New tools for neutrino interactions: INCL and the role of de-excitation

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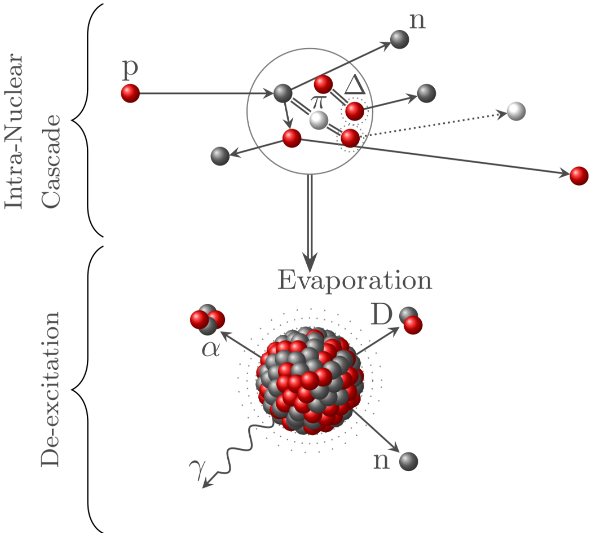
Introduction

INCL

De-excitation

Results

- Neutrino energy reconstruction
- Leading proton kinematics
- STV
- Comparison to data
- Vertex Activity



ν energy reconstruction

Flux model · Detector model · Neutrino interaction model · Oscillation Probability

$$N^{ND}_{\nu_\alpha}(E_\nu) = \Phi^{ND}_{\nu_\alpha}(E_\nu) \times \epsilon^{ND}(E_\nu) \times \sigma^{ND}_{\nu_\alpha}(E_\nu)$$

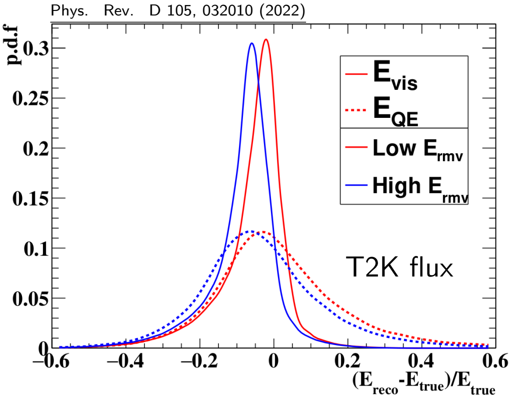
$$N^{FD}_{\nu_\beta}(E_\nu) = \Phi^{FD}_{\nu_\beta}(E_\nu) \times \epsilon^{FD}(E_\nu) \times \sigma^{FD}_{\nu_\beta}(E_\nu) \times P_{\nu_\alpha \to \nu_\beta}(E_\nu)$$

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**:

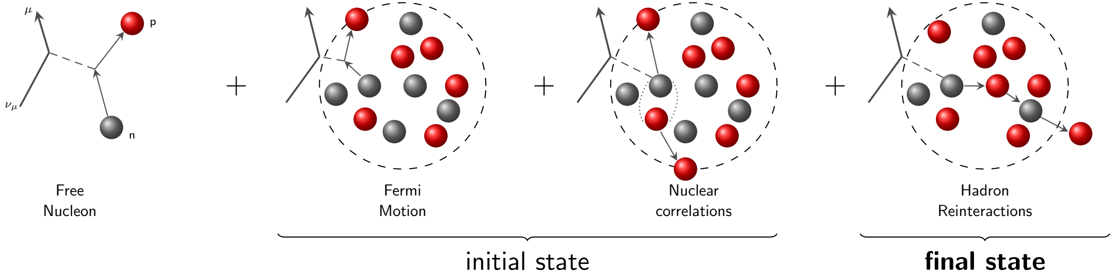
$$E_\nu^{vis} = E_\mu + \mathrm{T_N}$$



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

Importance of nuclear effects

μ + 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**.

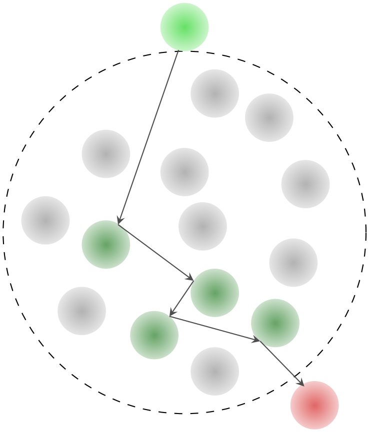
Current work

My work: compare present cascade model (NuWro) with a different cascade (INCL). INCL does not have a neutrino vertex (**yet!**), so neutrino interaction comes from NuWro.

