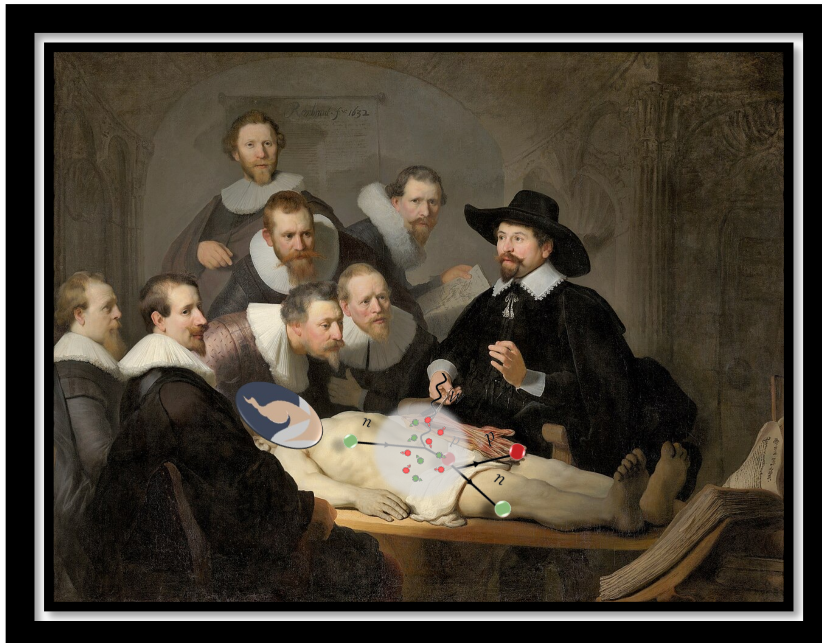
Dissecting Neutrino Event Generators

A look at what's inside (and what could be wrong)



The anatomy lesson of neutrino generators

Rembrandt van Rijn (2024)

Stephen Dolan

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CERN

Focus of this lectures

- There is not time to cover all the interesting physics associated with neutrino interaction modelling in generators
- You'll get a slightly biased choice of topics!
- We'll stay mostly qualitative, I'll try to give a conceptual overview of the topics most relevant to ongoing experiments
- Lots of places to learn more:

- INSS lecture slides
- From eV to EeV (Formaggio and Zeller)
- NuSTEC White Paper
- Xsecs for Oscillations (Katori and Martini)
- e-scat vs nu-scat (SuSAv2 group)
- Semi-inclusive interactions (Donnelly talk at ECT* 2018)
- K. McFarland's Lectures
- S. Boyd's Lectures
- T. Golan's thesis
- G. Megias' thesis
- GiBUU based summaries (1,2)

(Which I liberally borrowed material from when making these slides!)

Overview

- Inputs to Generators: Neutrino-nucleon interactions
  - QE, RES and DIS
- Inputs to Generators: Neutrino-nucleus interactions
  - Nuclear effects
- Neutrino event generators
  - Filling in gaps in our inputs
- Benchmarking generators with measurements
  - Inclusive successes and exclusive failures
- Why do we care?
  - Neutrino interactions for neutrino oscillations
- Don’t Panic! The future of neutrino interaction simulations

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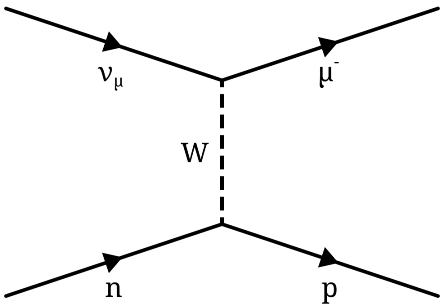
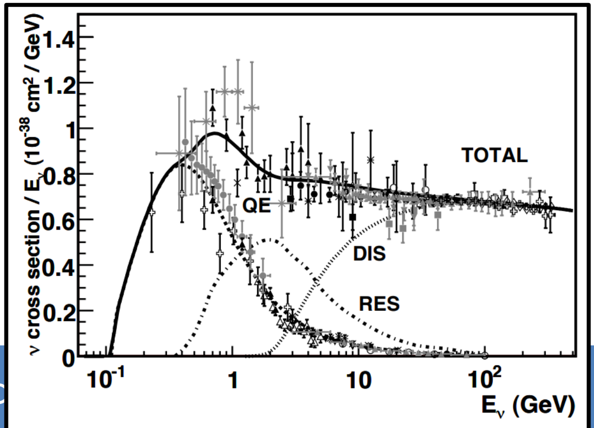
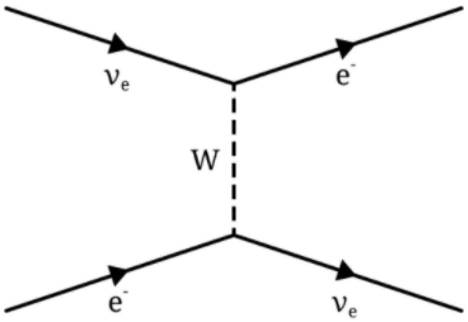
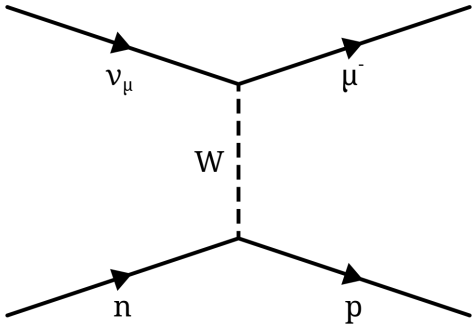




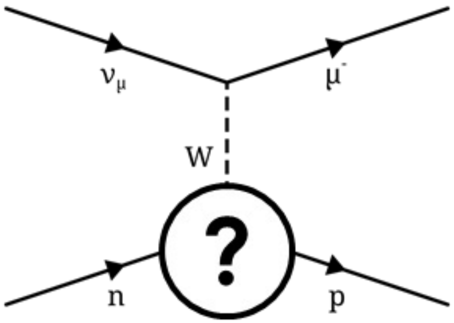
Recap of neutrino scattering



Point-like: Masters homework problem



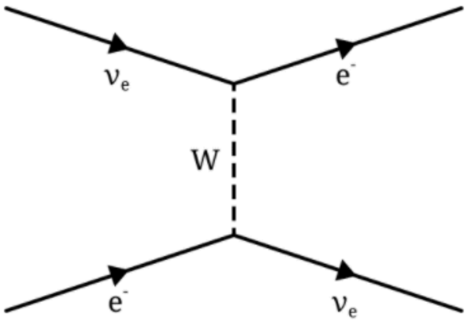
Nucleon: mostly harmless



Nucleus: very hard

- Cross-Sections for **point-like neutrino scattering** with electrons or quarks are relatively **easy to calculate**
- In most experiments, **neutrinos interact with nucleons or a nucleus**

Recap of neutrino scattering



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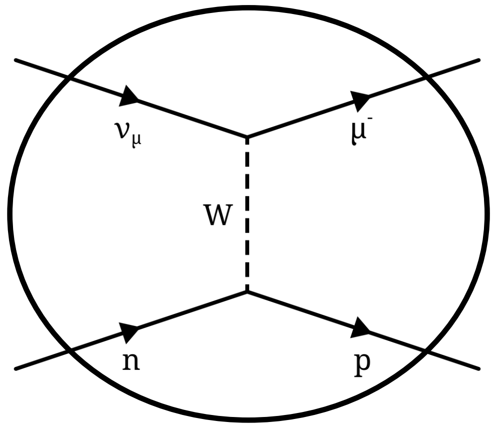

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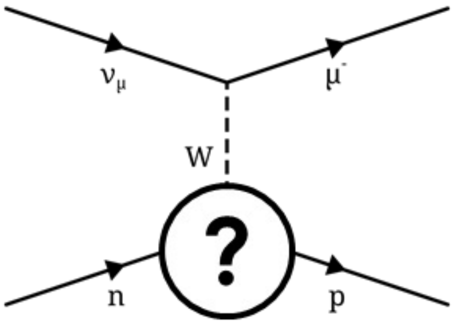

Nucleus: very hard

- Cross-Sections for **point-like neutrino scattering** with electrons or quarks are relatively **easy to calculate**
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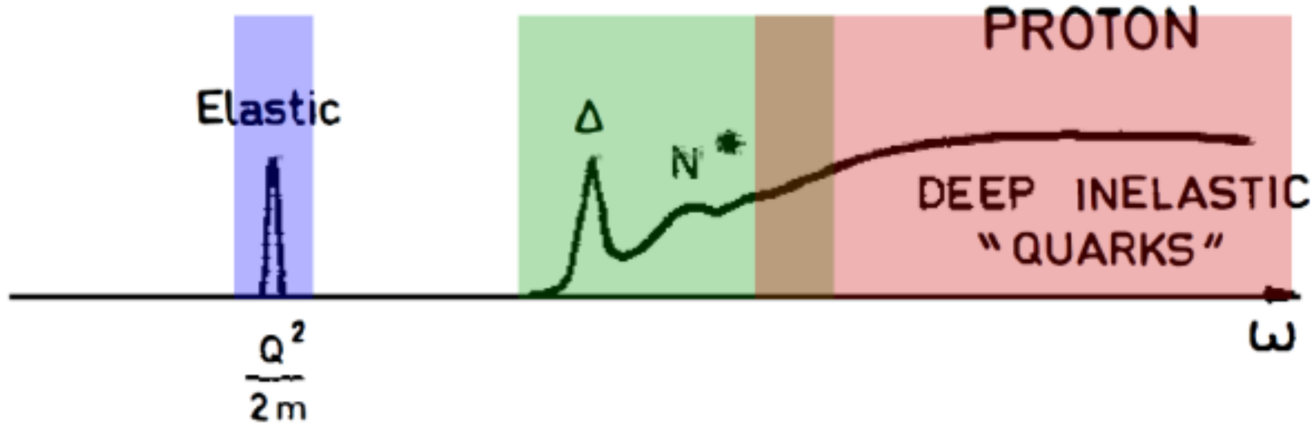
- Next slides describe our baseline models for simulating neutrino-nucleon interactions that go into event generators

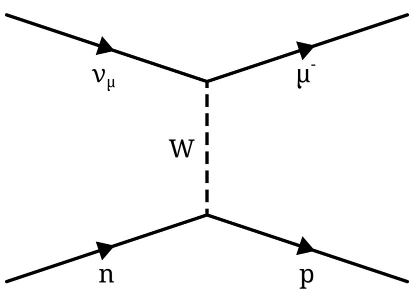
Neutrino nucleon scattering

See Aaron's lectures

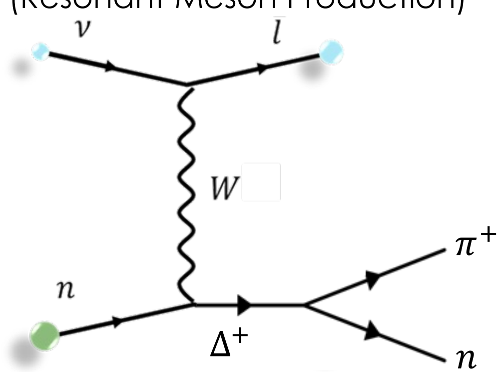


(ω = energy transfer, sometimes called q_0 and sometimes ν)

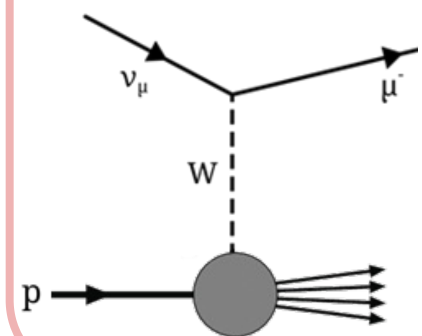
CCQE
(Quasi-elastic Scattering)



CCRES
(Resonant Meson Production)



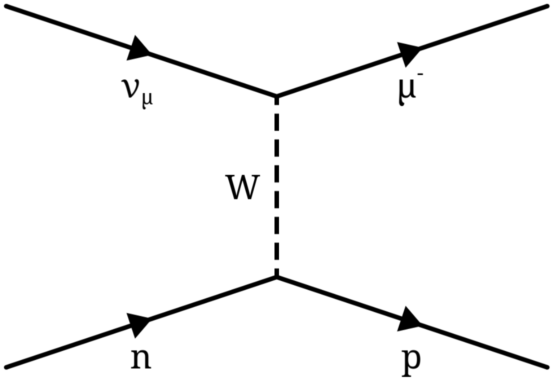
CCDIS
(Deep Inelastic Scattering)



Increasing Energy Transfer

Quasi-elastic Scattering

See Aaron's lectures

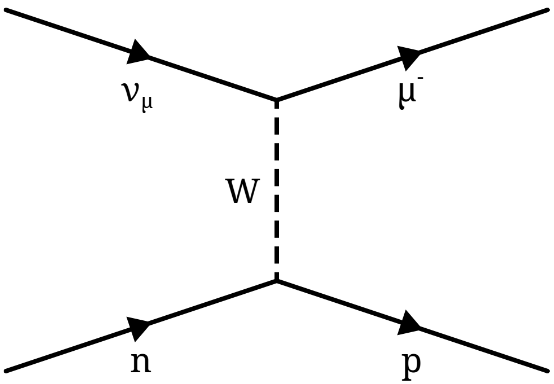


- Let's work with the "easiest" neutrino-nucleon interaction: CCQE
  (= charged current quasi elastic)

$$M \sim \frac{g_W^2}{8}\frac{1}{M_W^2}[\bar{u}_\mu \gamma_\mu (1-\gamma_5) u_\nu][\bar{u}_p(\ldots)u_n]$$

Quasi-elastic Scattering

See Aaron's lectures



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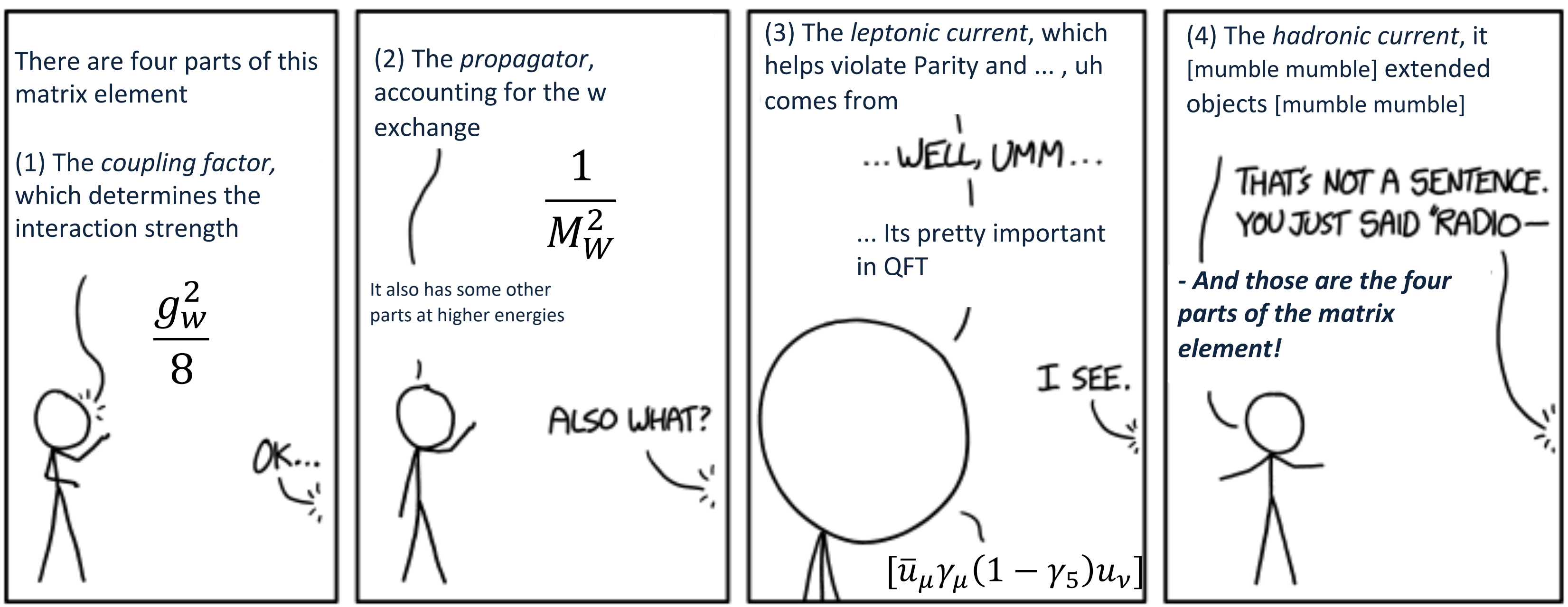

Adapted from XKCD

The hadronic current

Equation shamelessly lifted from
G. Perdue's other 2012 INSS lecture

$$J_H^\beta = \bar{u}_p \left[f_{1V}\gamma^\beta + i\frac{\xi f_{2V}}{2M}\sigma^{\beta\delta}q_\delta + \frac{f_{3V}}{M}q^\beta + f_A\gamma^\beta\gamma_5 + \frac{f_p}{M}q^\beta\gamma_5 + \frac{f_{3A}}{M}\left(P_p^\beta + P_n^\beta\right)\gamma_5 \right] u_n$$

$$M = \left(M_p + M_n\right)/2 \qquad q = p_\nu - p_\mu = P_p - P_n \qquad \xi = \mu_p - \mu_n \qquad \sigma^{\mu\nu} = \frac{i}{2}\left[\gamma^\mu, \gamma^\nu\right]$$

ξ is the difference between proton and neutron anomalous magnetic moments

- A long and horrible expression for generalised scattering of an extended object

See Aaron's lectures

- The f factors are the "form factors"
  - Their Fourier transform represent a physical distribution
  - Dipole → exponential
- Most can be constrained via electron scattering with one exception
  - Their Fourier transform represent a physical distribution
  - f_A, we guess the form of! One free parameter: M_A

$$f_A\left(q^2\right) = \frac{f_A(0)}{\left(1 - \frac{q^2}{M_A^2}\right)^2}$$

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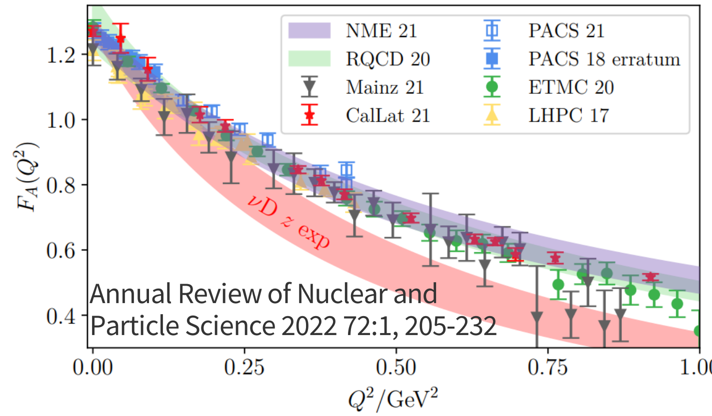
Aside: recent lattice QCD updates

- Some generators benefit from recent calculations from LQCD
- These suggest a dipole doesn't work
- See Aaron's slides for more details!



Llewellyn-Smith CCQE

See Aaron's lectures

- Putting this all together gets us to the cross section for neutrino-nucleon interactions we have in our generators:

$$\frac{d\sigma}{d|q^2|}\begin{pmatrix}\nu n \to \ell^- p \\ \bar{\nu} p \to \ell^+ n\end{pmatrix} = \frac{M^2 G^2 \cos^2\theta_c}{8\pi E_\nu^2}\left[A(q^2) \mp B(q^2)\frac{(s-u)}{M^2} + \frac{C(q^2)(s-u)^2}{M^4}\right]$$

$$(s-u = 4ME_\nu + q^2 - m^2)\,.$$

Neutrino reactions at accelerator energies, Llewellyn Smith, 1972

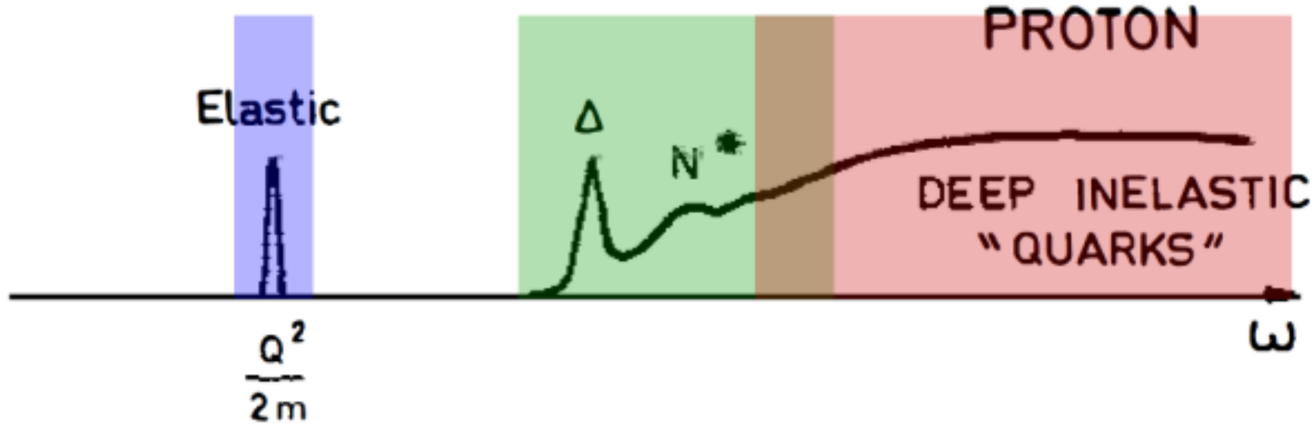
$$A \simeq \frac{t}{M^2}\left(|f_{1V}|^2 - |f_A|^2\right) + \frac{t^2}{4M^2}\left(|f_{1V}|^2 + \xi^2|f_{2V}|^2 + |f_A|^2 + 4\xi \mathrm{Re}\left(f_{1V}f_{2V}^*\right)\right) + \frac{t^3\xi^2}{16M^6}|f_{2V}|^2$$

$$B \simeq \frac{1}{M^2}\left(\mathrm{Re}\left(f_{1V}f_A^*\right) + \xi\mathrm{Re}\left(f_{2V}f_A^*\right)\right)t \qquad C = \frac{1}{4}\left(|f_{1V}|^2 + |f_A|^2 - \frac{\xi^2|f_{2V}|^2}{4M^2}t\right)$$

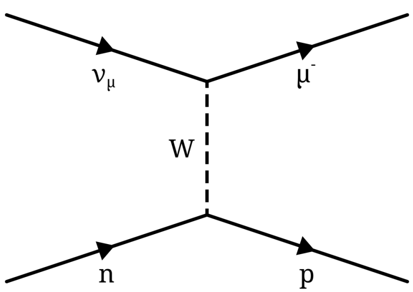
- It's a long expression, but only one unknown (in a dipole model): M_A

Neutrino nucleon scattering

See Aaron's lectures



CCQE
(Quasi-elastic Scattering)



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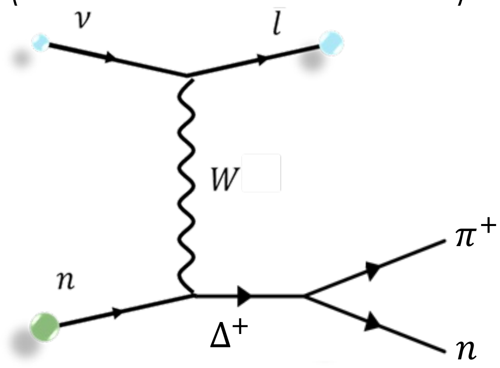

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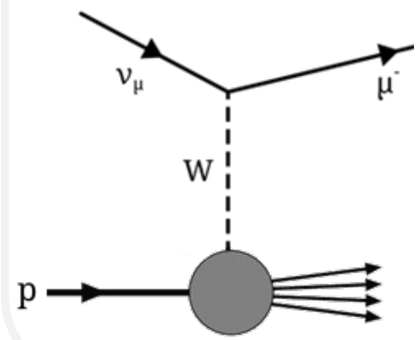
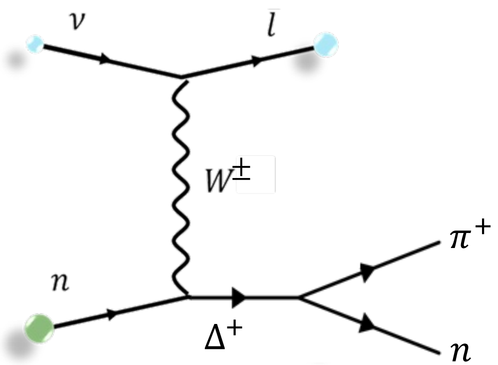


Increasing Energy Transfer

Resonant Pion Production

See Minoo's lectures

CCRES



- Neutrinos can excite a nucleon into a resonance state, which decays to give a nucleon + meson final state
- The dominant resonance is $\Delta(1232)$ but others can contribute, as can non-resonant pion production
- And the contributions from each should have interference terms …
- Resonance models are complicated!
- Whilst CCQE scattering on the nucleon can described fully with 1 variable the multi-particle final state for SPP requires 4:

$$\frac{d\sigma}{dWdQ^2d\Omega_\pi}$$

Contains polar and azimuthal angle

CC Single Pion Production (SPP) final states

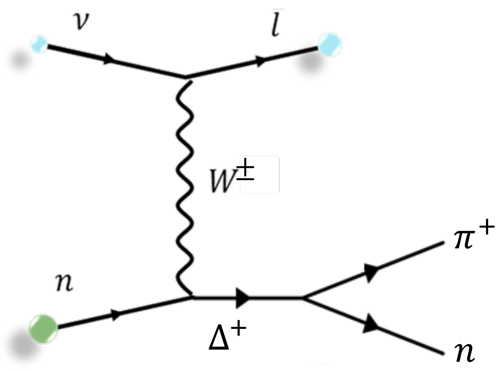
$$\nu_\mu p \rightarrow \mu^- p \pi^+, \qquad \overline{\nu}_\mu p \rightarrow \mu^+ p \pi^-$$
$$\nu_\mu n \rightarrow \mu^- p \pi^0, \qquad \overline{\nu}_\mu p \rightarrow \mu^+ n \pi^0$$
$$\nu_\mu n \rightarrow \mu^- n \pi^+, \qquad \overline{\nu}_\mu n \rightarrow \mu^+ n \pi^-$$

D. Rein and L. Sehgal, Ann. Phys. 133, 79 (1981)

Resonant Pion Production

See Minoo's lectures

CCRES



Current Matrix Elements from a Relativistic Quark Model*

R. P. Feynman, M. Kislinger, and F. Ravndal

Lauritsen Laboratory of Physics, California Institute of Technology, Pasadena, California 91109

(Received 17 December 1970)

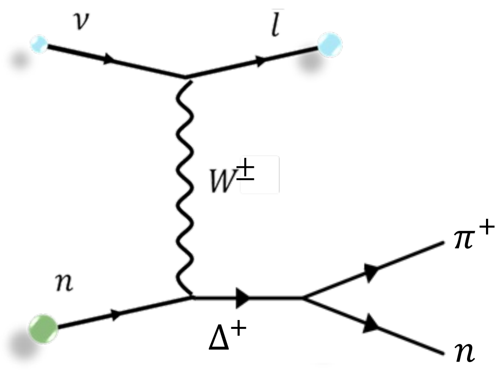
- The model's used in today's neutrino generators are often based on an approximate model from the 1970s

ficing theoretical adequacy for simplicity. We shall choose a relativistic theory which is naive and obviously wrong in its simplicity, but which is definite and in which we can calculate as many things as possible – not expecting the results to agree exactly with experiment, but to see how closely our "shadow of the truth" equation gives a partial reflection of reality. In our attempt to maintain simplicity, we shall evidently have to violate known principles of a complete relativistic field theory (for example, unitarity). We shall attempt to modify our calculated results in a general way to allow, in a vague way, for these errors.

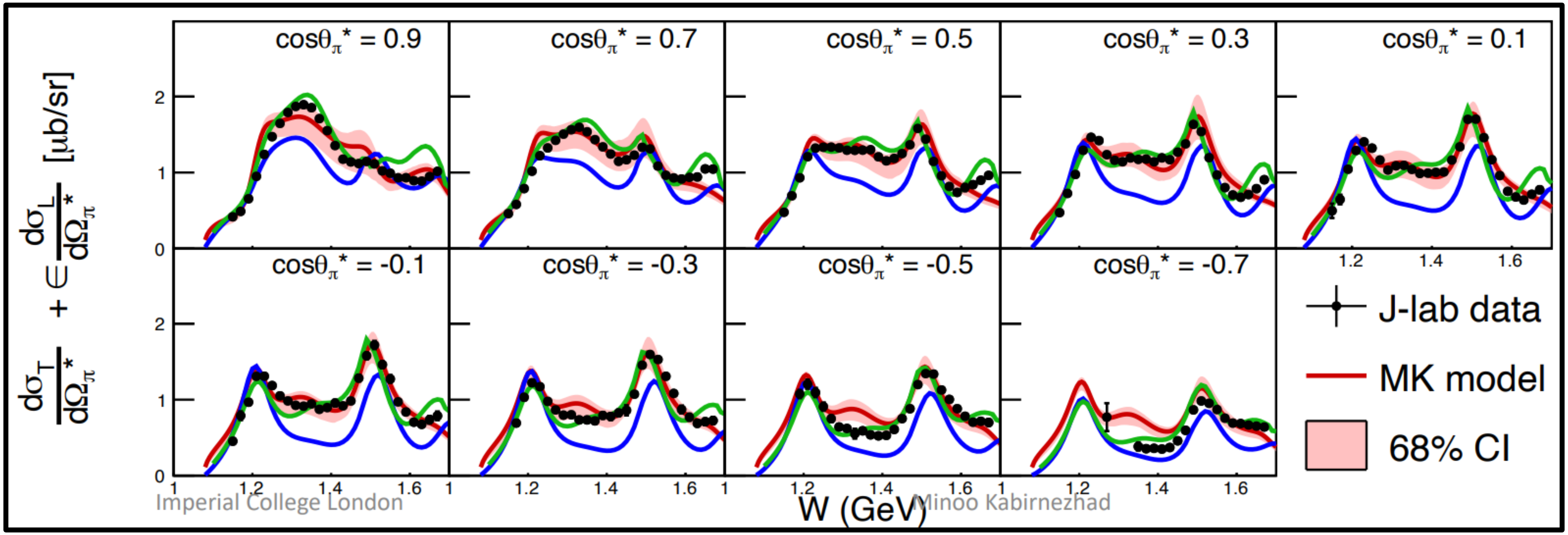
Resonant Pion Production

See Minoo's lectures

CCRES

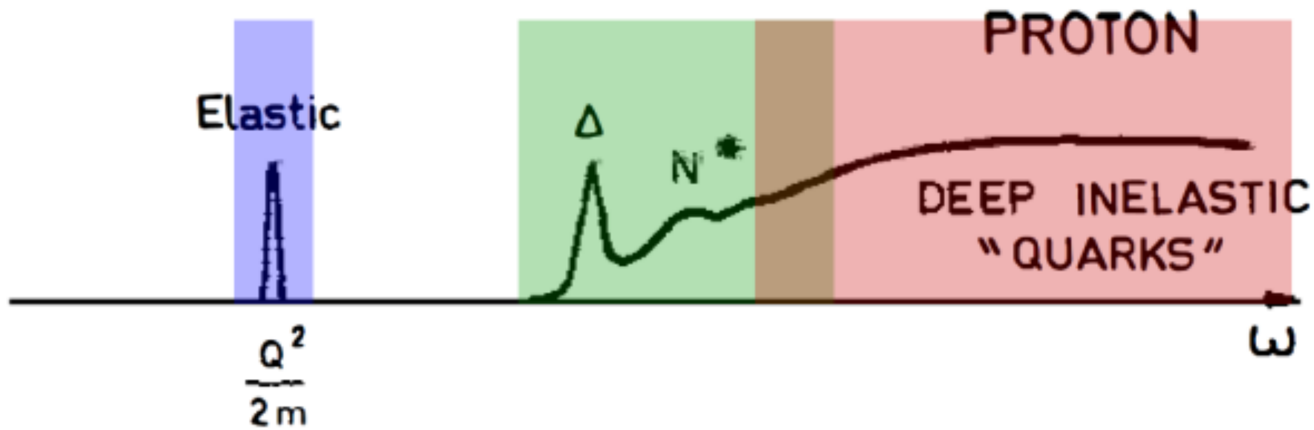


- **New theory calculations** tuned to precision electron scattering data are on the horizon
  - E.g.: [MK model at NuINT 2022]
- The axial component remains a challenge



Neutrino nucleon scattering

See Minoo's lectures



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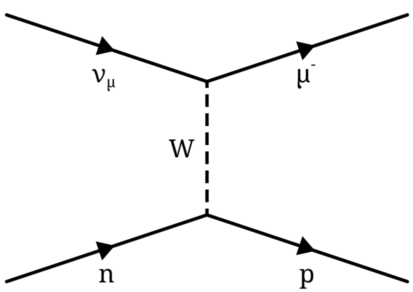

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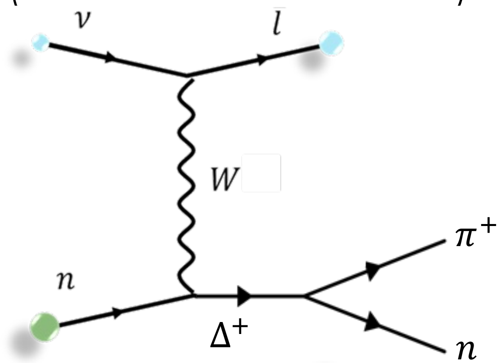

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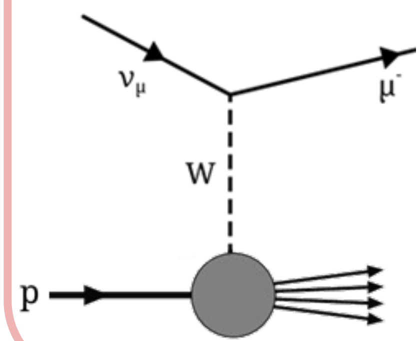
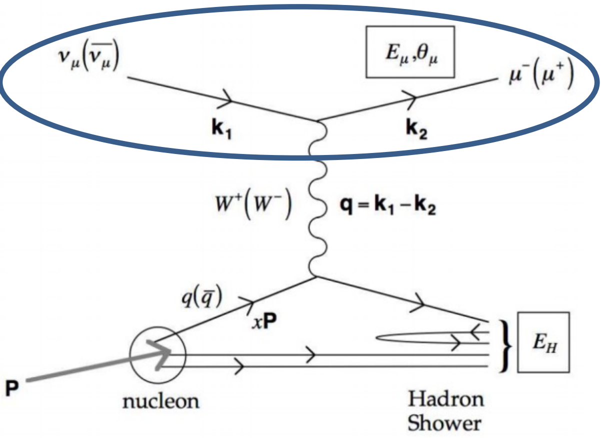


Increasing Energy Transfer

Deep inelastic scattering

See Minoo's lectures

CCDIS



- Given enough energy, neutrinos can resolve the quarks within a nucleon. This is deep inelastic scattering.
- At high energies, the *inclusive* (i.e. integrating over possible hadronic final states) cross-section is fairly well understood (perturbative QCD):

$$\frac{d^2\sigma^{\nu,\overline{\nu}}}{dx\,dy} = \frac{G_F^2 M E_\nu}{\pi\,(1+Q^2/M_{W,Z}^2)^2}\left[\begin{array}{c}\frac{y^2}{2}2xF_1(x,Q^2) + \left(1-y-\frac{Mxy}{2E}\right)F_2(x,Q^2)\\ \pm y\left(1-\frac{y}{2}\right)xF_3(x,Q^2)\end{array}\right]$$

Bjorken x and y

$$x = \frac{Q^2}{2M\nu} = \frac{Q^2}{2ME_\nu y}$$

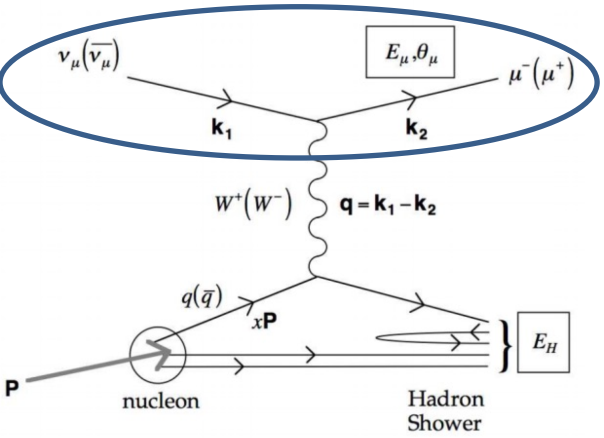
$$y = E_{had}/E_\nu$$

$$Q^2 = -m_\mu^2 + 2E_\nu(E_\mu - p_\mu\cos\theta_\mu)$$

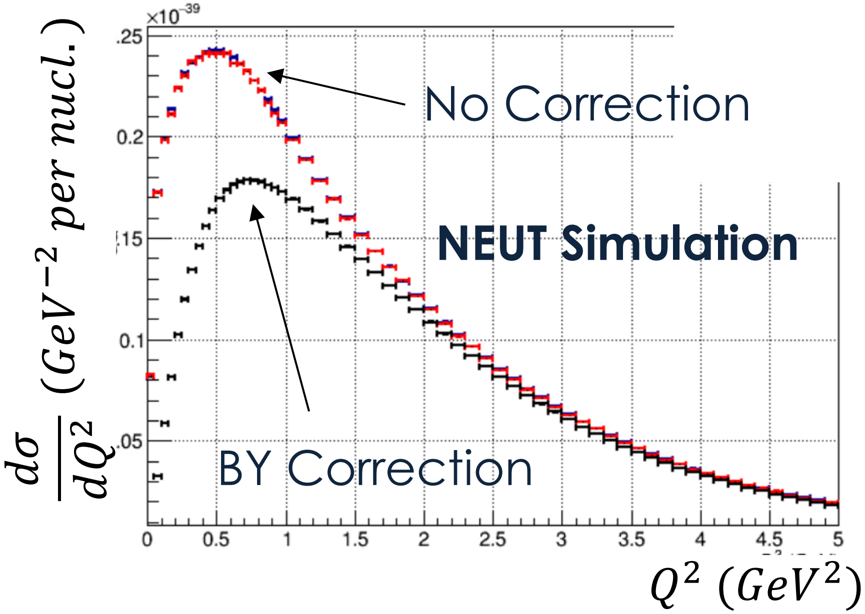
Deep inelastic scattering

See Minoo's lectures

CCDIS



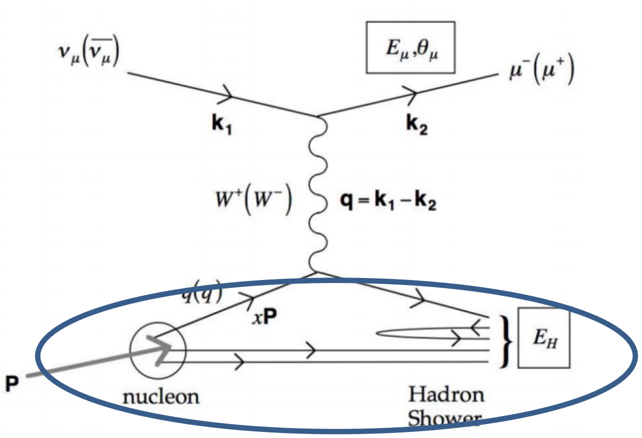
- At low energies (or actually low Q^2) QCD becomes non- perturbative.
- Bodek-Yang: extrapolate down to low Q^2 assuming some parametrised scaling. Fix the details with e-scattering, apply to ν- scattering
- But this is an empirical treatment that comes with uncertainties



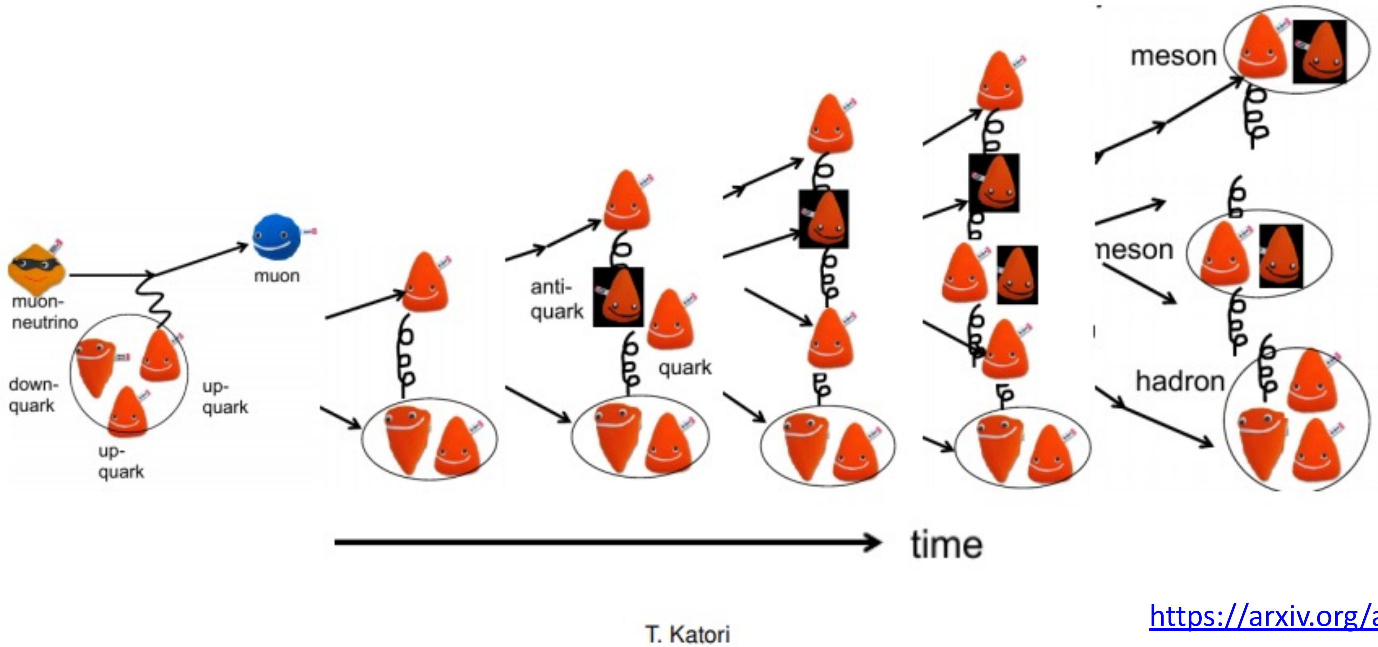
https://arxiv.org/abs/1012.0261

Deep inelastic scattering

CCDIS



- The hadronic side of DIS interactions requires more empirical treatments
- Often the PYTHIA generator is used, but this is really built for much higher energies than used in most neutrino experiments



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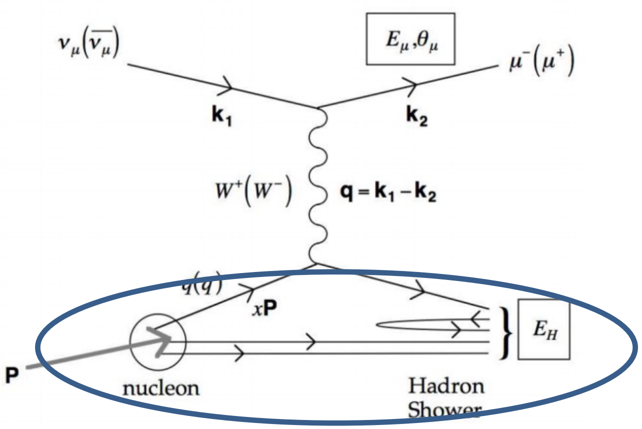

