The NEUT Neutrino Interaction Simulation

Status and recent highlights

Stephen Dolan, *Yoshinari Hayato, Luke Pickering, Clarence Wret*




On behalf of many other NEUT contributors

stephen.joseph.dolan@cern.ch

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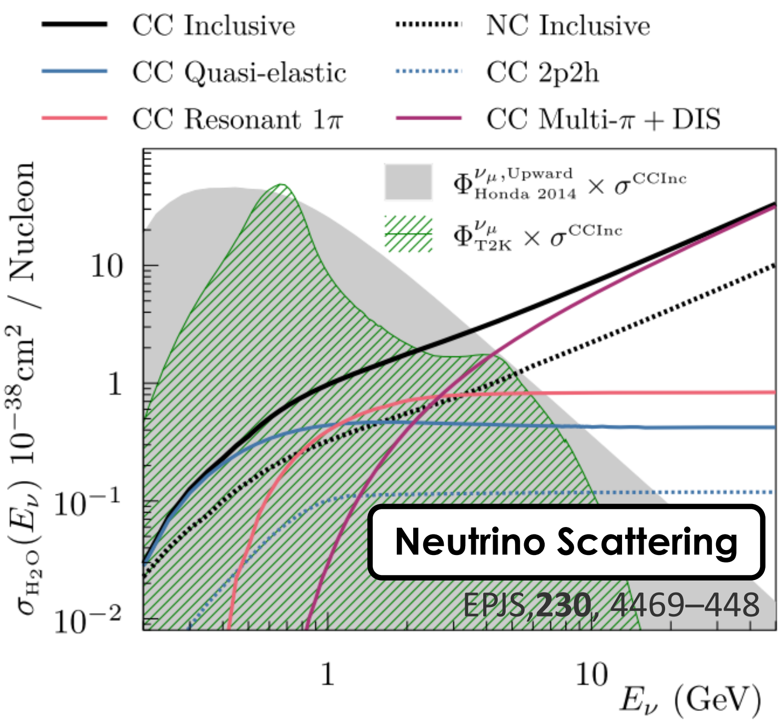
What is NEUT

- NEUT simulates neutrino interactions with nuclei with E_ν from ~10 MeV to 10 TeV



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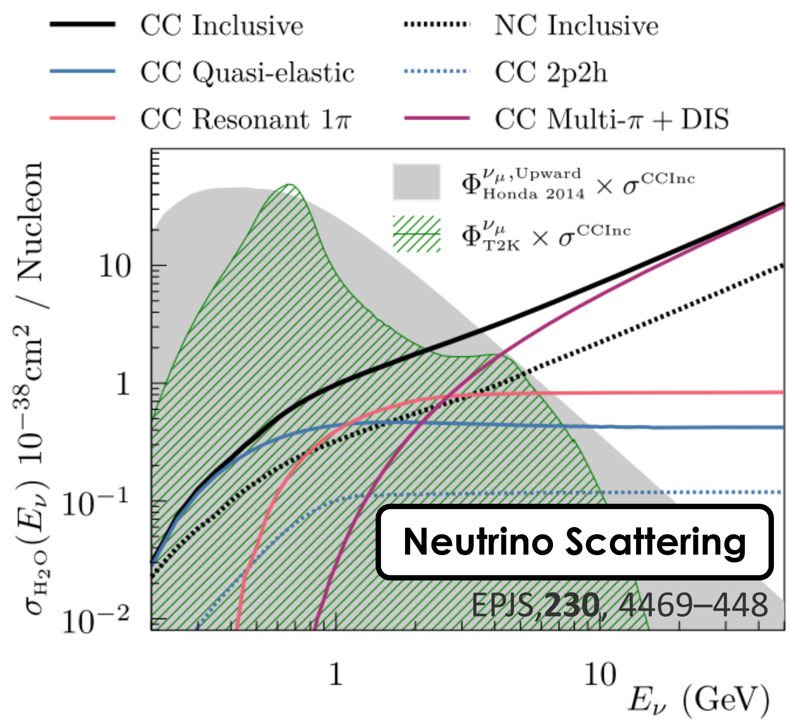

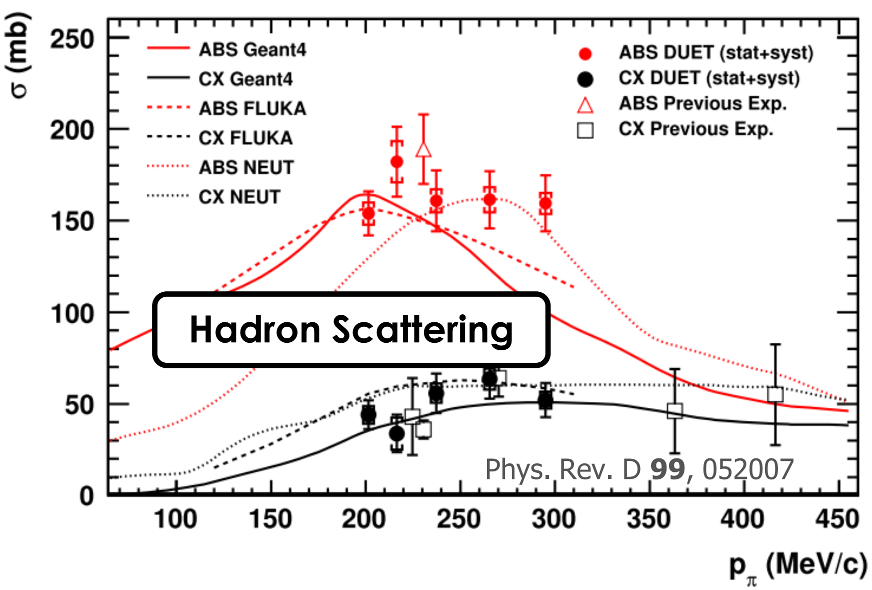

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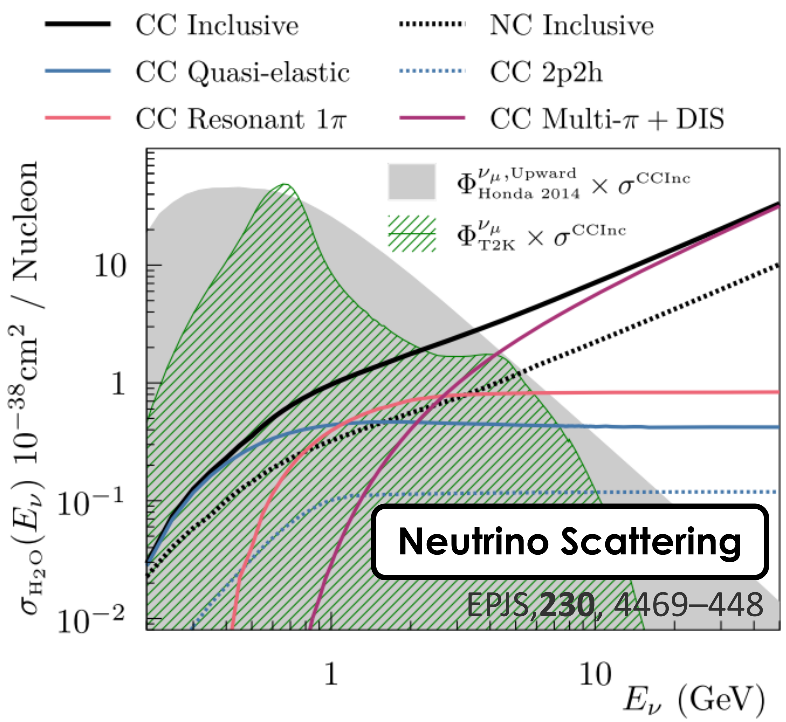
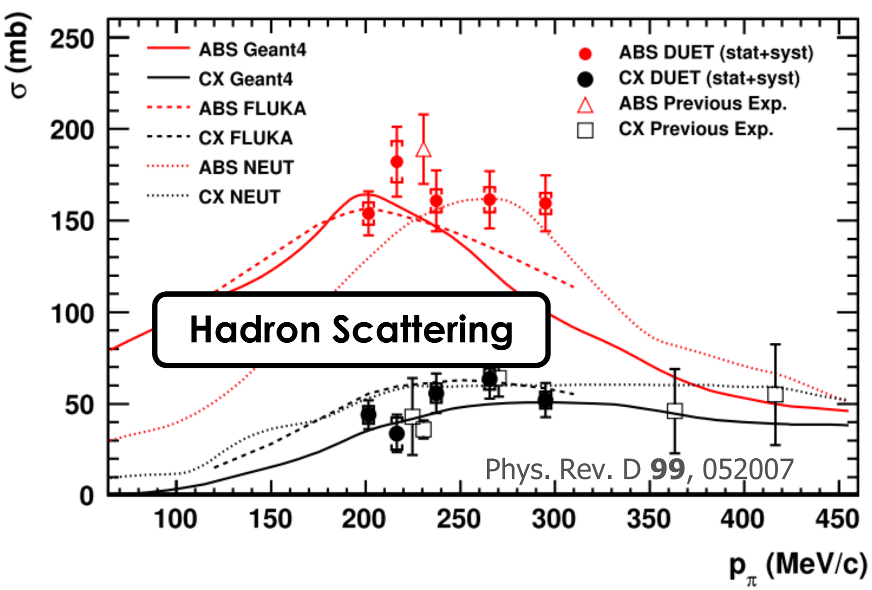
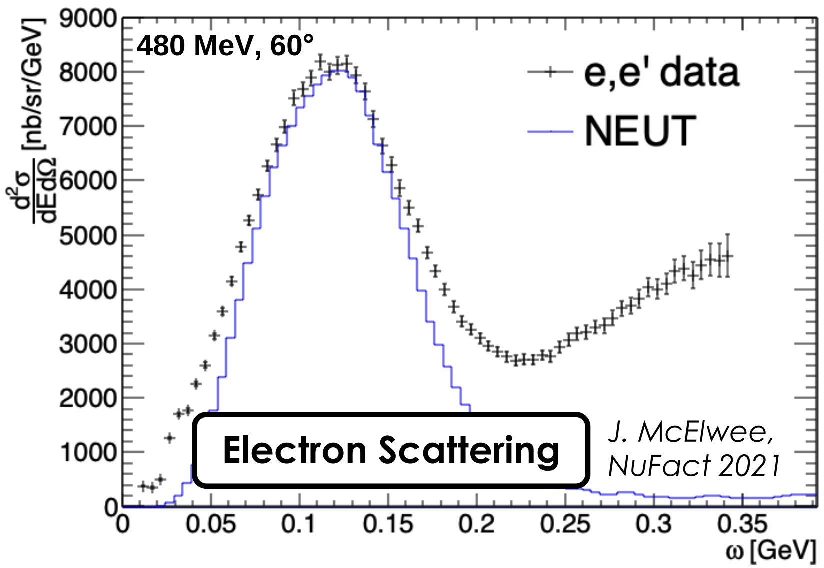
- It can now simulate QE electron-nucleus scattering







