UNBIASED RECONSTRUCTION OF CALORIMETRIC VARIABLES FOR CROSS-SECTION ANALYSES

NuXTract 2023 - Towards a consensus in neutrino cross sections

2-6 October 2023, CERN

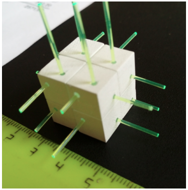
Katharina Lachner | Methods Session | 3 October 2023

Outline

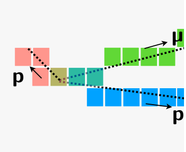
Motivation

Case study for the SuperFGD of the T2K ND280 upgrade:

- Hadronic system in ν_μCC-interactions contains valuable information
- Proton reconstruction threshold [1]: 300 MeV/c momentum
- Vertex activity: 38% of $\nu_\mu CC0\pi$ events have un-tracked protons
- Particles with momenta below track reconstruction still deposit energy $\Rightarrow$ calorimetry!



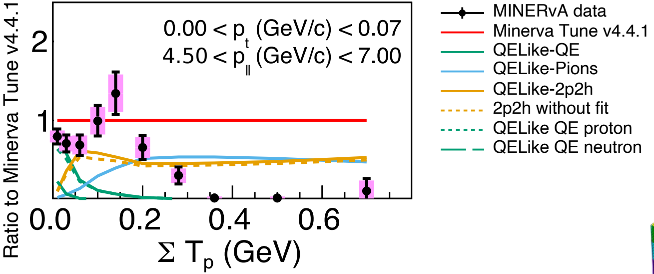
[2]



Minerνa: μ and p kinematics in CC0π

Recent $\frac{\mathrm{d}^3\sigma}{\mathrm{d}p_{\mu,\,\parallel}\,\mathrm{d}p_{\mu,\,t}\,\mathrm{d}\Sigma T_p}$ measurement by Minerνa [3]:

- Analysis reconstructs ΣT_p calorimetrically from visible/available energy in CC0π (CCQE-like) samples
- Discrepancy between ref. model and data at low $p_{\mu,\,t}$:



Calorimetry in practice

- **Visible energy in detector units**: $\mathrm{d}L/\,\mathrm{d}x$, e.g. scintillation light yield [p.e.], or ionisation charges created in a TPC
- **Visible energy in energy units**: $\mathrm{d}Q/\,\mathrm{d}x$, calibrated detector readout, corrected for inefficiencies
- **Energy loss**: $\mathrm{d}E/\,\mathrm{d}x$, the energy lost by the particle to create the visible energy, accounting for material effects

Calorimetry in practice

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linear

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linear

non-linear

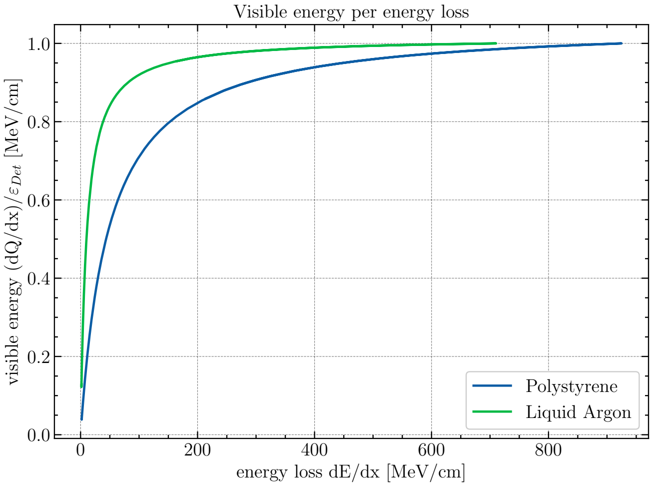
Energy loss in matter

- Energy loss in the material follows Bethe-Bloch eq.
- Corresponding visible energy is post detector effects
  - Scintillators: Quenching effects
  - TPCs: Recombination
- Resulting measured visible energy does not correspond linearly to the energy loss of the particle
- Birks law offers an approximation [4]

$$\frac{\mathrm{d}Q}{\mathrm{d}x} \propto \frac{1}{1 + c \cdot \frac{\mathrm{d}E}{\mathrm{d}x}} \cdot \frac{\mathrm{d}E}{\mathrm{d}x}$$

- Alternative: modified box model $\uparrow \cdot \ln(A + B \cdot \frac{\mathrm{d}E}{\mathrm{d}x})$ [5]

Visible energy vs. energy loss



Proton stopping power from [6], material constants from [5, 7].

Reconstruction for plastic scintillators

$$\mathrm{d}E_{\text{hit}}^{\text{reco}} = corr_{Birks}^{-1}\left(\frac{\mathrm{d}Q}{\mathrm{d}x},\ \text{material}\right) \times \mathrm{d}Q$$

for visible energy $\mathrm{d}Q$ in a track segment $\mathrm{d}x$, and:

- Empirical calibration turning light yield[1] to visible energy: $\mathrm{d}Q[MeV] = \mathrm{d}L[p.e.]/(c_{calib} \cdot \varepsilon_{eff})$ from cosmics/test beam
- $corr_{Birks}^{-1}(\mathrm{d}x, E) = \frac{1}{1 - c_B \cdot \mathrm{d}E/\mathrm{d}x}$, with Birks' const. c_B

Note: this should be applied on *individual* particles

[1]After correction for fibre attenuation.

