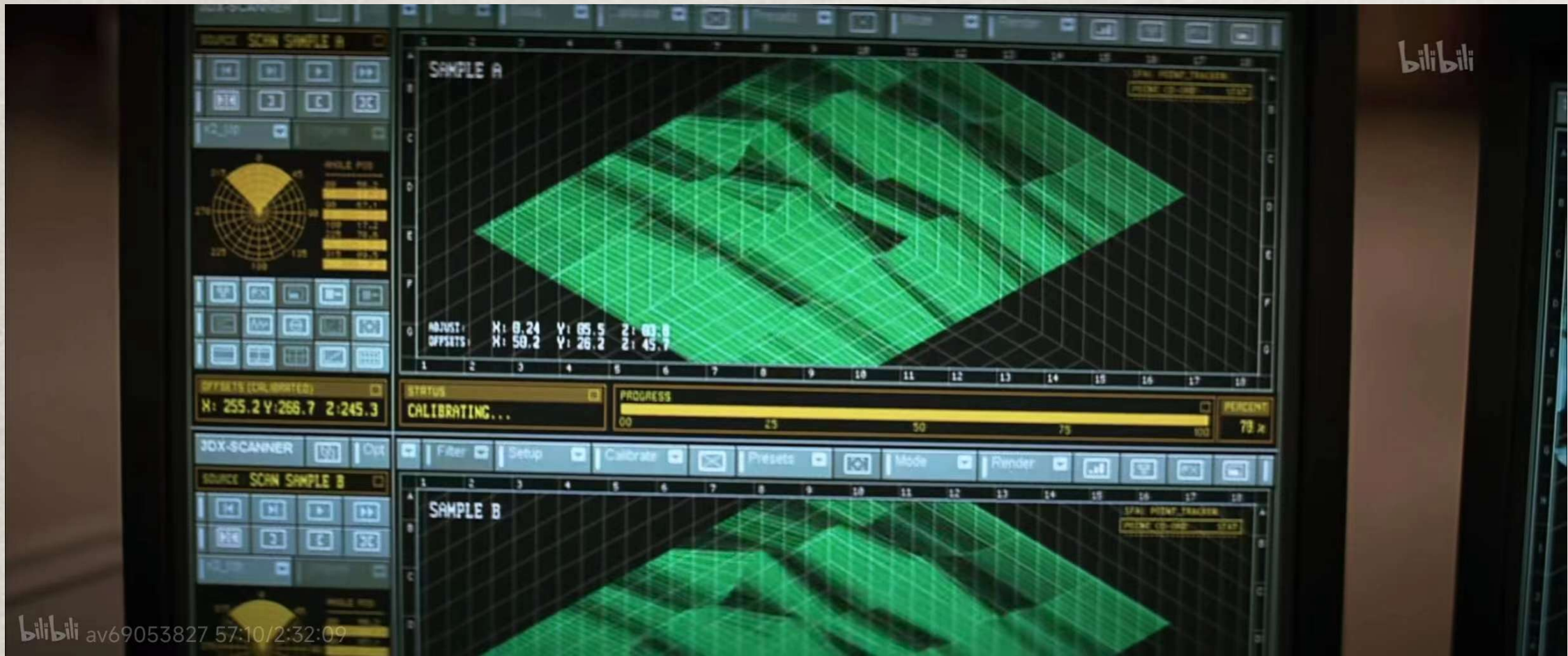


4



BALLISTICS TEST IN THE DARK KNIGHT

5



6



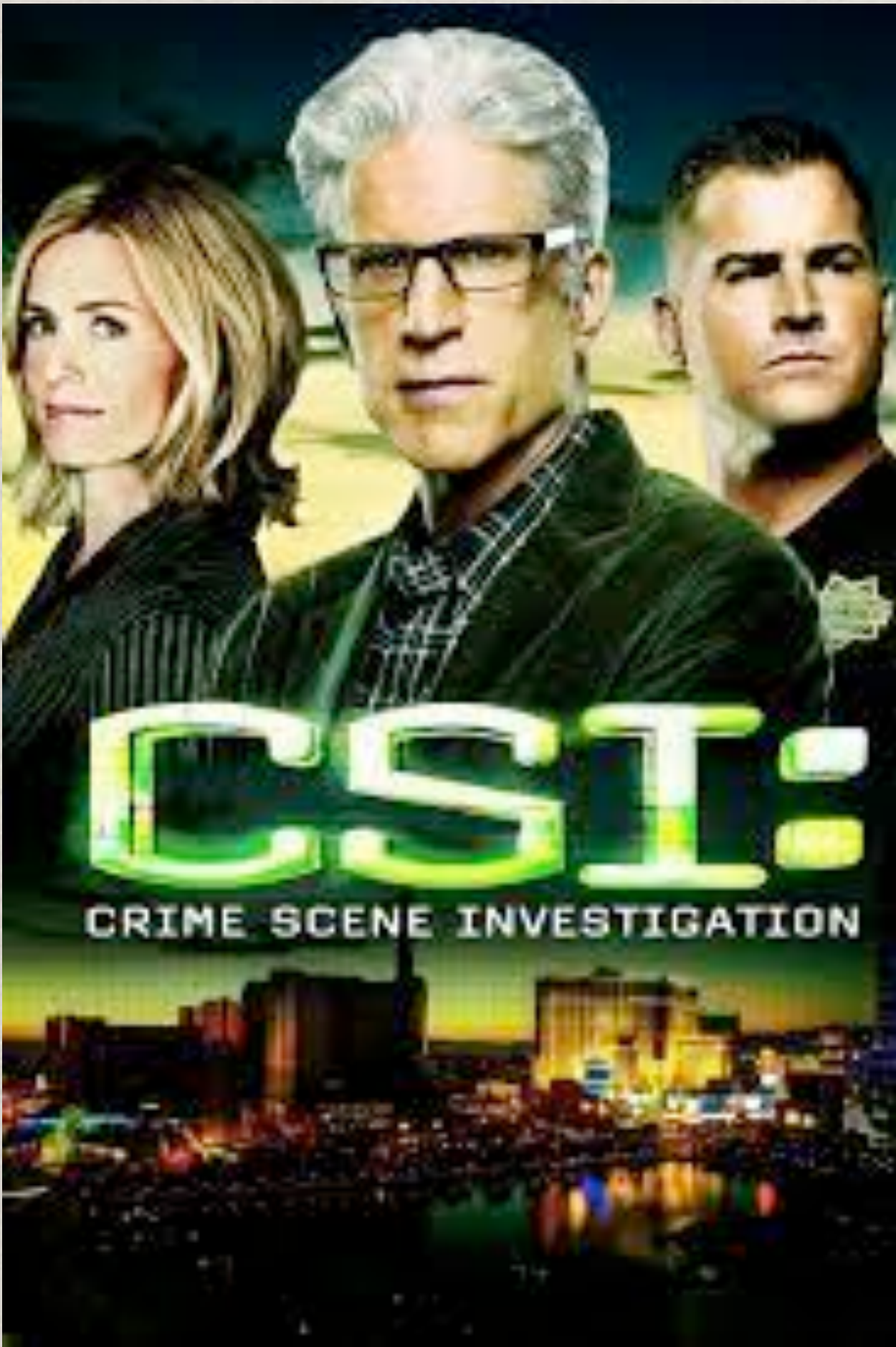
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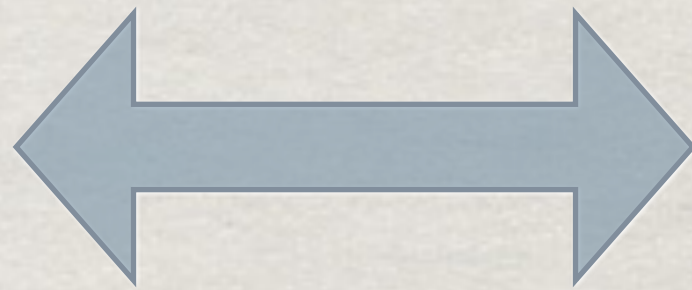
8



RECO IS COOL



height
weight
skin color
...



Particle?

energy
type
...

where



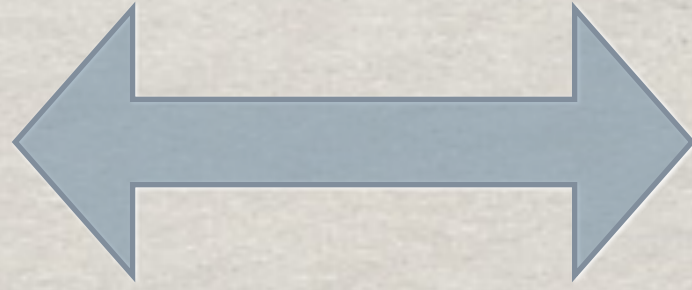
vertex/track

when



time

what



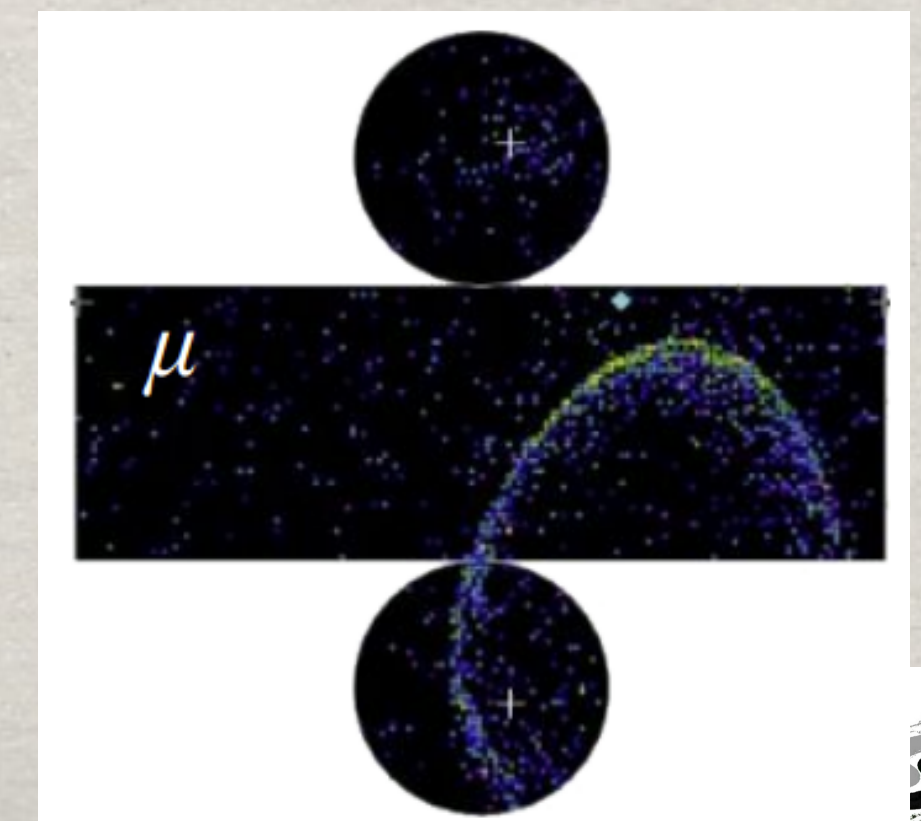
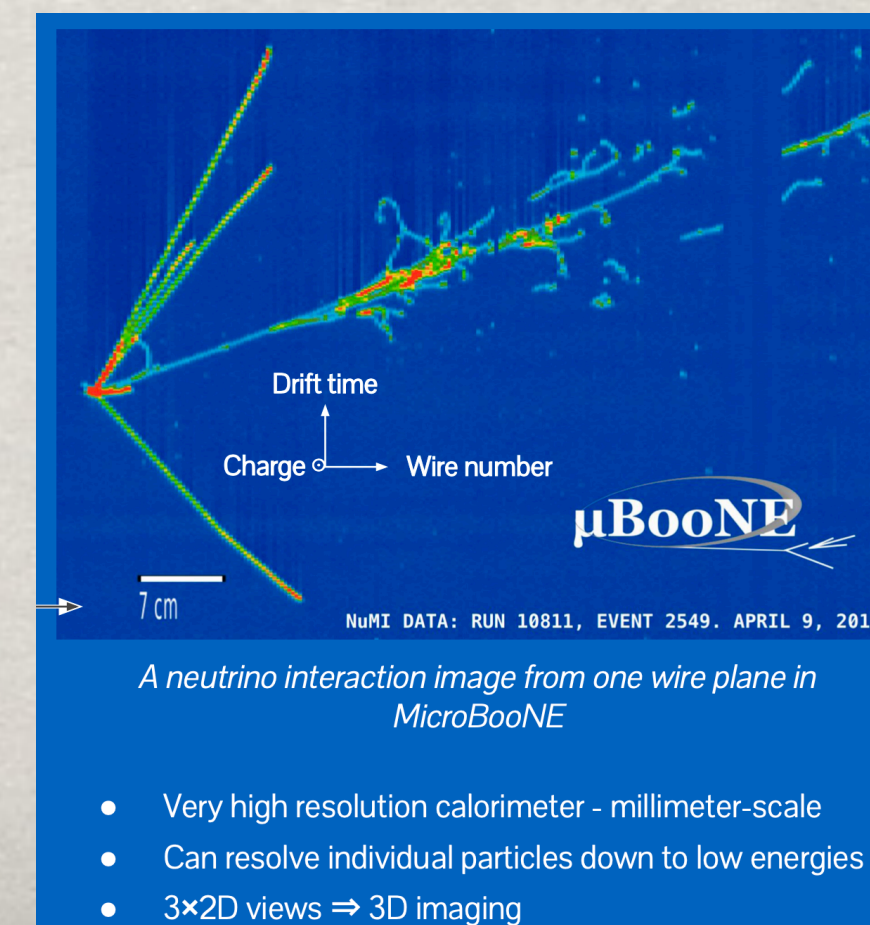
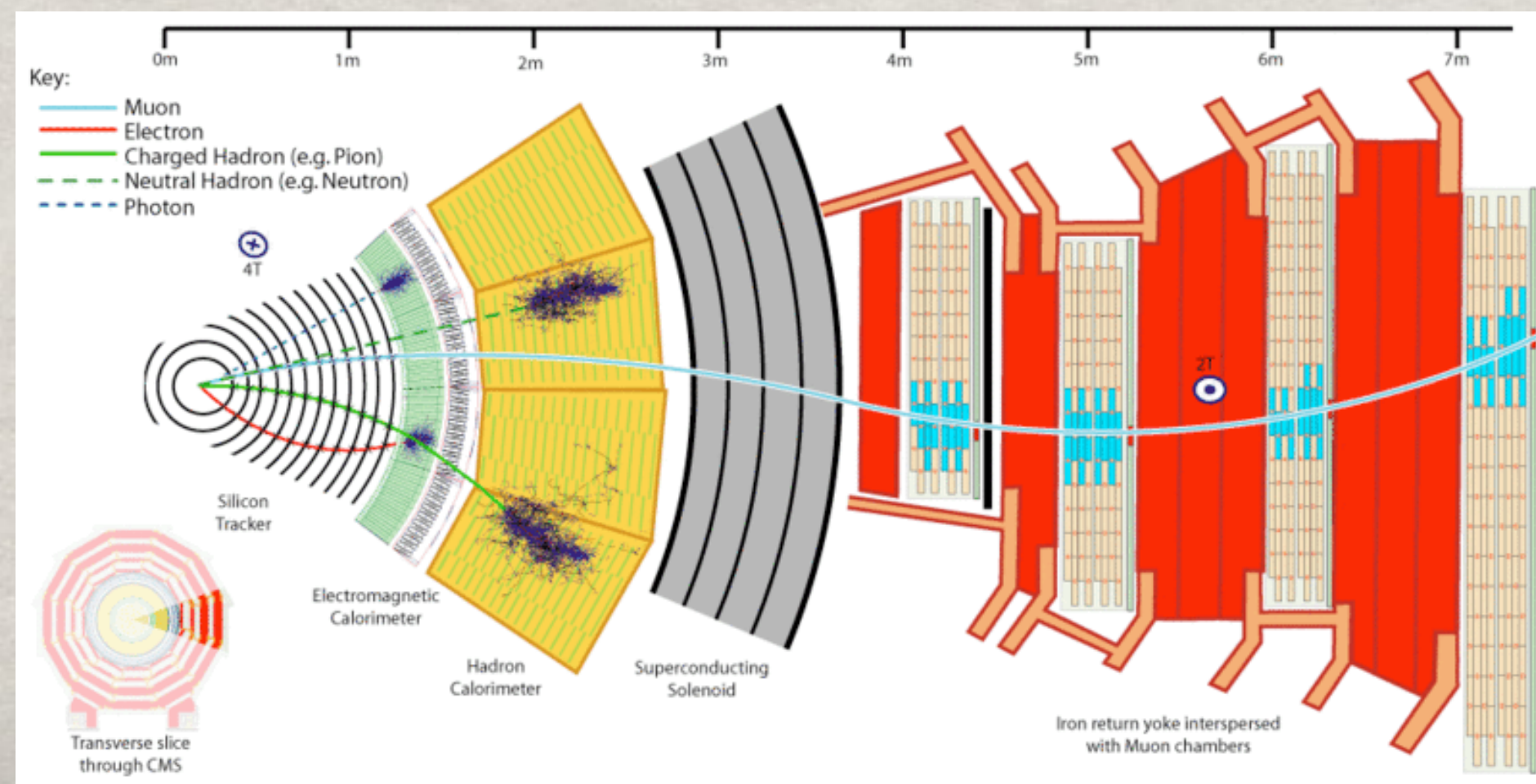
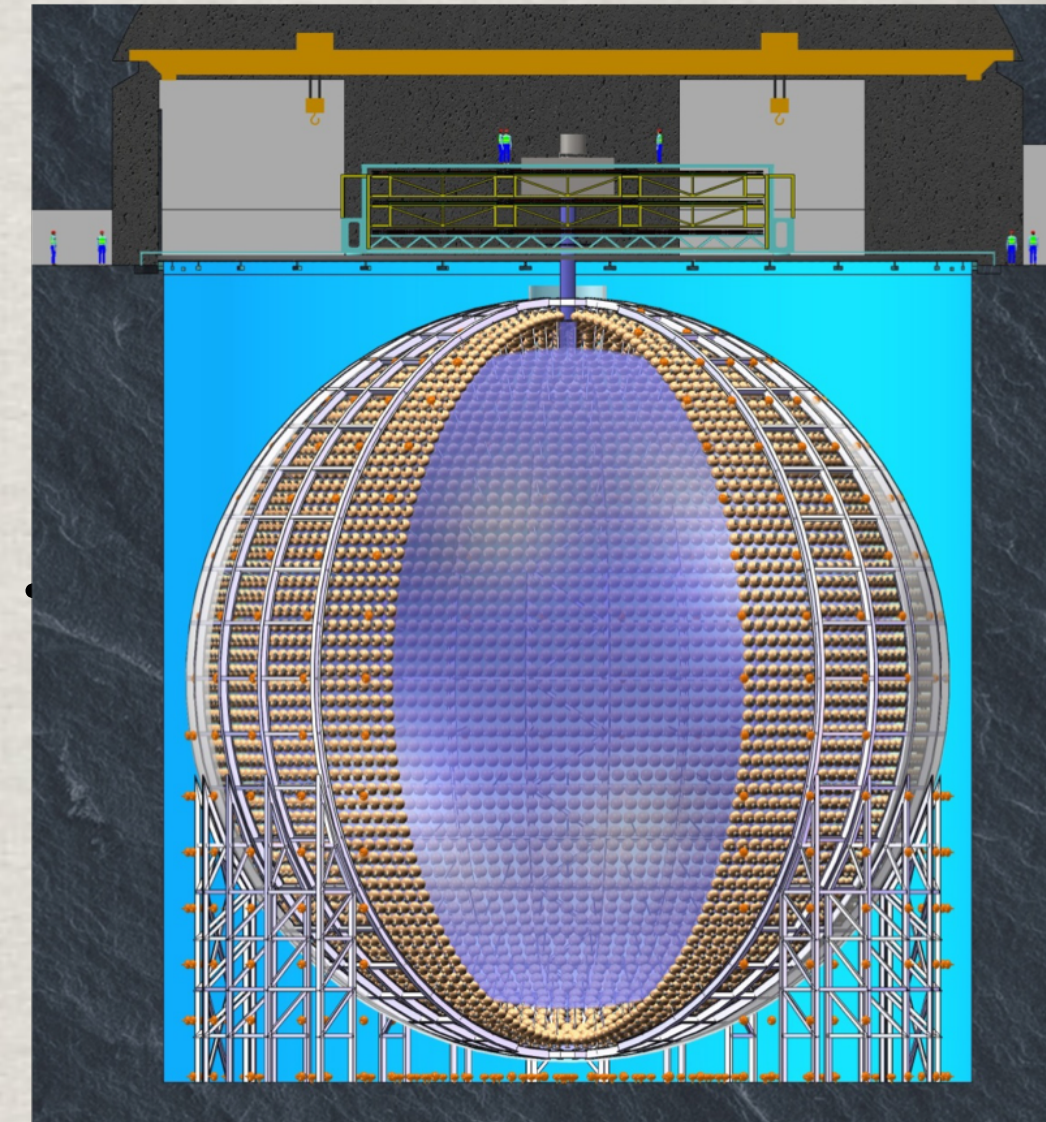
physics
process



RECO IS CHALLENGING

❖ CSI@JUNO objectives:

- ❖ Identify particle type: e^+ , α , β , γ , **neutron**/proton, μ ...
- ❖ Determine particle properties: position, energy, track, direction...
- ❖ **Know yourself, Liquid Scintillator detector**
 - ❖ pros: low energy threshold, **high energy resolution** and ? ...
 - ❖ cons: unsegmented, neither track info, nor Cherenkov rings...

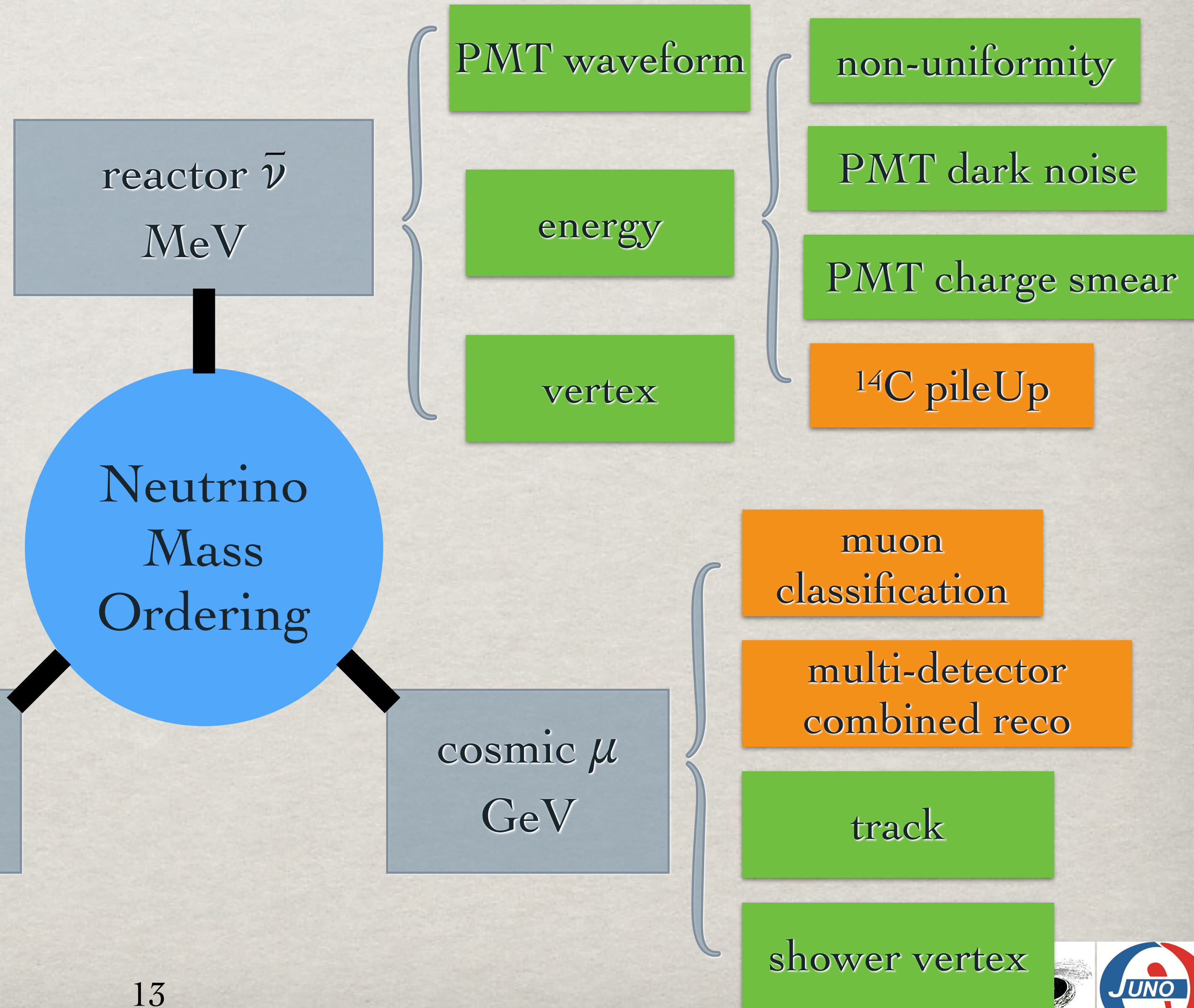
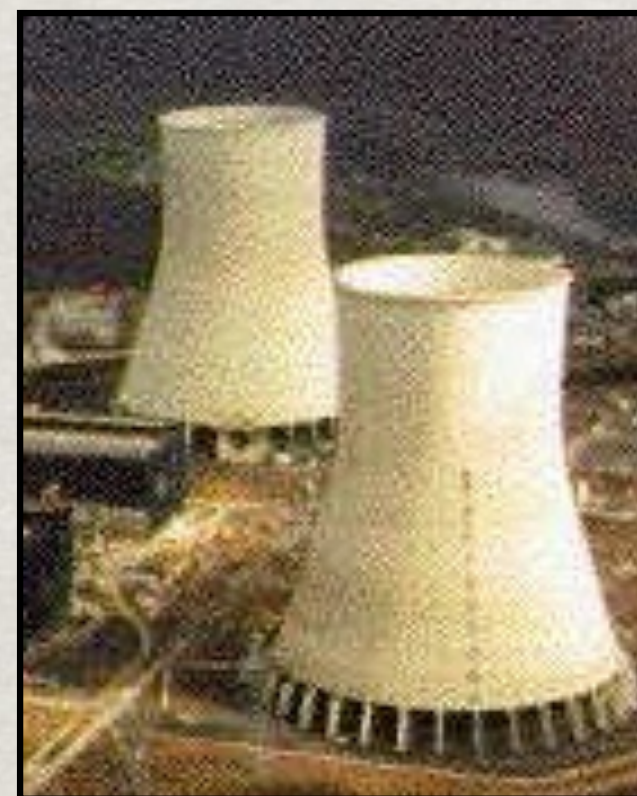
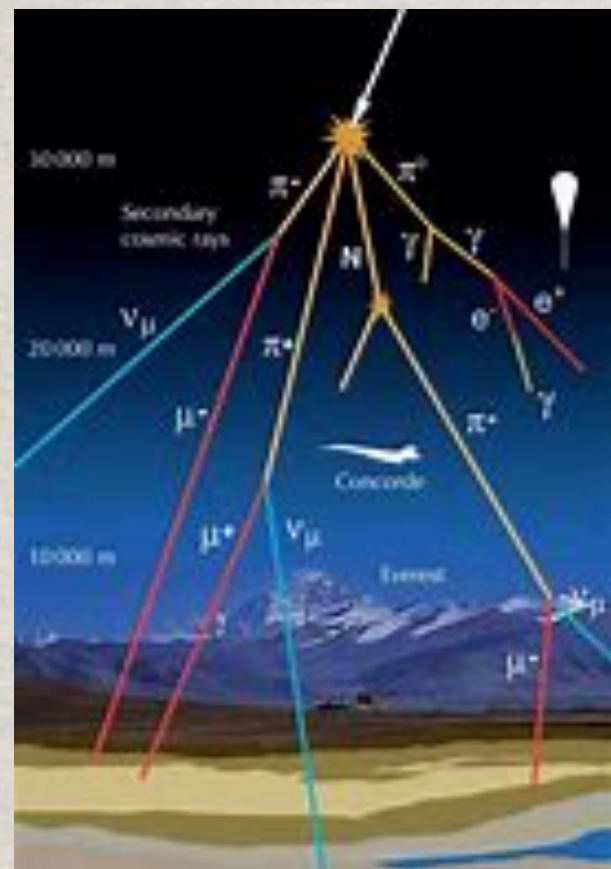


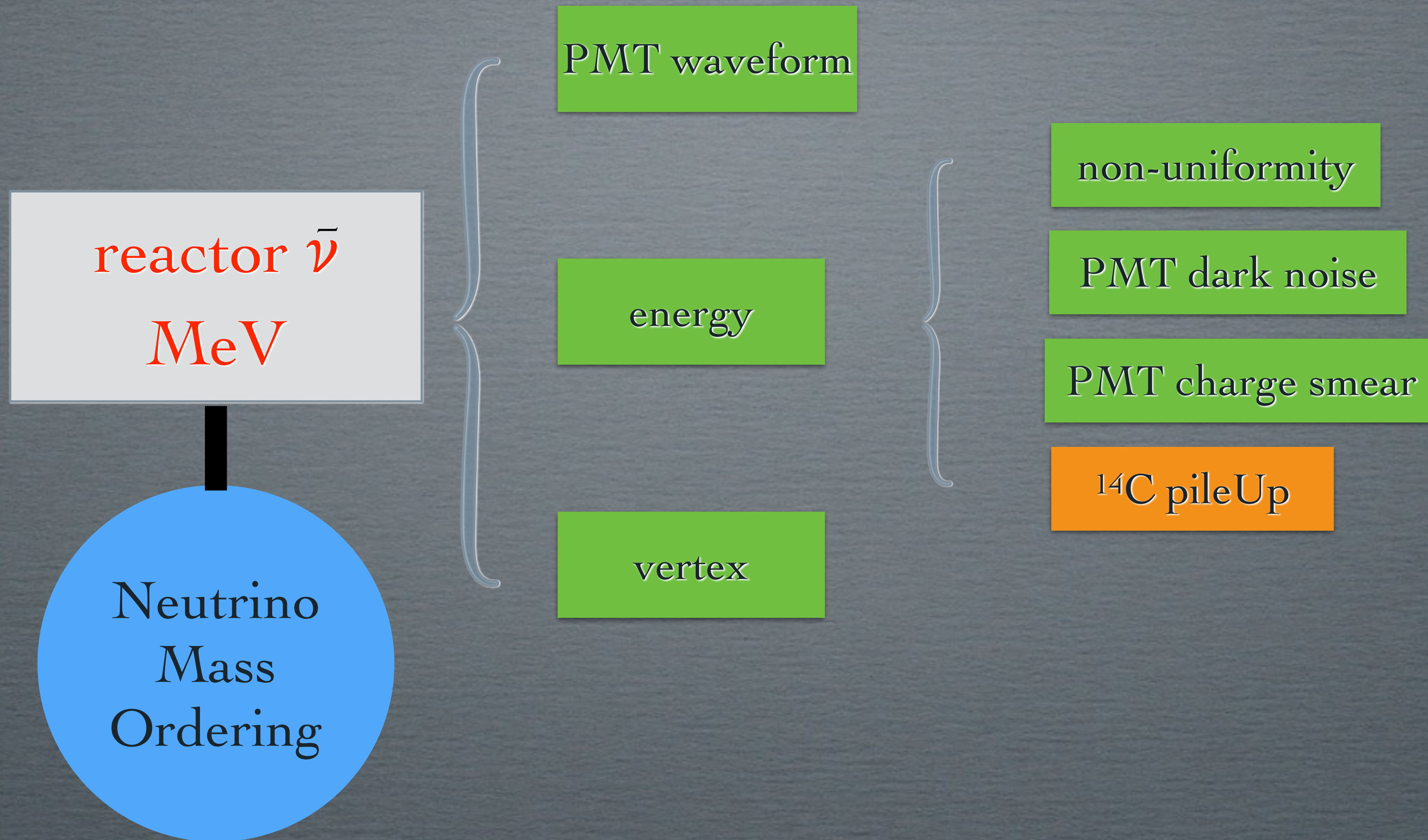
RECO IS CHALLENGING

❖ CSI@JUNO objectives:

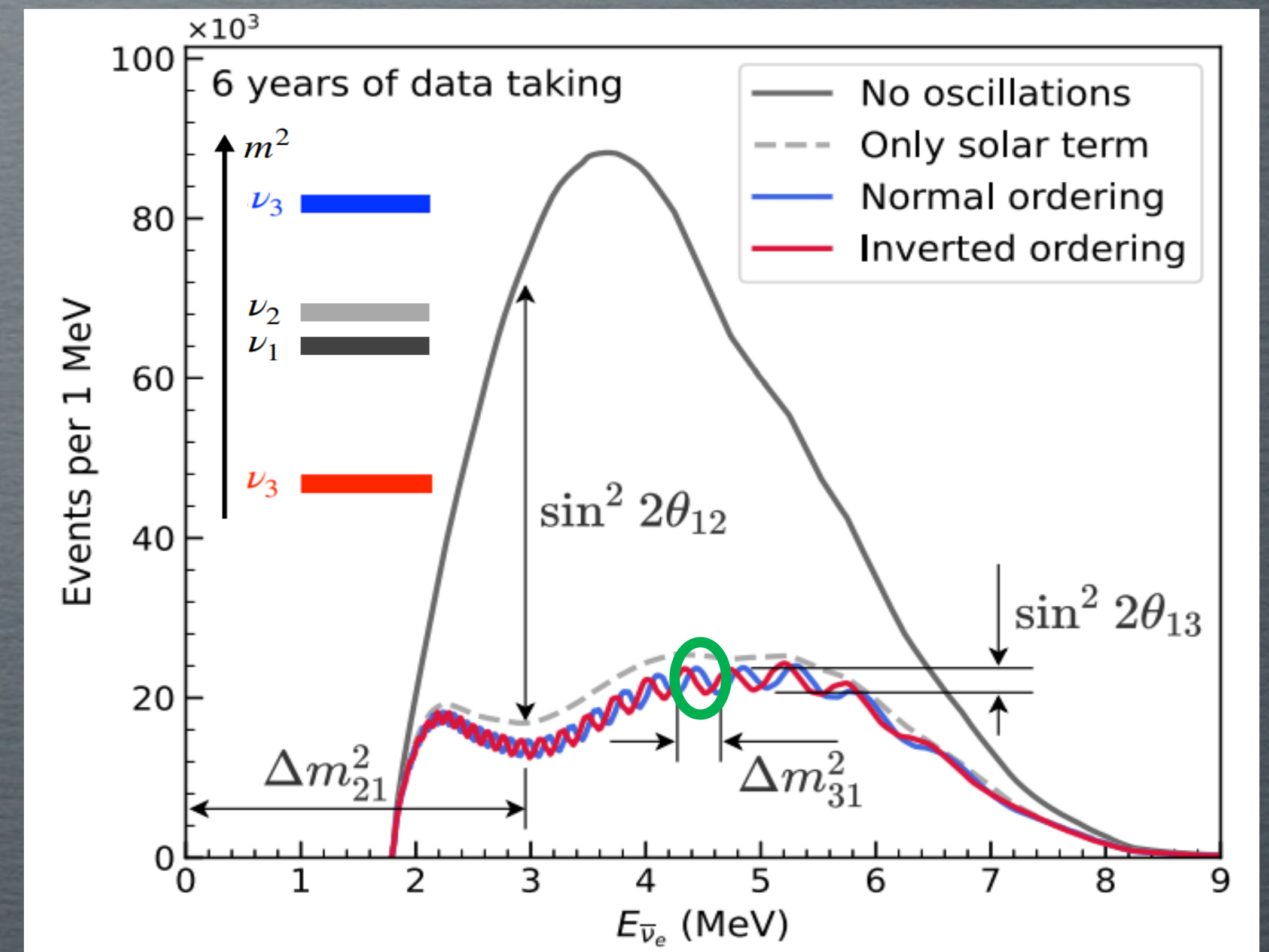
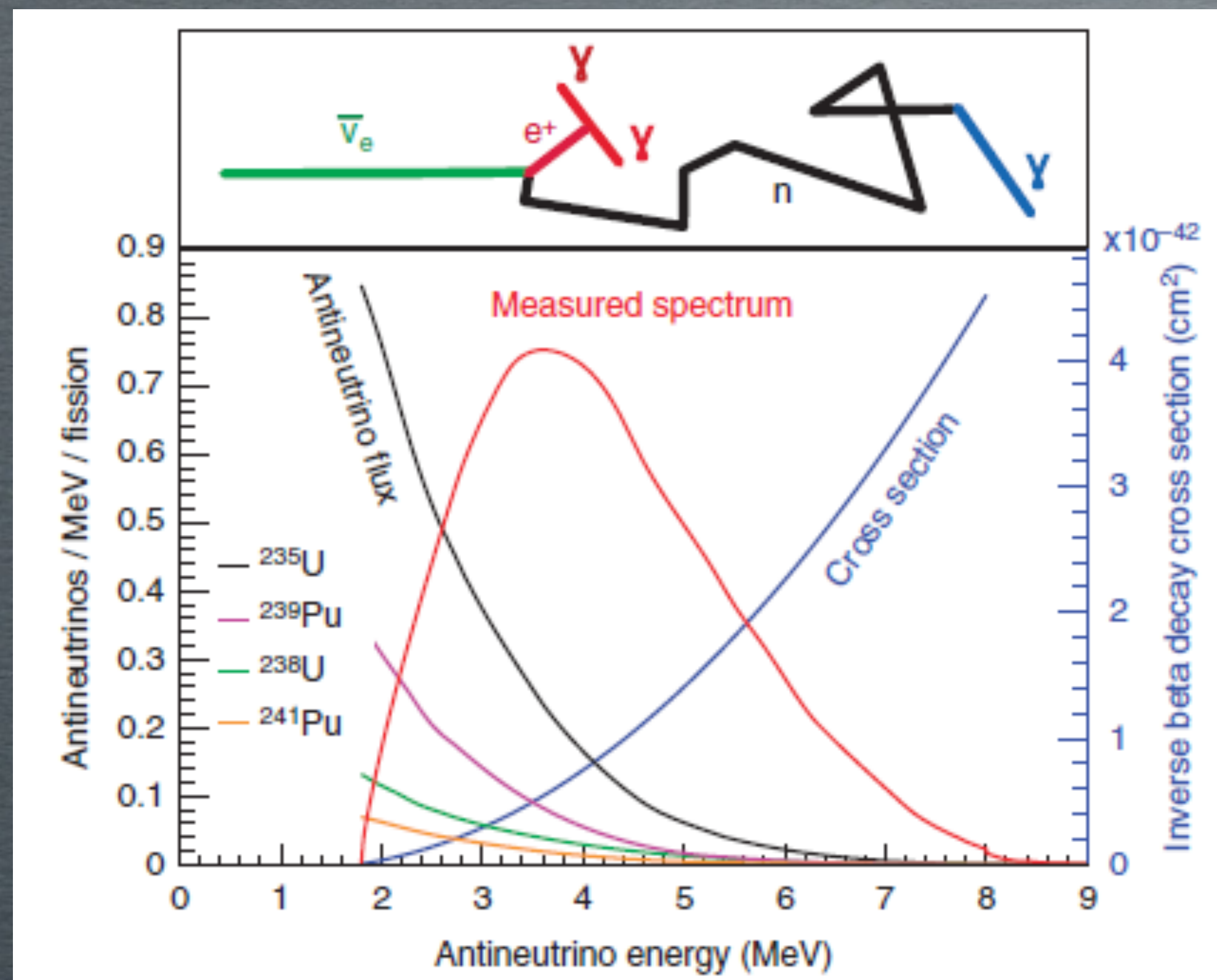
- ❖ Identify particle type: e^+ , α , β , γ , neutron/proton, μ ...
- ❖ Determine particle properties: position, energy, track, direction...
- ❖ **Know your suspect, particle behavior in JUNO:**
 - ❖ charged particles deposit energy and emit scintillation photons, together with negligible Cherenkov light
 - ❖ particle topology: point/ball-like source (MeV region); track or shower (GeV region)
 - ❖ ~~multiple crime scenes~~ $\longleftrightarrow$ ~~coincident signals~~

RECO IS IMPORTANT



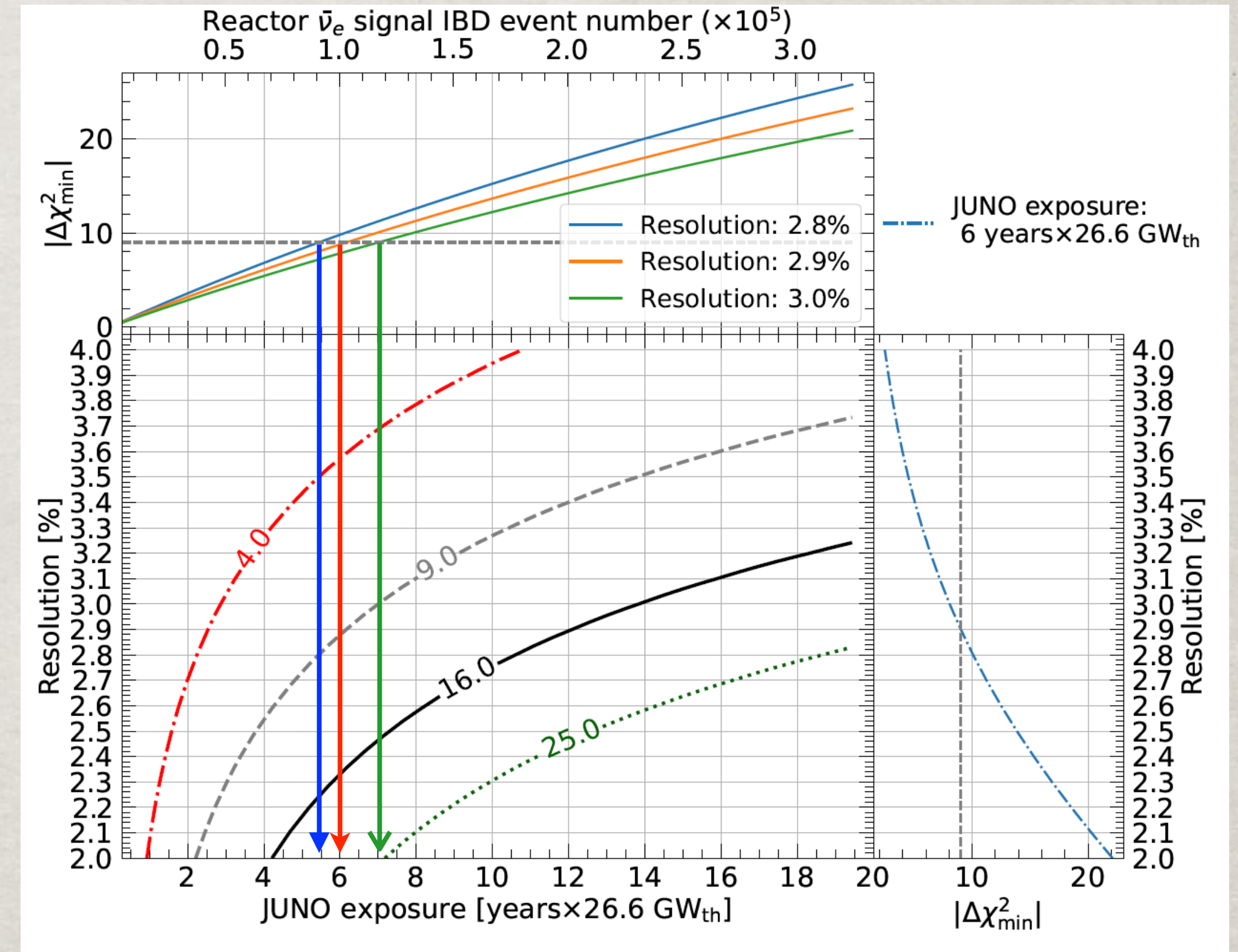


ENERGY RECO



REACTOR NEUTRINOS

	DETECTOR TARGET MASS	ENERGY RESOLUTION
KamLAND	1000 t	6%/√E
D. Chooz	8+22 t	8%/√E
RENO	16 t	
Daya Bay	20 t	
Borexino	300 t	5%/√E
JUNO	20000 t	3%/√E



- ❖ Challenging: un-precedented energy resolution
- ❖ Important: better resolution $\rightarrow$ better sensitivity

ENERGY RECO.

