Study of final-state interactions of protons in neutrino-nucleus scattering with INCL and NuWro cascade models

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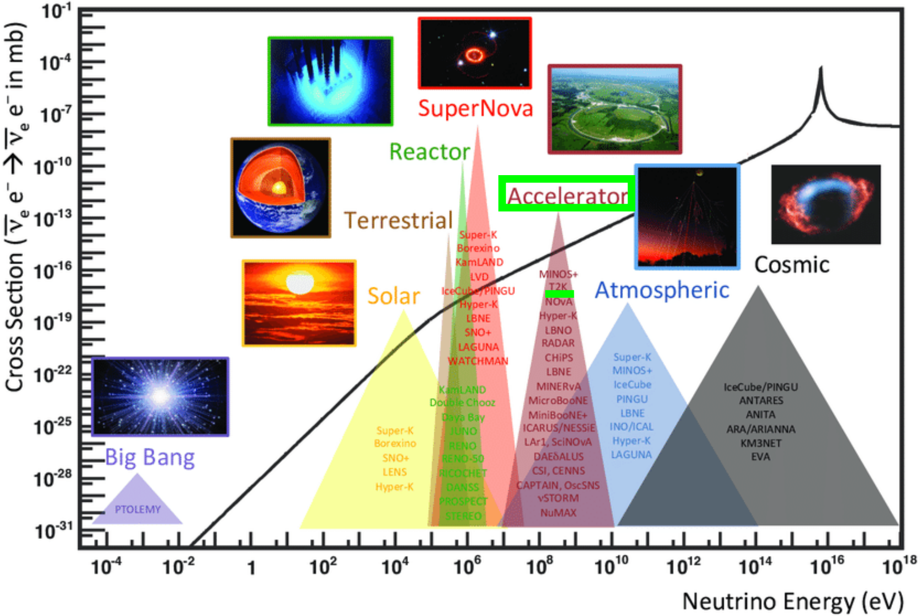
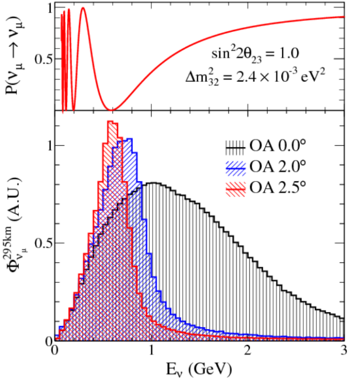


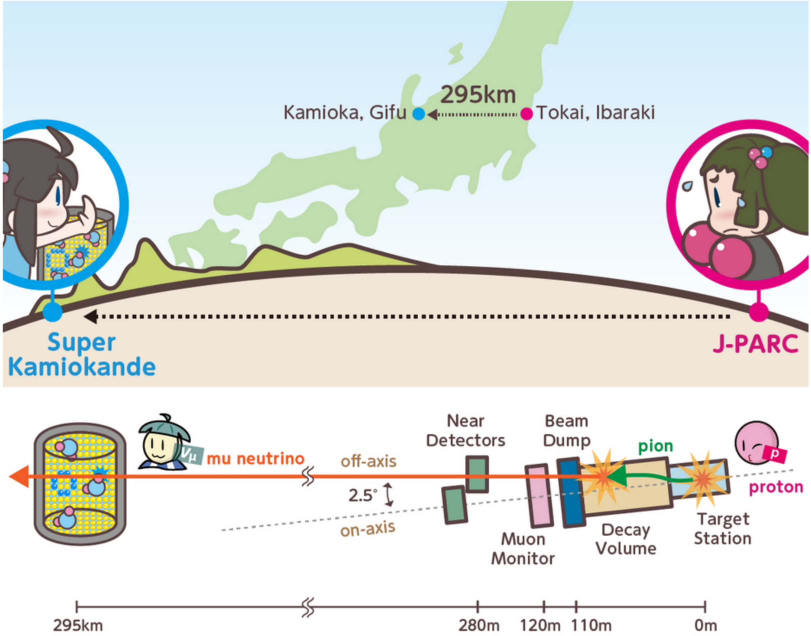
Cross Section ($\overline{\nu}_e e^- \to \overline{\nu}_e e^-$ in mb)
Neutrino Energy (eV)
SuperNova
Reactor
Terrestrial
Accelerator
Solar
Atmospheric
Cosmic
Big Bang
PTOLEMY
Super-K Borexino SNO+ LENS Hyper-K
Super-K Borexino KamLAND LVD IceCube/PINGU Hyper-K LBNE SNO+ LAGUNA WATCHMAN
KamLAND Double Chooz Daya Bay JUNO RENO RENO-50 RICOCHET DANSS PROSPECT STEREO
MINOS+ T2K NOvA Hyper-K LBNO RADAR CHiPS LBNE MINERvA MicroBooNE MiniBooNE+ ICARUS/NESSiE LAr1, SciNOvA DAEδALUS CSI, CENNS CAPTAIN, OscSNS vSTORM NuMAX
Super-K MINOS+ IceCube PINGU LBNE INO/ICAL Hyper-K LAGUNA
IceCube/PINGU ANTARES ANITA ARA/ARIANNA KM3NET EVA

