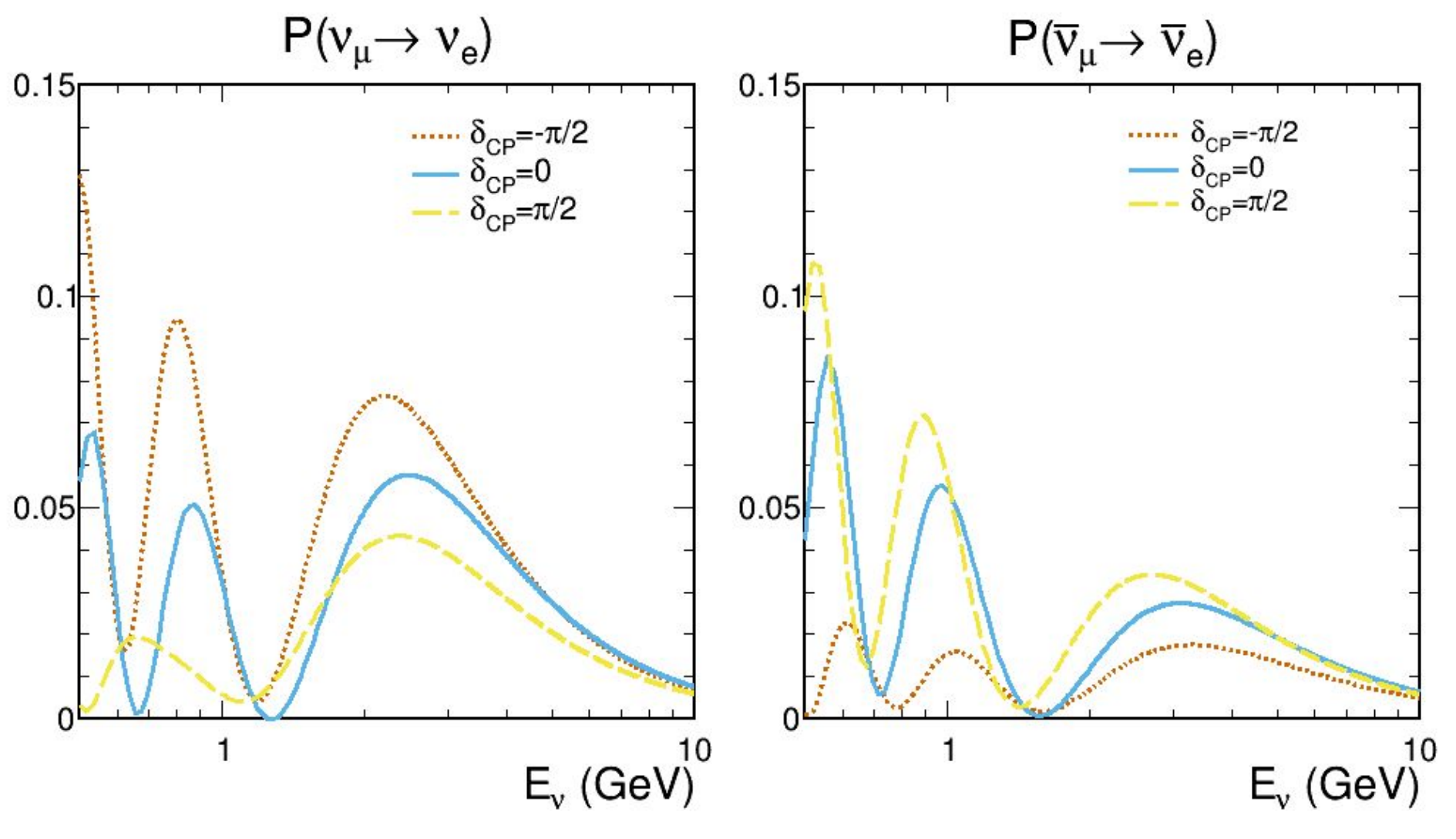
Study of the neutrino energy reconstruction from final state particles and effects related to the simulation of the physics of neutrino interactions in DUNE

Ginevra De Lauretis on behalf of the DUNE collaboration

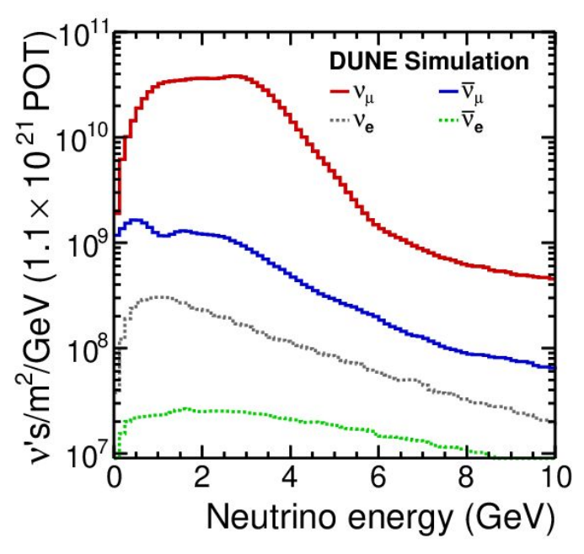
Motivation and contest

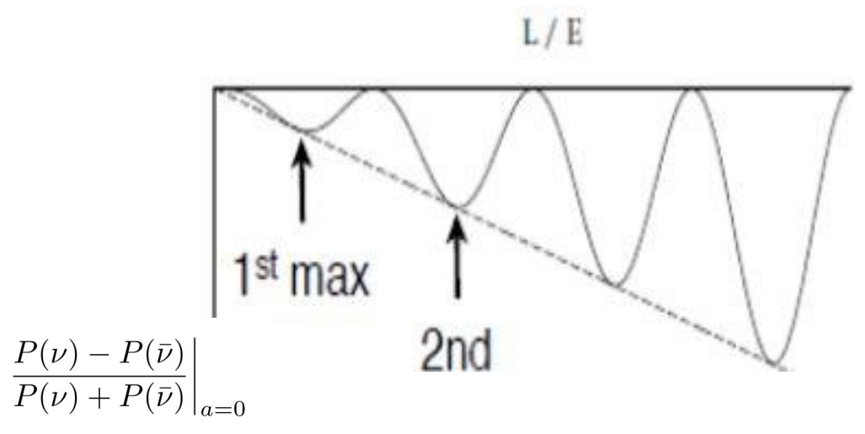
DUNE

Wide band beam covering the first two $\nu_\mu \rightarrow \nu_e$ oscillation maxima
High potentiality to extract information from the energy spectrum of detected neutrinos



