Improving Final-State Interaction Modelling with INCL in the NEUT Event Generator

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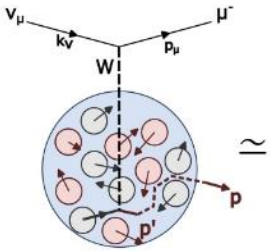
University of Sheffield

The NEUT Event Generator

Neutrino-Nucleus interaction simulator, maintained "in-house" byT2K/SK with experimental needs in mind

Simulates processes for 100 MeV - few-TeV neutrinos for a range of nuclear targets (H, …, C, O, … ,Pb)

In NEUT, neutrino interactions with nuclei are reduced into:



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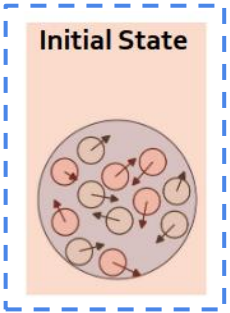

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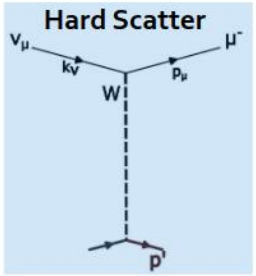

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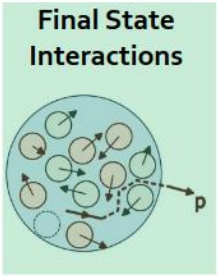
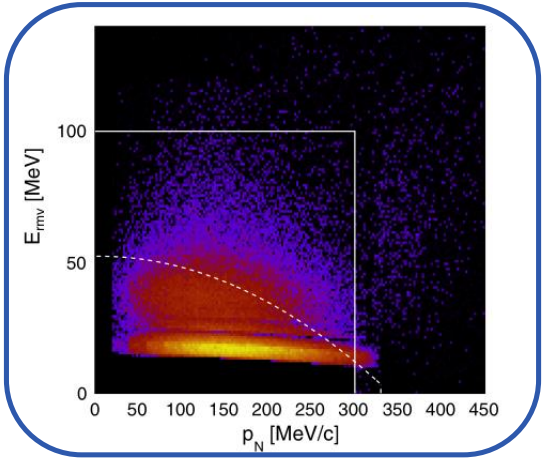


[L. Pickering, NuFact 2024](#)

SF model

Kinematic calculations

Cascade Model



Spectral function: Probability of finding a nucleon with an energy E_M and momentum p_M

Broken into two contributions (both seen here): $P_{MF} + P_{SRC}$

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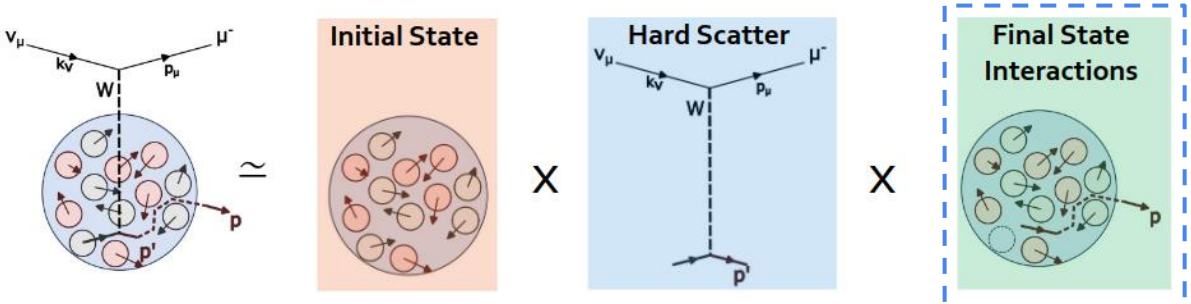


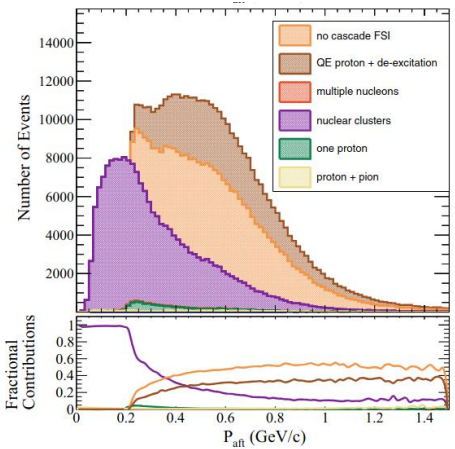
[L. Pickering, NuFact 2024]

SF model *Kinematic calculations* *Cascade Model*

FSI: Re-interactions of the hadron produced at the hard scatter with nucleons in the nucleus

NEUT uses the **Bertini cascade** model, a semi-classical "billiard ball" approach

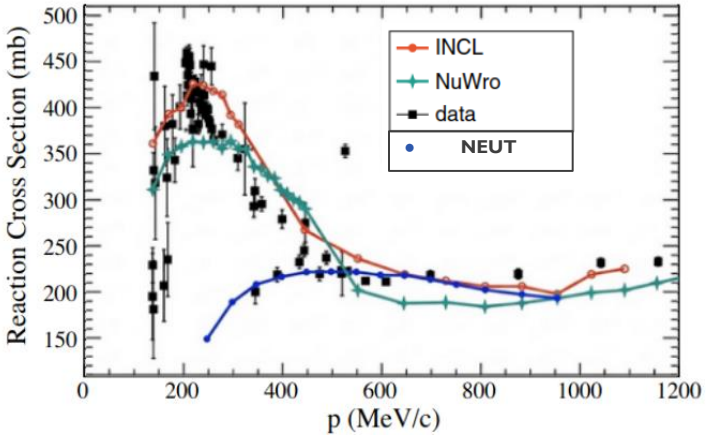
Other FSI models exist, with previous work integrating the INCL++ cascade into NuWro showing promising results



