Uncertainties in modelling neutrino Interactions for oscillation experiments

Stephen Dolan

stephen.joseph.dolan@cern.ch

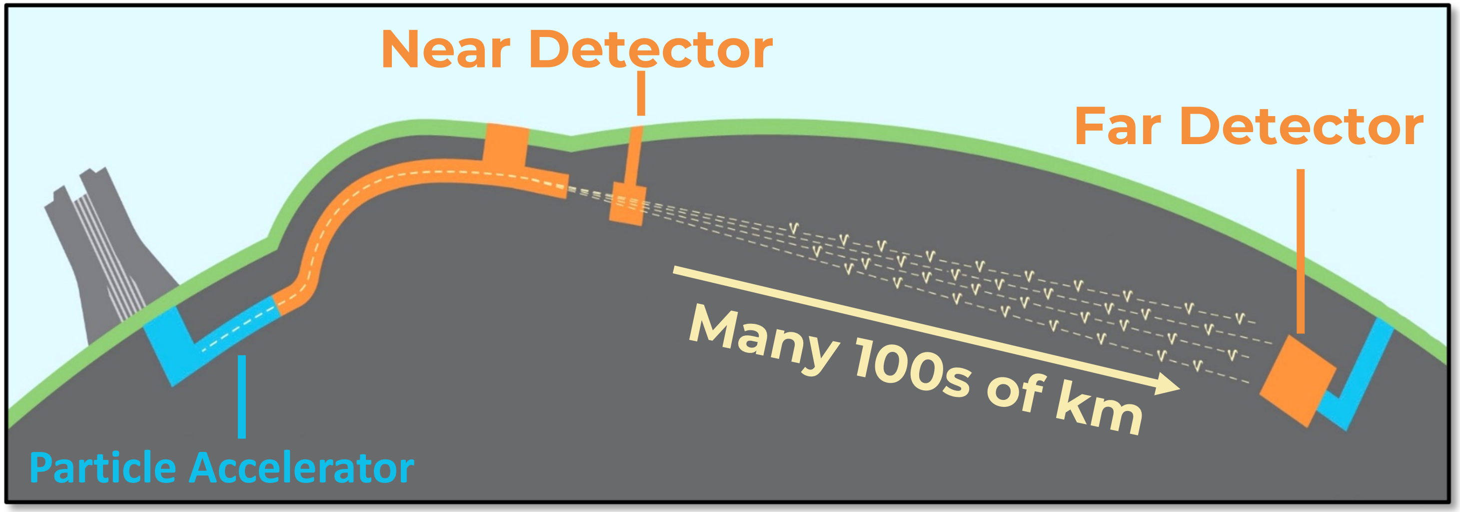
NOW 2022

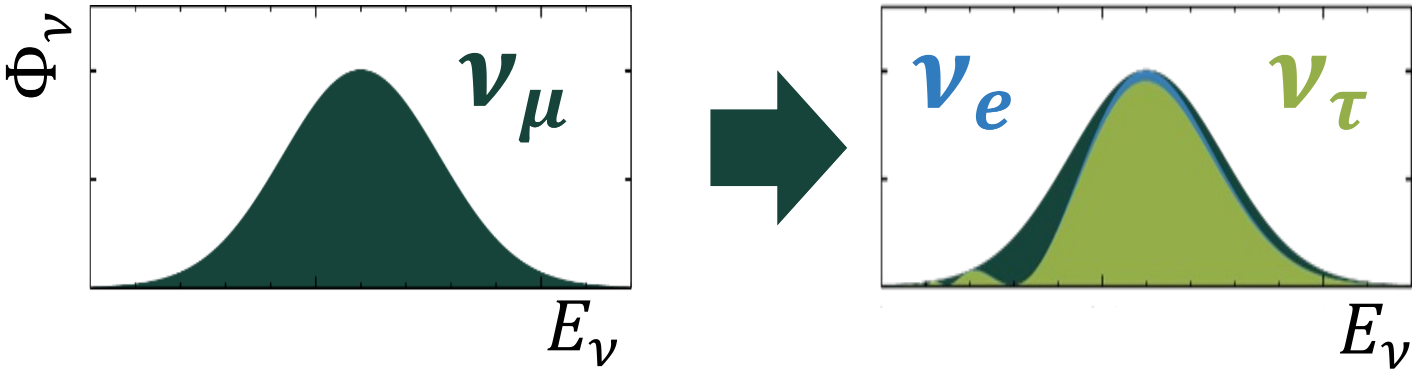
Neutrino Oscillation Workshop

Outline

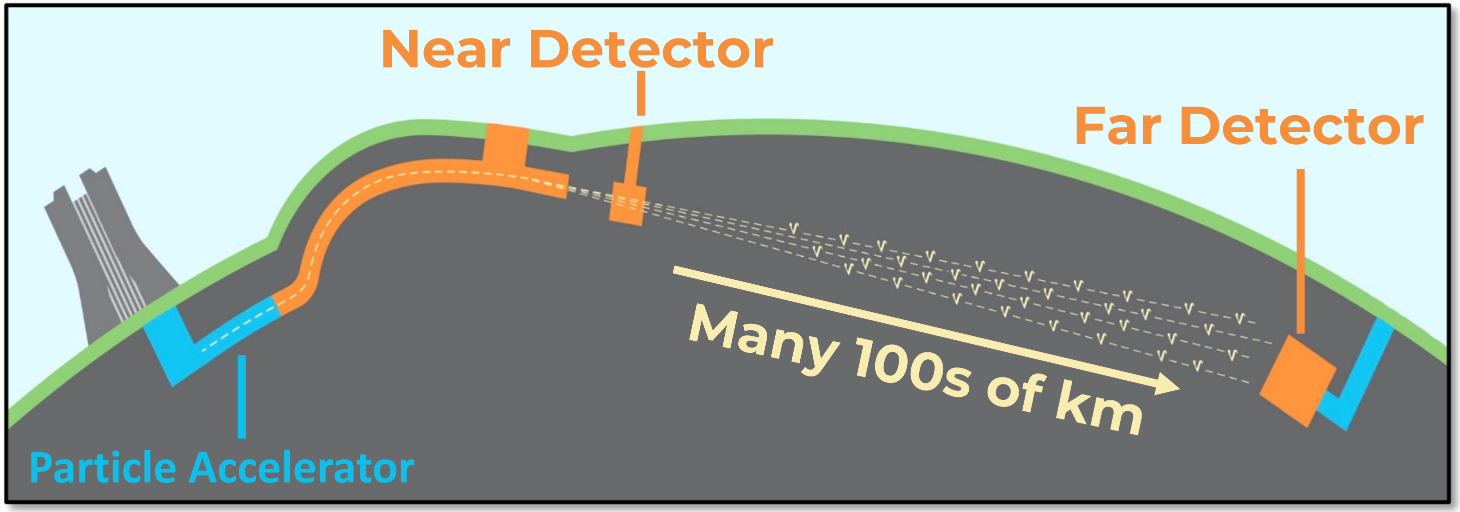
- Why we care about neutrino interaction modelling
  - And what it is that we need to model well
- Simulating neutrino interactions using event generators
  - And why they are usually "wrong"
- What uncertainties we need to control better to make DUNE and Hyper-K a success
  - Reviewing some recent and upcoming publications

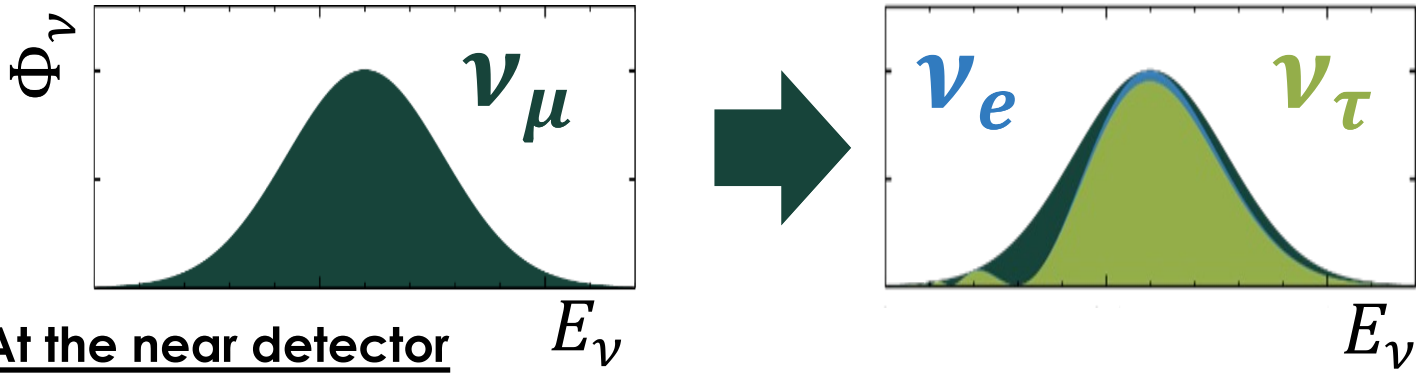
Why care about cross sections?





Why care about cross sections?





<u>At the near detector</u>

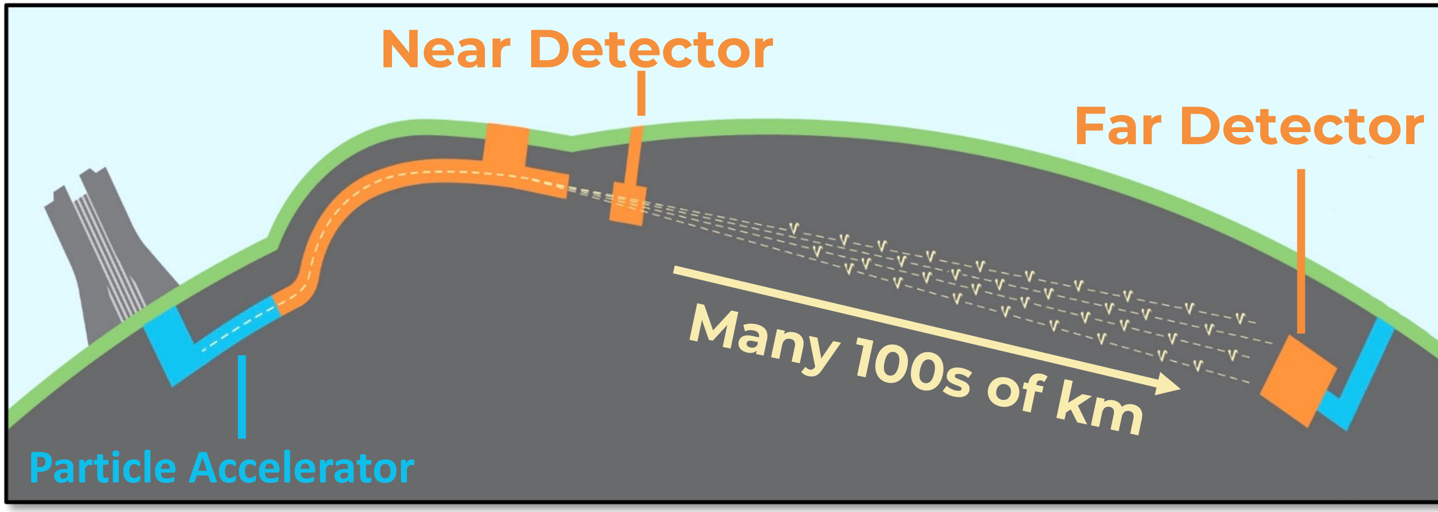
$$N_\mu(E_\nu) = \sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

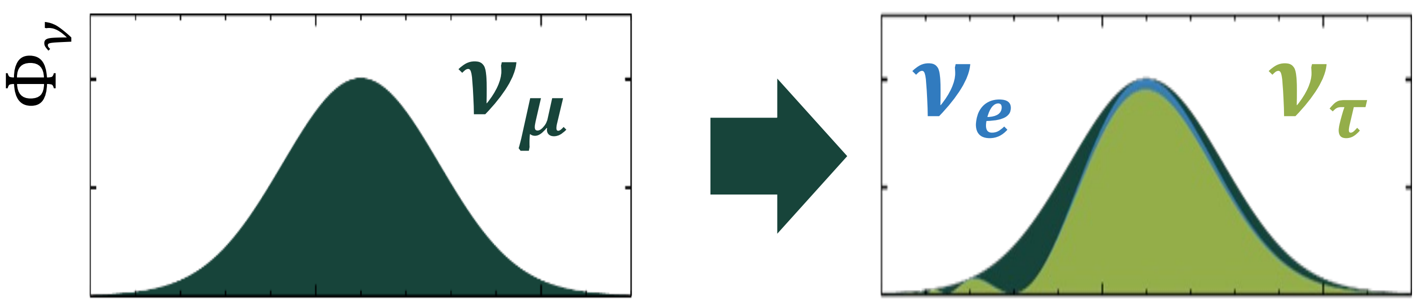
Interaction cross section

Neutrino flux

Detector effects

Why care about cross sections?





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

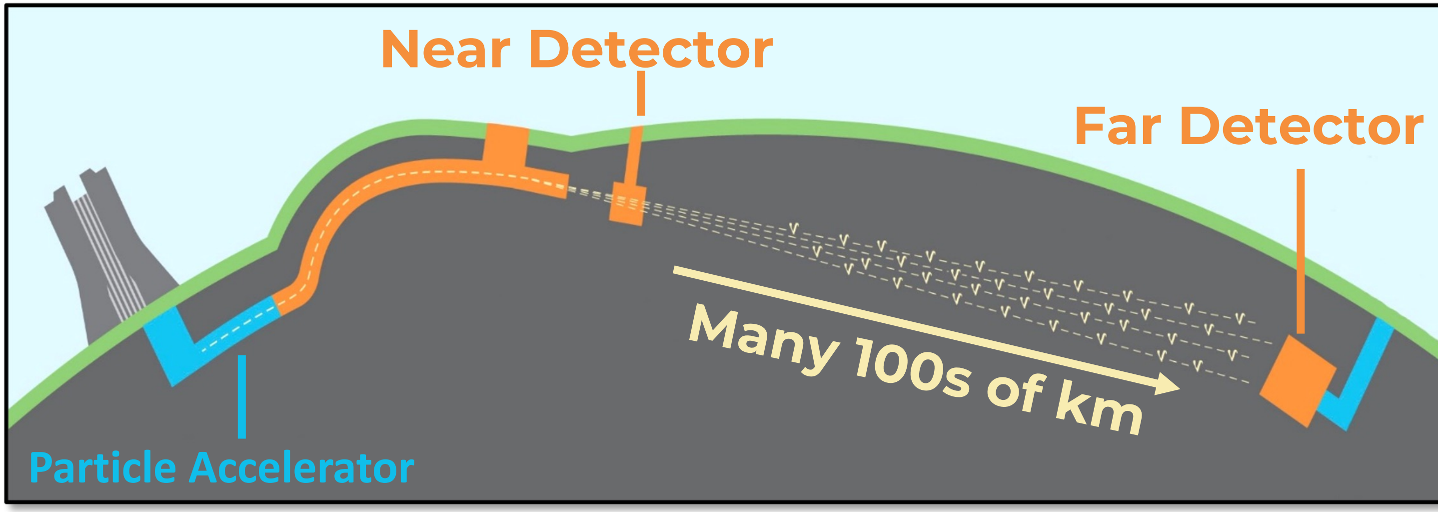
At the far detector

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

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

Oscillation probability

Why care about cross sections?



Current uncertainties

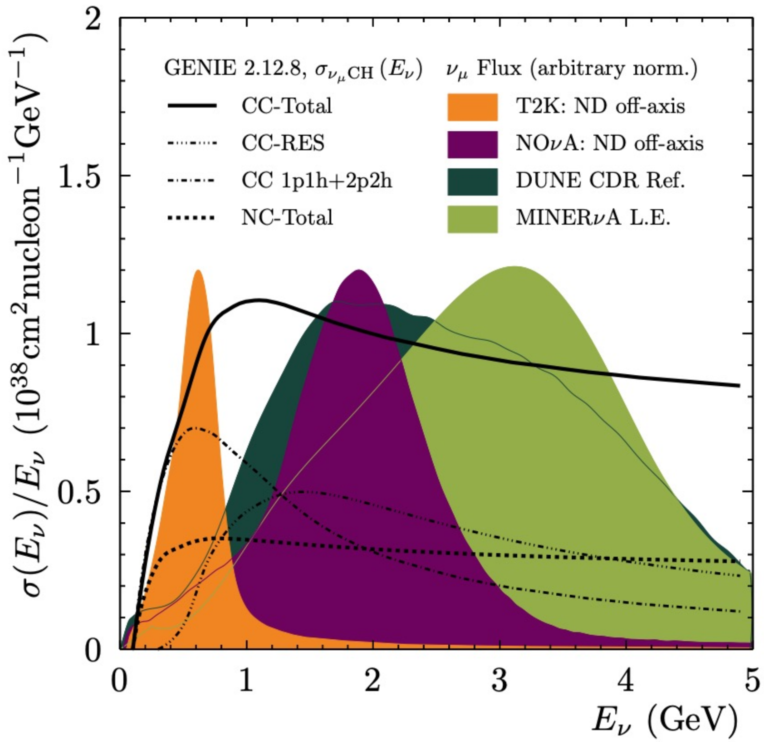
Source (NOvA)	$N(\nu_e)$
$\sigma_{\nu N}$ and FSI	7.7%
Total Syst.	**9.2%**

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

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

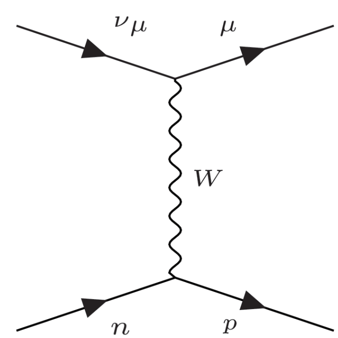
NEUTRINO 2022
XXX International Conference on Neutrino Physics and Astrophysics

Neutrino-nucleus cross sections



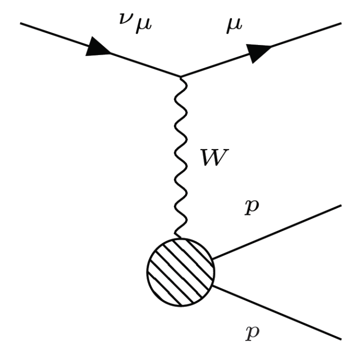
CC-QE

(Charged-Current Quasi-Elastic)



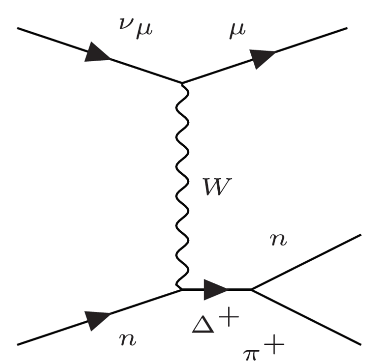
CC-2p2h

(Two-Particle-Two-Hole)



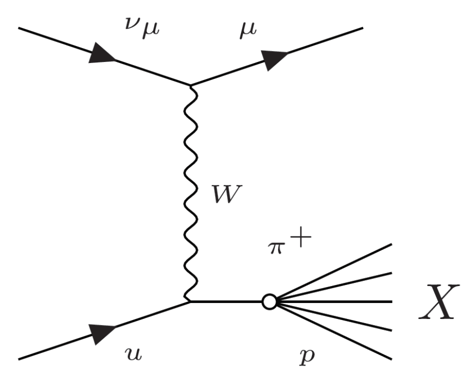
CC-SPP

(Single Pion Production)