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*     ------------------------------------------------
*
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*     ( input )
*       IPAR      : PARICLE CODE
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*       DIRNEU(3) : NEUTRINO DIRECTION
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*       1983.11.27 ; First version by M.Nakahata
*       1985.11.06 ; K.KAJITA SMALL  MODIFICATION
*                       ( FOR MULTI PION    DELTA PI  --> N PI PI)
*                       ( FORWARD BACKWARD PION MULTIPLICITY )
*       1988.09.08 ; T.KAJITA CROSS SECTION AT W=1.3-1.4 WITH N(PAI)=2
*                       IS ADDED.
*       1988.10.08 ; T.KAJITA  SMALL MOD. FLAG INO16 IS SET IN THIS PROGRAM
*       1988.10.18 ; T.KAJITA  FERMI MOTION OF NUCLEON IS INCLUDED
*       1995.02.25 ; K.Kaneyuki for S.K.
*                    APIVCT -> NEAPIVCT
*       1995.10.29 ; K.Knaeyuki BUG FIX
*       1997.12.12 ; Y.Hayato   To use IFREE to determine FREE or BOUND.
*       1999.08.03 ; M.Shiozawa modify procedure for re-calculate
*                    the pion multiplicity
*       2006.06.12 ; Y.Hayato   Not to use IFREE nor INO16
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*       2007.11.05 ; G.Mitsuka  p/n ratio is calculated
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*       2007.11.10 ; T.Tanaka   add upmu mode
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*                               Target nucleon chosen based on comparison of xsec
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*       2016.07.26 ; C.Bronner  Cleaning/commenting for new release
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NEUT has a rich history:

- Developed in the 1980s for atmospheric neutrino and nucleon decay studies
- Used for SuperKamiokande's (SK) Nobel prize winning analysis of neutrino oscillations!
- Recent development target the needs of the SK, Hyper-K, T2K and NINJA collaborations
- NEUT developers are predominantly those who are using NEUT for analyses

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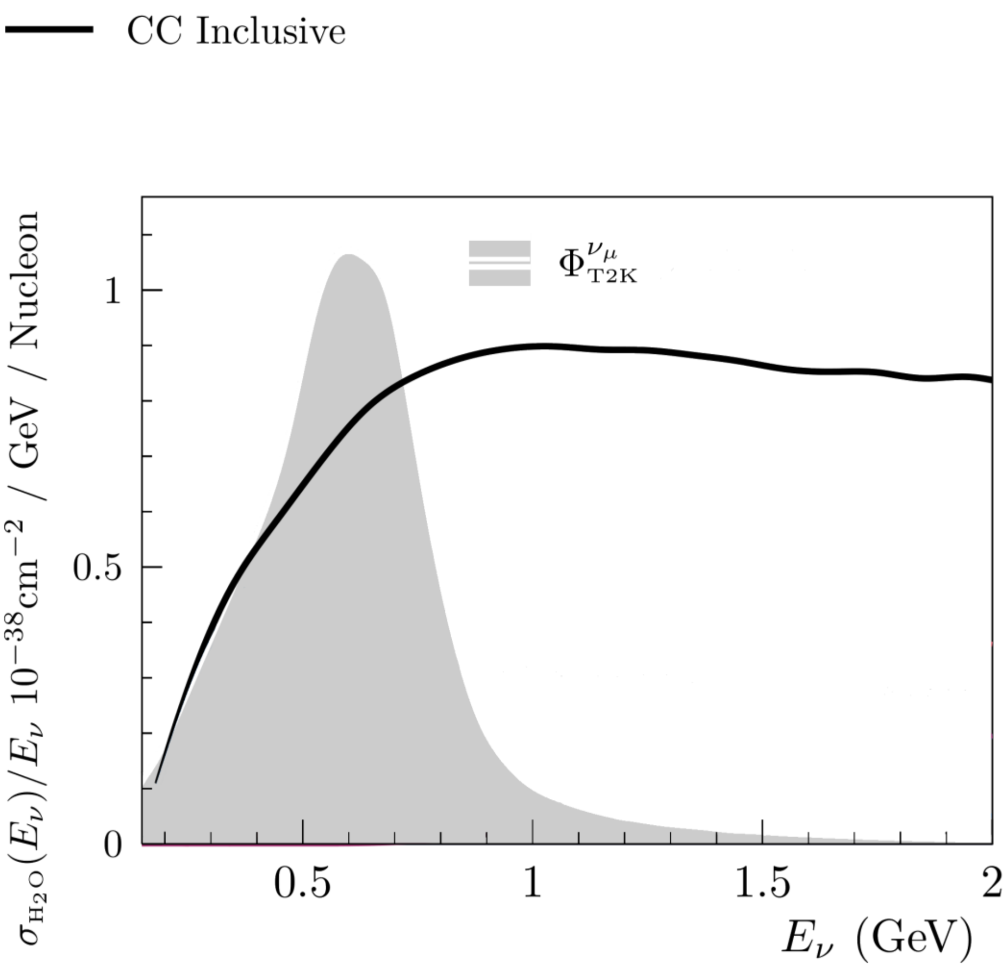
- Randomly select E_ν based on the product of an input flux and NEUTs total $\sigma(E_\nu)$ model



Example for if we generate only CC events

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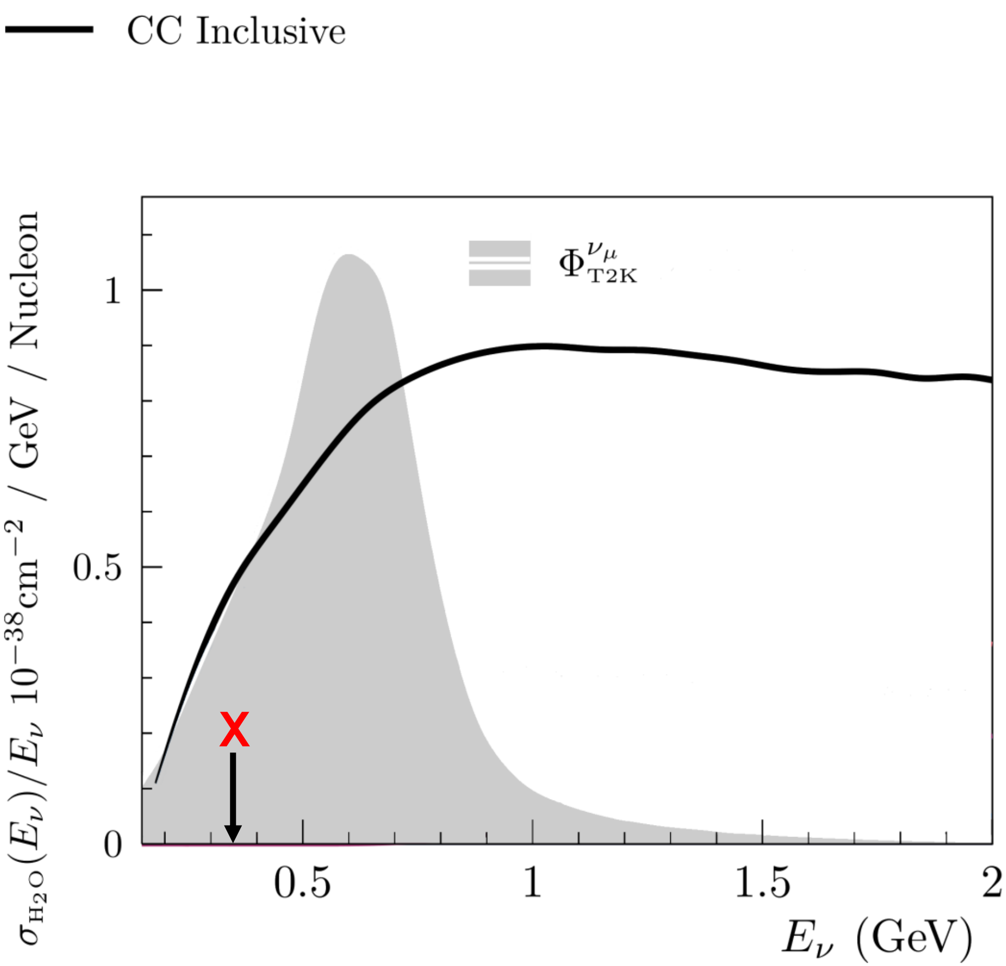

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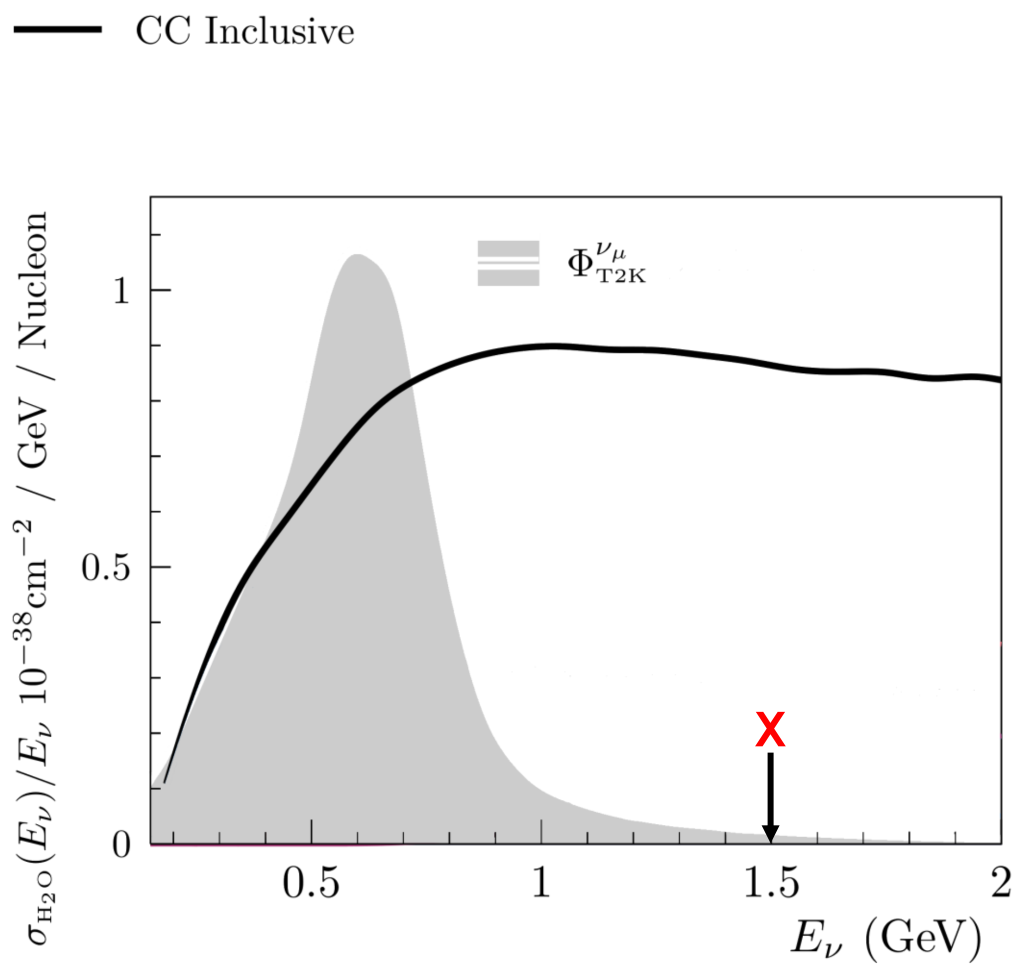