- ❖ Simple total PE method: $E \sim \text{total PE}$
- ❖ Maximum likelihood method*
 - ❖ optical model independent
 - ❖ calibration data driven
 - ❖ taking into account differences among PMTs
- ❖ Main factors for energy resolution:
 - ❖ photon statistics
 - ❖ energy non-uniformity*
 - ❖ PMT dark noise

METHOD PRINCIPLE

NIMA 1001 (2021) 165287

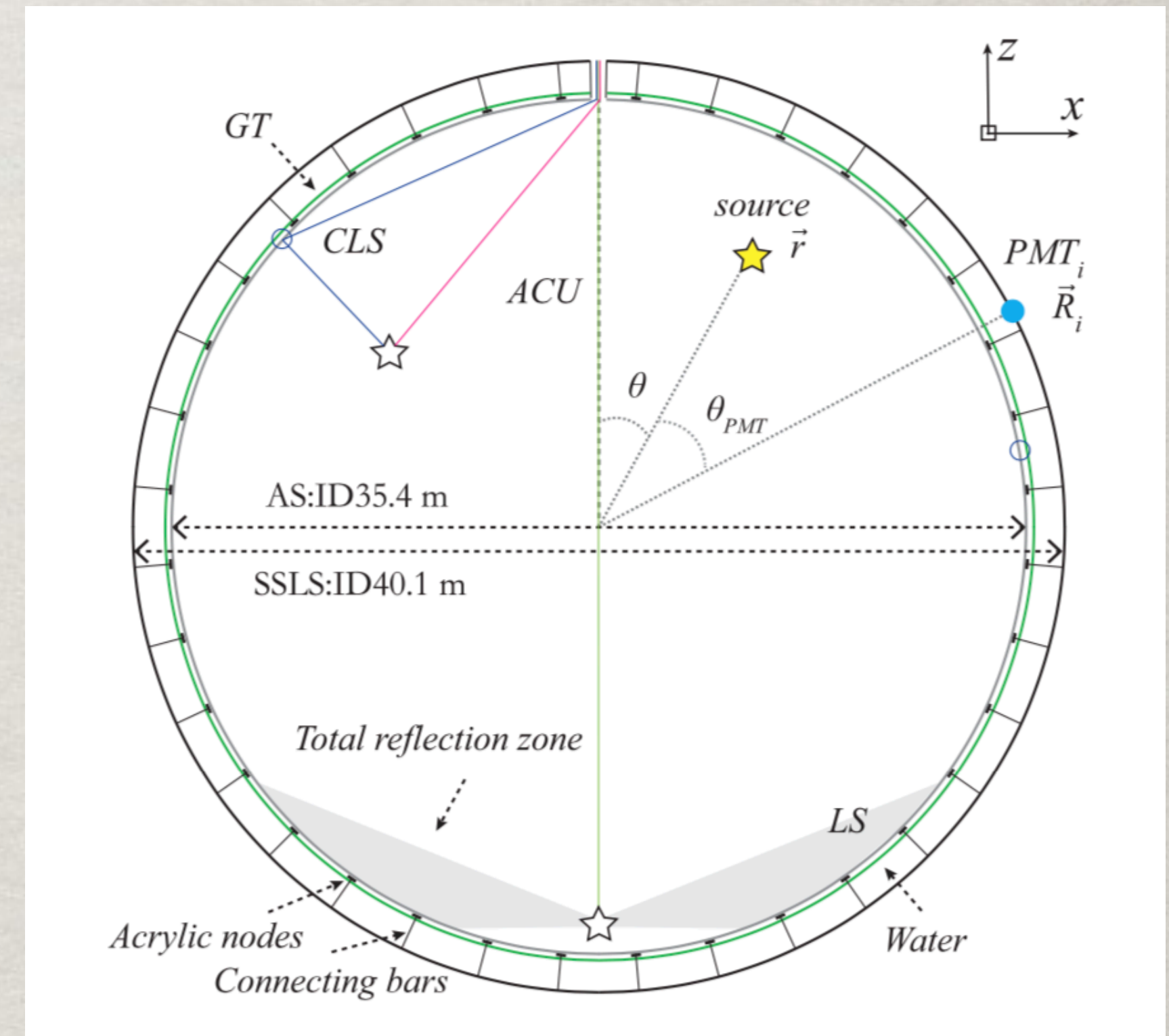
- ❖ Step1: use calibration data to construct the expected number of PhotoElectron per unit E $\hat{\mu}(r, \theta, \theta_{PMT})$ for PMTs
- ❖ Step2: maximize the likelihood function

$$\mathcal{L}(\{k_i\} | r, \theta, \phi, E_{vis}) = \prod_i \mathcal{L}(k_i | r, \theta, \phi, E_{vis}) = \prod_i \frac{e^{-\mu_i} \cdot \mu_i^{k_i}}{k_i!}$$

$$\mu_i = E_{vis} \cdot \hat{\mu}_i$$

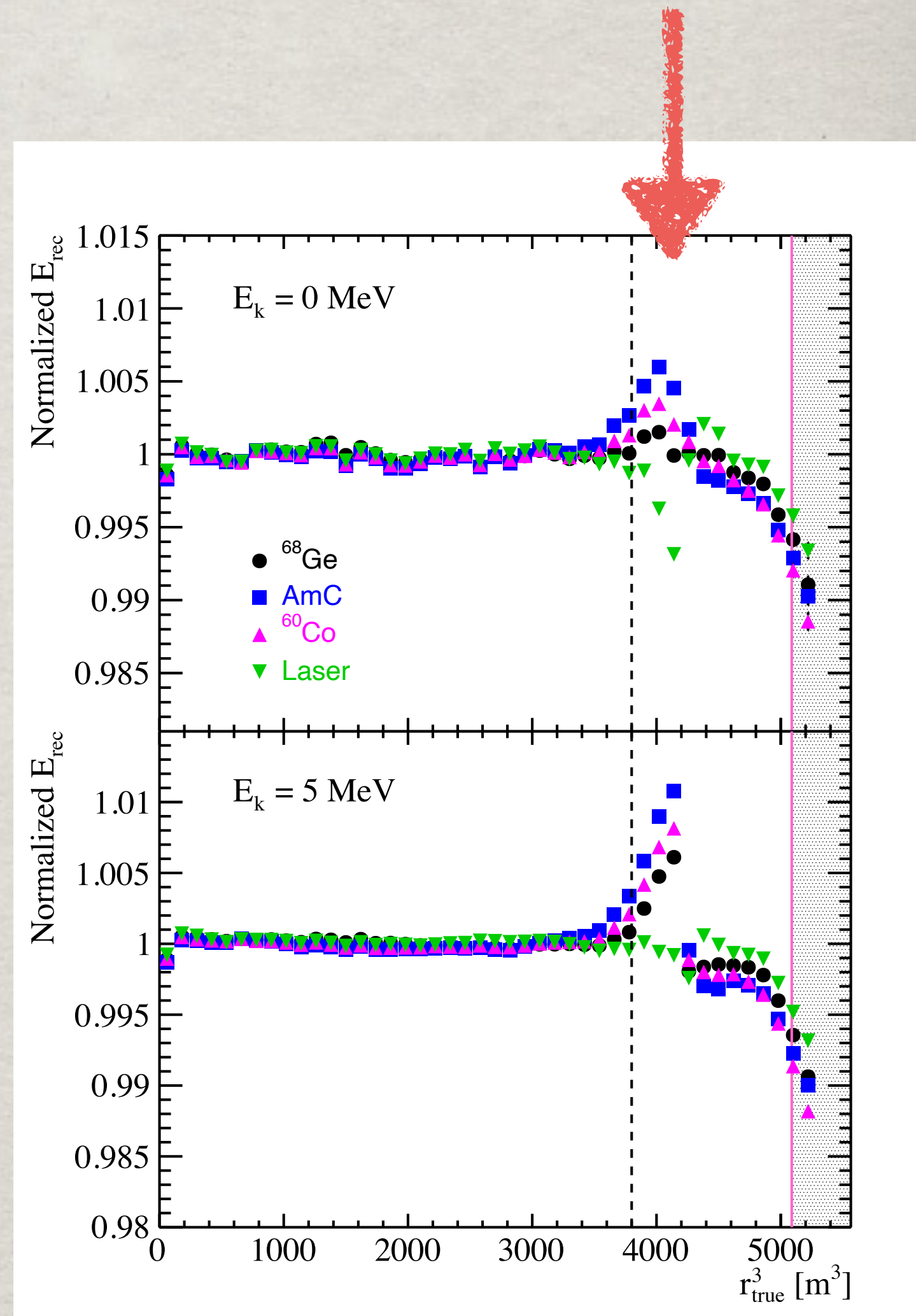
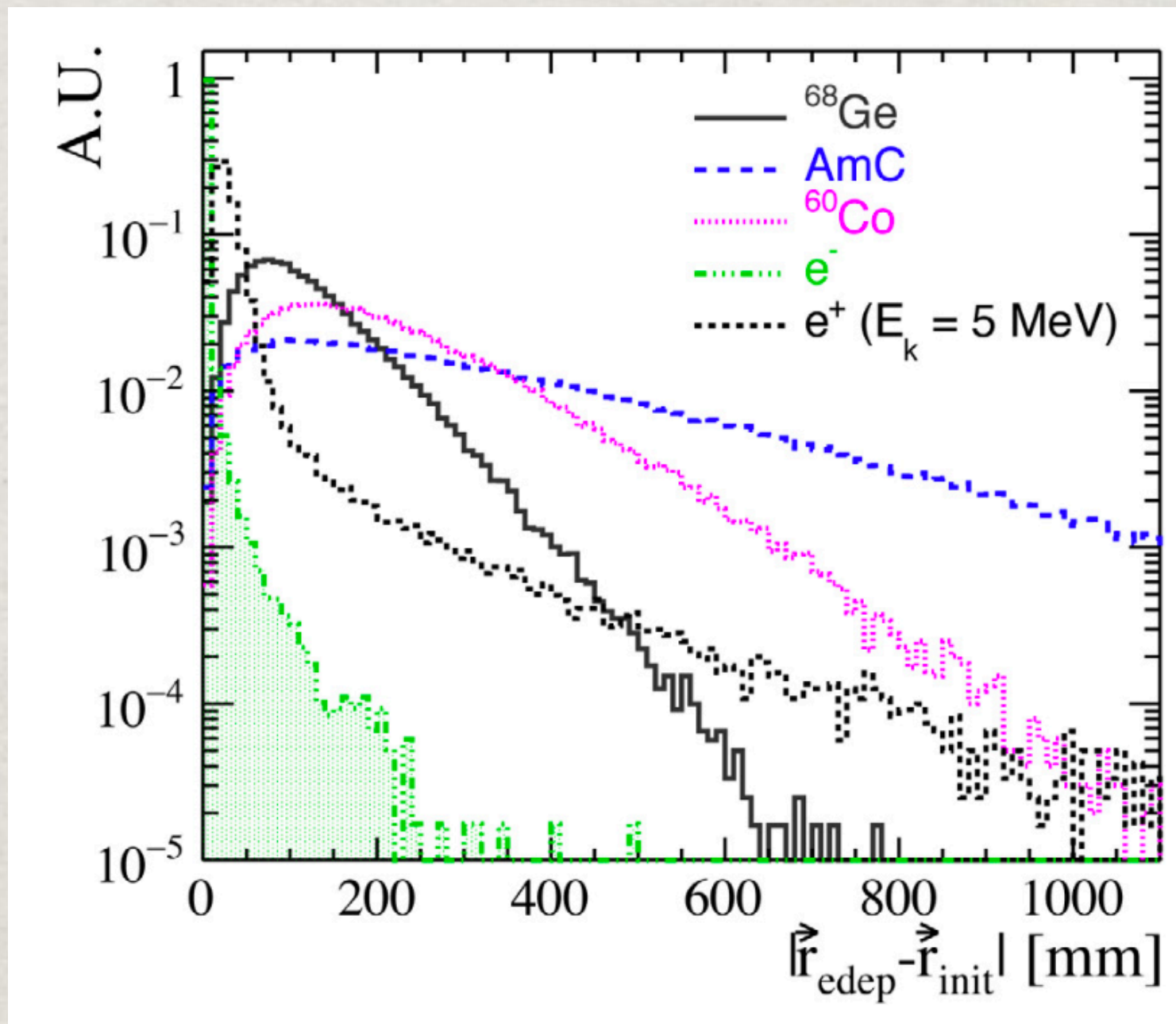
* $\{k_i\}$ — detected PE for PMTs

E_{vis} — visible energy



SOURCE CHOICE

Source	Type	Energy [MeV]
^{68}Ge	γ	2×0.511
^{60}Co	γ	$1.173 + 1.333$
AmC	$(n,H)\gamma$	2.22
Laser	op	1



- ❖ Obvious energy non-uniformity in the total reflection region
- ❖ Laser(^{68}Ge) is better at high(low) energy

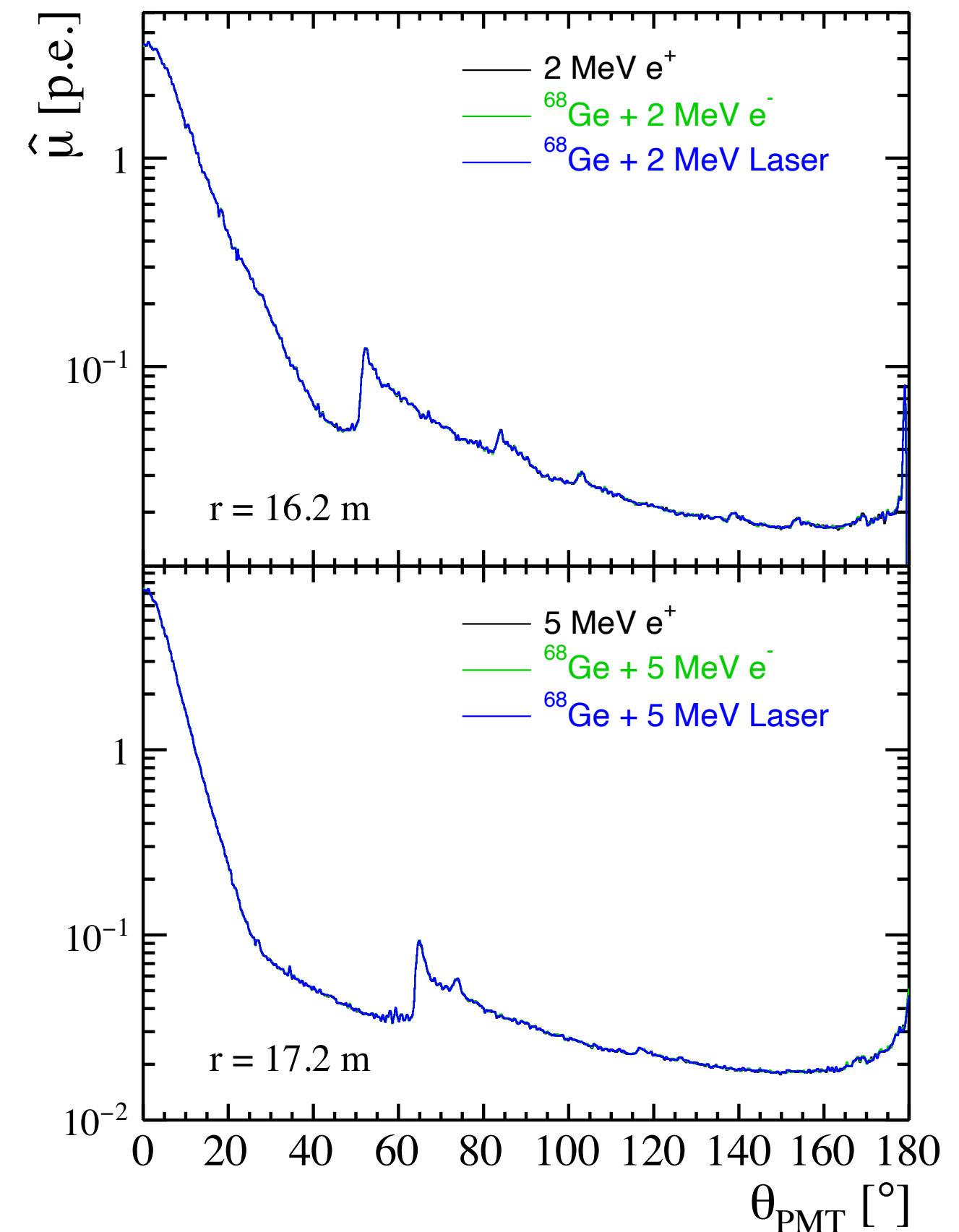
COMBINED SOURCE

- ❖ Energy deposition of positron in LS
 - ❖ kinetic part: point-like
 - ❖ annihilation part: ball-like
- ❖ Use combined source Laser+ ^{68}Ge to mimic positron

$$\hat{\mu}^{comb} = \frac{1}{E_{vis}} \cdot (E_{vis}^{Ge} \cdot \hat{\mu}^{Ge}(r, \theta, \theta_{PMT}) + E_k \cdot \hat{\mu}^L(r, \theta, \theta_{PMT}))$$

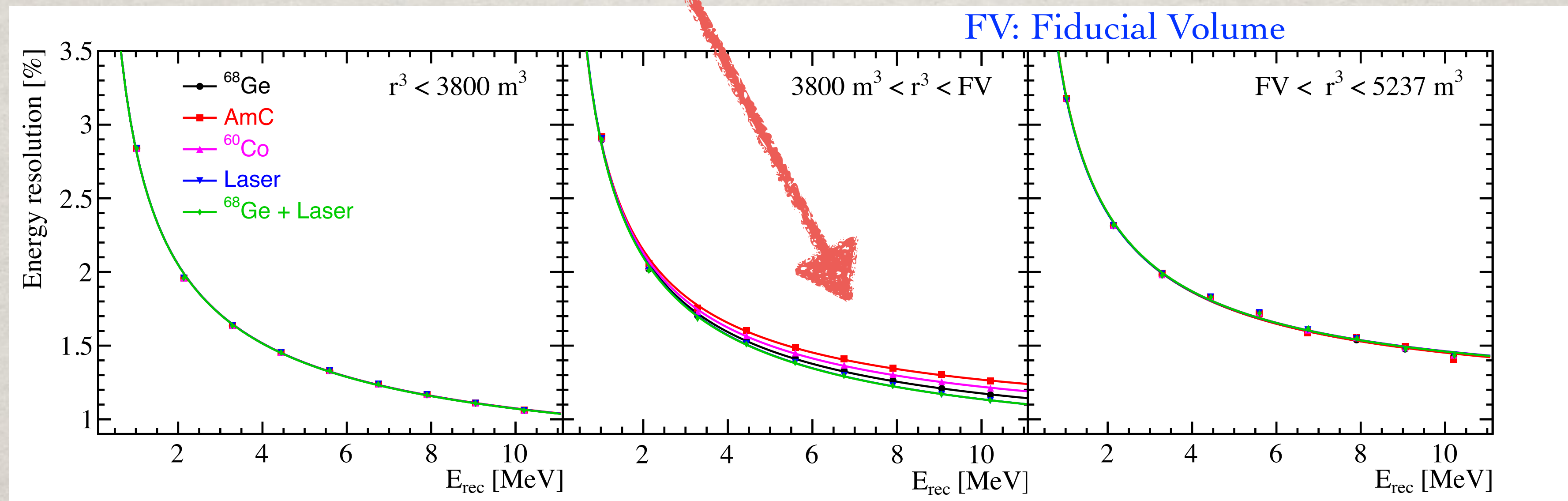
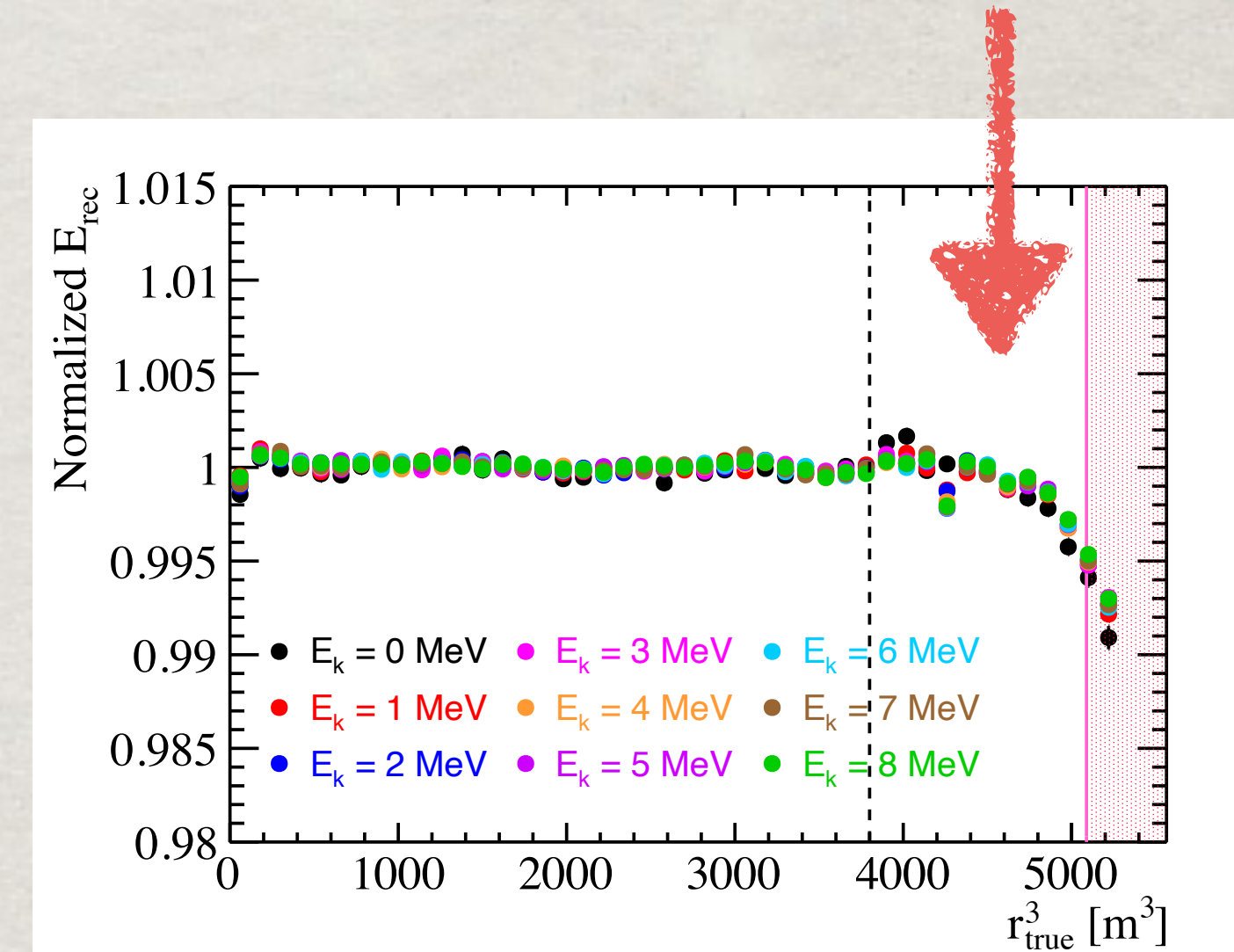
$$E_{vis} = E_{vis}^{Ge} + E_k$$

* E_k — kinetic energy of e^+



PERFORMANCE

❖ Combined source improves the energy-uniformity (consequently energy resolution) in the total reflection region



VERTEX/ENERGY
COMBINED RECO

TIME LIKELIHOOD

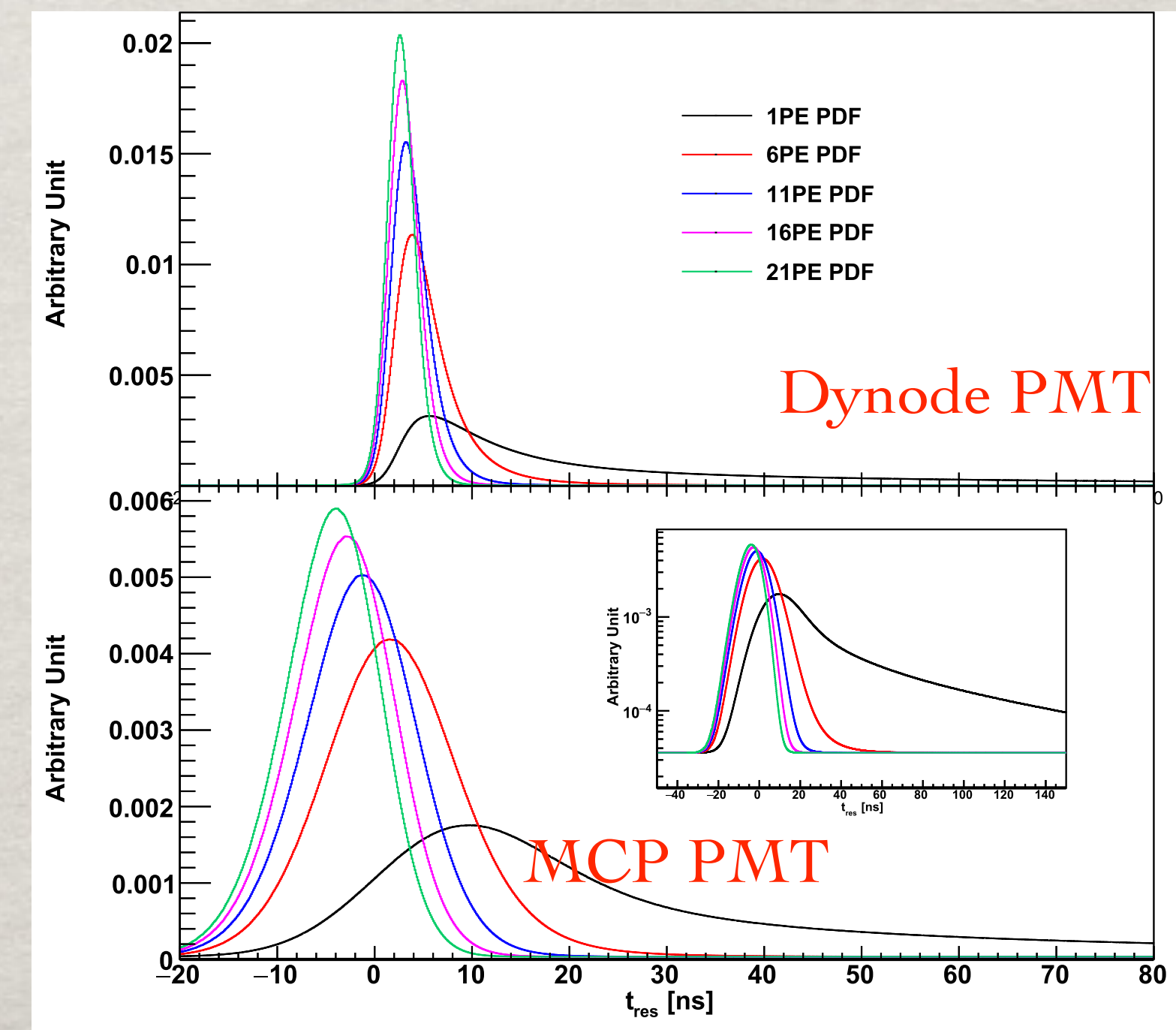
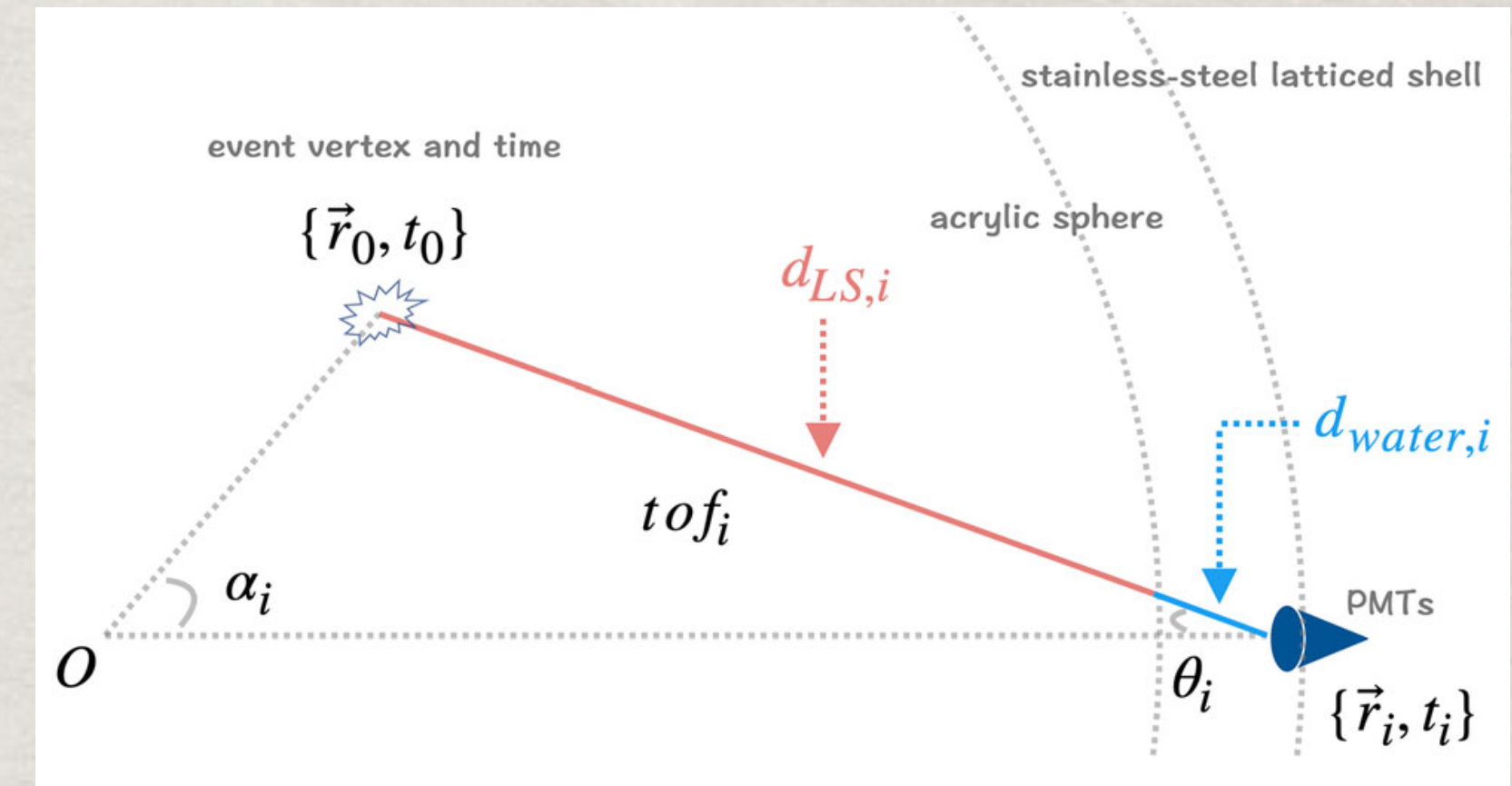
❖ Define residual time

$$t_{\text{res}}^i(\vec{r}_0, t_0) = t_i - \text{tof}_i - t_0,$$

❖ Construct pdf $p(t_{\text{res}})$

❖ Minimize likelihood function

$$\mathcal{L}(\vec{r}_0, t_0) = -\ln \left(\prod_i p(t_{\text{res}}^i) \right).$$



LIKELIHOOD METHOD

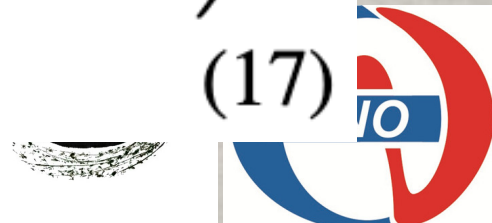
Nucl.Sci.Tech. 34 (2023) 6, 83

Method	PMT input info	reco target
QMLE	charge only	r, E
TMLE	time only	r
QTMLE	charge & time	r, E

$$\mathcal{L}(q_1, q_2, \dots, q_N | \mathbf{r}, E_{\text{vis}}) = \prod_{\text{unfired}} e^{-\mu_j} \prod_{\text{fired}} \left(\sum_{k=1}^{+\infty} P_Q(q_i | k) \times P(k, \mu_i) \right), \quad (15)$$

$$\mathcal{L}(t_{1,r}, t_{2,r}, \dots, t_{N,r} | \mathbf{r}, t_0) = \prod_{T-\text{valid hit}} \frac{\sum_{k=1}^K P_T(t_{i,r} | r, d_i, \mu_i^l, \mu_i^d, k) \times P(k, \mu_i^l + \mu_i^d)}{\sum_{k=1}^K P(k, \mu_i^l + \mu_i^d)}, \quad (16)$$

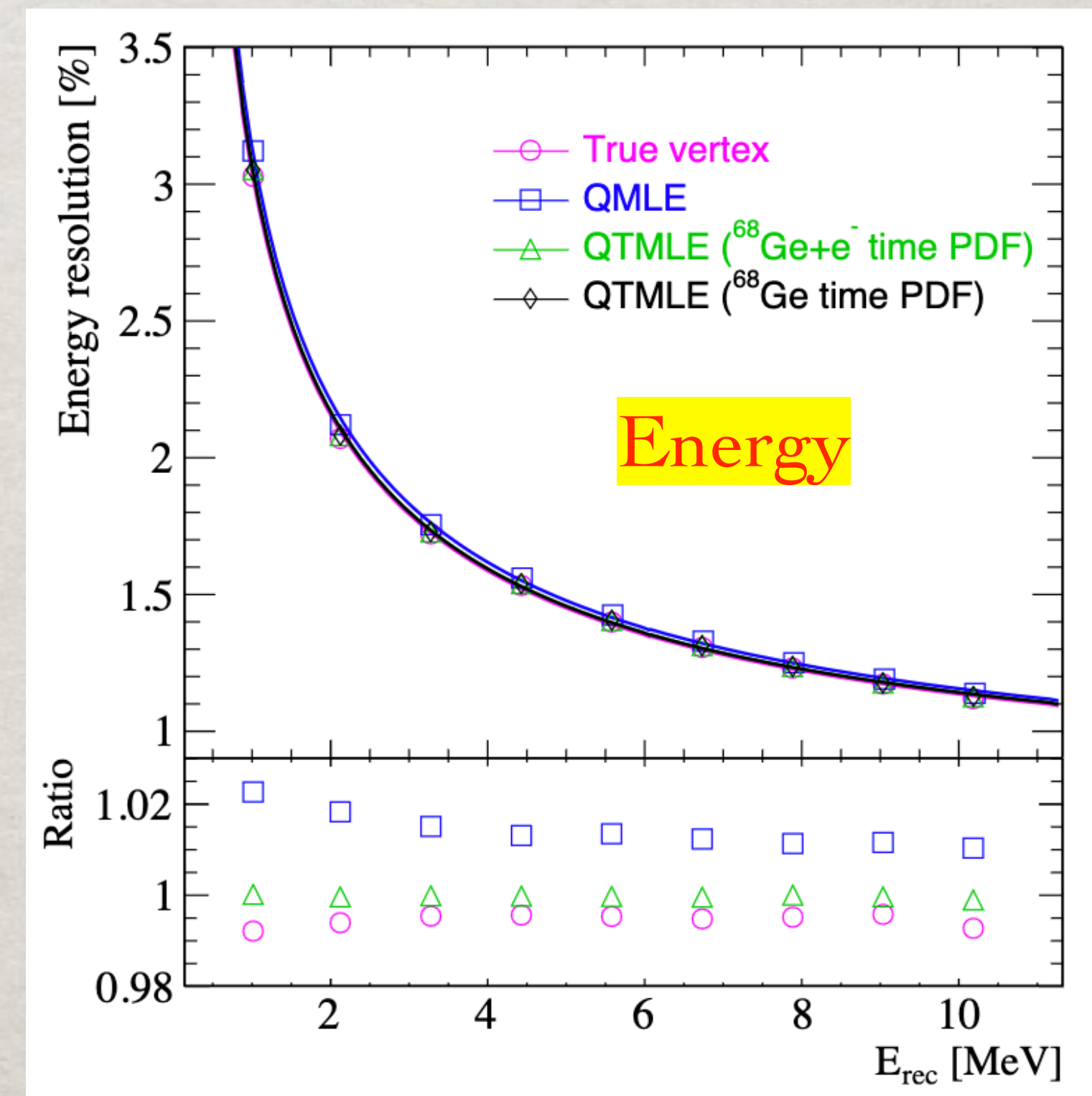
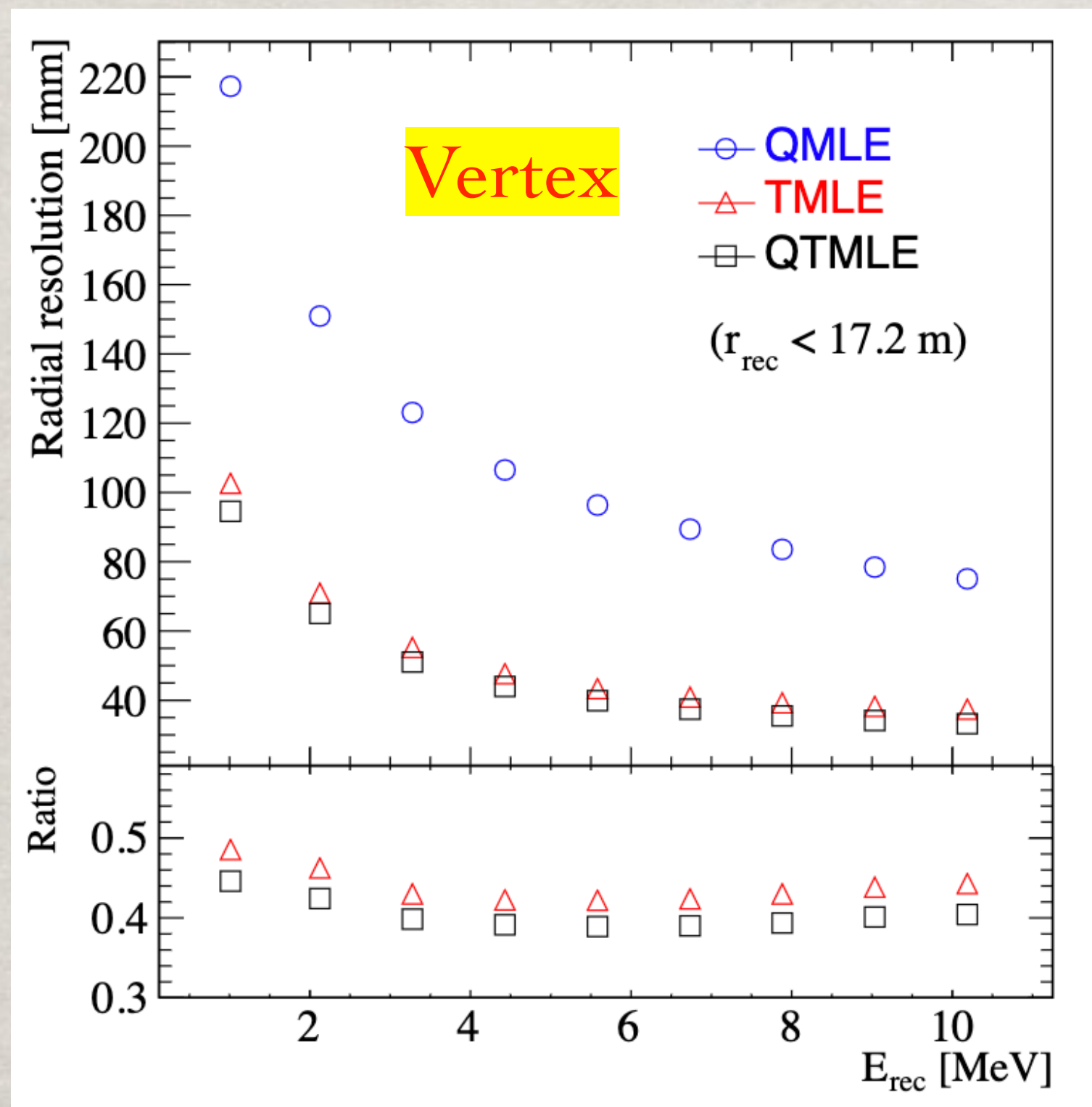
$$\mathcal{L}(q_1, q_2, \dots, q_N; t_{1,r}, t_{2,r}, \dots, t_{N,r} | \mathbf{r}, t_0, E_{\text{vis}}) = \prod_{\text{unfired}} e^{-\mu_j} \prod_{\text{fired}} \left(\sum_{k=1}^{+\infty} P_Q(q_i | k) \times P(k, \mu_i) \right) \prod_{T-\text{valid hit}} \left(\frac{\sum_{k=1}^K P_T(t_{i,r} | r, d_i, \mu_i^l, \mu_i^d, k) \times P(k, \mu_i^l + \mu_i^d)}{\sum_{k=1}^K P(k, \mu_i^l + \mu_i^d)} \right). \quad (17)$$