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"I would not trust PYTHIA for anything with less than 6 pions"

S. Prestel (a PYTHIA author)

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Deep inelastic scattering

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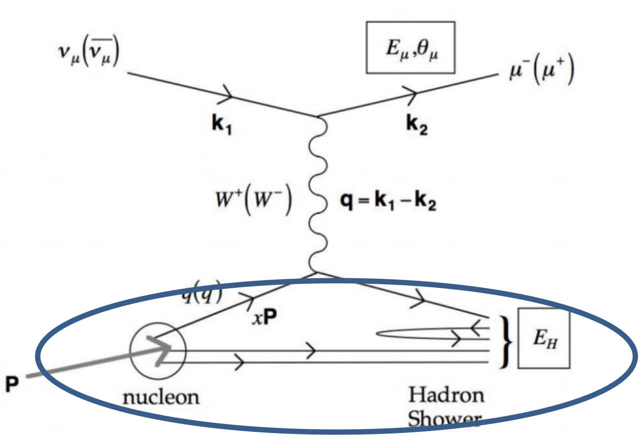

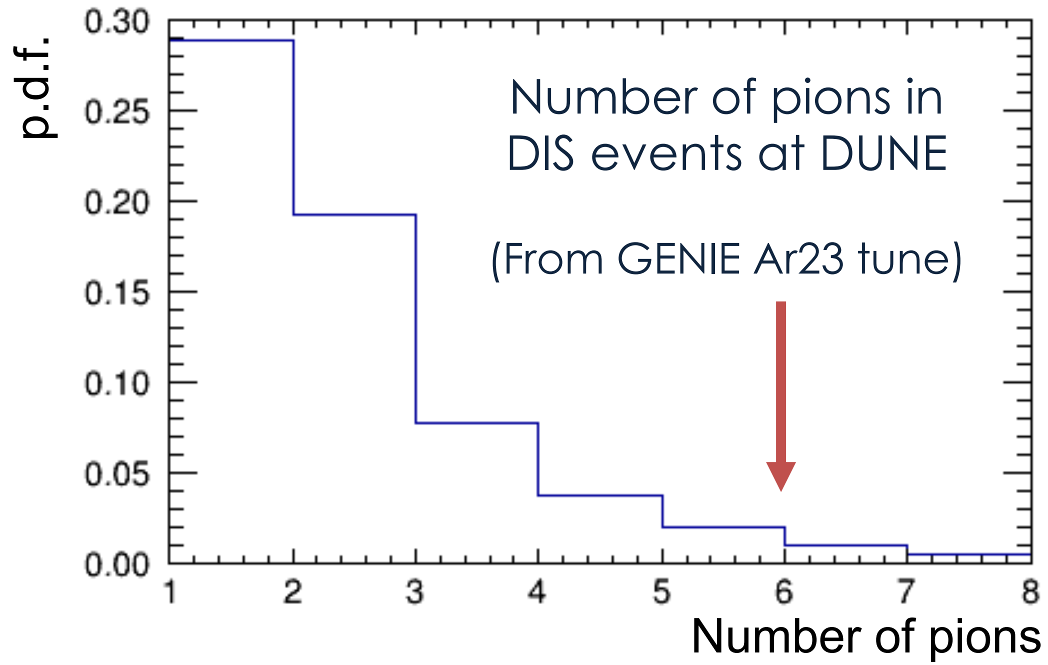

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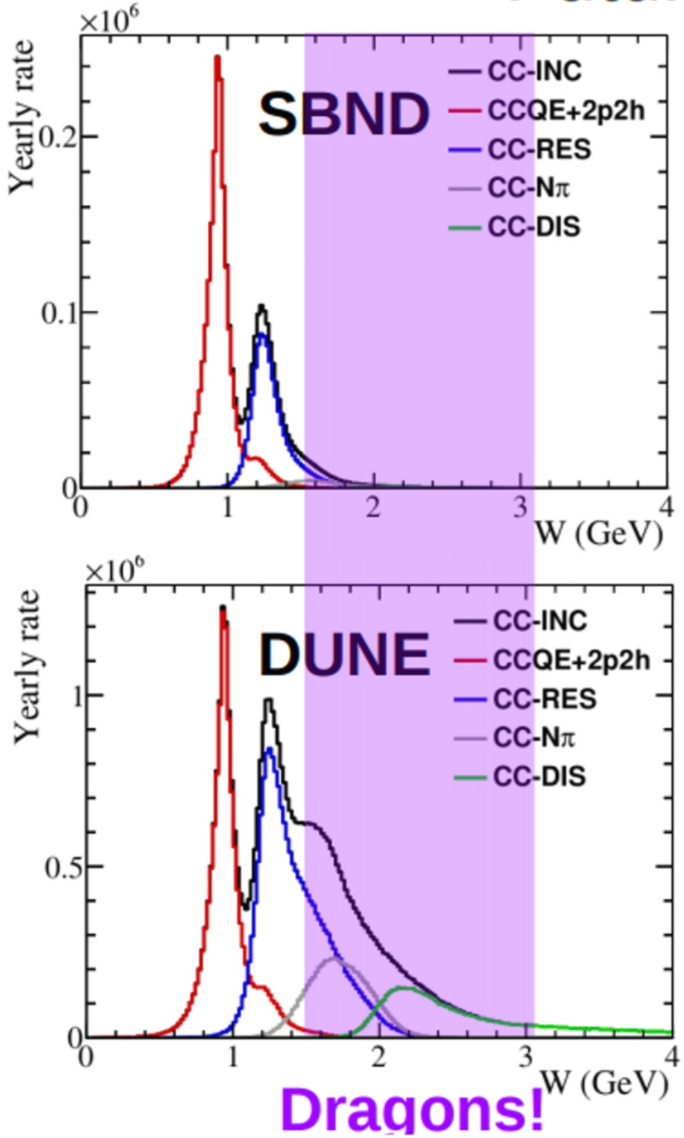
Future (^{40}Ar)



- Low-W, CC0π and Δ region well covered by SBN data
- Timely data to guide ongoing theory efforts
- DUNE (ND here) has a significant high-W component
- Not well covered by theory
- No relevant data on ^{40}Ar

23

W = hadronic invariant mass

C. Wilkinson, NuPhys 2018

Summary so far

- Weak Interactions with neutrinos
  - Point-like scattering is “easy” to calculate
  - Interactions with nucleons is more challenging **due to their finite extent**

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- Weak Interactions with neutrinos
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- Neutrino-nucleon interactions
  - QE: almost calculable with some form factors
  - RES: **much more difficult**, lots of diagrams to consider
  - DIS: easy for *inclusive* high Q^2, hard at low Q^2, **hadronic side a total guess**

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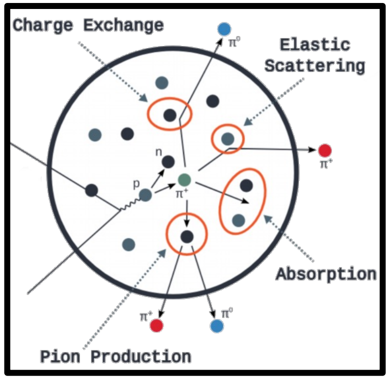
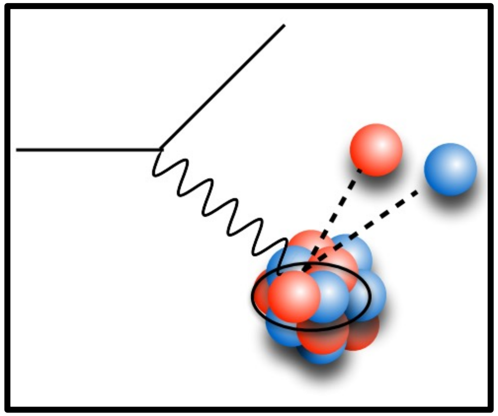
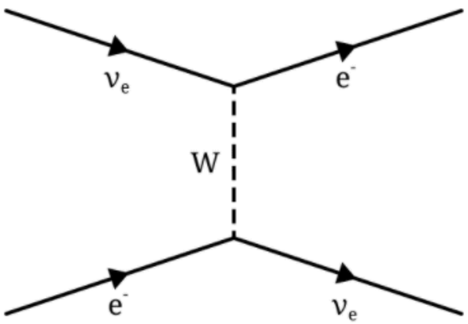
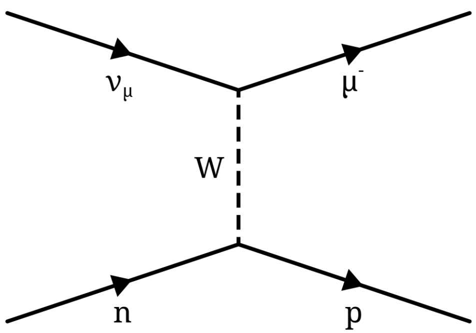




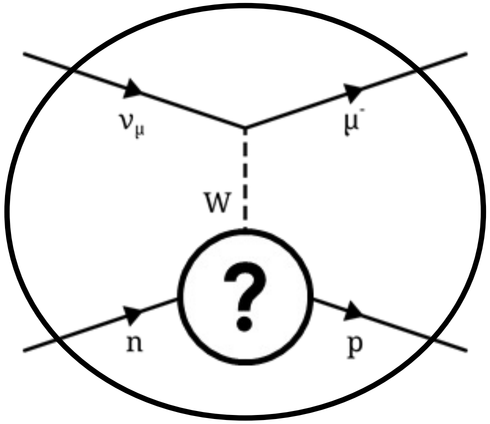
Beyond nucleon scattering



Point-like: Masters homework problem



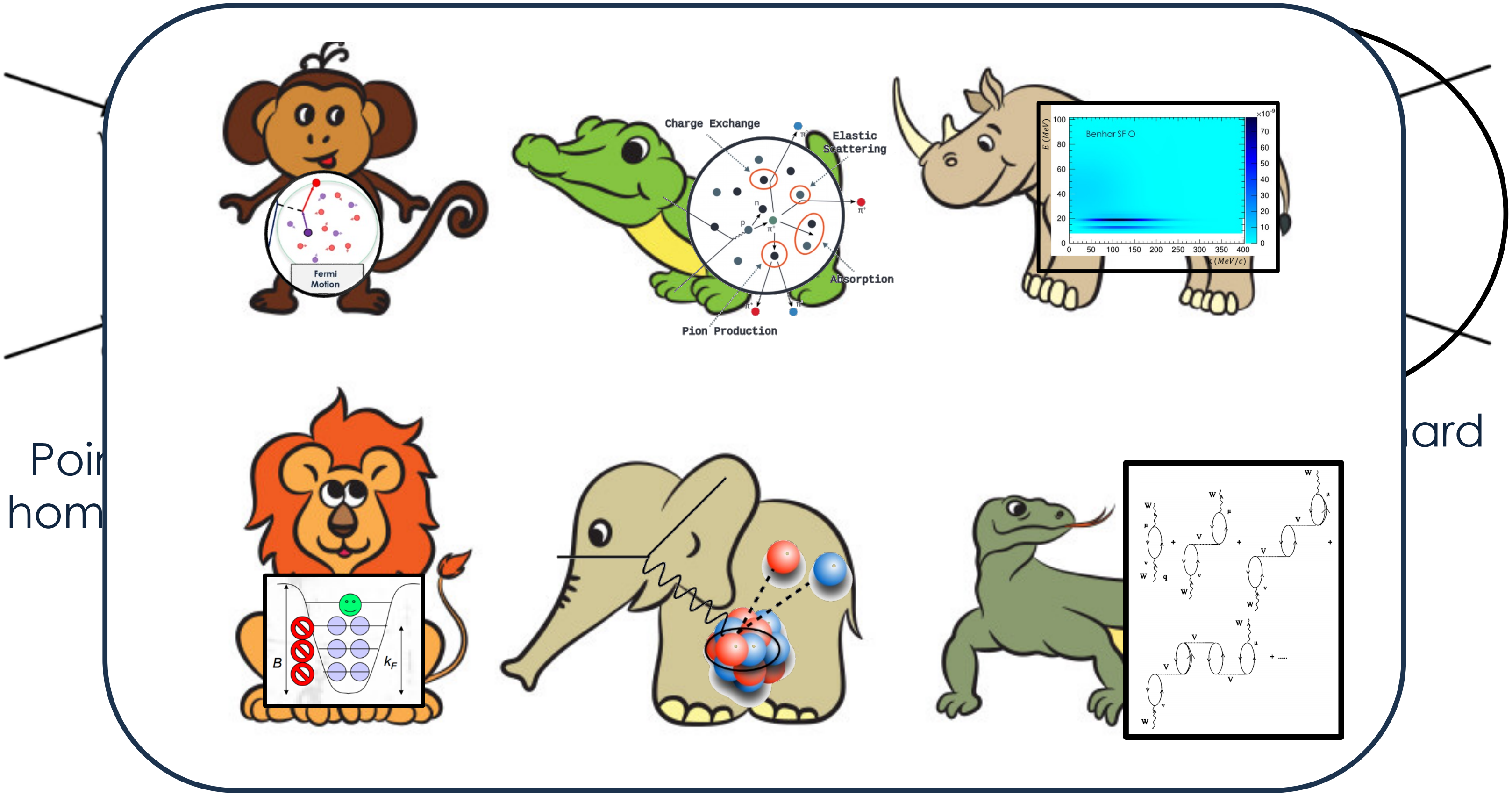
Nucleon: mostly harmless



Nucleus: very hard

- I leave most details to other talks (e.g. Noemi's and Kajetan's)
- Here we will just do a little bit of nuclear effect zoology to see what goes into our generators

Beyond nucleon scattering



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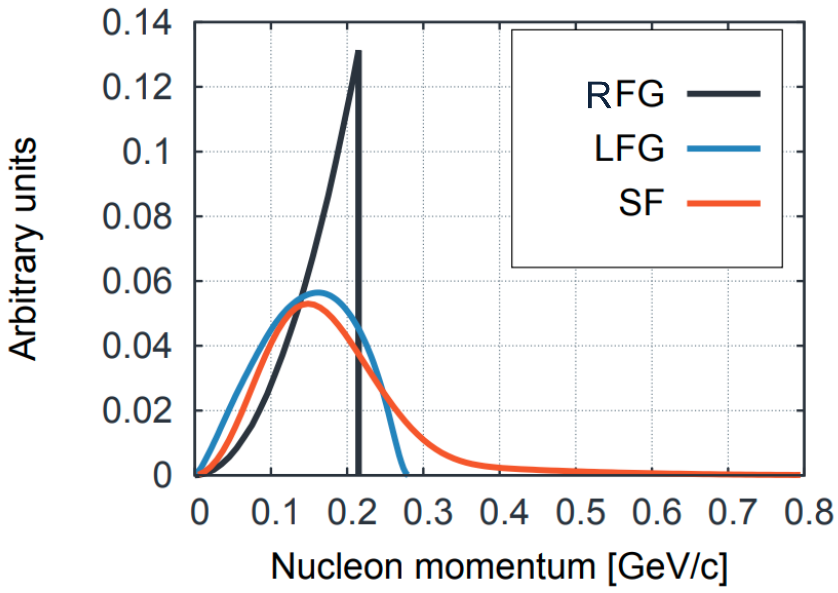
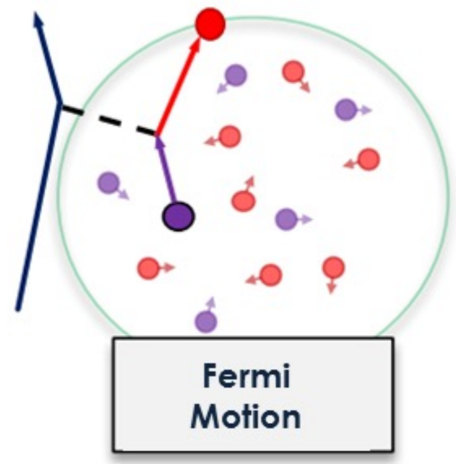
Nuclear effects in a nutshell

- **Fermi Motion**
  - Nucleons are moving targets
  - Their momenta are not so different than typical E_ν for our experiments …





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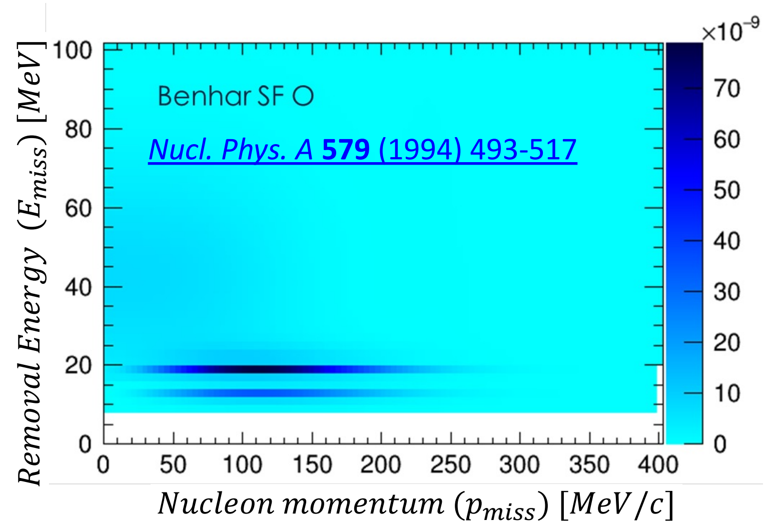
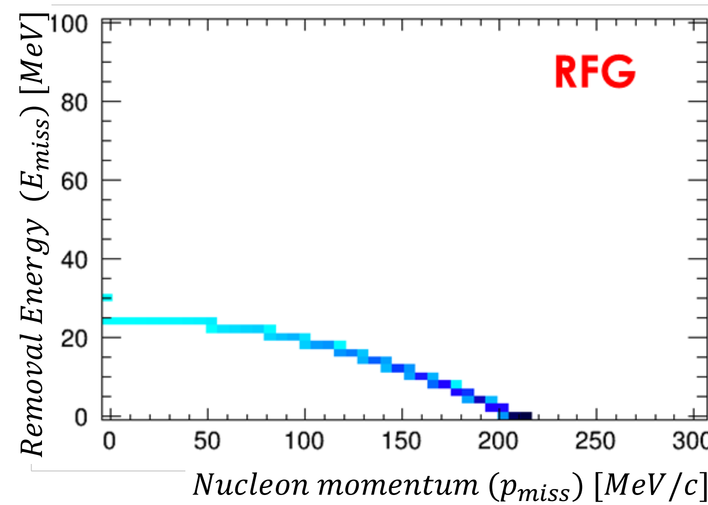
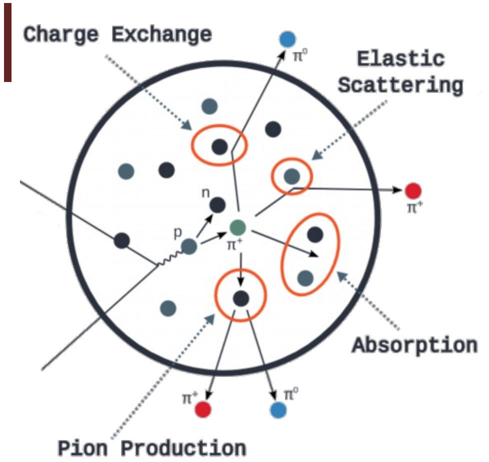
  - Some amount of energy is needed to free them
  - Most models predict that removal energy and Fermi motion should be correlated





Nuclear effects in a nutshell



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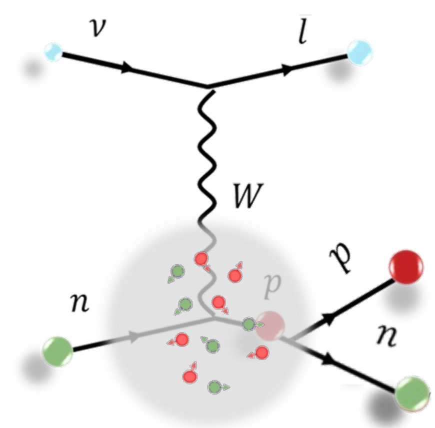
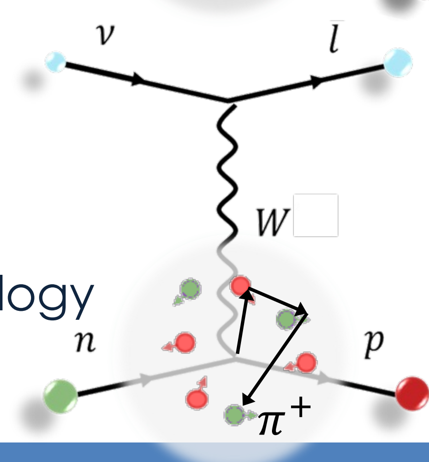


- **Final Stat Interactions (FSI)**
  - Hadrons don't exit the nucleus cleanly
  - They can re-interact inside the nucleus
  - Distorts kinematics and changes the final state topology
  - Full calculation also changes *inclusive* cross section



Nuclear effects in a nutshell

- **Multi-nucleon Interactions**
  - Nucleons are interacting with each other inside the nucleus
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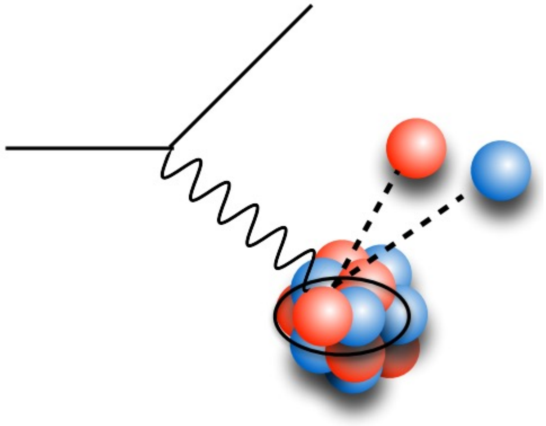
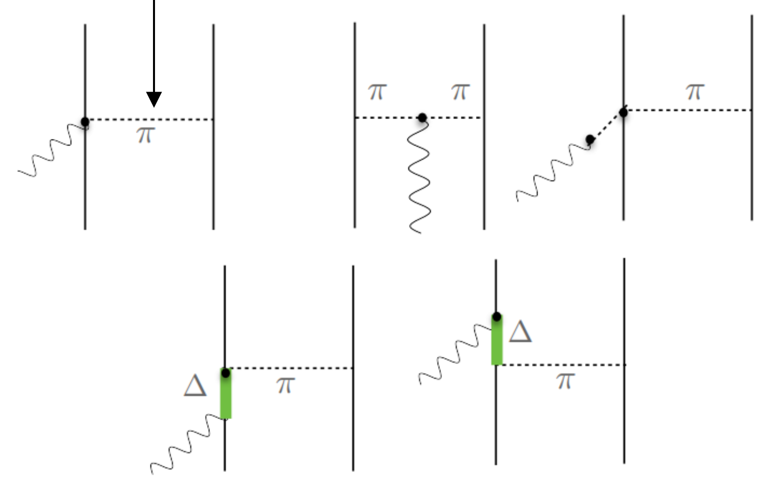
  - Multi-nucleon "2p2h" final states



"Meson-exchange currents" (MEC)



N. Rocco INSS 2019

Nuclear effects in a nutshell

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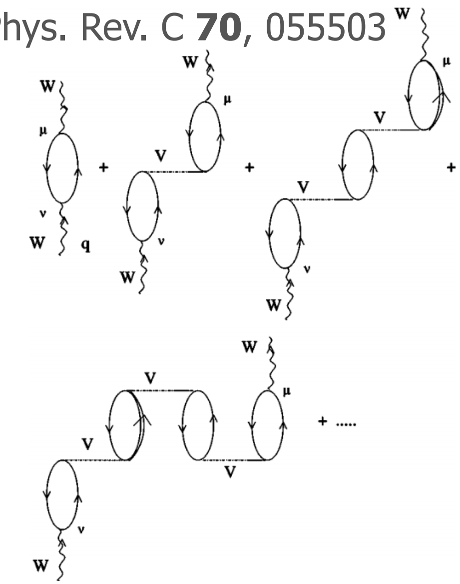
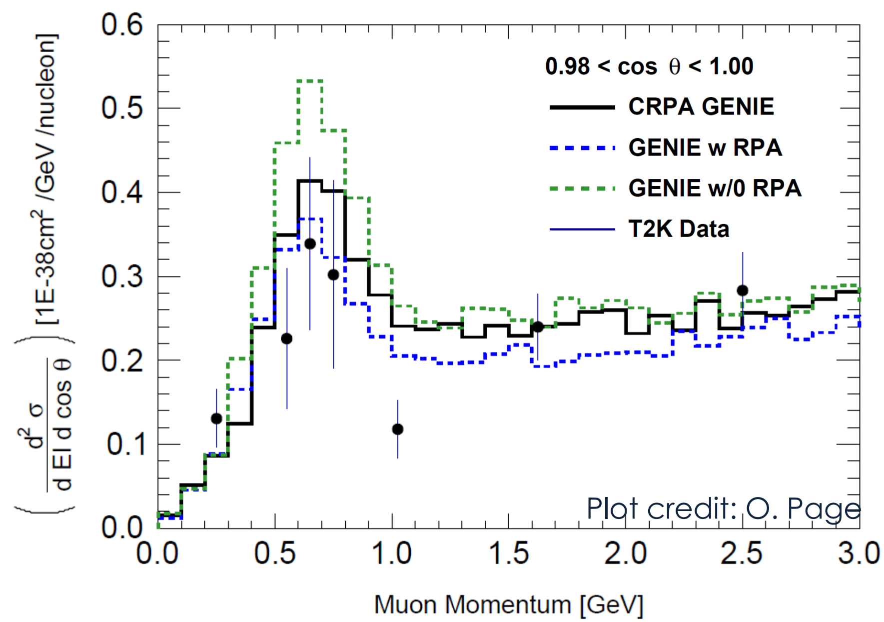
Phys. Rev. C **70**, 055503





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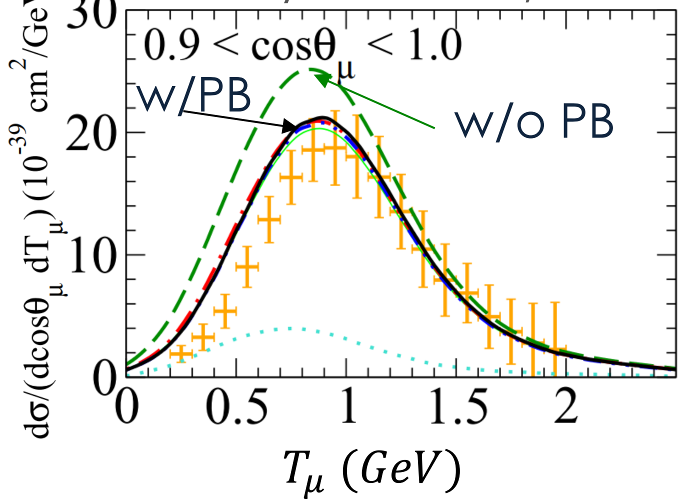
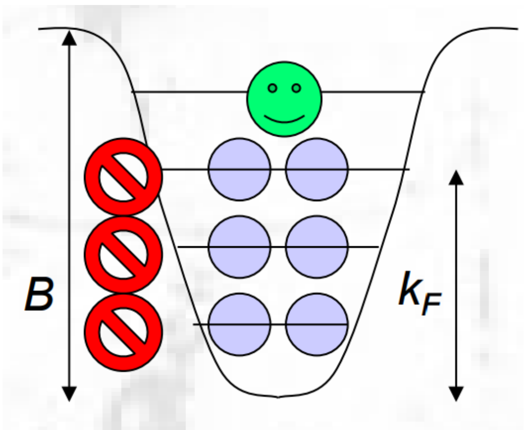
  - Difficult physics, usually parameterised and treated via "RPA" (random phase approximation)
- **Pauli Blocking**
  - Nucleons cannot be excited into nuclear states that are already filled
  - Reduction of cross section at low energy transfer

Phys. Rev. C **100**, 045501





Borrowed from K. McFarland's INSS 2014 lectures

Consequences of nuclear effects

- **Altered cross section**
  - Nuclear effects significantly alter the cross section with respect to the nucleon case

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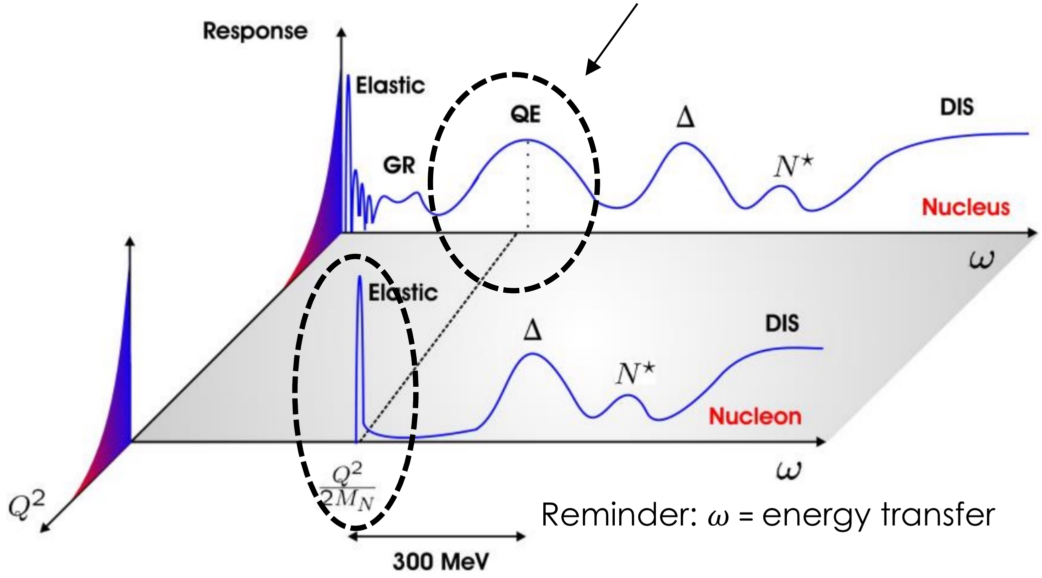
Fermi motion spreads the cross section, removal energy shifts it!



Reminder: ω = energy transfer

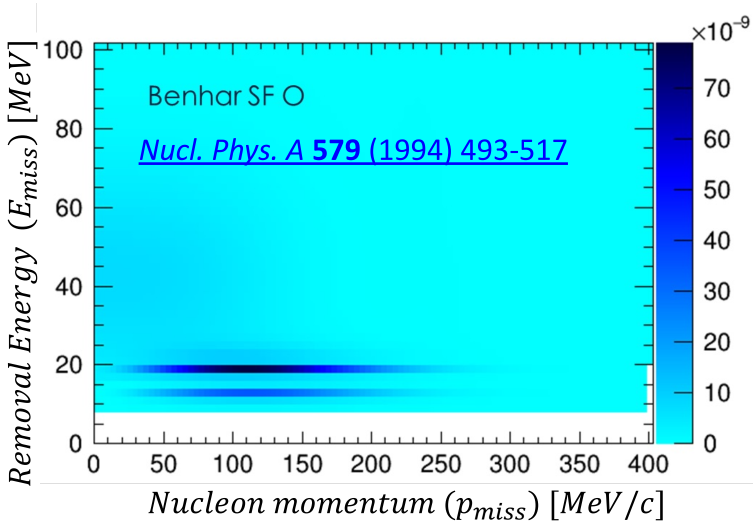


Fig. from N. Jachowicz

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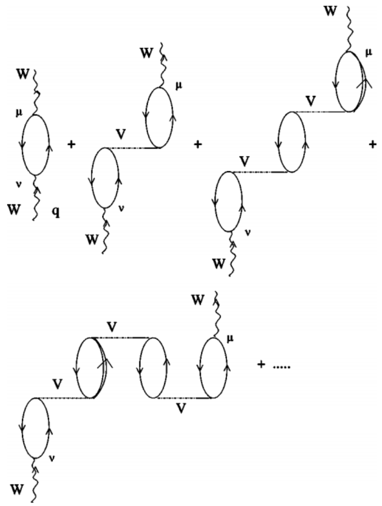
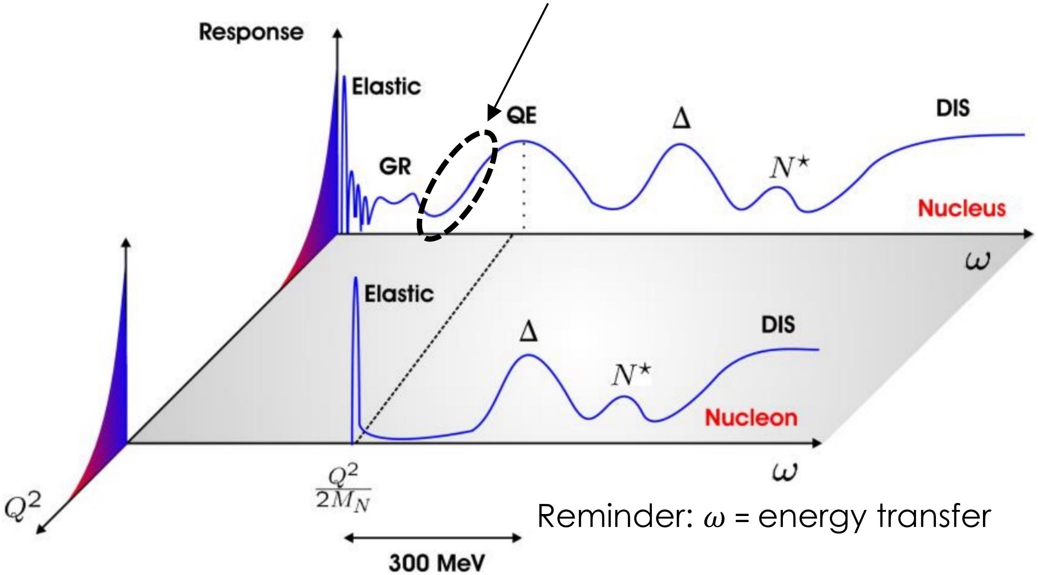
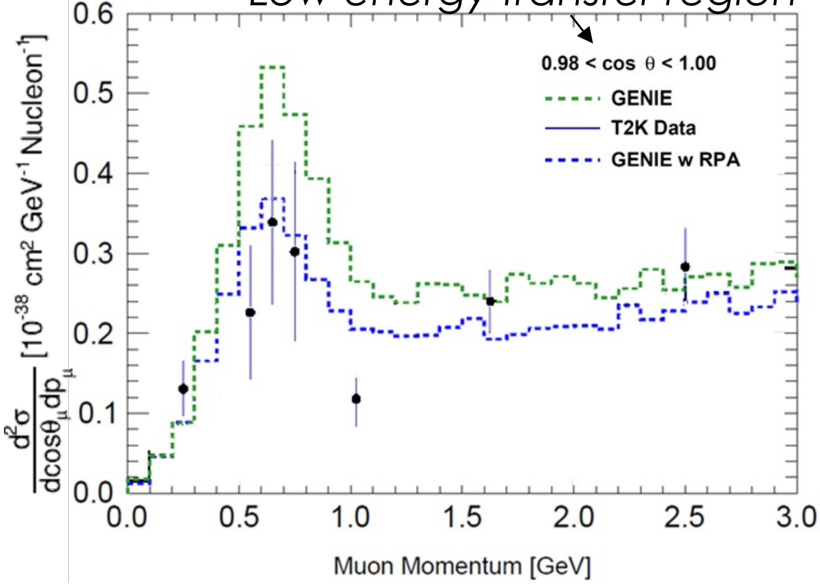


RPA and Pauli blocking further suppresses the cross section at low energy transfers



Reminder: ω = energy transfer

Low energy transfer region



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Consequences of nuclear effects

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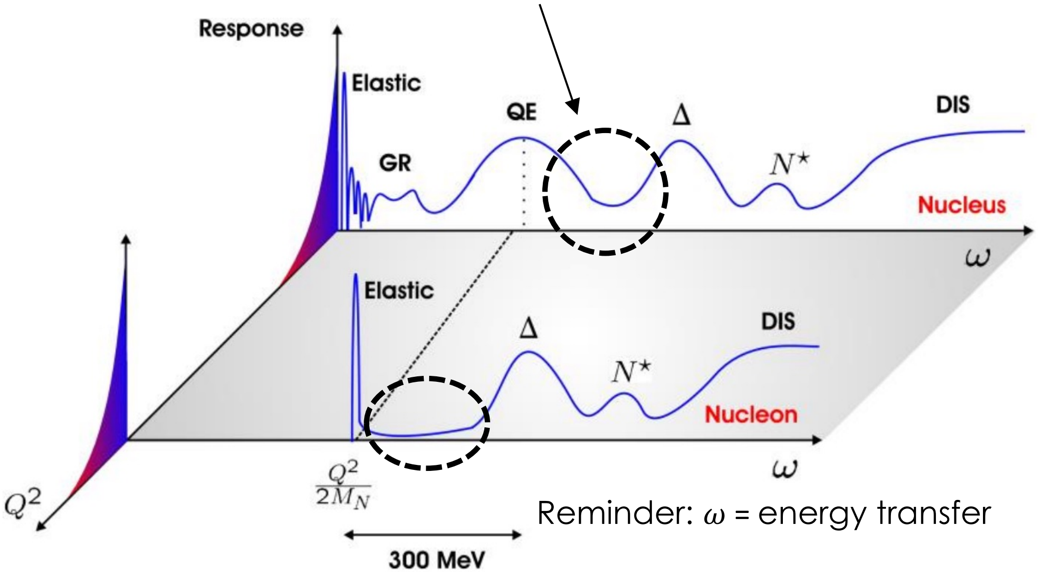
2p2h adds a contribution where there previously wasn't any "the dip region"



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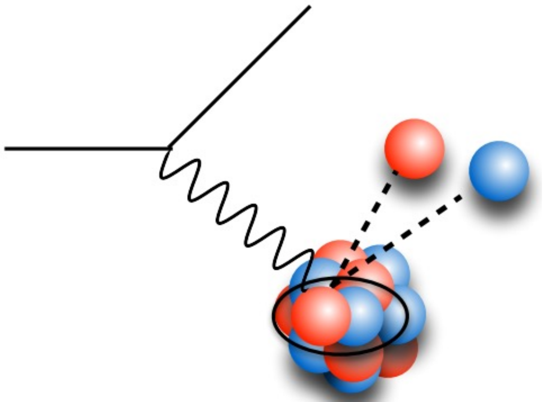

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Consequences of nuclear effects

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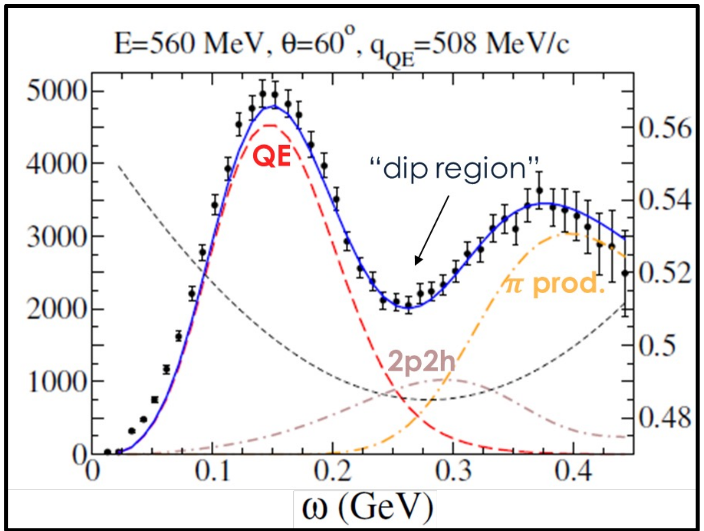
Electron scattering data



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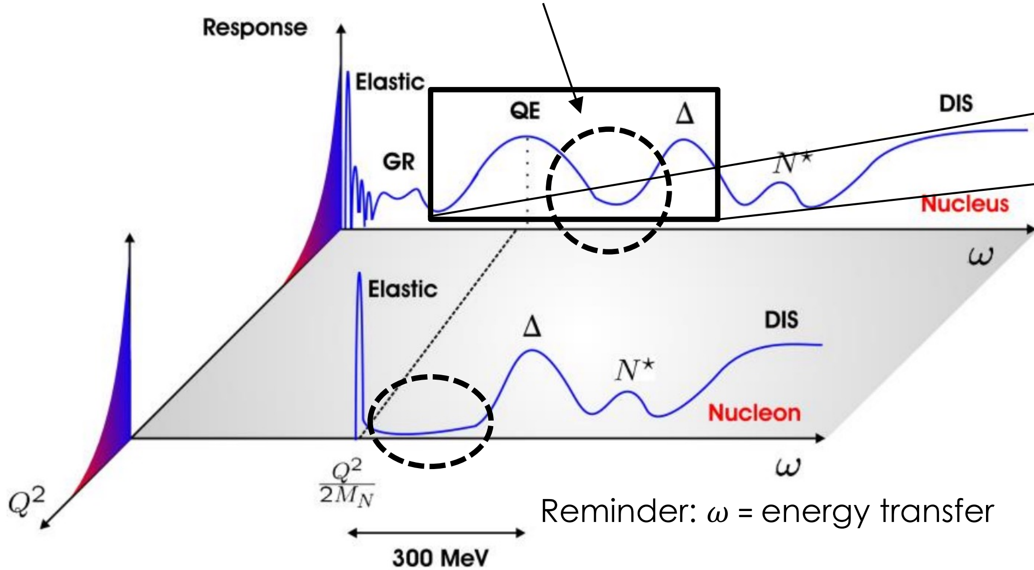

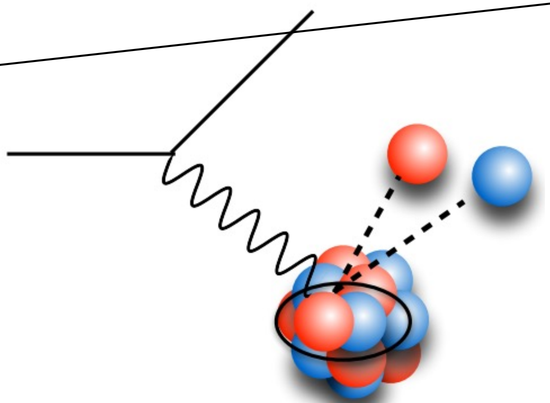

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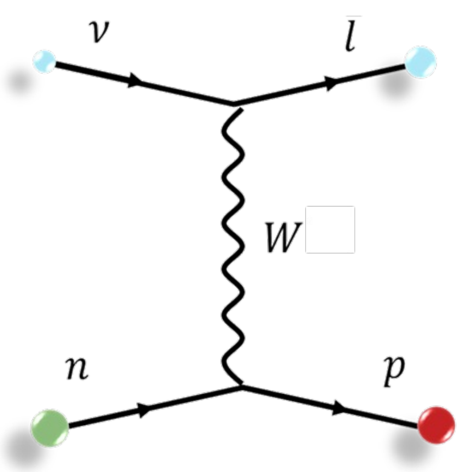
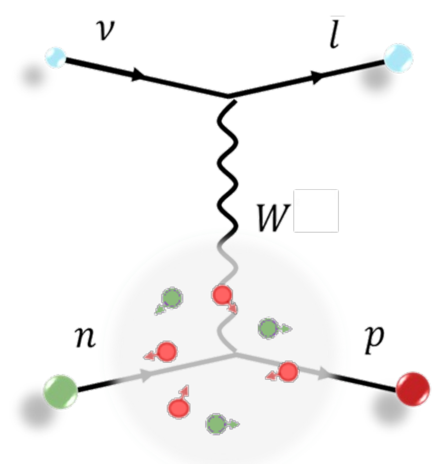
Consequences of nuclear effects

- **Altered cross section**
  - Nuclear effects significantly alter the cross section with respect to the nucleon case
- **Increased dimensionality**
  - Less constrained particle kinematics



$$\frac{d\sigma_{\nu\ell}}{\mathrm{dQ}^2}$$

CCQE on the nucleon is fully constrained with one kinematic variable

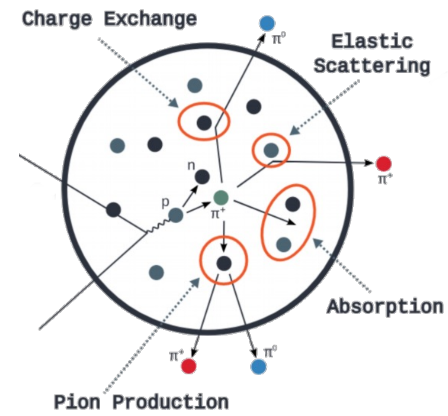


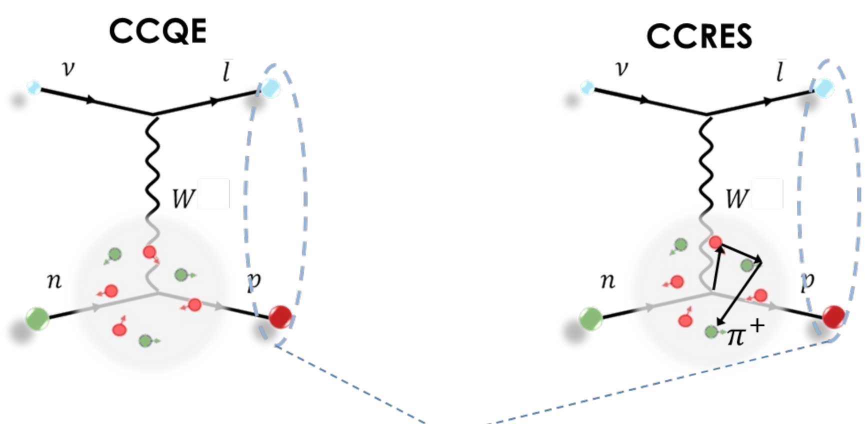
$$\frac{d^5\sigma_{\nu\ell}}{d\Omega\left(\hat{k}'\right)d\Omega(p_N)\mathrm{dE}_{\ell}'}$$

CCQE on the nucleus needs five!