Neutrino event generators

Space-like approach:

- The nucleus is a **continuous medium**
- mean free path: $\lambda_{free} = (\sigma\rho(r))^{-1}$
- probability to propagate **without** interaction: $P(\Delta x) = \exp(-\Delta x/\lambda)$



INCL (CEA, France)
Time-like approach:
Each nucleon of the target and **each particle** of the projectile are given a position and a momentum. They are all propagated until two of them get close enough to interact with each other.
INCL is **benchmarked** to an extensive list of **experimental data**
(J. Korean Phy. Soc. 59, 791 (2011))

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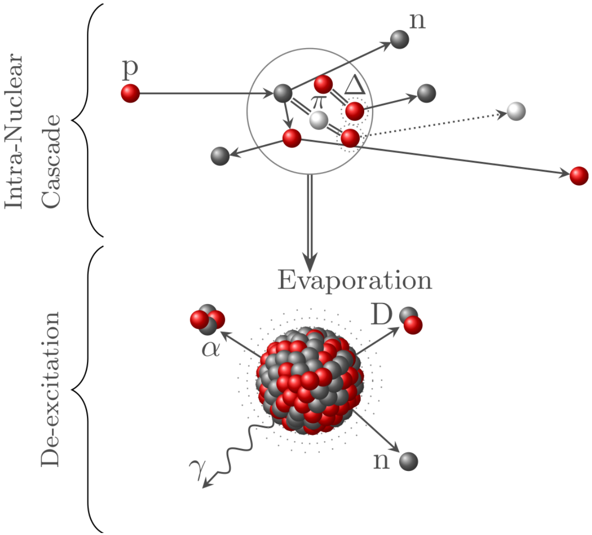


Cascade ingredients

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.

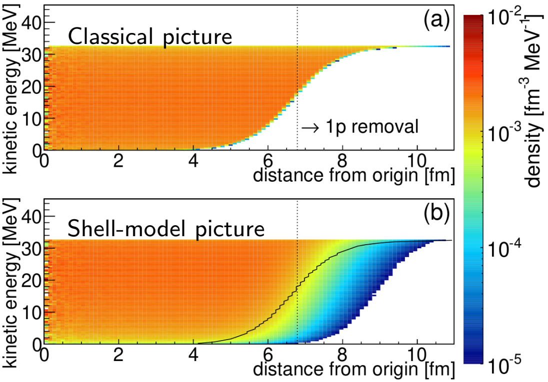
Pauli Blocking

the phase-space below Fermi momentum is occupied and restricted

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)

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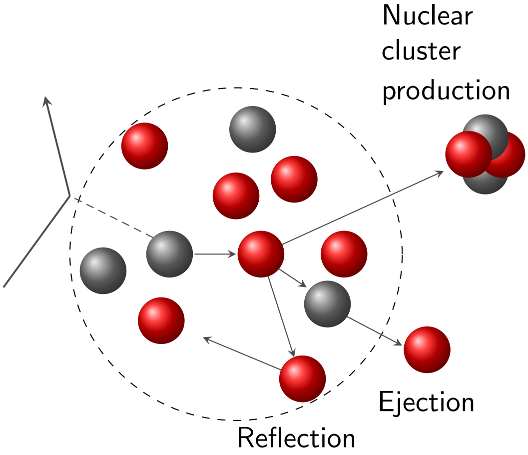

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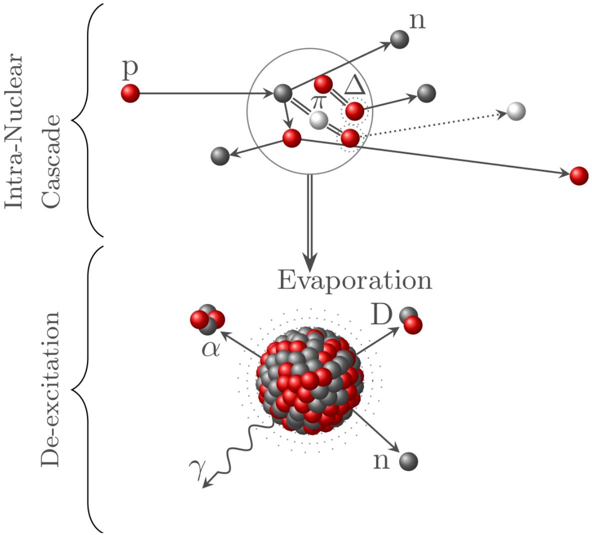
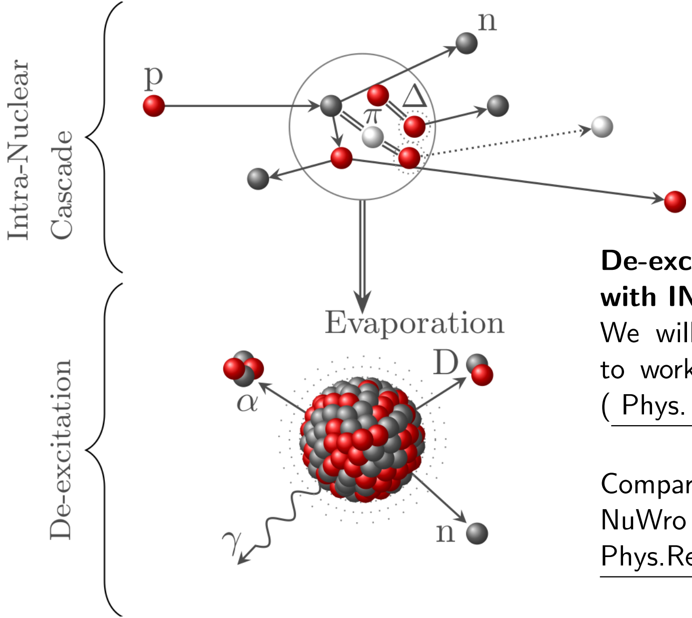