T2K: design

See also Vlada's presentation



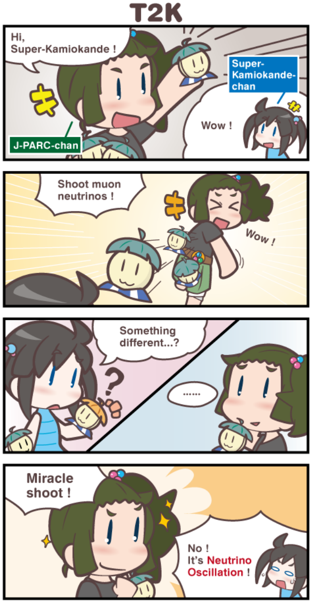
Phys. Rev. D 87, 012001 (2013)



T2K: ν rate measurement

$$\overbrace{R^{\nu'}_{FD}\left(E_\nu\right)}^{\nu\ \text{rate}} = \underbrace{\Phi^{\nu}\left(E_\nu\right)}_{\nu\ \text{flux}} \otimes \overbrace{P^{\nu\to\nu'}_{osc}}^{\text{oscillation probability}} \otimes \underbrace{\sigma^{\nu'}\left(E_\nu\right)}_{\nu\ \text{cross-section}} \otimes \overbrace{\varepsilon}^{\text{detector acceptance}}$$

In order to get accurate neutrino rate, we need to **measure** neutrino energy **precisely**.



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T2K: ν beam

- **protons** hit the target and produce a **pion beam**
- **pions** decay and produce **neutrinos** and **muons**
- muons are stopped in the beam dump

Because of such construction of the neutrino beam, we **do not know** neutrino energy **precisely**!

ν energy reconstruction

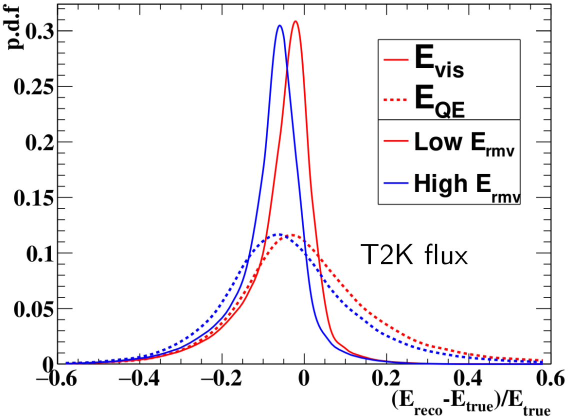
Energy reconstruction using only muon kinematics (works well for **quasi-elastic reaction**):

$$E_\nu^{QE} = \frac{m_p^2 - (m_n - E_B)^2 - m_\mu^2 + 2(m_n - E_B)E_\mu}{2((m_n - E_B) - E_\mu + p_\mu \cos\theta_\mu)}$$

Energy reconstruction using **muon and kinetic energy of the nucleon**:

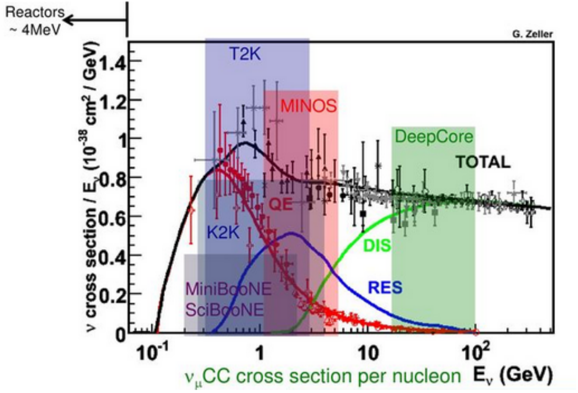
$$E_\nu^{vis} = E_\mu + \mathrm{T_N}$$

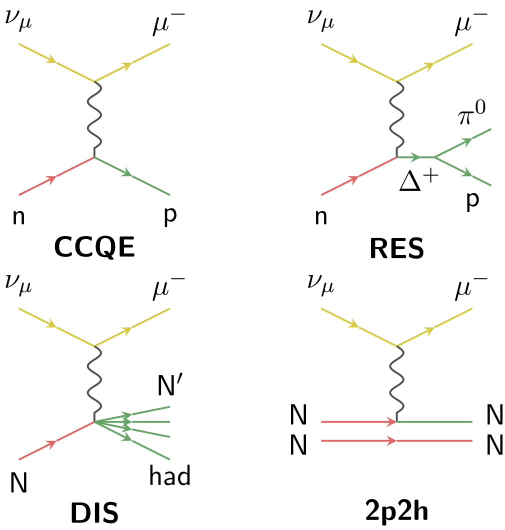
Phys. Rev. D 105, 032010 (2022)



E_ν^{vis}, dashed line — QE formula
solid line — μ + N formula

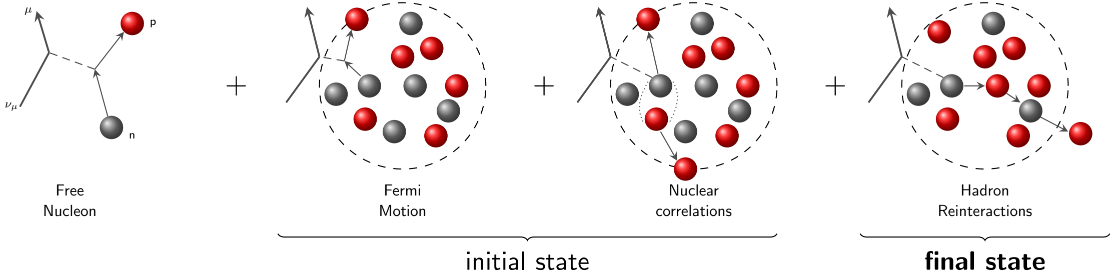
E_ν^{QE} works fine for the **CCQE** (Charged Current Quasi-Elastic) channel, where we have only μ and a proton in the final state. It is **less accurate** for other channels.