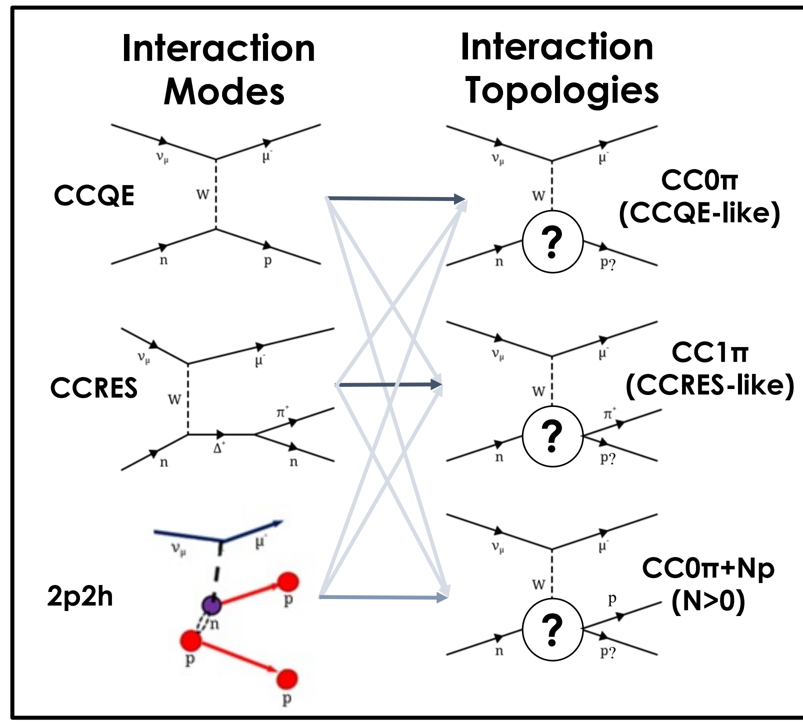
Consequences of nuclear effects

- **Altered cross section**
  - Nuclear effects significantly alter the cross section with respect to the nucleon case
- **Increased dimensionality**
  - Less constrained particle kinematics
- **Altered hadronic final state**
  - Final state interactions hide/distort the interaction channel



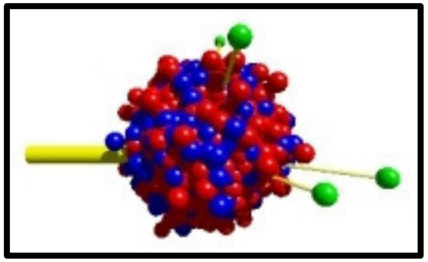


Final state interactions (FSI) can cause different interaction modes to have the same final state



Overview

- Inputs to Generators: Neutrino-nucleon interactions
  - QE, RES and DIS
- Inputs to Generators: Neutrino-nucleus interactions
  - Nuclear effects
- Neutrino event generators
  - Filling in gaps in our inputs
- Benchmarking generators with measurements
  - Inclusive successes and exclusive failures
- Why do we care?
  - Neutrino interactions for neutrino oscillations
- Don't Panic! The future of neutrino interaction simulations



Meet the generators

Experiments model all this using **neutrino interaction event generators**

NEUT **GENIE** **NuWro** **AChilLES** **GiBUU**

- Used by T2K, SK, Hyper-K
- Updated according to experiments needs

- Very widely used
- Large dev team separate from experiments

- Wide range of models available
- Driven by theory
- Few developers

Meet the generators

Experiments model all this using **neutrino interaction event generators**

NEUT | **GENIE** | **NuWro** | **AChilLES** | **GiBUU**

AChilLES:
- New generator from theorists
- Only QE for the moment, but with novel FSI
- e/nu-scattering equivalence built in from the ground-up

GiBUU:
- Full theory in its own right
- Predicts nu/e/hadron scattering in the same framework
- Very different philosophy to other generators
- Few developers

Meet the generators

Experiments model all this using **neutrino interaction event generators**

NEUT **GENIE** **NuWro** **AChilLES** **GiBUU**

- Most generators contain many possible model configurations
- "GENIE" or "NEUT" on a plot does not imply a particular one
- These configs sometimes have … creative naming schemes
  - E.g. GENIE's "G21_11c_02_11b" model
  - This page decodes some of them

Meet the generators

Experiments model all this using **neutrino interaction event generators**

NEUT **GENIE** **NuWro** **AChilLES** **GiBUU**

- To be used in **experimental analyses**, generators must be able to produce fully exclusive neutrino interactions. I.e.:
  - The full list of final state particles
  - The 4-momentum of each one
  - For all interaction channels

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GENIE

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  - The full list of final state particles
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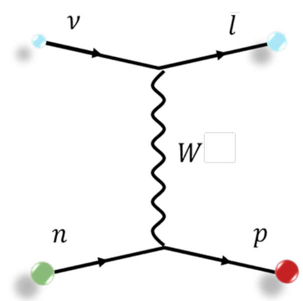
- The generators **take theory inputs where possible**, but ultimately *ad-hoc* approximations to "fill in the gaps" are needed

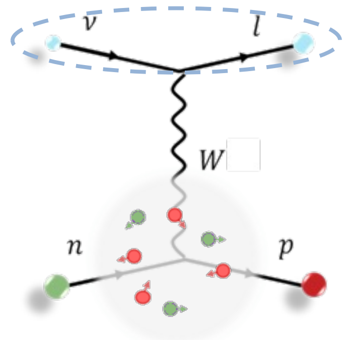
Theory inputs

Four broad types of theory inputs to event generators:

- **Nucleon-level calculation only**

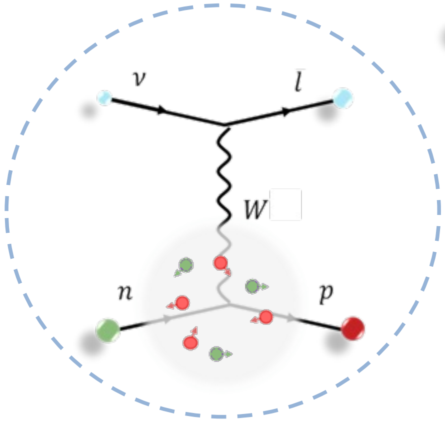


- **Inclusive calculations**



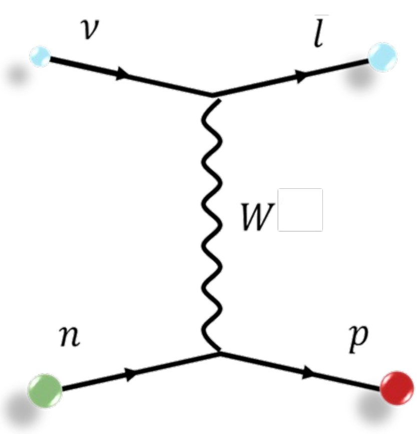
- **Factorized calculations**

- **Exclusive calculations**



Neutrino-nucleon calculations

The most basic inputs are only neutrino-nucleon calculations: no nuclear effects



$$\frac{d\sigma}{d|q^2|}\begin{pmatrix}\nu n \to \ell^- p \\ \bar{\nu} p \to \ell^+ n\end{pmatrix} = \frac{M^2 G^2 \cos^2\theta_c}{8\pi E_\nu^2}\left[A(q^2) \mp B(q^2)\frac{(s-u)}{M^2} + \frac{C(q^2)(s-u)^2}{M^4}\right]$$

$$(s-u = 4ME_\nu + q^2 - m^2)\,.$$

Generators are forced to "dress" the interaction with nuclear effects themselves

Luke's python generator does exactly this!

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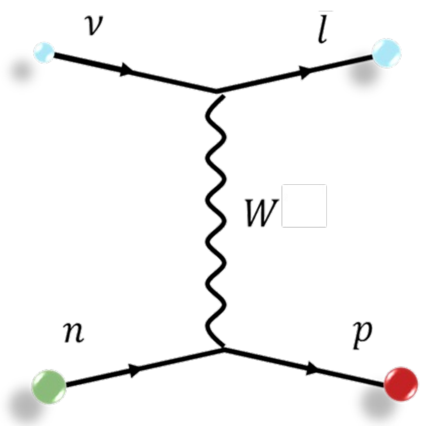

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Luke's python generator does exactly this!

This is often still the level of input we work with

E.g.:

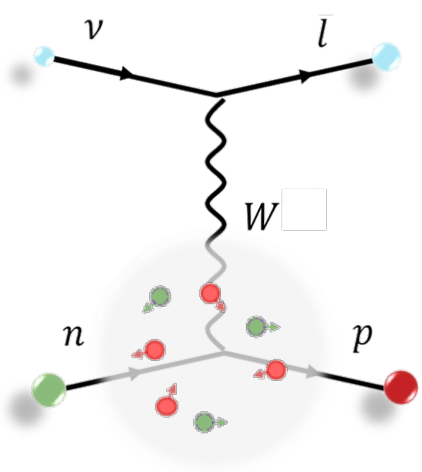
- CCQE GENIEv2 or NEUT's "Smith-Moniz" Fermi gas model
- All RES interactions in GENIE or NEUT

Inclusive calculations

Inclusive calculations come "pre-integrated" over hadron kinematics

All of the nuclear dynamics lives in here

$$\frac{d^2\sigma_{\nu l}}{d\Omega(\hat{k}')dE'_l} = \frac{|\vec{k}'|}{|\vec{k}|}\frac{G^2}{4\pi^2}L_{\mu\sigma}W^{\mu\sigma}$$



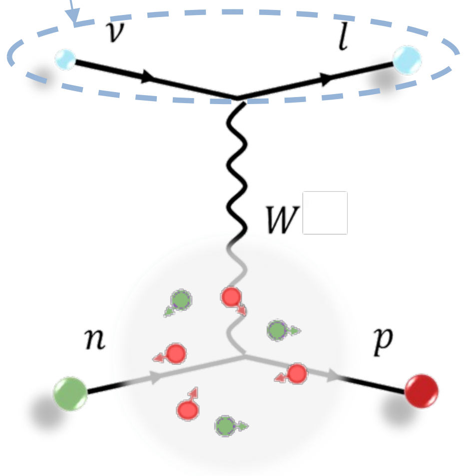
E.g. Inclusive quasielastic charged-current neutrino-nucleus reactions, J. Nieves et al, 2004

Nuclear effects are "baked in" to the model used for the integration

Inclusive calculations

Inclusive calculations come "pre-integrated" over hadron kinematics

Only predicts lepton kinematics!



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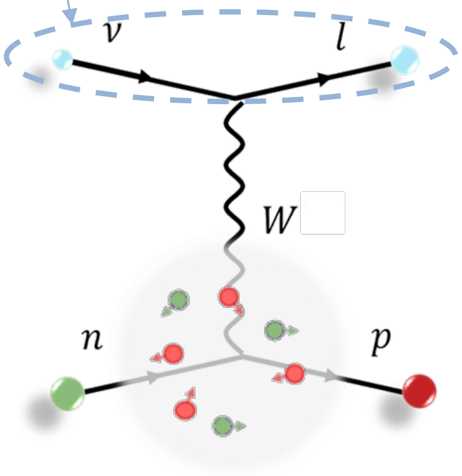


E.g. Inclusive quasielastic charged-current neutrino-nucleus reactions, J. Nieves et al, 2004

Nuclear effects are "baked in" to the model used for the integration

This is what we have for most 2p2h and some CCQE models

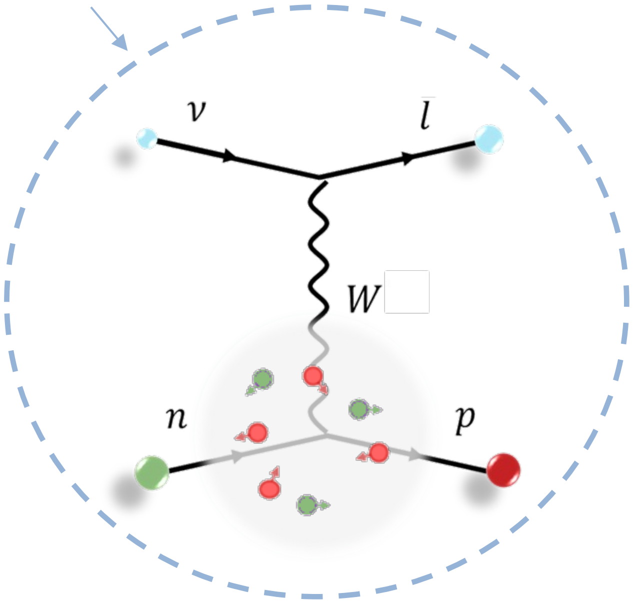
E.g.:

SuSA or Valencia 2p2h

SuSAv2 or CRPA in GENIE v3

Exclusive calculations

Exclusive model: can describe all final state particle kinematics



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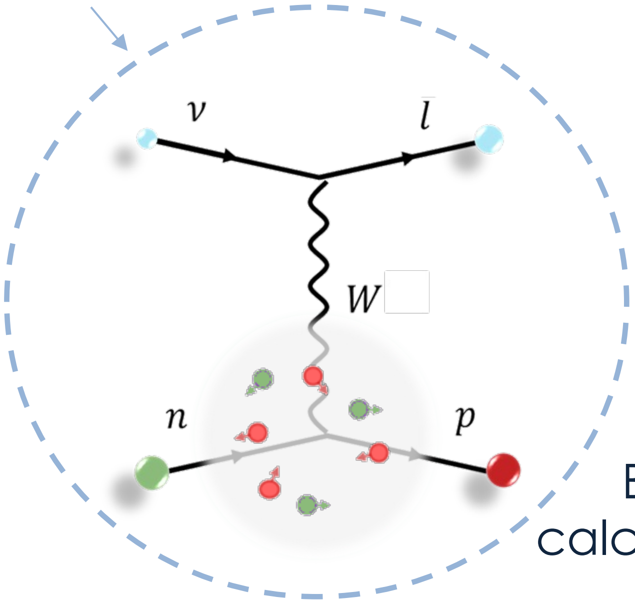

All of the nuclear dynamics still lives in here

$$\frac{d^5\sigma_{\nu\ell}}{d\Omega(\hat{k}')d\Omega(p_N)\mathrm{dE}_{\ell'}} \sim L_{\mu\sigma}W^{\mu\sigma}$$

E.g. Semi-inclusive charged-current neutrino-nucleus reactions, O. Moreno et al, 2014

Some theory models can do this, e.g. Relativistic Mean Field (RMF)

But now this is much more challenging to calculate and to implement in event generators

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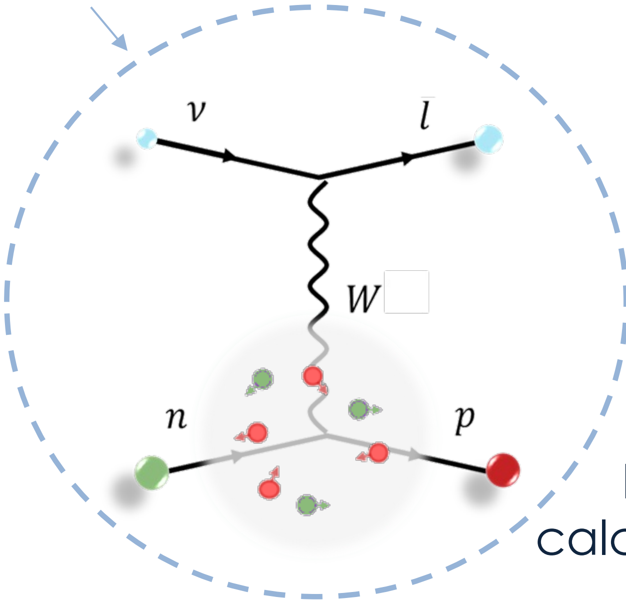

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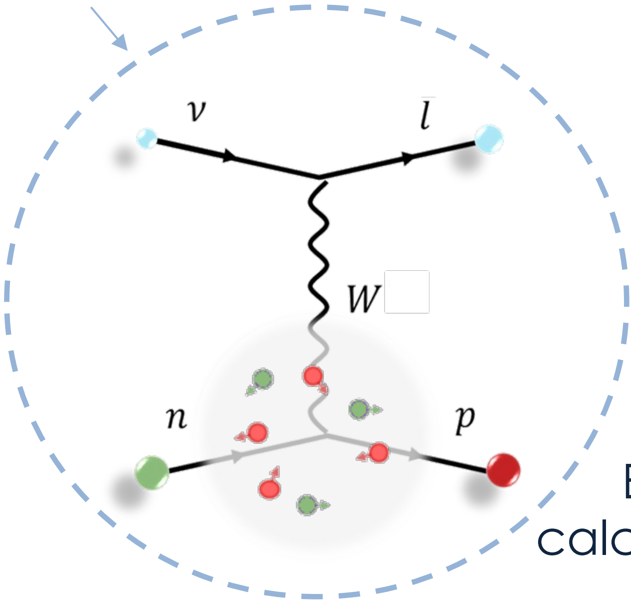
No generator does this …

Exclusive calculations

Exclusive model: can describe all final state particle kinematics



All of the nuclear dynamics still lives in here

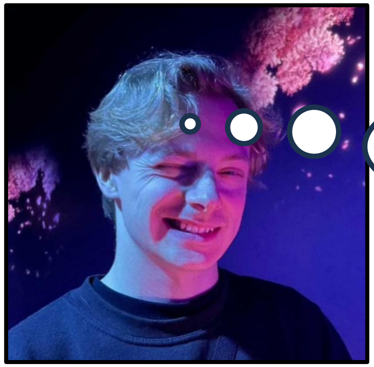
$$\frac{d^5\sigma_{\nu\ell}}{d\Omega(\hat{k}')d\Omega(p_N)\mathrm{dE}_{\ell'}} \sim L_{\mu\sigma} W^{\mu\sigma}$$

E.g. Semi-inclusive charged-current neutrino-nucleus reactions, O. Moreno et al, 2014

Some theory models can do this, e.g. Relativistic Mean Field (RMF)

But now this is much more challenging to calculate and to implement in event generators

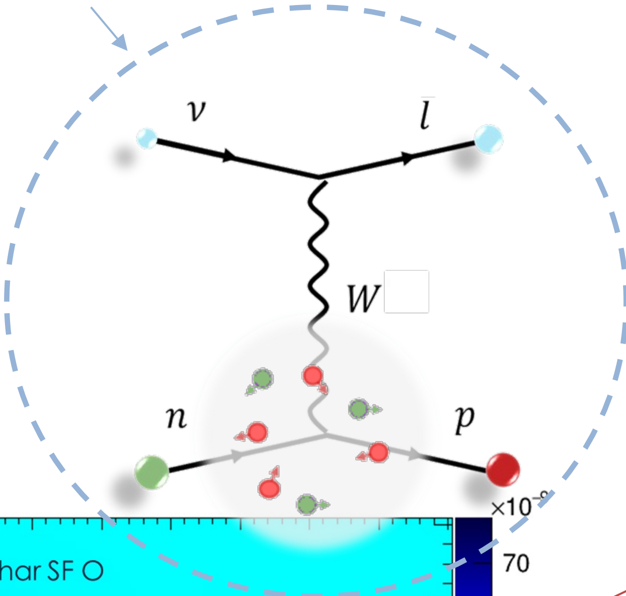
No generator does this …

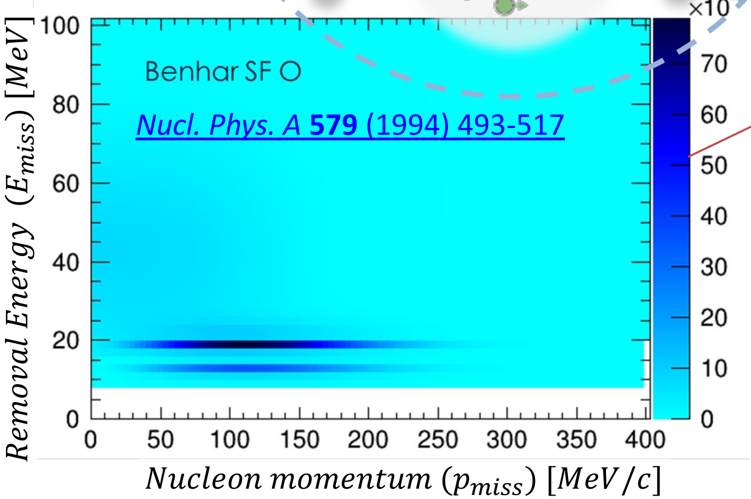


You might want to take a look at my NEUT branch

Factorized Calculations

Exclusive model: can describe all final state particle kinematics





Plane Wave Impulse Approximation (PWIA)

If we assume an interaction with a **single**, non-relativistic nucleon and that there's **no FSI or RPA correlations** we can write the cross section like this:

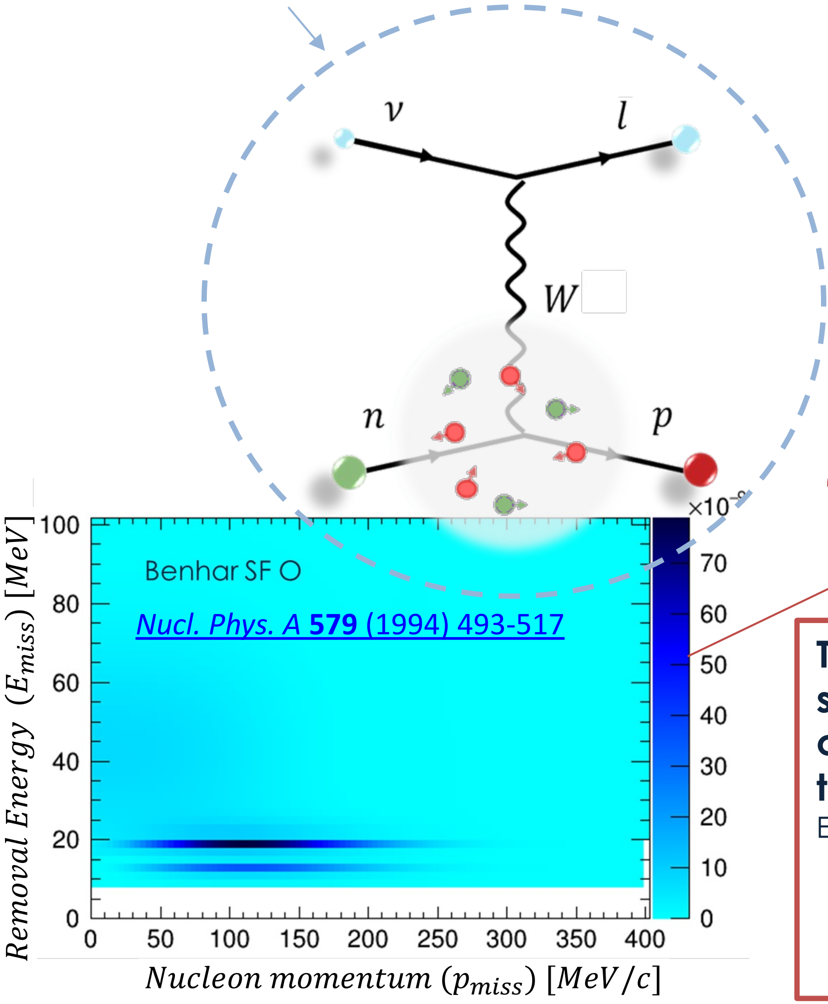
$$\frac{d^5\sigma_{\nu\ell}}{d\Omega(\hat{k}')d\Omega(p_N)\mathrm{dE}_{\ell}'} \sim S(E_m, \boldsymbol{p}_m)\mathrm{L}_{\mu\nu}\mathrm{W}^{\mu\nu}\delta(\omega + M - E_m - E_{p'})$$

"Spectral Function"

Single nucleon tensor contraction
(no nuclear effects)

Factorized Calculations

Exclusive model: can describe all final state particle kinematics



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"Spectral Function"

Single nucleon tensor contraction
(no nuclear effects)

This is what some newer generators use for CCQE – some predictive power for nucleon kinematics. An FSI cascade is added on top *ad hoc* but this only affects the nucleon.

E.g.:
- SF in NEUT
- SF in NuWro
- Starting point in Achilles
- Fermi-gas QE in GENIE v3

What can I calculate?

- Summarising what the theory inputs give us:

Theory input	What kinematics can I calculate?
Nucleon-level calculation	Lepton and nucleon before FSI
Inclusive calculation	Lepton only
Factorized calculation	Lepton and nucleon before FSI
Exclusive calculation	Lepton and nucleon

* Possible to include in an ad-hoc way, but doesn't reliably allow for a calculation for alteration of outgoing nucleon kinematics

See e.g.: Phys. Rev. D **91**, 033005

What can I calculate?

- Summarising what the theory inputs give us:

Theory input	What kinematics can I calculate?	How accurate is the calculation?
Nucleon-level calculation	Lepton and nucleon before FSI	Do not trust!
Inclusive calculation	Lepton only	As accurate as the underlying theory
Factorized calculation	Lepton and nucleon before FSI	Approximations can limit predications
Exclusive calculation	Lepton and nucleon	As accurate as the underlying theory

* Possible to include in an ad-hoc way, but doesn't reliably allow for a calculation for alteration of outgoing nucleon kinematics

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What can I calculate?

- Summarising what the theory inputs give us:

Theory input	What kinematics can I calculate?	How accurate is the calculation?	FSI/RPA?
Nucleon-level calculation	Lepton and nucleon before FSI	Do not trust!	Not included
Inclusive calculation	Lepton only	As accurate as the underlying theory	Can be included
Factorized calculation	Lepton and nucleon before FSI	Approximations can limit predications	Not without approximations*
Exclusive calculation	Lepton and nucleon	As accurate as the underlying theory	Can be included

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See e.g.: Phys. Rev. D **91**, 033005

What can I calculate?

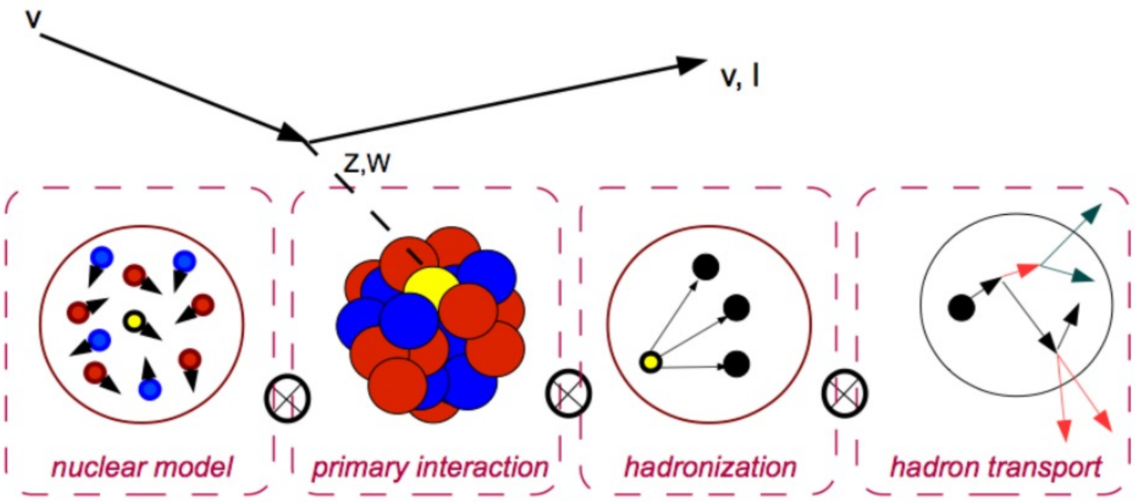
- Summarising what the theory inputs give us:

Theory input	What kinematics can I calculate?	How accurate is the calculation?	FSI/RPA?	Example use in generators
Nucleon-level calculation	Lepton and nucleon before FSI	Do not trust!	Not included	Most nonQE/2p2h + older QE calcs.
Inclusive calculation	Lepton only	As accurate as the underlying theory	Can be included	Most 2p2h, SuSAv2 / CRPA QE in GENIEv3
Factorized calculation	Lepton and nucleon before FSI	Approximations can limit predications	Not without approximations*	SFQE in NEUT, NuWro, AChilLES. Default QE in GENIEv3
Exclusive calculation	Lepton and nucleon	As accurate as the underlying theory	Can be included	Not yet widely available

* Possible to include in an ad-hoc way, but doesn't reliably allow for a calculation for alteration of outgoing nucleon kinematics

See e.g.: Phys. Rev. D **91**, 033005

Filling in the gaps



- Generators take theory inputs where possible, but we found these are often limited:
  - Only capable of predicting a subset of observables
  - Only valid within some range of kinematic phase space
  - Only valid for certain processes

- Need to “fill in the gaps” to get to a useable event simulation

Summary so far

- Weak Interactions with neutrinos
  - Point-like scattering is "easy" to calculate
  - Interactions with nucleons is more challenging due to their finite extent

- Neutrino-nucleon interactions
  - QE: almost calculable with some form factors
  - RES: much more difficult, lots of diagrams to consider
  - DIS: easy for *inclusive* high Q^2, hard at low Q^2, hadronic side a total guess

- Neutrino-nucleus interactions
  - Nuclear effects: there are lots of them, they **significantly change the cross section**
  - **Not all models can predict everything!**

Summary so far

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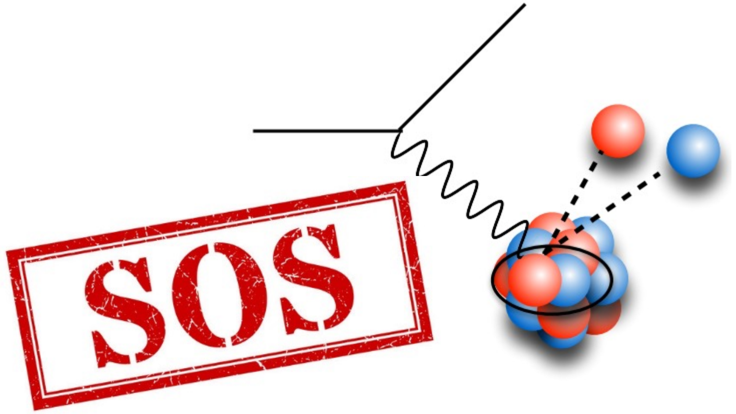
- Neutrino-nucleus interactions
  - Nuclear effects: there are lots of them, they significantly change the cross section
  - Not all models can predict everything!

- Neutrino event generators
  - Many generators on the market, each with different use cases
  - Take theory where possible, but **need to "fill the gaps"** for a complete calculation
  - **This limits generators predictive power**

Example: 2p2h

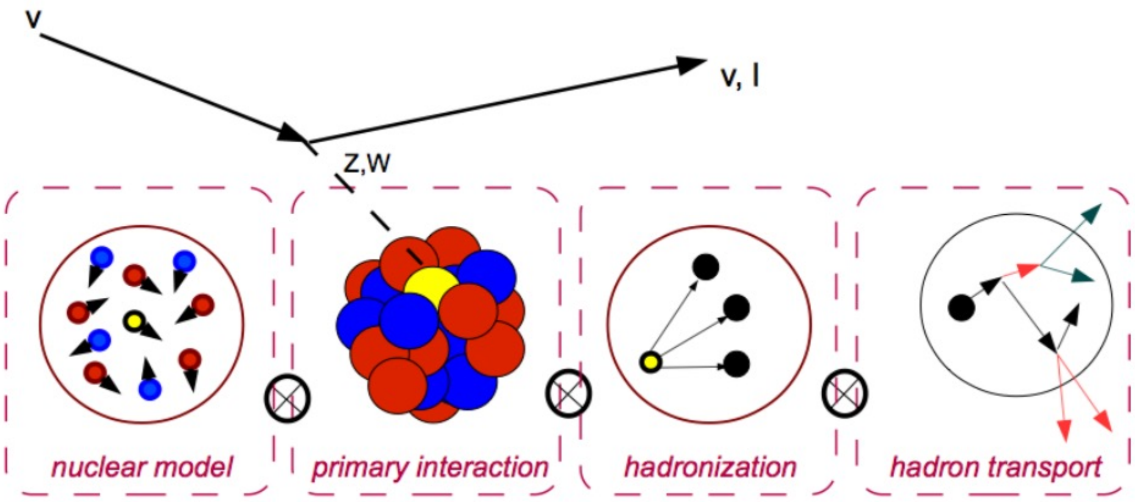


- Theory give us: $\frac{d^2\sigma}{dq_0 dq_3}$
(The "inclusive" cross section)

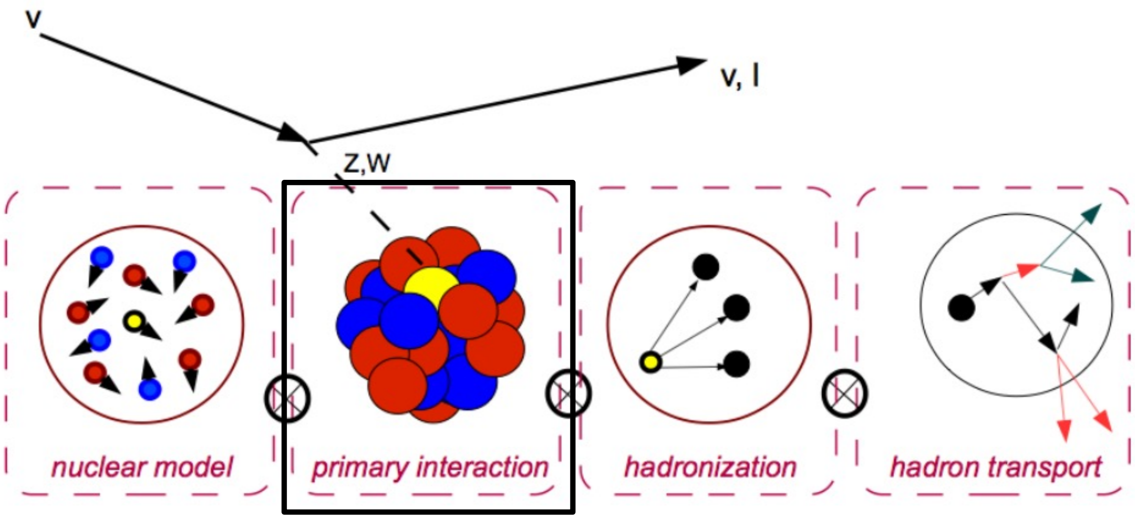
- Exclusive cross section: $\frac{d^8\sigma}{dq_0 dq_3 d\boldsymbol{p}_1 d\boldsymbol{p}_2}$
(what we actually need)

- How do we get there!?