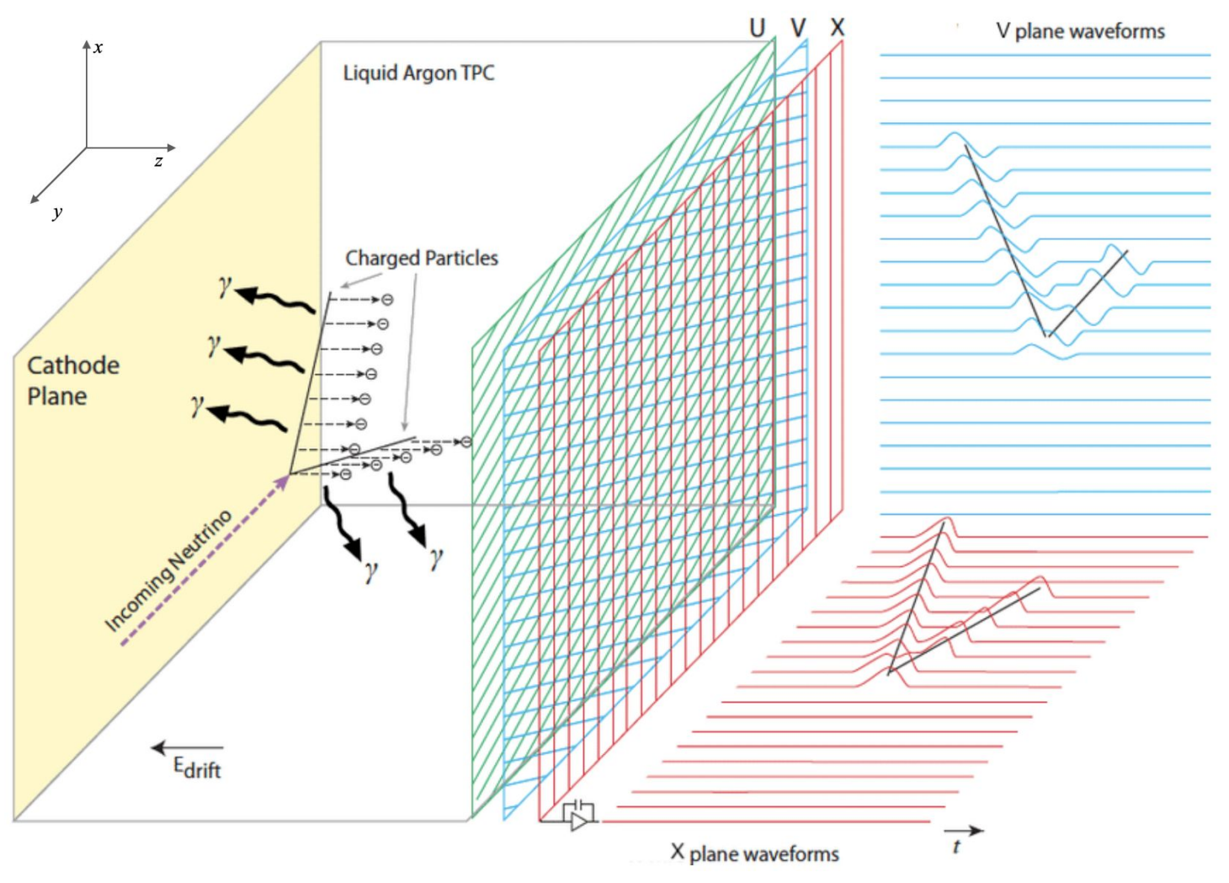
Normal hierarchy, L = 1300 km

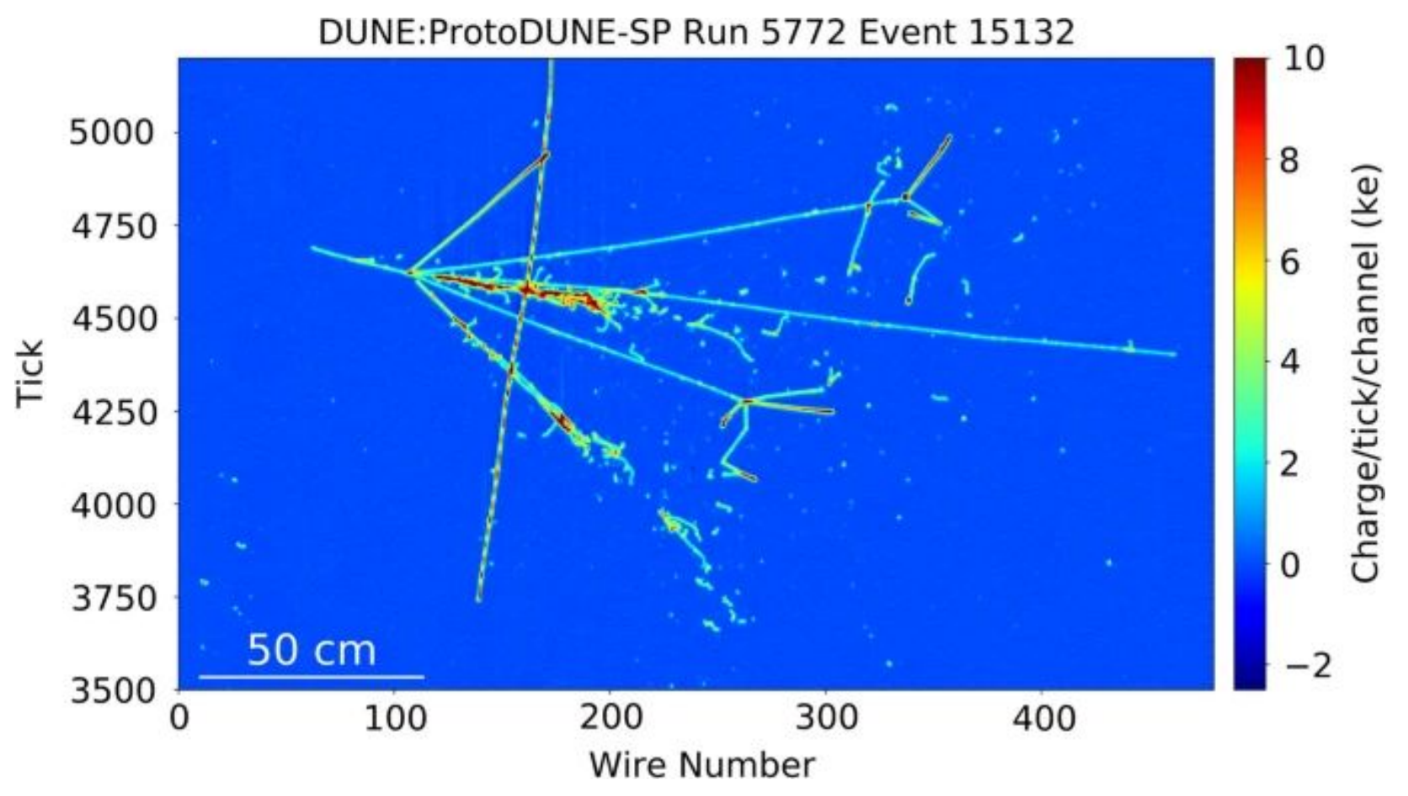




LAr TPC and particles reconstruction

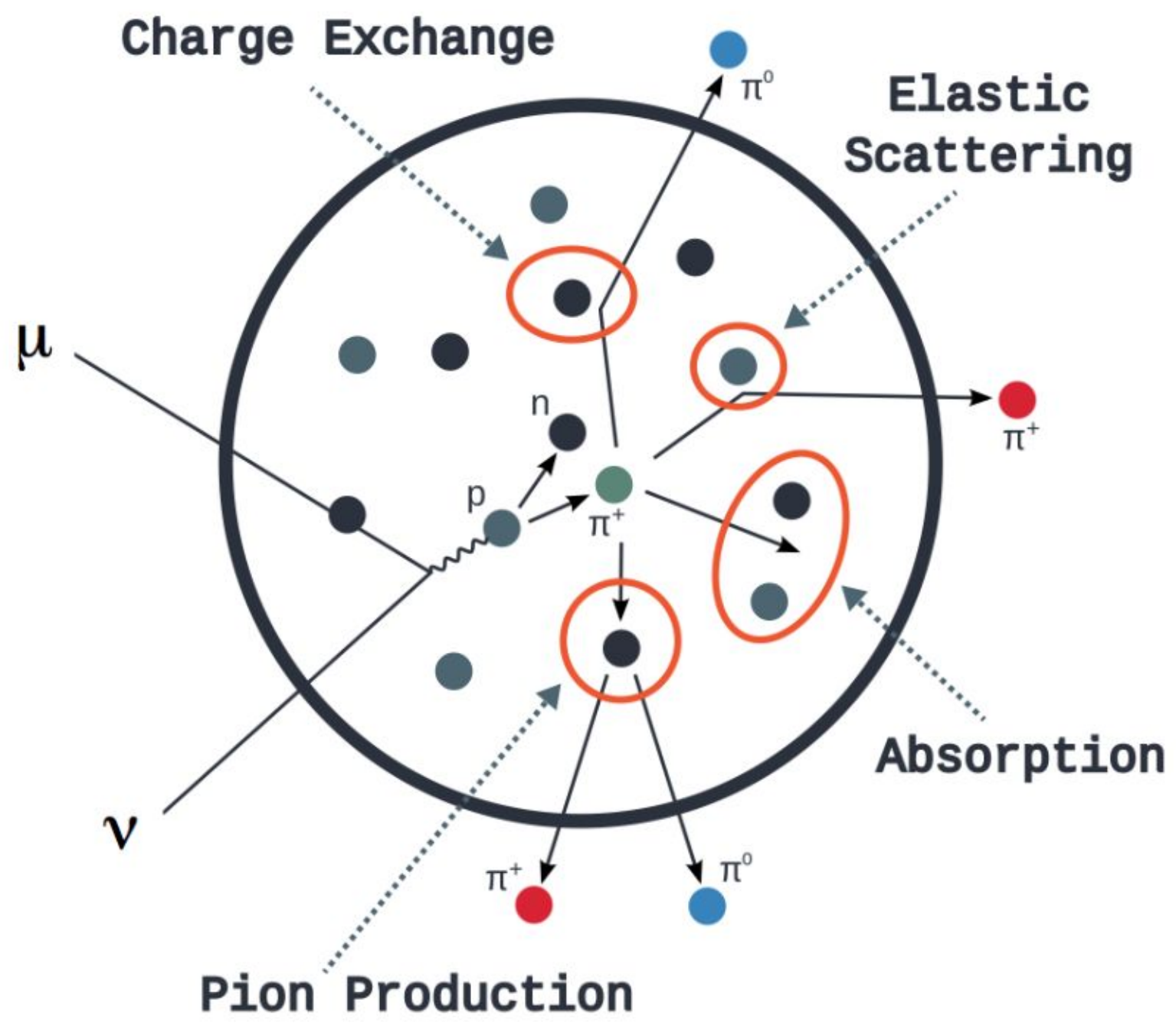
- Neutrinos interact with LAr nuclei. Their energy and flavour reconstructed from particles in final state via ionization
  - charged particles measured by dE/dx
  - neutral particles observed via interactions and their charged secondaries