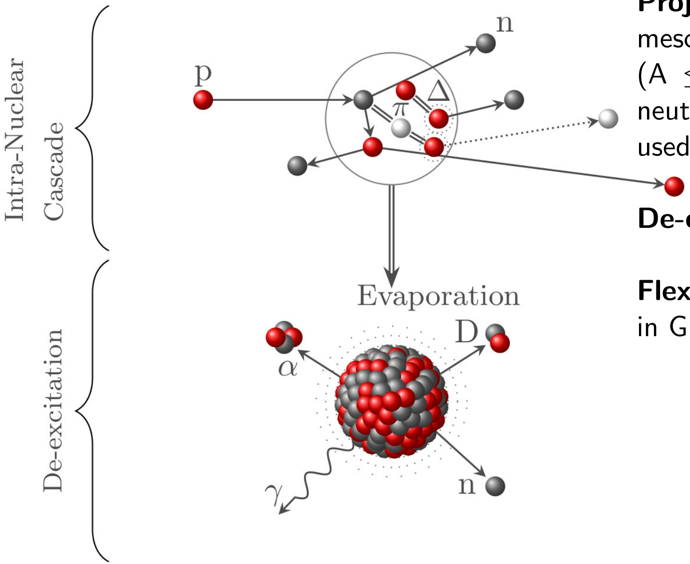
Importance of nuclear effects

$\mu + \text{N}$ formula gives us more **opportunities**, but also it creates more **challenges** for modelling and we need to **understand better nuclear effects** also on neutrons and protons.



We will focus on **CCQE** ν reaction channel and the **Final State Interactions (FSI)** that are described by **cascade models**.

Liège Intra Nuclear Cascade



Projectiles: baryons (nucleons, Λ, Σ), mesons (pions and Kaons) or light nuclei ($A \leq 18$). **No neutrinos** yet! We use neutrino vertex from **NuWro** (widely used ν-nucleus MC generator).

De-excitation: ABLA, SMM, GEMINI

Flexible tool: has been implemented in GEANT4 and GENIE

Phys.Rev.C 87, 014606 (2013)
Phys.Rev.C 90, 054602 (2014)
Phys.Rev.C 96, 054602 (2017)

Cascade ingredients

Potential

Each nucleon in the nucleus has its **position and momentum** and moves **freely** in a square potential well. Nuclear model is essentially **classical**, with some additional ingredients to mimic quantum effects.

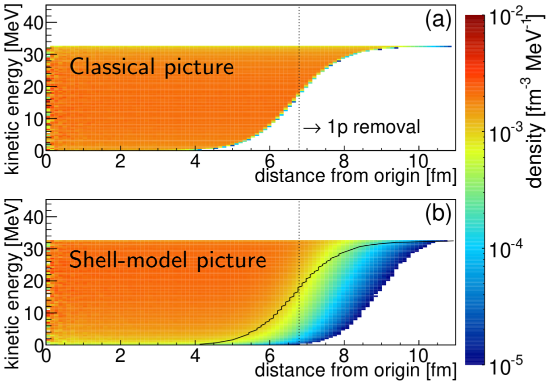
Pauli Blocking

- **strict**: blocked is $p < p_{Fermi}$
- → **statistical**: count only nearby nucleons
- strict for the first event and statistical for the subsequent ones

Events inside cascade

- decay/collision
- reflection/transmission with probability to **leave the nucleus as a nuclear cluster**

Space–kinetic-energy density of protons in ^{208}Pb



Phys.Rev.C 91, 034602 (2021)

Cascade ingredients

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Pauli Blocking

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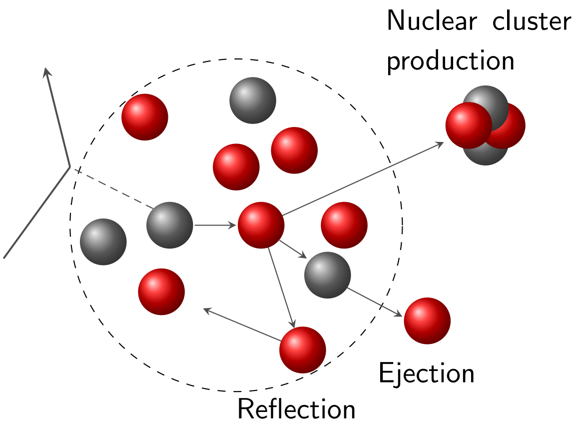
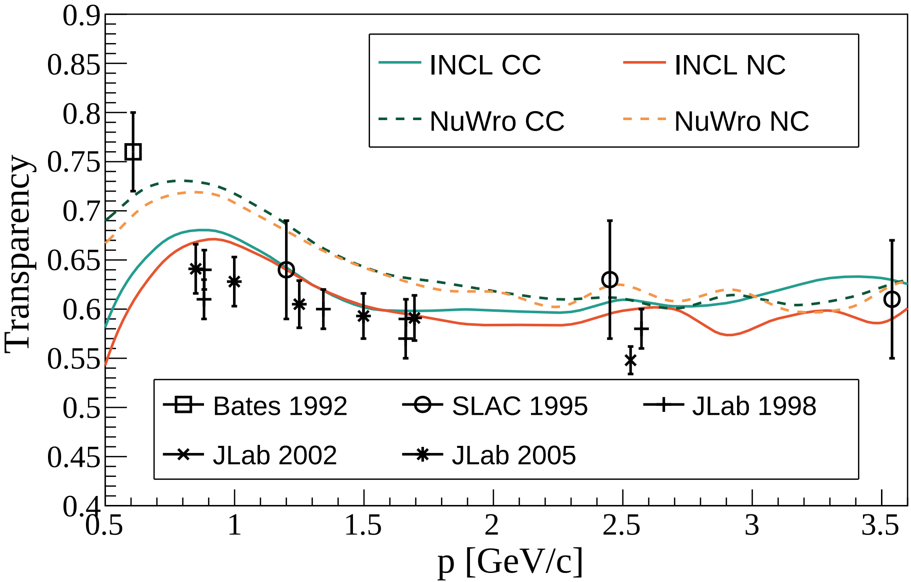
Events inside cascade

