# Simulating neutrino interactions and their impact on oscillation experiments

*Part 2*

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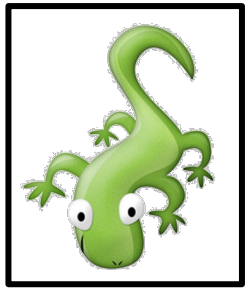
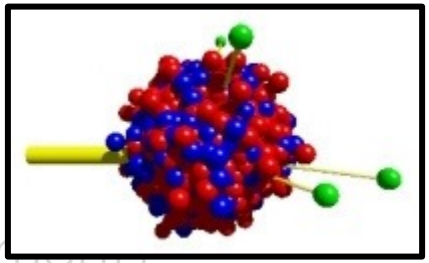
# Summary so far

- 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!**
- 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**

# Overview

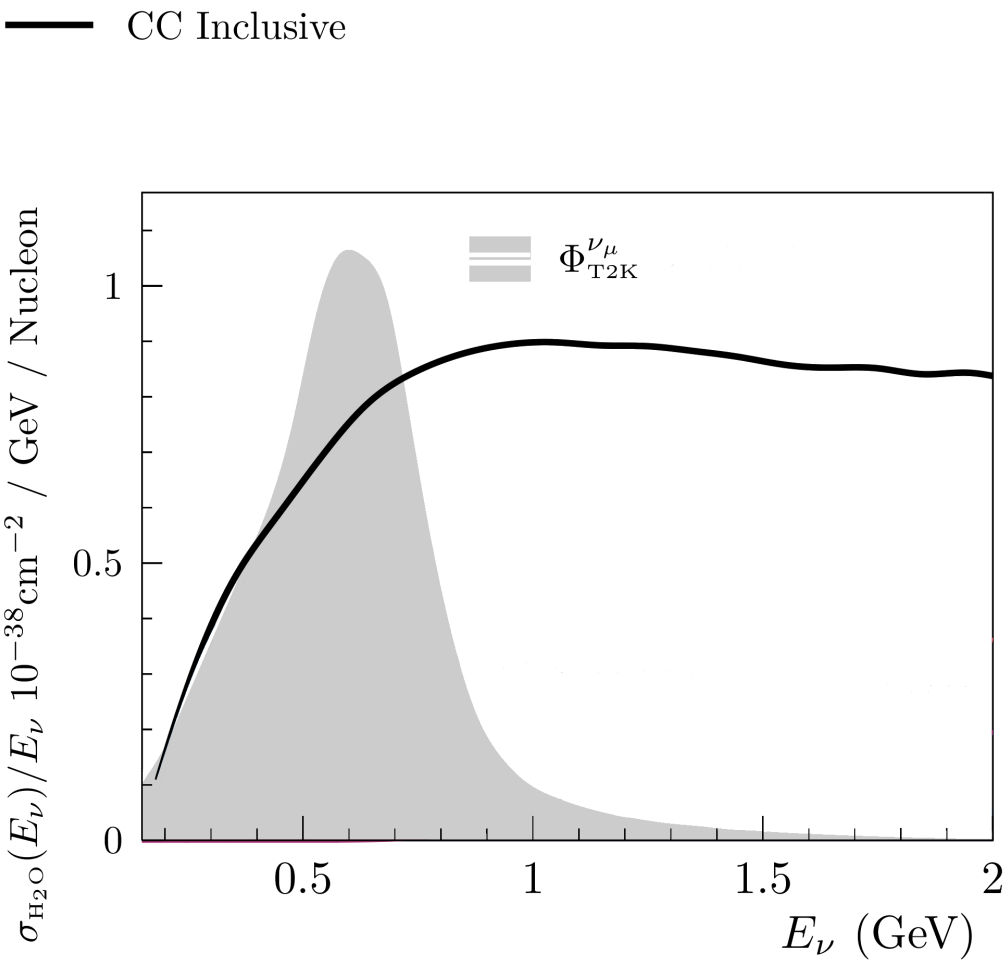
- Neutrino Interactions: A History
  - Weak interactions from Fermi to SM
- Neutrino-nucleon interactions
  - QE, RES and DIS
- Neutrino-nucleus interactions
  - Nuclear effects
  - The rise and fall of $M_A = 1.3\ GeV$
- Neutrino event generators
  - Theory inputs
  - **Filling in the gaps**
- Neutrino-nucleus interaction measurements
  - Inclusive successes and exclusive failures
- Why do we care?
  - Neutrino interactions for neutrino oscillations
  - Neutrino energy reconstruction
- Don't Panic! The future of neutrino interaction simulations





# Event Generation

- Randomly select $E_\nu$ 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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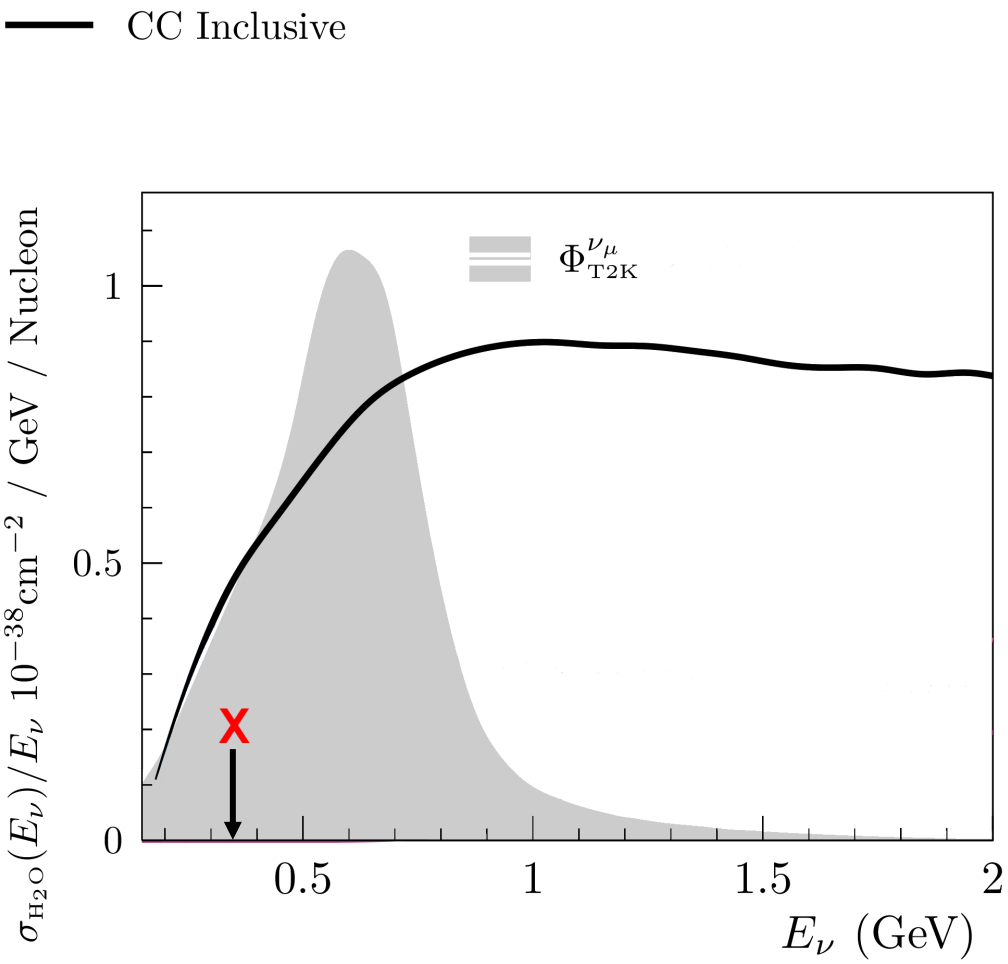


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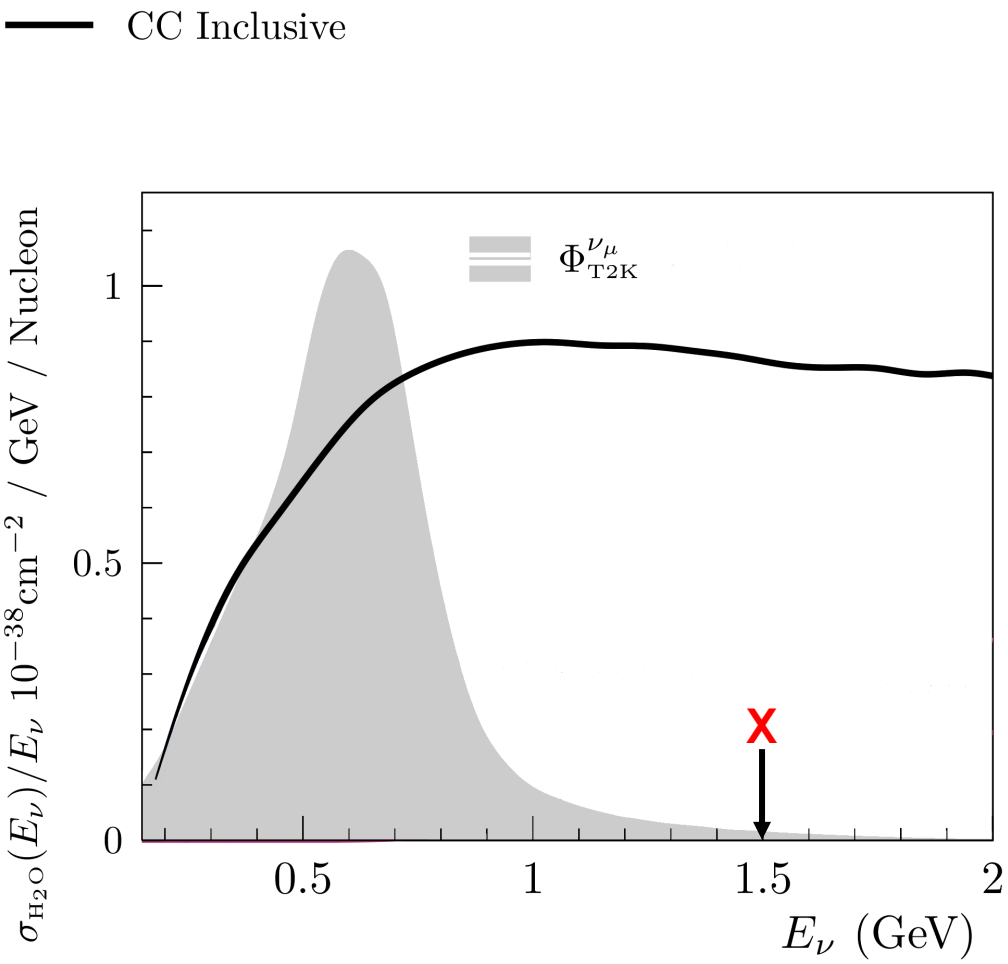


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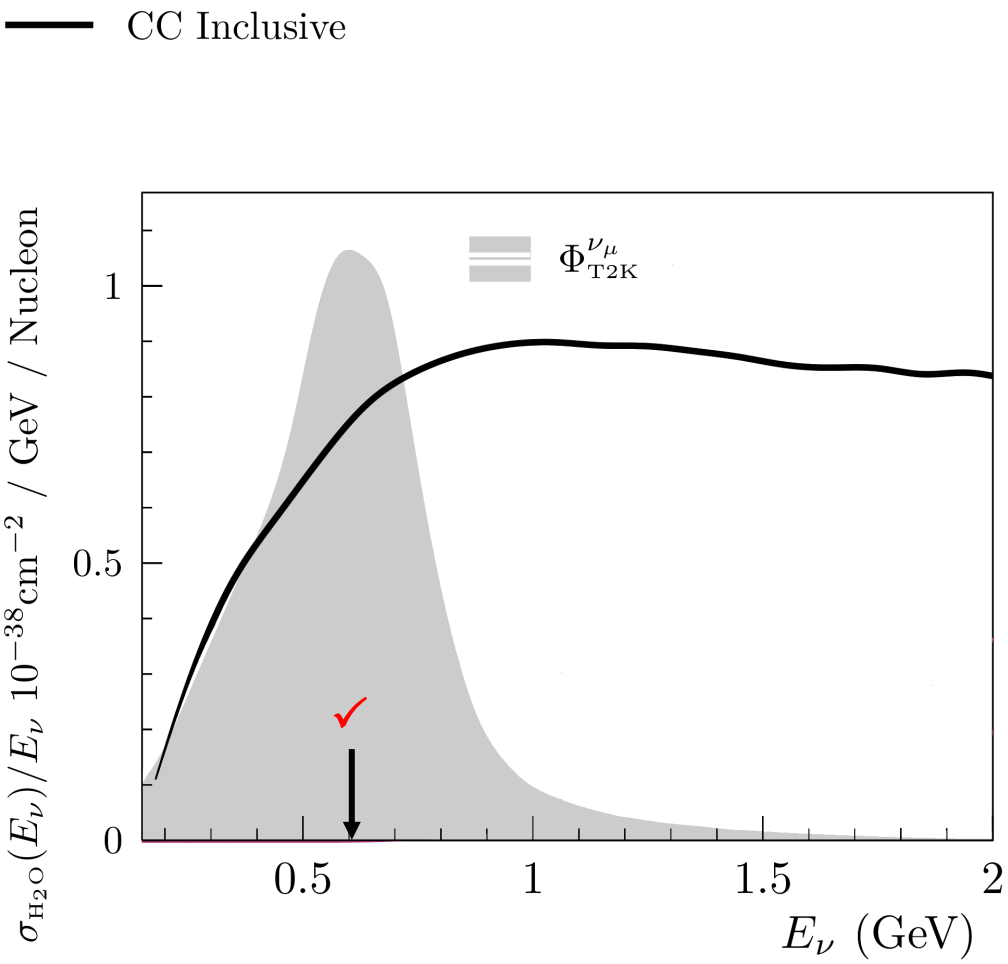


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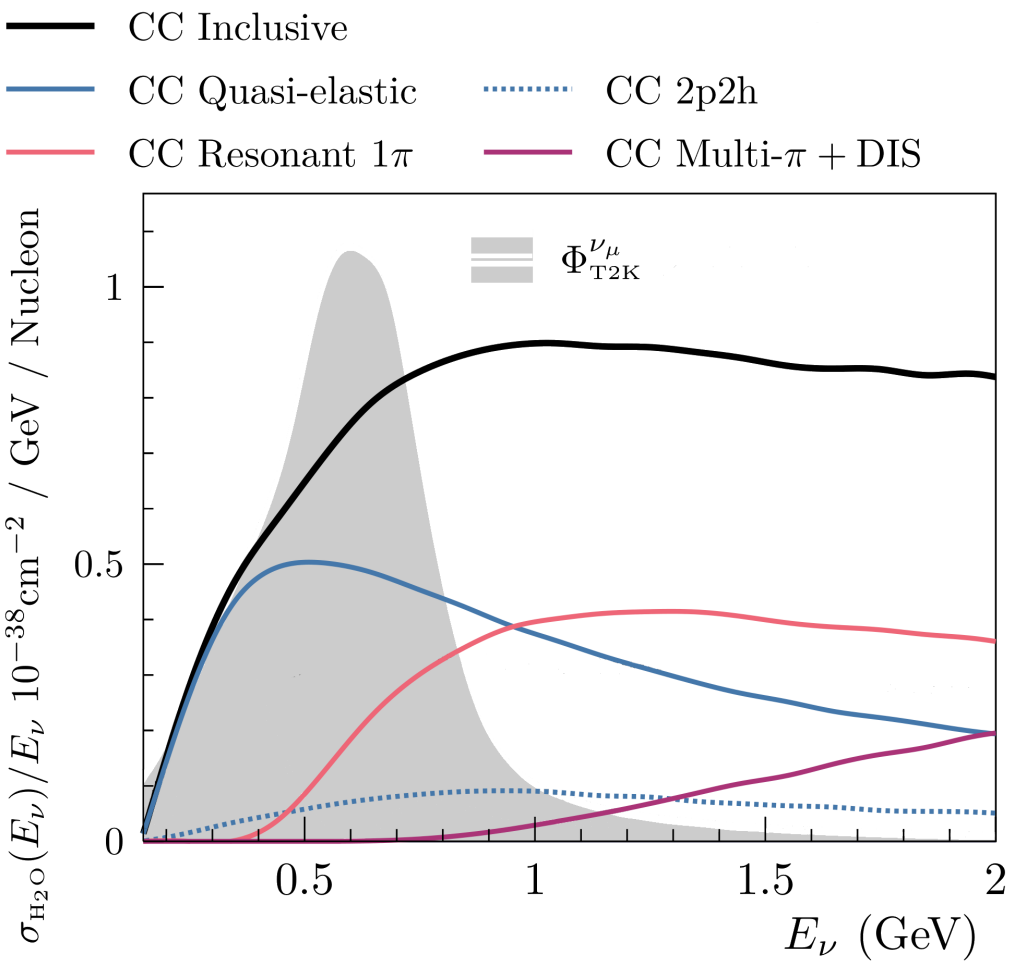


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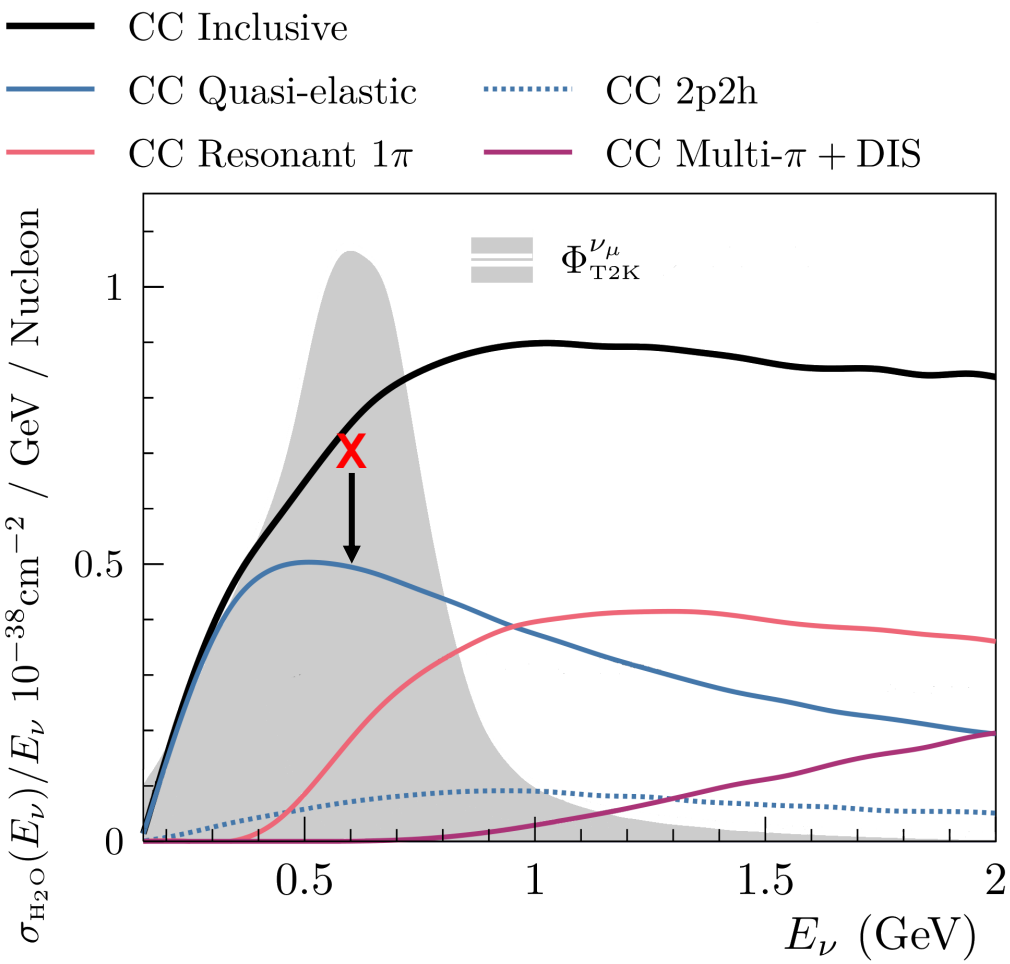


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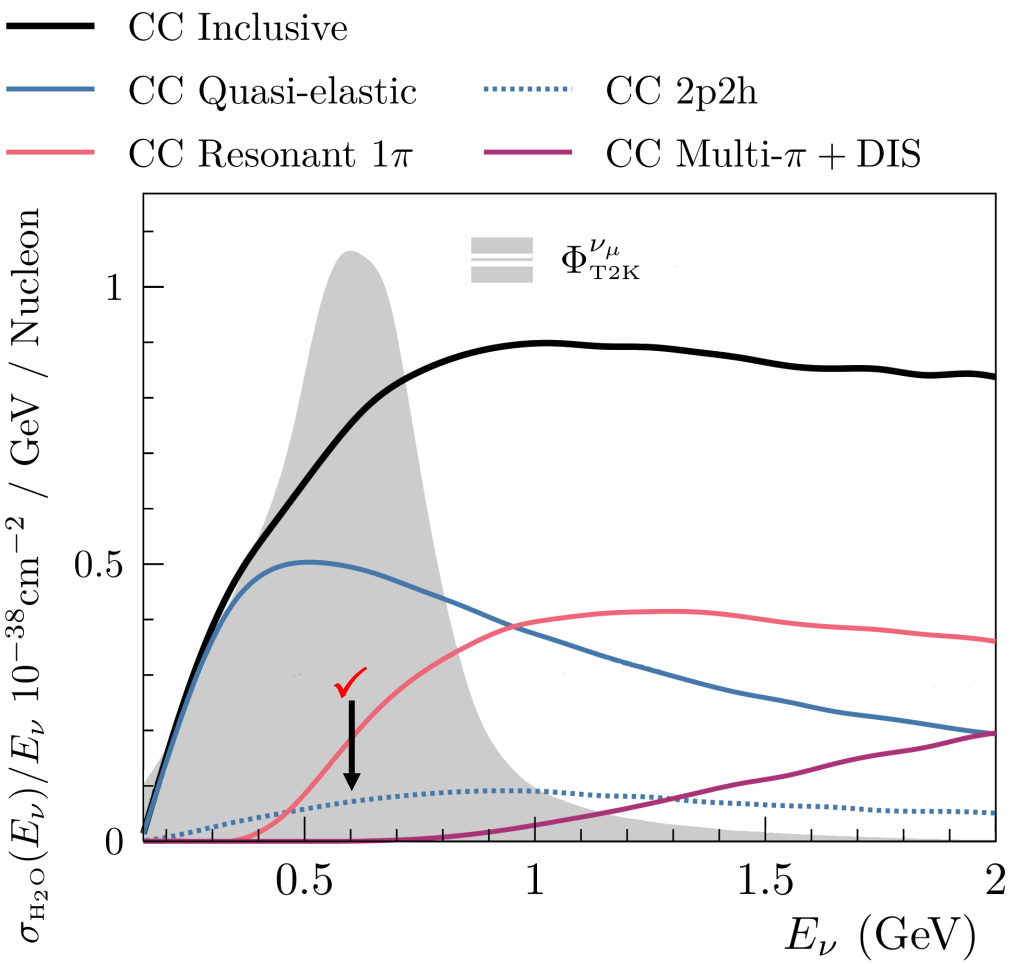


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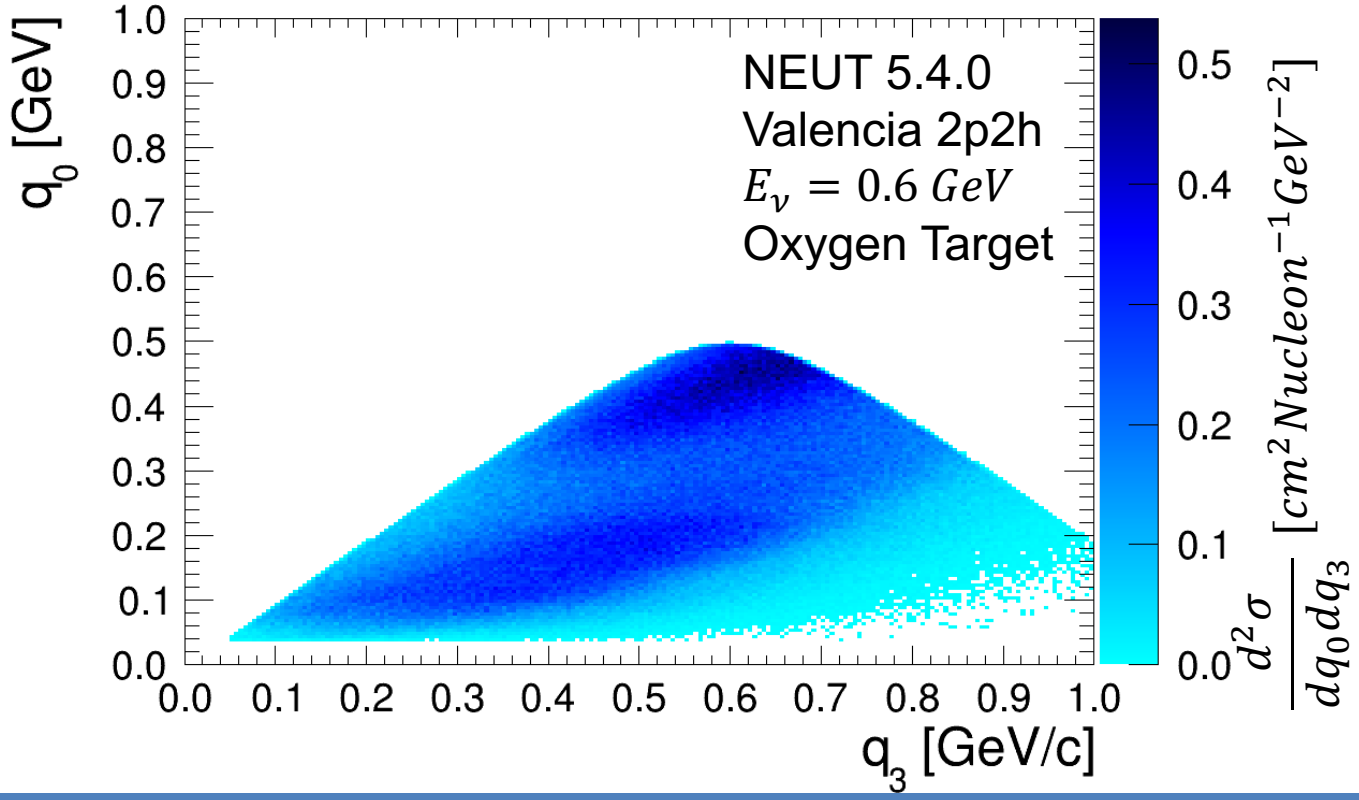

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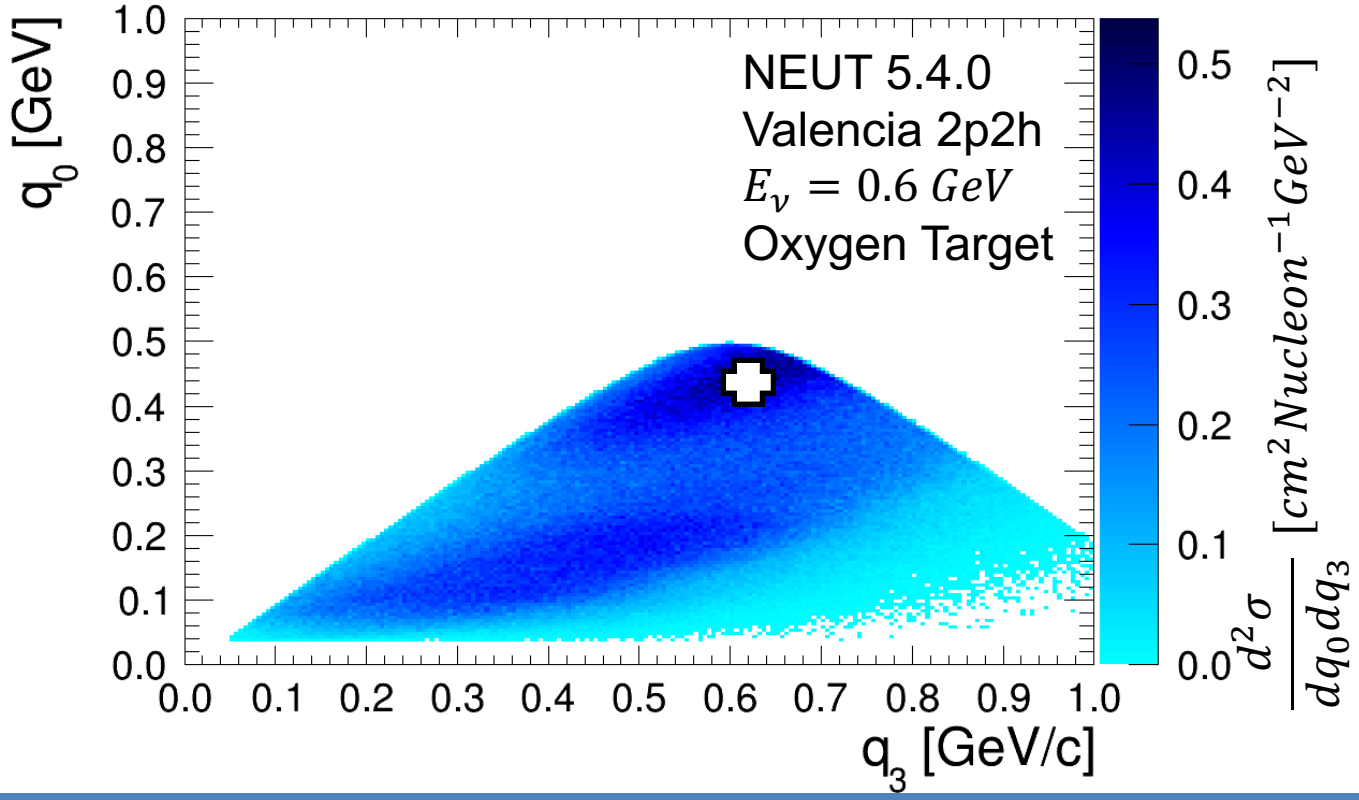
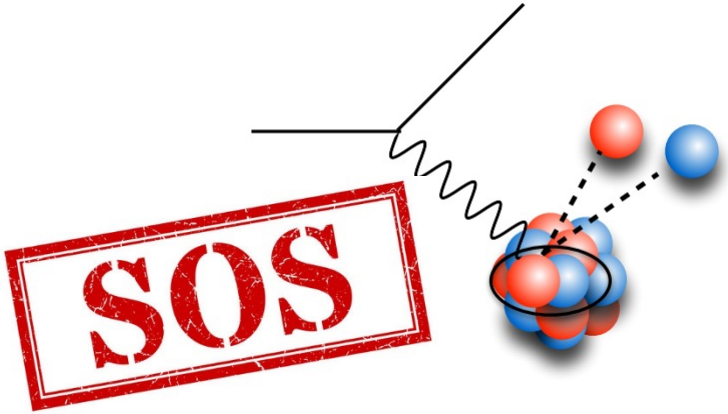


# Example: 2p2h

- 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!?



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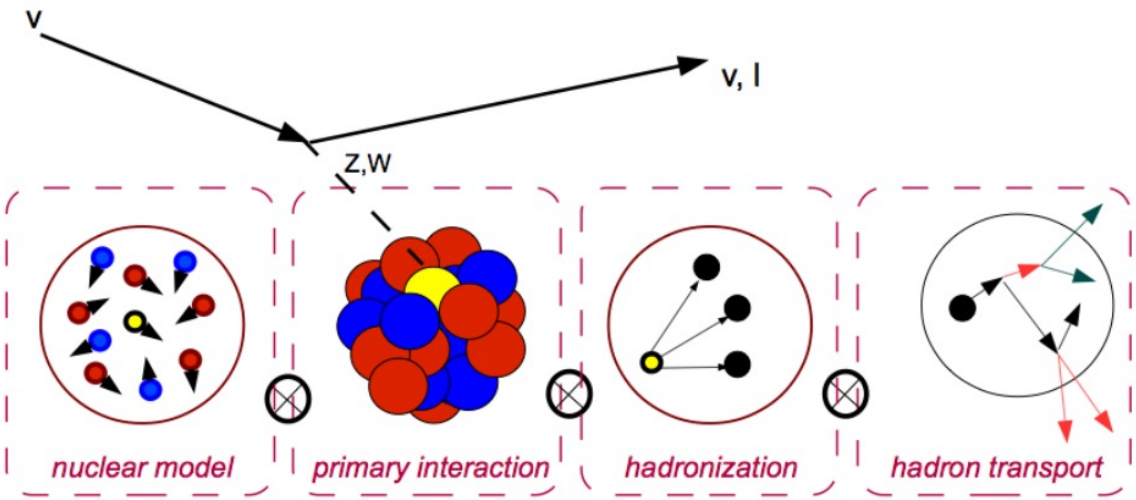

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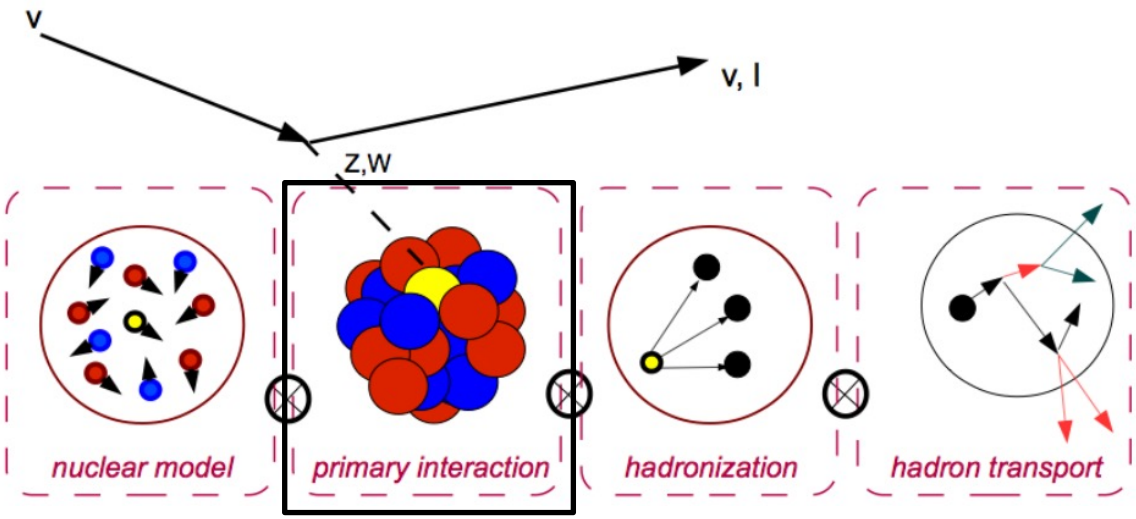
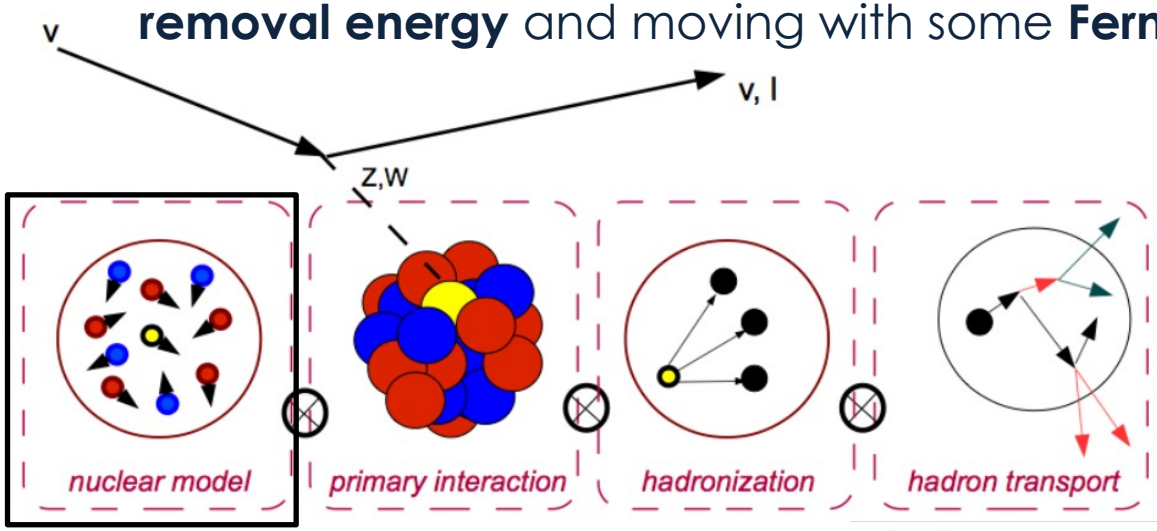
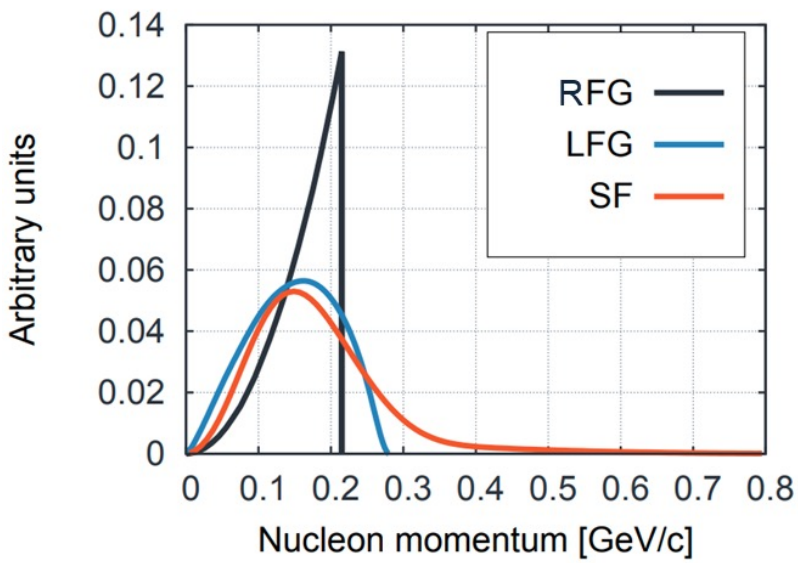


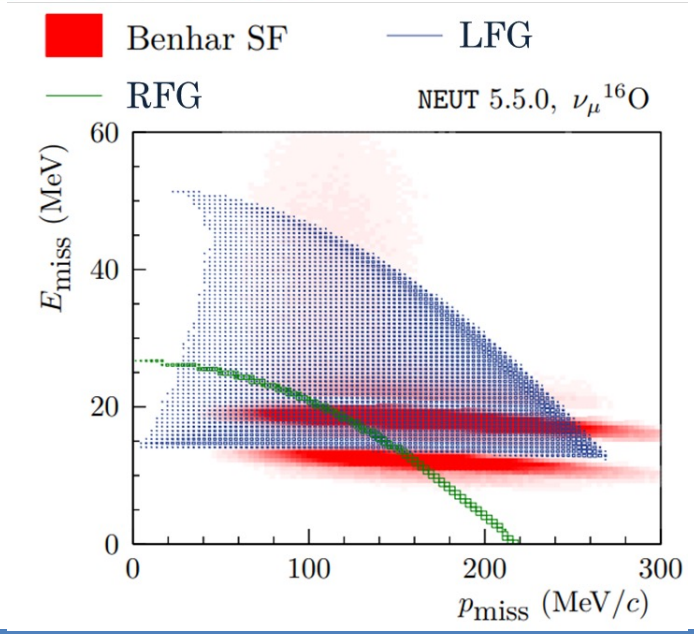

- Generators need to "dress" our primary interaction with extra physics

# Fermi motion

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



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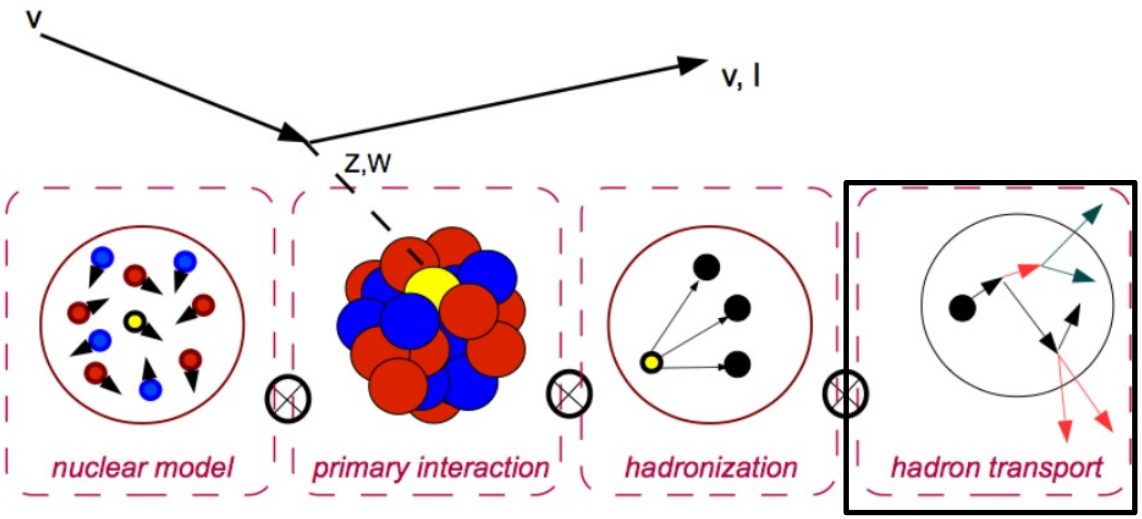
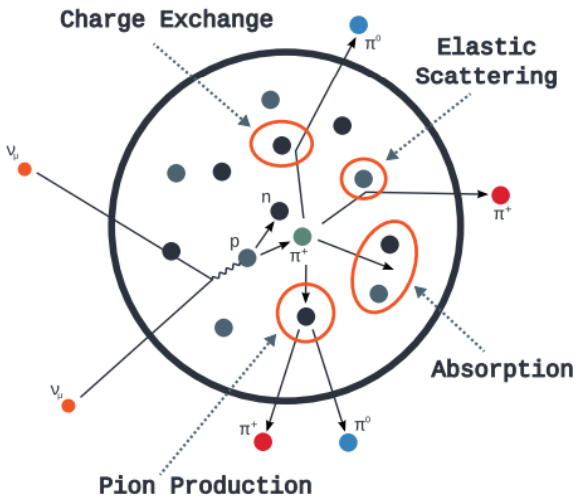



