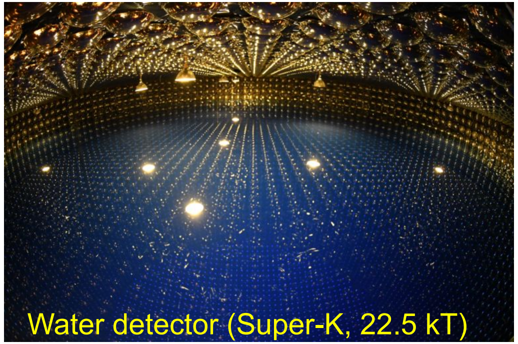
Theia LBL status

Guang Yang

Oct. 2024

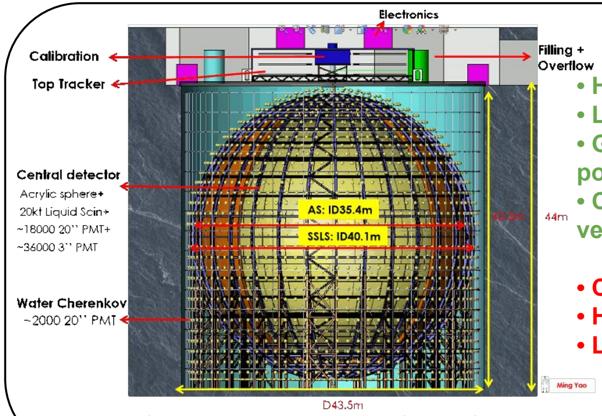
A DUNE Phase II Detector: Water-based Liquid Scintillator (WbLS)

- A different nuclear target based on a combination of two mature technologies.


Water detector (Super-K, 22.5 kT)

- Excellent Transparency
- Directionality
- Particle ID
- Cheap
- Potential for large Isotopic Loading

- No access to physics below the Cherenkov threshold
- Low light yield

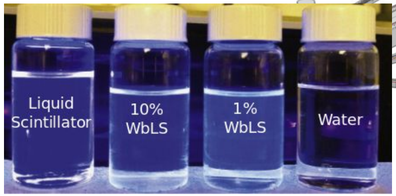


Liquid Scintillator detector (JUNO, 22.5 kT)

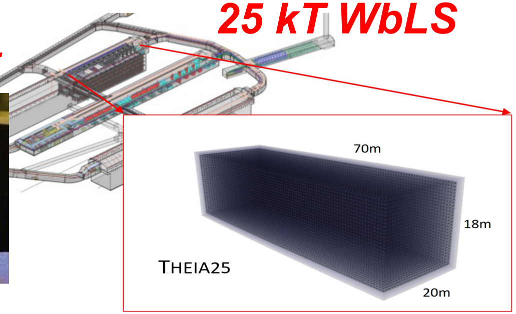
- High light yield
- Low energy threshold
- Good energy and position resolutions
- Can be radiologically very clean

- Costy
- High absorption
- Limited directionality

WbLS produced at BNL

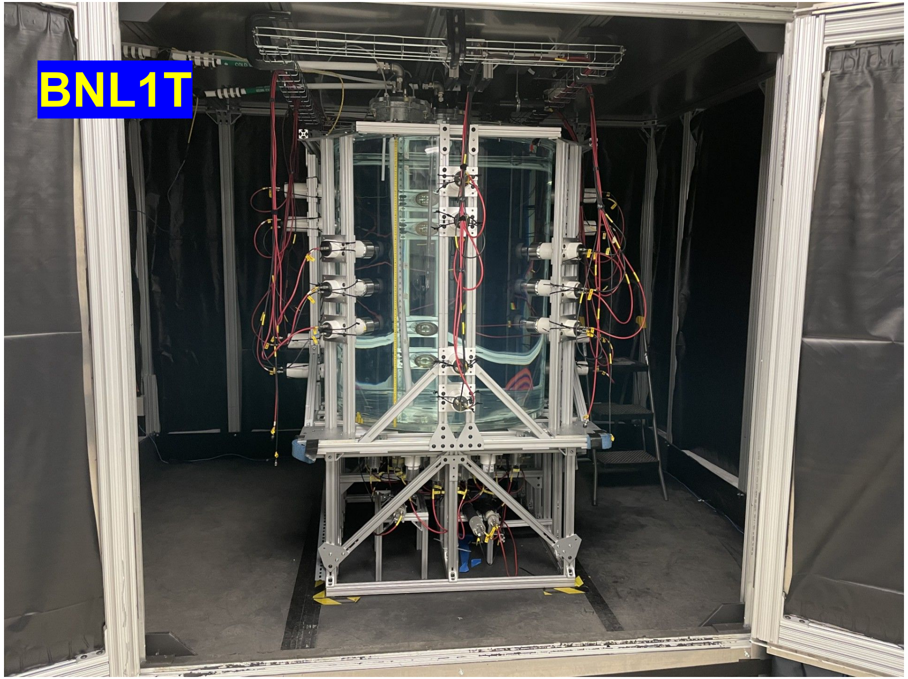


25 kT WbLS



- ***Good timing:*** ***sub-ns timing enables Cherenkov/Scintillation light separation***
- ***High LY:*** ***> 500 photons per MeV with 5% concentration enables access to the low-energy neutrinos with low background***
- ***Supernova pointing:*** ***10° angular resolution and electron antineutrino detection***
- ***Low-energy beam neutrino detection:*** ***enables the use of multiple oscillation maxima***
- ***All physics capabilities:*** ***arXiv. 1911.03501***

Many detectors demonstrating the technology



PAPER

Design, construction, and operation of a 1-ton Water-based Liquid scintillator detector at Brookhaven National Laboratory

X. Xiang[1,2], G. Yang[1,3,4], S. Andrade[1], M. Askins[3,4], D.M. Asner[1], A. Baldoni[5], D.F. Cowen[5], M.V. Diwan[1], S. Gokhale[1], S. Hans[1,6], J. Jerome[1], G. Lawley[7], S. Linden[1], G.D. Orebi Gann[3,4], C. Reyes[1], R. Rosero[1], N. Seberg[1], M. Smiley[3,4], N. Speece-Moyer[1], B. Walsh[1], J.J. Wang[8], M. Wilking[9] and M. Yeh[1]

▴ Hide full author list

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Journal of Instrumentation, Volume 19, June 2024

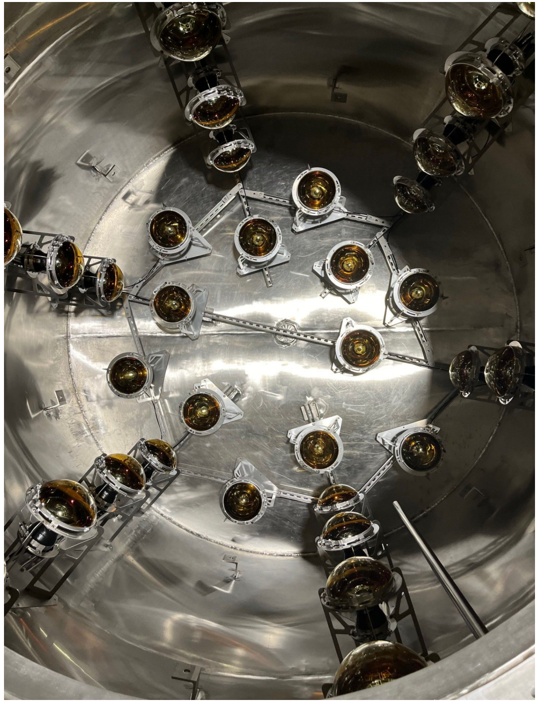
Citation X. Xiang *et al* 2024 *JINST* **19** P06033

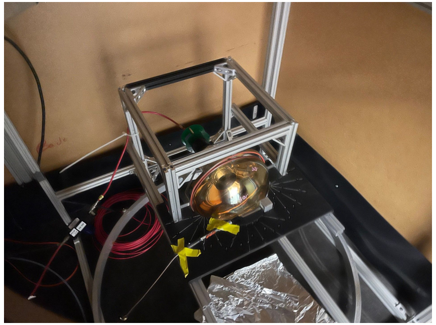
DOI 10.1088/1748-0221/19/06/P06033

We have constructed and operated a 1-ton scale Water-based Liquid Scintillator detector tank. The details of the instrumentation and the initial data are described above in detail. The detector was operated with a new cocktail of WbLS based on mixing organic scintillator based on DIN (di-isopropylnaphthalene), and it is compatible with loading such a detector with metals such as Gadolinium. The initial results indicate stability better than a few percent per month. With a mixture of 1% organic scintillator in water, the total light yield (Cherenkov and non-Cherenkov) is significantly enhanced. The non-Cherenkov light yield is measured to be 127.6 ± 19.8 (syst.) ± 17.6 (stat.) photons per MeV for muons. The primary source of known systematic uncertainties is due to our understanding

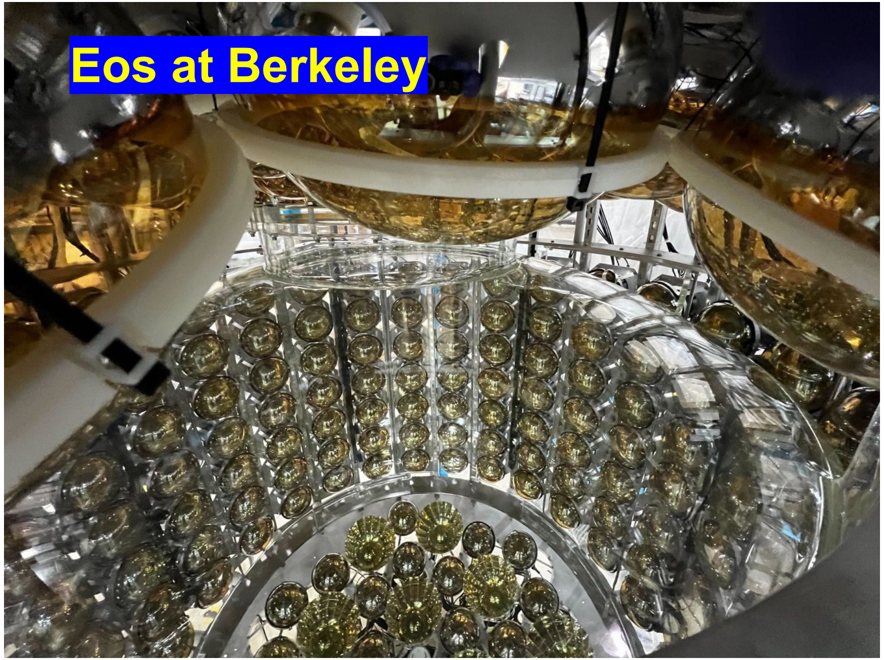
Brookhaven National Laboratory

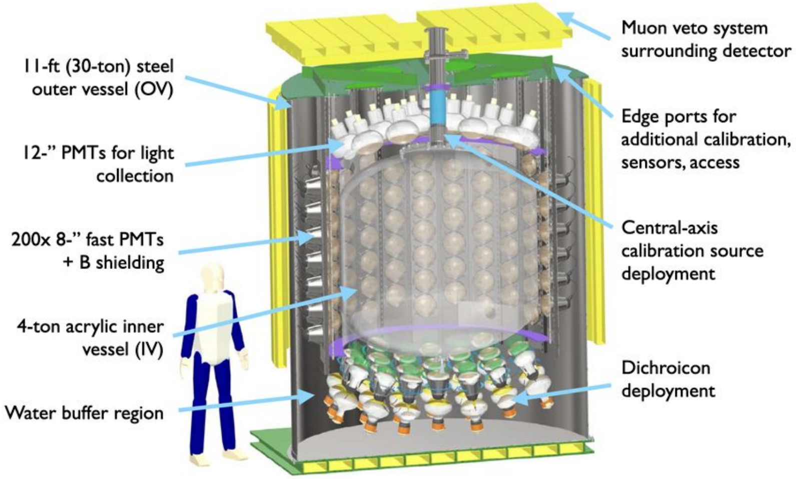
Many detectors demonstrating the technology





Many detectors demonstrating the technology





Eos: conceptual design for a demonstrator of hybrid optical detector technology

T. Anderson[1], E. Anderssen[2], M. Askins[2,3], A.J. Bacon[4], Z. Bagdasarian[2,3], A. Baldoni[1], N. Barros[5,6], L. Bartoszek[7], M. Bergevin[8], A. Bernstein[8] Show full author list

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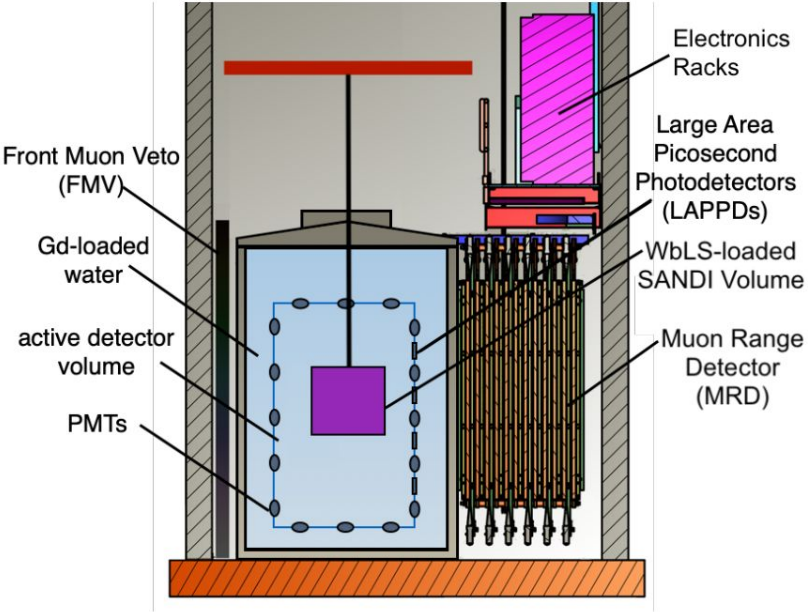
Journal of Instrumentation, Volume 18, February 2023