Reconstruction for TPCs

$$\mathrm{d}E_{\mathrm{hit}}^{\mathrm{reco}} = corr_{Birks}^{-1}\left(\frac{\mathrm{d}Q}{\mathrm{d}x},\ \mathrm{material}\right) \times \mathrm{d}Q$$

for visible energy $\mathrm{d}Q$ in a track segment $\mathrm{d}x$, and:

- Empirical calibration for attenuation (drift dist.) to visible energy read out as waveform, from cosmics/test beam
- $corr_{Birks}^{-1}(\mathrm{d}x, E) = \frac{1}{1-\alpha\cdot\mathrm{d}E/\mathrm{d}x}$, with $\alpha = k/(\tilde{E}\cdot\rho)$ for electric field $\tilde{E}$, material constant k and density ρ [5]

Note: this should be applied on *individual* particles

Visible energy $\leftrightarrow$ energy loss?

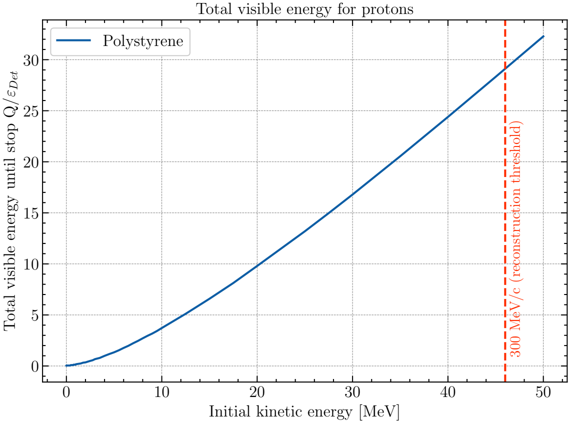
- Reconstruction of visible energy can be tuned with testbeams and cosmics (*single* particles)
- However, reconstruction of energy loss in *multi-track* events can lead to biased results
- Two choices for an analysis using calorimetric variables:
  A. Reconstruct energy loss assuming some number of particles in each detector hit
  B. Present result as differential cross section in terms of visible energy

A: Convert to MeV assuming 1 particle

- Assume a single particle in each reconstructed hit
  - Imprecise (and biased) for all reconstructed hits that contain summed energy deposit from multiple particles
- Alternatively, make assumptions on the expected number of particles
  - Model bias from any assumption on particle multiplicity
- But: truth is well defined
- Can unfold to a well-defined cross section

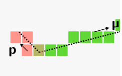
Example event in the SuperFGD

Reconstruct E_{kin} for given total Q...

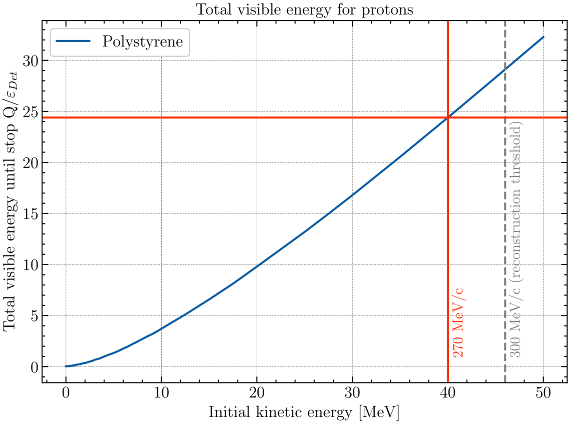


Example event in the SuperFGD

Reconstruct E_{kin} for given total Q assuming 1 proton...



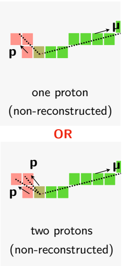
one proton
(non-reconstructed)

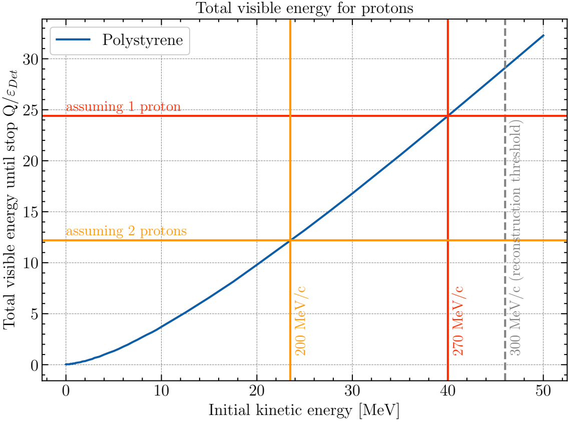


⇒ could be one proton at 40 MeV...

Example event in the SuperFGD

Reconstruct E_{kin} for given total Q assuming 1 vs. 2 protons:





⇒ could be one proton at 40 MeV or two at 23 MeV each.

How likely is this?

