Simulations and cascades: using INCL to boost nuclear models for neutrino interactions

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Outlook

1. Detection of neutrinos
2. ν - nucleus interaction simulation
3. Final state interactions (FSI) studies
4. Experimental observables sensitive to nuclear effects
5. Comparison to data
6. Production of nuclear clusters in neutrino interactions

ν energy reconstruction

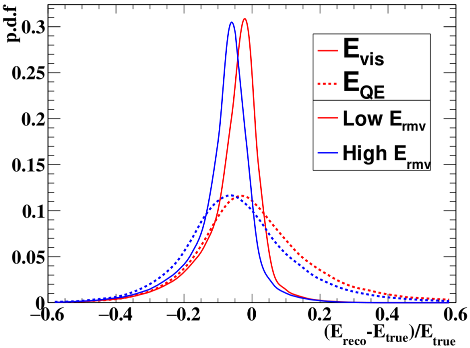
Energy reconstruction using only muon kinematics:

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

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

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

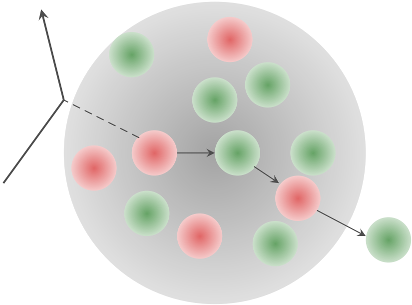
With ND280 upgrade, we can detect protons and neutrons at **low threshold** so we can measure the neutrino energy with the second formula which allows much **better resolution**, as shown in the figure.



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

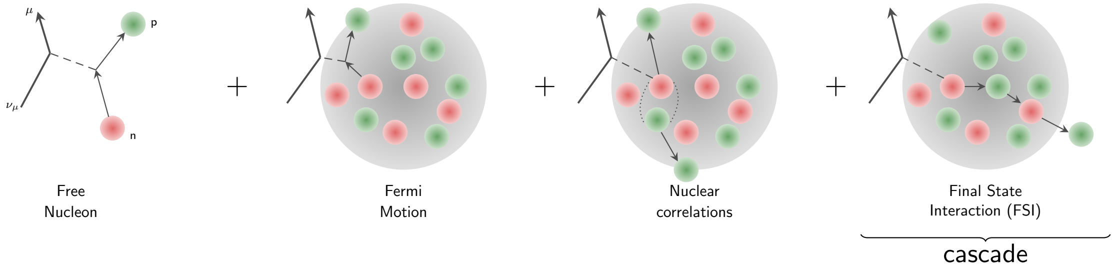
Importance of nuclear effects

$\mu + \mathrm{N}$ 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 need **not only** a better detector, but also better **modelling** of the neutrino-nucleus interactions, e.g. improved Monte-Carlo generators!

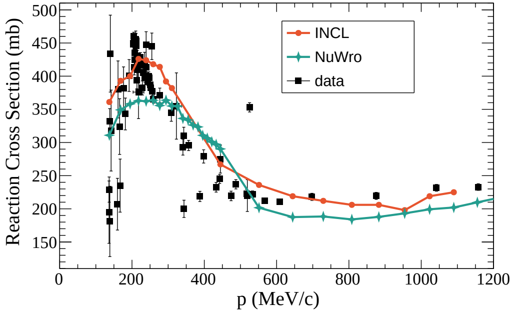
Factorization scheme



We will focus on **cascades**.

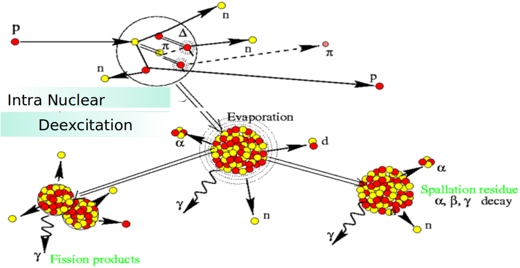
Liège Intranuclear Cascade model

Projectiles: baryons (nucleons, Λ, Σ), mesons (pions and Kaons) or light nuclei (A⩽18). Shows a **remarkable agreement** with an exhaustive list of experimental data.