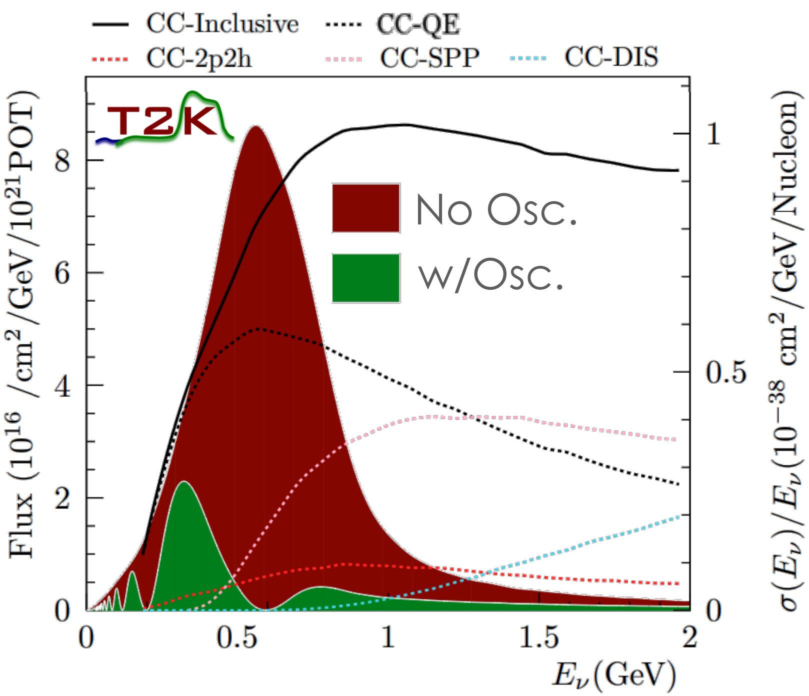
CC-DIS

(Deep Inelastic Scattering)



See talks from K. McFarland and L. Alvarez Ruso

Neutrino-nucleus cross sections

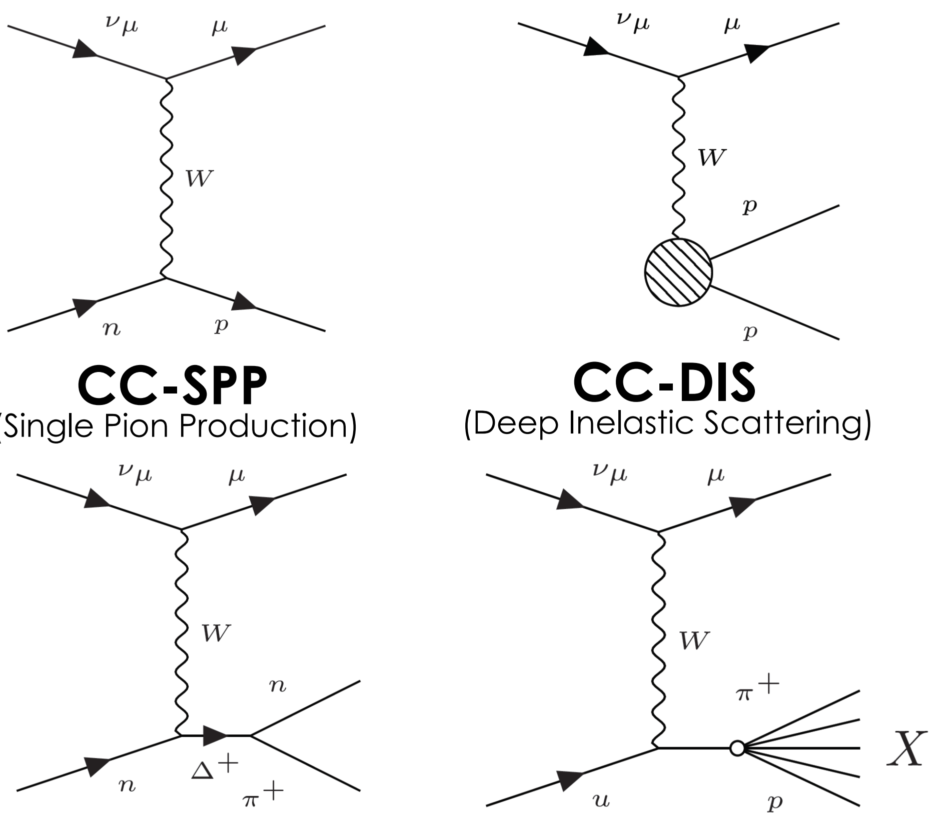


CC-QE
(Charged-Current Quasi-Elastic)

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

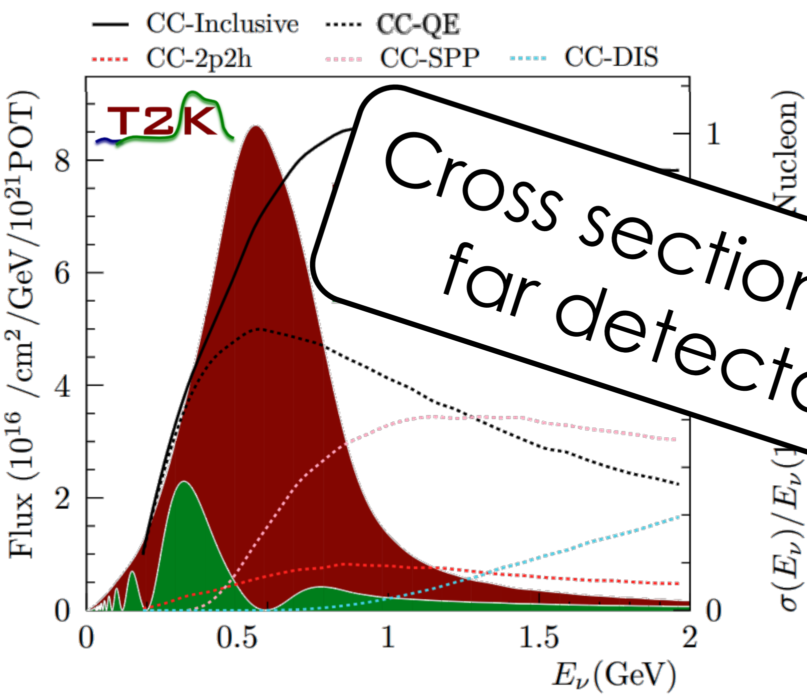
CC-SPP
(Single Pion Production)

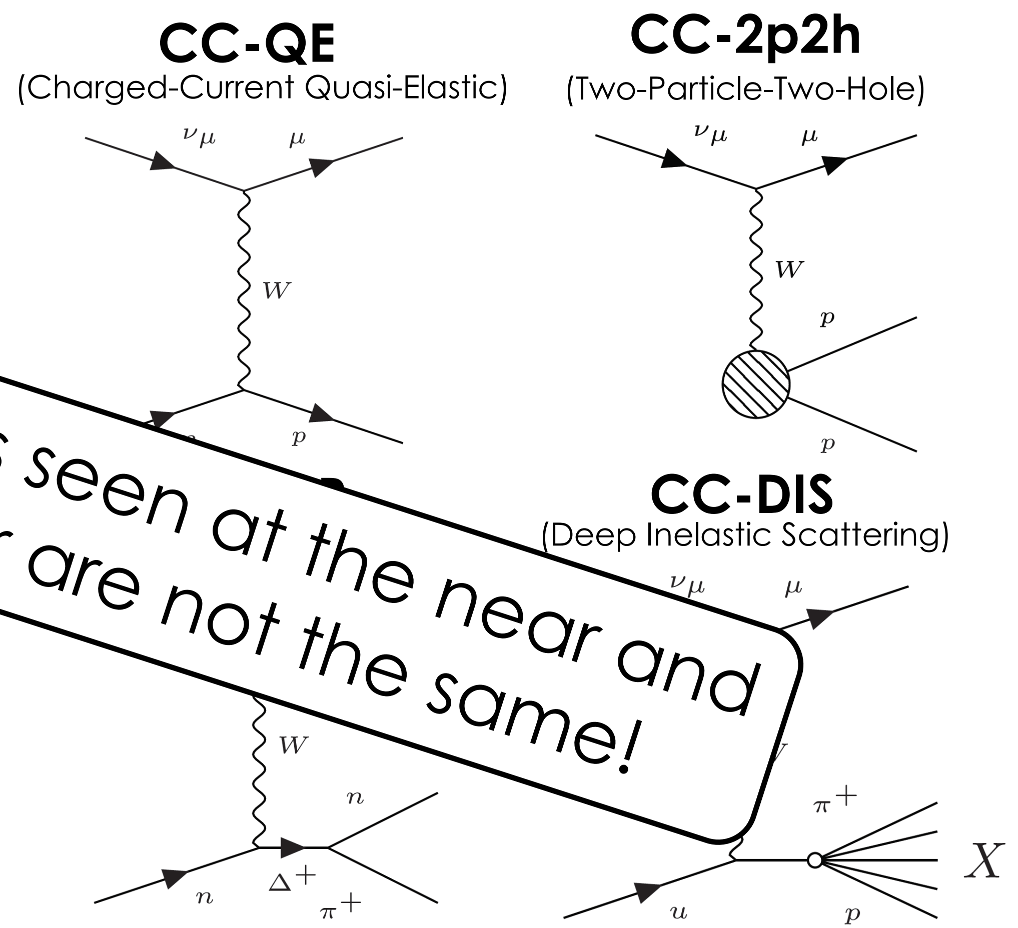
CC-DIS
(Deep Inelastic Scattering)



See talks from K. McFarland and L. Alvarez Ruso

Neutrino-nucleus cross sections

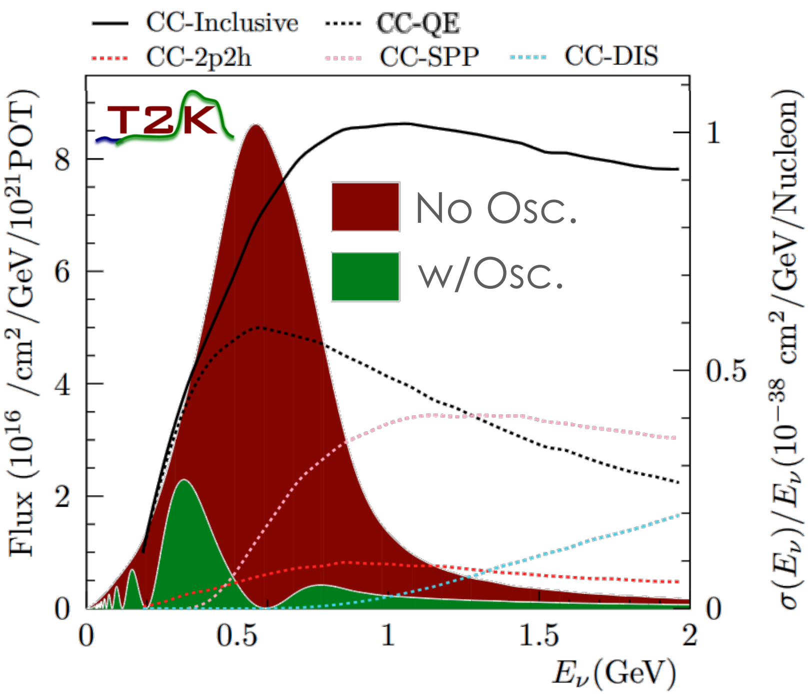




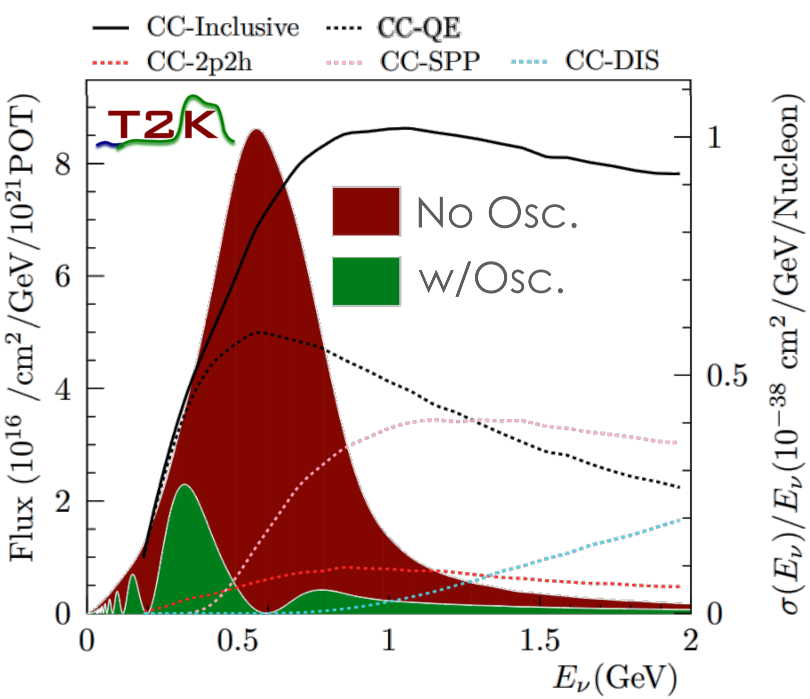
Cross sections seen at the near and far detector are not the same!