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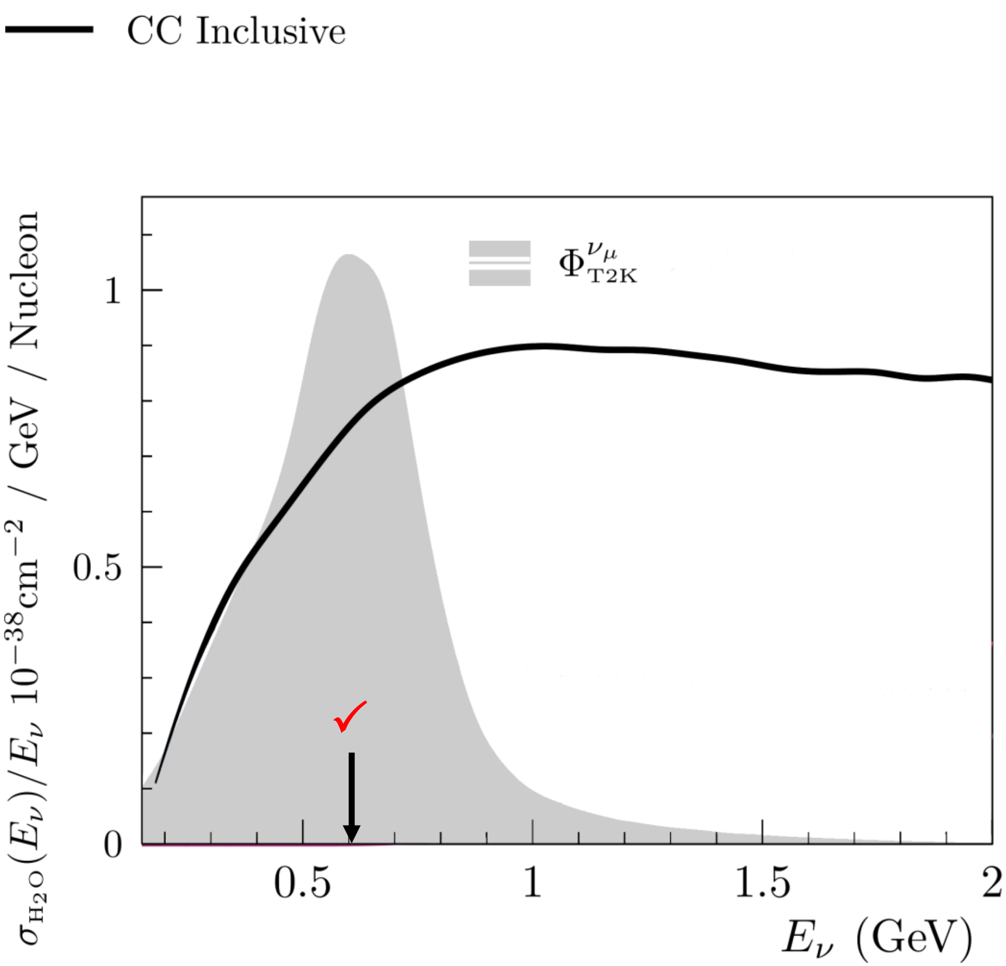

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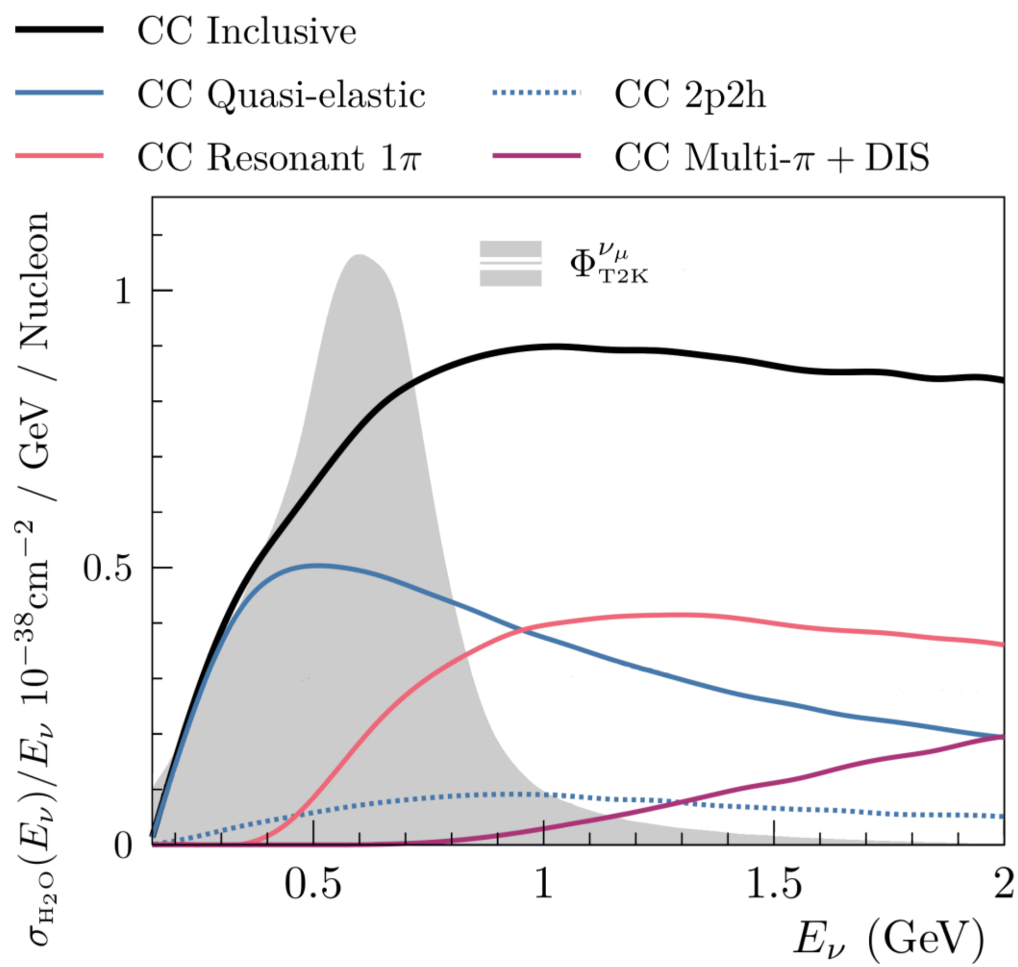

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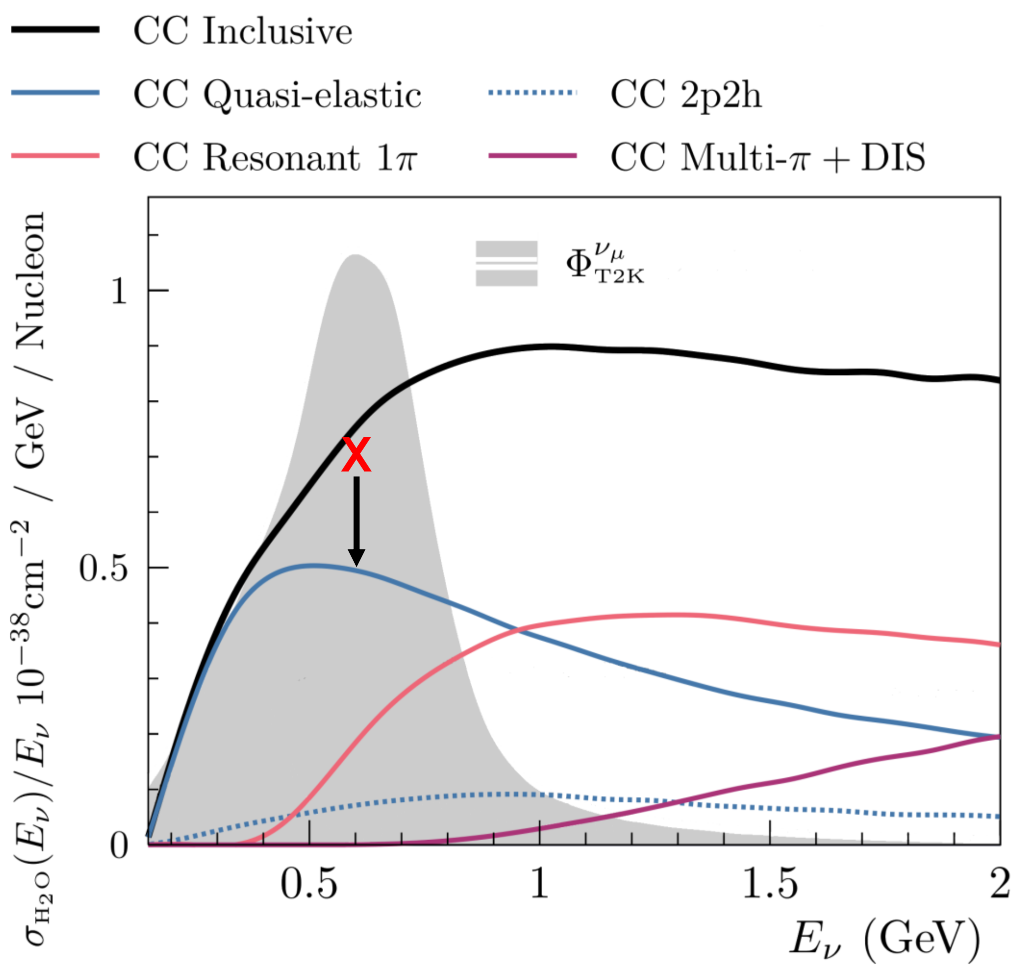

