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

Anna Ershova

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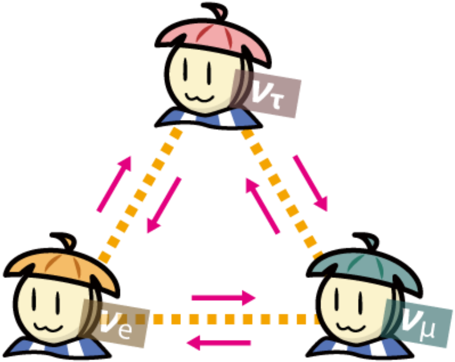
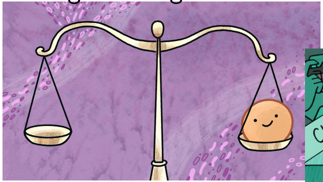
Physique des 2 Infinis et des Origines

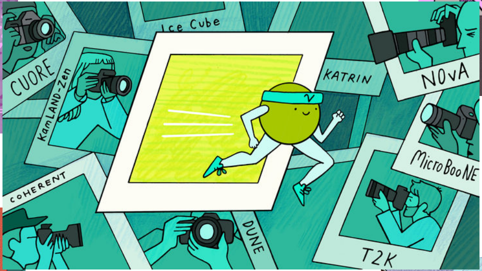
Outlook

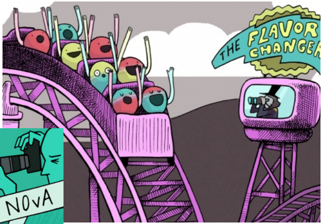


Mysterious neutrinos

Mass generating mechanism?

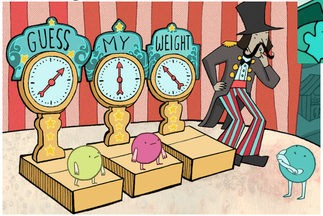






Oscillation parameters?

ν weight?



CP violation in lepton sector?

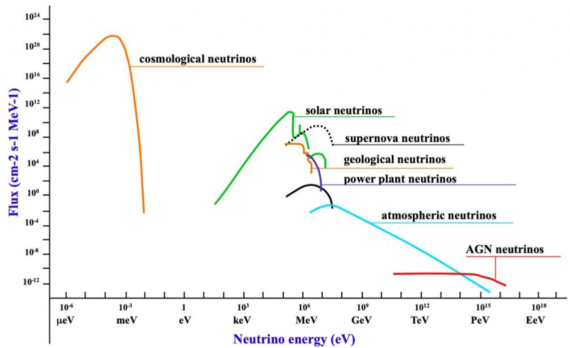
Sterile neutrinos?

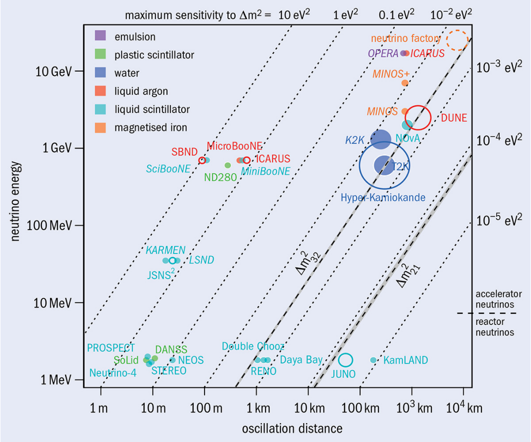
...

Mass hierarchy?