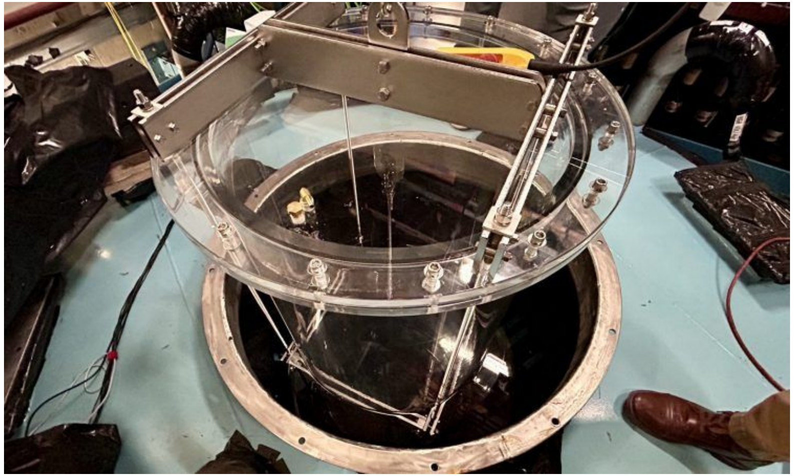
Citation T. Anderson *et al* 2023 *JINST* **18** P02009

DOI 10.1088/1748-0221/18/02/P02009

Many detectors demonstrating the technology

ANNIE at Fermilab





PAPER

Deployment of Water-based Liquid Scintillator in the Accelerator Neutrino Neutron Interaction Experiment

M. Ascencio-Sosa[1], Z. Bagdasarian[2,3], J.F. Beacom[4], M. Bergevin[5], M. Breisch[6], G. Caceres Vera[7], S. Dazeley[5], S. Doran[1], E. Drakopoulou[8], S. Edayath[1] Show full author list

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Journal of Instrumentation, Volume 19, May 2024

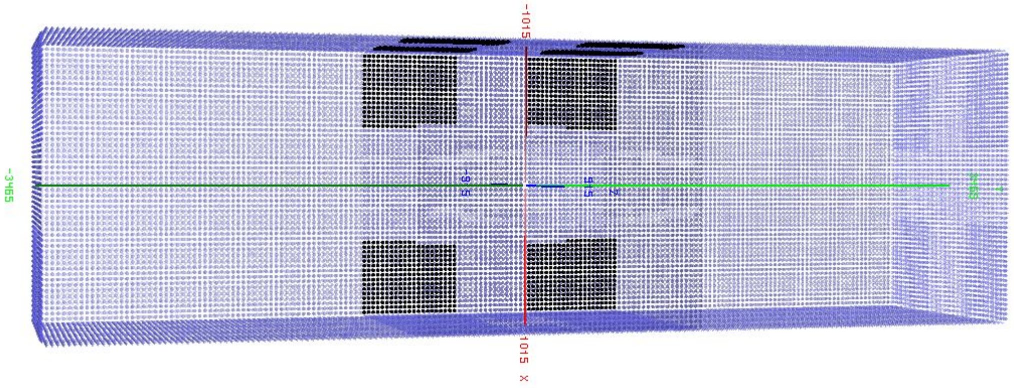
Citation M. Ascencio-Sosa *et al* 2024 *JINST* **19** P05070

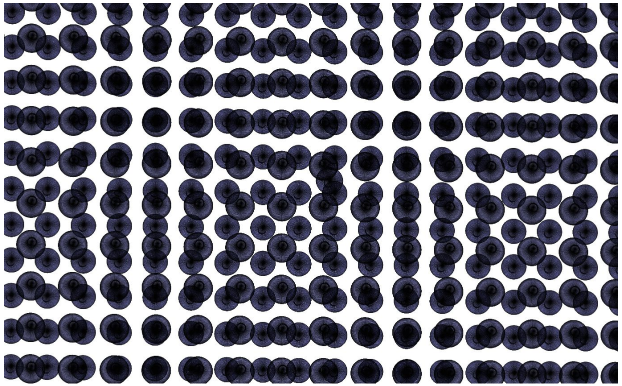
DOI 10.1088/1748-0221/19/05/P05070

Theia - 25 kt detector

40% photo-coverage with > 40,000 PMTs

5% Water-based Liquid Scintillator





Fast energy reconstruction - Methodology

Muon can be measured with Cherenkov ring.

- **Energy excluding muon ~ Total scintillation light - muon energy equivalent scintillation light**

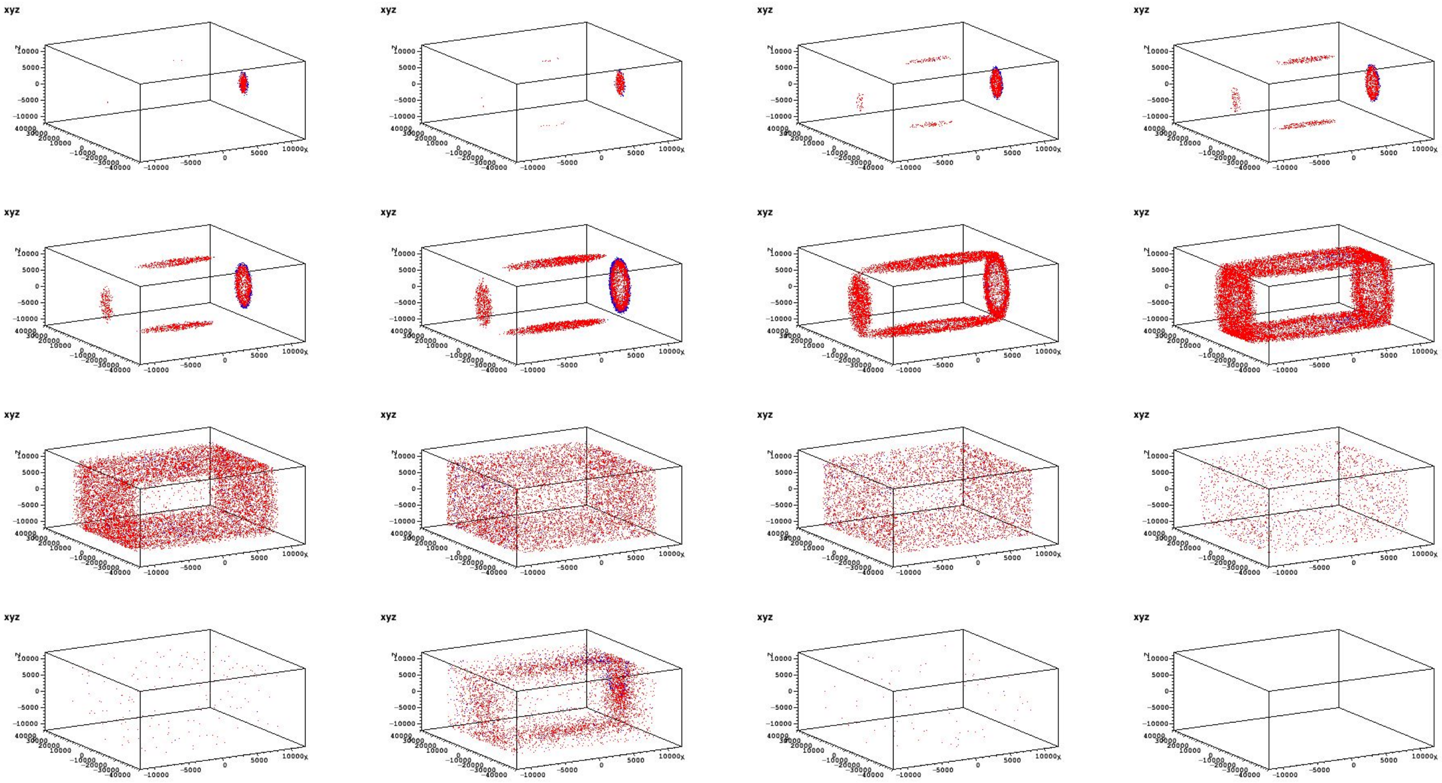
In addition, pions may be measured with Cherenkov ring if above Ch. threshold.

- **Energy excluding muon and pions ~ Total scintillation - muon energy scintillation - pion energy scintillation**

All remaining energy may be measured calorimetrically.

Neutrino and antineutrino interaction with DUNE spectra with 5% WbLS target

600 MeV muon with 2ns scintillator decay time



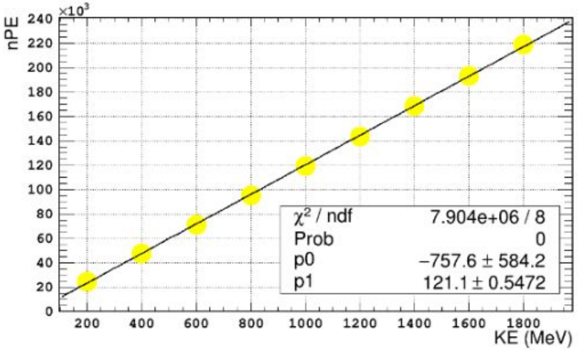
Lepton response and smearing

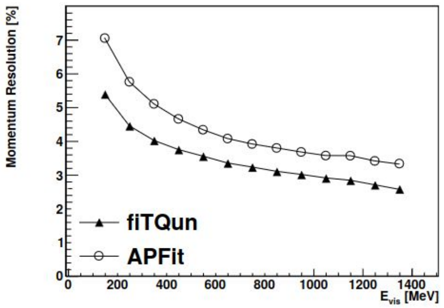
PTEP 2019 (2019) 5, 053F01

FiTQun performance ==>

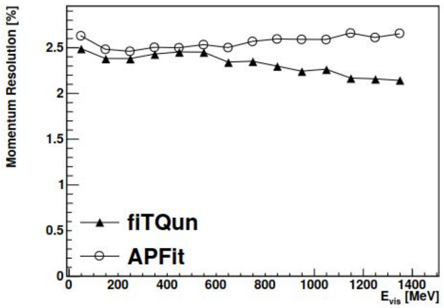
Using these momentum resolutions as functions of energy for muon.

Muon scintillation light vs. KE WbLS



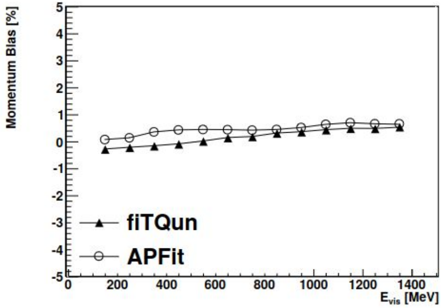


(a) Momentum resolution of true single-electron events.

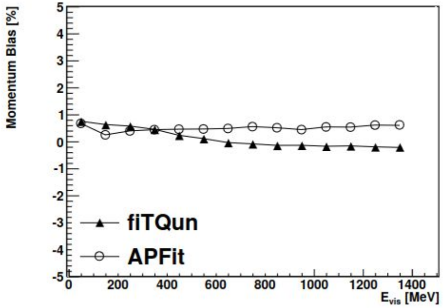


(b) Momentum resolution of true single-muon events.

Super-K performance



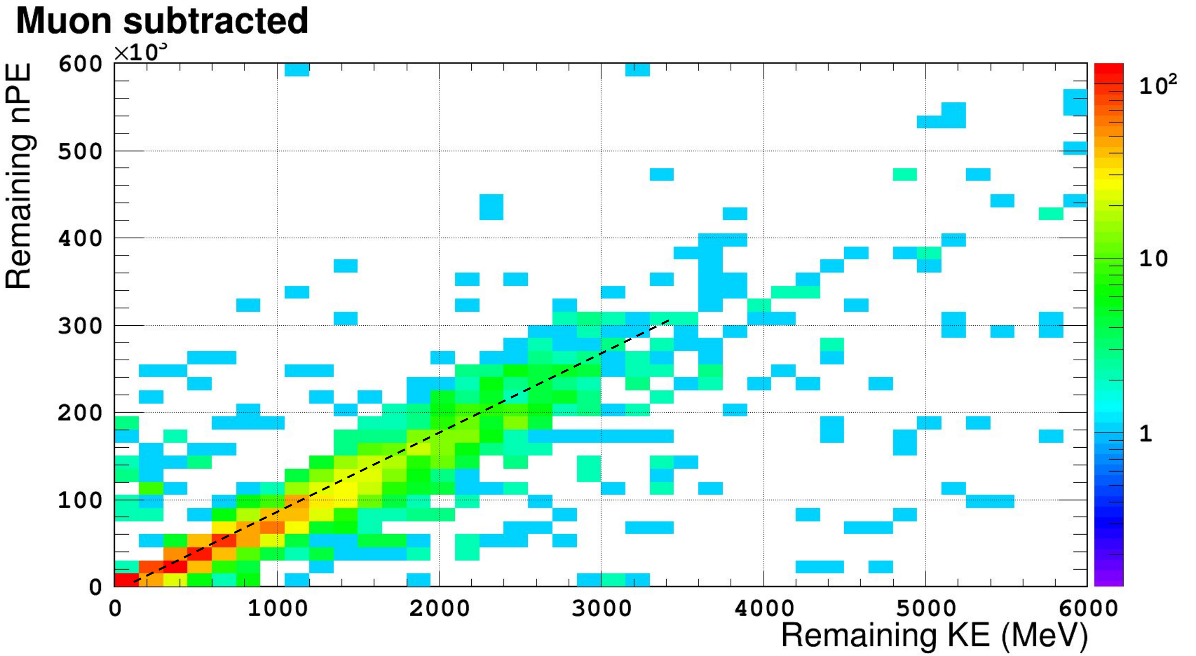
(c) Momentum bias of true single-electron events.