- We now have a nucleon inside the nucleus, but it still needs to gets out: **Final State Interactions**



# Final state interactions

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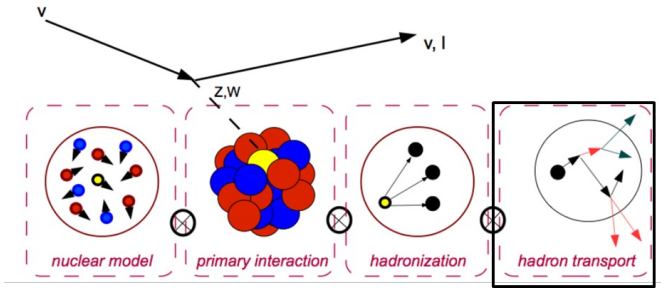


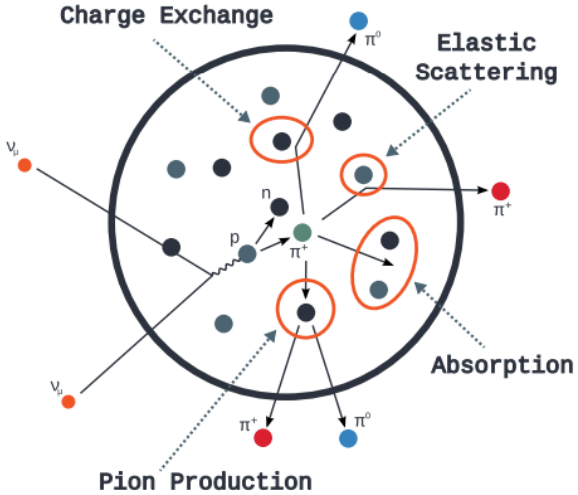


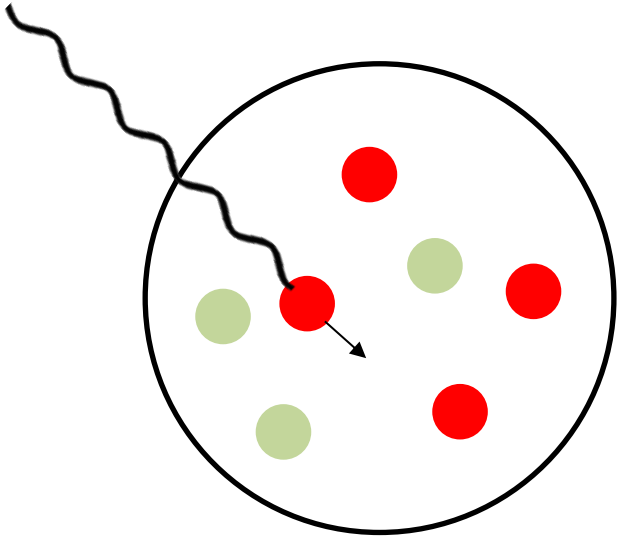

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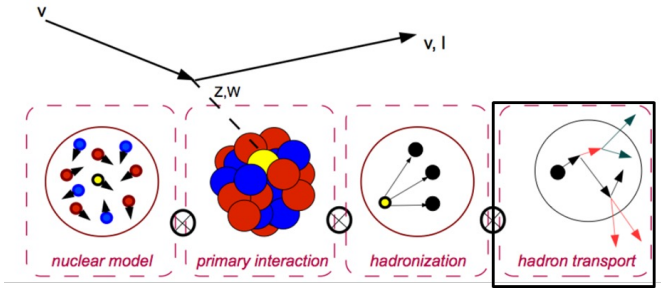


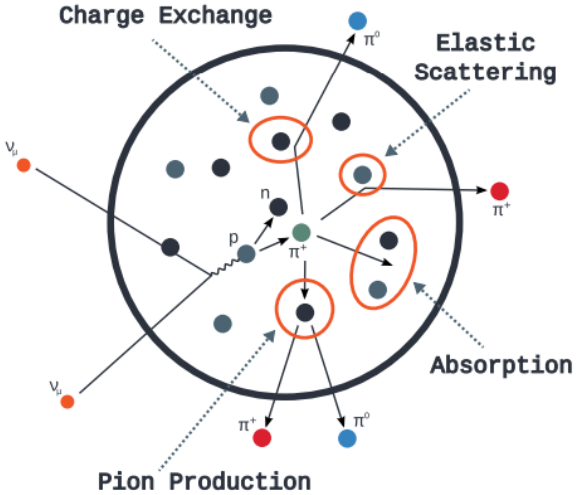


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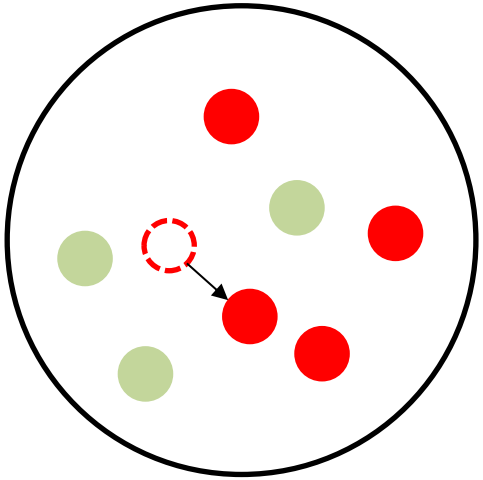

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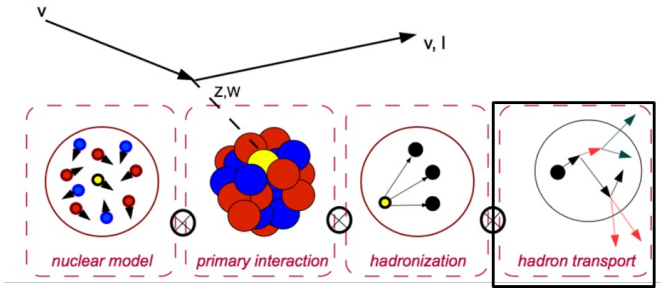


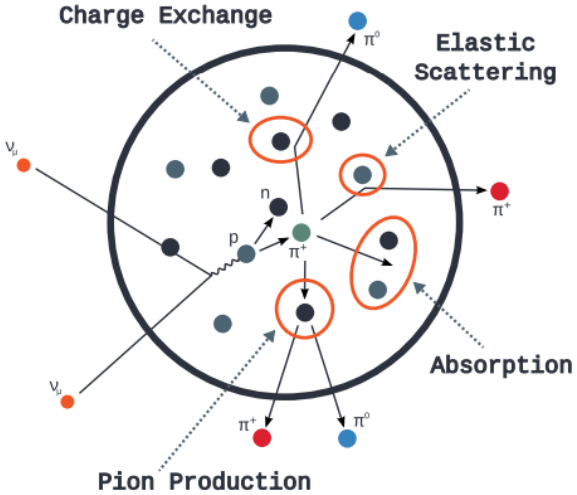


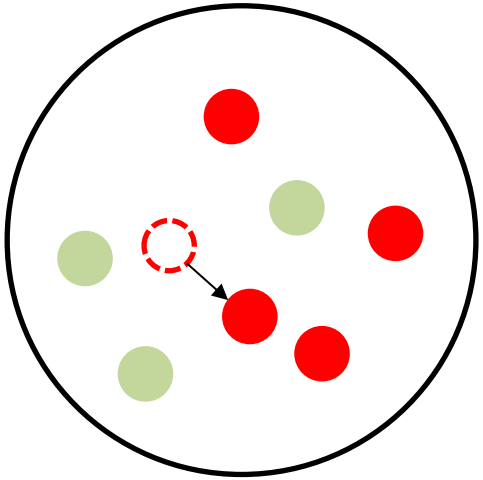

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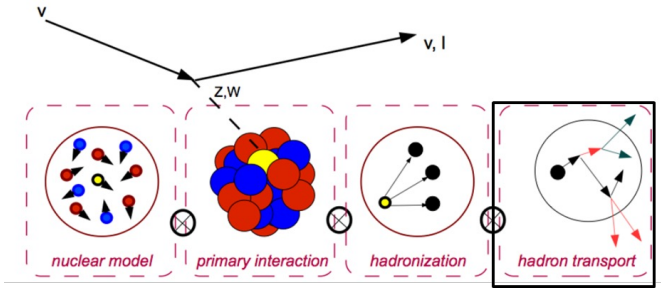


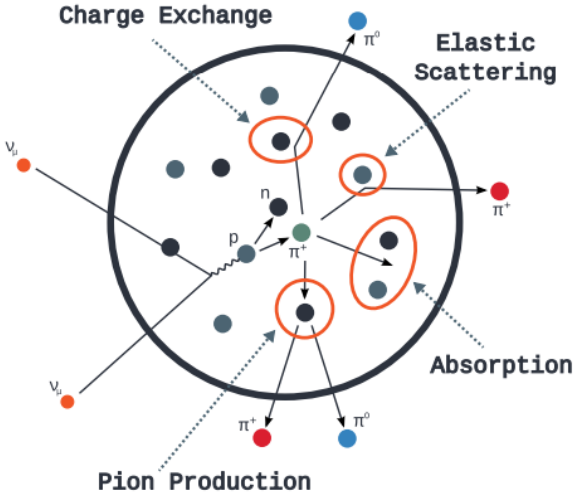


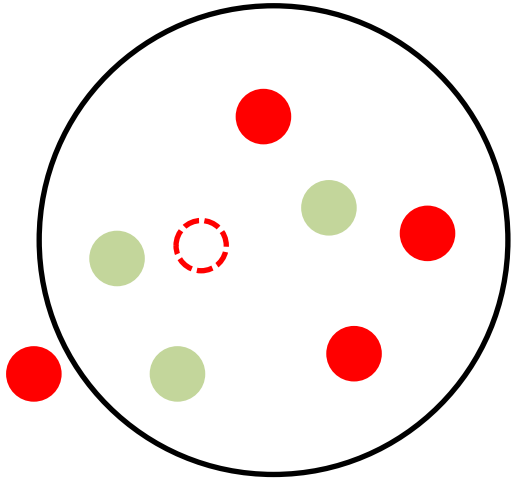

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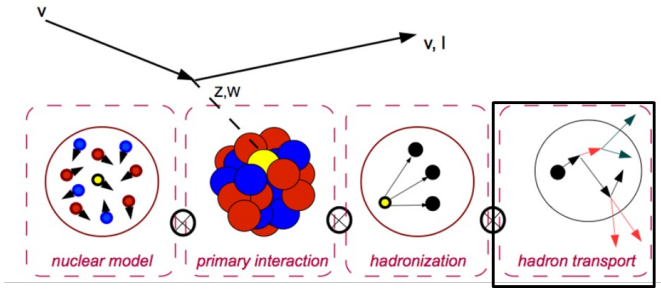


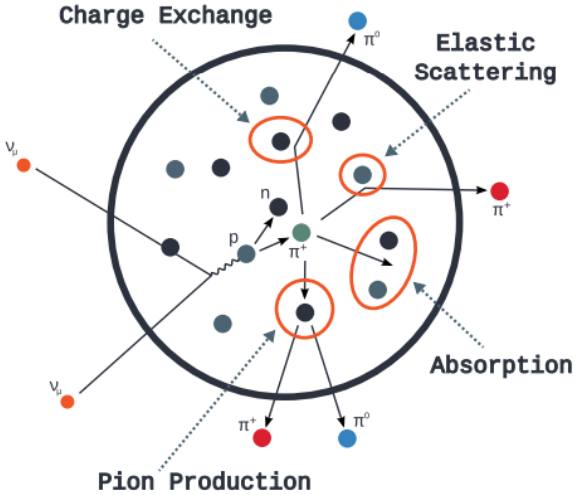


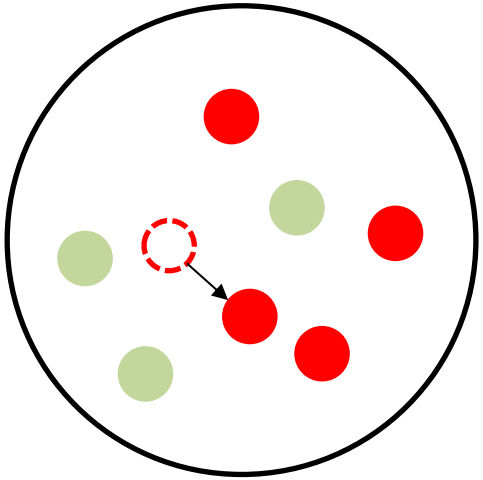

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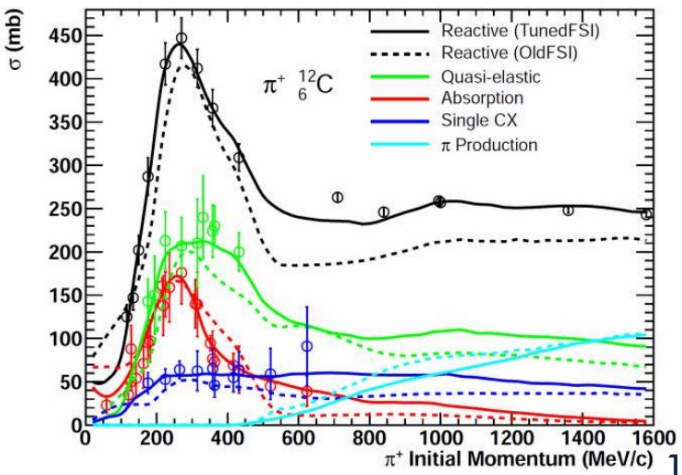


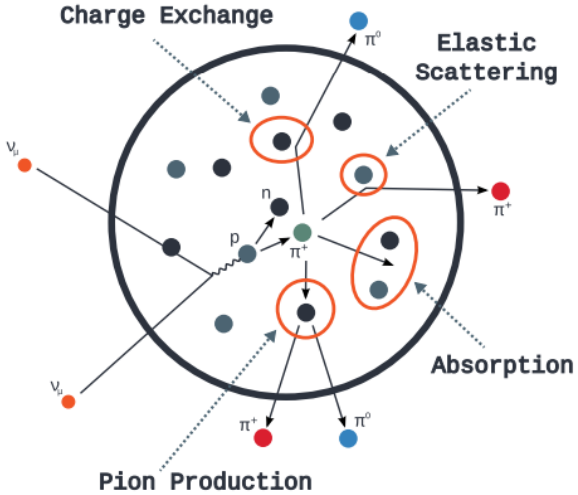


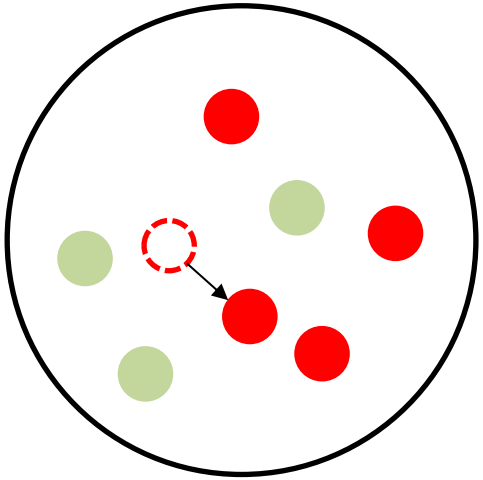

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See e.g.: Phys. Rev. D **99**, 052007

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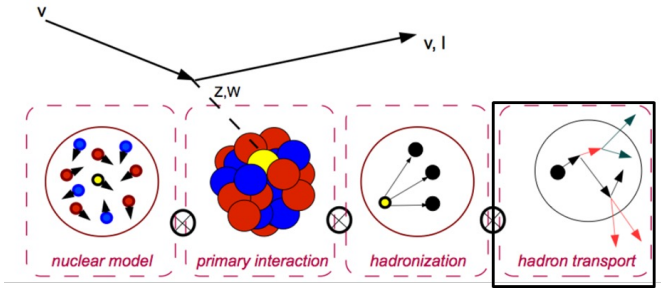
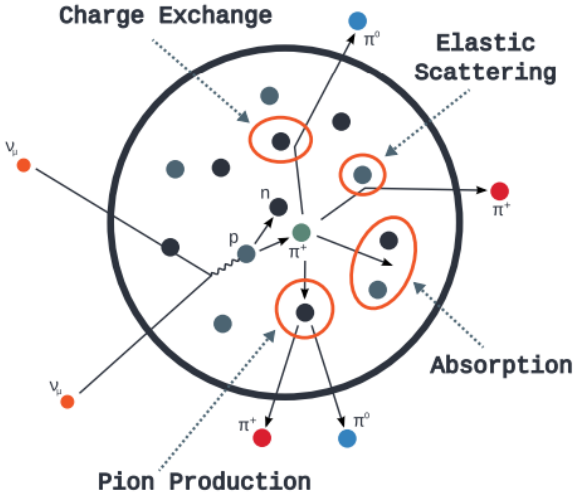
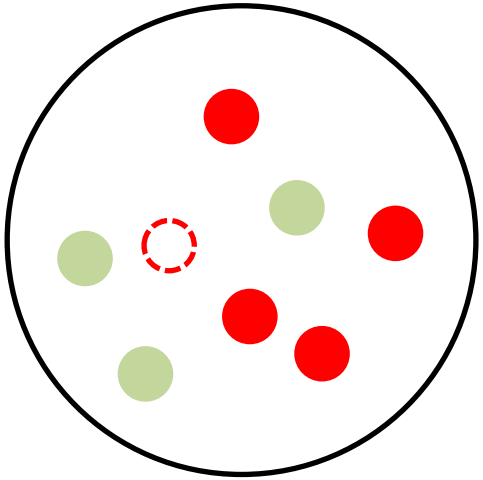
- Intranuclear cascade models: classical billiard ball scattering within the nucleus




Absorption



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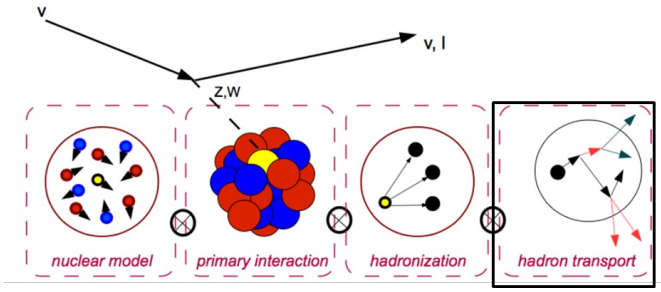
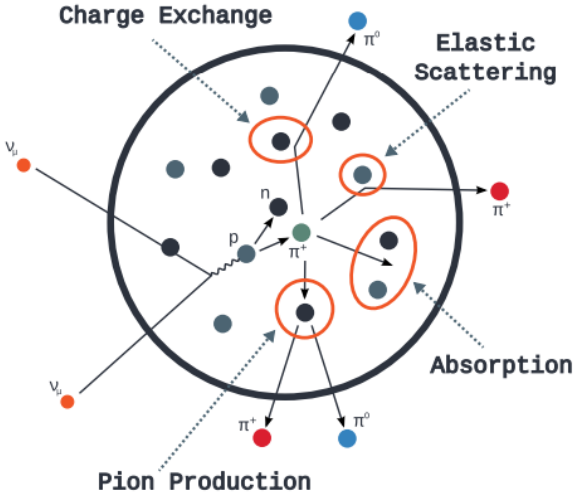
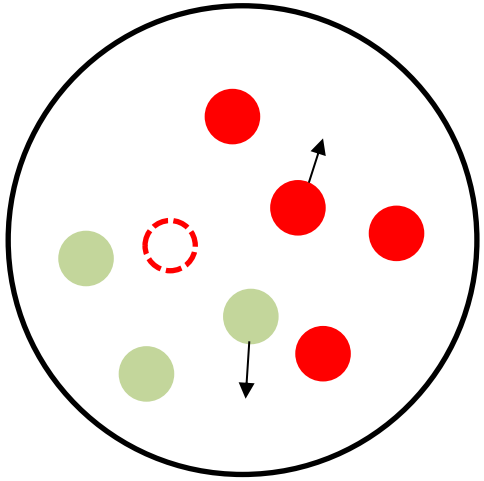



Charge Exchange



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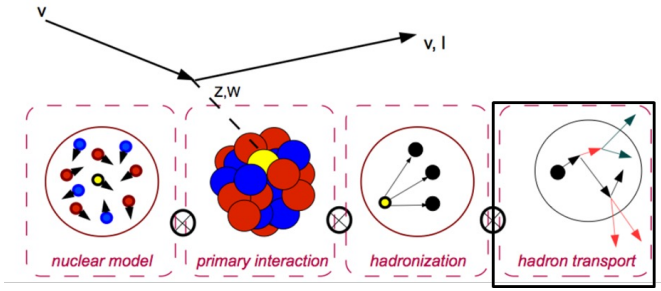
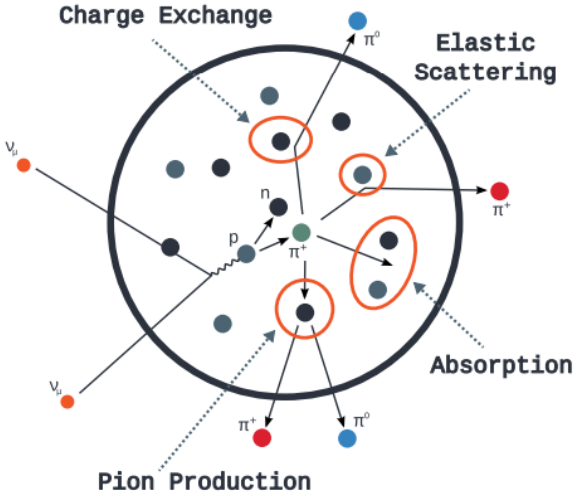
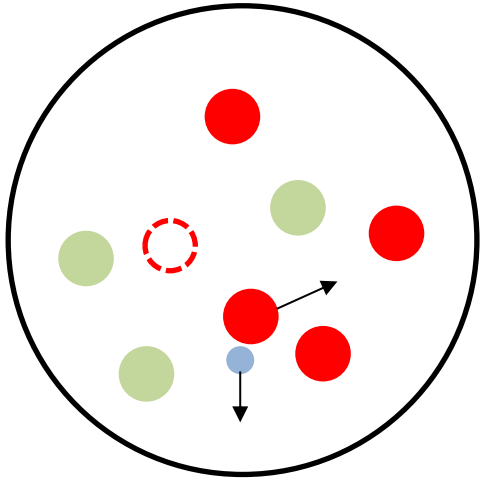



Pion Production



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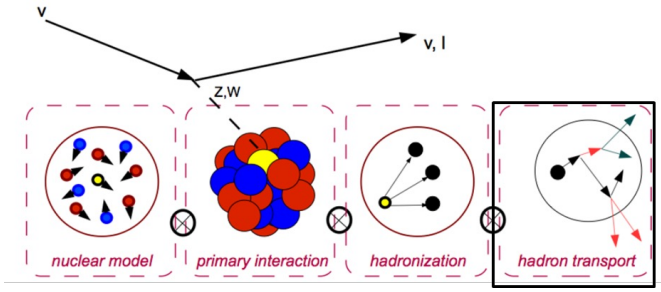
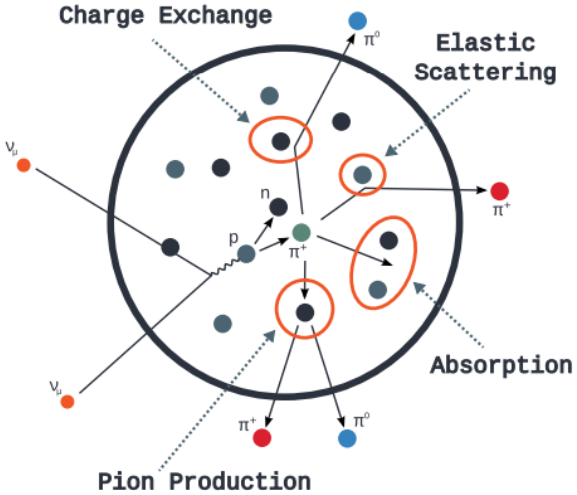
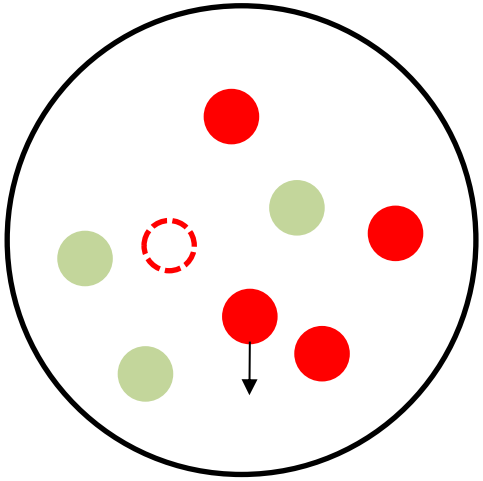



Elastic scatter



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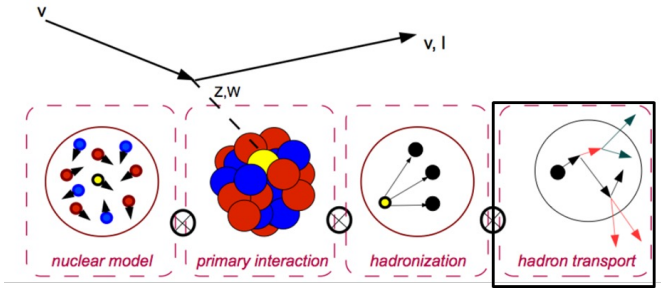
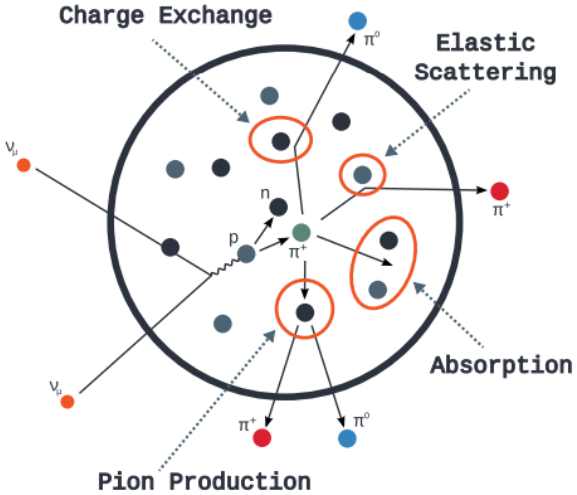
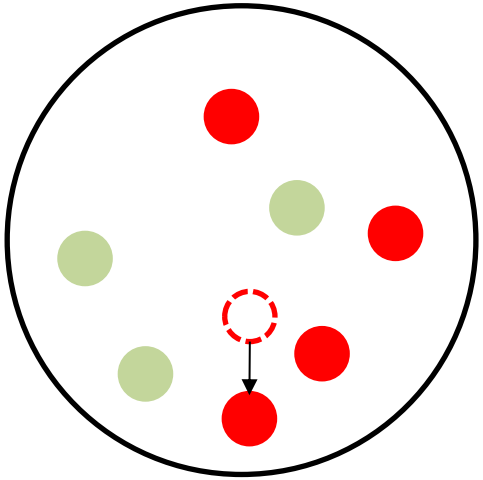


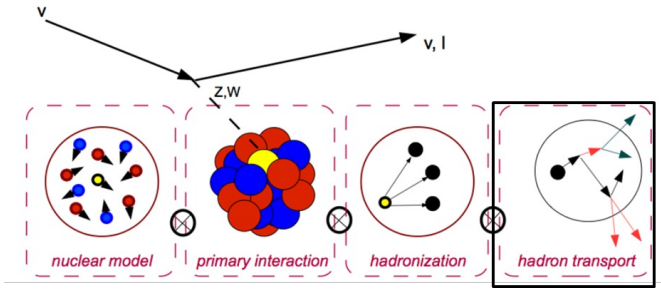



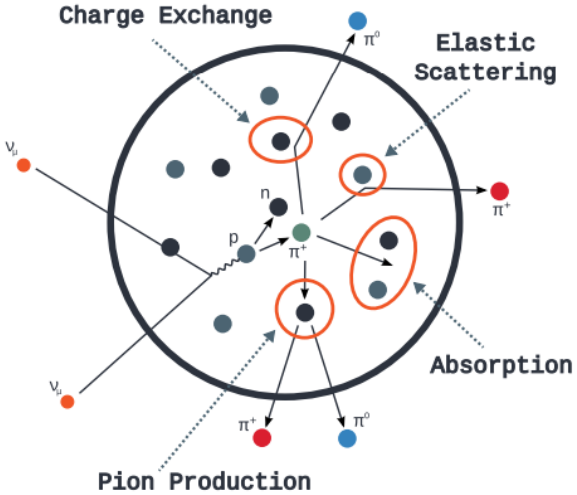



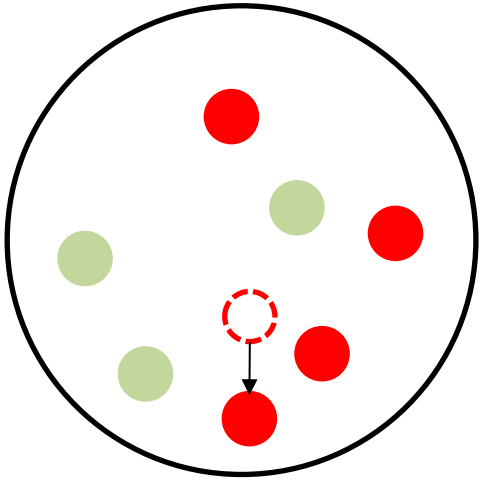
1. Step the particle through the nucleus a distance equal to its mean free path between interactions
2. Check whether it's outside the nucleus, if it is add this particle to the final state and stop FSI for it
3. Use MC methods to determine if it interacts or not, if it does choose a process according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



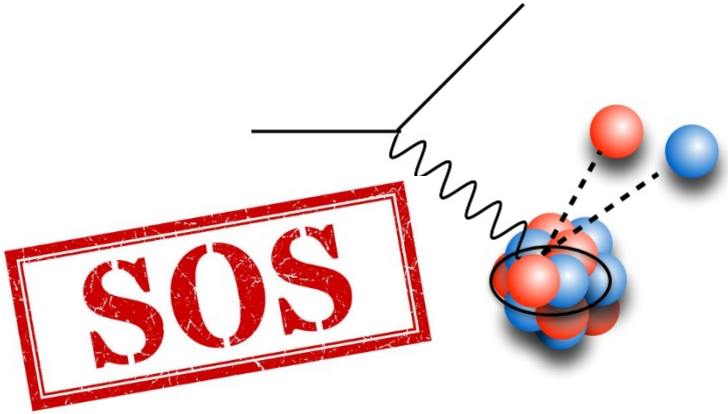
- Note that FSI is totally factorised from the rest of the interaction
- Unlike theory-treatments of FSI, cascades don't change the cross section as a function of lepton kinematics

# 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!?



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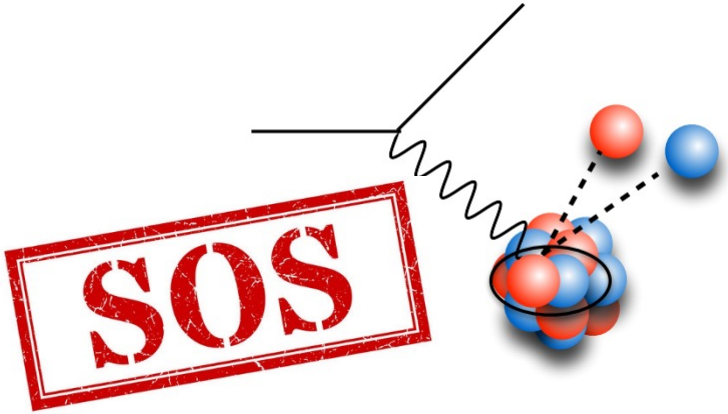


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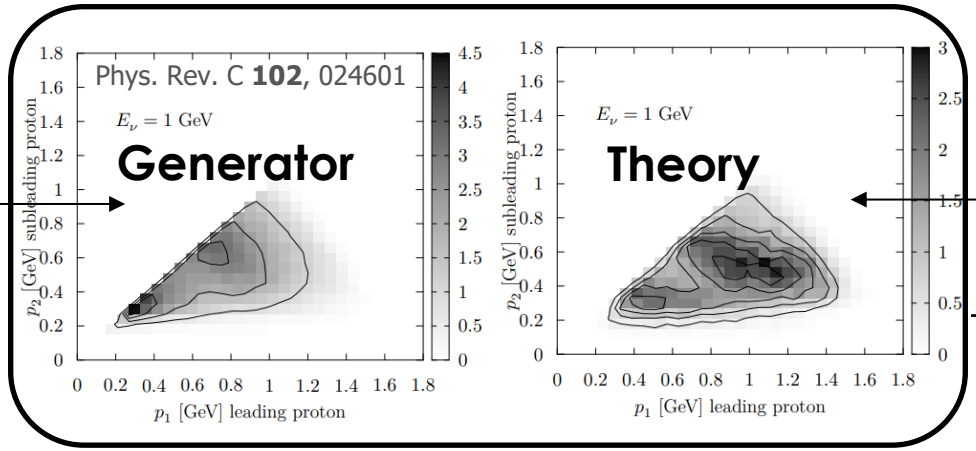
- How do we get there!?

***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"
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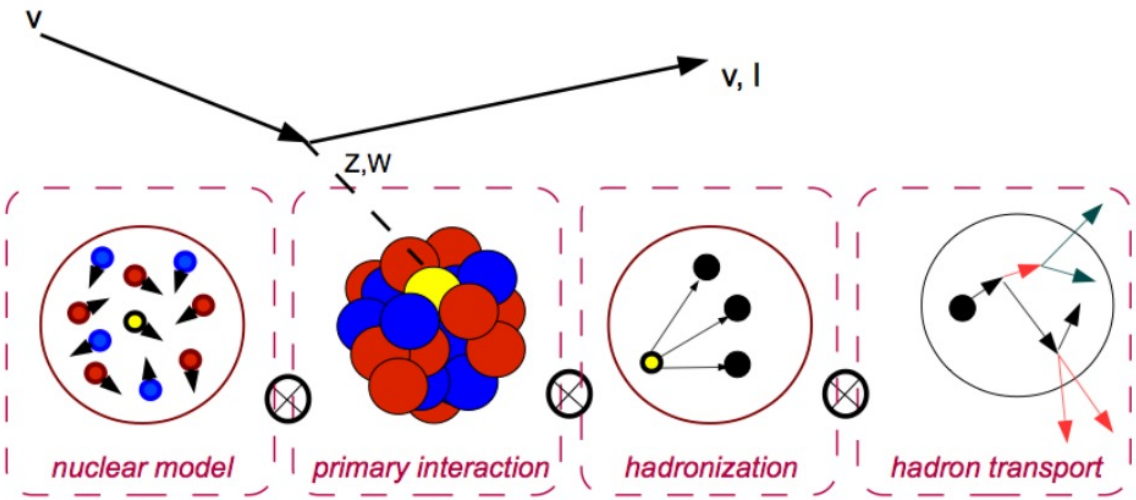
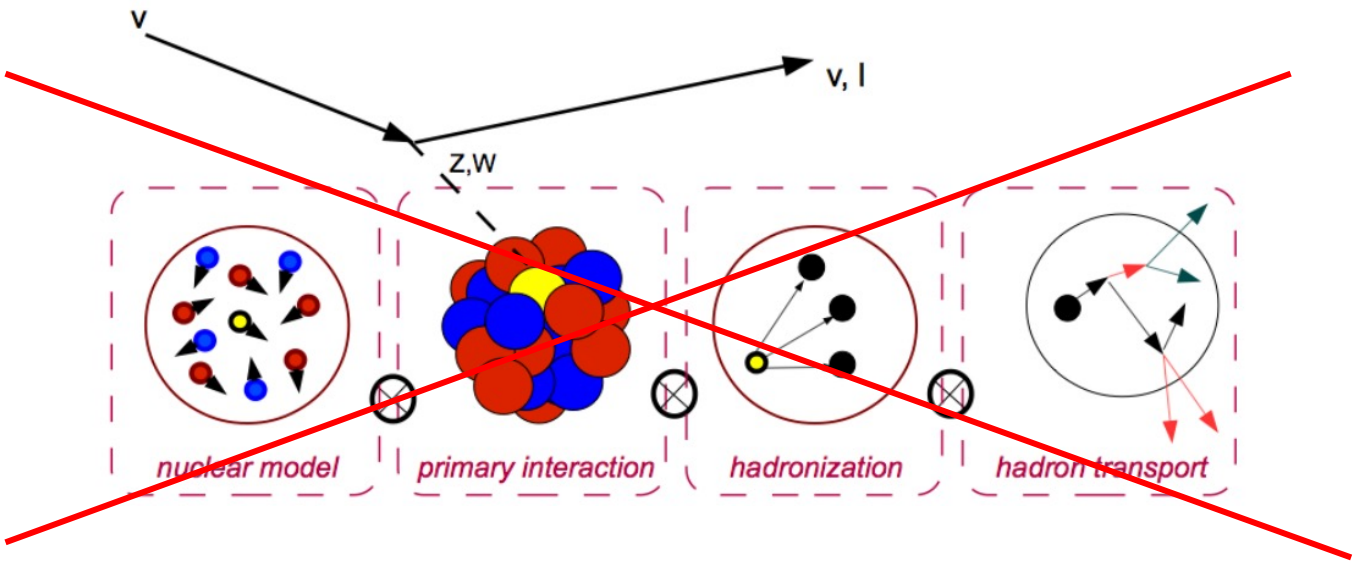
# A generator's view of $\nu N$ scattering



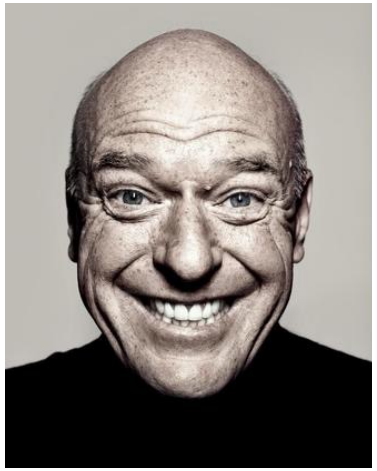

- This approach allows generators to produce complete simulations from incomplete theory inputs
- But, does it work?