- "Electronic bubble chamber" with **very good energy and space resolution**
  - charged particles at ionization minimum deposit ~10k electrons/mm of path
  - space resolution ~1.5 mm

Neutrinos interactions final state particles

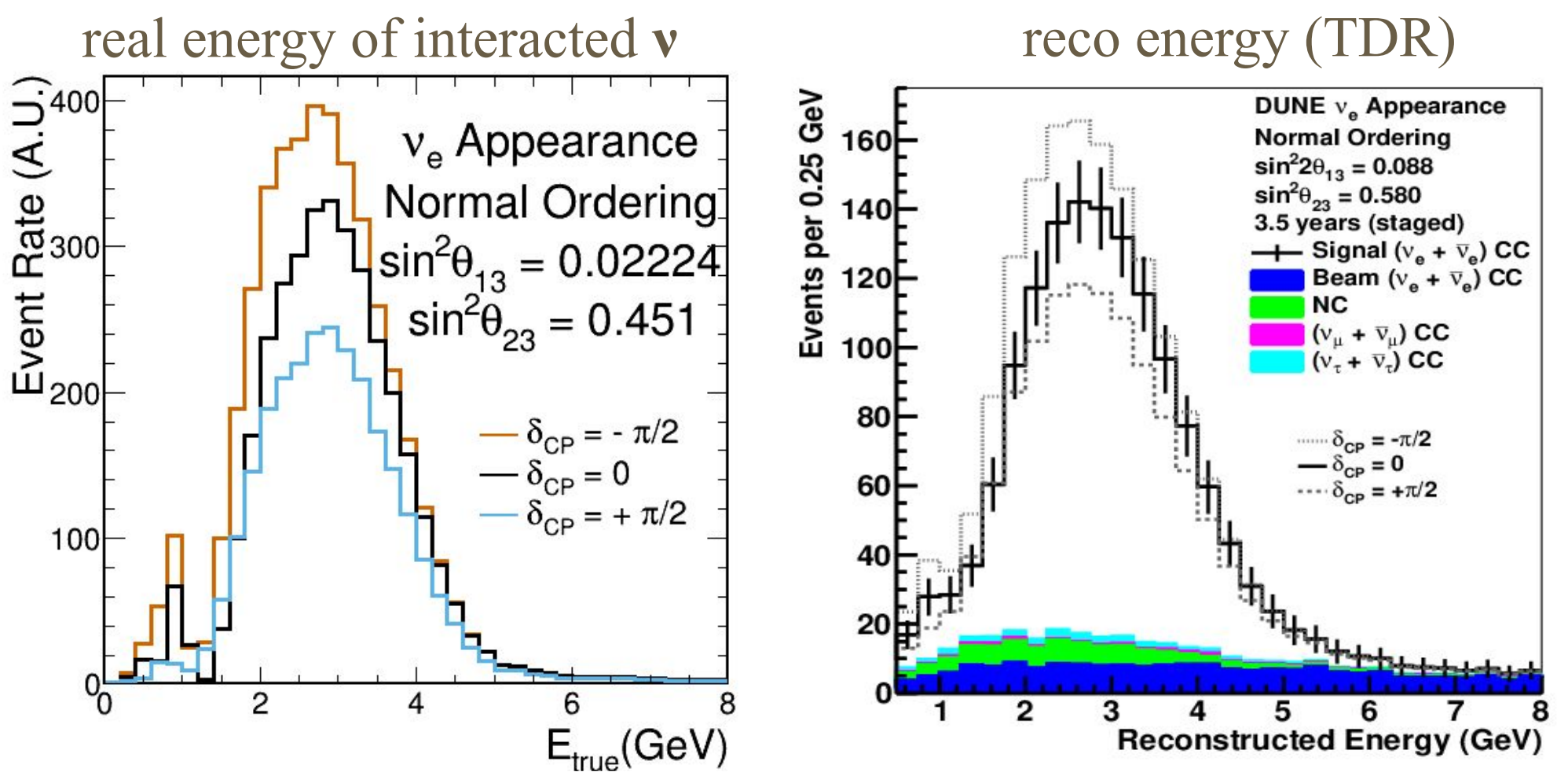


❖ Charged lepton of the corresponding flavour
❖ Nuclear effects: Fermi momentum and binding energy of the struck nucleon
❖ Hadronic cascade from nuclear rescattering and reinteractions