Example: proton-12 C interaction cross section as a function of the proton momentum

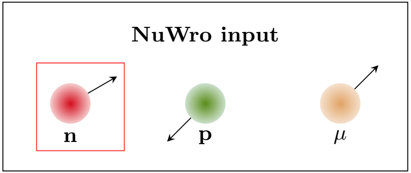
The INCL cascade is coupled to the **deexcitation codes**: ABLA, SMM or GEMINI++



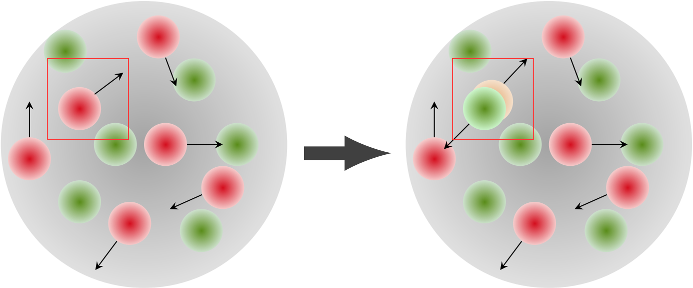
Flexible tool that has been implemented in GEANT4 and GENIE.

More information: Phys.Rev.C 87, 014606 (2013) , Phys.Rev.C 90, 054602 (2014)

Using INCL with NuWro input

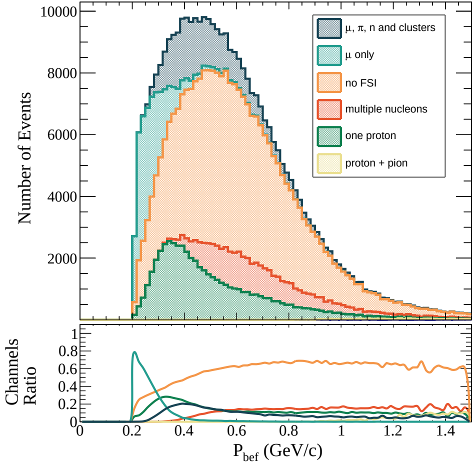


We substitute the chosen **INCL neutron** with **proton** and **muon** from NuWro. We use NuWro sample with **CCQE** events on **CH** target.

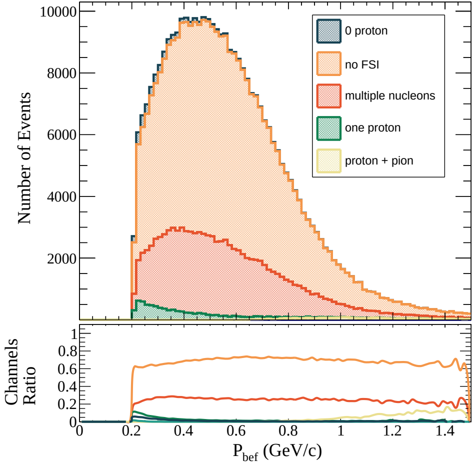


INCL nucleus

Proton momentum before FSI



INCL

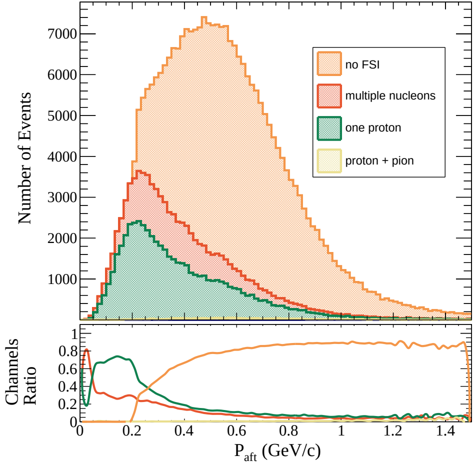


NuWro

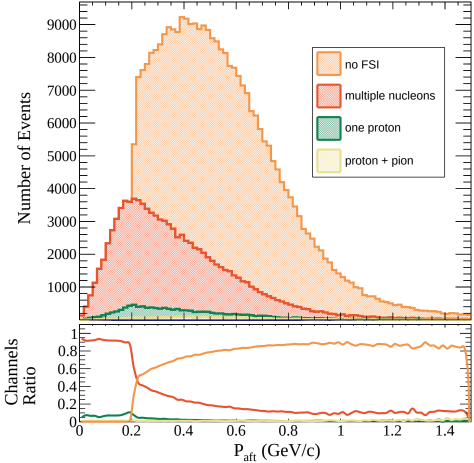
Reaction channels

	Channel	NuWro SF	INCL+NuWro SF
	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 + other nucleons or nuclear clusters	26.21%	11.68%
	1p + π production	0.96%	0.62%