A generator's view of an interaction



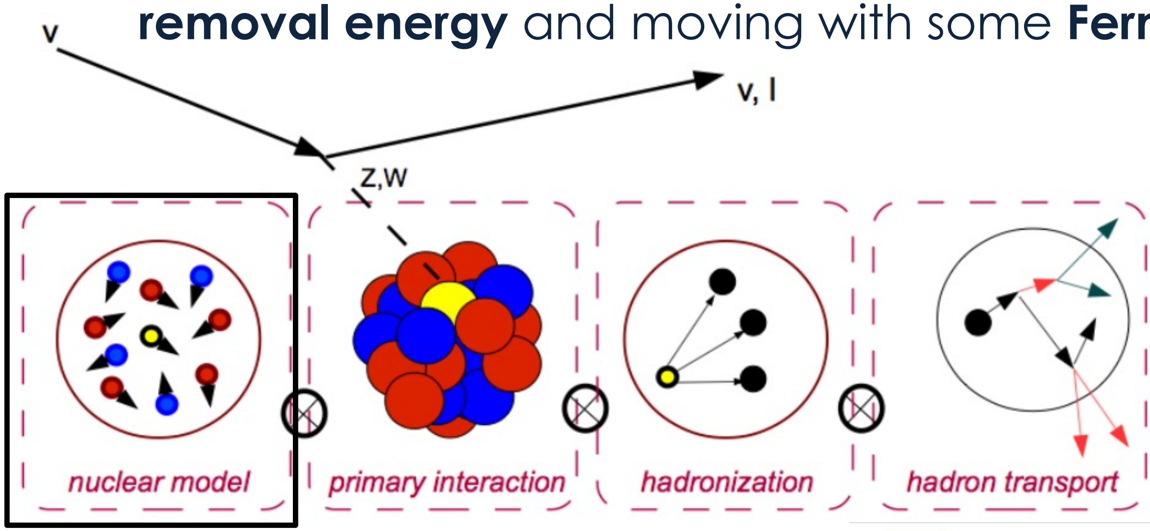
A generator's view of an interaction

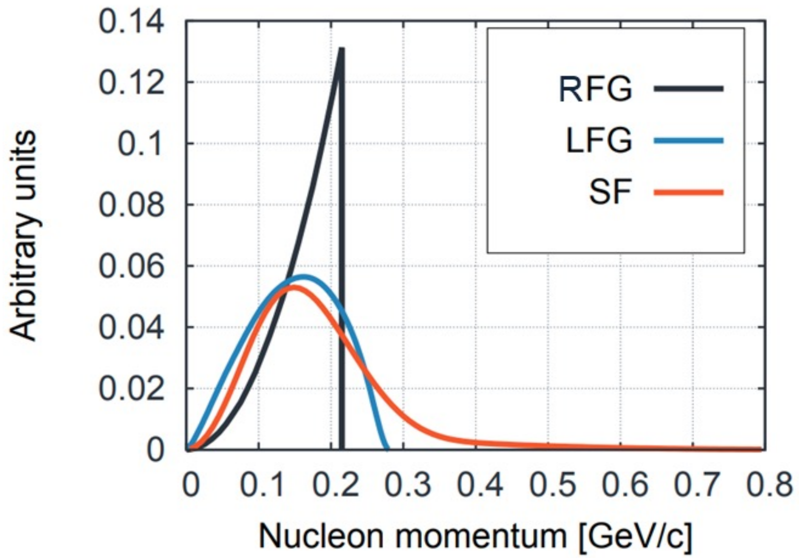


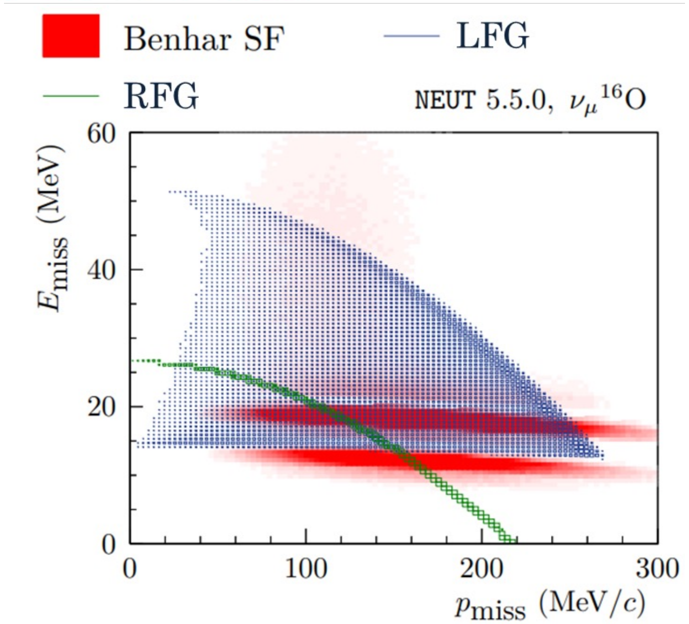
- Generators need to "dress" our primary interaction with extra physics

Fermi motion

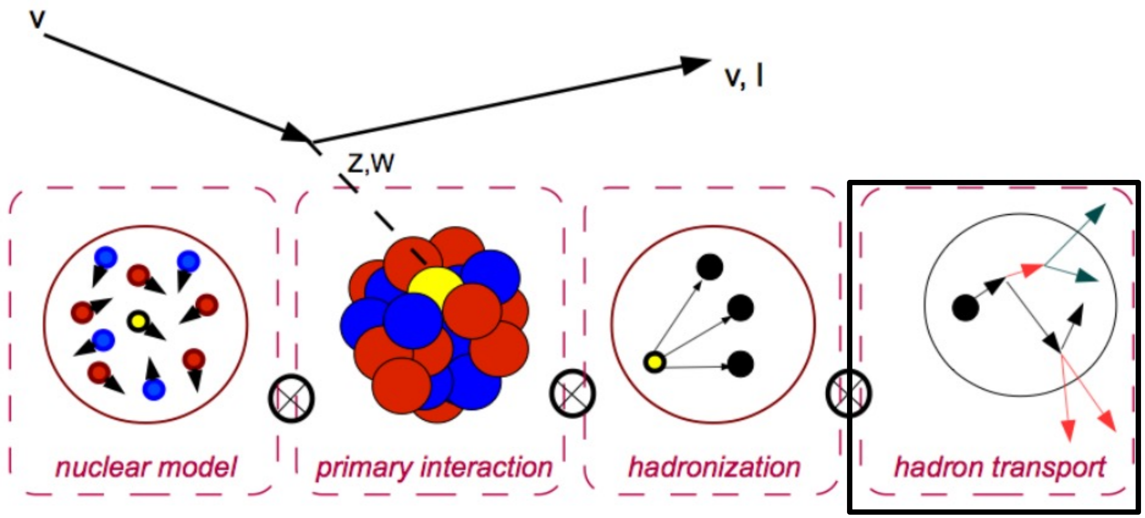
- Choose nucleon(s) inside the nucleus bound with some **removal energy** and moving with some **Fermi motion**



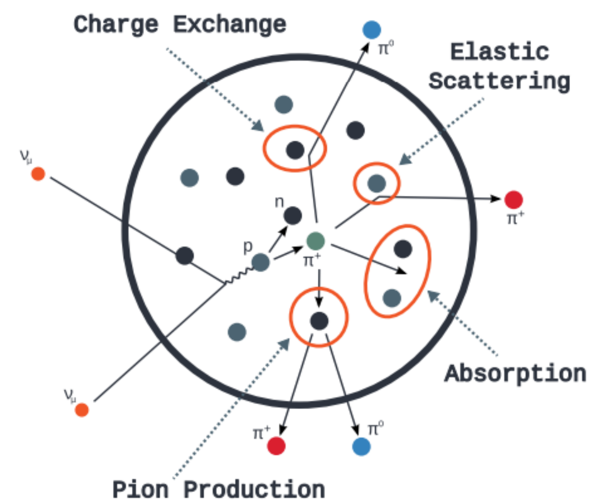




Final state interactions

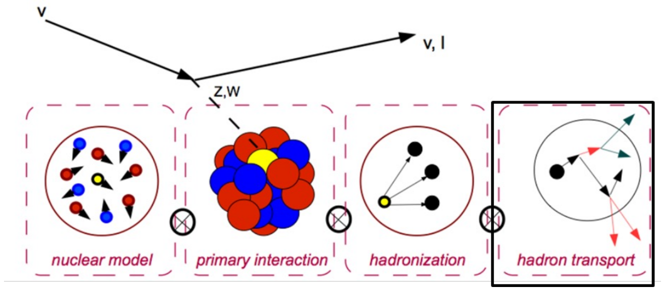


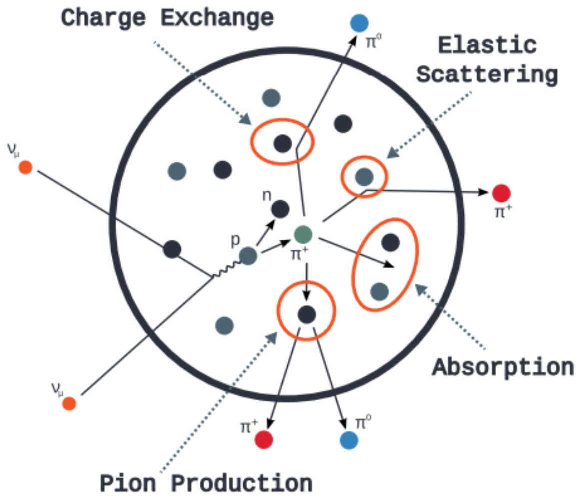
- We now have a nucleon inside the nucleus, but it still needs to gets out: **Final State Interactions**

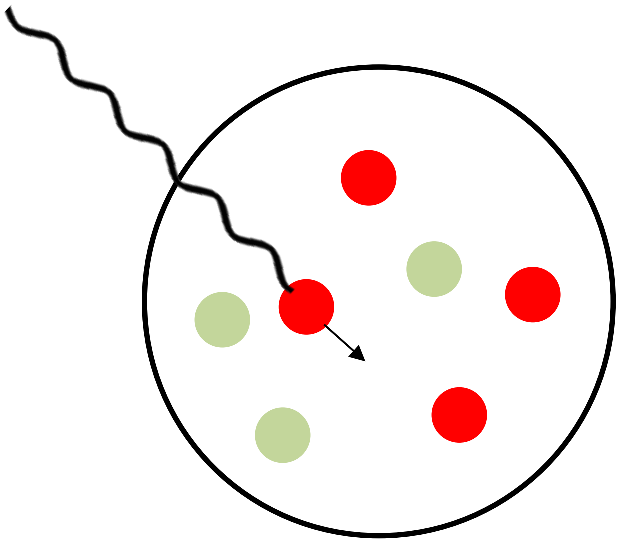


Final state interactions

- Intranuclear cascade models: classical billiard ball scattering within the nucleus







Final state interactions

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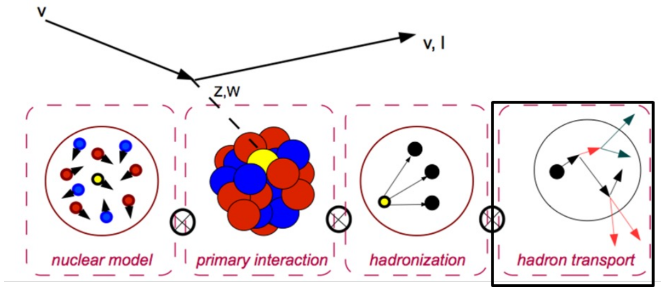
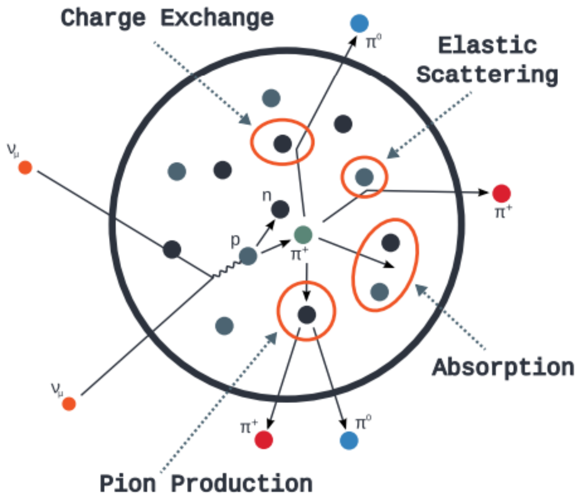
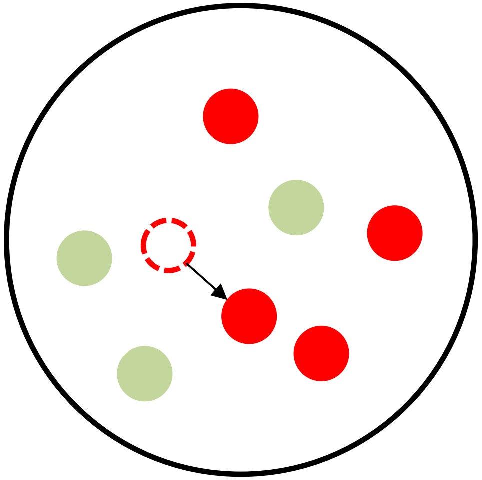


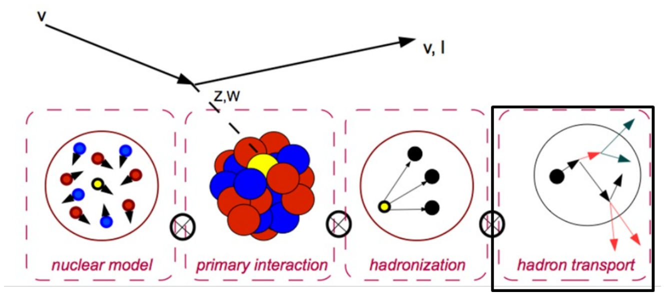


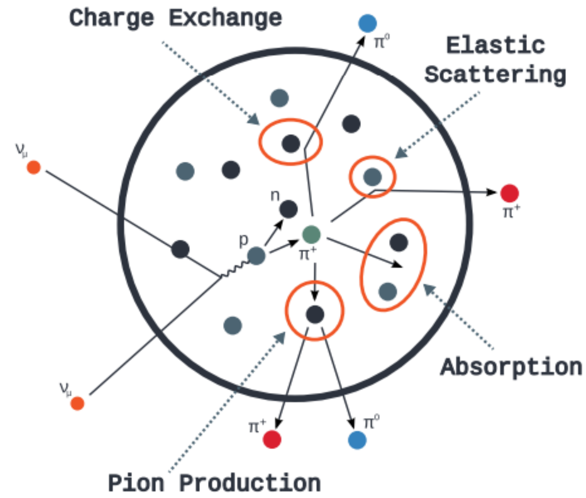
1. Step the particle through the nucleus a distance equal to its mean free path between interactions

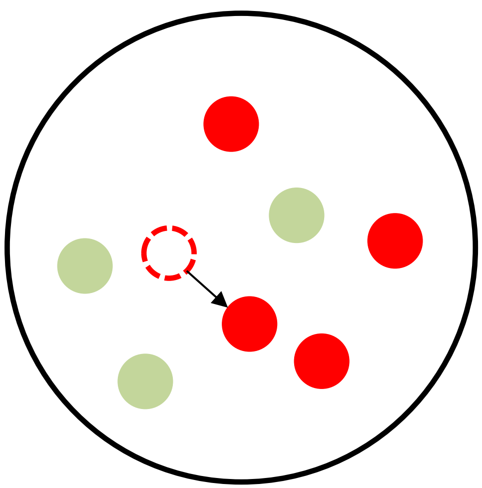


Final state interactions

- Intranuclear cascade models: classical billiard ball scattering within the nucleus





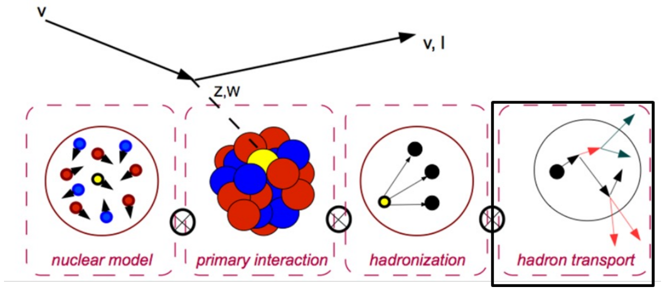


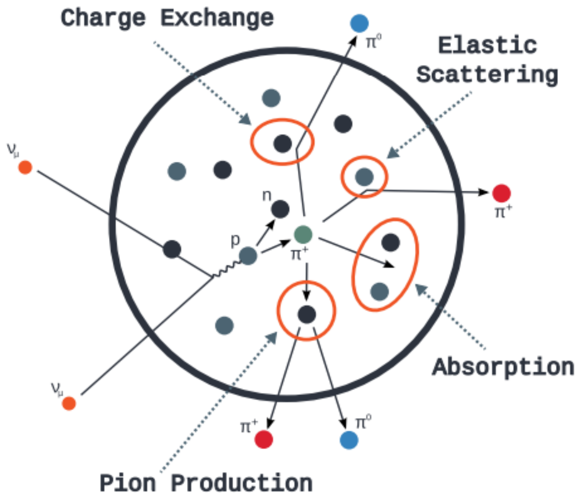
1. Step the particle through the nucleus a distance equal to its mean free path between interactions

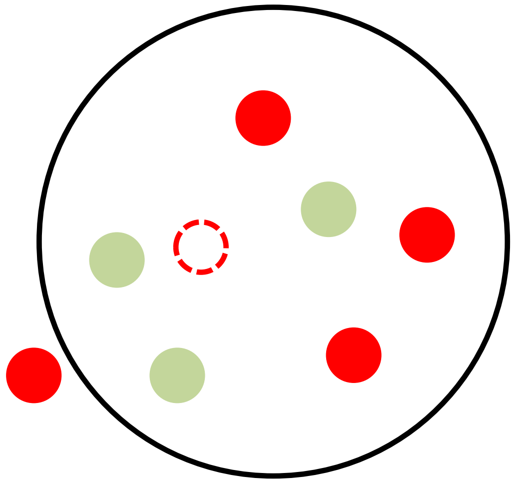
2. Check whether it's outside the nucleus, if it is add this particle to the final state and stop FSI for it

Final state interactions

- Intranuclear cascade models: classical billiard ball scattering within the nucleus







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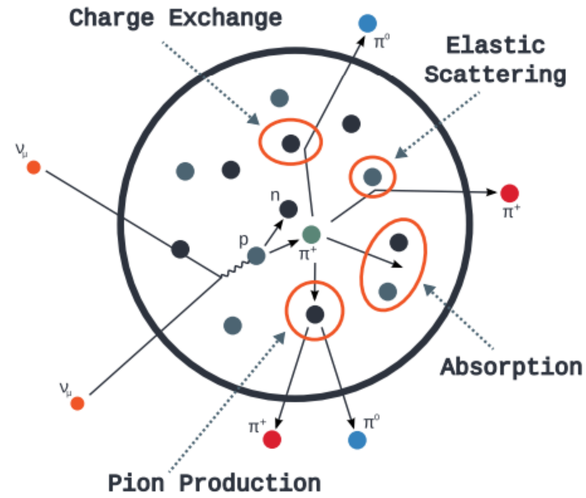
Final state interactions



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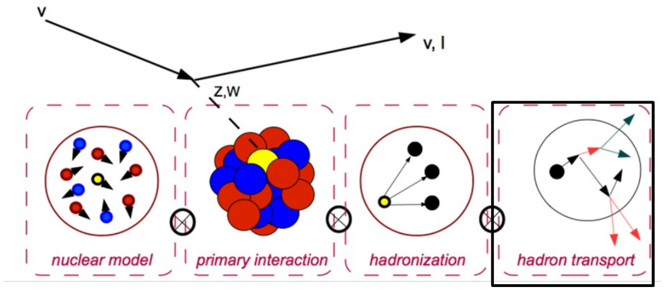

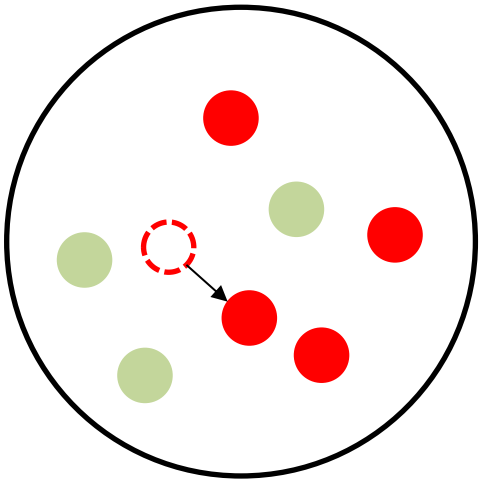

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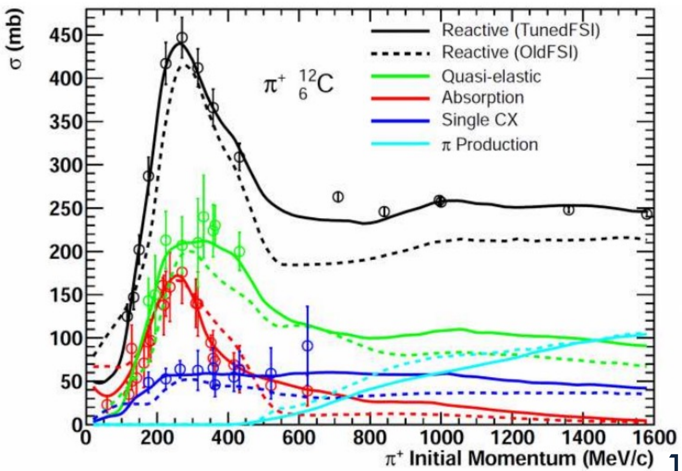
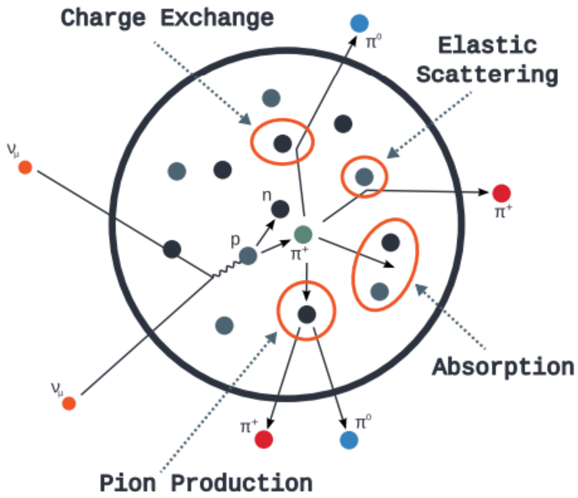
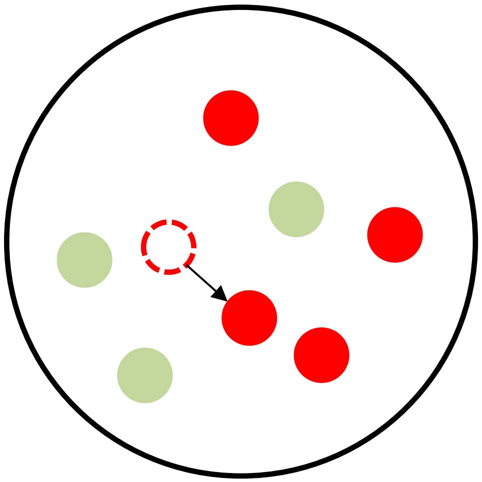
Final state interactions







1. Step the particle through the nucleus a distance equal to its mean free path between interactions

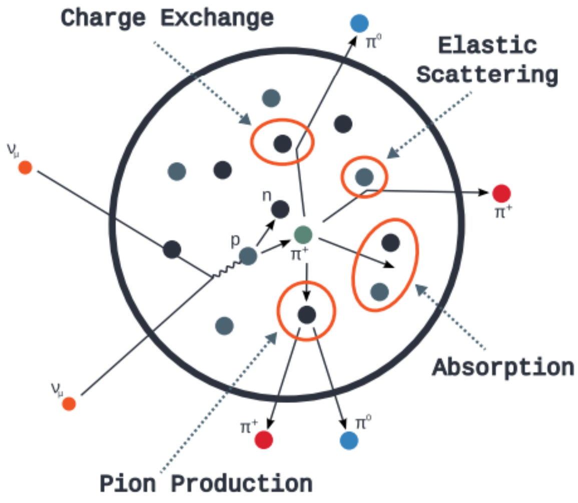
2. Check whether it's outside the nucleus, if it is add this particle to the final state and stop FSI for it

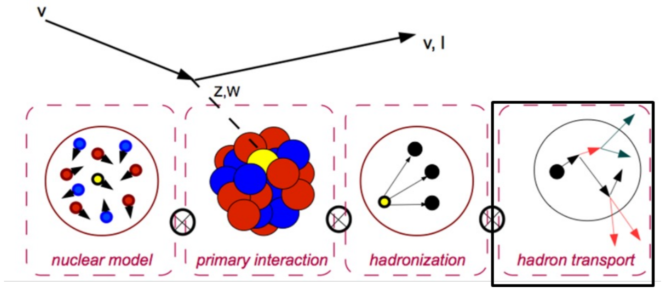
3. Use MC methods to determine if it interacts or not, if it does choose a process according to its cross section

See e.g.: Phys. Rev. D **99**, 052007

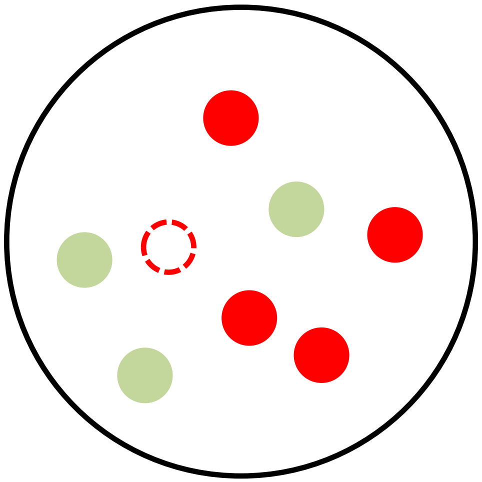
Final state interactions

- Intranuclear cascade models: classical billiard ball scattering within the nucleus





Absorption



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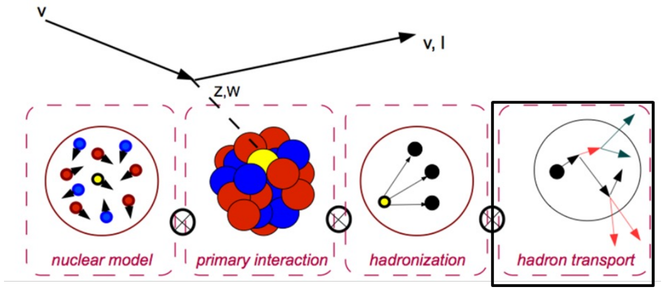
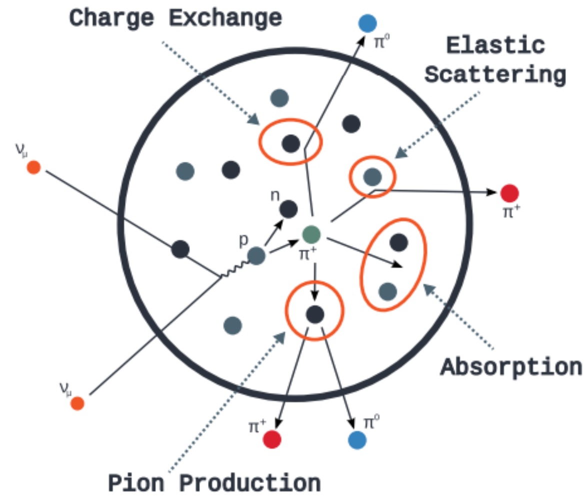
4. Generate the interaction

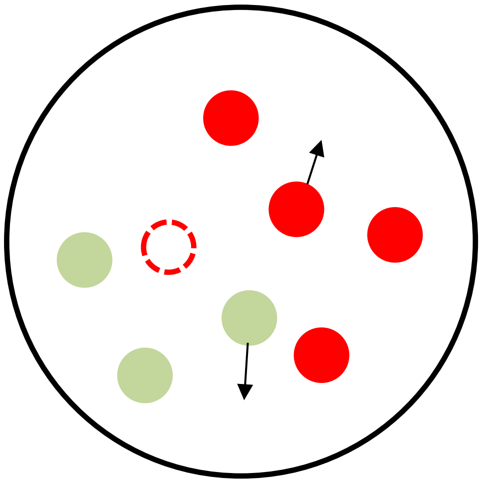
Final state interactions

- Intranuclear cascade models: classical billiard ball scattering within the nucleus





Charge Exchange



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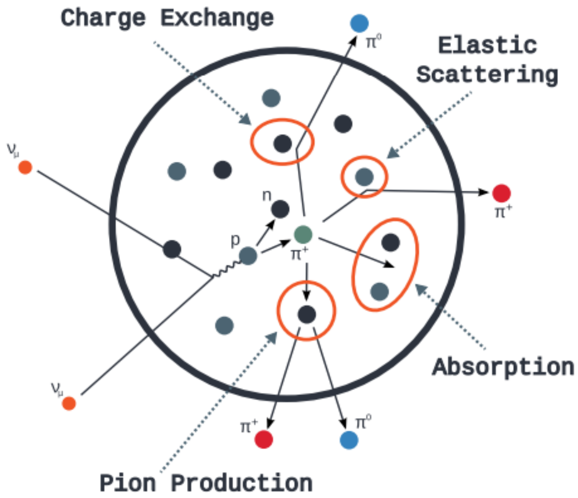
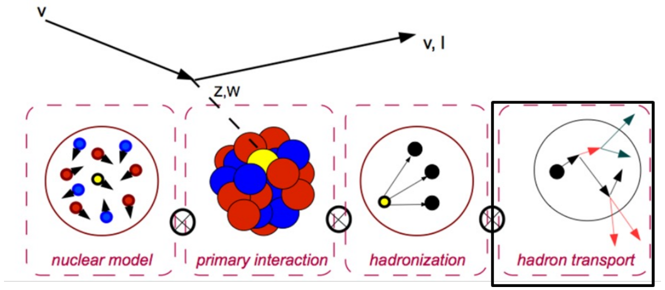
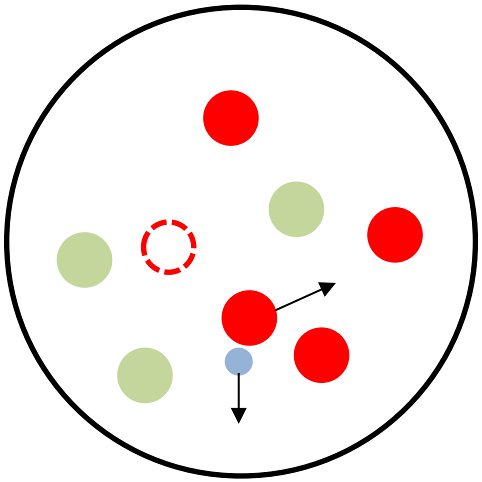
Final state interactions



- Intranuclear cascade models: classical billiard ball scattering within the nucleus



Pion Production



1. Step the particle through the nucleus a distance equal to its mean free path between interactions

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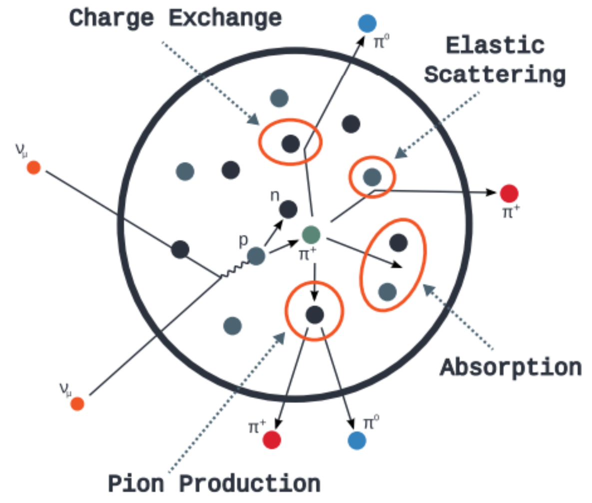
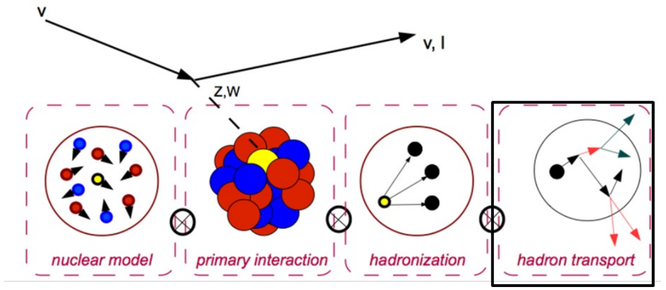
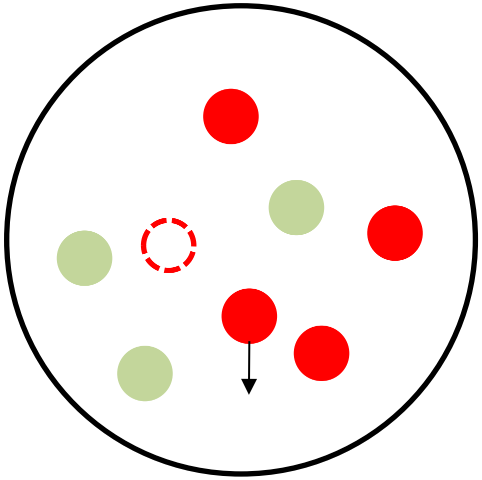
Final state interactions



- Intranuclear cascade models: classical billiard ball scattering within the nucleus



Elastic scatter



1. Step the particle through the nucleus a distance equal to its mean free path between interactions

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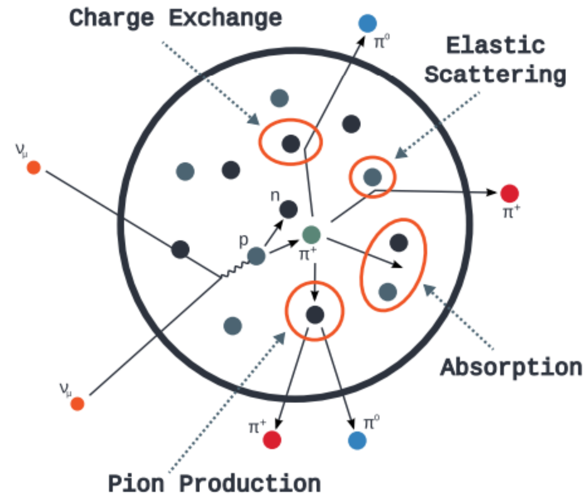
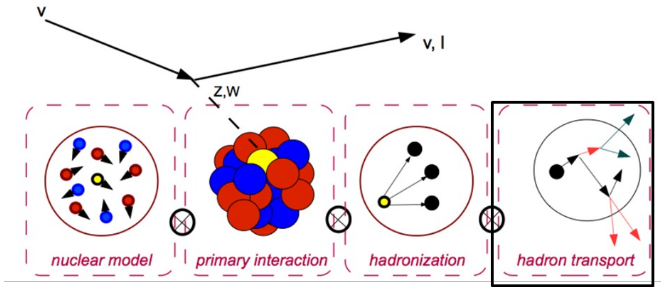
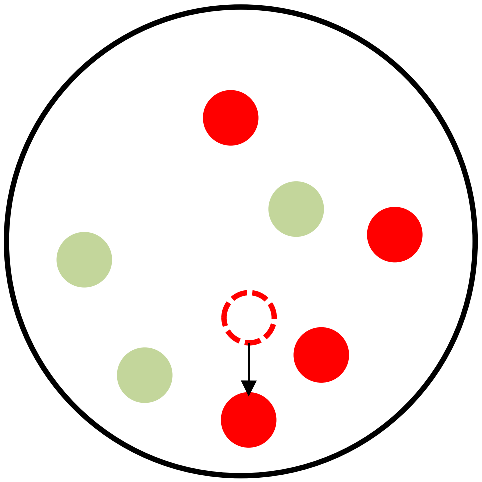
Final state interactions



- Intranuclear cascade models: classical billiard ball scattering within the nucleus

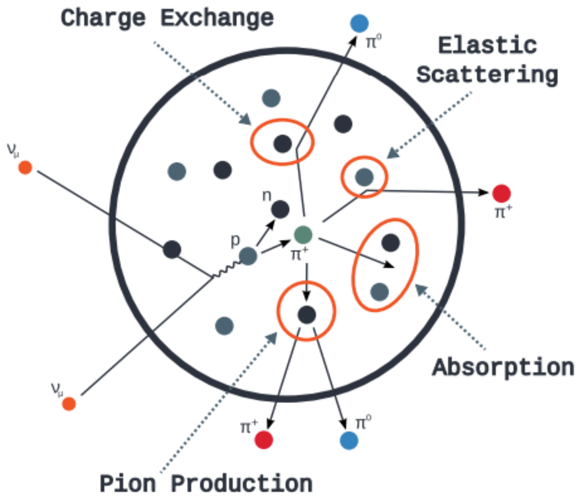


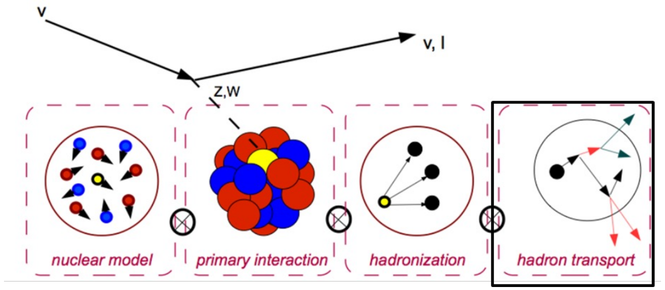


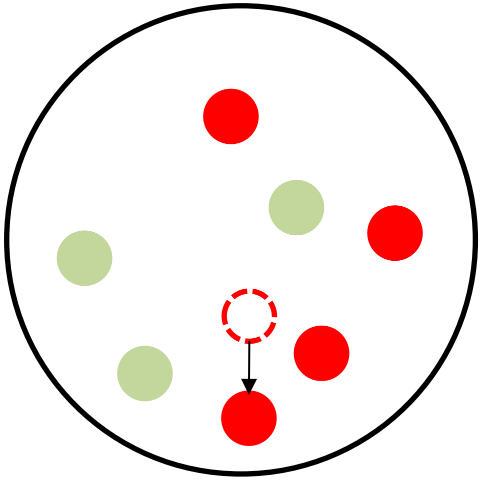
1. Step the particle through the nucleus a distance equal to its mean free path between interactions
2. Check whether it's outside the nucleus, if it is add this particle to the final state and stop FSI for it
3. Use MC methods to determine if it interacts or not, if it does choose a process according to its cross section
4. Generate the interaction
5. Return to 1.

Final state interactions

- Intranuclear cascade models: classical billiard ball scattering within the nucleus

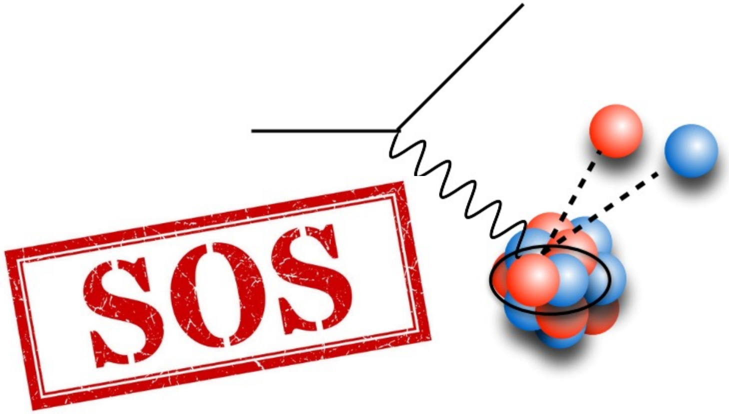






- Note that FSI is totally factorised from the rest of the interaction
- Unlike theory-treatments of FSI, cascades don't change the cross section as a function of lepton kinematics

Example: 2p2h

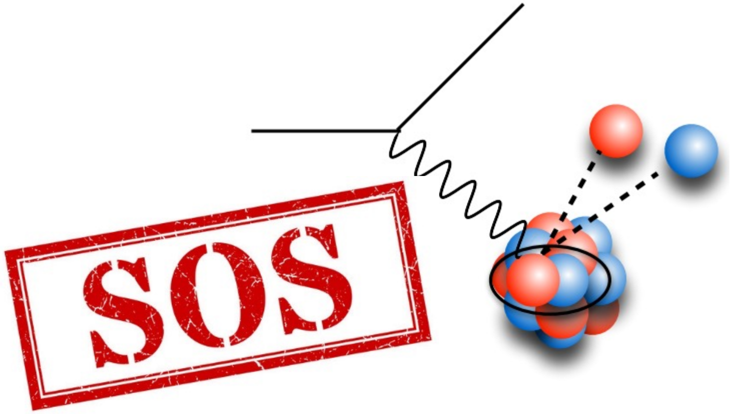


- Theory give us: $\frac{d^2\sigma}{dq_0 dq_3}$
(The "inclusive" cross section)

- Exclusive cross section: $\frac{d^8\sigma}{dq_0 dq_3 d\boldsymbol{p}_1 d\boldsymbol{p}_2}$
(what we actually need)

- How do we get there!?

Example: 2p2h



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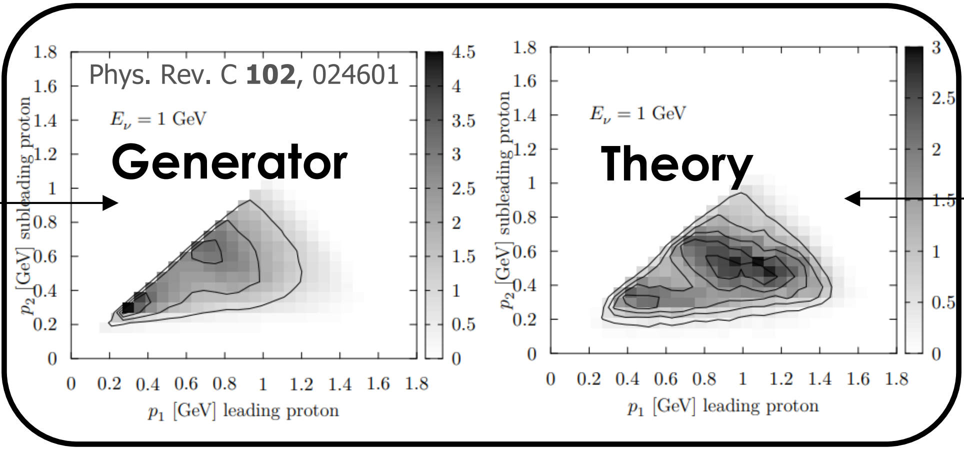
  (The "inclusive" cross section)
- Exclusive cross section: $$\frac{d^8\sigma}{dq_0 dq_3 d\boldsymbol{p}_1 d\boldsymbol{p}_2}$$
  (what we actually need)
- How do we get there!?

Generate remaining particle kinematics using a best-guess approach

- Sample struck nucleons 4-momenta independently from some spectral function and combine into a 2-nucleon "cluster"
  - **Assumption: *no correlations between nucleon's momentum/energy***
- Give 4-momentum transfer (q_0, q_3) to the cluster
- "Decay" the cluster to two nucleons
  - **Assumption: *momentum transfer shared evenly between the nucleons***
- Put both nucleons through an FSI cascade
  - **Assumption: the FSI model is reasonable**
  - **Assumption: *FSI doesn't change the inclusive cross section***

Example: 2p2h

Generator attempts at semi-exclusive cross section



Recent theory calculation of semi-exclusive cross section

Generate remaining particle kinematics using a best-guess approach

- Sample struck nucleons 4-momenta independently from some spectral function and combine into a 2-nucleon "cluster"
  - **Assumption: *no correlations between nucleon's momentum/energy***
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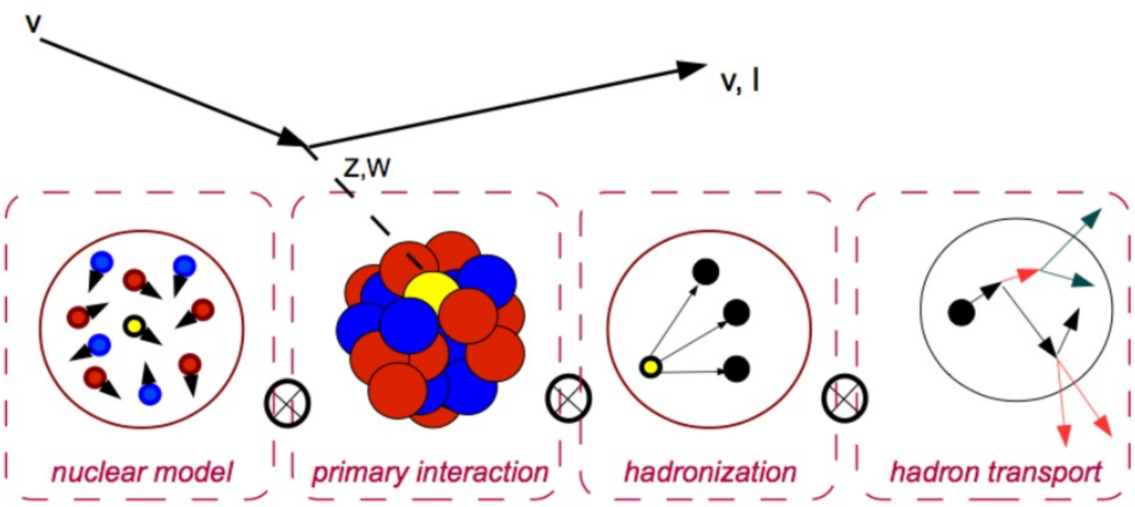
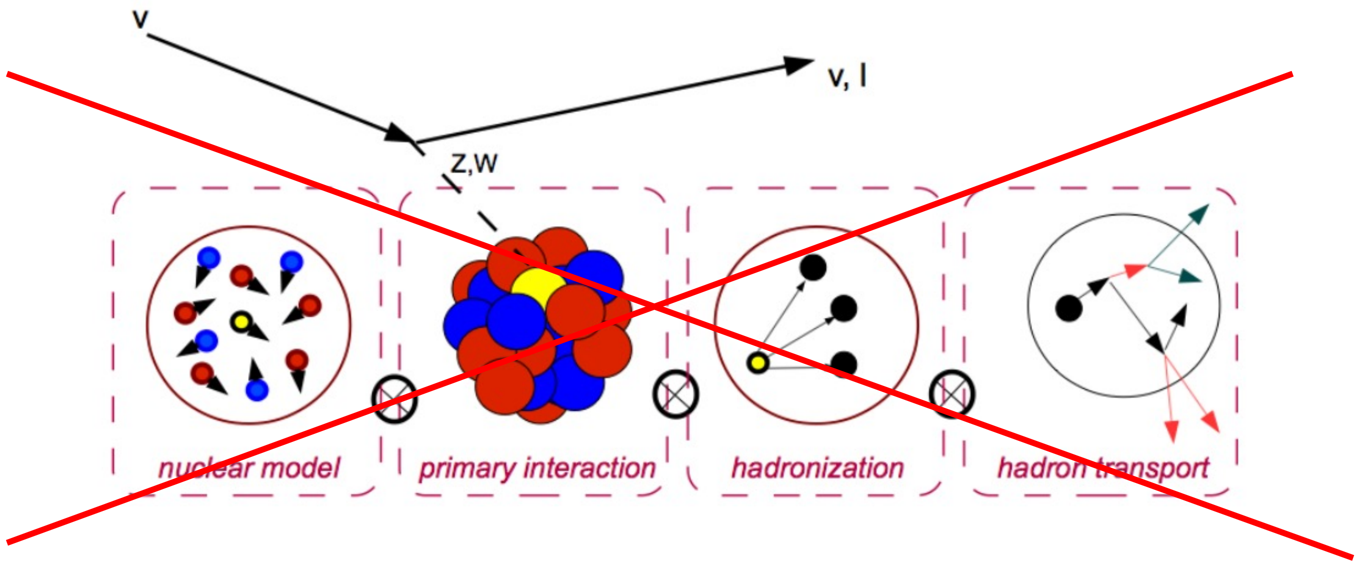
A generator's view of νN scattering



- This approach allows generators to produce complete simulations from incomplete theory inputs
- But, does it work?