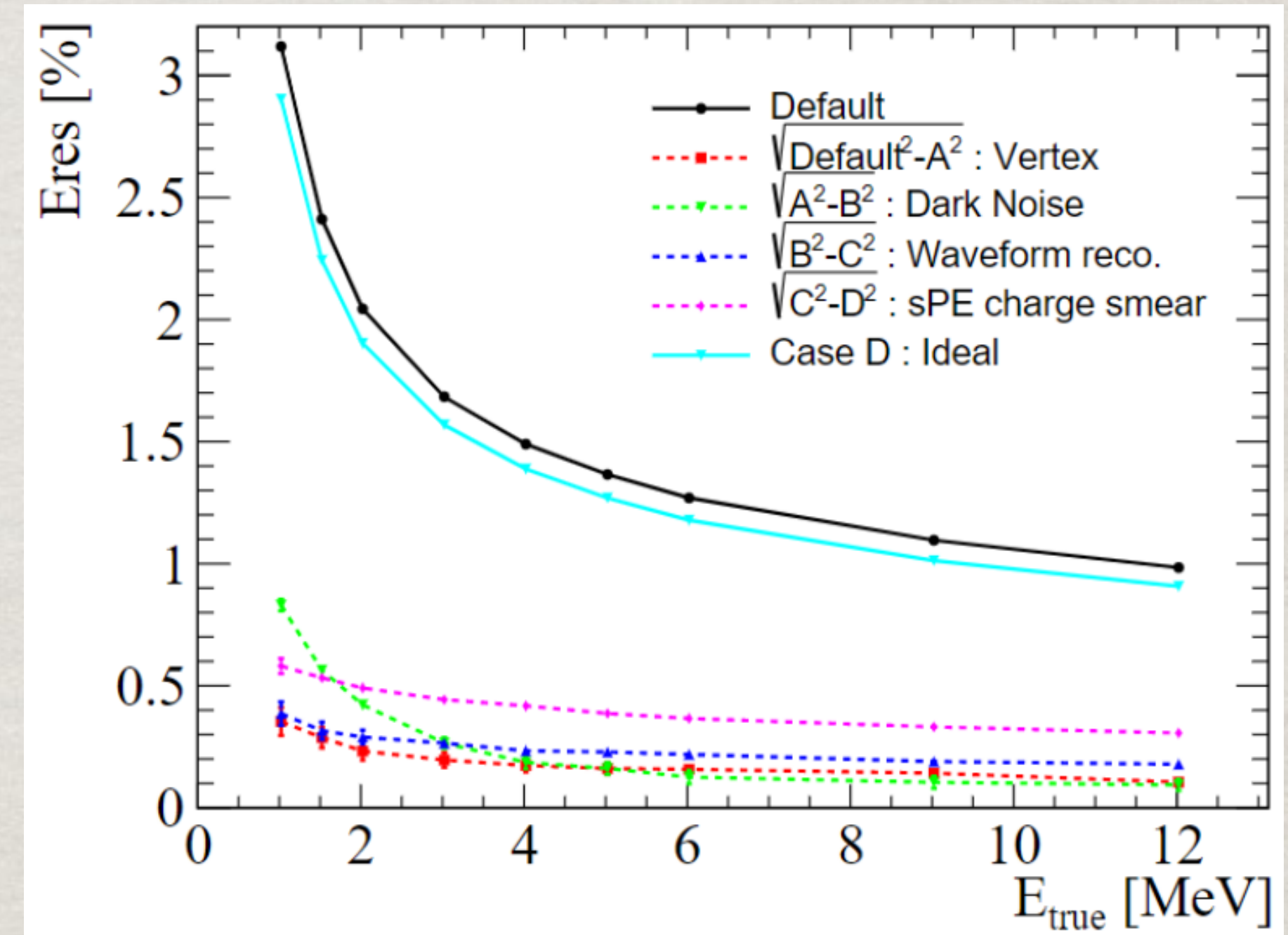
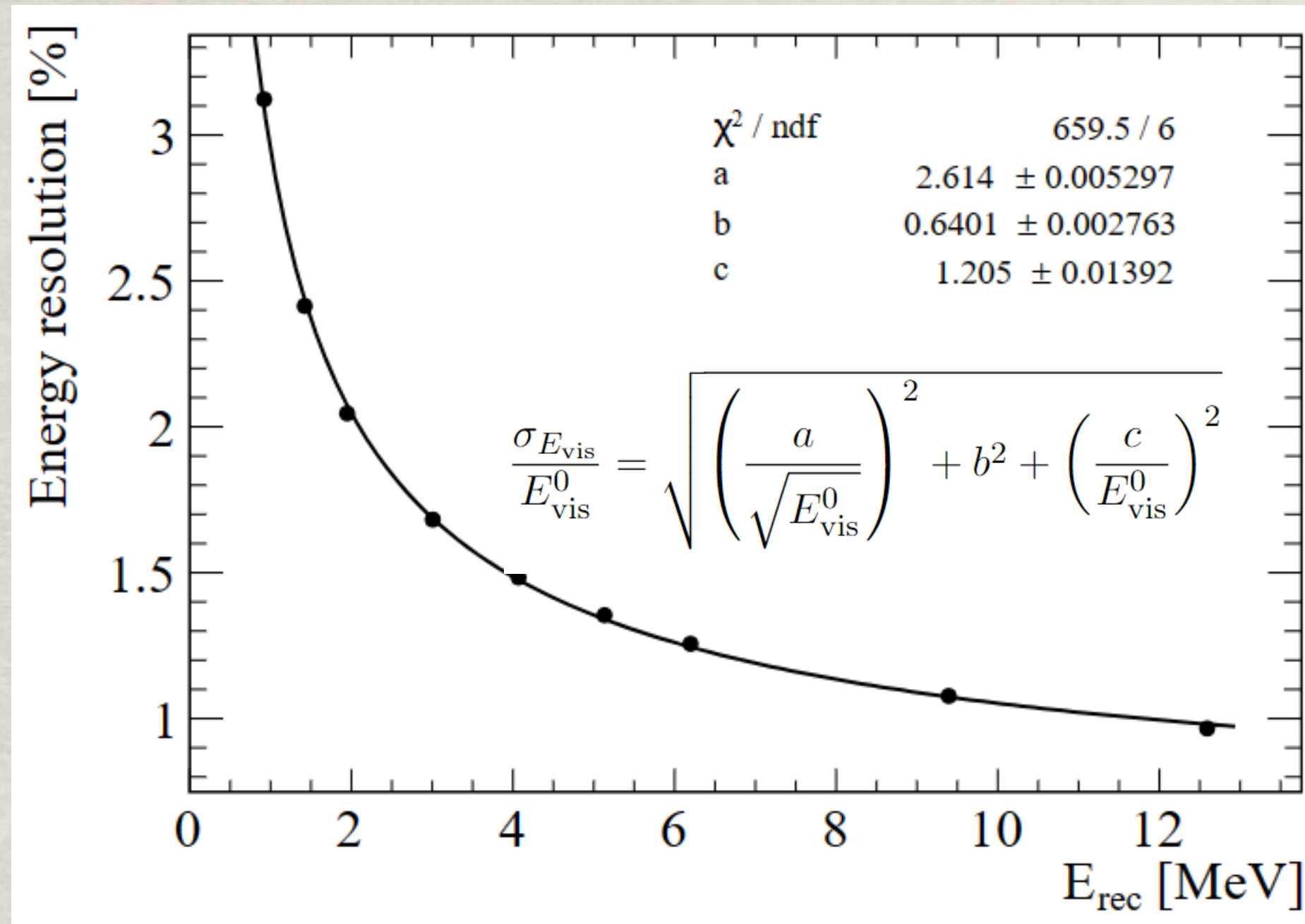
PERFORMANCE COMPARISON

Nucl.Sci.Tech. 34 (2023) 6, 83

- ❖ R_{res} depends mainly on PMT time info, charge info also helps
- ❖ Impact of R_{res} on E_{res} is $\leq 0.6\%$ for QTMLE



REACTOR NEUTRINOS



- ❖ Latest predicted Eres **2.95% @ 1 MeV**
- ❖ Decomposition of the Energy Resolution
 - ❖ PMT dark noise, charge smearing

Chin. Phys. C 49 (2025) 1, 013003

PMT WAVEFORM PHOTON COUNTING

PMT WAVEFORM PHOTON COUNTING

Eur.Phys.J.C 85 (2025) 1, 69

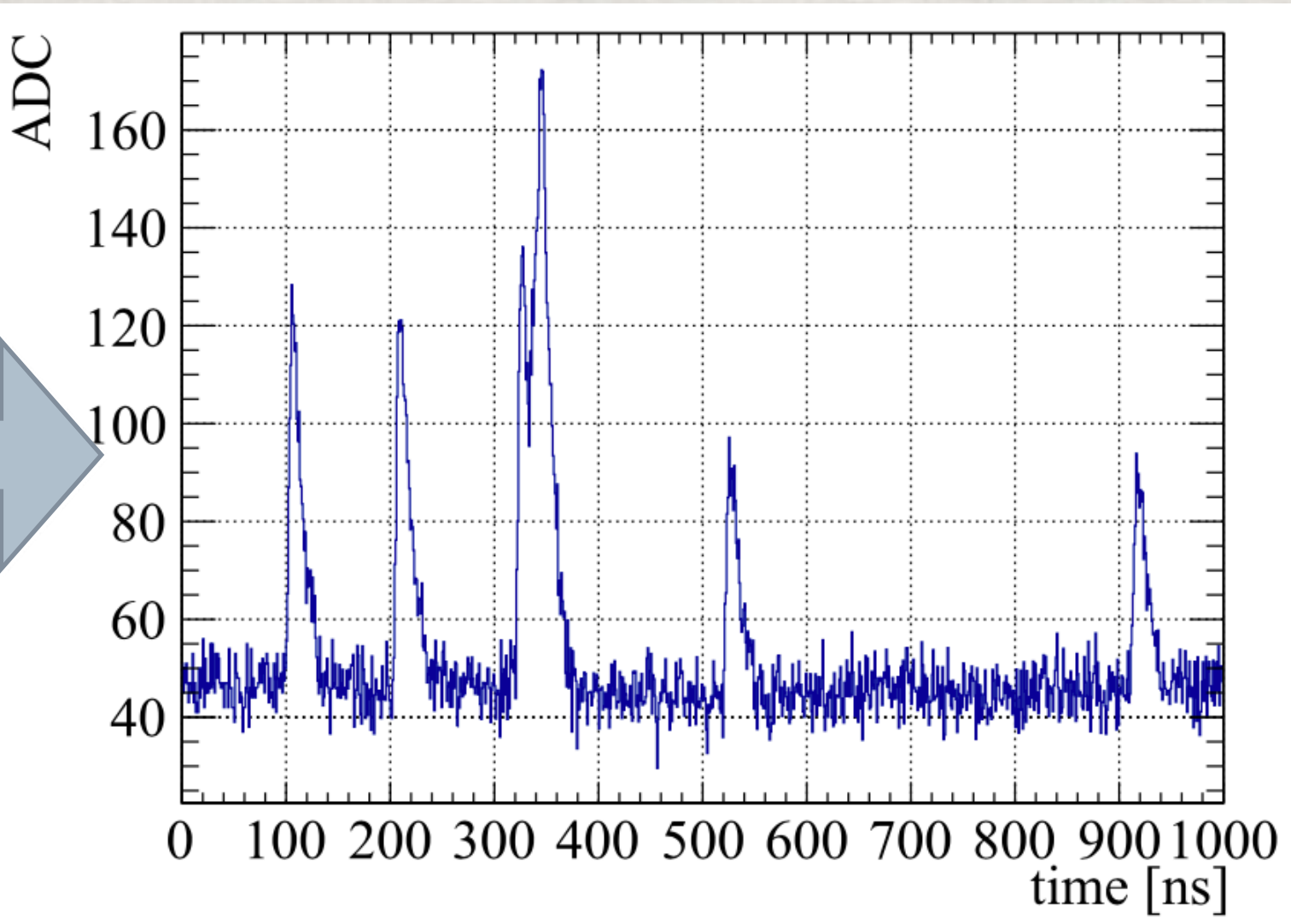
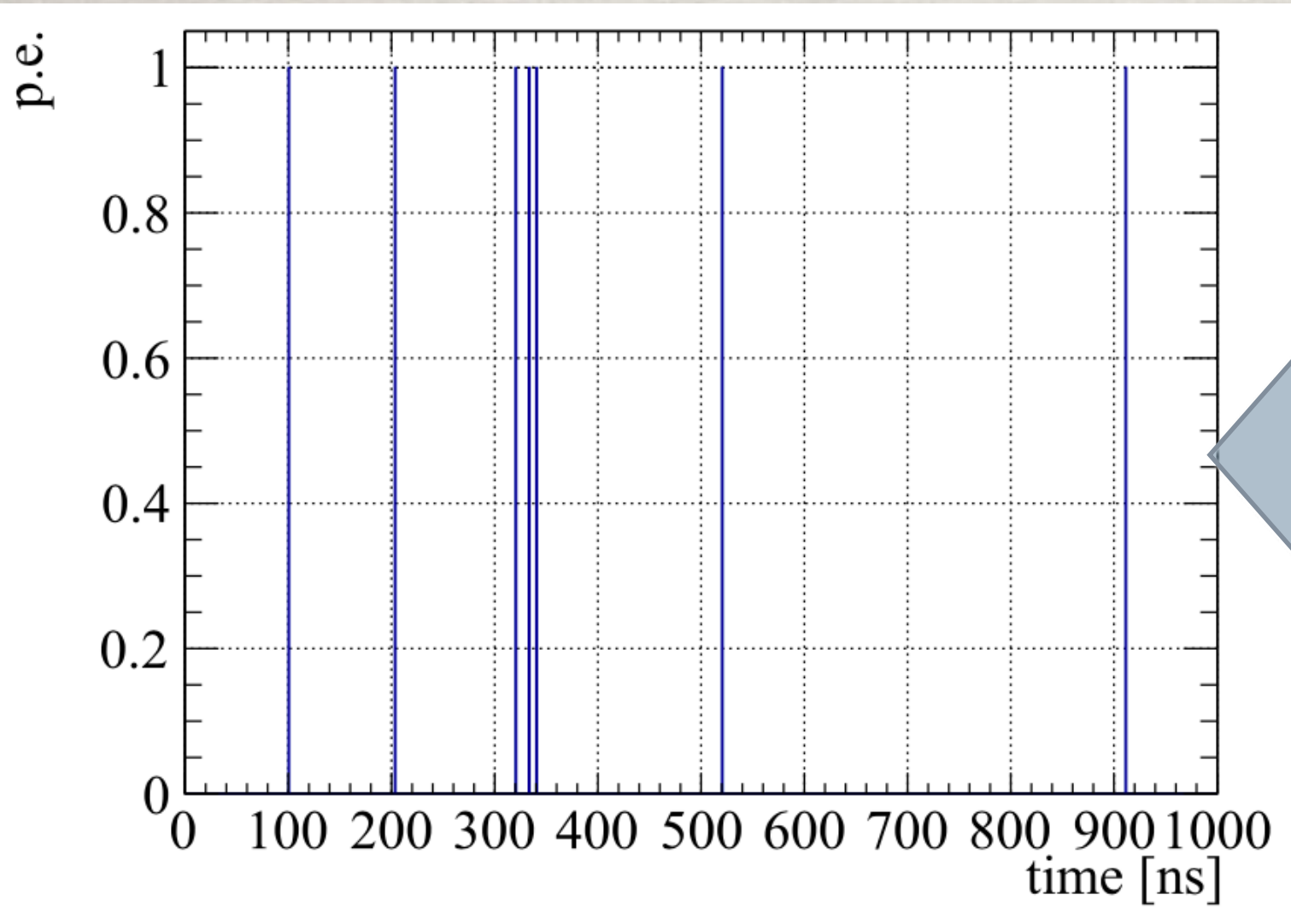


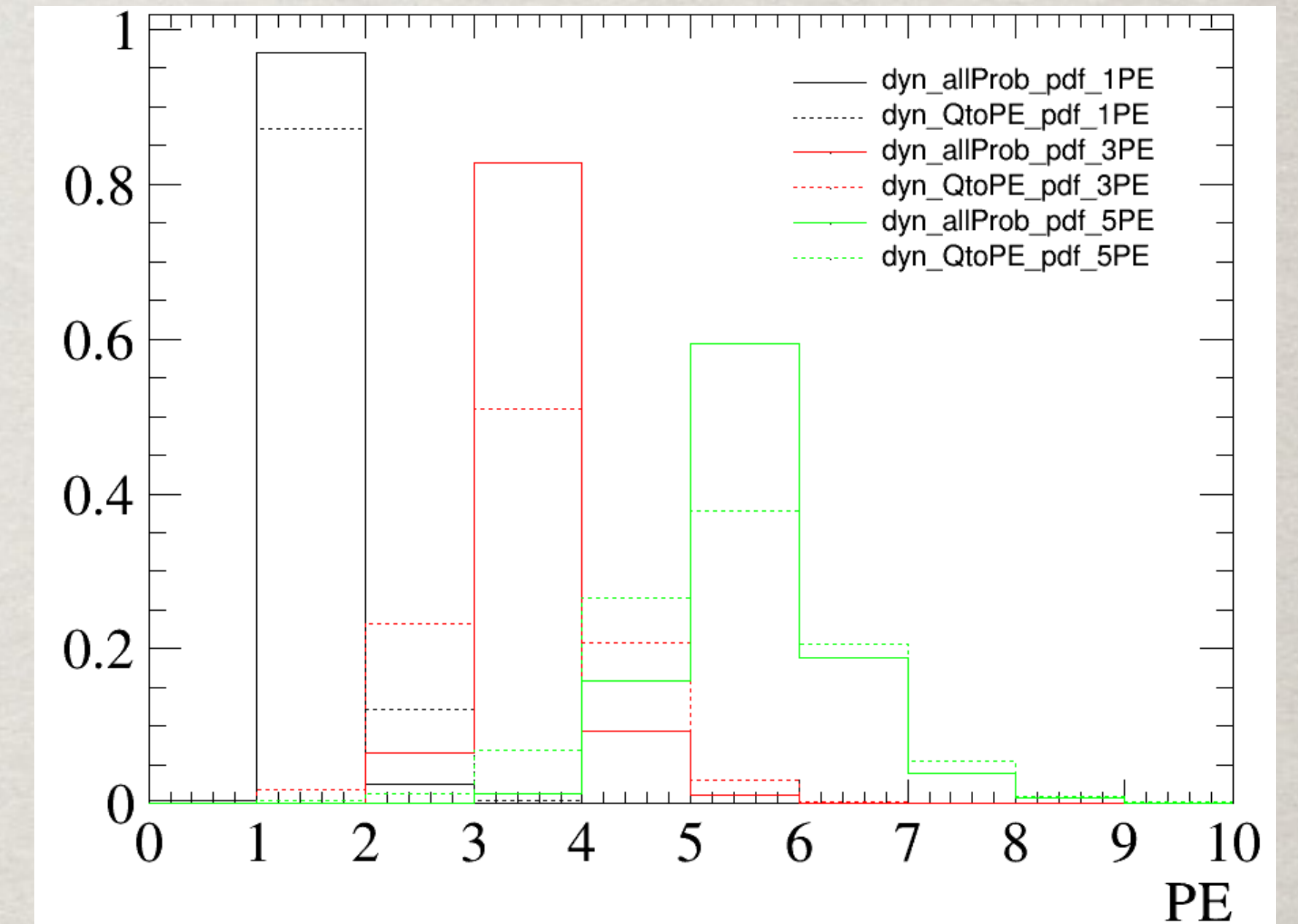
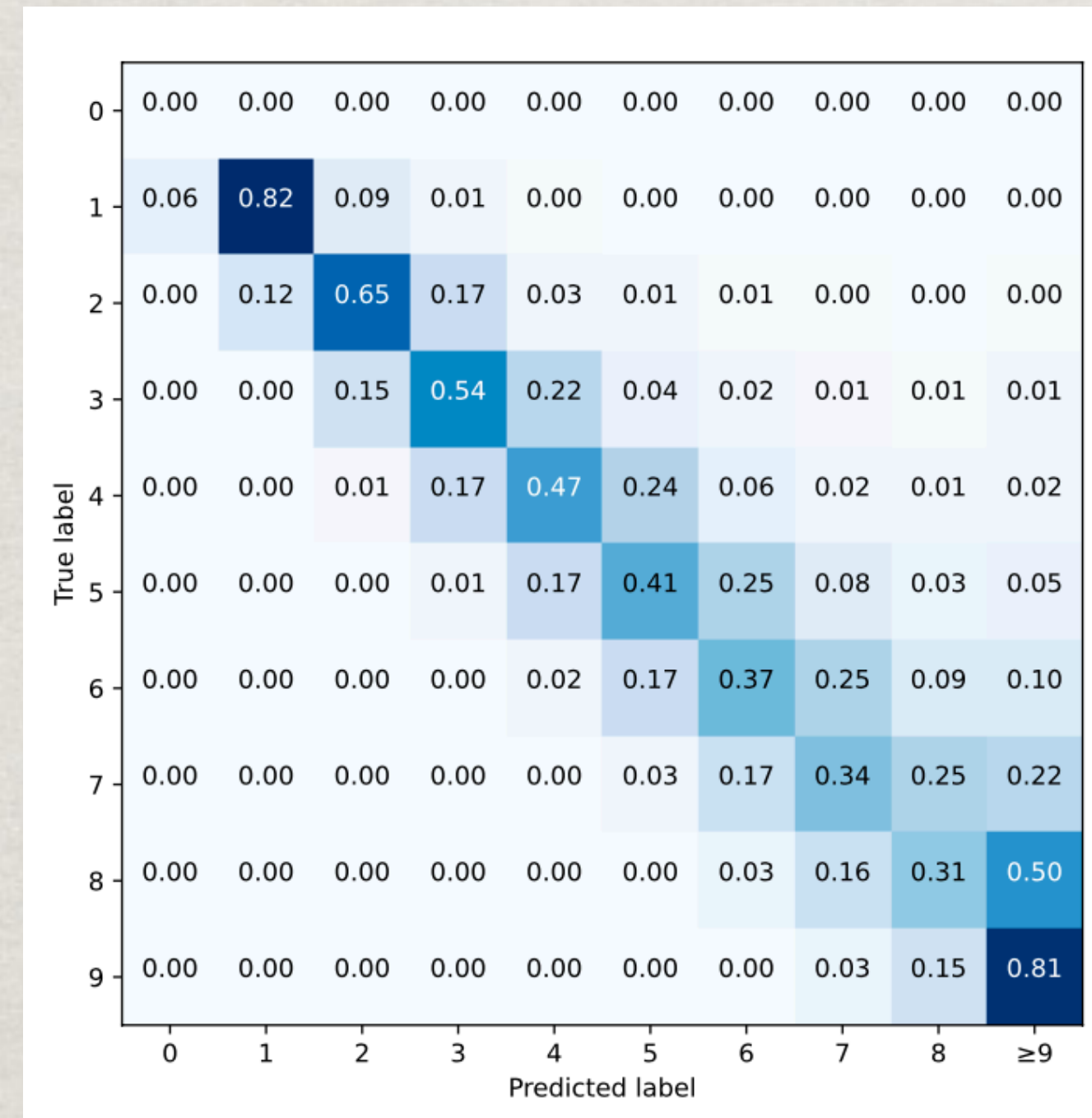
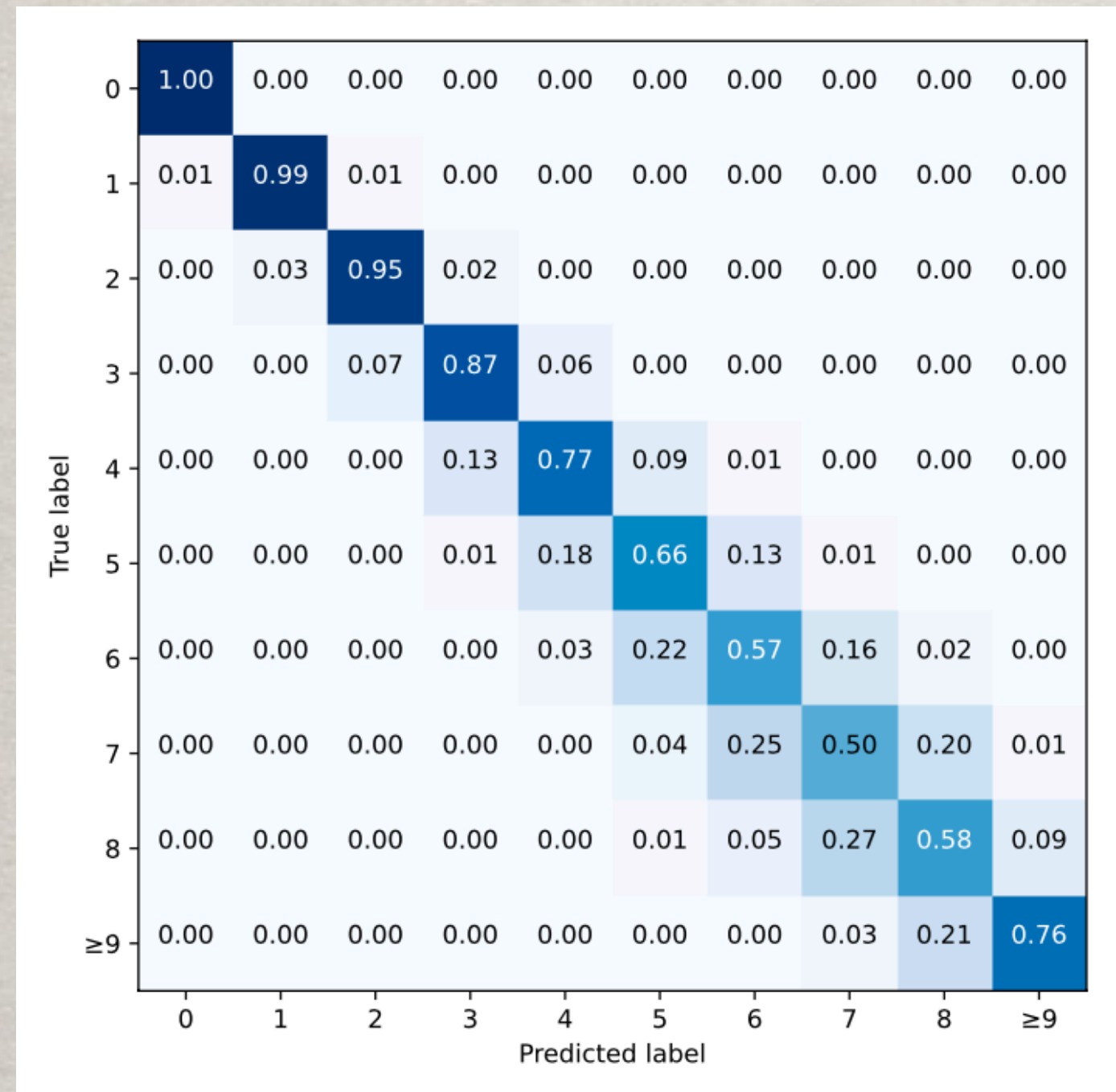
Table 2: Modified RawNet architecture. For convolutional layers, numbers inside parentheses refer to filter length, stride size, and number of filters. For gated recurrent unit (GRU) and fully-connected layers, numbers inside the parentheses indicate the number of nodes.

Layer	Input	Output shape
Strided -conv	Conv(3,3,128) BN LeakyReLU	(128, 140)
Res block	Conv(3,1,128) BN LeakyReLU Conv(3,1,128) BN LeakyReLU MaxPool(3)	(128, 46)
Res block	Conv(3,1,256) BN LeakyReLU Conv(3,1,256) BN LeakyReLU MaxPool(3)	(256, 1)
GRU	GRU(1024)	(1024,)
Speaker embedding	FC(128)	(128,)
Output	FC(10)	(10,)

- ❖ Input: pre-processed PMT waveform within 420ns signal window
- ❖ Model: Customized RawNet
- ❖ Output: $\{p_k\}$ the probability for predicting ($k=0,1, \dots \geq 9$) PEs



PHOTON COUNTING PERFORMANCE



- ❖ Left: Confusion matrix of RawNet
 - ❖ 99% (95%, 87%) accuracy for 1PE (2PEs, 3PEs)
 - ❖ Accuracy decreases rapidly as nPEs increases
- ❖ Right: Confusion matrix based on charge classification
 - ❖ The accuracy is markedly inferior to that of RawNet

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ENERGY RECONSTRUCTION

Note	Algo. Name	Observable	Likelihood: $\kappa \leq K_T$	Likelihood: $\kappa > K_T$
Charge, Time, Maximum Likelihood Estimation	QTMLE (reference)	q (charge)	$\mathcal{L}(q_i \mu_i) = \sum_{k=1}^{+\infty} P_Q(q_i k)P(k, \mu_i)$	
PE, Time, Maximum Likelihood Estimation	PETMLE (ideal)	k (true PEs)	$\mathcal{L}(k_i \mu_i) = P(k_i, \mu_i)$	
Charge, Probability, Time, Maximum Likelihood Estimation	QPTMLE (realistic)	$\{p_k\}$, q	$\mathcal{L}(\{p_k^i\} \mu_i) = \sum_{k=0}^9 R_{K_T k} p_k^i P(k, \mu_i).$	$\mathcal{L}(q_i \mu_i) = \sum_{k=1}^{+\infty} P_Q(q_i k)P(k, \mu_i)$
Charge, PE, Time, Maximum Likelihood Estimation	QPETMLE (100% accuracy)	$k(p_k=1)$, q	$\mathcal{L}(k_i \mu_i) = P(k_i, \mu_i)$	
Charge, Confusion Matrix, Time, Maximum Likelihood Estimation	QCTMLE	κ ($p_{\kappa}:\text{max}$), q	$) = \sum_{k=0}^9 C_{k\kappa_i} \times P(k, \mu_i)$	

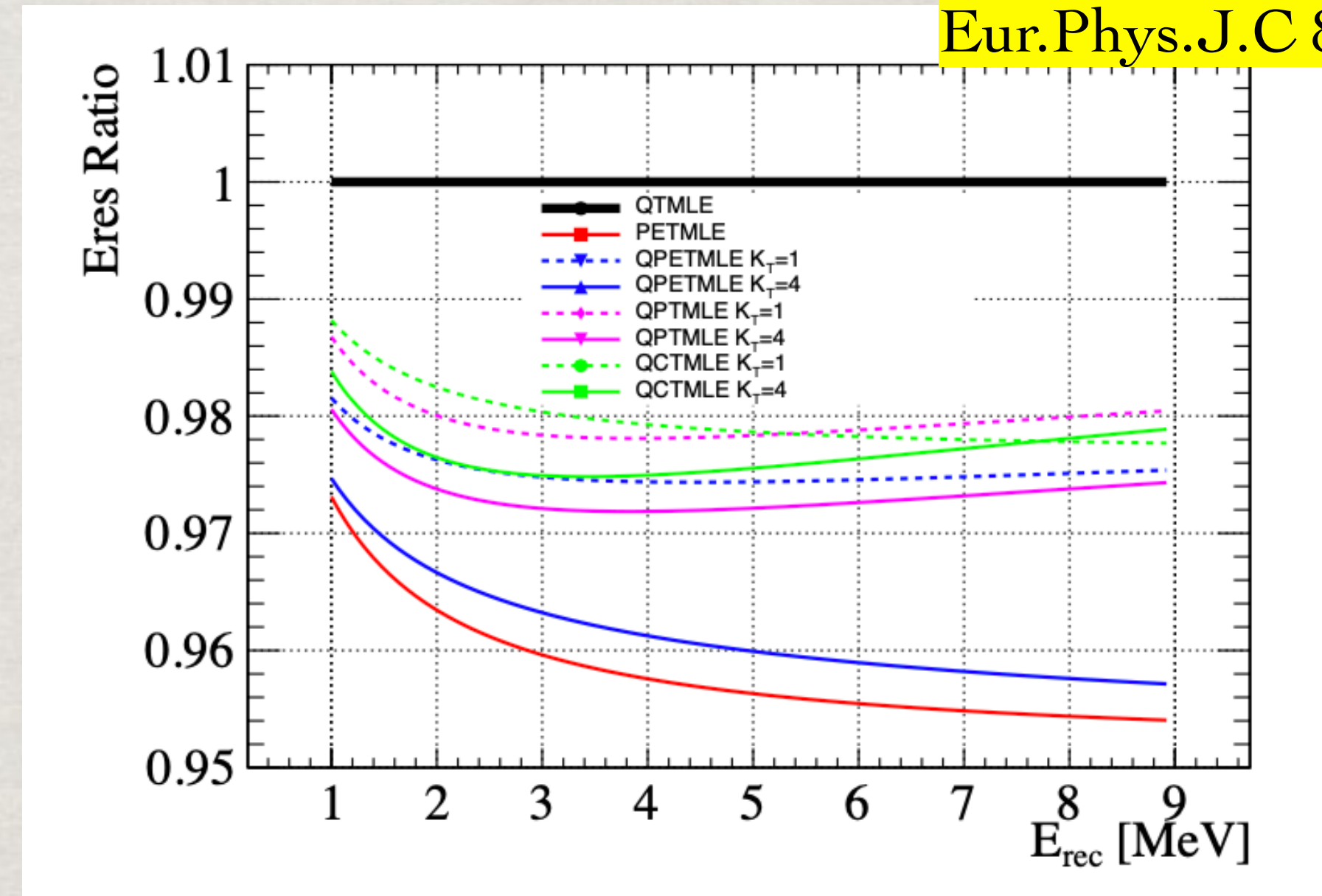
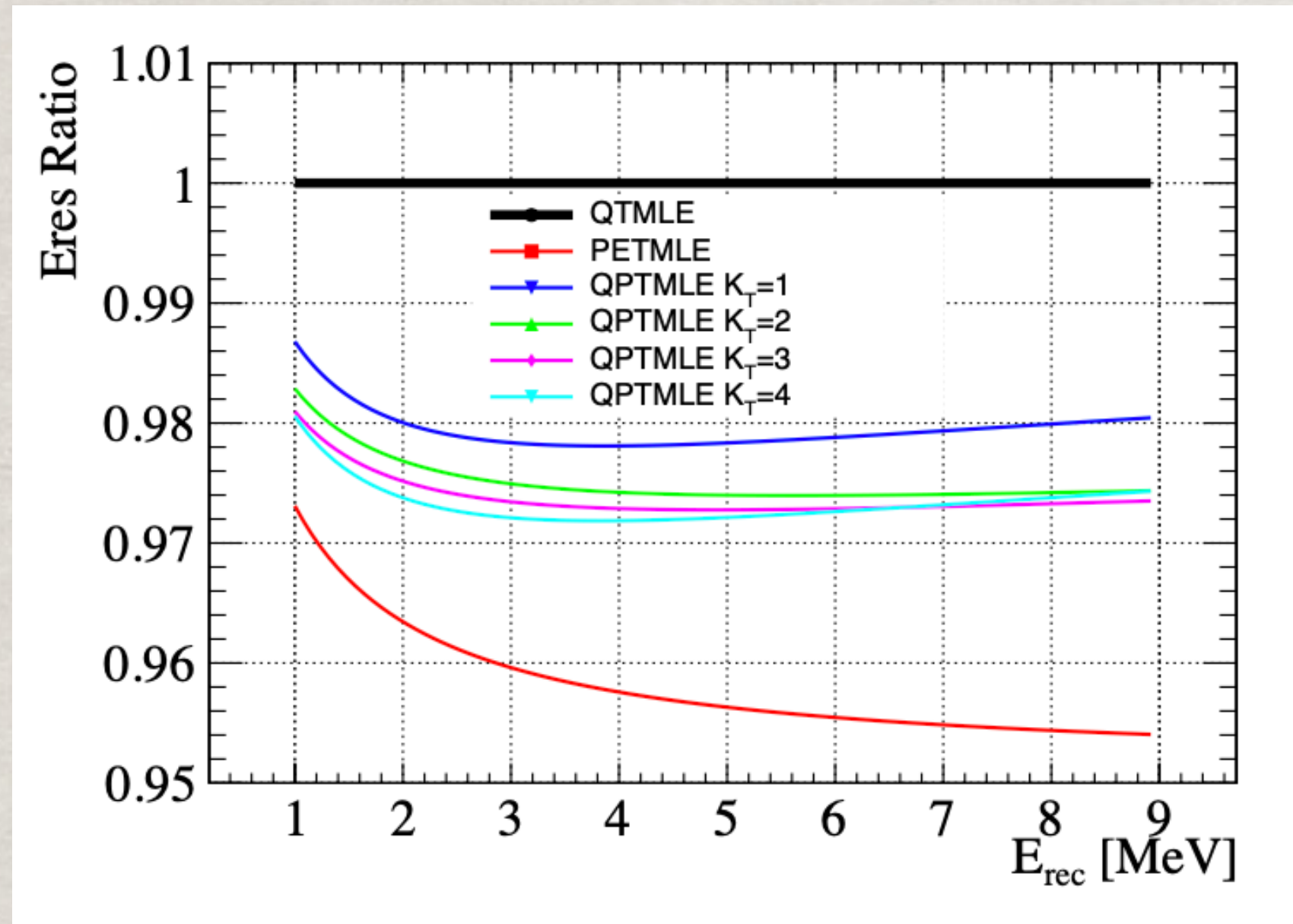
where μ_i is the expected nPEs for the i-th PMT, $P(k, \mu_i)$ is just the Poisson probability of observing k p.e. given μ_i and $P_Q(q_i|k)$ is the charge pdf for k p.e..

$$R_{K_T k} = \sum_{\kappa=0}^{K_T} C_{k\kappa},$$

confusion matrix $C_{k\kappa'}$



RELATIVE IMPROVEMENT



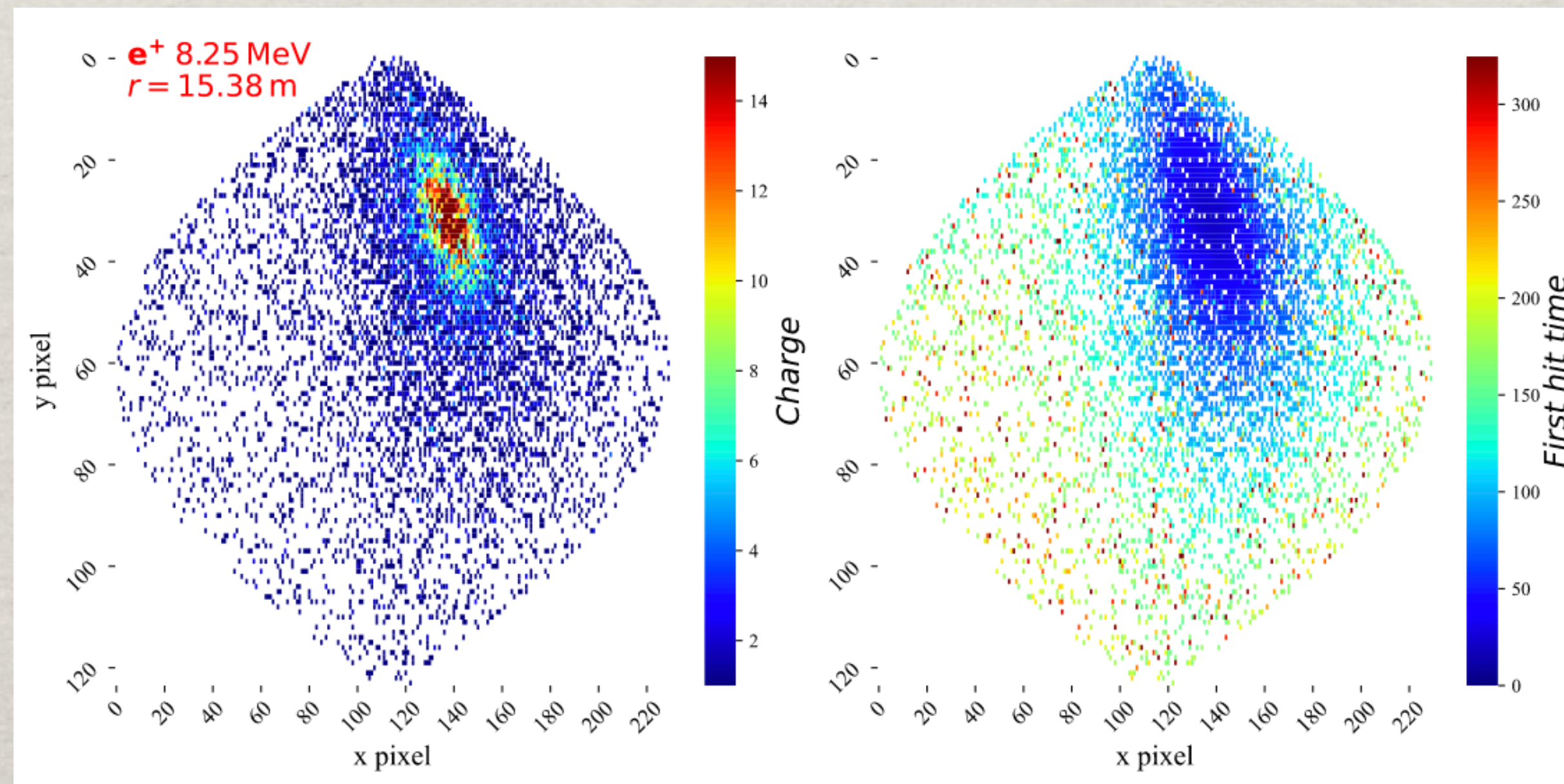
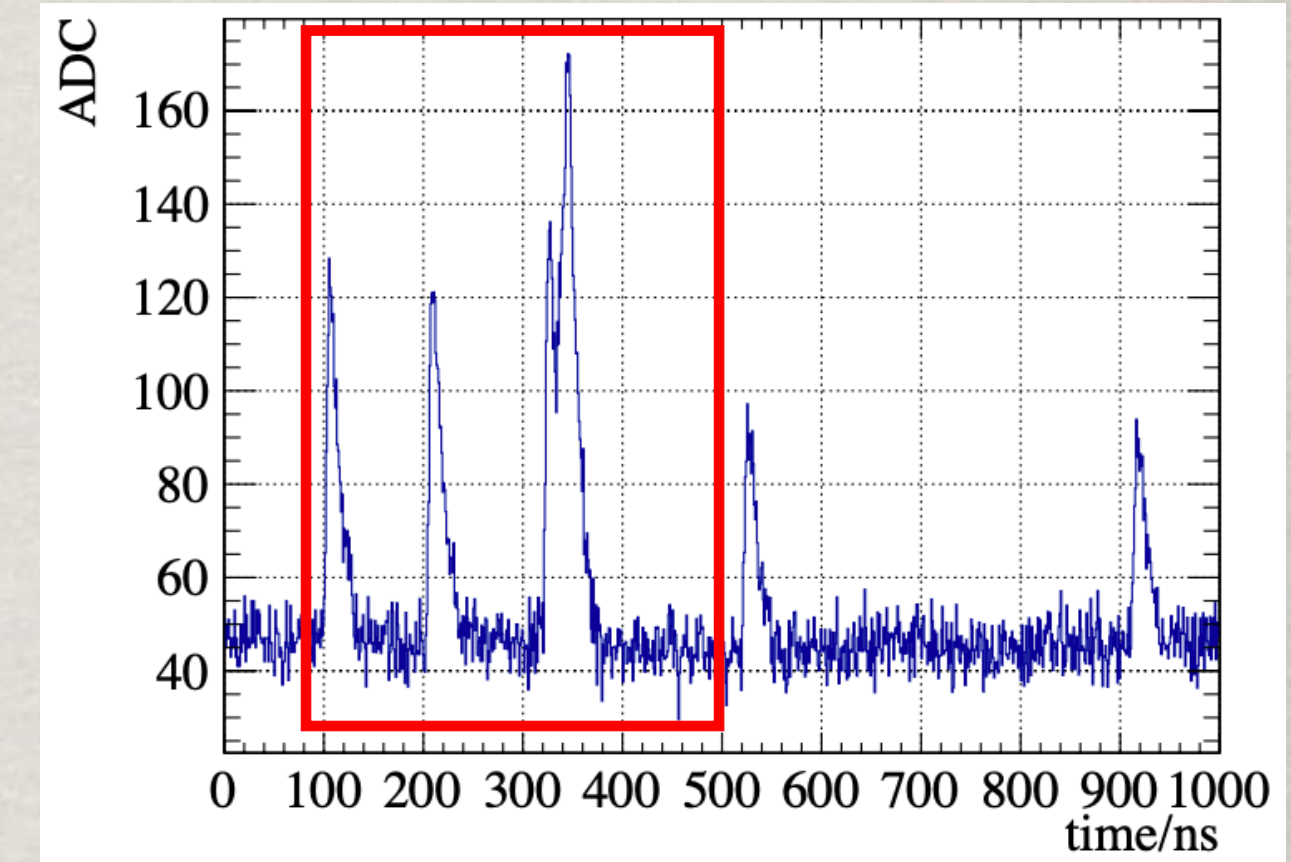
Eur.Phys.J.C 85 (2025) 1, 69