See talks from K. McFarland and L. Alvarez Ruso

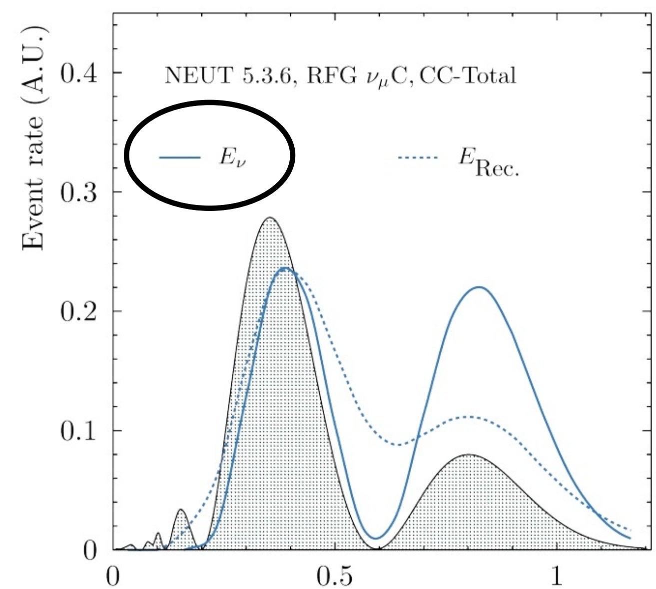
Event rates to oscillation parameters



Event rates to oscillation parameters



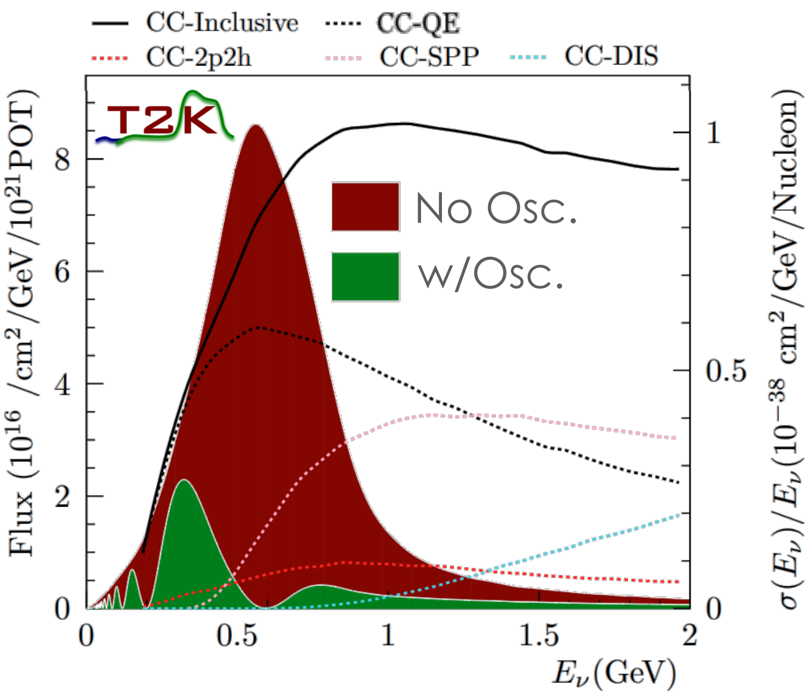
What we would like to measure



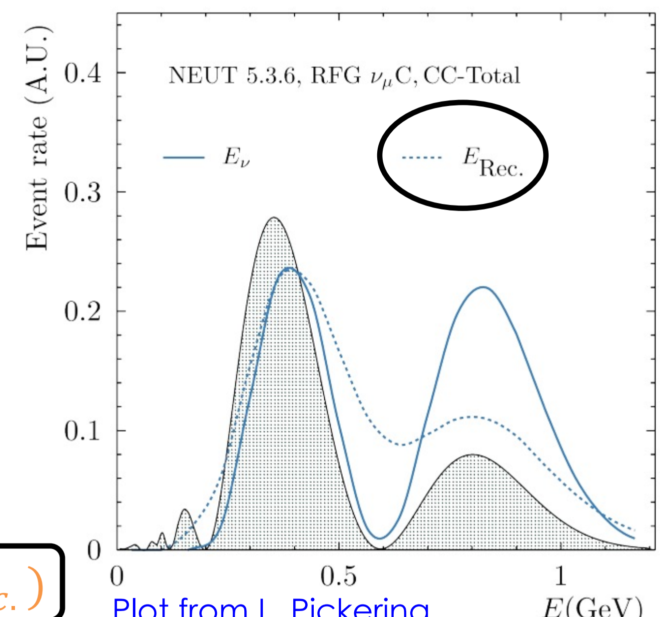
Plot from L. Pickering

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

Event rates to oscillation parameters



What we can actually measure

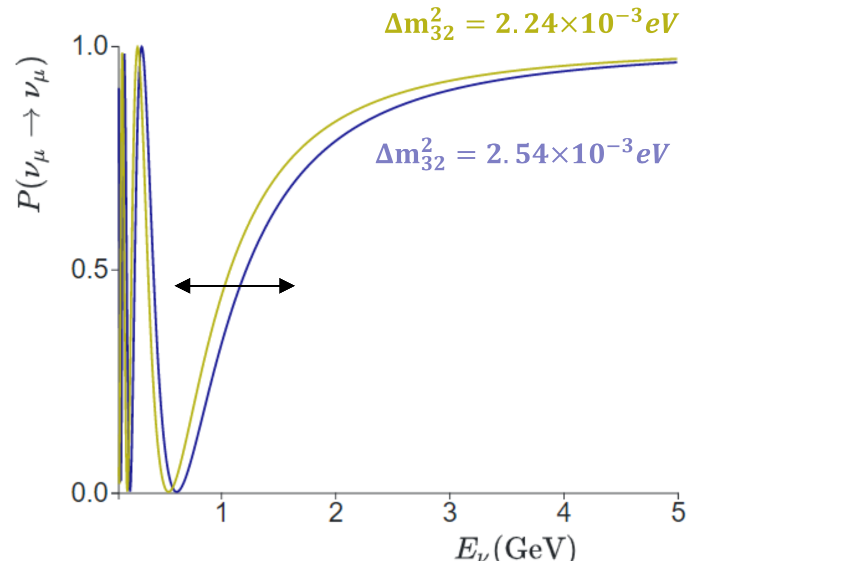


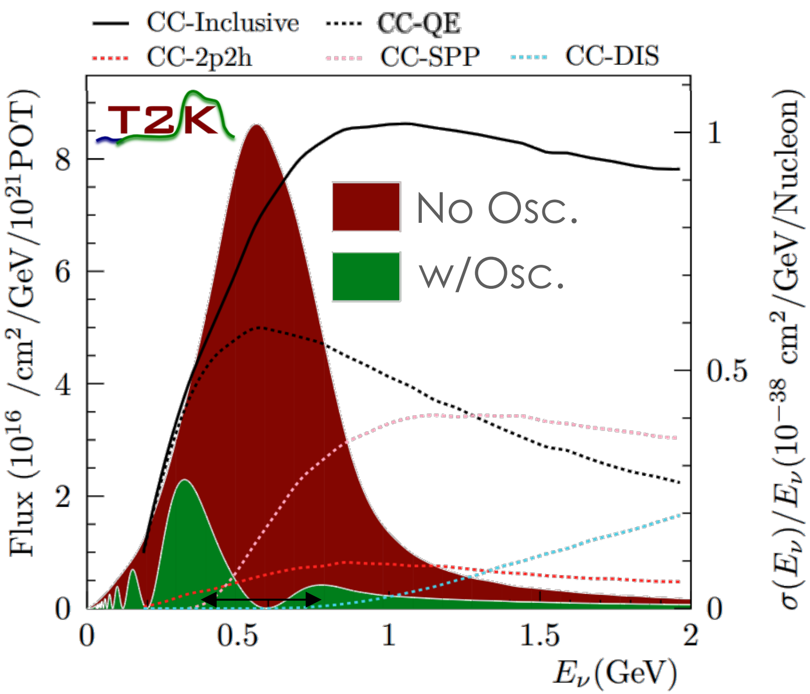
Plot from L. Pickering

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

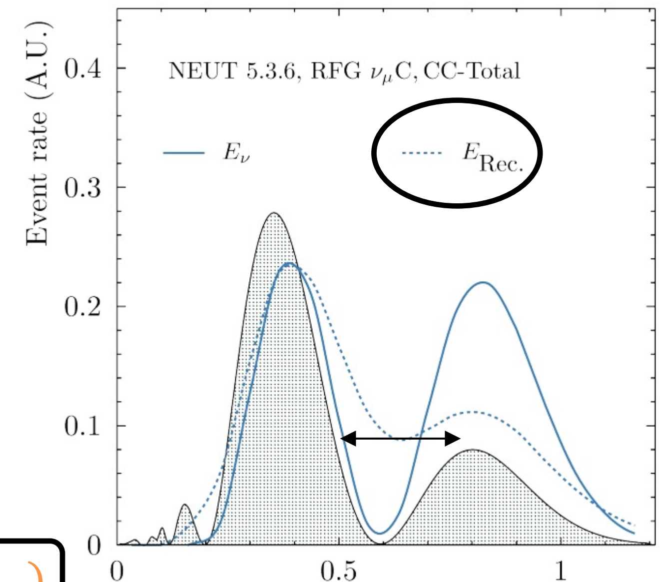
Event rates to oscillation parameters

- For a precision probe of oscillation parameters, reconstructing the shape of the oscillated spectrum is crucial





What we can actually measure

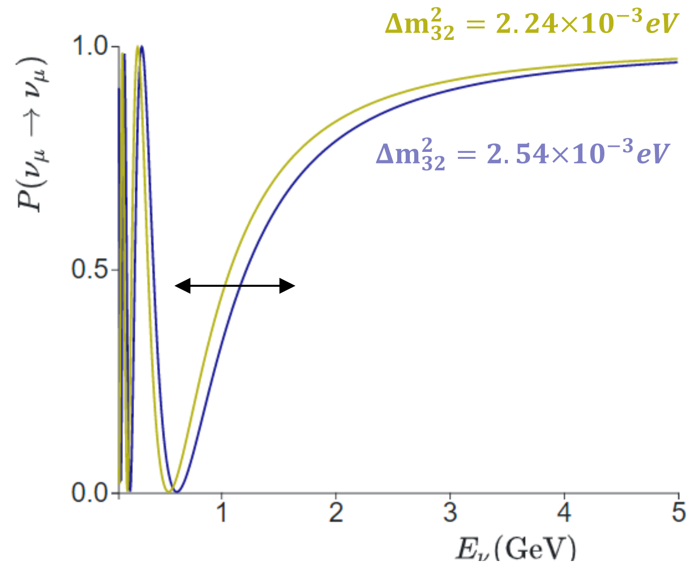


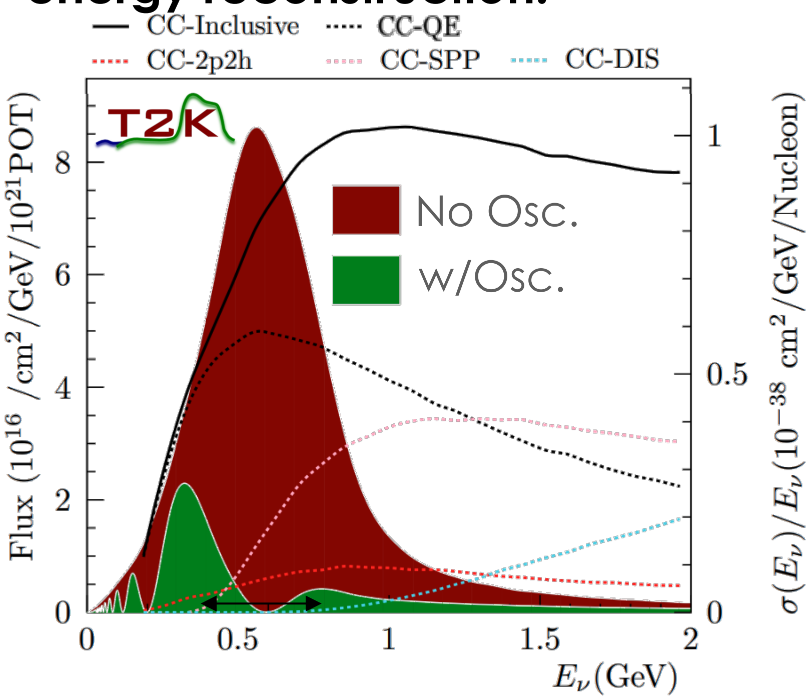
Plot from L. Pickering

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

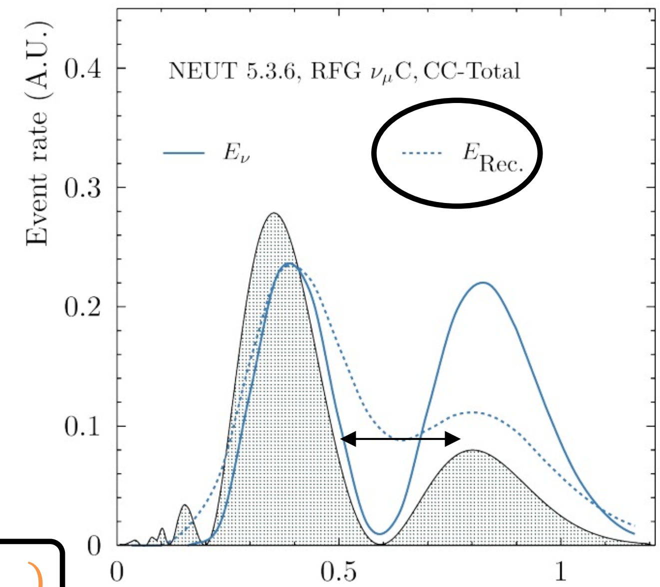
Event rates to oscillation parameters

- For a precision probe of oscillation parameters, reconstructing the shape of the oscillated spectrum is crucial
- **Require a good control over cross section energy dependence and energy reconstruction!**





What we can actually measure

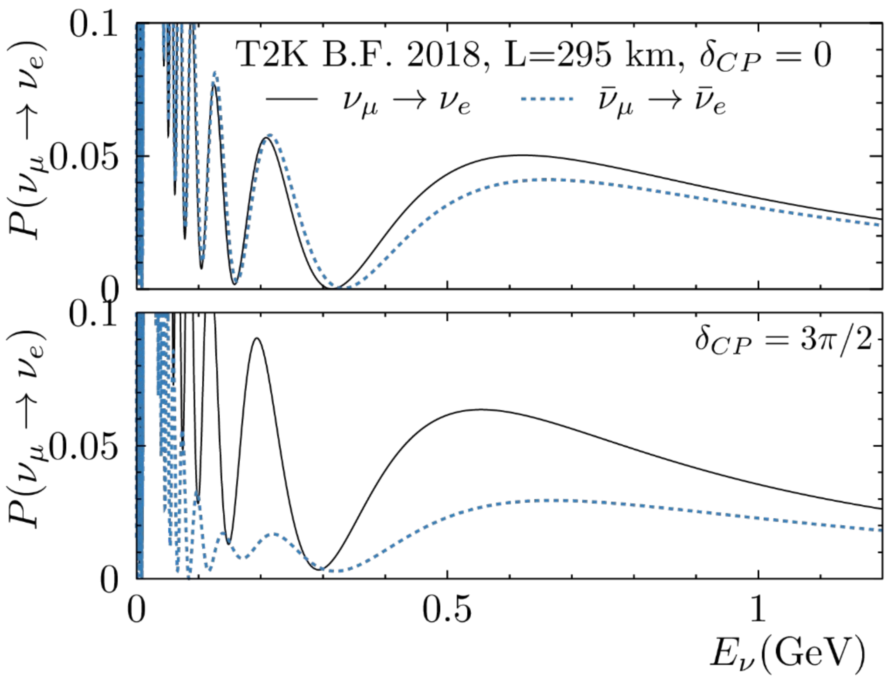


Plot from L. Pickering

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

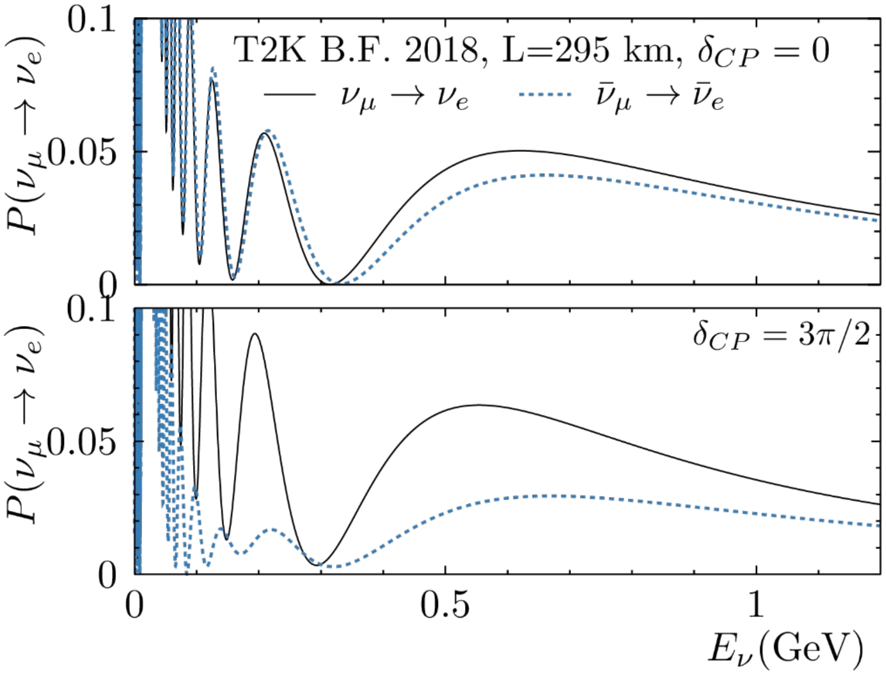
Event rates to oscillation parameters

- For a precision probe of oscillation parameters, reconstructing the shape of the oscillated spectrum is crucial
- **Require a good control over cross section energy dependence and energy reconstruction!**
- Constraints on δ_{CP} rely on differences between electron neutrino and anti-neutrino appearance



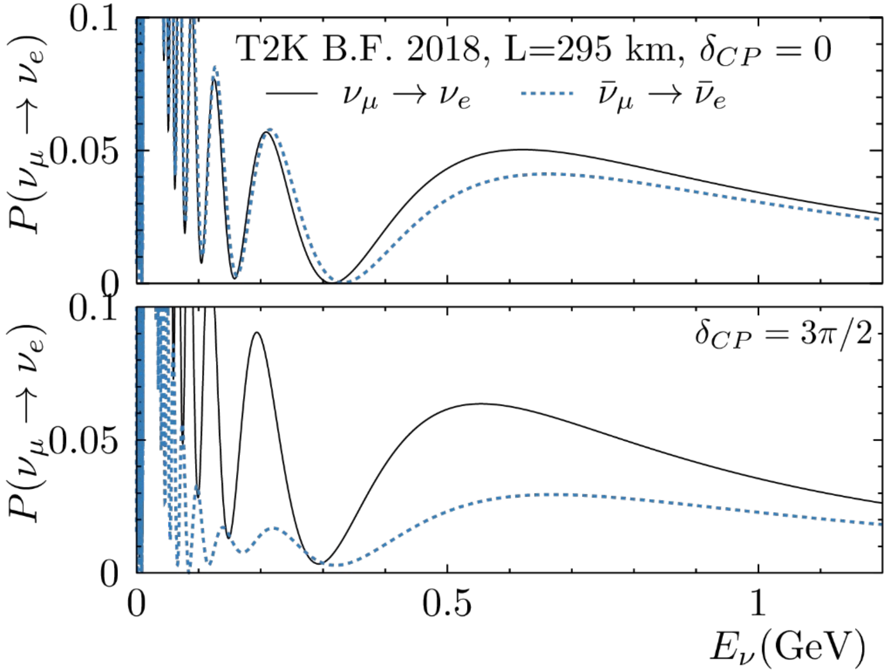
Event rates to oscillation parameters

- For a precision probe of oscillation parameters, reconstructing the shape of the oscillated spectrum is crucial
- **Require a good control over cross section energy dependence and energy reconstruction!**
- Constraints on δ_{CP} rely on differences between electron neutrino and anti-neutrino appearance
- But we mainly measure muon neutrino interactions at the near detector



Event rates to oscillation parameters

- For a precision probe of oscillation parameters, reconstructing the shape of the oscillated spectrum is crucial
- **Require a good control over cross section energy dependence and energy reconstruction!**
- Constraints on δ_{CP} rely on differences between electron neutrino and anti-neutrino appearance
- But we mainly measure muon neutrino interactions at the near detector
- **A good modelling of ν_e/ν_μ cross section ratio is essential**



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*

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*

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

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

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

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

Outline

- Why we care about neutrino interaction modelling
  - And what it is that we need to model well

- Simulating neutrino interactions using event generators
  - And why they are usually “wrong”

- What uncertainties we need to control better to make DUNE and Hyper-K a success
  - Reviewing some recent and upcoming publications

A generator's view of νN scattering

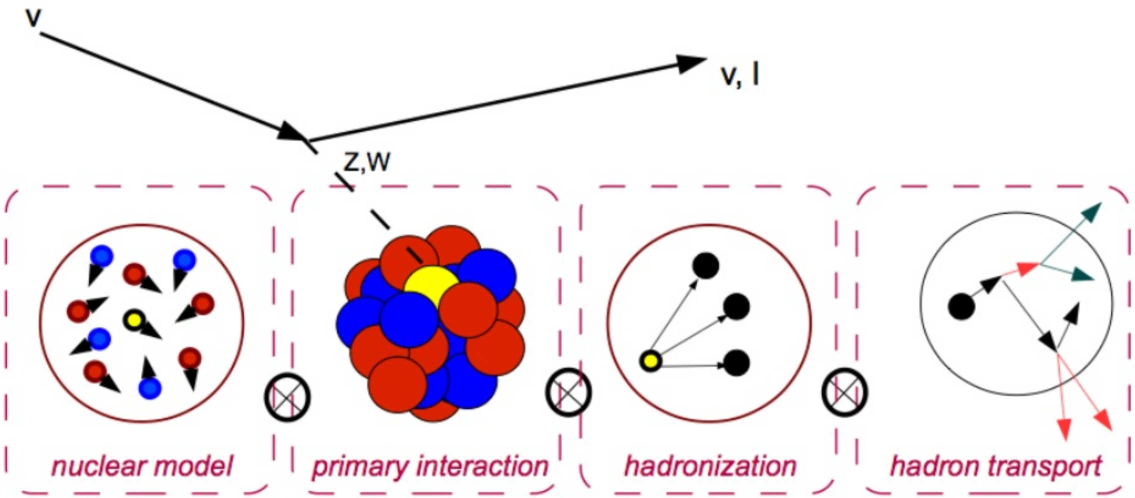
(true for at least some generators some of the time)

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

See S. Gardiner's talk for many more details

A generator's view of νN scattering

(true for at least some generators some of the time)



- Take theory inputs where possible, but these are often limited
  - Only capable of predicting a subset of observables
  - Only valid within some range of kinematic phase space
  - Only valid for certain processes
- Stitch them together

- Fill in the gaps with fudges, guesses and approximations

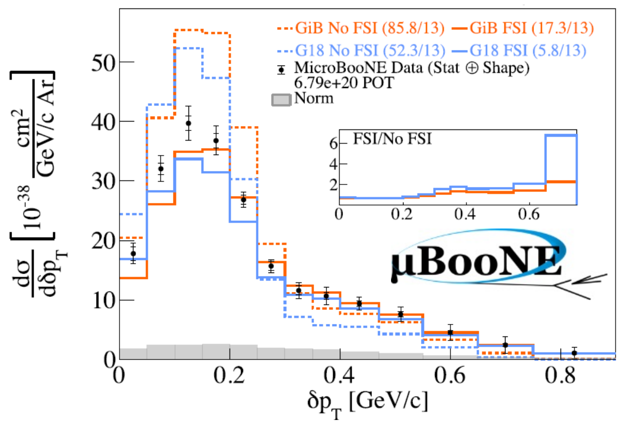
Generators vs data: a horror story

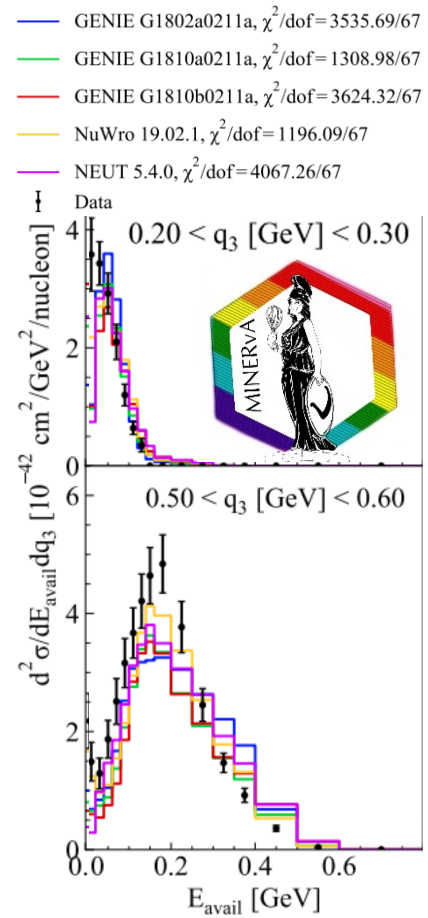
- No generator can come close to describing global lepton nucleus scattering data