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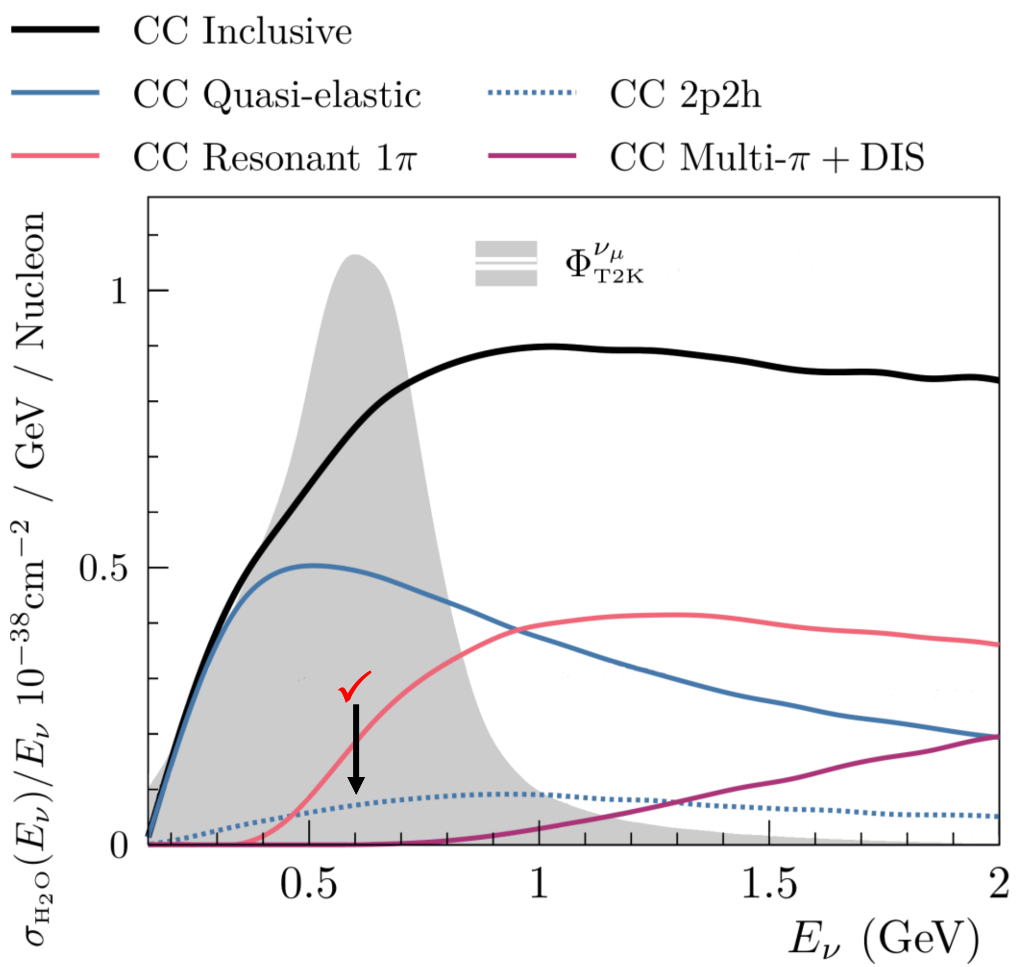
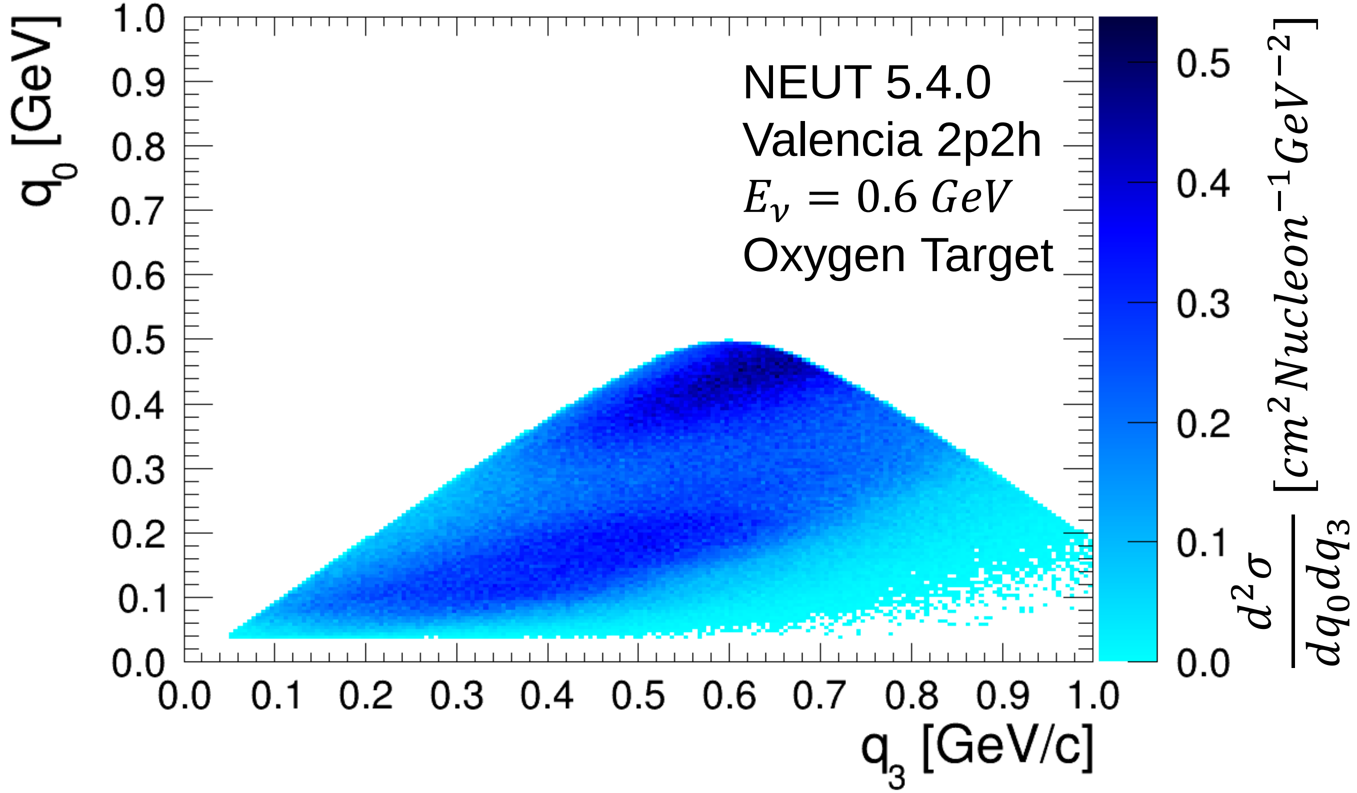


Example for if we generate only CC events

NEUT Event Generation

- Select **outgoing particle kinematics** according to differential cross section for the chosen interaction channel at the chosen E_ν



NEUT Event Generation

- Generate **remaining particle kinematics** at the vertex using a best-guess approach

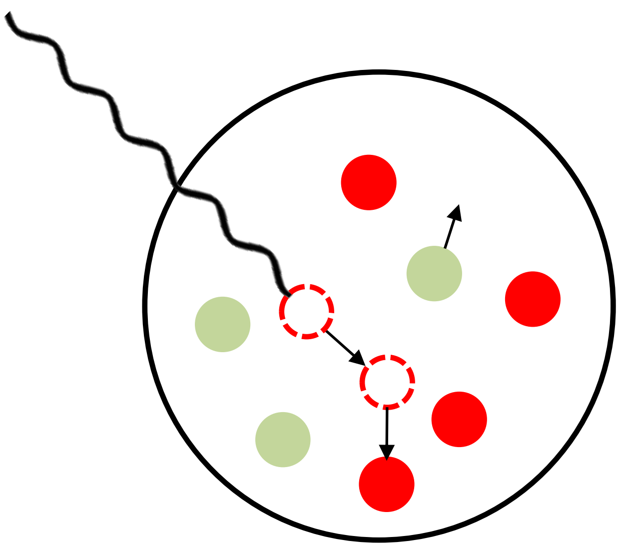
2p2h example:

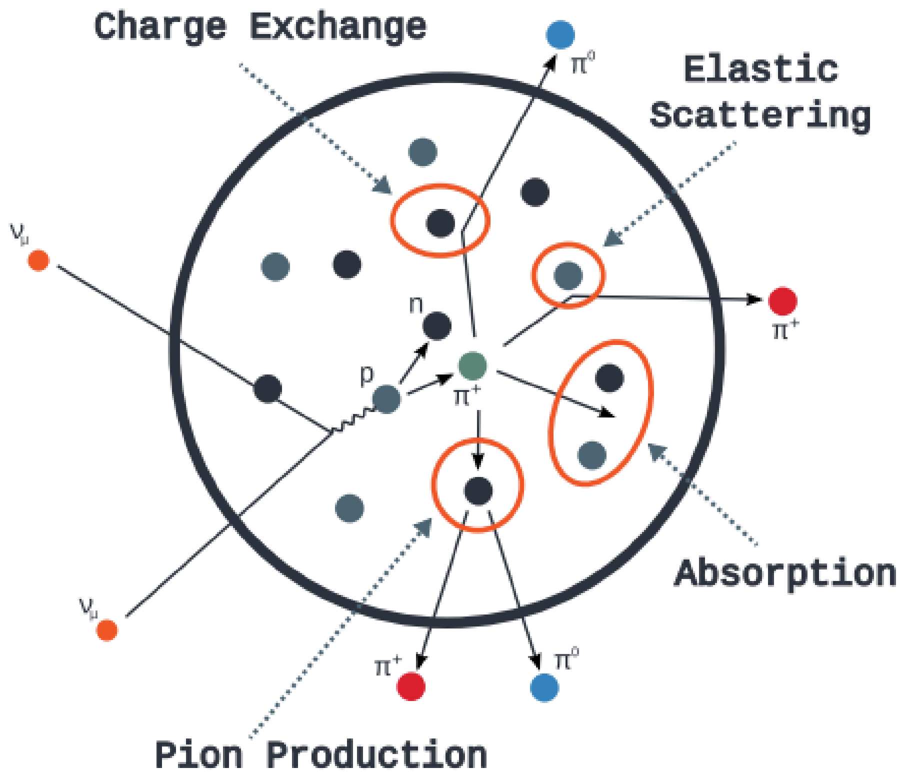
$$\frac{d^2\sigma}{dq_0 dq_3} \to \frac{d^8\sigma}{dq_0 dq_3 d\boldsymbol{p}_1 d\boldsymbol{p}_2}$$

- Sample struck nucleon 4-momentum independently from a Fermi gas model and combine into a 2-nucleon cluster
    - Assumption: *no correlations between momentum and energy of struck nucleons*
- Give 4-momentum transfer (q_0, q_3) to the cluster
- "Decay" the cluster to two nucleons
    - Assumption: 4-*momentum transfer is shared evenly between the two nucleons*

NEUT Event Generation

- Put all outgoing hadrons individually through **FSI cascade** to get a finished event





NEUT Models

Quasi Elastic Scattering (QE/1p1h)*

- Smith-Moniz Relativistic Fermi Gas
- *Nieves et al.* Local Fermi Gas (with RPA** and *Bourguille et al.* removal energy treatment)
- *Benhar et al.* Spectral Function
- SuSAv2 and HF-CRPA via reweighting of Spectral Function

JHEP **2021**, 4 (2021)

* The list of the nuclear models (νA) availble is shown, each model has a choice of nucleon interaction (νN) treatment (i.e. the form factor model)

**RPA = Random Phase Approximation. RPA is a treatment of the suppression of the cross section due to nuclear screening effects.

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- Preliminary version of *M. Kabirnezhad* single pion production model
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* The nucleon Res models are shown, they all use a relativistic Fermi gas nuclear model