ν_e appearance energy spectrum

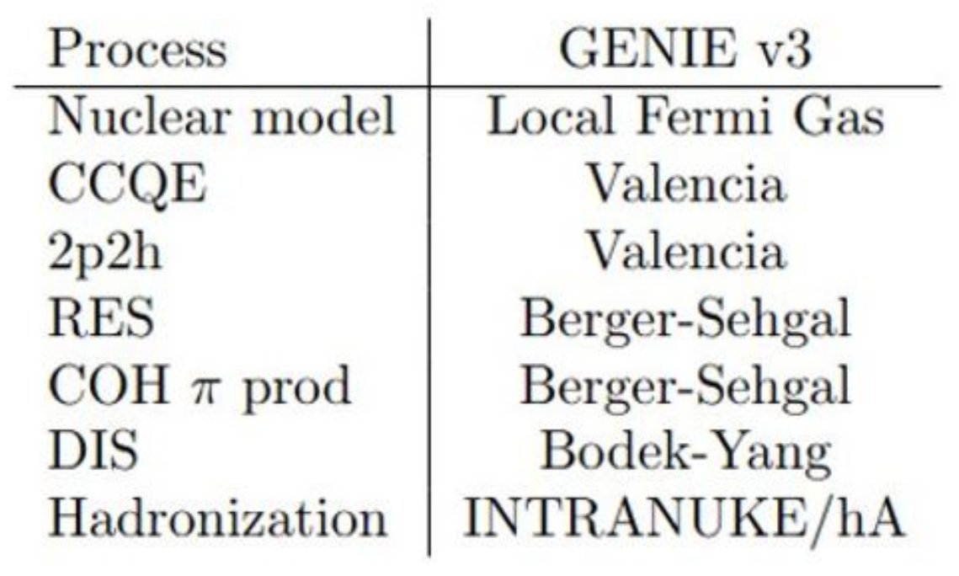
Convolution of :

- incoming neutrino flux
- oscillation probability
- neutrino nucleus cross sections
- detector resolution


real energy of interacted ν
reco energy (TDR)