- ❖ Using the photon counting information for PMTs with ($\kappa \leq K_T$) PEs can improve the energy resolution
- ❖ The improvement becomes smaller as K_T increases due to the dropping accuracy for high PEs
- ❖ Additional checks were done to validate the results

VERTEX RECO WITH ML

PRINCIPLES

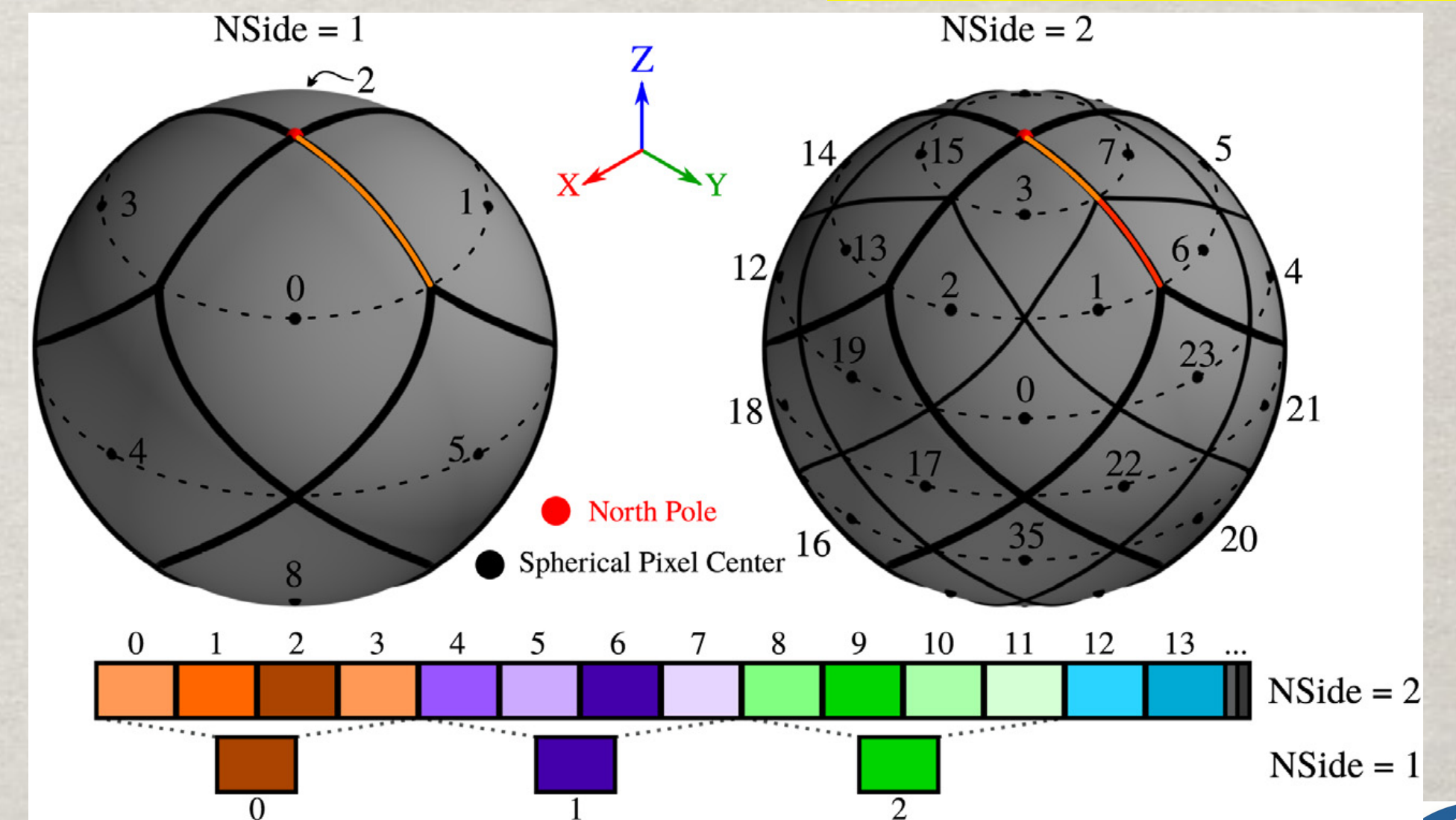
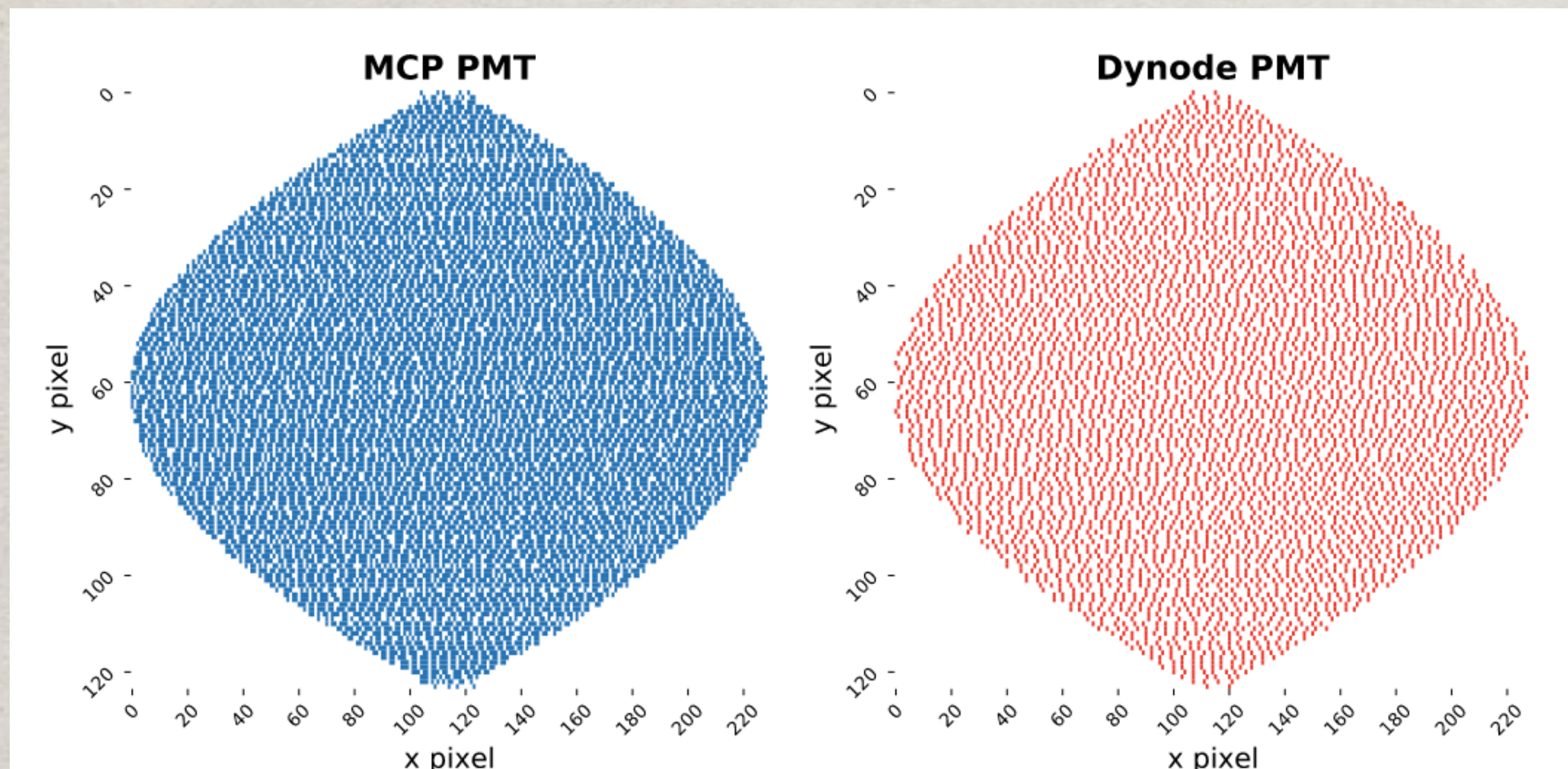
- ❖ Large number of PMTs $O(10^4)$ installed on a sphere
- ❖ each PMT as a pixel $\rightarrow$ JUNO as a Camera
- ❖ ensemble of PMTs charge/time form an image
- ❖ Image is highly vertex and energy dependent
- ❖ Vertex/energy reconstruction $\longleftrightarrow$ Image recognition



INPUTS

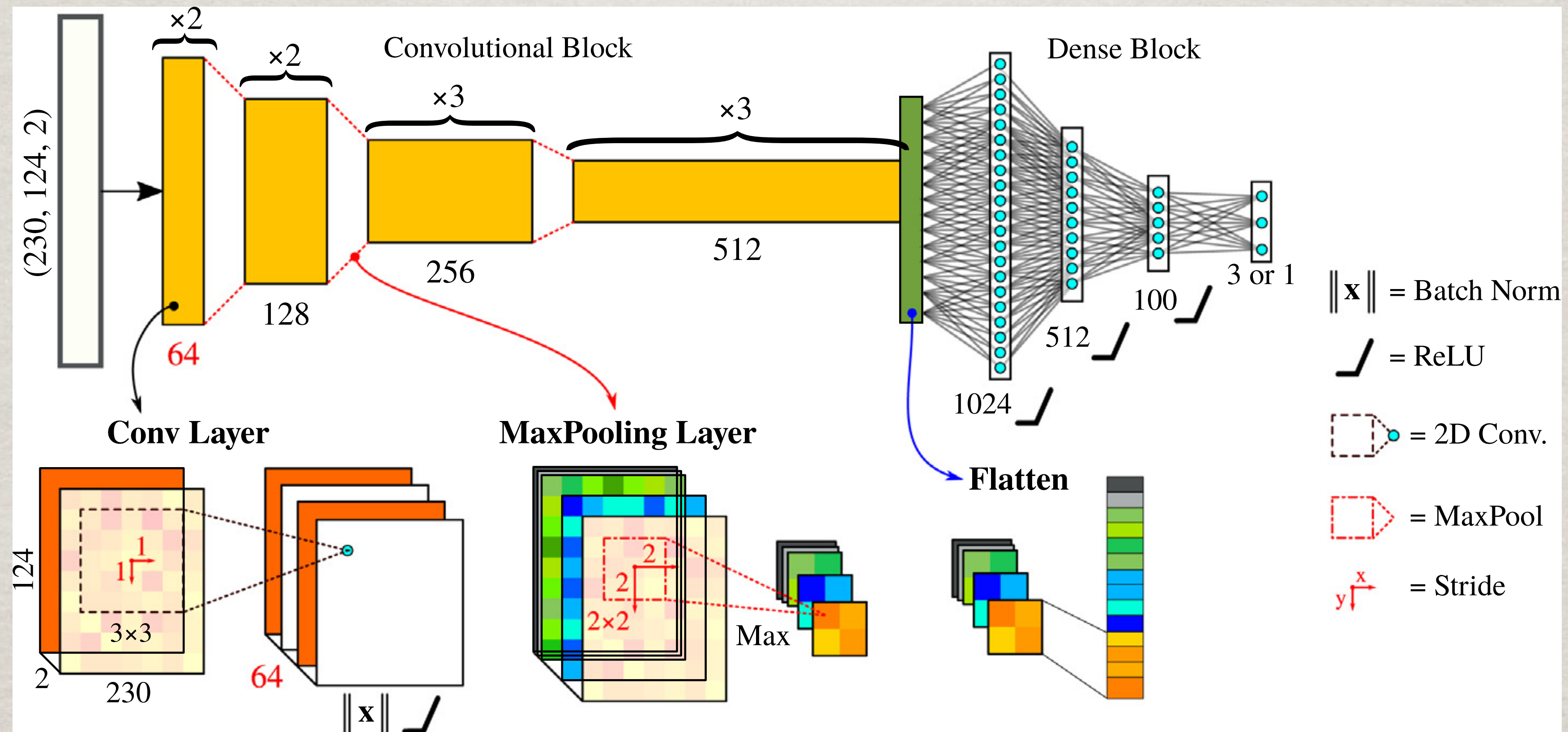
- ❖ Large number of PMTs $O(10^4)$ installed on a sphere
- ❖ Method 1: projection to 2D plane $\rightarrow$ Plane CNN
- ❖ Method 2: HEALPix $\rightarrow$ plane/spherical CNN
- ❖ Method 3: 3D models such as pointNet++/Transformer

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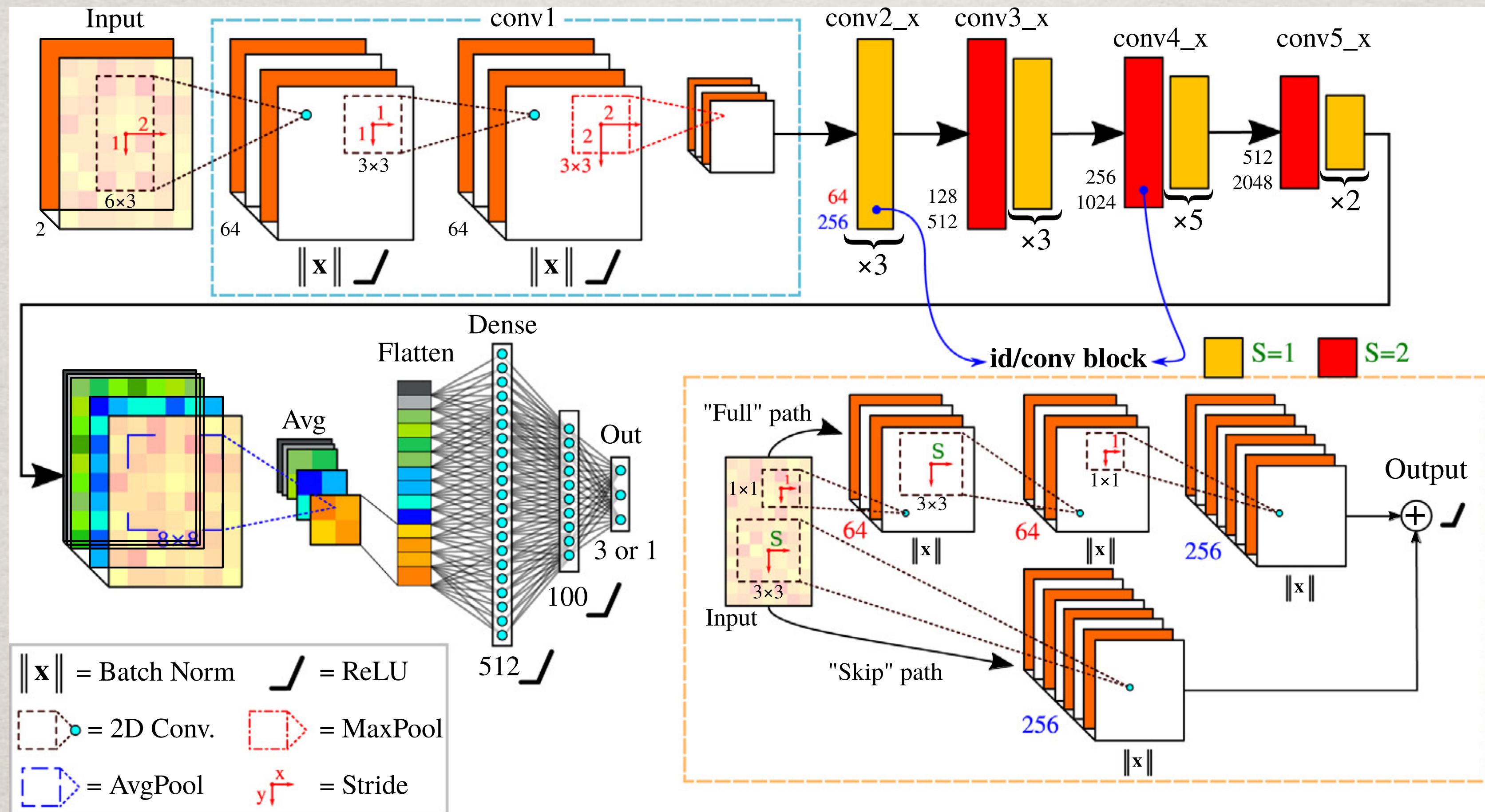
MODELS: VGG-J

NIMA 1010 (2021) 165527



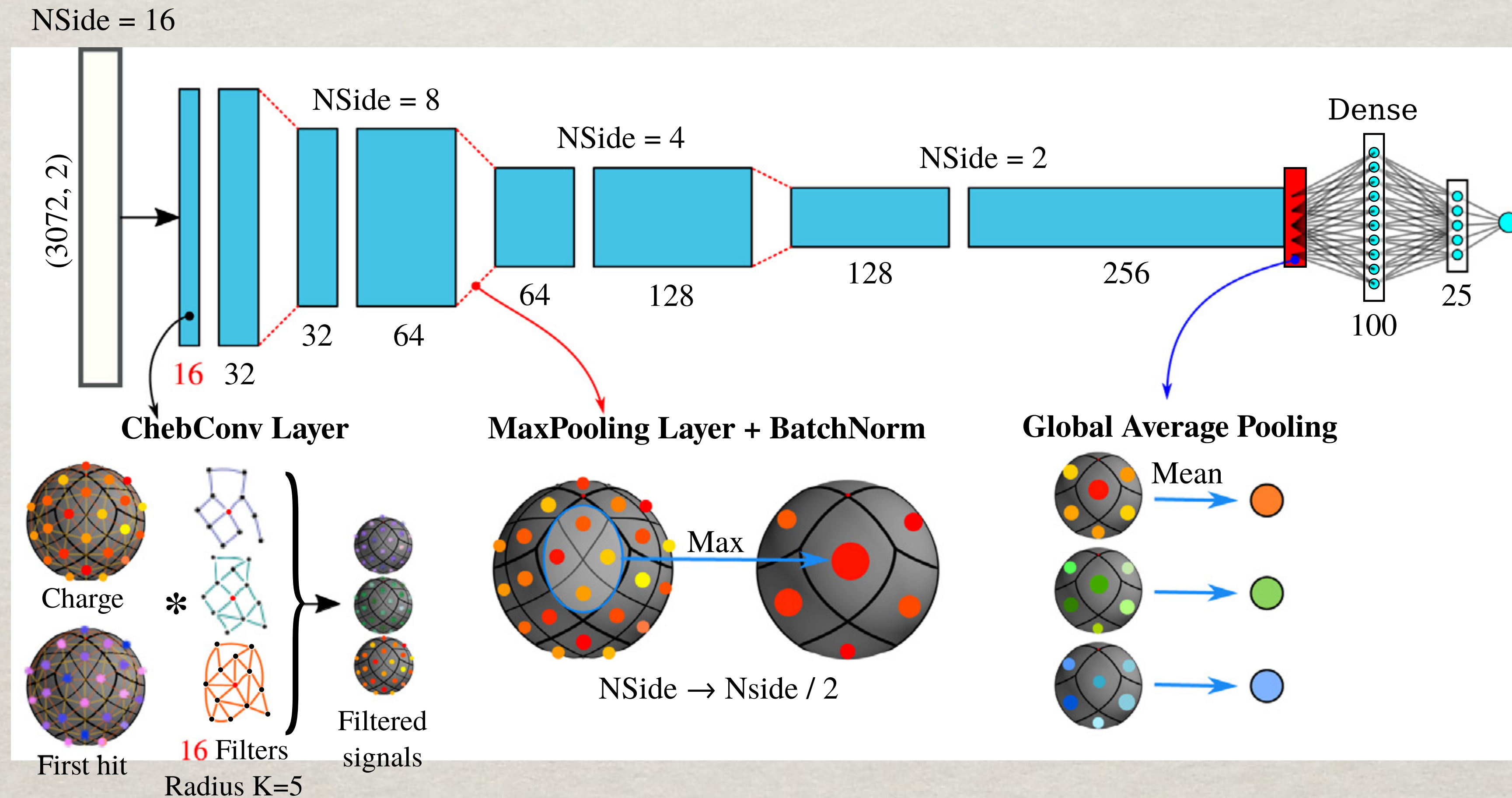
MODELS: RESNET-J

NIMA 1010 (2021) 165527



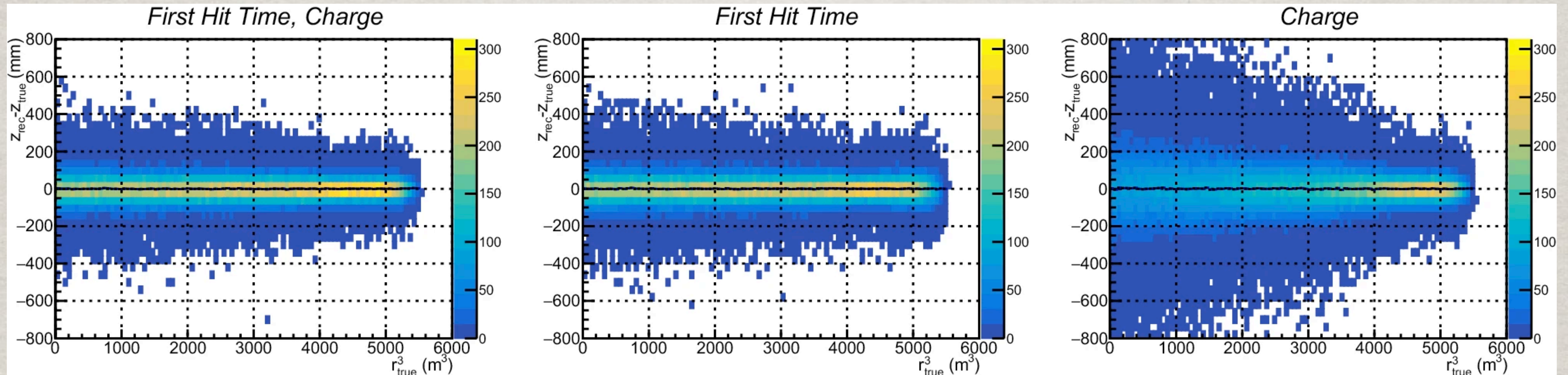
MODELS: GNN-J

NIMA 1010 (2021) 165527

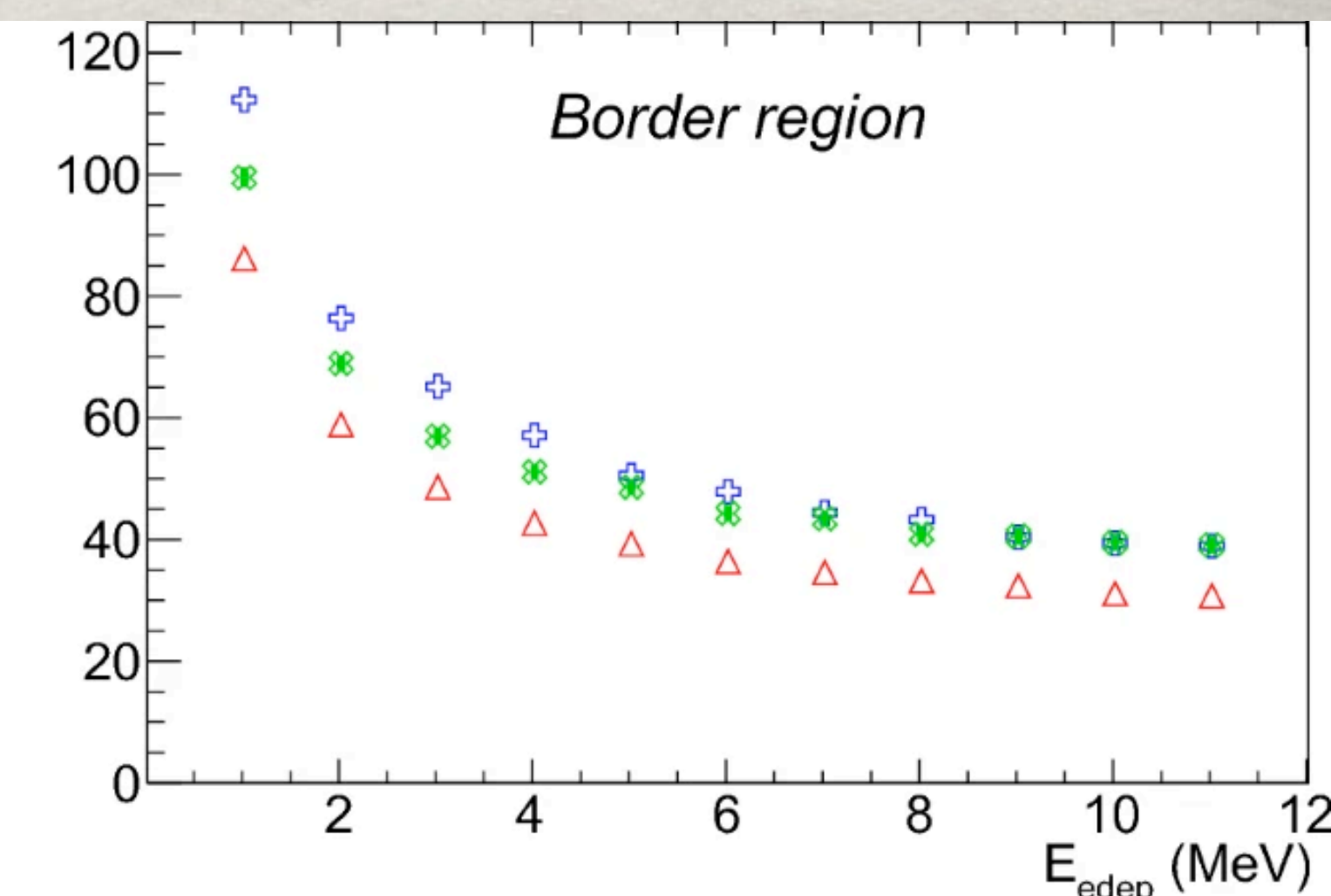
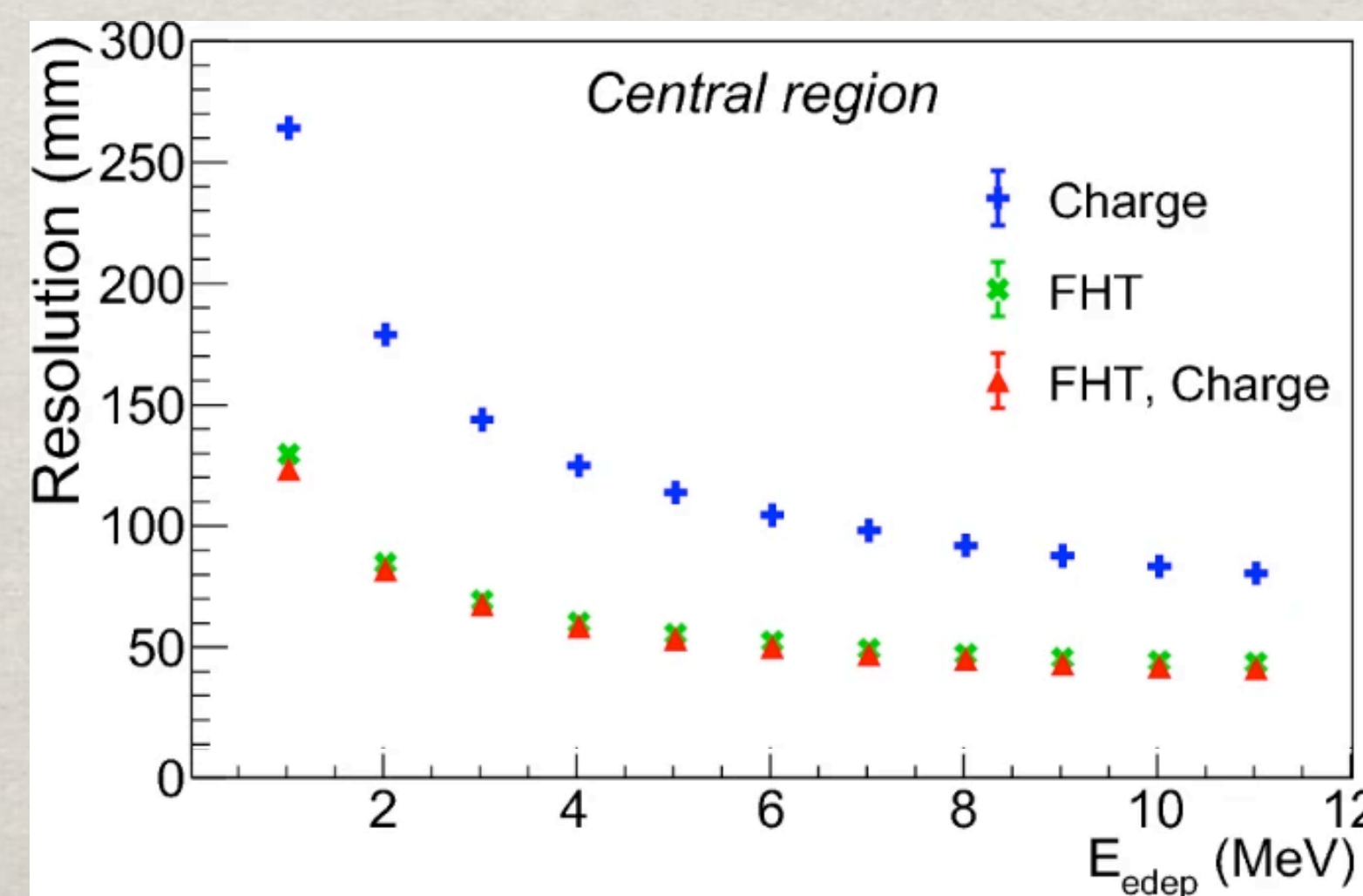


VERTEX: CHARGE VS TIME

Nucl.Sci.Tech. 33 (2022) 7, 93

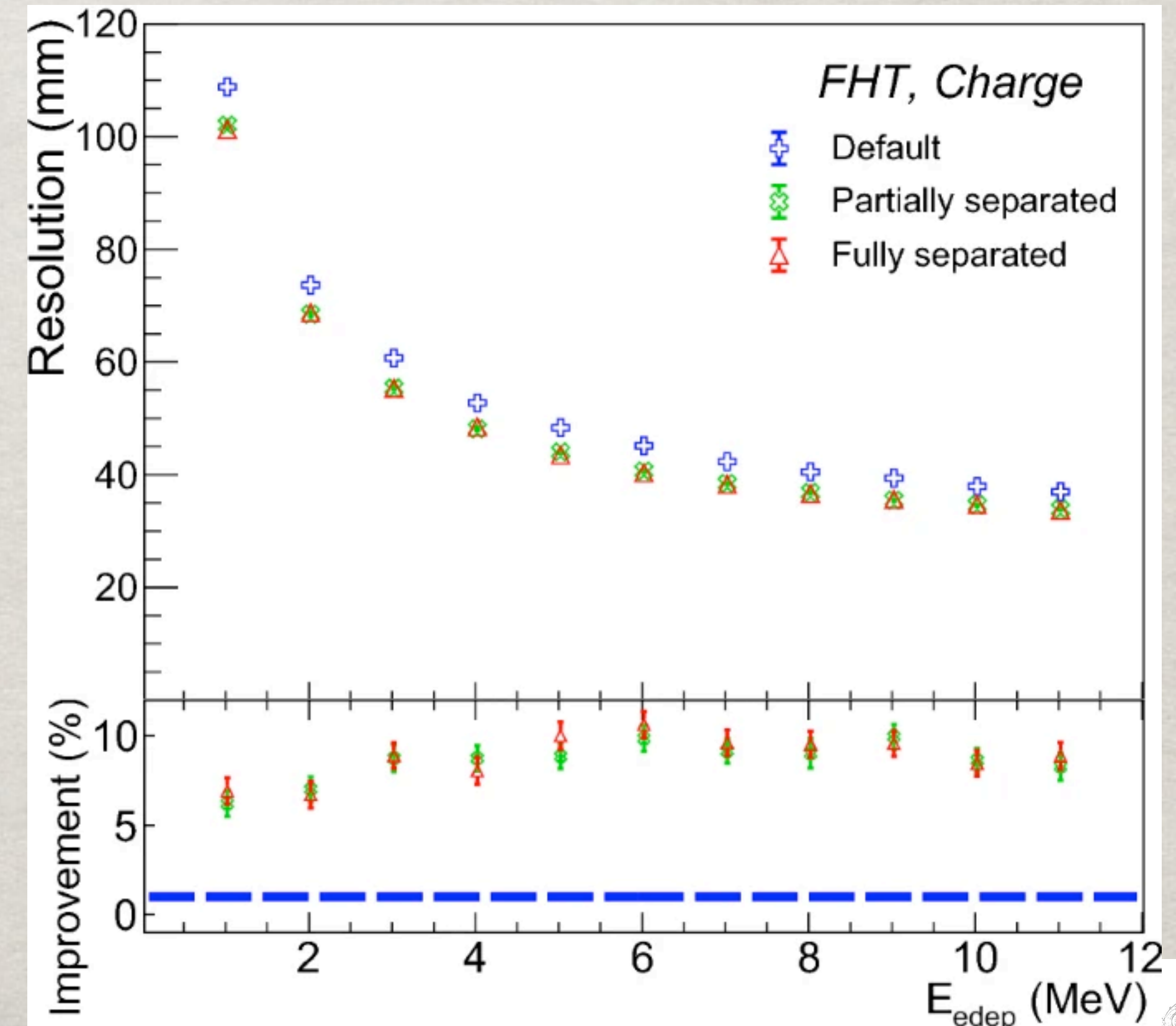
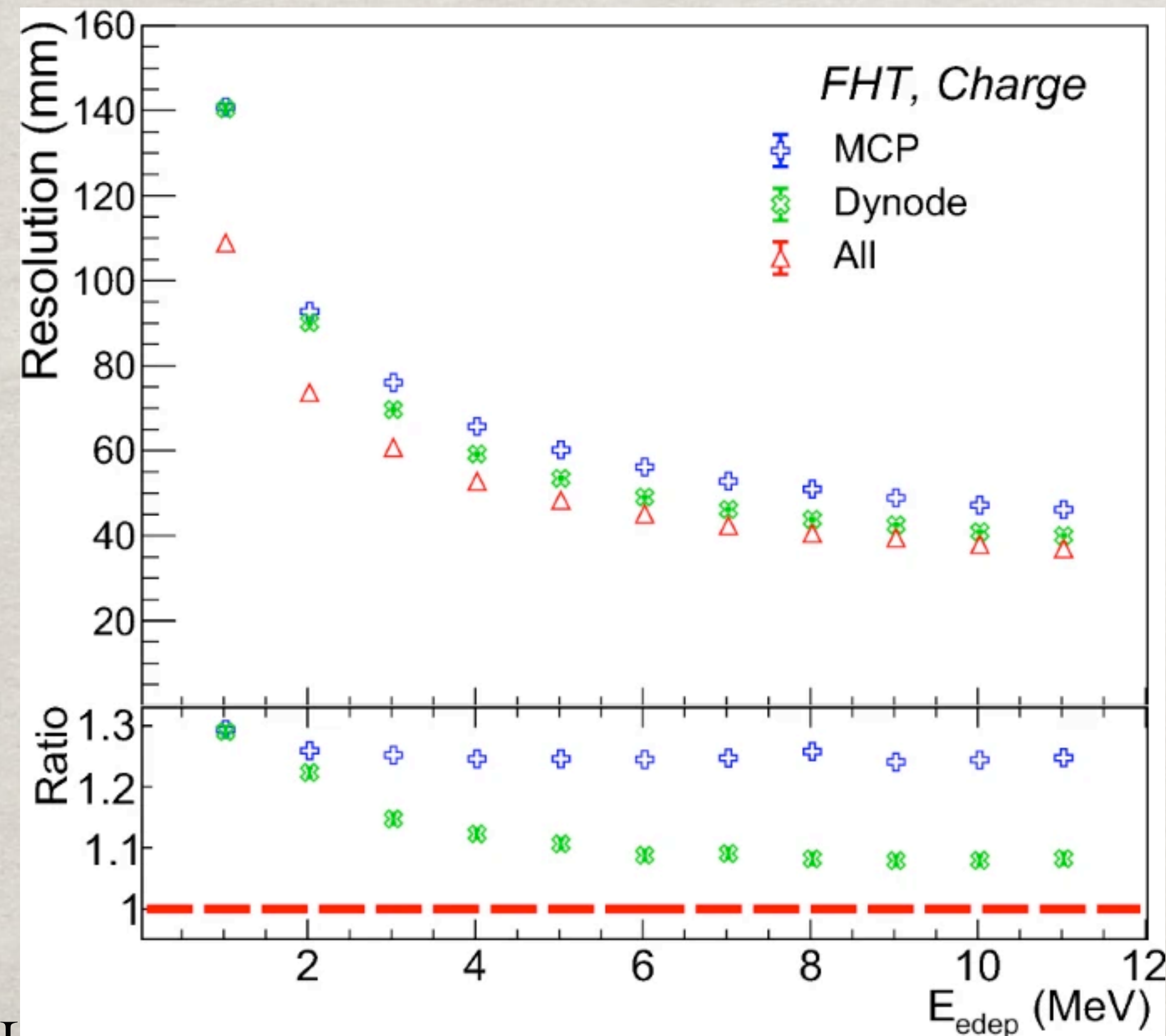


❖ Charge also helps constrain the Vertex, especially in the border region



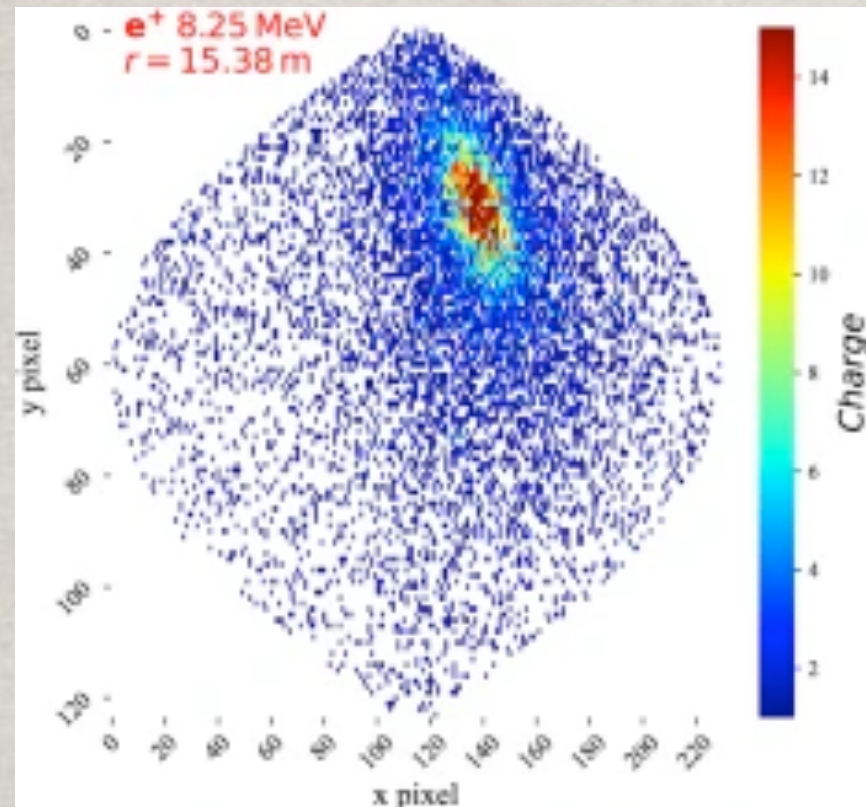
VERTEX: MCP VS DYNODE

- ❖ Comparison between MCP PMTs and Dynode PMTs Nucl.Sci.Tech. 33 (2022) 7, 93
- ❖ Number: 12612 vs 5000; Time resolution(σ_{tts}): 12 ns vs 2.8 ns
- ❖ Separating charge/time info by PMT type gives the best performance

