Role of deexcitation in the final-state interactions of protons in neutrino-nucleus interactions

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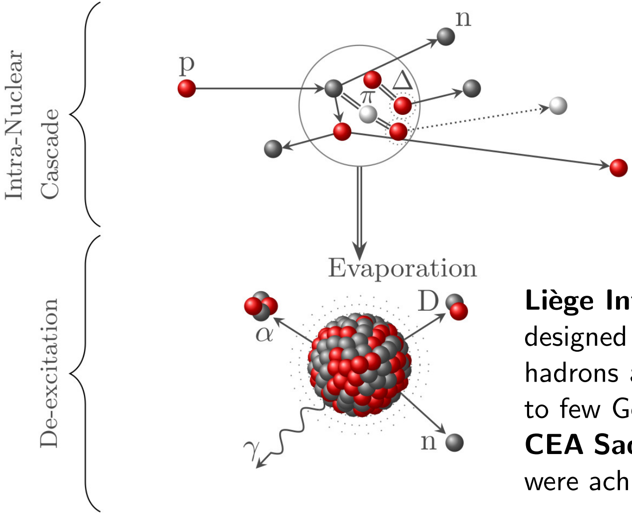
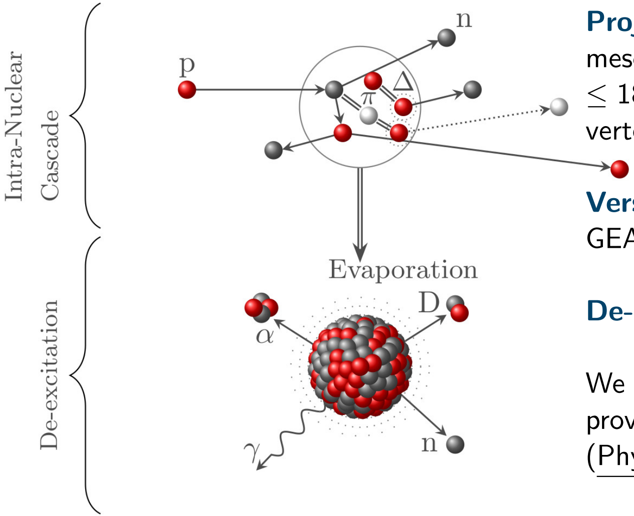


Liège Intra Nuclear Cascade: is a code initially designed to simulate nuclear reactions induced by hadrons and light nuclei in the few tens of MeV to few GeV range. Its development is ongoing at **CEA Saclay**, and the results presented in this talk were achieved there.

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**

Versatile tool: has been implemented in GEANT4, GENIE, and other

De-excitation: ABLA, SMM, GEMINI

We will use **ABLA**, since it is proved to work for the **light nuclei** (Phys. J. Plus 130, 153 (2015))

Neutrino simulation results:
PRD 106, 3 (2022), PRD 108, 11 (2023)

Cascade ingredients of INCL

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.

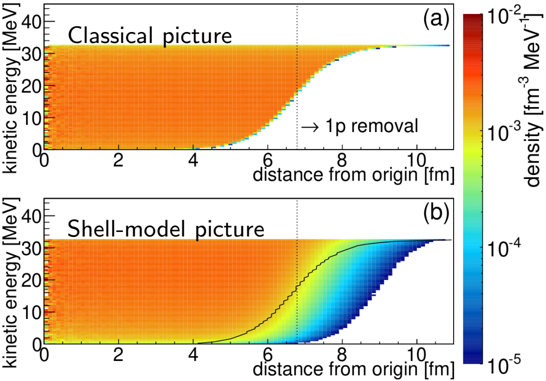
Pauli Blocking

- **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)

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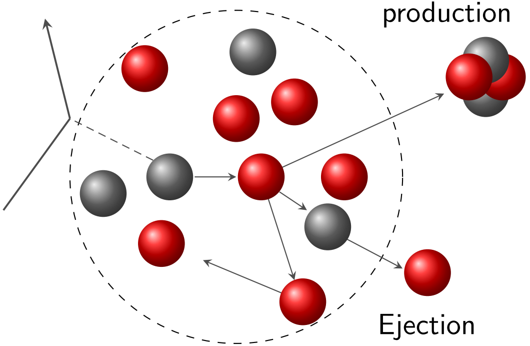
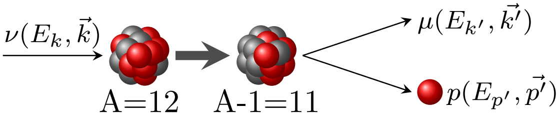


