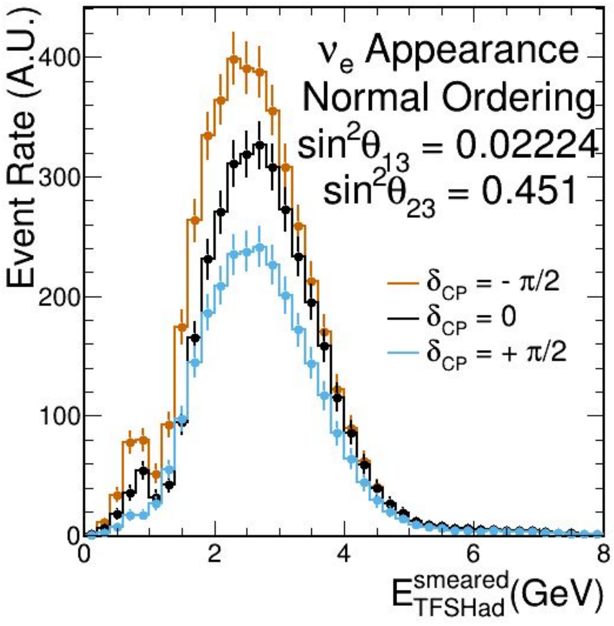
Study of the neutrino energy reconstruction from final state particles and effects related to the simulation of the physics of neutrino interactions in DUNE

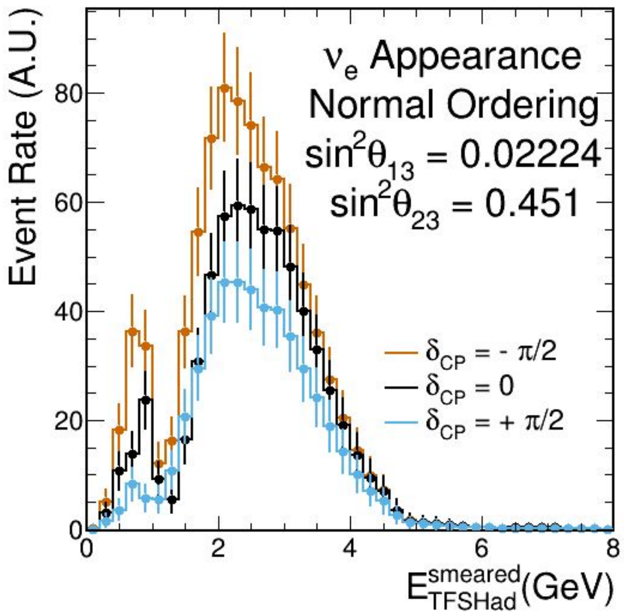
Ginevra De Lauretis - 10/06/2024

Plots for approval

$$E^{smeared}_{TFSHad} = E^{smeared}_{\ell} + \sum_{i}^{p,n,\pi,\, other} T^{smeared}_{i}$$



1. 1 proton 0 π
2. $p_{\text{protons}} > 300\,\text{MeV}$



- Reconstructed energy spectra I would like to present in Neutrino poster
- Plots to be approved
- I will give an outline of the elements that I used to describe these two plots

GENIE simulation

- GENIE v3
- FD flux file
- Cross sections
- Neutrino oscillation probabilities
- Normalization

GENIE simulation was done generating 10^4 ν_μ $\bar{\nu}_\mu$ interactions in Ar40 with GENIE v3.04.00 tune G1810a0211a which includes the following models

Modelling CMC	Ground state	Cross-section								Hadronization	FSI
		quasi-elastic	2p2h	resonance	shallow and deep inelastic	coherent π	diffractive π	ΔS=1 quasi-elastic	ΔS=1 inelastic		
G18_10a	LFG	NAV w/ dipole $F_A(Q^2)$	NSV	BS tuned (2020)	BY tuned (2020)	BS	Rein	Pais	ASAV (opt.) (ν only)	AGKY tuned (2020) AG	hA18
G18_10b											hN18
G18_10c											INCL
G18_10d											G4B

DUNE input flux given to the simulation is FD flux taken from: https://glaucus.crc.nd.edu/DUNEFluxes/ corresponds to the one use in TDR

The cross sections were taken from GENIE data releases corresponding to the version and tune I used: https://scisoft.fnal.gov/scisoft/packages/genie_xsec/