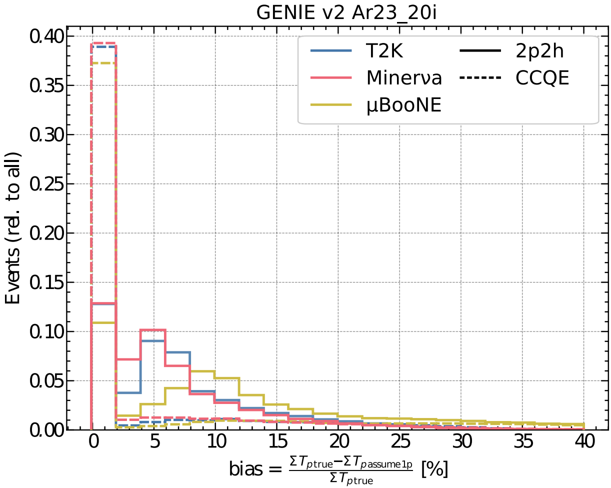
- Depends on proton multiplicity and energy split
- Determine bias event by event:

$$\text{bias} = \frac{\sum T_{p,\,\text{true}} - \sum T_{p,\,\text{assume }1p}}{\sum T_{p,\,\text{true}}}$$

- Small study based on predicted fluxes (via NUISANCE):
  - Focus on true CCQE and 2p2h interactions post FSI
  - Compare GENIE v2 for T2K, Minerνa, and μBooNE
  - Compare GENIE v2 to NEUT 5.6.0 SF, LFG for T2K
  - Work in progress for more models!

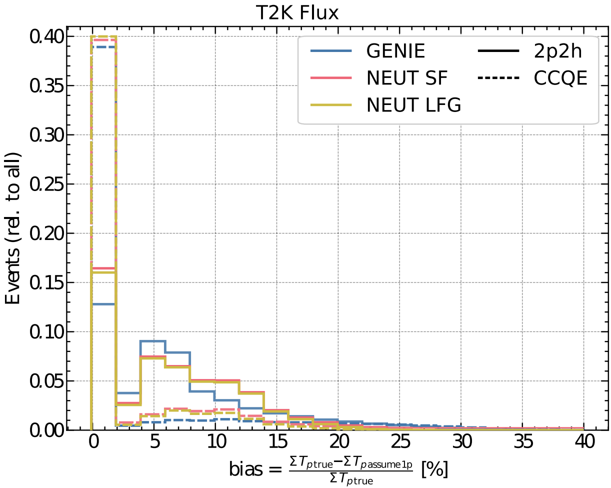
Bias in post FSI CCQE and 2p2h

Predictions from GENIEv2 for T2K, Minerνa, and μBooNE:



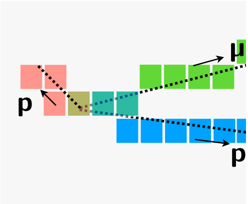
Bias in post FSI CCQE and 2p2h

Comparing different models, at predicted fluxes for T2K:

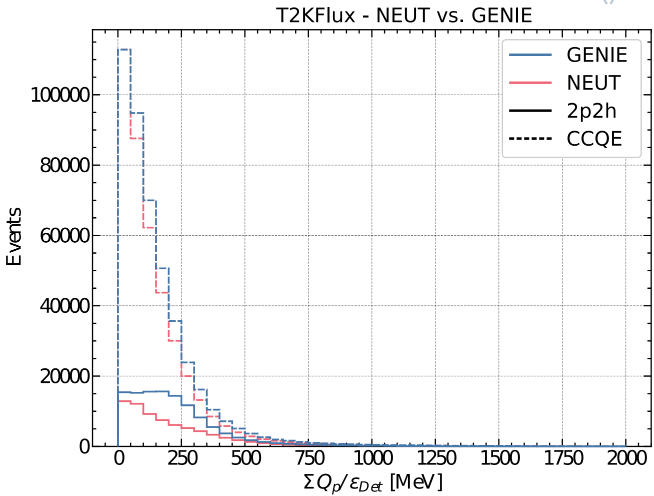


B: Analysis using visible energy

- Extract differential cross section in terms of visible energy
- No assumption on the number of particles in the hadronic system required ⇒ avoids potential bias
- But: would require new models to be forward-folded
- Result is detector-specific



Example: ΣQ from NEUT vs. GENIE



$\Rightarrow$ Can still see difference between models in ΣQ_p

Forward folding to detector units

If we had the perfect tool to display new models forward-folded alongside experimental data...

- Unclear how to compare *how wrong* models are w.r.t. one detector vs. another
- Might be hard for a theorist to draw conclusions about new model
  - "What does it mean for my model to have too few events at low SuperFGD proton light yield?"

See Lukas's talk for more details on forward folding [previous talk].