symmetrymagazine.org

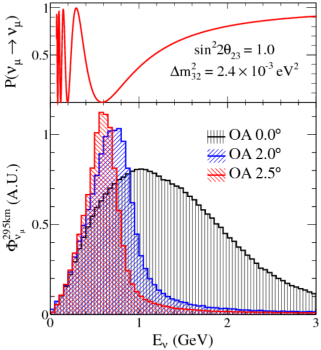
Neutrino studies



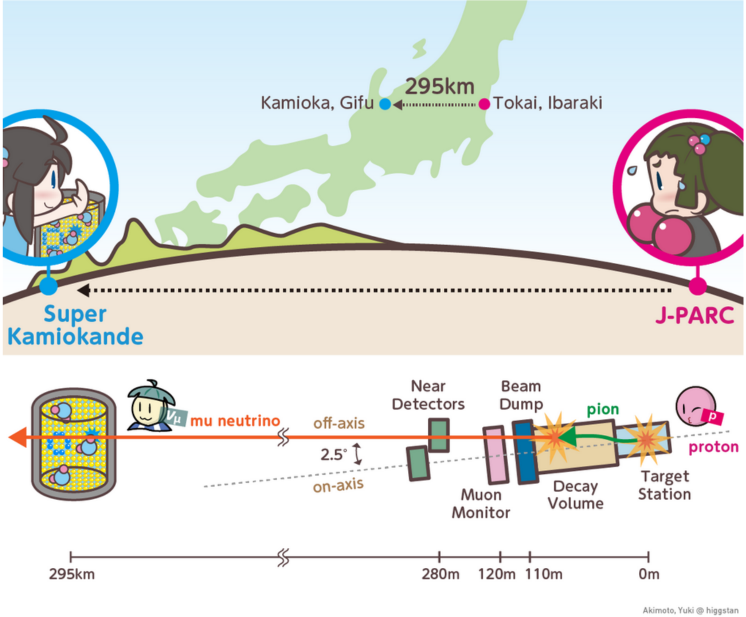


T2K: design

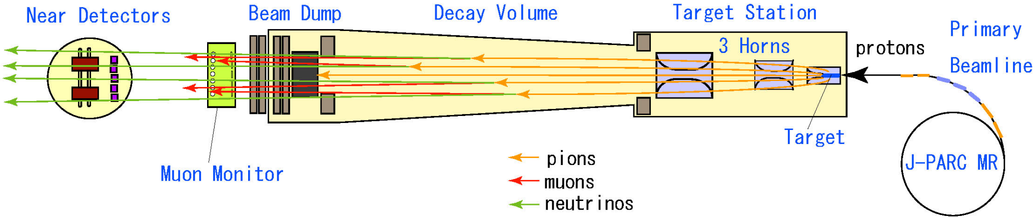
The **off-axis** configuration allows a better **focus** of ν energy at the **peak** of ν oscillation probability.



Phys. Rev. D 87, 012001 (2013)



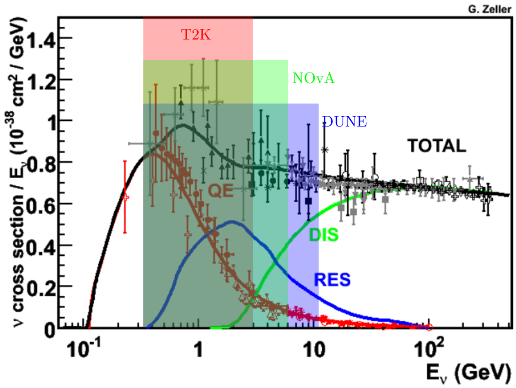
T2K: ν rate measurement

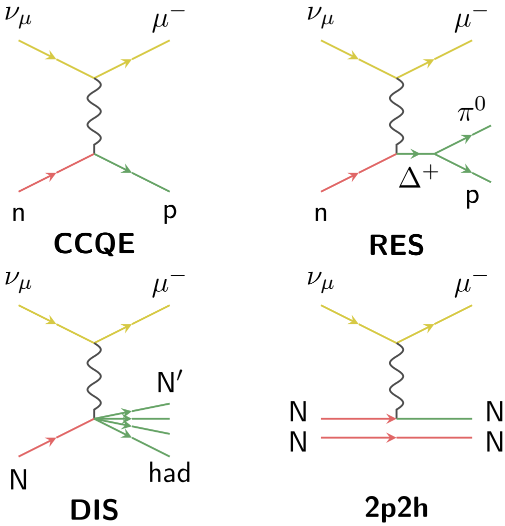


$$\overbrace{R^{\nu'}_{FD}(E_\nu)}^{\nu\ \textbf{rate}} = \underbrace{\Phi^{\nu}(E_\nu)}_{\nu\ \textbf{flux}} \otimes \overbrace{P^{\nu\rightarrow\nu'}_{osc}(E_\nu)}^{\textbf{oscillation probability}} \otimes \underbrace{\sigma^{\nu'}(E_\nu)}_{\nu\ \textbf{cross-section}} \otimes \overbrace{\varepsilon(E_\nu)}^{\textbf{detector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

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

ν energy reconstruction





CCQE is the most important channel for T2K, and in this presentation we will focus on it

ν energy reconstruction

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

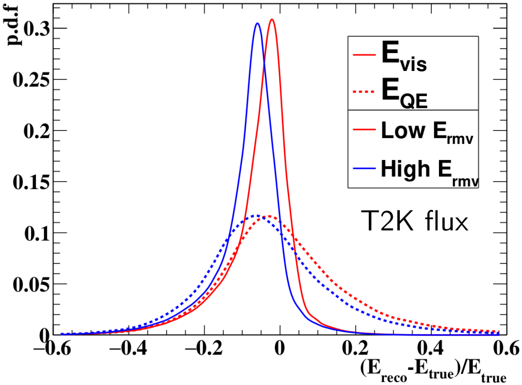
$$E_\nu^{QE} = \frac{m_p^2 - (m_n - E_B)^2 - m_\mu^2 + 2(m_n - E_B)E_\mu}{2((m_n - E_B) - E_\mu + p_\mu \cos\theta_\mu)}$$

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

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

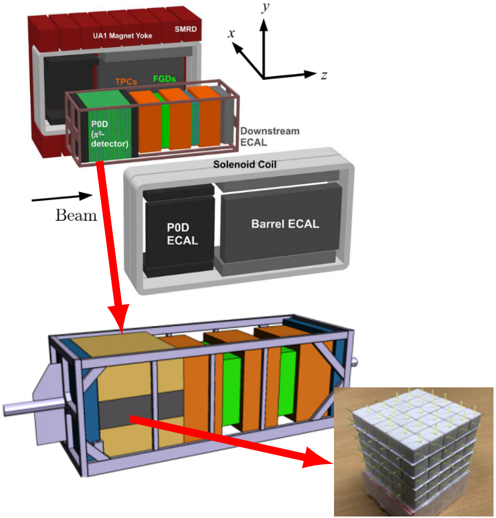
The community is moving from **inclusive** measurements (using only the outgoing lepton) to **exclusive** ones where also the **hardonic part**.

