ν_μCC-0π cross-section measurement with calorimetric information in the SuperFGD

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Motivation

- Discrepancies between models and data in ν_μCC interactions without pions (ν_μCC-0π) at low energy transfer q_0 [1]
- Nuclear effects dominate systematic uncertainties for current T2K oscillation analyses
- SuperFGD track reconstruction threshold for protons: 300 MeV/c [2]
- Calorimetric approach allows to include protons below track reconstruction threshold in an inclusive variable: ΣT_p

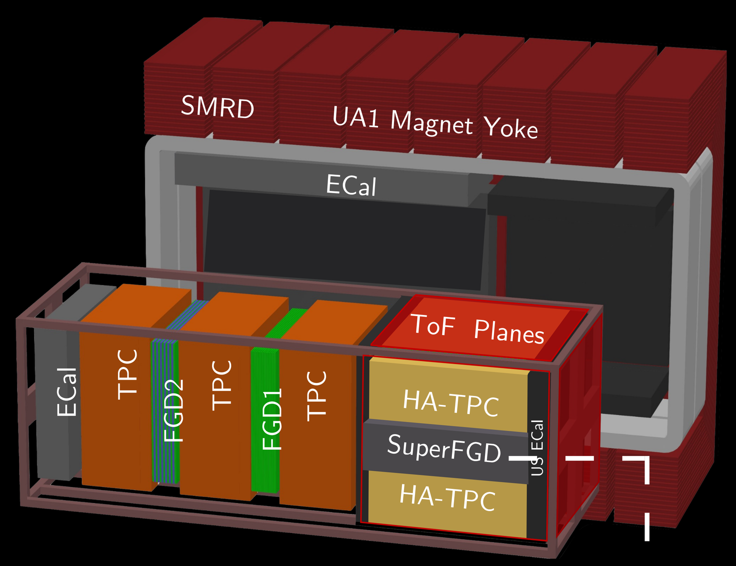
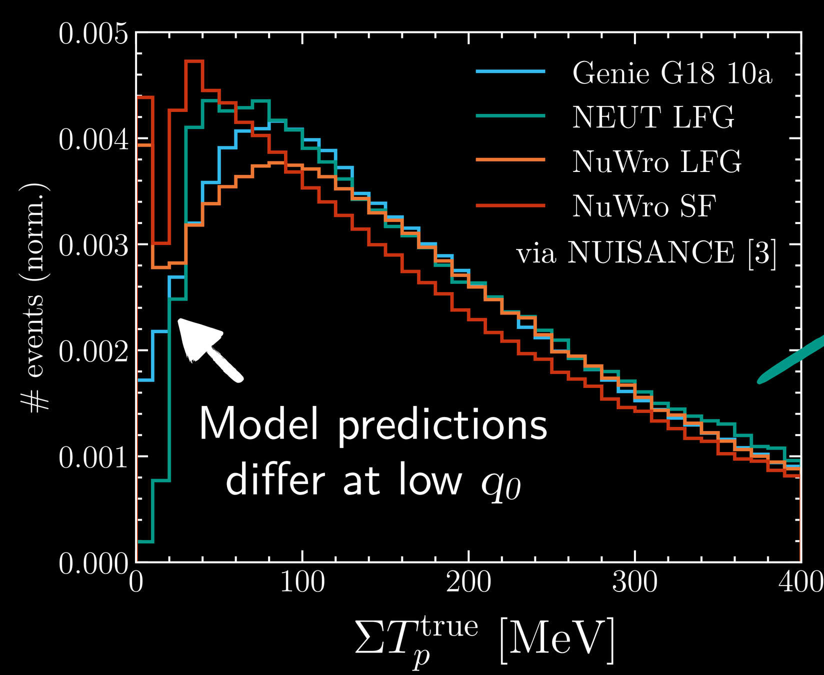


Fig. 1: Schematic of T2K's Upgraded Near Detector ND280.