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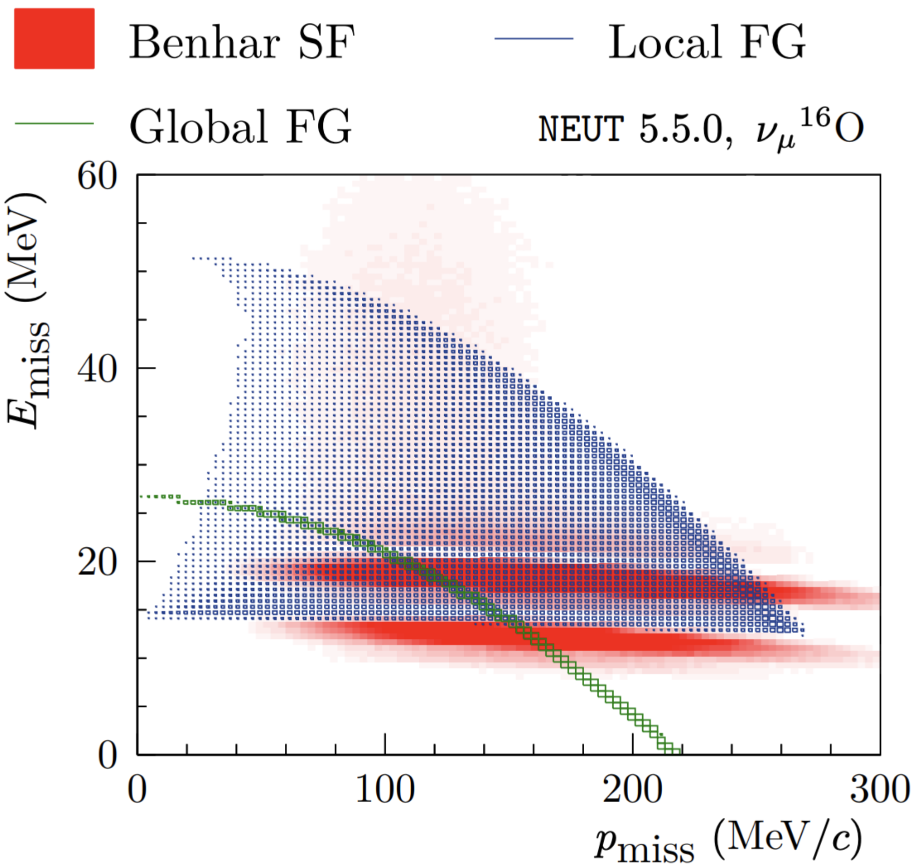
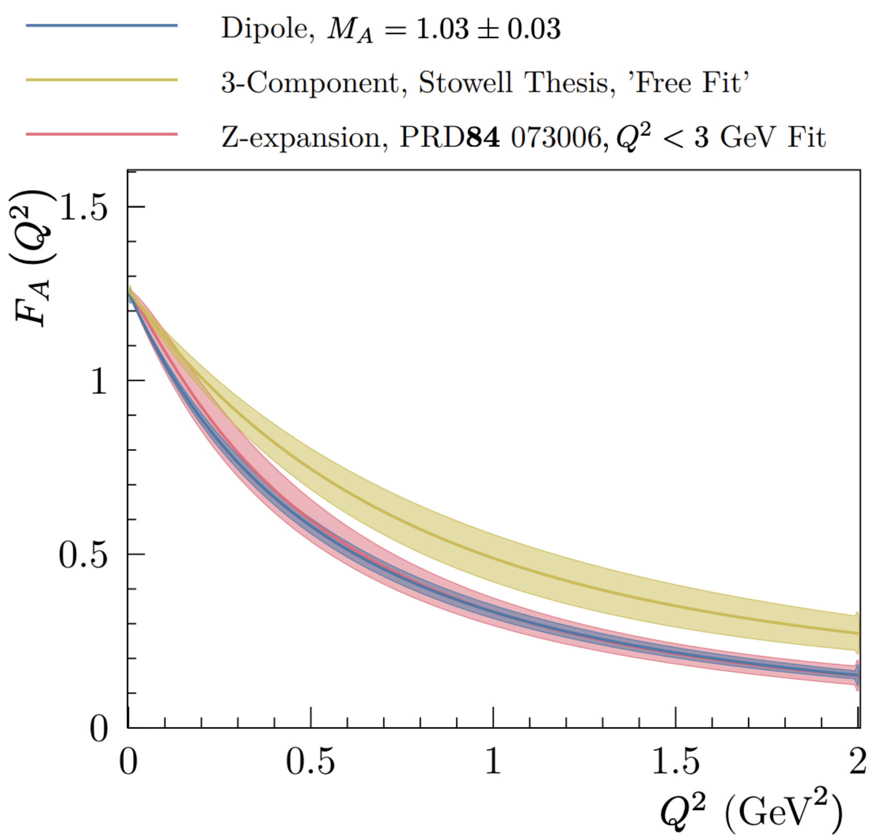
Final State Interactions (FSI)

- Pion FSI uses the *Salcedo et al.* cascade model
- Nucleon FSI uses a cascade model based on the work of *Bertini et al.*

Some QE model details

- NEUT's three models use different nuclear ground states,
- Each model can interface with different parametrisations of axial form factors
- Wide model spread allows improved evaluation of analysis uncertainties

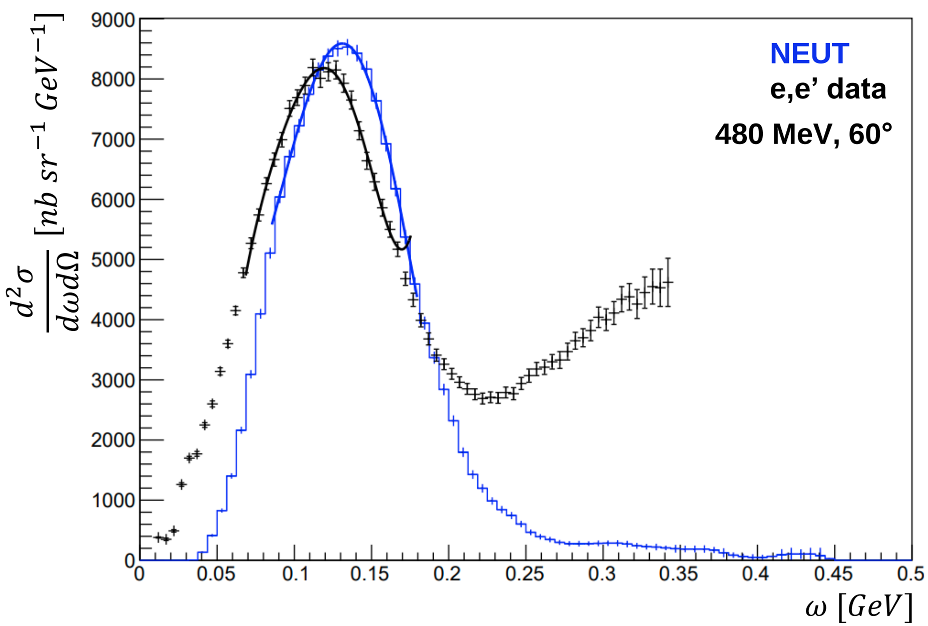


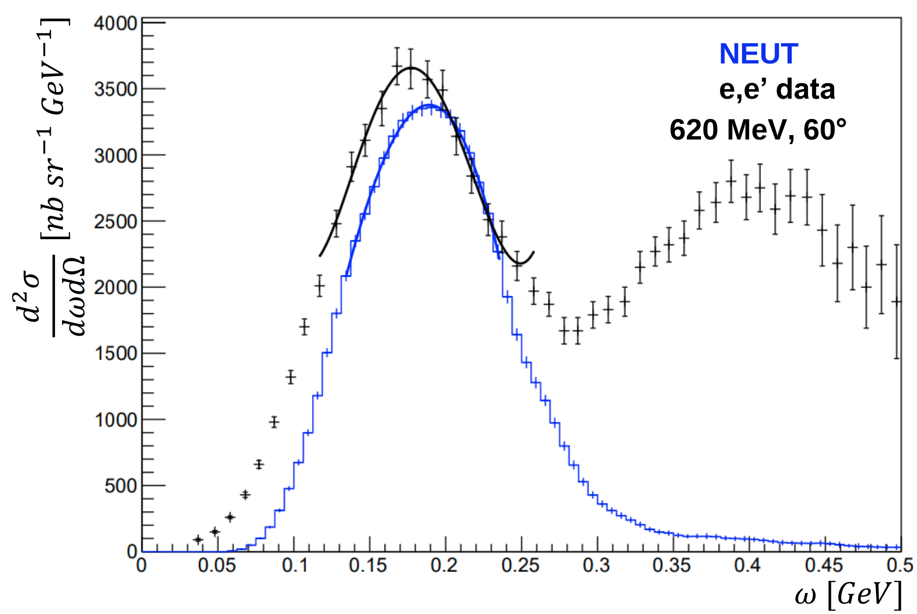


Validating QE with e,e' scattering

- New work within NEUT allows the simulation of electron-nucleus scattering
  - Start with NC neutrino scattering
  - Alter the coupling and form factors
  - Modify the coulomb corrections

- Allows use of precision e,e' data to validate neutrino scattering predictions





Tuning QE with e,e' scattering

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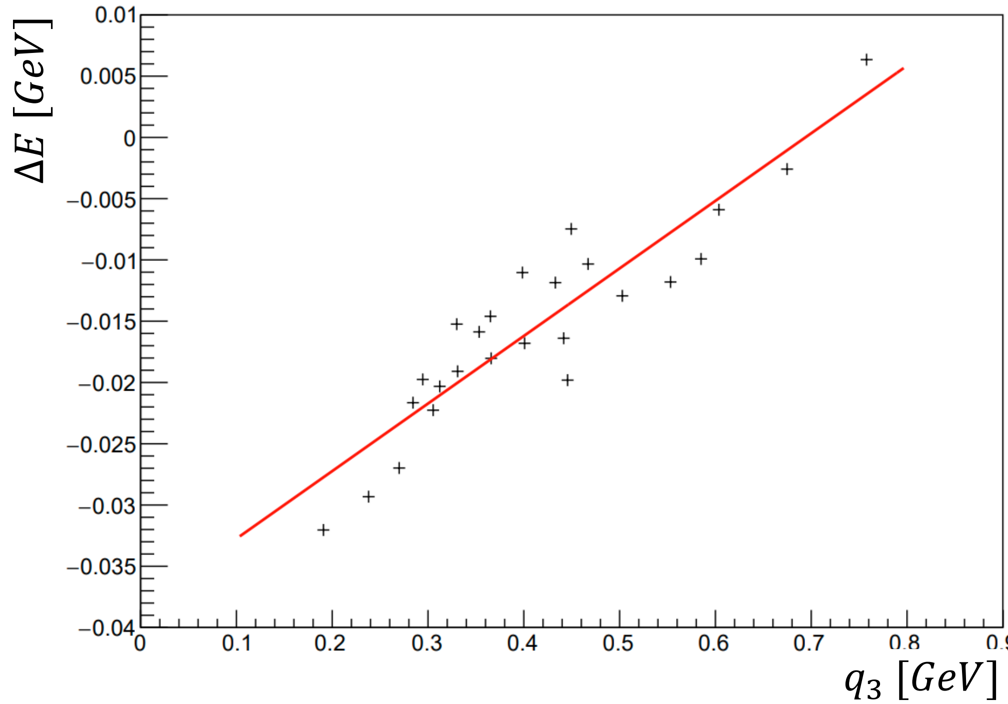
- Encouragingly we find the dependence is exactly that predicted by the Relativistic Mean Field model!