(d) Momentum bias of true single-muon events

Reconstructing energy with PE vs. KE relation

Muon KE subtracted energy vs. Muon PE subtracted nPE



Scintillation light => all particles KE except muons including those below Cherenkov threshold

Energy resolution summary table

Energy resolution			
Decay time	μ-only using Cherenkov	μ and π using Cherenkov	μ, π and p using Cherenkov
2 ns	12.7%	9.209%	9.112%
15 ns	12.4%	8.989%	9.10%
45 ns	11.51%	7.844%	8.301%

These are the peak resolution, feed-down effect exists.

Fitting framework

Used as a NOvA major oscillation analysis framework

Used as DUNE TDR framework

Frequentist-based log-likelihood fit with MINUIT

Mach3 is being worked out for our OA as well.

DUNE TDR

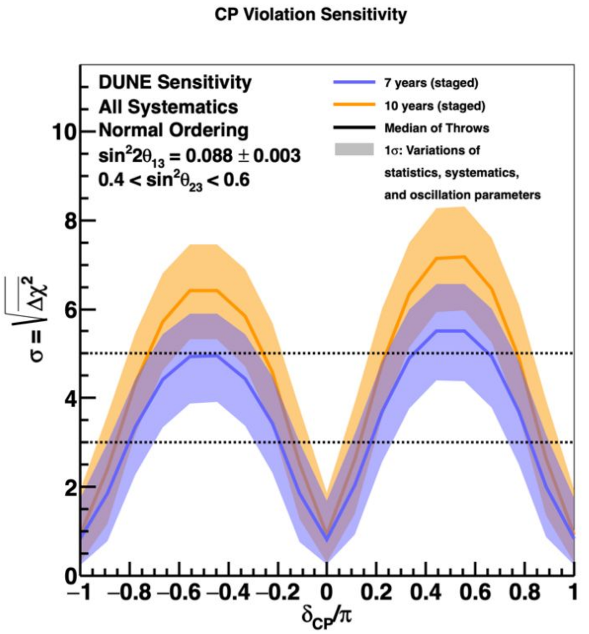
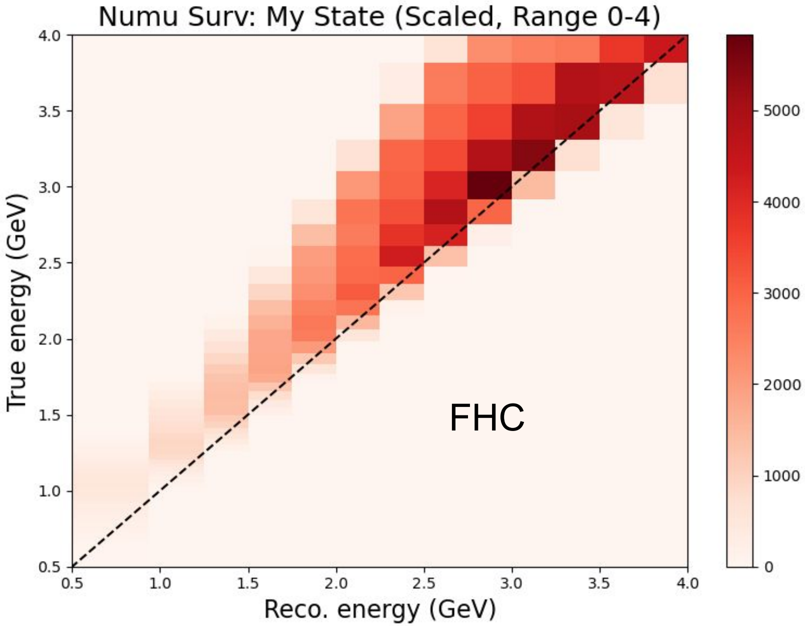
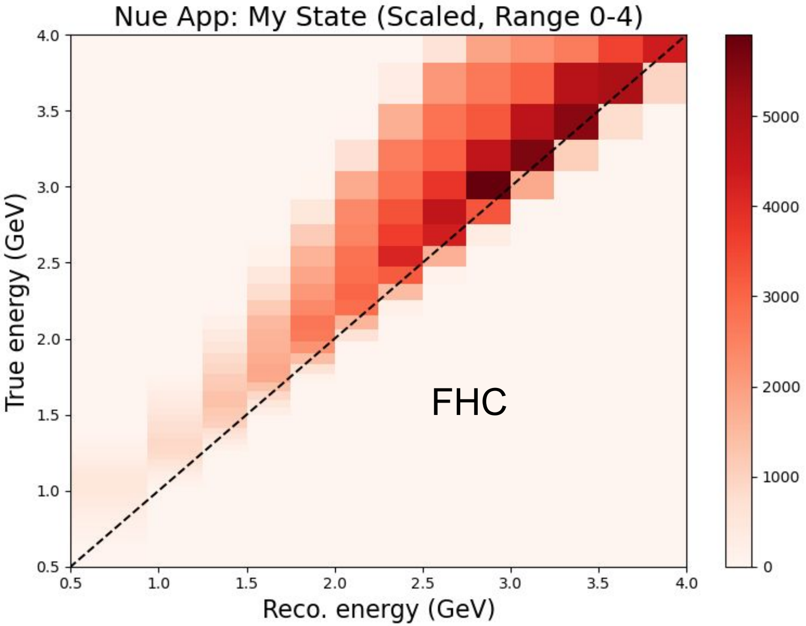


Figure 5.17: Significance of the DUNE determination of CP-violation (i.e.: $\delta_{CP} \neq 0$ or π) as a function of the true value of δ_{CP}, for seven (blue) and ten (orange) years of exposure. True normal ordering is assumed. The width of the transparent bands cover 68% of fits in which random throws are used to simulate statistical variations and select true values of the oscillation and systematic uncertainty parameters, constrained by pre-fit uncertainties. The solid lines show the median sensitivity.

Energy response - WbLS





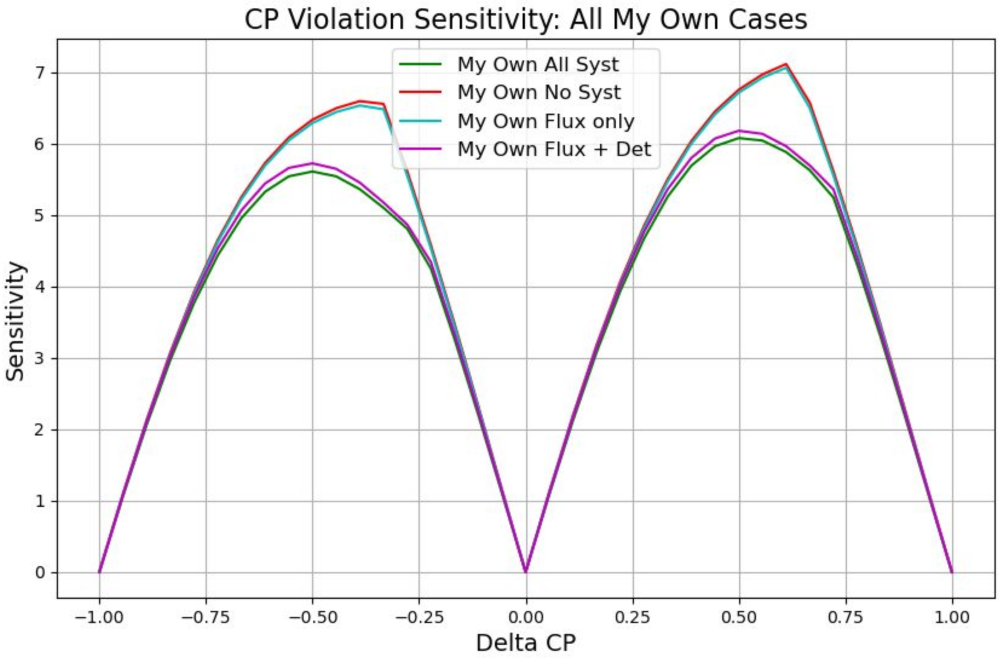
Sensitivity figures

Caveats:

- WbLS same FV event rate as LAr
- All the systematic uncertainties are the same as LAr in TDR, such as flux, cross section and detector.
- The background is the same as LAr in TDR, such as intrinsic, wrong-sign and NC.
- The PID performance is the same as LAr in TDR.
- ND+FD fit, where ND samples are the same as LAr in TDR.
- POT is 624 kw-mw-yr, approximately 10 years of staged runtime.
- Theta13 constrained by NuFIT, theta23 unconstrained.
- Normal ordering only.

Sensitivity figure

WbLS energy response + LAr final state



Water vs. Ar in GENIE - will be used for weighting events

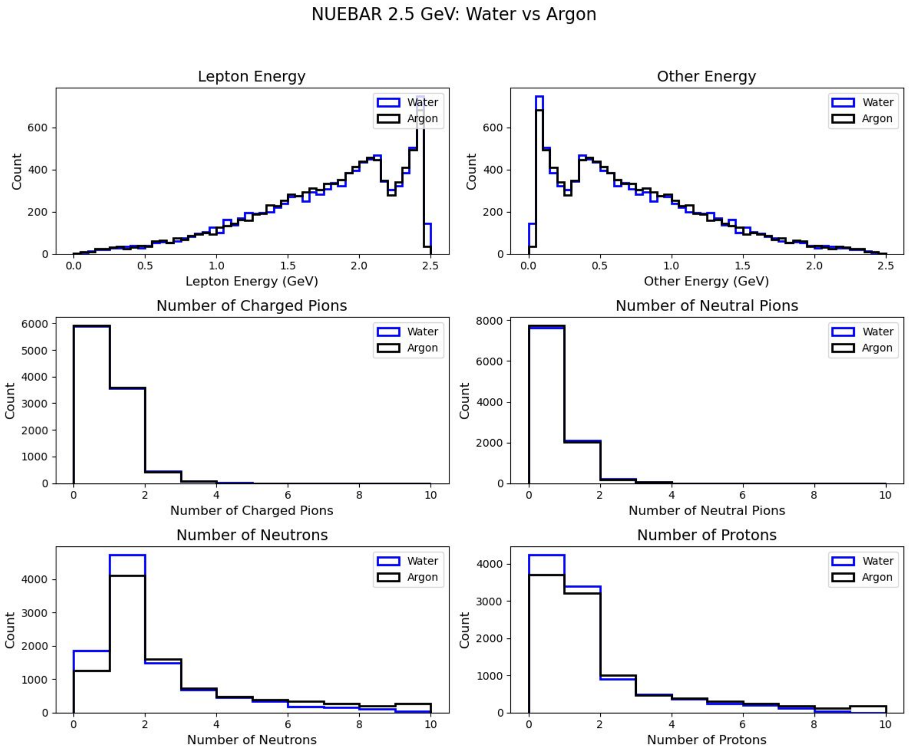
Targets are water and Ar with GENIE:

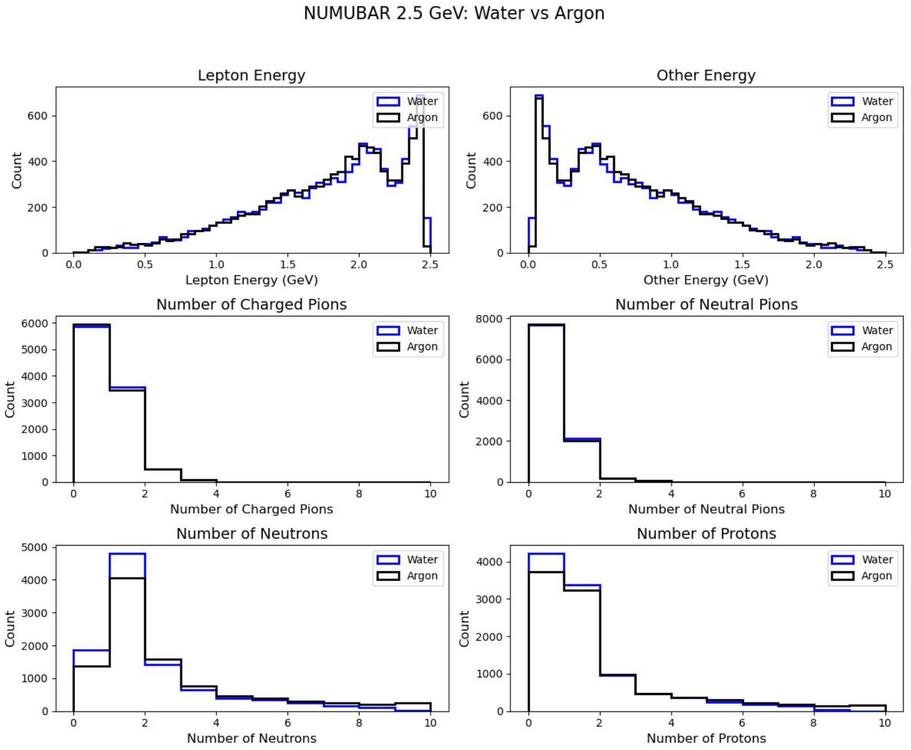
- v2_12_10c
- Cross section setting DefaultPlusValenciaMEC

Reasoning

- ***Water has simpler nuclear system and should have less hadronic particles, especially neutrons than LAr thus the energy smearing should be less bad.***
- ***Direct comparison between LAr final state and water final state with the same lepton and hadron smearing should directly tell the impact of simpler nuclear system.***

Water vs. Ar in GENIE - will be used for weighting events



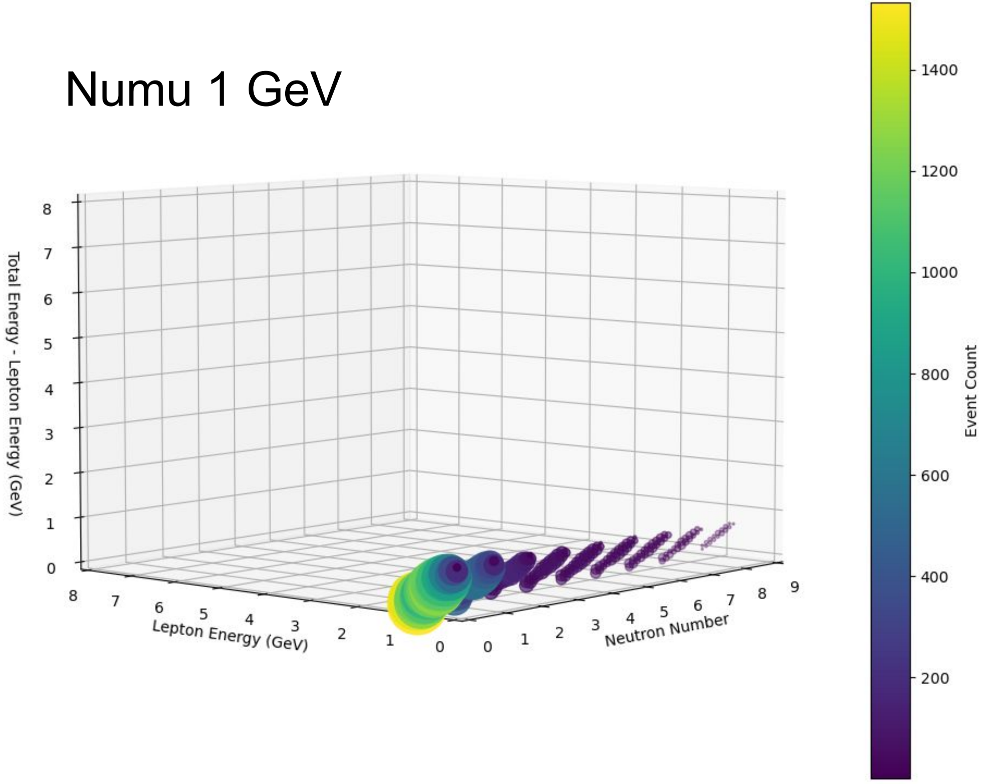


Event reweighting

Events can be reweighted to account for the difference in the LAr and water final state particles.