Event generators

- **GENIE:** G1810a0211a
- **GiBUU**: detailed description of nuclear effects

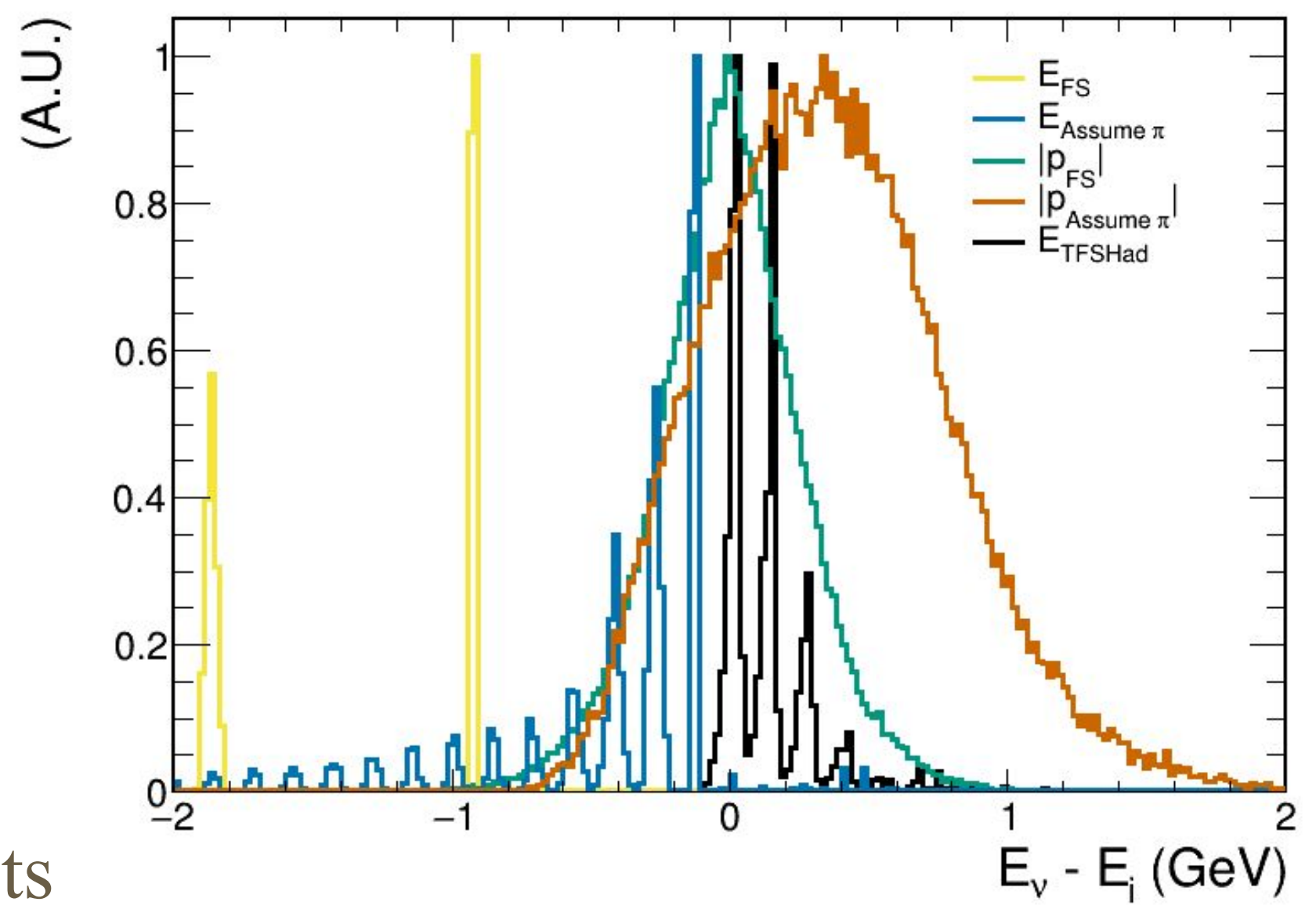


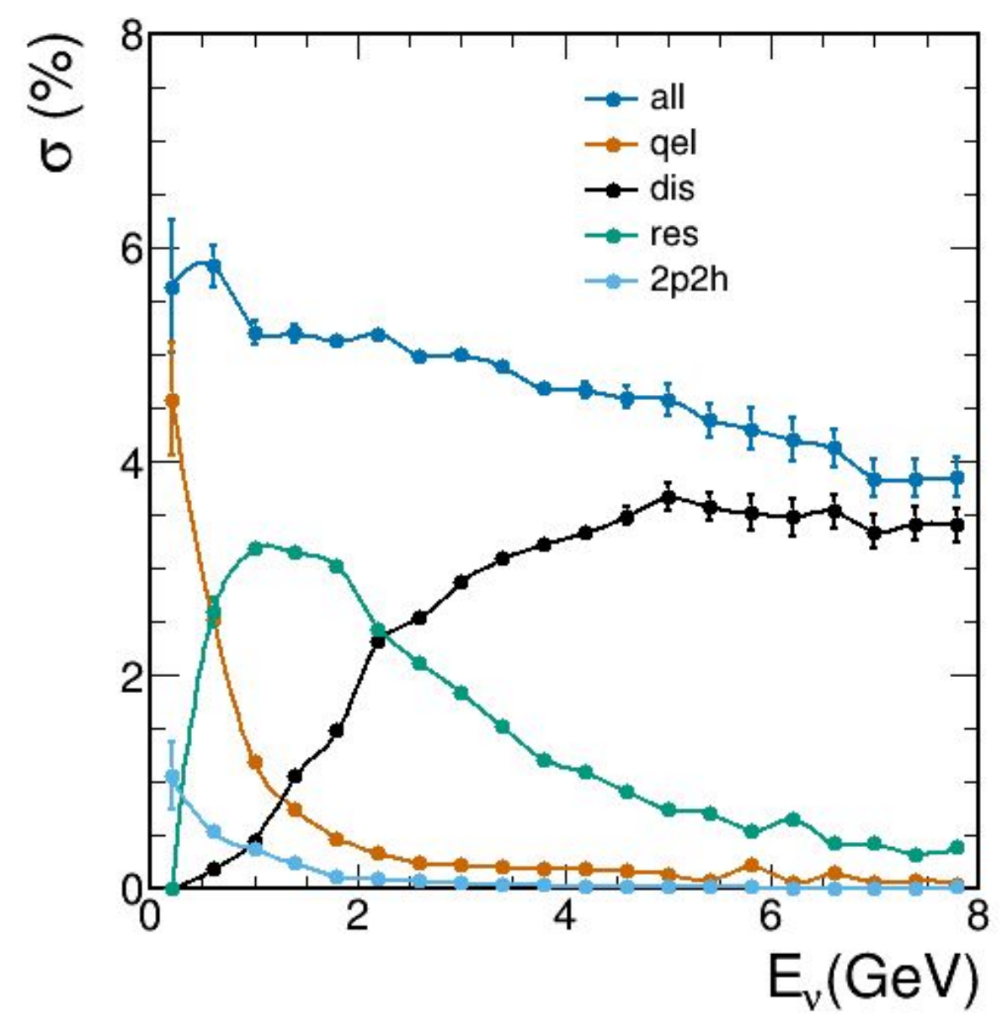
Process	GENIE v3
Nuclear model	Local Fermi Gas
CCQE	Valencia
2p2h	Valencia
RES	Berger-Sehgal
COH π prod	Berger-Sehgal
DIS	Bodek-Yang
Hadronization	INTRANUKE/hA

Simulation and results

How to compute E_ν from observed particles?

1. Total true final state energy: $E_{FS}^{\text{true}} = E_\ell + \sum_i^{p,n,\pi,oth} E_i$
2. Assume that all hadrons are π : $E_{\text{assume }\pi}^{\text{true}} = E_\ell + \sum_i^{p,n,\pi,oth} (T_i + m_\pi)$
3. True momentum $\left|p_{FS}^{\text{true}}\right| = \left|p_\ell + \sum_i^{p,n,\pi,oth} \vec{p}_i\right|$
4. $\left|p_{\text{assume }\pi}^{\text{true}}\right| = \left|\vec{p}_\ell + \sum_i^{p,n,\pi,oth} \left(\vec{p}_i \times \sqrt{(T_i + m_\pi)^2 - m_\pi^2}\right)\right|$
5. Neglect hadron masses : $E_{TFSHad}^{\text{true}} = E_\ell + \sum_i^{p,n,\pi,oth} T_i$



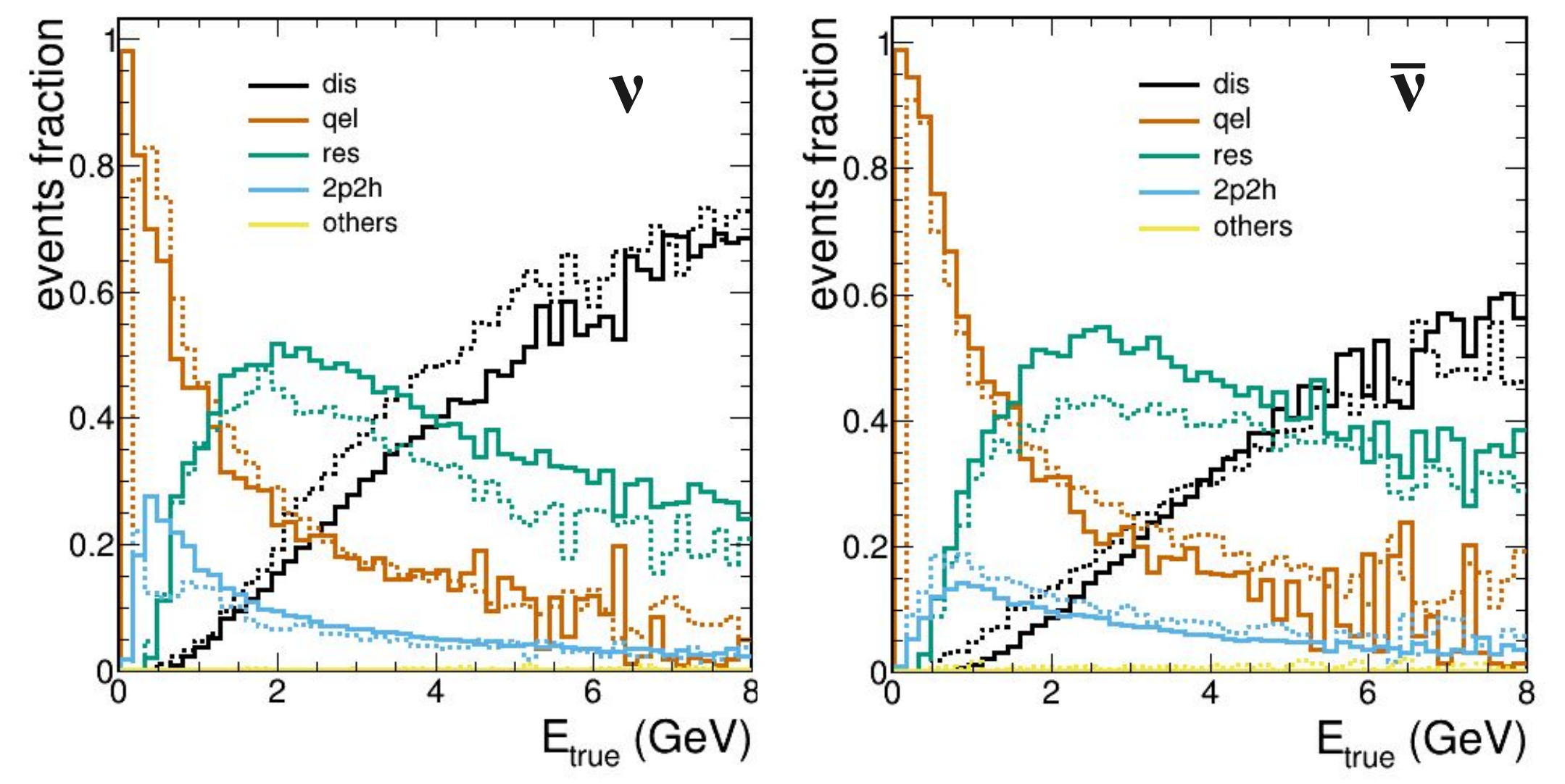


Adding masses (not necessarily created by E_ν) results in large bias and bad resolution

Best method: neglect hadron masses (use only E_k)
Neutrons included in the energy budget