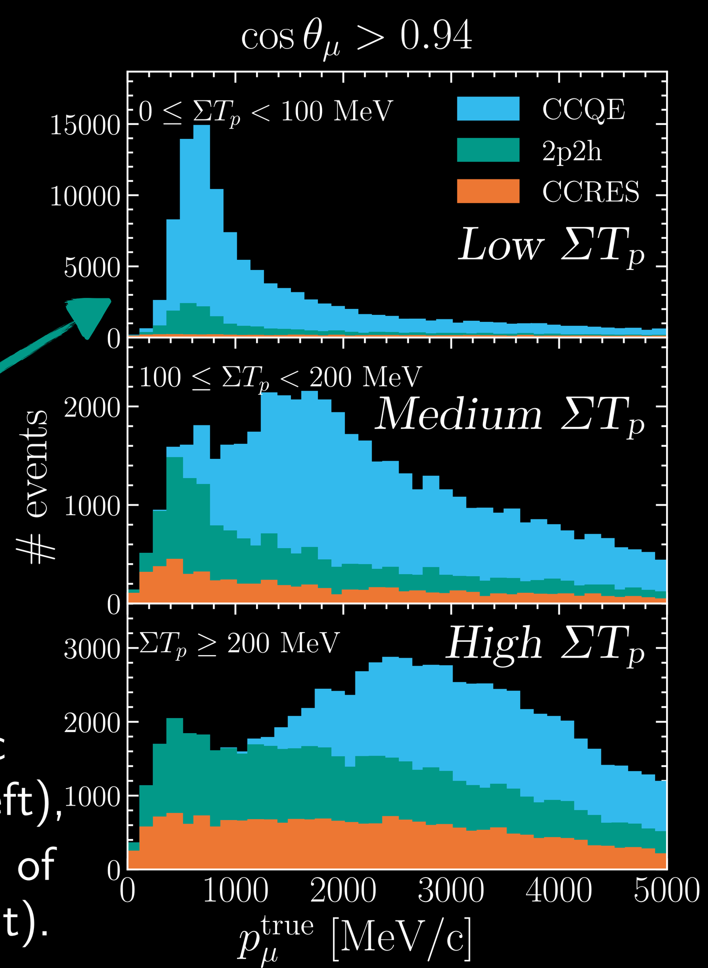


Fig. 2: Kinetic energy in the hadronic system ΣT_p for true ν_μCC-0π events (left), and slices of ΣT_p for low q_0 as function of muon momentum (for NEUT LFG, right).

Reconstruction of Calorimetric Variables

Proton light yield (ΣQ_p)

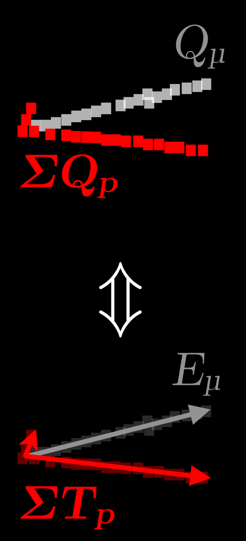
In pion-less topologies the sum of proton light yields, ΣQ_p, corresponds to the total measured light yield minus that of muons:

$$\Sigma Q_p = \Sigma Q_{SuperFGD} - Q_\mu \quad (1)$$

Light yield in vertex activity, ΣQ_{va}, can be extracted by additionally subtracting light yield of reconstructed proton tracks:

$$\Sigma Q_{va} = \Sigma Q_p - Q_p^{track} \quad (2)$$

These reconstructed quantities can be used to infer proton energies.



Proton energies (ΣT_p)

Birks' law [4] offers an empirical description of the correspondence between light yield and particle energy loss in a given distance dx:

$$\frac{dQ}{dx} = \varepsilon_{eff} \cdot \frac{dE}{dx} \cdot \frac{1}{1 + c_B \cdot \frac{dE}{dx}} \quad (3)$$

with scintillation efficiency ε_{eff} and Birks constant c_B. In integrated form this relates the total light yield to a particles initial kinetic energy T:

$$Q(T) = k \cdot \left(a \cdot T - \ln(a \cdot T)\right) \quad (4)$$

with material constants a and k.