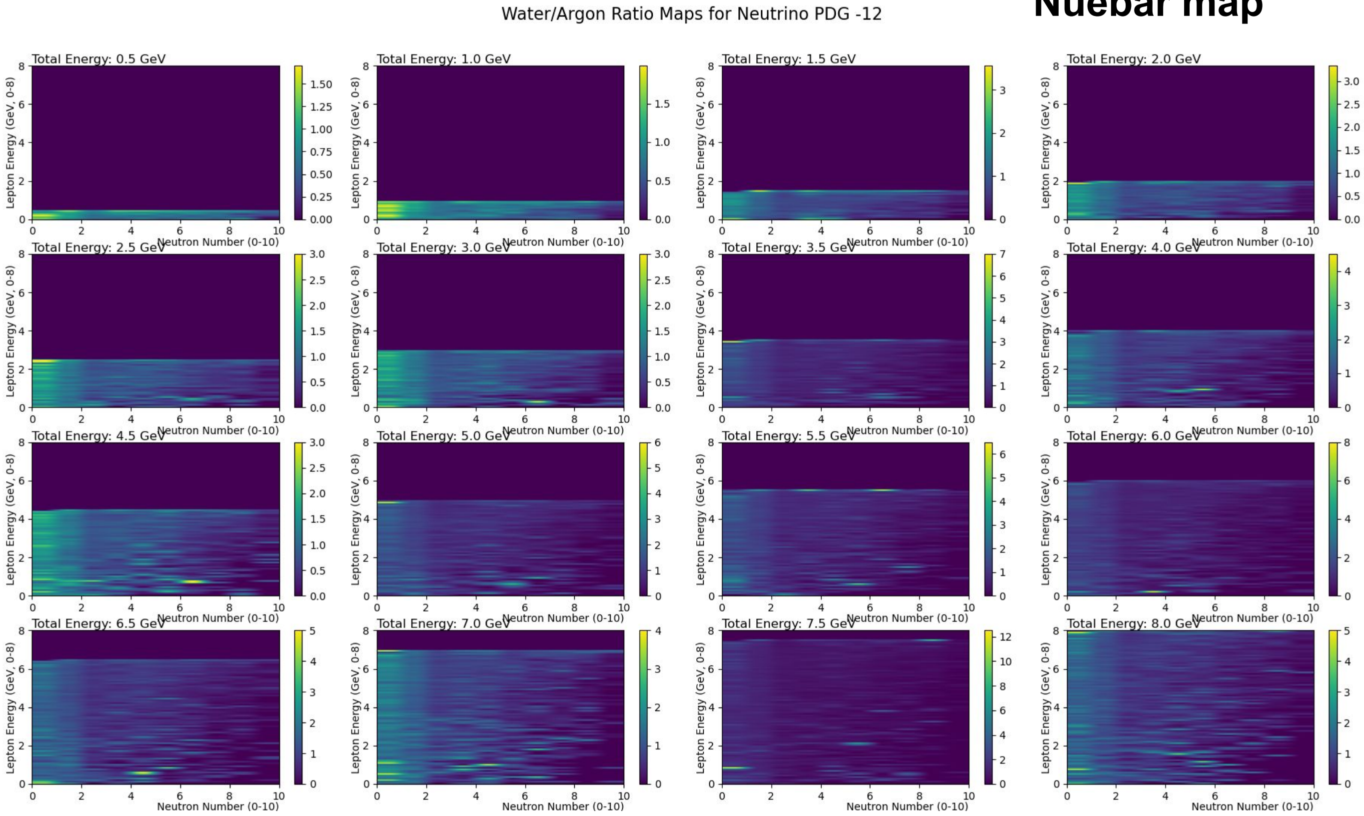
3D reweighting: for each flavor, neutrino energy, lepton energy and neutron number.

Numu 1 GeV

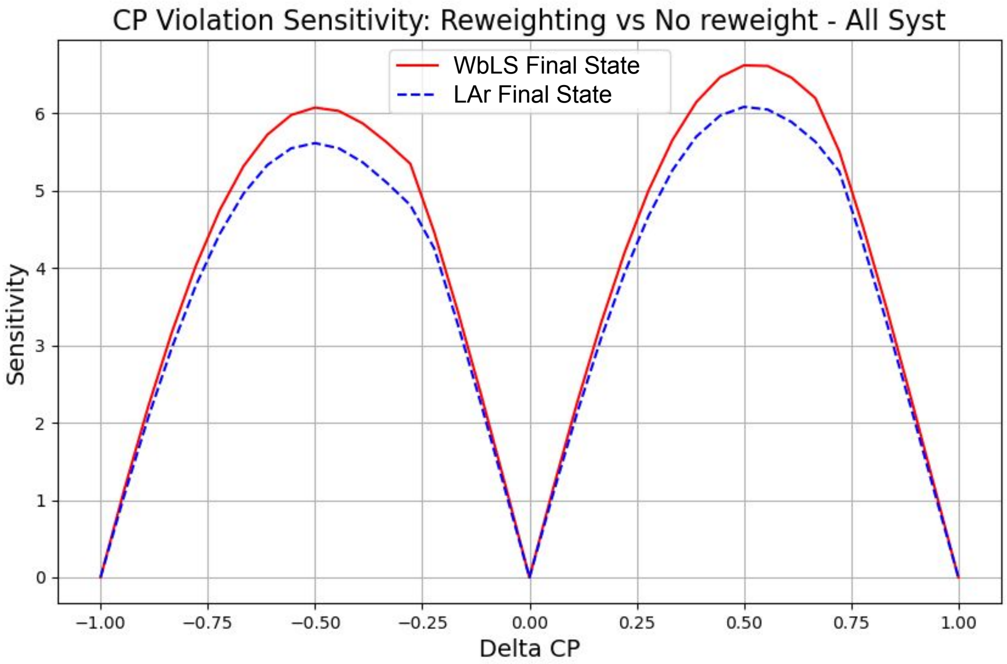


Reweighting map

Nuebar map



Reweighted results



Next thing: Fancier reconstruction + better ND model

The work flow of getting final sensitivity exists.

Started looking at the benefits of the additional water target.

A fancier reconstruction takes into account multi-ring samples with realistic PID information is being considered.

More realistic ND model that can constrain the systematics is under construction.

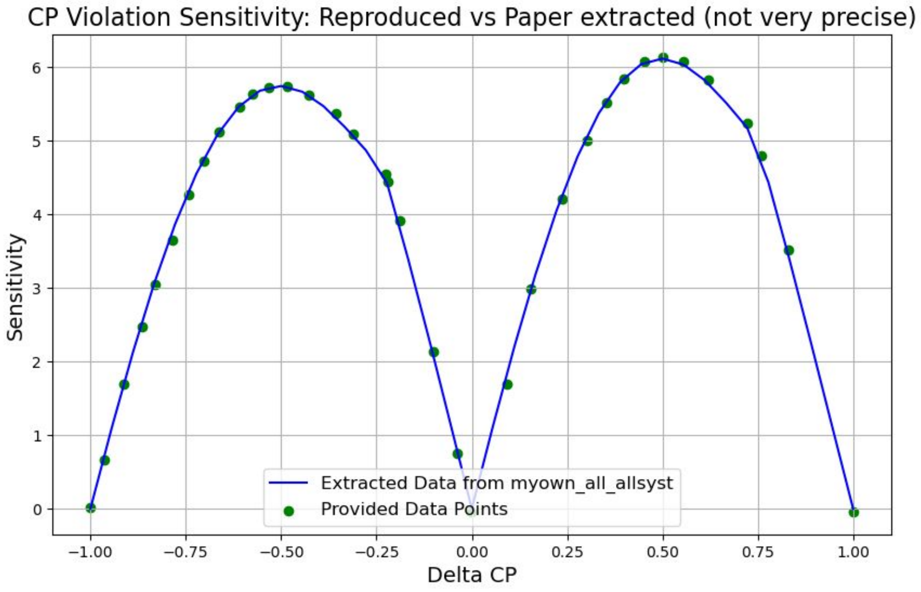
End

Cafana with nominal setting

Able to reproduce the state file from the original nominal CAF files

Able to perform the fit with the nominal state files

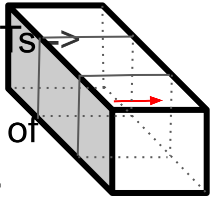
Points are extracted from TDR



Simulation with ratpac

Geometry

- Considering a 25-kt Theia, 40% coverage results in >46,000 20-inch PMTs -> too heavy for simulation.
- Instead, having 14 big sensitive regions and look at the detailed location of each hit, with quantum efficiency from Hamamatsu R14688 without TTS.



Physics model

- Various GENIE versions (2_12 for today) are ready for the neutrino interaction.
- Various G4 models are ready for the particle propagation, default QGSP_BERT.

WbLS Optical model

- Scintillation code in RAT is based on GLG4Sim with model parameter inputs.
- Light yield from measurement: here.
- Rayleigh scattering from BNL measurement.
- *Absorption length from combination of BNL LABPPO measurement and Pope+Smith for water.*
- Refractive index, scintillation rise time and spectrum are from measurements.

Output information

- Ratpac output root with true PE location and time.
- PMT Transit time spread, charge can be added, but not at the moment.

Event containment

Water radiation length is about 36 cm-> given 10 radiation length, we will contain almost all gammas.

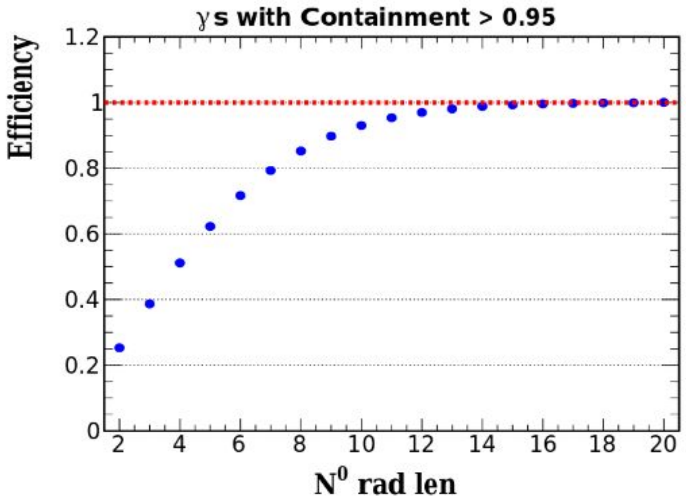
Requirement of 10 radiation length on the downstream face and four side faces makes our fiducial mass ~ 11 kton.

- This number can/should be optimized.

The events were simulated within a small box

Region (2m x 2m x 2m), but should be

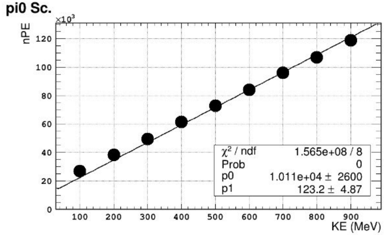
extendable to 11kton.

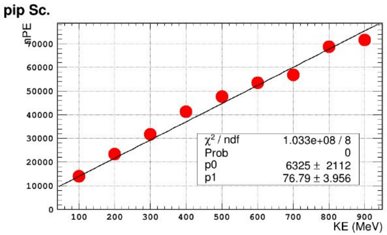


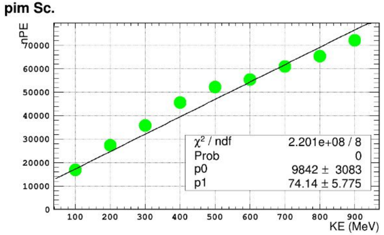
Energy response in the WbLS (5%)

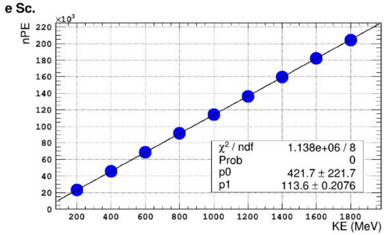
Scintillation light

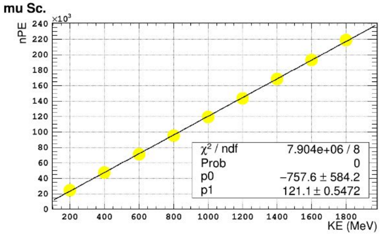
Very linear!