Phys. Rev. D 105, 032010 (2022)



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

Upgrade of ND280 detector

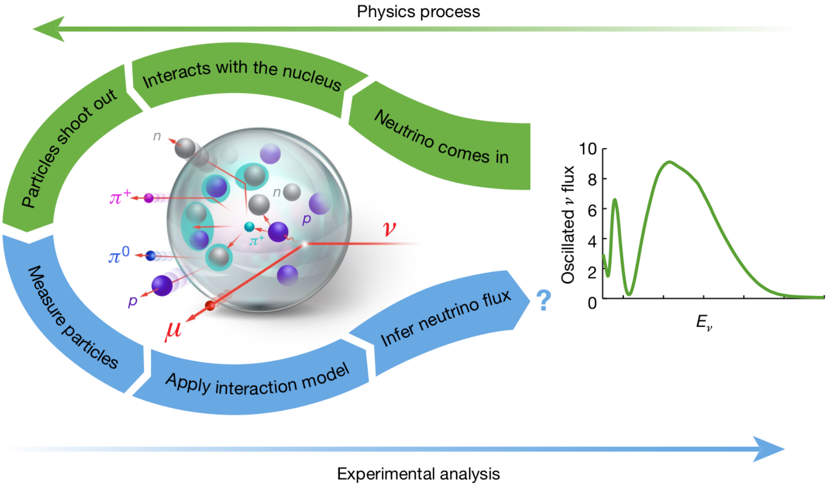


- better reconstruction efficiency of **high angle muons**: **angular acceptance** close to SK 4π acceptance
- ability to detect **neutrons**
- lower **proton** momentum threshold
- ν **energy reconstruction** using also hadronic part

Upgrade will give us access to a **new phase space** with which we can constrain better the **nuclear models** used in the oscillation analysis. IRFU has a major contribution to the T2K upgrade: new HA-TPC with the resistive MicroMegas technology.

Importance of nuclear effects

We need **not only** a better detector, but also better **modelling** of the neutrino-nucleus interactions, e.g. improved Monte-Carlo generators!



My work

- I use INCL use for the first time to predict **exclusive final states of neutrino interactions**
- INCL model features various **novelties**, including the **production of nuclear clusters** (e.g., deuterons, α particles)
- De-excitation process (that we model with ABLA) was **never modelled and studied** in neutrino physics before

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

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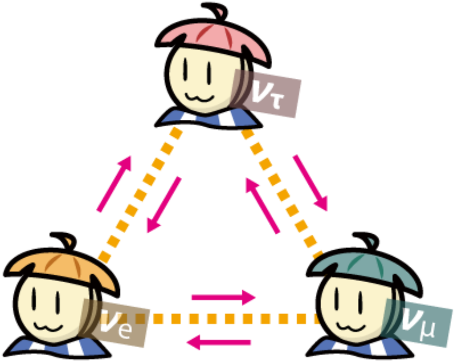
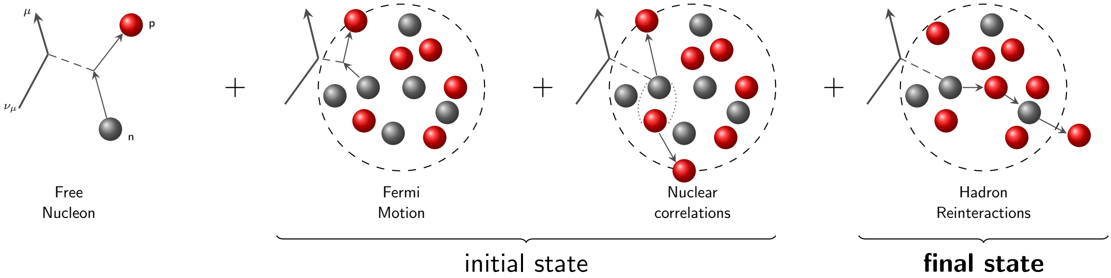
[8] *ETH Zurich, Institute for Particle Physics and Astrophysics, Zurich, Switzerland*
[9] *Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia*


ν_τ
ν_e
ν_μ

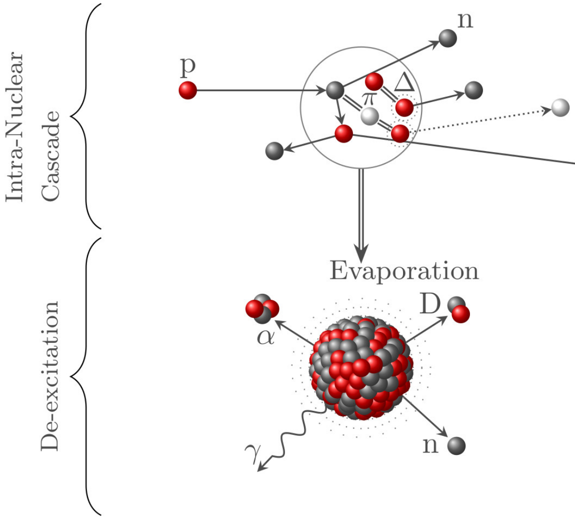
Simulation of nuclear effects

Simulation allows us to **factorize** neutrino interaction and simulate in in few stages:



I 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

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

Flexible tool: has been implemented in GEANT4 and GENIE

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.