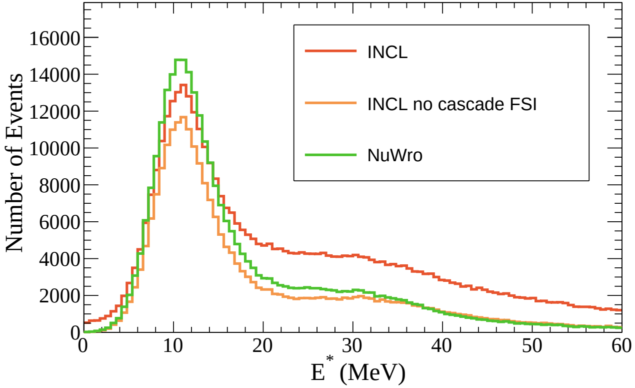
De-excitation



De-excitation models coupled with INCL: ABLA, SMM, GEMINI
We will use **ABLA**: proved to work for the **light nuclei** (Phys. J. Plus 130, 153 (2015))

Comparison of INCL and NuWro cascades is presented in Phys.Rev.D, 106 032009 (2022).

Excitation energy



Excitation energy

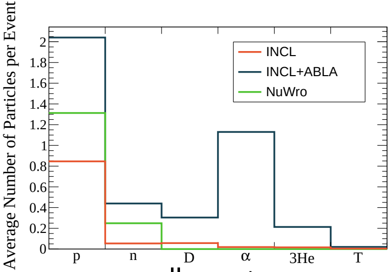
$$E = E_\nu + {}^{12}_{6}M - \sum_i E_i,\ p = p_\nu - \sum_i p_i$$

$$E^* = \sqrt{E^2 - p^2} - M_{rem}$$

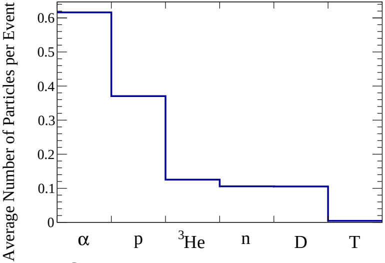
We have excitation energy even **without FSI** due to fundamental ν interaction and it will be dealt with ABLA producing **de-excitation particles** ('binding energy' does not stay in the nucleus, it becomes observable in the final state)

In **presence of FSI** we produce additional excitation energy which is different for INCL and NuWro (INCL tend to have stronger FSI and produces more excitation in FSI then NuWro)

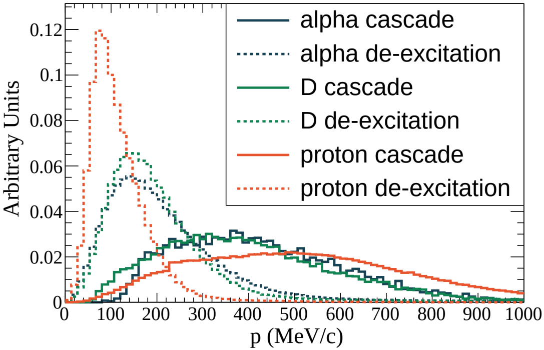
Production of the nuclear clusters (α, deuterons, tritons...)



all events



no-FSI events with de-excitation



Momentum of nuclear clusters produced during the cascade and de-excitation

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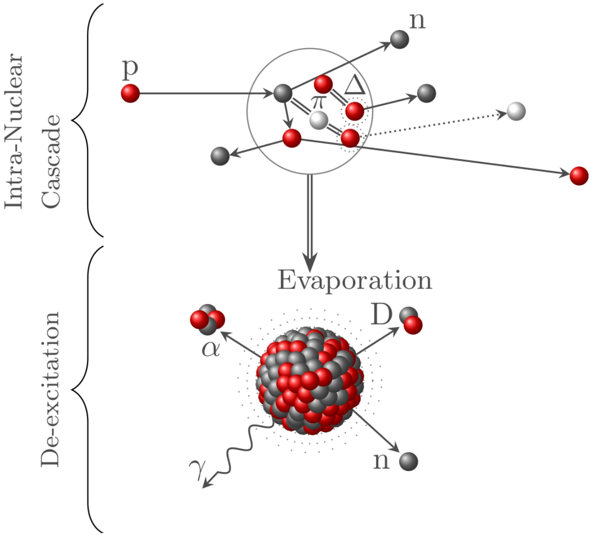