Proton momentum after FSI



INCL



NuWro

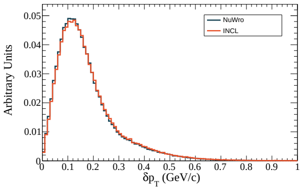
Variables of interest

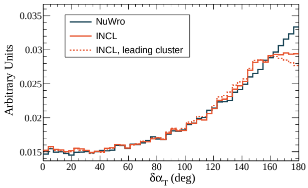
FSI **affects proton's kinematics** that gives systematics in ν energy reconstruction.
We use **Single Transverse Variables (STV)** for better FSI estimation.

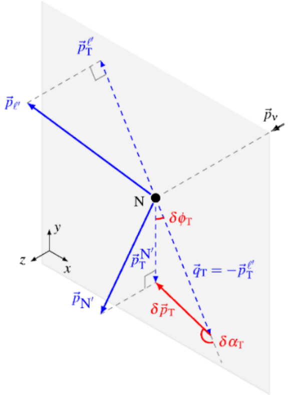
sensitive to FSI: $\delta\alpha_T = arccos\frac{-\vec{k}'_T \cdot \delta\vec{p}'_T}{k'_T \cdot \delta p'_T}$

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

additional variable: $\delta\phi_T = arccos\frac{\vec{k}'_T \cdot (\vec{p}'_p)_T}{k'_T \cdot (p'_p)_T}$

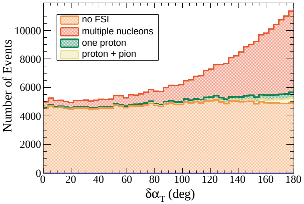


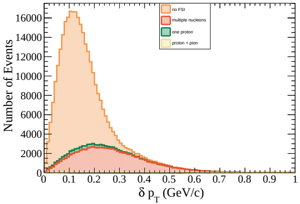


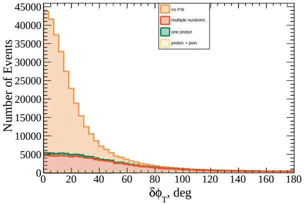


Phys. Rev. C, 94(1), 2016

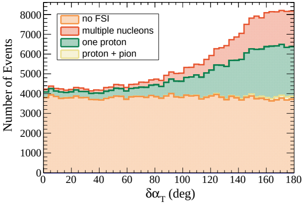
Single Transverse Variables (STV)

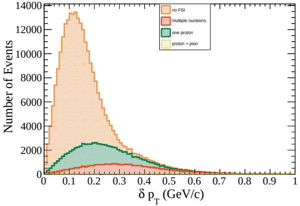


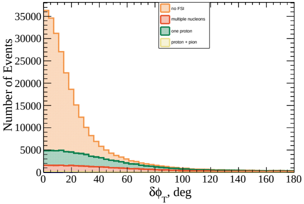




NuWro







INCL

Comparison to T2K data

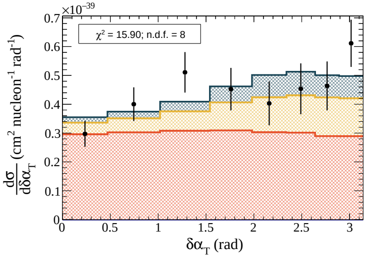
Cuts:

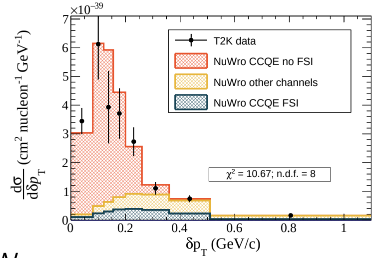
$p_\mu > 250$

$450 < p_p < 1000$

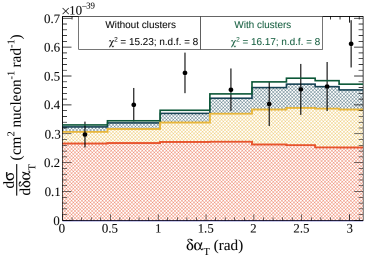
$\cos(\Theta_\mu) > -0.6$

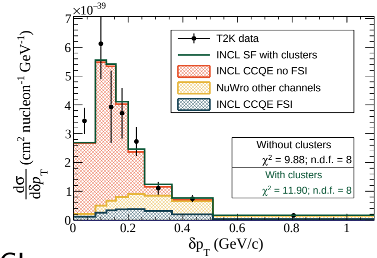
$\cos(\Theta_p) > 0.4$





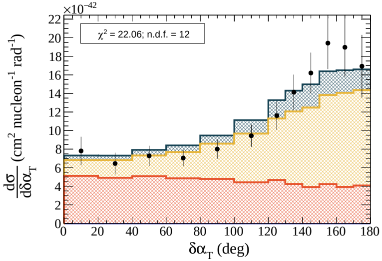
NuWro

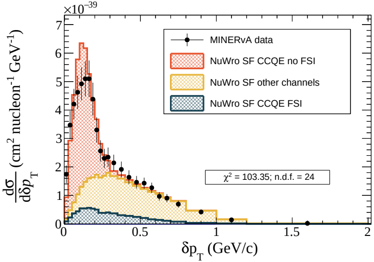




INCL

Comparison to MINERvA data

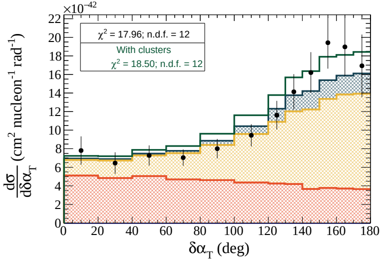


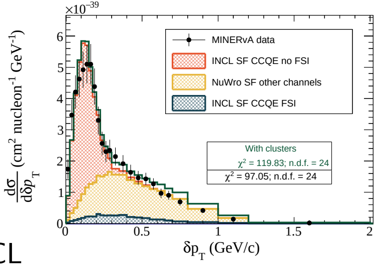


NuWro

Cuts:

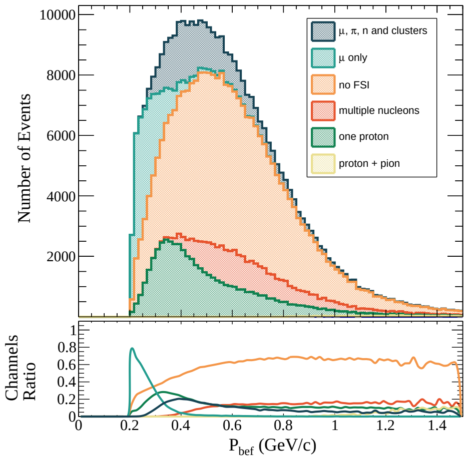
$$1500 < p_\mu < 10000$$
$$450 < p_p < 1200$$
$$\Theta_\mu < 20$$
$$\Theta_p < 70$$





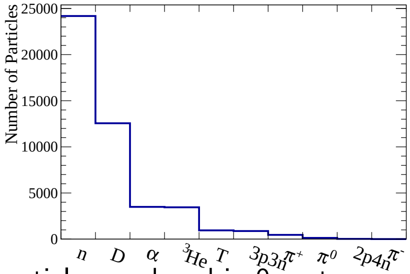
INCL

What is produced in 0 proton events



proton momentum before FSI

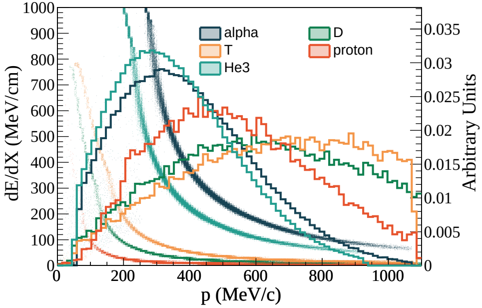
- can we **misidentify** nuclear clusters as protons?
- **how far** nuclear clusters can travel? Do we see them as a **track** or **vertex activity**?
- can we **see** their energy **deposited** in the detector?