Excitation energy calculation

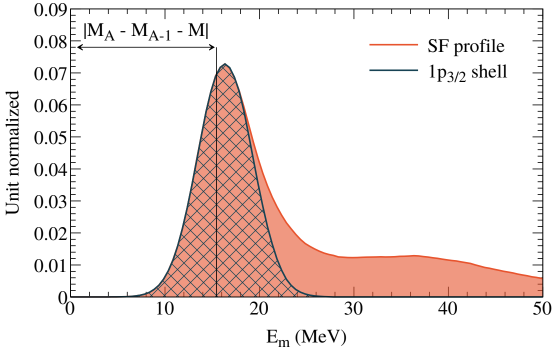


Experimental definition:

$$E_x^{\text{exp}} = E_{missing} - \underbrace{(M_A - M_{A-1} - M)}_{constant}$$

- A constant shift of missing energy by ∼15.4 MeV leads to **non-physical, negative values**
- We use experimental data (J. Phys. G: Nucl. Part. Phys. 16 507 (1999)) to simulate discrete levels

M_{A-1} is the rest mass of the $A-1$ nucleus
M_A is the rest mass of the initial A nucleus
M is the rest mass of the target nucleon
$E_{missing}$ is the missing energy
For interaction on carbon,
$M_A - M_{A-1} - M = 15.4$ MeV



We assume all strength below the peak comes from the symmetric $1p_{3/2}$ shell

Experimental data used for the carbon spectral function

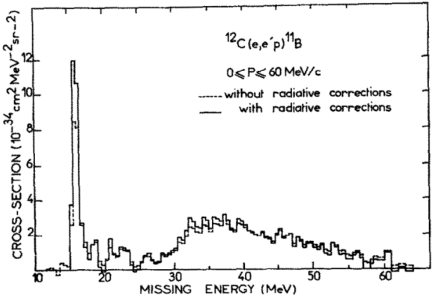


Fig. 7. Energy spectrum of the ^{12}C(e, e'p) reaction before and after the radiative corrections.

Nuclear Physics A262 (1976) 461-492

Experimental data used to simulate the discrete levels

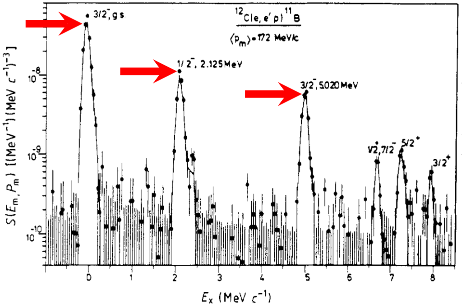
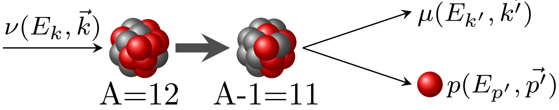


Figure 22. Excitation-energy spectrum of ^{11}B observed in the reaction ^{12}C(e,e'p). Both negative and positive-parity final states are shown.

J.Phys.G: Nucl.Part.Phys. 16 507 (1990)

Excitation energy calculation



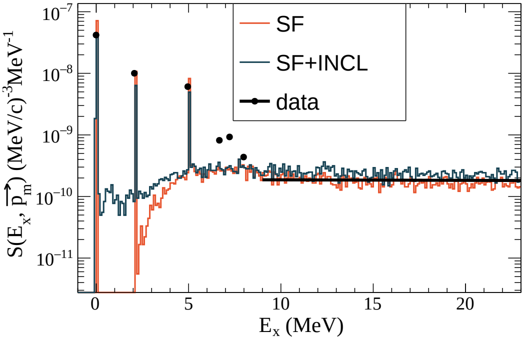
M_R^* is the mass of the excited remnant
M_R is the rest mass of the remnant
T_R is the kinetic energy of the excited remnant
p_m is the missing momentum