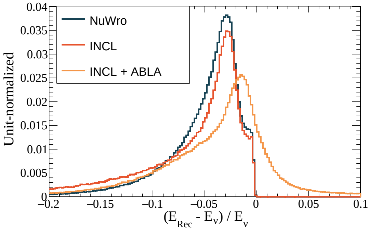
Neutrino energy reconstruction

proton only:

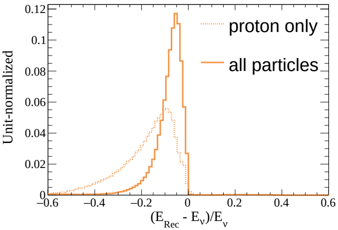
$$E_{rec} = E_{\mu} + T_p$$

all particles:

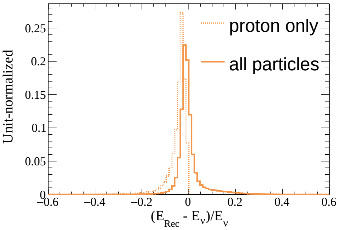
$$E_{rec} = E_{\mu} + \sum_i T_i$$



"all particles" reconstruction

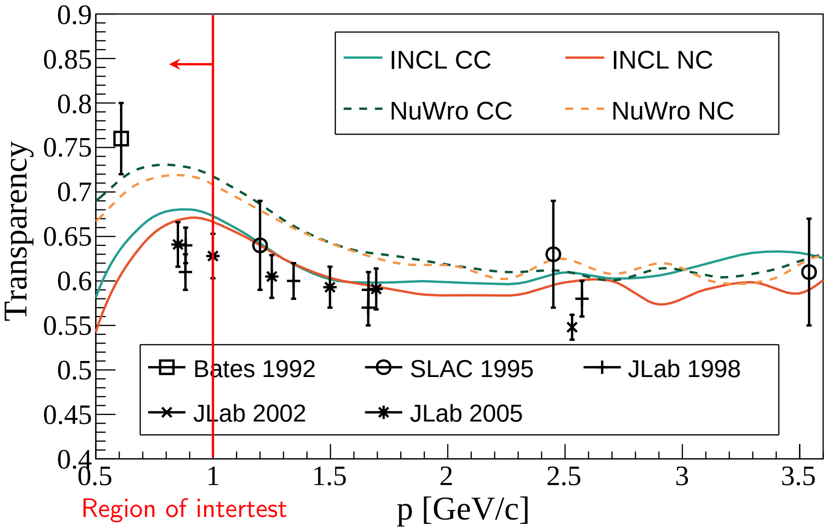


INCL+ABLA cascade FSI



INCL+ABLA no cascade FSI

Explanation of $E_{rec} > E_{\nu}$ in backup



Here transparency is a probability for proton to leave the nucleus "un-touched".

Transparency **will not be changed** with de-excitation.

Channels classification

These are the possible **proton FSI** channels:

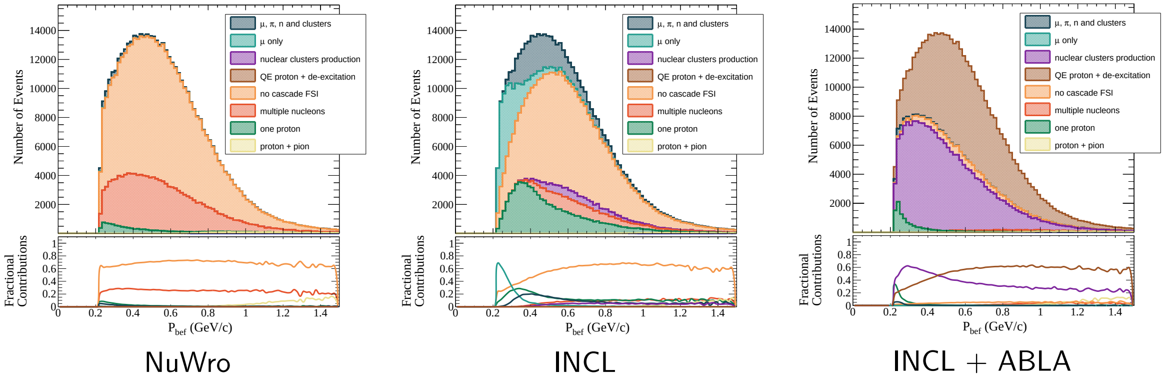
- **No FSI:** no change of energy of the highest momentum proton, no extra final state particles
- **One Proton:** change of energy of the highest momentum proton, no extra final state particles.
- **Multiple nucleons:** production of extranucleons but no pions and nuclear clusters in the final state
- **Proton + Pion**
- **0 proton events**

For INCL:

- μ **only:** full proton reabsorption
- μ, π, neutrons and nuclear clusters, no proton in the final
- **Nuclear cluster production:** multiple nucleons + nuclear clusters state

Proton momentum before FSI

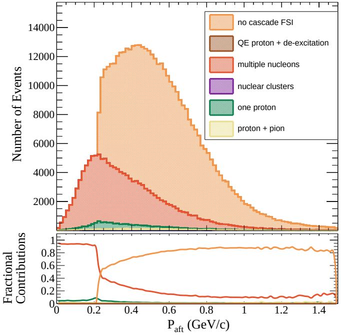
INCL cascade features a significant fraction of **events without a proton** in the final state. With de-excitation, we almost **do not have** events with no proton in the final state. Now the **nuclear cluster** production is a part of the "multiple nucleons" channel.