# A generator's view of $\nu N$ scattering

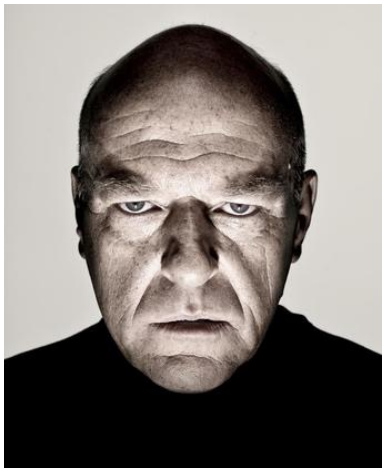



- Generators do what they can with what they work with
- But the "gap filling" implies significant approximations which limit their predictive power
- When relying on generators, it's crucial to consider what these approximations are and to assign associated systematic uncertainties

# General rule of thumb



Lepton kinematics
(except maybe at low energy transfers)

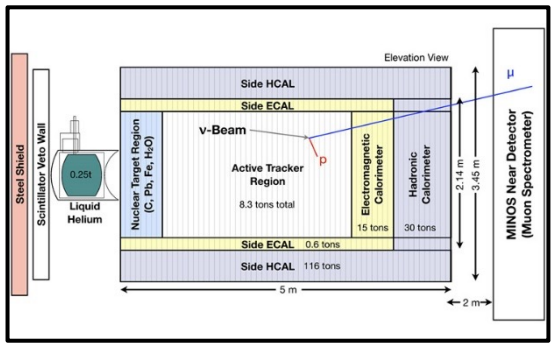


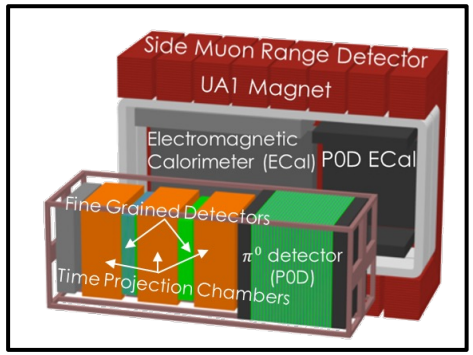
Lepton-hadron correlations

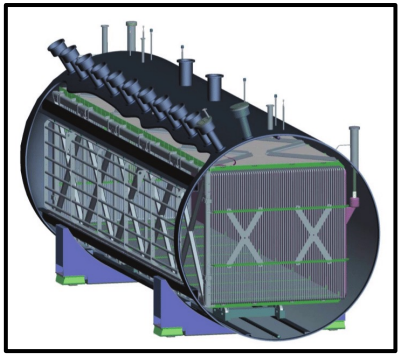
KEEP CALM
AND
MEASURE dσ/dx

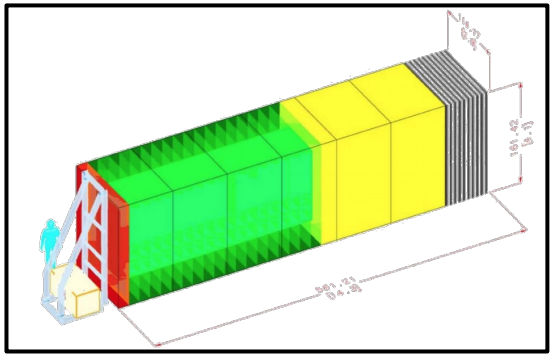
# Overview

- Neutrino Interactions: A History
  - Weak interactions from Fermi to SM
- Neutrino-nucleon interactions
  - QE, RES and DIS
- Neutrino-nucleus interactions
  - Nuclear effects
  - The rise and fall of $M_A = 1.3\ GeV$
- Neutrino event generators
  - Theory inputs
  - Filling in the gaps
- Neutrino-nucleus interaction measurements
  - Inclusive successes and exclusive failures
- Why do we care?
  - Neutrino interactions for neutrino oscillations
  - Neutrino energy reconstruction
- Don't Panic! The future of neutrino interaction simulations

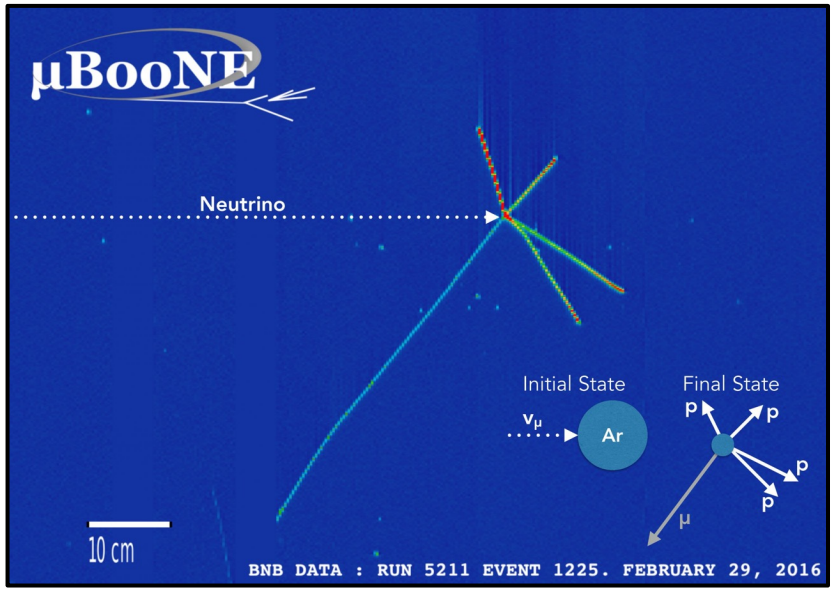


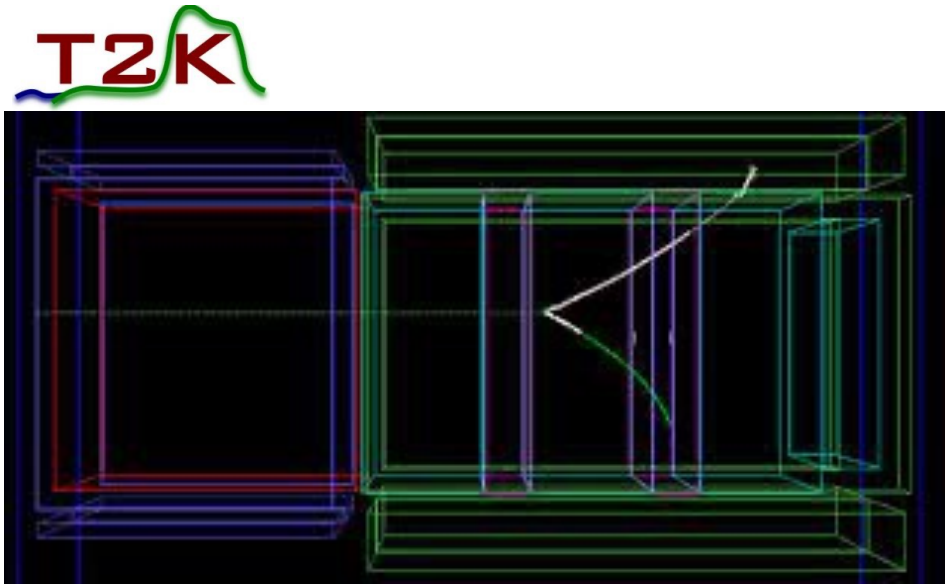





# An experiment's view of an interaction



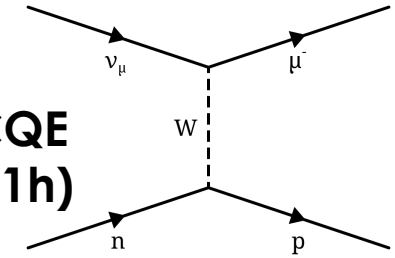




- See Deborah's talk for details on how these measurements are made!

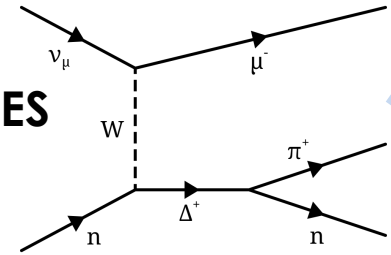
# CC0π measurements

**Interaction Modes**

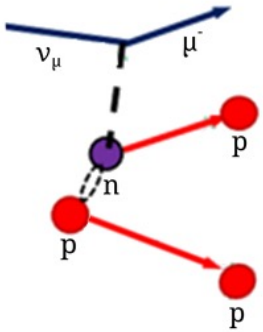
**CCQE (1p1h)**



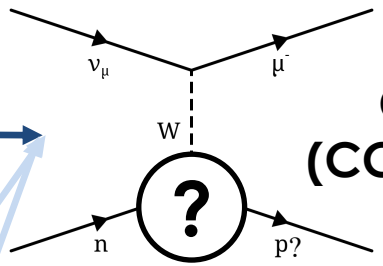

**CCRES**



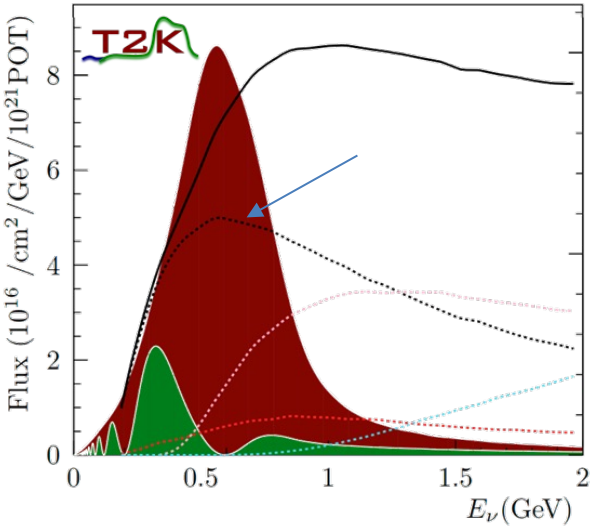

**2p2h**




**Interaction Topologies**



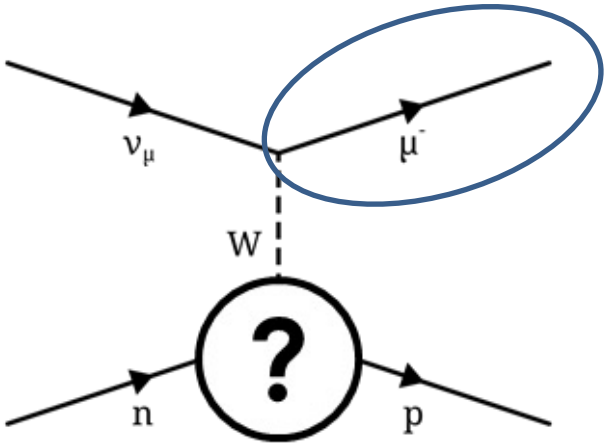

**CC0π (CCQE-like)**




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

# Which observables?

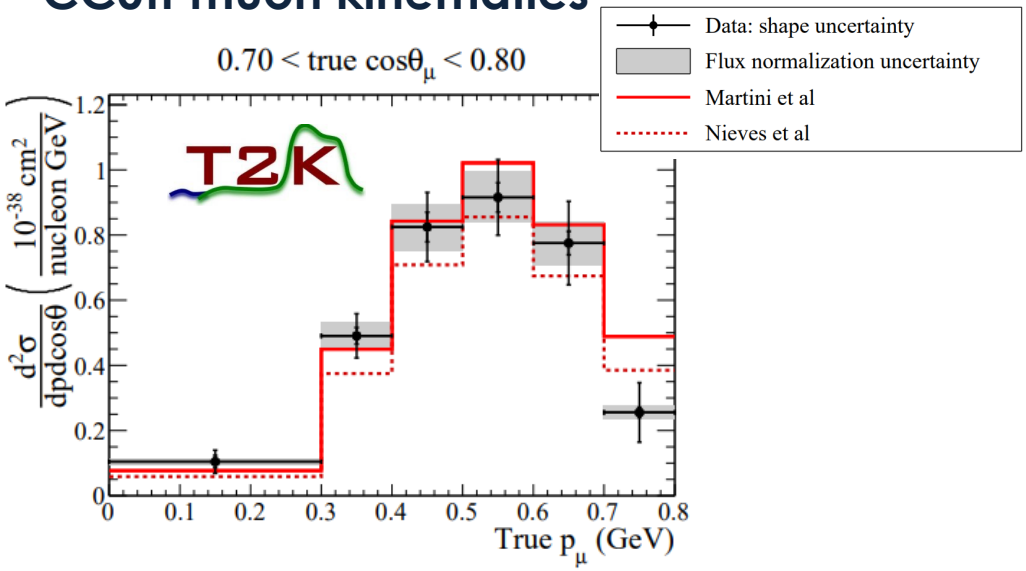
*Just the muon?*

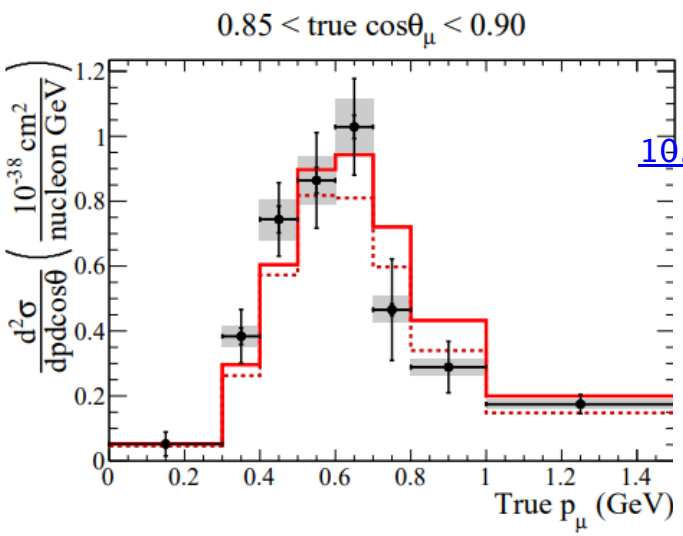


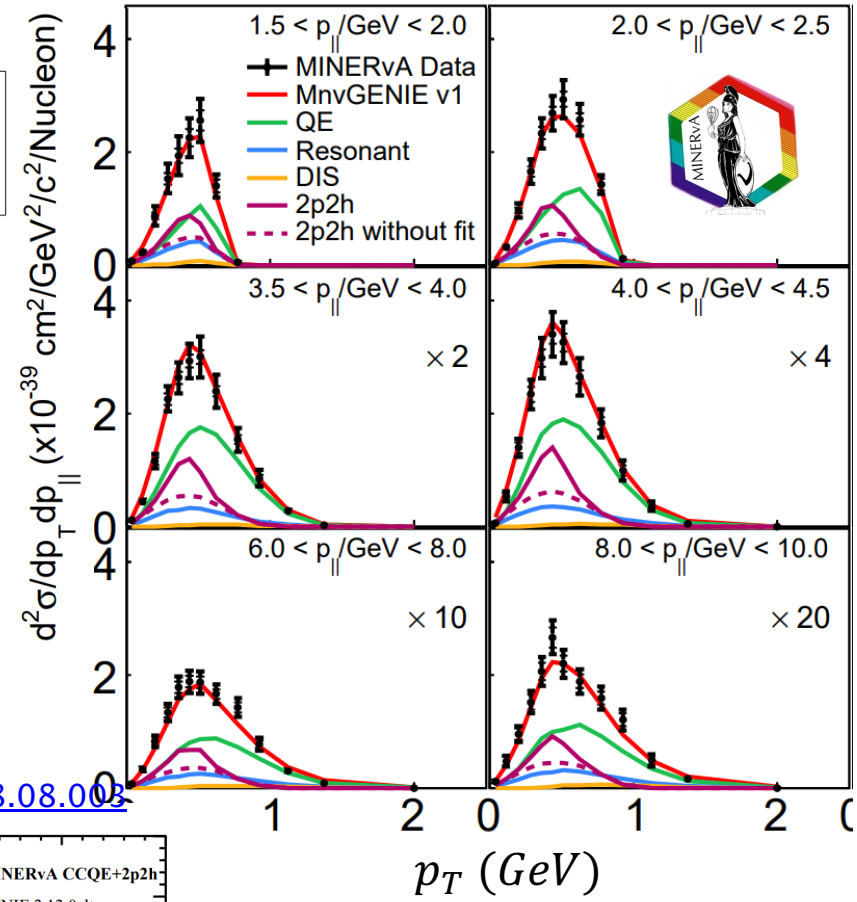
# Our current models vs data

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

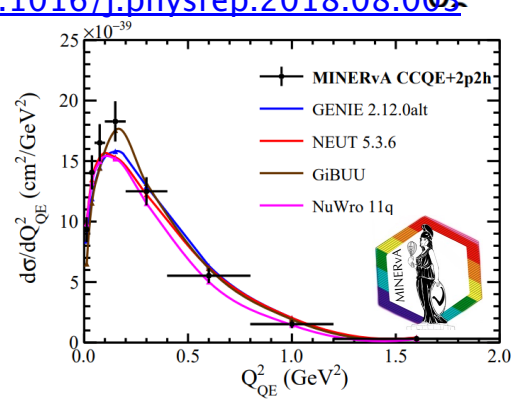
## CC0π muon kinematics



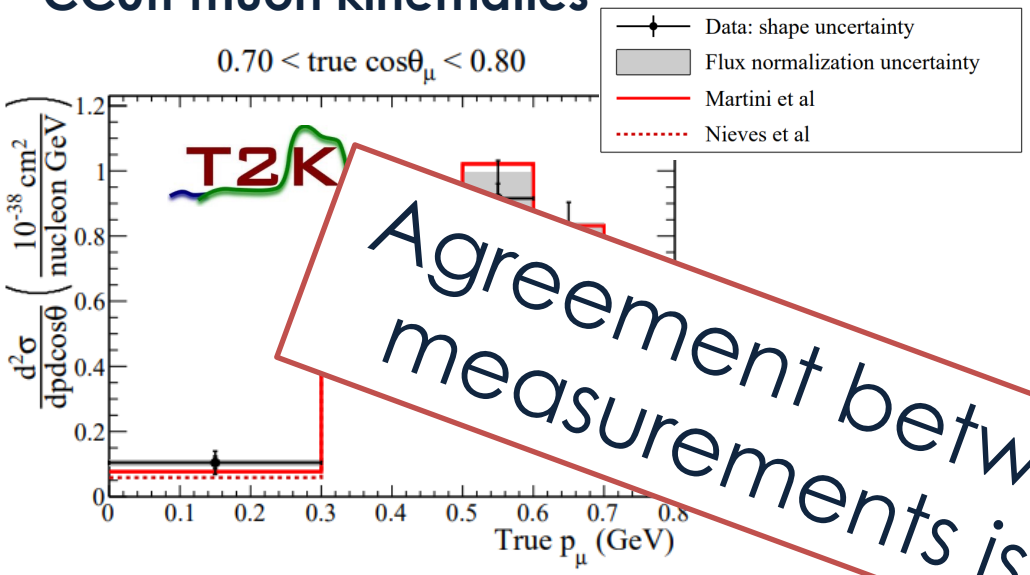

10.1016/j.physrep.2018.08.003

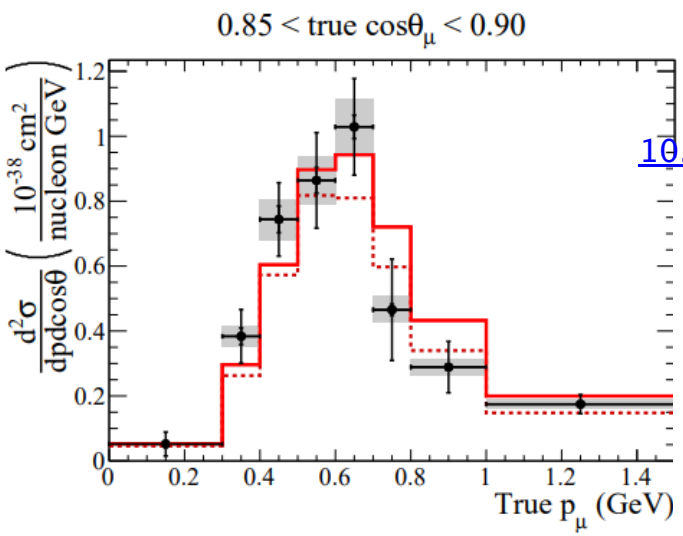


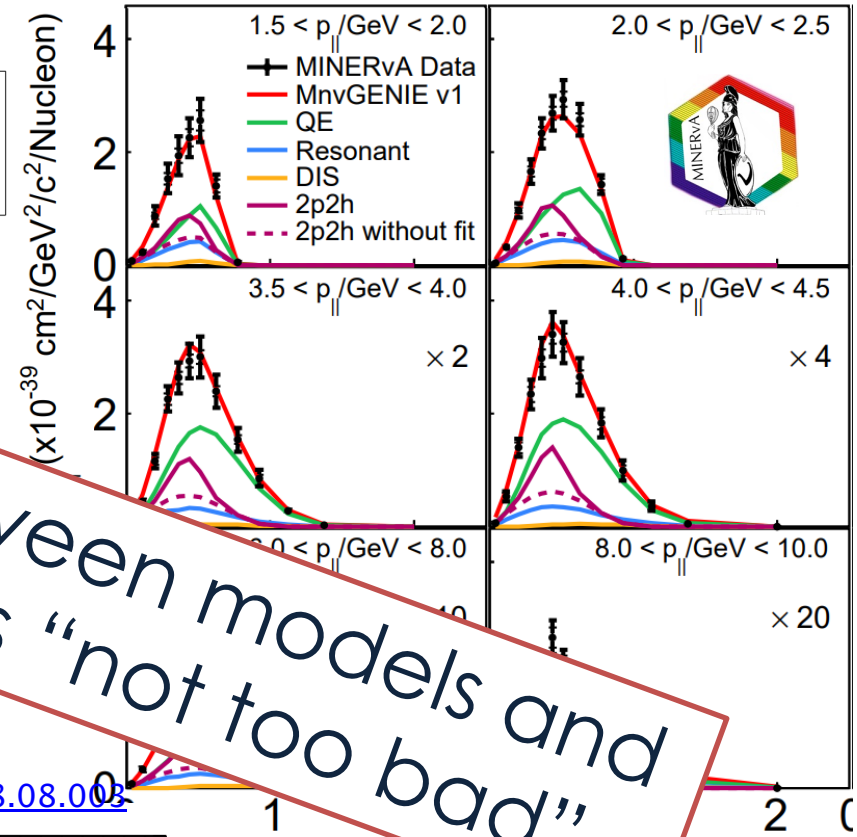
# Our current models vs data

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

## CC0π muon kinematics

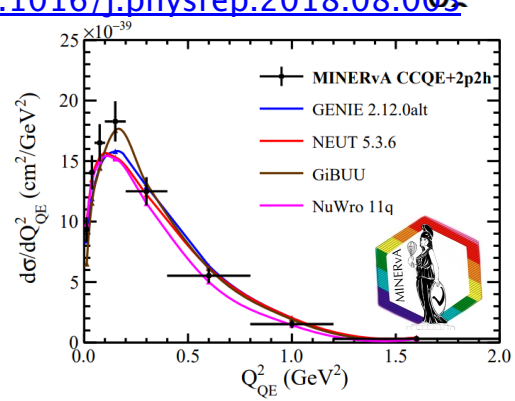


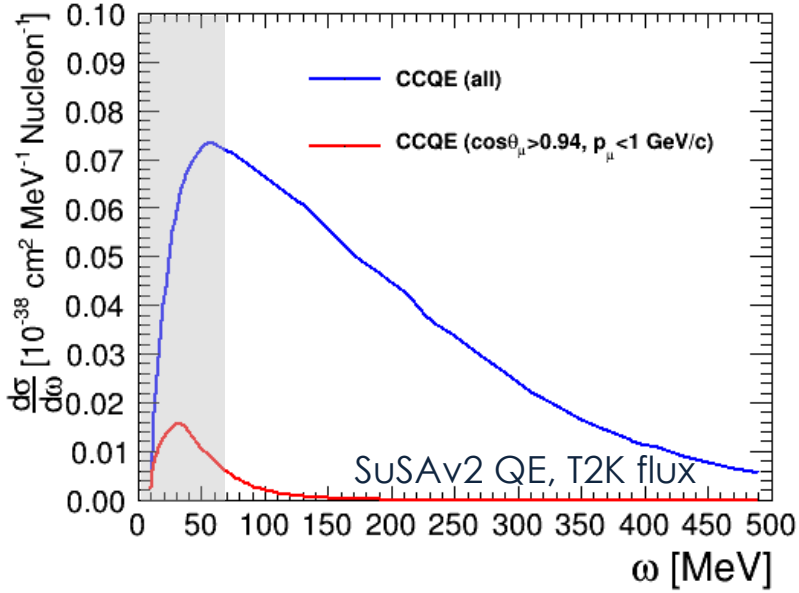

Agreement between models and measurements is "not too bad"

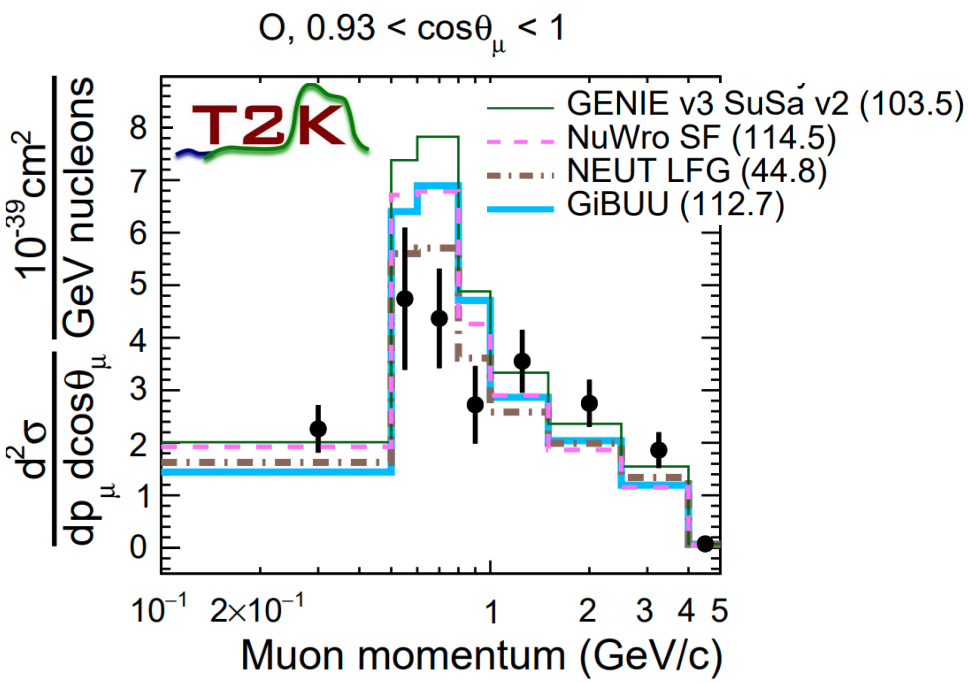
10.1016/j.physrep.2018.08.003

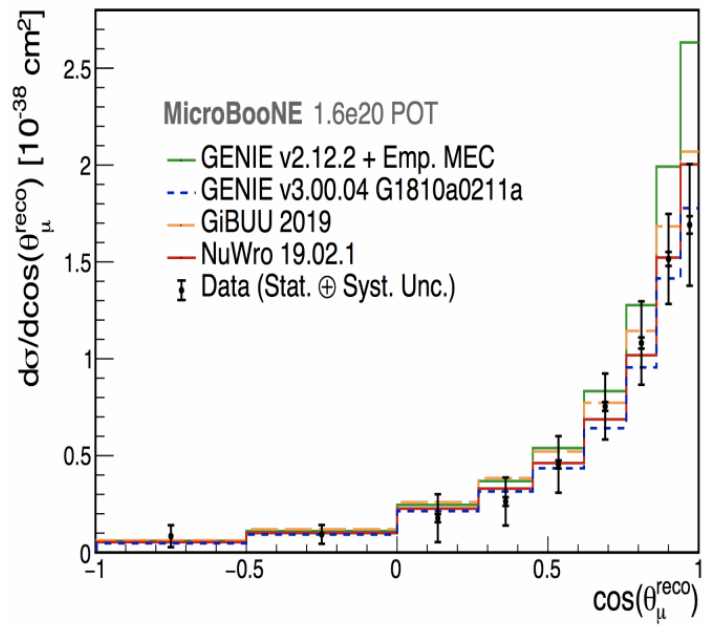


# Forward Angles

- The very forward region is especially sensitive to interactions with low energy transfer ($\omega$)
- Things don't look so good here …

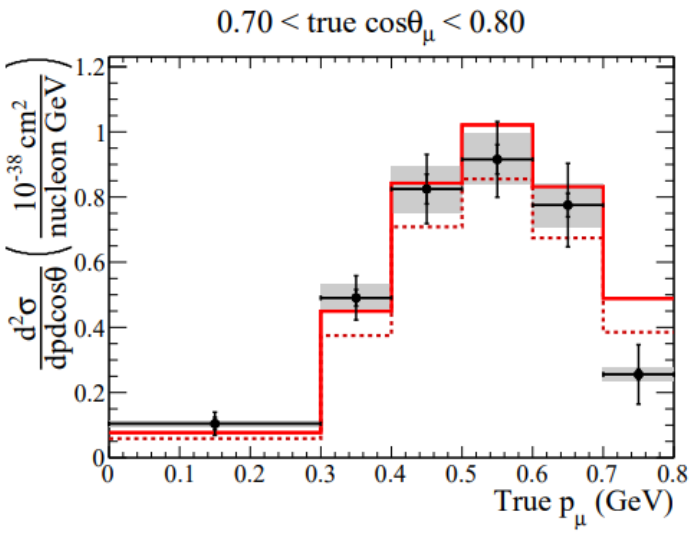


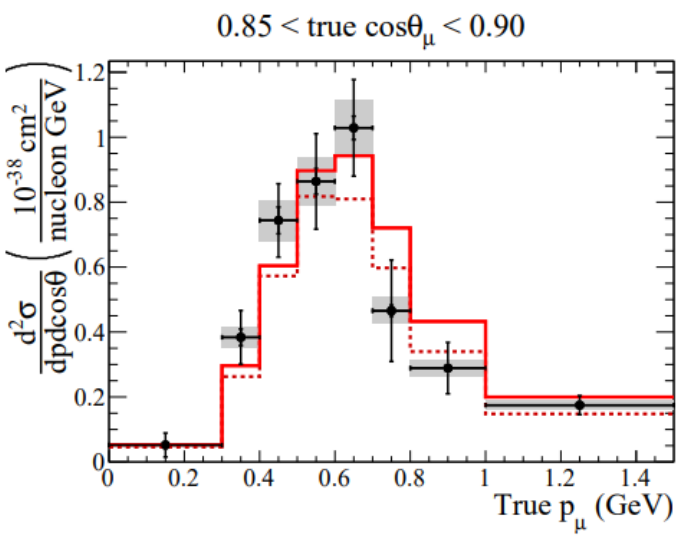




Phys. Rev. Lett 123,131801 (2019)

# Does this make sense?

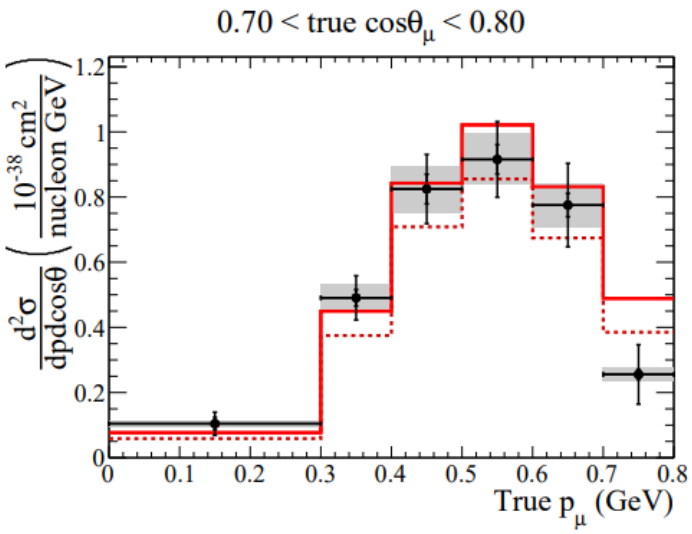


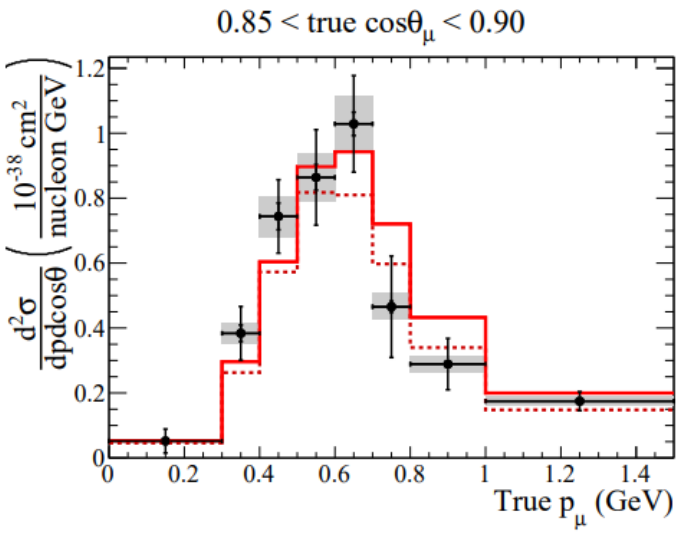




**We describe intermediate muon kinematics in CC0π measurements quite well with most models**

Expected?

# Does this make sense?




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

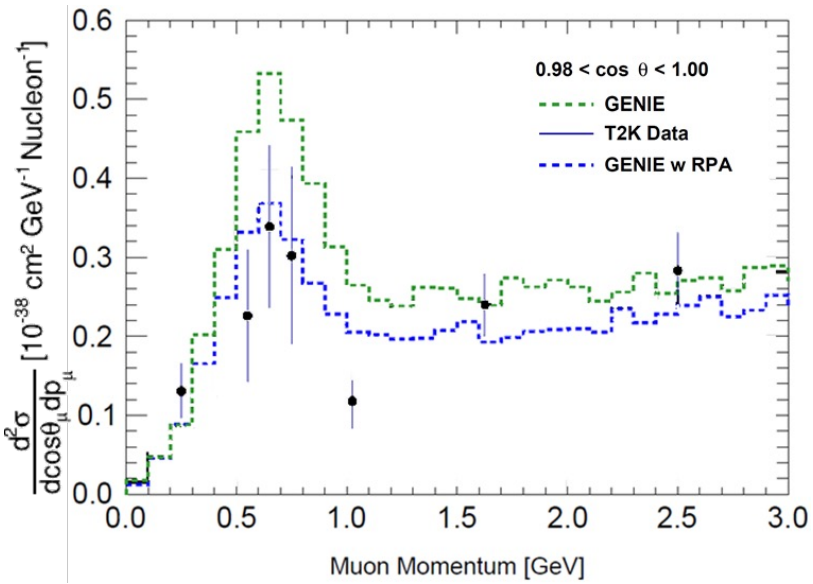
Expected?

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?

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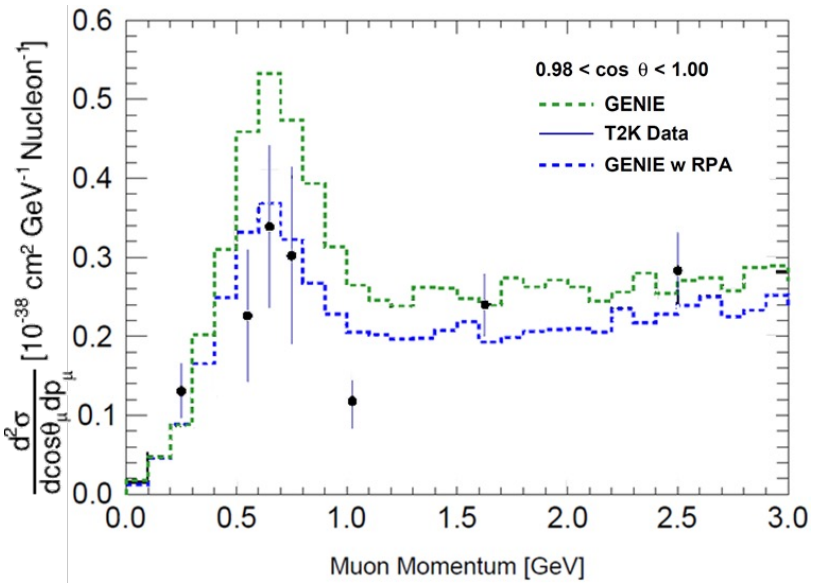



Expected?

Yes!

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

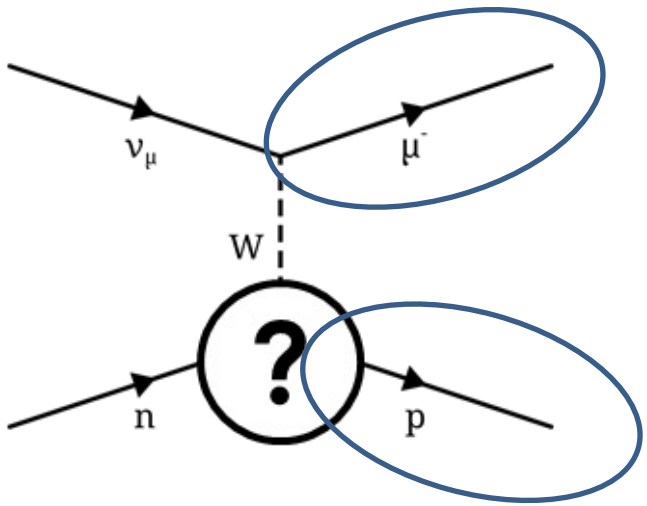
**Models with RPA do better here**

Makes sense!

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

# Which observables?

*Lepton and proton?*



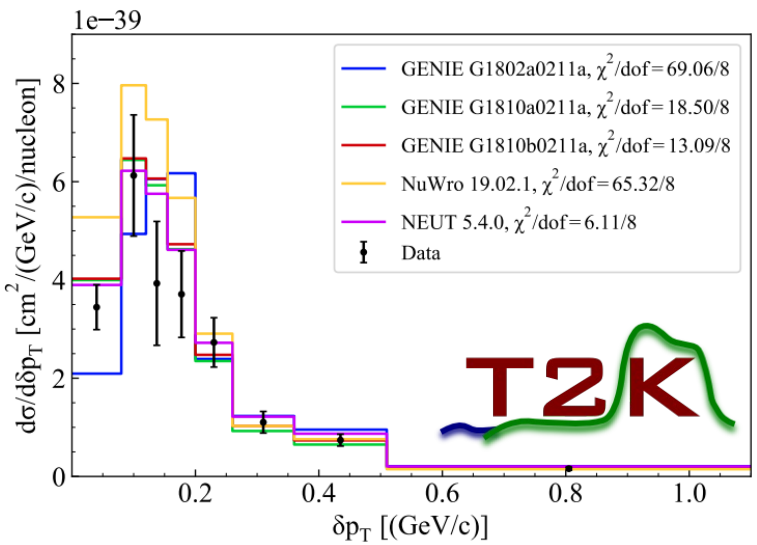

Correlations between the muon and proton kinematics allow us to disentangle nuclear effects from neutrino energy

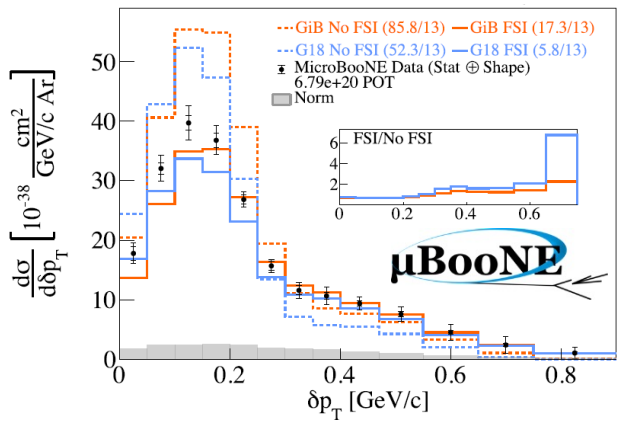
# Generators vs data: a horror story

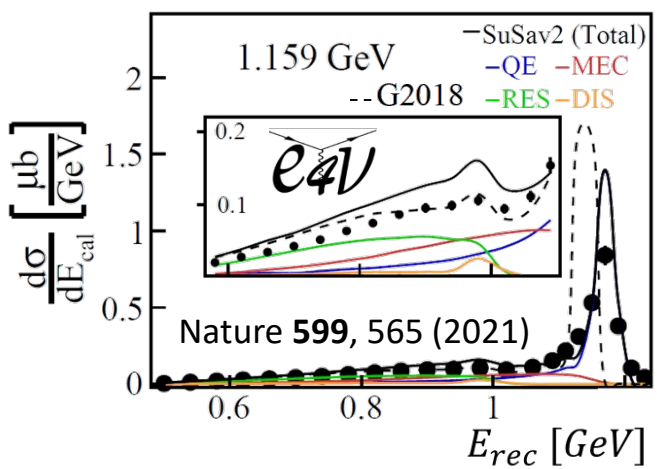
- No generator can come close to describing global data measuring lepton-hadron correlations
  - All models are "wrong", but they are each wrong in different ways

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

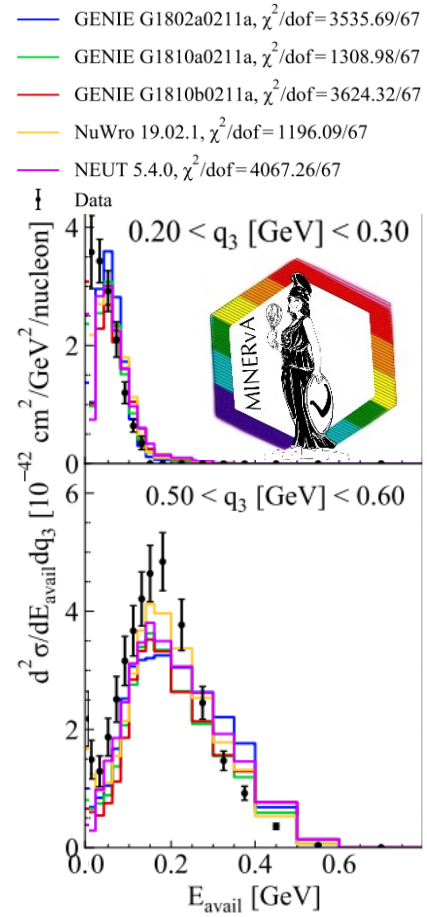
$$\chi^2_{allModels} \gg N_{bins}$$



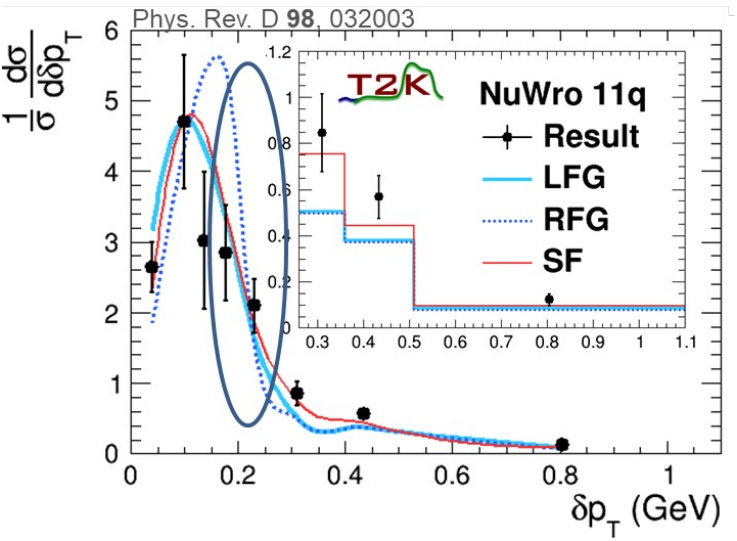




Nature **599**, 565 (2021)

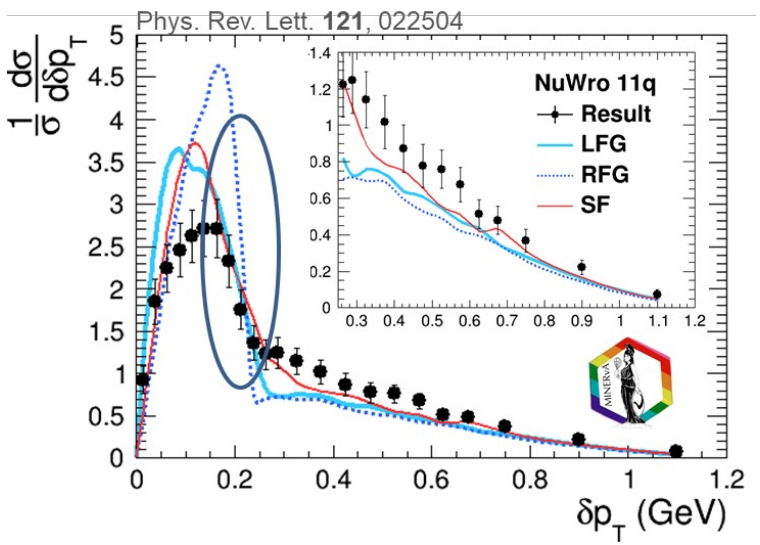


# Does this make sense?

Stephen Dolan



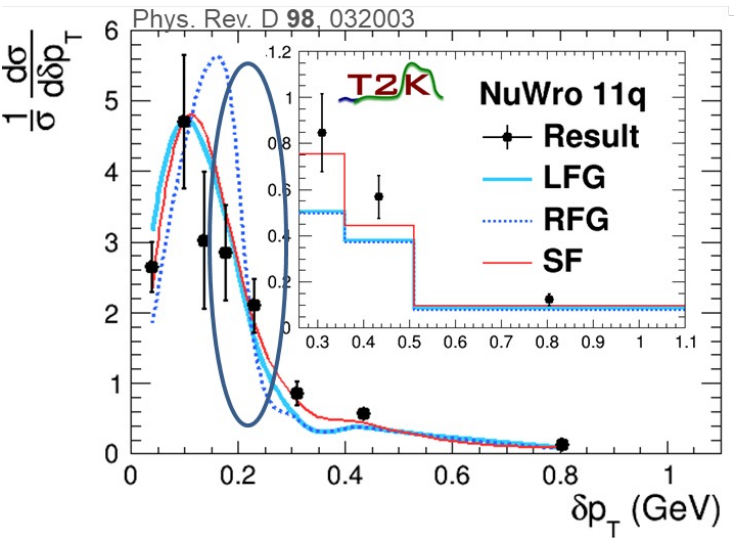

**We describe lepton-nucleon correlations badly**

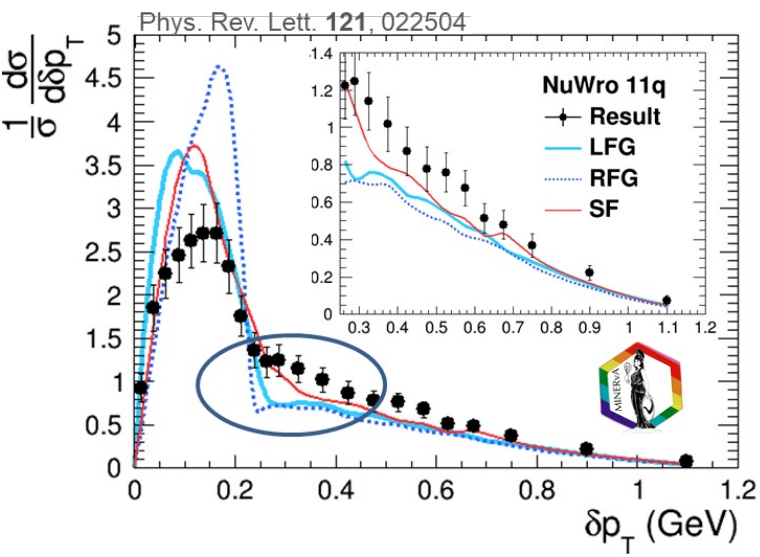



**Exclusive or factorized models do better here**

# 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**

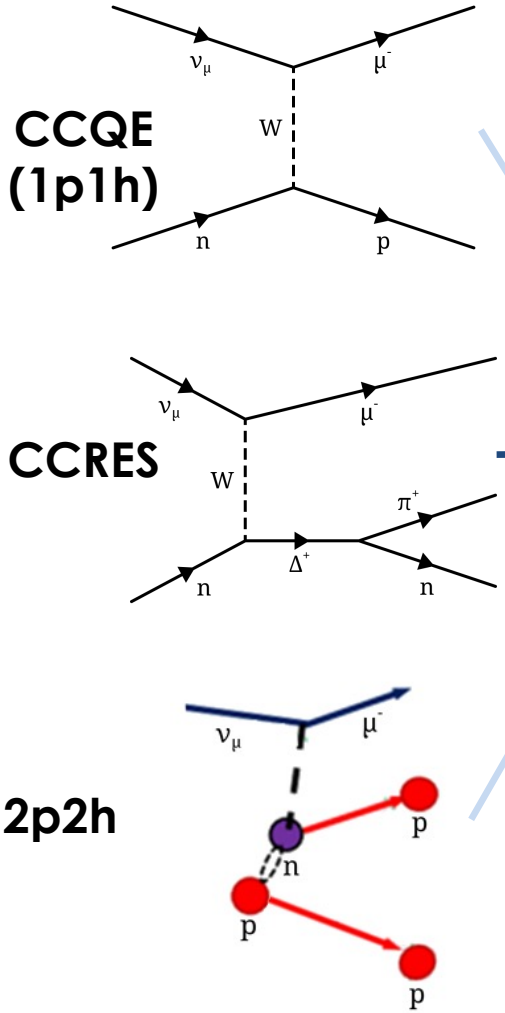
Makes sense!