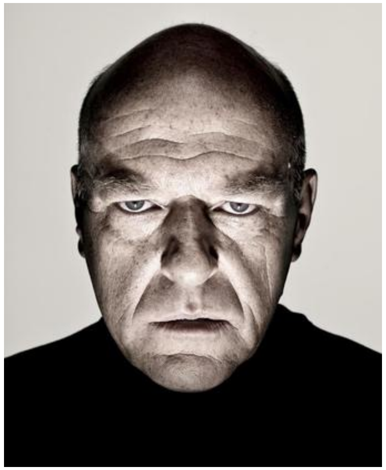
A generator's view of νN scattering



- Generators do what they can with what they work with
- But the "gap filling" implies significant approximations which limit their predictive power
- When relying on generators, it's crucial to consider what these approximations are and to assign associated systematic uncertainties

General rule of thumb

Lepton kinematics
(except maybe at low energy transfers)

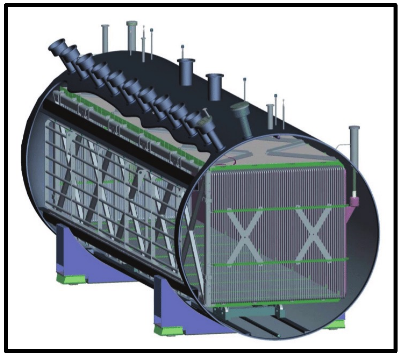


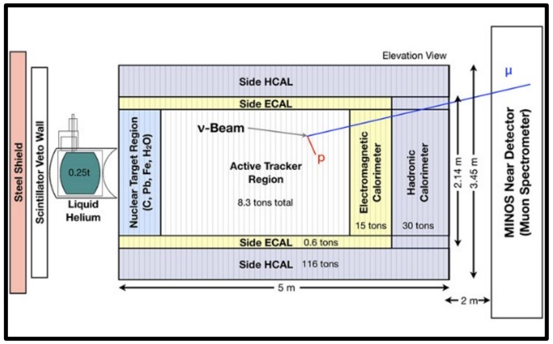
Lepton-hadron correlations

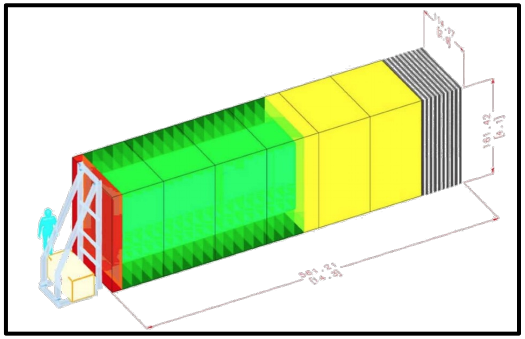

KEEP CALM
AND
MEASURE dσ/dx

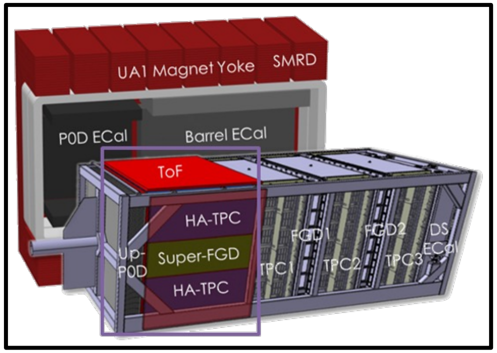
Overview

- Inputs to Generators: Neutrino-nucleon interactions
  - QE, RES and DIS
- Inputs to Generators: Neutrino-nucleus interactions
  - Nuclear effects
- Neutrino event generators
  - Filling in gaps in our inputs
- Benchmarking generators with measurements
  - Inclusive successes and exclusive failures
- Why do we care?
  - Neutrino interactions for neutrino oscillations
- Don’t Panic! The future of neutrino interaction simulations

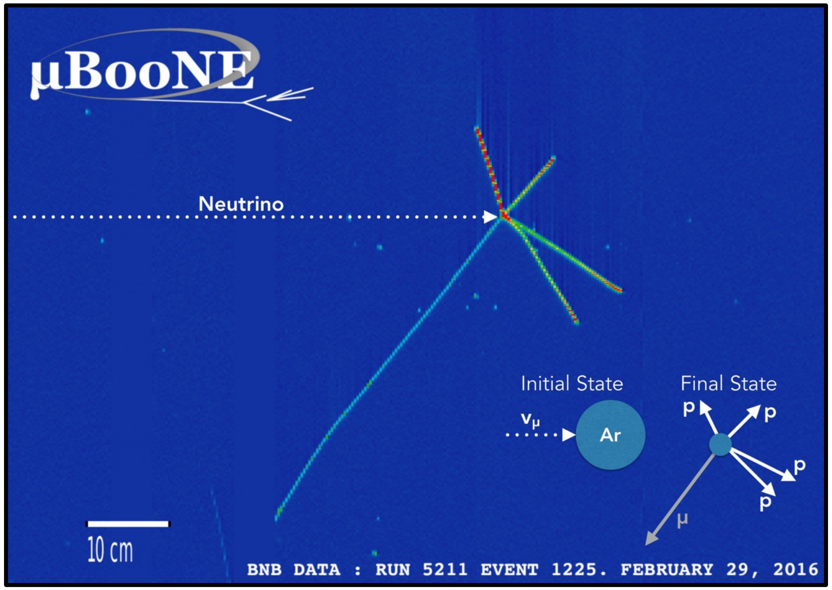


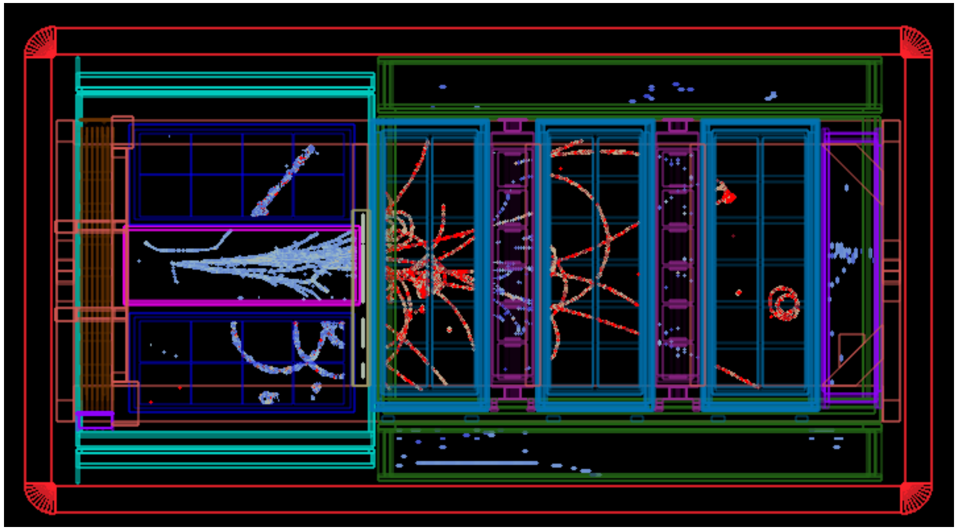






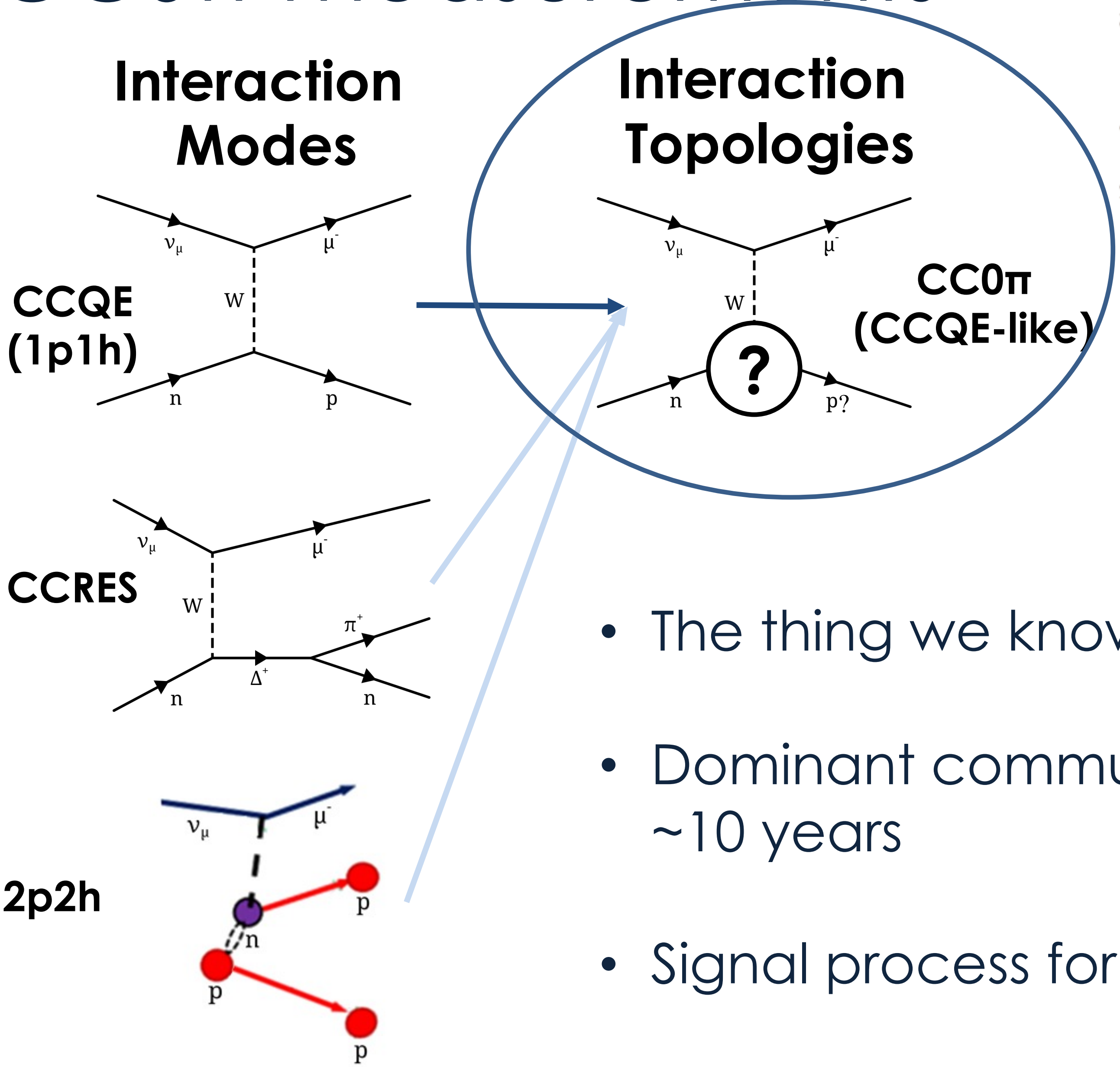
An experiment's view of an interaction

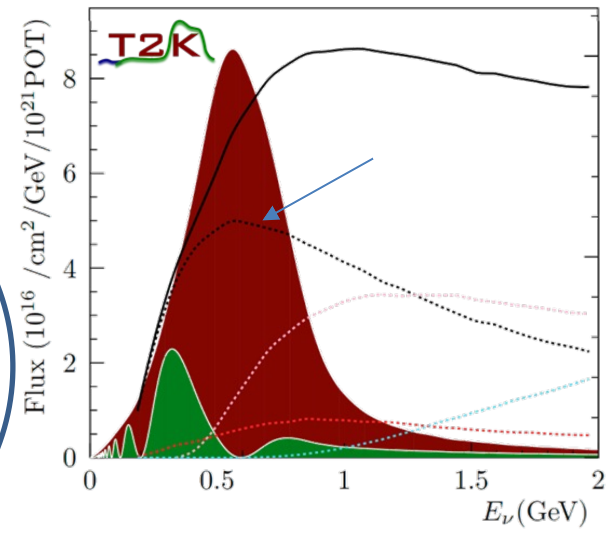




- See Deborah's talk for details on how these measurements are made!

CC0π measurements

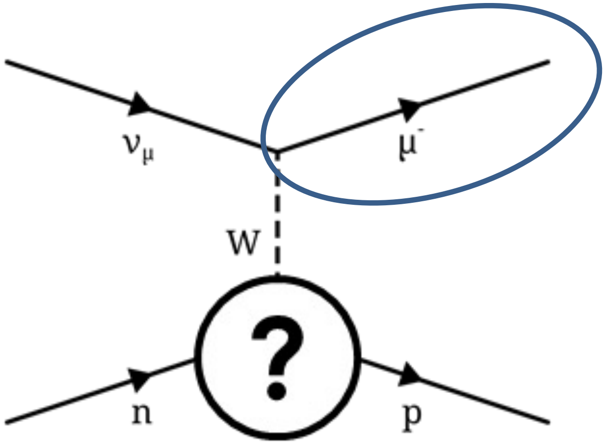




- The thing we know "best"
- Dominant community focus for ~10 years
- Signal process for T2K/HK

Which observables?

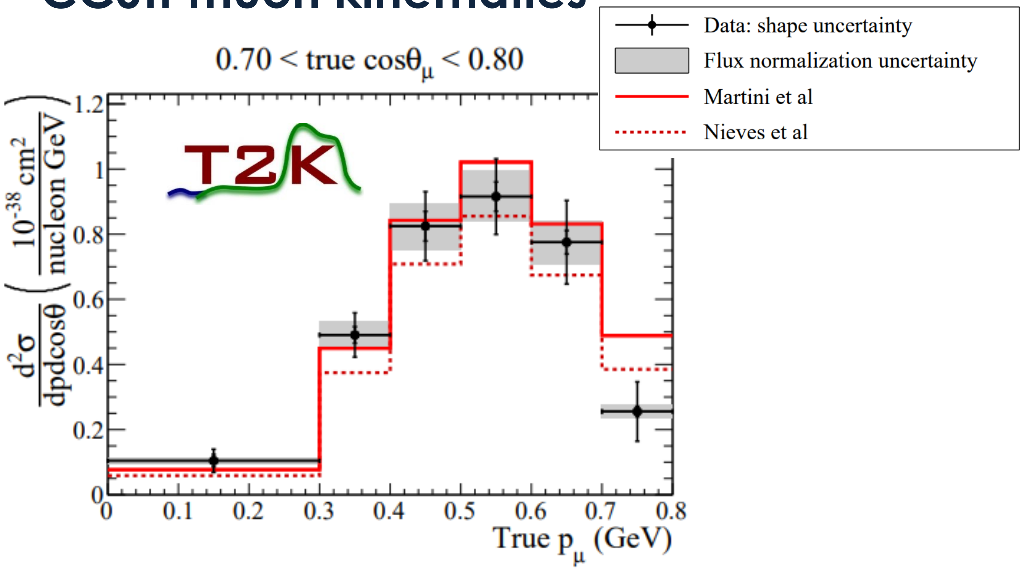
Just the muon?

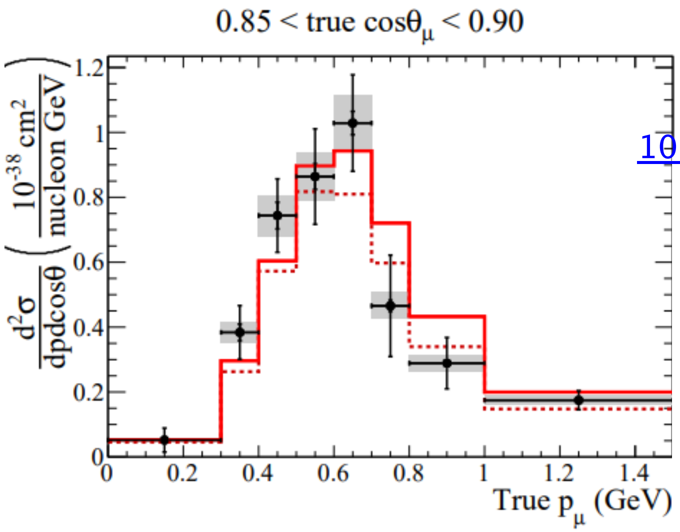


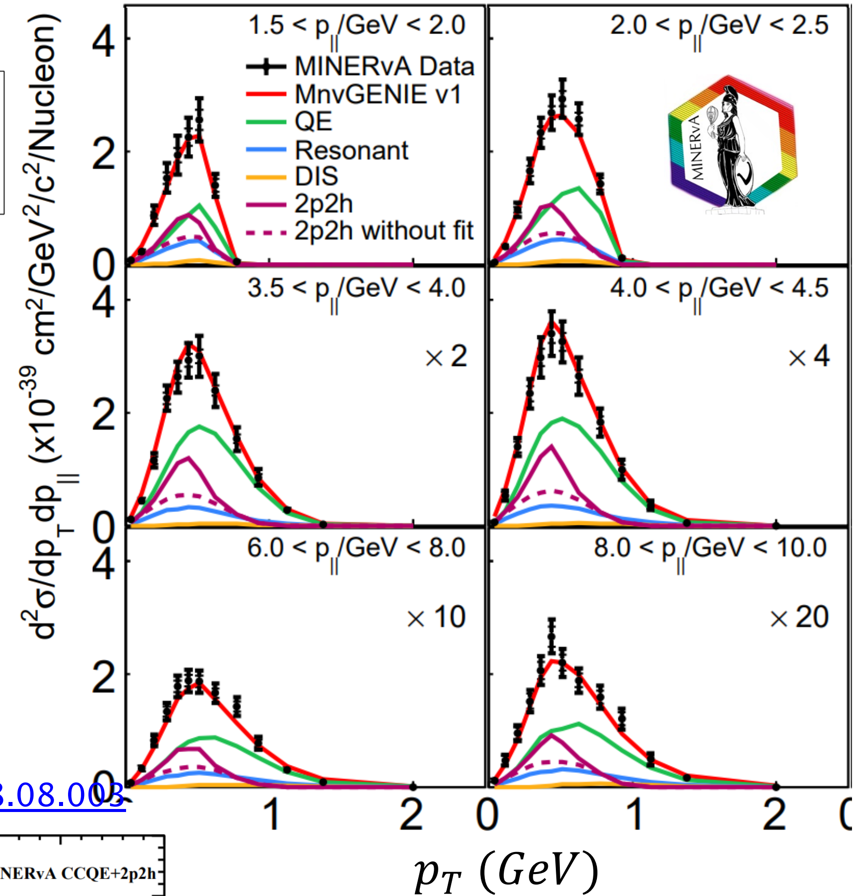
Our current models vs data

Phys. Rev. D **99**, 012004

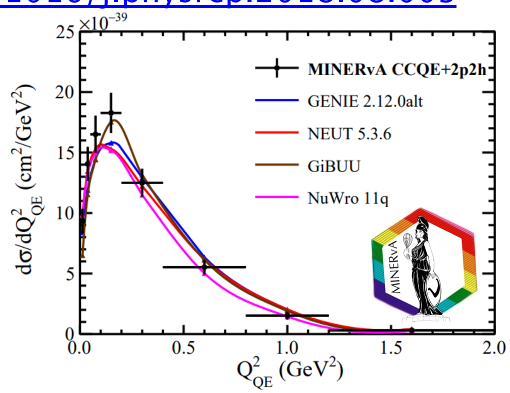
CC0π muon kinematics





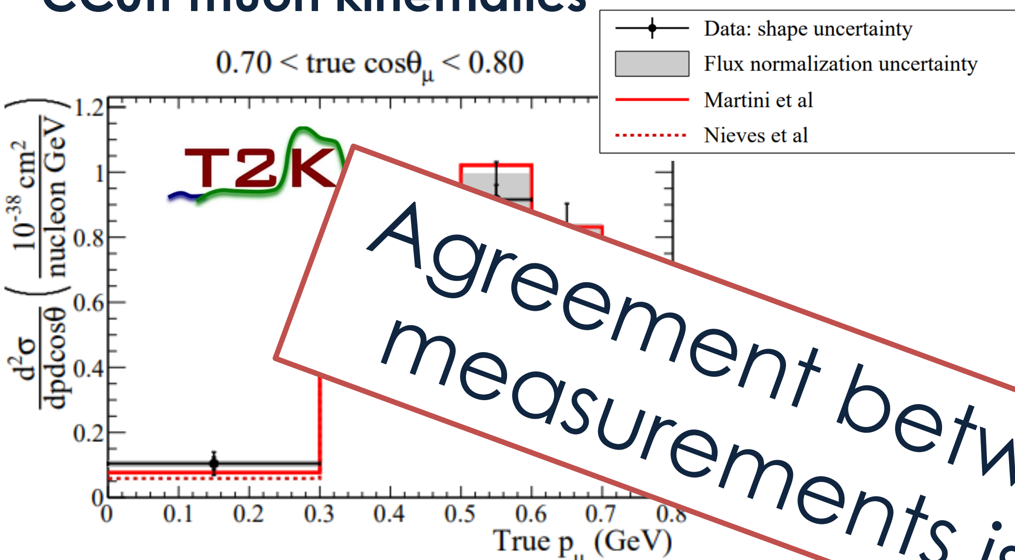


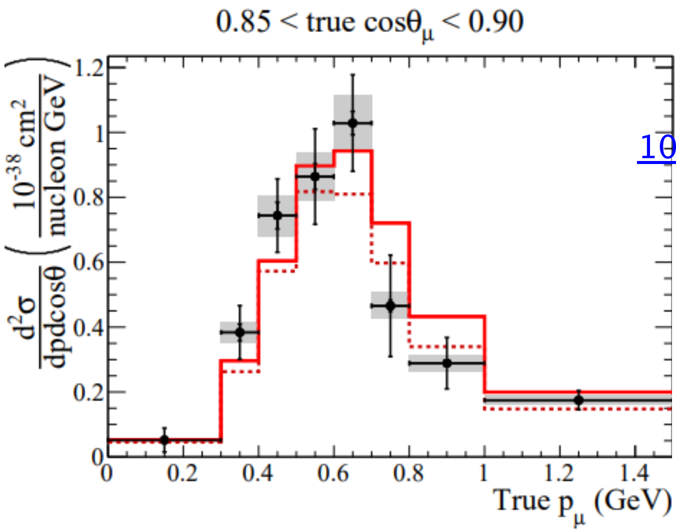
10.1016/j.physrep.2018.08.003



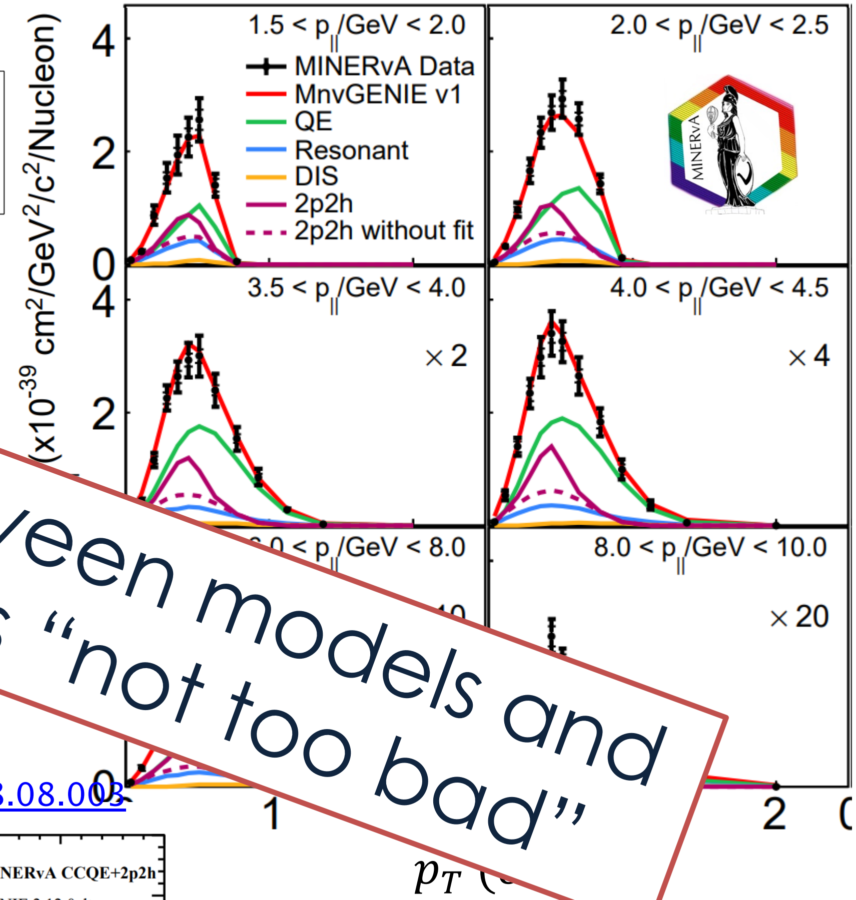
Our current models vs data

CC0π muon kinematics





Phys. Rev. D **99**, 012004



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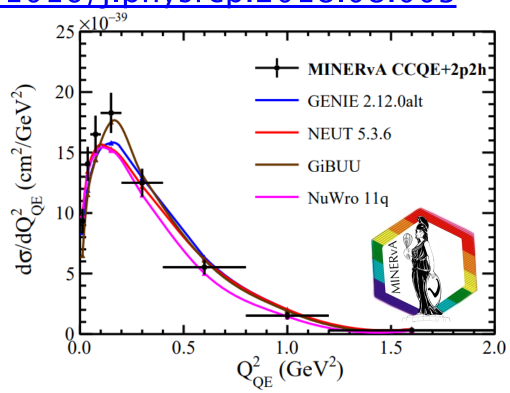
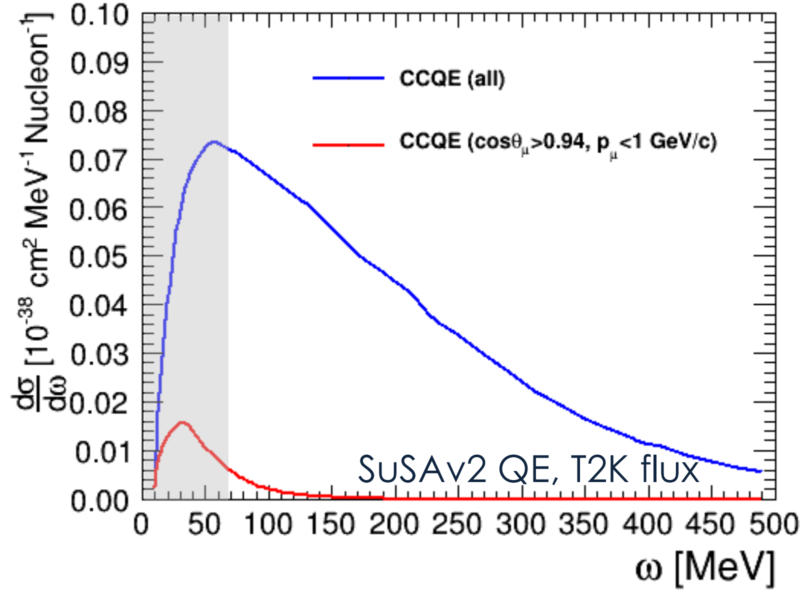


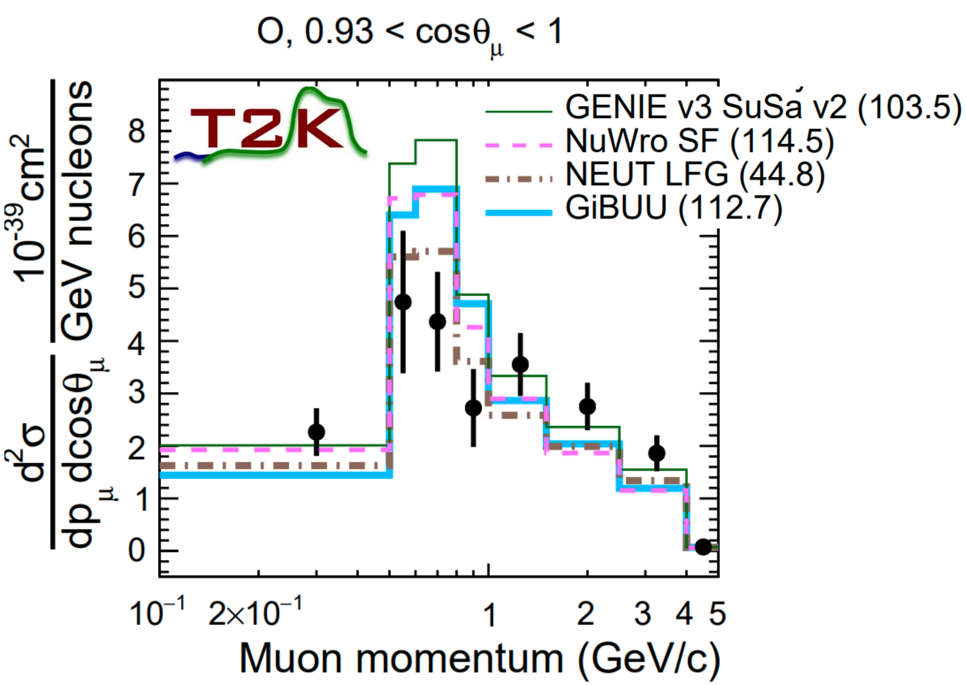
Agreement between models and measurements is "not too bad"

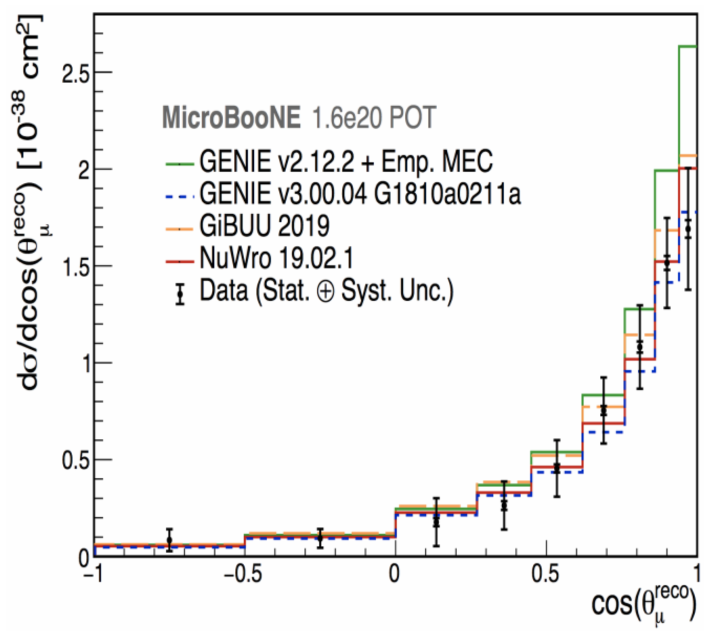
Forward Angles

- The very forward region is especially sensitive to interactions with low energy transfer (ω)

- Things don't look so good here …

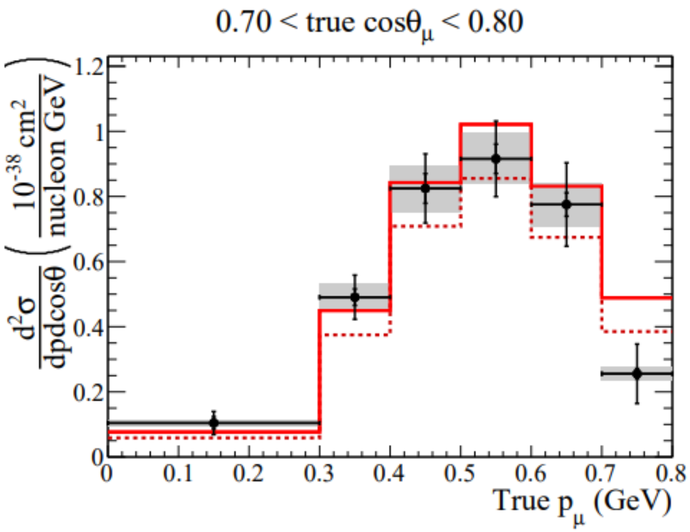


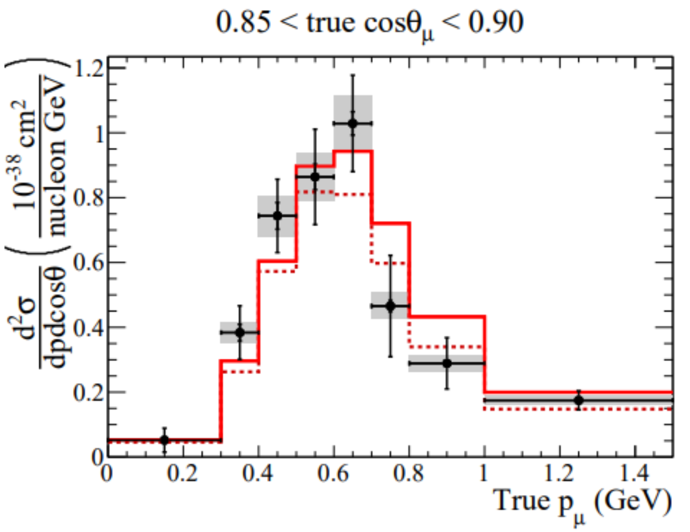




Phys. Rev. Lett 123,131801 (2019)

Does this make sense?

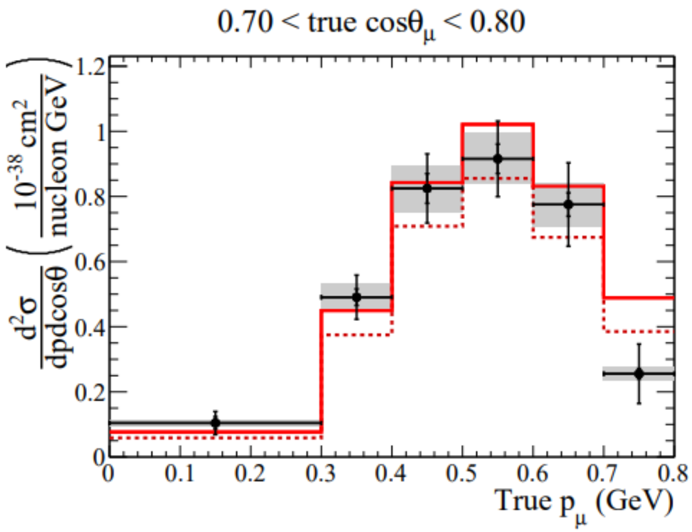


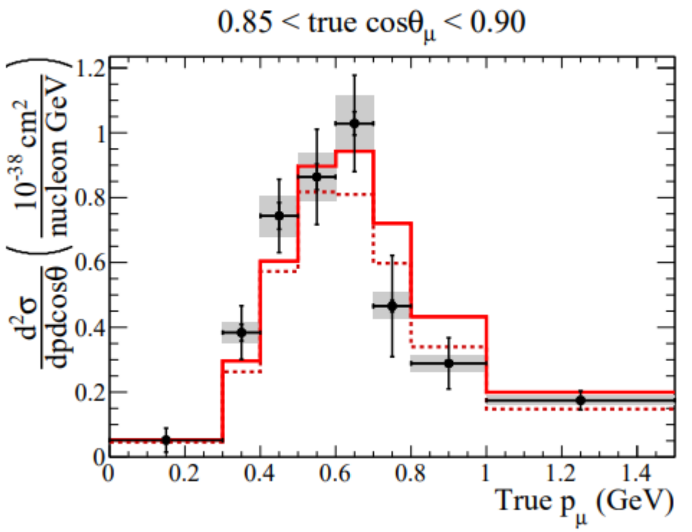


We describe intermediate muon kinematics in CC0π measurements quite well with most models

Expected?

Does this make sense?





We describe intermediate muon kinematics in CC0π measurements quite well with most models

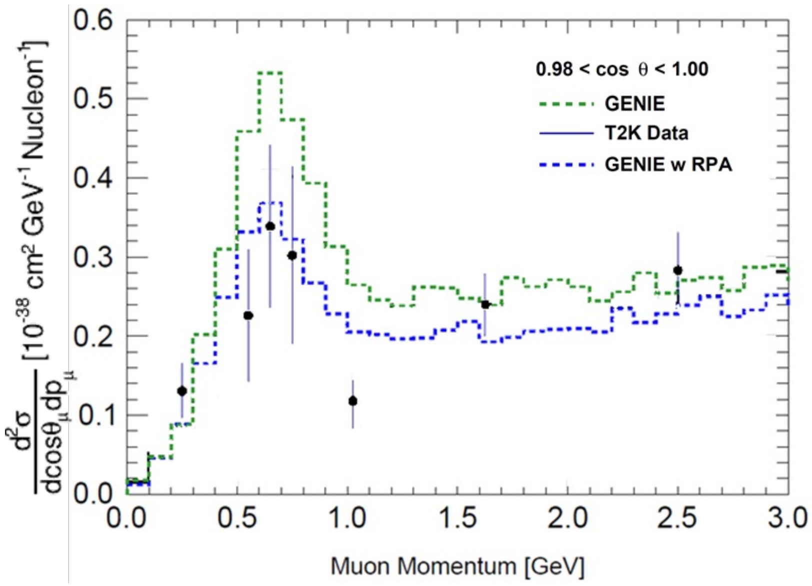
Expected?

Yes!

- Generator approximations are reasonable
- The details of the hadron kinematics don't matter so much
- The impact of FSI is small

Does this make sense?

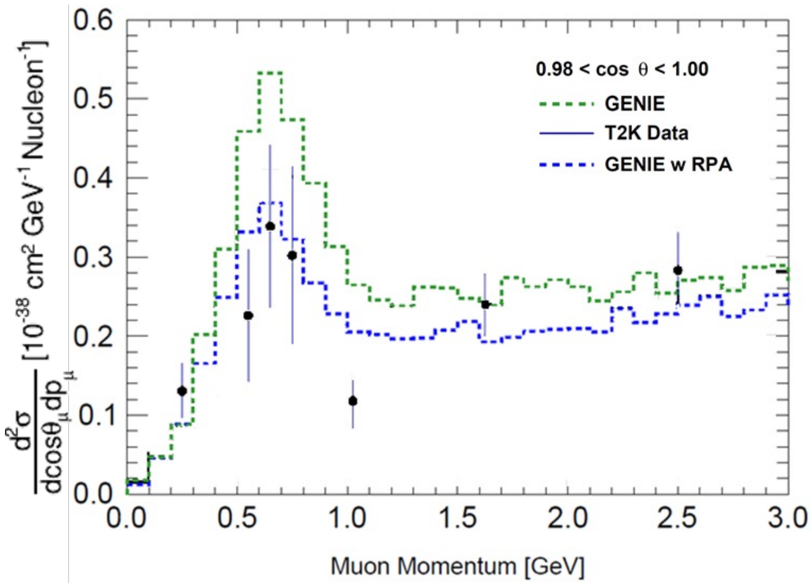
We describe forward going muon kinematics in CC0π measurements badly in many models



Expected?

Models with RPA do better here

Does this make sense?



We describe forward going muon kinematics in CC0π measurements badly in many models

Expected?

Yes!

- Generator approximations for many models are not valid at low momentum transfer

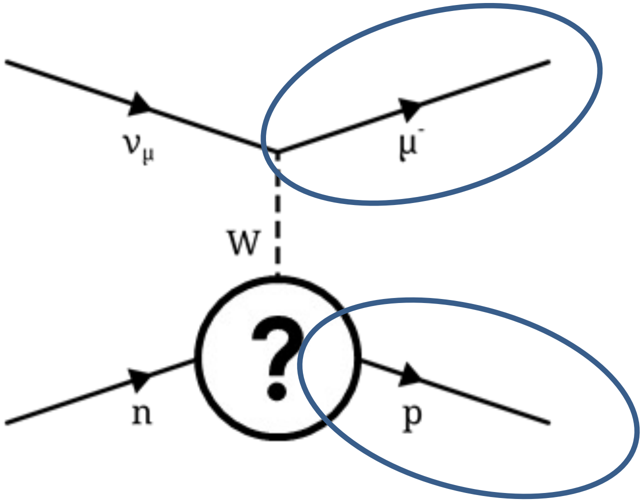
Models with RPA do better here

Makes sense!

- Provides some modelling of physics beyond the generator's approximations

Which observables?

Lepton and proton?



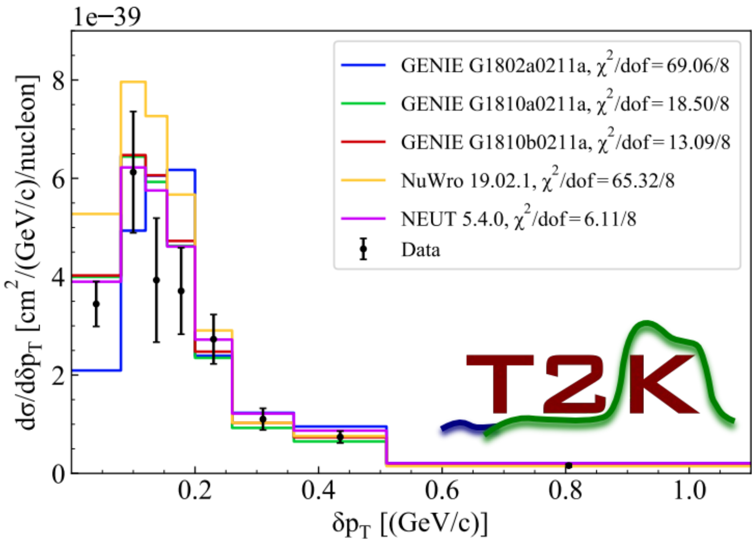
Correlations between the muon and proton kinematics allow us to disentangle nuclear effects from neutrino energy

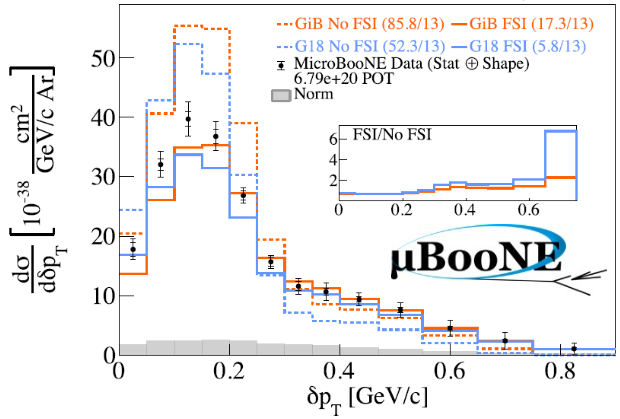
Generators vs data: a horror story

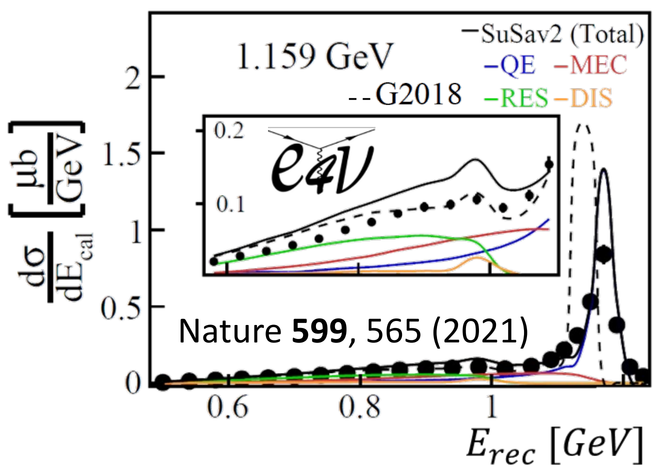
- No generator can come close to describing global data measuring lepton-hadron correlations
  - All models are “wrong”, but they are each wrong in different ways

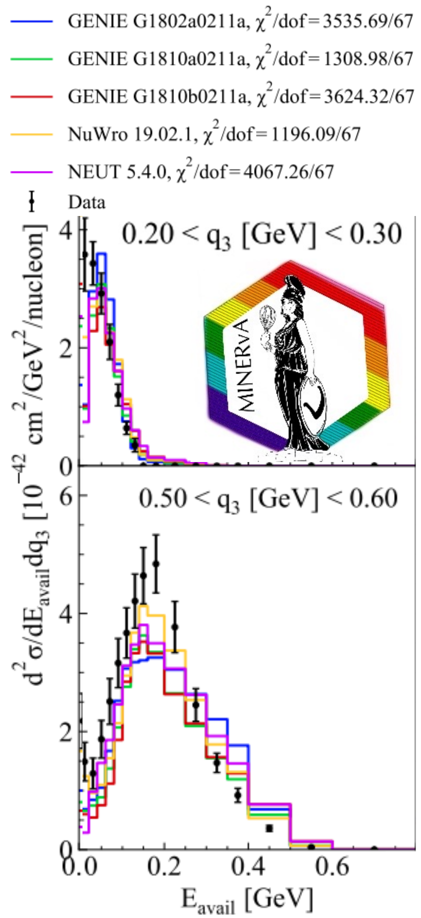
See many more informative generator comparisons in the TENSIONS 2019 report (arXiv:2112.09194)

$$\chi^2_{allModels} \gg N_{bins}$$

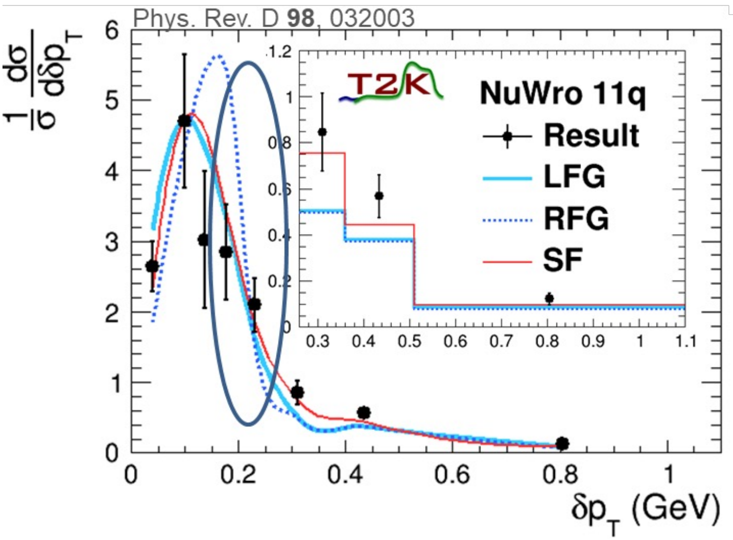




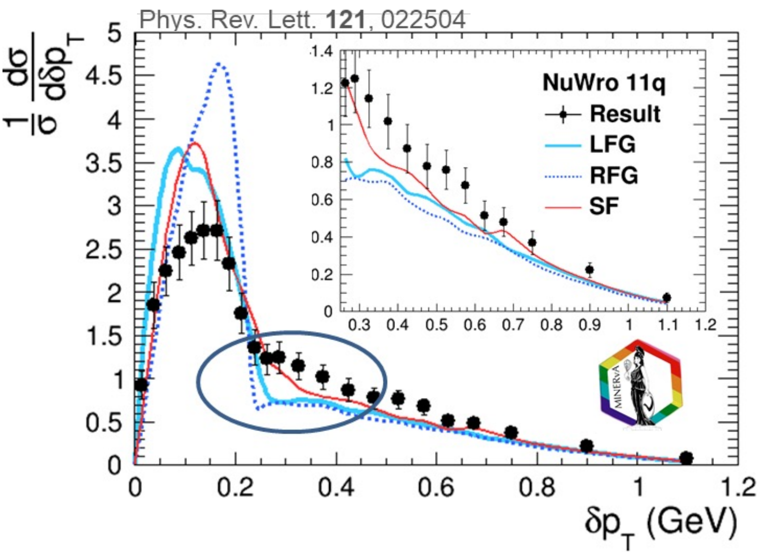




Does this make sense?