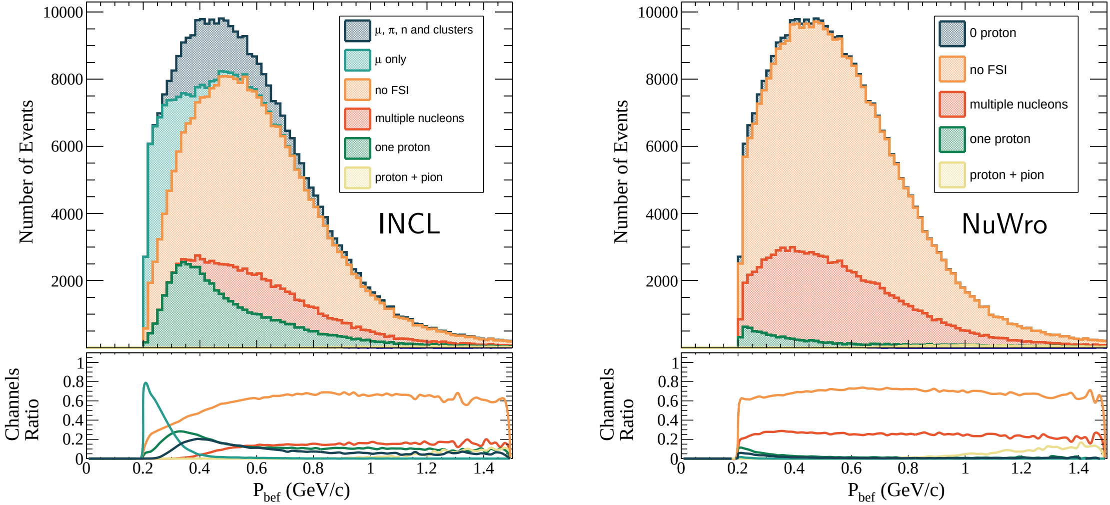
- decay/collision
- reflection/transmission with probability to **leave the nucleus as a nuclear cluster**



Nuclear transparency

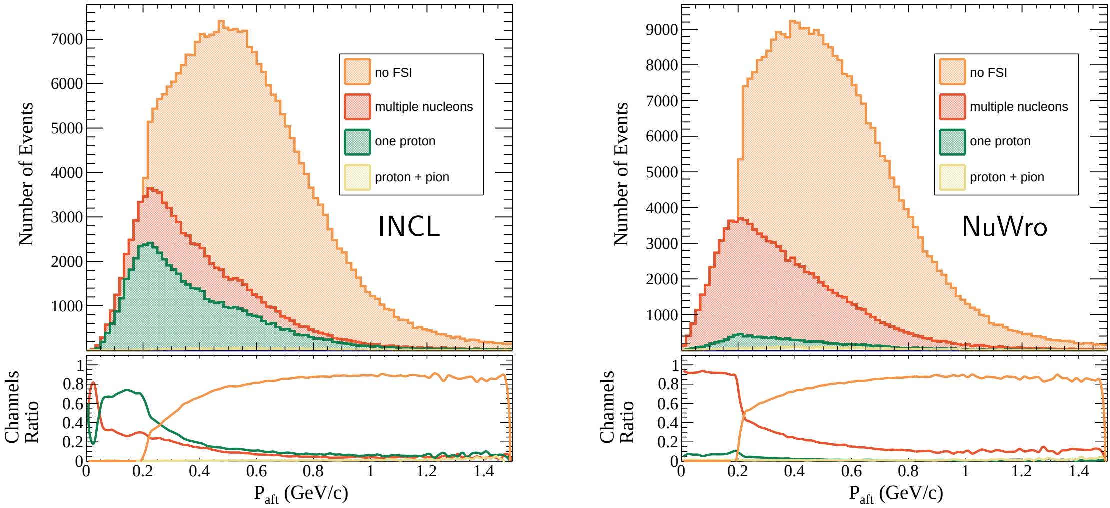


Proton momentum before FSI



INCL FSI simulation features a significant fraction of events **without a proton** in the final state, especially low momentum protons region.