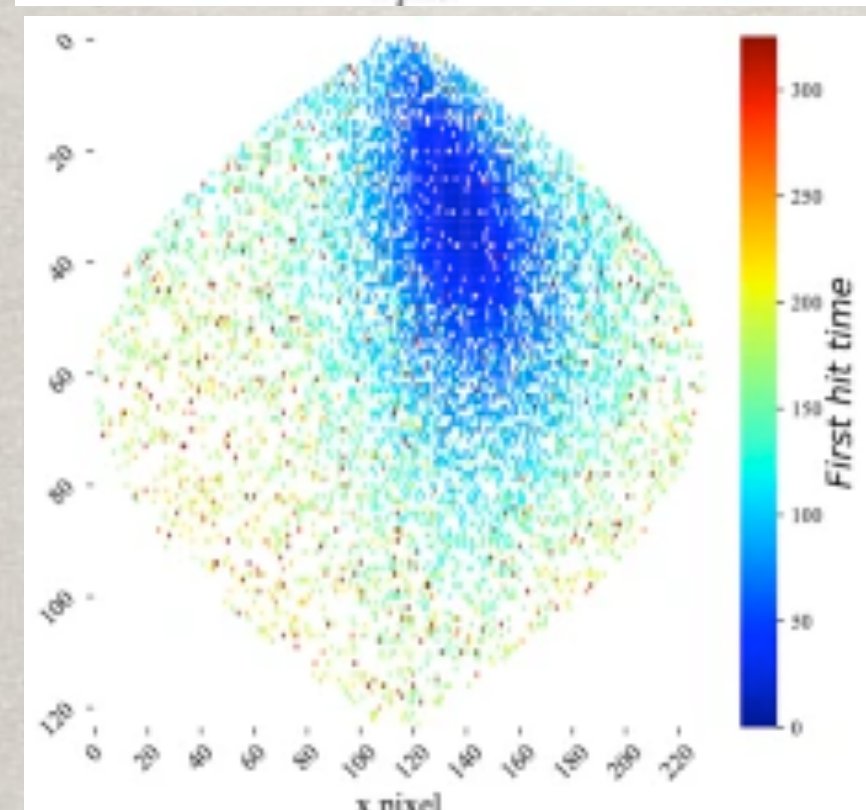


VERTEX: ADDITION OF 2ND HIT

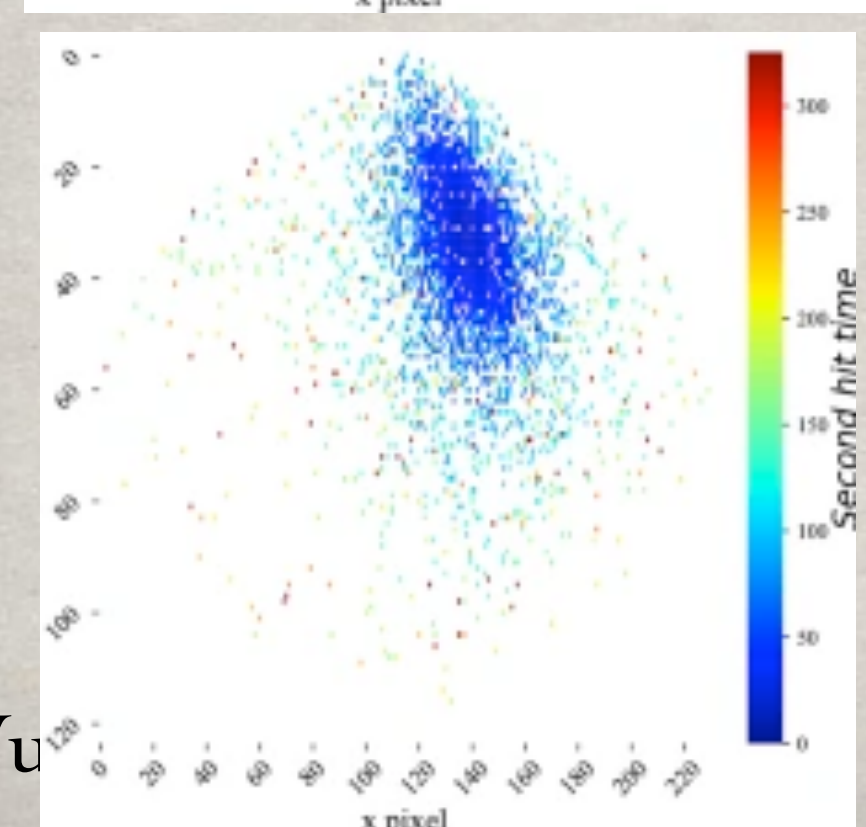
Nucl.Sci.Tech. 33 (2022) 7, 93



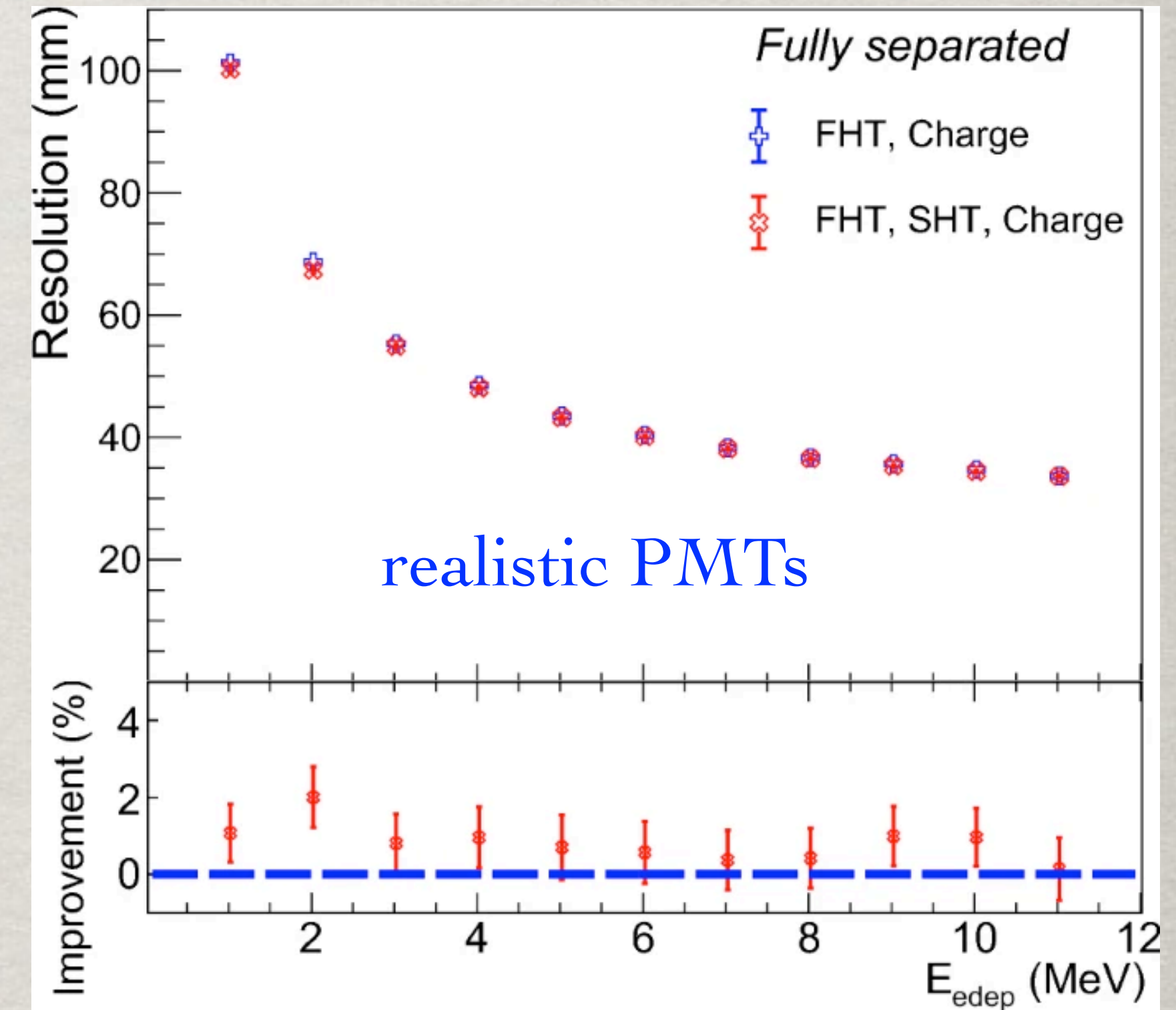
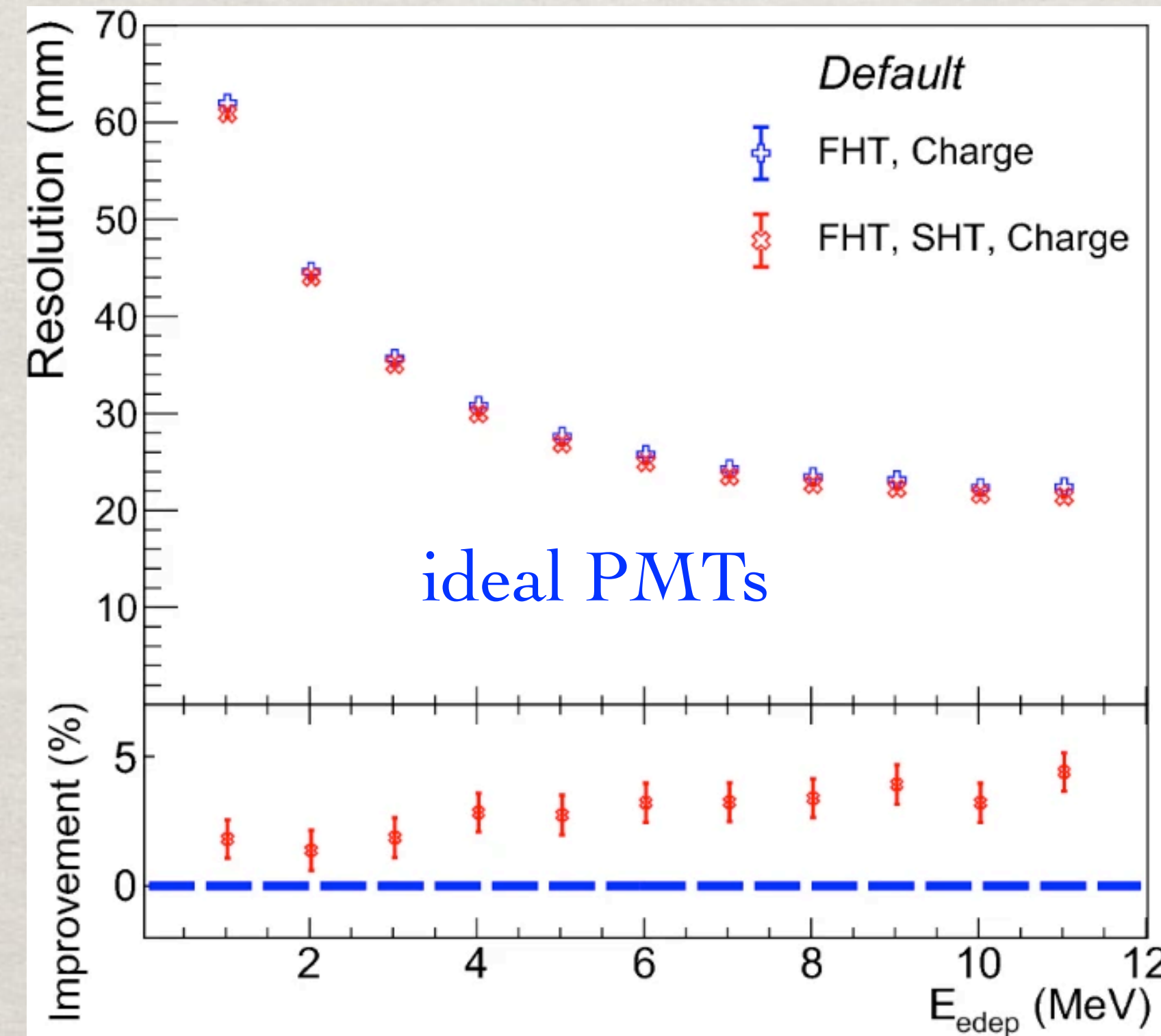
Charge



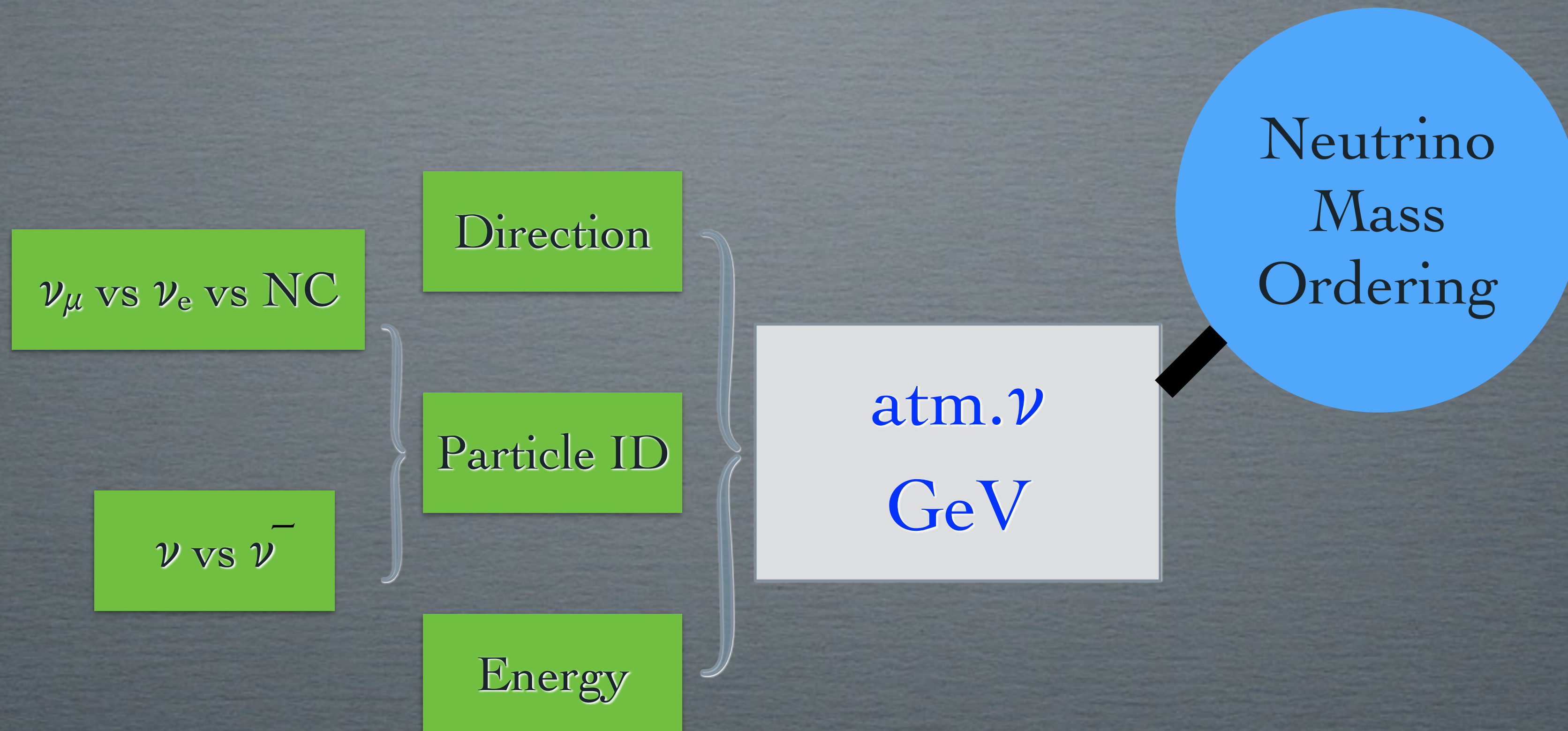
FHT:
t(1st Hit)



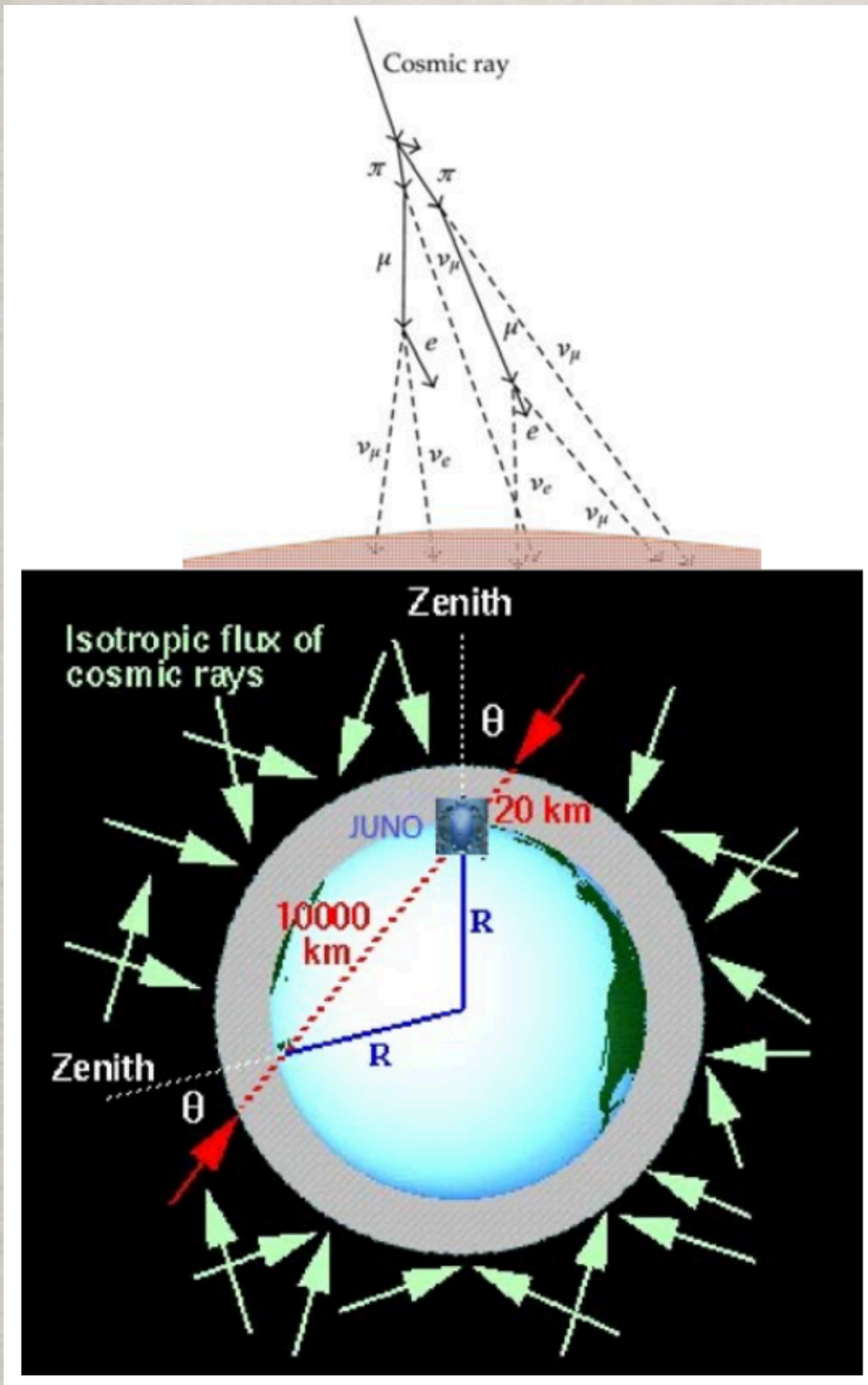
SHT:
t(2nd Hit)



- ❖ Later hits are also useful in principle
- ❖ PMT Time resolution is the key

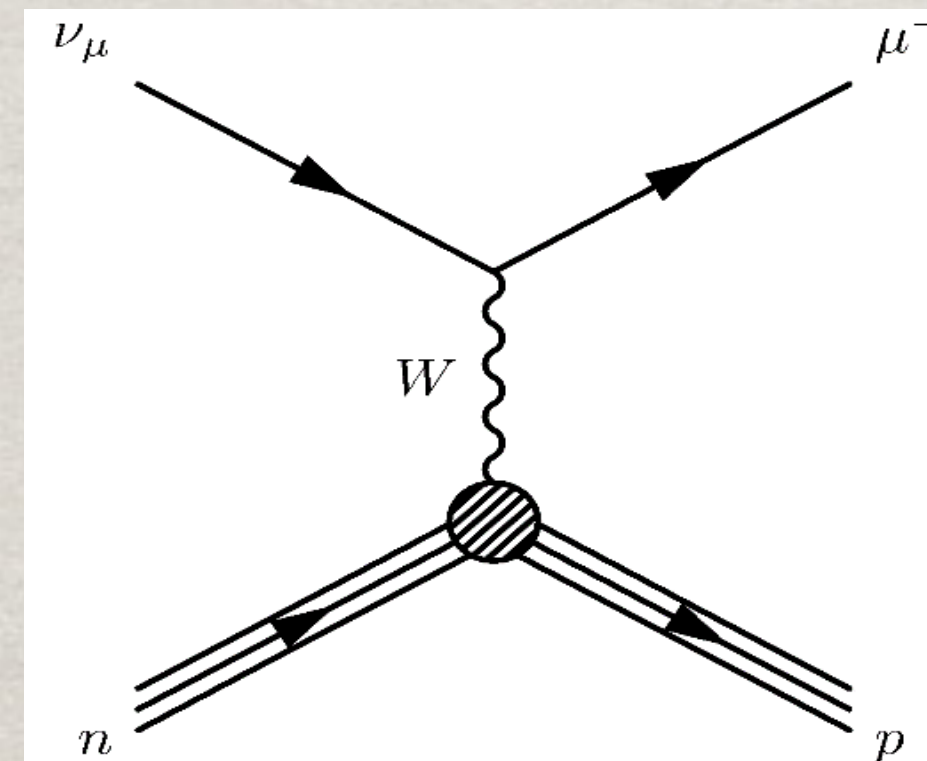


ATM. ν OSCILLATION

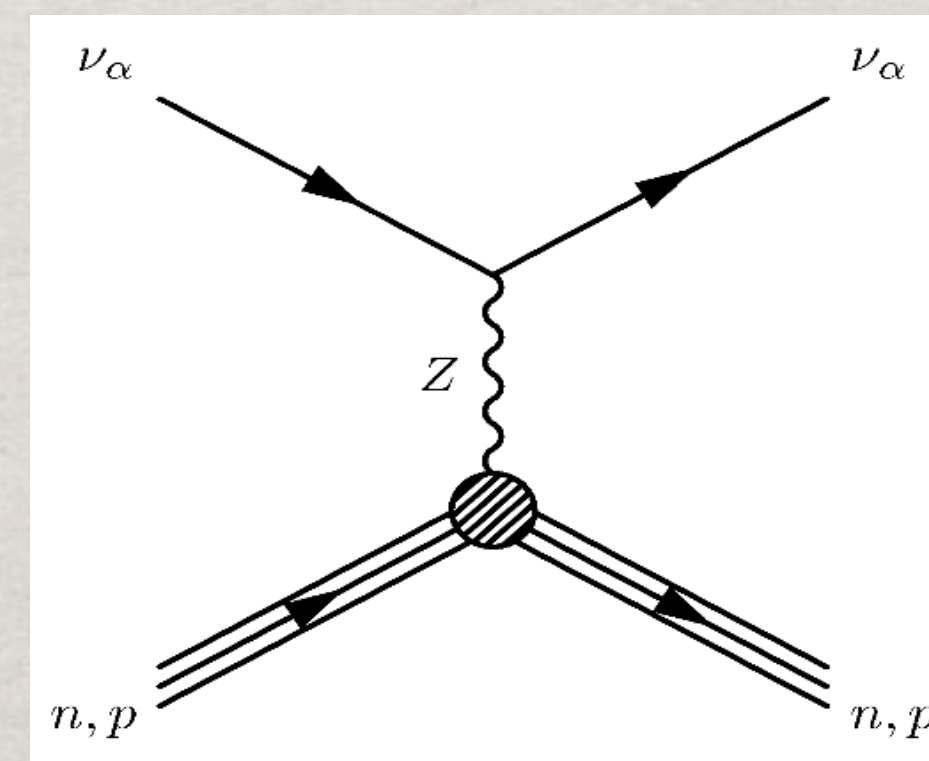


- ✱ **Production:** Cosmic Rays interact with Earth's atmosphere, decay of secondary mesons
- ✱ **Propagation:** oscillation in matter, sensitive to NMO
- ✱ **Detection:** interact with nuclei via Charge Current (CC) or Neutral Current (NC)

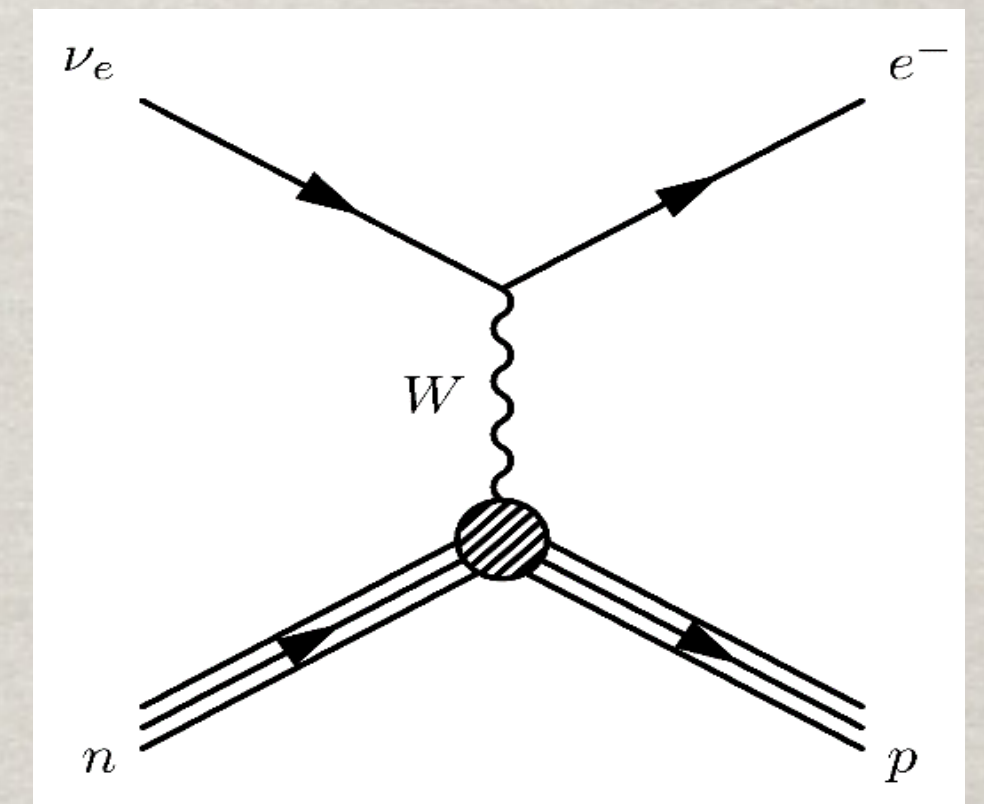
ν_μ CC Event



NC Event

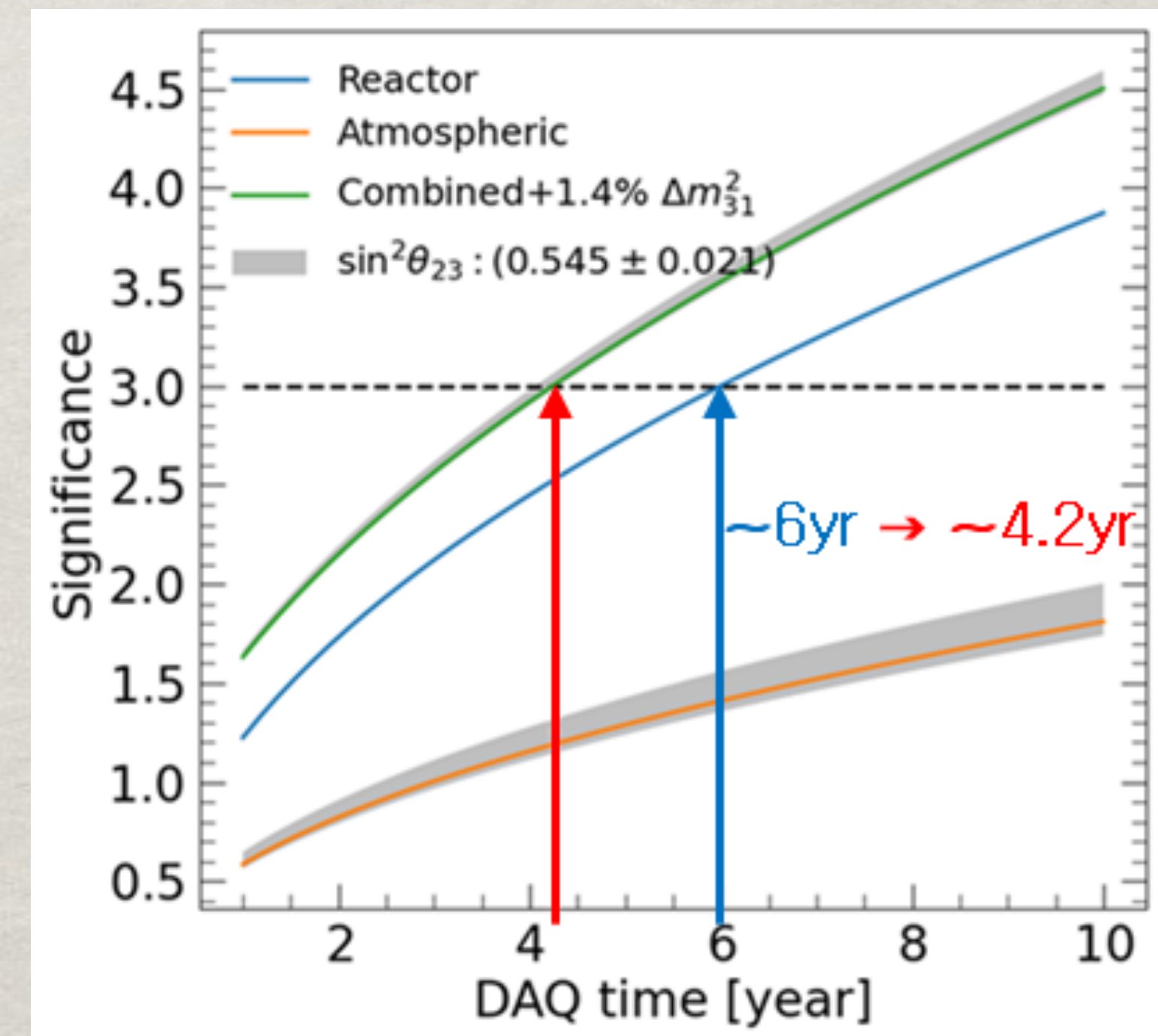
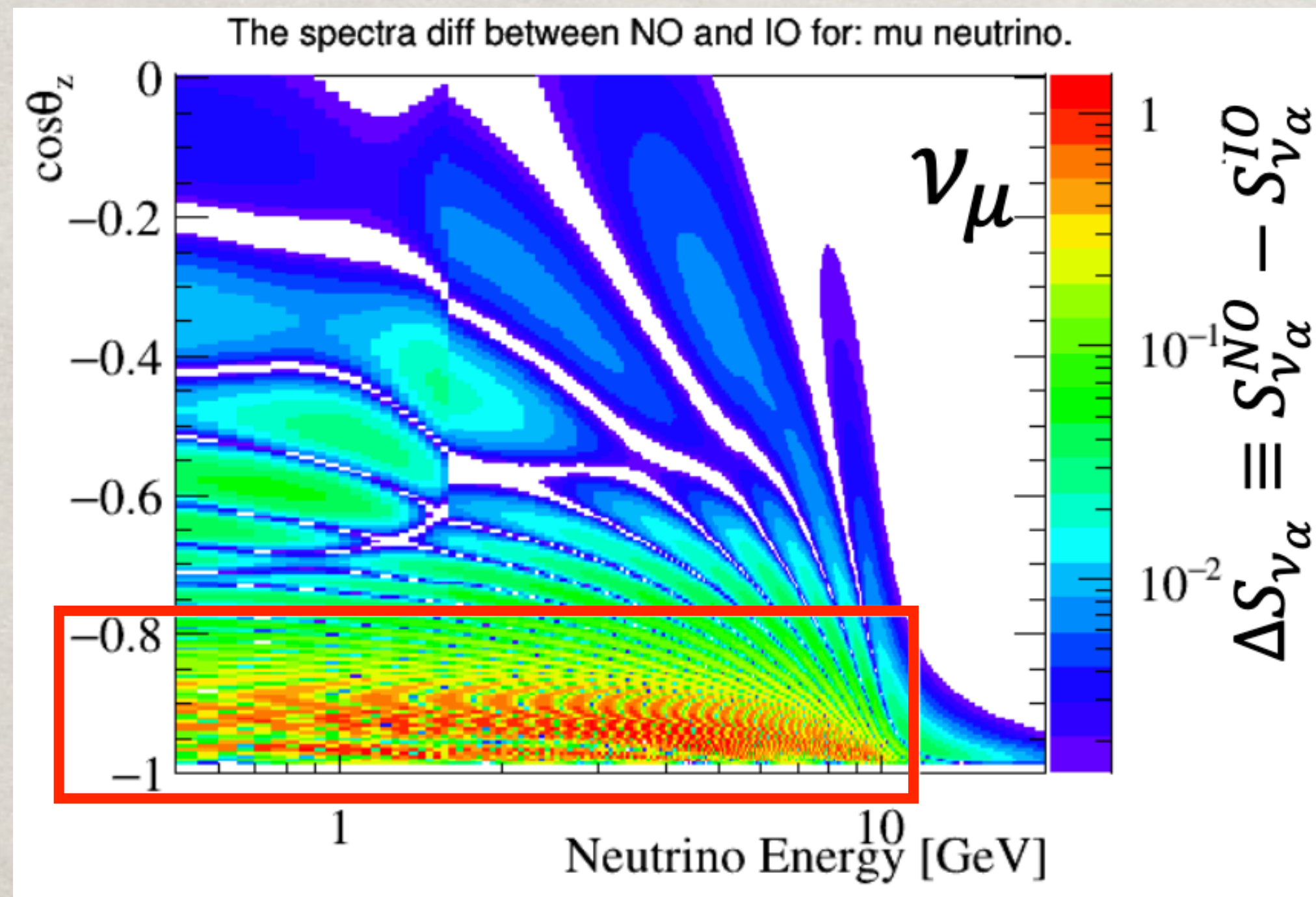


ν_e CC Event

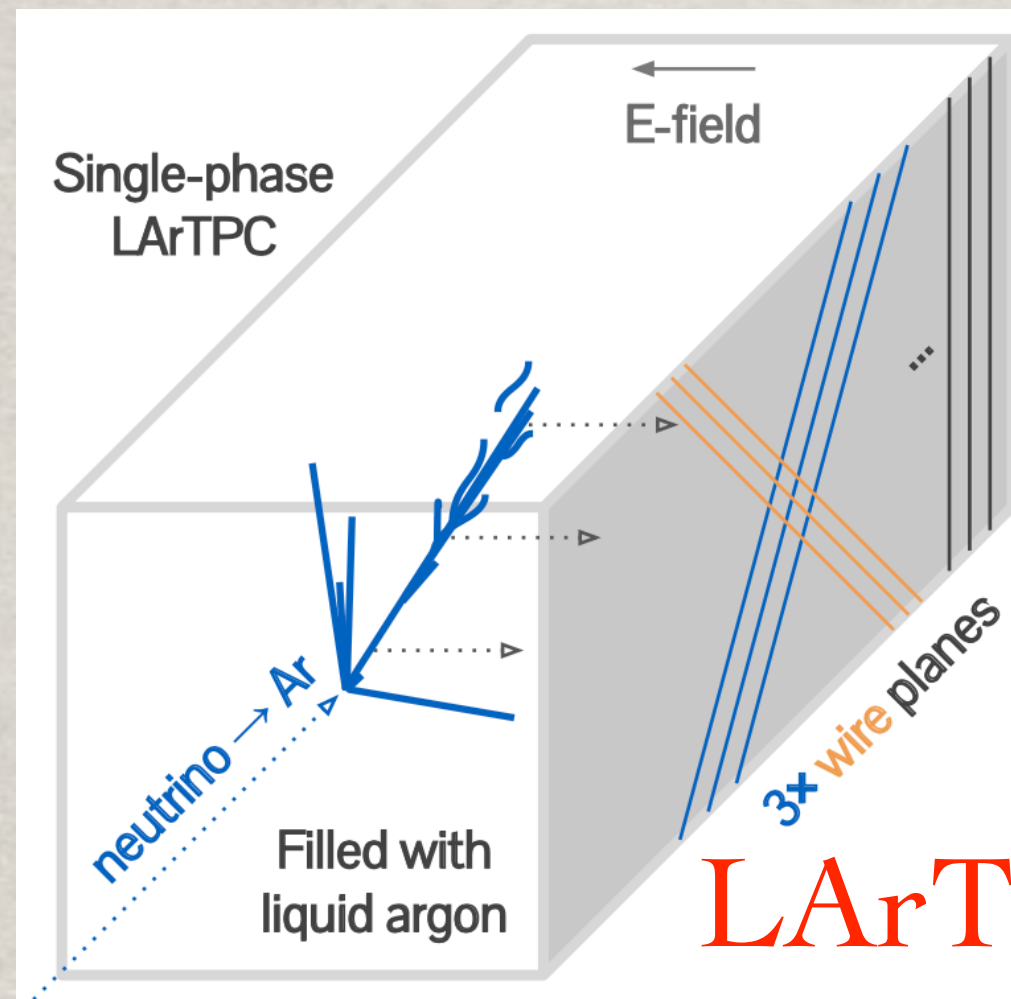


ATM. ν @ JUNO

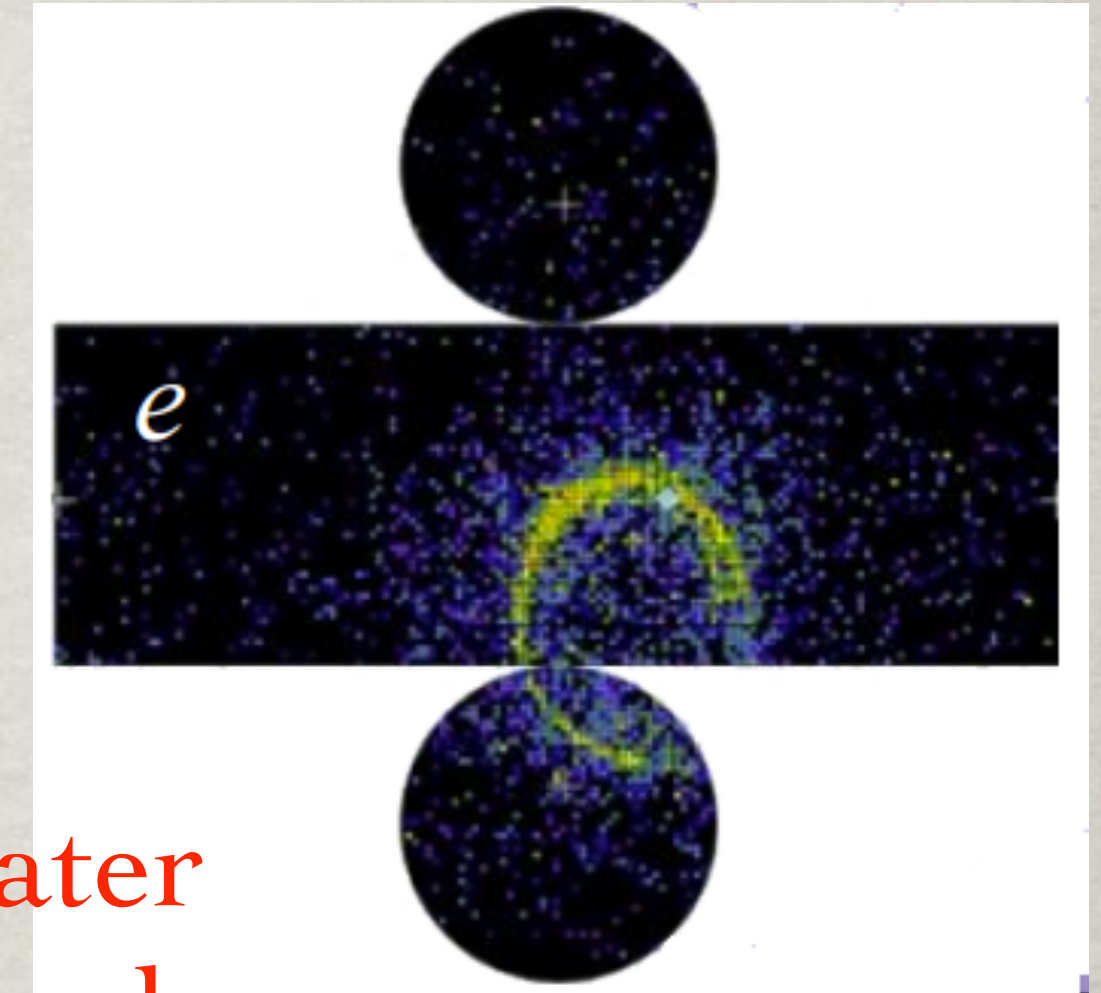
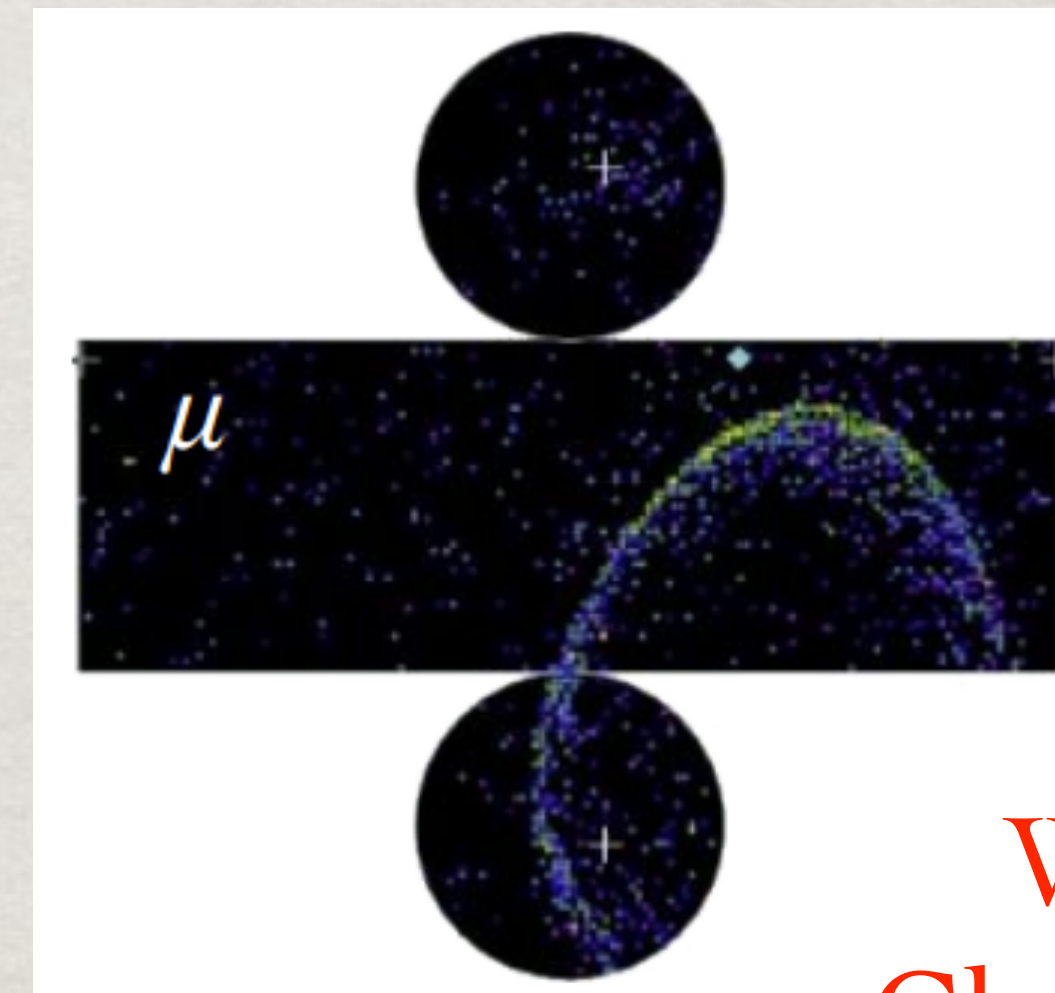
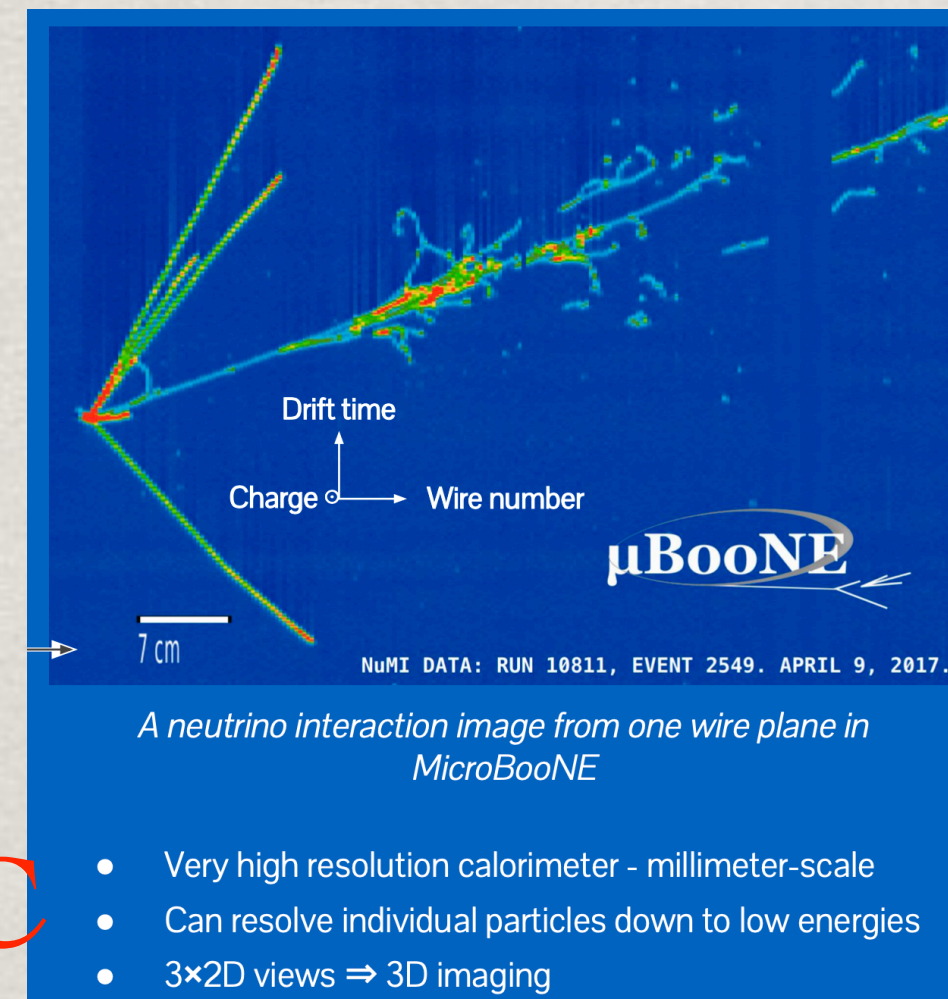
- ❖ Measurement of atm. ν oscillation at JUNO could further boost the NMO sensitivity
- ❖ Key ingredients: directionality, flavor identification, ν vs $\bar{\nu}$