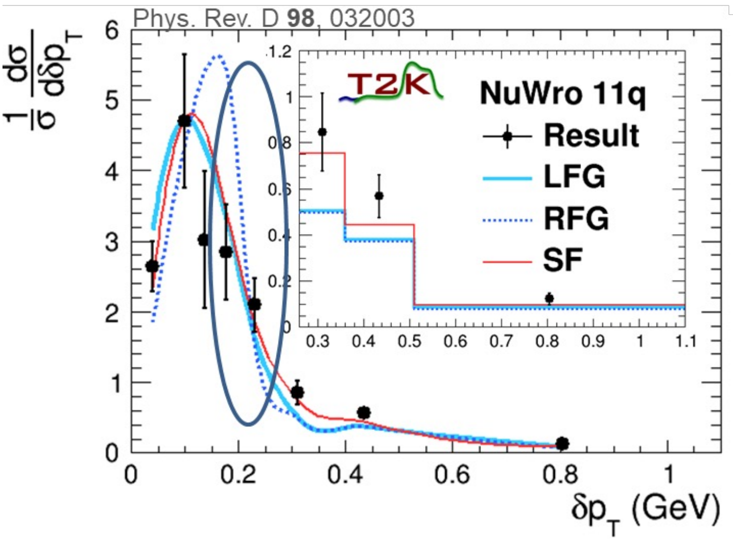
We describe lepton-nucleon correlations badly



Exclusive or factorized models do better here

Does this make sense?

Stephen Dolan

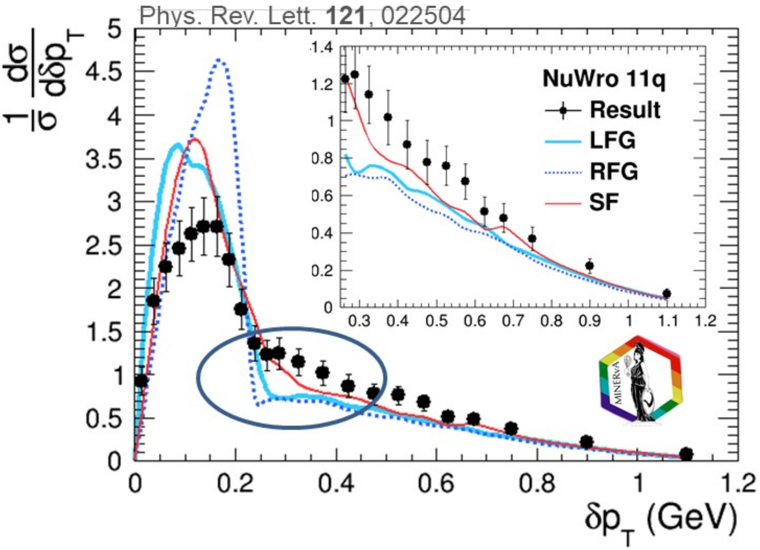


We describe lepton-nucleon correlations badly

Expected?

Yes!

- Most of our models rely on *ad-hoc* model combinations to predict nucleon kinematics



Exclusive or factorized models do better here

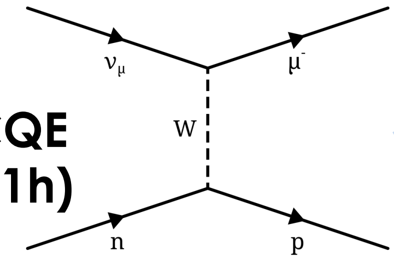
Makes sense!

- Fewer approximations in predictions of nucleon kinematics

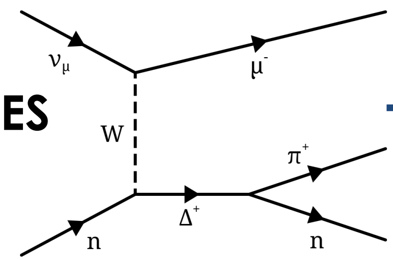
What can we measure

Interaction Modes

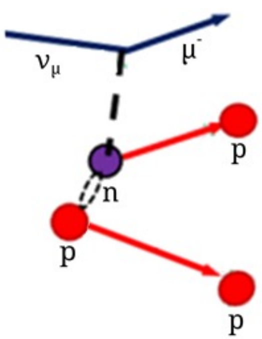
CCQE (1p1h)



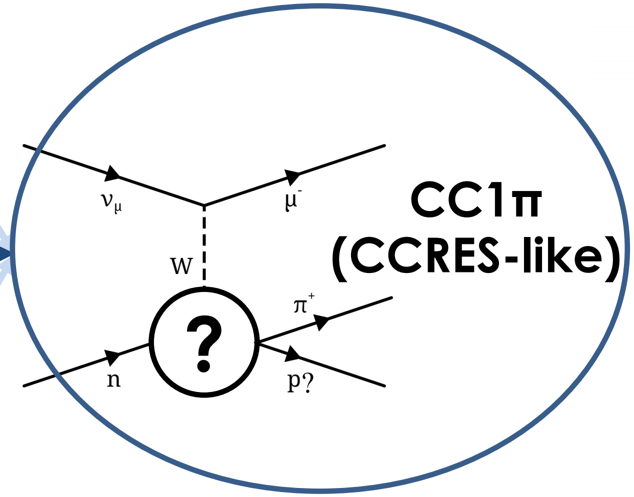
CCRES

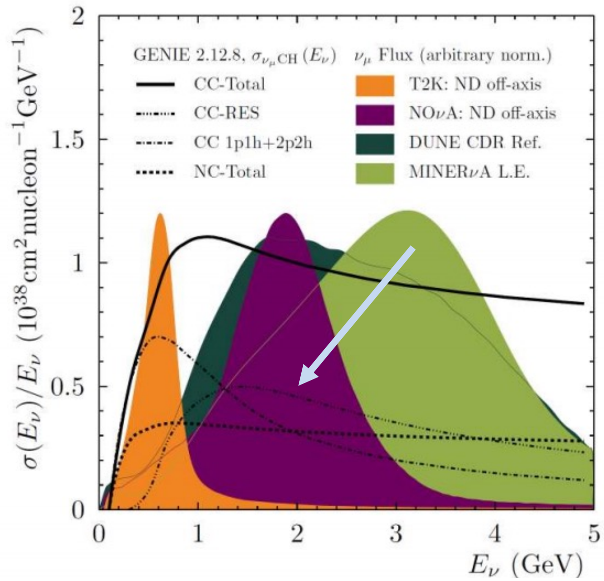


2p2h



Interaction Topologies



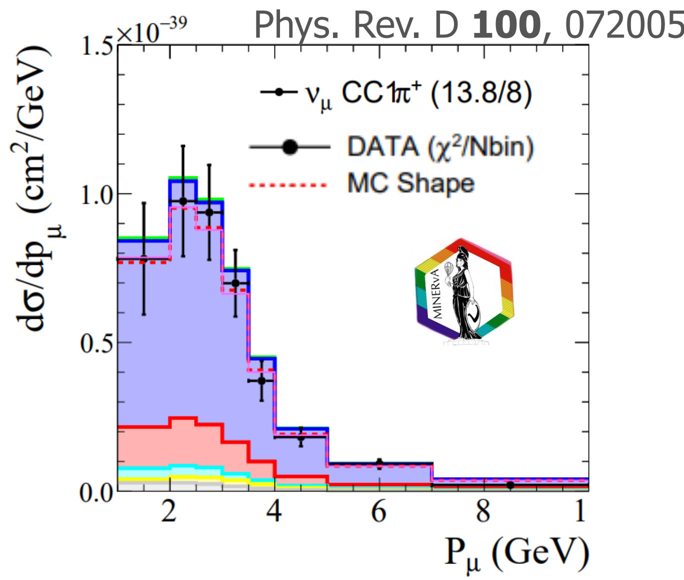


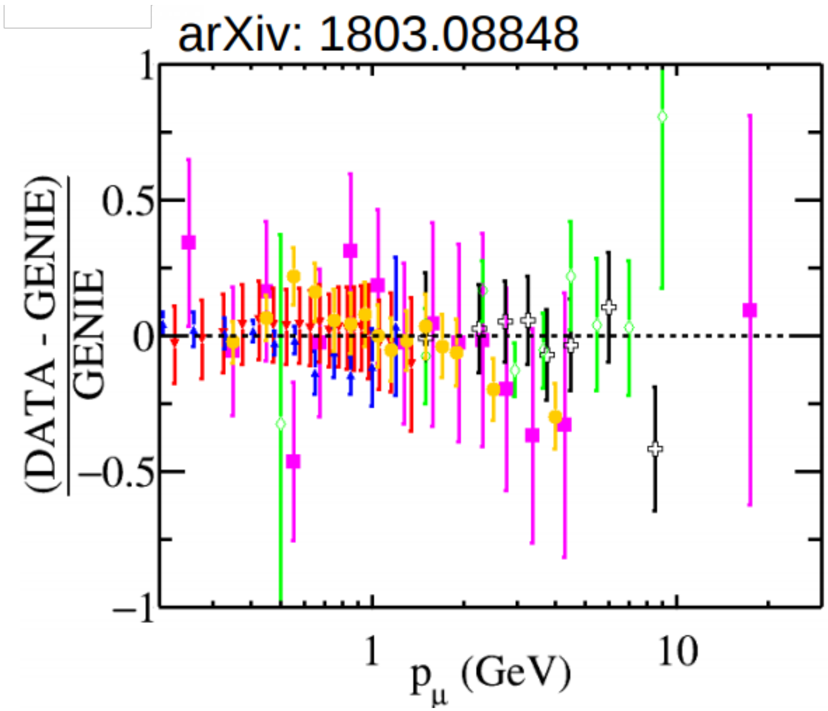
- Key contributor to all experiments
- The thing we don't understand well at all …

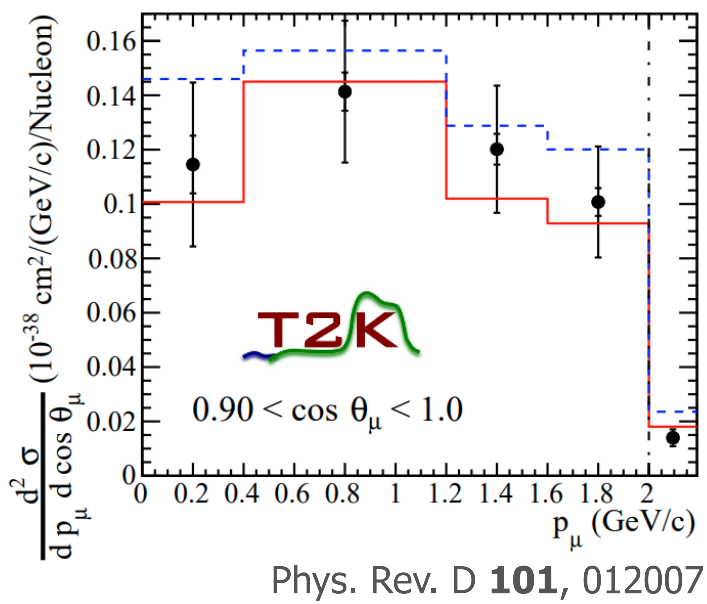
Pion production measurements

Similar story:

- Models generally able to predict lepton kinematics reasonably well
  - Even in the forward region!



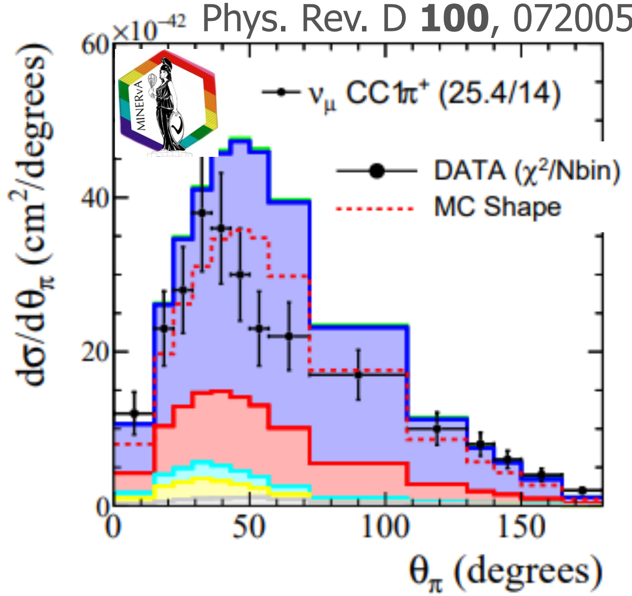


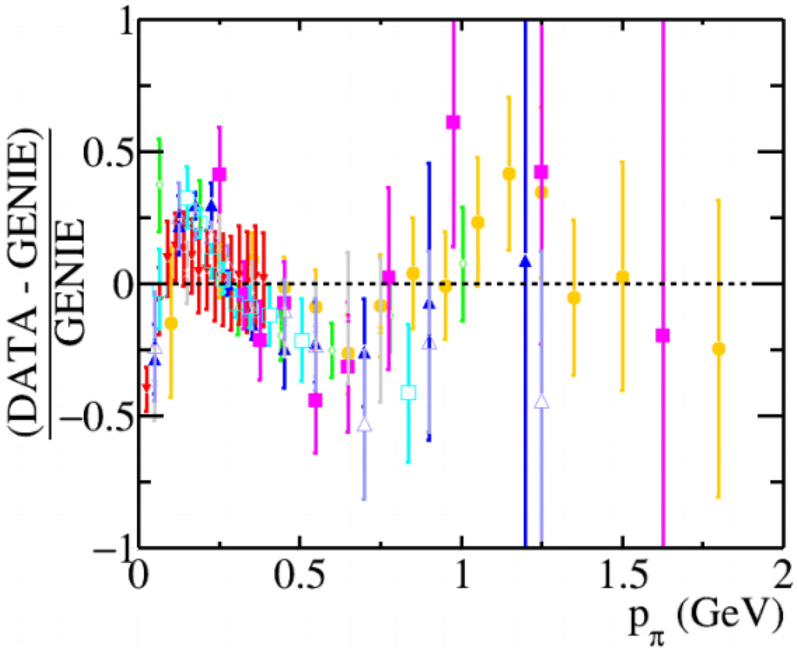


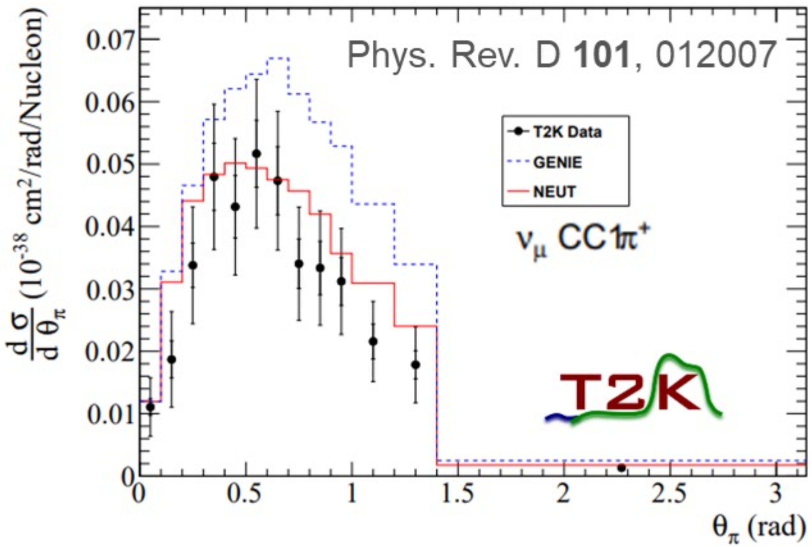
Pion production measurements

Similar story:

- Models generally able to predict lepton kinematics reasonably well
  - Even in the forward region!
- But pion kinematics are poorly described across experiments

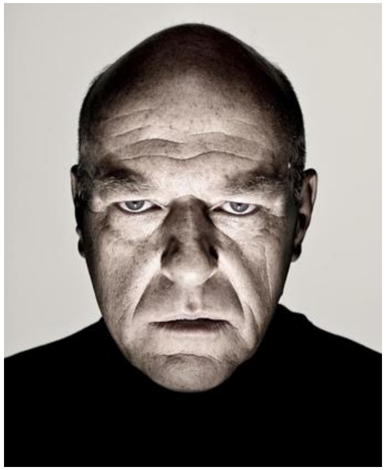






So, how did we do?

Lepton kinematics
(except maybe at low energy transfers)



Lepton-hadron correlations

Overview

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- Neutrino event generators
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- Benchmarking generators with measurements
  - Inclusive successes and exclusive failures
- Why do we care?
  - Neutrino interactions for neutrino oscillations
- Don't Panic! The future of neutrino interaction simulations

Three things we need to model

(a non exhaustive list)

1. The energy dependence of neutrino cross sections
   - *So we know how to extrapolate from our near to far detectors*

See Clarence's lectures

Three things we need to model

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1. The energy dependence of neutrino cross sections
   - *So we know how to extrapolate from our near to far detectors*

2. The smearing of our neutrino energy reconstruction
   - *So we can infer the shape of the oscillated spectrum*

See Clarence's lectures

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1. The energy dependence of neutrino cross sections
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2. The smearing of our neutrino energy reconstruction
   - *So we can infer the shape of the oscillated spectrum*

3. Differences in the cross section for ν_e/ν_μ (and $\nu/\bar{\nu}$)
   - *So we can use ν_e appearance to probe CP-violation*

See Clarence's lectures

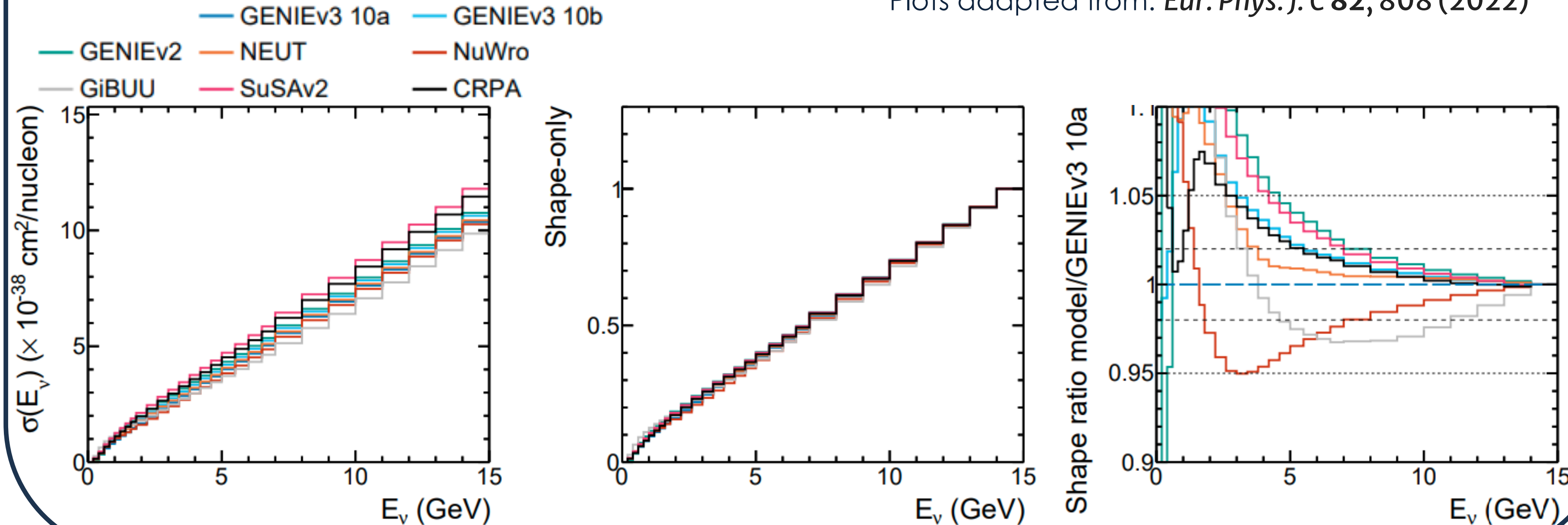
Three things we need to model

(a non exhaustive list)

1. The energy dependence of neutrino cross sections
   - *So we know how to extrapolate from our near to far detectors*

- Models differ by 5-10% in the region of interest for DUNE and Hyper-K
- Significant, given the expected statistics for DUNE and Hyper-K

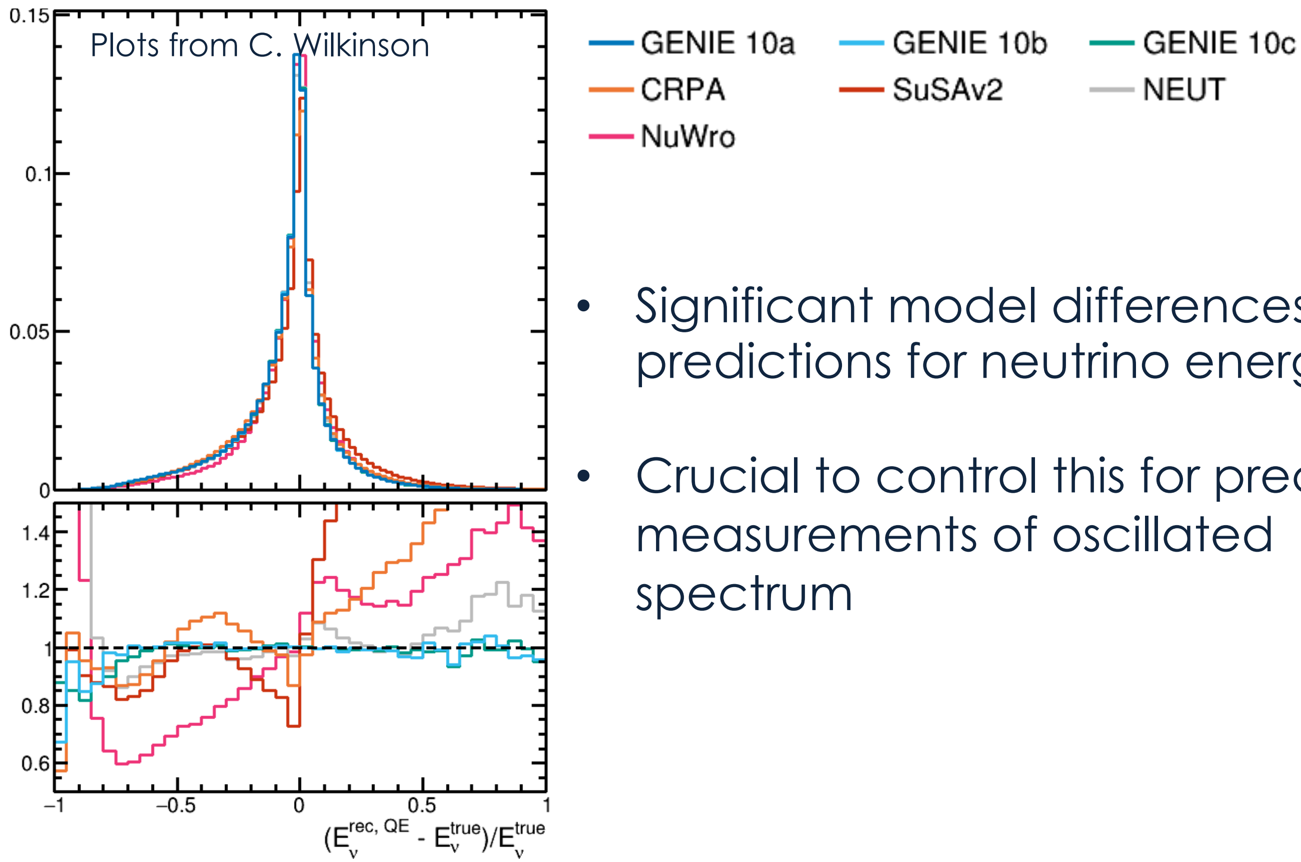
Plots adapted from: *Eur. Phys. J. C* **82**, 808 (2022)



Three things we need to model

(a non exhaustive list)

2. The smearing of our neutrino energy reconstruction
   - *So we can infer the shape of the oscillated spectrum*

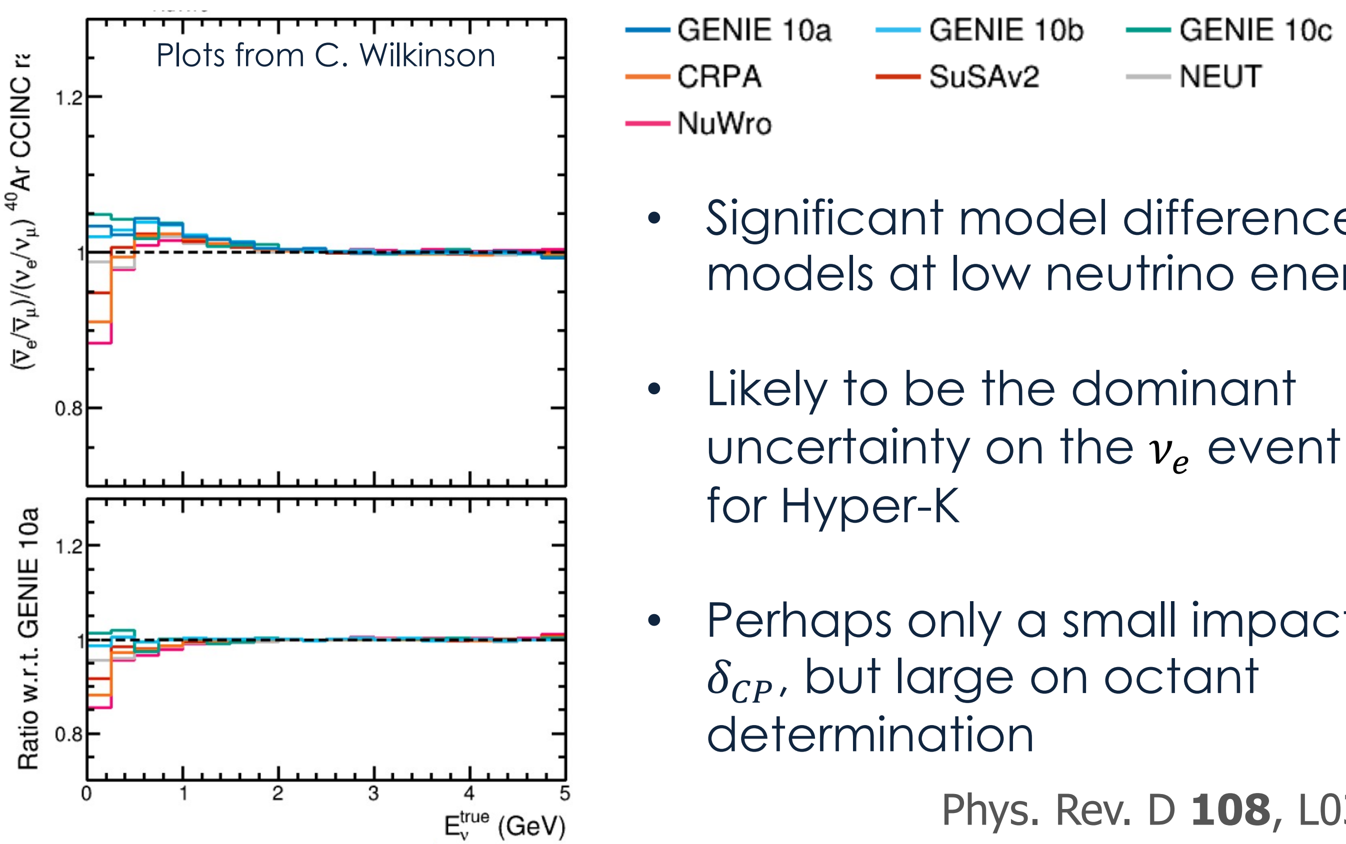


- Significant model differences in predictions for neutrino energy bias
- Crucial to control this for precision measurements of oscillated spectrum

Three things we need to model

(a non exhaustive list)

3. Differences in the cross section for ν_e/ν_μ (and $\nu/\bar{\nu}$)
   - *So we can use ν_e appearance to probe CP-violation*



- Significant model differences in models at low neutrino energies
- Likely to be the dominant uncertainty on the ν_e event rate for Hyper-K
- Perhaps only a small impact on δ_{CP}, but large on octant determination

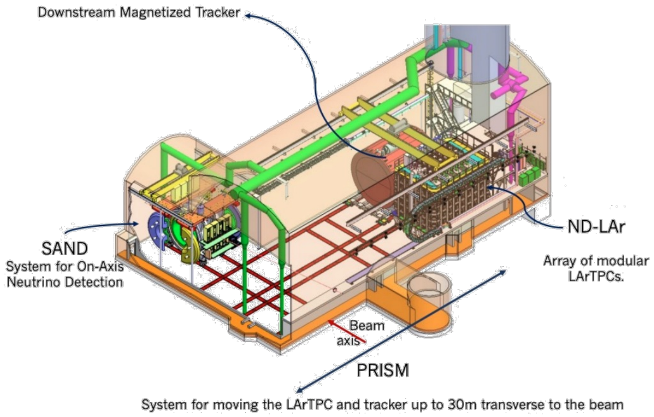
Phys. Rev. D **108**, L031301

Overview

- Inputs to Generators: Neutrino-nucleon interactions
  - QE, RES and DIS
- Inputs to Generators: Neutrino-nucleus interactions
  - Nuclear effects
- Neutrino event generators
  - Filling in gaps in our inputs
- Benchmarking generators with measurements
  - Inclusive successes and exclusive failures
- Why do we care?
  - Neutrino interactions for neutrino oscillations
- Don’t Panic! The future of neutrino interaction simulations

Path to Precision Measurements

Improved near detector capabilities



Engagement with the nuclear theory community

Dedicated lepton-nucleus cross-section measurement programs

Undetectable, you say?

"I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do." *Wolfgang Pauli, 1930*

Well, have I got νs for you!

“I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do.” *Wolfgang Pauli, 1930*

Well, have I got νs for you!

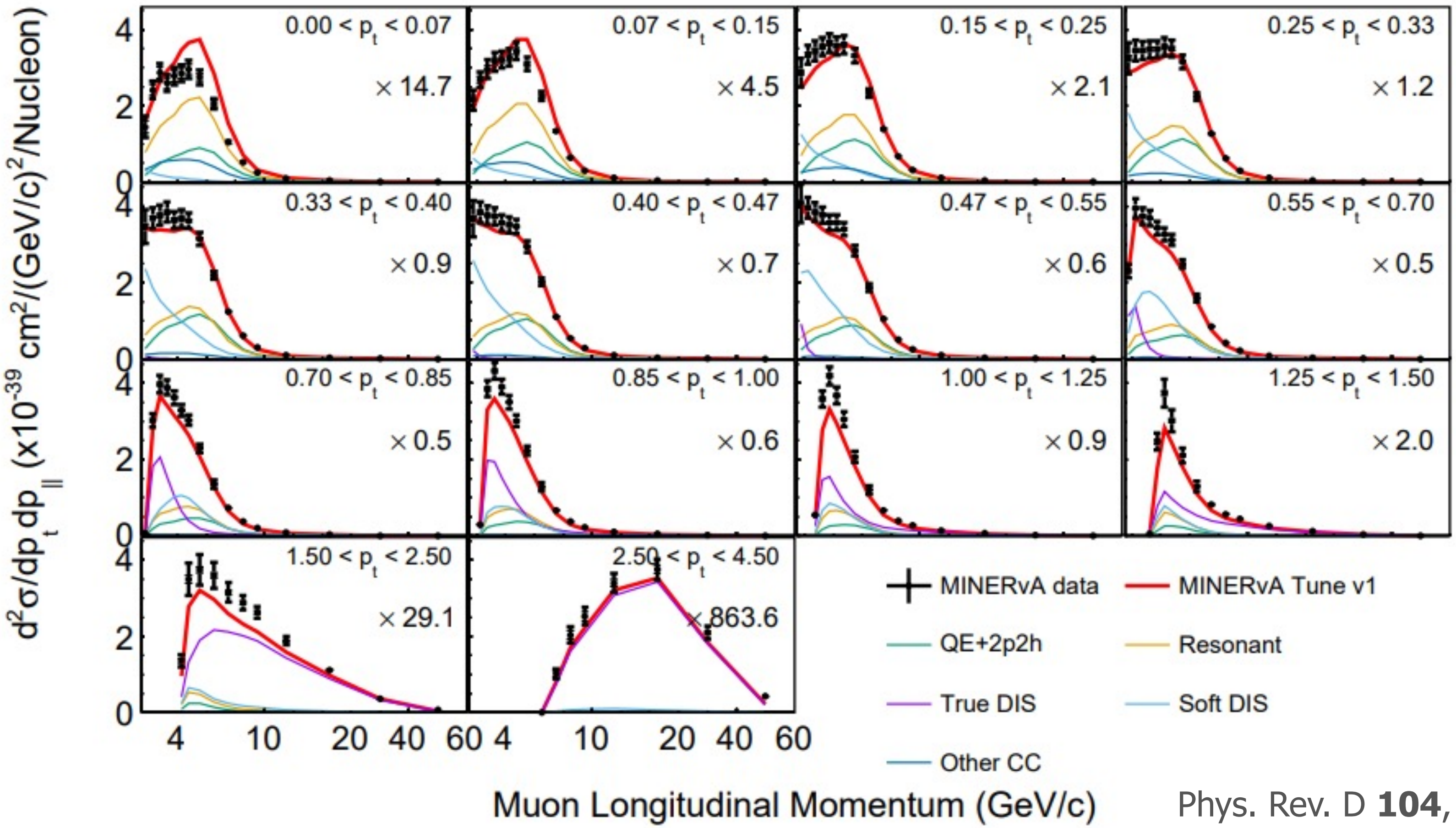
MINERvA

Phys. Rev. D **104**, 092007

Using these criteria, a sample of 4,105,696 interactions was selected. The simulation predicts an average selection efficiency of 64% in the p_t-$p_{||}$ phase space, where

"I have done something very bad today by proposing a particle that cannot be detected; it is something no theorist should ever do." *Wolfgang Pauli, 1930*

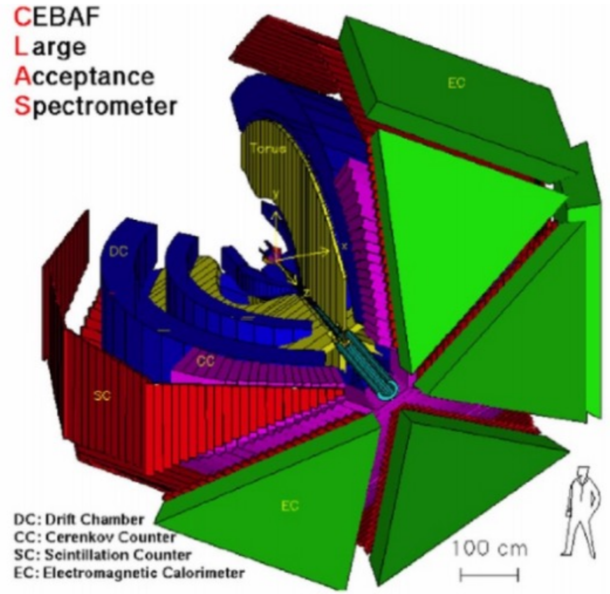
Well, have I got νs for you!