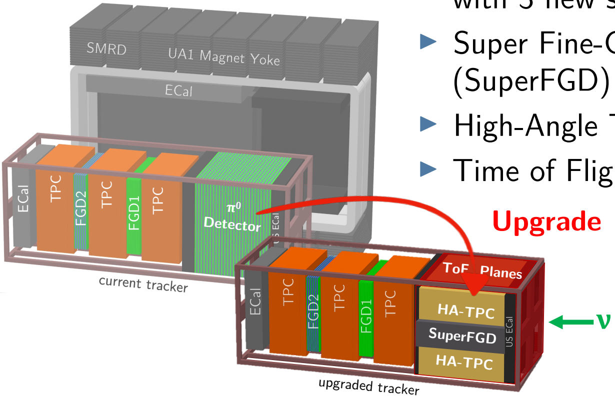
Summary

- Valuable information on nuclear effects in calorimetric variables such as the hadronic energy
- Reconstructed particle energy loss is potentially biased when the particle multiplicity is unknown
  - Aside: this could also affect neutrino energy reconstruction if based on total visible energy
  - Ongoing study to evaluate different model predictions
- Forward folding: approach to avoid bias by working with visible energy instead, at the cost of providing results that may be harder to interpret
- How can we best present results of analyses using calorimetric variables?

Backup

The Off-Axis Near Detector ND280

- Original geometry:



- Replacing the π^0 detector with 3 new sub-detectors
- Super Fine-Grain-Detector (SuperFGD)
- High-Angle TPCs (HA-TPCs)
- Time of Flight planes (ToF)

[8, 9]

Energy loss for 1 particle

$\mathrm{d}Q$ caused by one particle:

$$\frac{\mathrm{d}E}{\mathrm{d}x}\left(\frac{\mathrm{d}Q}{\mathrm{d}x}\right)_{1p} = \frac{1}{1 - c_B \frac{\mathrm{d}Q}{\mathrm{d}x}} \cdot \frac{\mathrm{d}Q}{\mathrm{d}x} \tag{1}$$

Energy loss for 2 particles

$\mathrm{d}Q$ caused by two particles (with equal initial E_{kin} for simplicity):

$$\frac{\mathrm{d}E_{tot}}{\mathrm{d}x}\left(\frac{\mathrm{d}Q_1}{\mathrm{d}x}+\frac{\mathrm{d}Q_2}{\mathrm{d}x}\right)_{2p} = \frac{\mathrm{d}E_1}{\mathrm{d}x}\left(\frac{\mathrm{d}Q_1}{\mathrm{d}x}\right)+\frac{\mathrm{d}E_2}{\mathrm{d}x}\left(\frac{\mathrm{d}Q_2}{\mathrm{d}x}\right) \tag{2}$$

$$\text{assume } \frac{\mathrm{d}Q_1}{\mathrm{d}x} = \frac{\mathrm{d}Q_2}{\mathrm{d}x} = \frac{1}{2}\frac{\mathrm{d}Q}{\mathrm{d}x} \Rightarrow \frac{\mathrm{d}E_1}{\mathrm{d}x} = \frac{\mathrm{d}E_2}{\mathrm{d}x} = \frac{1}{2}\cdot\frac{\mathrm{d}E_{tot}}{\mathrm{d}x} \tag{3}$$

$$\frac{\mathrm{d}E_{tot}}{\mathrm{d}x}\left(\frac{\mathrm{d}Q_1}{\mathrm{d}x}+\frac{\mathrm{d}Q_2}{\mathrm{d}x}\right)_{2p} = \left(\frac{1}{1-c_B\cdot\frac{1}{2}\cdot\frac{\mathrm{d}Q}{\mathrm{d}x}}\cdot\frac{1}{2}\cdot\frac{\mathrm{d}Q}{\mathrm{d}x}\right)\cdot 2 \tag{4}$$

$$= \frac{1}{1-c_B\cdot\frac{1}{2}\cdot\frac{\mathrm{d}Q}{\mathrm{d}x}}\cdot\frac{\mathrm{d}Q}{\mathrm{d}x} \tag{5}$$

$$\neq \frac{\mathrm{d}E}{\mathrm{d}x}\left(\frac{\mathrm{d}Q}{\mathrm{d}x}\right)_{1p} \tag{6}$$

$\Rightarrow \mathrm{d}E_{tot}/\,\mathrm{d}x$ at a given $\mathrm{d}Q/\,\mathrm{d}x$ depends on particle multiplicity!

Energy loss for N particles

$\mathrm{d}Q$ caused by N particles, equally split between them:

$$\frac{\mathrm{d}E}{\mathrm{d}x}\left(\frac{\mathrm{d}Q}{\mathrm{d}x}\right)_{n\,p} = \frac{1}{1 - c_B \cdot \frac{1}{N} \cdot \frac{\mathrm{d}Q}{\mathrm{d}x}} \cdot \frac{\mathrm{d}Q}{\mathrm{d}x} \tag{7}$$

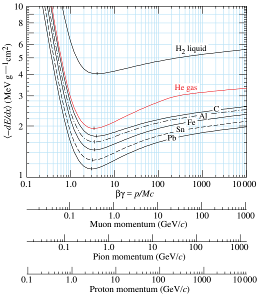
Bethe-Bloch Equation

Stopping power in units of energy per density:

$$-\frac{\mathrm{d}E}{\mathrm{d}x} = Kz^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

Where:

- $K = 4\pi N_A r_e^2 m_e c^2$
- W_{max} ... max. energy transfer to e^-
- I ... mean excitation energy
- $\delta(\beta\gamma)$ ... density correction



[10]