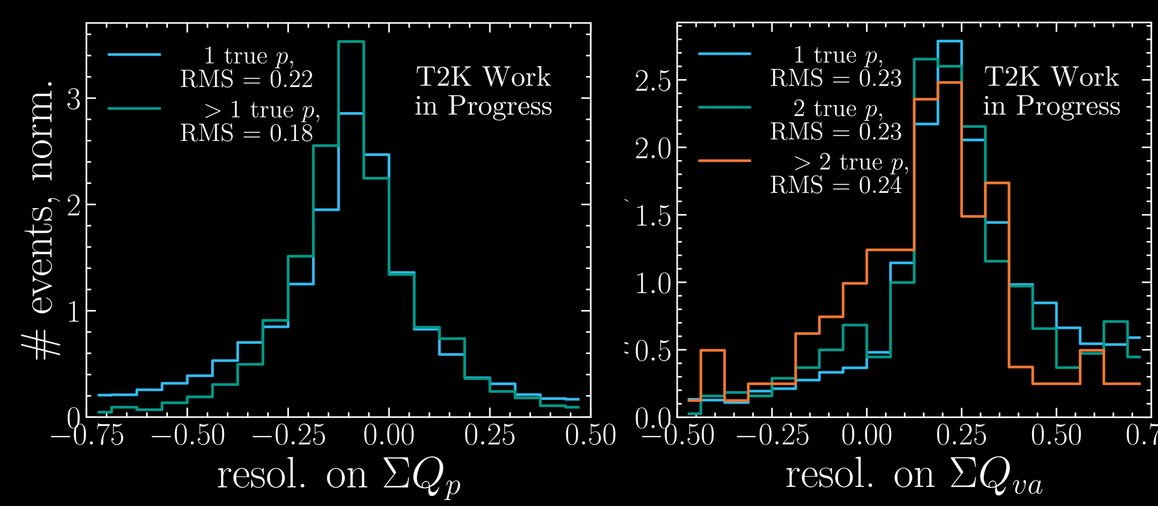


Fig. 3: Resolution for ΣQ_p (left) and ΣQ_{va} (right) in selected ν_μCC-0π events.