INCL++ for Neutrino Generators

University of Sheffield

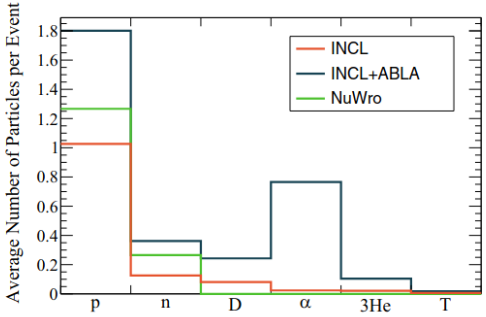
Improved p-C low momentum proton cross section prediction



Plot from PHYSICAL REVIEW D 106, 032009 (2022), with NEUT prediction overlaid

p-C reaction cross section predictions used to benchmark cascade modelling

Introduction of Light Nuclei Production (clustering)

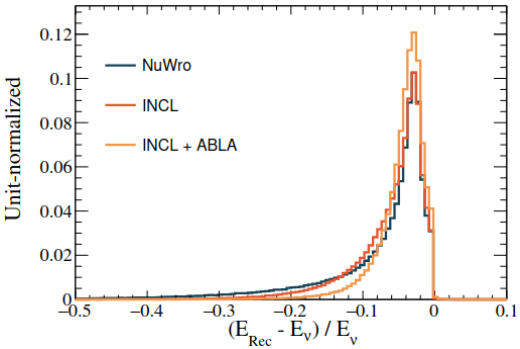


Plot from PHYSICAL REVIEW D 108, 112008 (2023)

INCL + ABLA predicts T2K events on carbon cause fragmentation and produce clusters fairly often

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

If detectable, introducing clusters in models improves neutrino energy reco



A. Ershova, e4nu 2025

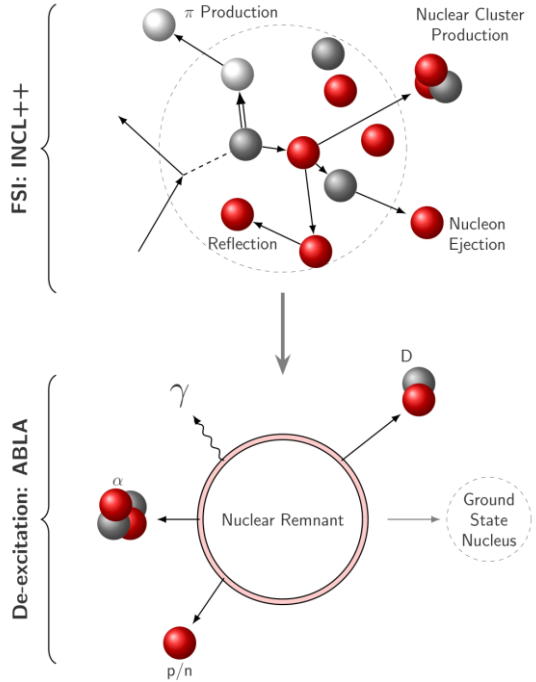
Intranuclear Cascade Liege ++ (INCL)

Liege Intranuclear Cascade (INCL): simulates struck nucleon re-interactions within a target nucleus, designed for hadron/light nucleus-induced reactions on nuclei from a few MeV to 10-20 GeV (ref)

- Evolves entire nucleus through time
- **Nucleons:** reflect off the potential, interact with other nucleons, decay
- **Final states:** hadrons, nuclear clusters (D, T, 3He, alpha), and excited nuclear remnants with an excitation energy:

$$E^* = \sqrt{(E_\nu + M_A - E_{\text{lep}} - \sum_N E_{\text{had}})^2 - |\mathbf{p}_\nu - \mathbf{p}_{\text{lep}} - \sum_N \mathbf{p}_{\text{had}}|^2} - M_{A-N}$$

Coupled to a **de-excitation** routine (ABLA), modelling nuclear remnant relaxation after FSI



The Spectral Function and de-excitation

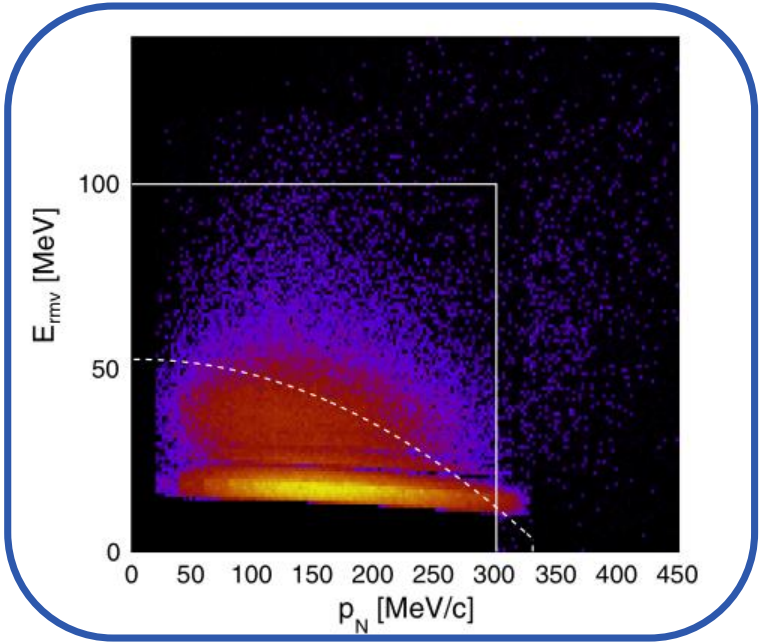
Previous work only looked into Mean Field (MF) contribution: simple 1 proton outputs (1p1h)