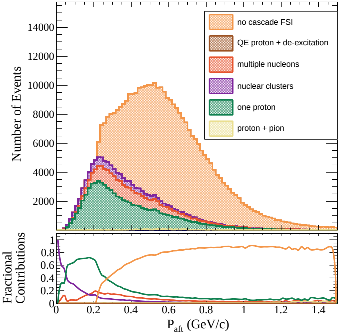
In INCL+ABLA, 98% of "multiple nucleons" events contain clusters.

Proton momentum after FSI

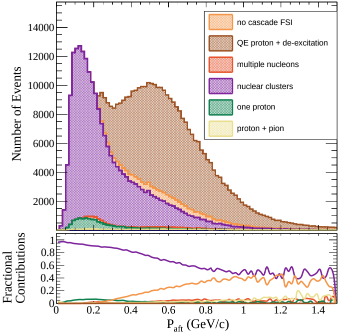
We "bring back" events from 0 proton channel, they **contribute to the low momentum** region of the distribution.



NuWro



INCL



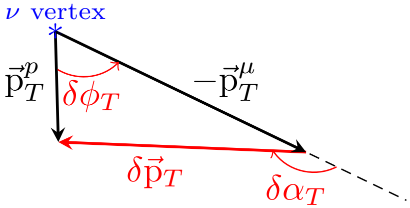
INCL + ABLA

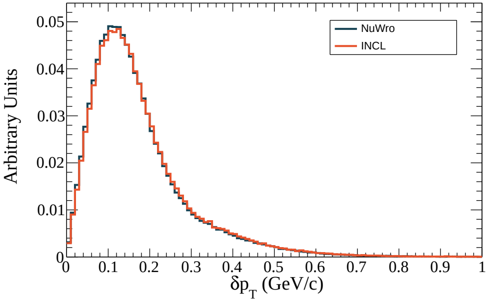
Variables of interest

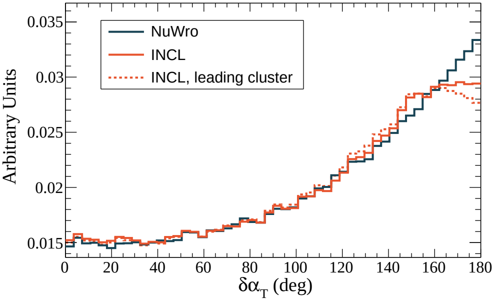
We use **Single Transverse Variables (STV)** that allow to disentangle different effects for better FSI estimation. STV are **observable** and **measurable**.

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

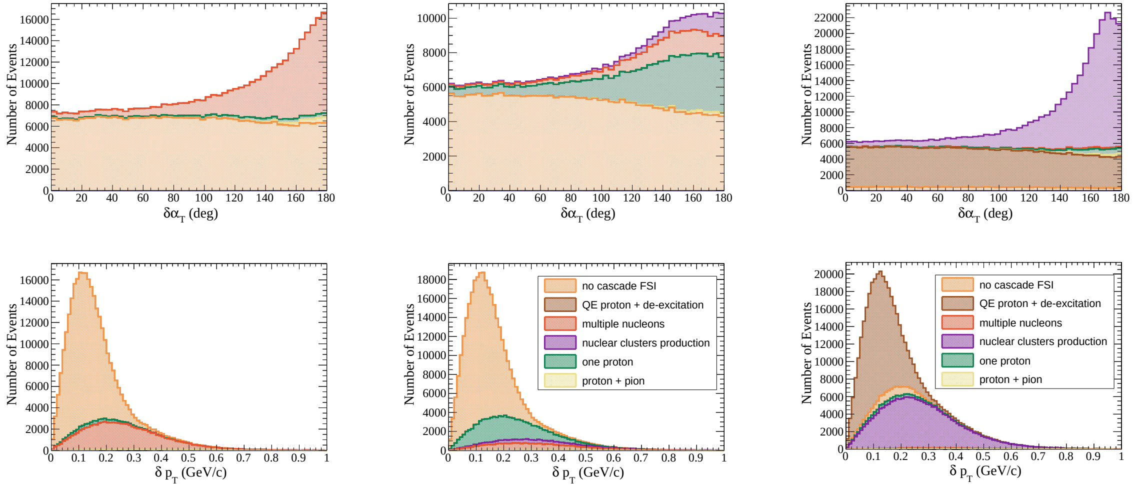
sensitive to Fermi Motion: $\delta\vec{p_T} = \vec{p_T^p} + \vec{p_T^\mu} = \vec{p_T^n}$