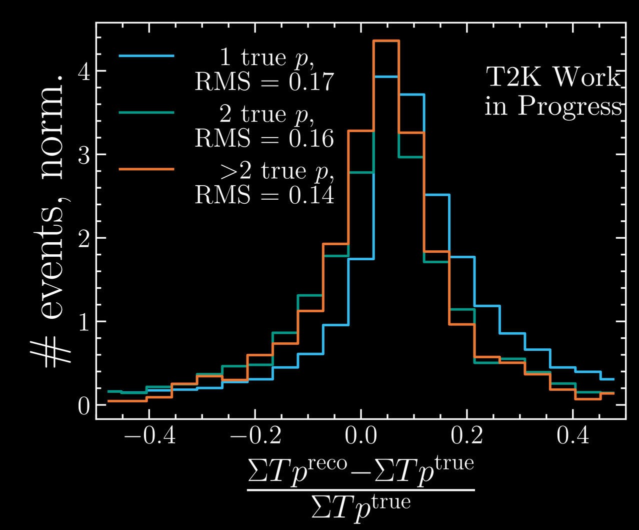
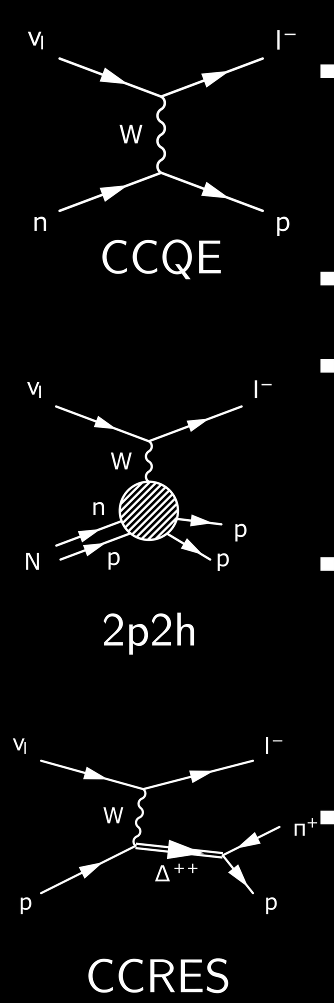
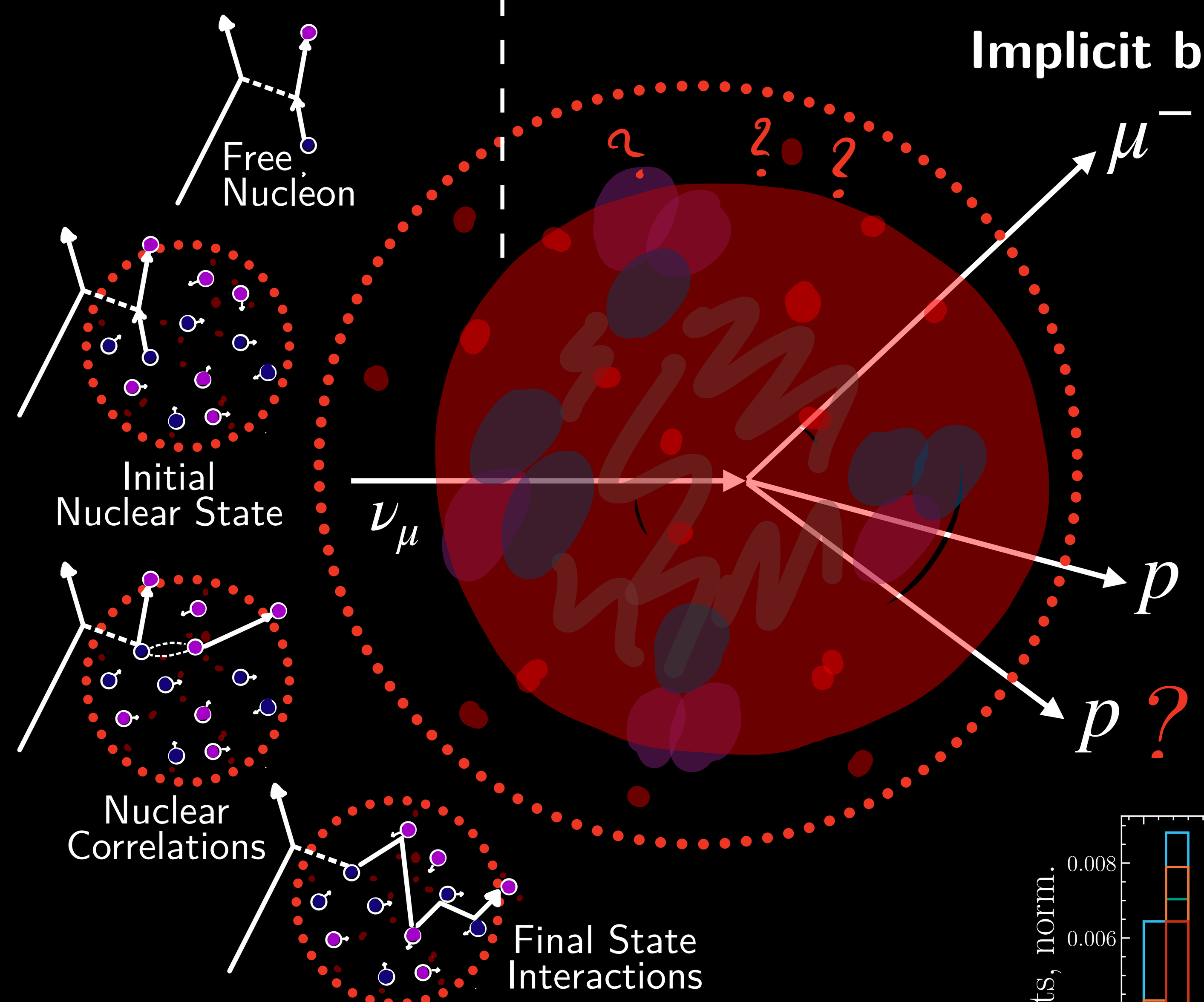