Spectral function E_{miss} values directly affect mean field excitation energy for 1p1h:

$$E^* = E_{miss} - (M_A - M_{A-1} - M_N) = E_{miss} - 18.4\,\mathrm{MeV}$$

Only considering MF 1p1h

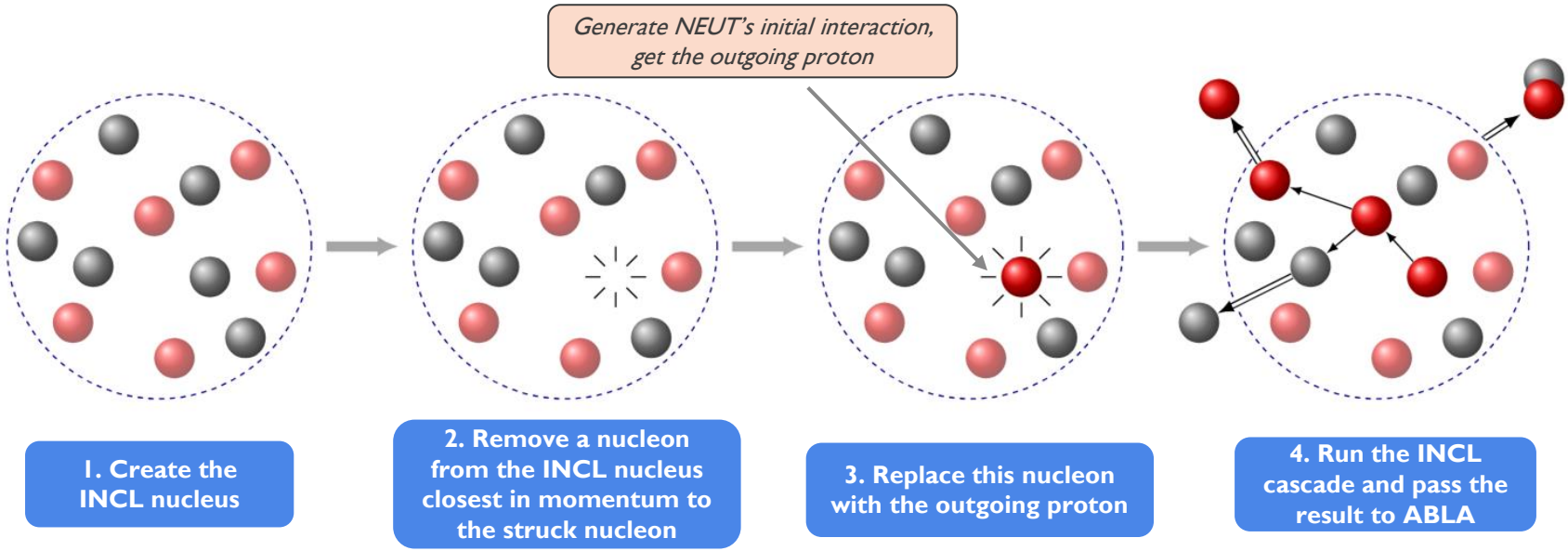
$$P_{sf} = P_{MF} + P_{SRC}$$



Benhar spectral function model, from PHYSICAL REVIEW D 109, 072006 (2024)

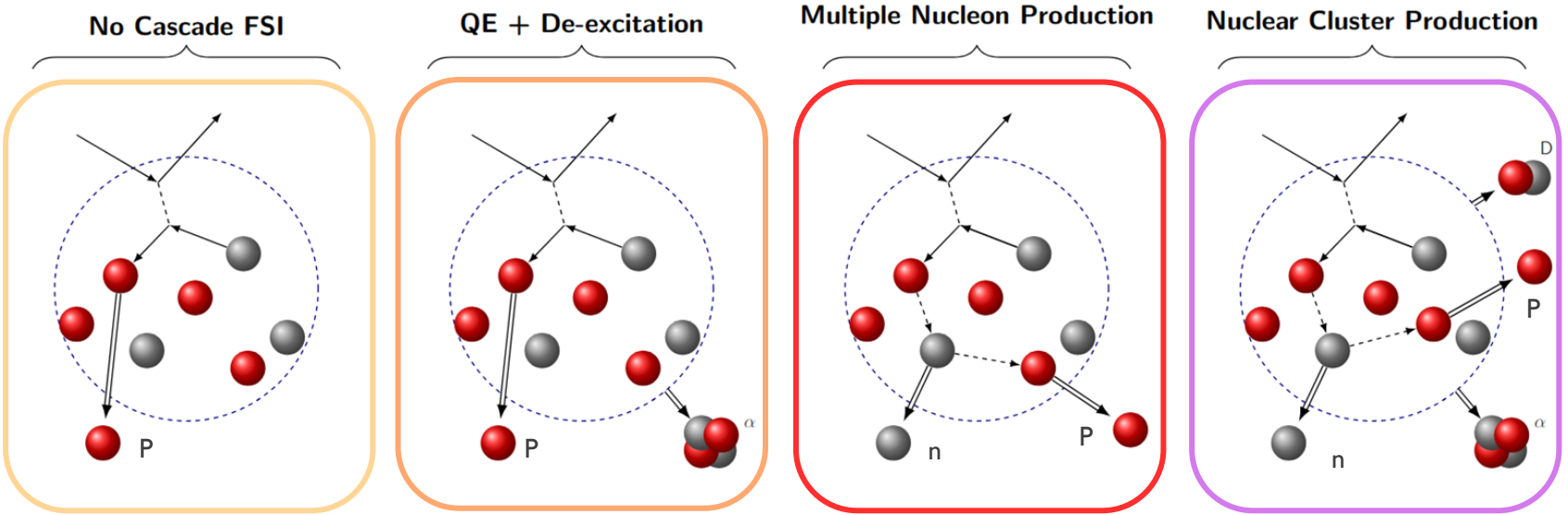
Using INCL for neutrino FSI (1p1h)