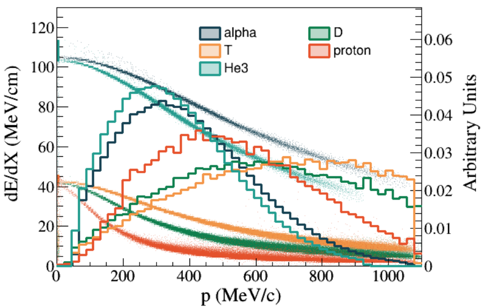
particles produced in 0 proton events

Geant4 simulation

We have created a **Geant4 simulation** of the **uniform CH block**.

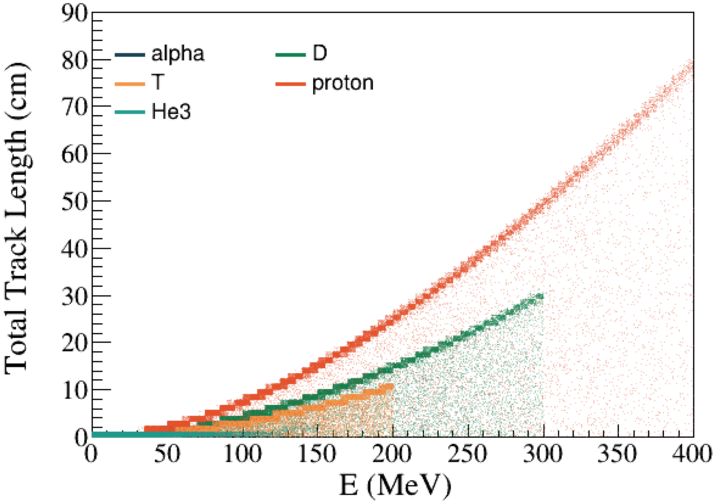


energy loss by ionization



visible energy loss by ionization (with Birks correction)

Total path length dependence on kinetic energy



Nuclear clusters reconstruction and identification

How often do nuclear clusters travel enough to be **reconstructed as a track**?

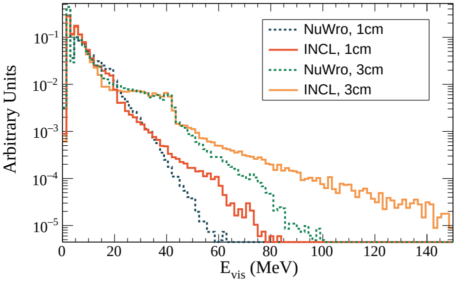
	α	^{3}He	T	D	proton
Travels more than 1 cm, %	0.3	1.3	60	72	87
Travels more than 3 cm, %	0	0	34	51	74

Can we **identify** nuclear clusters?

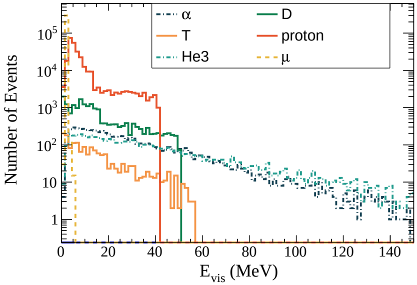
	α	^{3}He	D	T	proton	total misidentification
α	-	0	0	0	0	0
^{3}He	0	-	0	0	0	0
D	0	0	-	0	18%	18%
T	0	0	5%	-	6%	11%
proton	0	0	0	0	-	0

Vertex activity

The distributions have two components depending if the particles leave the sphere or if they release all their energy inside the sphere.



total vertex activity



INCL 3 cm, vertex activity per particle

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

Conclusion and prospects

Present detector acceptance **does not give access** to the most important for FSI characterization **low momentum protons**. **New detectors** with lower thresholds will **need reliable nuclear models** of FSI to confront the new data.