Fig. 4: Resolution for ΣT_p assuming a proton multiplicity of 1.

Nuclear Effects



- Main contributing interaction modes for ν_μCC-0π at ND280: CC-QE, CC-2p2h, and CC-RES
- Interactions mainly on carbon
- Correlations between nucleons cause emission of additional nucleons or nuclear clusters
- Final state interactions (FSI) of hadrons exiting the nucleus: absorption effects or emission of nucleons or pions
- Multiple theoretical models describing these effects exist, and differ in resulting hadron multiplicities in the final state



Implicit bias in ΣT_p induced by proton multiplicity

- Due to the non-linearity in Birks' law (Eq. 3, 4), the reconstruction of ΣT_p requires making an assumption on expected proton multiplicities
- For vertex activity, particle multiplicities are non-reconstructable and have to be inferred from a reference model
- This is a source of intrinsic model dependence in the measurement of ΣT_p
- Model dependence of ΣT_p needs to be cautiously evaluated to ensure it is a suitable variable for cross-section extraction

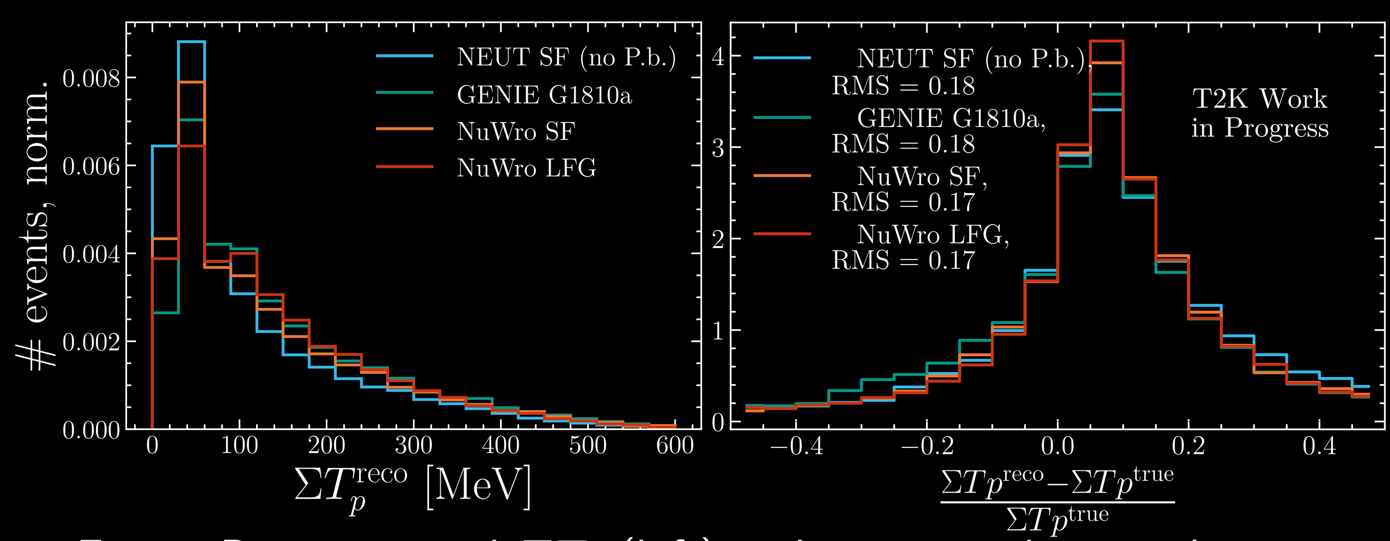


Fig. 5: Reconstructed ΣT_p (left) and corresponding resolutions (right) for a set of different generators in selected ν_μCC-0π events.

Analysis Status and Outlook

- ν_μCC-0π selection in the SuperFGD is complete, and detector systematics are in development
- Good efficiencies and purities are obtained across relevant ranges of calorimetric ΣQ_p and ΣT_p
- Reliability of ΣT_p will determine if it can be used as a variable for cross-section extraction → ongoing work
- ΣQ_p as an alternative, unbiased analysis variable kept in detector units is being explored in parallel to potentially present a forward-folded analysis result

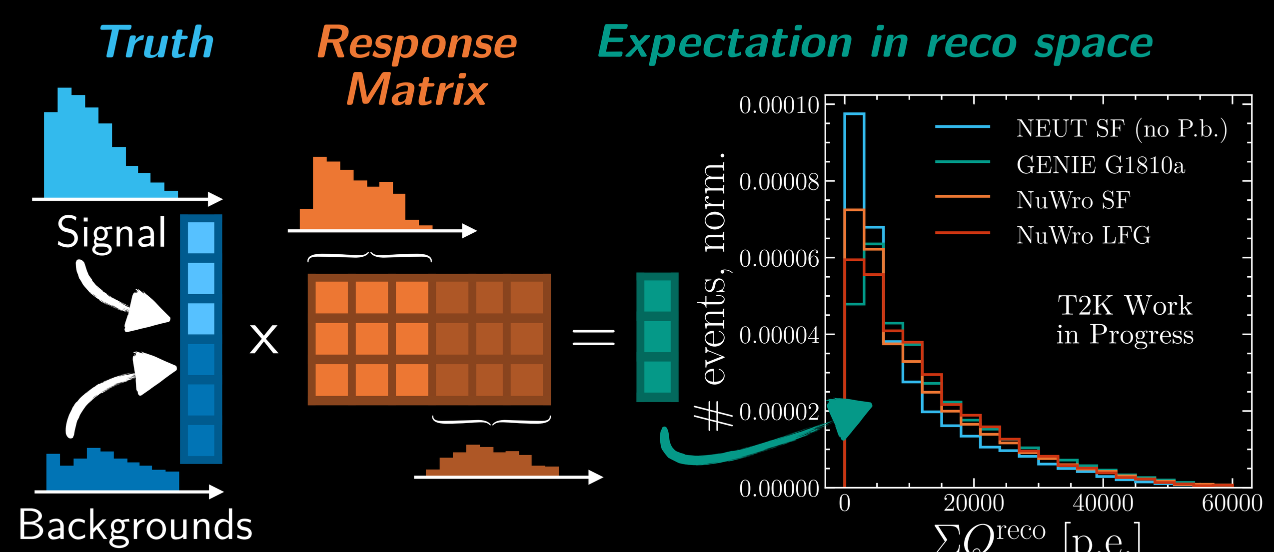


Fig. 6: Illustration of forward folding approach [5] and generator comparison of ΣQ_p (in detector units).