For the continuous spectrum part, we can calculate excitation energy as:

$$E_x = M_R^* - M_R, \text{where:}$$

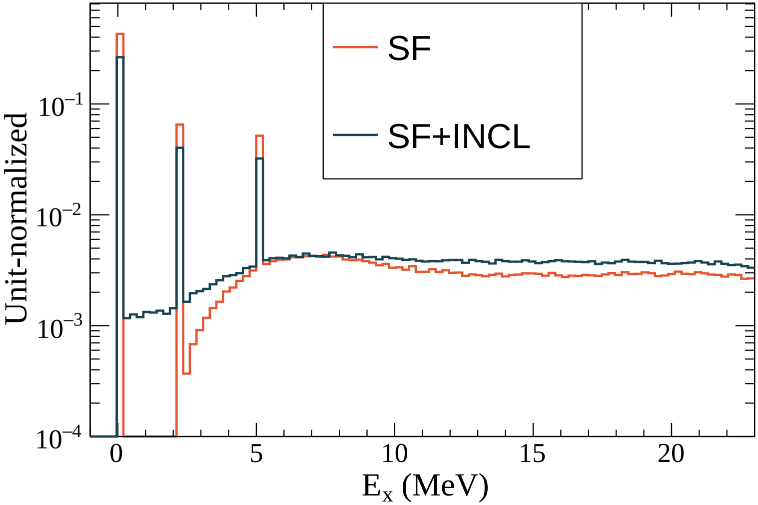
$$M_R^* = \sqrt{(E_k + M_A - E_{k'} - E_{p'})^2 - |\vec{p}_m|^2}$$

Otherwise, we model **3 discrete peaks** with strength of 79%, 12%, and 9% (**p-shell**)



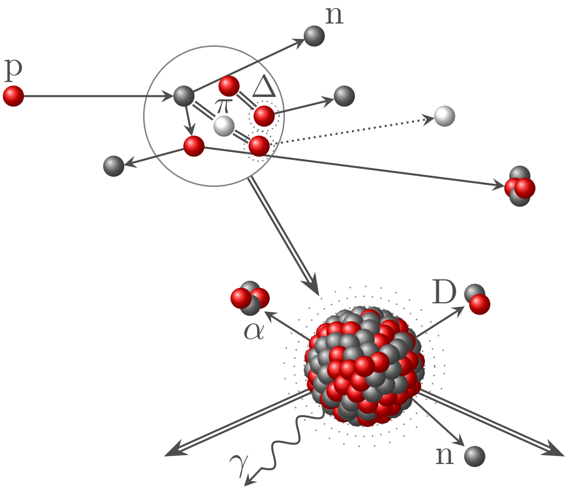
Excitation energy of the nuclear remnant after neutrino interactions for 169.5 $< p_m <$ 174.5 MeV

Excitation energy calculation



Final distribution of the excitation energy

We use INCL+ABLA to simulate **neutrino CCQE** events with the **T2K** energy spectrum. We compare the obtained results to **NuWro**.



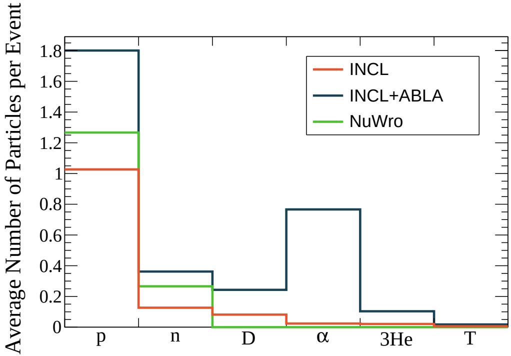
In the paper Phys.Rev.D 106, 3 (2022) we show the **nuclear cluster production for the first time** in FSI.

In the paper Phys.Rev.D 108, 11 (2023) we study the impact of the subsequent **de-excitation modelling**, that predicts **more nuclear clusters**.

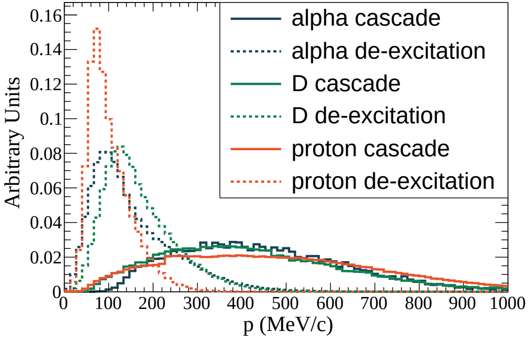
Important! Gamma production during de-excitation is just a **small fraction** of possible scenarios

Production of the nuclear clusters

ABLA features a **massive production** of particles with **low momentum**.