Proton momentum after FSI



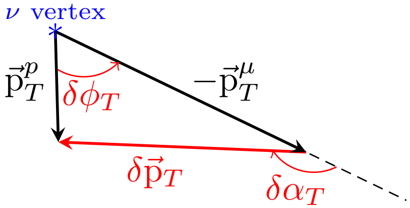
The FSI part of the distribution is **closer to zero for NuWro** → NuWro Pauli Blocking is **less strict** than INCL.

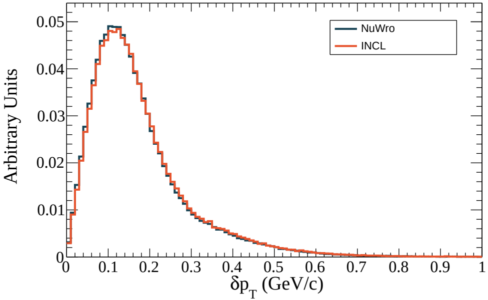
Variables of interest

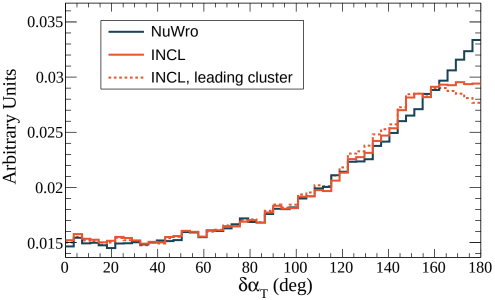
We use **Single Transverse Variables (STV)** that allow to disentangle different effects for better FSI estimation. STV are **observable** and **measurable**.

sensitive to FSI: $\delta\alpha_T = arccos\frac{-\vec{k}'_T \cdot \delta\vec{p}'_T}{k'_T \cdot \delta p'_T}$

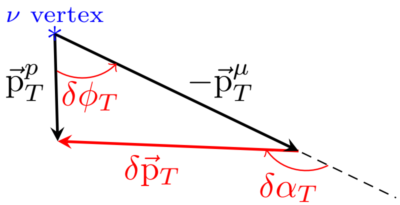
sensitive to Fermi Motion: $\delta\vec{p_T} = p_T^{\vec{p}} + p_T^{\vec{\mu}} = p_T^{\vec{n}}$