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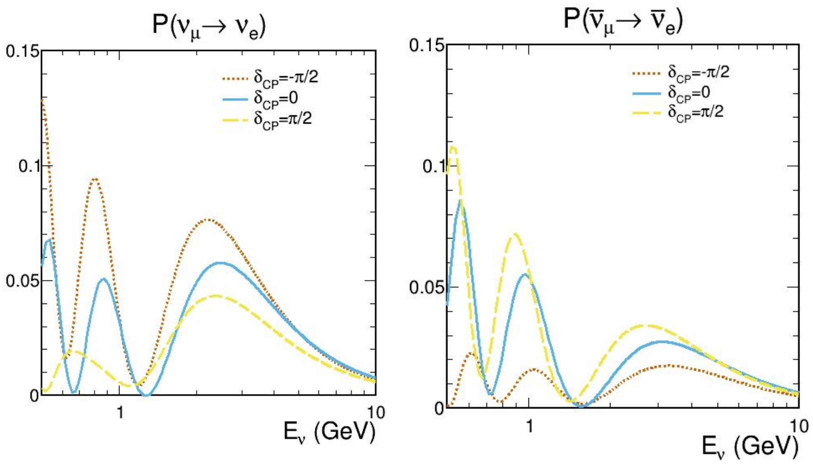
globes v3.2.16
configuration file took from: https://arxiv.org/src/2103.04797v2/anc
oscillation parameters from NuFIT v5.2

with SK atmospheric data	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.4$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.012}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
$\sin^2\theta_{23}$	$0.451^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.569^{+0.016}_{-0.021}$	$0.412 \to 0.613$
$\theta_{23}/^\circ$	$42.2^{+1.1}_{-0.9}$	$39.7 \to 51.0$	$49.0^{+1.0}_{-1.2}$	$39.9 \to 51.5$
$\sin^2\theta_{13}$	$0.02225^{+0.00056}_{-0.00059}$	$0.02052 \to 0.02398$	$0.02223^{+0.00058}_{-0.00058}$	$0.02048 \to 0.02416$
$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.94$
$\delta_{CP}/^\circ$	232^{+36}_{-26}	$144 \to 350$	276^{+22}_{-29}	$194 \to 344$
$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ eV^2}$	$+2.507^{+0.026}_{-0.027}$	$+2.427 \to +2.590$	$-2.486^{+0.025}_{-0.028}$	$-2.570 \to -2.406$



The two plots show the probability of oscillation $\nu_\mu \to \nu_e$ (and same for antineutrinos) in the energy region which will be covered by DUNE wide band beam. The probability shows that we are in correspondence of the first two maxima of the oscillation, respectively at ~2.5 GeV and ~0.7 GeV. The plot was done using GLoBES v3.2.16 and the configuration file used in dune TDR, which assumes a baseline of 1284.9 km. The parameters of oscillation are not the same used in the TDR though, but they were taken by NuFIT 5.1 (2022) results. These oscillation probabilities have been used in all the plots that required to include oscillation probabilities which will be presented in the next slides.

GENIE simulation

Phase I : 1.10e21 POT, 20 kton
Phase II: 2.21e21 POT, 40 kton

- GENIE v3
- FD flux file
- Cross sections
- Neutrino oscillation probabilities
- Normalization

$$N_{\text{event}}(E_\nu) = \underbrace{\phi(E_\nu)}_{\nu.\text{m}^{-2}.\text{POT}^{-1}} \times \underbrace{\sigma(E_\nu)}_{10^{-38}\text{cm}^2} \times p_\alpha \times POT \times \underbrace{\mathcal{N}_A \frac{m_{FD}}{M(Ar)}}_{\text{Number of argon targets}},$$

The normalization for GENIE simulation was done by using the flux, the cross sections and the that I just described and multiplied them by the **factor**.

- ❖ At the time I did different check with TDR normalization in which I considered the 3.5y scenario and I found a total number of 1060 for δ_{CP}= 0 (TDR was 1092).
- ❖ Then I started using a normalization based on the 1000 kton MW yr . Since I am using only neutrinos I considered 500 kton MW yr (50 in Phase I + 450 Phase II)