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
- **Pion FSI**: INCL models Δ resonance decay
- We want to continue the study of the detector response **of clusters**

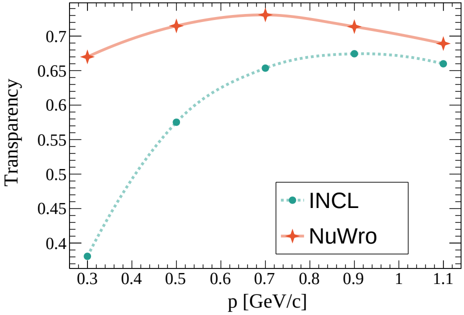
The paper ▸ arXiv:2202.10402 has been **submitted to the Phys. Rev. D**

BACKUP

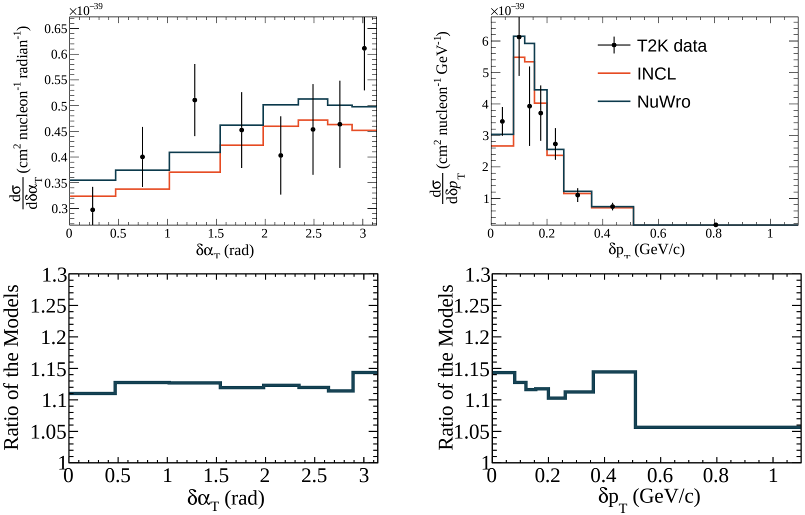
Transparency

The **larger FSI strength** in INCL suggests a **larger dissipation of energy** across the nucleus through interactions.

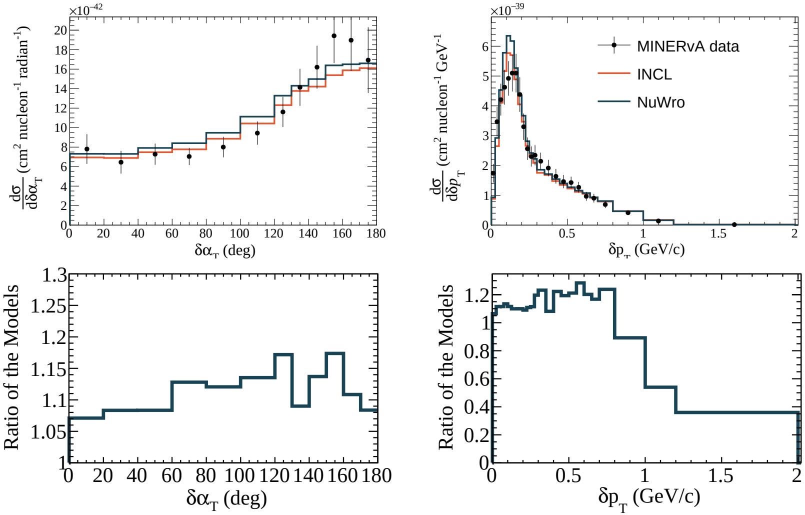
The nuclear model of INCL includes the probability to **form nuclear clusters** during the attempt of the nucleon to leave the nucleus. The events with no proton in the final state are in the large majority due to **charge exchange in NuWro** (91% of neutron production) while in INCL the probability of **nuclear cluster and neutron production** in events without protons in the final state is similar (around 30% each).



Comparison to T2K data

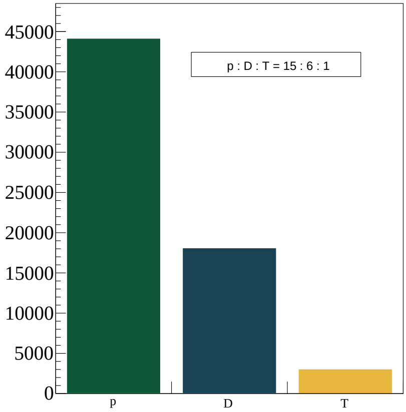


Comparison to MINERvA data



Nuclear clusters emission check

^{12}C bombarded by 175 MeV neutrons



Progress in NUCLEAR SCIENCE and TECHNOLOGY, Vol. 1, p.69-72 (2011)