* Phys. Rev. C 90, 035501, Eur. Phys. J. C. (2019) 79: 293

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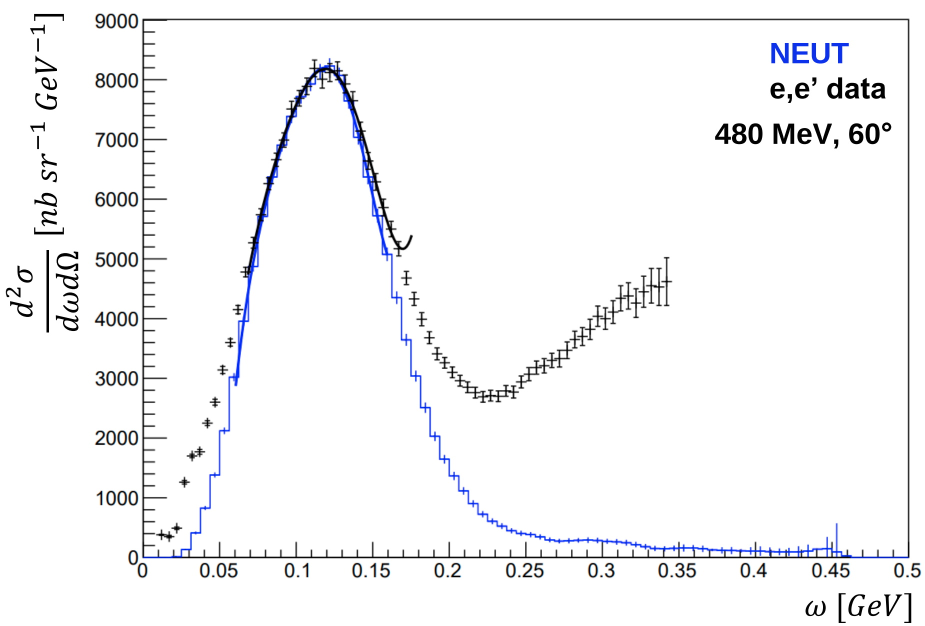
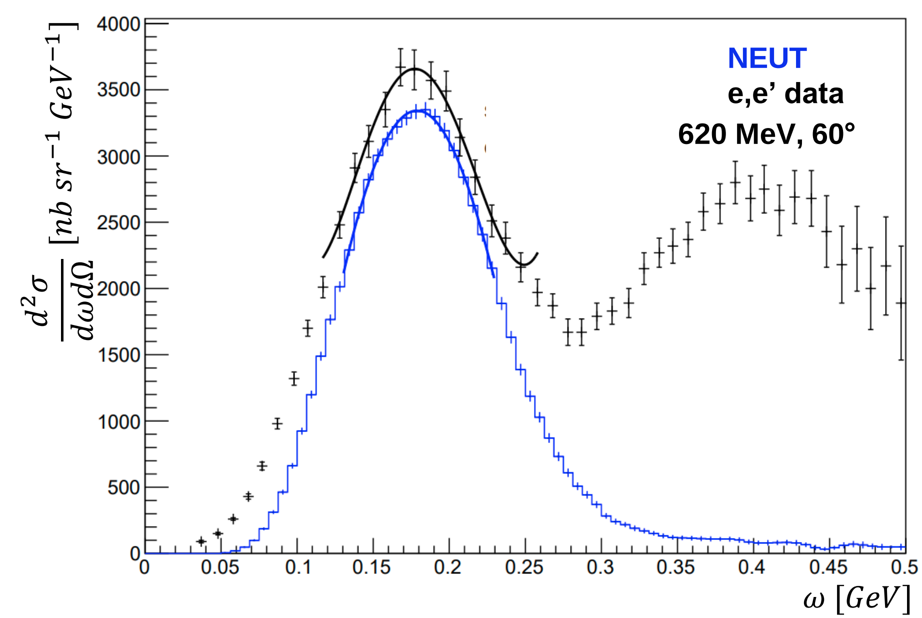
- Implement an optional "correction" to make the spectral function model removal energy have a momentum transfer dependence



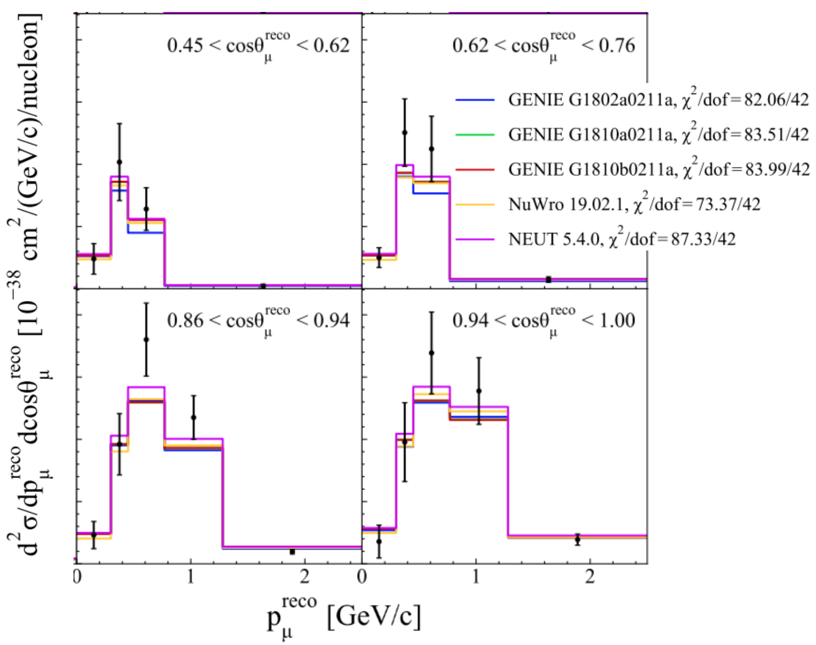


Comparisons to data

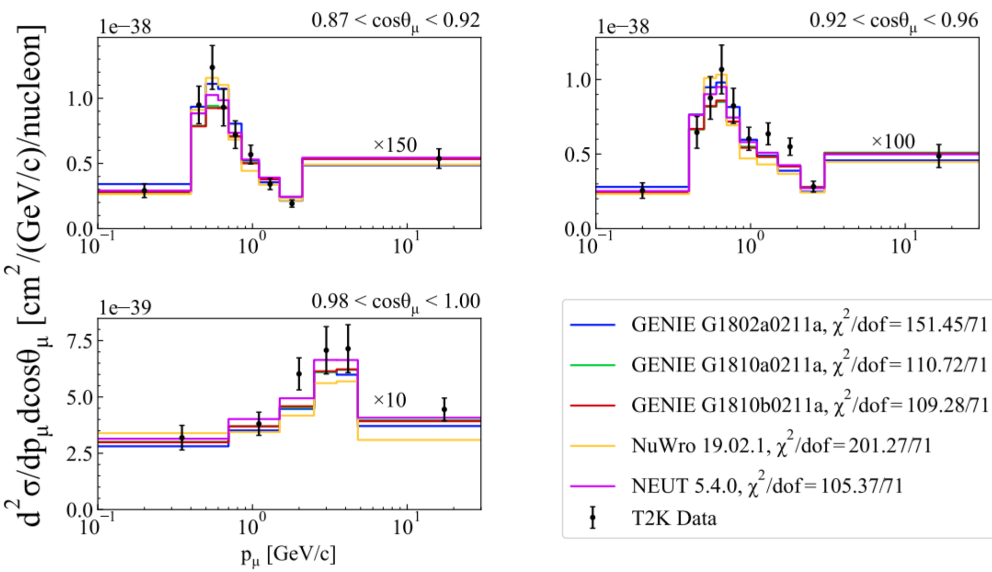
arXiv:2112.09194

- NEUT is shown using its LFG QE model and Berger-Segal RES model
- Only a subset of all data points used to calculate the χ^2 are shown

MicroBooNE Inclusive



T2K Inclusive

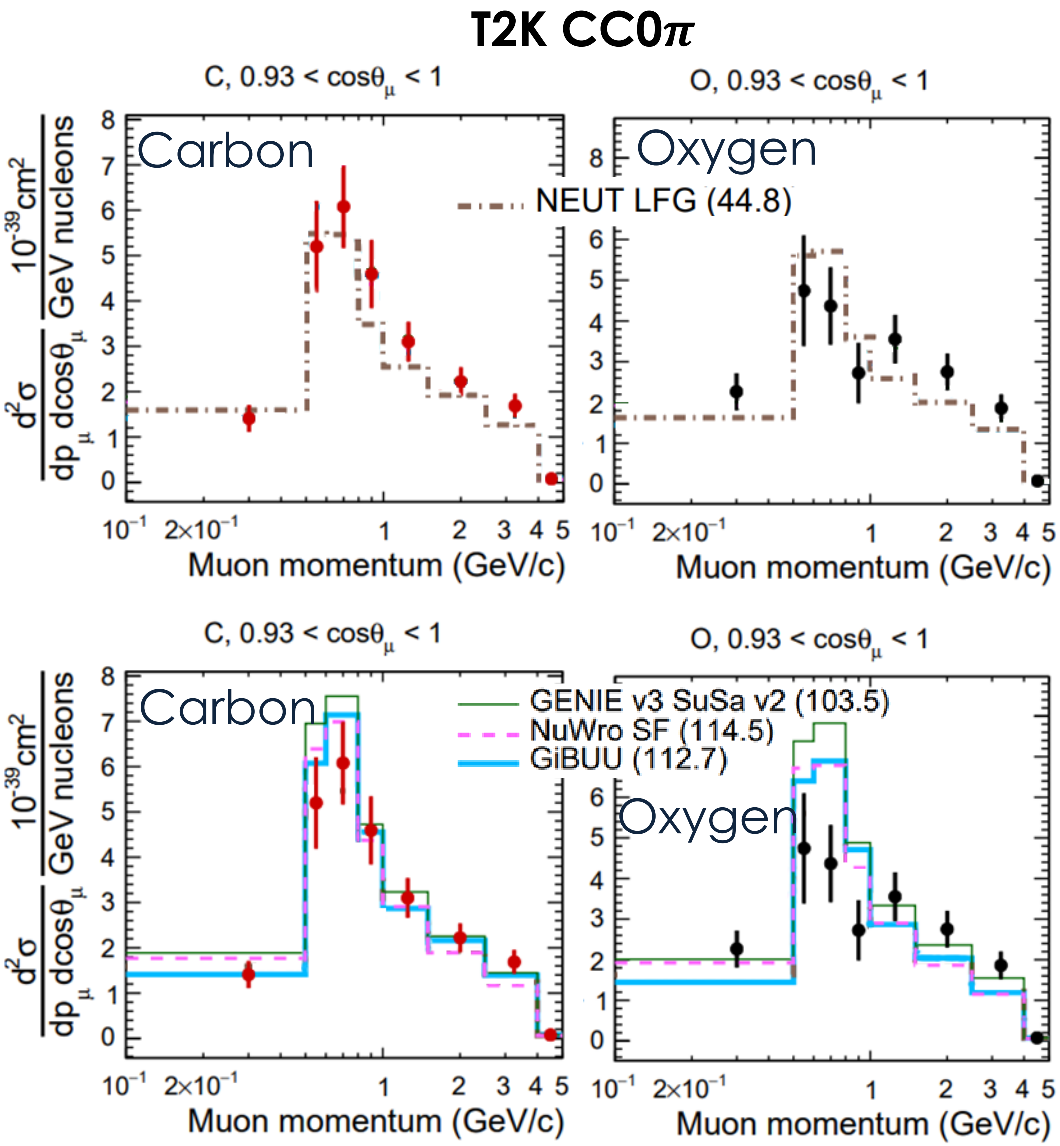


- Whilst NEUT is unable to describe the data quantitatively, it's qualitative agreement with data and other generators is reasonable

These informative generator comparisons are are from the TENSIONS 2019 workshop report