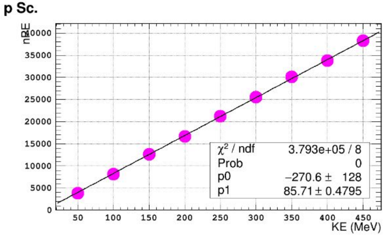


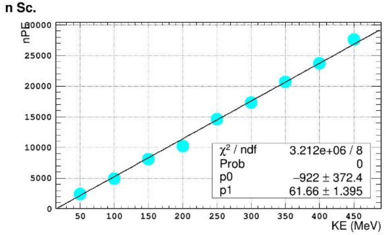










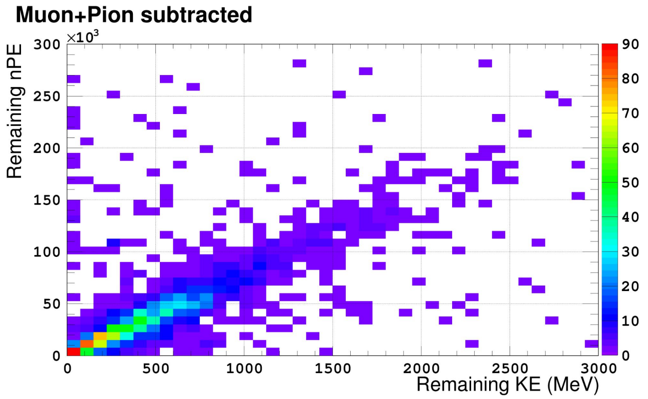


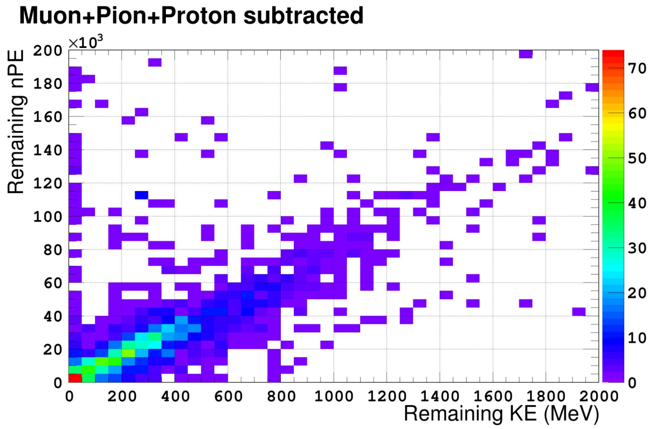
Pion and proton above the Cherenkov threshold

The pion above the Cherenkov threshold can be reconstructed with the Cherenkov ring, assuming the same momentum resolution as the muon.

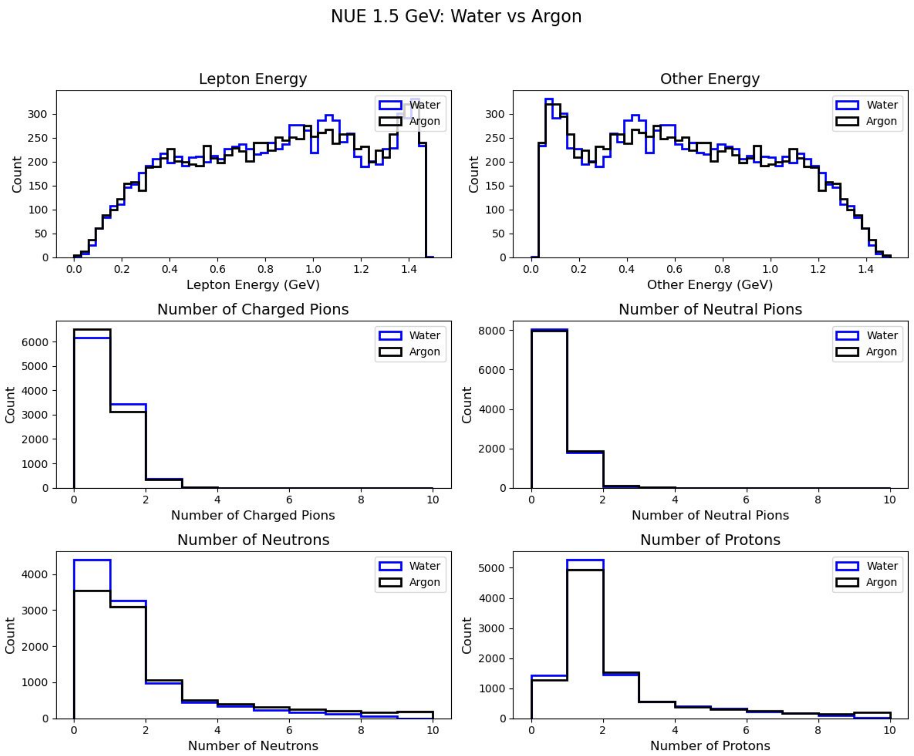
The remaining energy is reconstructed with the scintillation light.

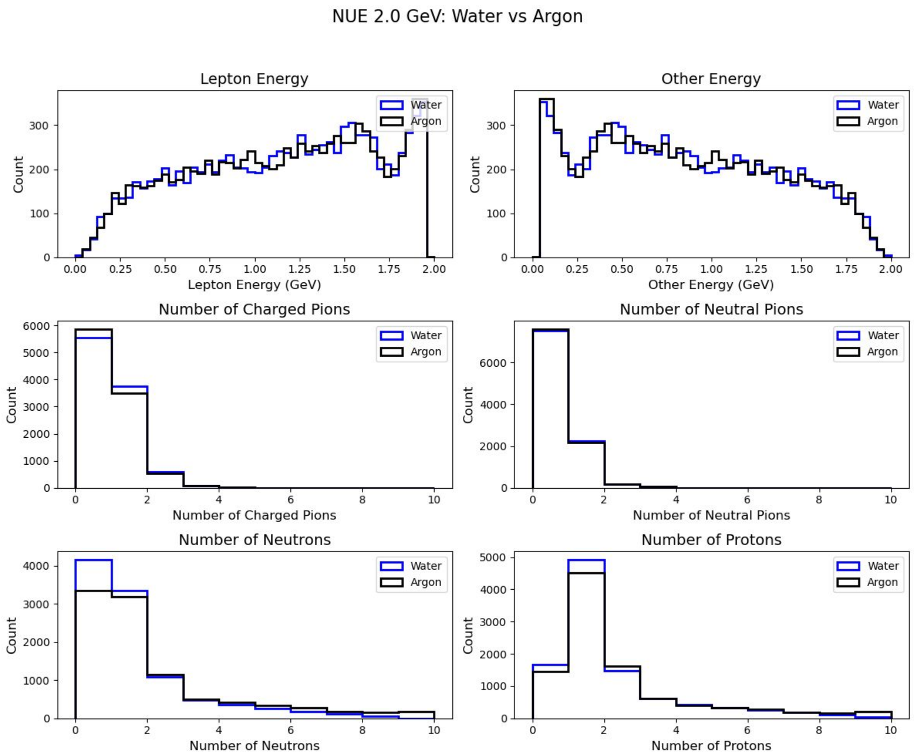
The same thing can be done for the proton as well.



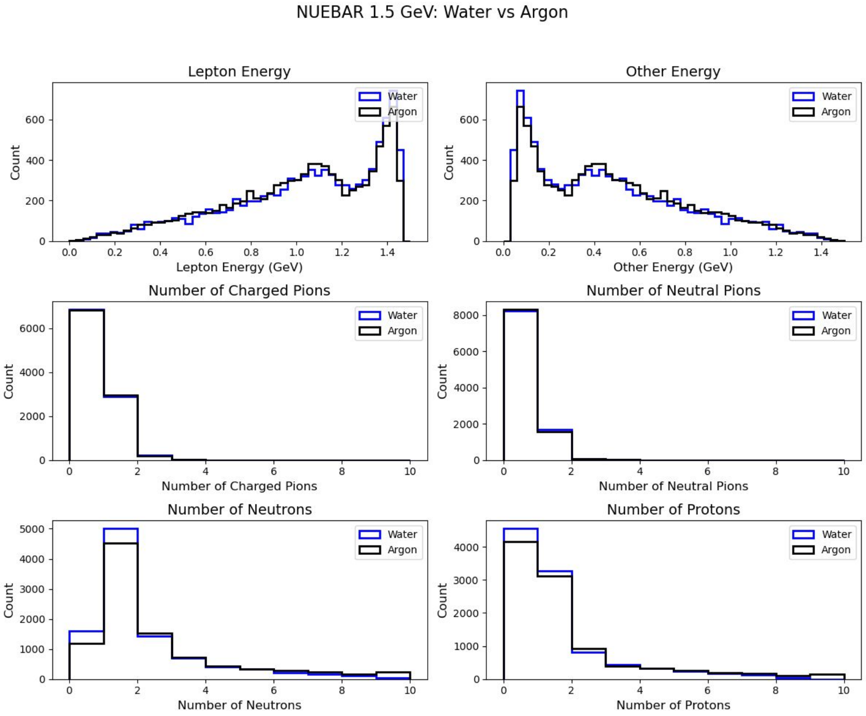


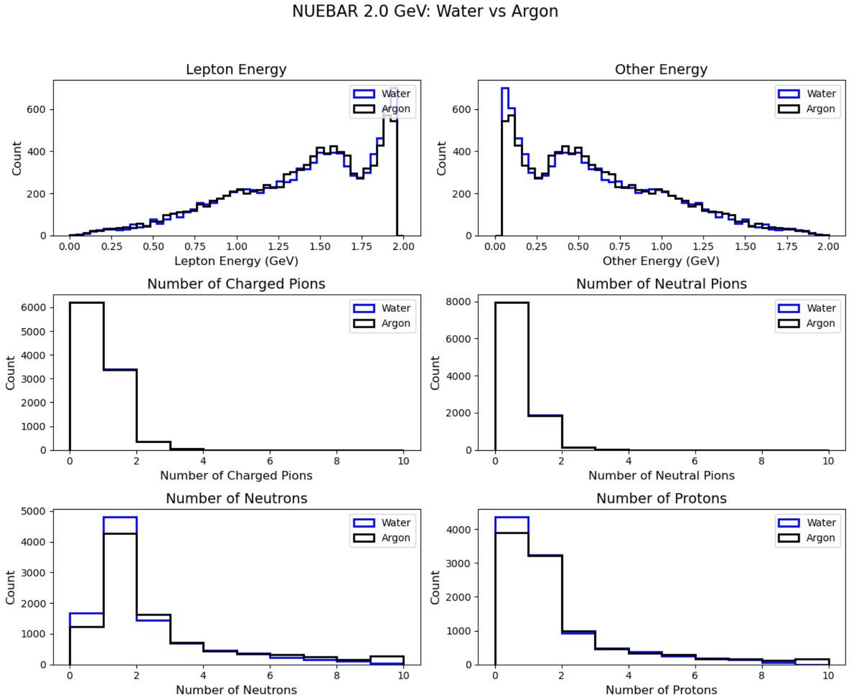
Water vs. Ar in GENIE - will be used for weighting events



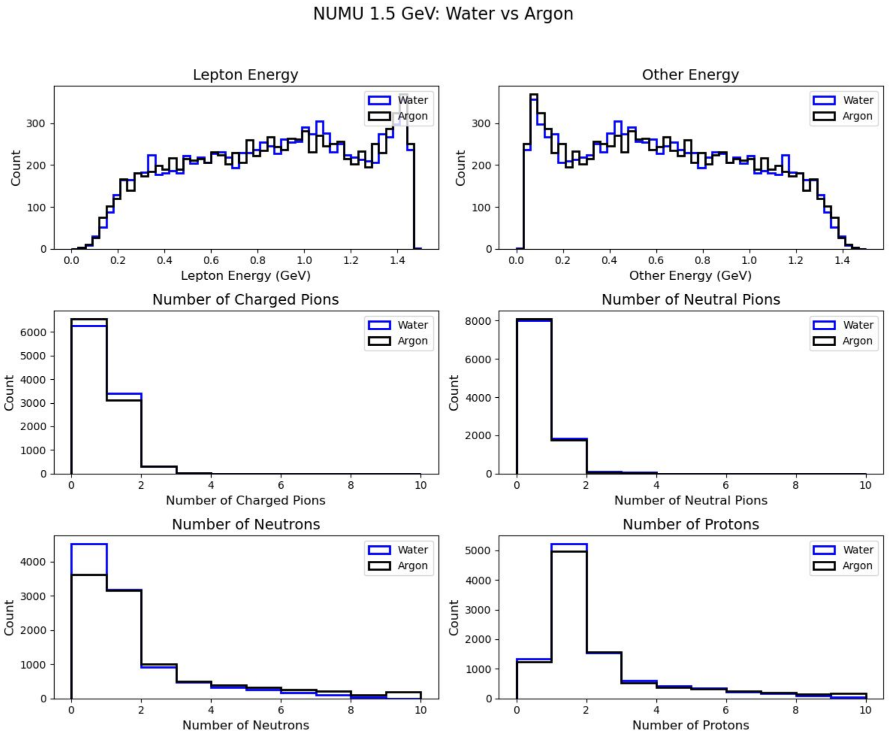


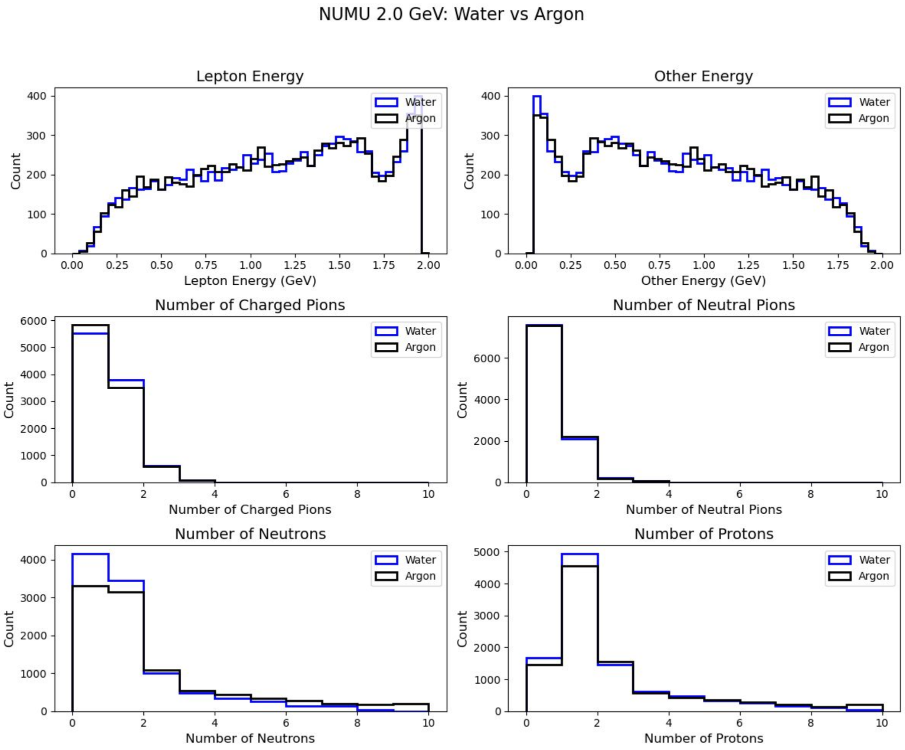
Water vs. Ar in GENIE - will be used for weighting events