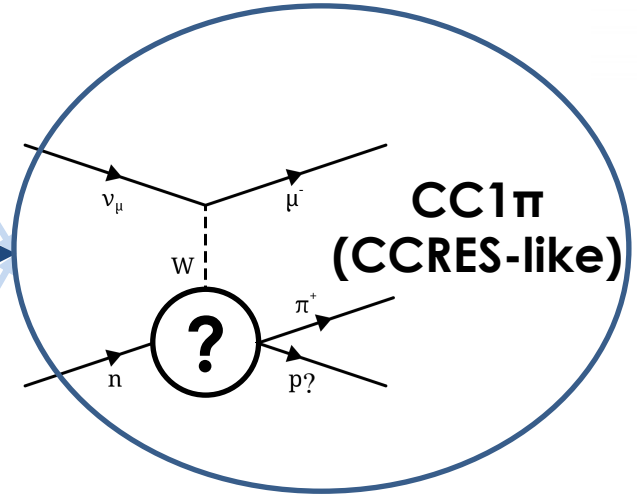
- Fewer approximations in predictions of nucleon kinematics

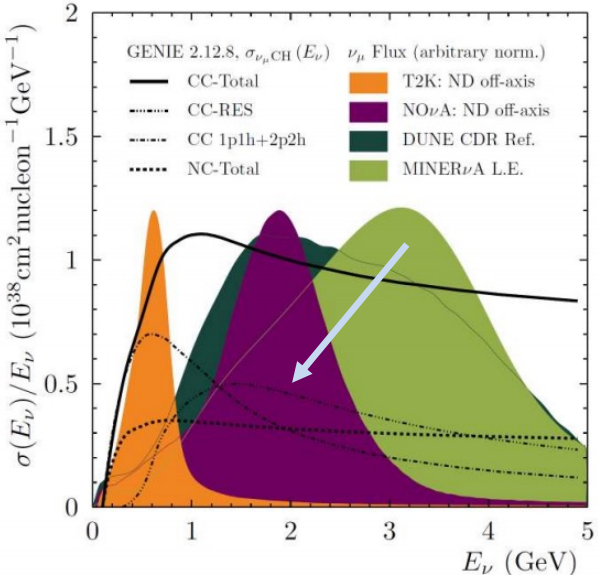
# What can we measure

**Interaction Modes**

**Interaction Topologies**



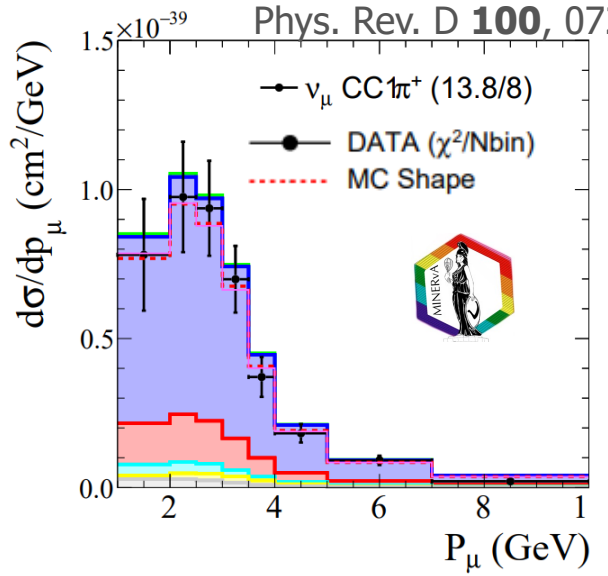

- Key contributor to all experiments
- The thing we don't understand well at all …

# Pion production measurements

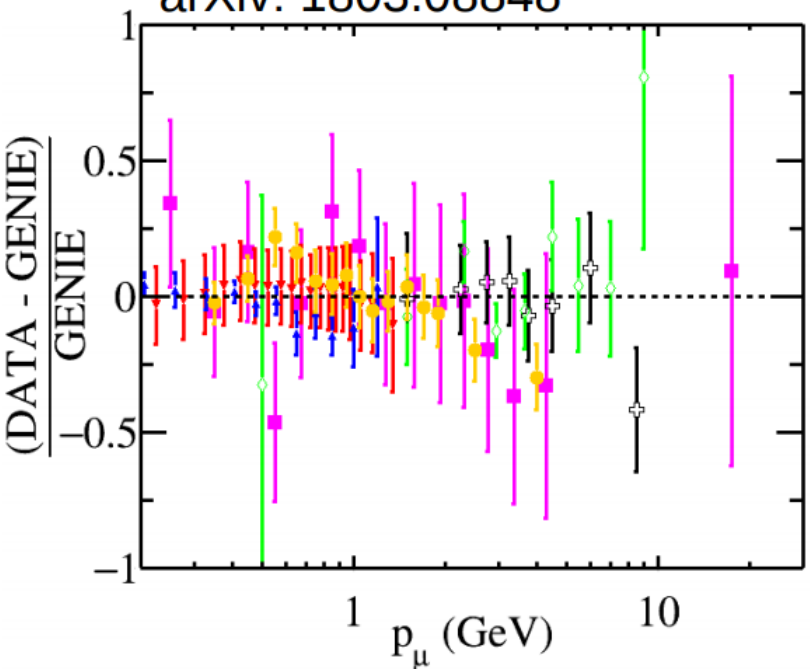
**Similar story:**

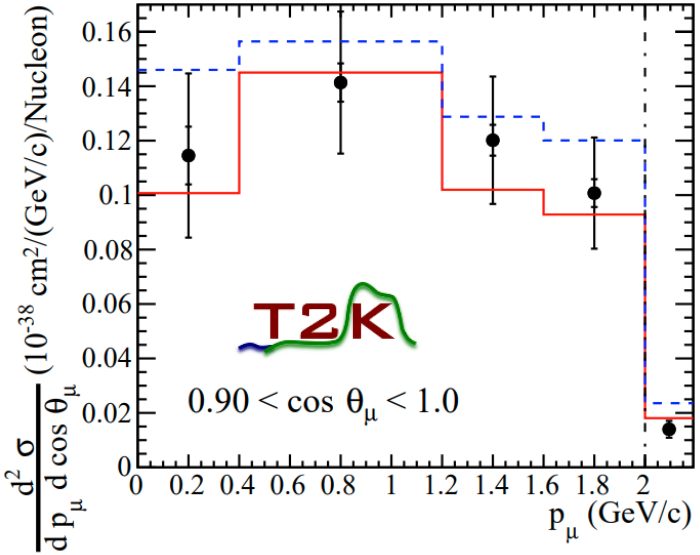
- Models generally able to predict lepton kinematics reasonably well
  - Even in the forward region!

Phys. Rev. D **100**, 072005




arXiv: 1803.08848



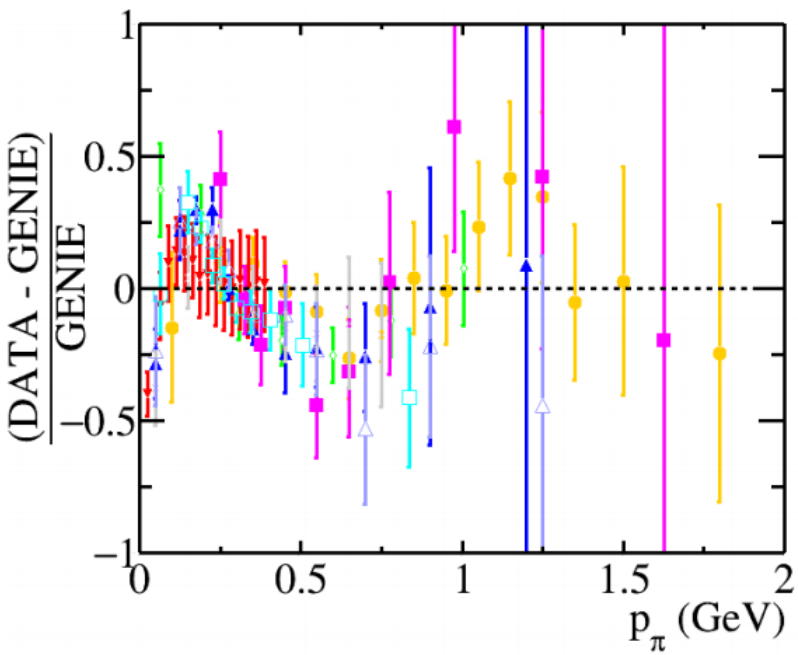



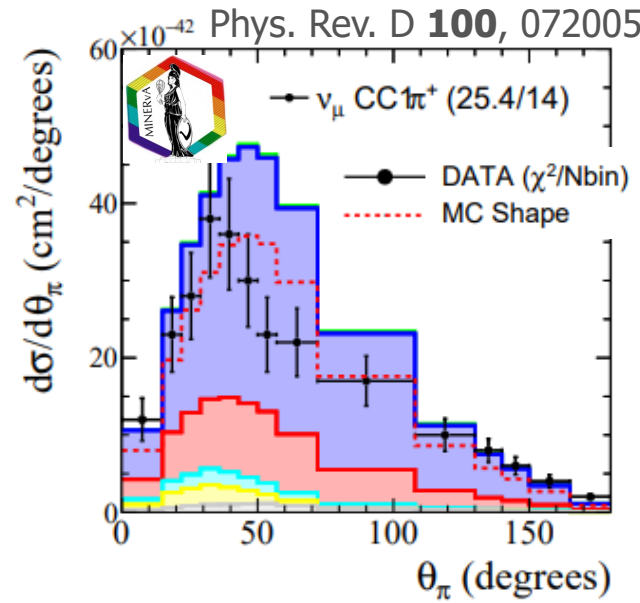

Phys. Rev. D **101**, 012007

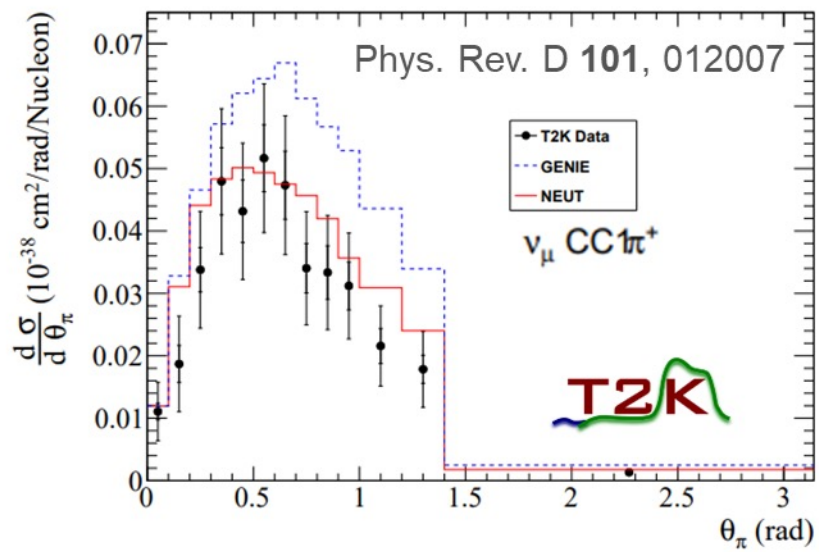
# Pion production measurements

**Similar story:**

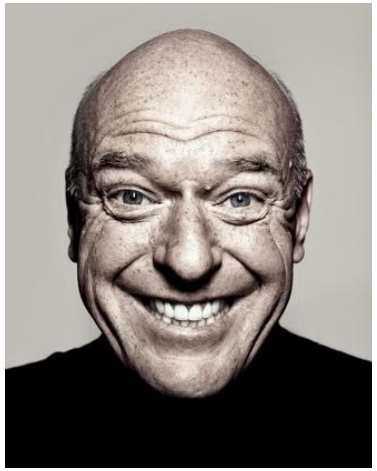
- Models generally able to predict lepton kinematics reasonably well
  - Even in the forward region!
- But pion kinematics are poorly described across experiments



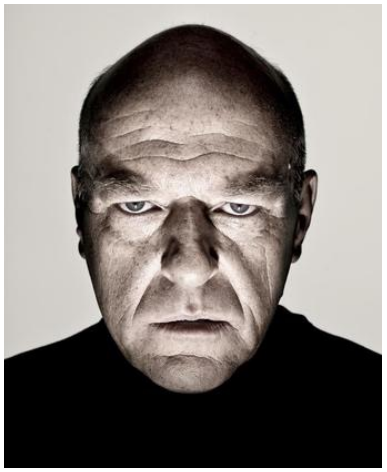



# So, how did we do?



Lepton kinematics
(except maybe at low energy transfers)

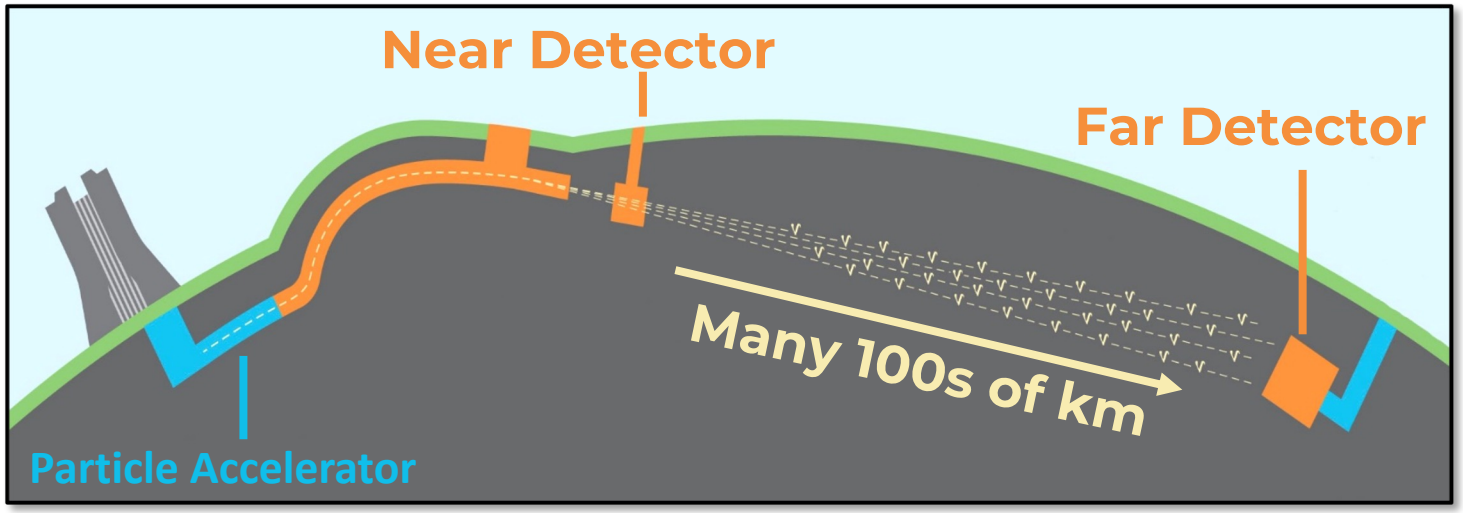


Lepton-hadron correlations

# Overview

- Neutrino Interactions: A History
  - Weak interactions from Fermi to SM
- Neutrino-nucleon interactions
  - QE, RES and DIS
- Neutrino-nucleus interactions
  - Nuclear effects
  - The rise and fall of $M_A = 1.3\ GeV$
- Neutrino event generators
  - Theory inputs
  - Filling in the gaps
- Neutrino-nucleus interaction measurements
  - Inclusive successes and exclusive failures
- Why do we care?
  - Neutrino interactions for neutrino oscillations
  - Neutrino energy reconstruction
- Don't Panic! The future of neutrino interaction simulations

# Accelerator-Based Experiments



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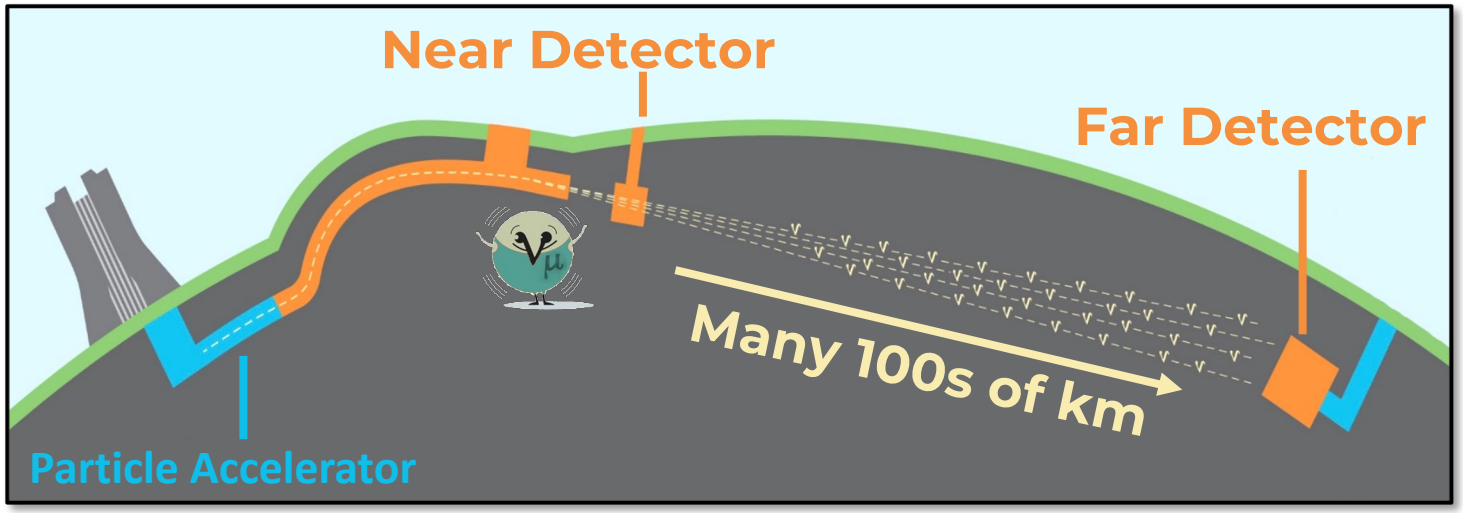


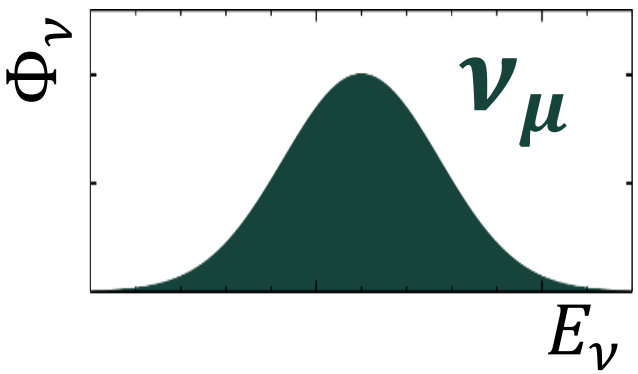

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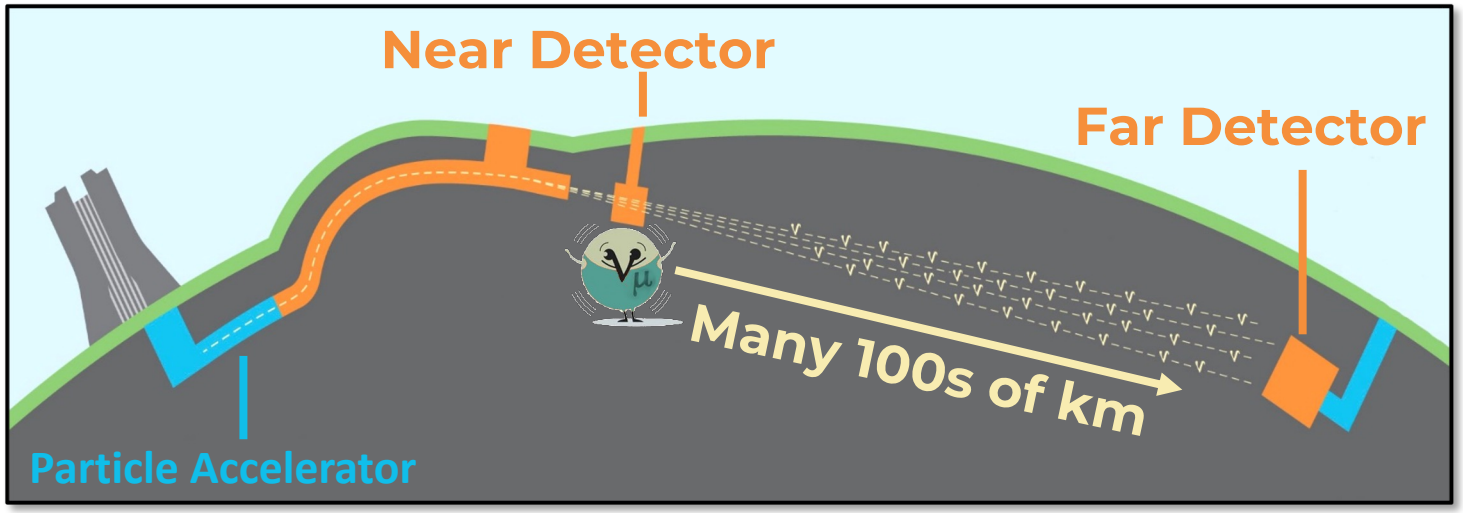
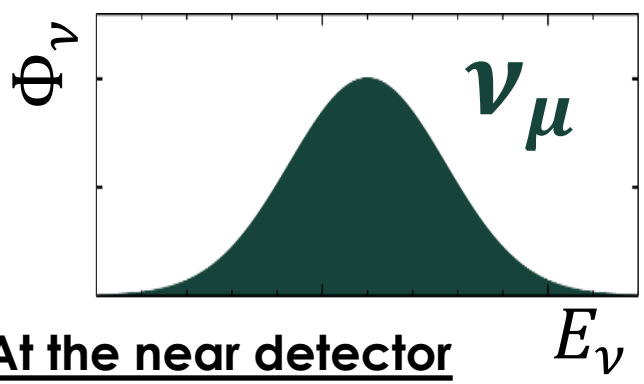


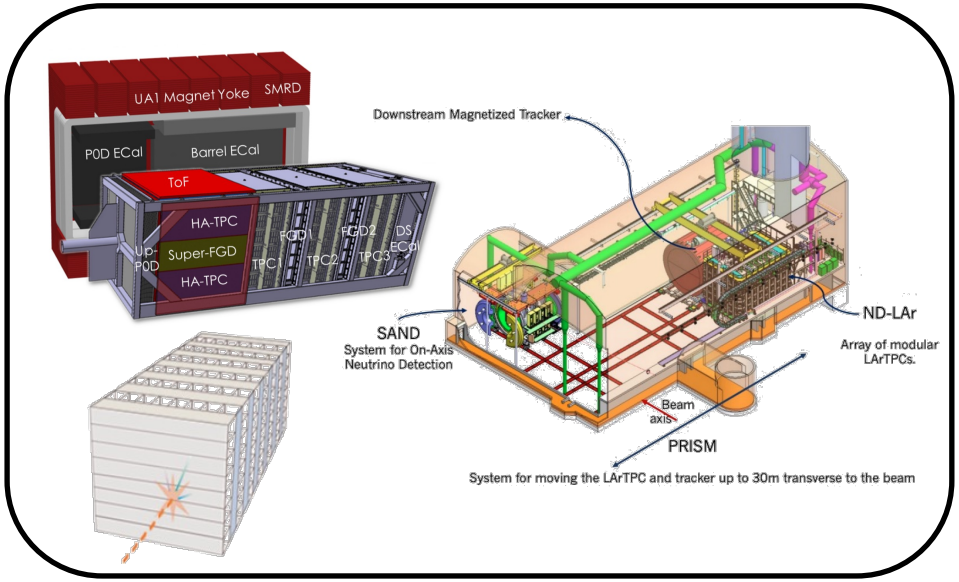

**At the near detector**

$$N_\mu(E_\nu) = \sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

Interaction cross section

Neutrino flux

Detector effects



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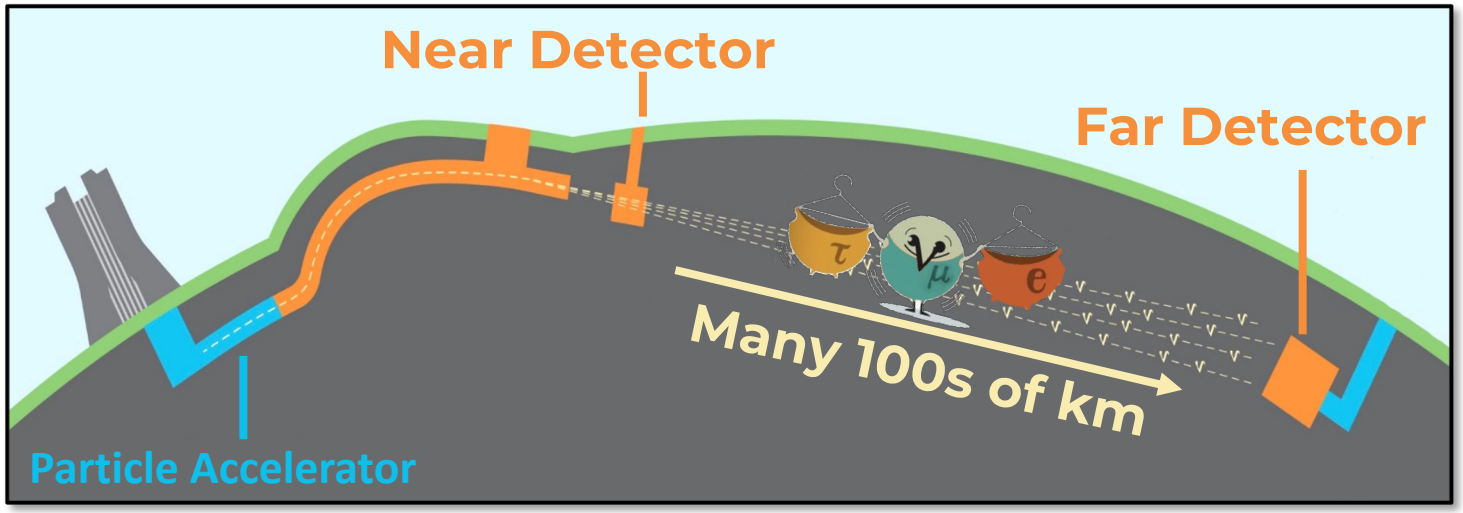


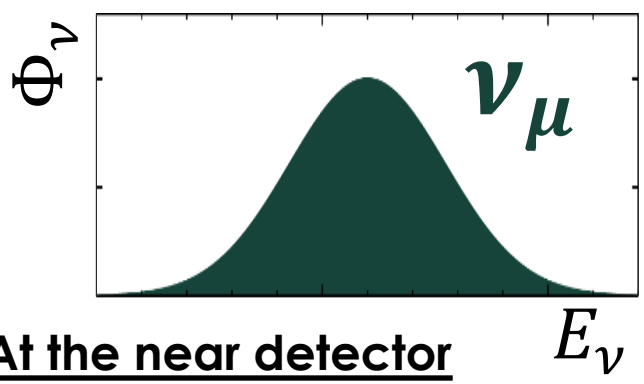


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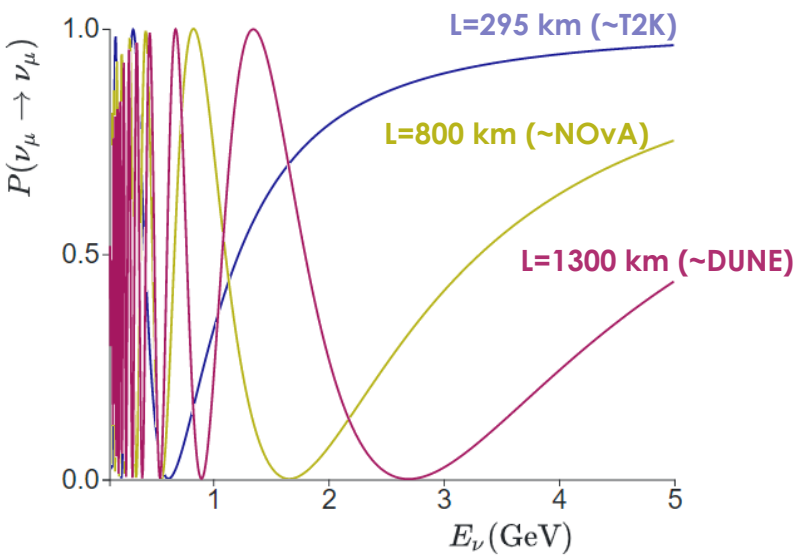

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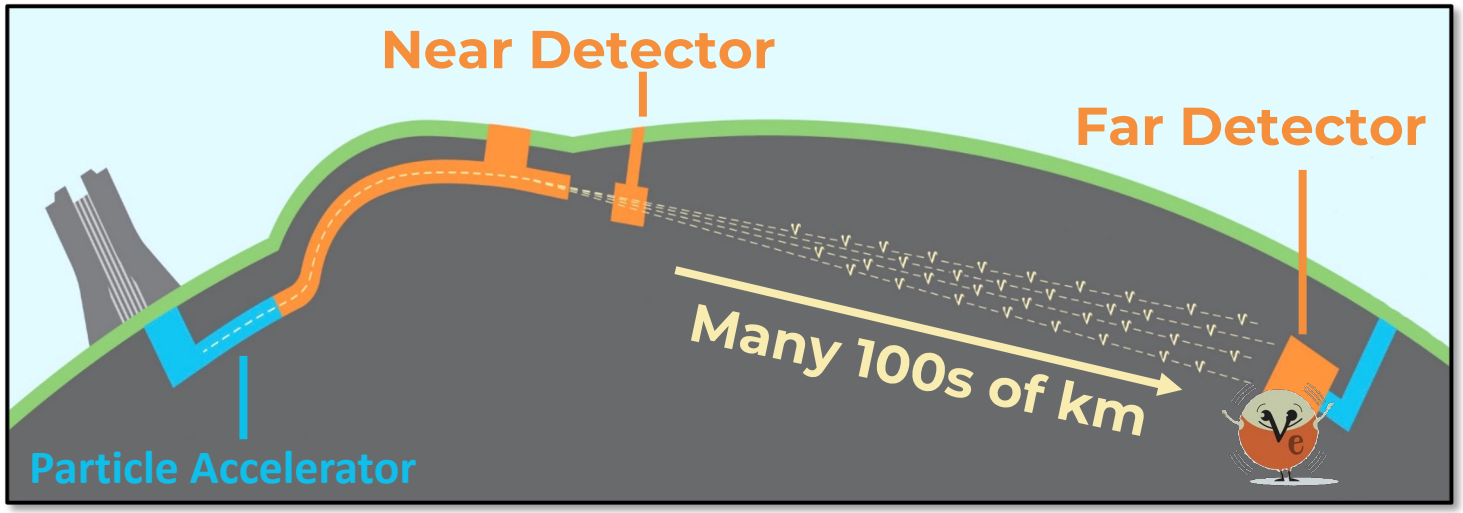


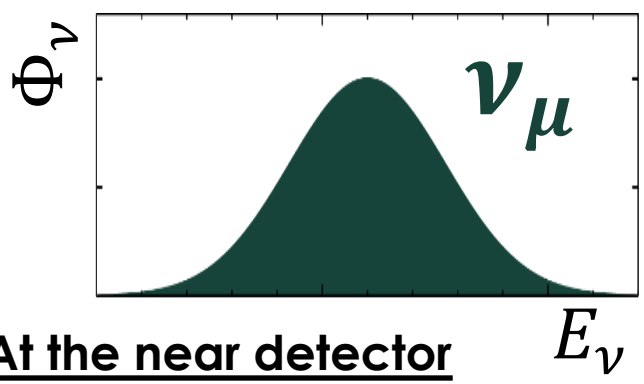


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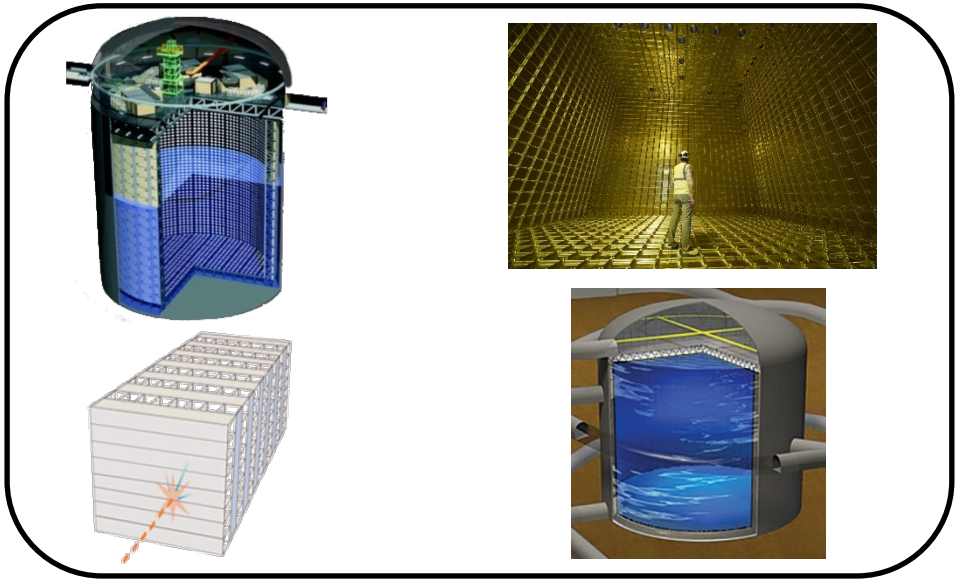

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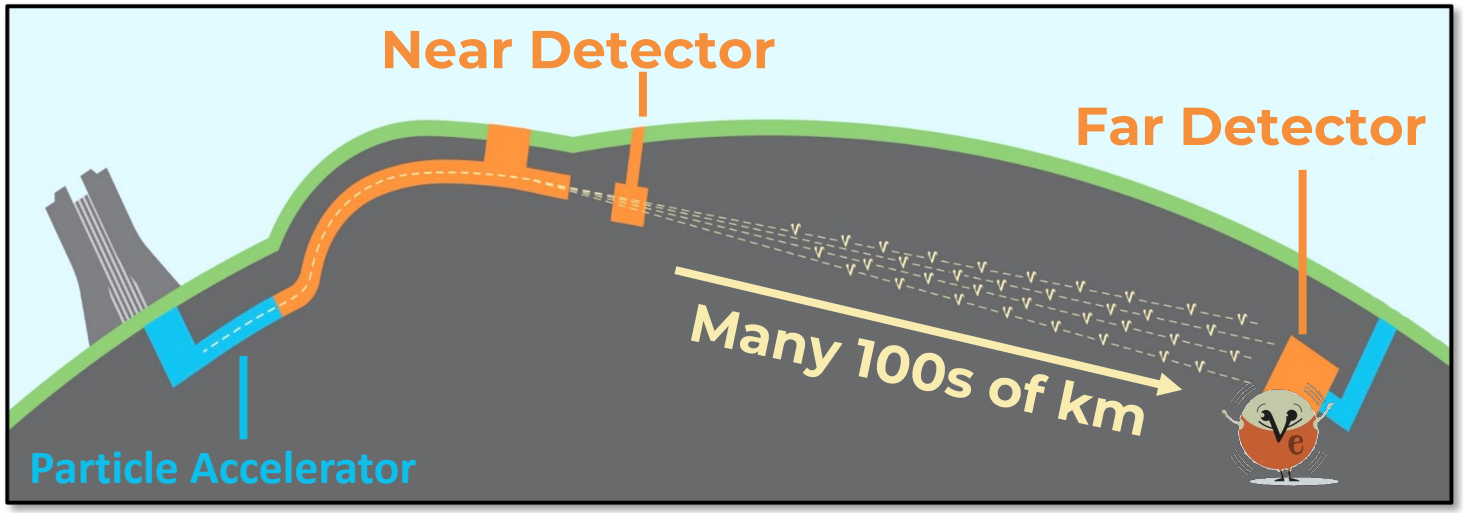