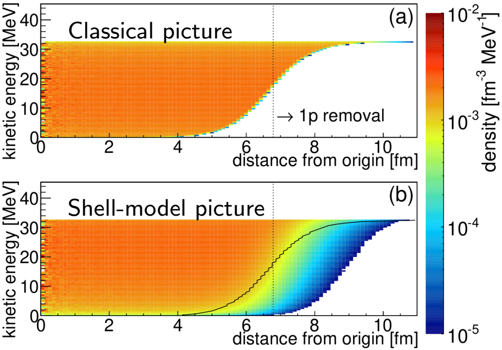
Pauli Blocking

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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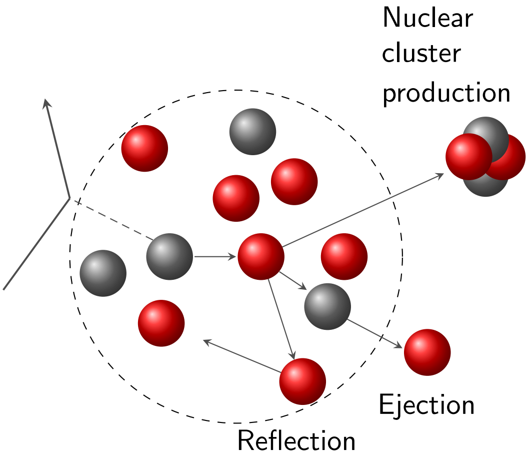
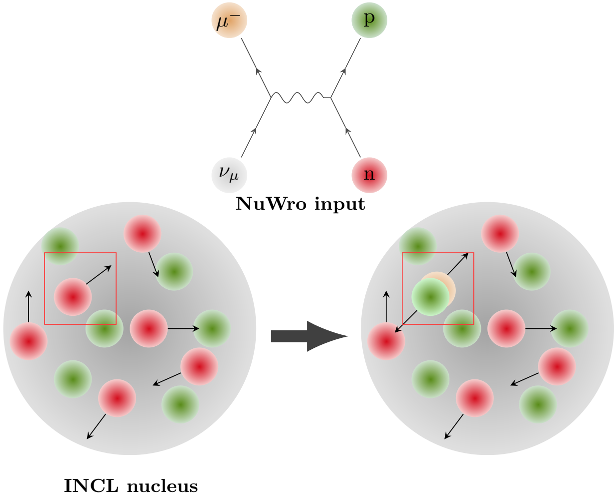


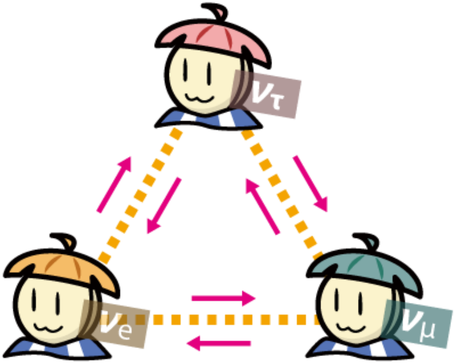
Using INCL with NuWro input



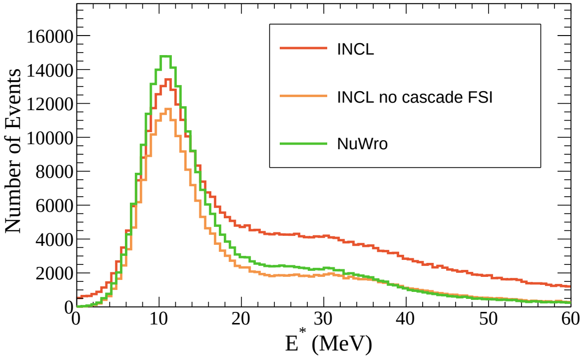
I use **NuWro sample** (one of the many generators on the market) to model ν **CCQE** reaction on **carbon** target. I want to compare **FSI cascades** modelled by **INCL** and **NuWro**.

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

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


ν_τ
ν_e
ν_μ

Excitation energy



Excitation energy

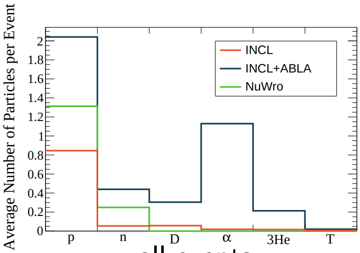
$$E = E_\nu + {}^{12}_{6}M - \sum_i E_i, \; p = p_\nu - \sum_i p_i$$