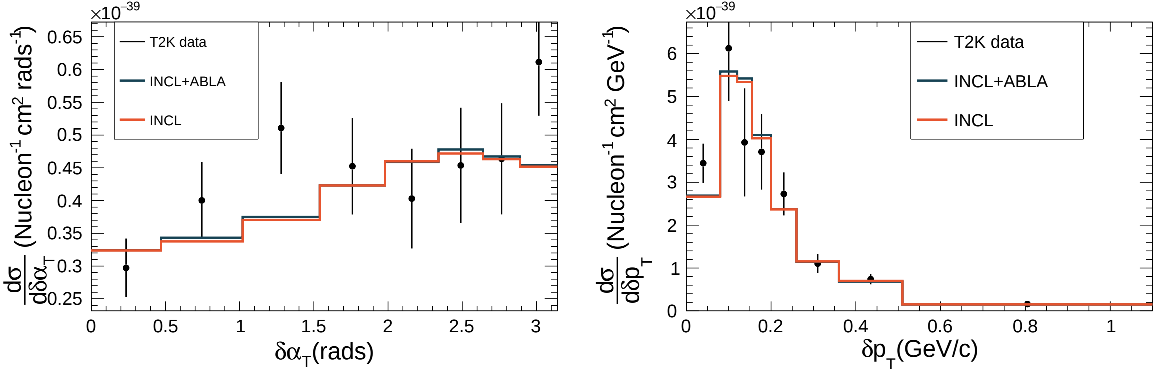
STV



NuWro INCL INCL + ABLA

Comparison to T2K data: INCL + ABLA

Current detector **threshold is too large**, so we **cannot really see the effect** of de-excitation.

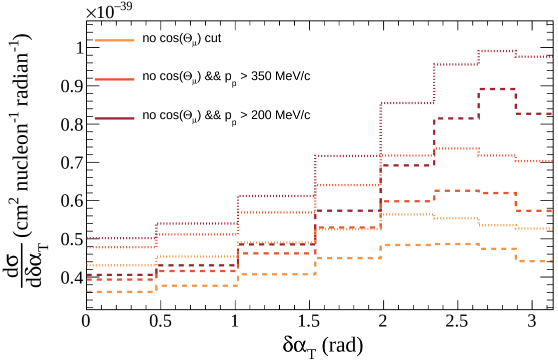


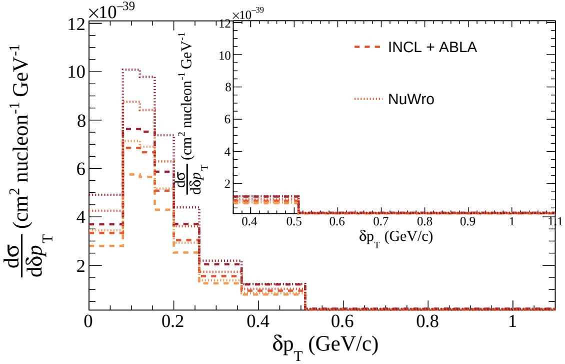
Cuts (MeV): $p_\mu > 250$; $450 < p_p < 1000$; $\cos(\Theta_\mu) >$ -0.6; $\cos(\Theta_p) > 0.4$

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

What if we change cuts to mimic better sensitivity?

We start to distinguish models from $p_p > 200$ MeV/c

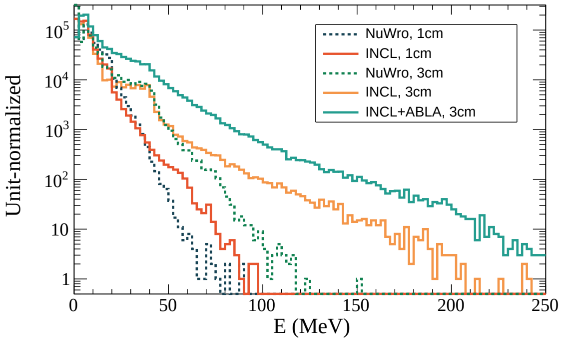




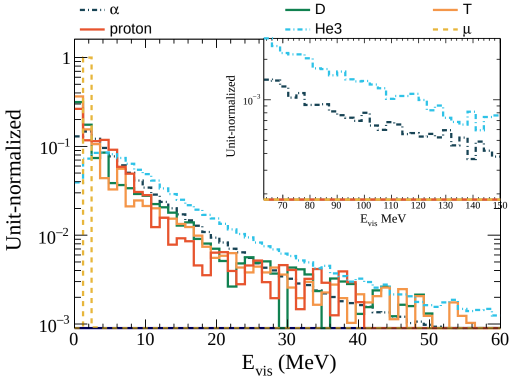
Vertex Activity

We define vertex activity as **visible energy deposited** (with Birks correction) in a 1(3) cm sphere **around** the neutrino interaction vertex. We distinguish **two types** of VA:

- **per event**: sum of energy deposits of all particles produced in a given event
- **per particle type**: energy deposit separately for different particle types



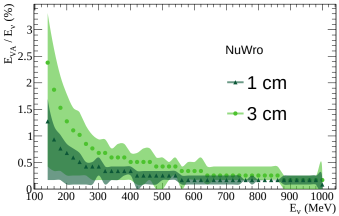
VA per event



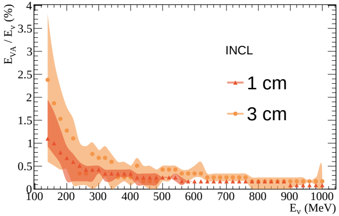
VA per particle type (3 cm)

Vertex Activity as a fraction of neutrino energy

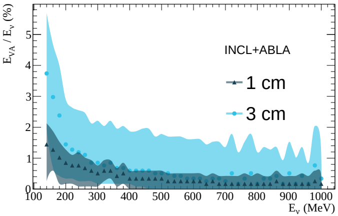
Here VA is the energy we see in the detector. In order to reach a precision on neutrino energy reconstruction at **percent level** (as requested for precise oscillation measurements), the vertex activity plays a **relevant role** up to several hundreds of MeV, especially when the **energy released by de-excitation** is considered.



NuWro



INCL

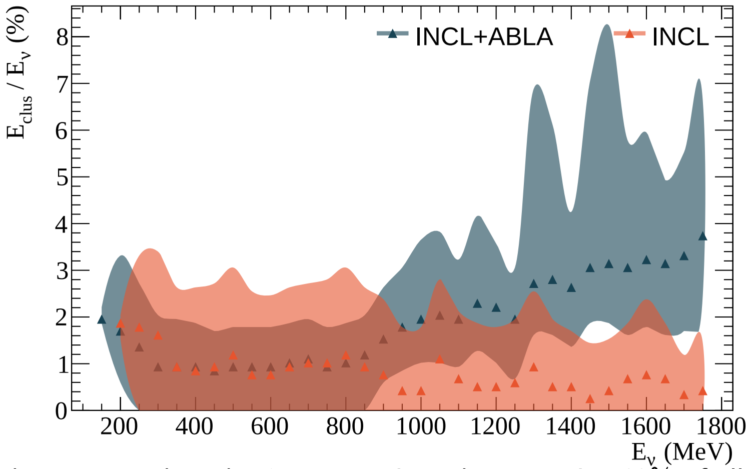


ABLA

The bands correspond to the 1σ uncertainty that contains 68% of all events.

E_{kin} of non-leading particles as a fraction of neutrino energy

The **actual fraction** of neutrino energy going to the kinetic energy of the subleading hadrons is **non-negligible**. It is larger than energy observed in the detector because of quenching



The bands correspond to the 1σ uncertainty that contains 68% of all events.

Conclusion

We compared the simulation of the final-state interactions between the **NuWro** and **INCL** cascade models in CCQE events. We coupled INCL cascade to the ABLA de-excitation model.

- "transparent events" are **not** transparent: nuclear clusters may be produced
- INCL+ABLA simulation features **massive difference** in nucleon kinematics in comparison to NuWro
- INCL cascade features a significant fraction of events **without a proton** in the final state, especially low proton momentum before FSI region
- An essential novelty of this study is the **simulation of nuclear cluster production** during cascade and de-excitation. It is important for the understanding of the **vertex activity** and calorimetric method of ν **energy reconstruction**
- it is crucial to have models that can adequately describe **vertex activity**, which needs to be corrected back for a precise reconstruction of the total neutrino energy but is so **difficult to observe**

Prospects

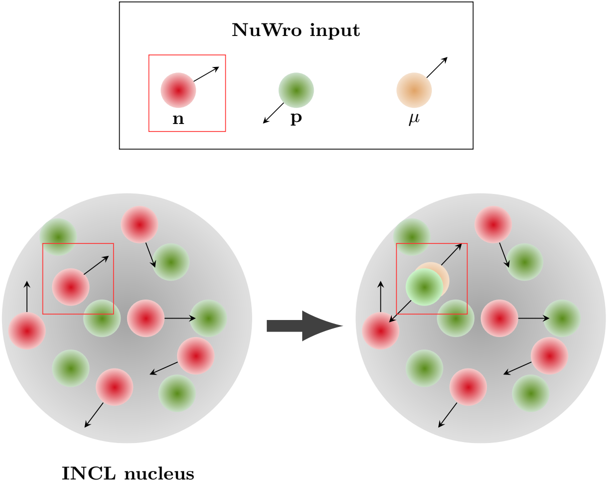
New generation of detectors starts to use the **exclusive** FSI

- ND280 upgrade of T2K to improve the detector threshold
- SK-Gd project: add gadolinium to SK to enhance the neutron detection efficiency
- The LAr program in USA is dedicated to measuring all the particles in the final state

The **de-excitation study** will be published soon. There is still plenty of work to be done: **neutron secondary interaction** studies, $\bar{\nu}$ simulation and **pion FSI**.