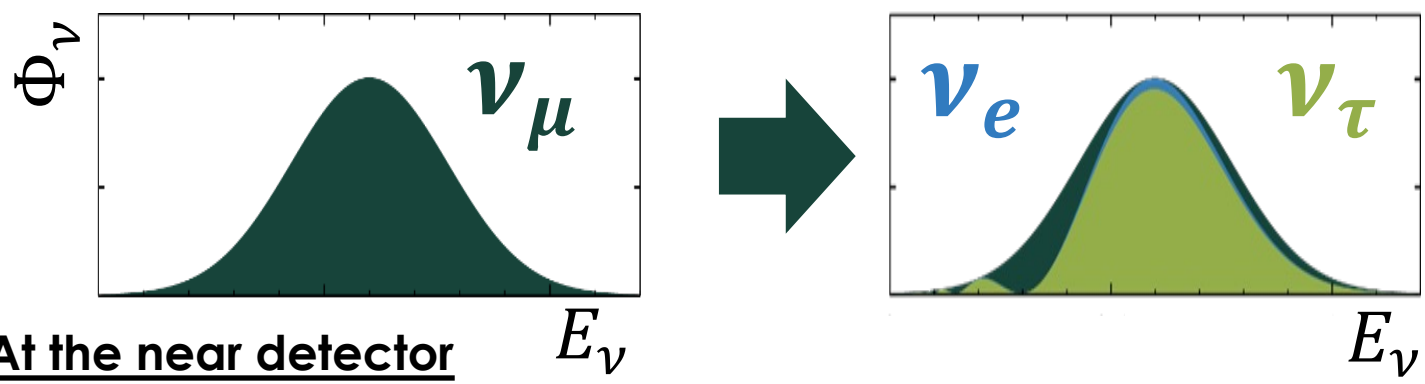


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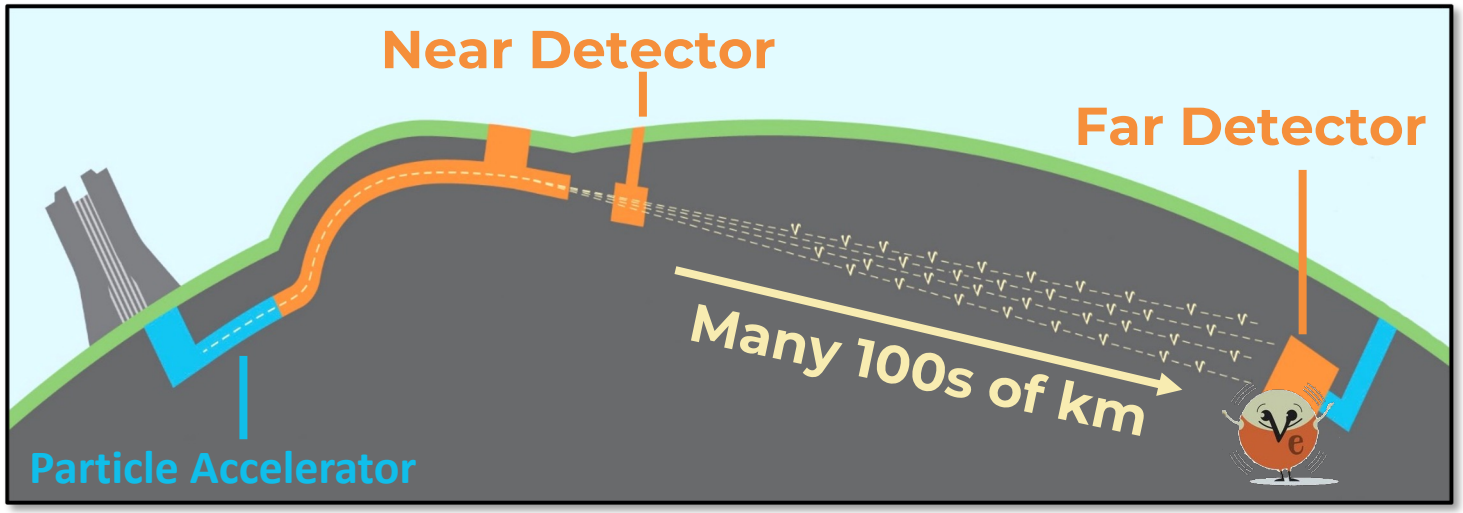


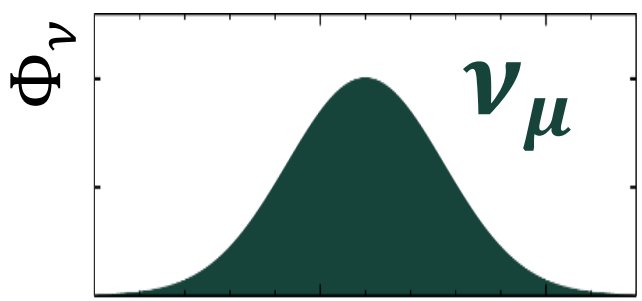


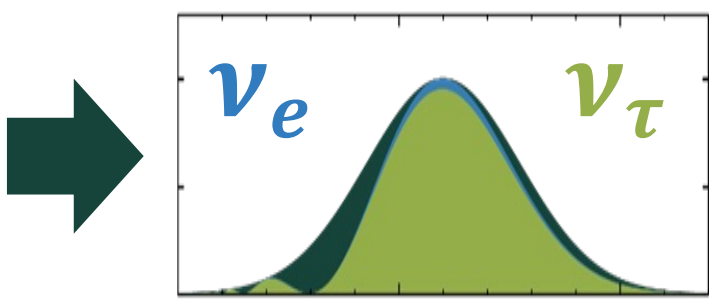


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**At the far detector**

$$N_\mu(E_\nu) = P(\nu_\mu \to \nu_\mu)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

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Oscillation probability

# Accelerator-Based Experiments

**Current long-baseline experiments**

| | T2K | NOvA |
|---|---|---|
| **Baseline** | 295 km | 800 km |
| $N_\mu^{rec}$ ($\nu$-mode) | 318 | 211 |
| $N_\mu^{rec}$ ($\bar{\nu}$-mode) | 137 | 105 |
| $N_e^{rec}$ ($\nu$–mode) | 94 | 82 |
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*Reconstructed events in samples at the experiment's far detectors*

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## Current systematic uncertainties

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

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

NEUTRINO 2022

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# Accelerator-Based Experiments

## Future long-baseline experiments

*Coming 2027-2032*

| | Hyper-K | DUNE |
|---|---|---|
| | *arXiv:1805.04163* | *arXiv:2002.03005* |
| **Baseline** | 295 km | 1300 km |
| $N_\mu^{rec}$ ($\nu$-mode) | ~10000 | ~7000 |
| $N_\mu^{rec}$ ($\bar{\nu}$-mode) | ~14000 | ~3500 |
| $N_e^{rec}$ ($\nu$–mode) | ~2000 | ~1500 |
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*Approximate late-stage projections for reconstructed events in samples at the experiment's far detectors*

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# Accelerator-Based Experiments

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*Coming 2027-2032*

*2002.03005*

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Crucial to reduce uncertainties related to neutrino interaction cross sections

## At the far detector

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# Where are we so far?

- Current neutrino oscillation experiments are mostly **statistics limited**
- Systematic uncertainties related to neutrino-nucleus interactions are often dominant and **are unacceptably large for the next generation of experiments**
- Key questions:
  1. *Why is modelling neutrino interactions so difficult?*

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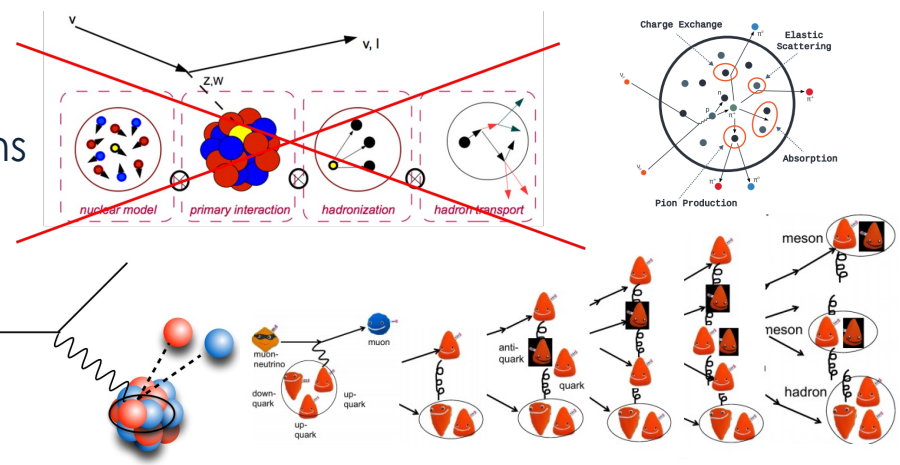
*See last lecture!*

- Challenging nucleon-level calculations for RES and DIS interactions
- Myriad of nuclear effects to deal with
- Incomplete theory inputs mean approximations in event generators



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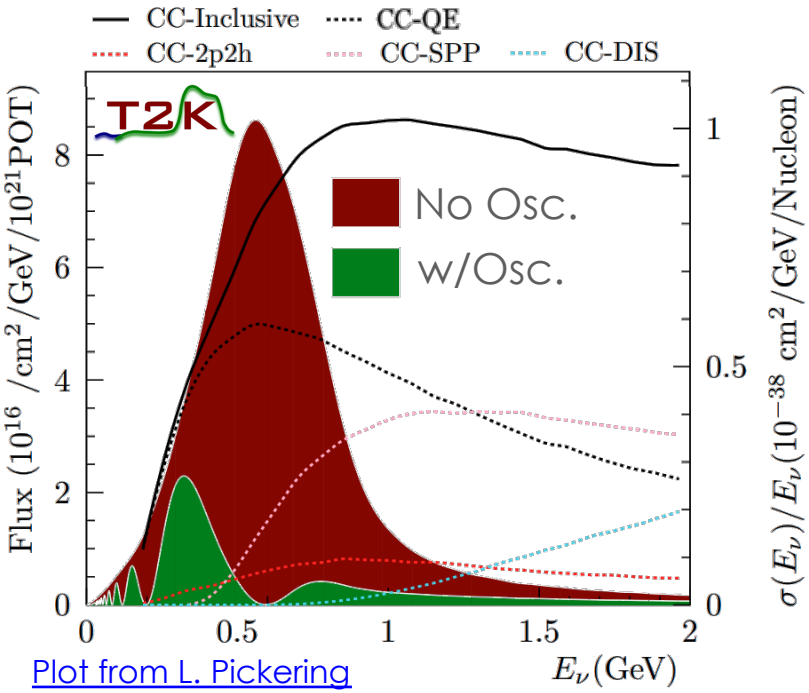
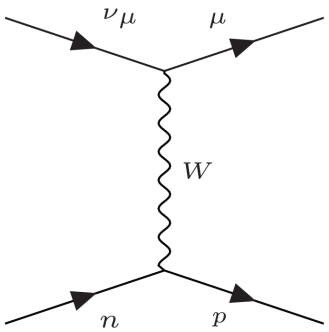
# Neutrino-nucleus cross sections

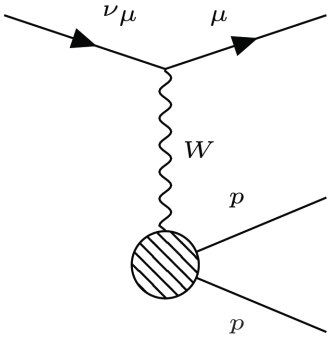



Plot from L. Pickering

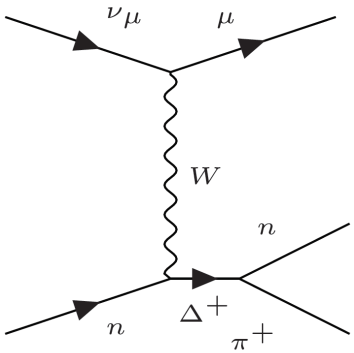
**CC-QE**
(Charged-Current Quasi-Elastic)



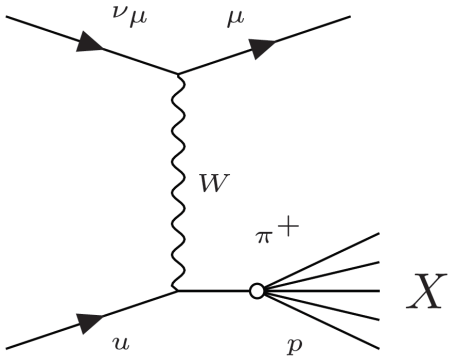

**CC-2p2h**
(Two-Particle-Two-Hole)



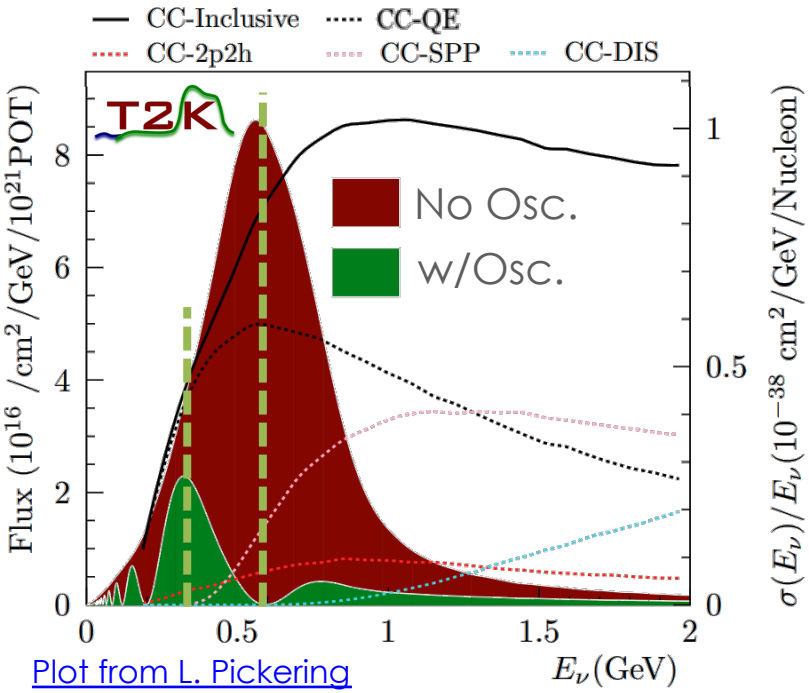

**CC-SPP**
(Single Pion Production)




**CC-DIS**
(Deep Inelastic Scattering)



# Event rates to oscillation parameters

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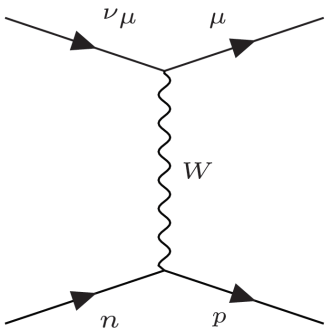


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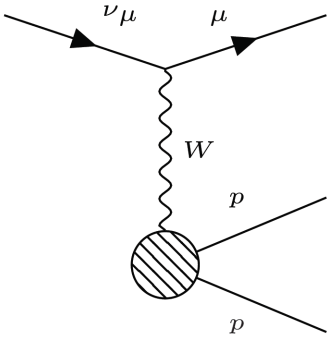
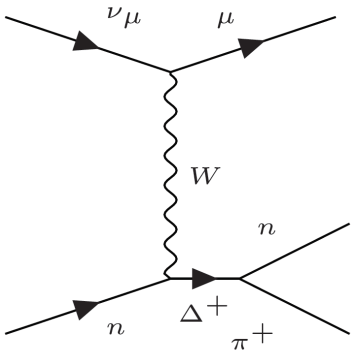
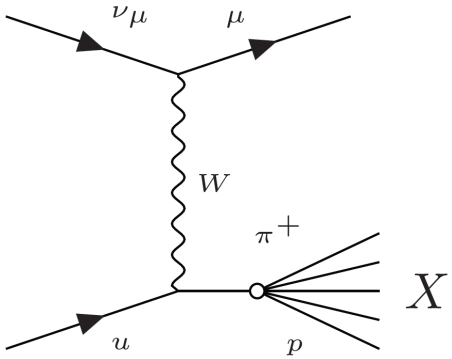


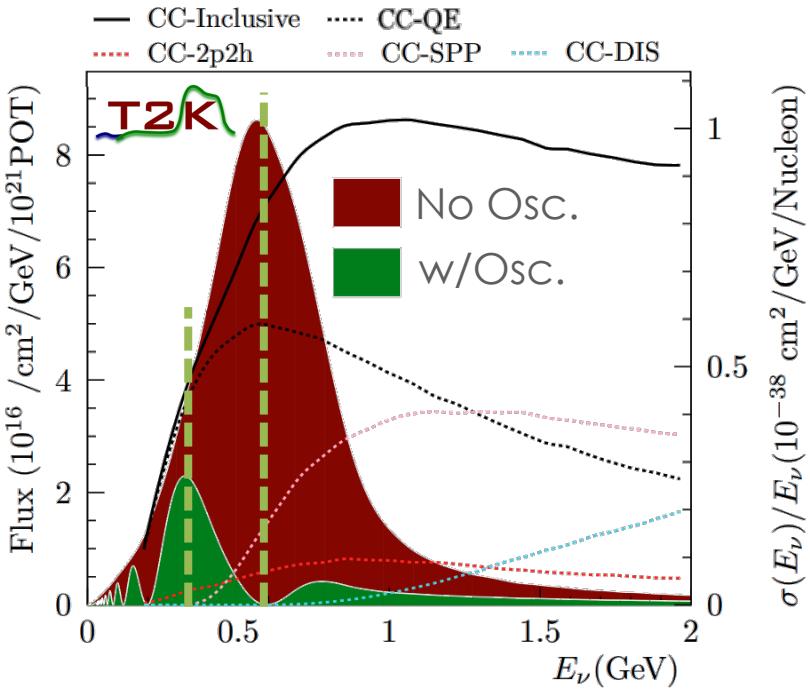

**CC-SPP**
(Single Pion Production)




**CC-DIS**
(Deep Inelastic Scattering)



# Event rates to oscillation parameters




- Near / far ratios don't fully cancel systematics:
  - Dramatic change in $E_\nu$ distribution due to oscillations
  - $\nu_\mu$ at ND vs $\nu_e$ at FD (for appearance)
  - Different ND/FD design, acceptance

**At the near detector**

$$N_\mu(E_\nu) = \sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

Interaction cross section

Neutrino flux

Detector effects

**At the far detector**

$$N_\mu(E_\nu) = P(\nu_\mu \to \nu_\mu)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

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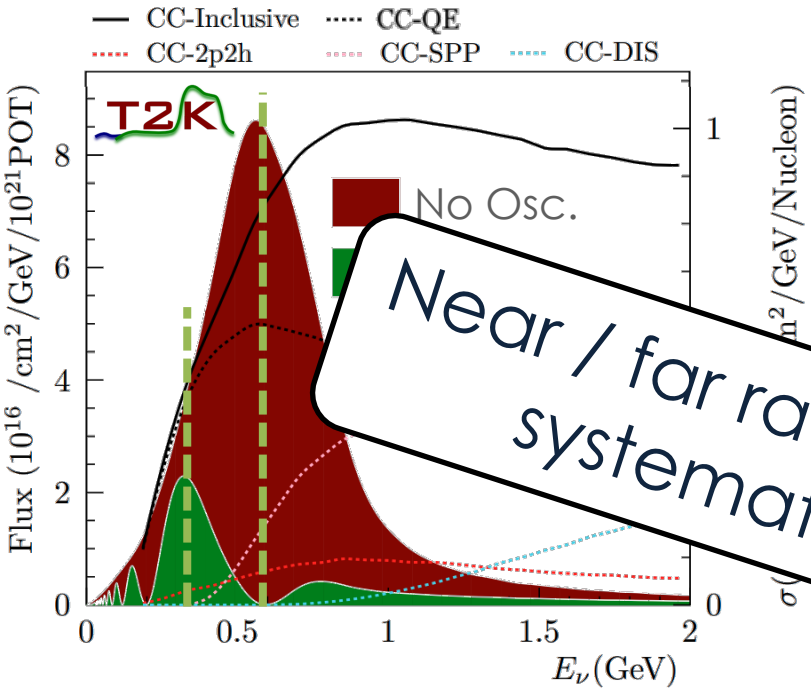
Oscillation probability

# Event rates to oscillation parameters

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Near / far ratios don't fully cancel systematic uncertainties!

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Oscillation probability

# Where are we so far?

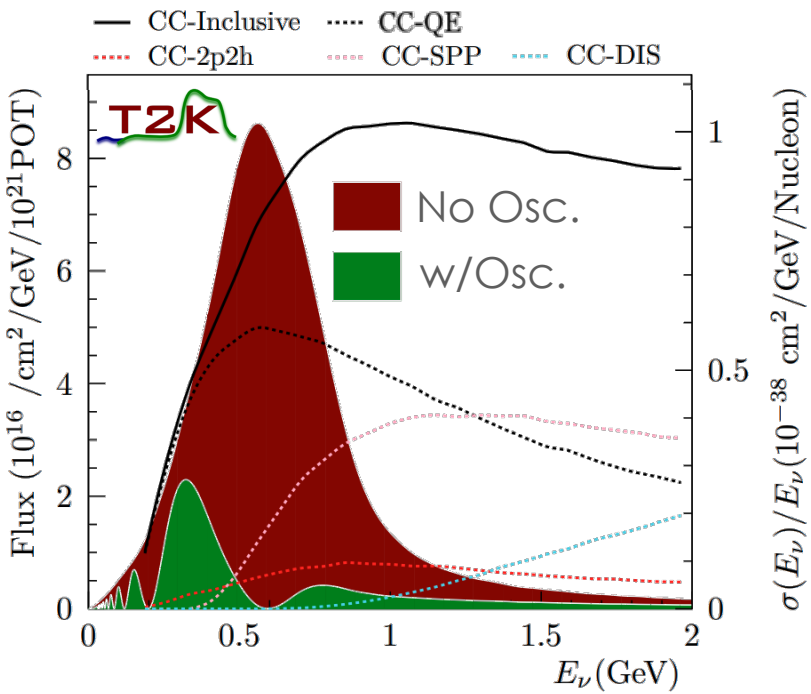
- Key questions:

  1. *Why is modelling neutrino interactions so difficult?*

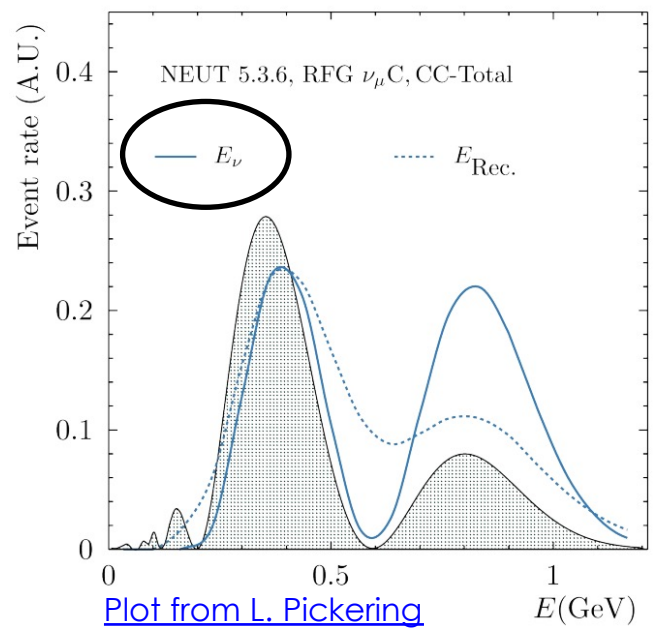
  2. *Why does the near detector not allow a better cancellation of uncertainties?*

  3. ***What exactly do we need to understand in order to reduce uncertainties on oscillation measurements?***

# Event rates to oscillation parameters




What we would like to measure




Plot from L. Pickering

$$N_\ell(E_\nu) = P(\nu_\mu \to \nu_\ell)(E_\nu)\, \sigma(E_\nu)\, \Phi_\nu(E_\nu)\, \epsilon(E_\nu)$$

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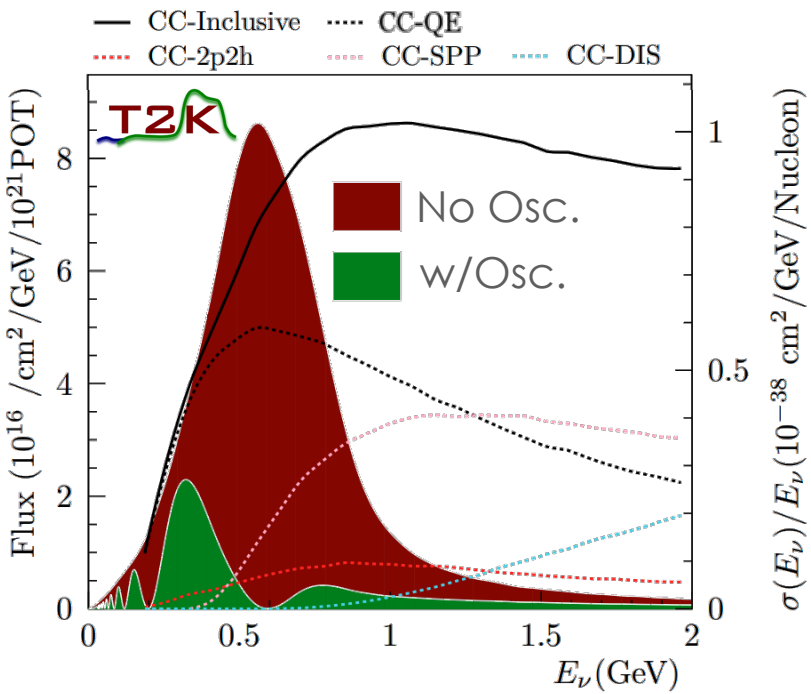
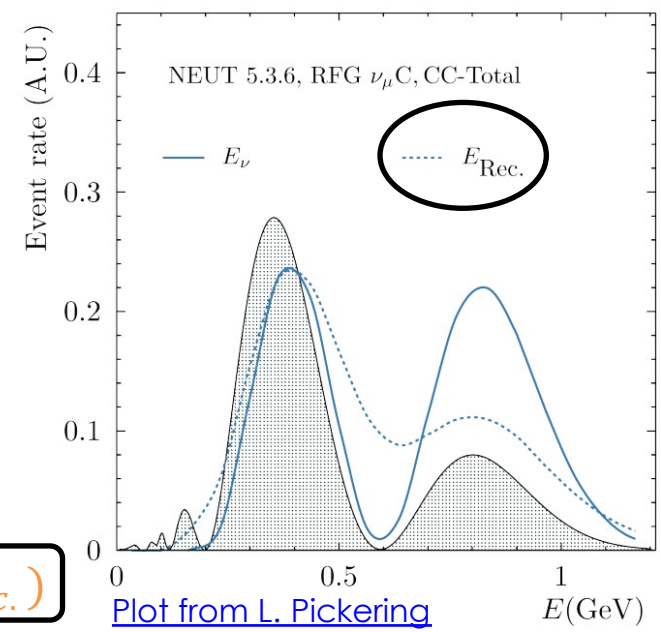



What we can actually measure

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$$N_\ell(E_{Rec.}) = P(\nu_\mu \to \nu_\ell)(E_\nu)\, \sigma(E_\nu)\, \Phi_\nu(E_\nu)\, \epsilon(E_\nu)\, S(E_\nu, E_{Rec.})$$

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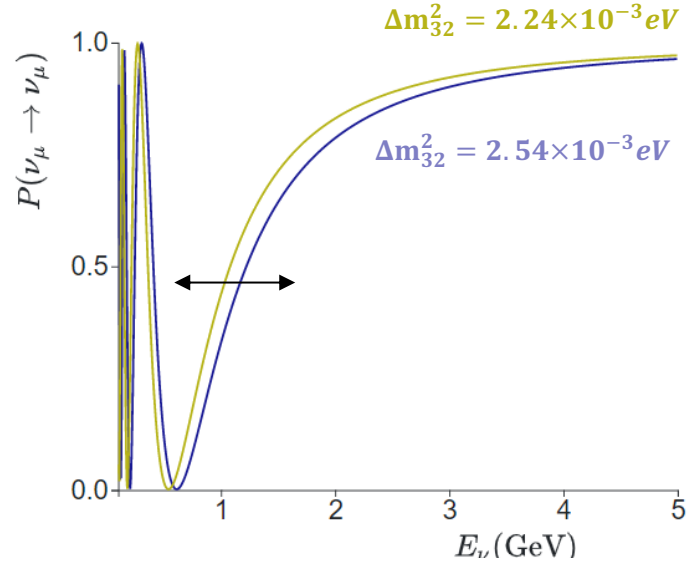


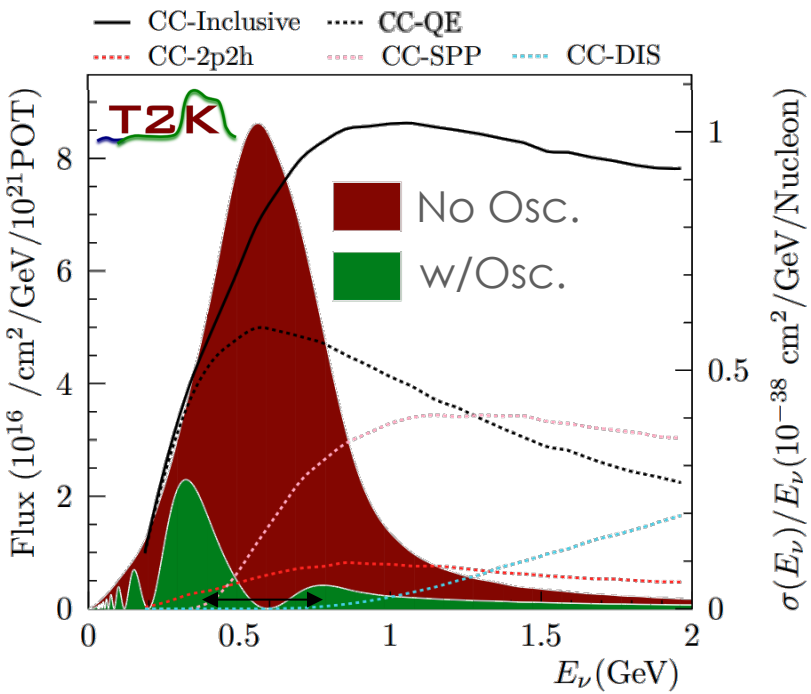


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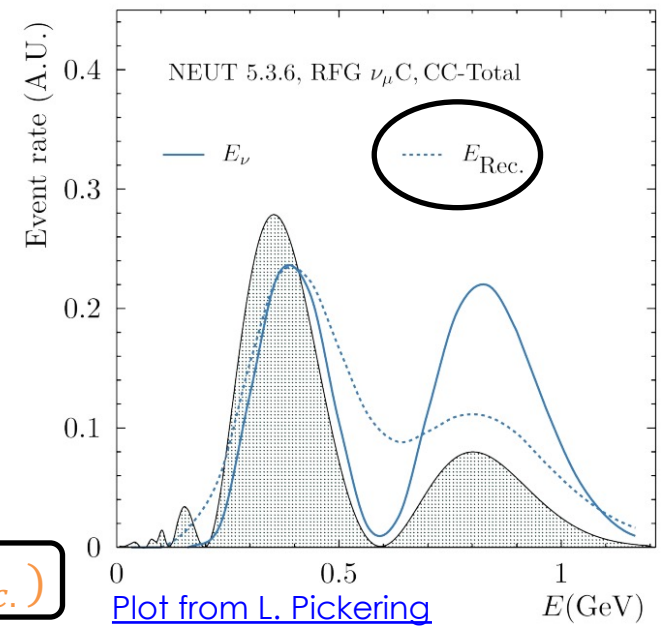


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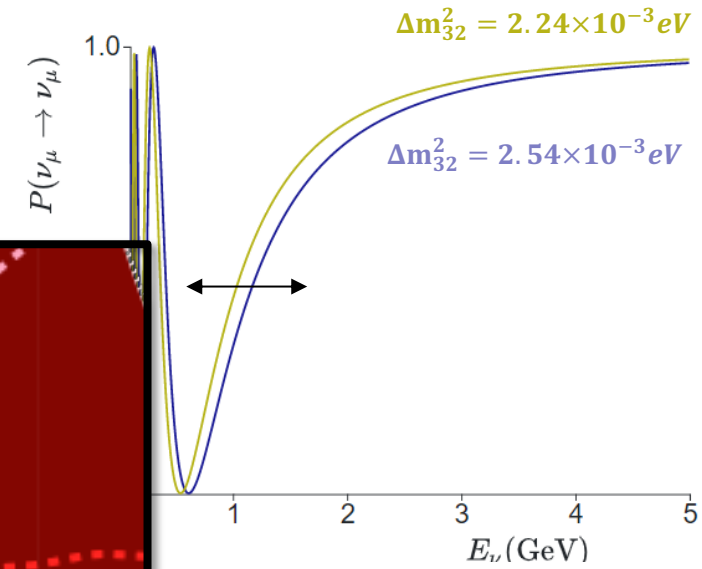


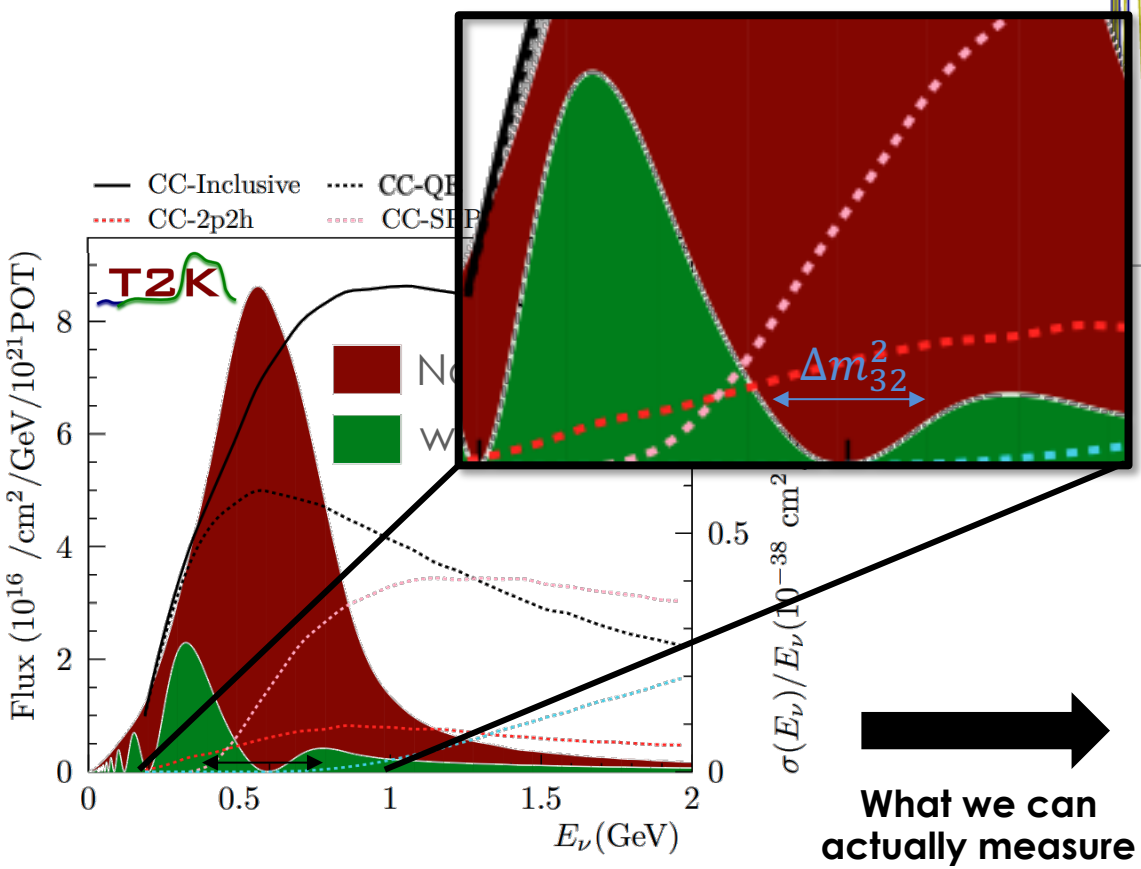


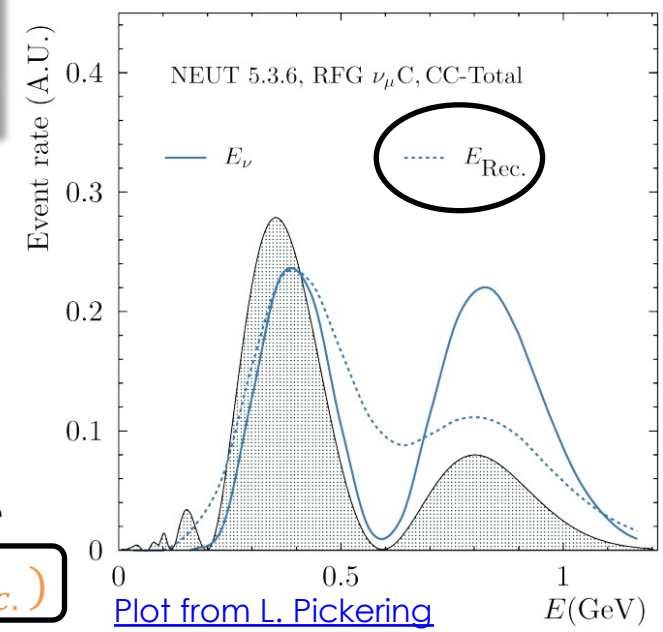


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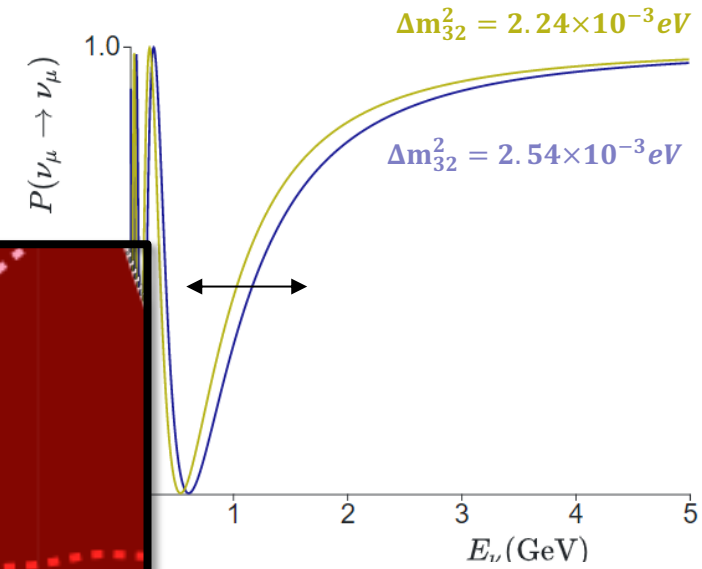


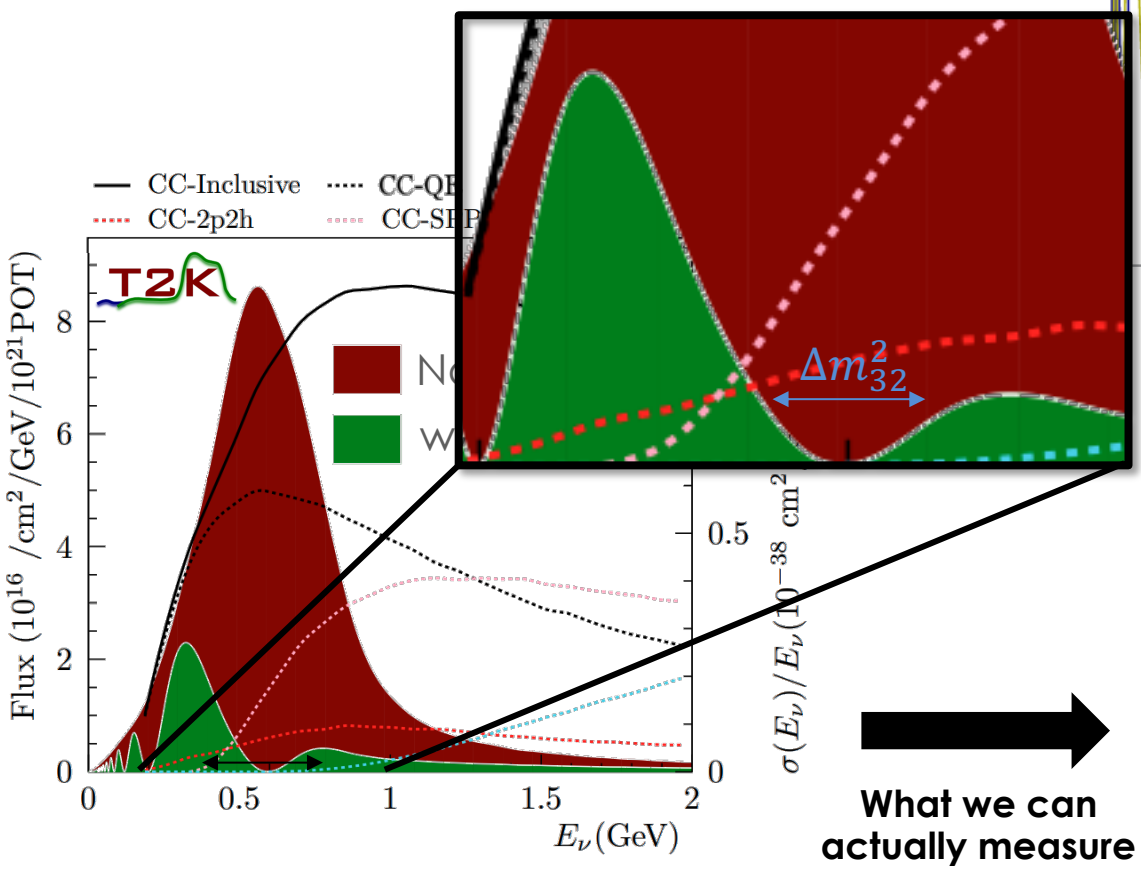


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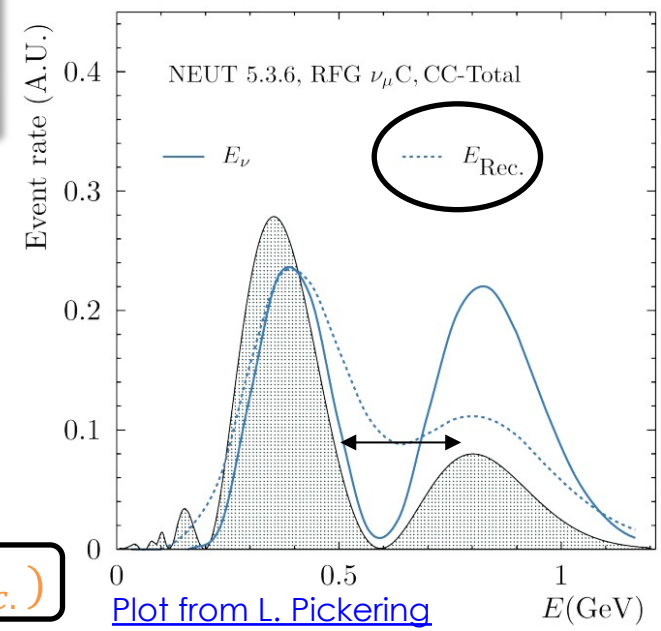