ARTICLE

Production of protons, deuterons, and tritons from carbon bombarded by 175 MeV quasi mono-energetic neutrons

Shusuke HIRAYAMA[1*], Yukinobu WATANABE[1], Masateru HAYASHI[1], Yuuki NAITO[1], Takehito WATANABE[1,5]
Riccardo BEVILACQUA[2], Jan BLOMGREN[2], Leif NILSSON[2], Angelica ÖHRN[2],
Michael ÖSTERLUND[2], Stephan POMP[2], Alexander PROKOFIEV[3], Vasily SIMUTKIN[2],
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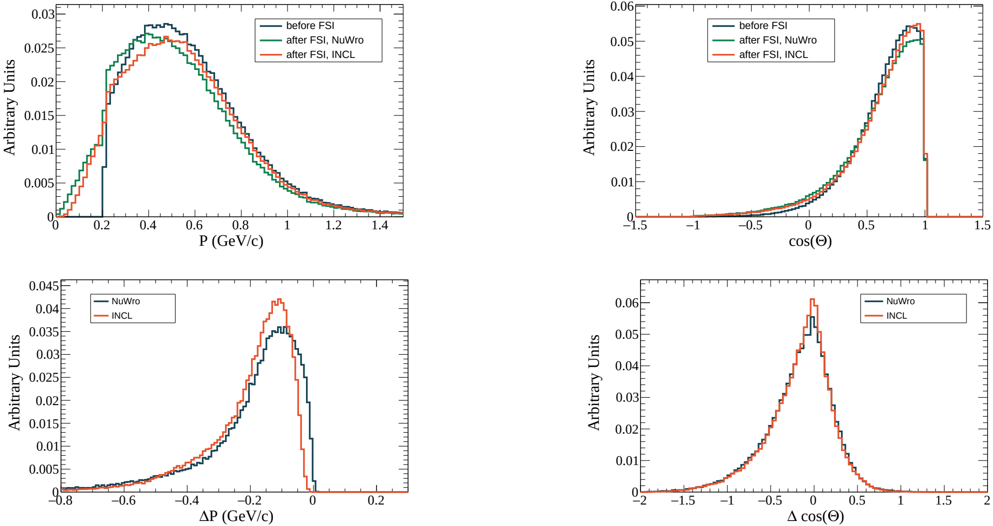
[5]*Los Alamos National Laboratory, Los Alamos, NM 87545, USA*

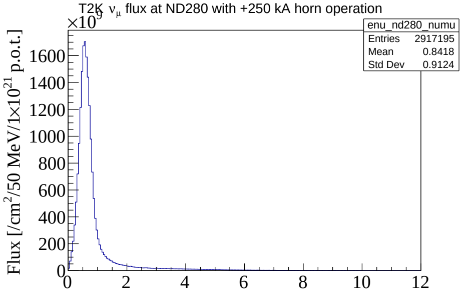
Ratio $\approx 10 : 3 : 1$

Momentum and cos(Θ) shape comparison

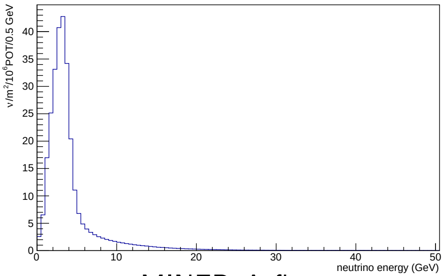


Comparison to data

Normalization, as **"other channels"** part are always taken from **NuWro**.