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

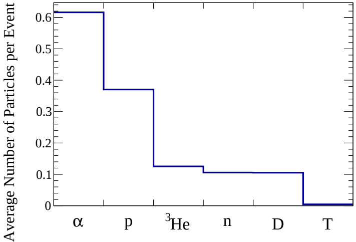
We have excitation energy even **without FSI** due to fundamental ν interaction and it will be dealt with ABLA producing **de-excitation particles** ('binding energy' does not stay in the nucleus, it becomes observable in the final state)

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)

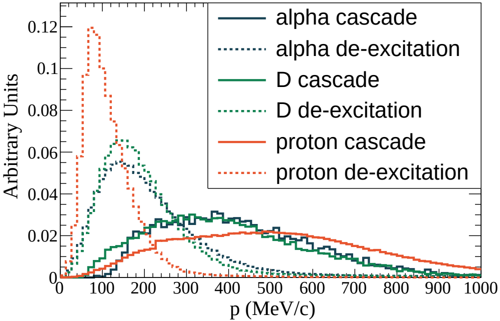
Production of the nuclear clusters (α, deuterons, tritons...)



all events



no FSI events with de-excitation



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

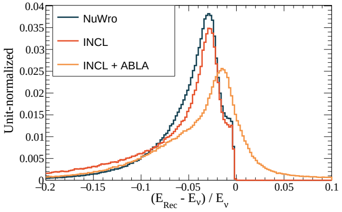
Neutrino energy reconstruction

proton only:

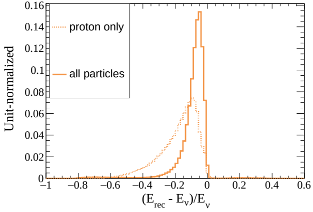
$$E_{rec} = E_{\mu} + T_p$$

all particles:

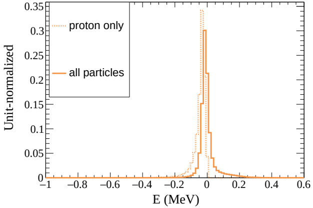
$$E_{rec} = E_{\mu} + \sum_i T_i$$



"all particles" reconstruction



INCL+ABLA cascade FSI



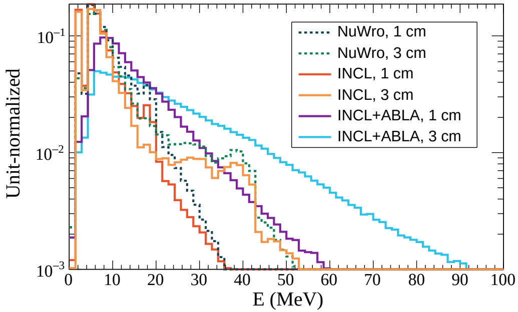
INCL+ABLA no cascade FSI

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

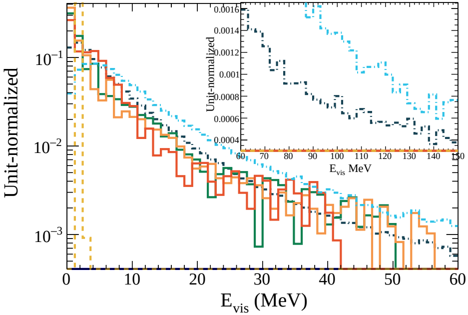
Vertex Activity

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

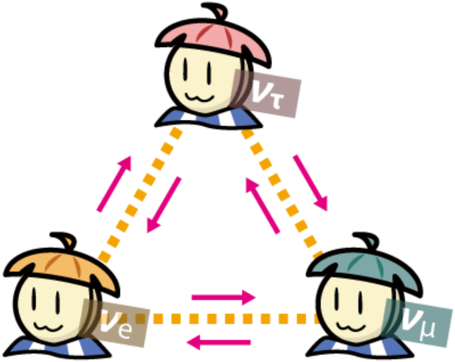


VA per event

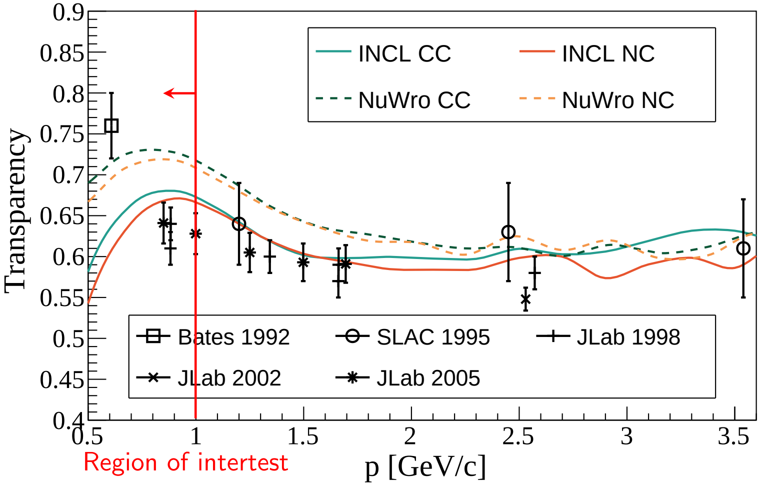


VA per particle type (3cm)

1. Introduction
2. Liège Intranuclear Cascade model (INCL)
3. **Results**
   - Neutrino energy reconstruction
   - Leading proton kinematics
   - Experimental observables