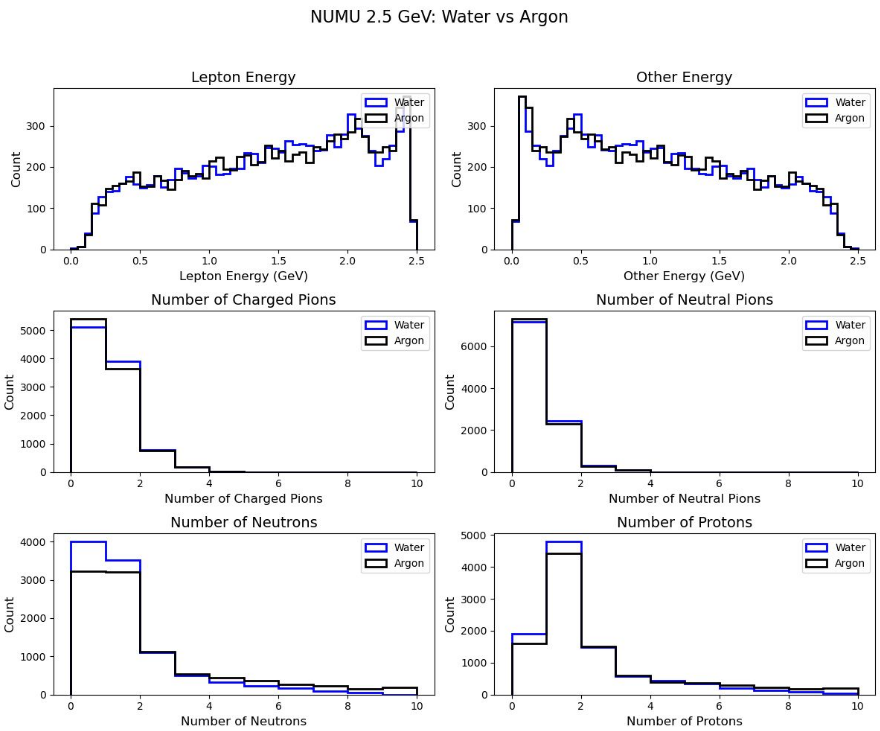


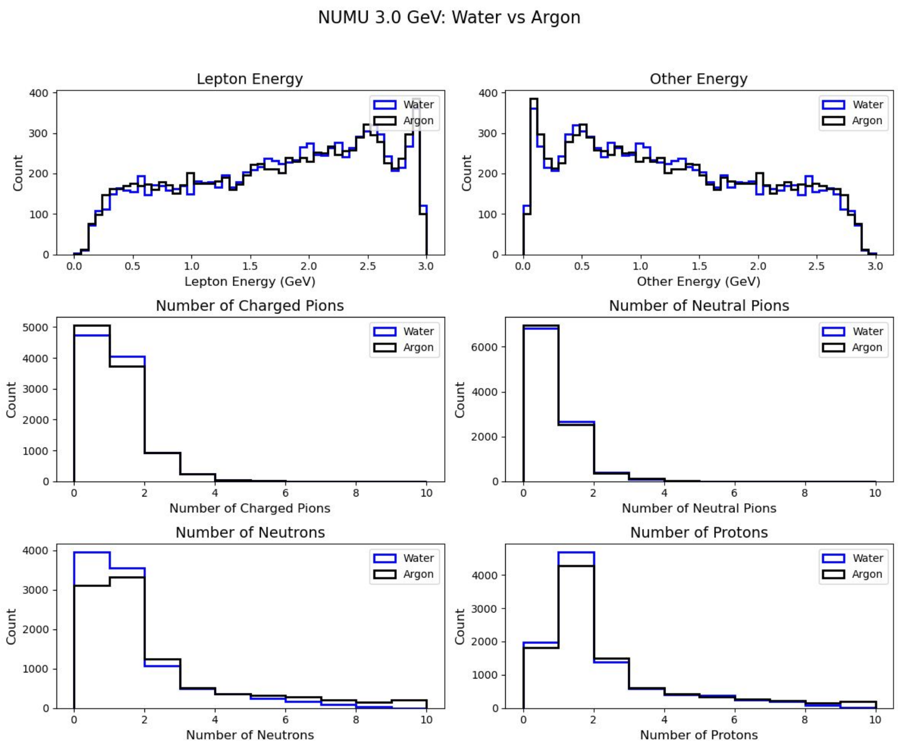
Water vs. Ar in GENIE - will be used for weighting events





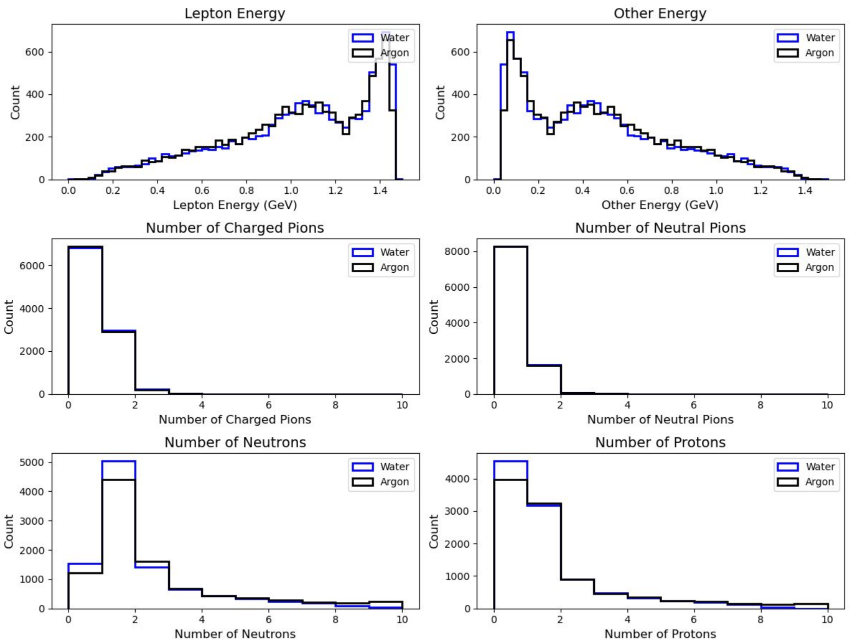
Water vs. Ar in GENIE - will be used for weighting events