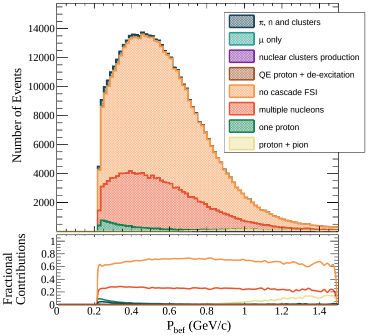
Average number of particles per event produced by INCL, INCL+ABLA, and NuWro.



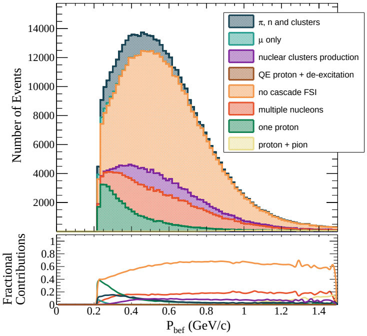
Momentum of nuclear clusters produced during the cascade and de-excitation

Proton momentum before FSI

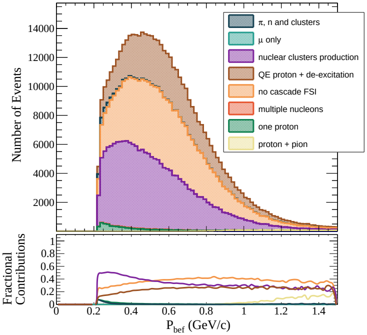
- Large fraction of "no FSI" events (i.e. proton untouched) is now **feature production of other particles** (and nuclear clusters) in the final state due to de-excitation
- Events with **only nucleon production** now feature **nuclear cluster production**



NuWro



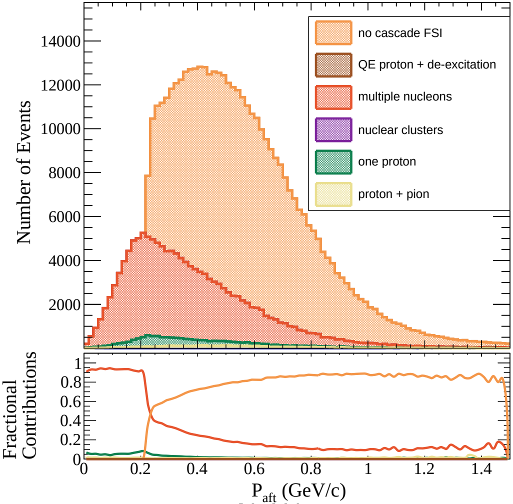
INCL



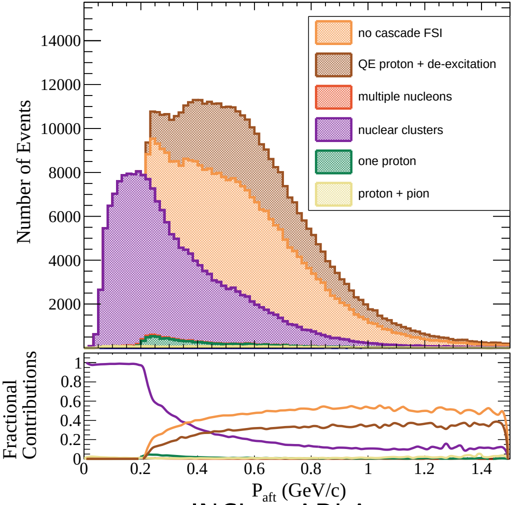
INCL + ABLA

Proton momentum after FSI

INCL+ABLA simulation features **massive difference** in nucleon kinematics in comparison to NuWro