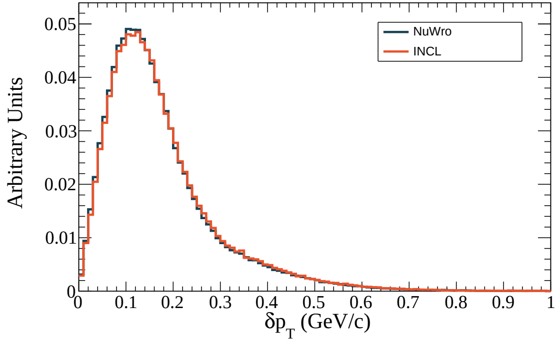


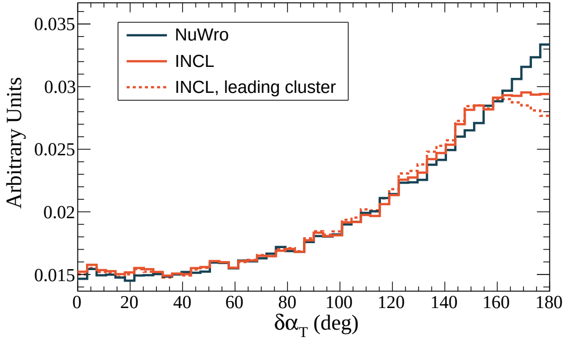




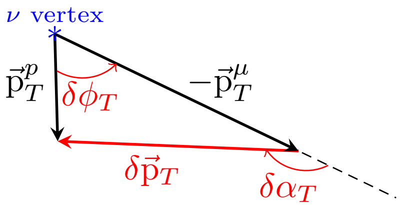
Single Transverse Variables

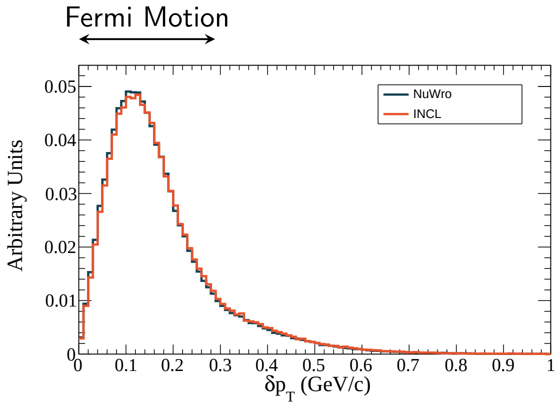


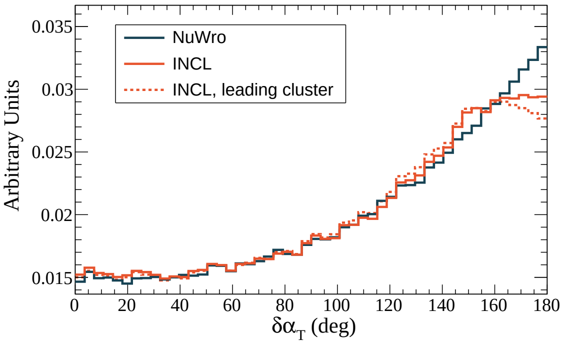




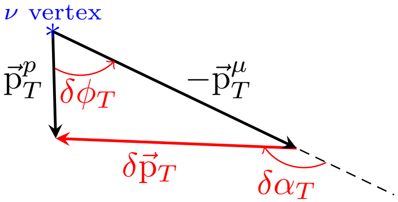
Single Transverse Variables



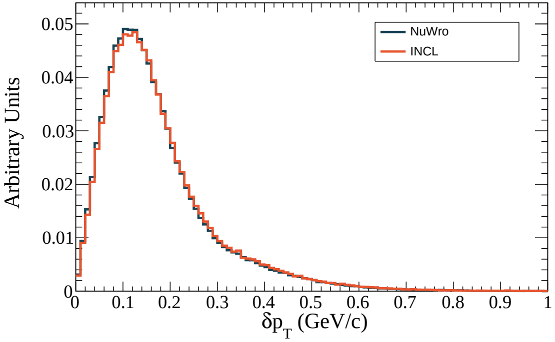


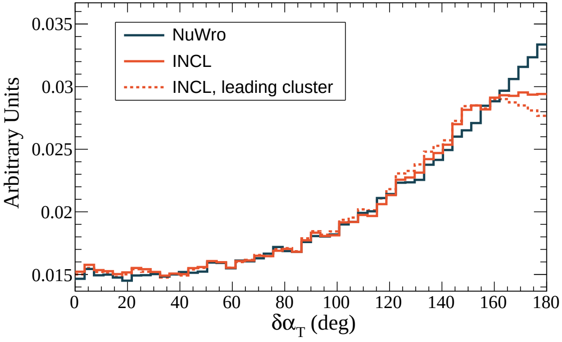


Single Transverse Variables

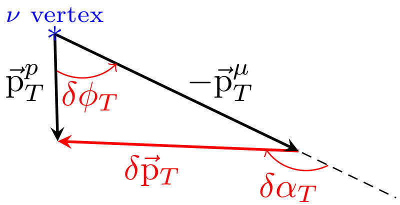


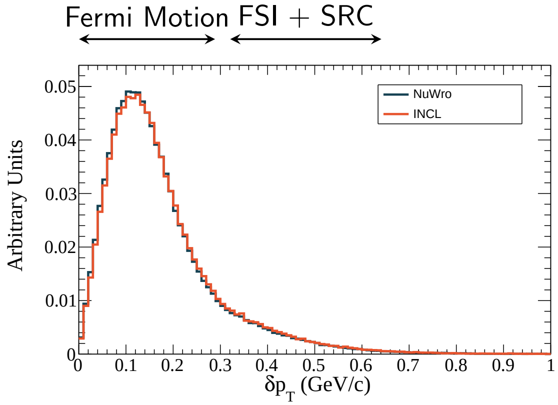
Fermi Motion FSI + SRC

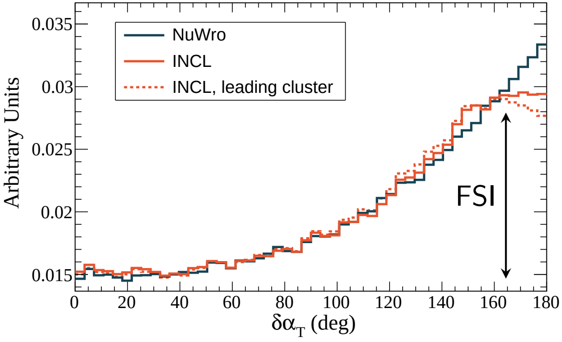




Single Transverse Variables







Comparison to T2K data

Current detector **threshold is too large**, so we **cannot see the difference** between INCL and NuWro.

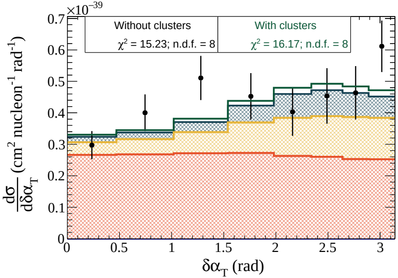
Cuts (MeV):

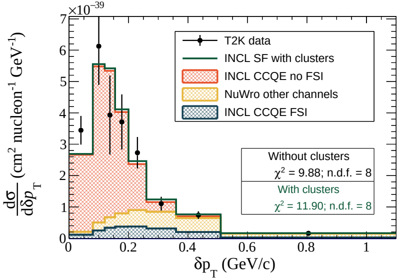
$p_\mu > 250$

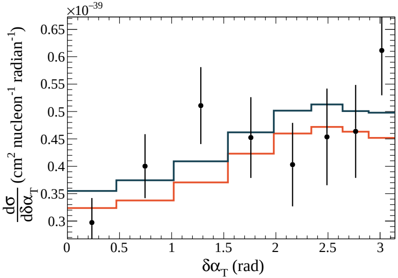
$450 < p_p < 1000$

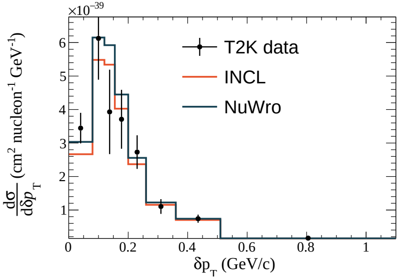
$\cos(\Theta_\mu) > -0.6$

$\cos(\Theta_p) > 0.4$









Comparison to MINERνA data in backup

T2K data taken from Phys.Rev. D, 98 032003 (2018)

Nuclear clusters reconstruction and identification

Geant4 simulation of the **CH scintillator**.
How often do nuclear clusters travel enough to be **reconstructed as a track**?