Phys. Rev. D **104**, 092007

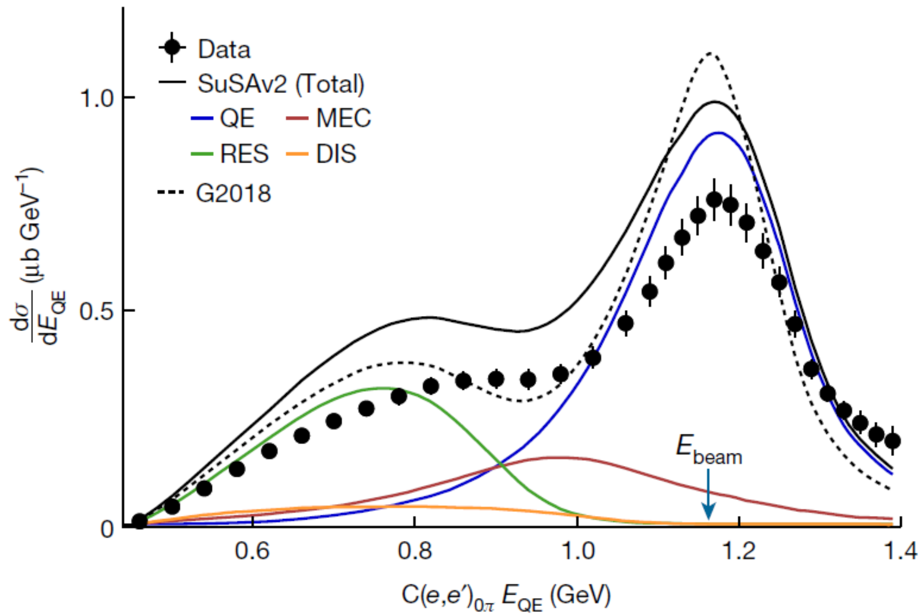
Tailored electron scattering

Nature **volume 599**, pages565–570 (2021)

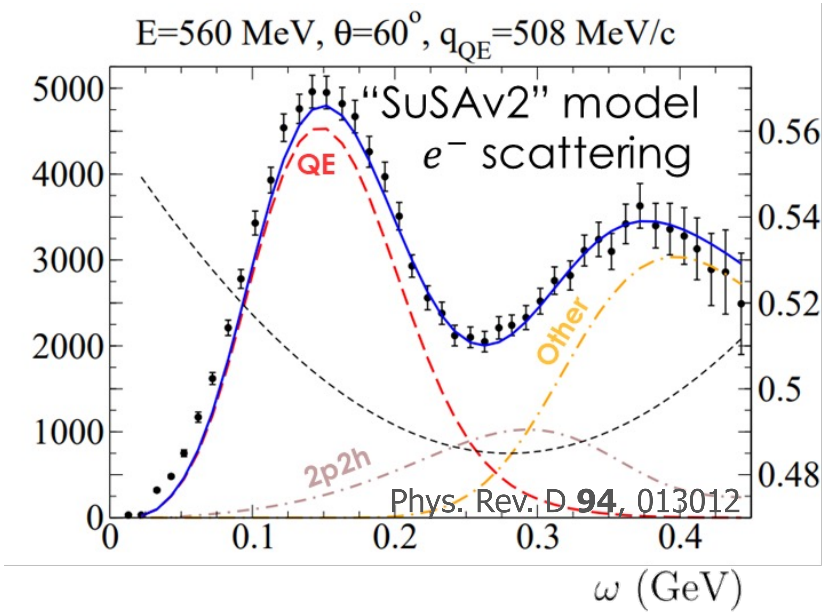


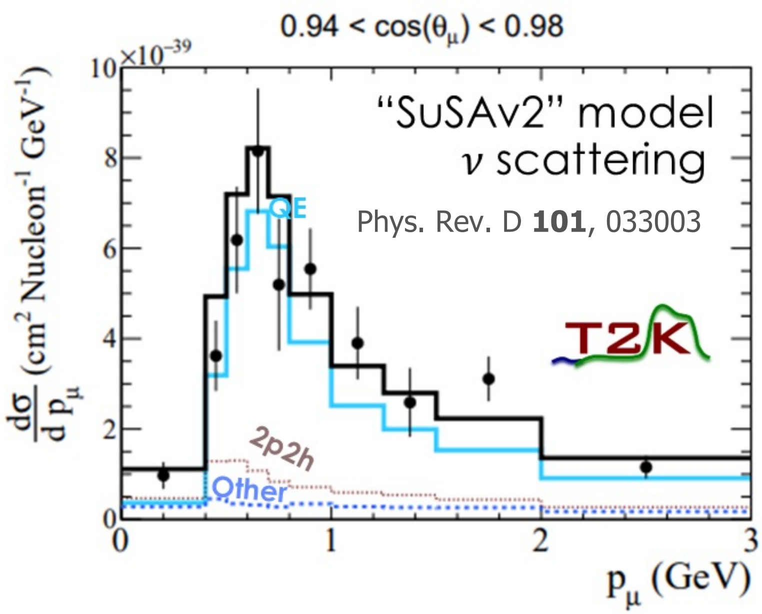
- Our models are becoming more able to make neutrino and electron scattering predictions in the same framework

- New data from CLAS (e-scatting): specifically to help better understand neutrino scattering



New models, new constraints

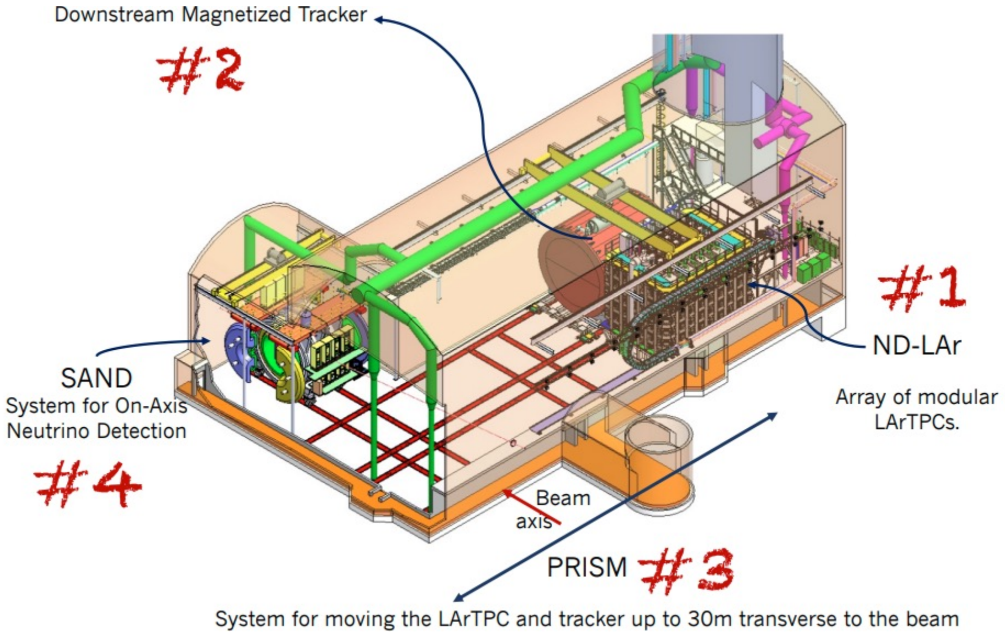




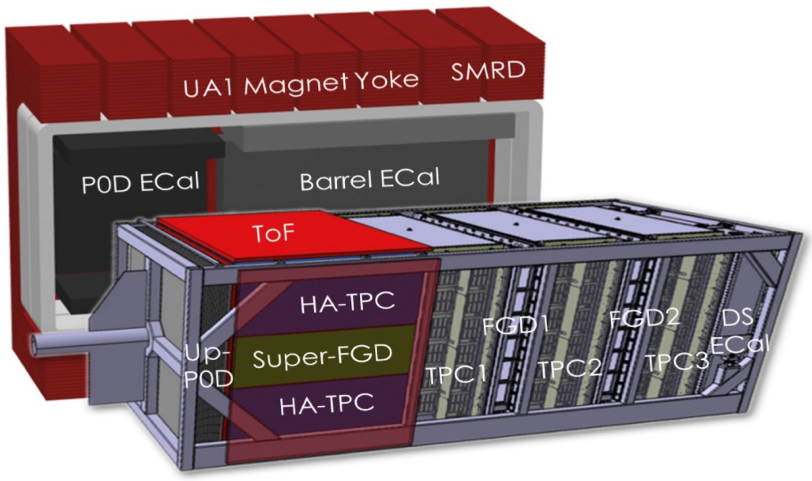
- New models, successful in describing electron scattering data, are now being implemented in neutrino interaction simulations
- Such models that describe e^- and ν interactions in the same framework can be directly constrained by precision e^- data
- New theoretical efforts are allowing models to be more predictive

Improved near detectors

DUNE Near Detector

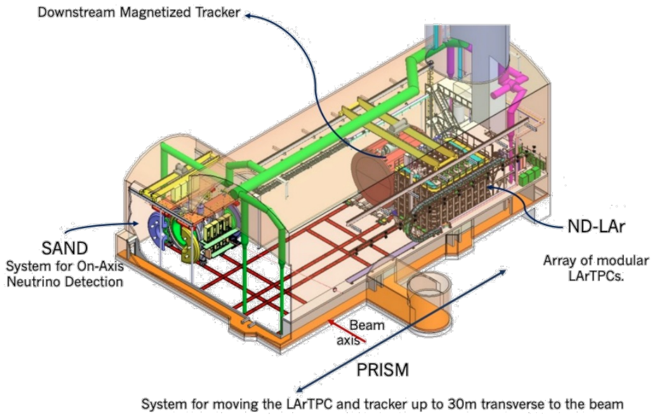


Upgraded T2K/Hyper-K Near Detector

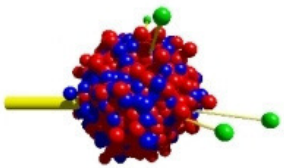


How can you help

Improved near detector capabilities



Engagement with the nuclear theory community



GiBUU

Genie — UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

NuWro — Wroclaw Neutrino Event Generator

Dedicated lepton-nucleus cross-section measurement programs

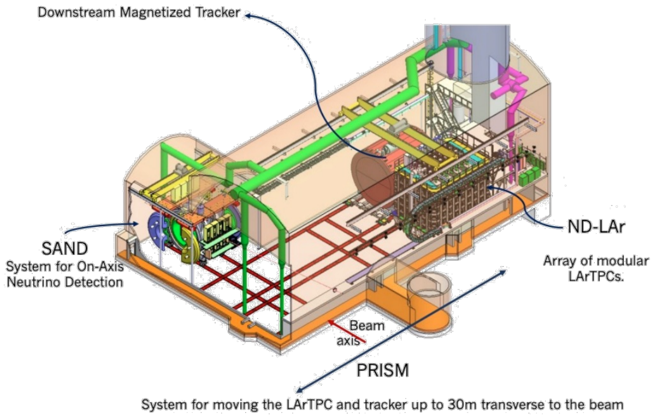
SBN Program

MINERvA

e4ν

How can you help

Improved near detector capabilities



Engagement with the nuclear theory community

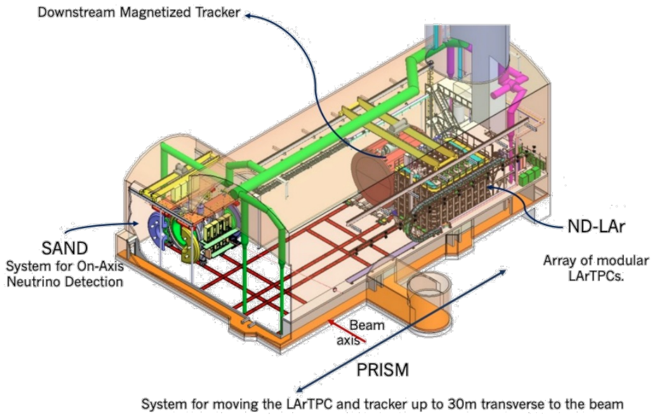
GiBUU

Dedicated lepton-nucleus cross-section measurement programs

Make new cross-section measurements

How can you help

Improved near detector capabilities



Engagement with the nuclear theory community

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NuWro
Wroclaw Neutrino Event Generator

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Improve near-detector performance

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e4…

Make new cross-section measurements

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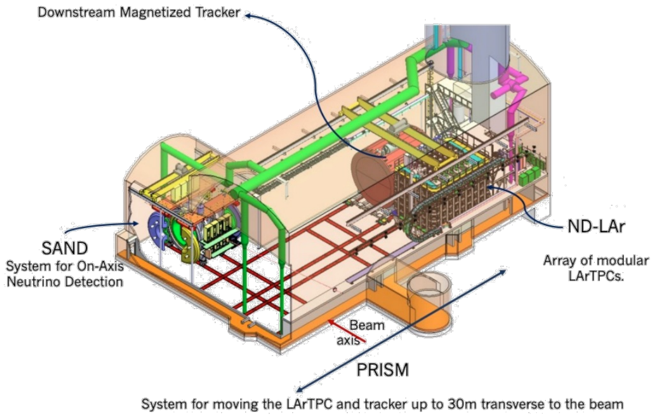
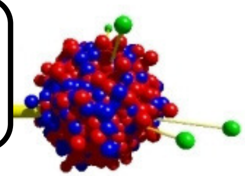


Improve near-detector performance

Engagement with the nuclear theory community

Implement new models in our generators



GiBUU

Genie

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

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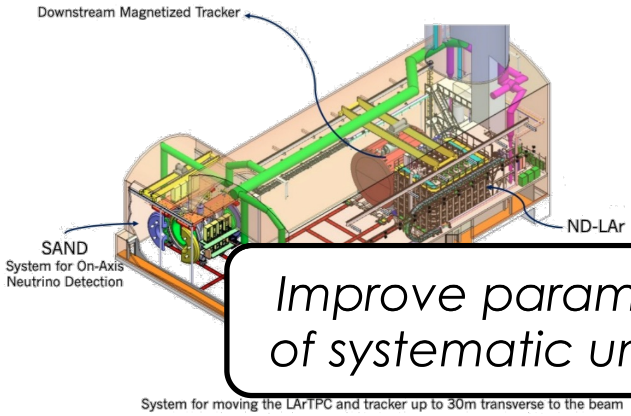
MINERvA

Make new cross-section measurements

How can you help

Improved near detector capabilities



Improve parameterisation of systematic uncertainties

Improve near-detector performance

Engagement with the nuclear theory community

Implement new models in our generators

GiBUU

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Make new cross-section measurements

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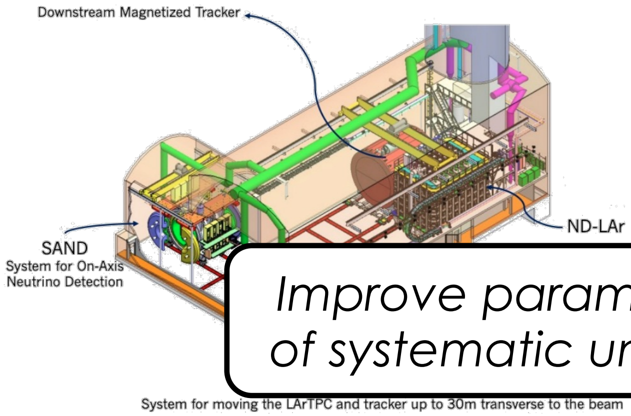


Improve parameterisation of systematic uncertainties

Improve near-detector performance

Engagement with the nuclear theory community

Implement new models in our generators

GiBUU

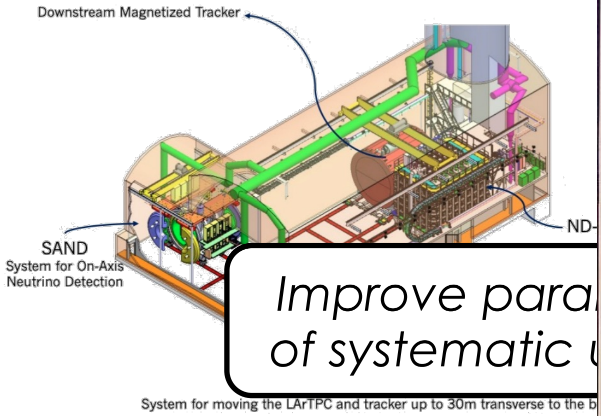
Confront generators with the latest measurements

...dicated lepton-nuc... ...ection measurement programs

Make new cross-section measurements

How can you help

Improved near detector capabilities



Improve para
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Improve near-detector performance

Engagement with the nuclear theory community

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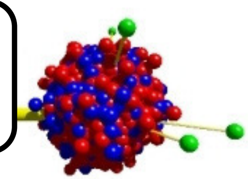

GiBUU

UNIVERSAL NEUTRINO GENERATOR

NuWro
Wrocław Neutrino Event Generator

front generators with
latest measurements

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SBN Program

MINERvA

Make new cross-section measurements

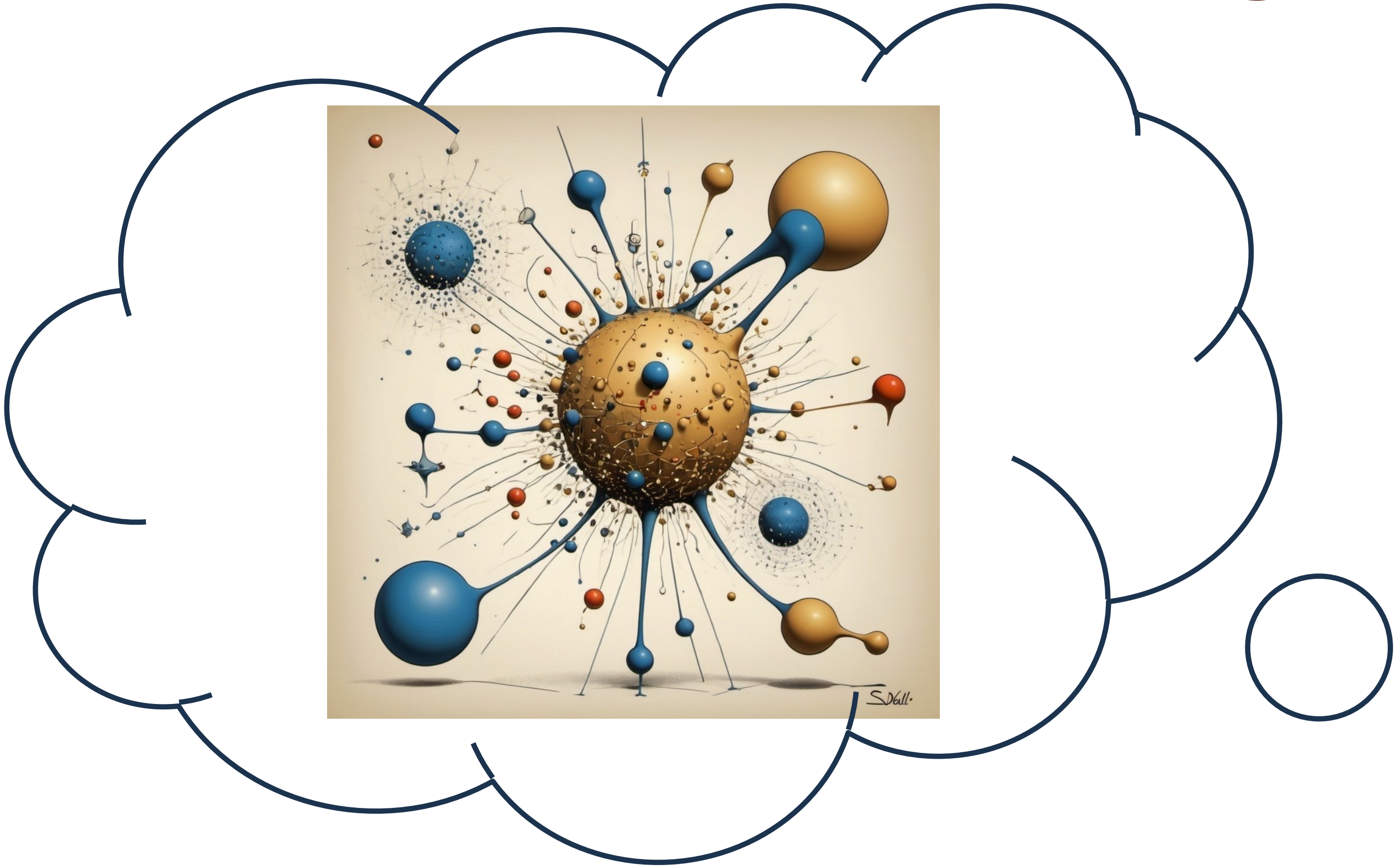
Take-home messages

I think I can safely say that nobody understands neutrino-nucleus interactions

R. Feynman

(But an understanding of them is crucial for oscillation experiments)

Take-home messages

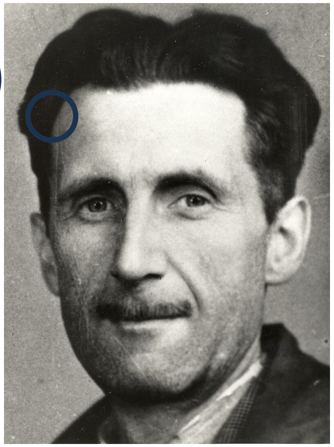


Have no fear of fully exclusive microscopic interaction theories, for we will never reach them

S. Dali

(anytime soon, at least for SIS/DIS)

Take-home messages



All neutrino event generator models are wrong, but some are more wrong than others*

G. Orwelll

*or wrong in different ways

Take-home messages

The golden age (of neutrino interaction models and measurements) is before us, not behind us.

W. Shakespeare

Backups

The precision era of ν oscillations?

Latest results

- **Indication of CP violation!**
- Currently largely limited by statistics … but not for long!

T2K, HYPER K, NOvA, SBN Program, DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Current systematic uncertainties

Source (T2K)	$N(\nu_e)$
$\sigma_{\nu N}$ and FSI	3.8%
Total Syst.	**5.2%**

NEUTRINO 2022
XXX International Conference on Neutrino Physics and Astrophysics

Source (NOvA)	$N(\nu_e)$
$\sigma_{\nu N}$ and FSI	7.7%
Total Syst.	**9.2%**

Phys. Rev. D **98**, 032012

- Tables show **largest** and **total** syst. uncertainty on samples most sensitive to CP-violation
- Current results have ~100 ν_e events, expect **1000-2000** for DUNE/HK

The precision era of ν oscillations?

Latest results

- **Indication of CP violation!**
- Cu... largely limited by st... for long!

Neutrino interaction uncertainties must be reduced for DUNE/Hyper-K to succeed

...rtainties

Source (T2K)	
$\sigma_{\nu N}$ and FSI	3.8%
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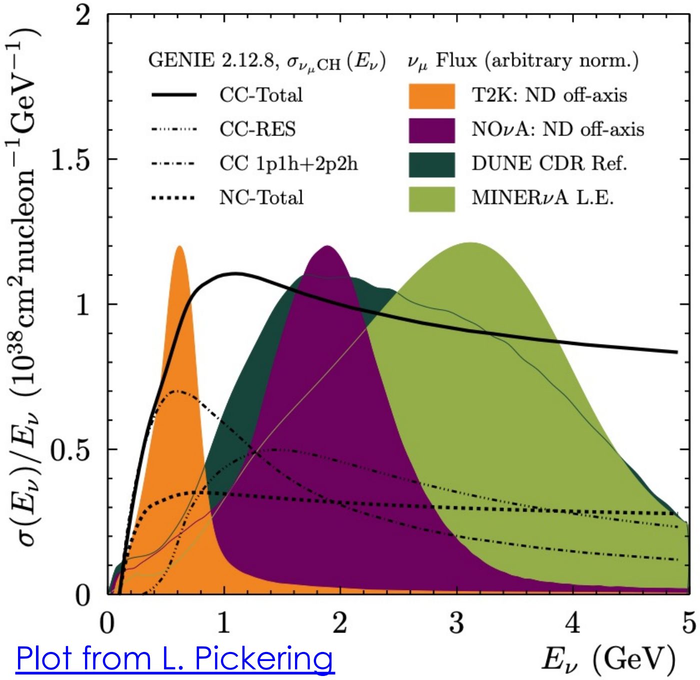
Phys. Rev. D **98**, 032012

- ...rgest and ...rtainty on sam... sensitive to CP-violation
- Current results have ~100 ν_e events, expect **1000-2000** for DUNE/HK

Neutrino nucleon scattering

See Aaron's lectures

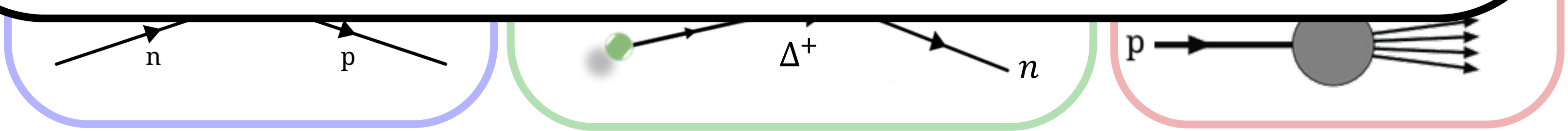
transfer, called q_0 nes ν)



Plot from L. Pickering

Whilst interaction channels live in **relatively narrow regions of energy transfer**, they are **spread out in neutrino energy**

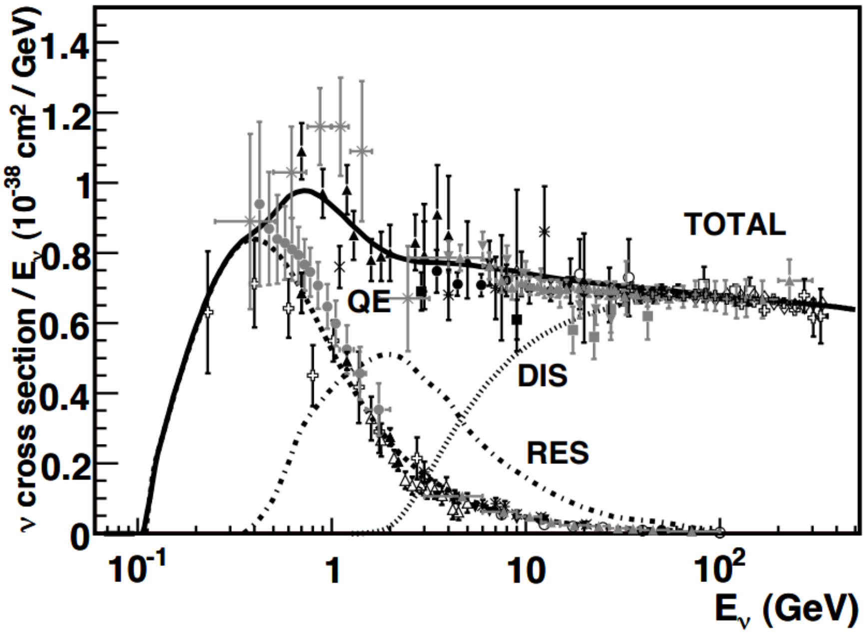
Few-GeV experiments must care about all the channels!

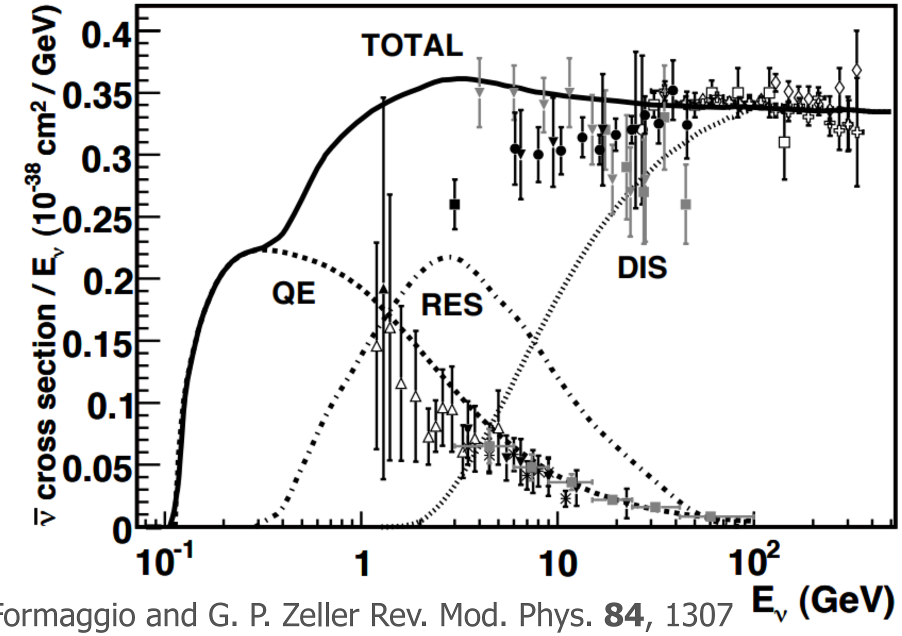


Increasing Energy Transfer

Neutrino-nucleon cross sections

- Discussed neutrino-nucleon interactions
- But it's been a long time since we've measured this process!
- Almost all modern experiments use nuclear targets

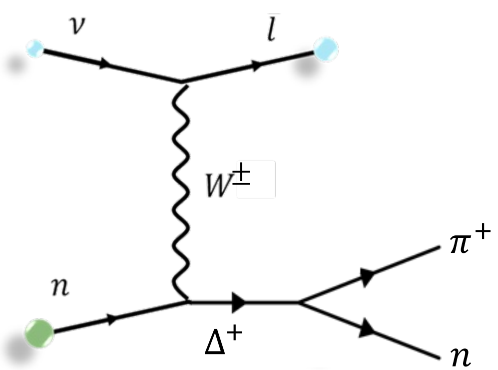




J. A. Formaggio and G. P. Zeller Rev. Mod. Phys. **84**, 1307

Resonant Pion Production

CCRES



Current Matrix Elements from a Relativistic Quark Model*

R. P. Feynman, M. Kislinger, and F. Ravndal
Lauritsen Laboratory of Physics, California Institute of Technology, Pasadena, California 91109
(Received 17 December 1970)

- The model's used in today's neutrino experiments are based on an approximate model from the 1970s

gence of the axial-vector current matrix elements. Starting only from these two constants, the slope of the Regge trajectories, and the masses of the particles, 75 matrix elements are calculated, of which more than $\frac{3}{4}$ agree with the experimental values within 40%. The prob-

ficing theoretical adequacy for simplicity. We shall choose a relativistic theory which is naive and obviously wrong in its simplicity, but which is definite and in which we can calculate as many things as possible – not expecting the results to agree exactly with experiment, but to see how closely our "shadow of the truth" equation gives a partial reflection of reality. In our attempt to maintain simplicity, we shall evidently have to violate known principles of a complete relativistic field theory (for example, unitarity). We shall attempt to modify our calculated results in a general way to allow, in a vague way, for these errors.

- The model includes its own form factors, including an axial part with an analogous M_A (and an additional uncertainty in the form factor numerator)

$$f_A\left(q^2\right) = \frac{f_A(0)}{\left(1 - \frac{q^2}{M_A^2}\right)^2}$$

- Theoretical developments are underway but it's safe to say CCRES is less well understood than CCQE!

DIS-RES Transition Region

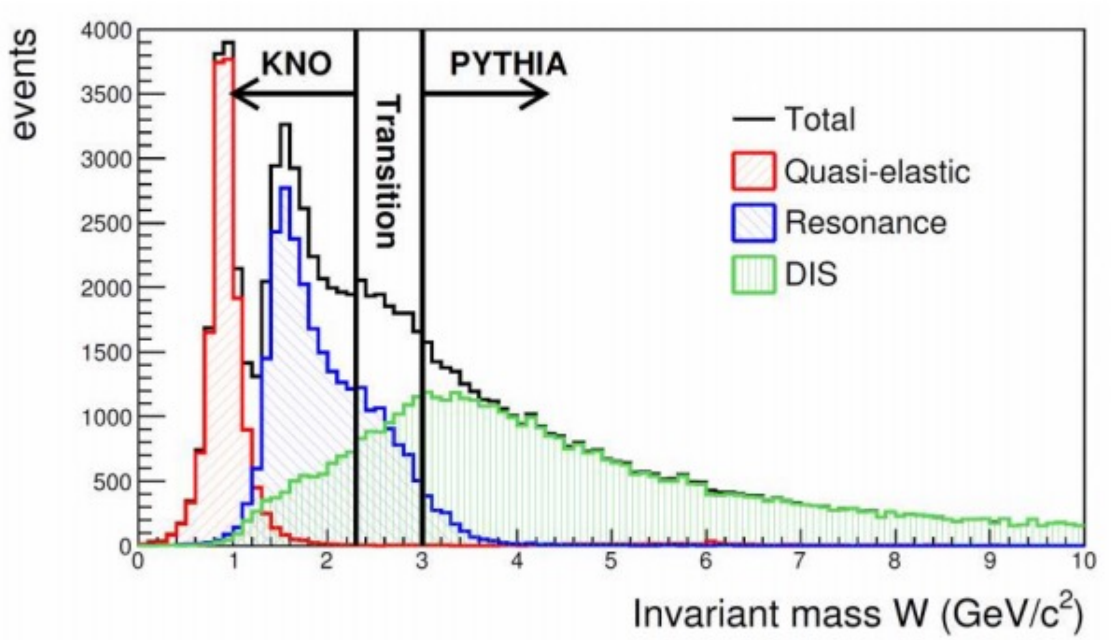
- There is no cut off where we better describe interactions in a DIS framework compared to In a RES framework

- In general we use models that extrapolate between regions which are definitely DIS (e.g. W>5 GeV) and that are definitively RES (e.g. W<2 GeV)

W = interaction invariant mass

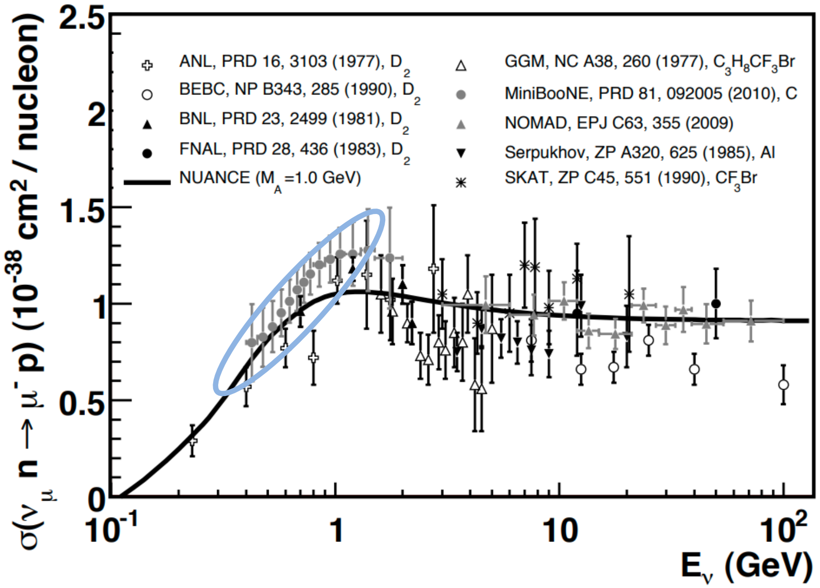
- Different simulations use different *ad-hoc* methods of dealing with this

- But this is a region that will be important for DUNE!

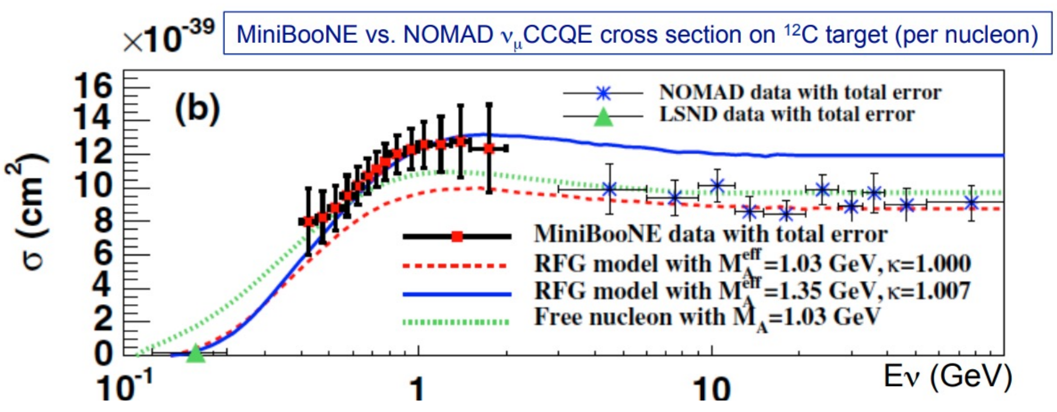


Example: nucleon axial mass "puzzle"

- Some heavier nuclear target experiments also try to measure M_A
- The MiniBooNE experiment (carbon-based target) prefers a much higher M_A to the bubble chambers

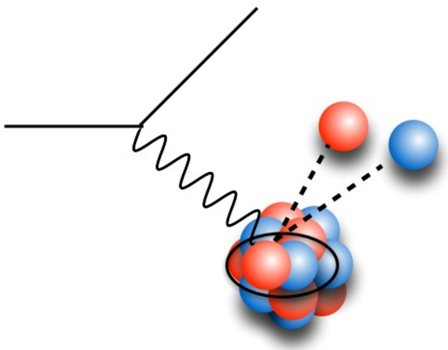


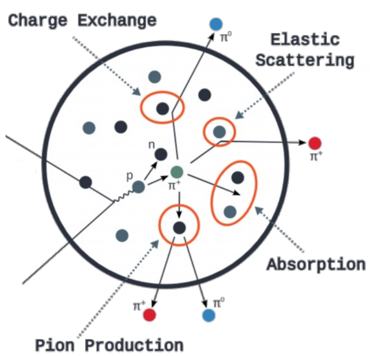
J. A. Formaggio and G. P. Zeller Rev. Mod. Phys. **84**, 1307



The nucleon axial mass "puzzle"

- What MiniBooNE really measured wasn't CCQE, they just looked for interactions with no mesons in the final state





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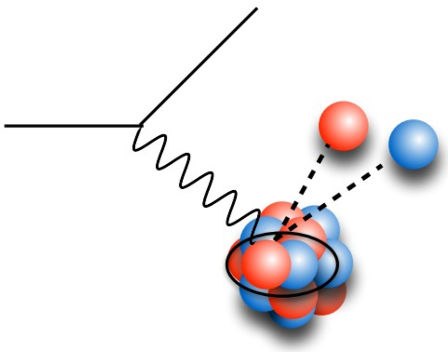
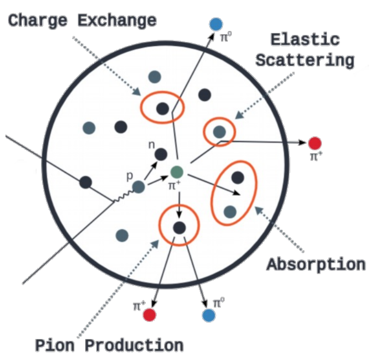
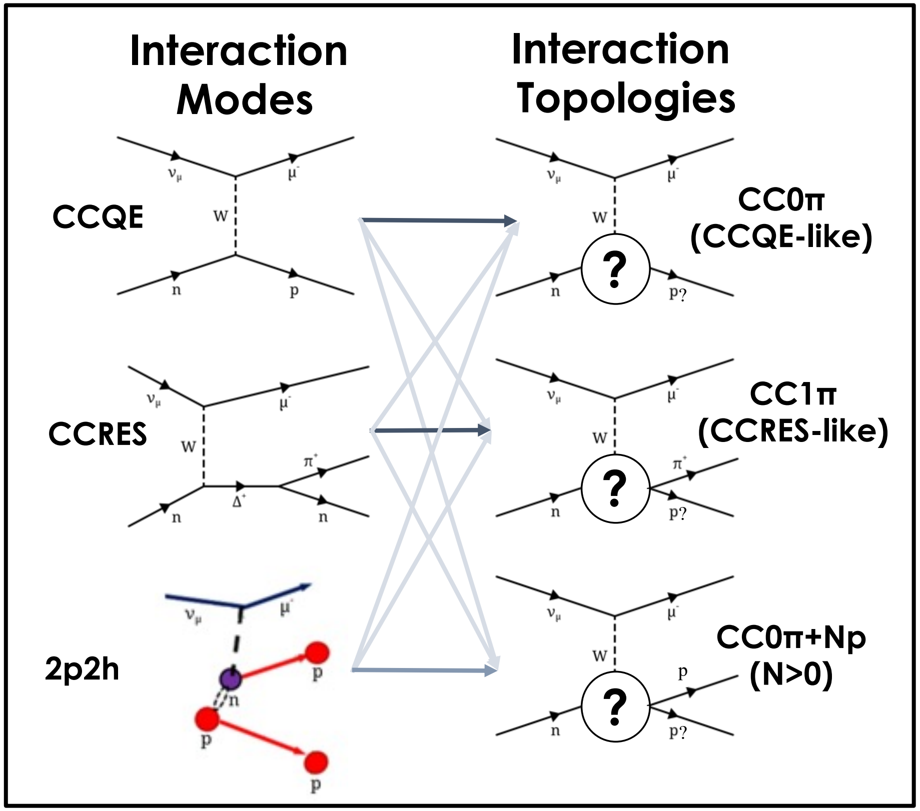
- What MiniBooNE really measured wasn't CCQE, they just looked for interactions with no mesons in the final state
- This should include contributions from 2p2h (and FSI with pion absorption)!





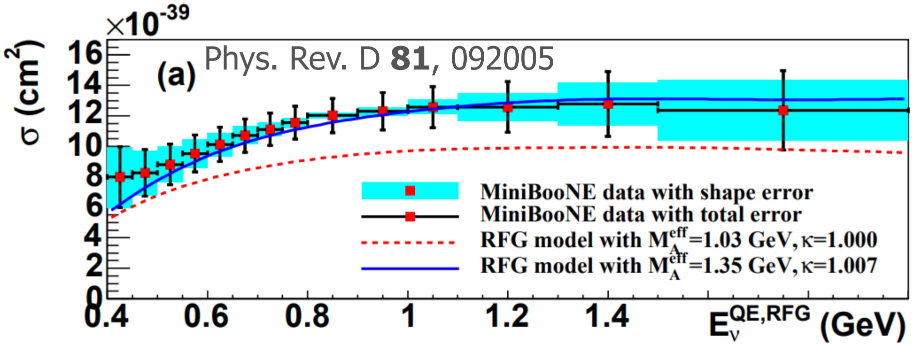


The nucleon axial mass “puzzle”

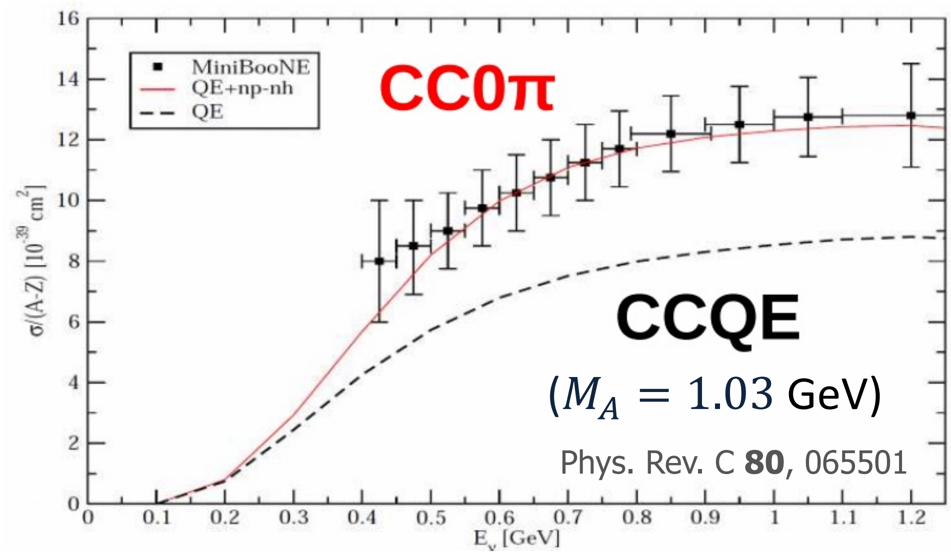
- What MiniBooNE really measured wasn’t CCQE, they just looked for interactions with no mesons in the final state

- This should include contributions from 2p2h (and FSI with pion absorption)!

If we only consider CCQE, M_A~1.3 GeV



But with 2p2h, M_A is compatible with 1.0 GeV suggested by bubble chambers



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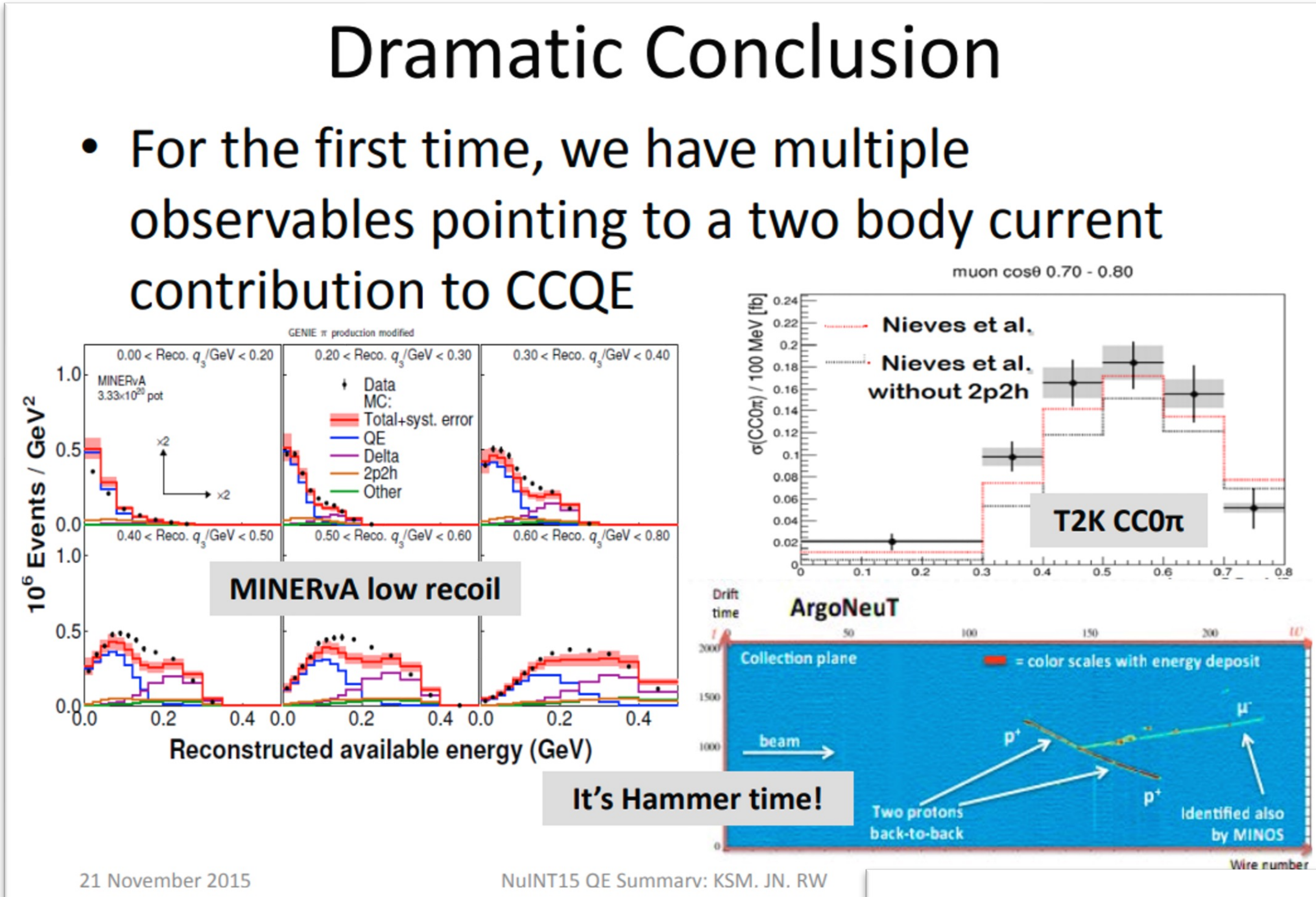


NuInt 2015 Summary
by Kevin McFarland

- It's time to say goodbye to $M_A^{effective}$

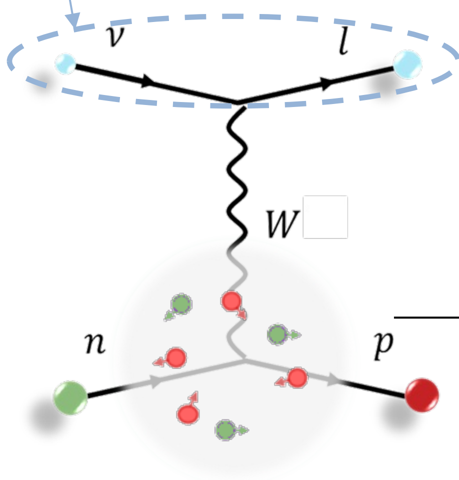
Inclusive calculations

All of the nuclear dynamics lives in here

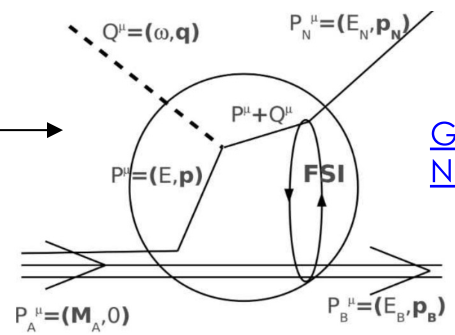
Inclusive calculations come "pre-integrated" over hadron kinematics

$$\frac{d^2\sigma_{\nu l}}{d\Omega(\hat{k}')dE_l'} = \frac{|\vec{k}'|}{|\vec{k}|}\frac{G^2}{4\pi^2}L_{\mu\sigma}W^{\mu\sigma}$$

Only predicts lepton kinematics!