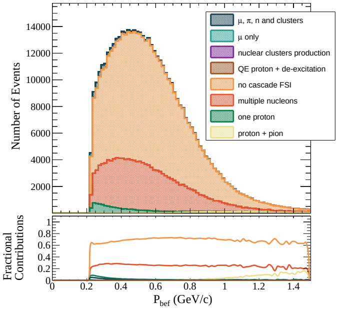
Nuclear transparency



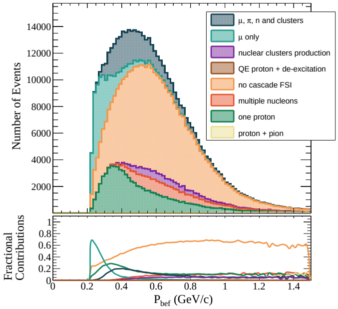
Here transparency is a probability for the **leading proton** to leave the nucleus "untouched".

Proton momentum before FSI

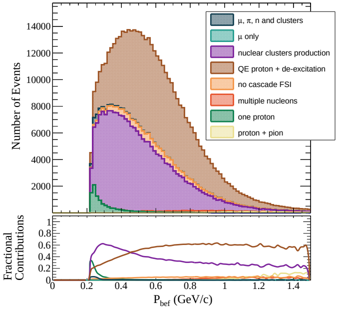
INCL cascade features a significant fraction of **events without a proton** in the final state. With de-excitation, we almost **do not have** events with no proton in the final state.



NuWro



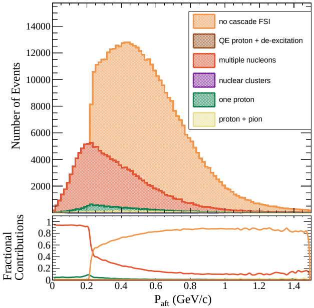
INCL



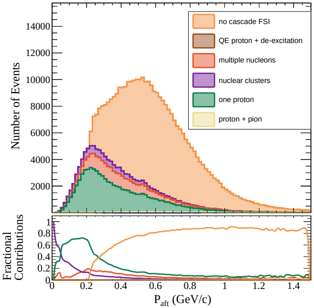
INCL + ABLA

Proton momentum after FSI

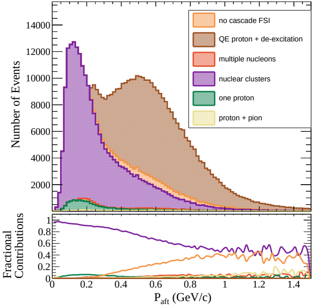
We "bring back" events from 0 proton channel, they **contribute to the low momentum** region of the distribution.



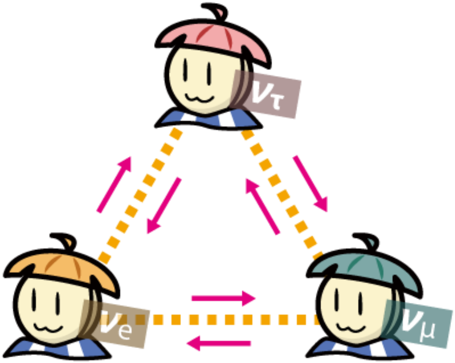
NuWro



INCL



INCL + ABLA



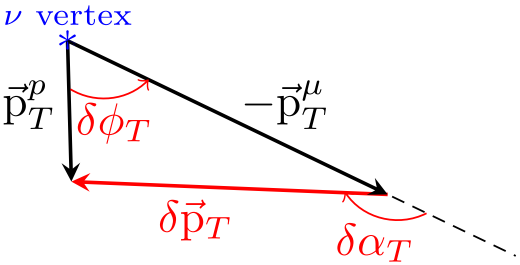
ν_τ
ν_e
ν_μ

Variables of interest

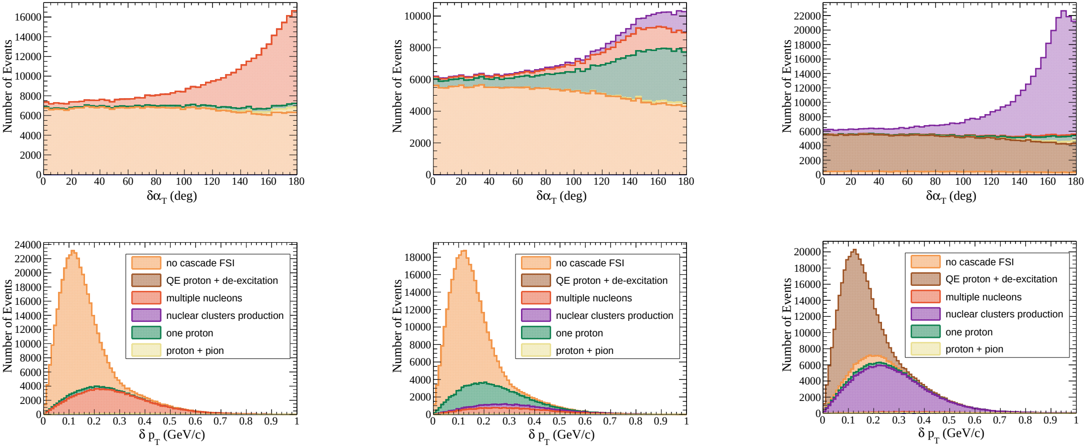
We use **Single Transverse Variables (STV)** that allow to disentangle different effects for better FSI estimation. STV are **observable** and **measurable**.