INCL is designed for nucleon-nucleus reactions, and is not designed for neutrino projectiles (yet!) so we must adapt both our generator and INCL to accommodate this:



INCL++ Interaction Channel Table

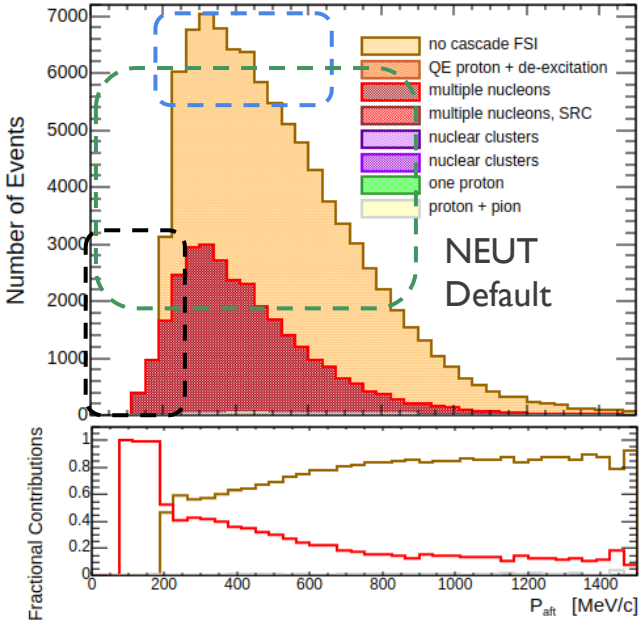
Due to the introduction of clusters and native de-excitation, study the FSI output channels based off numbers and types of ejected channels



Channels with dominant contributions. Also see pion production and single inelastically scattered protons

NEUT comparisons: CCQE 1p1h - I

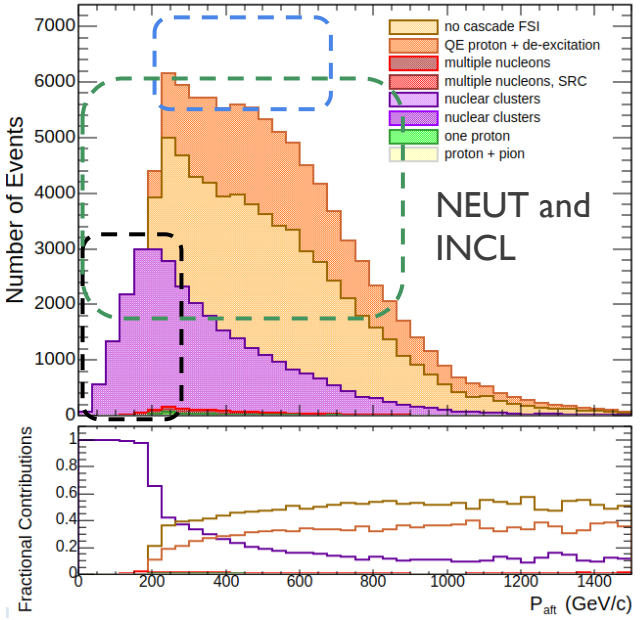
Leading proton distributions post FSI, broken down by channel



Lower peak when using INCL due to events with no final state protons

"Transparent" protons in INCL can be produced alongside nuclear clusters if the remnant de-excites

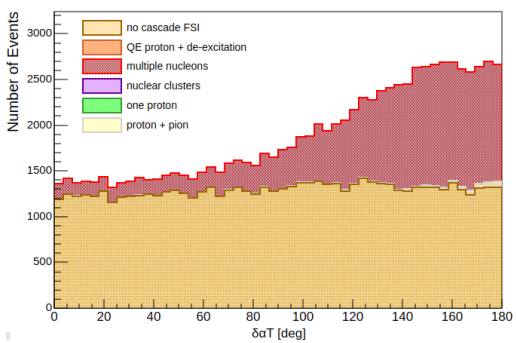
Increase in leading protons below p_f, almost always emitted alongside nuclear clusters



P_{aft} [MeV/C]

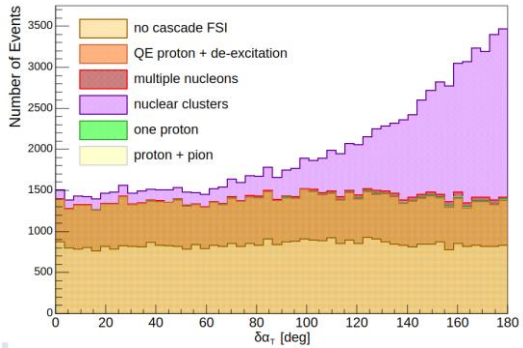
NEUT/NuWro comparisons CCQE 1p1h - II

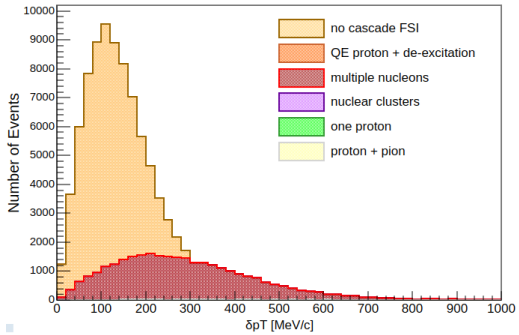
Transverse kinematic imbalance distributions, broken down by channel



$$|\delta\vec{\alpha}_T| = \arccos\left(\frac{-\vec{p_T^{\mu}} \cdot \delta\vec{p}_T}{p_T^{\mu} \cdot \delta p_T}\right)$$