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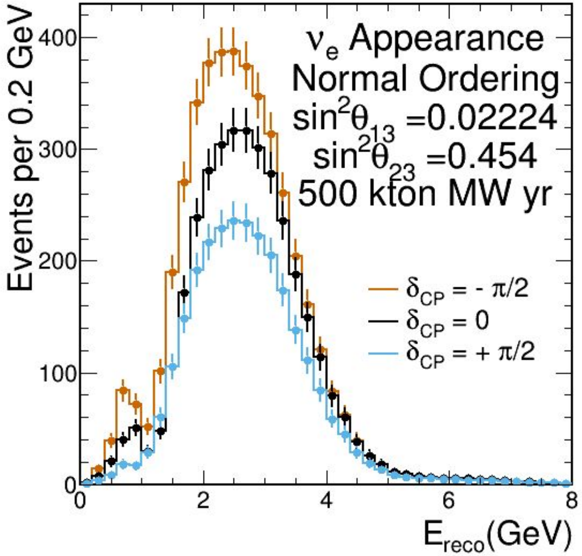


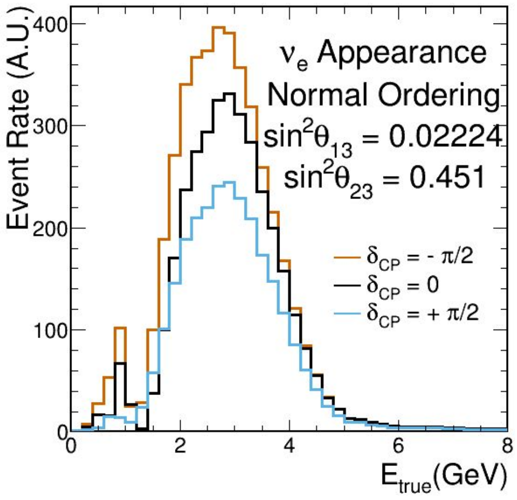
GiBUU simulation

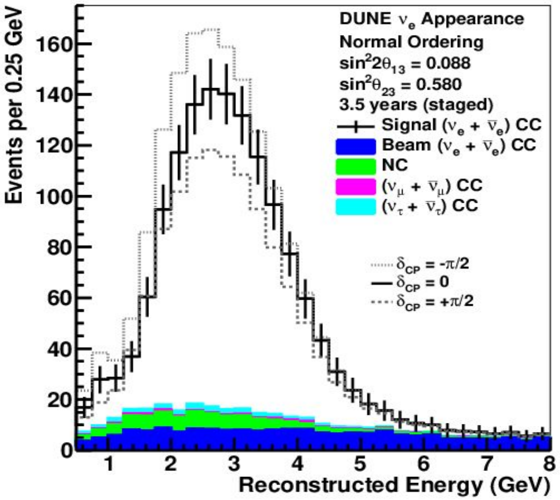
- GiBUU → 2023 release, GiBUU jobcard with DUNE configuration
- FD flux file
- Cross sections
- Neutrino oscillation probabilities
- Normalization

same as the ones used in GENIE

→ GiBUUs cross sections

Appearance spectra



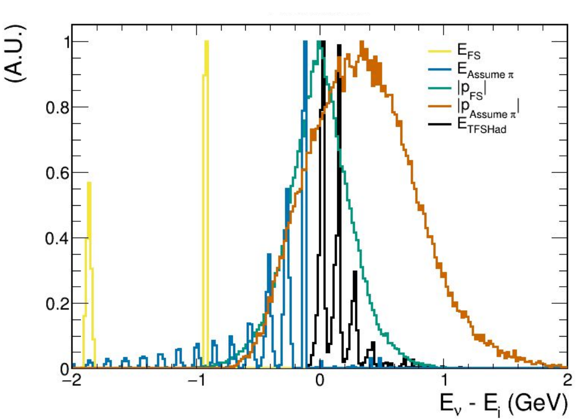


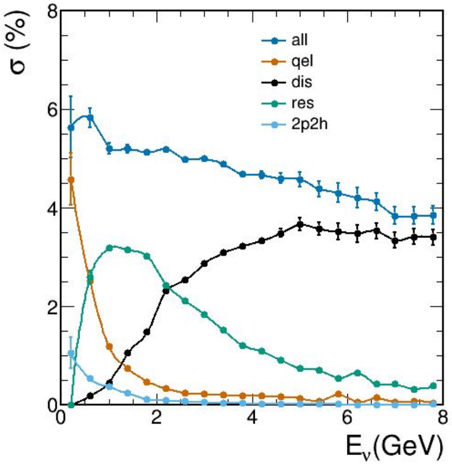
The plot on the left corresponds to the electron neutrino appearance spectrum for different values of δ_{CP}. The x axis shows the true neutrino energy variable coming from the generator, weighted for the probability of oscillation (see previous slide).
On the vertical axis the event rate in arbitrary units, was obtained following the normalization described in the previous slide. The plot is shown next to the TDR reconstructed energy spectrum in order to show how the reconstruction process (related to the systematics of the interaction and the detector resolution) affects the shape of the spectrum.