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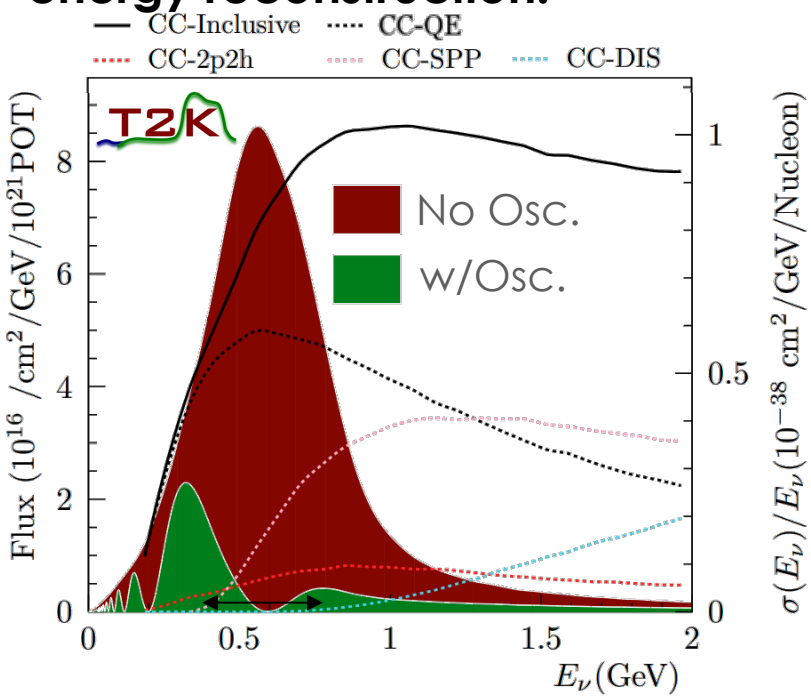


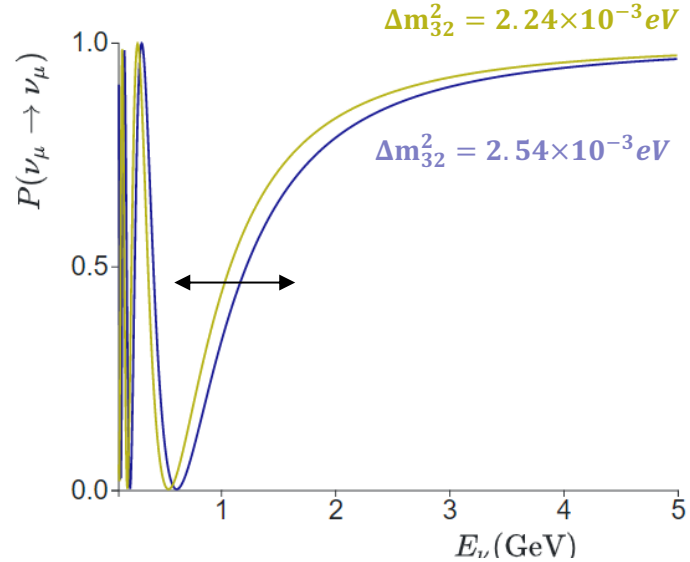


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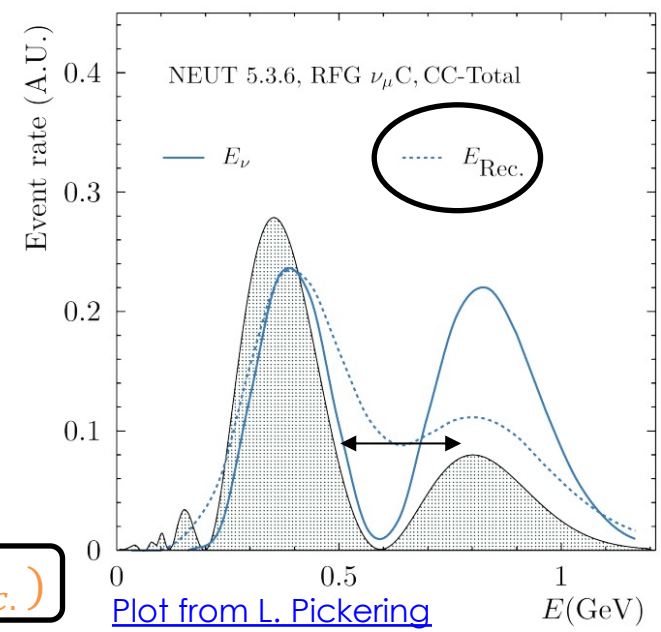


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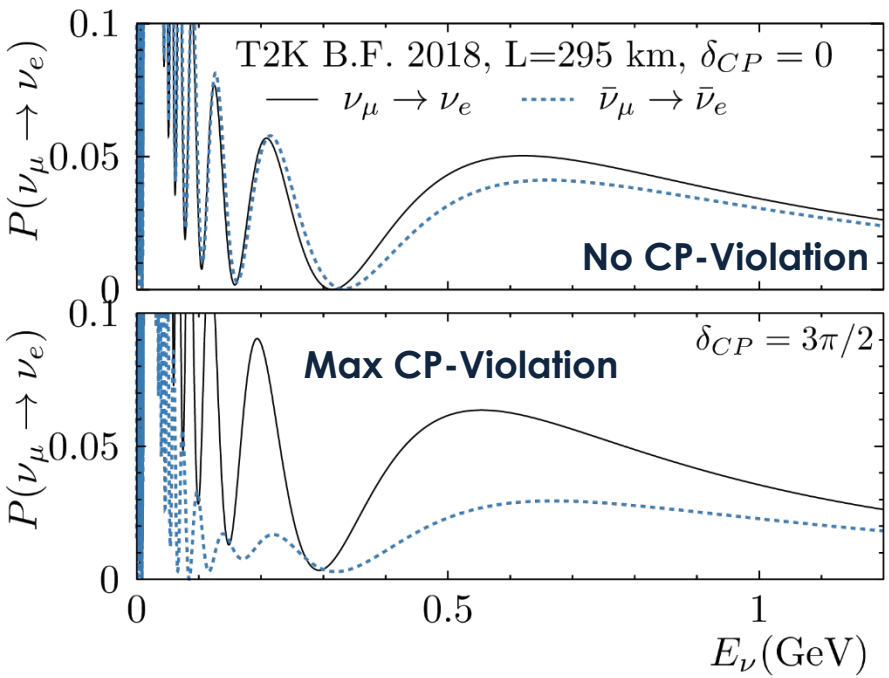

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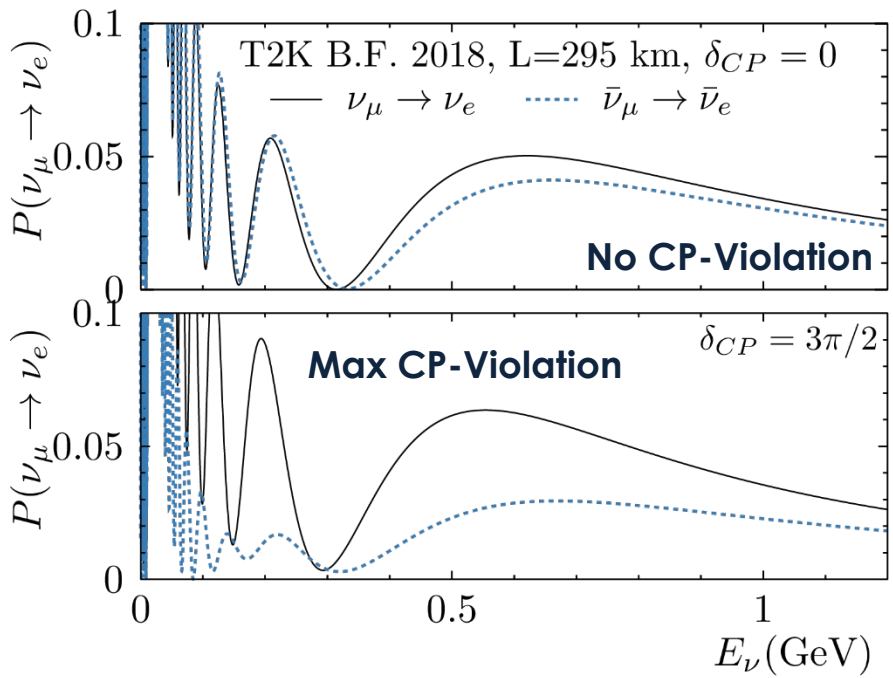

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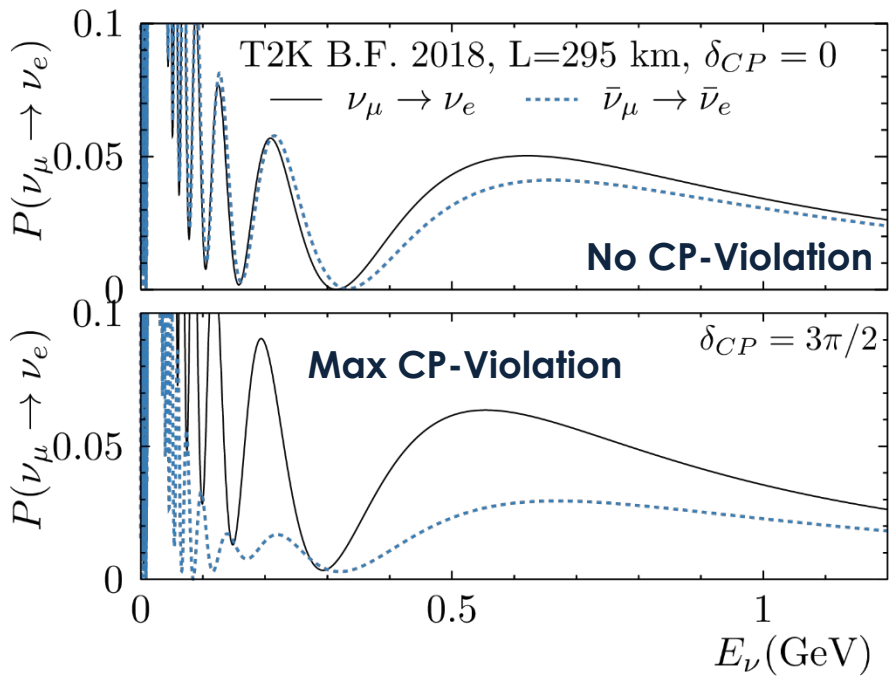

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(a non exhaustive list)

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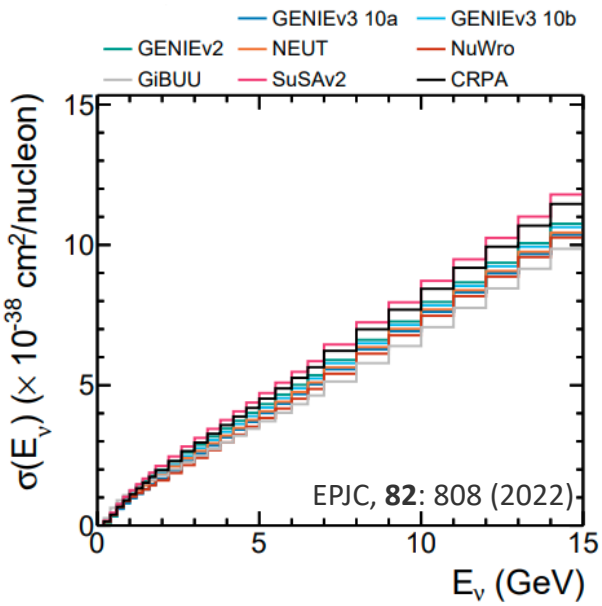

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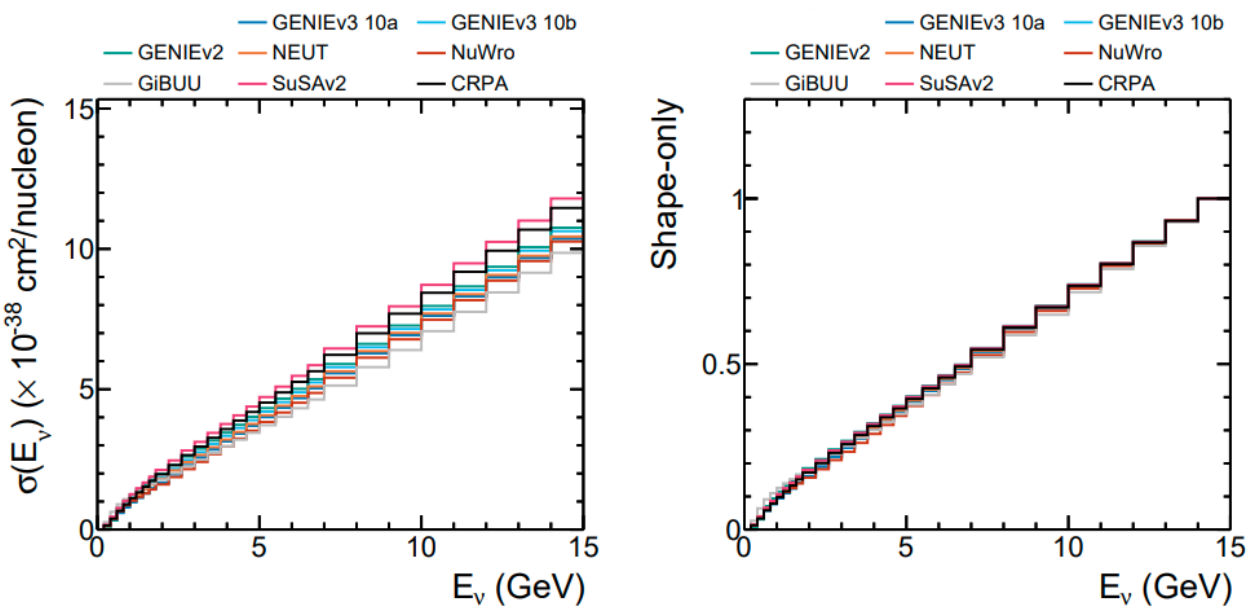
- What matters ND→FD extrapolation is the shape of total cross section as a function of $E_\nu$



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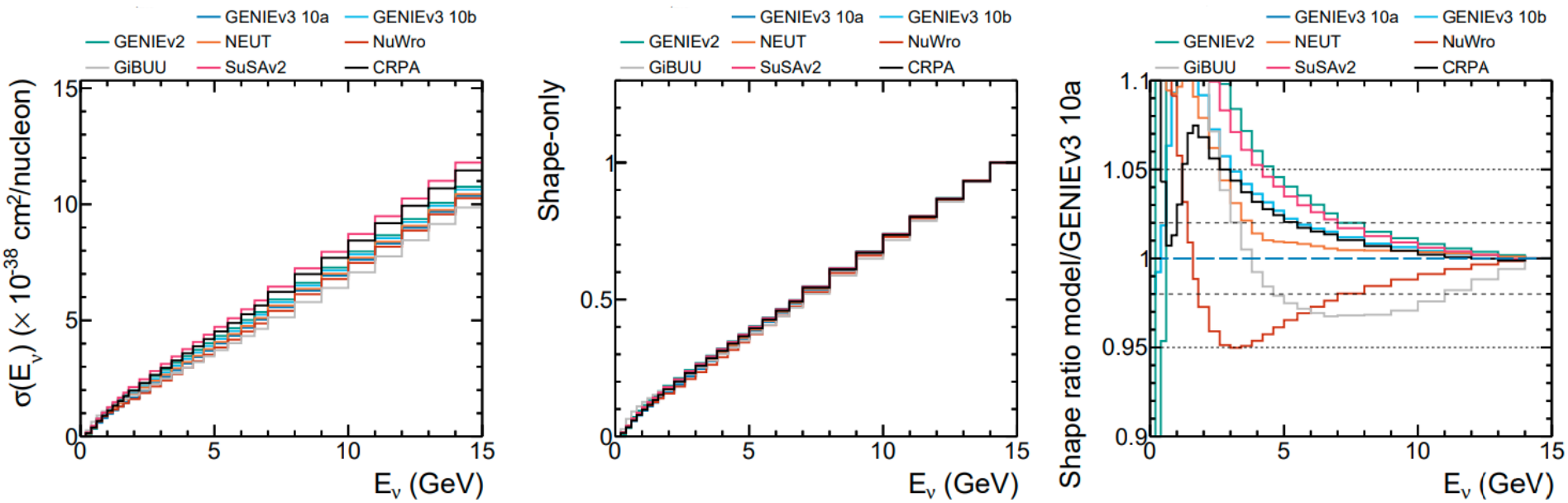

# Energy dependence

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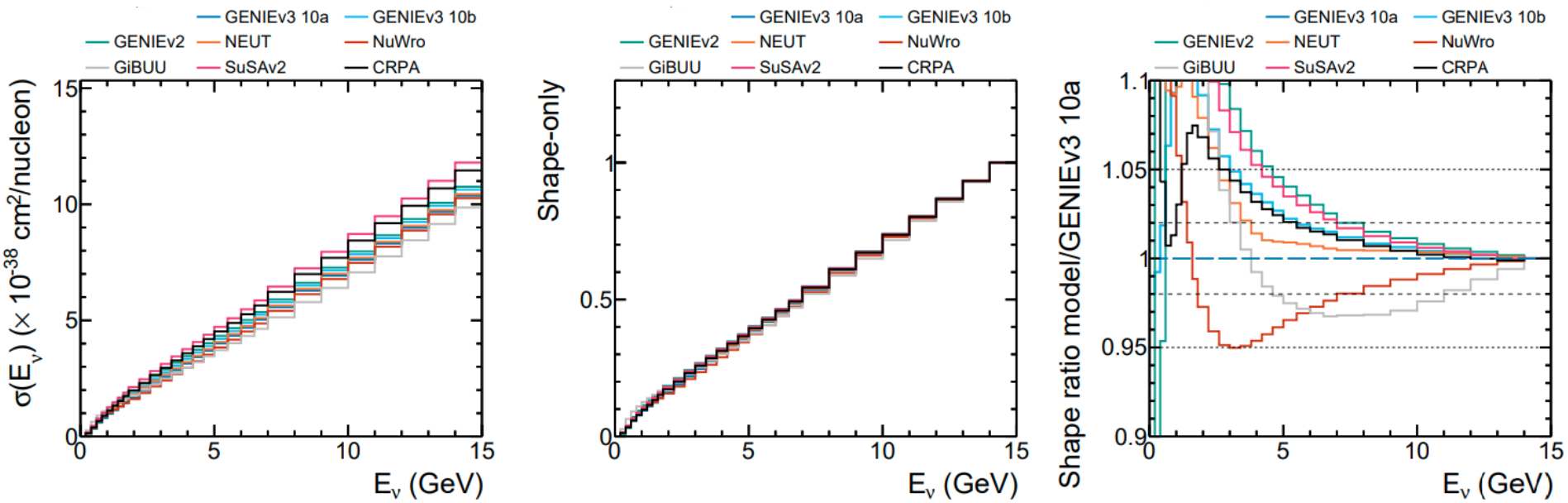
- Models differ by 5-10% in the region of interest for DUNE and Hyper-K
- Driven by different treatments of nuclear effects
- Significant, given the expected statistics for DUNE and Hyper-K
- Future measurements will aim to provide direct constraints on $\sigma(E_\nu)$
  - E.g. PRISM, or multi-detector measurements



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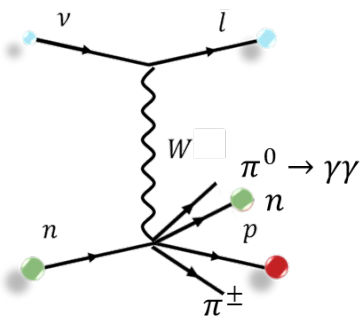
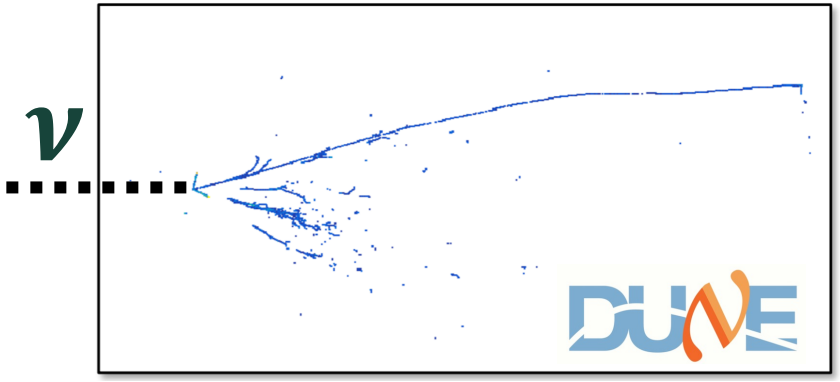
**"Calorimetric method"**

$$E_\nu = E_\ell + E_{had,vis}$$

- Add the lepton energy to the sum of all visible hadronic energy
- But not all hadrons deposit all their energy inside the detector



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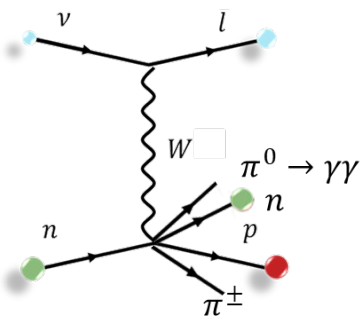
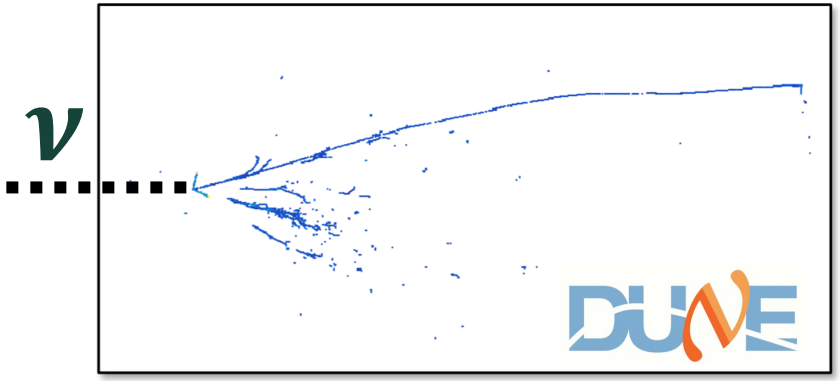
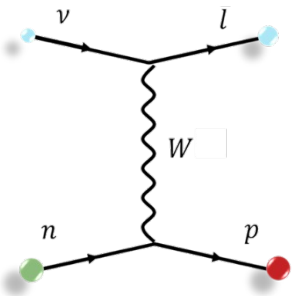


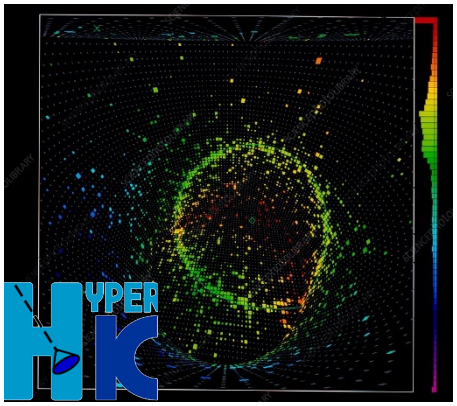



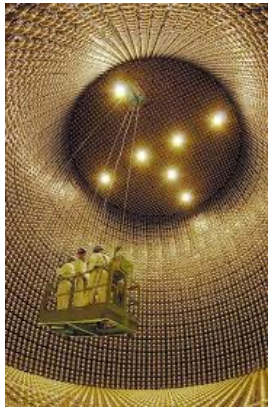

**"Kinematic method"**

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

- Uses only the outgoing lepton kinematics
- Assume elastic scatter off a stationary nucleon

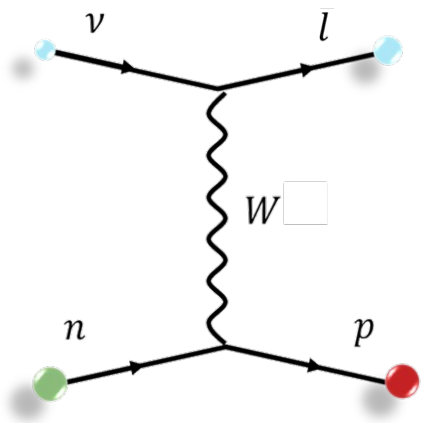


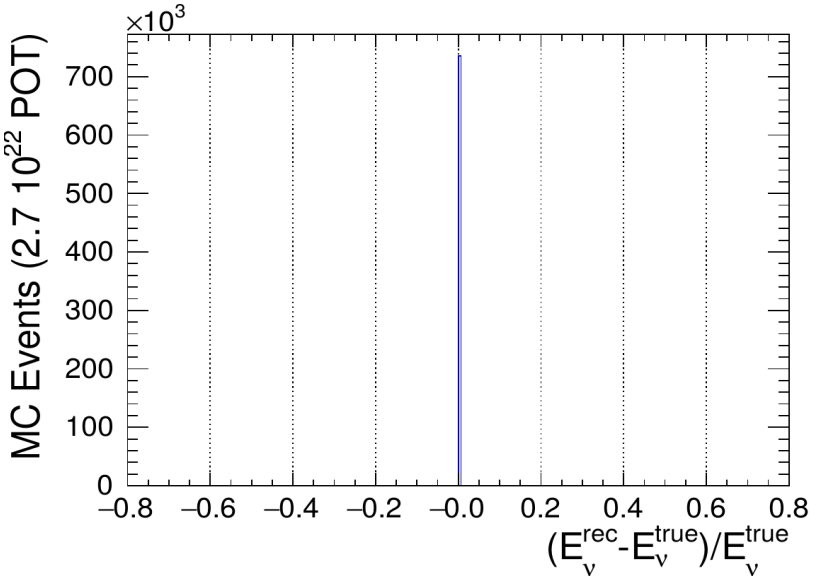



# Nuclear effects and $E_\nu$ (T2K/HK)

**CCQE (1p1h)**

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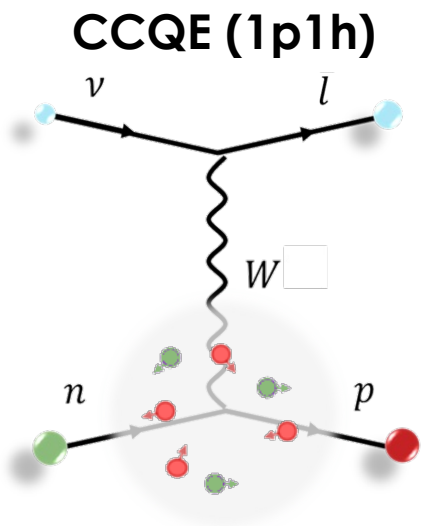
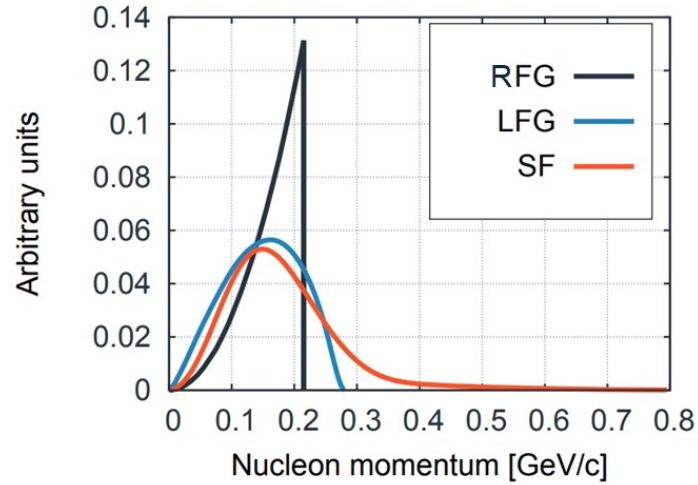
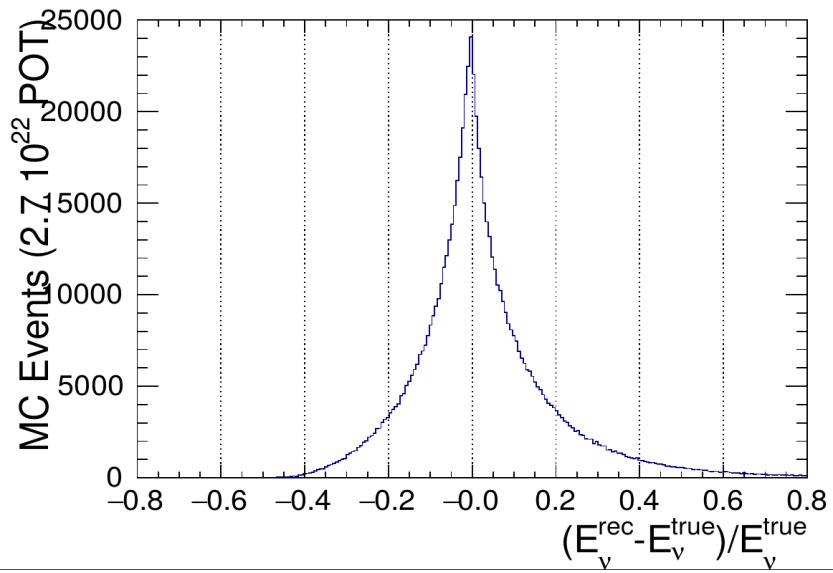
Proxy for $E_\nu$ from lepton kinematics is exact only for **CCQE elastic scattering** off a **stationary nucleon**

# Nuclear effects and $E_\nu$ (T2K/HK)

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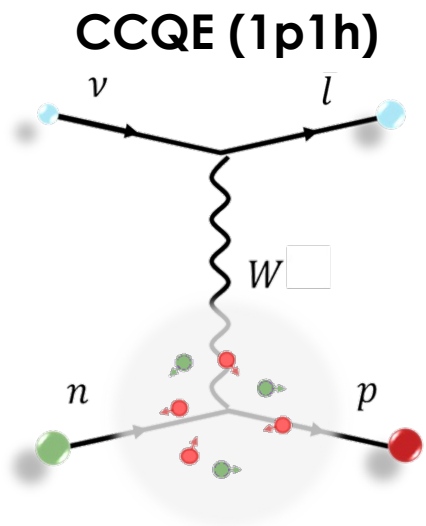
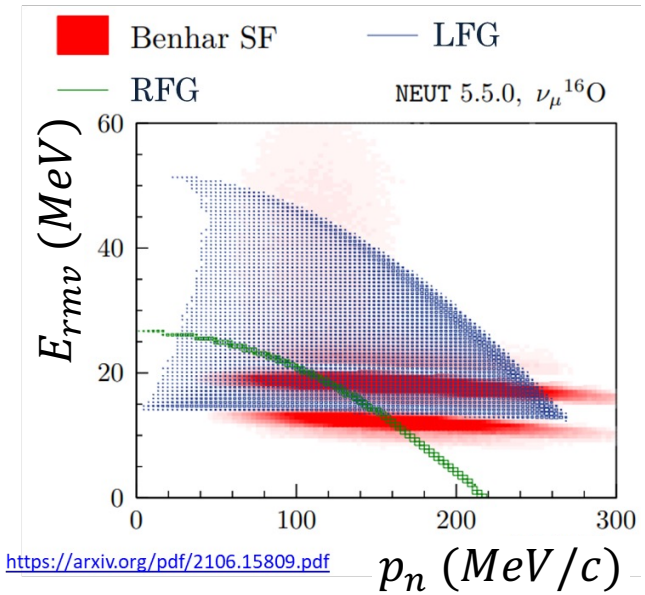
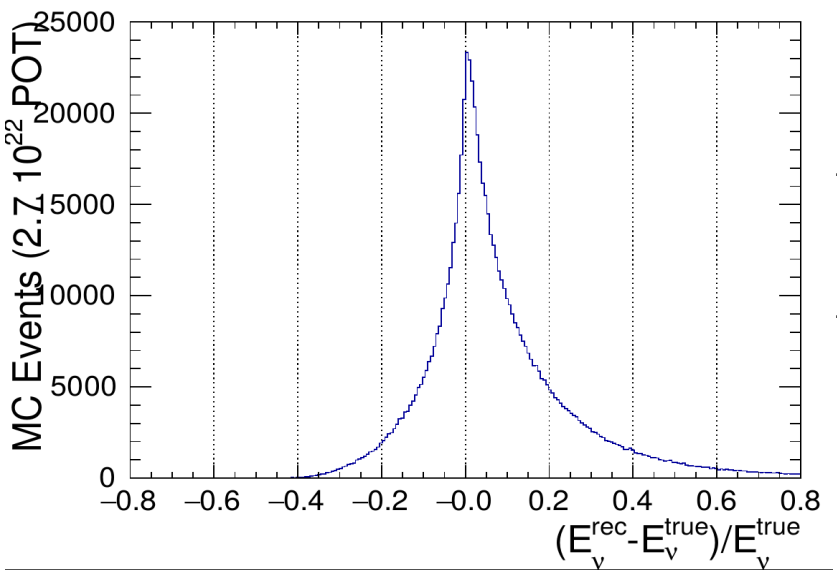
The motion of the nucleons inside the nucleus (*Fermi motion*) causes a **smearing** on $E_\nu$

# Nuclear effects and $E_\nu$ (T2K/HK)




https://arxiv.org/pdf/2106.15809.pdf




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

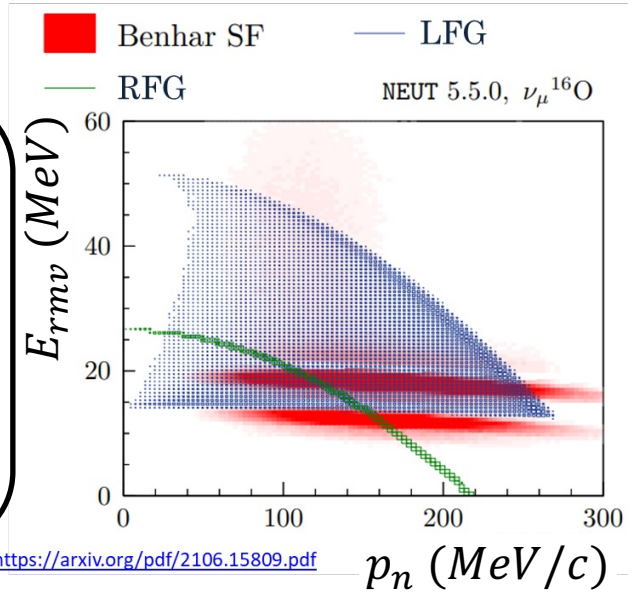
The motion of the nucleons inside the nucleus (*Fermi motion*) causes a **smearing** on $E_\nu$

The energy loss in the nucleus (to extract the struck nucleon from its shell) introduces a **bias**

# Nuclear effects and $E_\nu$ (T2K/HK)

**CCQE (1p1h)**

**Key point:** <u>it does not matter that there is a smearing/bias.</u> What matters is that the smearing/bias is different between plausible models

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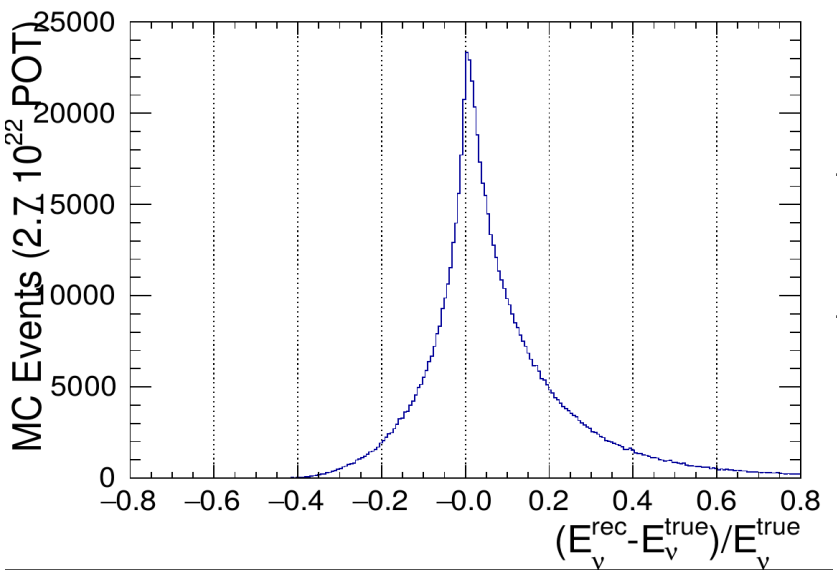


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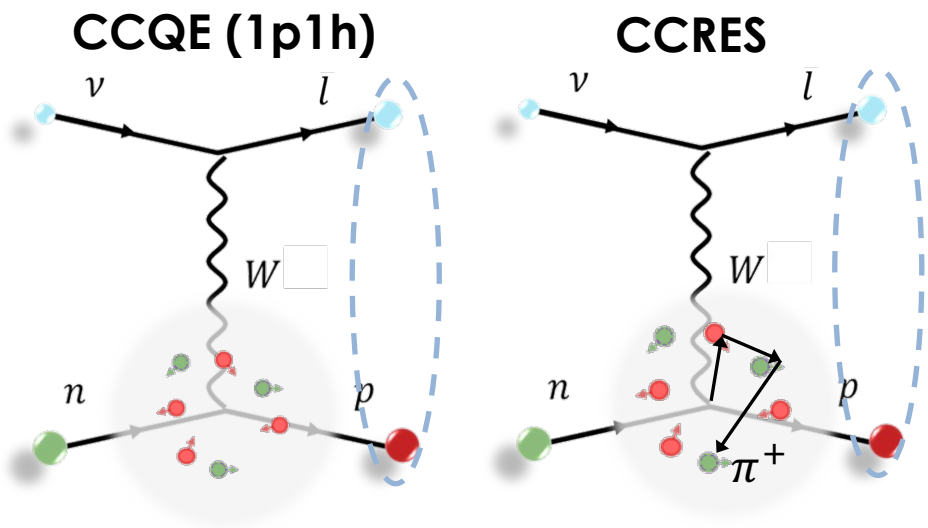
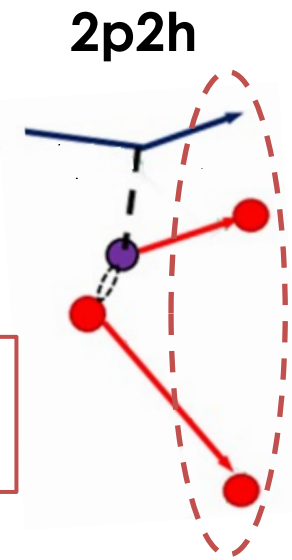
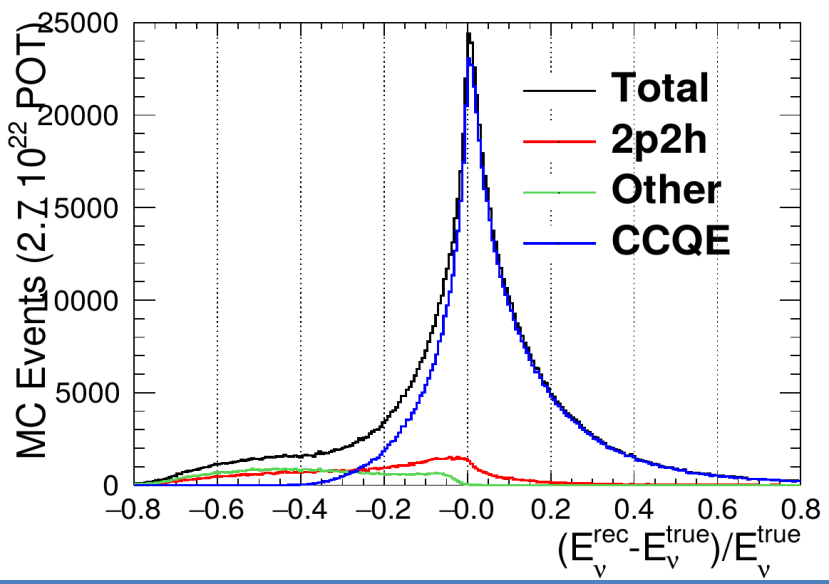



**Final state interactions** (FSI) can cause different interaction modes to have the same final state

Interactions off a bound state of two nucleons can result in **2p2h** final states