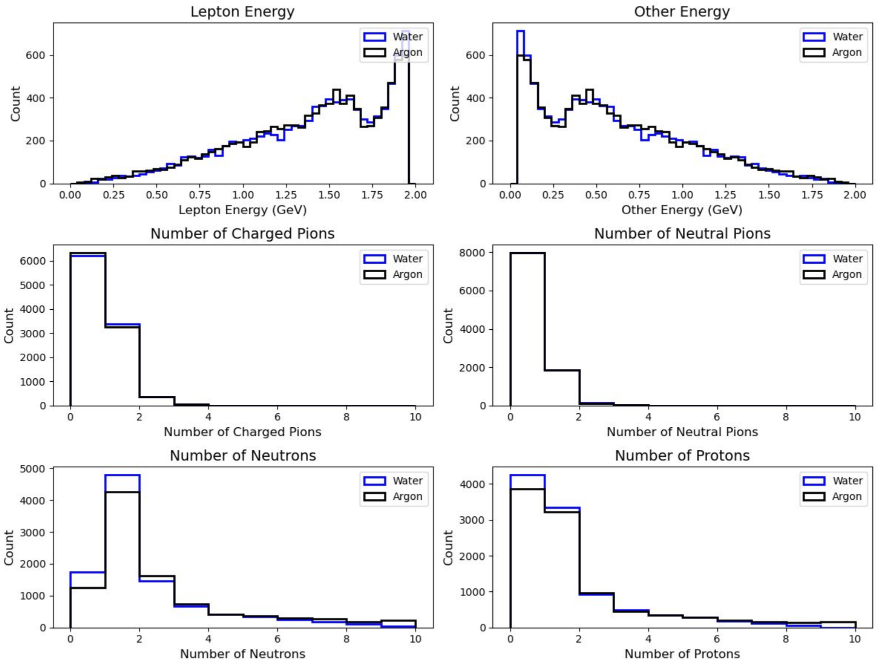


Water vs. Ar in GENIE - will be used for weighting events

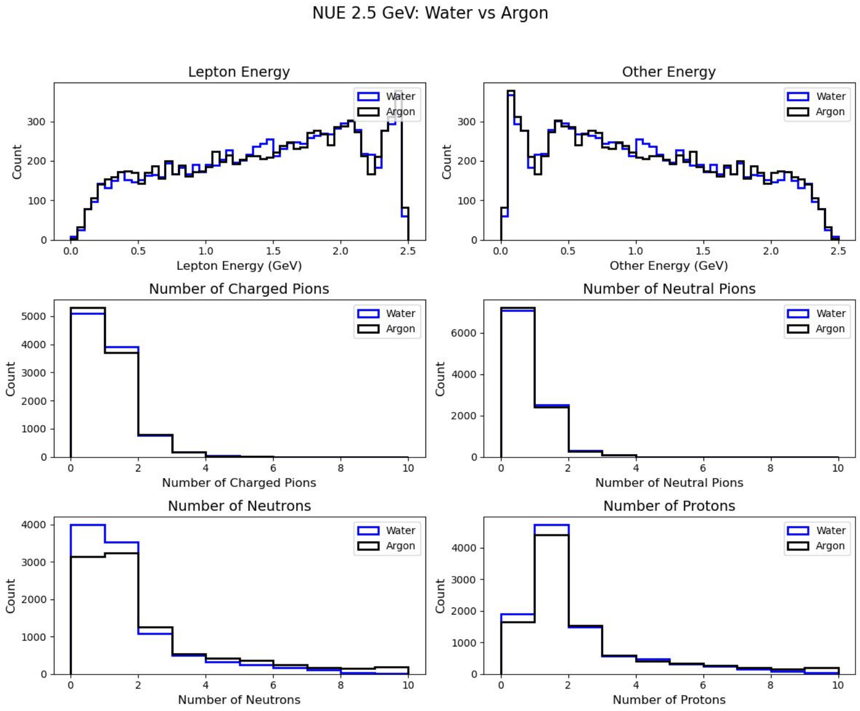
NUMUBAR 1.5 GeV: Water vs Argon

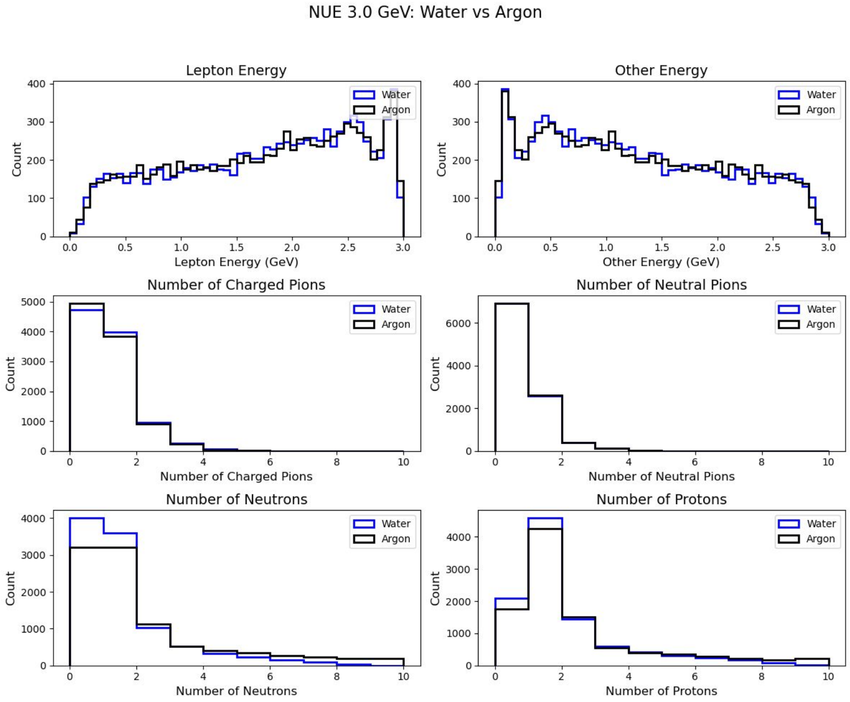


NUMUBAR 2.0 GeV: Water vs Argon

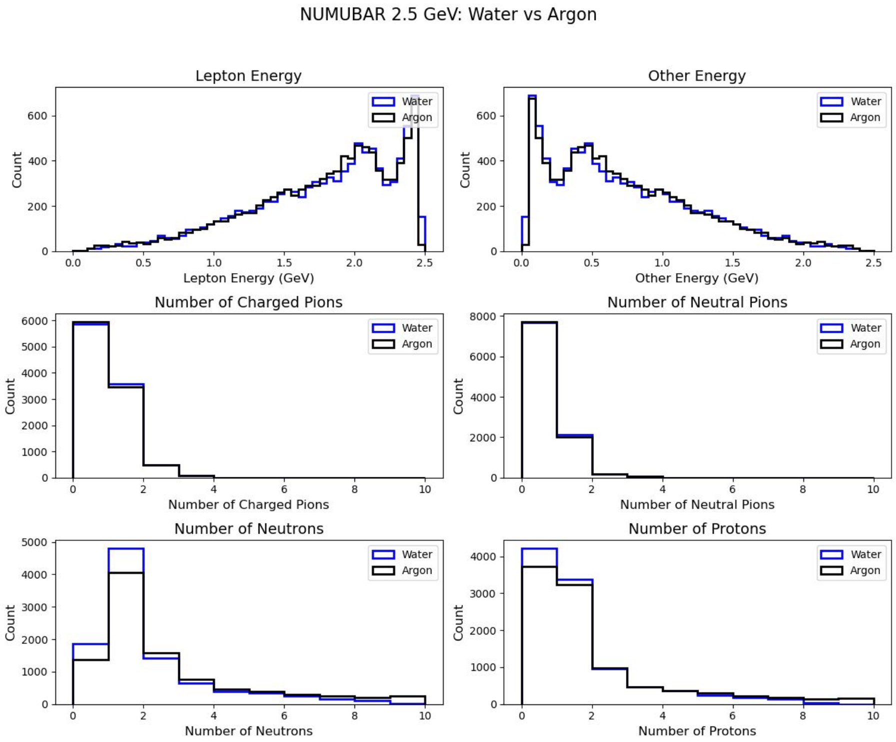


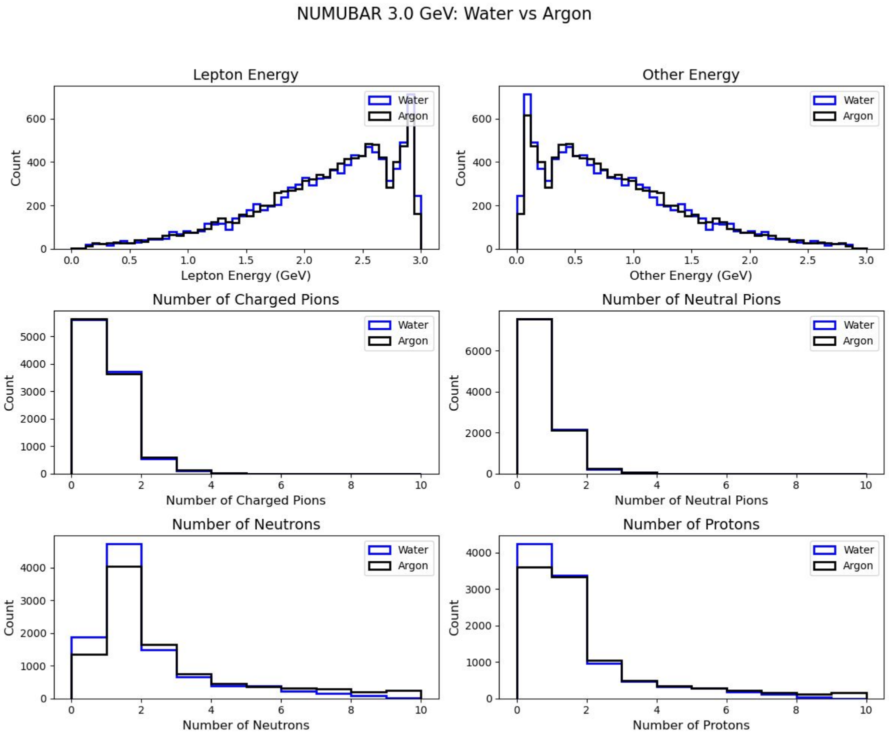
Water vs. Ar in GENIE - will be used for weighting events



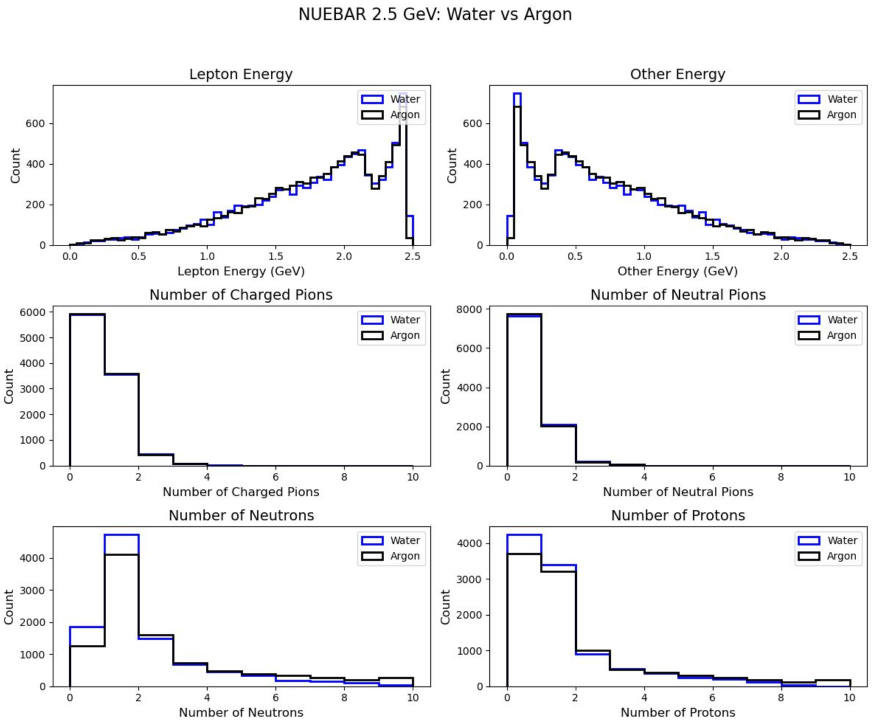


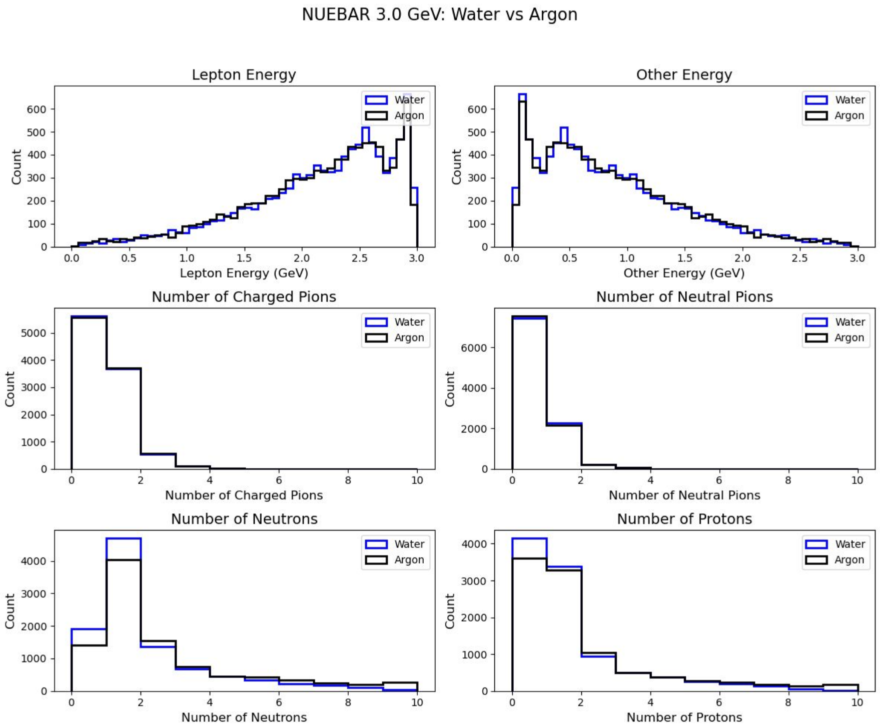
Water vs. Ar in GENIE - will be used for weighting events