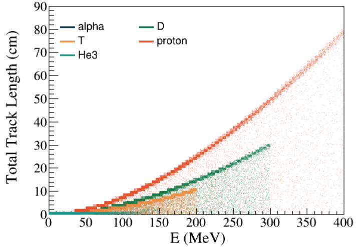
	α	^{3}He	T	D	proton
Travels > 1 cm, %	0.3	1.3	60	72	87
Travels > 3 cm, %	0	0	34	51	74

Can we **identify** nuclear clusters?

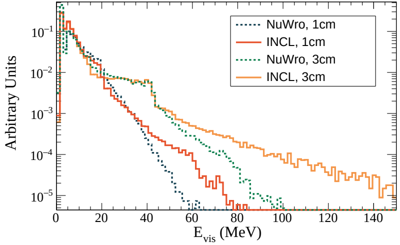
- **Deuteron** can be misidentified ($\sim$**20%** of events) as **protons**
- **Tritium** can be misidentified ($\sim$**10%**) equally as **proton** or **deuteron**
- Main source of misidentification: **inelastic events**

Nuclear clusters contribute to the **vertex activity** that needs to be accounted for to avoid the ν **energy reconstruction bias**.

Total track length vs. kinetic energy



Vertex activity per event



Summary

- We have compared the simulation of the final-state interactions between the **NuWro** and **INCL** cascade models in CCQE events
- Differences in the FSI models:
  - INCL FSI simulation features a significant fraction of events **without a proton** in the final state, especially low momentum protons region
  - INCL tends to **re-absorb** other particles produced during the cascade
  - An essential novelty of this study is the **simulation of nuclear cluster production** by INCL in FSI of neutrino interactions

A correct FSI simulation is **crucial** to achieving an **accurate ν energy reconstruction.**

Prospects

Future prospects:

- We want to repeat the same study for the **antineutrinos**: the leading particle will be **neutron** and its modelling is crucial for the upgrade
- We want to continue the study of the detector response **of clusters**

◦ CCQE **implementation** in INCL

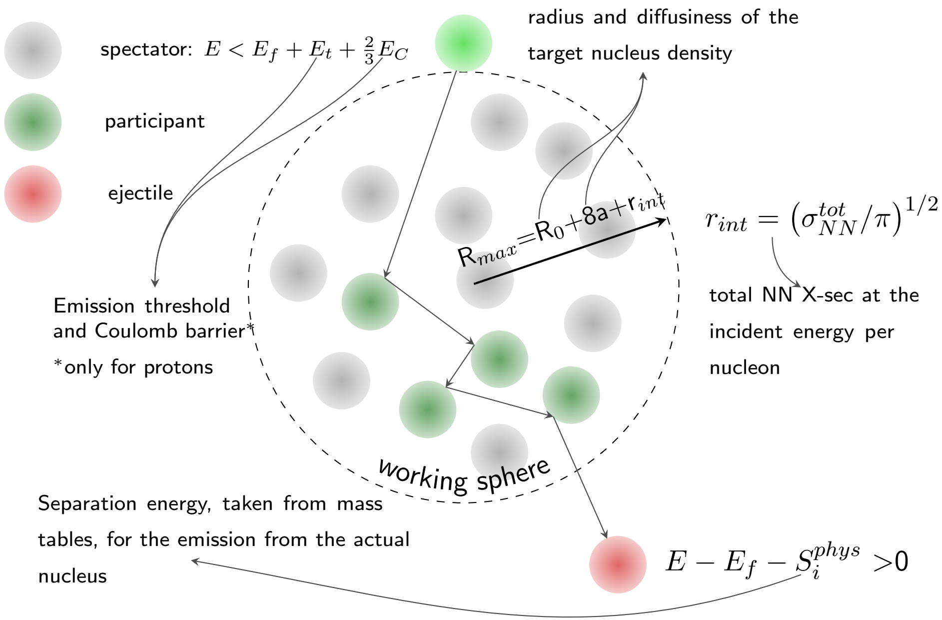
◦ **Neutron secondary interactions**: using INCL implemented in **Geant4**

The paper has been published:

‣ Phys.Rev.D, 106 032009 (2022)