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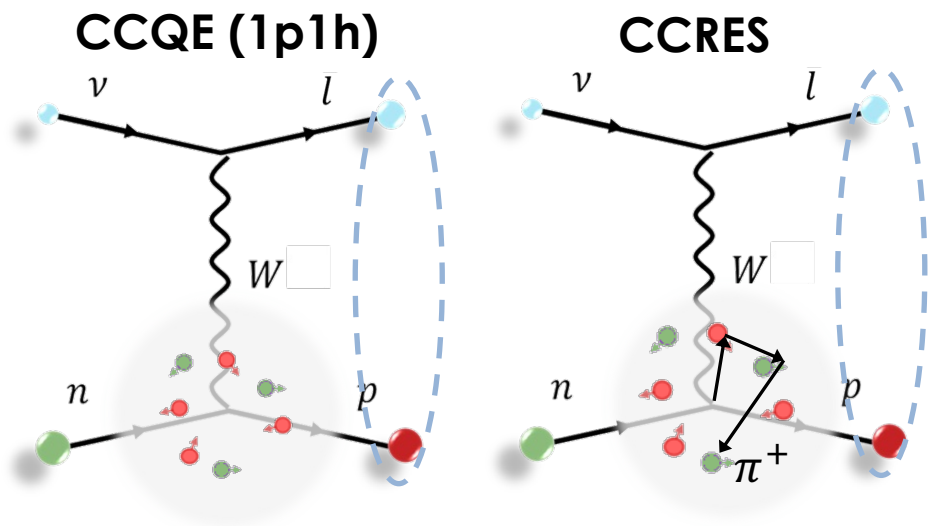
The motion of the nucleons inside the nucleus (*Fermi motion*) causes a **smearing** on $E_\nu$

The energy loss in the nucleus (to extract the struck nucleon from its shell) introduces a **bias**

Not a good proxy for non-CCQE events: 2p2h and CC1π with pion abs. FSI

# Nuclear effects and $E_\nu$ (T2K/HK)

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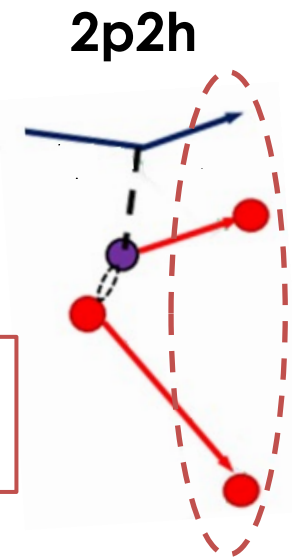


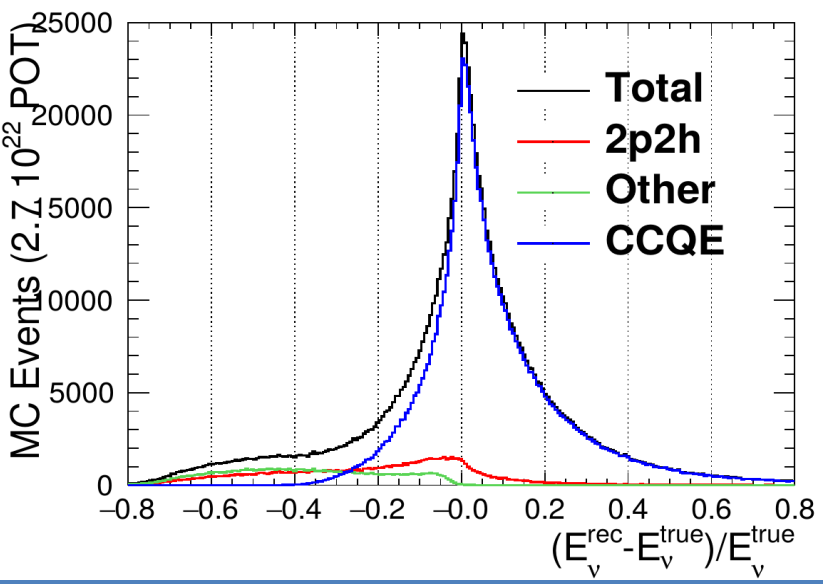


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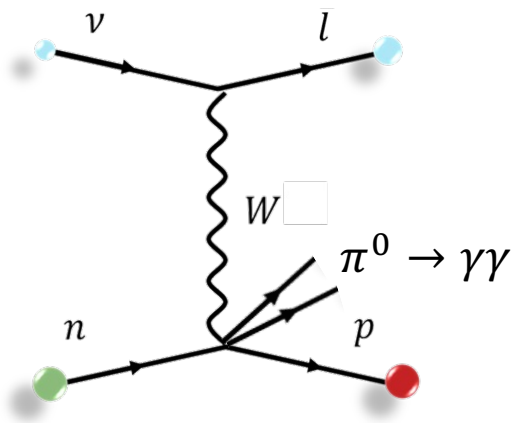
**First-order effects**

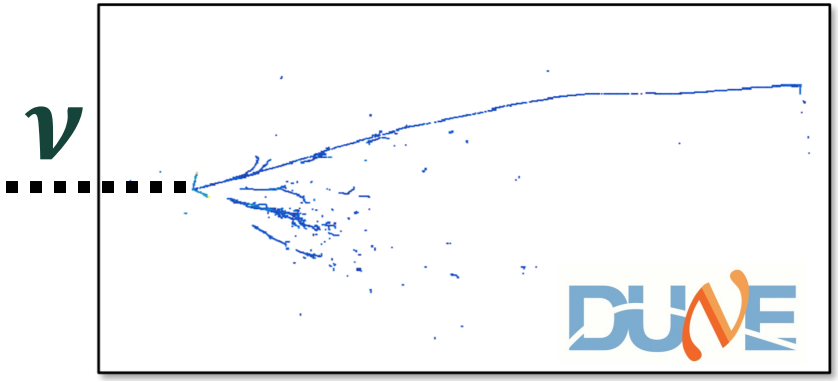
*Fermi motion* causes a **smearing** on $E_\nu^{QE}$

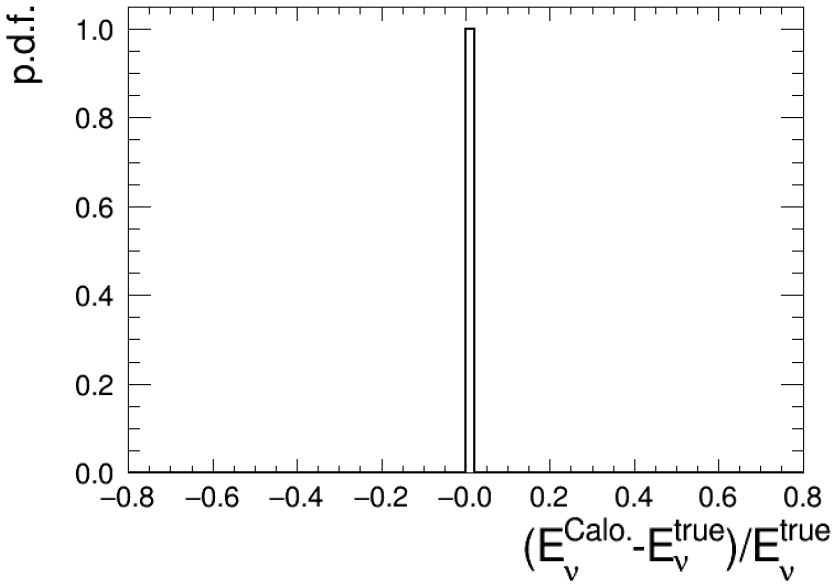
*Nuclear removal energy* effects introduce a **bias**

*2p2h* and pion abs. *FSI* cause further **bias**

# Nuclear effects and $E_\nu$ (DUNE/NOvA)



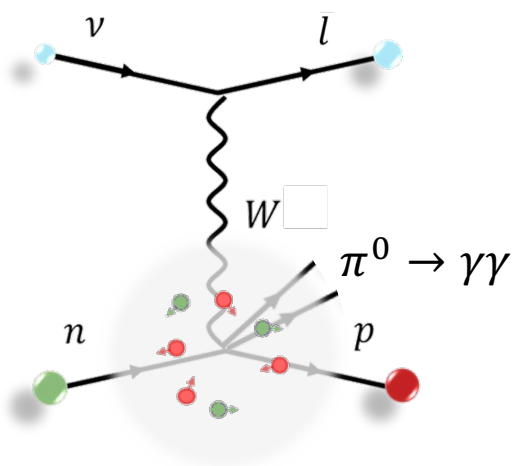




$$E_\nu = E_\ell + E_{had,vis} \approx E_\ell + \Sigma T_p + \Sigma T_{\pi^\pm} + \Sigma E_\gamma$$

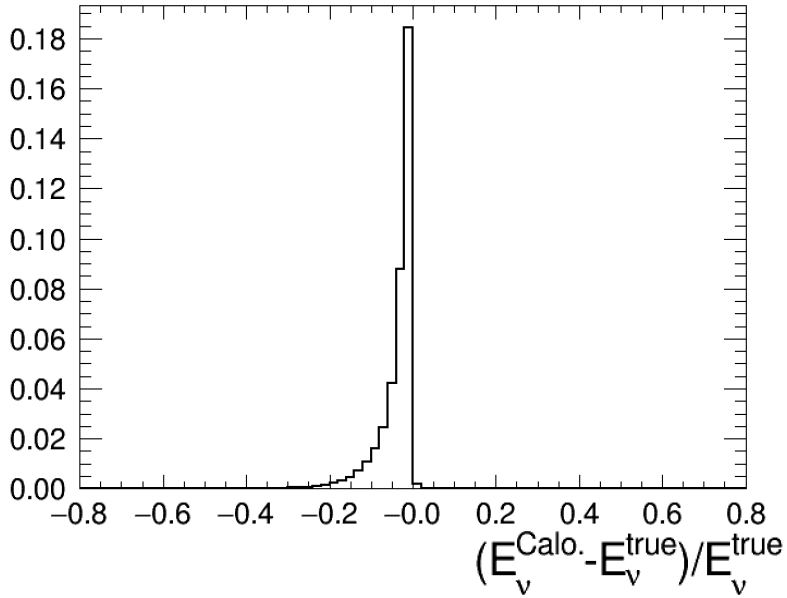
Calculation is exact only for interactions **without neutrons and charged pions** (ignore heavier mesons here) off a **free nucleon**

Usefulness is not restricted to QE-like interactions (no final state pions)

# Nuclear effects and $E_\nu$ (DUNE/NOvA)




All events without $n$ or $\pi^\pm$

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Impact of initial state effects (Fermi motion and removal energy) smaller than in QE approach

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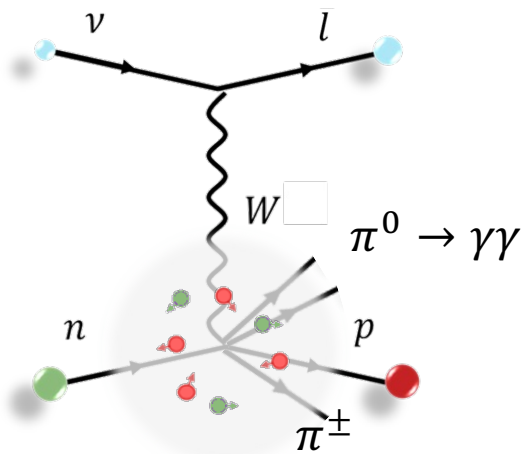


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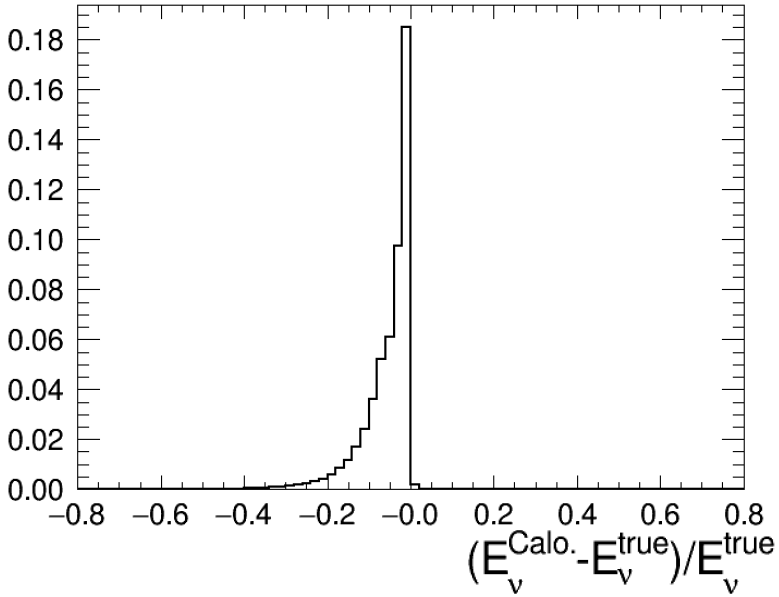


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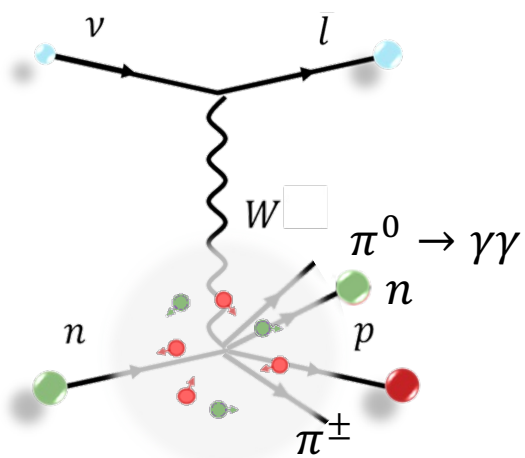


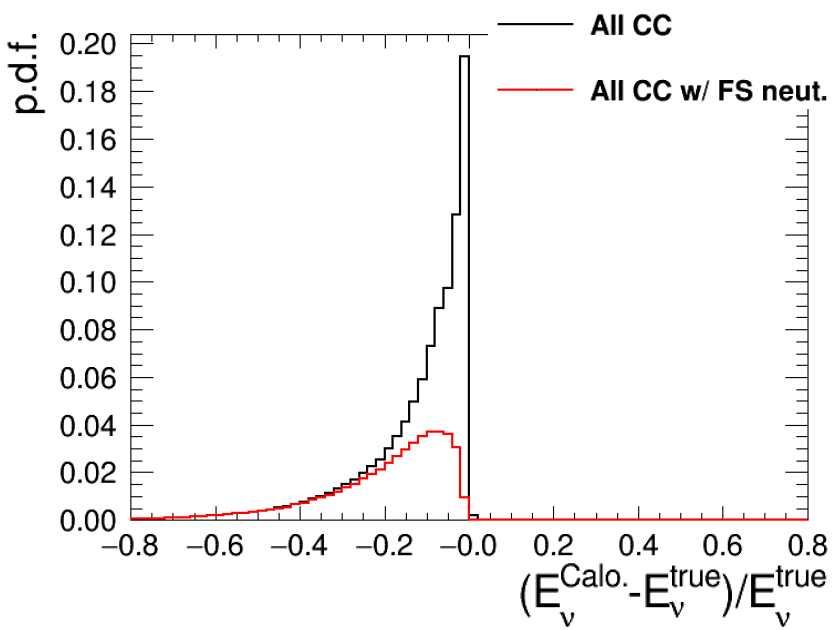


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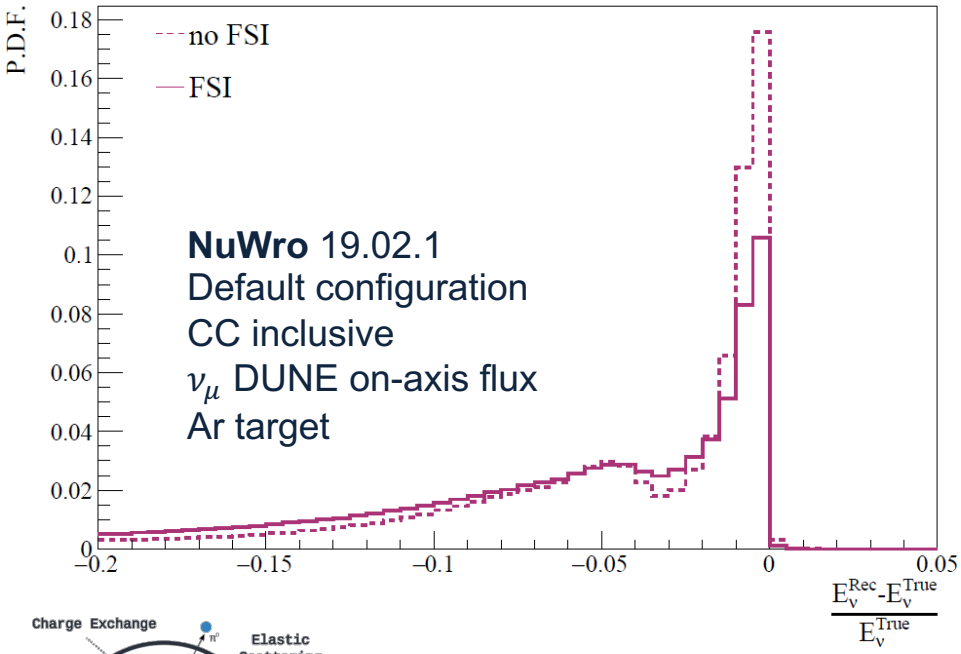
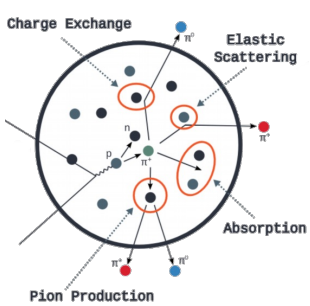
Fraction of $E_\nu$ in **Neutrons** is critical

# Neutrino energy reconstruction



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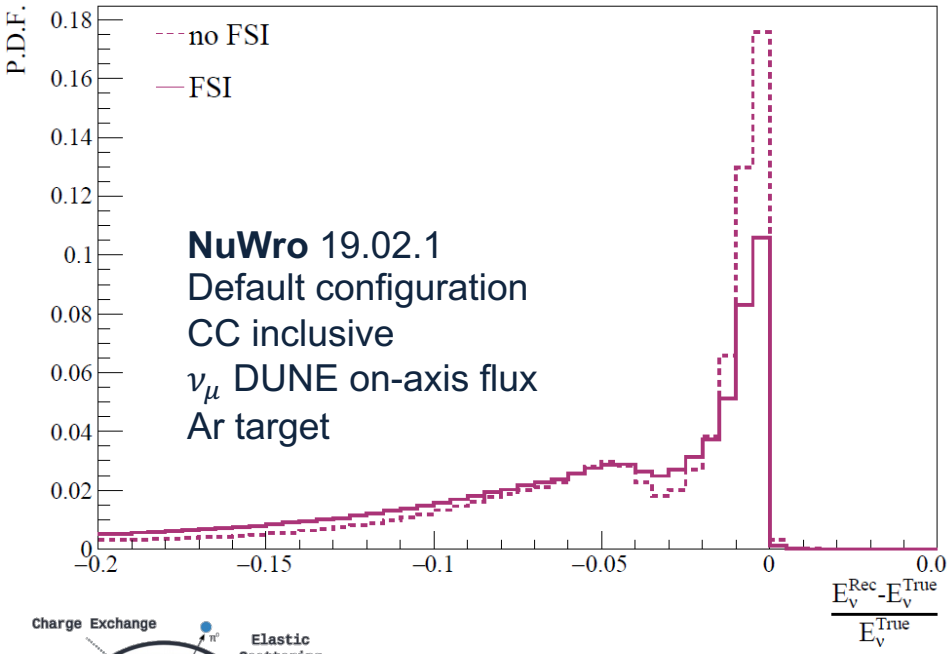


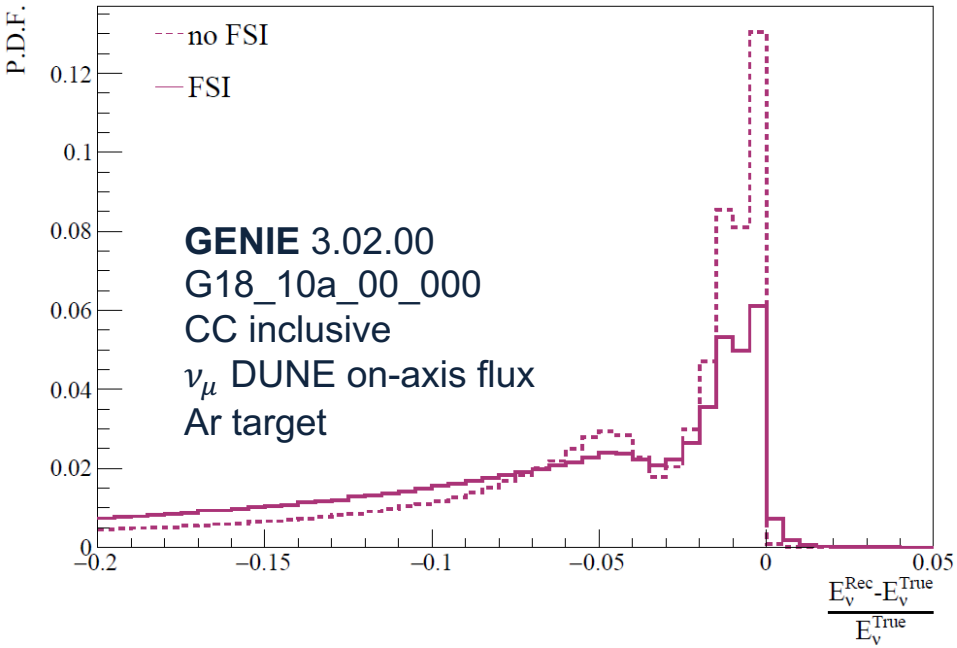


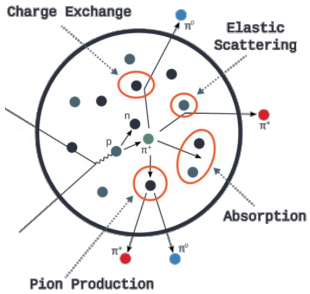

# What we need to know (a non exhaustive list!)

## T2K/HK

*("kinematic" $E_\nu$ proxy)*

*Critical*

- Nuclear ground state: **Fermi motion** and "**binding energy**"
- **2p2h** and **pion absorption FSI** contributions to 0π final states

## DUNE/NOvA/SBN

*("calorimetric" $E_\nu$ proxy)*

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- Fraction of energy found in **neutrons**
- Charged **pion multiplicity**

- Subtle nuclear physics processes are crucial in order to understand how we can translate from what our detectors see to true neutrino energy

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Neutrino interaction modelling is crucial for all upcoming experiments, but different experiments have different priorities: **complementary approaches**!

# 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*

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 $\nu_e/\nu_\mu$ (and $\nu/\bar{\nu}$)
   - *So we can use $\nu_e$ appearance to probe CP-violation*

# Differences in the $\nu_e/\nu_\mu$ cross section

- Ratio of $\nu_e$ to $\nu_\mu$ critical for future oscillation analyses
  - Measure $\nu_\mu$ at ND but need to know about $\nu_e$ to measure $\delta_{CP}$

- Lepton universality: only impact on CC cross-section is via $m_\mu$ vs $m_e$
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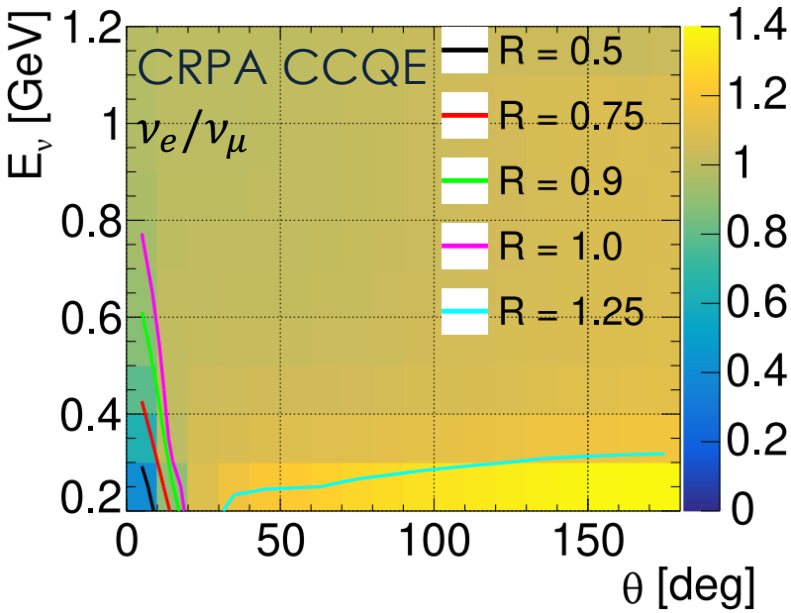


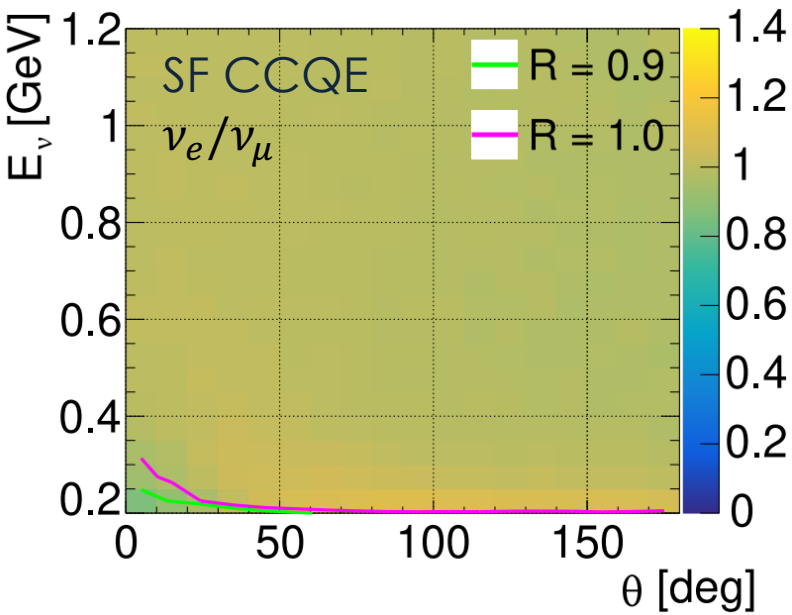


Phys. Rev. Lett. **123**, 052501
arXiv:2301.08065
Phys. Rev. C **96**, 035501

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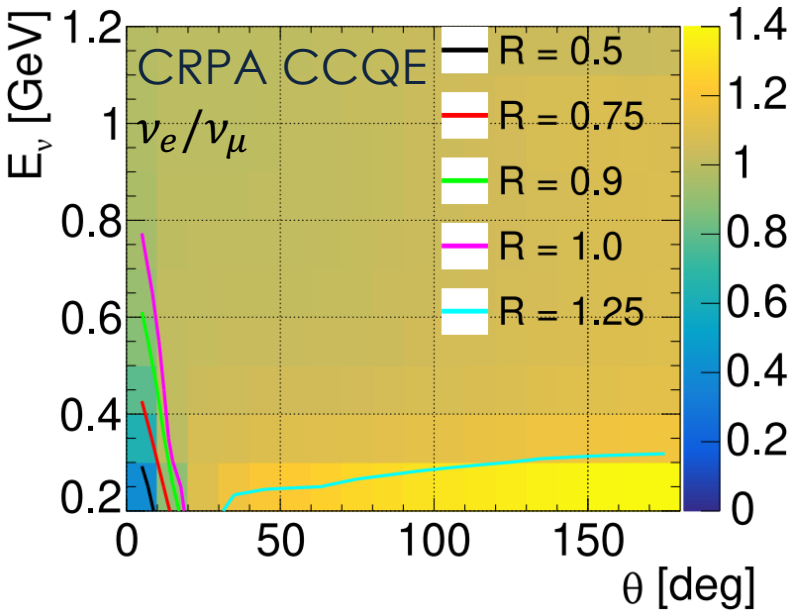


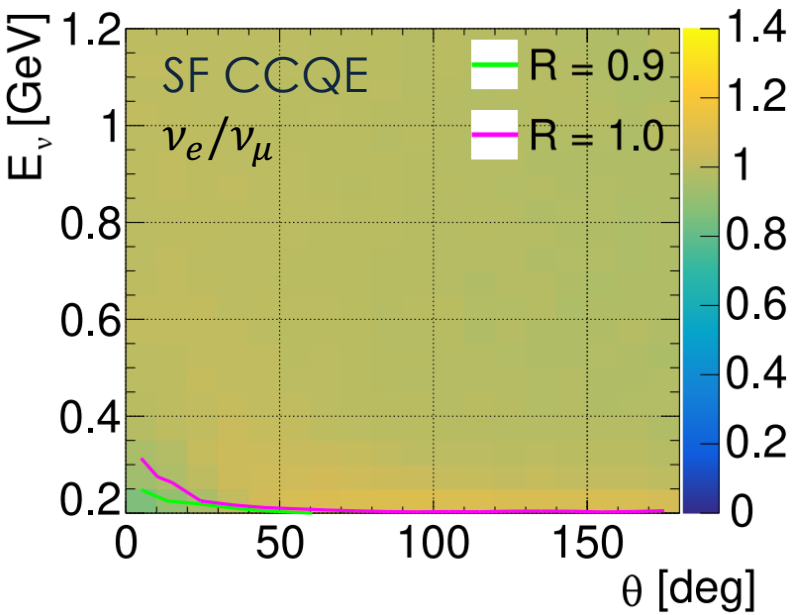


Flux integrated impact for Hyper-K:

- $\nu_e/\nu_\mu$: ~3%, $\bar{\nu}_e/\bar{\nu}_\mu$: ~1.5%, $\nu_e/\bar{\nu}_e$: ~1.5%

Phys. Rev. Lett. **123**, 052501
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Phys. Rev. C **96**, 035501

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Two key effects:

1. The CC cross-section is modified differently for $\nu_e$ and $\nu_\mu$

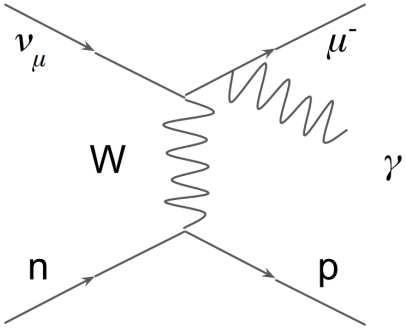


**Table 1 | Flavor ratio of inclusive cross sections**

| | $E_\nu$, GeV | | $\left(\frac{\sigma_e}{\sigma_\mu}-1\right)_{LO}$, % | $\frac{\sigma_e}{\sigma_\mu}-1$, % |
|---|---|---|---|---|
| T2K/HyperK | 0.6 | $\nu$ | $2.47 \pm 0.06$ | $2.84 \pm 0.06 \pm 0.37$ |
| | | $\bar{\nu}$ | $2.04 \pm 0.08$ | $1.84 \pm 0.08 \pm 0.20$ |
| NOvA/ DUNE | 2.0 | $\nu$ | $0.322 \pm 0.006$ | $0.54 \pm 0.01 \pm 0.22$ |
| | | $\bar{\nu}$ | $0.394 \pm 0.003$ | $0.20 \pm 0.01 \pm 0.19$ |

*Nature Communications* **volume 13**, Article number: 5286 (2022)
Phys. Rev. D **106**, 093006

# Differences in the $\nu_e/\nu_\mu$ cross section

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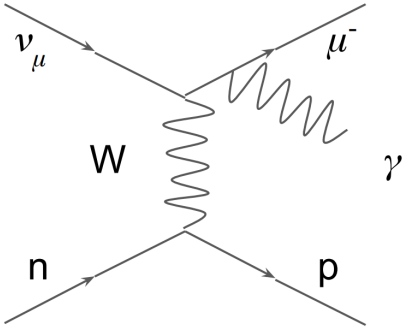
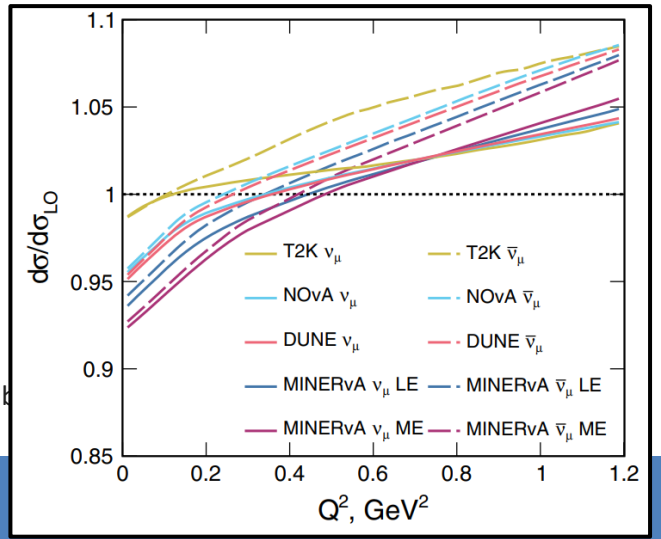



Two key effects:

1. The CC cross-section is modified differently for $\nu_e$ and $\nu_\mu$
2. Altered lepton kinematics and an additional photon can alter event selections and neutrino energy inference




*Nature Communications* **volume 13**, Article numb
Phys. Rev. D **106**, 093006

# Summary so far

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*
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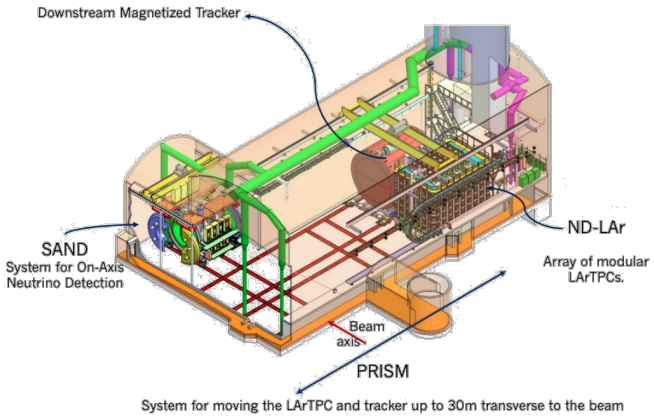
# Overview

- Neutrino Interactions: A History
  - Weak interactions from Fermi to SM
- Neutrino-nucleon interactions
  - QE, RES and DIS
- Neutrino-nucleus interactions
  - Nuclear effects
  - The rise and fall of $M_A = 1.3\ GeV$
- Neutrino event generators
  - Theory inputs
  - Filling in the gaps
- Neutrino-nucleus interaction measurements
  - Inclusive successes and exclusive failures
- Why do we care?
  - Neutrino interactions for neutrino oscillations
  - Neutrino energy reconstruction
- Don't Panic! The future of neutrino interaction simulations

# Path to Precision Measurements

**Improved near detector capabilities**




**Engagement with the nuclear theory community**

GiBUU

**Dedicated lepton-nucleus cross-section measurement programs**

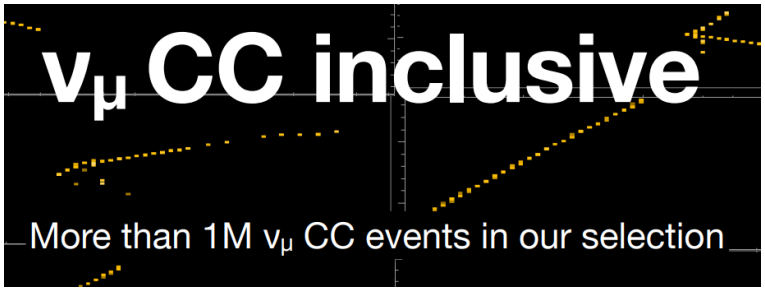
SBN Program

# 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 $\nu s$ for you!

L. Cremonesi

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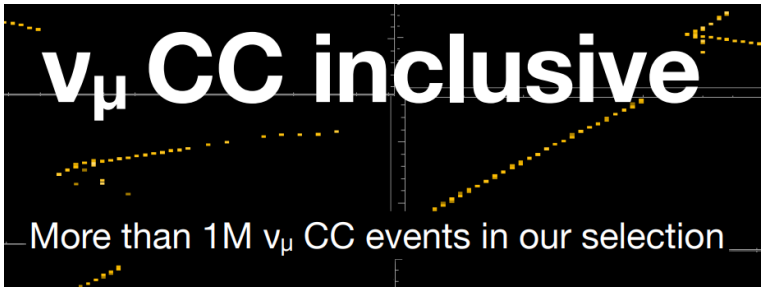


Phys. Rev. D **104**, 092007

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

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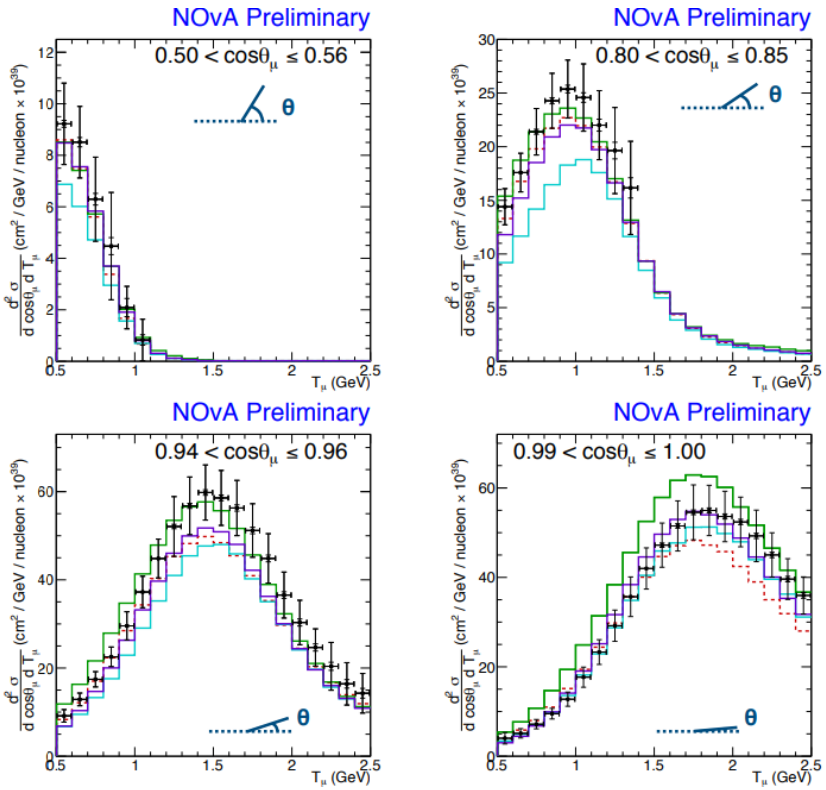
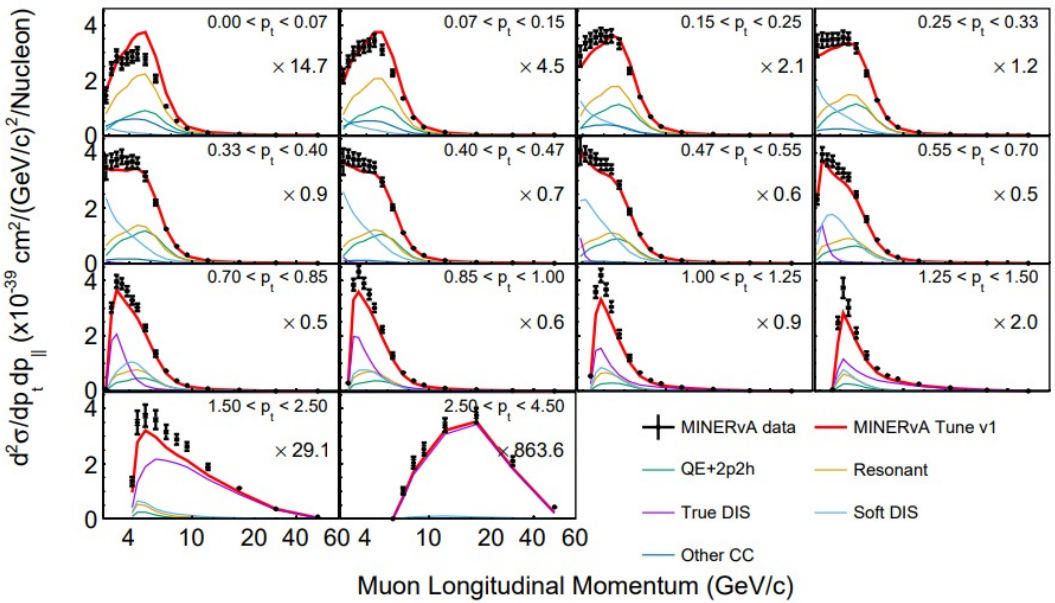
Data (Stat. + Syst.)
GENIE 3.00.06*
GiBUU 2019
NEUT 5.4.0
NuWro 2019