NuWro



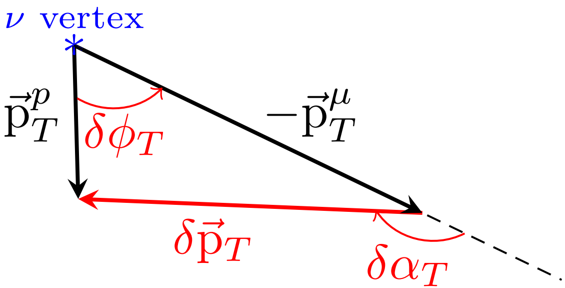
INCL + ABLA

Transverse kinematic imbalance

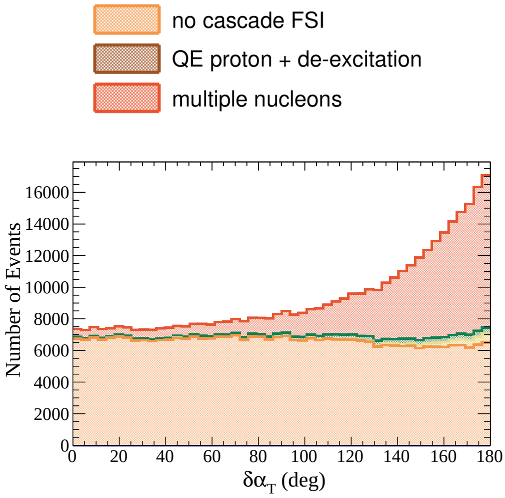
We use **Single Transverse Variables (STV)** that allow to disentangle different effects for better FSI estimation. STV are **observable** and **measurable**.

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

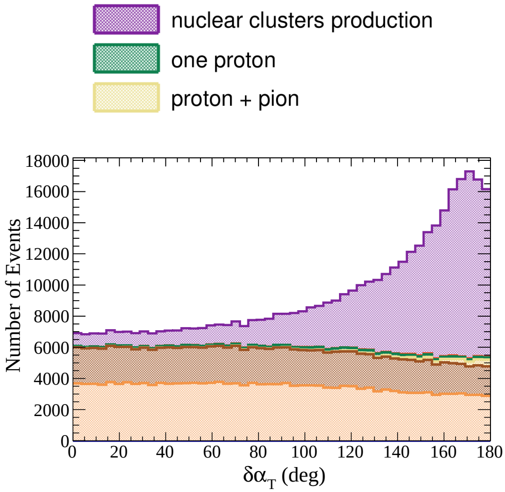
sensitive to Fermi Motion:
$$\delta p_{\vec{T}} = p_T^{\vec{p}} + p_T^{\vec{\mu}} = p_T^{\vec{n}}$$



High $\delta\alpha_T$ strongly depends on FSI and is affected by de-excitation and Pauli blocking

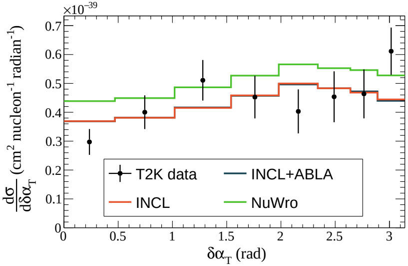


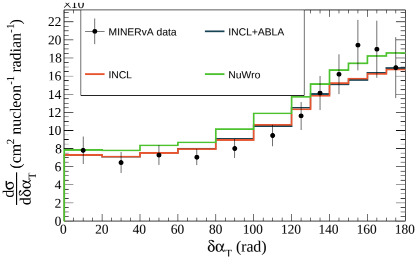
NuWro



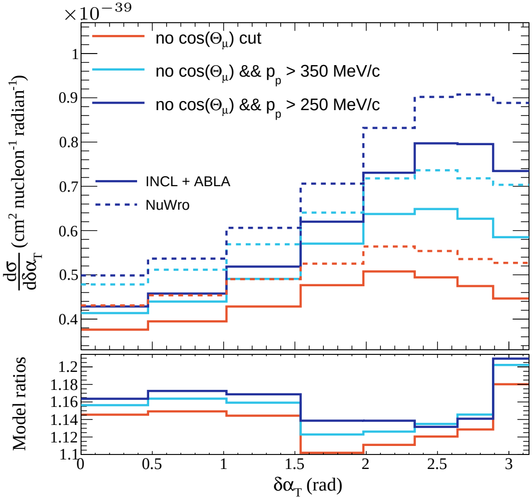
INCL+ABLA

Current detector threshold in ND280 and MINERvA scintillators is **too large**, so we **cannot see the difference** between INCL and NuWro





Lower threshold provides better sensitivity to distinguish models



Neutrino energy reconstruction

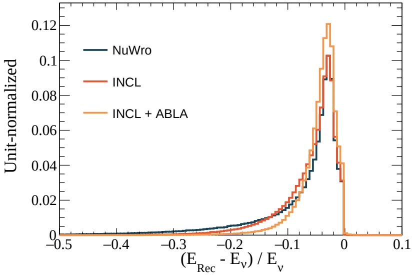
Using $\mu + p$ is **better** than using muon only, but here we show that we gain even **higher precision** by using all subleading particles

proton only:

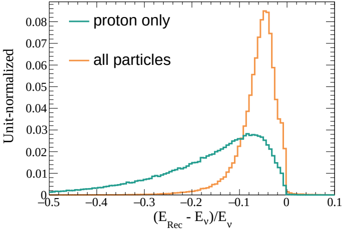
$$E_{rec} = E_\mu + T_p$$

all particles (including clusters)

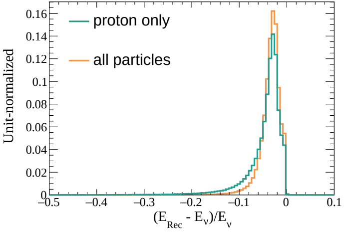
$$E_{rec} = E_\mu + \sum_i T_i$$



"all particles" reconstruction



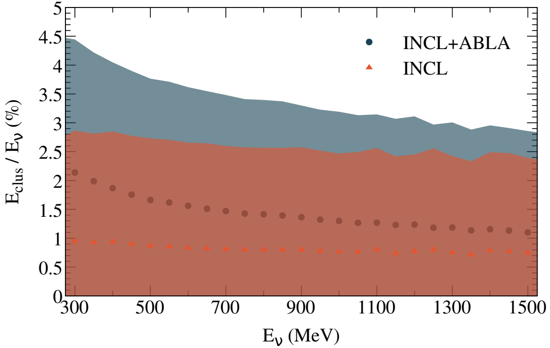
INCL+ABLA cascade FSI



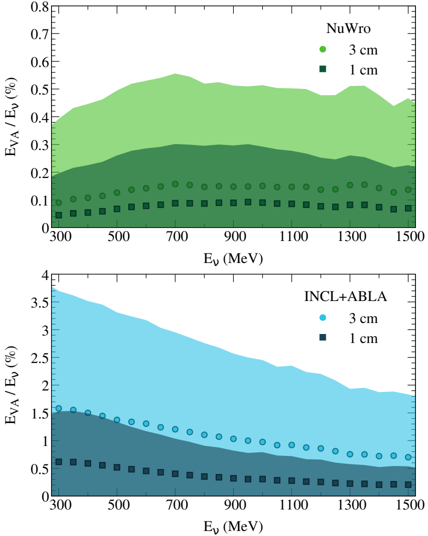
INCL+ABLA no cascade FSI

Vertex Activity as a fraction of neutrino energy

The **actual fraction** of neutrino energy going to the kinetic energy of the subleading hadrons is **non-negligible**.



What can be actually seen in the detector (Birks quenching applied):



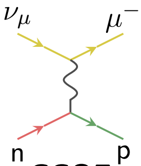
Summary

- the effort is ongoing to integrate **CCQE** reaction in INCL with subsequent implementation in **Geant4**
- "transparent events" are **no always** transparent: nuclear clusters may be produced
- INCL+ABLA simulation features **important difference** in nucleon kinematics in comparison to NuWro (and the other similar generator used in neutrino scattering)
- 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**

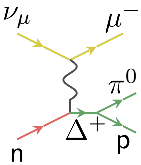
For **precise neutrino energy reconstruction** (e.g. "calorimetric method") is important to include **vertex activity** ($\sim 1 - 2\%$), and to have proper model of it to correct for detector quenching. Large portion of VA comes from the **de-excitation**.

BACK UP

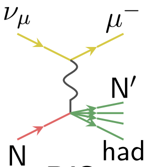
ν energy reconstruction



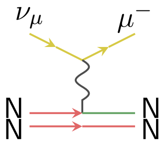
CCQE



RES



DIS



2p2h

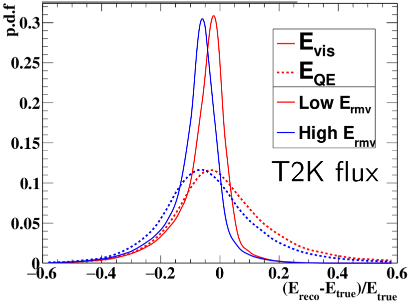
Energy reconstruction using only muon kinematics (works well for **quasi-elastic reaction**):