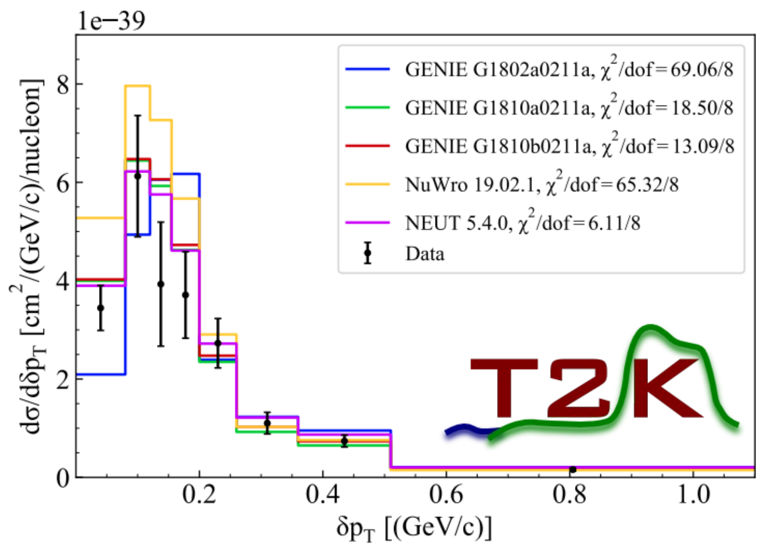
Generators vs data: a horror story

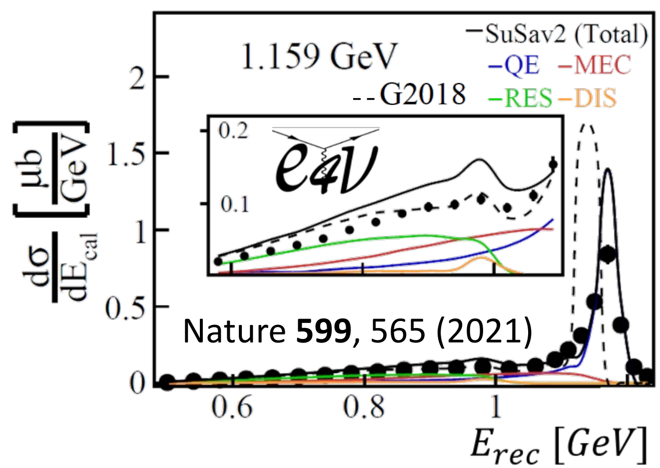
- No generator can come close to describing global lepton nucleus scattering data

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





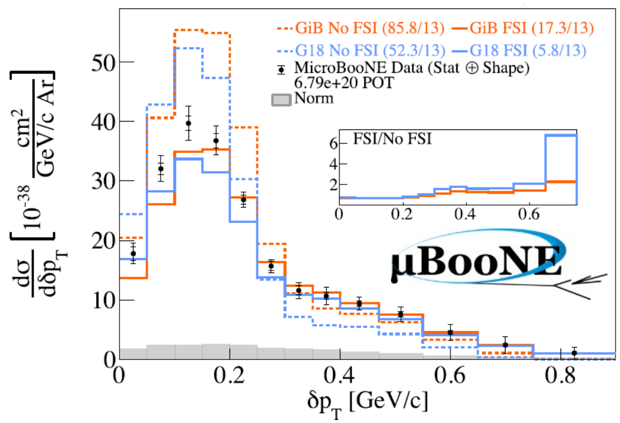


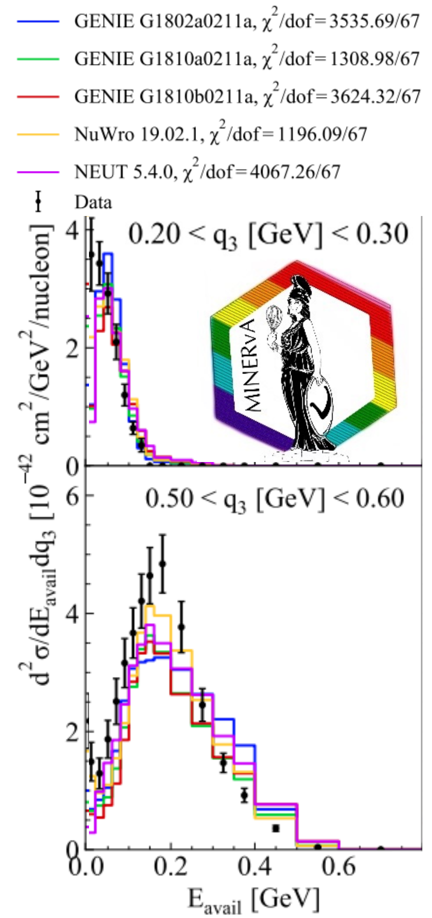


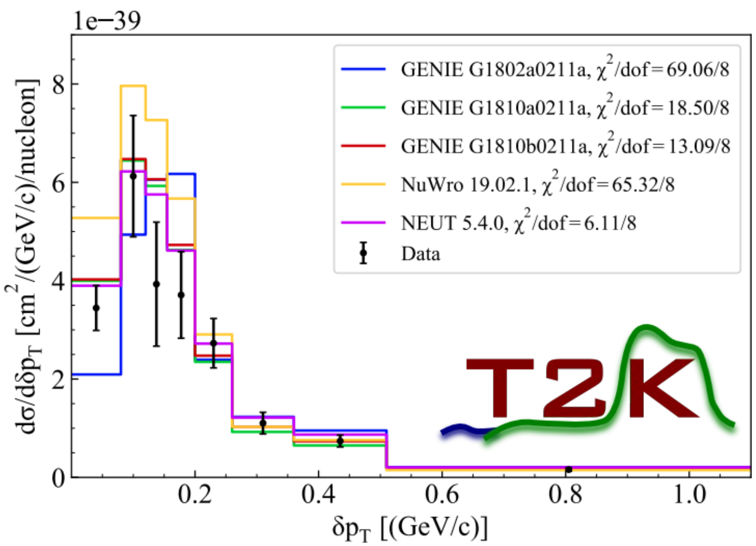
Generators vs data: a horror story

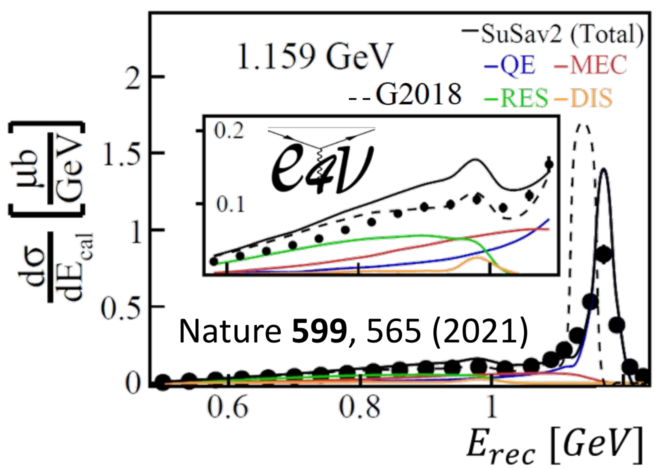
- No generator can come close to describing global lepton nucleus scattering data
  - All models are "wrong", but they are each wrong in different ways

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









Nature **599**, 565 (2021)

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

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

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

<u>Key question</u>

How do sensibly different model ingredients change the key predictions neutrino oscillation experiments rely (or will rely) on?

Outline

- Why we care about neutrino interaction modelling
  - And what it is that we need to model well
- Simulating neutrino interactions using event generators
  - And why they are usually “wrong”
- What uncertainties we need to control better to make DUNE and Hyper-K a success
  - Reviewing some recent and upcoming publications

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

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

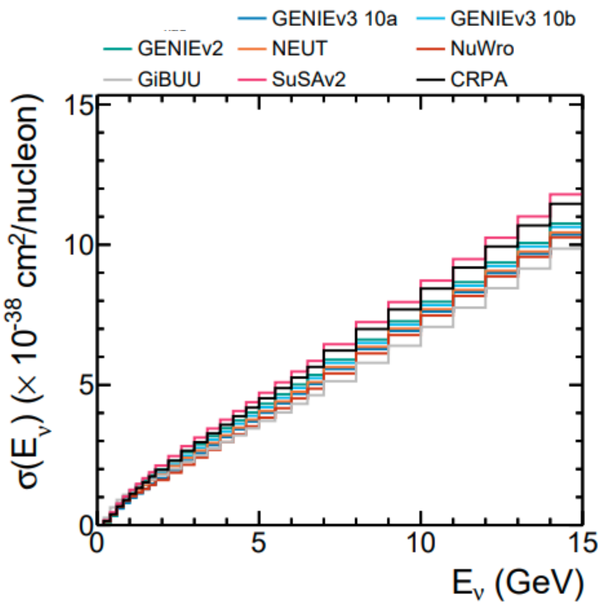
NEUT **GENIE** **NuWro** **AChilLES** **GiBUU**

Key question

How do sensibly different model ingredients change the key predictions neutrino oscillation experiments rely (or will rely) on?

Energy dependence

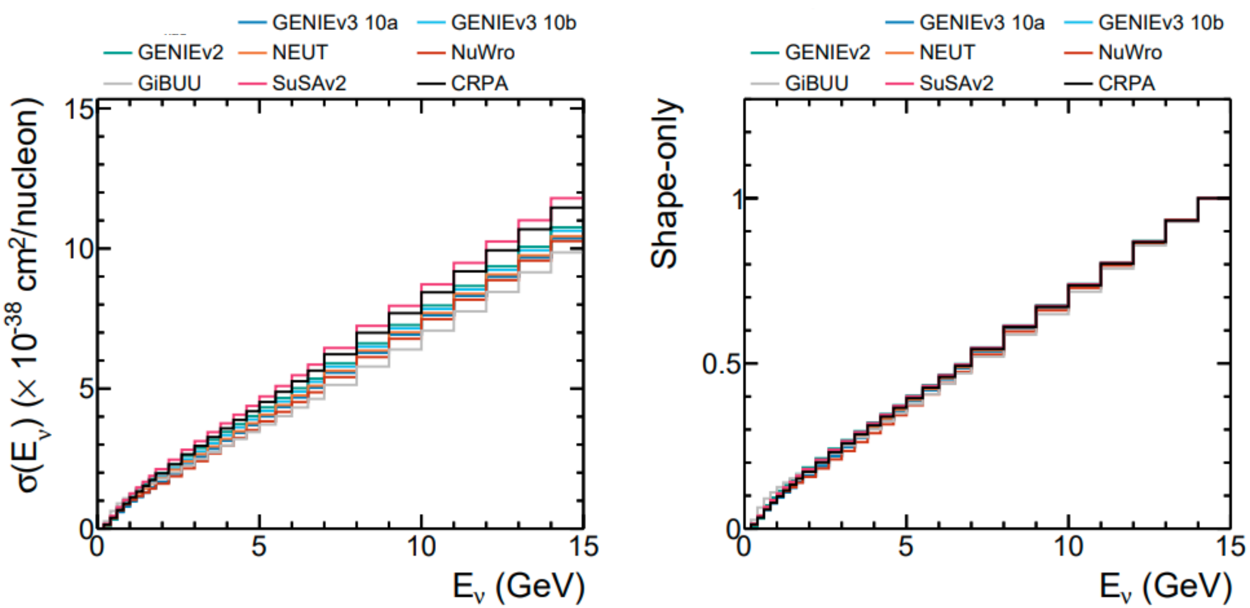
Plots from
Wilkinson, Dolan, Pickering, Wret,
A substandard candle: the low-ν method at few-GeV neutrino energies
arXiv 2203.11821, accepted by EPJC



Energy dependence

Plots from
Wilkinson, Dolan, Pickering, Wret,
A substandard candle: the low-ν method at few-GeV neutrino energies
arXiv 2203.11821, accepted by EPJC

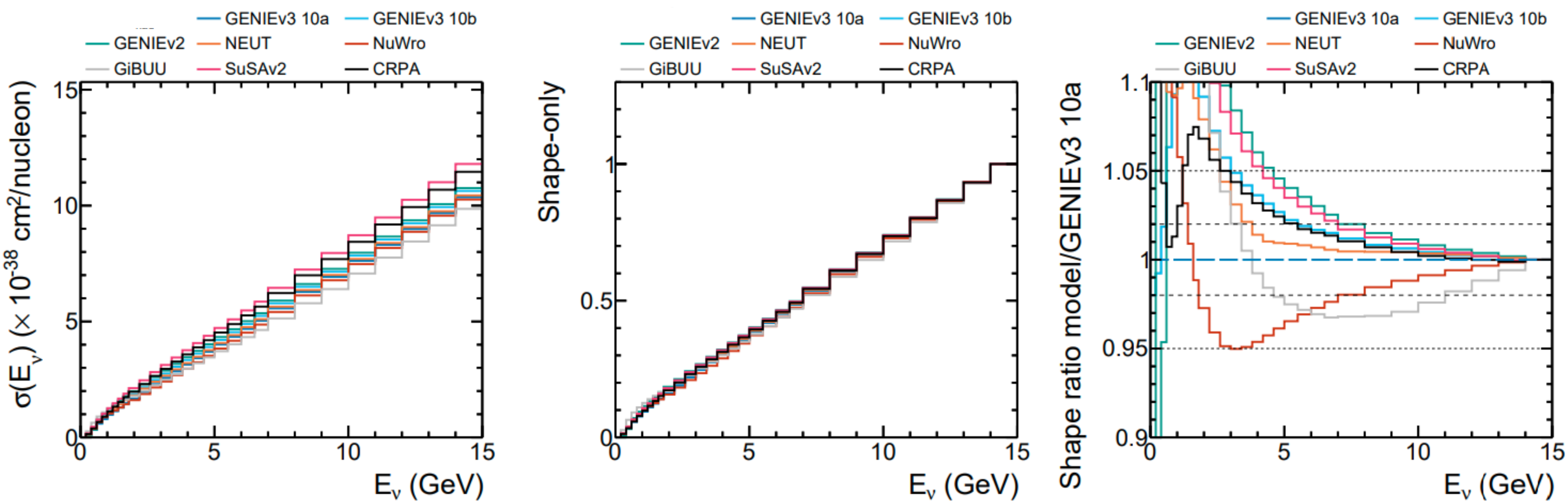
- What matters ND→FD extrapolation is the shape of total cross section as a function of E_ν



Energy dependence

Plots from
Wilkinson, Dolan, Pickering, Wret,
A substandard candle: the low-ν method at few-GeV neutrino energies
arXiv 2203.11821, accepted by EPJC

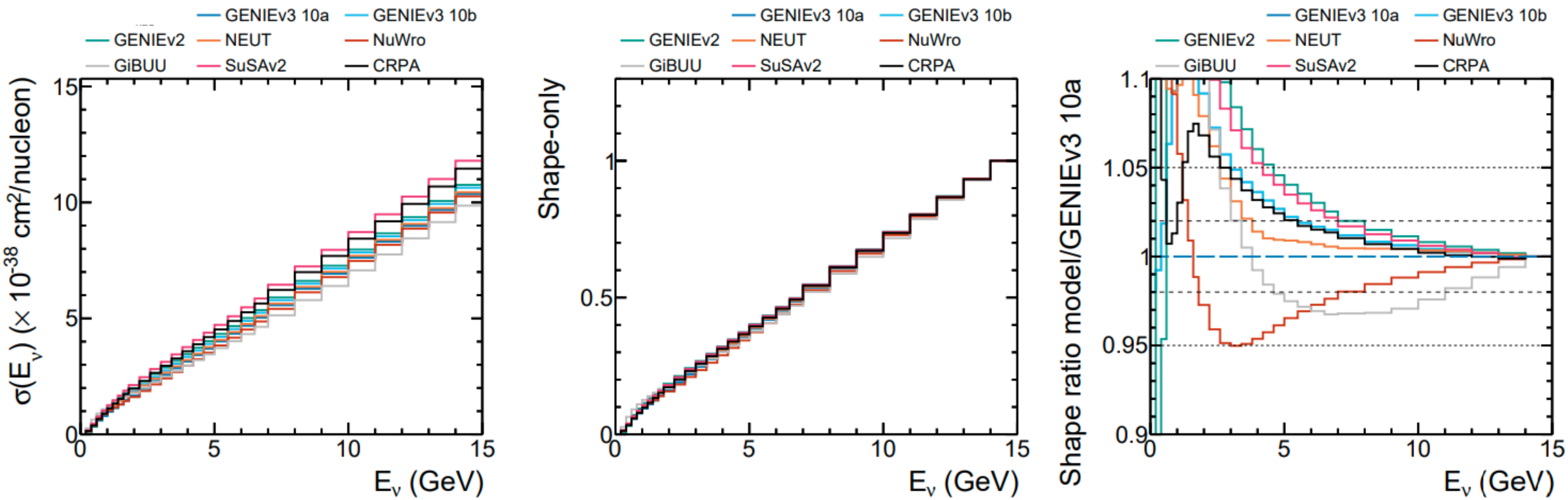
- What matters ND→FD extrapolation is the shape of total cross section as a function of E_ν
- Models differ by 5-10% in the region of interest for DUNE and Hyper-K



Energy dependence

Plots from
Wilkinson, Dolan, Pickering, Wret,
A substandard candle: the low-ν method at few-GeV neutrino energies
arXiv 2203.11821, accepted by EPJC

- What matters ND→FD extrapolation is the shape of total cross section as a function of E_ν
- Models differ by 5-10% in the region of interest for DUNE and Hyper-K
- Given expected statistics (~1000 ν_e, ~6000 ν_μ), this may be concerning
- Mitigation by direct measurements of cross section energy dependence (e.g. via multiple off-axis samples) is likely to be crucial



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

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

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

<u>Key question</u>

How do sensibly different model ingredients change the key predictions neutrino oscillation experiments rely (or will rely) on?