How to compute E_ν

The plot on the left shows the distribution resolution that we could get if we would ideally measure the neutrino energy as follows

1. Total true final state energy: $E_{FS}^{\mathrm{true}} = E_\ell + \sum_i^{p,n,\pi,oth.} E_i$
2. Assume all hadrons are pions: $E_{Assume\pi}^{\mathrm{true}} = E_\ell + \sum_i^{p,n,\pi,oth.} (T_i + m_\pi)$
3. Total Momentum: $|p_{FS}^{\mathrm{true}}| = |\vec{p}_\ell + \sum_i^{p,n,\pi,oth.} \vec{p}_i|$
4. $|p_{Assume\pi}^{\mathrm{true}}| = \left|\vec{p}_\ell + \sum_i^{p,n,\pi,oth.} \left(\hat{p}_i \times \sqrt{(T_i + m_\pi)^2 - m_\pi^2}\right)\right|$
5. $E_{TFSHad}^{\mathrm{true}} = E_\ell + \sum_i^{p,n,\pi,oth.} T_i$





The X axis shows the difference between the true neutrino energy variable coming from the GENIE simulation and the energy of the neutrino calculated calculated from the its final states.

- Not including the detector resolution, so it is completely ideal.
- Neutrons are also included in the energy budget, since they are treated as if they were reconstructed.

The plot on the right shows the behaviour of the resolution in the case in which we calculate the neutrino energy as E_{TFSHad}^{true}
The Y axis shows the percentage sigma which was calculated for each energy value as $\frac{E_\nu - E_{TFSHad}^{true}}{E_\nu}$

These two plots shows how the resolution is intrinsically limited by the interaction physics.

Smearing resolution

In the plots in which a smearing is applied the following process was applied.
For each type of particle the kinetic energy was smeared accordingly to the table on the right as:

Particle	Energy	Resolution
Electrons, Photons, ...	All	$\sigma = \left(\frac{0.15}{\sqrt{E(MeV)}} \oplus 1 \right) \%$
Neutral hadrons (neutrons...)	All	$\sigma = \frac{30}{\sqrt{E(GeV)}} \%$
Charged hadrons (protons...)	$K < K_1$	$\sigma = 3\%$
	$K_1 < K < K_2$	$\sigma = 1\%$
	$K > K_2$	$\sigma = \frac{30}{\sqrt{E(GeV)}} \%$

$$K \rightarrow K\,(1 + \sigma\, Gauss\,(0,1))$$

In particular for charged hadrons the smearing is based on the range of the particle.

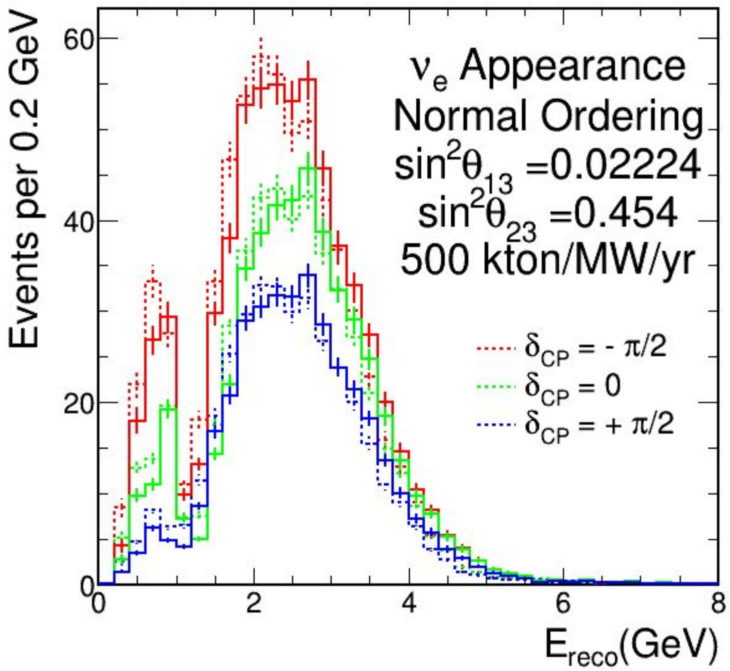
- if they don't interact (K > K2 which corresponds to LAr interaction length) they are reconstructed with hadronic calorimetry formula and a resolution of 30 %
- if they do interact a worst resolution is applied for short tracks (K<K1)
- these values are taken from an ICARUS analysis https://arxiv.org/abs/0812.2373
- brings to a total resolution effect of ~14 %
- just an example, can be implemented differently