Density Correction Term $\delta(\beta\gamma)$

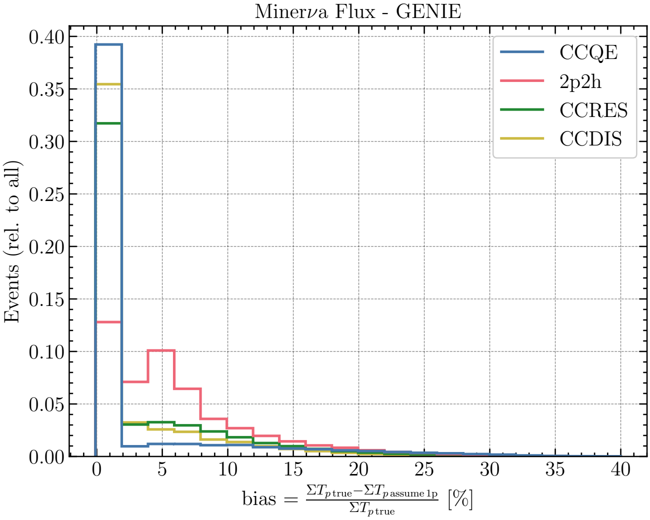
Density correction is calculated using Sternheimer parametrisation [11] with constants for polystyrene from [12]:

$$\delta(\beta\gamma) = \begin{cases} 2\ln(10)x + c & \text{if } x \geq x_1 \\ 2\ln(10)x + c + a(x_1 - x)^k & \text{if } x_0 \leq x < x_1 \\ 0 & \text{if } x < x_0 \text{ (nonconductors)} \end{cases}$$

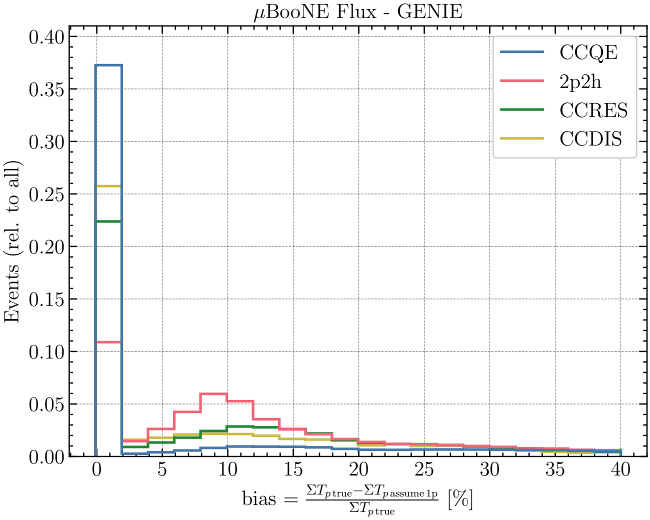
Where:

- $x = \log_{10}(\beta\gamma)$
- $x_0 = 0.1647$
- $x_1 = 2.5031$
- $c = -3.2999$
- $a = 0.16454$
- $k = 3.2224$

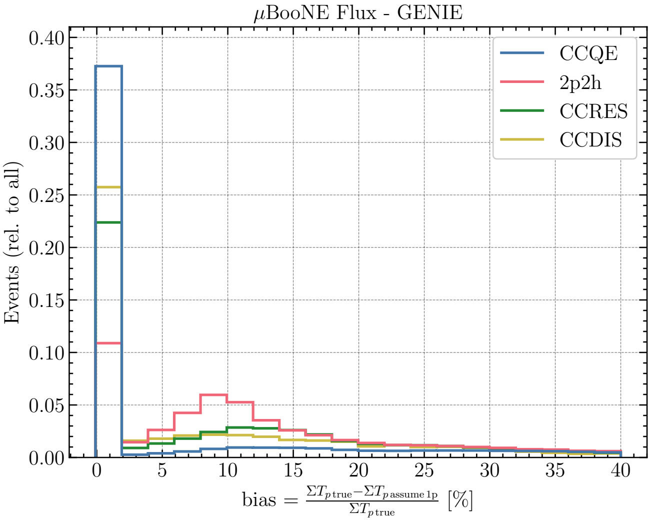
GENIEv2 Ar23_20i for Minerνa



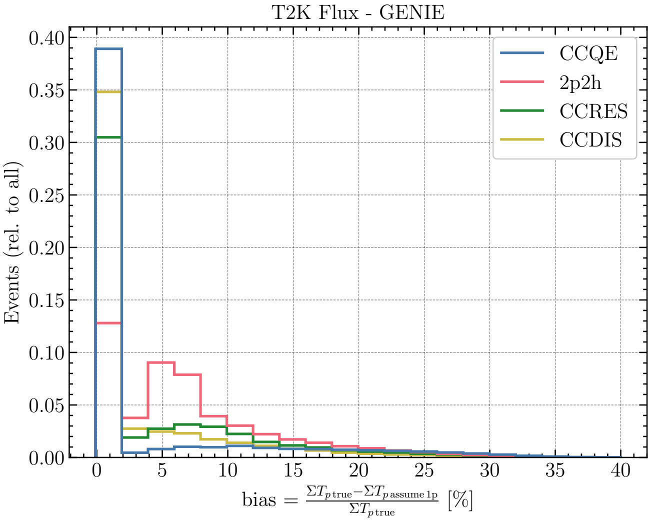
GENIEv2 Ar23_20i for μBooNE (LAr)