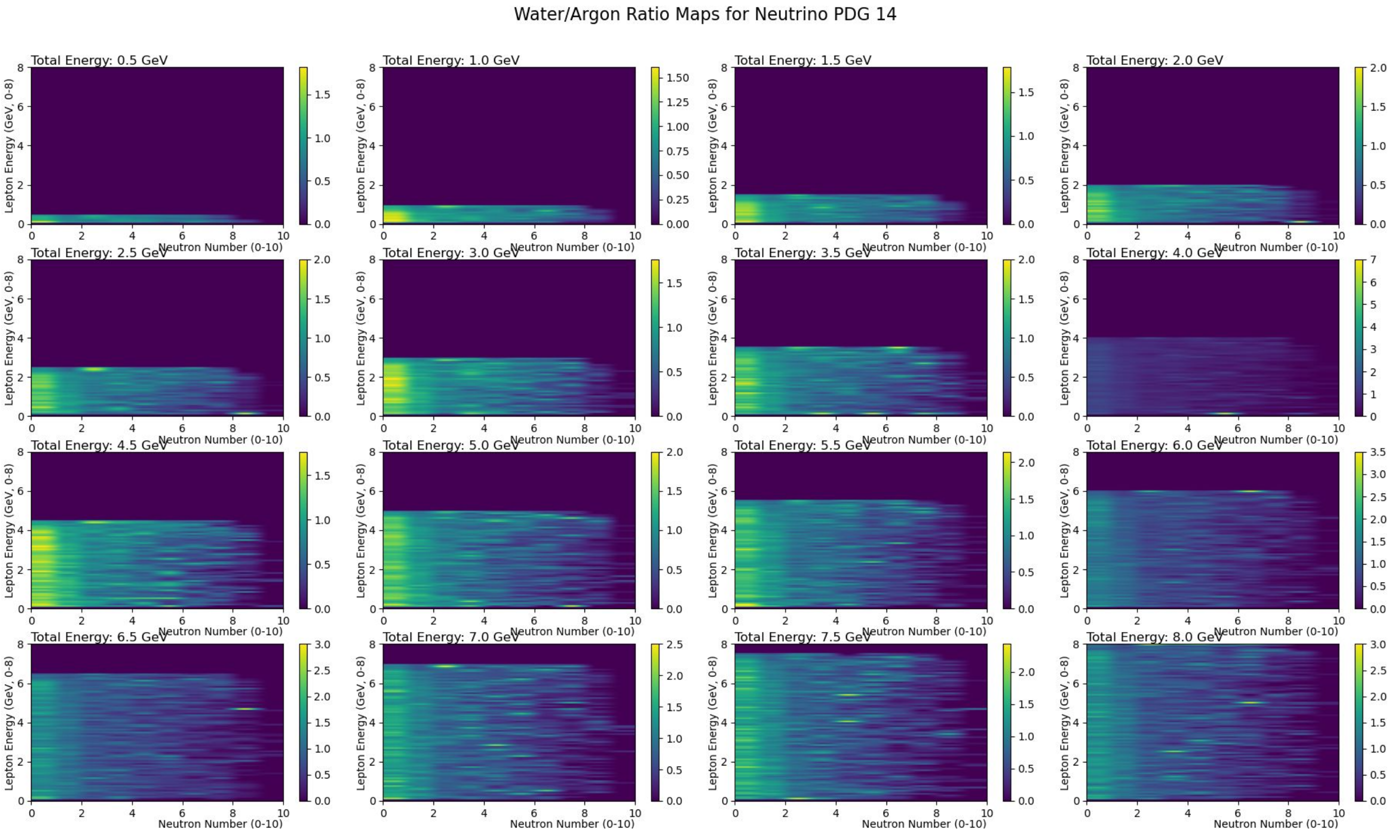


Water vs. Ar in GENIE - will be used for weighting events

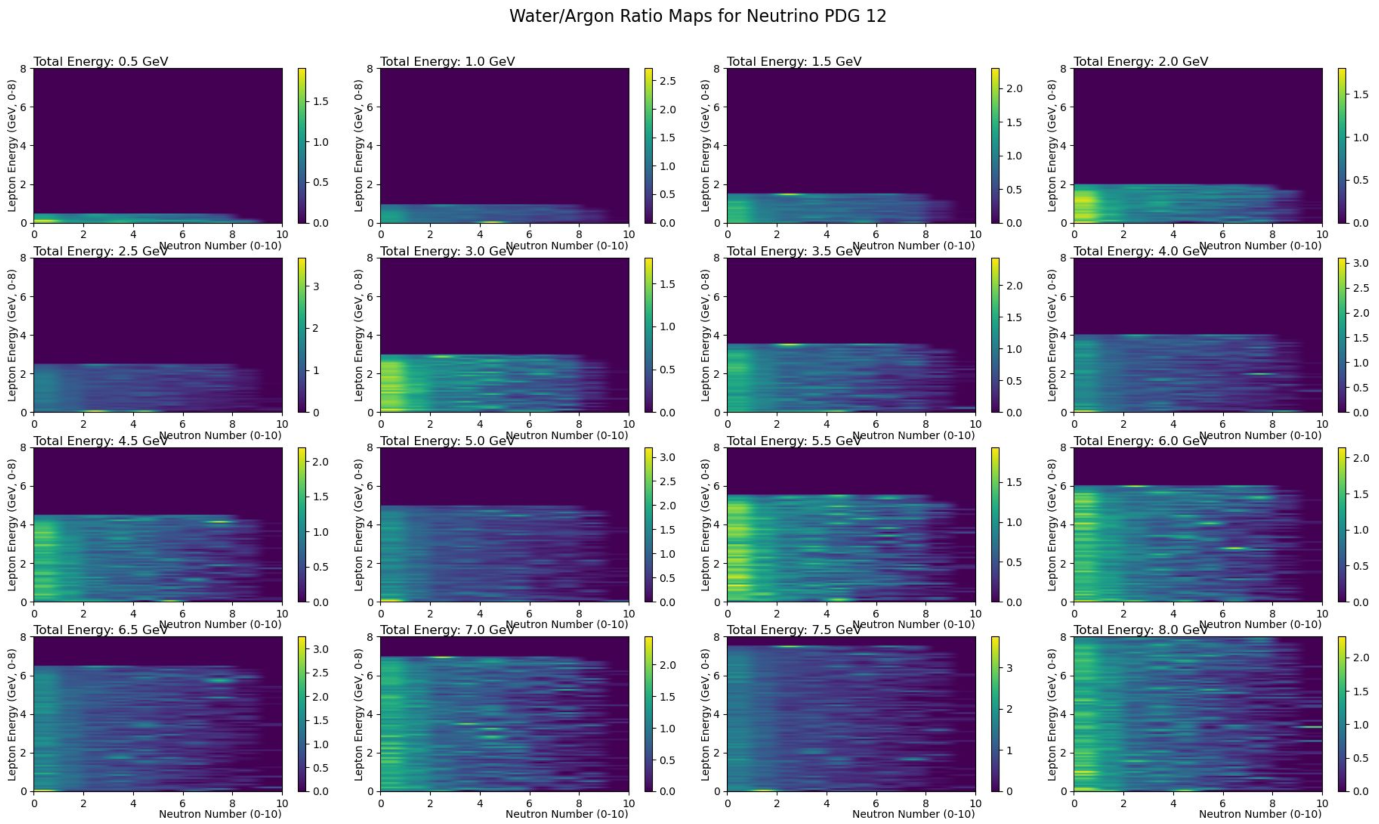




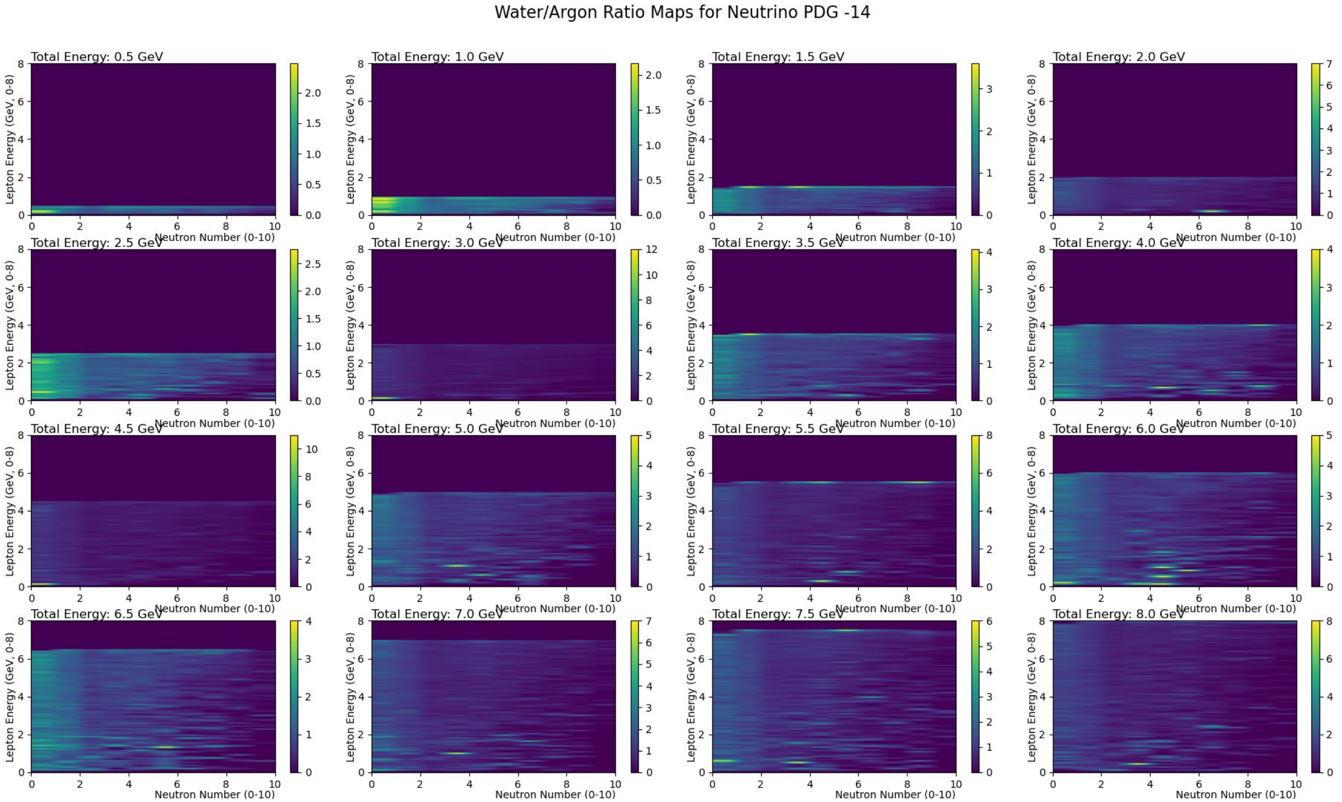
Reweighting map



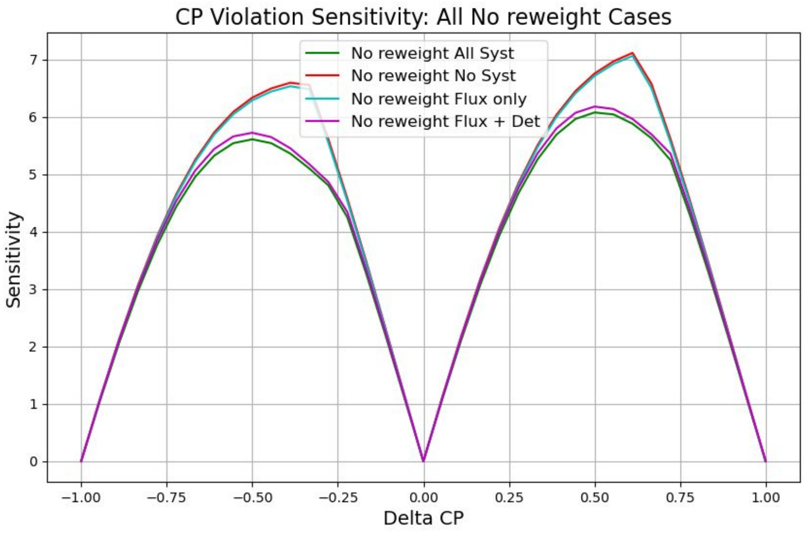
Reweighting map

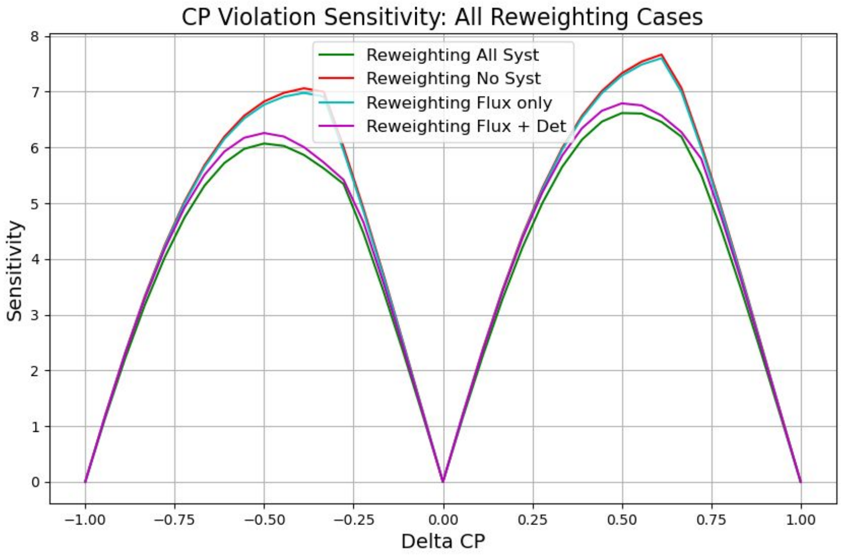


Reweighting map

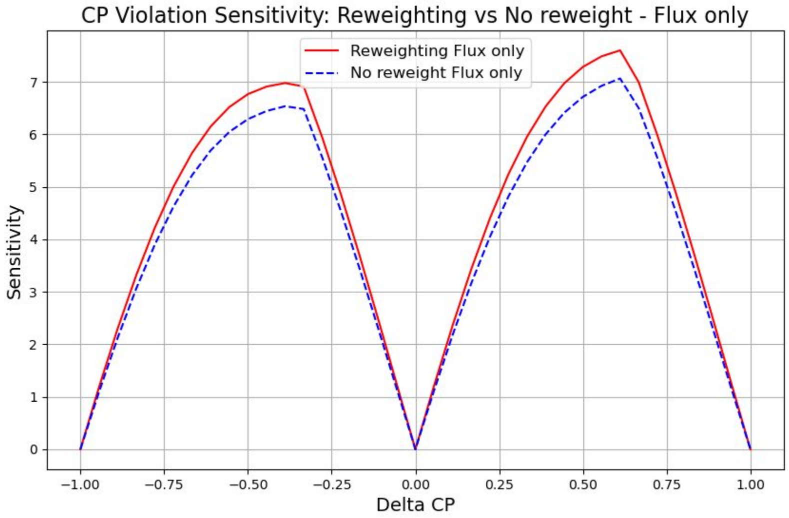


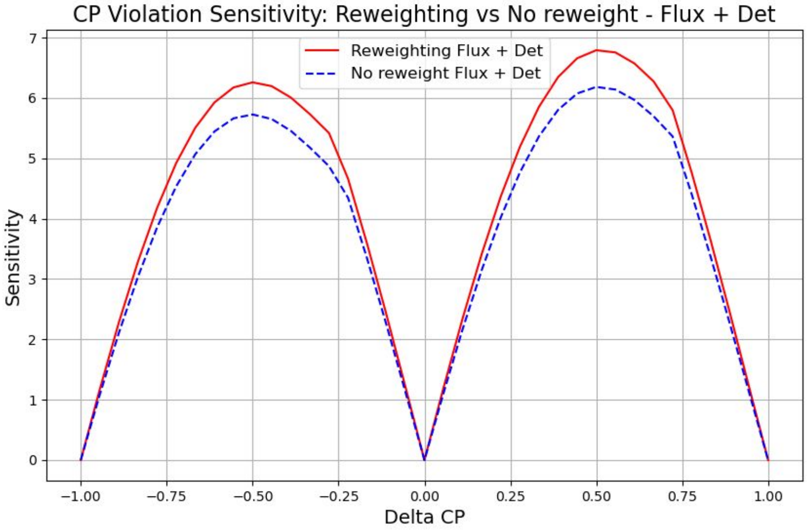
Reweighted results





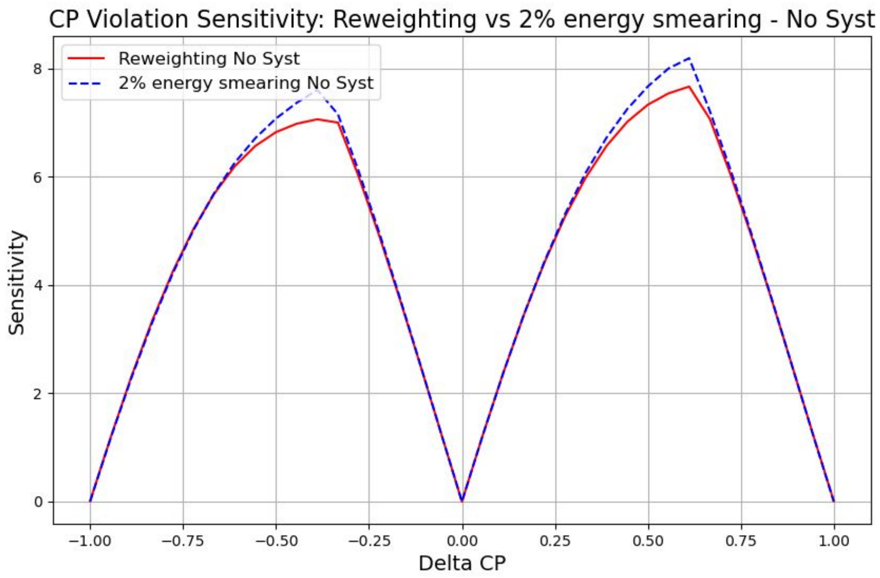
Reweighted results

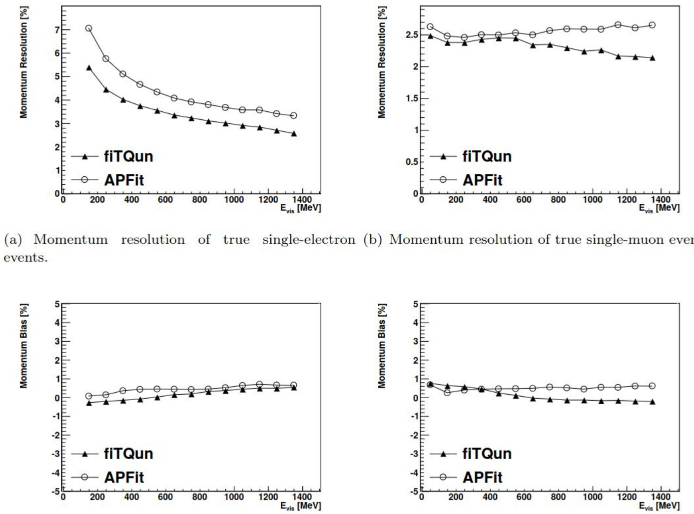




Before the allsyst result

Need a closure test to see the impact of the energy smearing





(a) Momentum resolution of true single-electron events.
(b) Momentum resolution of true single-muon events.
(c) Momentum bias of true single-electron events.
(d) Momentum bias of true single-muon events