CHALLENGES AND OPPORTUNITIES



LArTPC



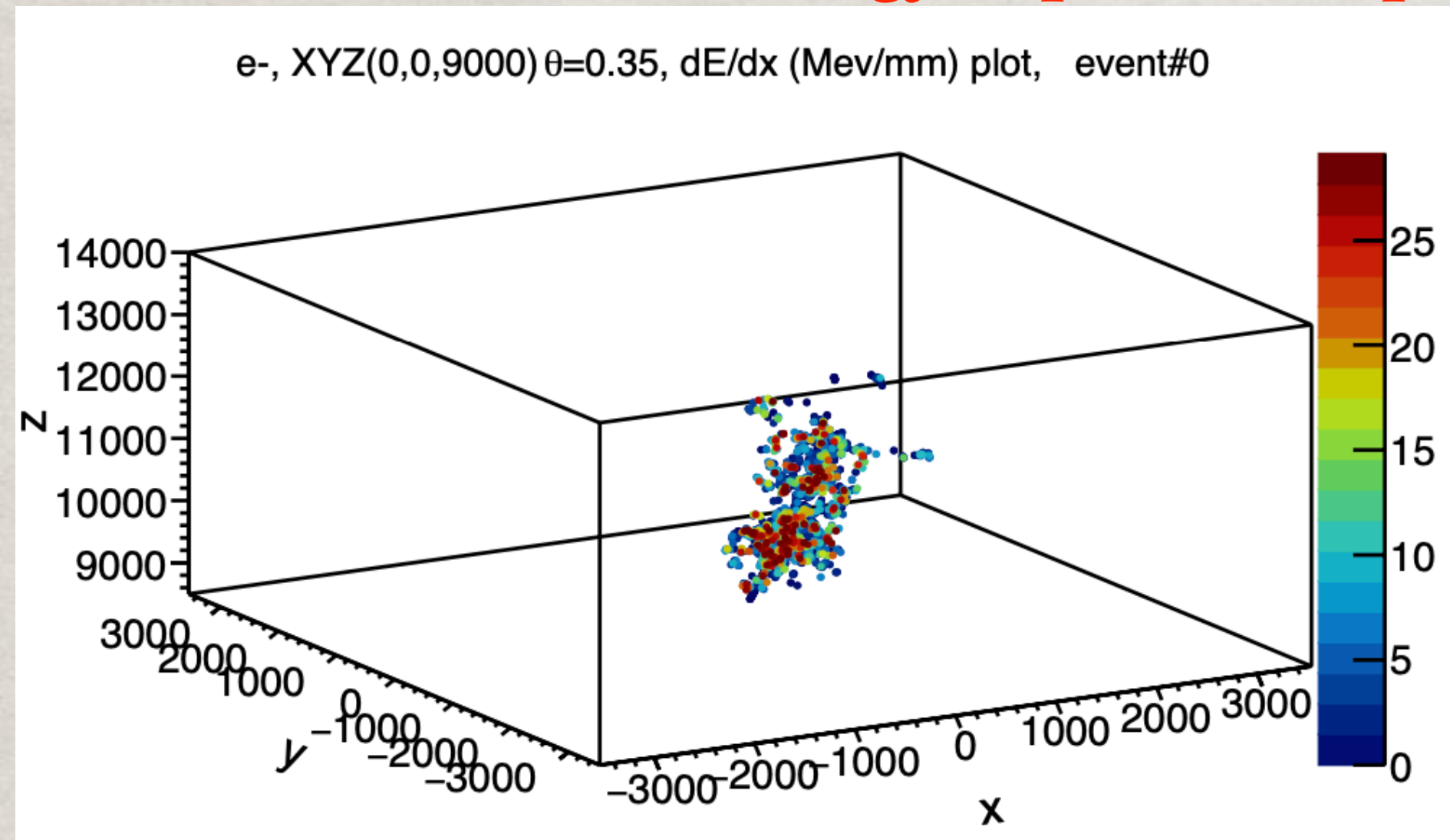
Water
Cherenkov

- ❖ Neither track information, nor Cherenkov rings for JUNO
- ❖ Advantages of JUNO: 1. large PMT coverage(78%), large volume; 2. excellent neutron tagging; 3. hadronic component visible in LS; 4. can measure distinctive isotopes

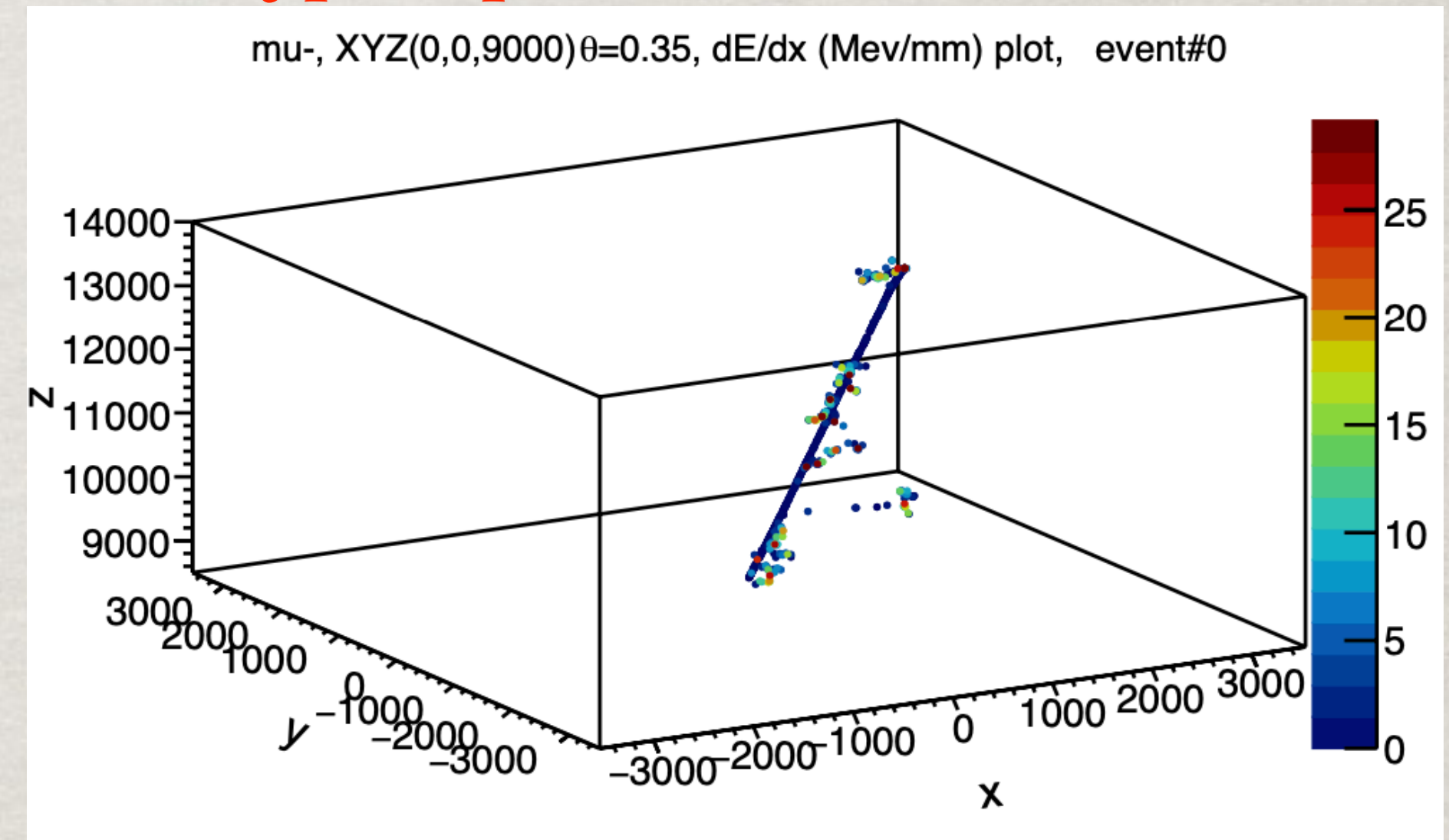
PARTICLE TOPOLOGY

Energy deposition topology in LS for different type of particles

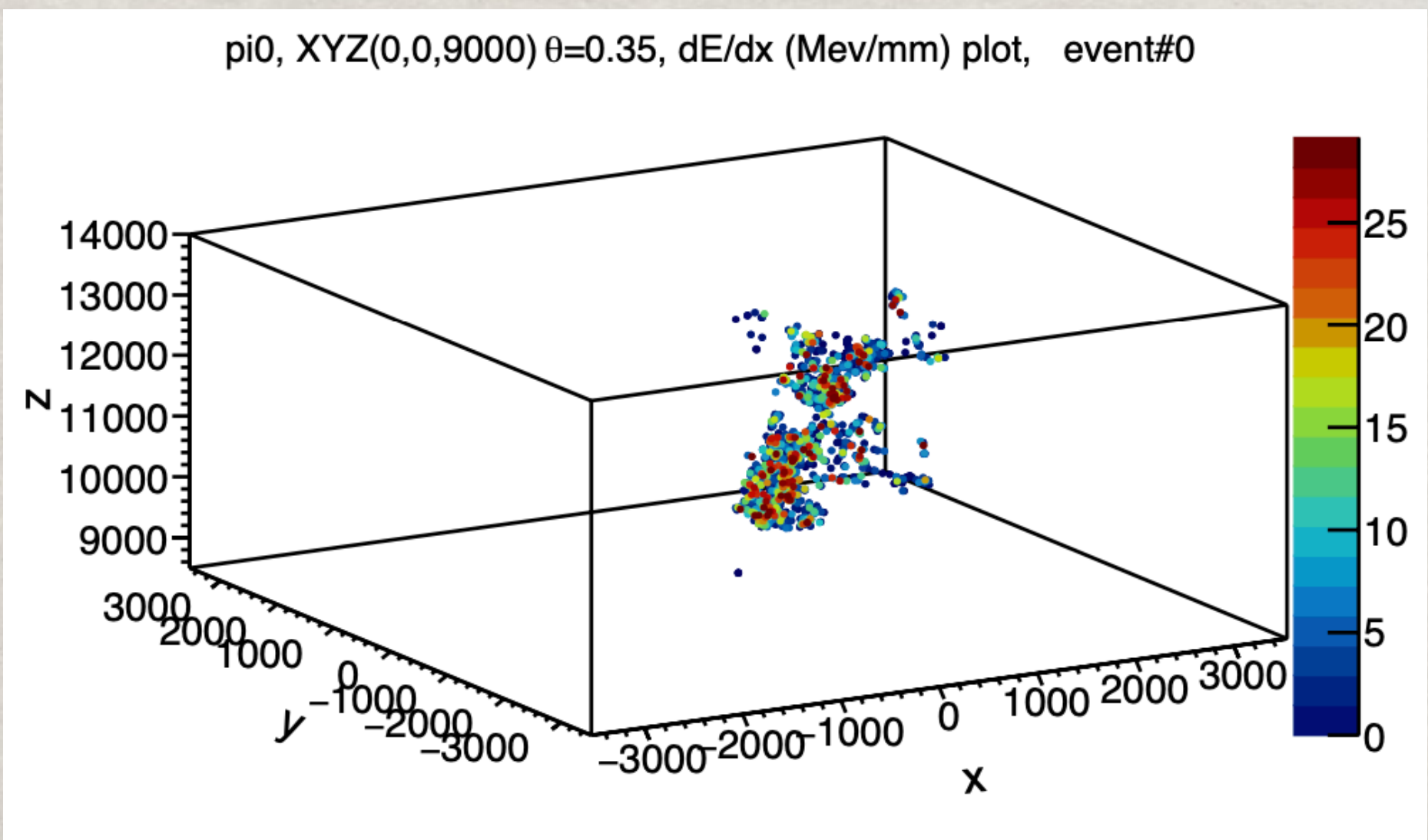
e



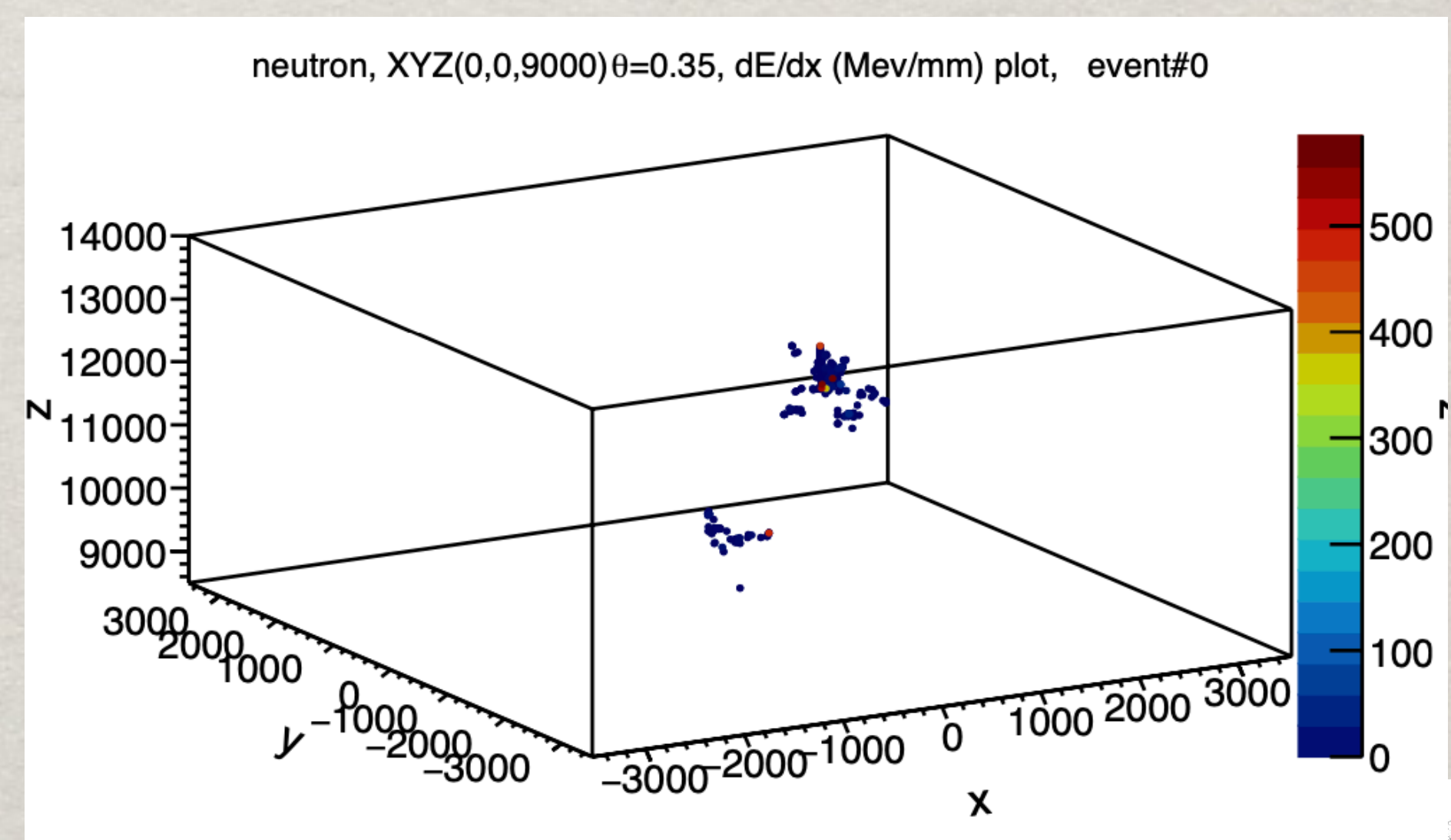
μ



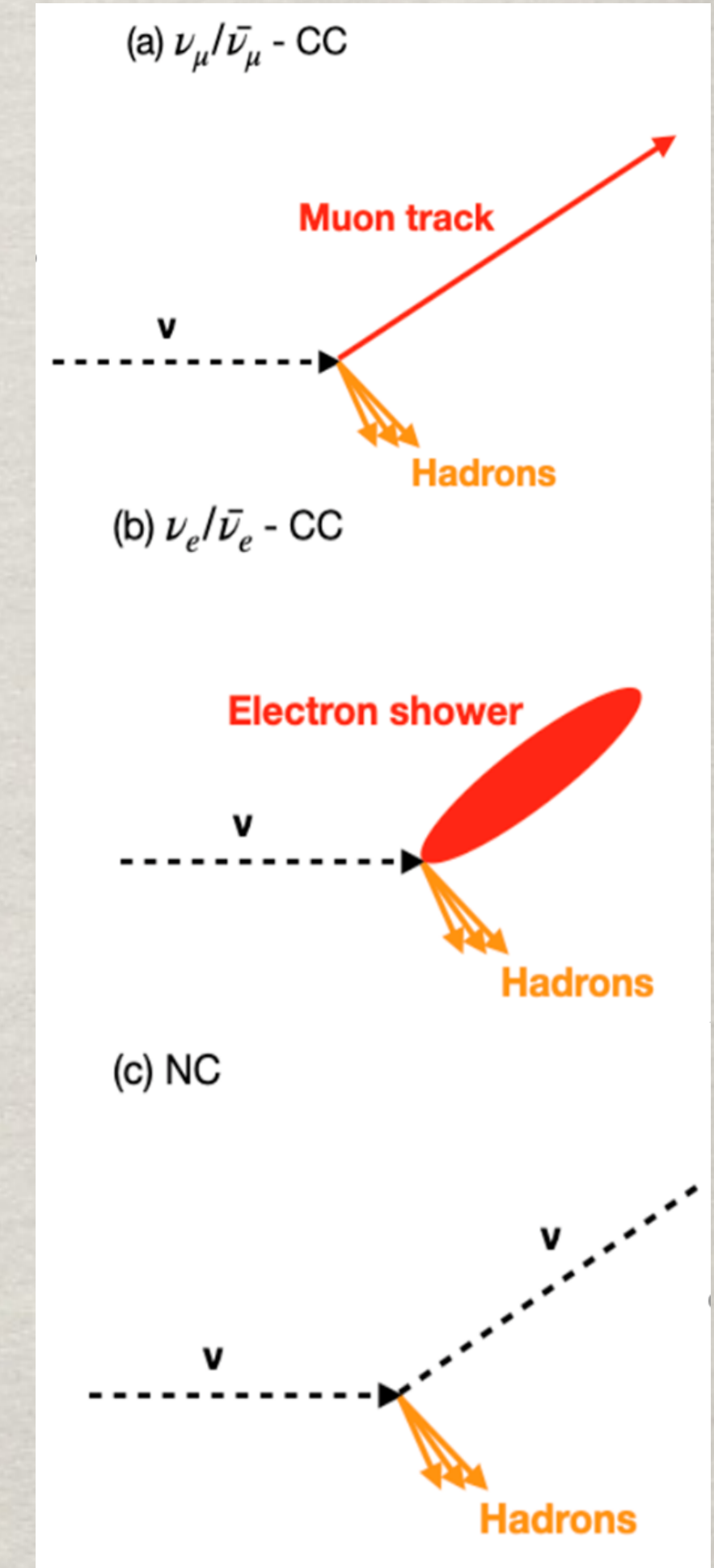
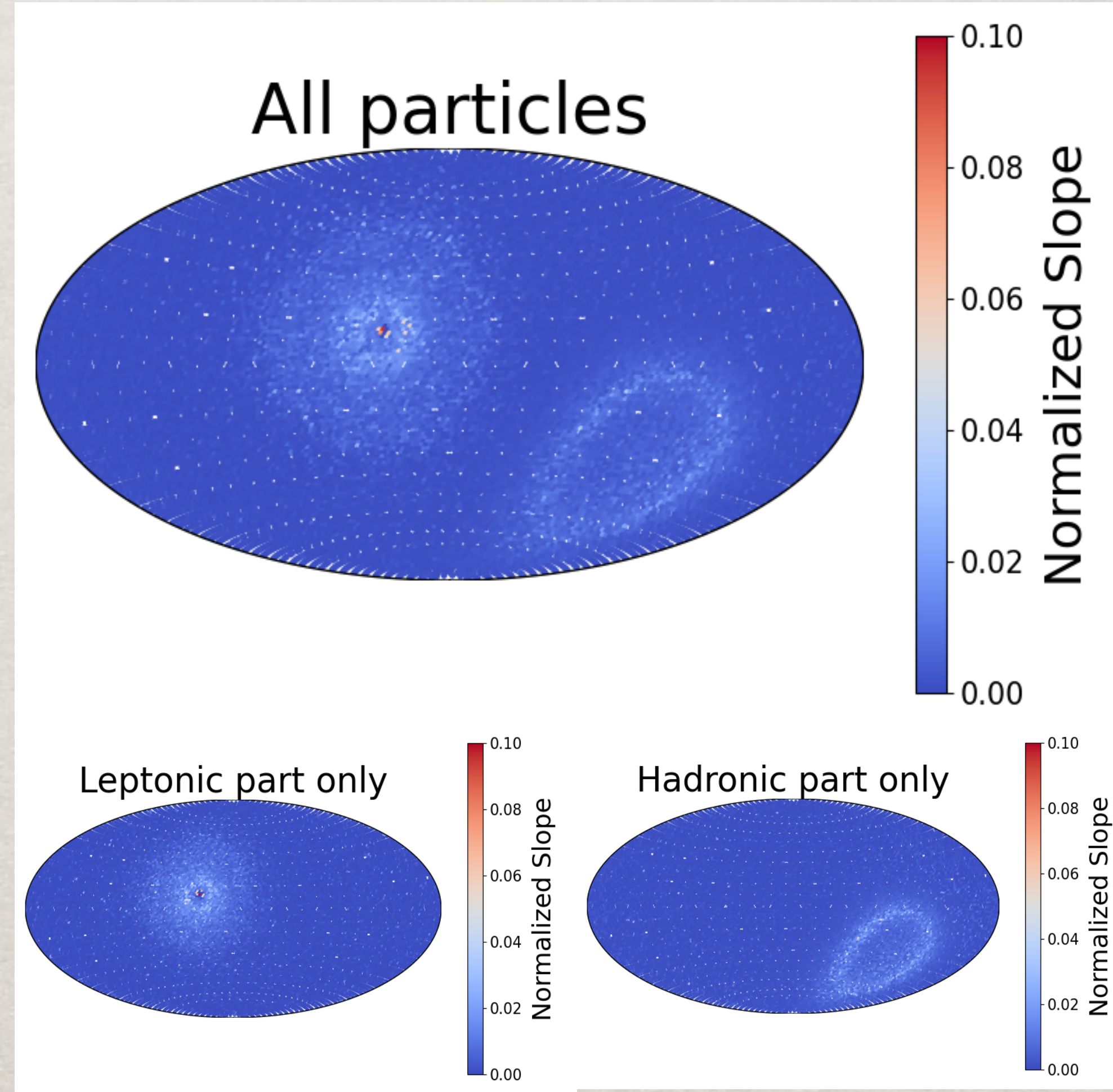
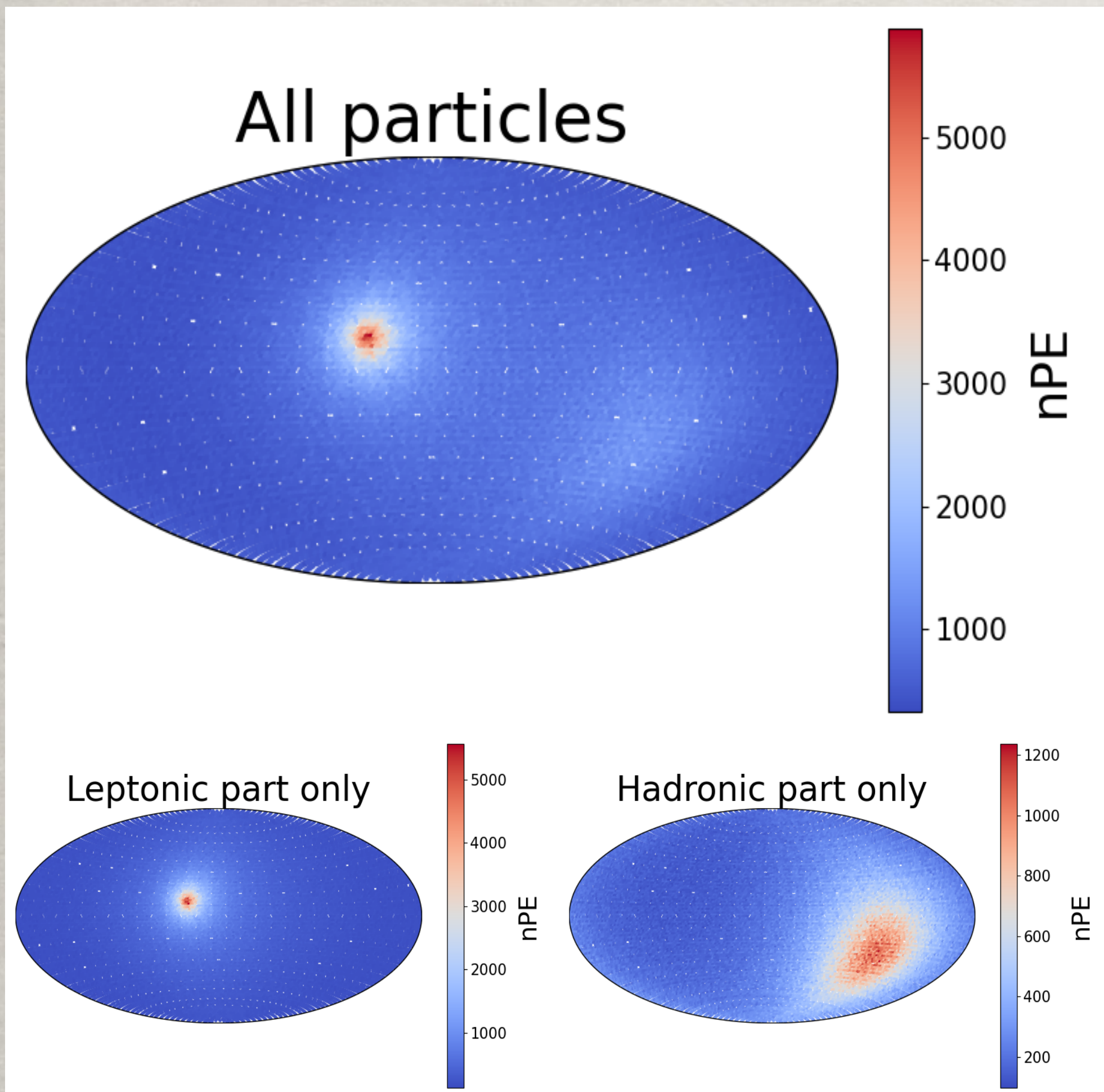
π^0



n

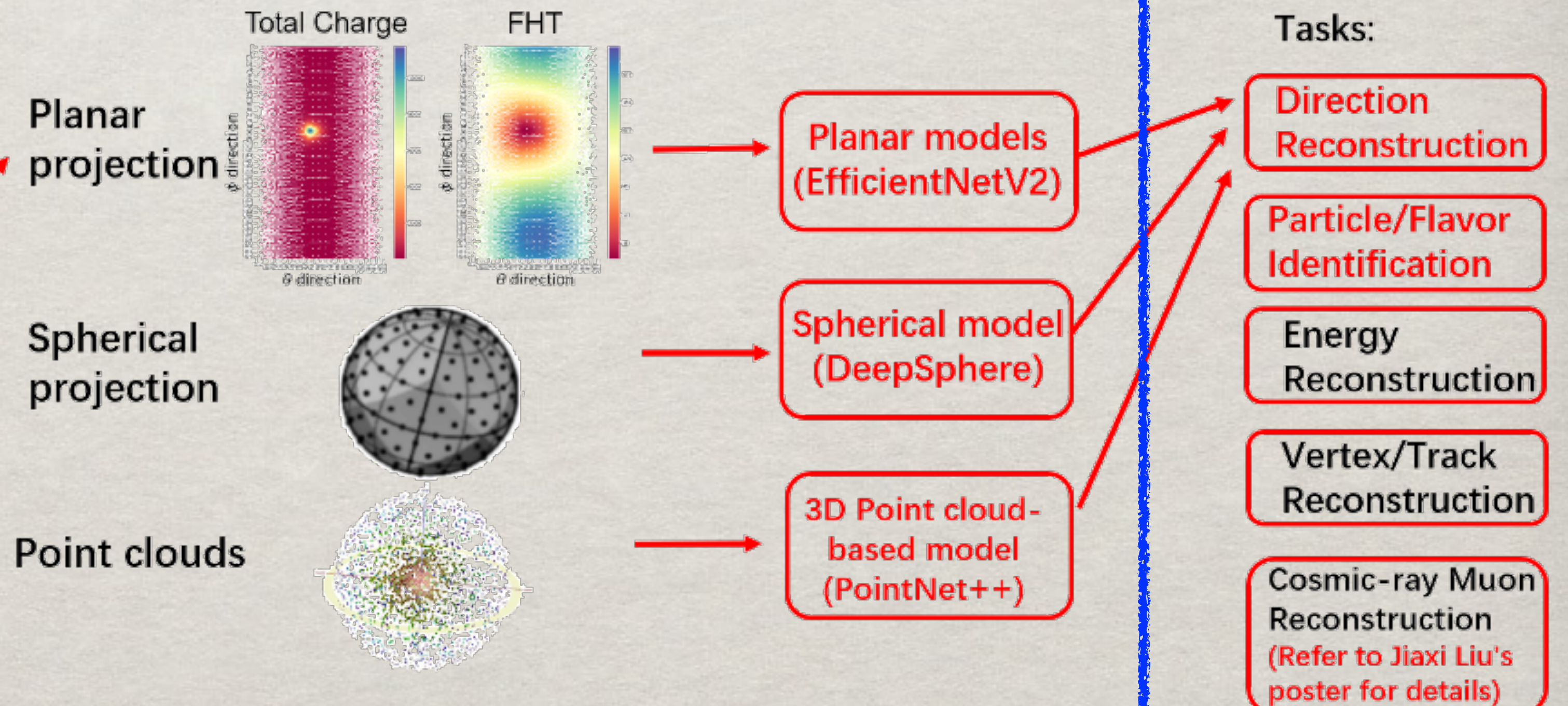
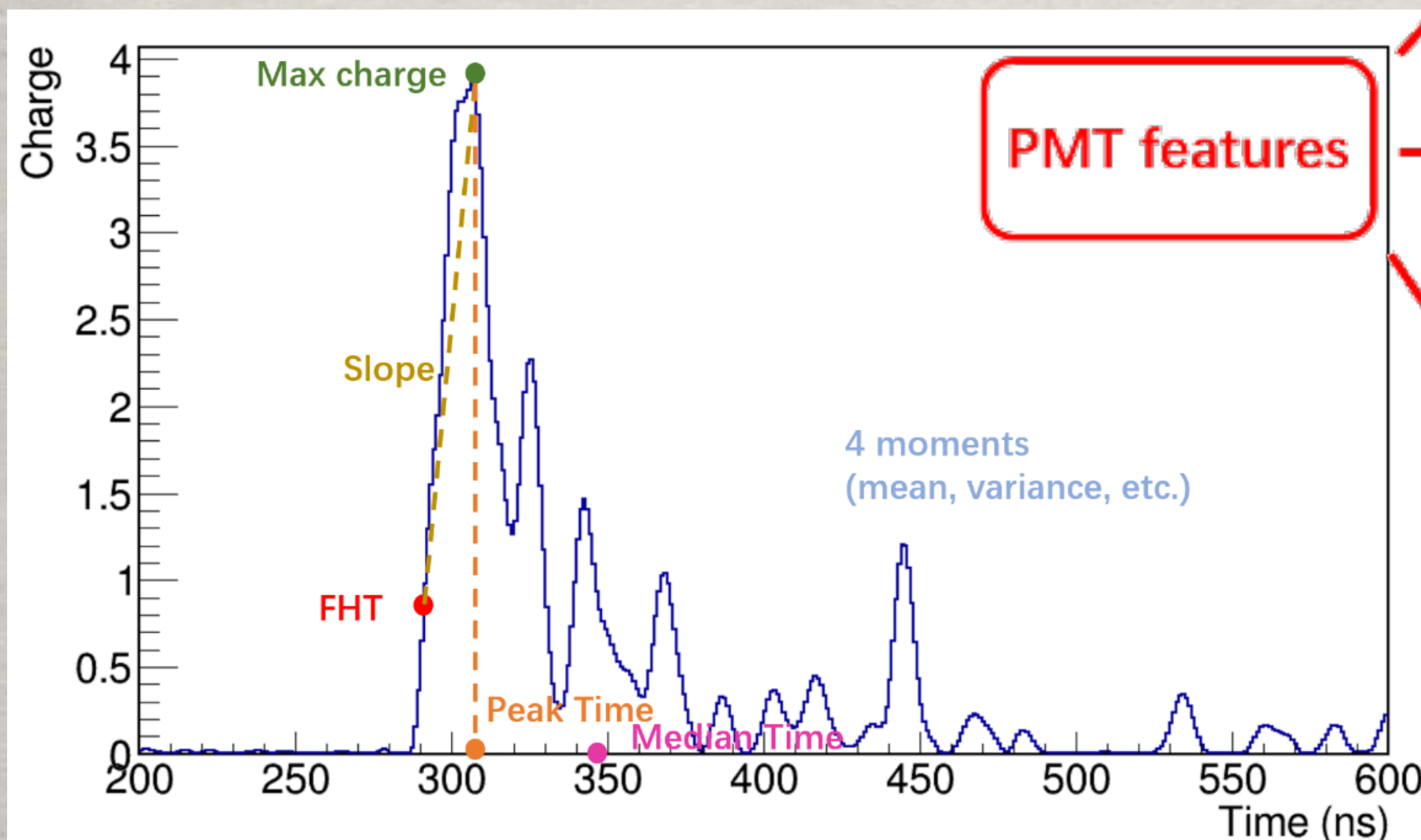
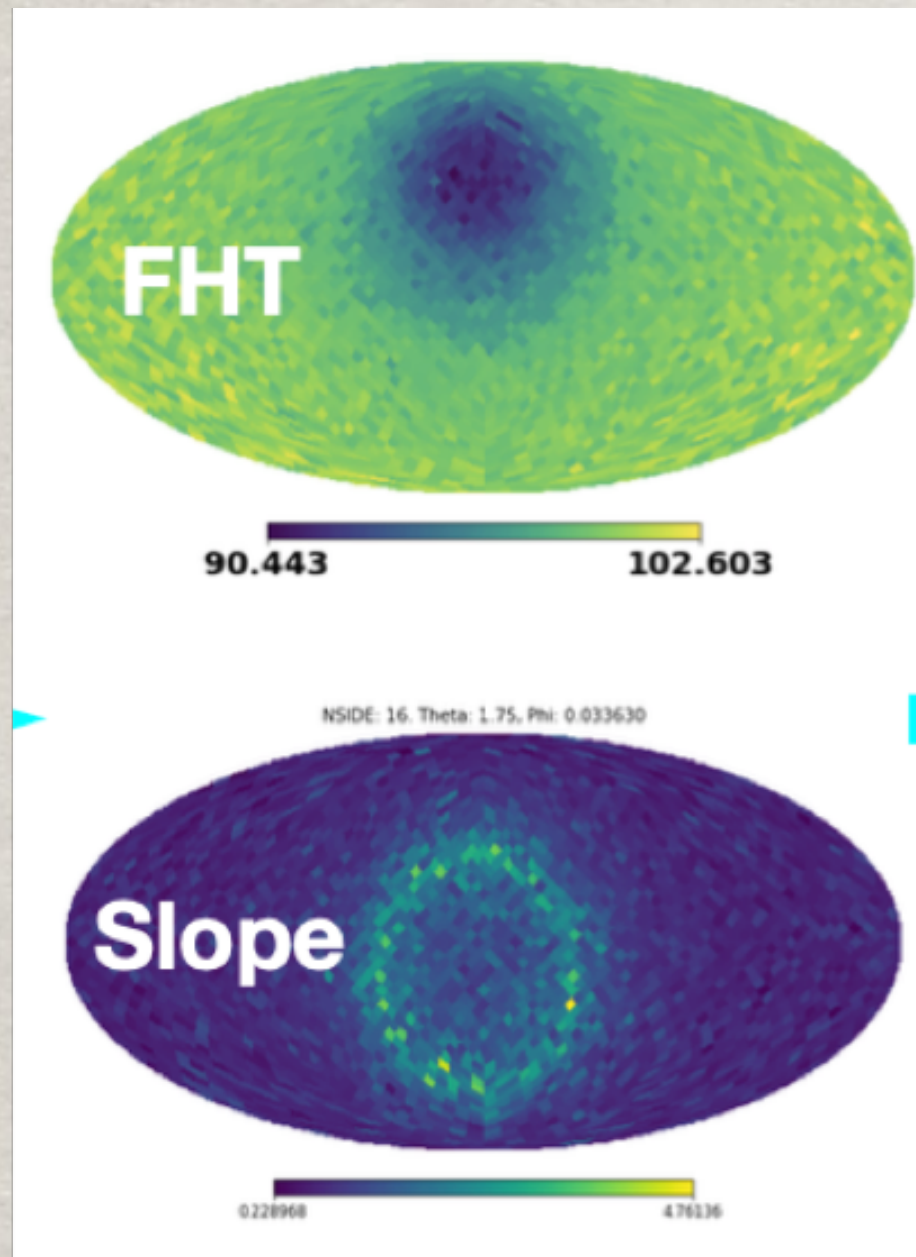


DETECTOR RESPONSE

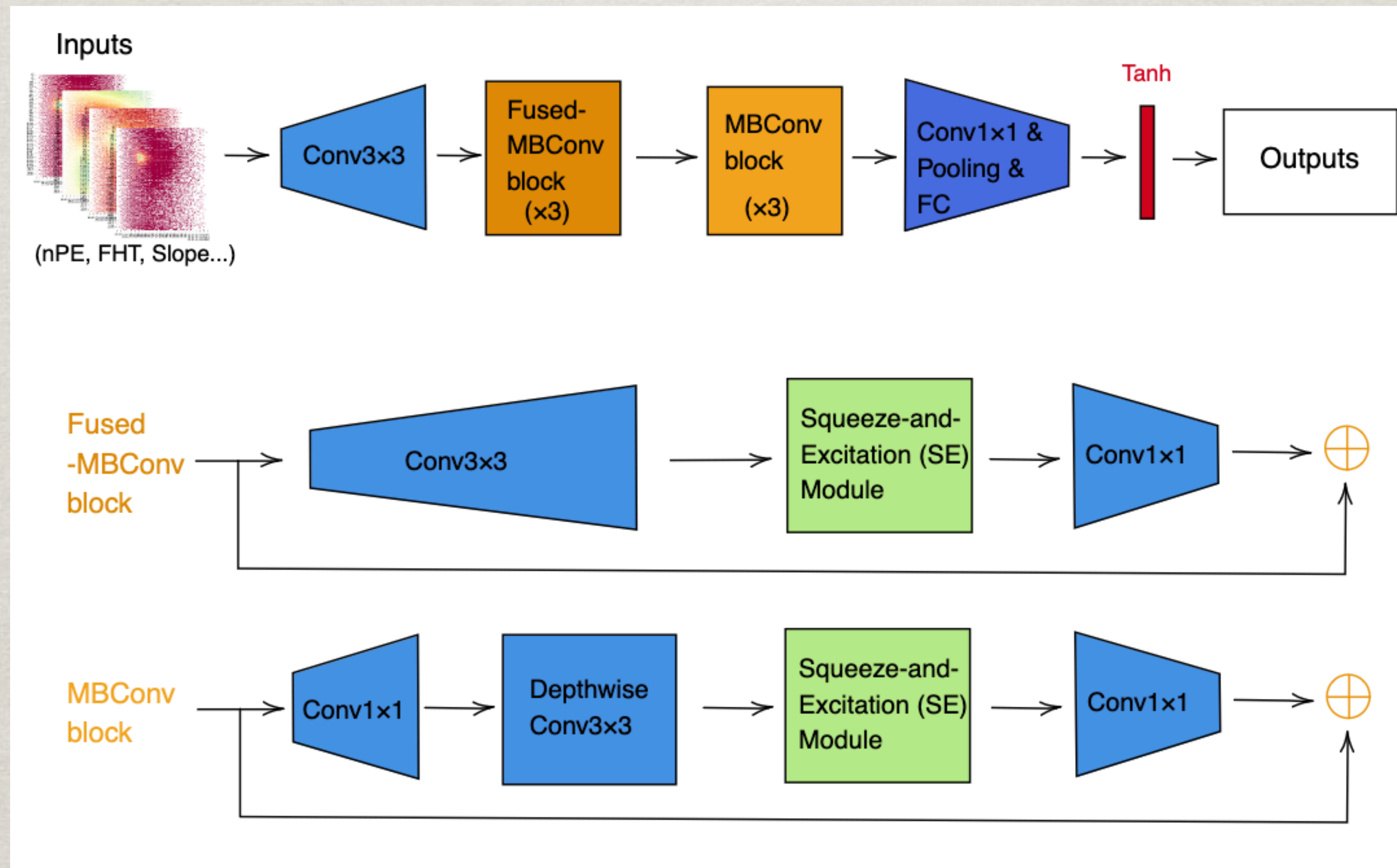


RECO/PID METHODOLOGY

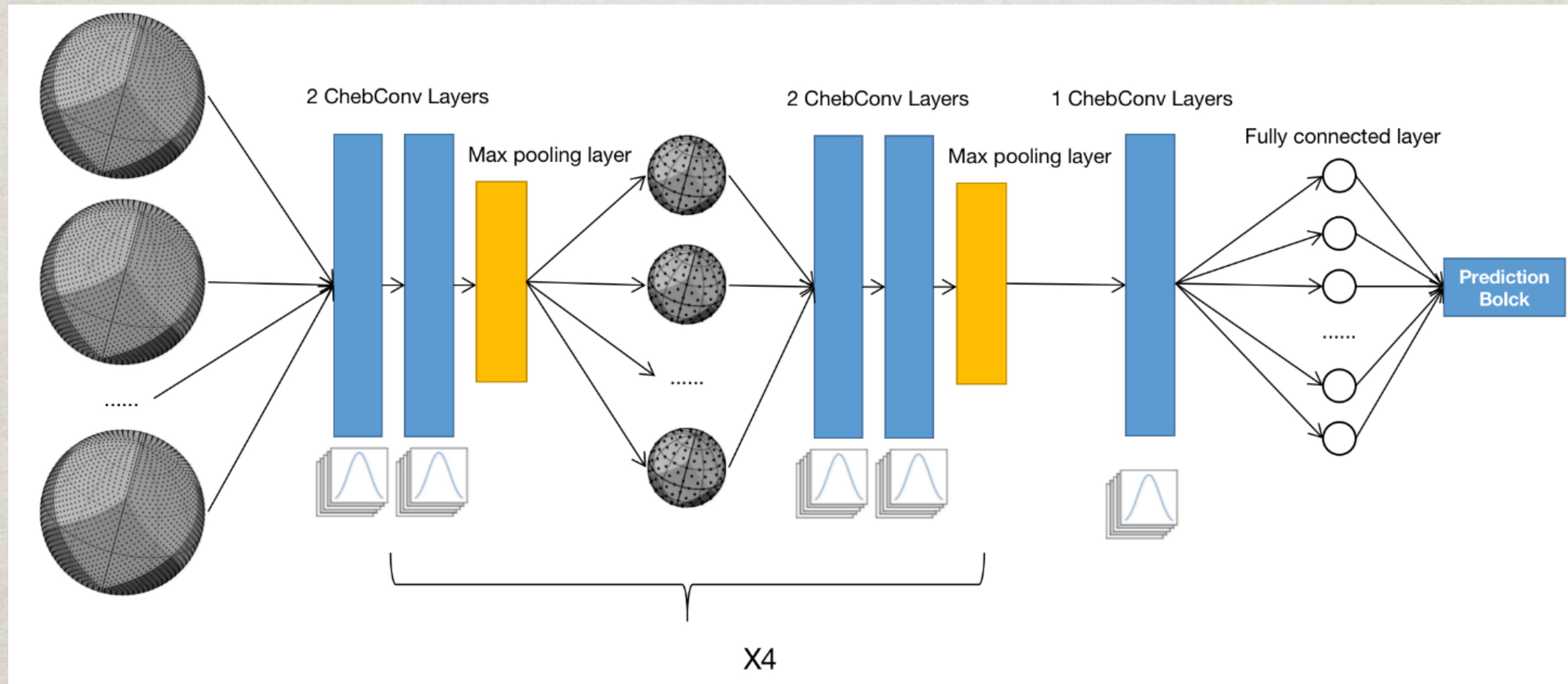
- ❖ Step 1: feature extraction from PMT waveforms
- ❖ Step 2: model building
- ❖ Step 3: optimization and validation