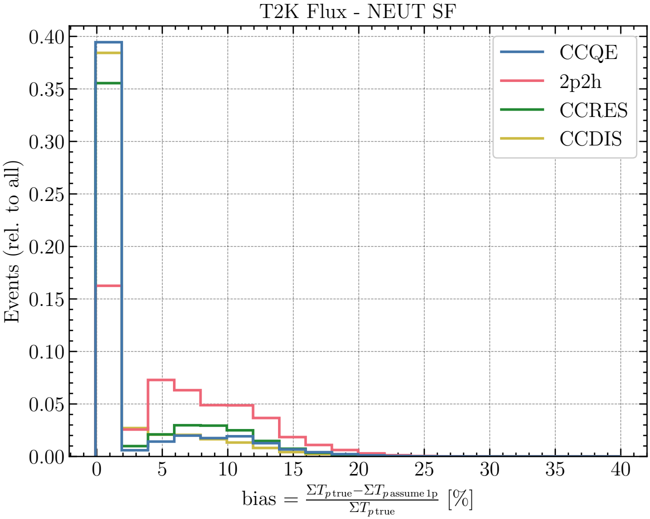
GENIEv2 Ar23_20i for μBooNE if **Polystyrene**



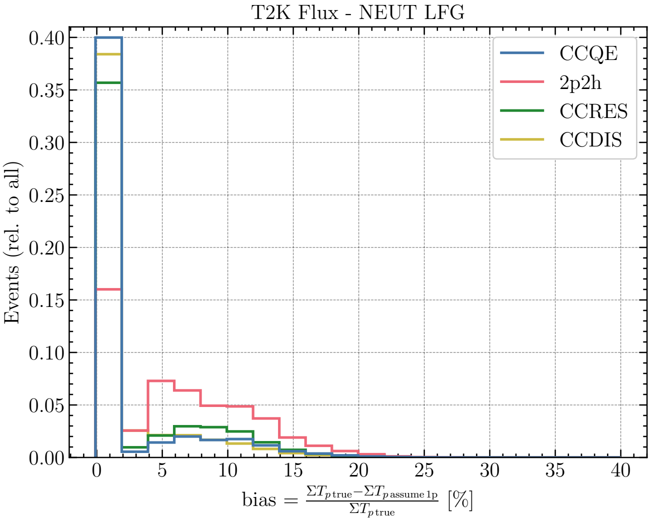
GENIEv2 Ar23_20i for T2K



NEUT 5.6.0 SF for T2K



NEUT 5.6.0 LFG for T2K



Reconstruction for TPCs (box model)

$$\mathrm{d}E_{\mathrm{hit}}^{\mathrm{reco}} = corr_{box}^{-1}\left(\frac{\mathrm{d}Q}{\mathrm{d}x},\ \mathrm{material}\right) \times \mathrm{d}Q$$

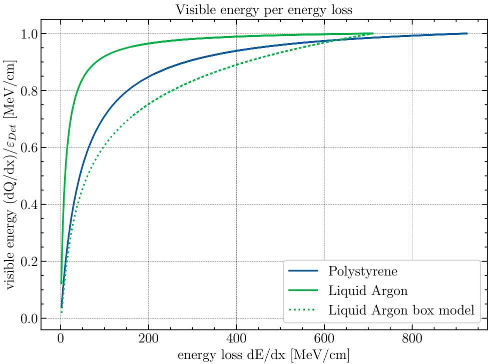
for visible energy $\mathrm{d}Q$ in a track segment $\mathrm{d}x$, and:

- Empirical calibration for ionisation charge readout (waveform) to visible energy, from cosmics/test beam
- $corr_{box}^{-1}(\mathrm{d}x, E) = \frac{1}{1 - B\alpha \cdot \mathrm{d}E/\,\mathrm{d}x} \cdot \ln(A + B\alpha \cdot \frac{\mathrm{d}E}{\mathrm{d}x})$, with $\alpha = 1/(\tilde{E} \cdot \rho)$ for electric field $\tilde{E}$, material constants A and B, and density ρ [5]

Note: this should be applied on *individual* particles

Modified box model in LAr

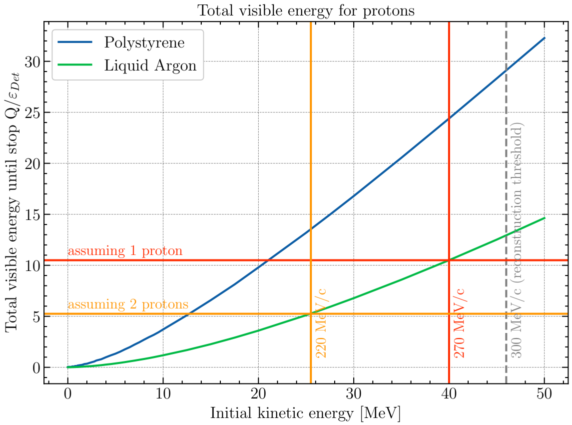
Plotting $\mathrm{d}Q/\,\mathrm{d}x$ for box model in addition:



Work in progress: The impact on bias evaluation when using the box model instead of Birks for LAr will be evaluated soon.