More cluster events at higher angles:
deaccelerated de-excitation protons are emitted alongside clusters

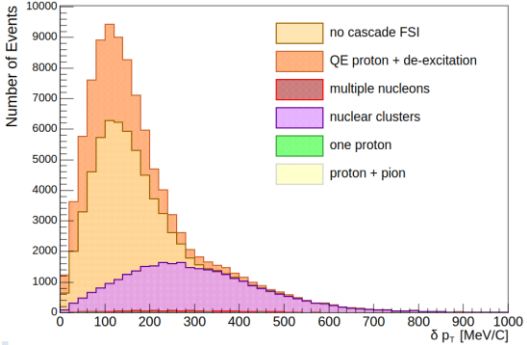




$$|\delta\vec{p_T}| = |\vec{p_T^{p}} + \vec{p_T^{\mu}}|$$

Similar shape, but with INCL:
-transparent events split into two channels

-multiple nucleon events now form with clusters

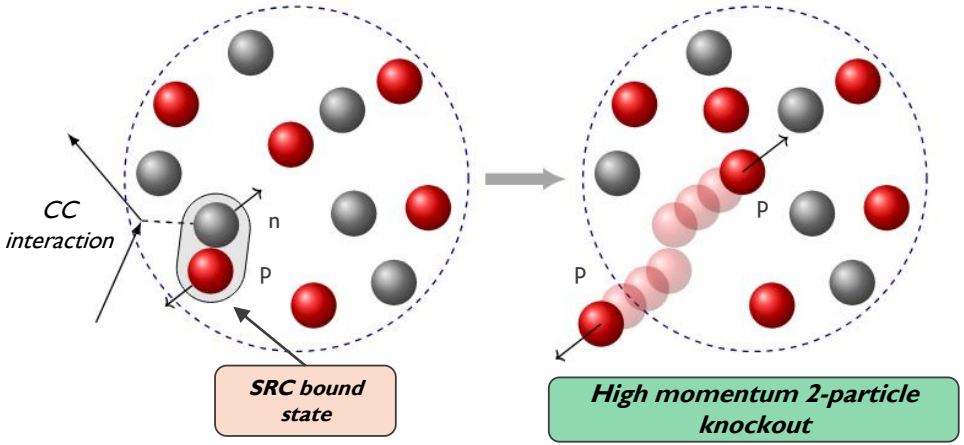


Short-range Correlation Modelling - Mo' Protons Mo' Problems

Short Range Correlations (SRCs): Bound pairs of high momentum nucleons found within the nucleus.

- SRCs form the other contribution to the spectral function
- The contribution to the spectral function from SRCs is not separable from the mean field (yet…)
- Freedom in how to define the SRC contribution in generators

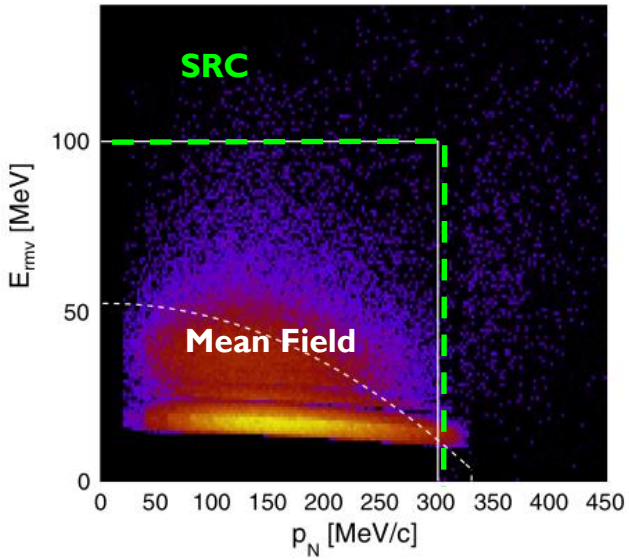
Excitation energy of the nucleus is very dependent on SRC definition



To simulate SRC events, if an event is within the SRC region, place a nucleon of equal and opposite momentum to the struck nucleon into the nucleus

Short-range Correlation Modelling - Mo' Protons Mo' Problems

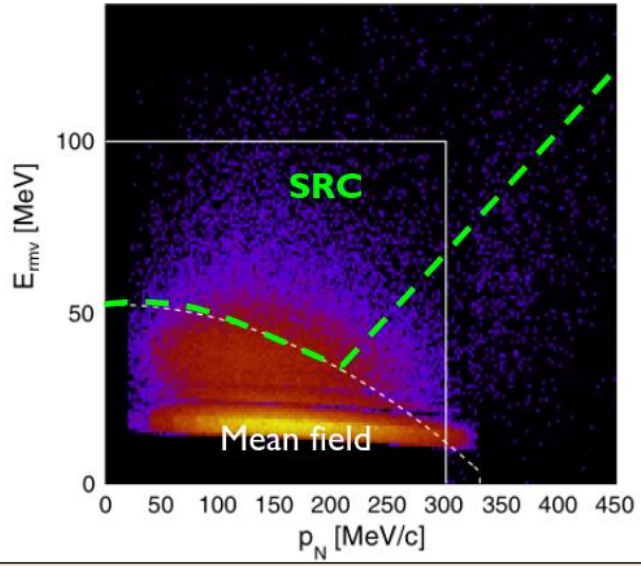
NEUT SRC - MF and SRC contribution



NEUT's SRC events are defined as:

- $p_N > 300$ MeV
- $E_{miss} > 100$ MeV

NuWro SRC - MF and SRC contribution



NuWro defines SRC with a function and a cut:

$$p_N > 330 \text{ or } E_{miss} > (52.27 + 0.0048\,p_N - 0.0004618\,p_N^2)$$

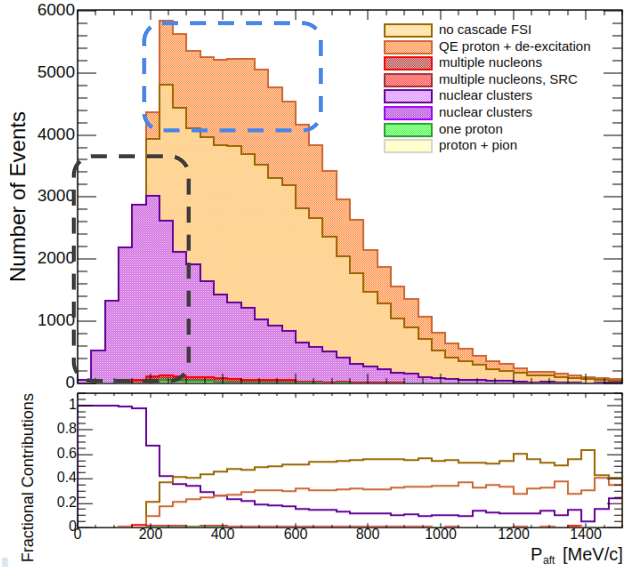
$$E_\nu - E_{lep} - T_p - T_{src} > 14\,\text{MeV}$$

CCQE pure MF: Effects of SRC Modelling

University of Sheffield

Leading proton distributions highlight effect of SRC modelling on FSI with INCL

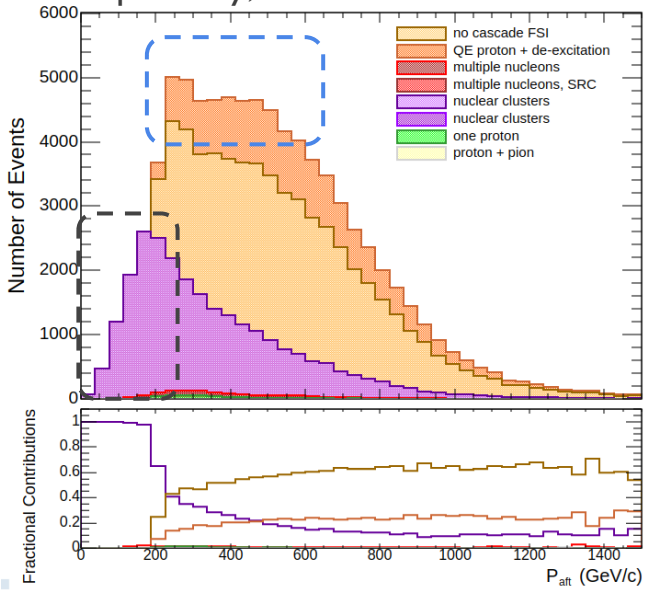
1p1h only, NEUT SRC model



Fewer ***transparent + de-excitation*** events:
fewer high missing energy, lower momentum protons in the NuWro MF distribution

Fewer events with nuclear clusters with NuWro SRC model:
excitation energies are lower due to change in MF missing energy distribution

1p1h only, NuWro SRC model



Total number of MF CCQE events has reduced as **SRC contribution to SF is greater for NuWro SRC**

Summary

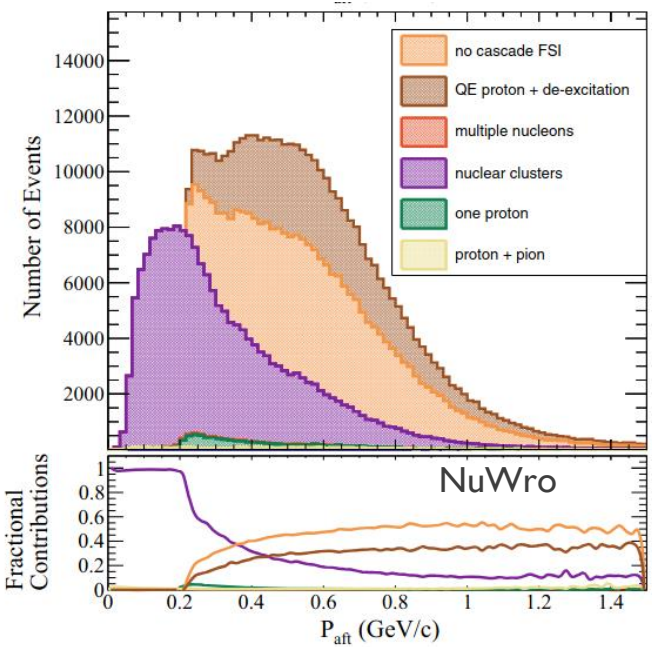
INCL++ is an FSI model which introduces nuclear clustering and a better handling of low energy nucleon interactions.