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



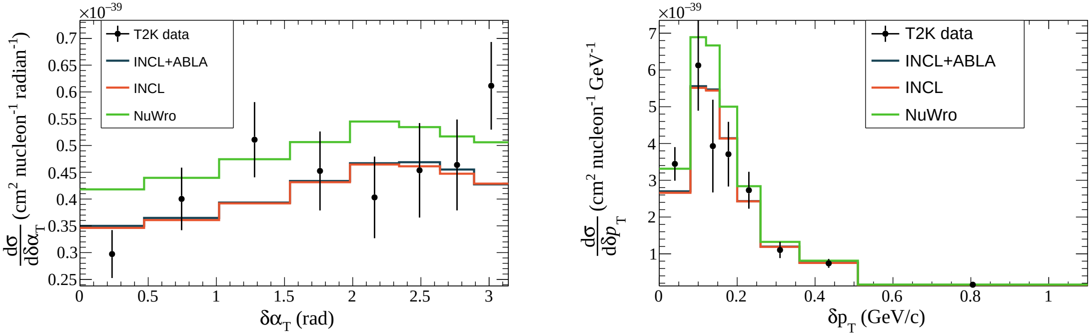
STV



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.

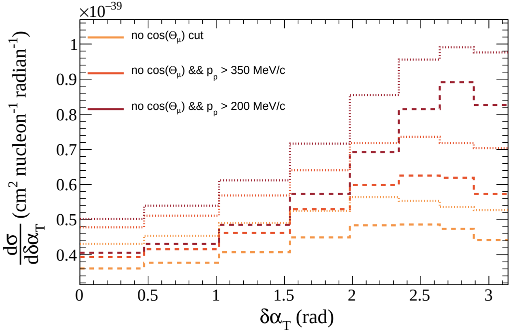


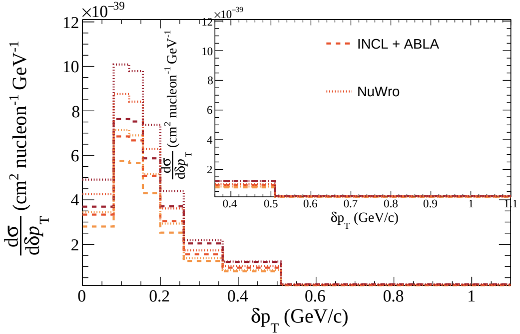
Cuts (MeV): $p_\mu > 250$; $450 < p_p < 1000$; $\cos(\Theta_\mu) >$ -0.6; $\cos(\Theta_p) > 0.4$

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





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 (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**

Prospects

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

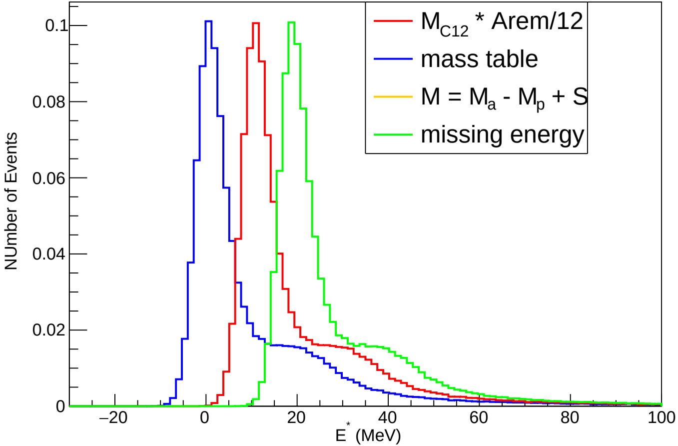
- ND280 upgrade of T2K to improve the detector threshold
- SK-Gd project: add gadolinium to SK to enhance the neutron detection efficiency
- The LAr program in USA is dedicated to measureing all the particles in the final state

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**.