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

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

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

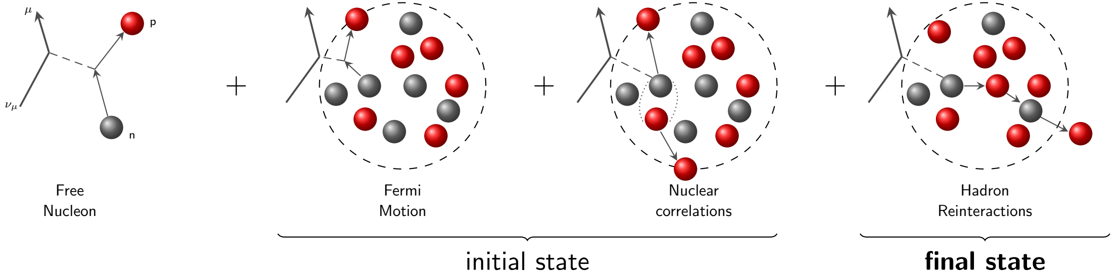
Phys. Rev. D 105, 032010 (2022)



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

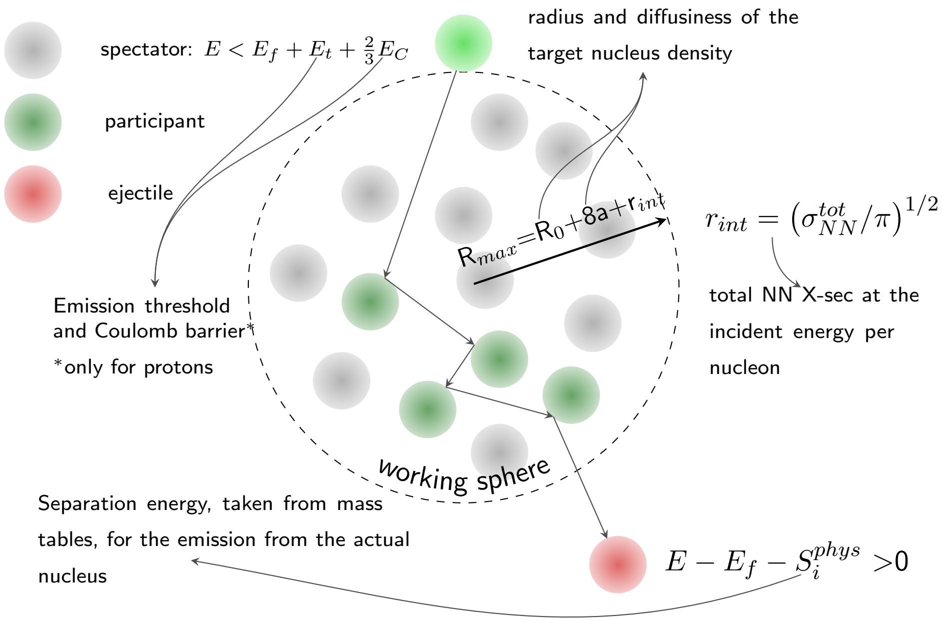
Importance of nuclear effects

$\mu + \mathrm{N}$ 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 will focus on **CCQE** ν reaction channel and the **Final State Interactions (FSI)** that are described by **cascade models** and on the nuclear **excitation energy**.

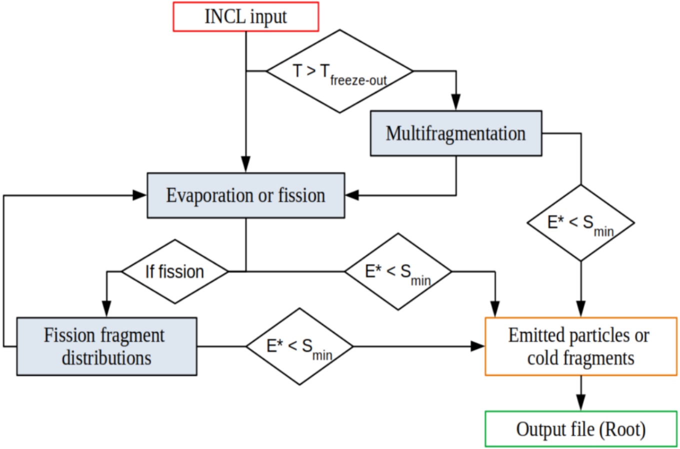
Standard INCL cascade



ABLA

The ablation model **ABLA** describes the **de-excitation** of an excited nuclear system through the emission of γ-rays, neutrons, light-charged particles, and intermediate-mass fragments (or fission in case of hot and heavy remnants).

Phys. Rev. C 105, 014623 (2022)



$$T_{freeze-out} = max\left[5.5, 9.33e^{\left(-2.82\times10^{-3}A_{rem}\right)}\right]$$

S_{min}—minimum particle separation energy