Neutrino energy reconstruction

- Many experiments reconstruct neutrino energy calorimetrically:

$$E_{rec} = E_{lep} + \sum T_p + \sum T_{\pi^\pm} + \sum E_{\pi^0}$$

- Principle biases (sources of unseen energy):
  - Charged pion masses
  - **Neutrons**

Neutrino energy reconstruction

- Many experiments reconstruct neutrino energy calorimetrically:

$$E_{rec} = E_{lep} + \sum T_p + \sum T_{\pi^\pm} + \sum E_{\pi^0}$$

- Principle biases (sources of unseen energy):
  - Charged pion masses
  - **Neutrons**

- **Crucial to model the fraction of energy that is unseen**

- Impacted by:
  - The energy transfer to the hadronic system
  - Final State Interactions (FSI)
  - Hadronization in inelastic scattering

Neutrino energy reconstruction

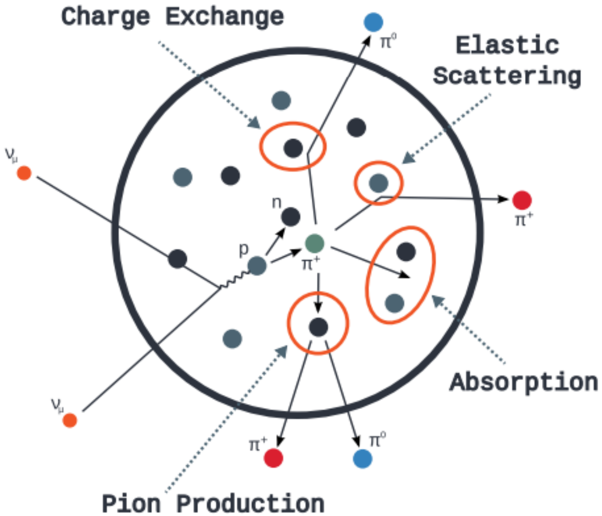
- Many experiments reconstruct neutrino energy calorimetrically:

$$E_{rec} = E_{lep} + \sum T_p + \sum T_{\pi^\pm} + \sum E_{\pi^0}$$

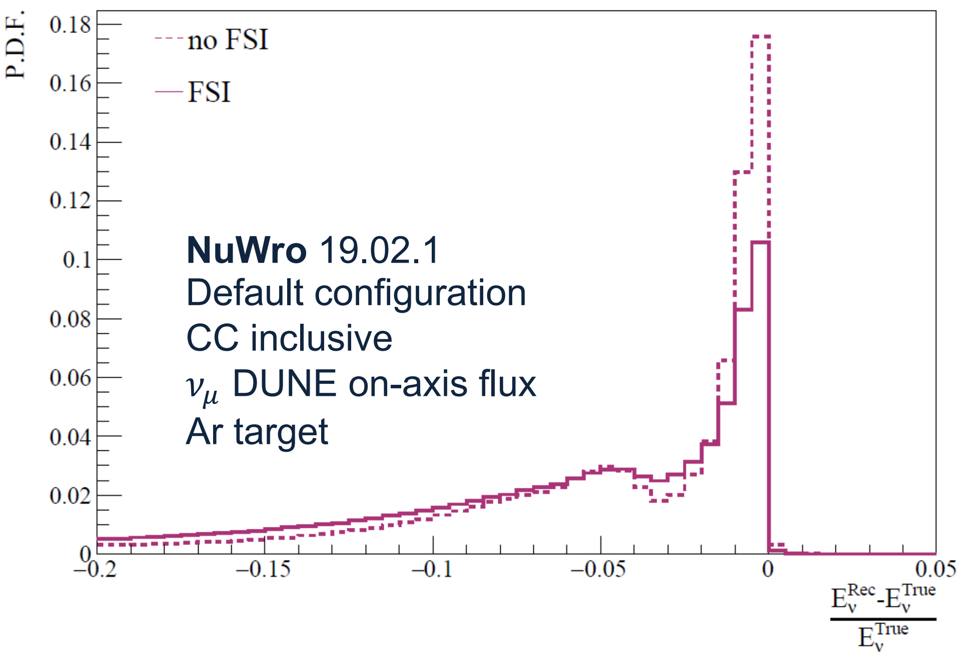
- Principle biases (sources of unseen energy):
  - Charged pion masses
  - **Neutrons**

- **Crucial to model the fraction of energy that is unseen**

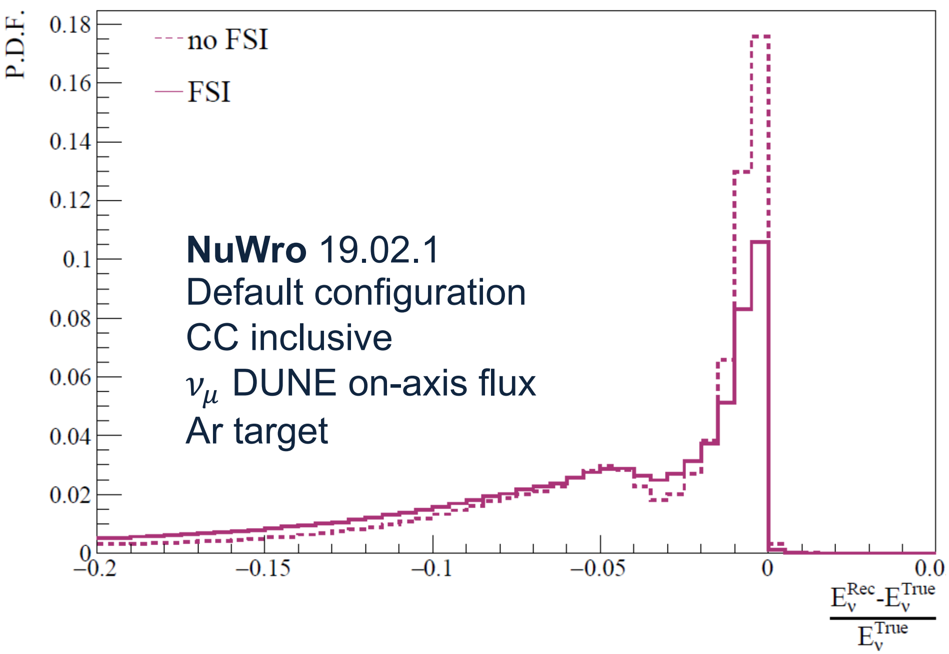
- Impacted by:
  - The energy transfer to the hadronic system
  - **Final State Interactions (FSI)**
  - Hadronization in inelastic scattering

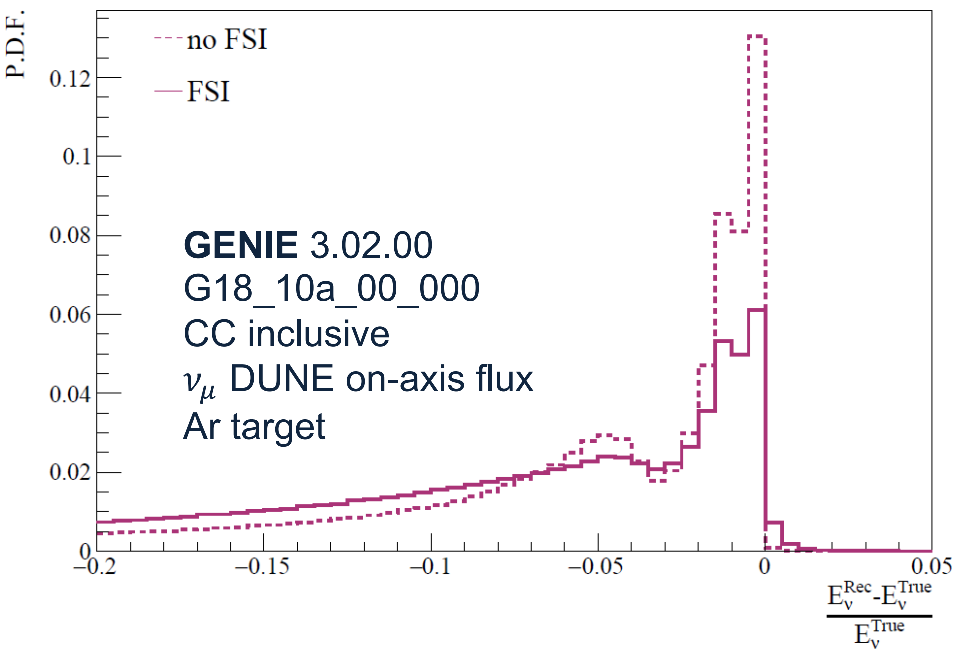


Neutrino energy reconstruction



Neutrino energy reconstruction

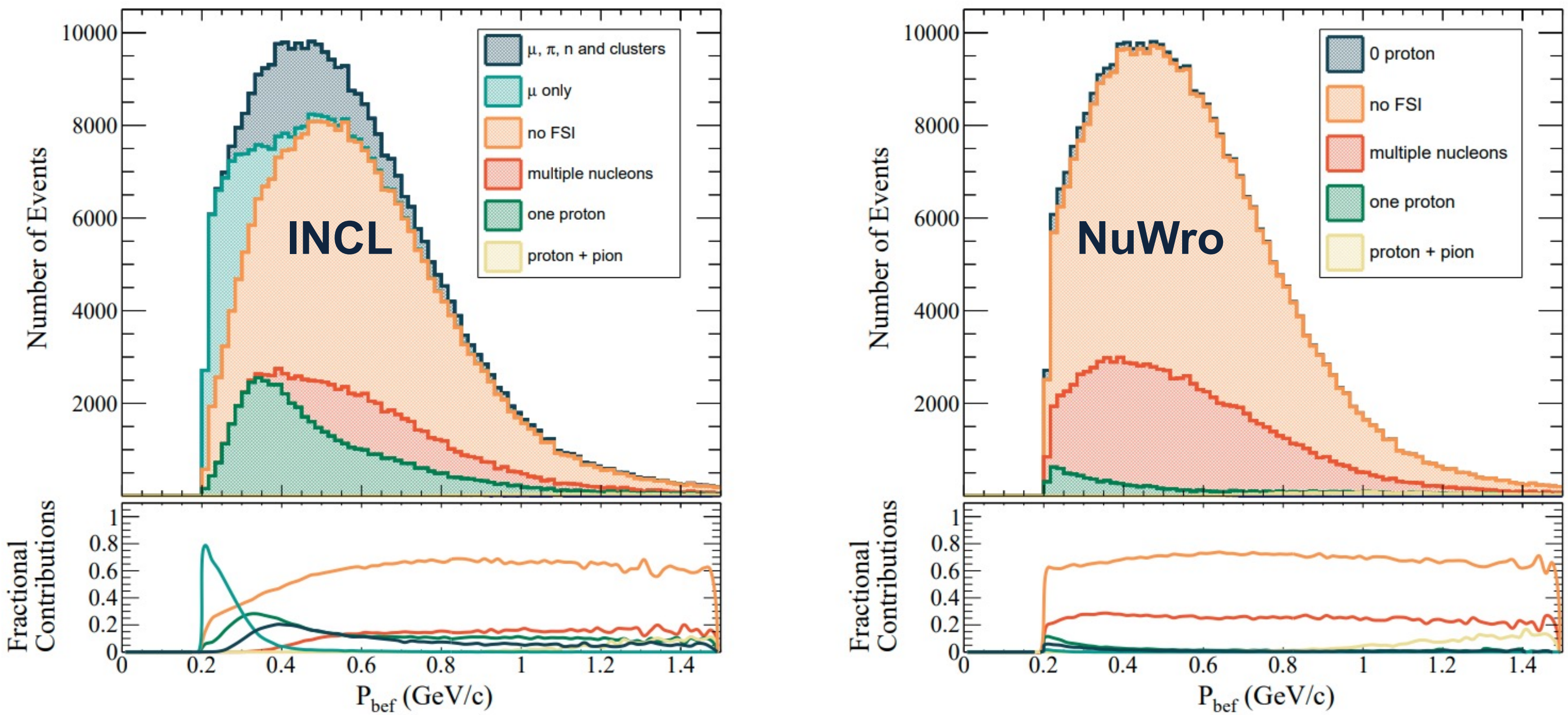




Advanced FSI cascades

Plots from
Ershova et al.,
Study of FSI of protons ith INCL and NuWro cascade models
Phys. Rev. D **106**, 032009

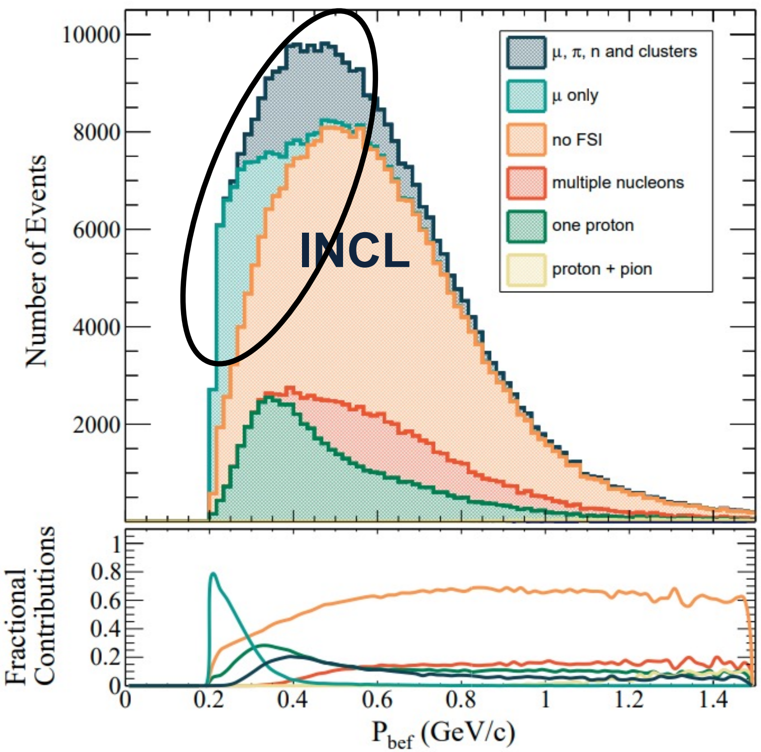
- More advanced treatment of FSIs is available via the INCL model (Phys. Rev. C **87** 014606)

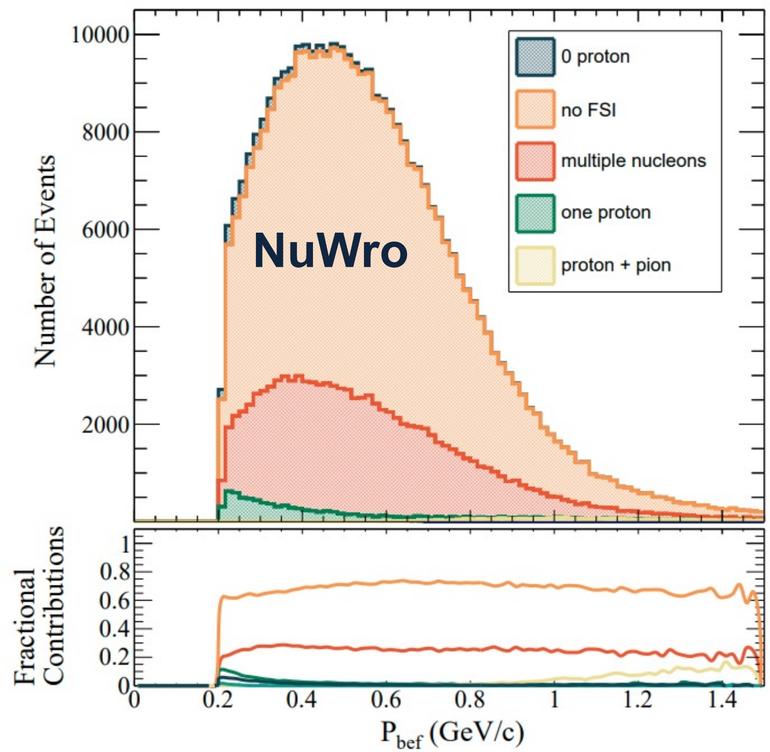


Advanced FSI cascades

Plots from
Ershova et al.,
Study of FSI of protons ith INCL and NuWro cascade models
Phys. Rev. D **106**, 032009

- More advanced treatment of FSIs is available via the INCL model (Phys. Rev. C **87** 014606)
- INCL's treatment of nucleon absorption and nuclear cluster production gives a different distribution of energy among outgoing hadrons
- Might expect a significant impact on neutrino energy smearing





FSI beyond the cascade

Plots from:
Franco-Patino et al., arXiv:2207.02086

See also:
Nikolakopoulos et al., Phys. Rev. C **105**, 054603

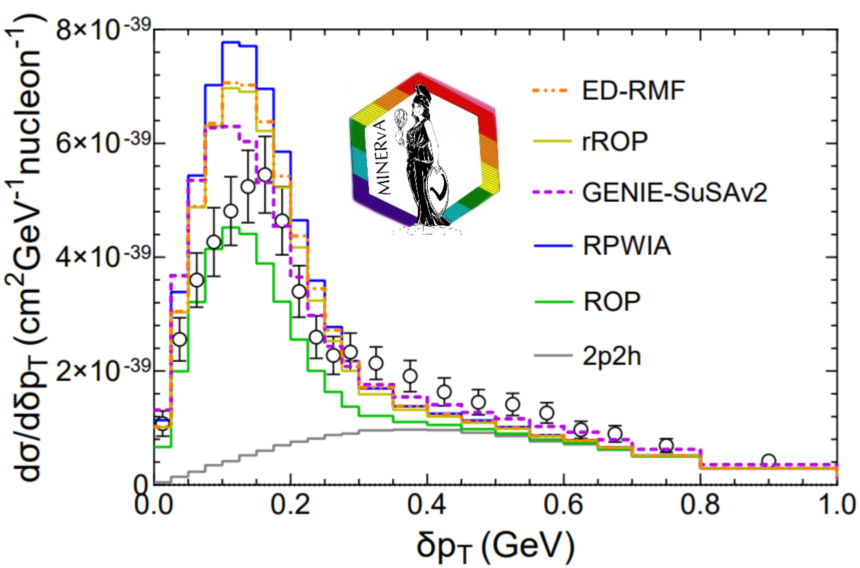
- Instead of cascades, FSI can be modelled via a distortion of the outgoing nucleon wave function by a nuclear potential
- Recent theory effort has allowed a calculation of exclusive observables with such treatments

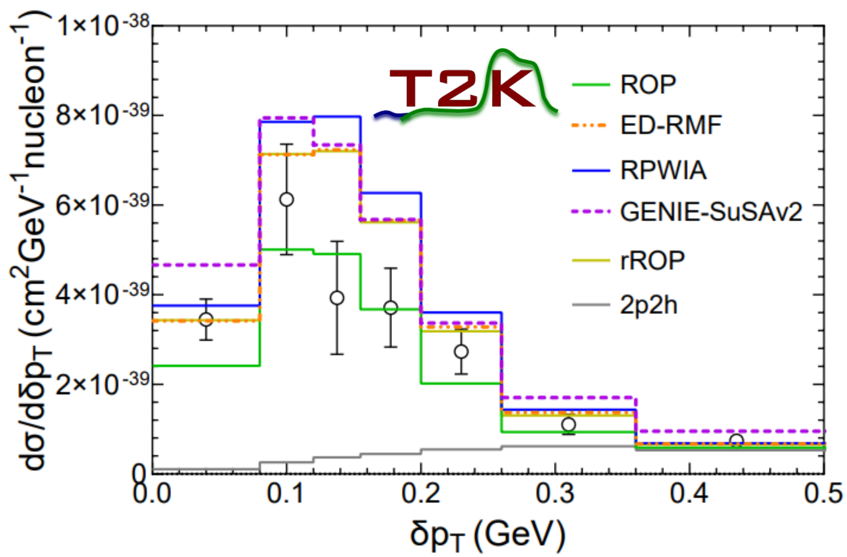
FSI beyond the cascade

Plots from:
Franco-Patino et al., arXiv:2207.02086

See also:
Nikolakopoulos et al., Phys. Rev. C **105**, 054603

- Instead of cascades, FSI can be modelled via a distortion of the outgoing nucleon wave function by a nuclear potential
- Recent theory effort has allowed a calculation of exclusive observables with such treatments
  - Example below: missing transverse momentum
  - In general: high δp_T → more missing hadronic energy → larger E_ν reconstruction bias