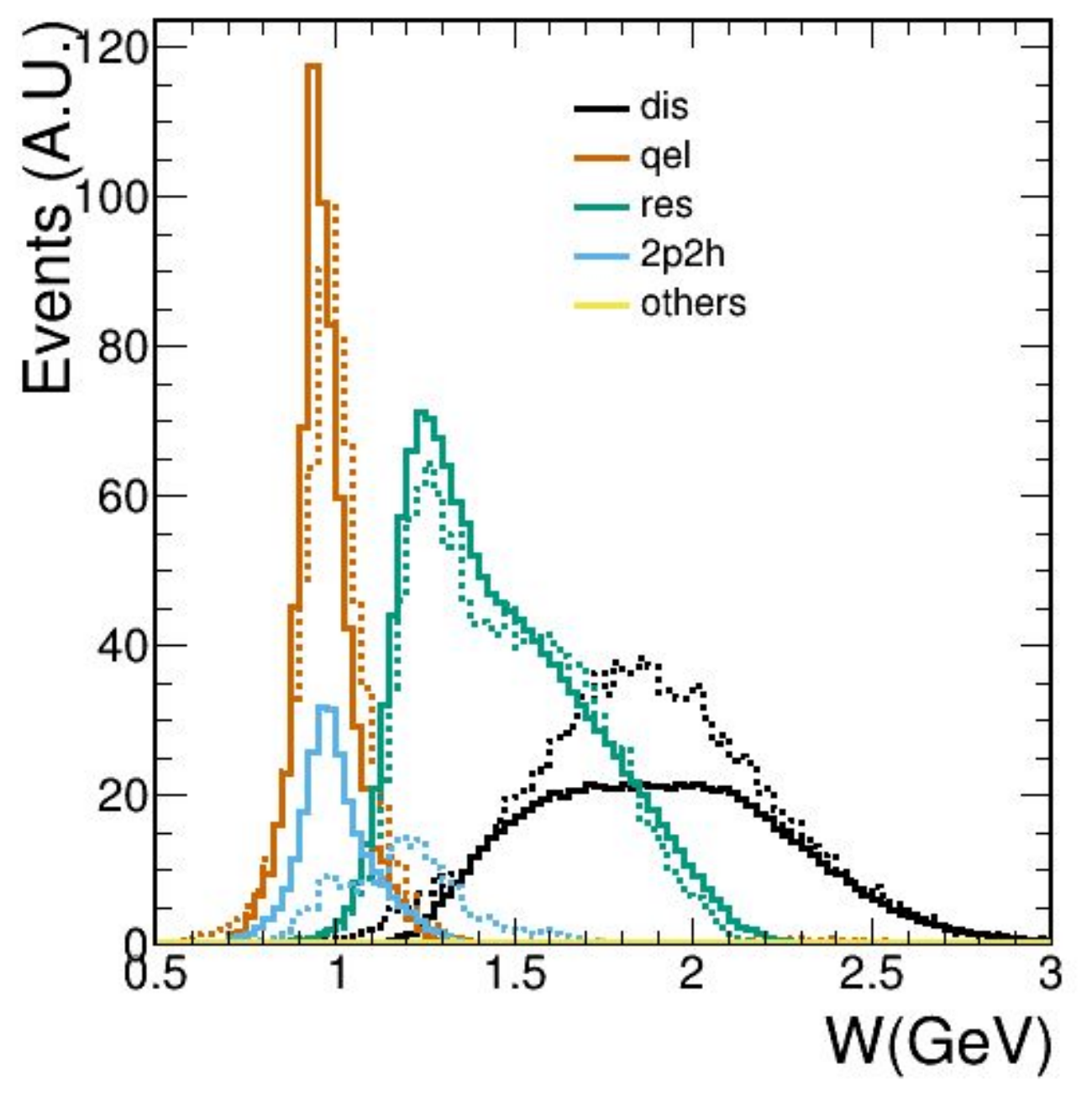
E_ν σ intrinsically limited by ν interaction physics
GENIE : σ = 5.5 %, bias = - 4%
GiBUU: σ = 6.2 %, bias = - 5%

Interaction processes: fractions of events as a function of energy



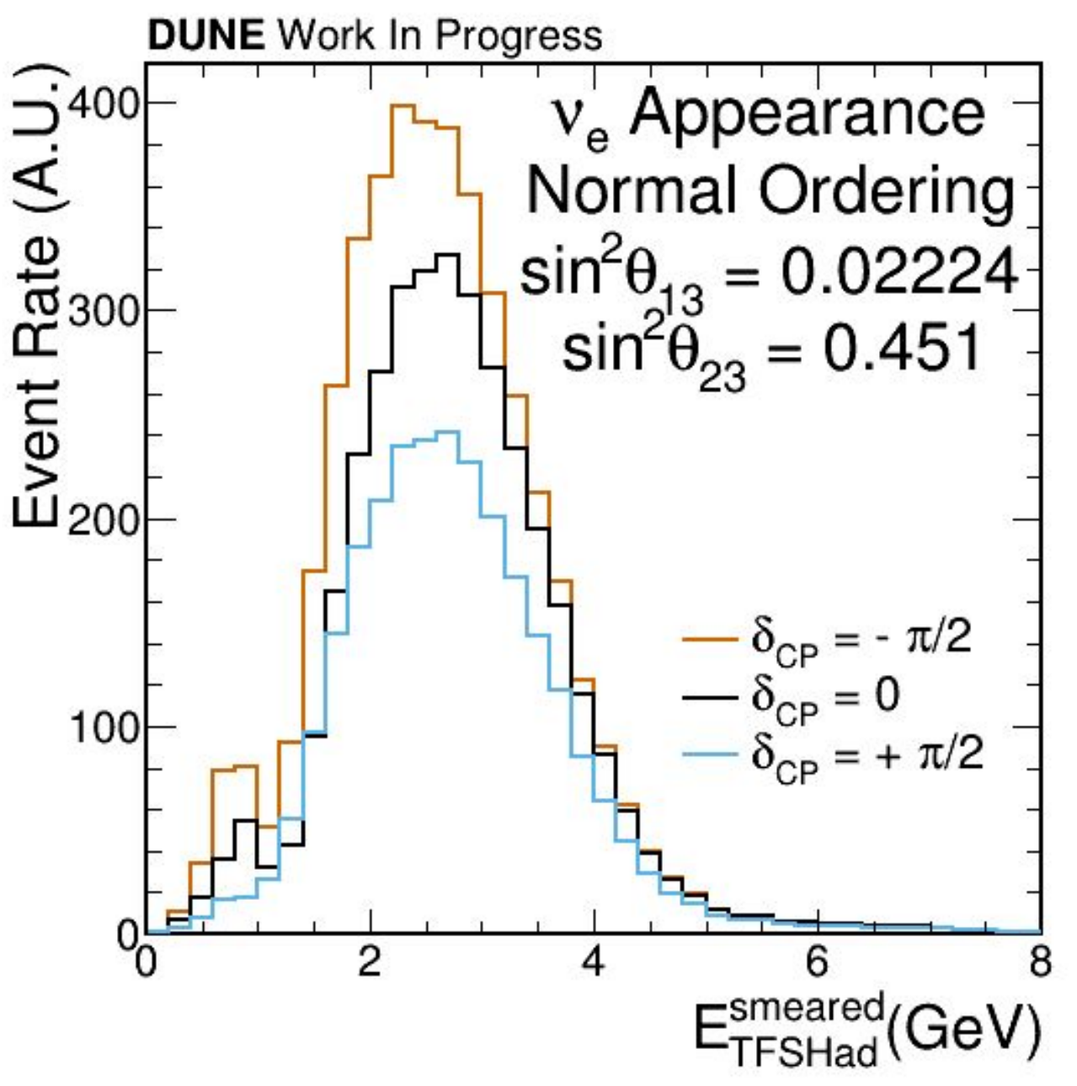
QE dominates at 2nd max
some model differences between GENIE and GiBUU for interplay between RES and DIS antineutrinos