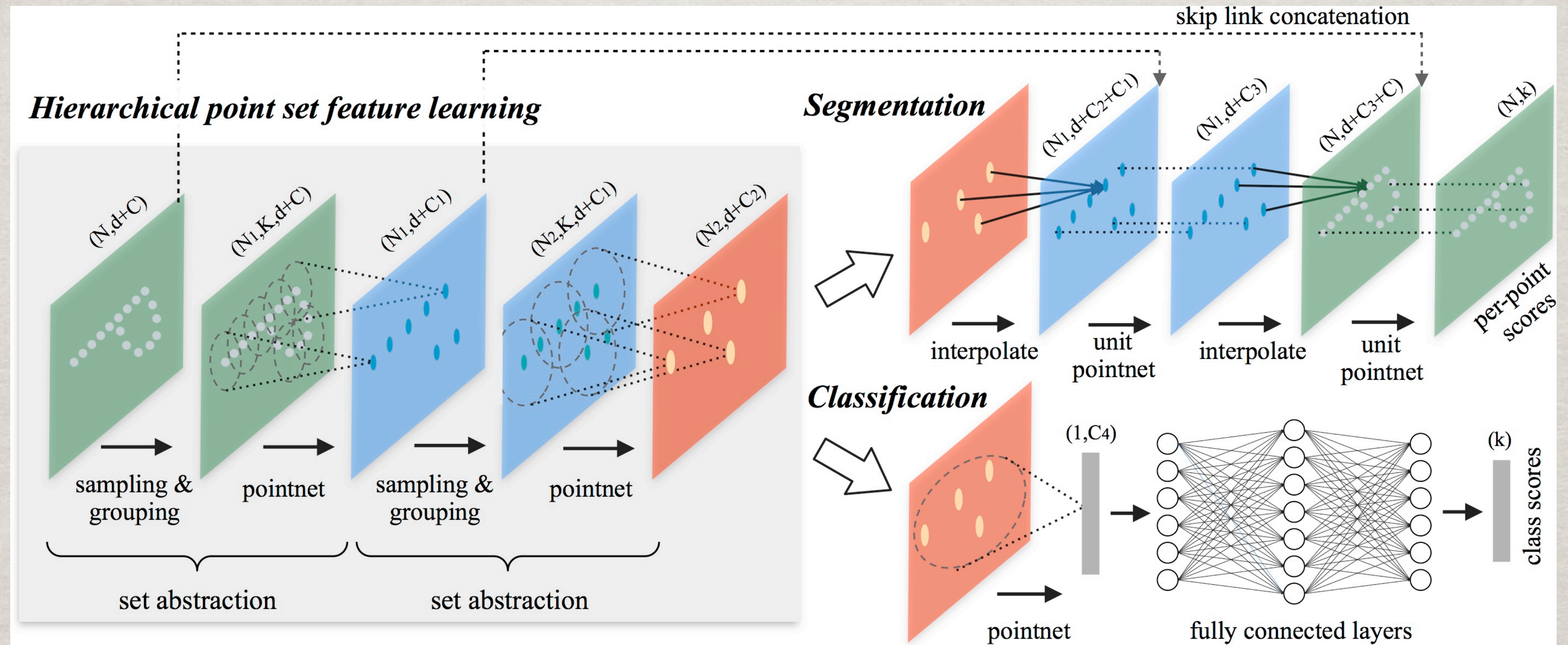
PLANE MODEL: EFFICIENTNETV2-S



SPHERICAL MODEL: DEEPSPHERE

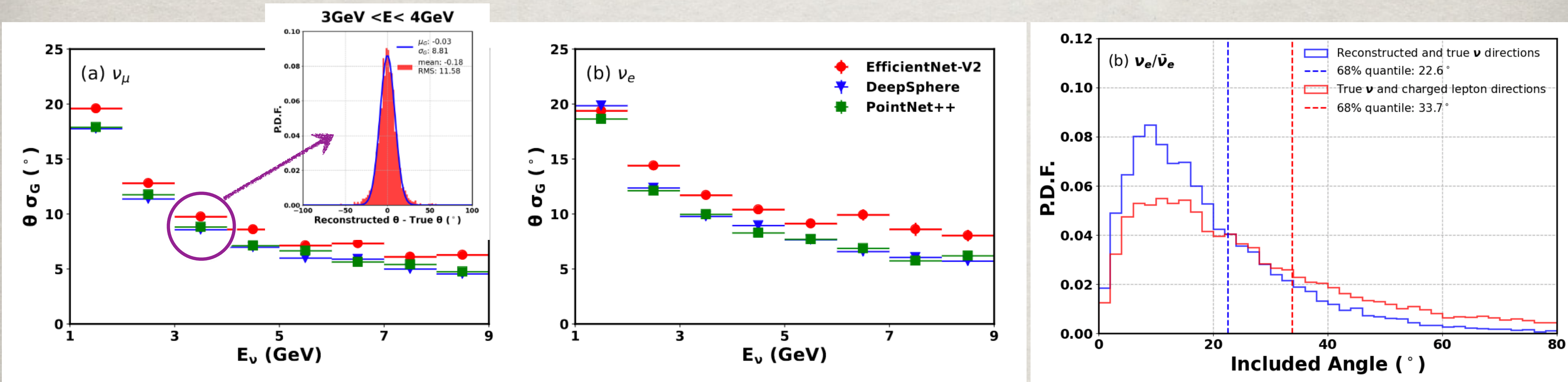


3D MODEL: POINTNET++



DIRECTIONALITY

Phys.Rev.D 109 (2024) 5, 052005



- ❖ 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 $E > 3\text{GeV}$

J. Phys. G: 43 (2016) 030401

Yellow Book

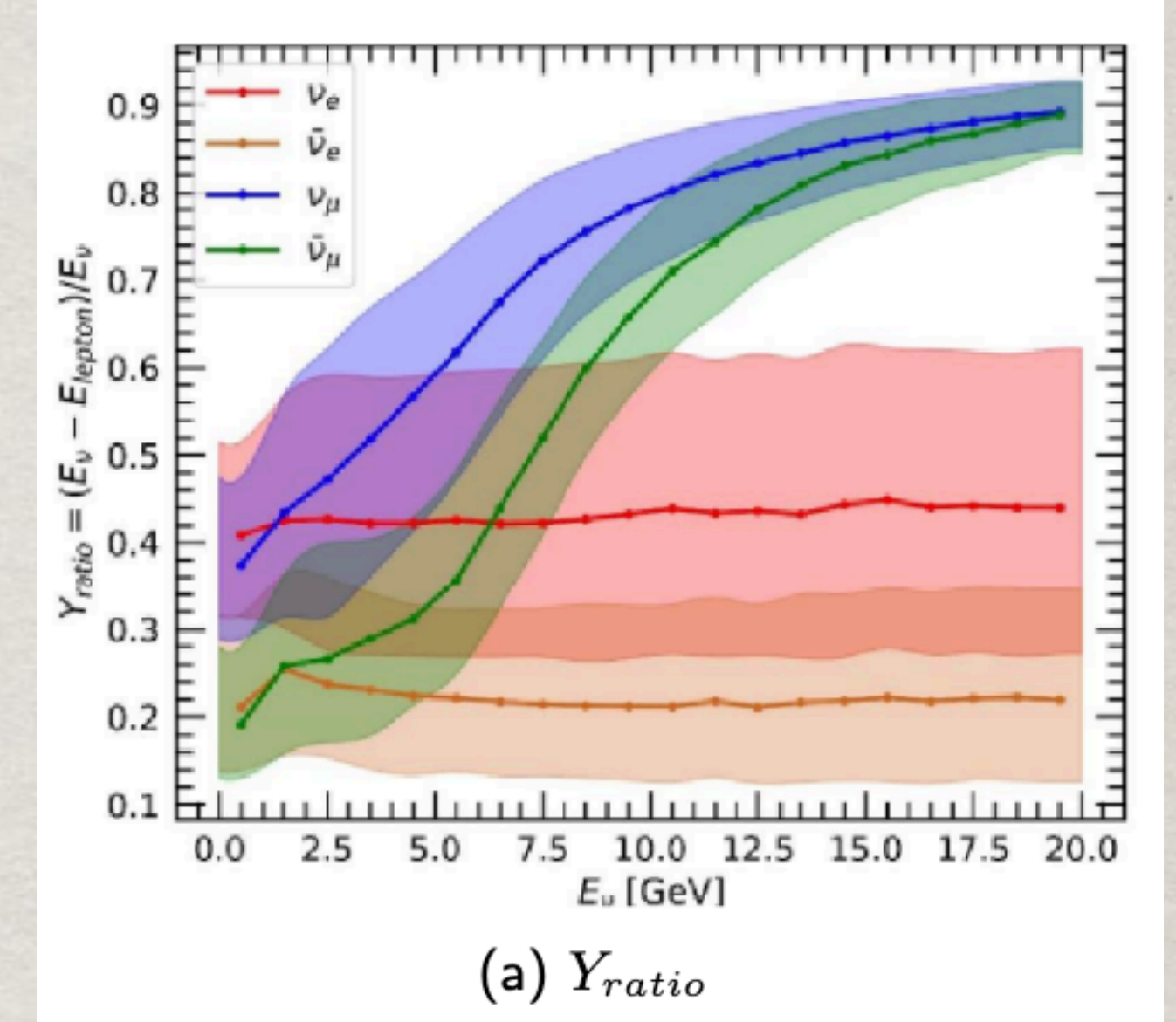
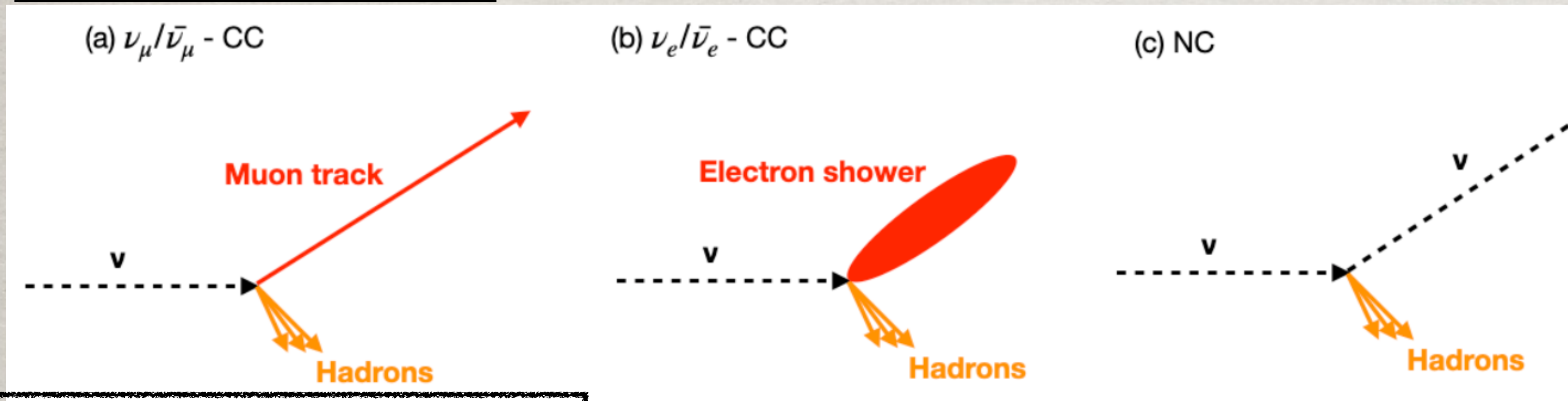
$$\sigma_{\theta\mu} = 1^\circ$$

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



PID STRATEGY

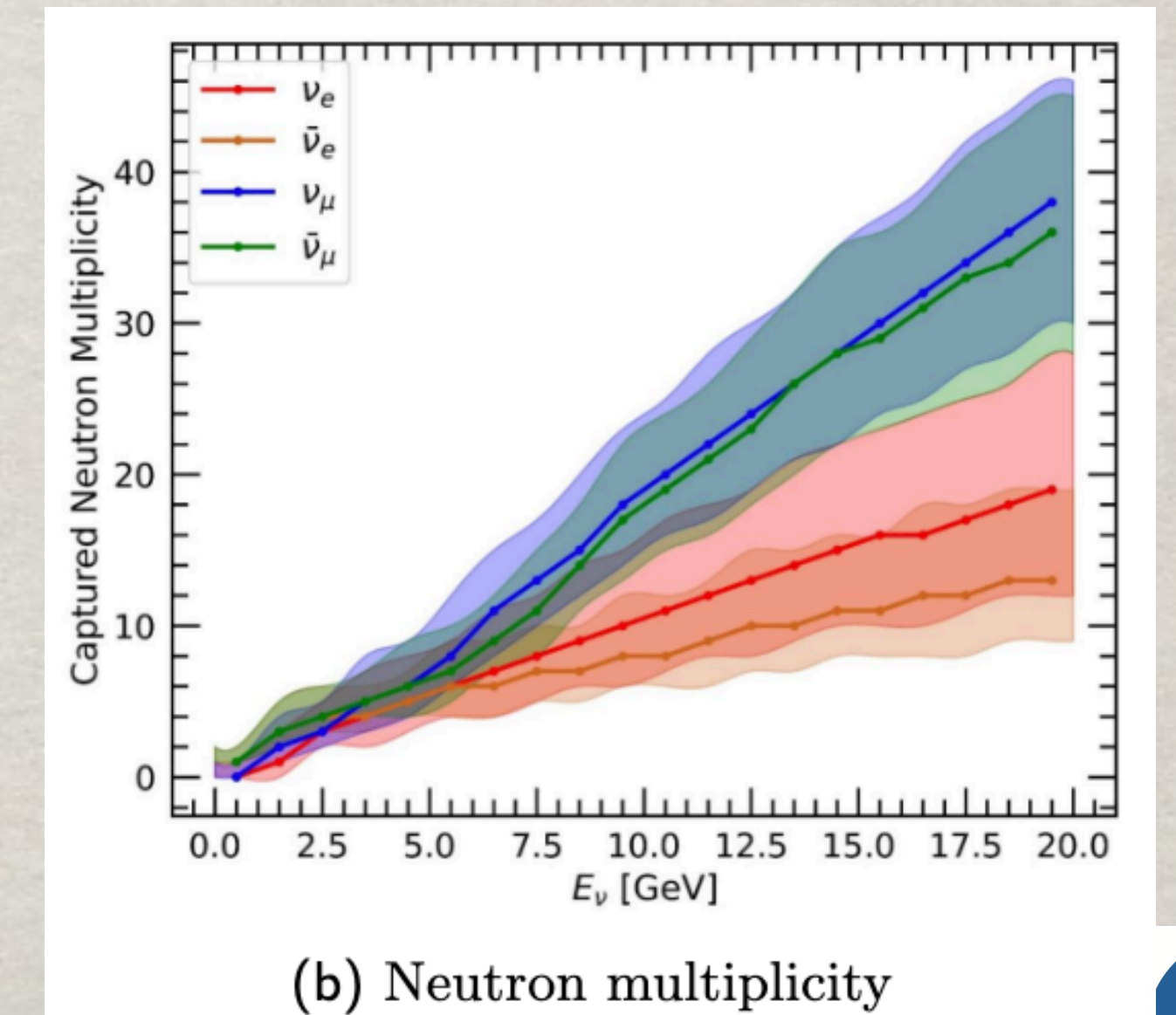
prompt trigger



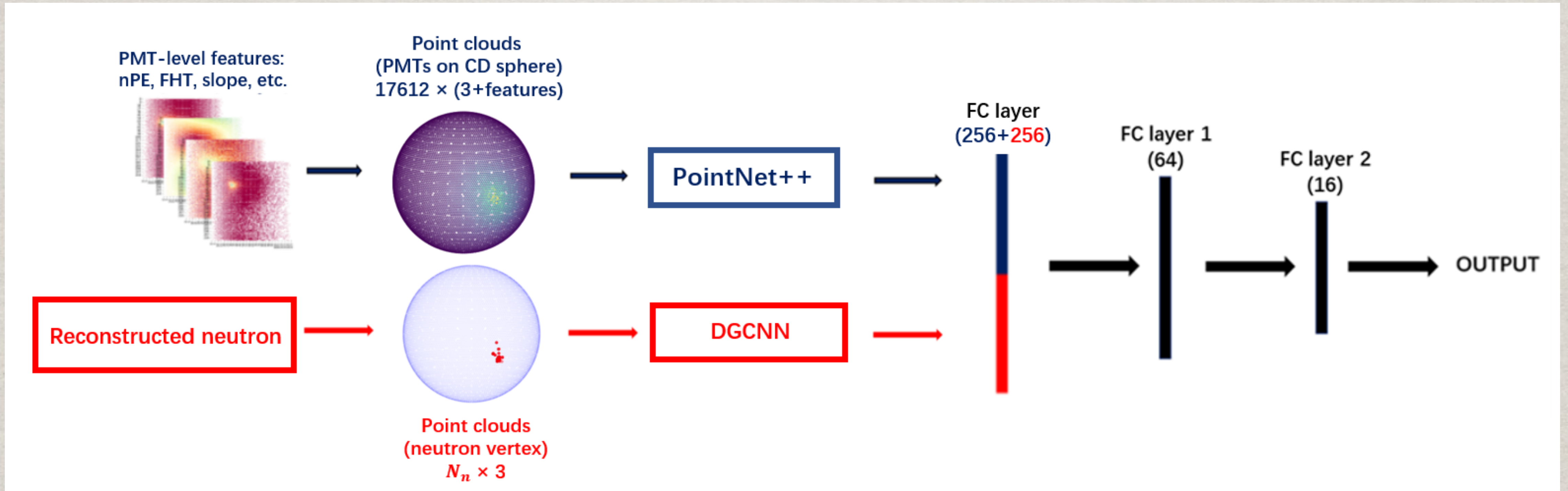
secondary triggers

neutron capture

- ❖ Both leptons & hadrons visible, different topology
- ❖ step1: CC-e/CC- μ /NC classification
- ❖ step2: $\bar{\nu}$ vs ν

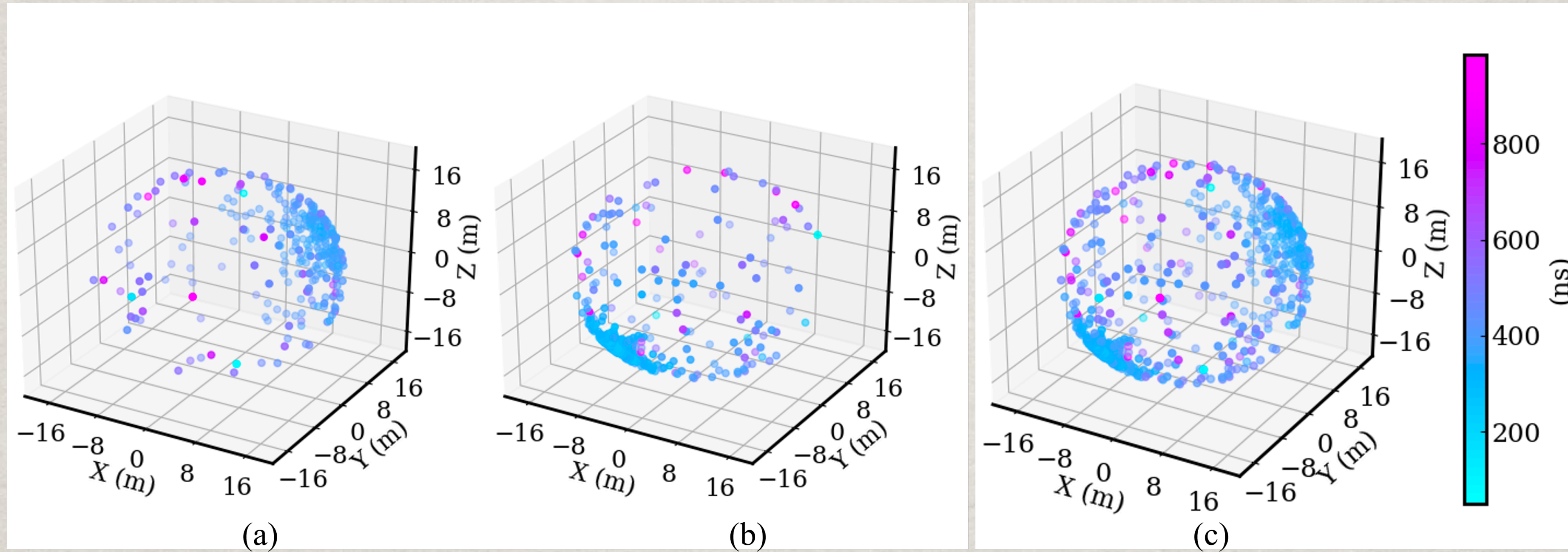


PID ML INPUT & MODEL: 1



- ❖ PMT features $\rightarrow$ PointNet++ (x, y, z, feature_i...)
- ❖ Neutron candidates $\rightarrow$ DGCNN (x, y, z)

PID ML INPUT & MODEL: 2



- ❖ **PMT features** $\rightarrow$ DeepSphere (x, y, z, feature_i...)
- ❖ **Neutron candidates** $\rightarrow$ DeepSphere (x, y, z, FHT, nPE)
- ❖ **Merged inputs:** DeepSphere (x, y, z, **feature_i...**, **FHT**, **nPE**)

PID PRELIMINARY PERFORMANCE

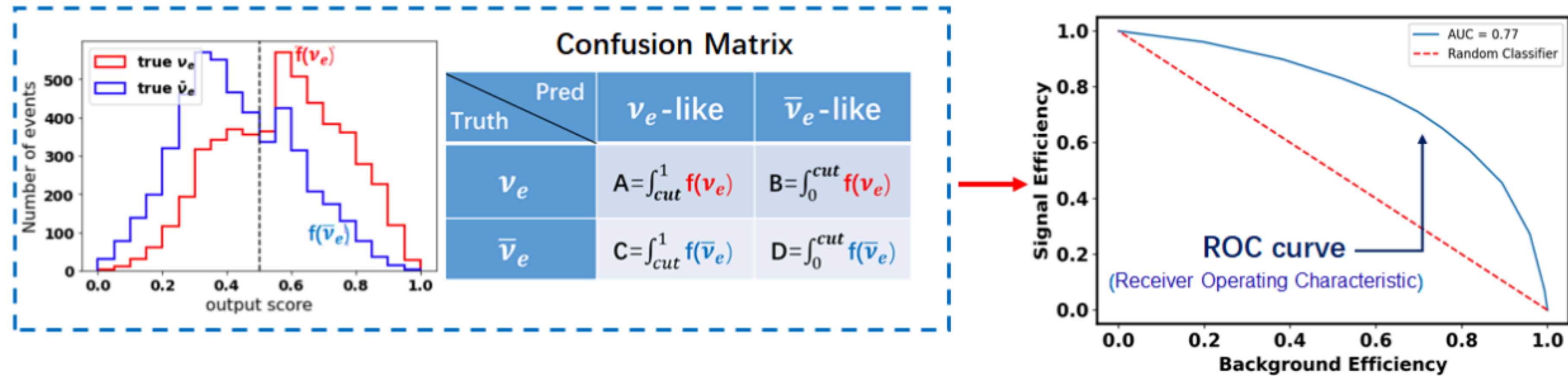
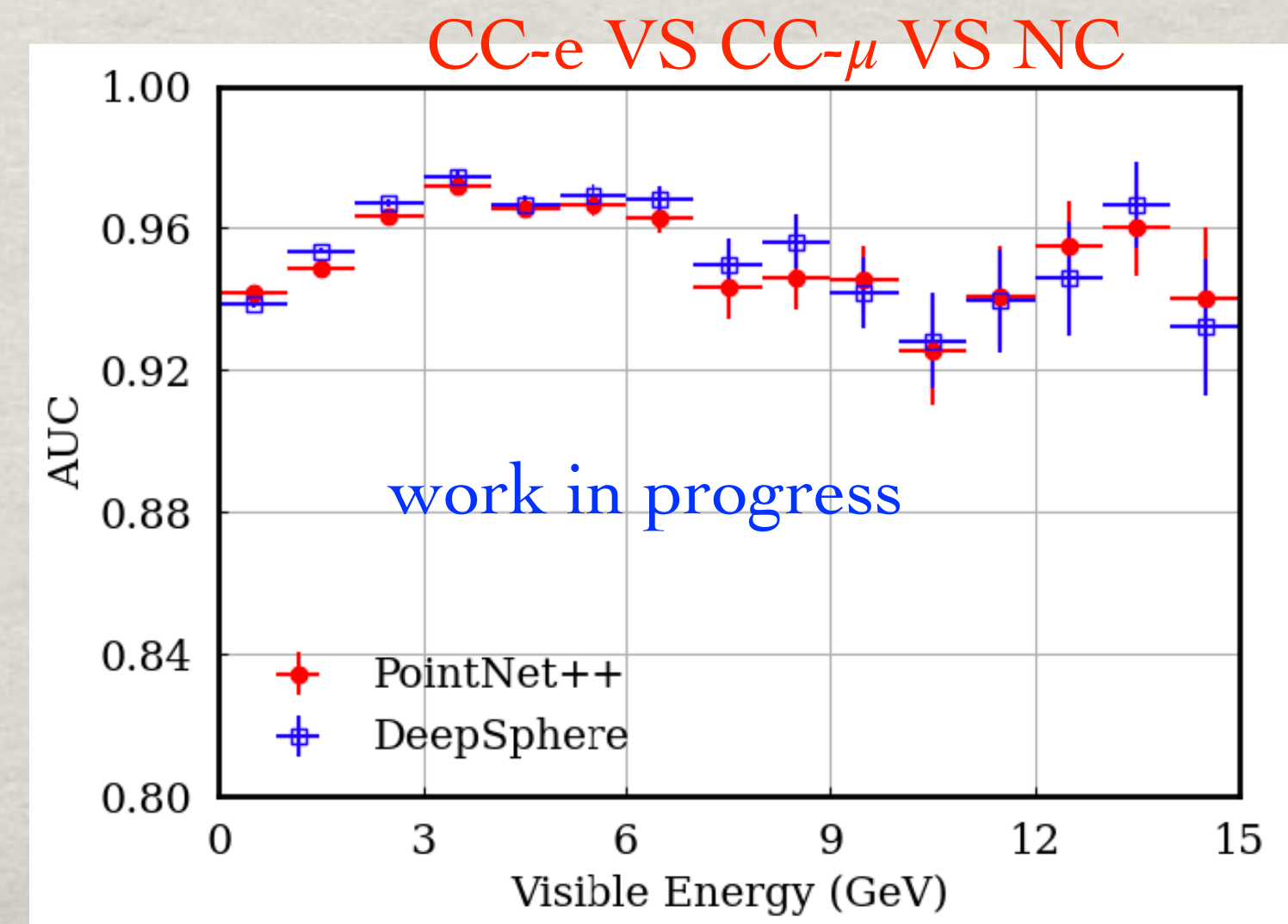
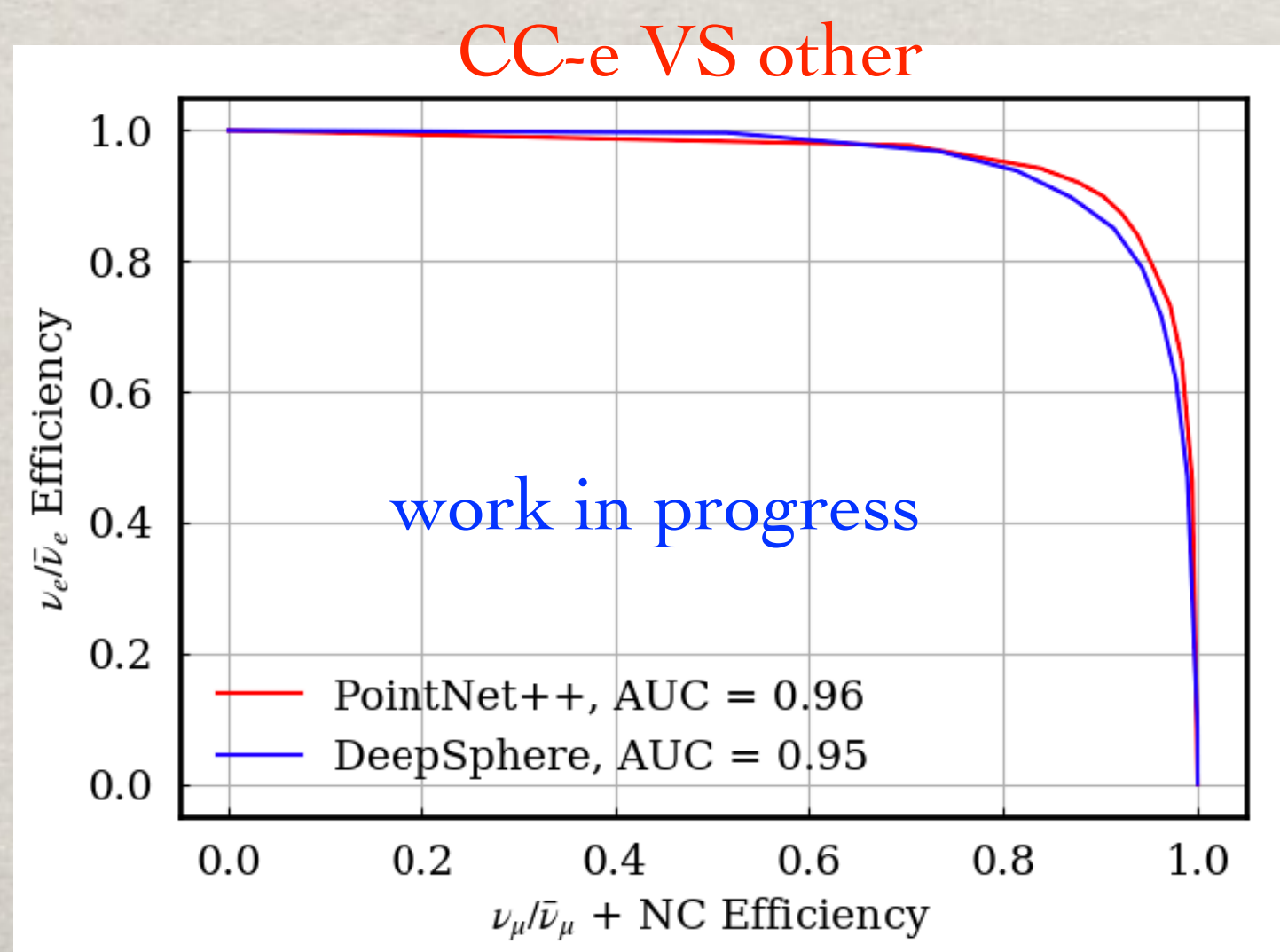


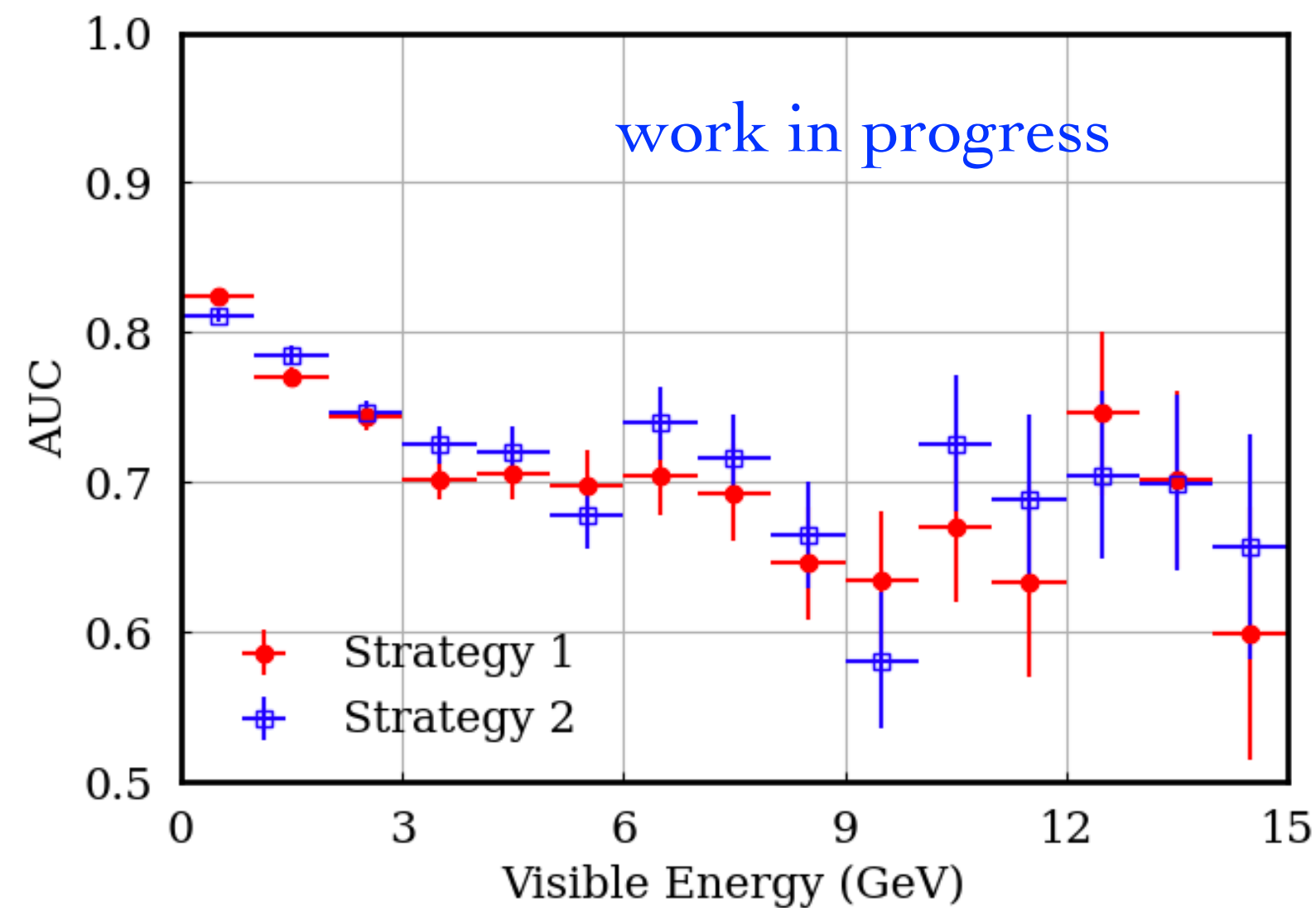
Fig. 8: Illustration of the AUC score using $\nu_e / \bar{\nu}_e$ classification as an example. The AUC score can be viewed as an optimisation of $\nu_e / \bar{\nu}_e$ efficiencies.



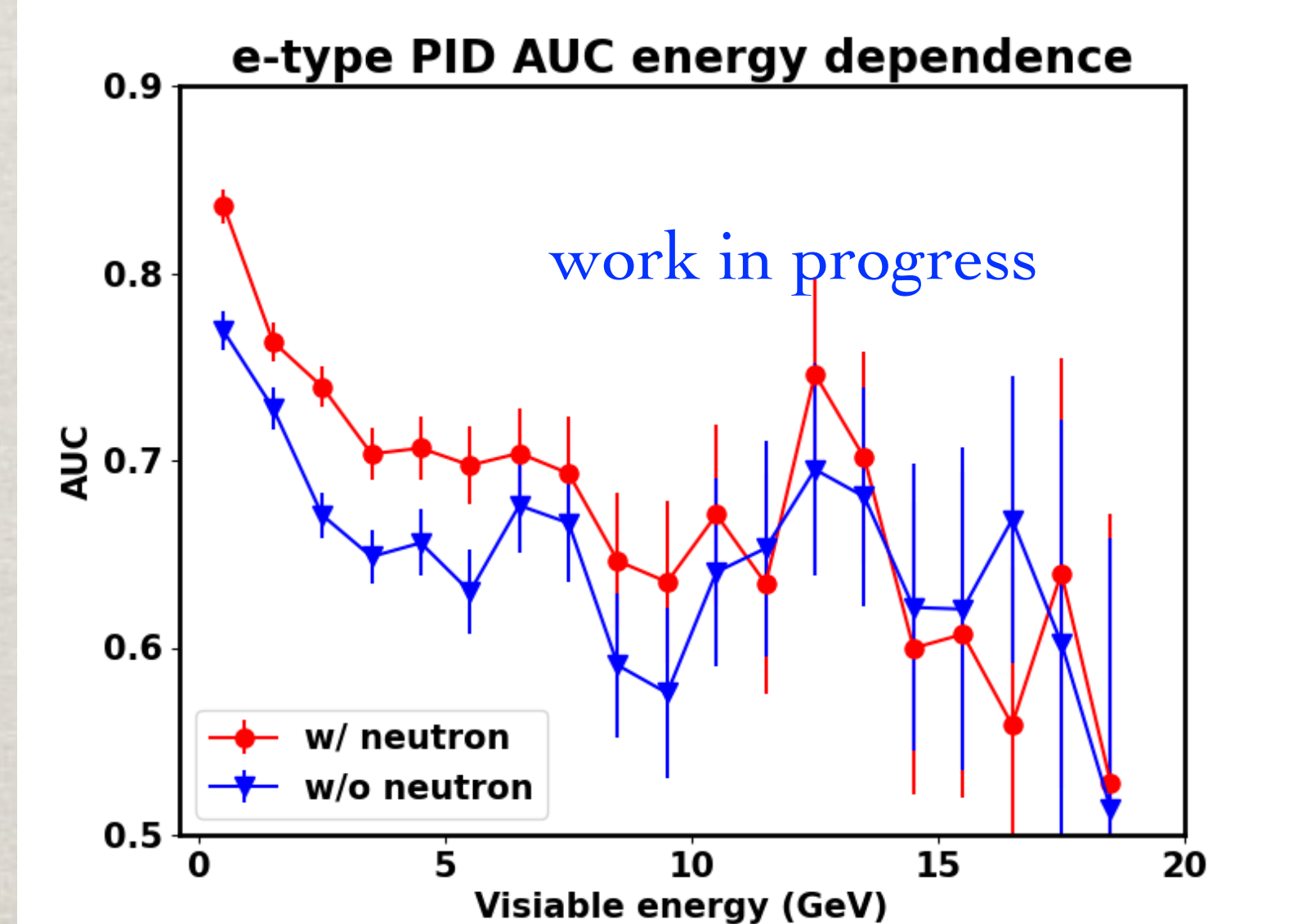
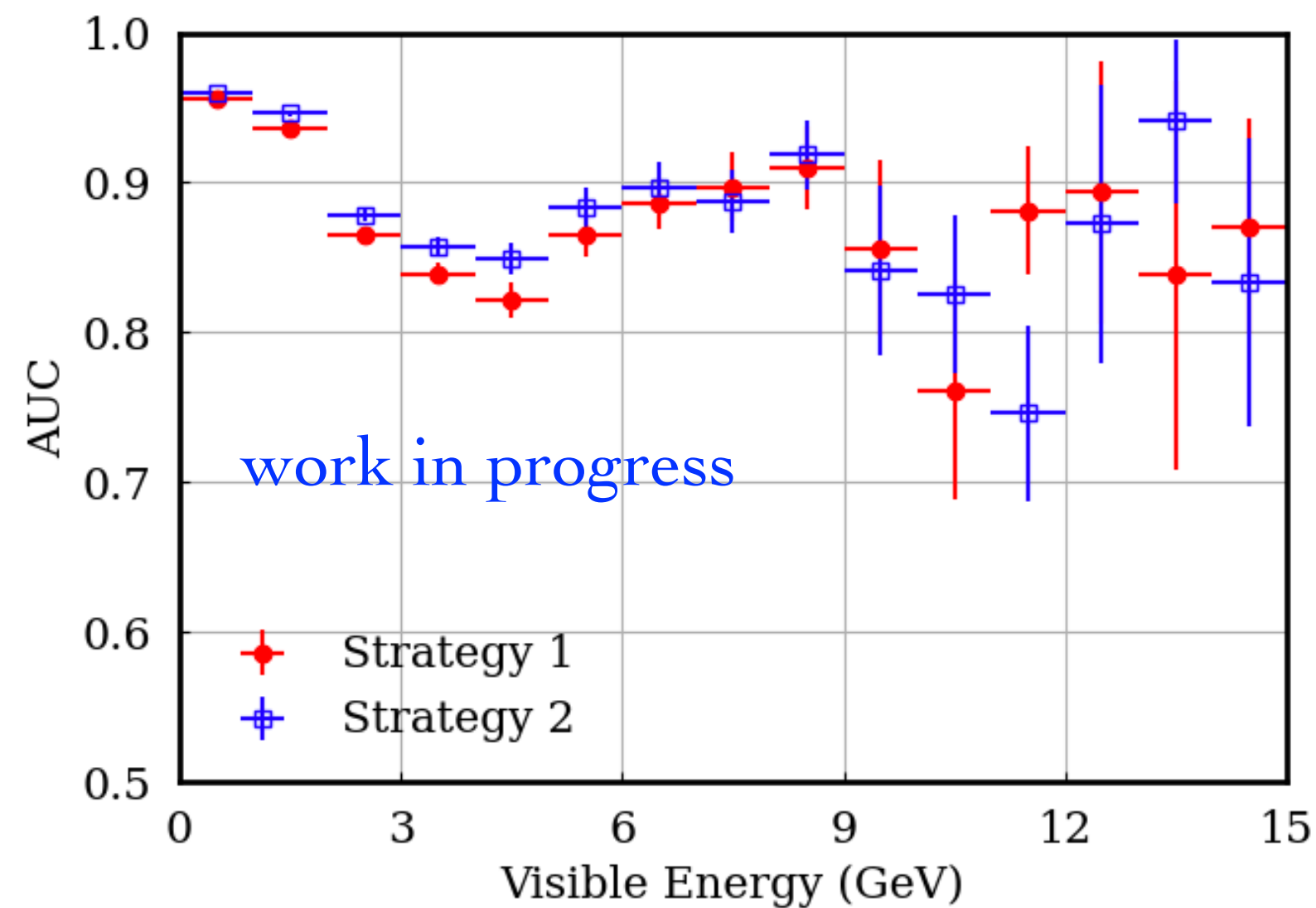
PID PRELIMINARY PERFORMANCE