Comparisons to data

Phys. Rev. D **101**, 112004

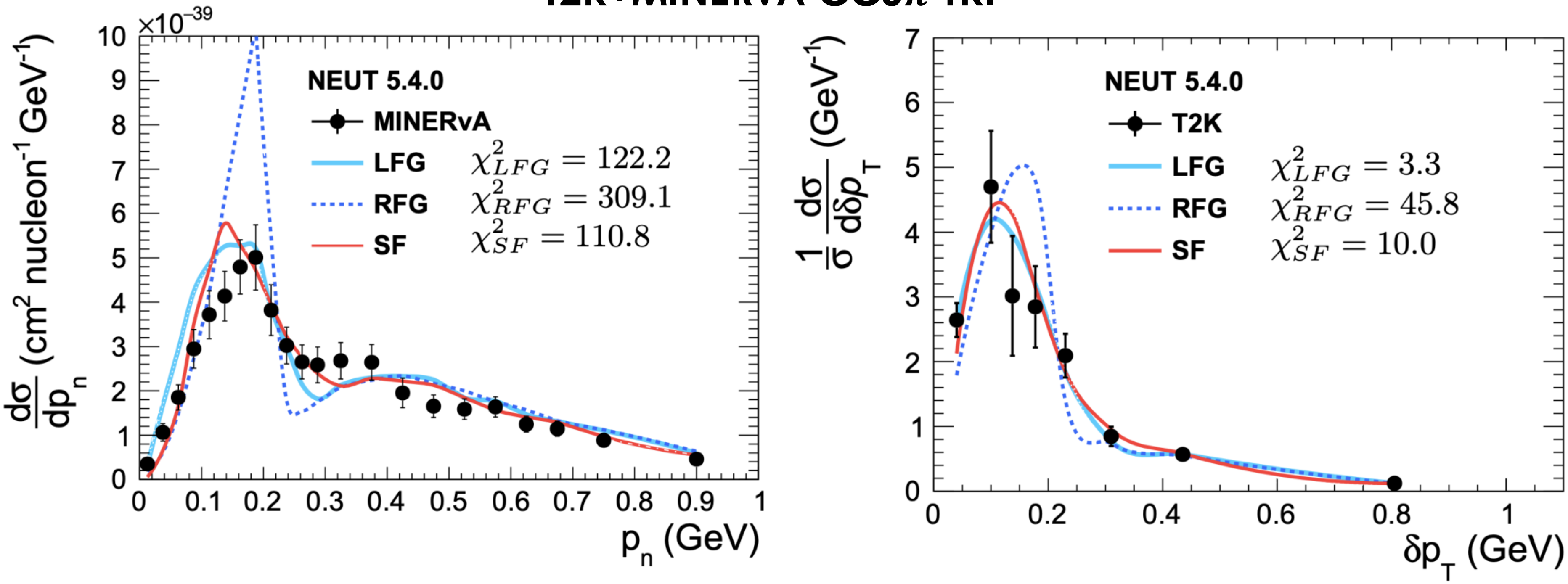


- NEUT's LFG model describes meson-less interactions at low energy and momentum transfer better than more sophisticated alternatives
- This is largely due to the substantial "RPA" suppression the LFG model employs
- Similar trends have been seen in MicroBooNE and MINERvA measurements
- Indicates a careful treatment of physics beyond the impulse approximation is required

Comparisons to data

arXiv:1810.06043

T2K+MINERvA CC0π TKI

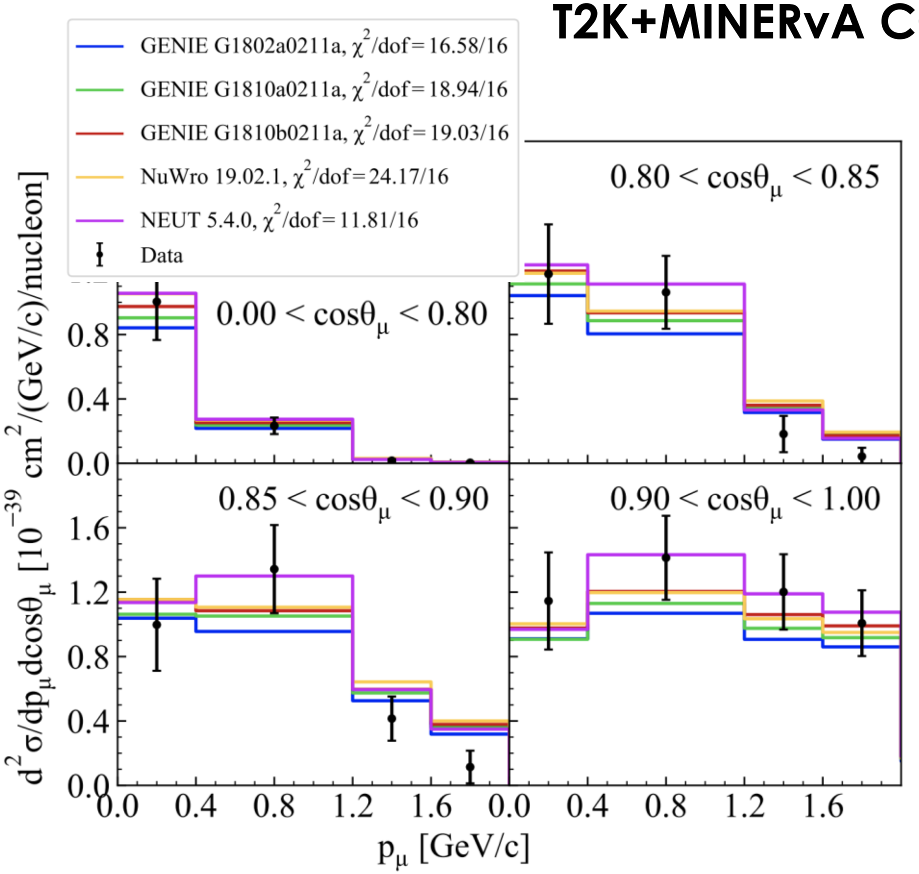


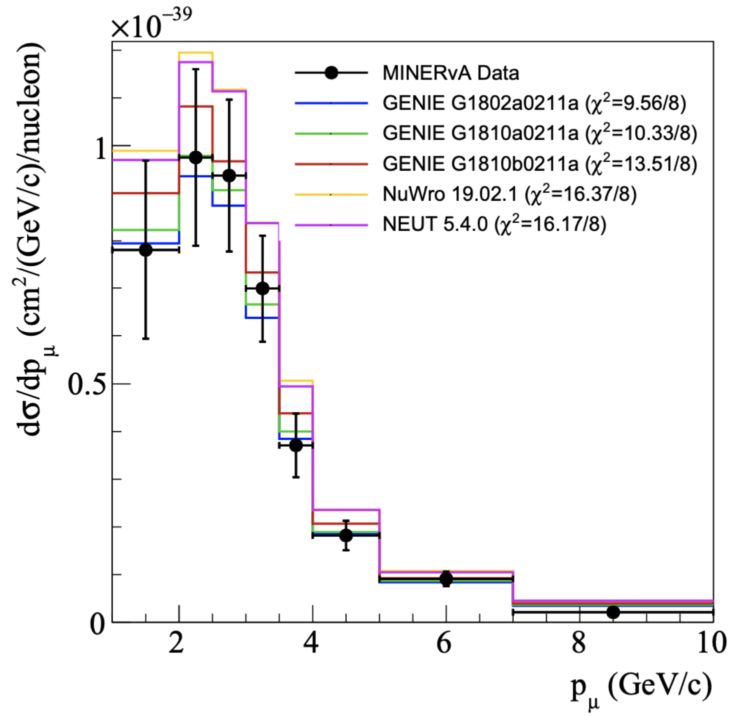
- No model is close to describing differential measurements in nucleon kinematics, but its clear that LFG and SF are superior to RFG (A.K.A GFG)

Comparisons to data

arXiv:2112.09194

T2K+MINERvA CC1π^+: lepton kinematics



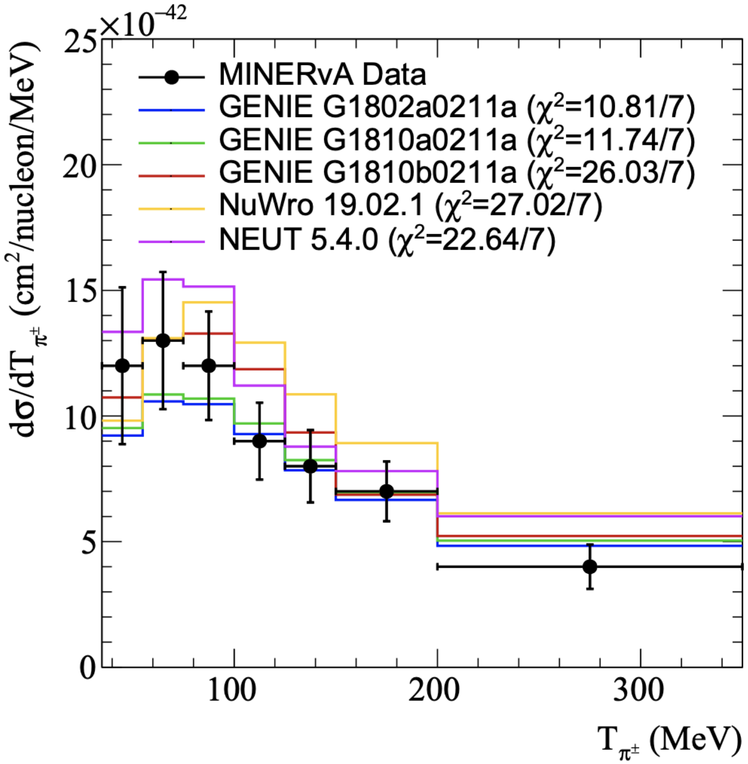


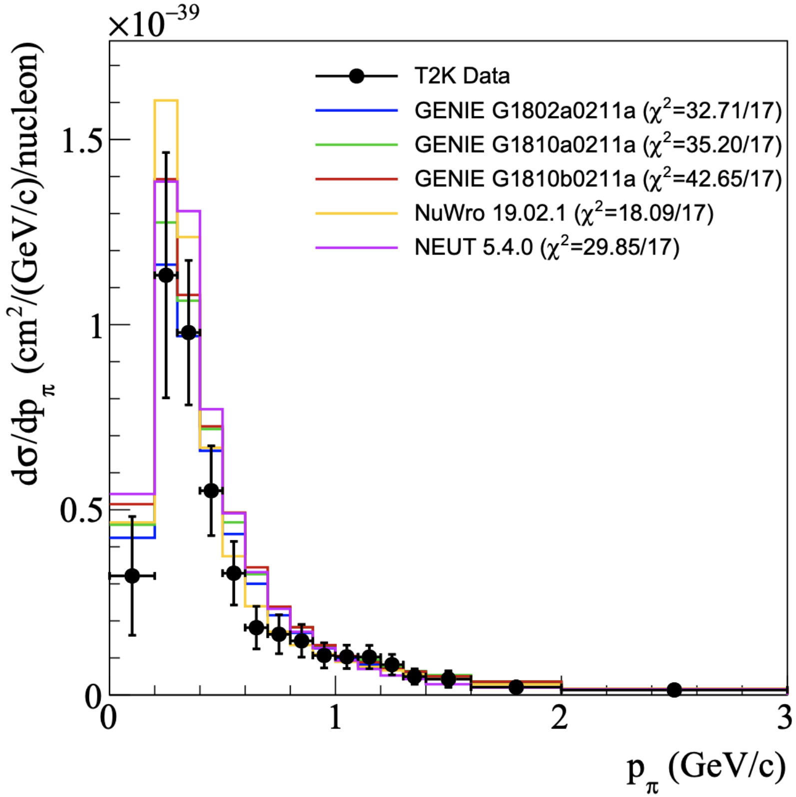
- NEUT provides a reasonable descriptions of T2K and MINERvA measurements of muon kinematics from single pion production interactions …