W hadronic invariant mass as a function of the process



GENIE and GiBUU shows differences in DIS and 2p2h

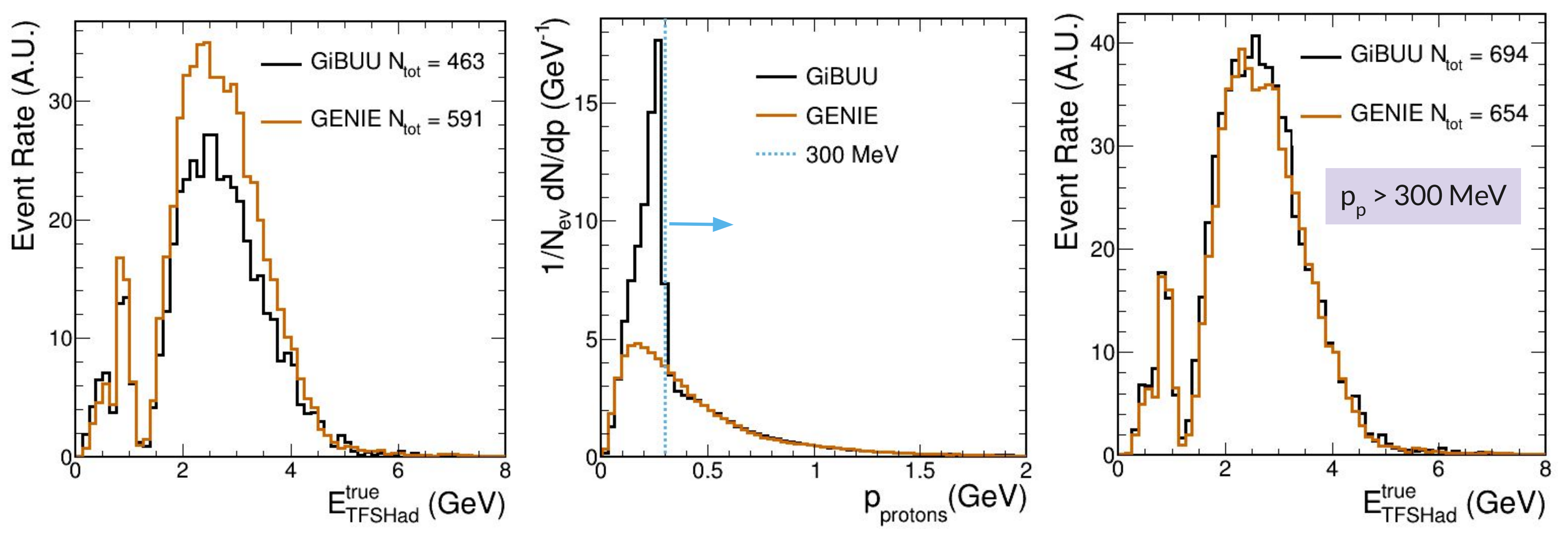
Reconstructed spectrum with best method for GENIE



Signal only no backgrounds, includes an optimistic particle-by-particle resolution smearing (~14% total resolution)

Is there a subsample with a better impact at the 2nd max?

1p0π sample: CCQE-like (ignoring neutrons)
NH $\delta_{CP} = 0$



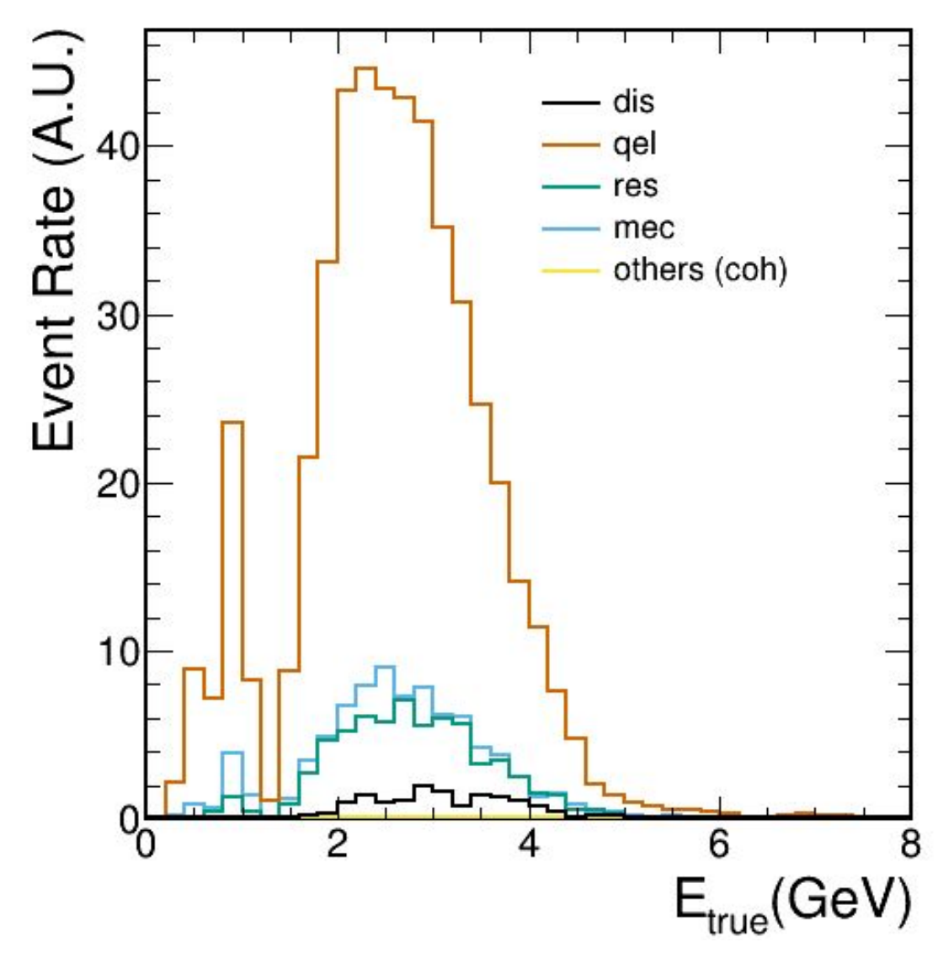
applying 300 MeV/c cut on proton momentum GENIE and GiBUU provide a similar results (less sensitive to nuclear rescattering)