BACK UP

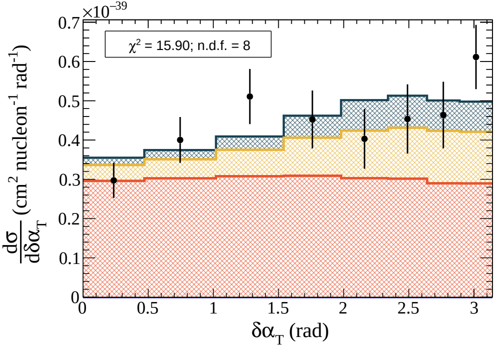
Standard INCL cascade

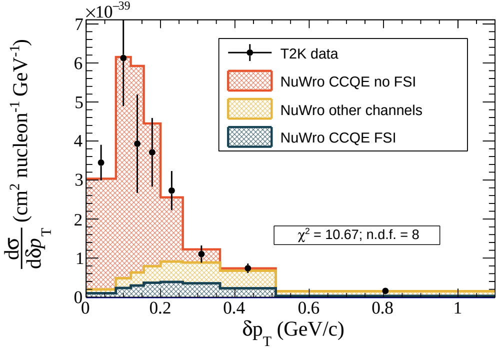


FSI channels

	Channel	NuWro	INCL
	no protons	1.37%	19.47%
	protons	98.63%	80.53%
no proton	absorption	4.45%	39.49%
	neutron+π production	3.40%	0.60%
	π production	0.21%	0%
	neutron knock-out	91.4%	29.58%
	nuclear cluster knock-out	0%	30.33%
proton	1 proton, no FSI	70.38%	68.49%
	1 proton only with FSI	2.45%	19.21%
	1p+nucleons/nucl. clusters	26.21%	11.68%
	1p+π production	0.96%	0.62%

NuWro comparison to T2K data





Comparison to MINERνA data

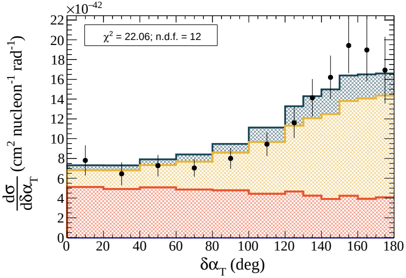
Cuts (MeV):

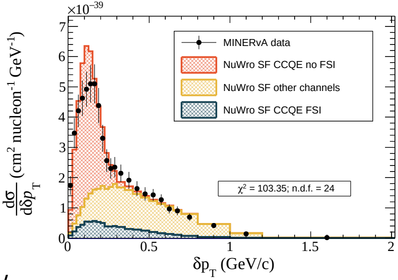
$1500 < p_\mu < 10000$

$450 < p_p < 1200$

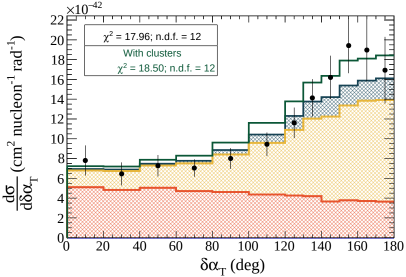
$\Theta_\mu < 20$

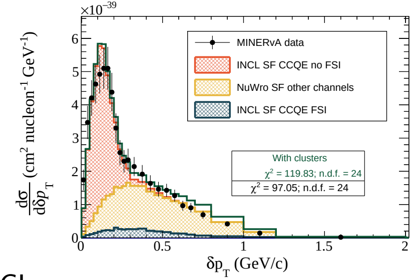
$\Theta_p < 70$





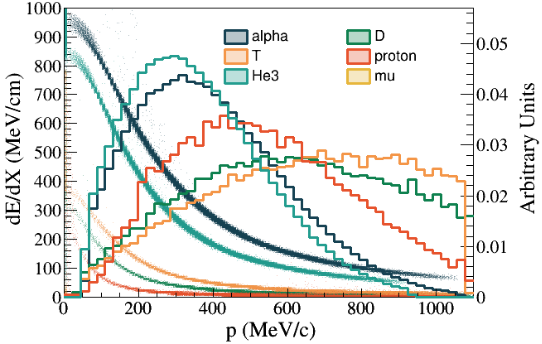
NuWro



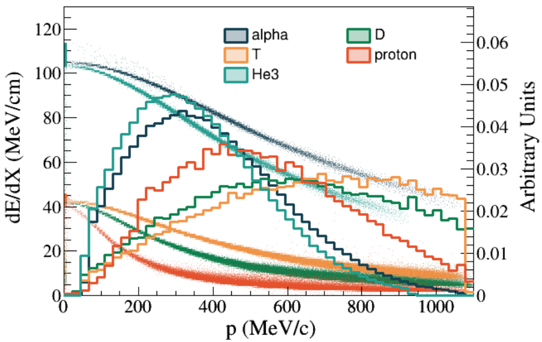


INCL

Nuclear clusters simulation

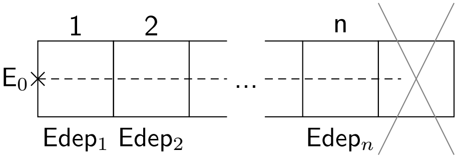


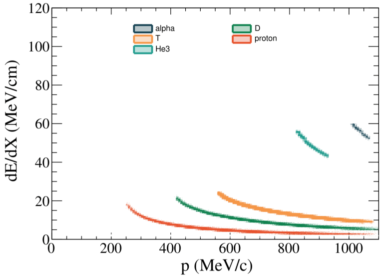
Energy loss by ionization



Visible energy loss by ionization (with Birks correction)

Particle identification algorithm





- **initial kinetic energy** E_0 is reconstructed as a sum of energy deposits along the whole track
- **momentum after passing 1 cm** is reconstructed using **5** mass hypotheses
- **for each momentum hypothesis**, the $\frac{dE}{dX}_{rec}$ is calculated using the $\frac{dE}{dX}$ dependence on momentum plot
- $\chi^2 = \sum \frac{\left(\frac{dE}{dX}_{sim} - \frac{dE}{dX}_{rec}\right)^2}{\sigma^2}$ is calculated for each hypothesis
- we choose hypothesis with the **lowest** χ^2