- The interface developed allows for straight integration of the INCL++ cascade into NEUT, allowing for data comparisons and fake data studies to be performed, with potential for reweightability in the future
- The introduction of nuclear clusters in FSI can lead to a better understanding of nuclear effects and improved neutrino energy reconstruction
- Introducing the INCL cascade with ABLA into NEUT increases number of final state channels and greatly reduces the number of purely transparent events through de-excitation
- SRC model choice affects FSI in INCL due to changes in the excitation energy calculation and the ratio of MF 1p1h to SRC events

Special thanks to Anna Beever for her invaluable support in getting this work to this point!
Also, thanks to Patrick Stowell, Sara Bolognesi, and Jean Davide-Chrisophe for INCL physics input and to Jake McKean and other members of the T2K NIWG for neutrino physics and NEUT input.

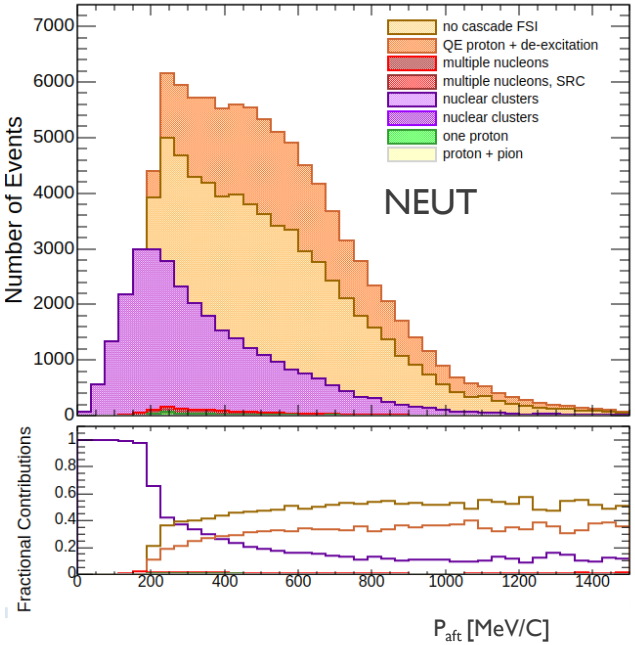
NEUT/NuWro validations

Leading proton distributions post FSI, broken down by channel



Plot from PHYSICAL REVIEW D 108, 112008 (2023)

Implementation in NEUT matches prior work, with some differences from initial interaction modelling

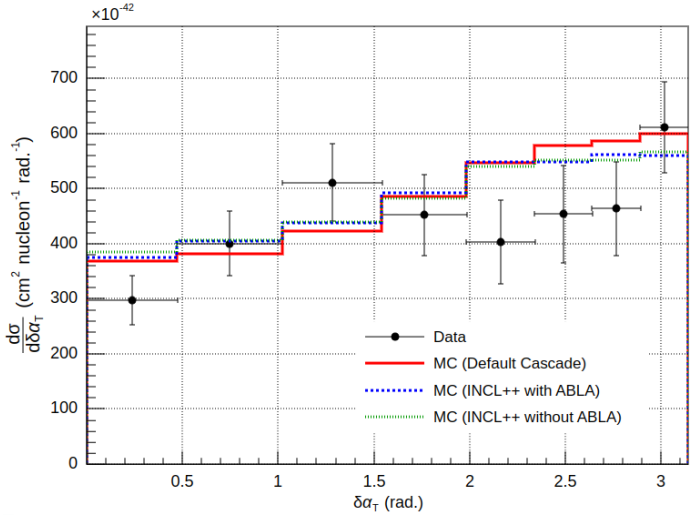


Annas comments

BACKUPs

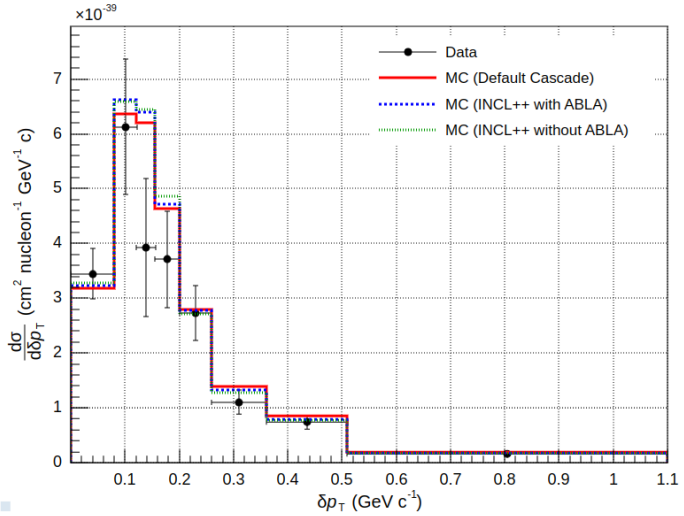
Preliminary Data Comparisons - T2K TKI

INCL++ can only use CCQE events at present, so using NEUT data for other channels



Apparent "reduction" in FSI strength for INCL is due to presence of non proton events in INCL