Smearing at 10-14 %

Just to get an example, I also tried to apply a smearing of some percent, independently from the particle, to see how it affects the energy spectrum

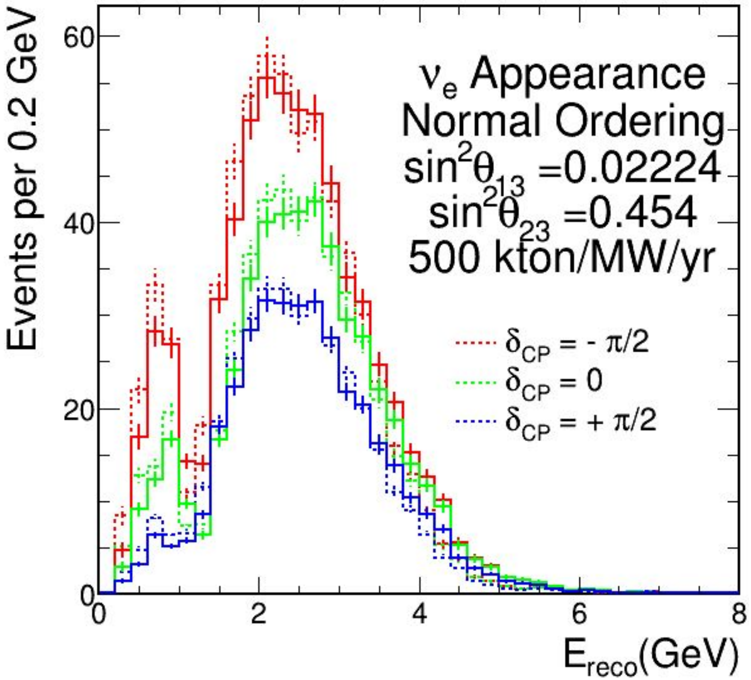
dashed: neglecting neutrons

continuous: 10 % smearing

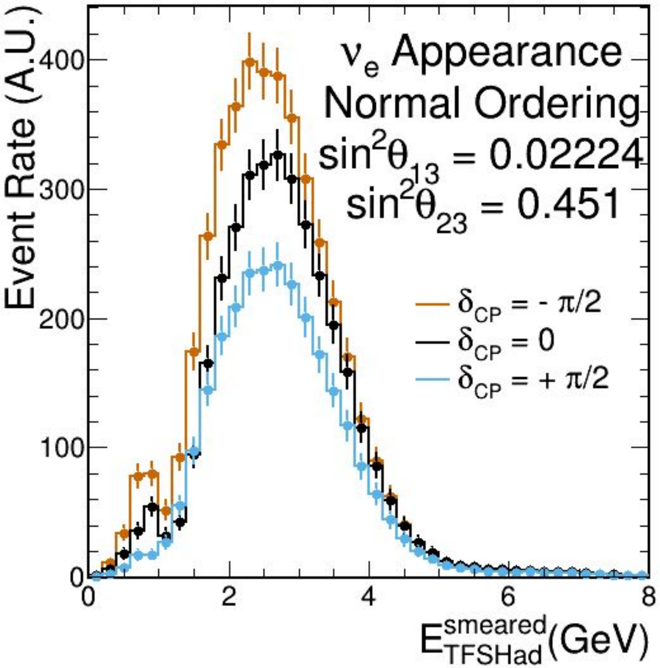


dashed: reconstruction by neglecting neutrons

continuous: 14 % smearing



Reconstructed spectrum



The plot shows the reconstructed appearance spectrum for ν_e in which the energy is reconstructed as

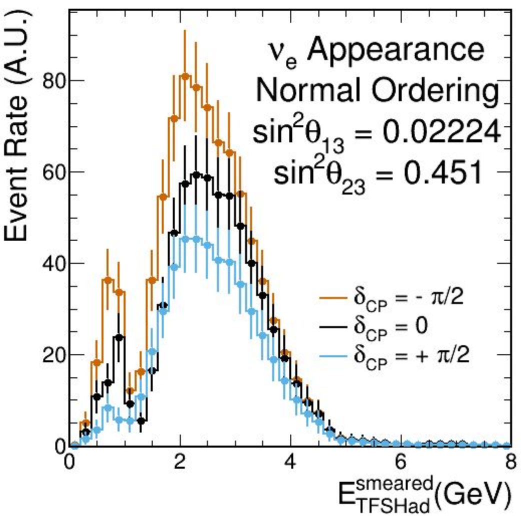
$$E^{smeared}_{TFSHad} = E^{smeared}_{\ell} + \sum_{i}^{p,n,\,\pi,\,other} T^{smeared}_{i}$$