E.g. Inclusive quasielastic charged-current neutrino-nucleus reactions, J. Nieves et al, 2004



G. Megias NuInt18 talk

RMF-FSI: Scattered nucleon w.f. is solution of Dirac eq. in presence of the same potentials used to describe the bound nucleon w.f.

In some calculations, the nuclear effects considered **includes the impact of Final State Interactions** (FSI) with a QM treatment

Like this, FSI changes the matrix element
- Affects cross section as a function of lepton *and* hadron kinematics!

Inclusive calculations

All of the nuclear dynamics lives in here

Inclusive calculations come "pre-integrated" over hadron kinematics

$$\frac{d^2\sigma_{\nu l}}{d\Omega(\hat{k}')dE'_l} = \frac{|\vec{k}'|}{|\vec{k}|}\frac{G^2}{4\pi^2}L_{\mu\sigma}W^{\mu\sigma}$$

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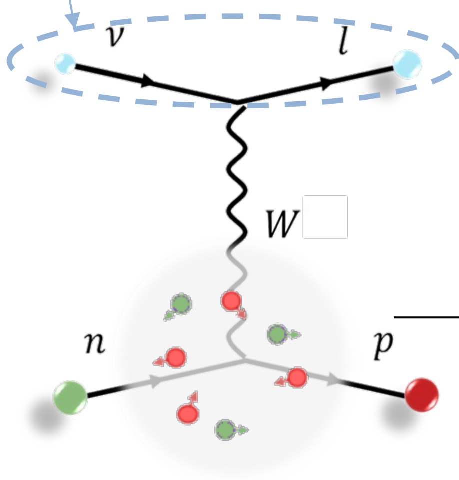

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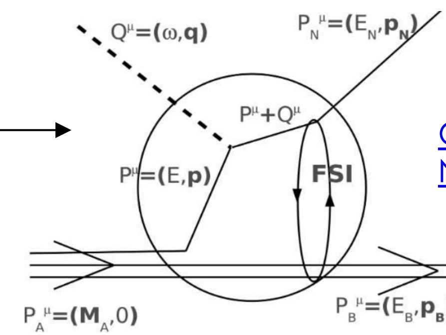

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In some calculations, the nuclear effects considered **includes the impact of Final State Interactions** (FSI) with a QM treatment

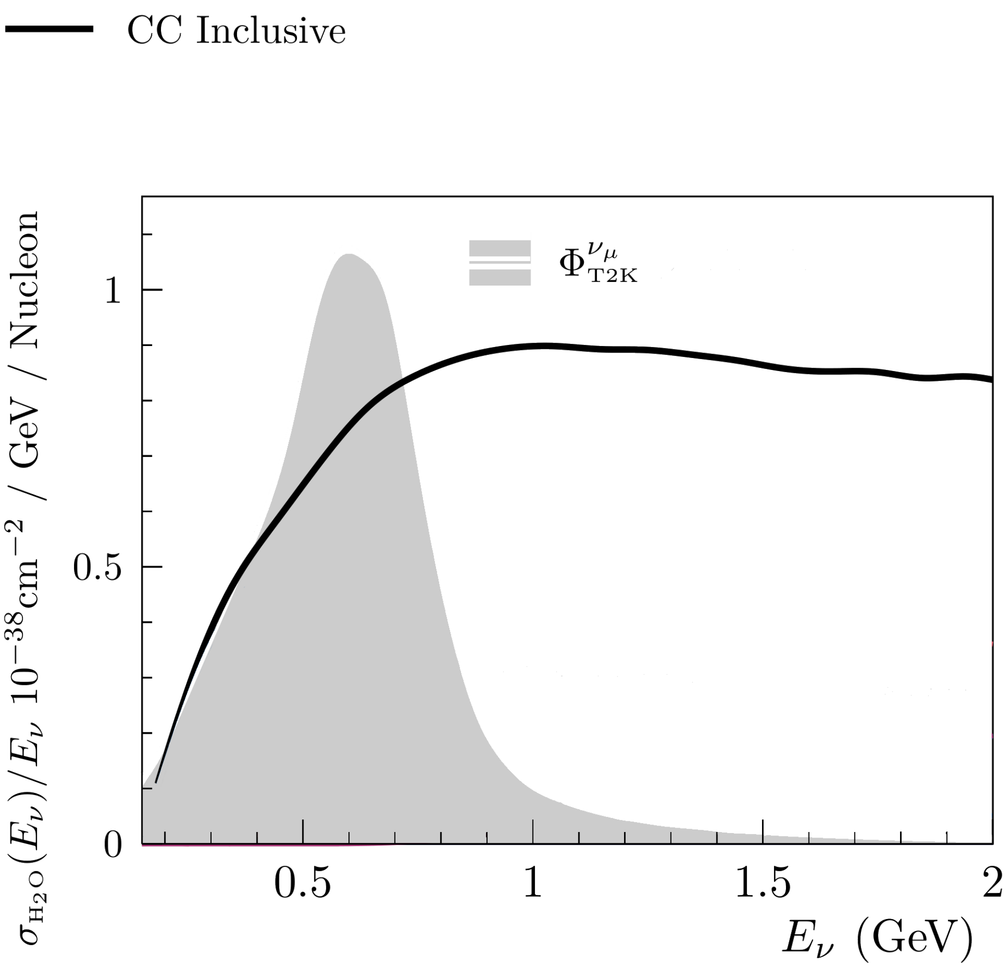
FSI like this is included in QE models, but not 2p2h

SuSA or Valencia 2p2h – no consideration of FSI

SuSAv2 or CRPA in GENIE v3 – impact of FSI on inclusive cross section is considered

Event Generation

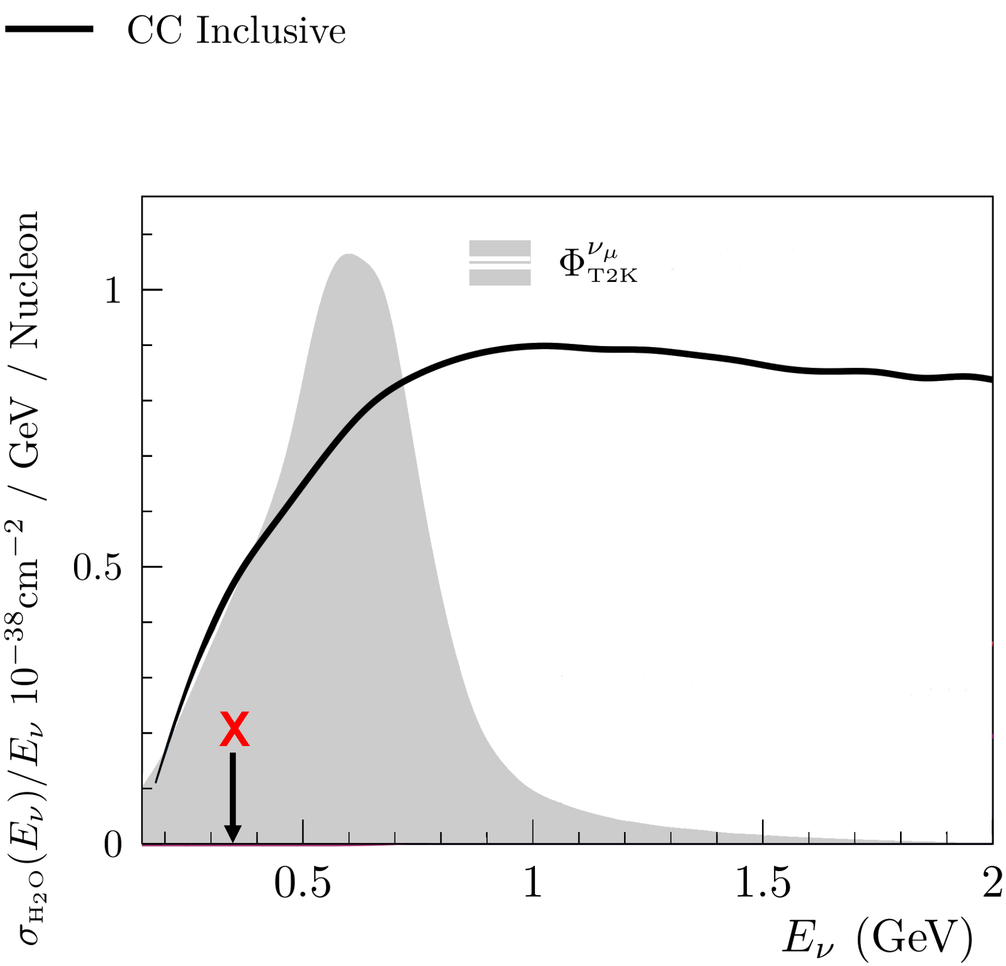
- Randomly select E_ν based on the product of an input flux and total $\sigma(E_\nu)$ model



Example for if we generate only CC events

Event Generation

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



Example for if we generate only CC events

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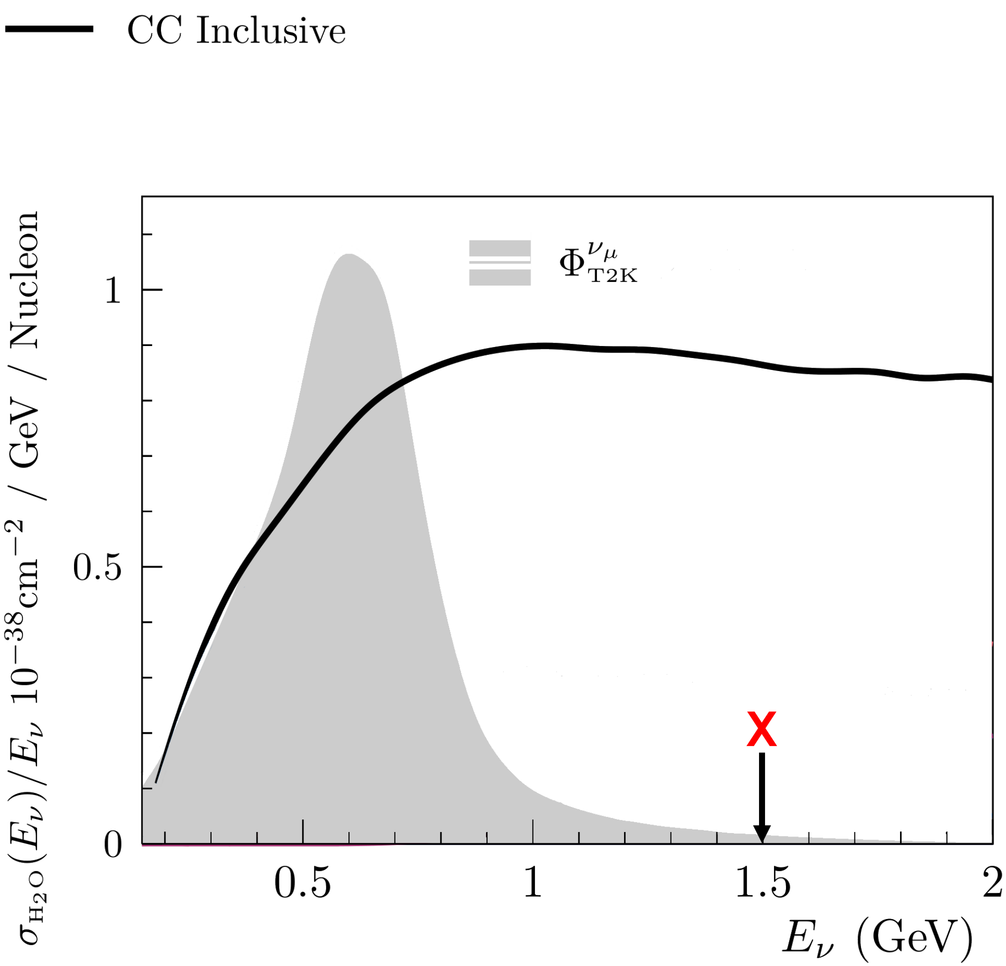
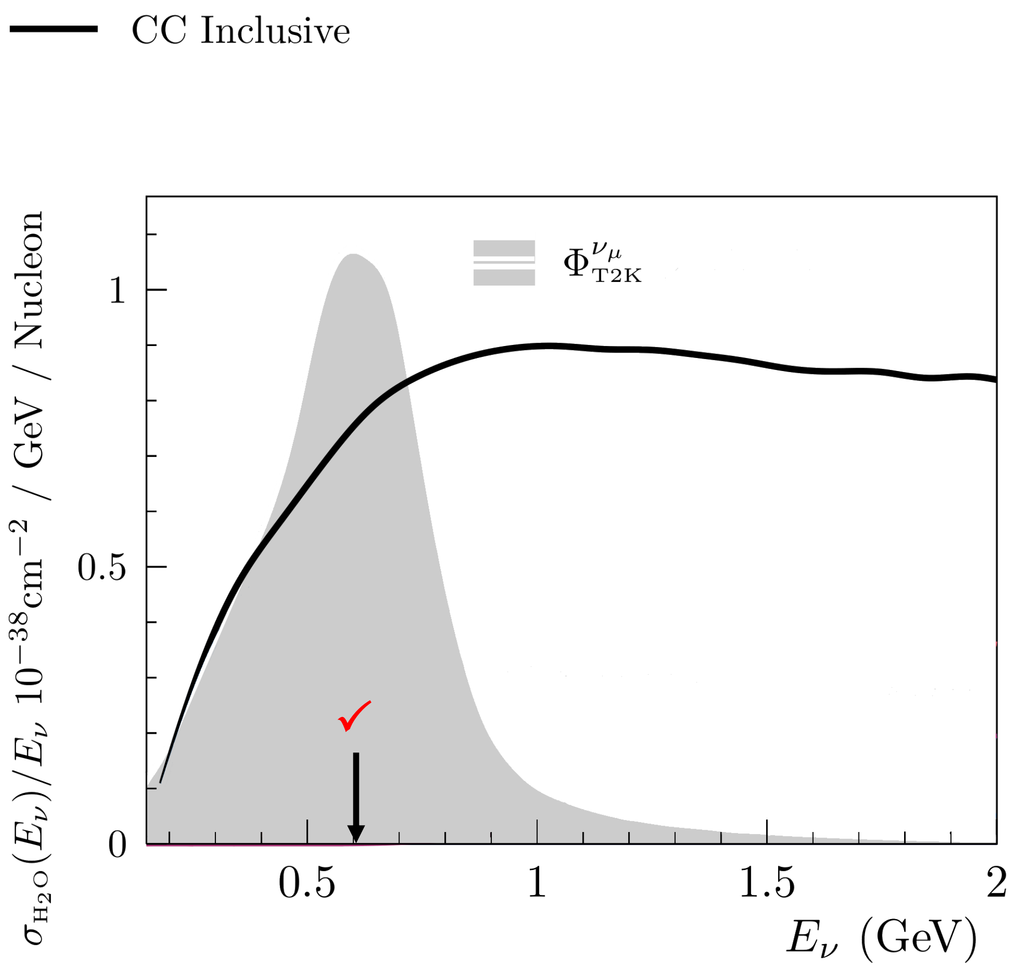


Example for if we generate only CC events

Event Generation

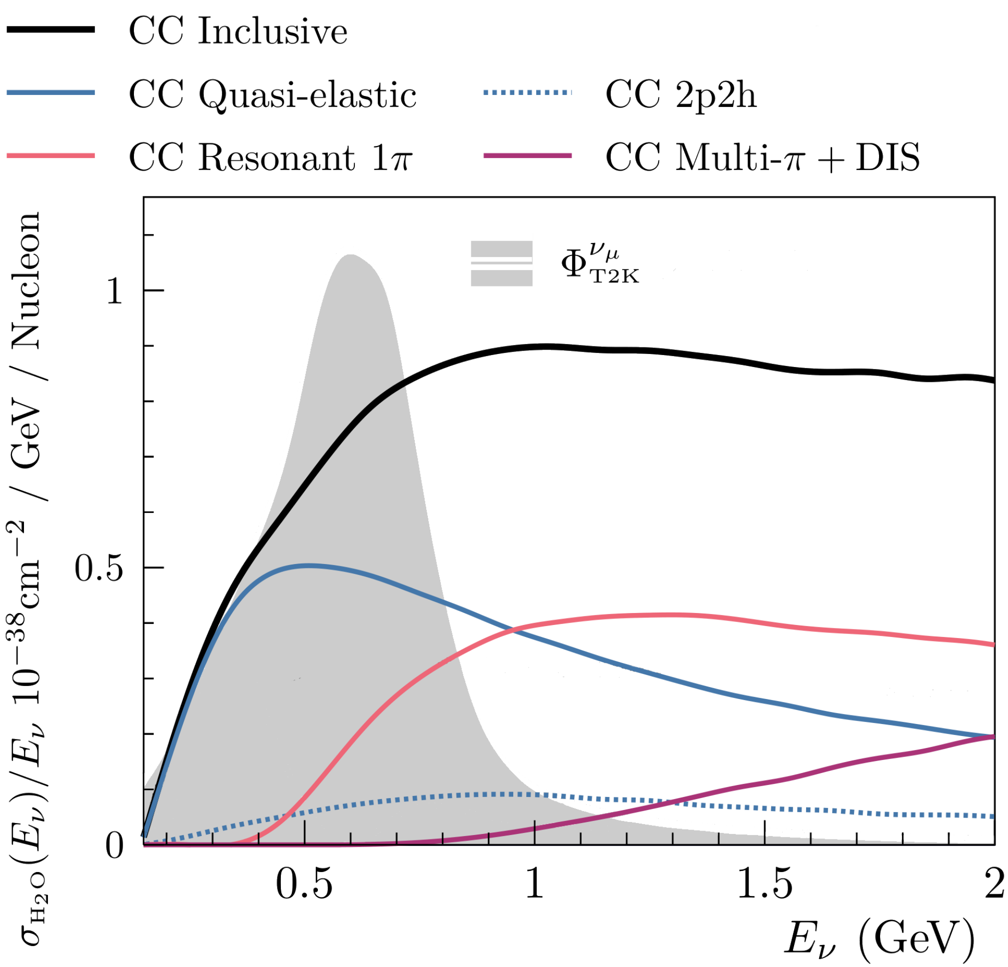
- Randomly select E_ν based on the product of an input flux and total $\sigma(E_\nu)$ model



Example for if we generate only CC events

Event Generation

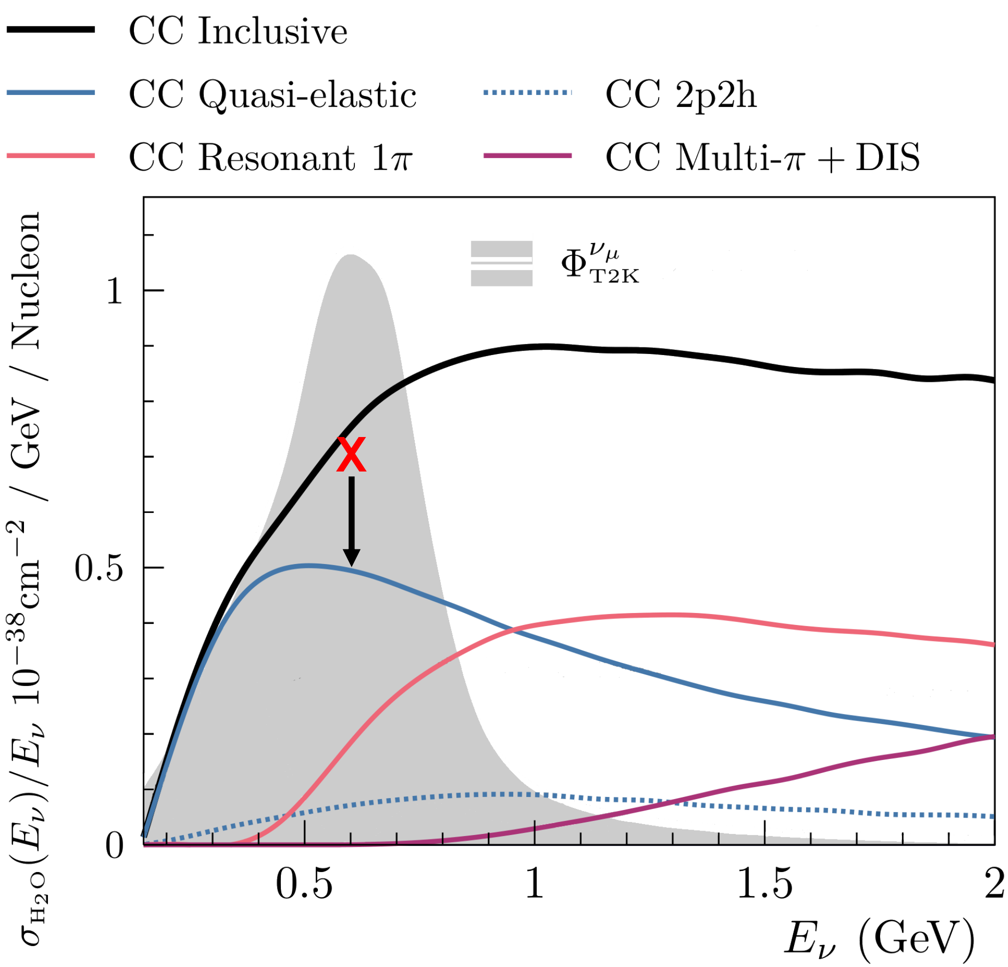
- Randomly select **interaction channel** based on their cross sections for the chosen E_ν



Example for if we generate only CC events

Event Generation

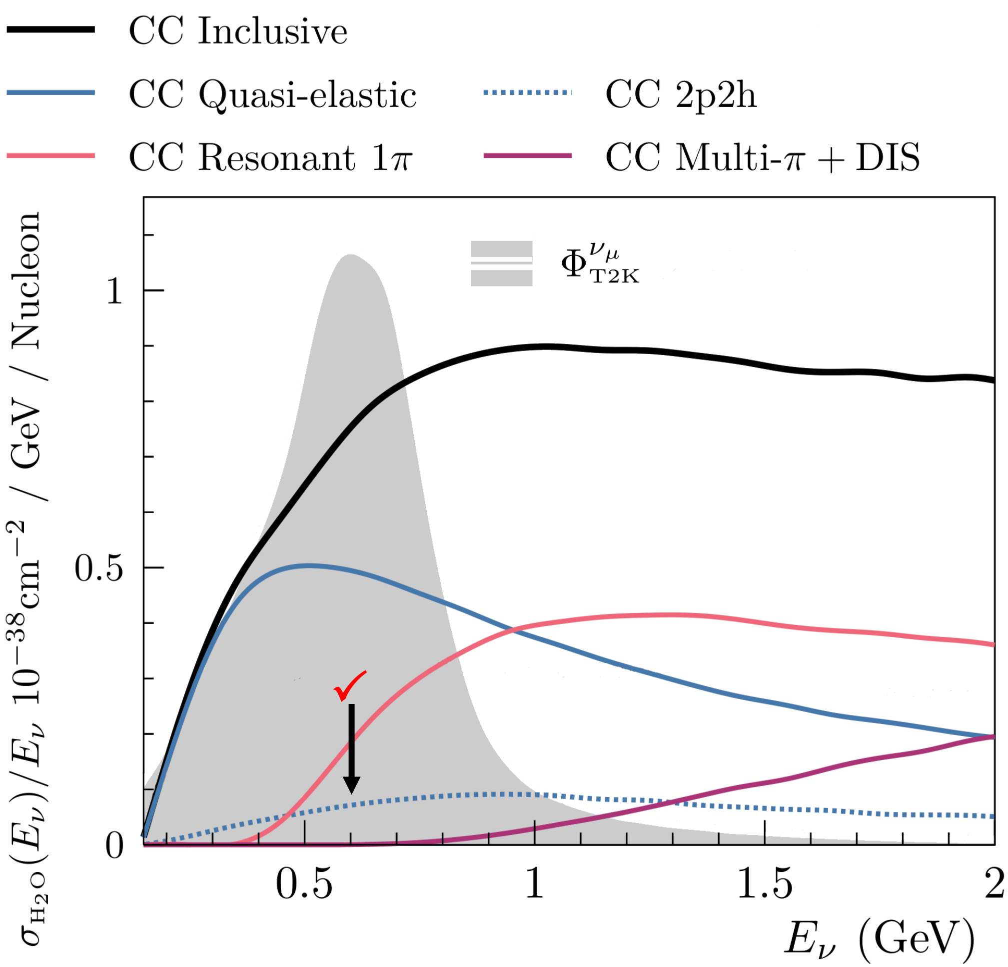
- Randomly select **interaction channel** based on their cross sections for the chosen E_ν



Example for if we generate only CC events

Event Generation

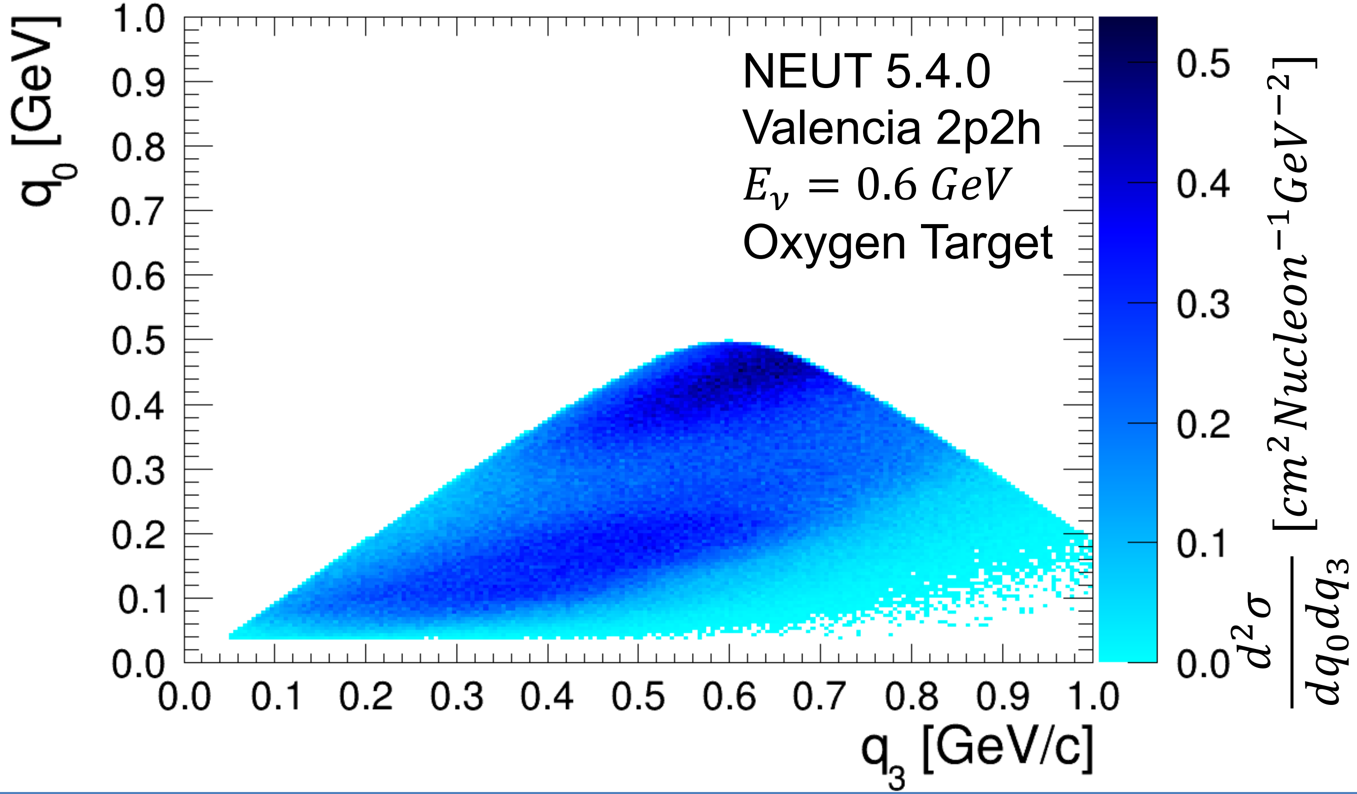
- Randomly select **interaction channel** based on their cross sections for the chosen E_ν



Example for if we generate only CC events

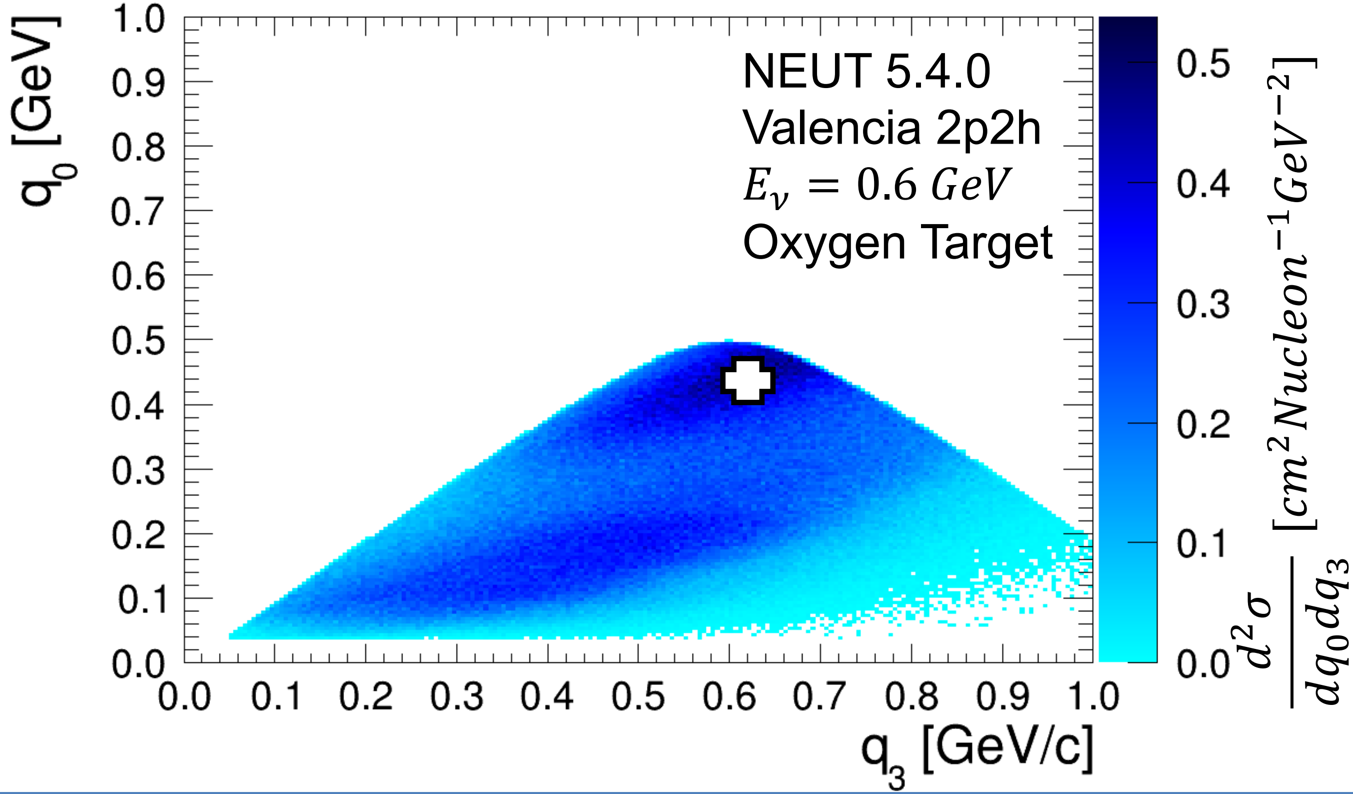
Event Generation

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



Event Generation

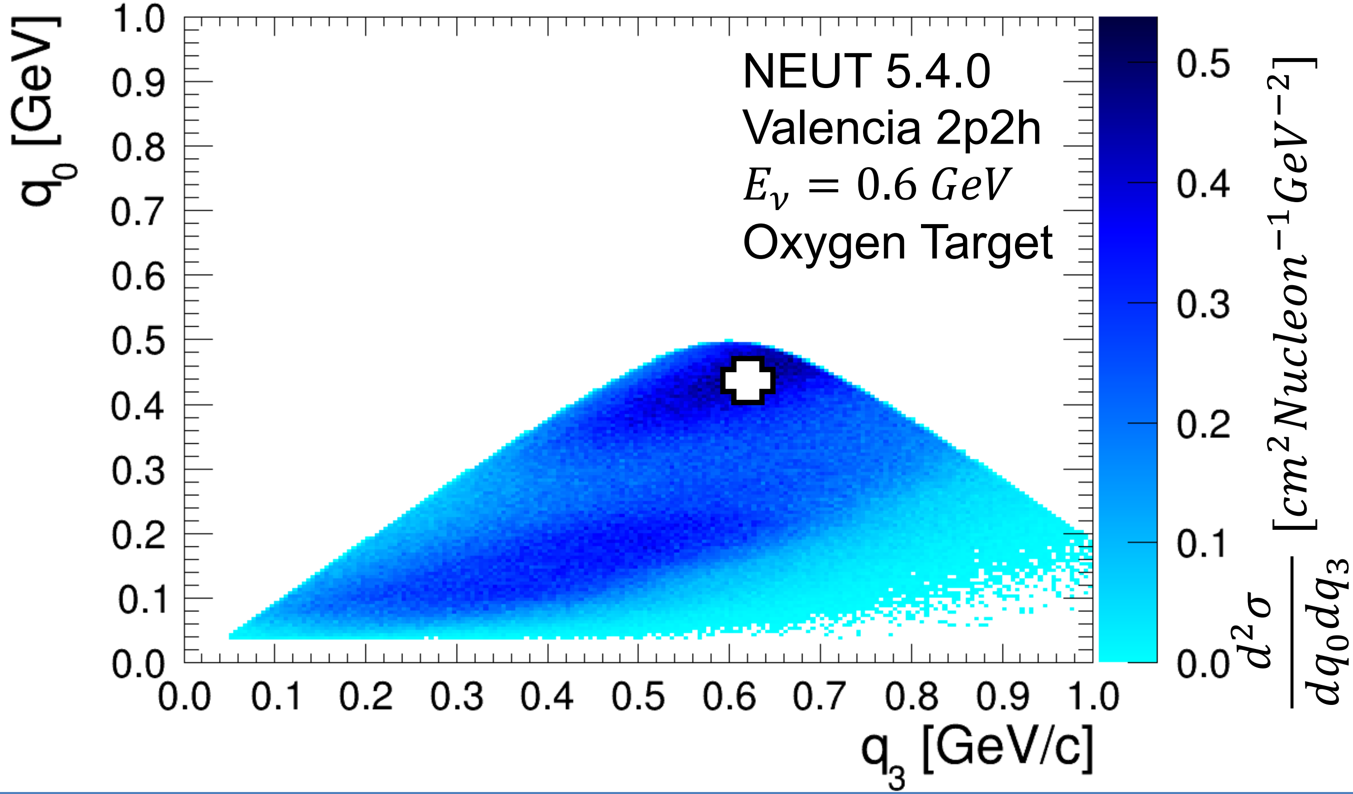
- Select **outgoing particle kinematics** according to differential cross section for the chosen interaction channel at the chosen E_ν



Event Generation

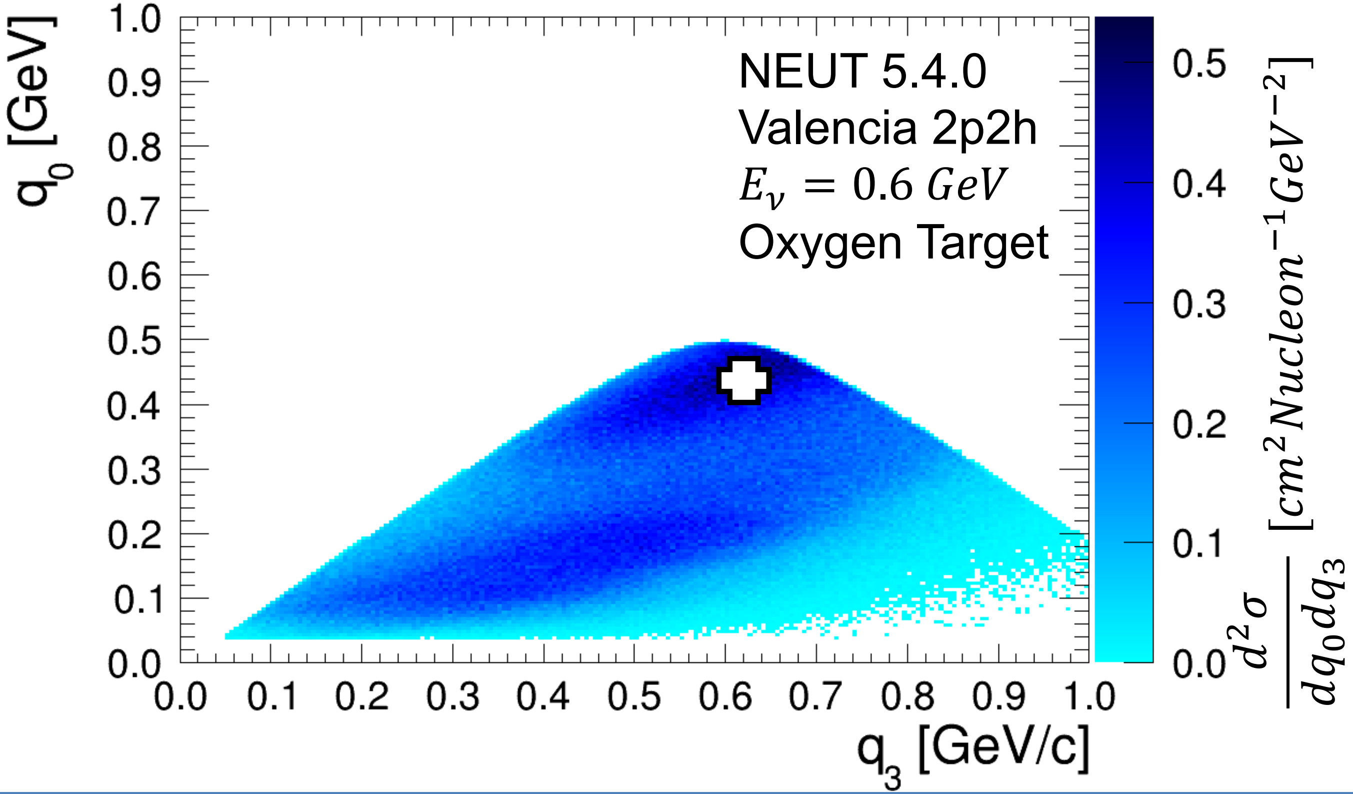
- Select **outgoing particle kinematics** according to differential cross section for the chosen interaction channel at the chosen E_ν
  - **Nucleon-level input**: for CCQE we sample in 1 dimension (more for nonQE): $d\sigma/dQ^2$
  - **Inclusive input**: for any interaction channel we sample in 2, e.g.: $d\sigma/dq_0 dq_3$
  - **Factorized/exclusive input**: for CCQE we sample in 5 dimensions (more for nonQE)

$$\frac{d^5\sigma_{\nu\ell}}{d\Omega(\hat{k}')d\Omega(p_N)\mathrm{dE}_{\ell'}} \sim L_{\mu\sigma}W^{\mu\sigma}$$



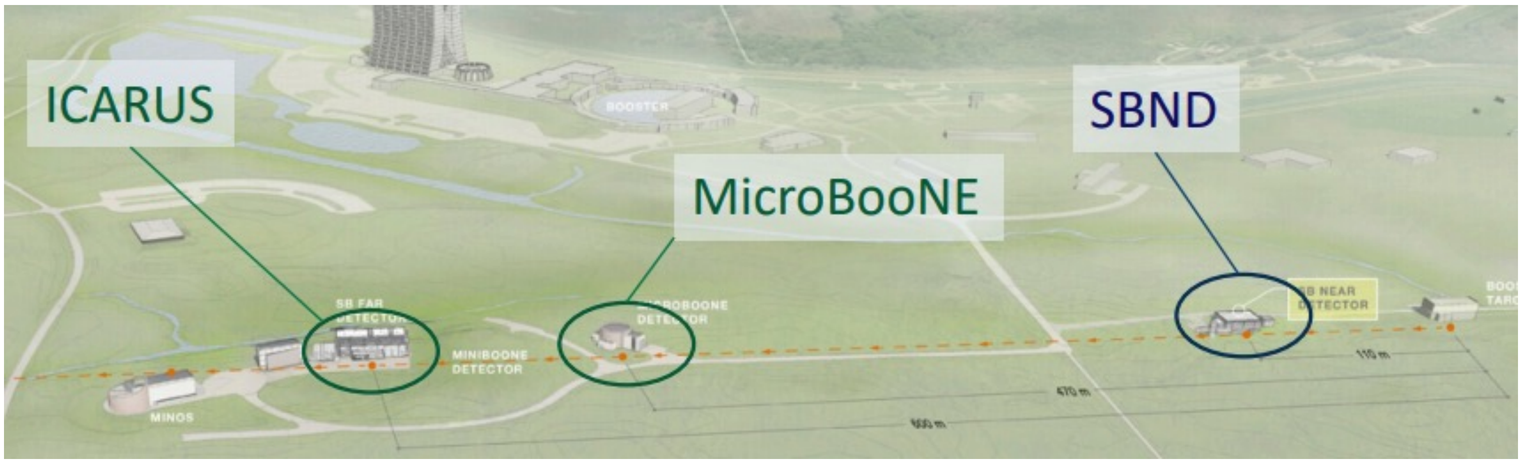
Event Generation

- Select **outgoing particle kinematics** according to differential cross section for the chosen interaction channel at the chosen E_ν
  - **Nucleon-level input**: gives us lepton kinematics in the struck nucleon rest-frame
  - **Inclusive input**: gives us lepton kinematics in the lab frame
  - **Factorized/exclusive input**: lepton + pre-FSI nucleon kinematics in the lab frame



A bright future for Argon

Short Baseline Program: Fermilab liquid Argon detectors in “Booster” beam (~0.8 GeV)



- **MicroBooNE**: already producing interesting results
- **ICARUS**: taking physics data
- **SBND:** enormous event rates coming soon (1M ν/y)

Beyond SBN:

- **DUNE “2x2” prototype:** measurements at DUNE energies