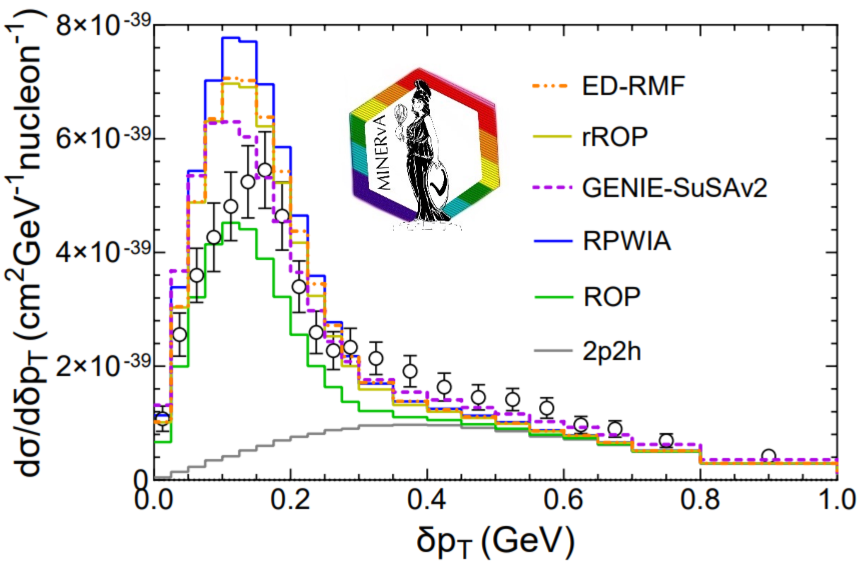


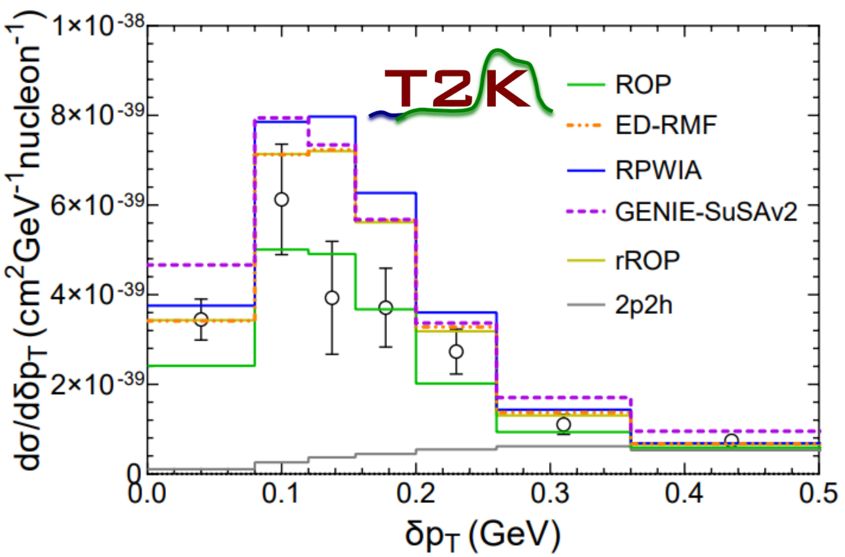
FSI beyond the cascade

Plots from:
Franco-Patino et al., arXiv:2207.02086

See also:
Nikolakopoulos et al., Phys. Rev. C **105**, 054603

- Instead of cascades, FSI can be modelled via a distortion of the outgoing nucleon wave function by a nuclear potential
- Recent theory effort has allowed a calculation of exclusive observables with such treatments
  - Example below: missing transverse momentum
  - In general: high $\delta p_T \rightarrow$ more missing hadronic energy $\rightarrow$ larger E_ν reconstruction bias
- Key conclusions
  - Significant differences in predictions for different nuclear potentials
  - Sometimes all of these deviate strongly from the cascade approach





Impact on analyses

Plot from:
DUNE physics TDR,
arXiv:2002.03005

- DUNE runs a study where it fits as data a model where **20% of final state proton energy** in its nominal model instead **goes into neutrons**
  - A **plausible consequence of alternative FSI models**

- At the same time, the cross section is altered to leave the proton momentum distribution unchanged
  - Another plausible change to the cross section model

Impact on analyses

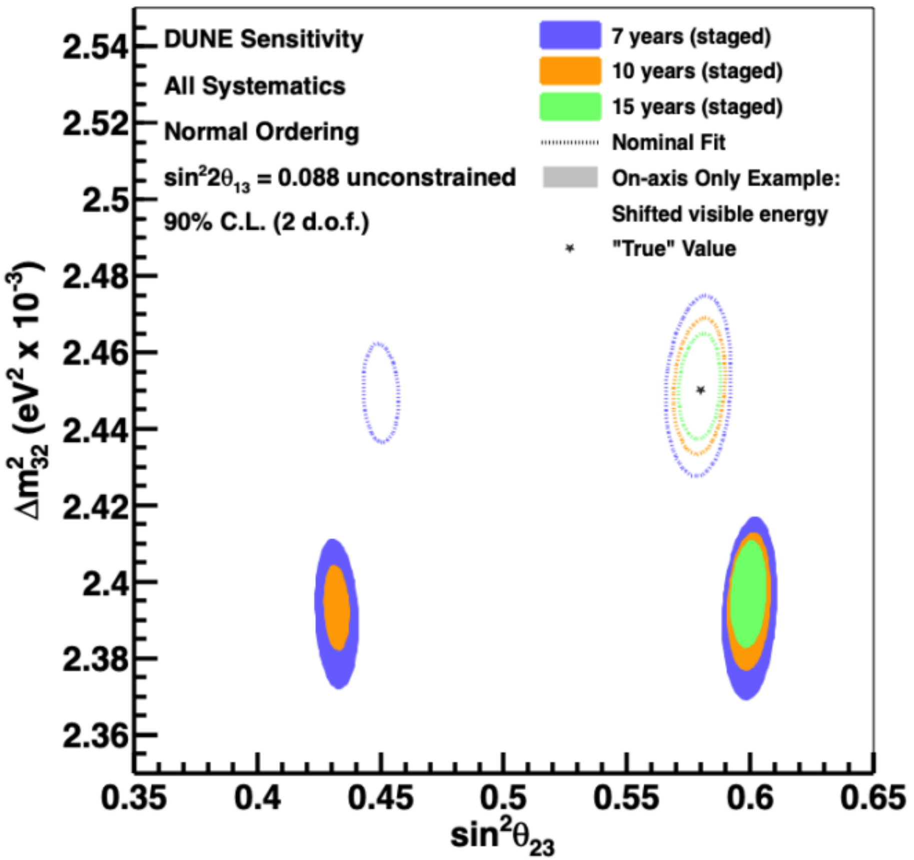
Plot from:
DUNE physics TDR, arXiv:2002.03005

- DUNE runs a study where it fits as data a model where **20% of final state proton energy** in its nominal model instead **goes into neutrons**
  - A **plausible consequence of alternative FSI models**

- At the same time, the cross section is altered to leave the proton momentum distribution unchanged
  - Another plausible change to the cross section model

- The result: **a large bias in oscillation parameters**

- Possible mitigation by creative use of the near detector
  - Off-axis samples
  - Additional nuclear targets



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

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

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

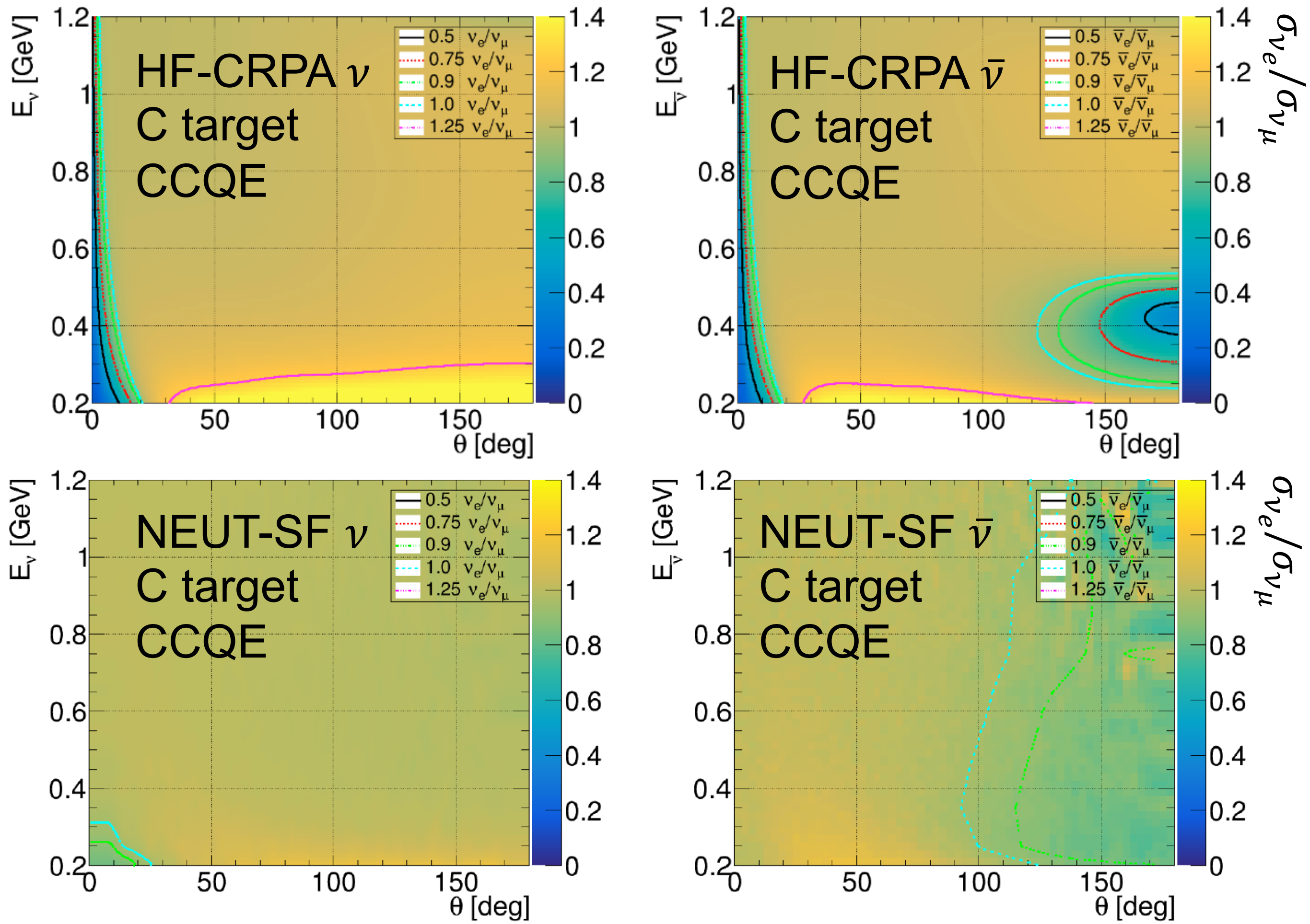
Key question

How do sensibly different model ingredients change the key predictions neutrino oscillation experiments rely (or will rely) on?

Electron vs muon neutrinos

Details in:
Dieminger et al., NEUTRINO 2022 poster
See also:
Nikolakopoulos et al., PRL **123**, 052501
Dolan et al., arXiv:2110.14601

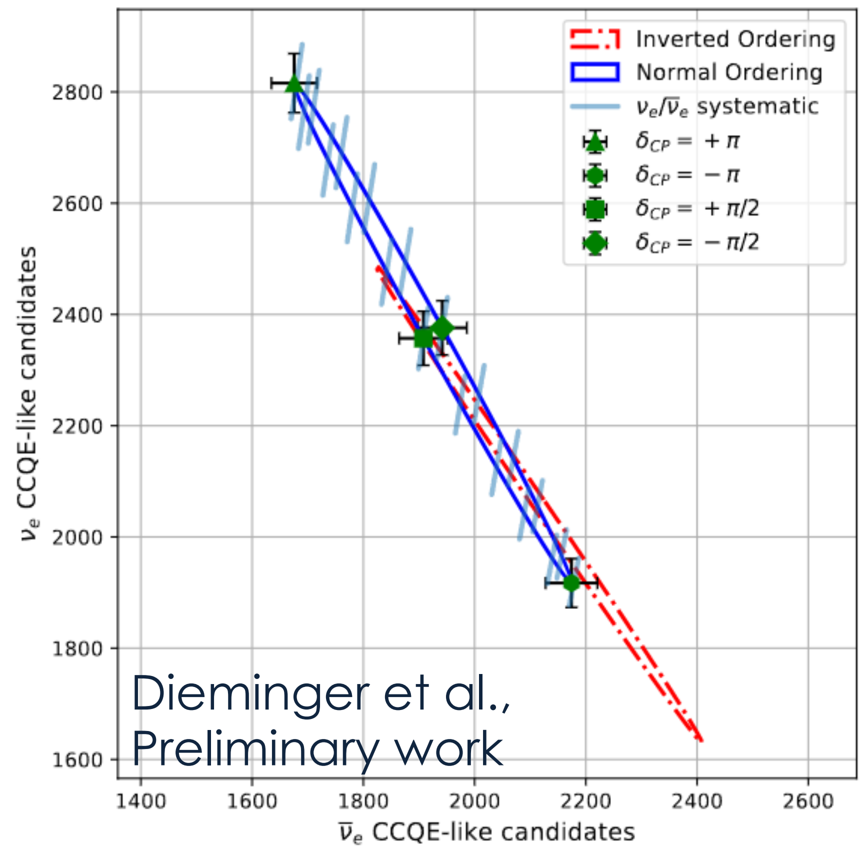
- Nuclear medium effects change the ν_e/ν_μ ratio
  - Changes the cross section close to phase space boundaries



Electron vs muon neutrinos

Details in:
Dieminger et al., NEUTRINO 2022 poster
See also:
Nikolakopoulos et al., PRL **123**, 052501
Dolan et al., arXiv:2110.14601

- Nuclear medium effects change the ν_e/ν_μ ratio
  - Changes the cross section close to phase space boundaries
- Considering the Hyper-K flux and taking model differences as a systematic uncertainty we find:
  - 2.2% on the ν_e/ν_μ ratio
  - 1.5% on the $\nu_e/\overline{\nu}_e$ ratio
- Comparable to expected Hyper-K statistical uncertainties and other systematic uncertainties
- Does not yet consider the impact of shape changes to the $\nu_e/\overline{\nu}_e$ appearance spectra



Dieminger et al., Preliminary work

Electron vs muon neutrinos

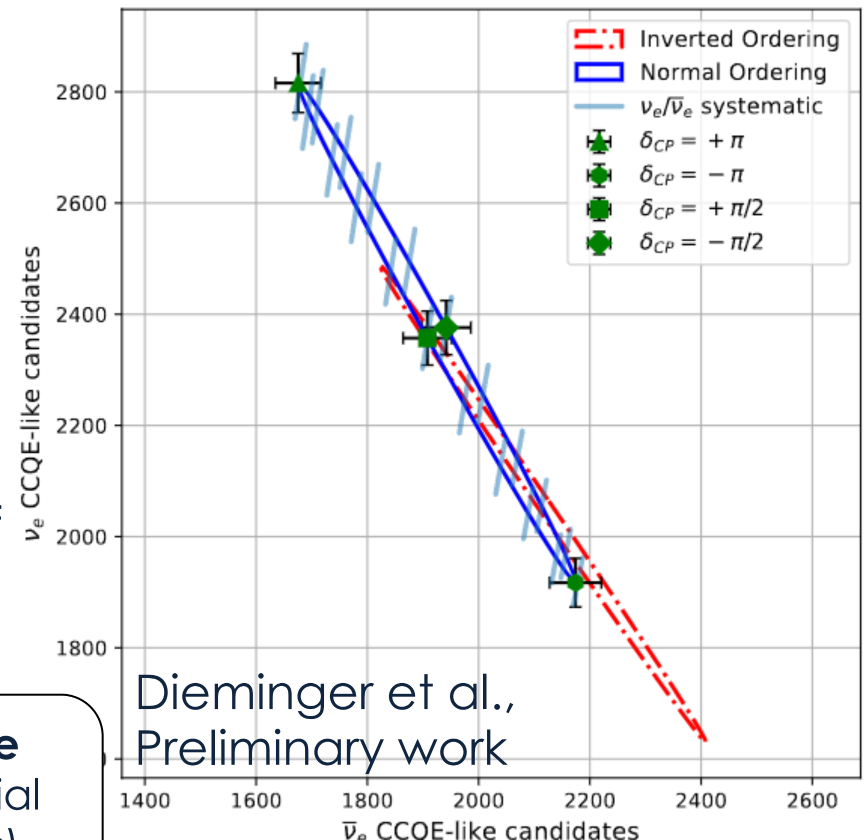
Details in:
Dieminger et al., NEUTRINO 2022 poster
See also:
Nikolakopoulos et al., PRL **123**, 052501
Dolan et al., arXiv:2110.14601

- Nuclear medium effects change the ν_e/ν_μ ratio
  - Changes the cross section close to phase space boundaries

- Considering the Hyper-K flux and taking model differences as a systematic uncertainty we find:
  - 2.2% on the ν_e/ν_μ ratio
  - 1.5% on the $\nu_e/\overline{\nu}_e$ ratio

- Comparable to expected Hyper-K statistical uncertainties and other systematic uncertainties

- Does not yet consider the impact of shape changes to the $\nu_e/\overline{\nu}_e$ appearance spectra



Additional few-% uncertainty related to **radiative corrections** to the cross section (and the potential impact of outgoing photons on event selections)
See: arXiv:2105.07939

Summary

- Uncertainties on the neutrino interactions physics most pertinent to future oscillation experiments are far from under control
- As we gather more data, experiments must consider a wider range of analysis failure modes due to a mismodelling of neutrino interactions

Summary

- Uncertainties on the neutrino interactions physics most pertinent to future oscillation experiments are far from under control

- As we gather more data, experiments must consider a wider range of analysis failure modes due to a mismodelling of neutrino interactions
  - This work is already happening!

T2K uncertainty model

NOvA uncertainty model

μBooNE uncertainty model

Summary

- Uncertainties on the neutrino interactions physics most pertinent to future oscillation experiments are far from under control

- As we gather more data, experiments must consider a wider range of analysis failure modes due to a mismodelling of neutrino interactions
  - This work is already happening!

T2K uncertainty model   NOvA uncertainty model   μBooNE uncertainty model

- Whilst we have a long way to go, we should not forget how far we have come!

Summary

- Uncertainties on the neutrino interactions physics most pertinent to future oscillation experiments are far from under control

- As we gather more data, experiments must consider a wider range of analysis failure modes due to a mismodelling of neutrino interactions
  - This work is already happening!

T2K uncertainty model

NOvA uncertainty model

μBooNE uncertainty model

- Whilst we have a long way to go, we should not forget how far we have come!

> "Most of our knowledge of neutrino cross sections in [the 0.1-20 GeV energy range] comes from early experiments ... conducted in the 1970s and 1980s"
>
> Formaggio and Zeller, Rev. Mod. Phys. **84**, 1307, **2013**

Summary

- Uncertainties on the neutrino interactions physics most pertinent to future oscillation experiments are far from under control

- As we gather more data, experiments must consider a wider range of analysis failure modes due to a mismodelling of neutrino interactions
  - This work is already happening!