T2K flux



MINERvA flux

- p_μ >250
- 450 $<p_p$ <1000
- $\cos(\Theta_\mu)$>-0.6
- $\cos(\Theta_p)$>0.4

- 1500 $<p_\mu$ <10000
- 450 $<p_p$ <1200
- Θ_μ <20
- Θ_p <70

Geant4 model

Physics list

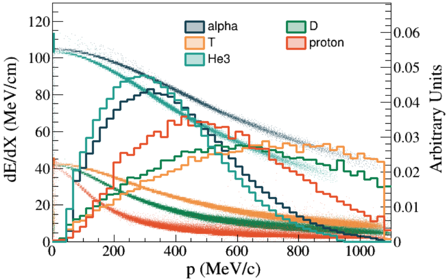
- G4EmStandardPhysics and G4EmExtraPhysics
- G4HadronPhysicsINCLXX
- G4DecayPhysics
- G4IonINCLXXPhysics

Detector construction

- World volume 1000x1000x1550 cm **half**size
- beginning of coordinates is in the **center** of the world volume
- **uniform** CH block 50 cm **less** in all dimensions
- CH density $= 1.06$ g/cm^3

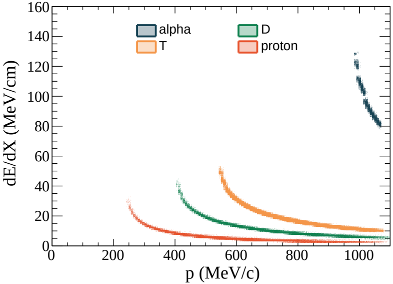
Particle identification algorithm

We want to estimate the fraction of nuclear clusters that can be misidentified
1st step: The track is summed into 1 cm blocks corresponding to the detector granularity. The last part of the track that it shorter than 1 cm is not used in the analysis



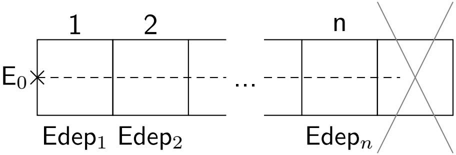
dE/dX for step

$\rightarrow$



dE/dX for 1 cm cubes

Particle identification algorithm

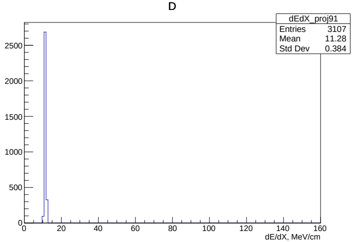


- **initial kinetic energy** is reconstructed as a sum of energy deposits along the whole track ($E_0 = \sum_{i=1}^{n} Edep_i + Edep_{last}$)
- **energ**y of the particle **after passing 1 cm** in the material is $E_1 = E_0 - Edep_1$; **momentum**: $p_1{}^j = \sqrt{(E_1 + m^j)^2 - m^{j2}}$, where $j = \{\alpha$, D, T, p$\}$
- **for each momentum hypothesis**, the $\frac{dE}{dX}_i$ is reconstructed using the $\frac{dE}{dX}$ from the previous slide with uncertainty σ
- $\chi^2 = \sum_{i=1}^{n} \frac{\left(Edep_i - \frac{dE}{dX}_i\right)^2}{\sigma_i^2}$ is calculated for each hypothesis
- we choose hypothesis with the **lowest** χ^2

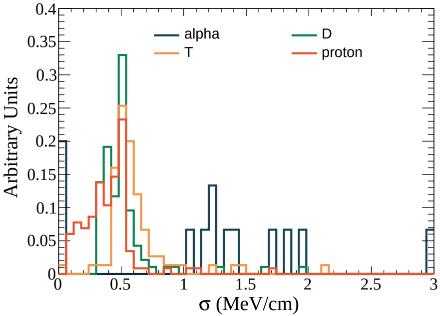
σ definition

To calculate σ, we need:

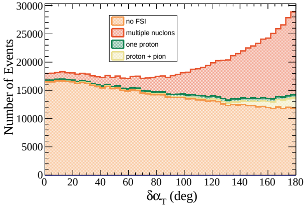
- take plot with dE/dX dependence on momentum
- find bin with the needed momentum
- to make a projection to dE/dX axis of this bin



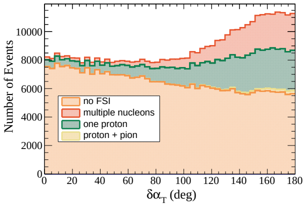
σ is RMS of this plot



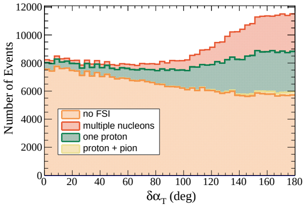
Comparison to data: RW model



NuWro GFG



INCL RW



INCL + NuWro GFG