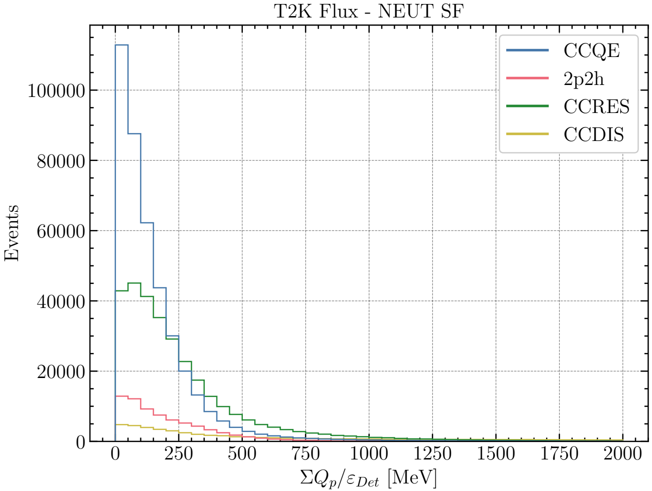
Example event in LAr

Reconstruct E_{kin} for given total Q assuming 1 vs. 2 protons:



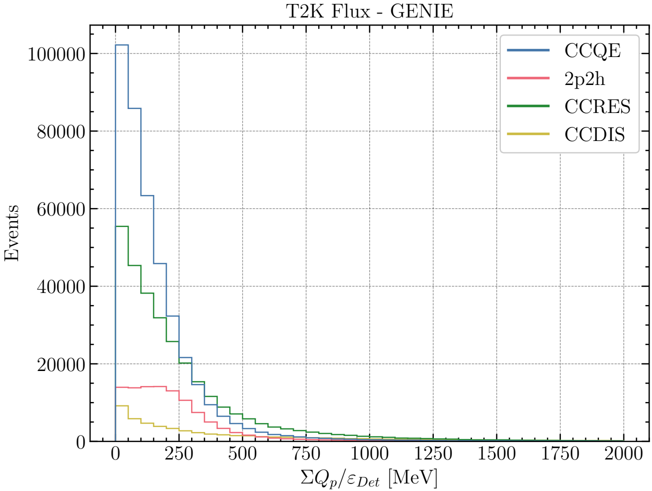
⇒ could be one proton at 40 MeV or two at 25.5 MeV each.

Proton ΣQ_p at T2K Flux[1]



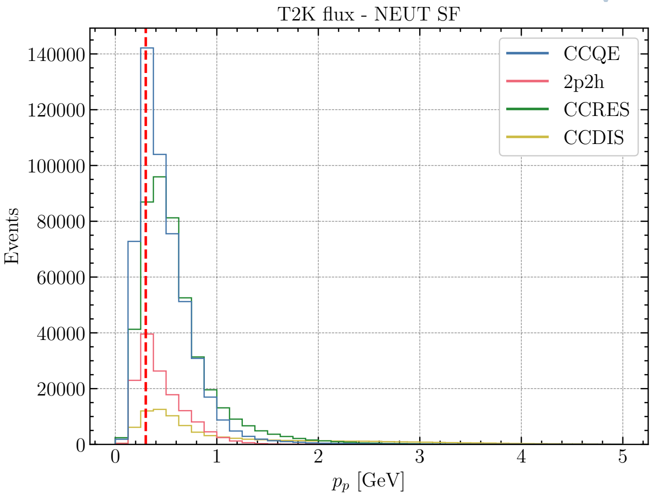
[1] NEUT 5.6.0 SF (post FSI), via NUISANCE

Proton ΣQ_p at T2K Flux, GENIE[1]



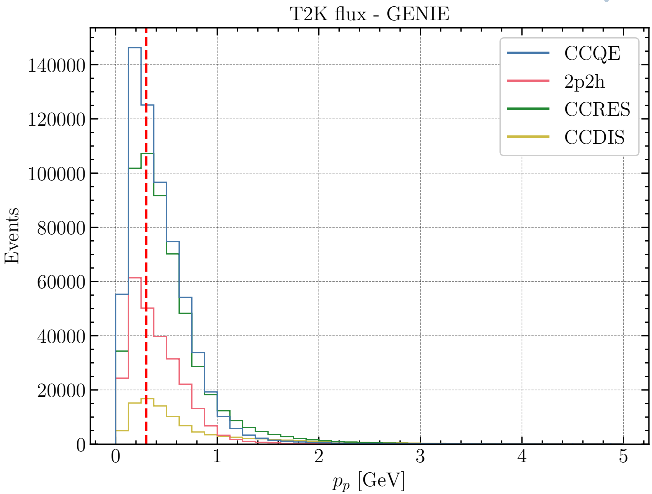
[1] NEUT 5.6.0 SF (post FSI), via NUISANCE

Proton momenta at T2K Flux[1]