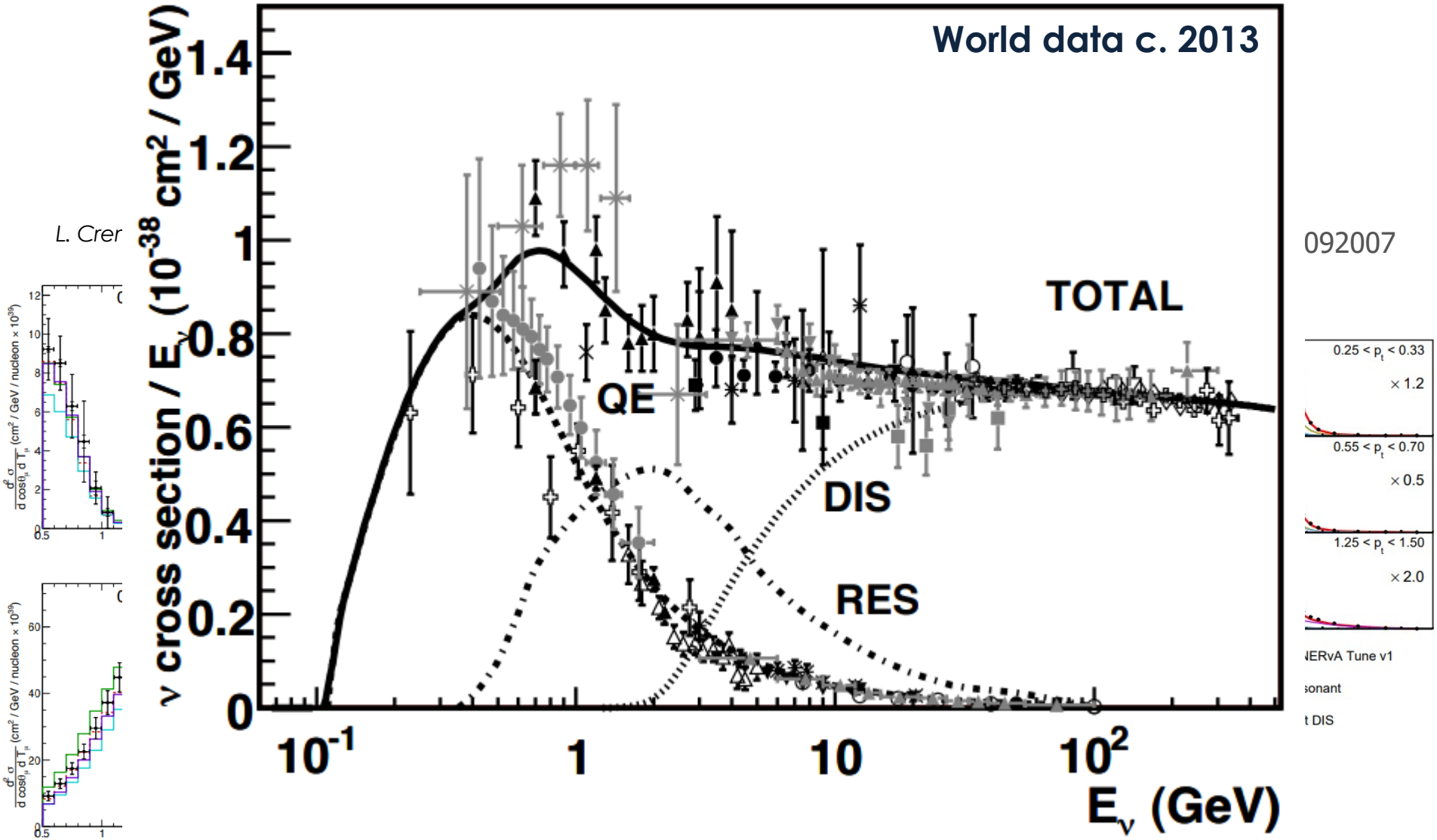
*L. Cremonesi*




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

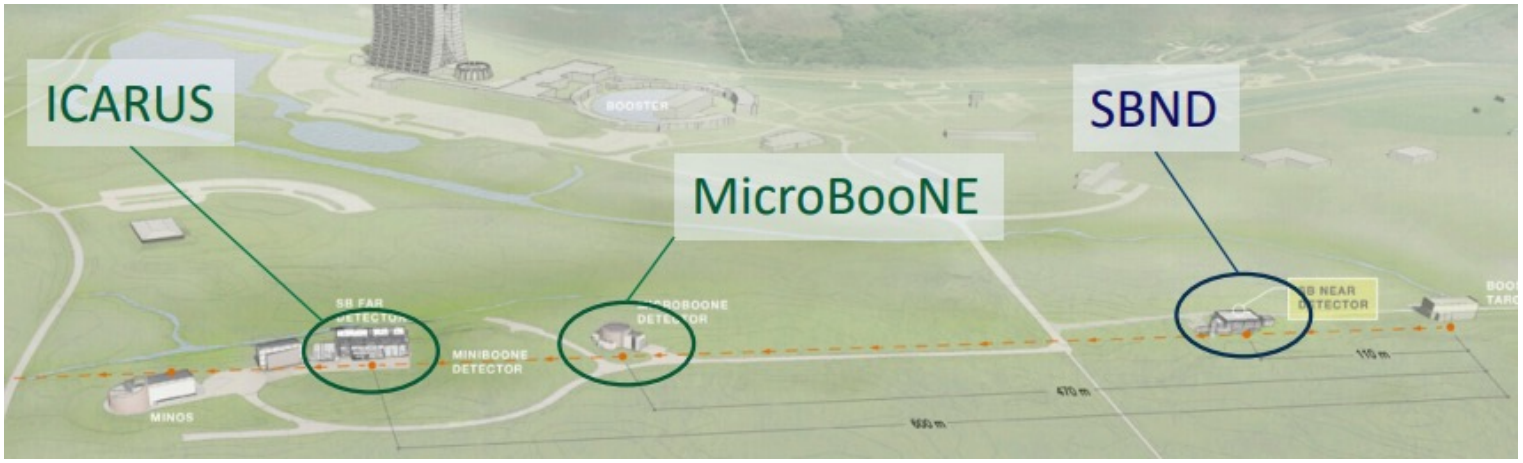


# Well, have I got $\nu s$ for you!



# A bright future for Argon

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



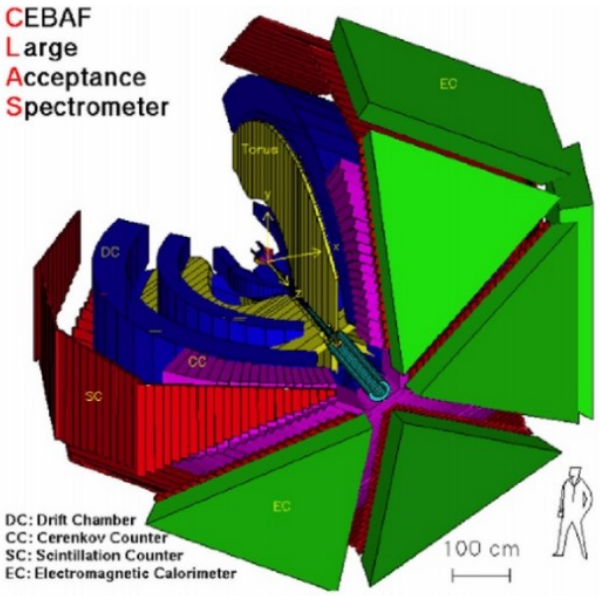

- **MicroBooNE**: already producing interesting results
- **ICARUS**: taking physics data
- **SBND:** enormous event rates coming soon (1M $\nu$/y)

Beyond SBN:

- **DUNE "2x2" prototype:** measurements at DUNE energies

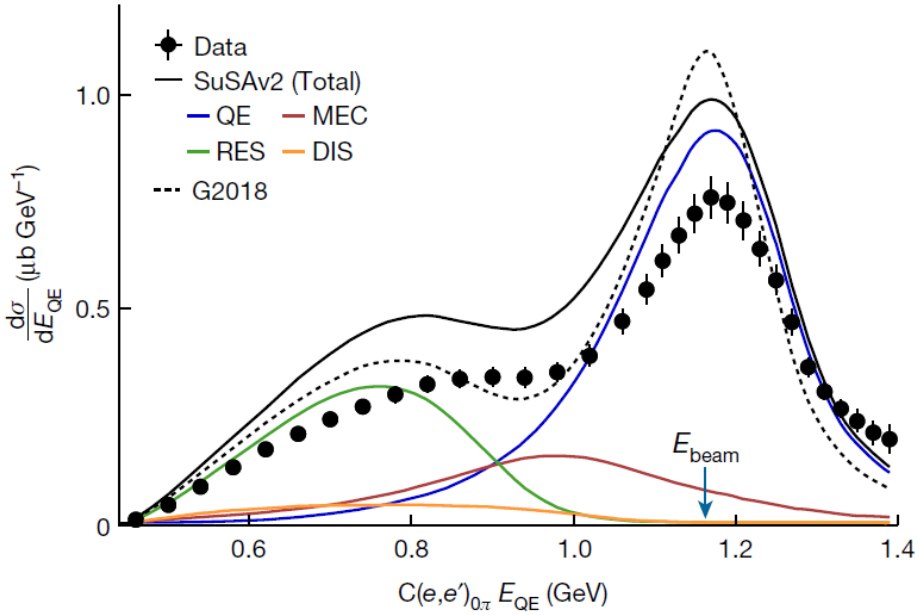
# Tailored electron scattering

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

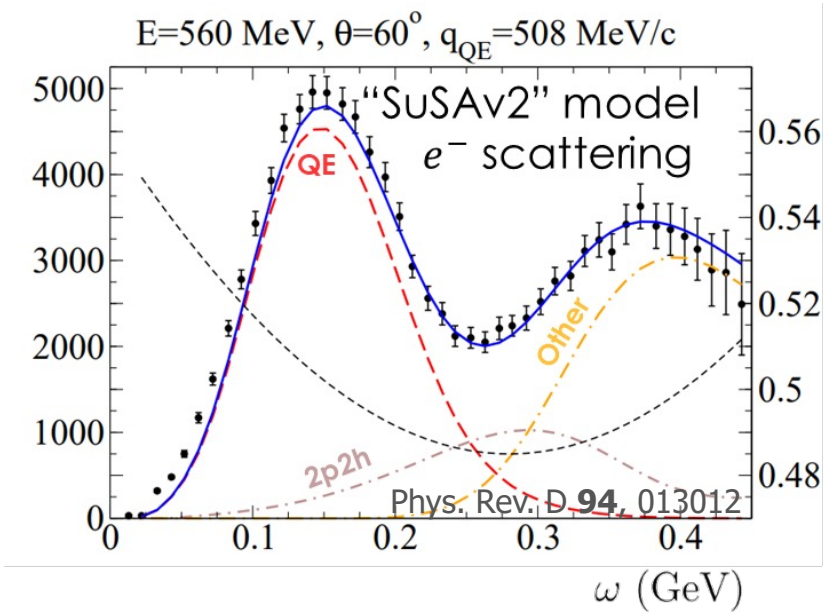


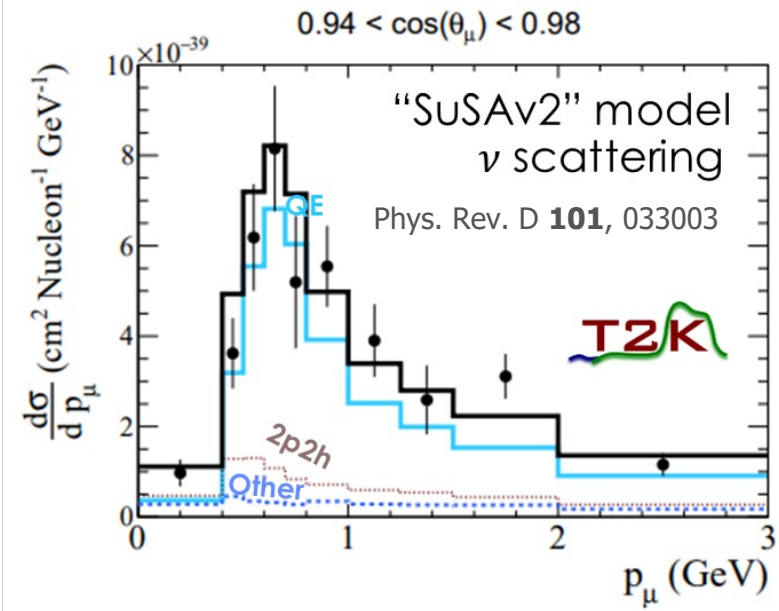

- Our models are becoming more able to make neutrino and electron scattering predictions in the same framework

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



# New models, new constraints

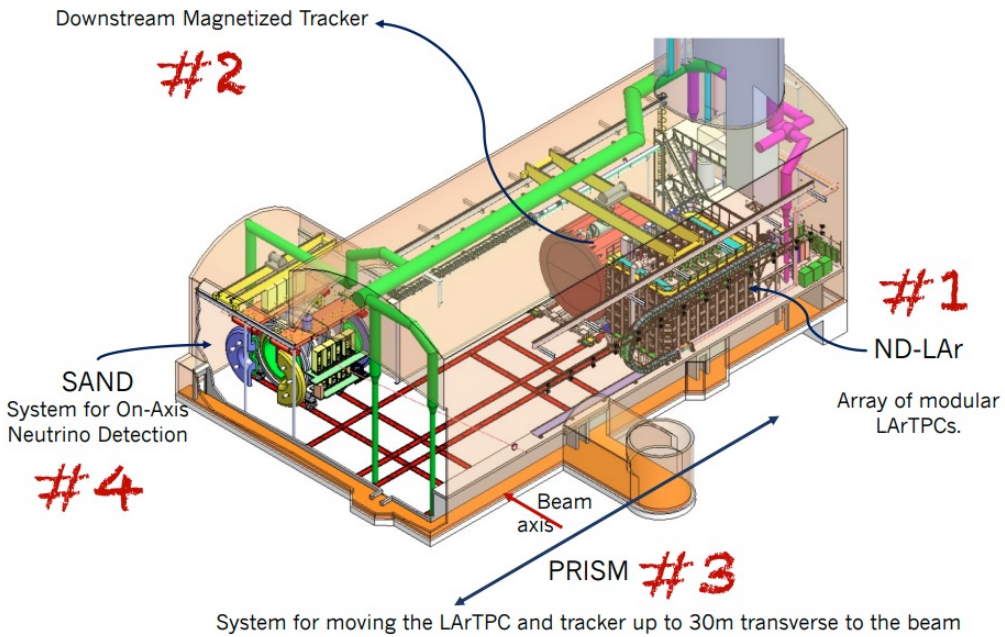


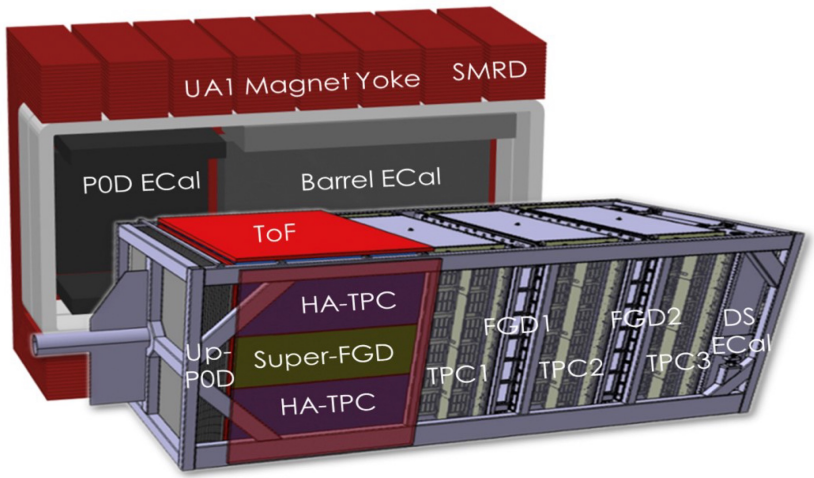

- New models, successful in describing electron scattering data, are now being implemented in neutrino interaction simulations
- Such models that describe $e^-$ and $\nu$ interactions in the same framework can be directly constrained by precision $e^-$ data
- New theoretical efforts are allowing models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

# Improved near detectors

**DUNE Near Detector**

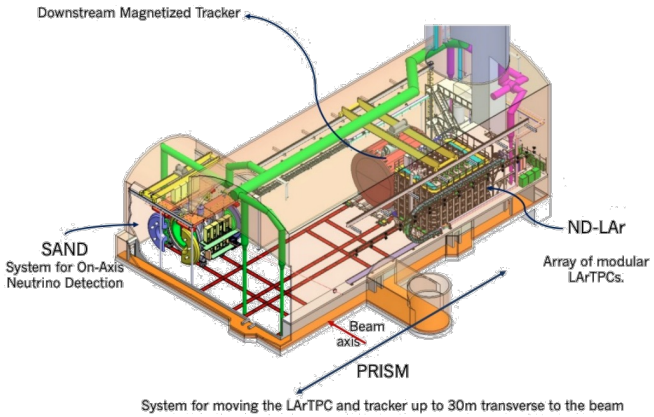



**Upgraded T2K/Hyper-K Near Detector**



# How can you help

**Improved near detector capabilities**



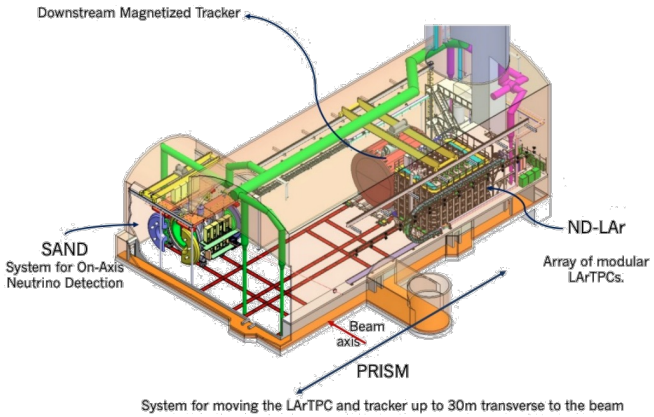

**Engagement with the nuclear theory community**

GiBUU

**Dedicated lepton-nucleus cross-section measurement programs**

# How can you help

**Improved near detector capabilities**

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SBN Program

*Make new cross-section measurements*

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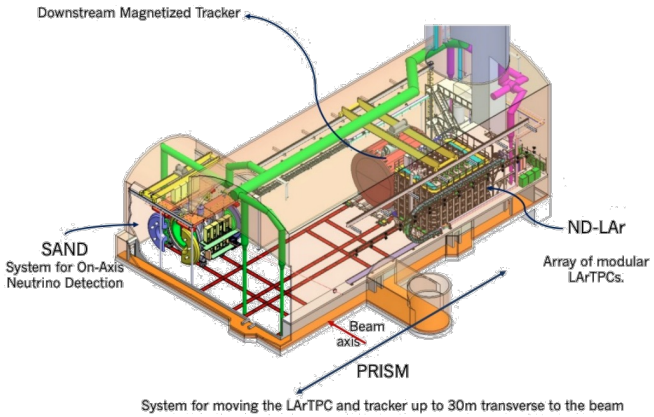
**Improved near detector capabilities**

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GiBUU

*Improve near-detector performance*

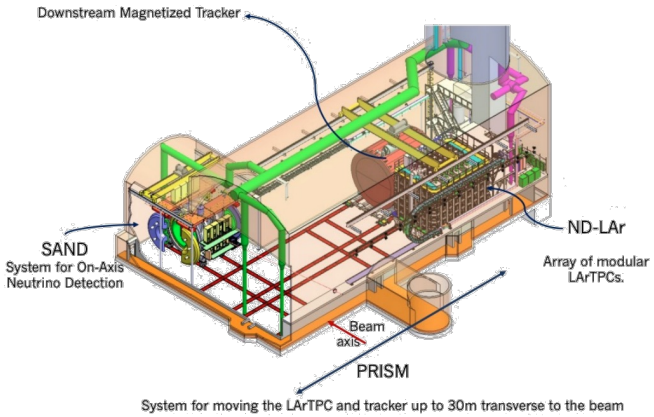
**dicated lepton-nucleus cross-section measurement programs**

SBN Program

*Make new cross-section measurements*

# How can you help

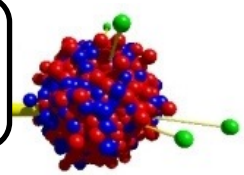
**Improved near detector capabilities**




*Improve near-detector performance*

**Engagement with the nuclear theory community**

*Implement new models in our generators*



GiBUU

Genie

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

NuWro Wroclaw Neutrino Event Generator

**Dedicated lepton-nucleus cross-section measurement programs**

SBN Program

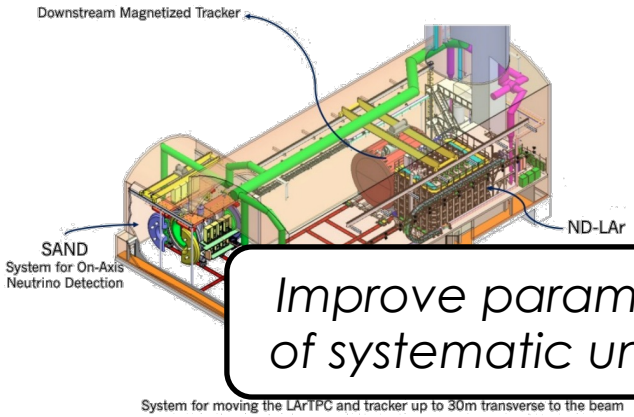
MINERvA

e4

*Make new cross-section measurements*

# How can you help

**Improved near detector capabilities**

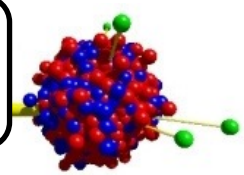



*Improve parameterisation of systematic uncertainties*

*Improve near-detector performance*

**Engagement with the nuclear theory community**

*Implement new models in our generators*



GiBUU

NuWro Wrocław Neutrino Event Generator

Genie UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

**Dedicated lepton-nucleus cross-section measurement programs**

SBN Program

MINERvA

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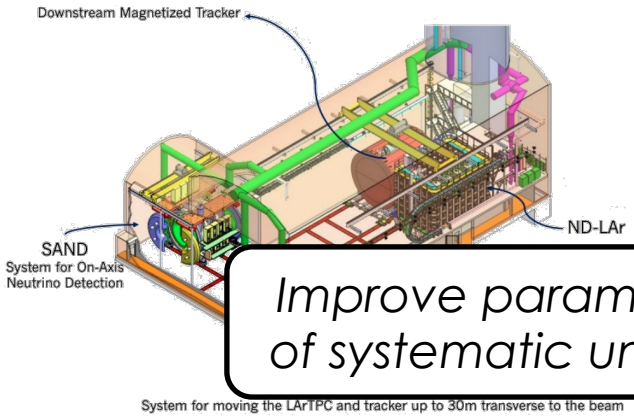
*Make new cross-section measurements*

# How can you help

**Improved near detector capabilities**

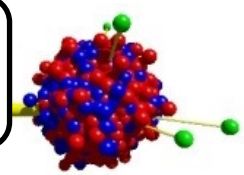



*Improve parameterisation of systematic uncertainties*

*Improve near-detector performance*

**Engagement with the nuclear theory community**

*Implement new models in our generators*



GiBUU

Genie

UNIVERSAL NEUTRINO GENERATOR

NuWro

Wrocław Neutrino Event Generator

*Confront generators with the latest measurements*

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SBN Program

MINERvA

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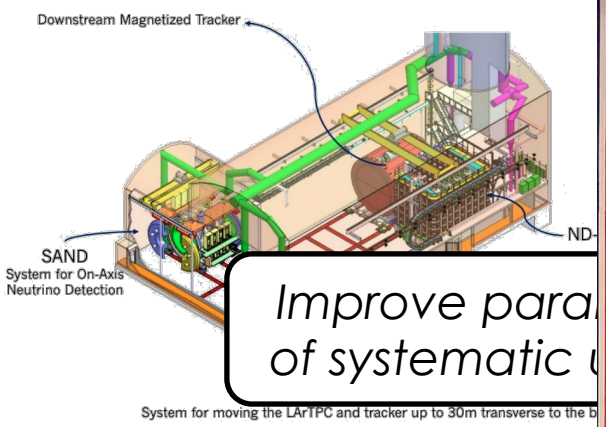
*Make new cross-section measurements*

# 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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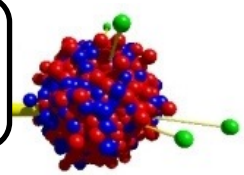

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Genie
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NuWro
Wrocław Neutrino Event Generator

*front generators with*
*latest measurements*

**ams**

SBN Program

MINERvA

e4

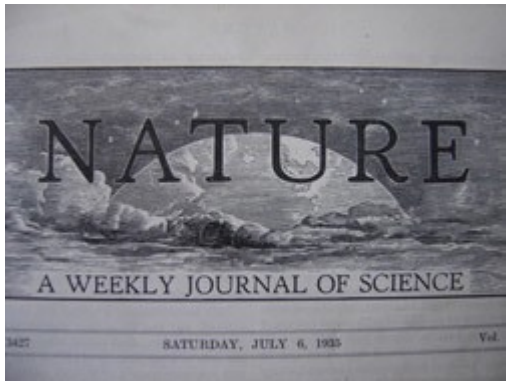
*Make new cross-section measurements*

# Summary

- A detailed understanding of neutrino-nucleus interactions is **crucial for current and future experiments** to realise their extraordinary goals (CP-violation, mass ordering, new BSM physics)
- This is a **challenging task**: neutrino interactions are complicated
- We've made **enormous progress** in the last 10 years, but **still have some way to go**
- **New data** from **new detectors** will be invaluable, offering dramatically improved probes of neutrino interactions
- Collaboration between **theory and experimental communities** will be crucial
- Expect plenty of **exciting new results** and a continued exponential growth of the field in the run up to DUNE & Hyper-K.

# Thanks for listening!

**c. 1930**



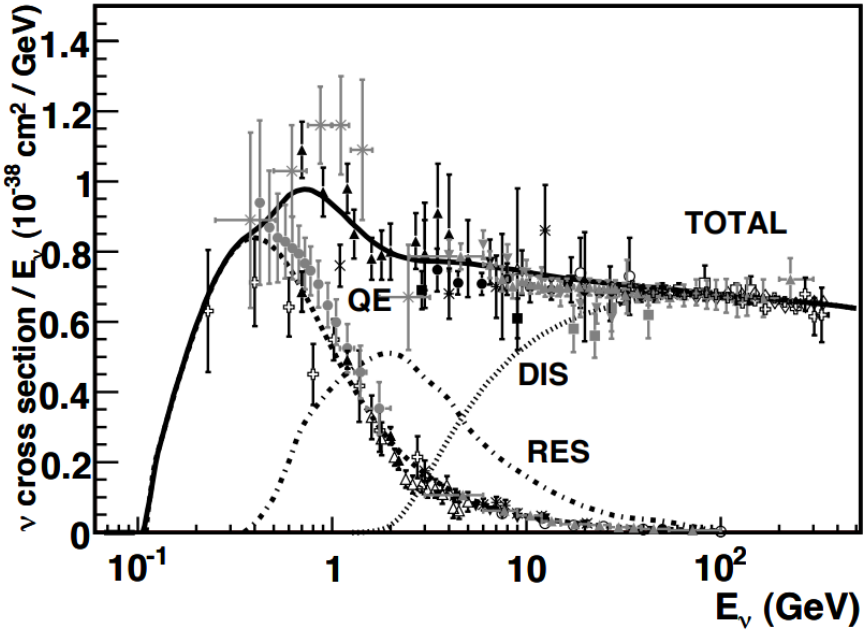

"[Fermi's theory of weak interactions] contains speculations too remote from reality to be of interest to the reader"

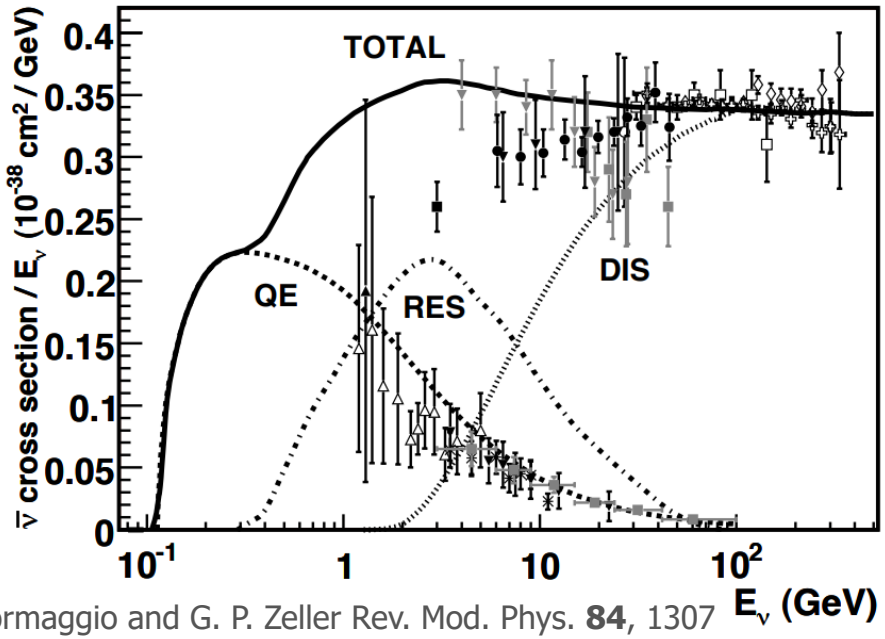
**2020**

# Backups

# 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

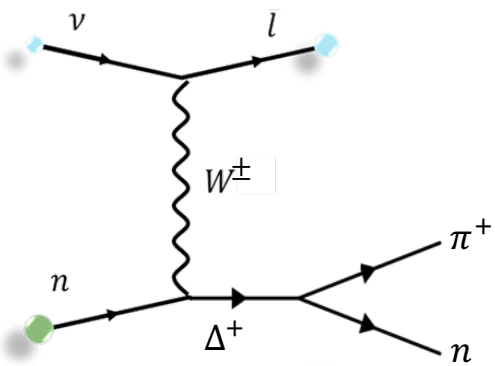



J. A. Formaggio and G. P. Zeller Rev. Mod. Phys. **84**, 1307

# 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)

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

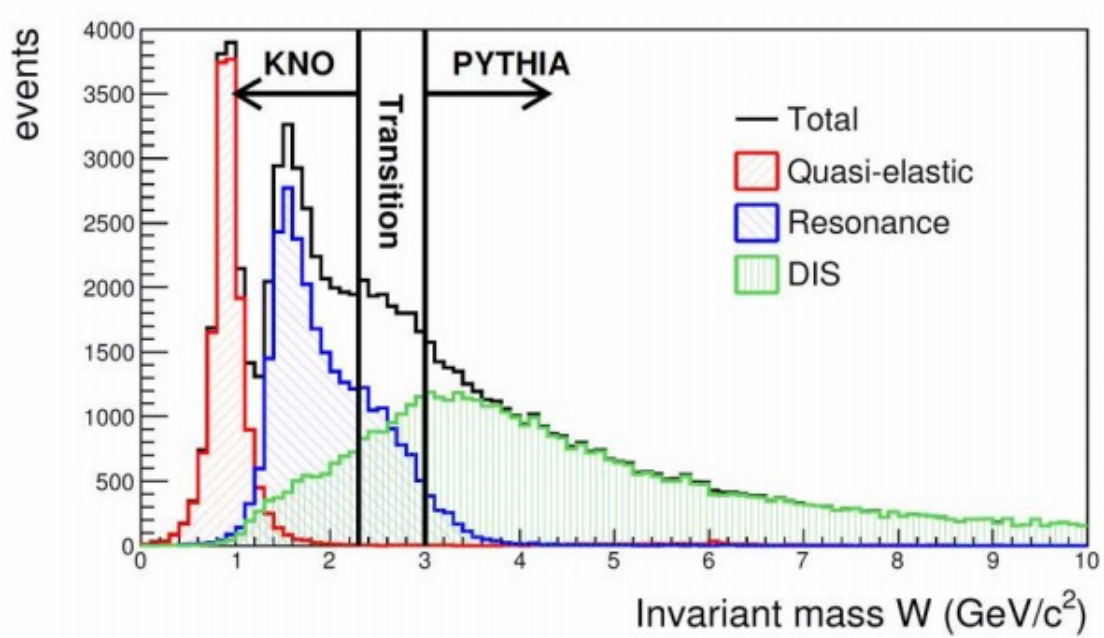
- Theoretical developments are underway but it's safe to say CCRES is less well understood than CCQE!

# 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!



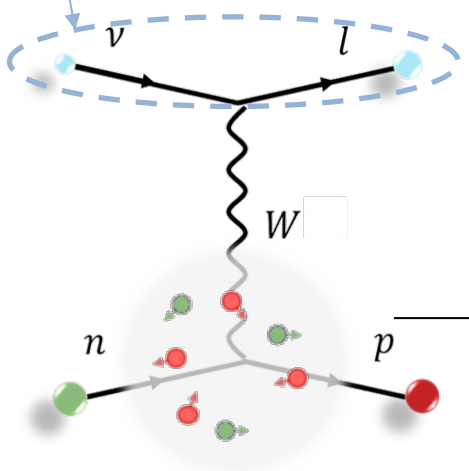
# Inclusive calculations

Inclusive calculations come "pre-integrated" over hadron kinematics

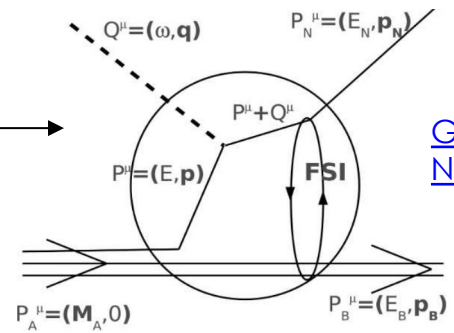
All of the nuclear dynamics lives in here

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

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!

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Inclusive calculations come "pre-integrated" over hadron kinematics

All of the nuclear dynamics lives in here

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

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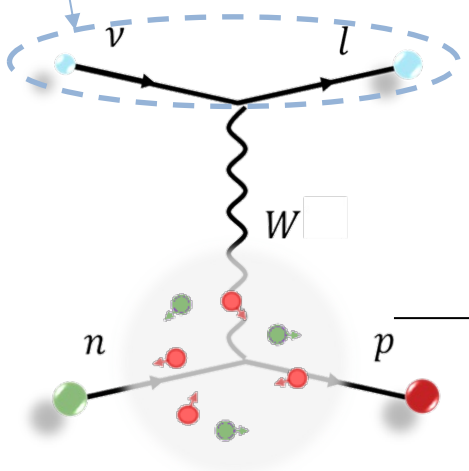


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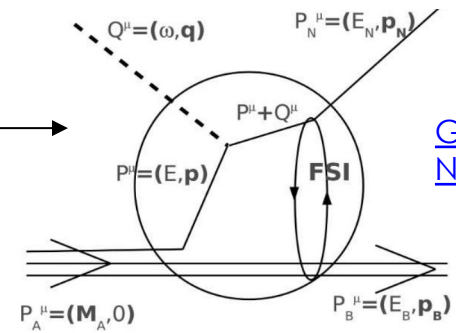


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In some calculations, the nuclear effects considered **includes the impact of Final State Interactions** (FSI) with a QM treatment

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

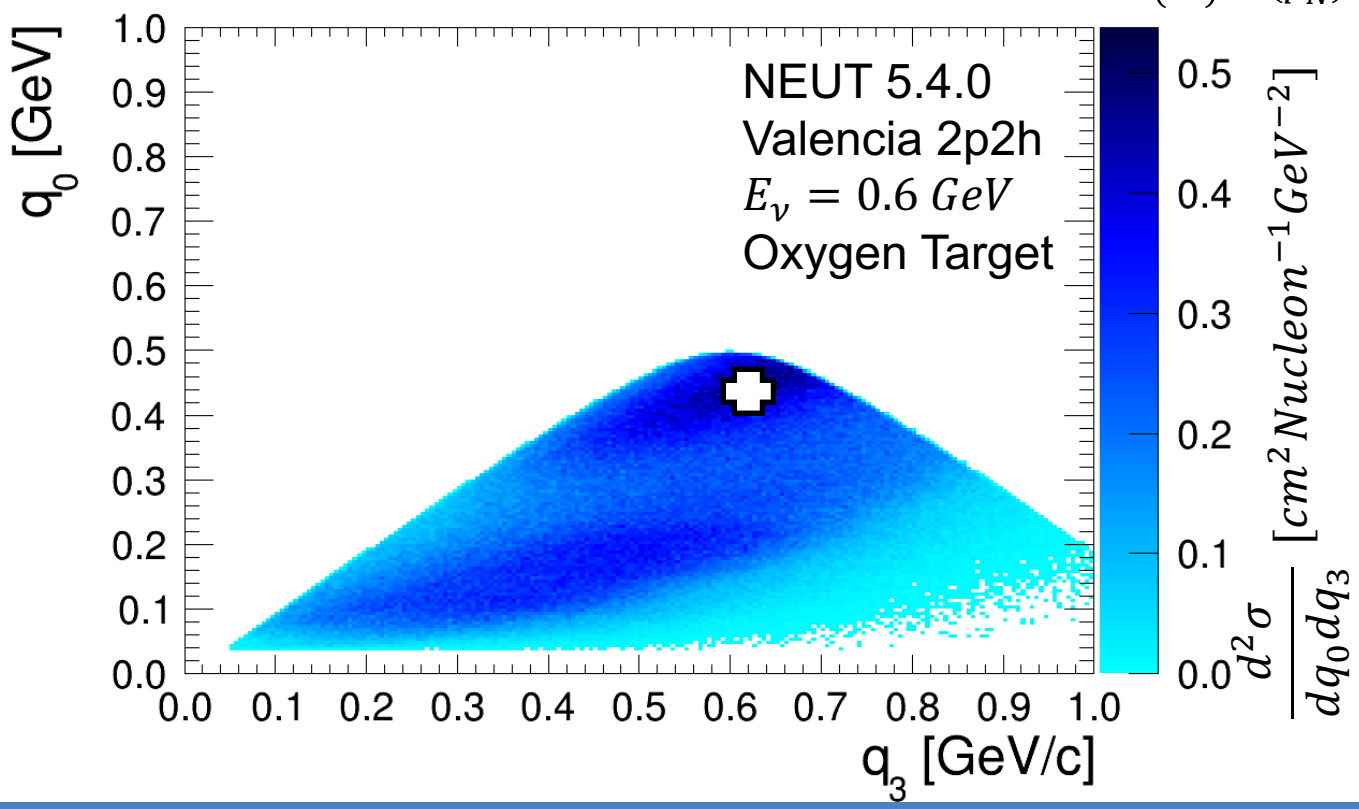
SuSA or Valencia 2p2h – no consideration of FSI

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

# Event Generation

- Select **outgoing particle kinematics** according to differential cross section for the chosen interaction channel at the chosen $E_\nu$
  - **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)

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



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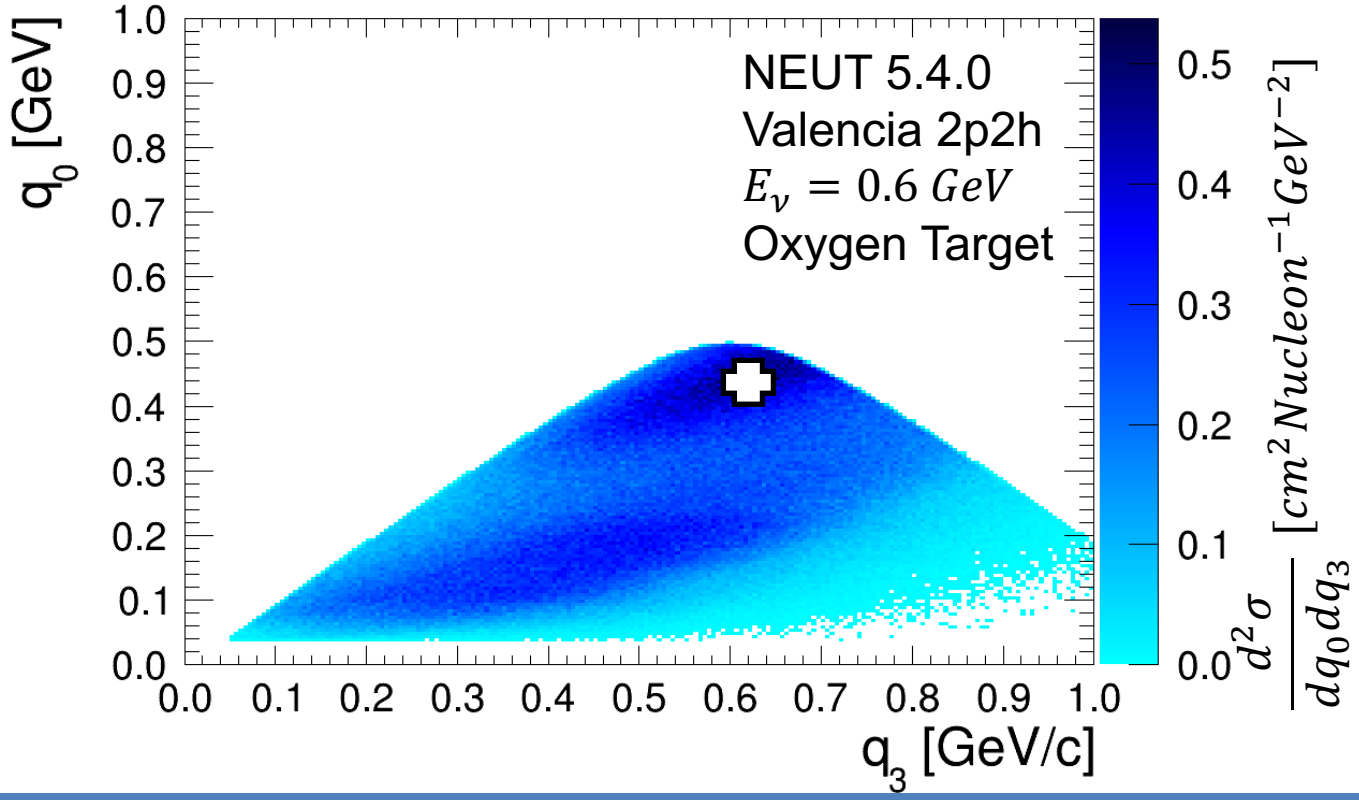
- Select **outgoing particle kinematics** according to differential cross section for the chosen interaction channel at the chosen $E_\nu$
  - **Nucleon-level input**: gives us lepton kinematics in the struck nucleon rest-frame
  - **Inclusive input**: gives us lepton kinematics in the lab frame
  -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