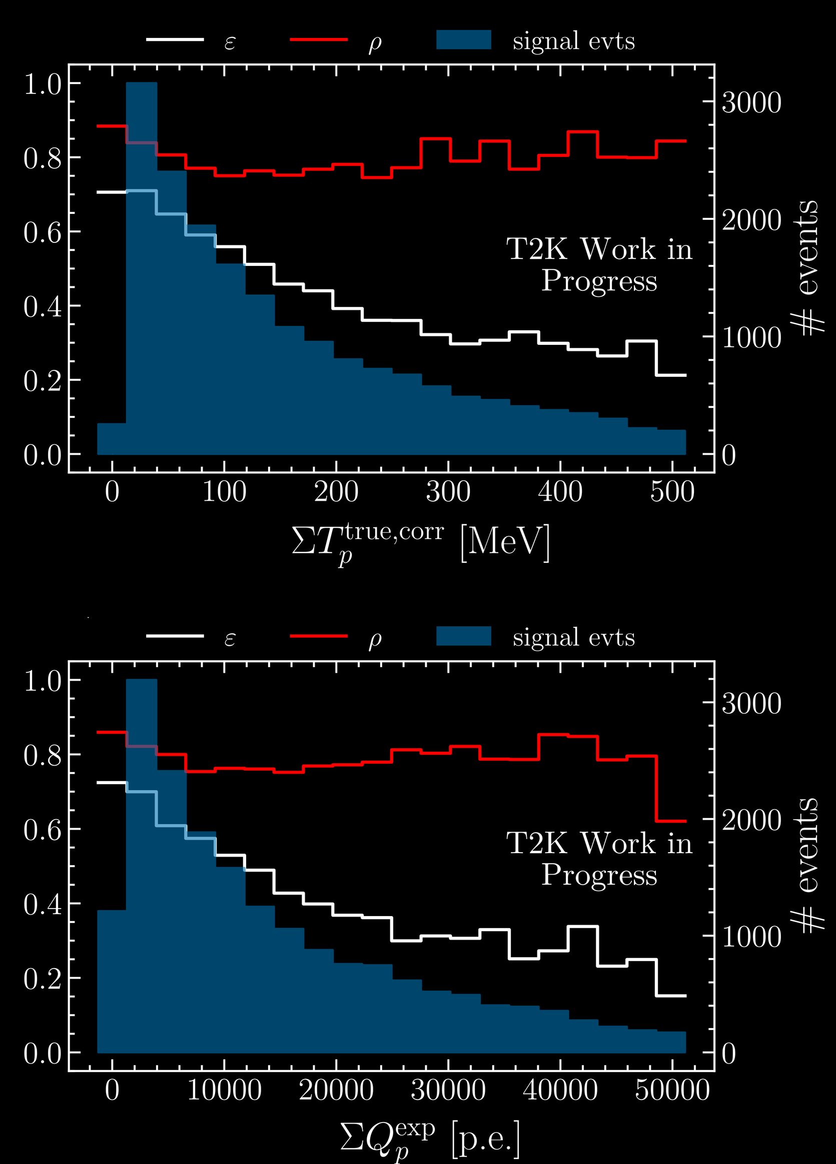


Fig. 7: Selection efficiency ε and purity ρ for ΣT_p (top) and ΣQ_p (bottom), corrected for (in-) efficiency in p_μ.

Conclusion

- The cross-section of neutrino interactions without pions at low energy transfer is not well understood
- Kinetic energy in the hadronic system provides a promising variable for T2K to access model differences in this region
- Calorimetric information inferred from light yield is a good handle on proton energies, without requiring a reconstructed track
- Material effects (i.e. Birks quenching) cause a non linear correspondence between light yield and particle energy
- Assumptions on particle multiplicities are required, and potentially introduce a bias on calorimetrically reconstructed ΣT_p
- An analysis of proton light yields kept in detector units offers an unbiased alternative

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References:
[1] D. Ruterbories et al. Physical Review Letters 129.2 (2022): 021803.
[2] K. Abe et al. T2K ND280 Upgrade TDR (2020): arXiv:1901.03750.
[3] Stowell, P. et al. JINST (2017): 12(01):P01016.
[4] J. B. Birks. Proceedings of Physical Society A (1951): 64(10), 874.
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