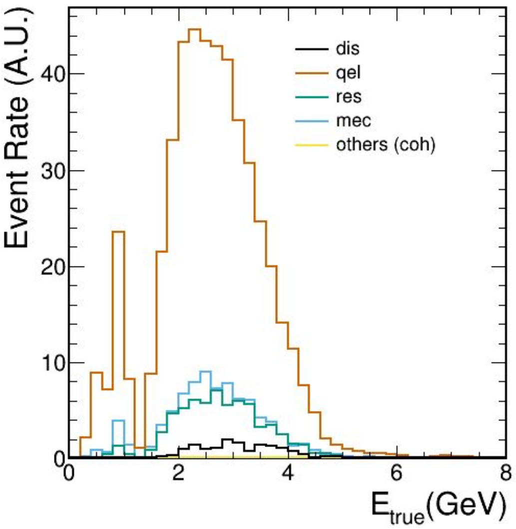
The distribution is shown for multiple values of δ_{CP}

The x axis shows the energy reconstructed as a sum of the outgoing lepton energy and the other particle's kinetic energies. On the top of that, a particle by particle smearing is applied, as explained in the previous slide.

It should be noticed that in this case neutrons are assumed to be reconstructed with a sigma = 30%/sqrt(E).
No cut on the energy of the final state particles was applied, nor topology selections in this plot.

Impact of δ_{CP} on 1p0π sample





1. 1 proton $0\,\pi$
2. $p_{\mathrm{protons}} > 300\,\mathrm{MeV}$

In these plot an event selection was applied on the generator output.
On the left we have the same reconstructed appearance spectrum for neutrinos for different δ_{CP}

- event selection applied at the level of the generator output and includes only the events with 1p and 0 pions in the final state.
- cut on the final momenta of the outgoing protons to be higher 300 MeV

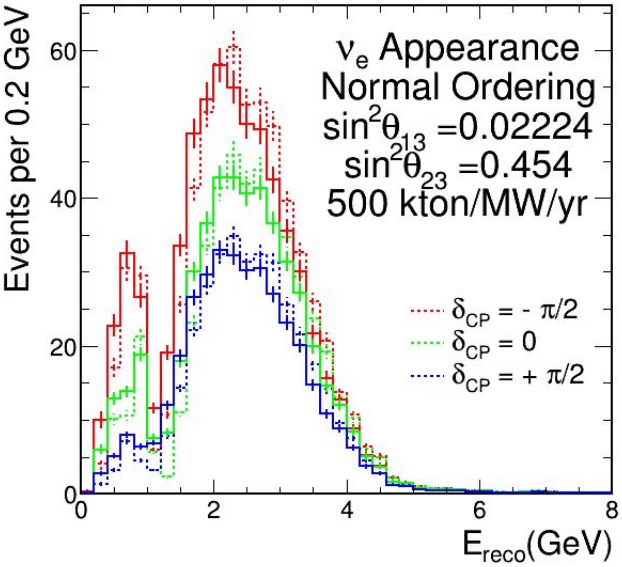
The cut on the proton is applied both in the reconstruction and in the selection, so in the chosen subsample there might be protons with low momenta which I am including in the energy budget.
It was introduced since there were some model differences with the GiBUU simulation which had an higher number of soft protons in the final state

The neutrons are ignored in the definition of the sample: there might be neutrons in the final state and they are reconstructed accordingly with the smearing described before.
On the right instead the event rate for kind of process after applying the event selection is shown. This plot aims at showing how the composition of the sample changes after having applied the event selection. On the X axis the true energy variable coming from the generator is plotted, weighted for the oscillation probability as it was done in all the other plots. The majority of the sample is made by QE processes but also RES and MEC enter in the subsample.

Backup

Including or excluding neutrons in the calculated variable

dashed: including neutrons
continuous: excluding neutrons



Neglect hadron masses	GENIE resolution (%)		GiBUU resolution (%)	
	w neutrons	**w/out**	**w neutrons**	**w/o**
	5.5	**13.6**	6.2	**14.7**