BACK UP

Using INCL with NuWro input



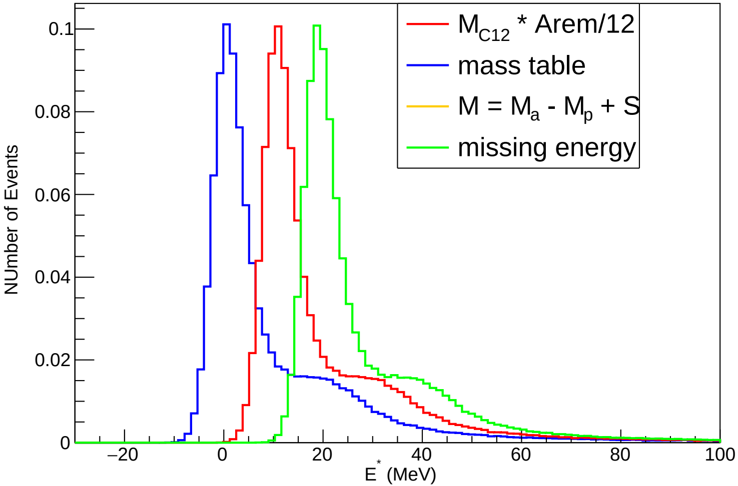
We use **NuWro sample** to model ν **CCQE** reaction on **carbon** target. We want to compare **FSI cascades** modelled by **INCL** and **NuWro**.

But there is no neutrino vertex implemented in INCL, so:

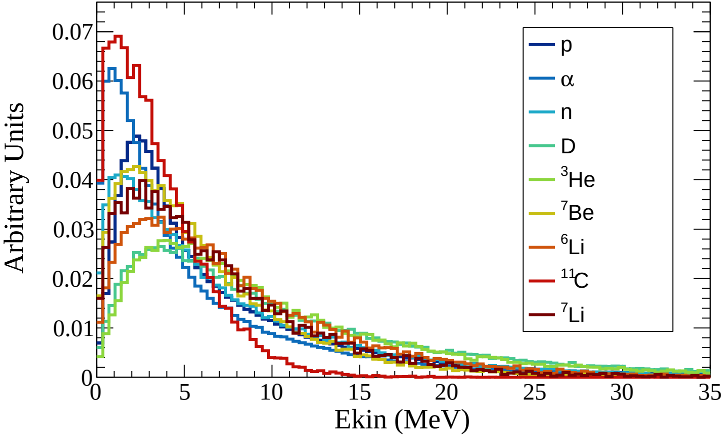
- we choose in INCL the neutron with the momentum closest to the NuWro neutron (on which ν reacted)
- we change this neutron to the reaction products: μ and proton

Why sometimes $E_{rec} > E_\nu$

NuWro, SF, excitation energy calculation

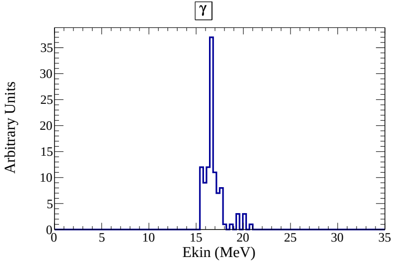


Particles produced in de-excitation



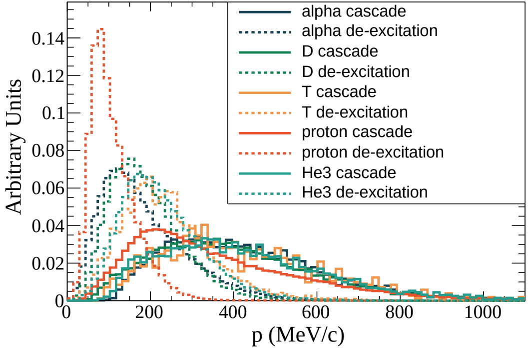
Kinetic energy of the **top 10** produced particles

ABLA mostly produces particles with **low energy**. Production of γ is **highly suppressed** (as expected) and is taking place when no other particle can be emitted.



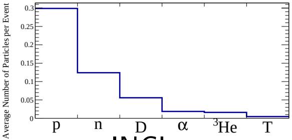
Kinetic energy of γ

Nuclear clusters in the detector

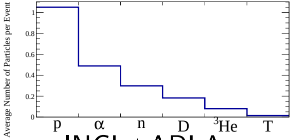


Momentum of nuclear clusters produced during the cascade and de-excitation

Nuclear clusters production



INCL



INCL+ABLA

Only INCL:

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

INCL + ABLA:

	α	^{3}He	T	D	proton
>1 cm, %	0.05	1	7.5	12.5	18.5
>3 cm, %	0	0	2	5	12