Comparisons to data

arXiv:2112.09194

T2K+MINERvA CC1π^+: pion kinematics

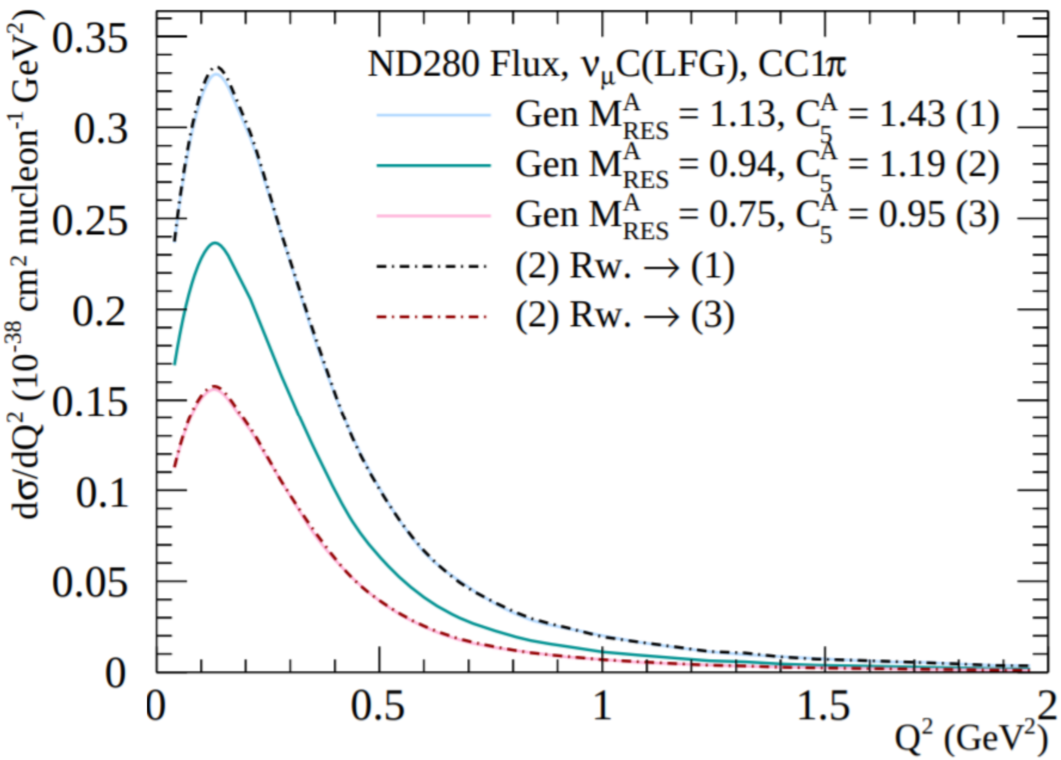




- … but no model can describe outgoing pion kinematic measurements

Event Re-weighting

- NEUT provides a wide range of interaction models, but it is clear none of these can fully describe global data
  - Any analysis must consider interaction modelling systematic uncertainties.
- NEUT and its accompanying tools provides the means to reweight the interaction model to propagate such uncertainties: a critical tool for T2K + SK



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- Example inexact reweighting "dials" (developed by the T2K collaboration):
  - QE SF shape and "optical potential" suppression,
  - Binding energy in Res interactions
  - 2p2h shape in energy and momentum transfer
  - QE SF reweight to CRPA or SuSAv2 models

Summary and future plans

- NEUT is a critical tool for T2K and SK analyses and will continue to be for the foreseeable future.
- Development work is usually carried out as it is required by its users.
- NEUT provides a wide range of interaction models and associated tools to propagate systematic uncertainties on their predictions
- Hadron and electron scattering simulation options allow model validations and tuning
- NEUT provides a reasonable description of lepton and hadron scattering data, comparably to other event generators

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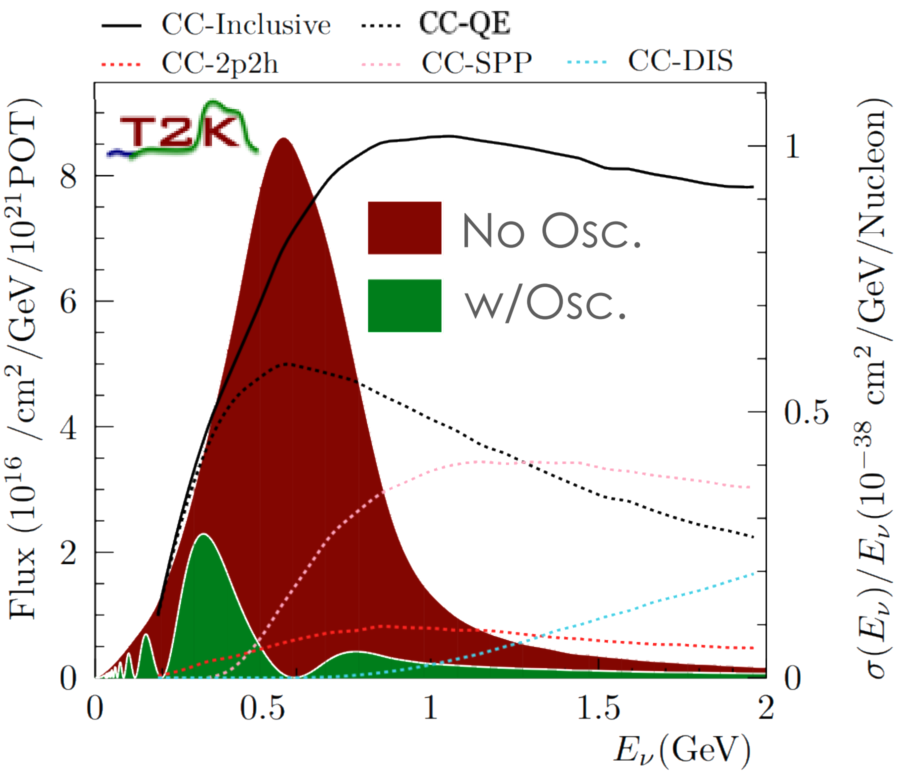
Near-term future goals

- Addition of DCC and MK single pion production models
- Implementation of SuSAv2 QE+2p2h and ED-RMF QE
- Exact nucleon FSI reweighting
- Update Pythia version
- Make NEUT open source

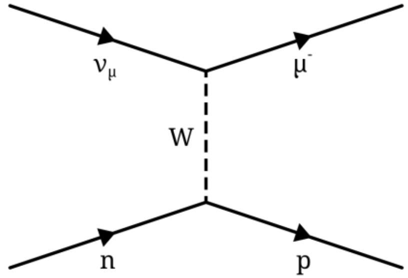
Backups

Model Diagrams



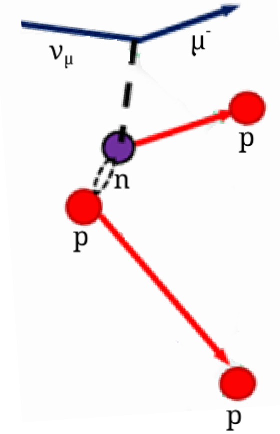
CC-QE

(Charged-Current Quasi-Elastic)



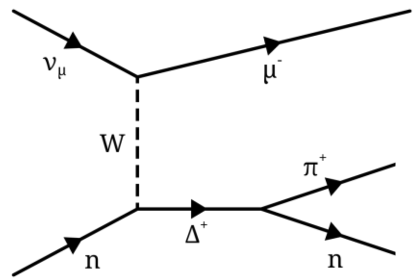
CC-2p2h

(two-particle two-hole)



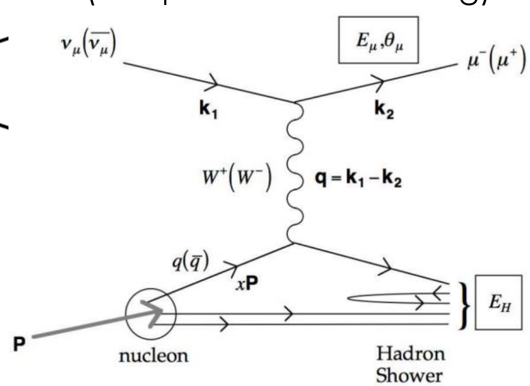
CC-SPP

(Single Pion Production)



CCDIS

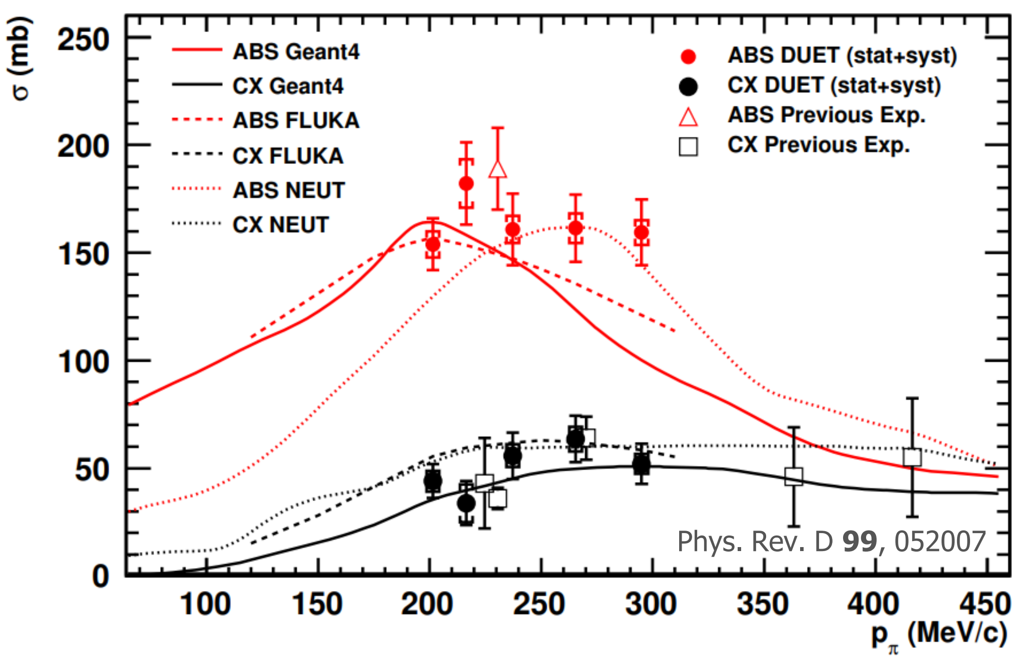
(Deep inelastic scattering)

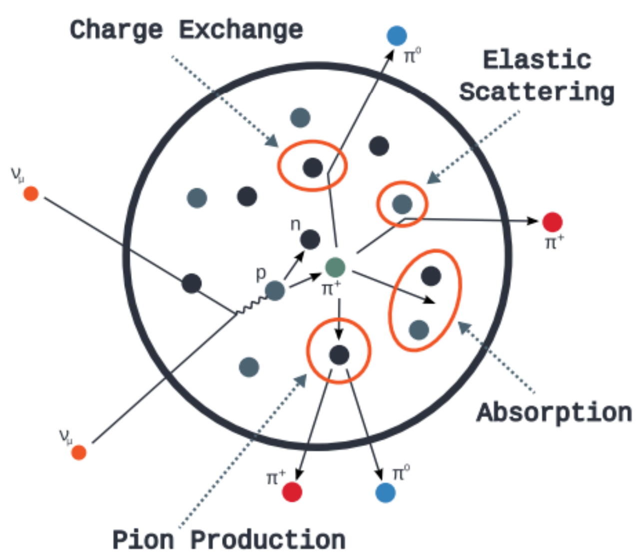


Tuning FSI with hadron scattering

- NEUT is additionally able to use the same physics from within its FSI model to predict hadron scatting data

- This was used by *Pinzon Guerra et al.* to develop a tuning of interaction probabilities within the FSI cascade





SIS custom hadron multiplicity

- For SIS interactions (with an invariant mass less than 2 GeV) a custom model for hadron multiplicity is used
- This is based on the work of *Bronner et al.* analysing bubble chamber data to establish a mean multiplicity of charged hadrons $< n_{ch} >$
- A separate multiplicity is obtained for neutrino and anti-neutrino interactions on protons and neutrons
- This mean multiplicity is then used to determine the probability of having different particle multiplicities in NEUT SIS interactions