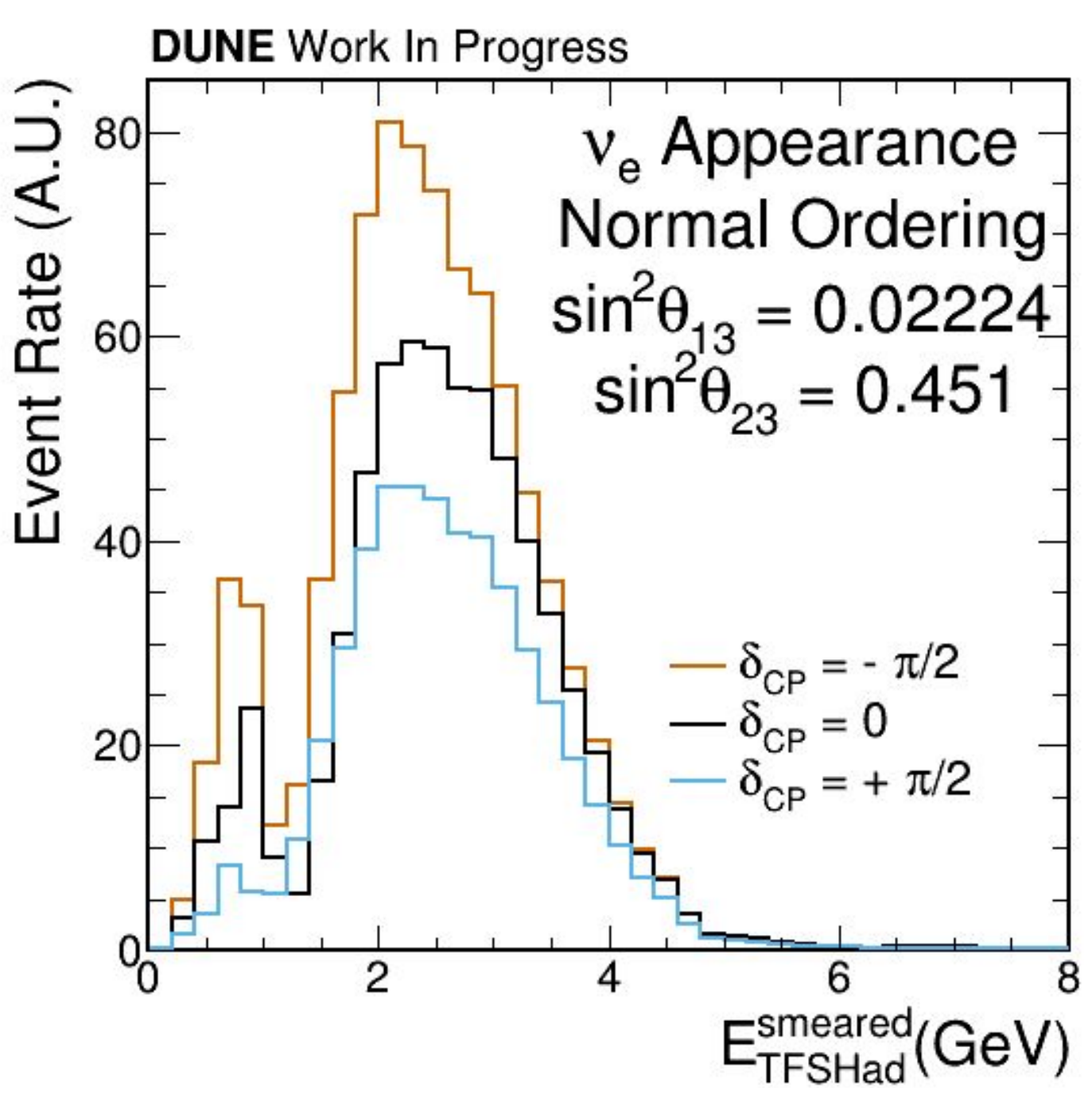
Benefit of separating out 1p0π sample

larger impact of the 2nd max

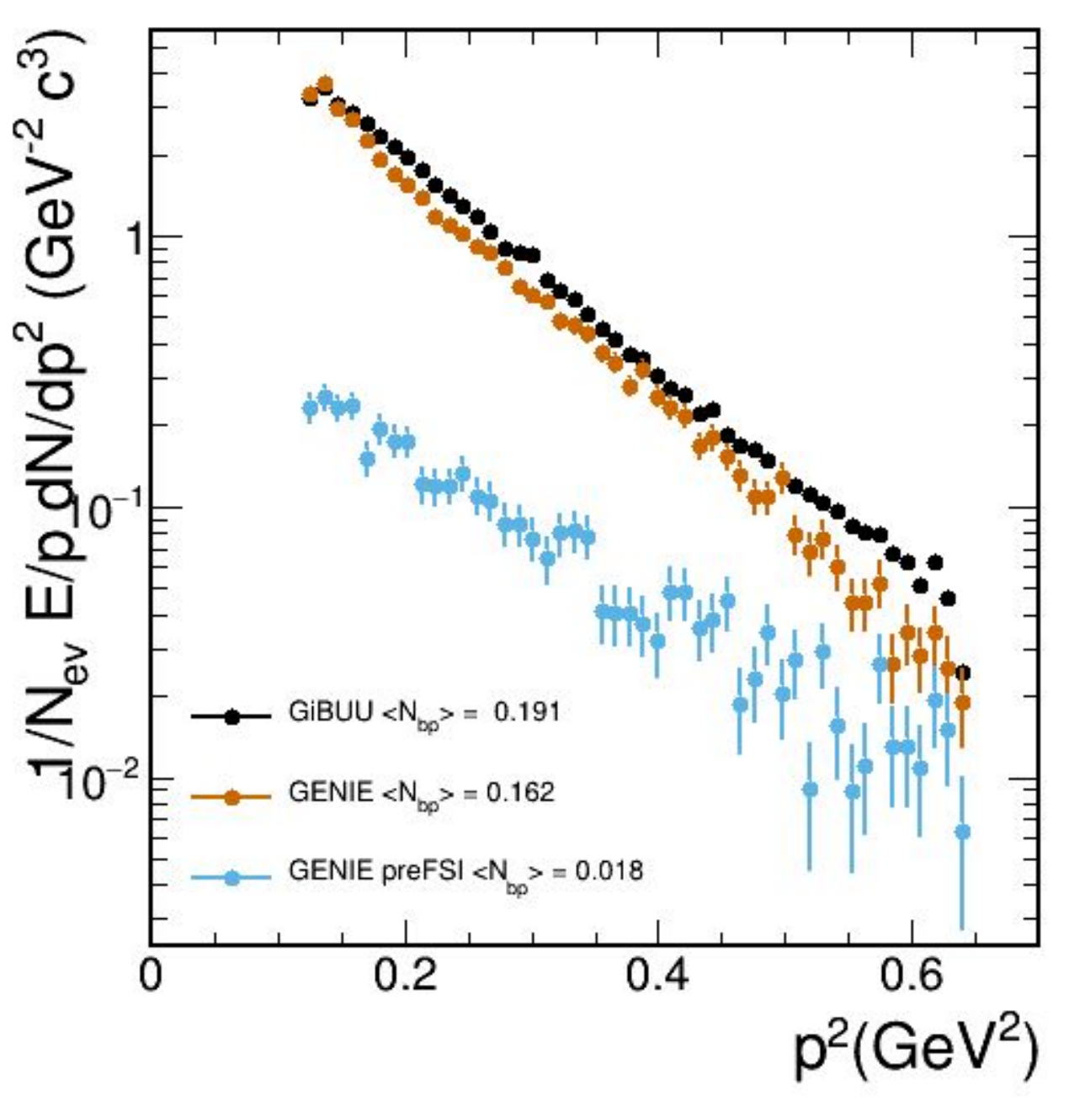
1. 1 proton 0 π
2. $p_{\text{protons}} > 300$ MeV

the CCQE-like sample is made mainly by QE interactions (neutrons ignored in the definition of the sample)





Backward going protons as data benchmark of nuclear effects



kinematically forbidden
probe of nuclear effects and rescattering
NOMAD measured an average rate (on carbon)

$$< N_{Bp} >_{350 \div 800 MeV/c} = \left[52.8 \pm 0.6(stat.) \pm 7(syst.) \right] \times 10^{-3}$$

and a slope parameter of **10.54 ± 0.20 ± 0.5**
while in this case (on argon)

$$< N_{Bp} >_{GiBUU} = (191.3 \pm 0.3) \times 10^{-3} \quad < N_{Bp} >_{GENIE} = (162.2 \pm 1.6) \times 10^{-3}$$

and a slope parameter respectively of **9.0±0.1** and **9.6±0.1**