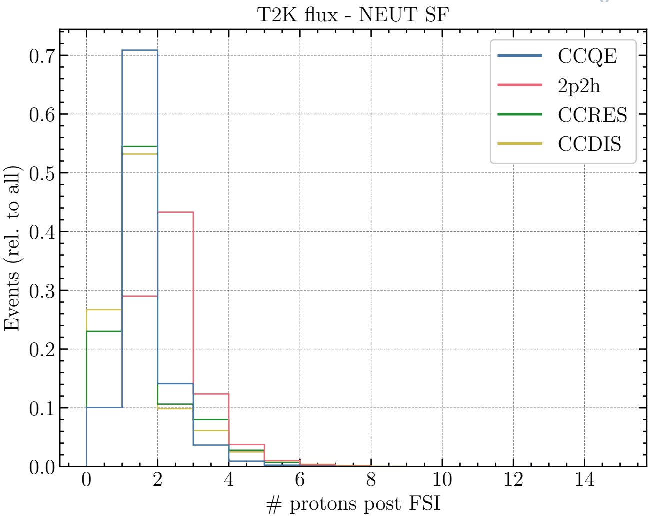
[1] NEUT 5.6.0 SF (post FSI), via NUISANCE

Proton momenta at T2K Flux, GENIE[1]



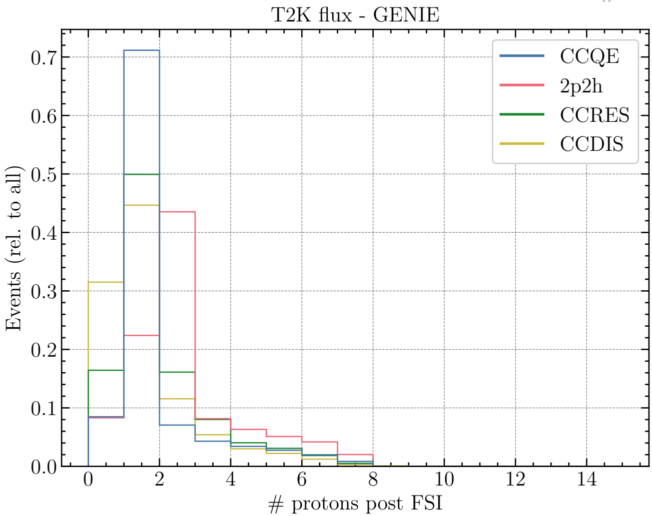
[1](post FSI), via NUISANCE

Proton multiplicity at T2K Flux[1]



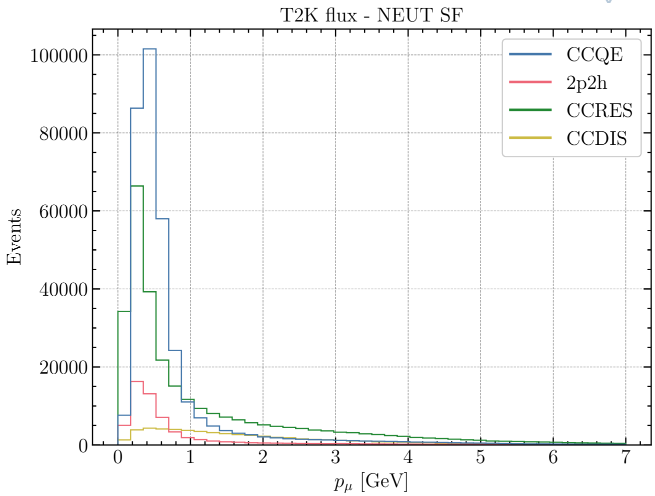
[1] NEUT 5.6.0 SF (post FSI), via NUISANCE

Proton multiplicity at T2K Flux, GENIE[1]



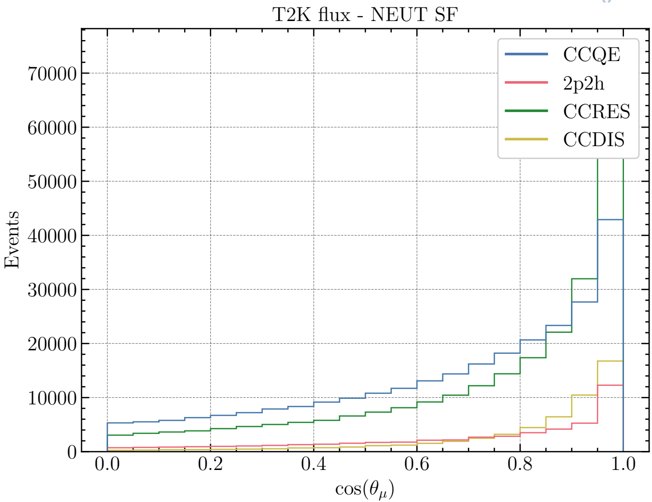
[1] (post FSI), via NUISANCE

Muon momenta at T2K Flux[1]



[1] NEUT 5.6.0 SF (post FSI), via NUISANCE

Muon angles at T2K Flux[1]



[1] NEUT 5.6.0 SF (post FSI), via NUISANCE

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[1] Stephen Dolan et al. Sensitivity of the upgraded t2k near detector to constrain neutrino and antineutrino interactions with no mesons in the final state by exploiting nucleon-lepton correlations. *Physical Review D*, 105(3):032010, 2022.

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