T2K uncertainty model

NOvA uncertainty model

μBooNE uncertainty model

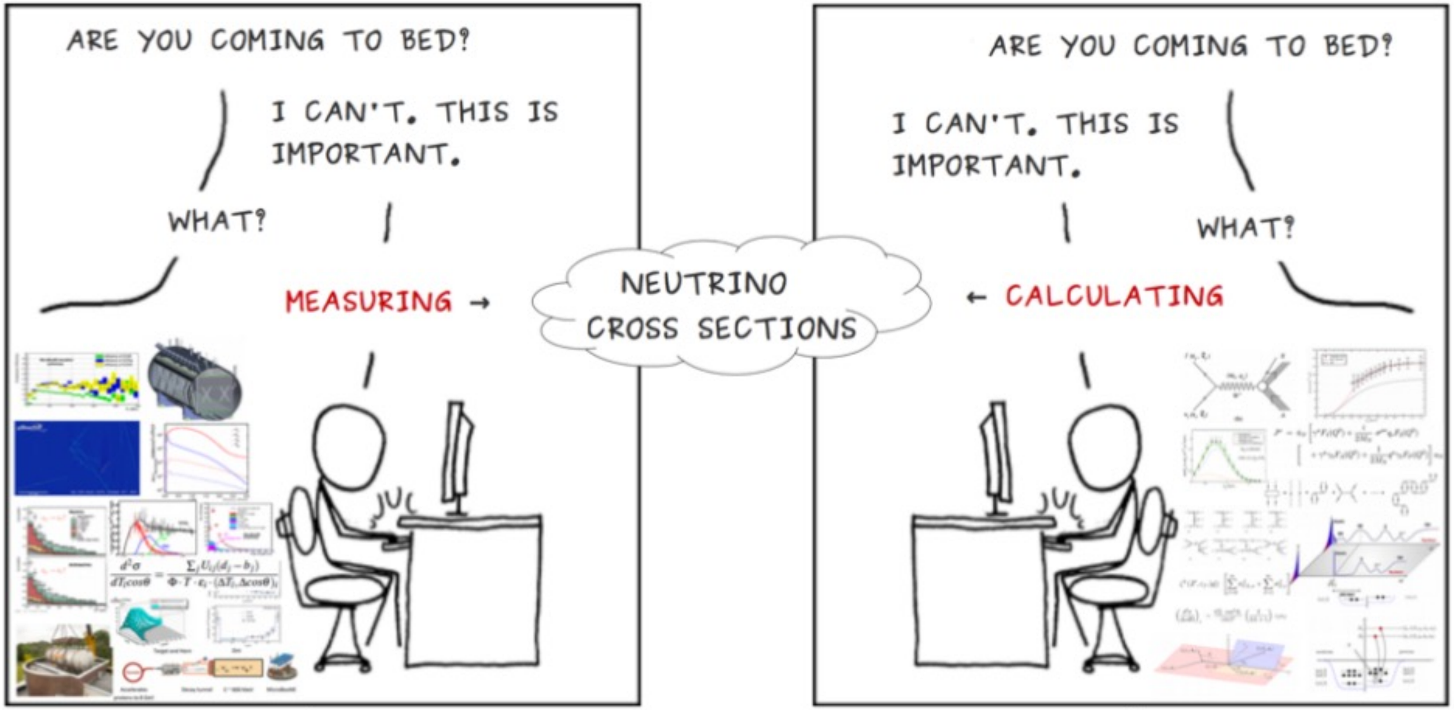
- Whilst we have a long way to go, we should not forget how far we have come!

> "Most of our knowledge of neutrino cross sections in [the 0.1-20 GeV energy range] comes from early experiments ... conducted in the 1970s and 1980s"
>
> Formaggio and Zeller, Rev. Mod. Phys. **84**, 1307, **2013**

- Continued collaboration between experimentalists, theorists and generator builders is crucial reach the level of precision demanded by DUNE and Hyper-K

The next steps …

Neutrino Experimentalist's Desk | **Nuclear Theorist's Desk**



- Need better models to reduce systematic uncertainties to eventually make precise measurements
- Need precise data to test and validate the assumptions and approximations to eventually improve the model

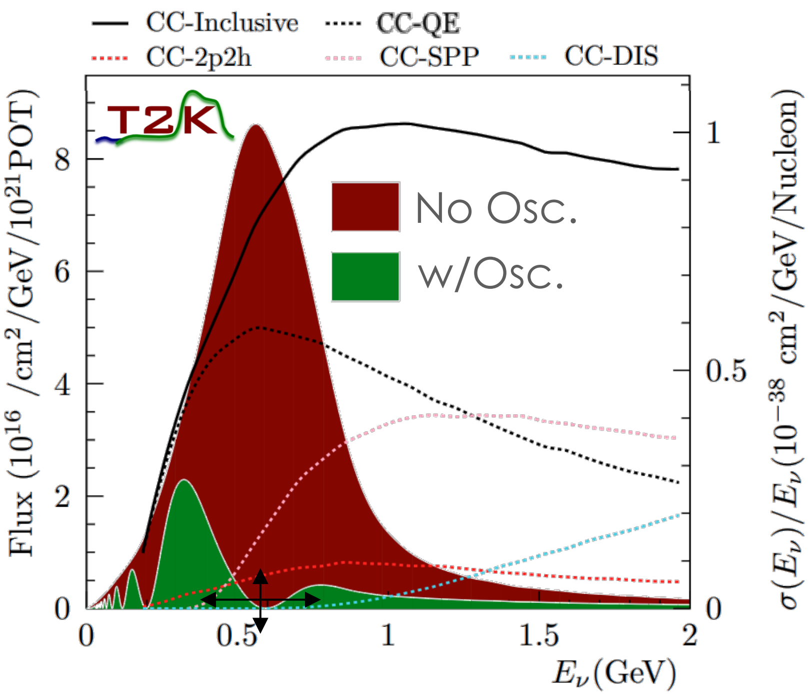
And they lived happily ever after…

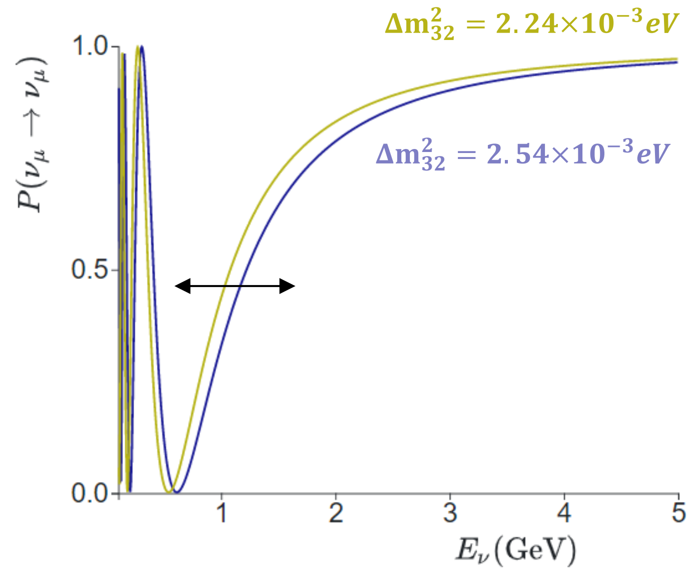
From Vishvas Pandey, [An overview of neutrino cross sections and challenges]

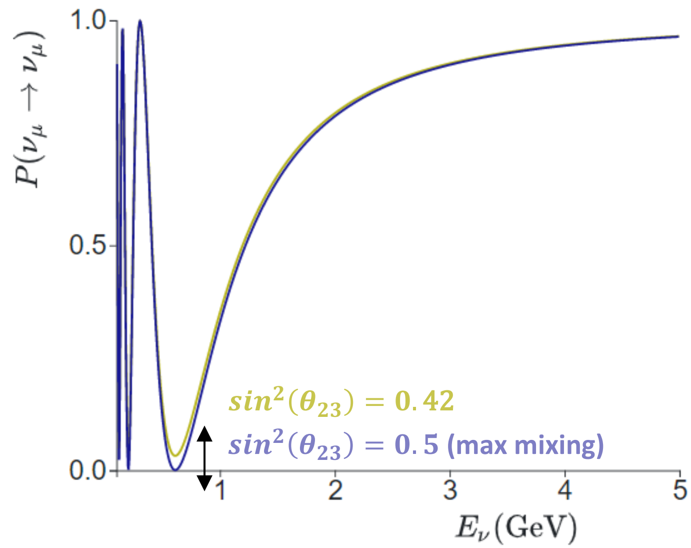
Backups

Event rates to oscillation parameters

- For a precision probe of oscillation parameters, reconstructing the shape of the oscillated spectrum is crucial

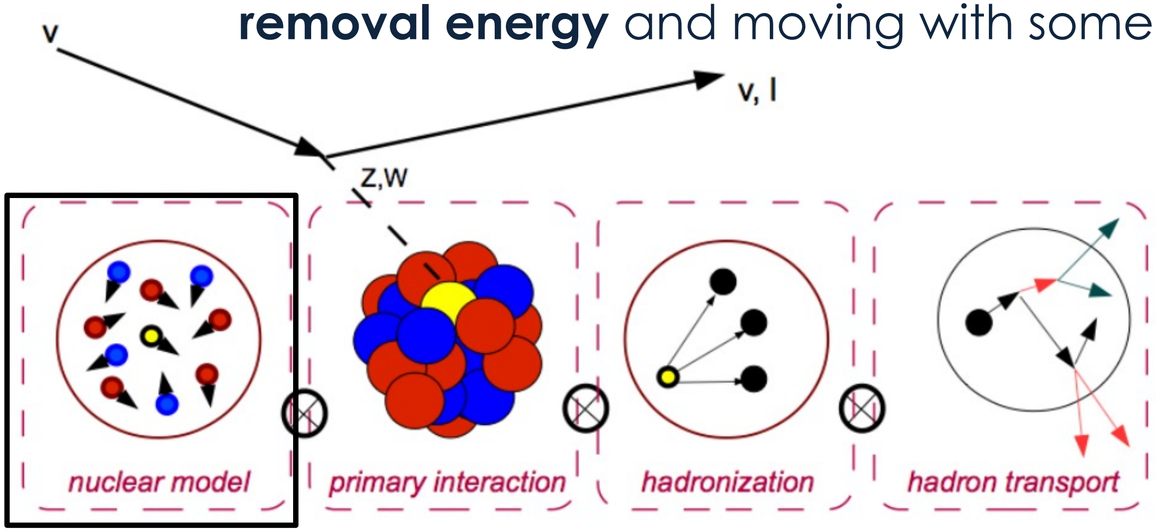


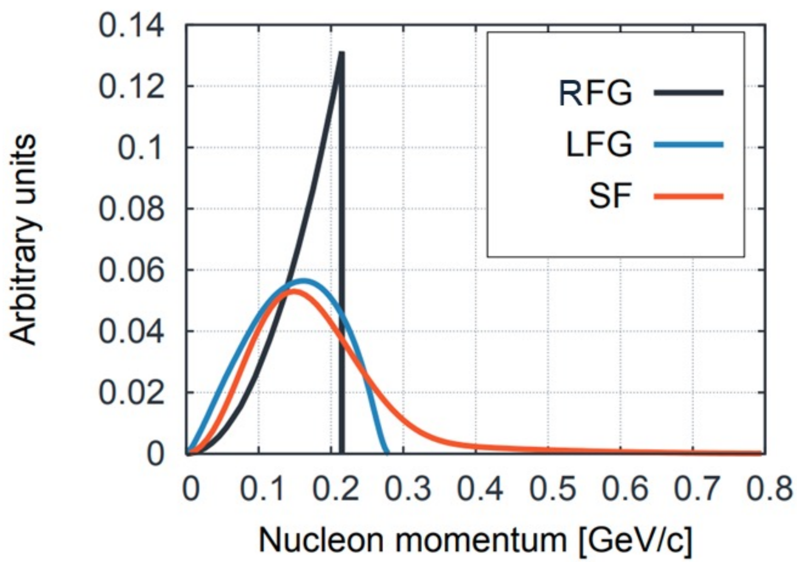




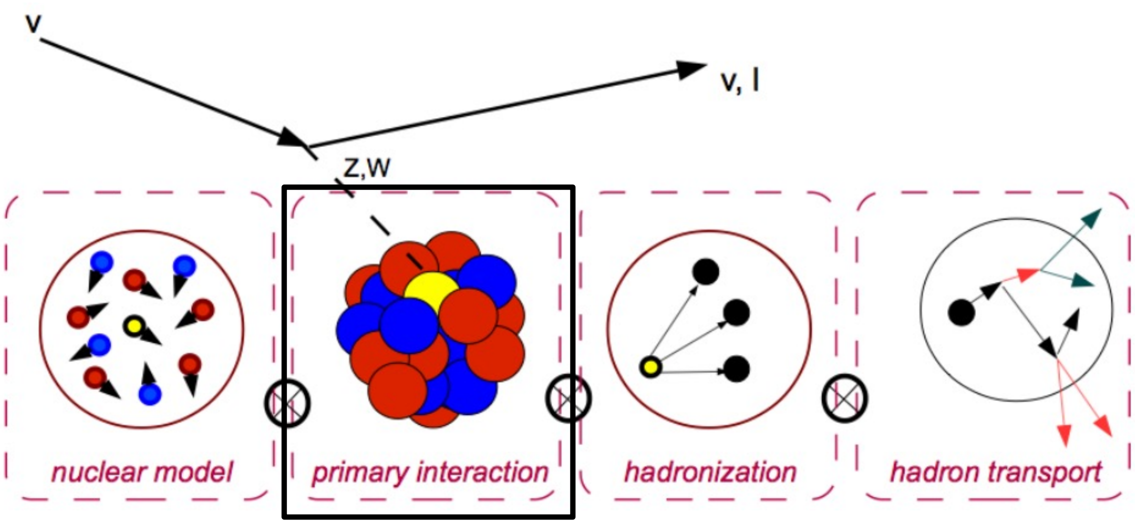
Fermi motion

- Start with a nucleon inside the nucleus, bound with some **removal energy** and moving with some **Fermi motion**



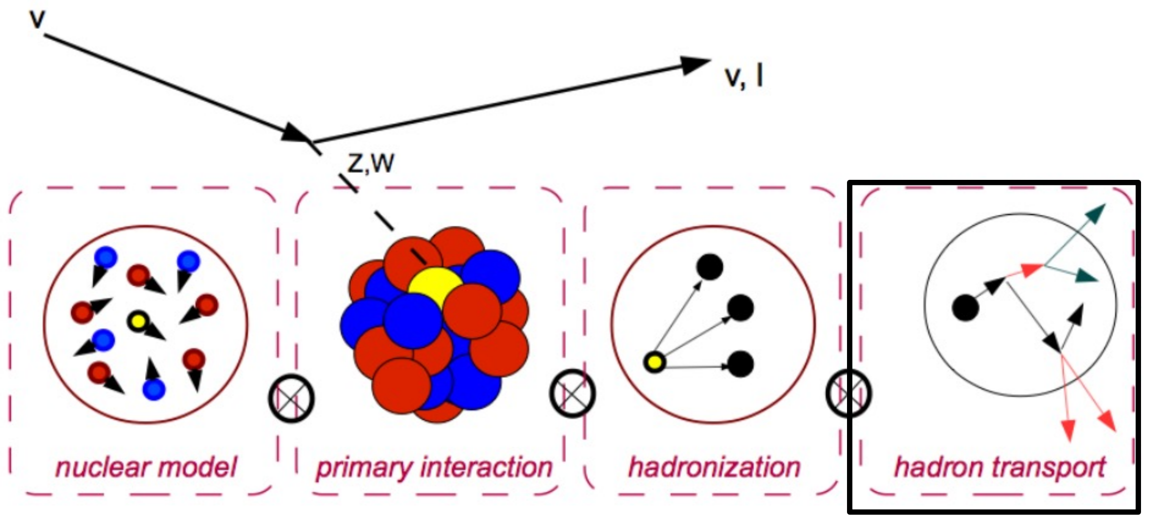


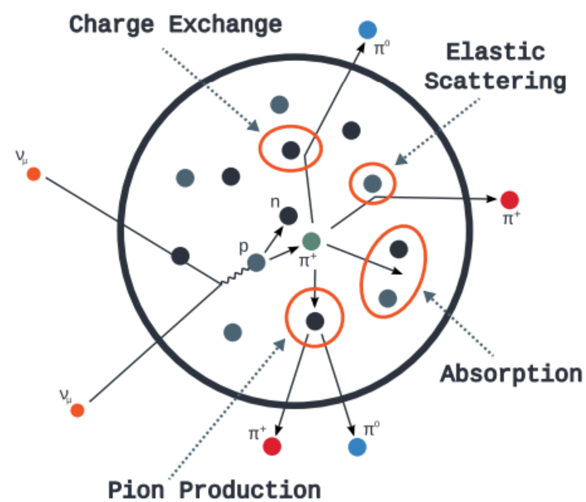
Neutrino-nucleon interaction



- We have a nucleon, now let's interact with it (usually treating it as if it was a free target)

Final state interactions



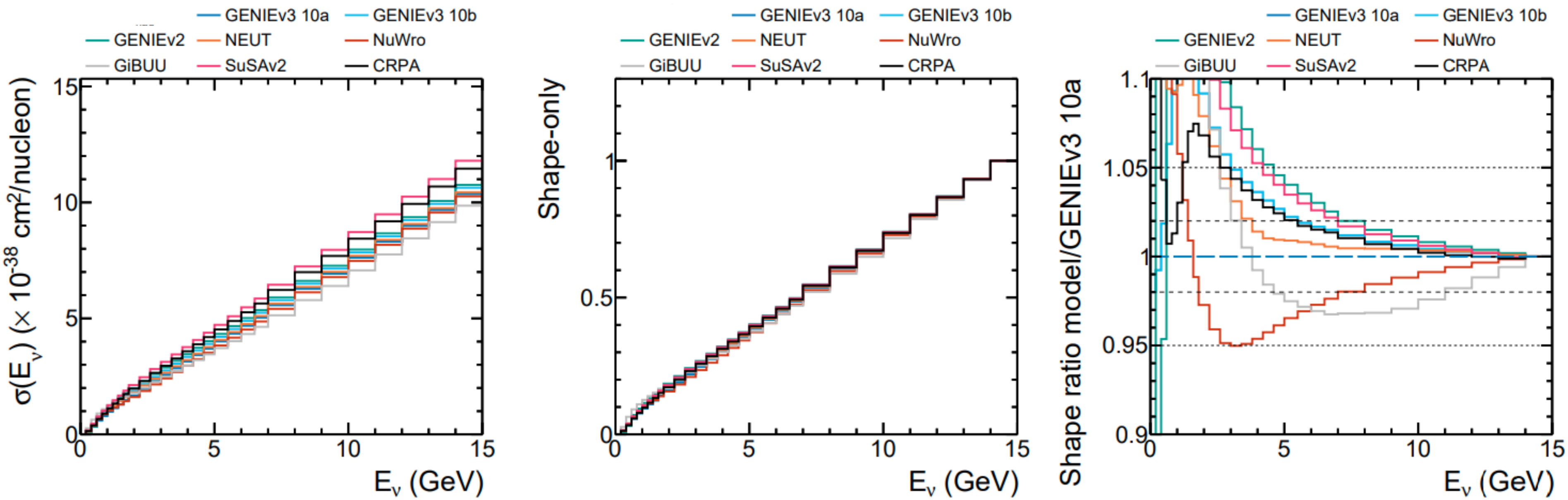


- We now have an outgoing nucleon inside the nucleus, it should be allowed to re-scatter before it gets out
- Such **Final State Interactions (FSI)** are simulated using semi-classical intranuclear cascade models