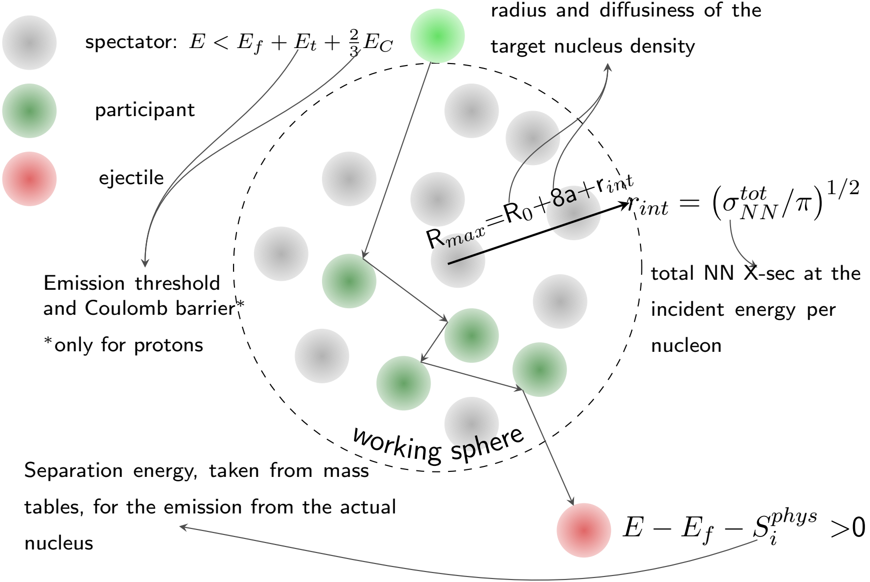
BACKUP

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

NuWro, SF, excitation energy calculation

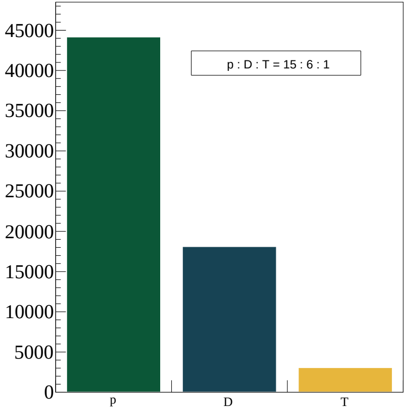


Standard INCL cascade



Nuclear clusters emission check

^{12}C bombarded by 175 MeV neutrons



INCL ratio

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

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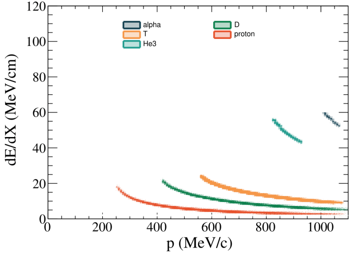
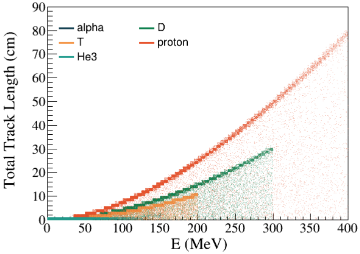
Paper ratio $\approx 10:3:1$

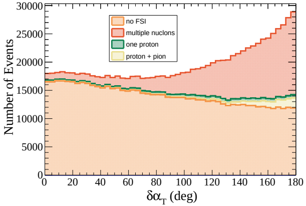
Vertex activity

- take INCL and NuWro simulation **event by event**
- check the energy of the cluster/proton/muon **after FSI**
- try to use **ionisation curve** from the Geant4 simulation
- if there is no data, it means that particle **travels less** than 1(3) cm. Than we **use Birks law directly**, calculating path from the plot

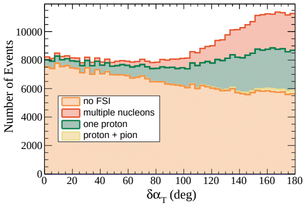




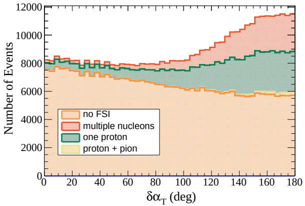
Comparison to data: RW model



NuWro GFG

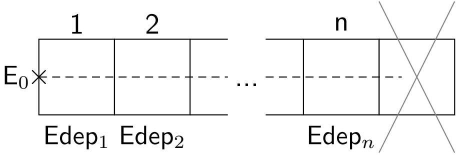


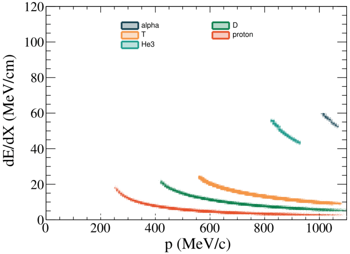
INCL RW



INCL + NuWro GFG

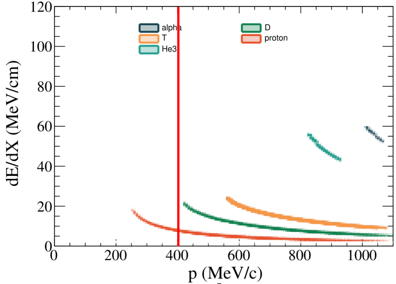
Particle identification algorithm

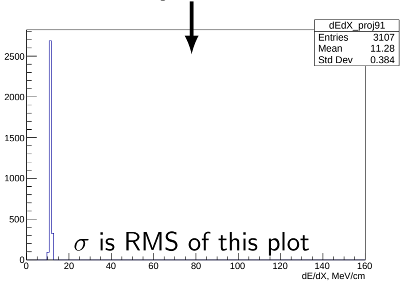




- **initial kinetic energy** E_0 is reconstructed as a sum of energy deposits along the whole track
- **momentum after passing 1 cm** is reconstructed using **5** mass hypotheses
- **for each momentum hypothesis**, the $\frac{dE}{dX}_{rec}$ is calculated using the $\frac{dE}{dX}$ dependence on momentum 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

σ definition





σ is RMS of this plot

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