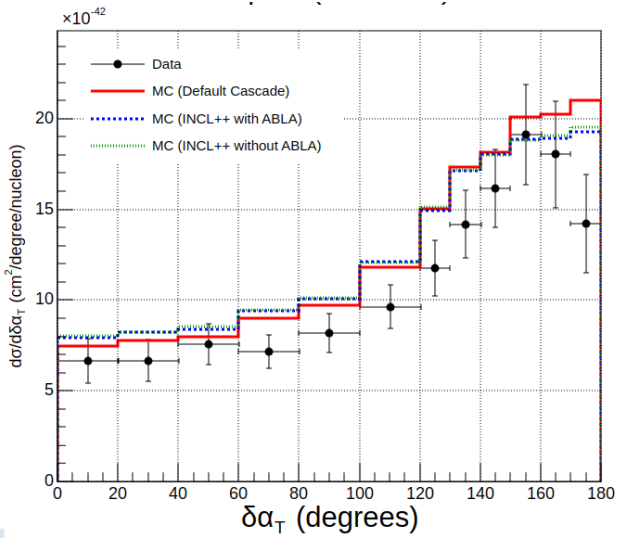
T2K's proton tracking threshold is 500MeV



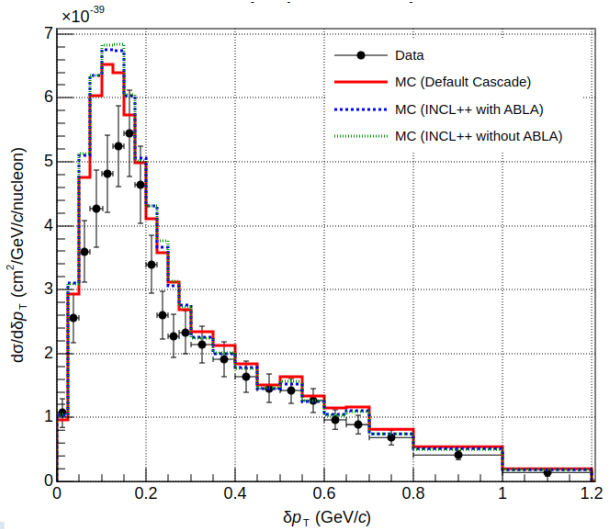
NEUT Cascade: 12.01 / 8
NEUT + INCL 10.85 / 8
NEUT + INCL + ABLA10.73 / 8

NEUT Cacsade: 8.47 / 8
NEUT + INCL 7.28 / 8
NEUT + INCL + ABLA 7.09 / 8

Preliminary Data Comparisons - MiNERva TKI



DaT
Neut cascade: 24.55 / 12
NEUT + INCL: 26.38 / 12
NEUT + INCL + ABLA 27.79 / 12



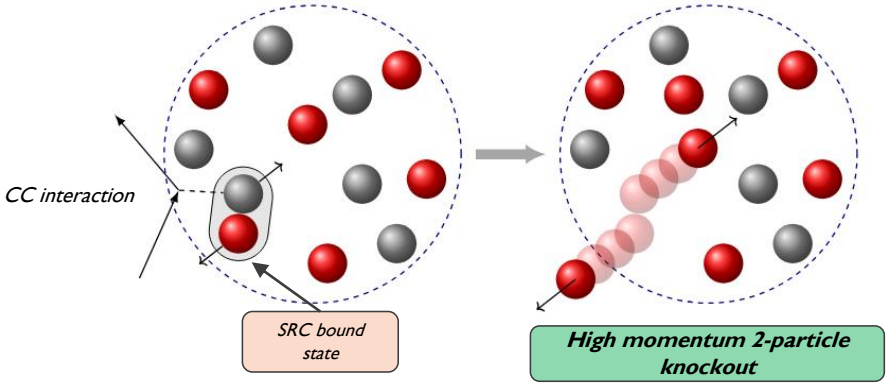
DpT
NEUT Cascade: 53.72 / 24
NEUT + INCL: 61.92 / 24
NEUT + INCL + ABLA: 65.79 / 24

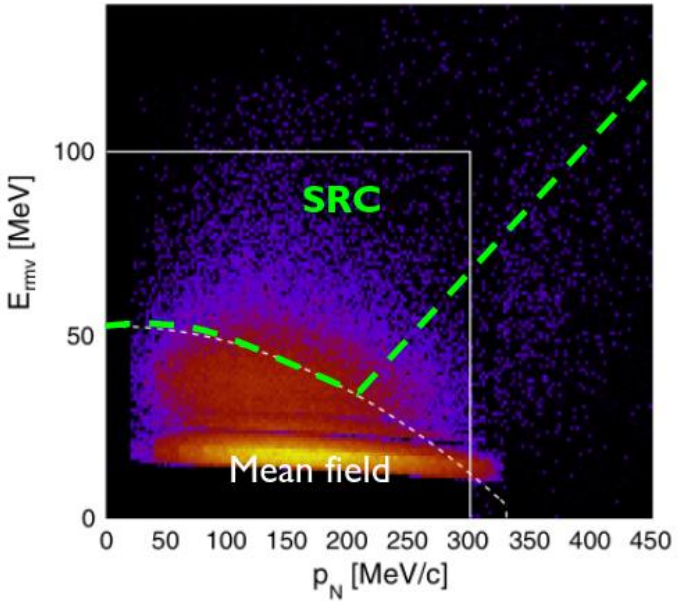
NEUT Cascade

Plot of nuisance generated total pN, overlaid and normalised, for bertini, INCL and INCL+ABLA

Short-range Correlation Modelling

SRC: High momentum nucleons (> p_f) existing in correlated bound pairs in the nucleus





Plot originally from PHYSICAL REVIEW D 109, 072006 (2024)

The contribution to the spectral function from SRC is not separable - event generators model this by using cuts on the total SF distribution

NuWro uses:

$$p_N > 330 \text{ or } E_{miss} > (52.27 + 0.0048\,p_N - 0.0004618\,p_N^2)$$

- **E_{miss} > 100 MeV**

rgba(255, 213, 150)

rgba(255, 169, 113)

rgba(255, 47, 47)

rgba(211, 122, 236)