Energy dependence

Plots from
Wilkinson, Dolan, Pickering, Wret,
A substandard candle: the low-ν method at few-GeV neutrino energies
arXiv 2203.11821, accepted by EPJC

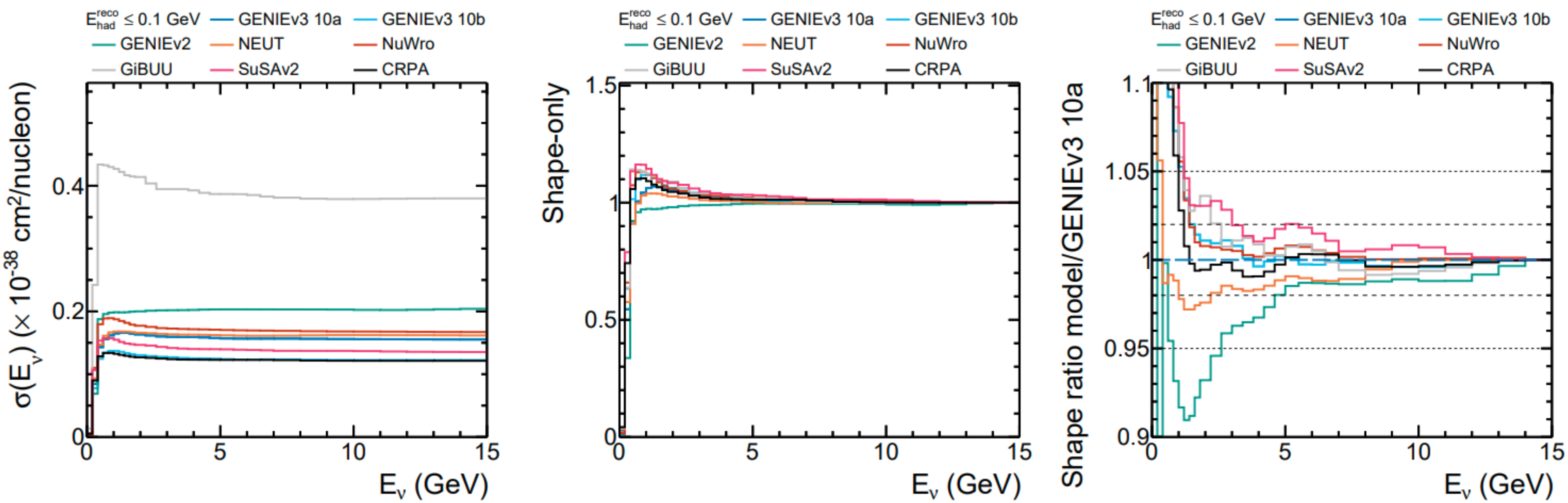
- What matters ND→FD extrapolation is the shape of total cross section as a function of E_ν
- Models differ by 5-10% in the region of interest for DUNE and Hyper-K



Energy dependence

Plots from
Wilkinson, Dolan, Pickering, Wret,
A substandard candle: the low-ν method at few-GeV neutrino energies
arXiv 2203.11821, accepted by EPJC

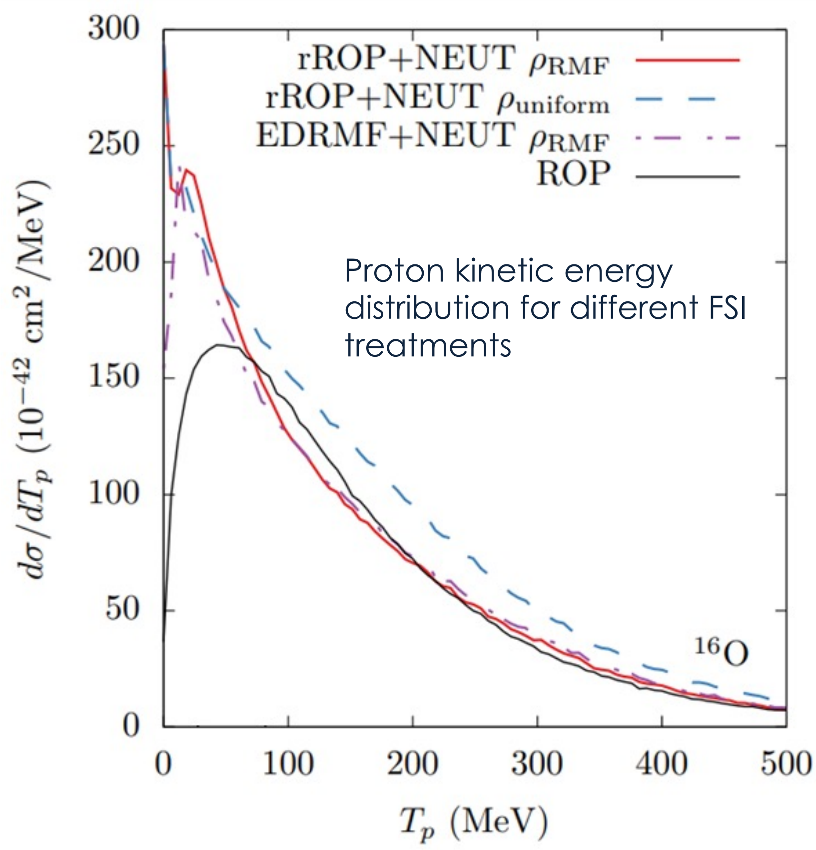
- What matters ND→FD extrapolation is the shape of total cross section as a function of E_ν
- Models differ by 5-10% in the region of interest for DUNE and Hyper-K
  - More when considering some specific regions of phase space



Impact on analyses

Plot from:
Nikolakopoulos et al., Phys. Rev. C **105**, 054603

- DUNE runs a study where it fits as data a model where **20% of final state proton energy** in its nominal model instead **goes into neutrons**
  - A **plausible consequence of alternative FSI models**
- At the same time, the cross section is altered to leave the proton momentum distribution unchanged
  - Another plausible change to the cross section model

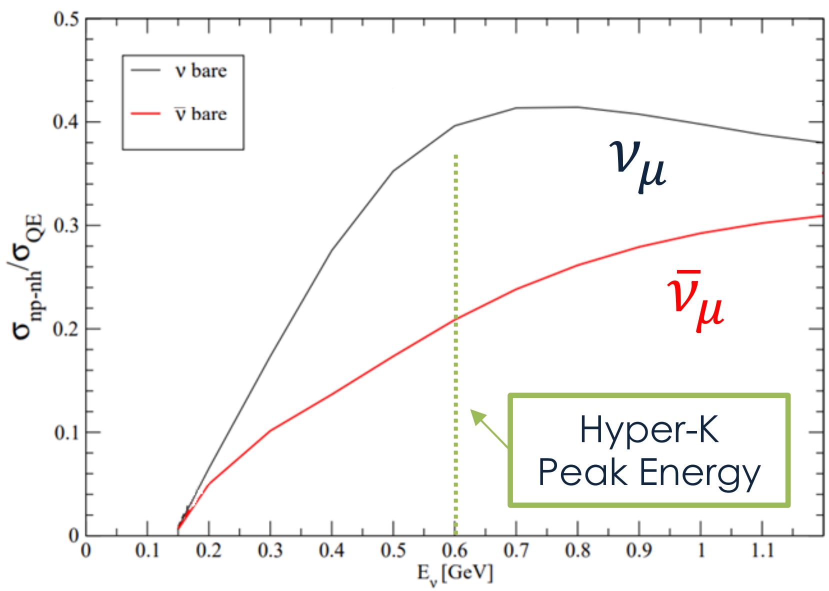


Neutrinos vs anti-neutrinos

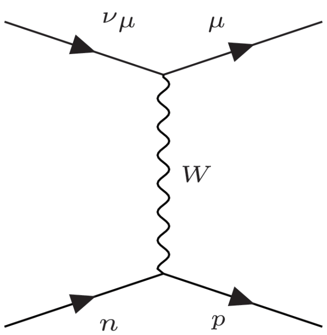
Plots from:
Martini et al.,
Phys. Rev. C **81**, 045502
Dolan et al.,
arXiv:2110.14601

See also:
Pandey et al.,
Phys. Rev. C **89**, 024601

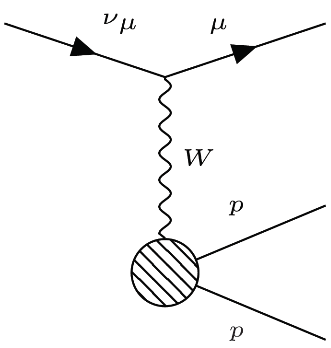
- Nuclear medium effects change the $\nu/\bar{\nu}$ ratio
  - 2p2h is expected to be much stronger for ν



CC-QE
(Charged-Current Quasi-Elastic)



CC-2p2h
(two-particle two-hole)



Neutrinos vs anti-neutrinos

Plots from:
Martini et al., Phys. Rev. C **81**, 045502
Dolan et al., arXiv:2110.14601

See also:
Pandey et al., Phys. Rev. C **89**, 024601

- Nuclear medium effects change the $\nu/\bar{\nu}$ ratio
  - 2p2h is expected to be much stronger for ν
  - RPA effects make further alterations

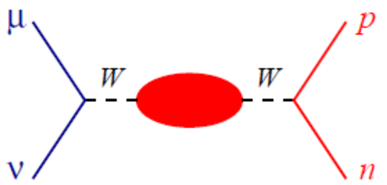
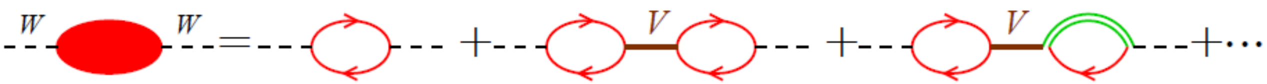
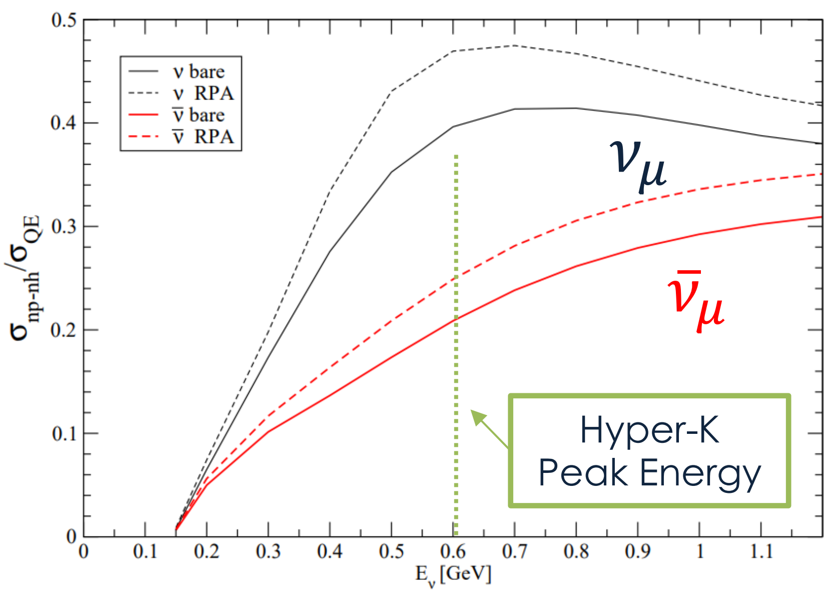


Figure from L. Alvarez-Ruso et al., https://doi.org/10.1063/1.3274146



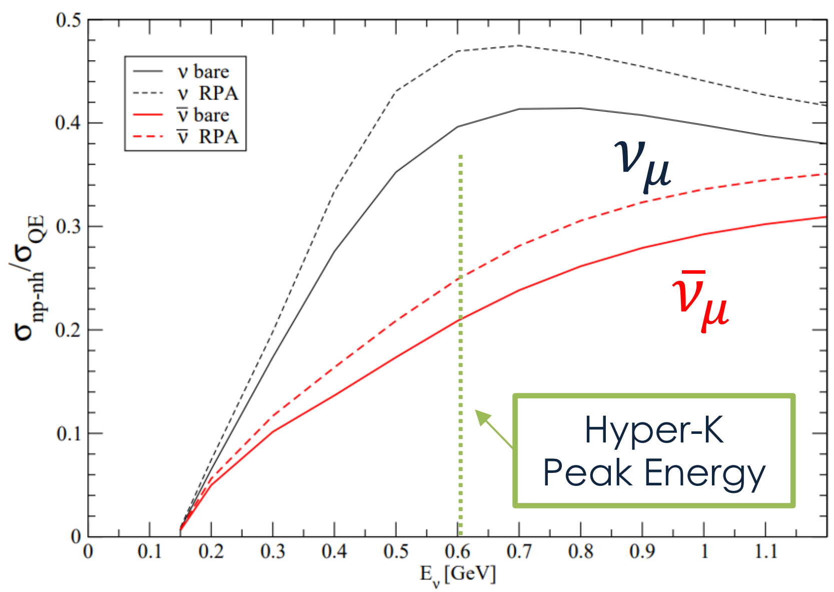


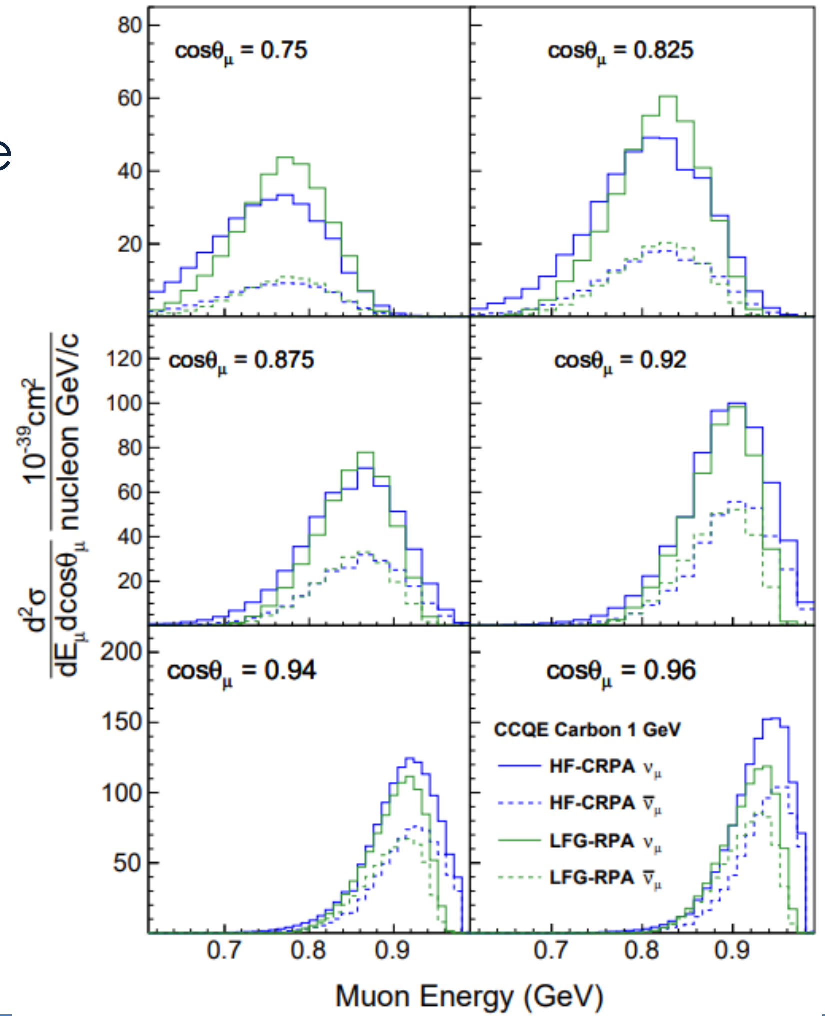
Neutrinos vs anti-neutrinos

Plots from:
Martini et al., Phys. Rev. C **81**, 045502
Dolan et al., arXiv:2110.14601

See also:
Pandey et al., Phys. Rev. C **89**, 024601

- Nuclear medium effects change the $\nu/\bar{\nu}$ ratio
  - 2p2h is expected to be much stronger for ν
  - RPA effects make further alterations
- The ratio is sensitive to the details of the modelling of each effect



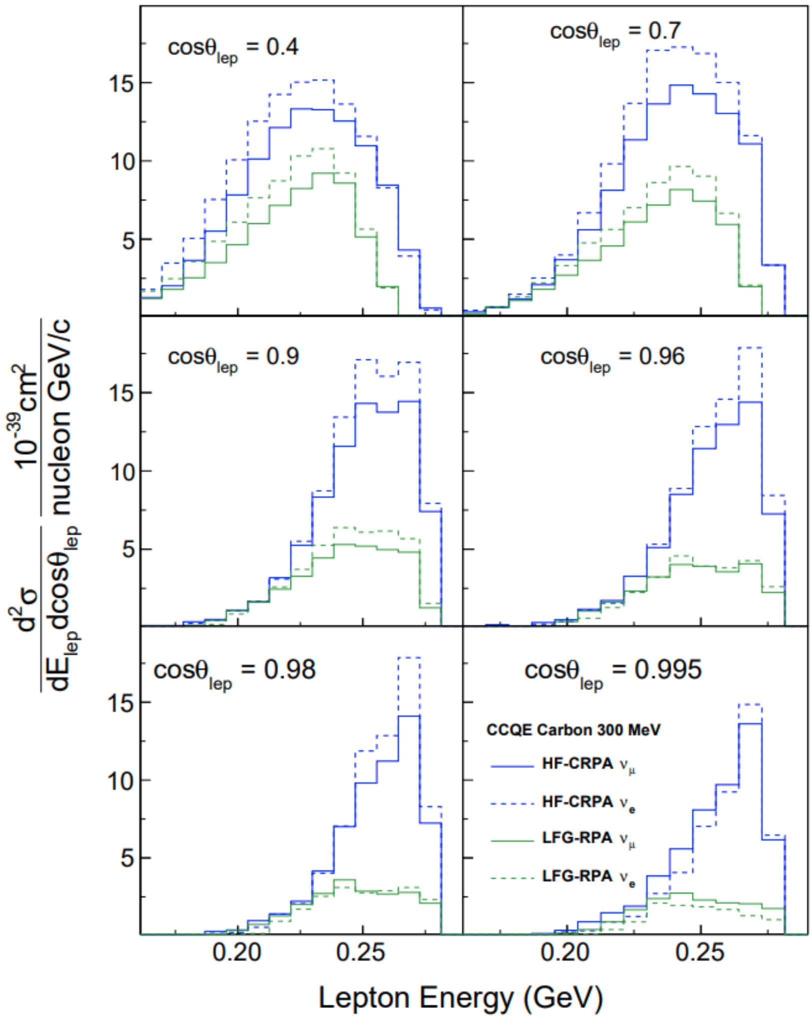


Electron vs muon neutrinos

Plots from:
Dolan et al.,
arXiv:2110.14601

See also:
Nikolakopoulos et al.,
PRL **123**, 052501

- Nuclear medium effects change the ν_e/ν_μ ratio
  - Changes the cross section close to phase space boundaries



Electron vs muon neutrinos

Additional few-% uncertainty related to **radiative corrections** to the cross section (and the potential impact of outgoing photons on event selections)
See: arXiv:2105.07939