- ❖ Discrimination between ν VS $\bar{\nu}$ was achieved
- ❖ Neutron information is important for ν_e VS $\bar{\nu}_e$ separation

ν_e VS $\bar{\nu}_e$

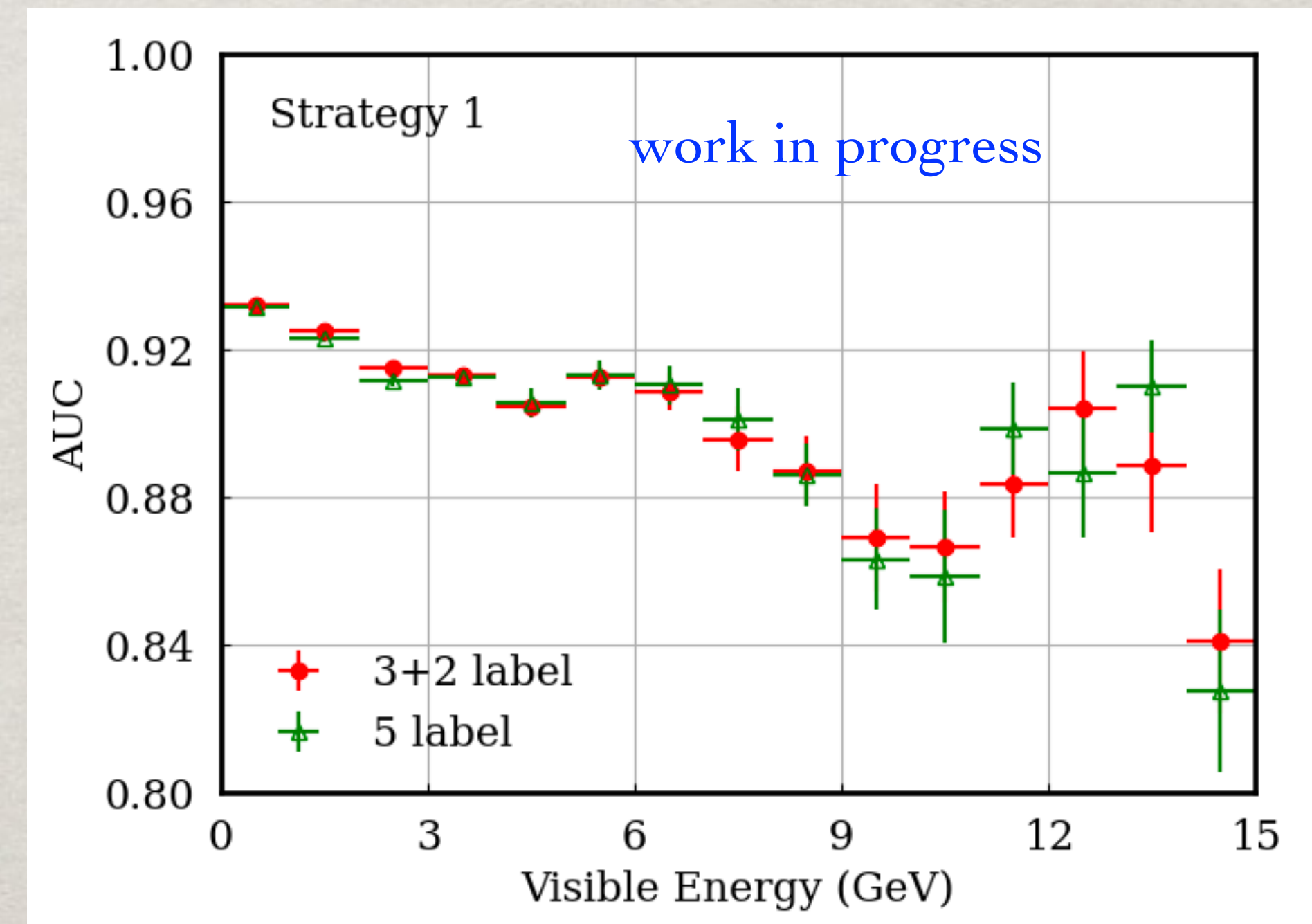
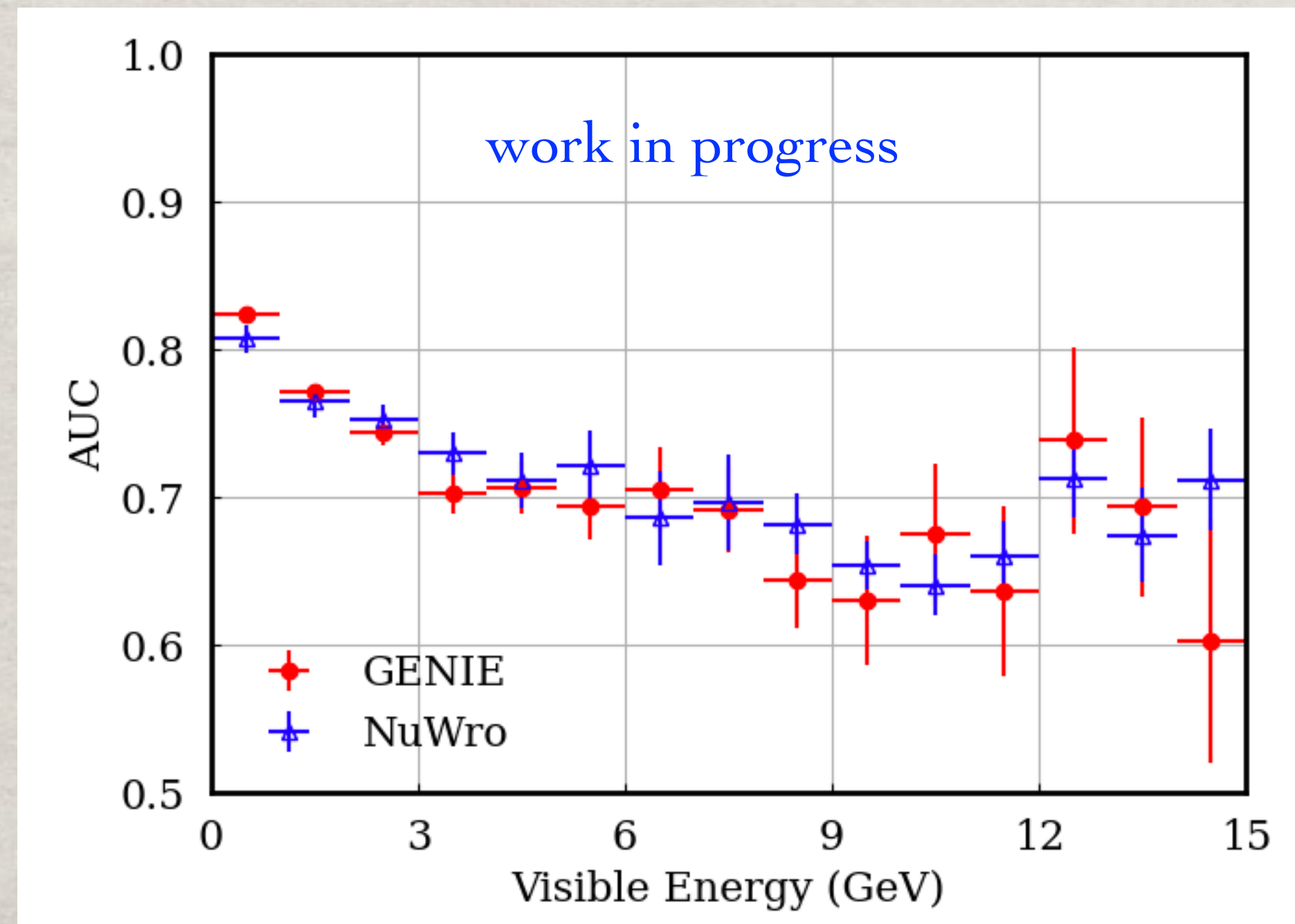


ν_μ VS $\bar{\nu}_\mu$



PID PRELIMINARY PERFORMANCE

- ❖ Consistent results between different event generators
- ❖ 5 categories classification yields consistent results as “step1+step2”



OTHER
INTERESTING
TOPICS

MORE INTERESTING TOPICS

- ❖ PMT de-noising, waveform reco
- ❖ ^{14}C pileUp identification
- ❖ Muon classification/combined reco
- ❖ Separation of Scintillation and Cherenkov photons?
- ❖ Multi-target reco (video segmentation)?
- ❖ Prompt-delay signals analyses
- ❖ And more...

SUMMARY

- ❖ With $O(10^4)$ PMTs and 20kton LS, JUNO provides lots of unique, interesting yet challenging problems for event reconstruction
- ❖ A few examples were presented
 - ❖ MeV reactor ν : vertex/energy reco
 - ❖ GeV atm. ν : directionality reco and PID
- ❖ Better performance and understanding of the detector, yielding faster, better results

THANK YOU!

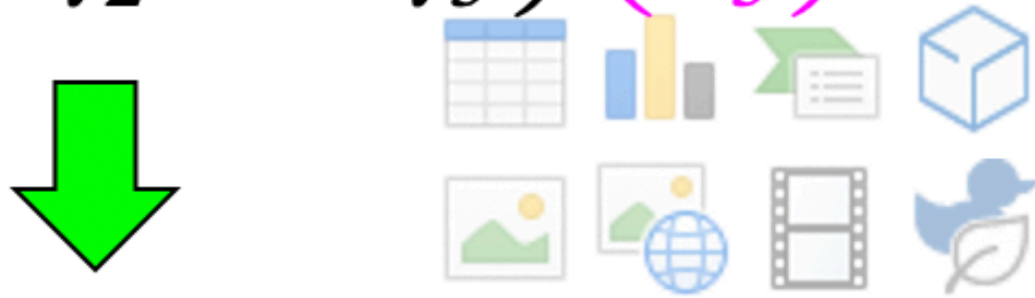
WE ARE HIRING

- ❖ Several postDoc openings at JUNO
- ❖ Commissioning, Reconstruction, Physics Analysis and more...
- ❖ Competitive salary!
- ❖ Email: luowm@ihep.ac.cn

BACK UP

三代中微子的框架内 由6个参数描述中微子振荡

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



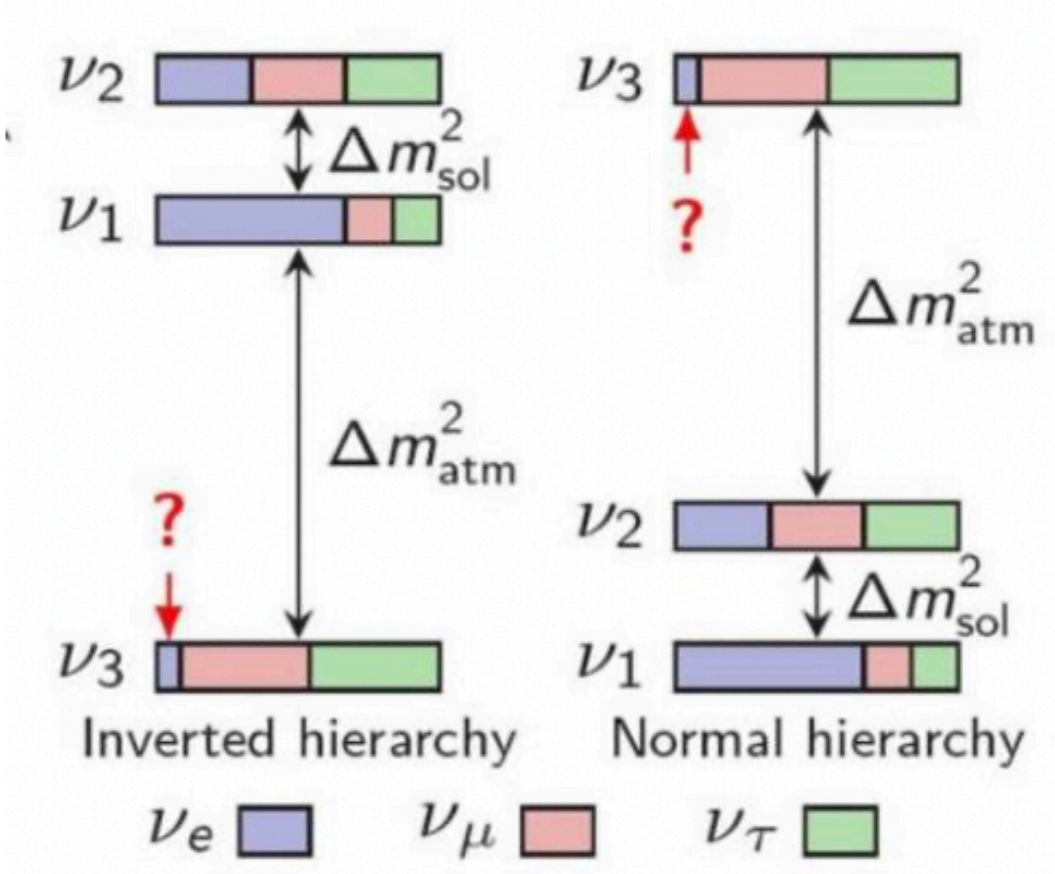
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & e^{-i\delta} & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\rho} & 0 & 0 \\ 0 & e^{i\sigma} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23} \sim 45^\circ$
大气中微子
加速器中微子

$\theta_{13} \sim 9^\circ$
反应堆中微子
加速器中微子

$\theta_{12} \sim 34^\circ$
太阳中微子
反应堆中微子

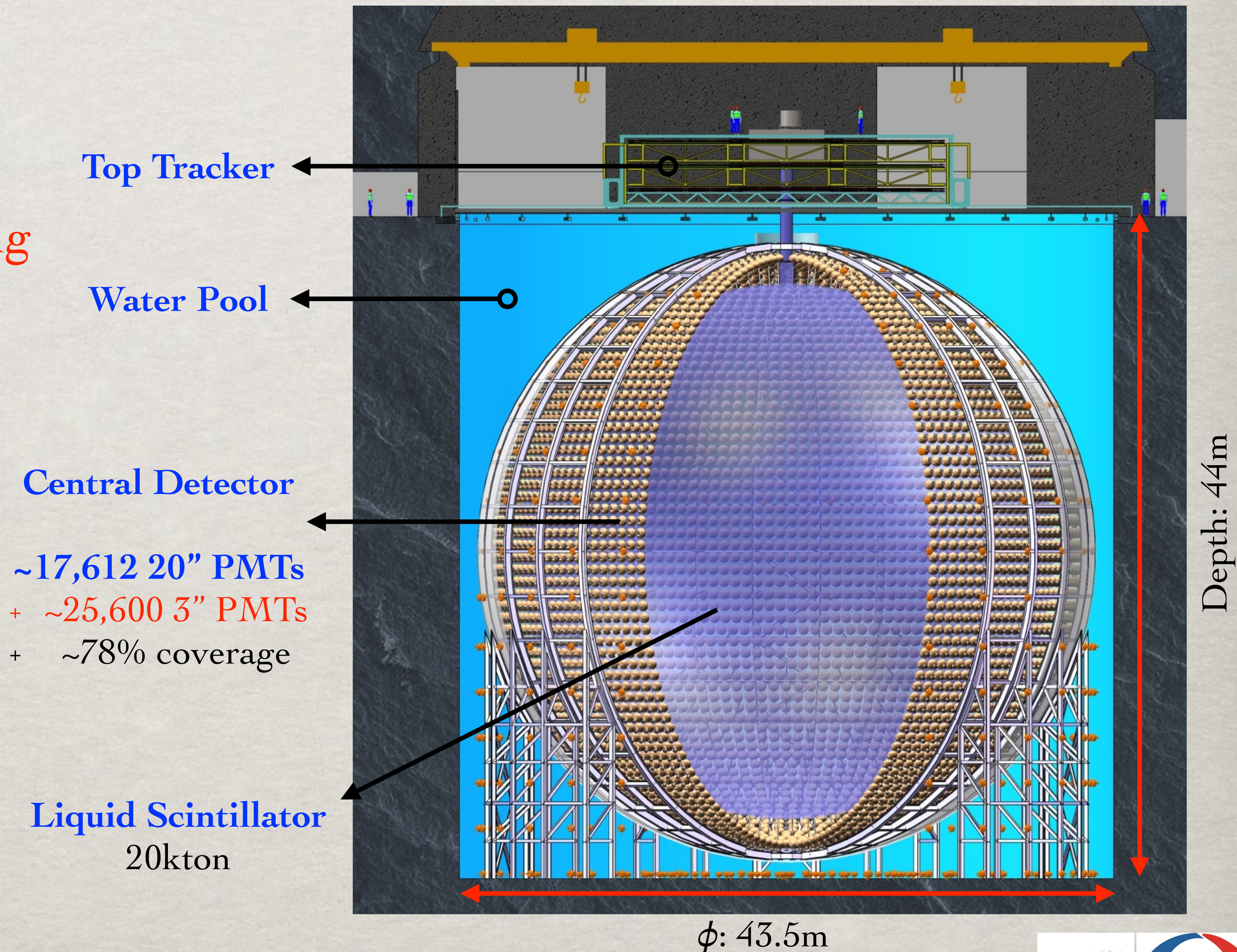
$\delta \sim -1/2\pi?$
加速器中微子



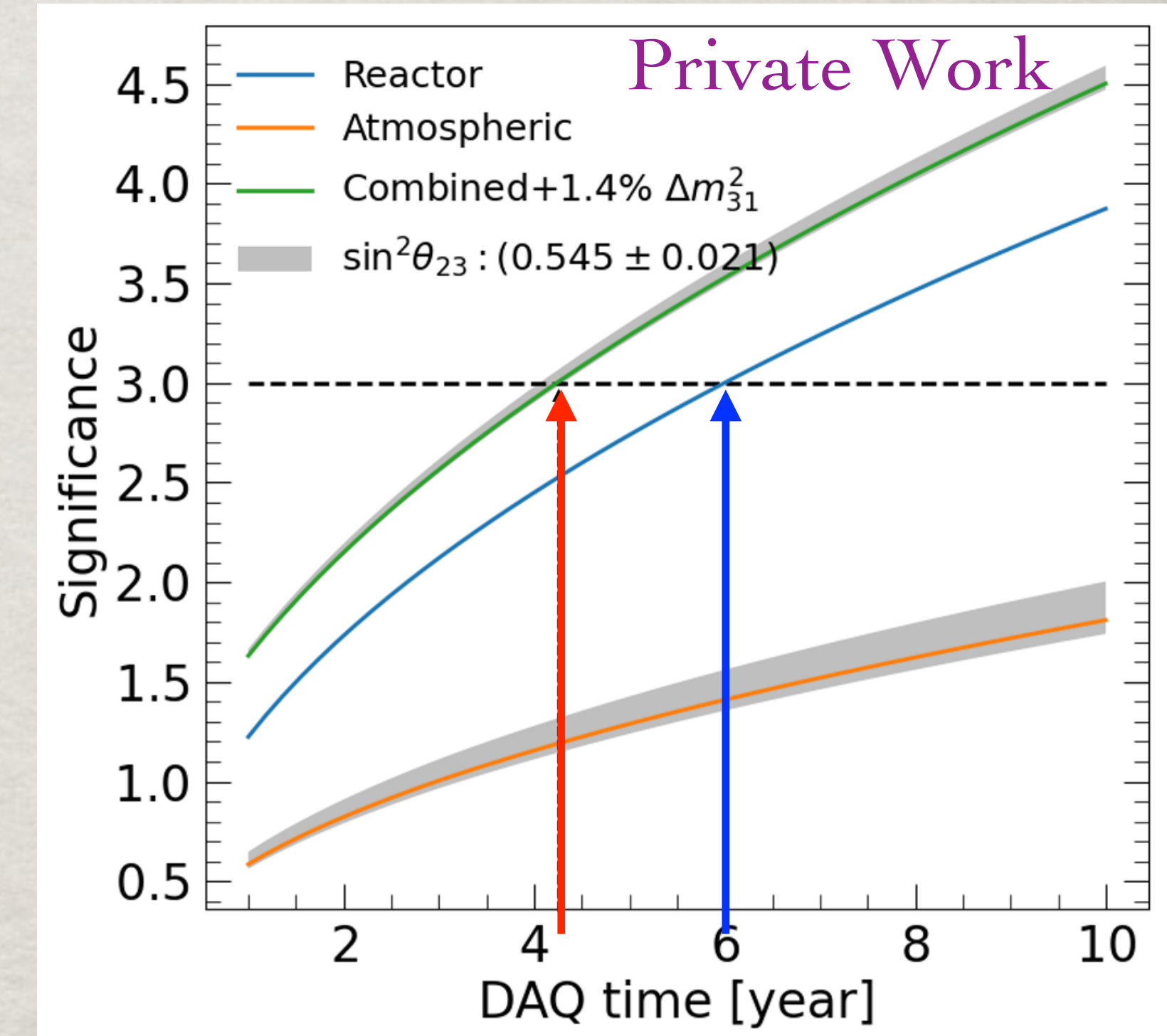
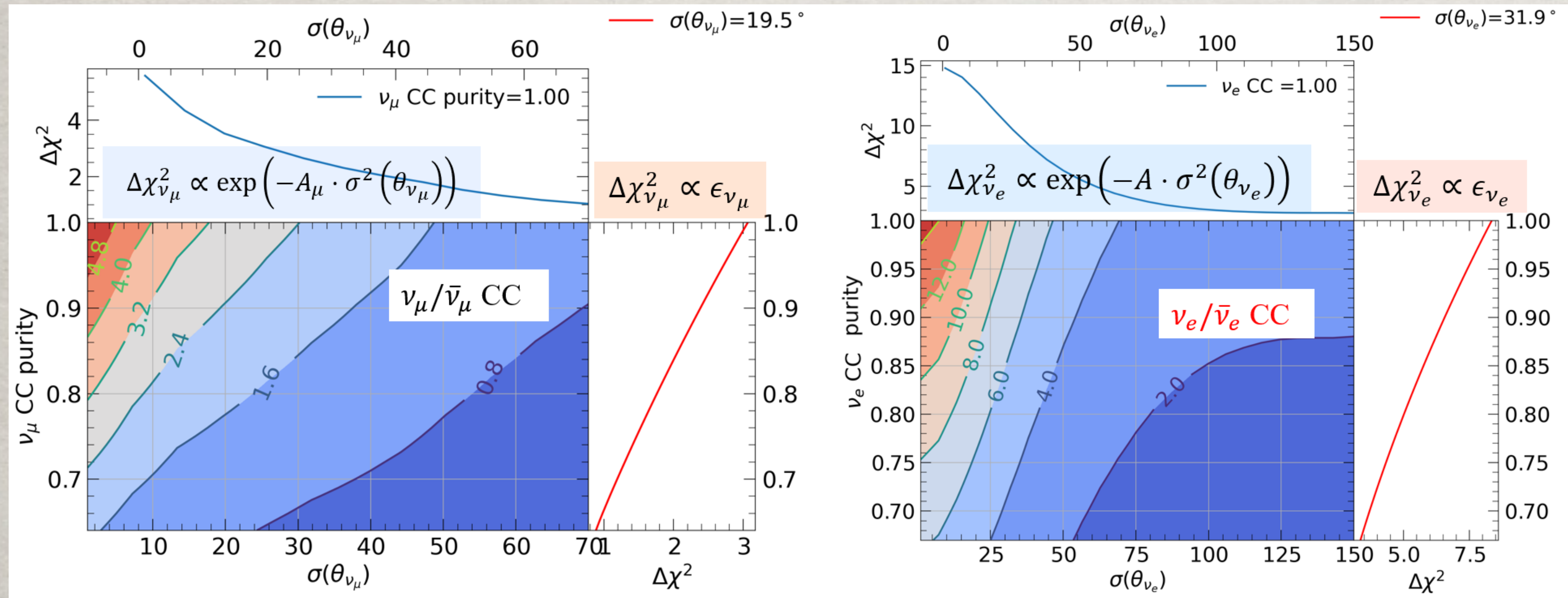
JUNO

- ❖ 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	8%@1MeV
RENO	16 t	
Daya Bay	20 t	
Borexino	300 t	5%@1MeV
JUNO	20000 t	3%@1MeV



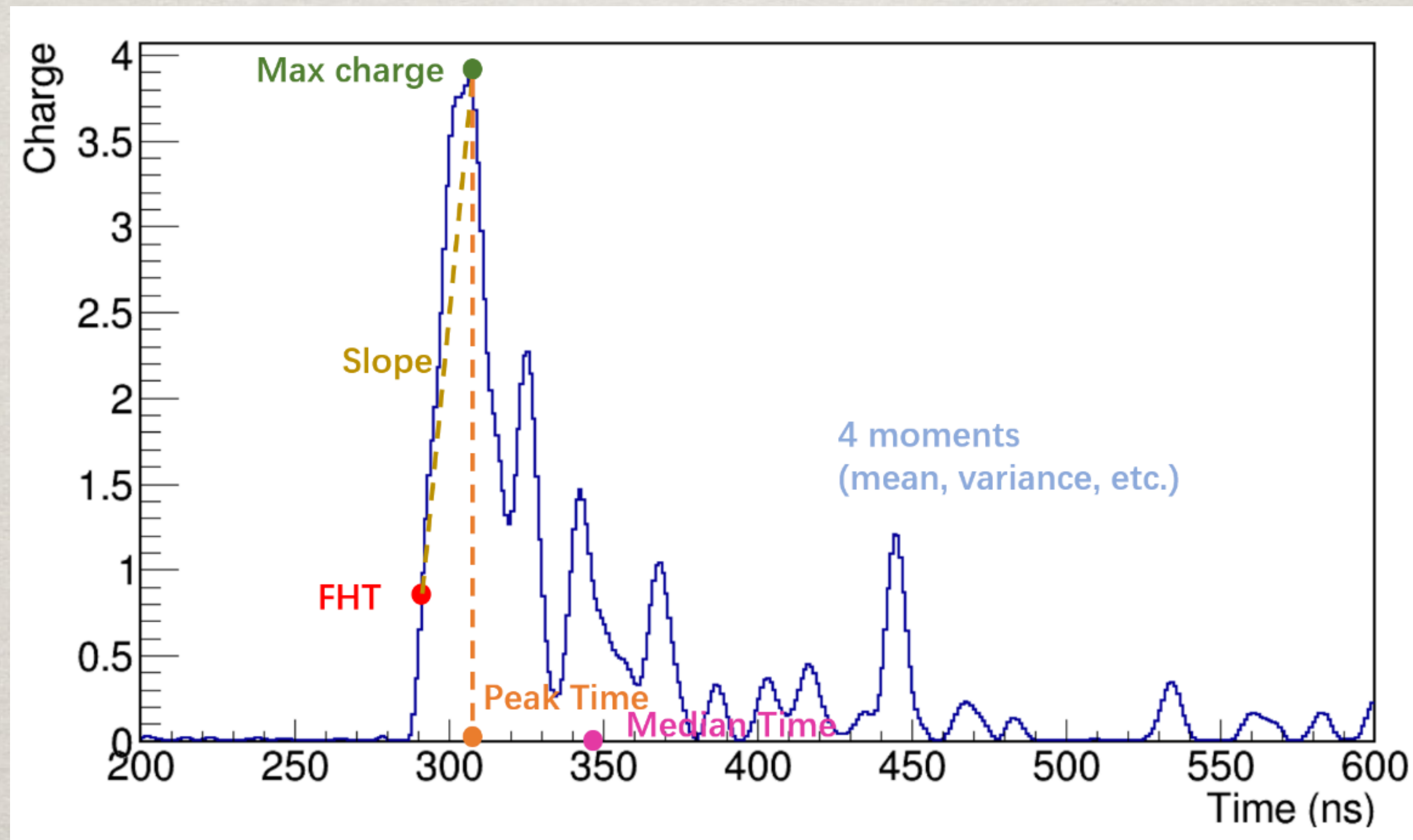
ATM. NEUTRINOS: IMPORTANCE



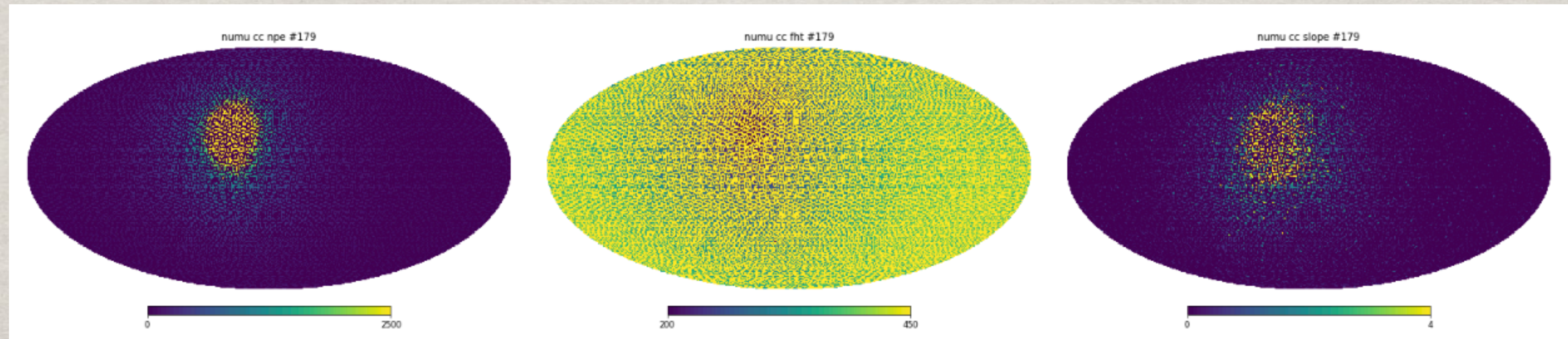
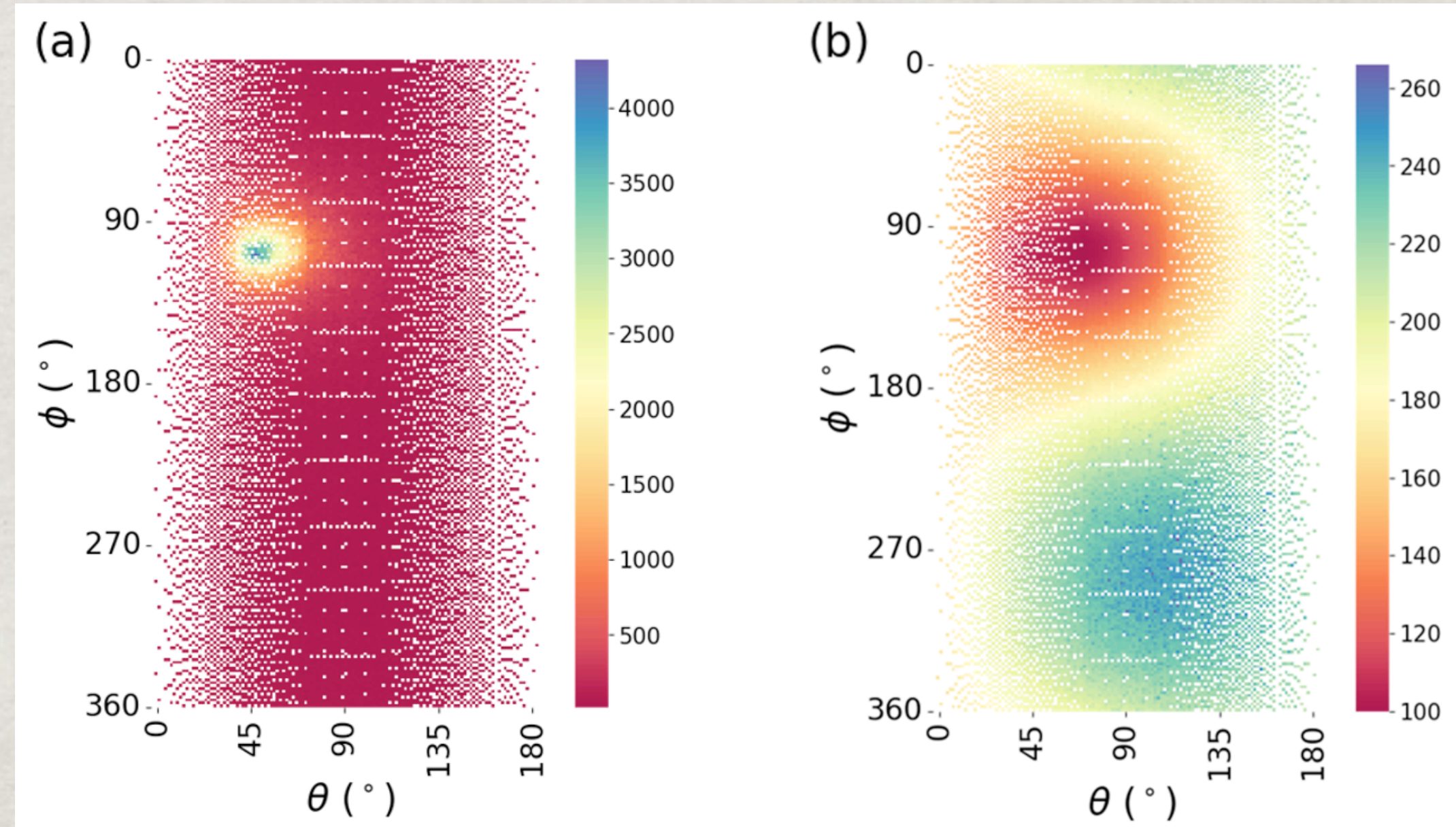
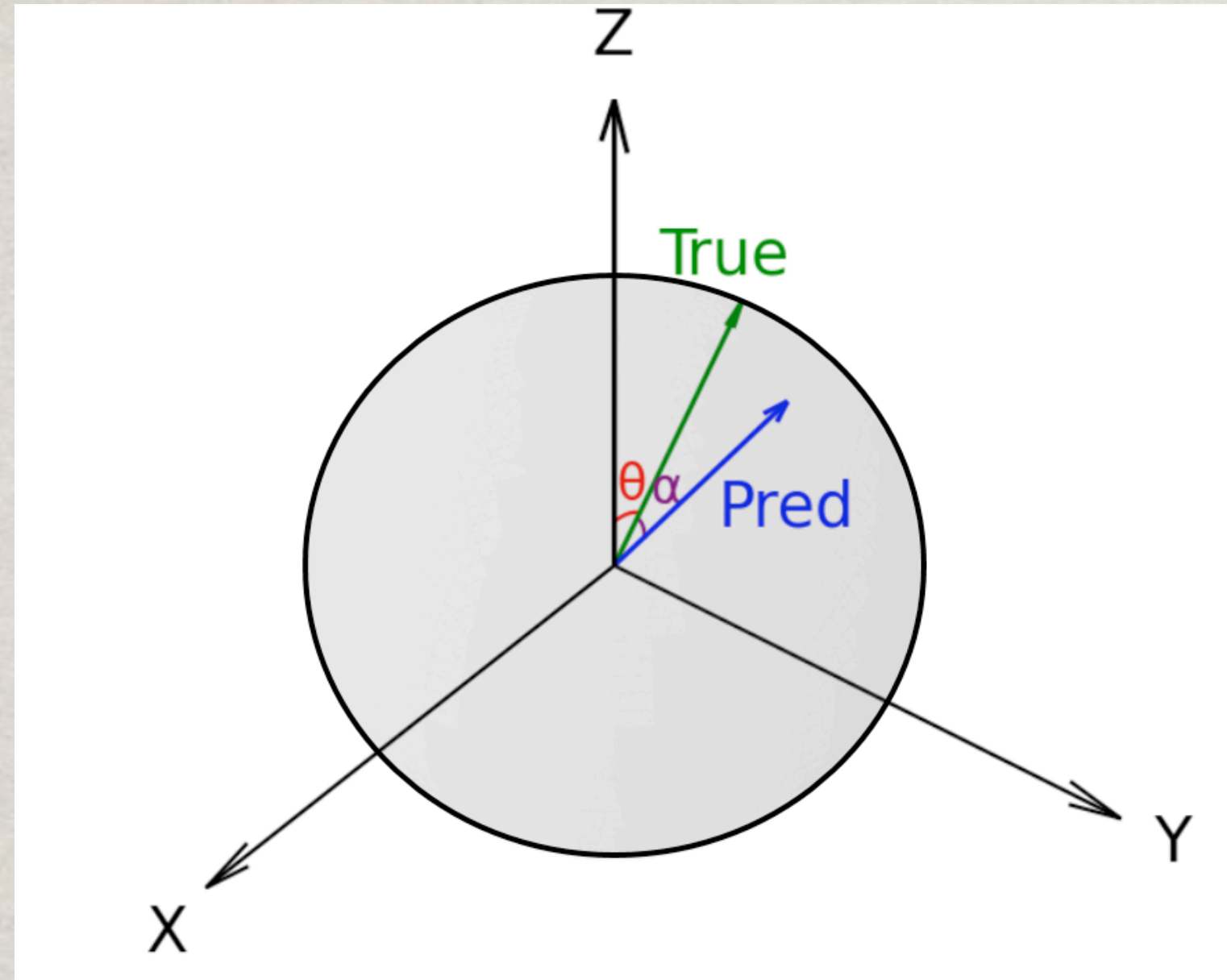
- ❖ Atm. NMO sensitivity largely depends on **angular resolution** and **flavor identification**
- ❖ **NMO 3σ : reactor alone(6y) $\rightarrow$ reactor + atm. (~ 4.2 y)**
- ❖ Major background for lots of analyses

INPUTS: PMT FEATURES

❖ Feature variables extracted from PMT waveforms



ATM. NEUTRINOS: DIRECTIONALITY

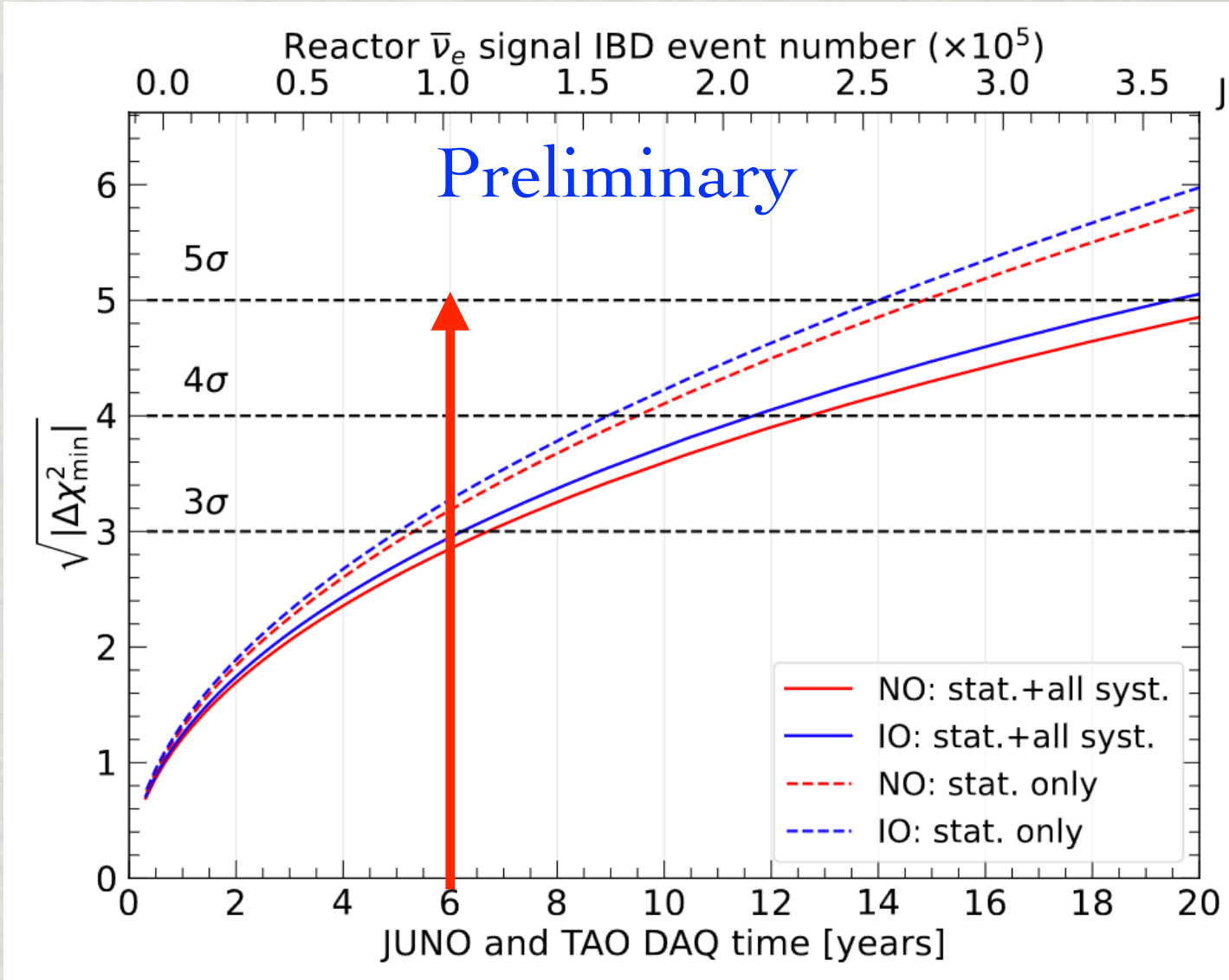
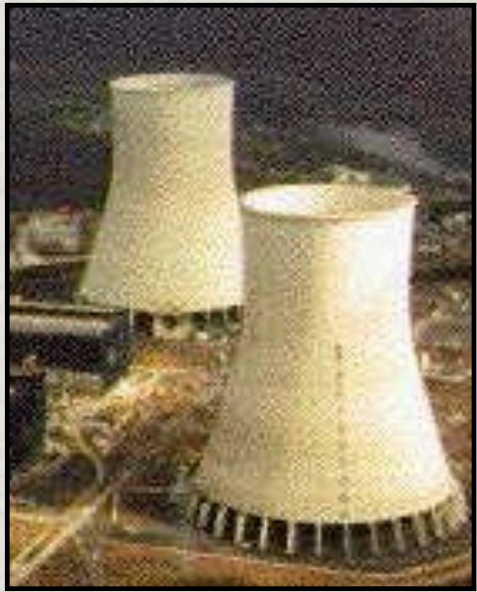


JUNO NMO SYNERGY

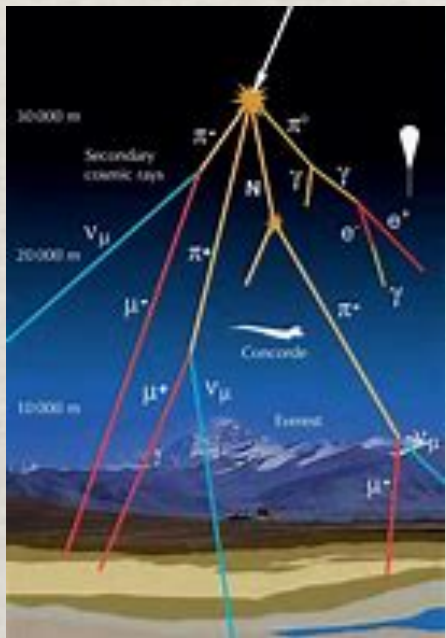
- ❖ NMO @ 6years $\Delta\chi^2$: Reactor(~ 9), **atm.(~ 1.96)**, $|\Delta m^2_{ee}|(4|1.5\%$ or $9|1\%)$
- ❖ **1.96 of atm. was estimated with assumptions**
- ❖ **Can we do better than Yellow Book?**

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

reactor ν
MeV



Neutrino
Mass
Ordering



atm. ν
GeV

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

