CP-Violation or Nuclear Excitation?

The crucial role of neutrino-nucleus interaction modelling in neutrino oscillation measurements

Stephen Dolan

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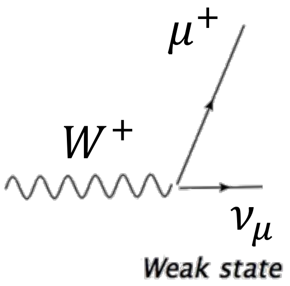
Overview

- **Neutrino Oscillations**
- Accelerator-Based Experiments
- $\boldsymbol{\nu}$ Interactions for $\boldsymbol{\nu}$ Oscillations
- Reconstructing Neutrino Energy
- The Path to Precision Measurements

Neutrino Oscillations

- Neutrinos are **produced** in particular weak eigenstates $(\nu_e, \nu_\mu, \nu_\tau)$



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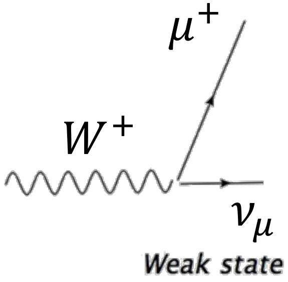

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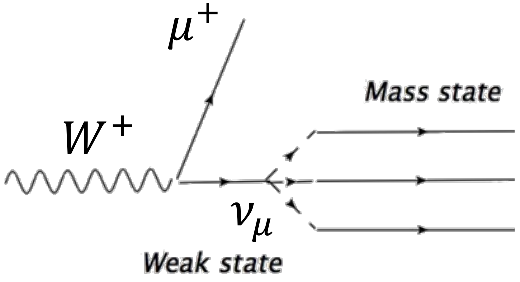

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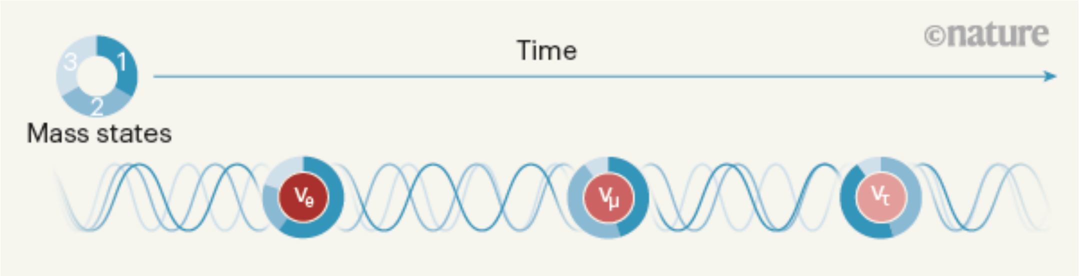

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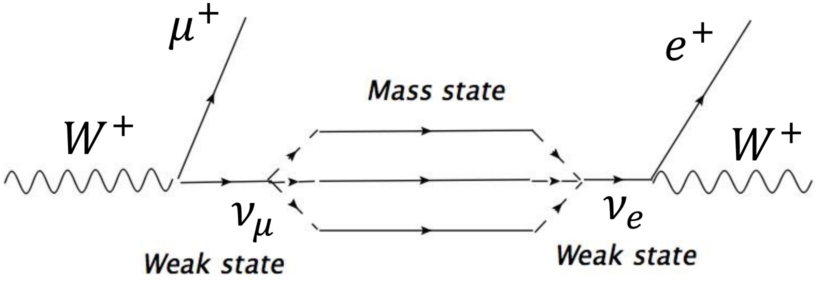

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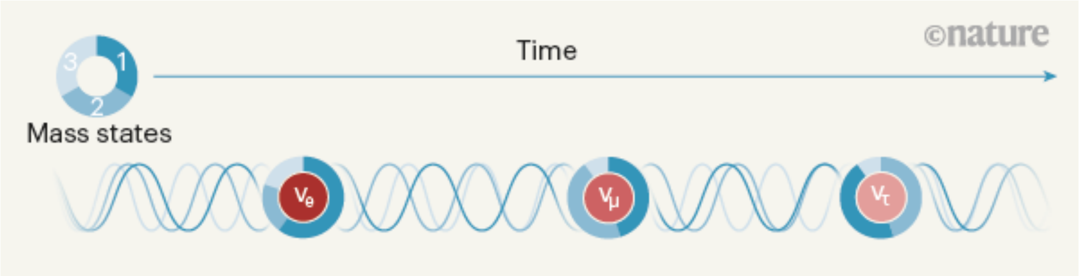

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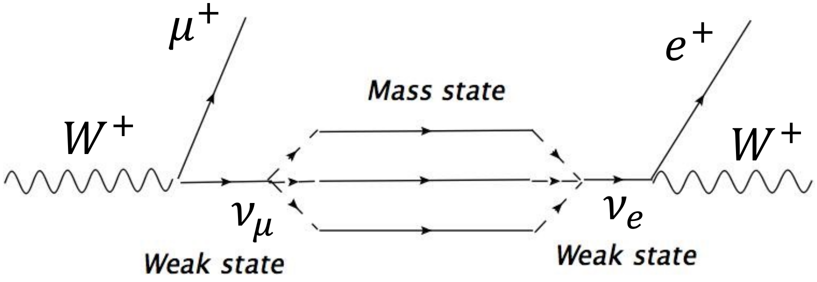

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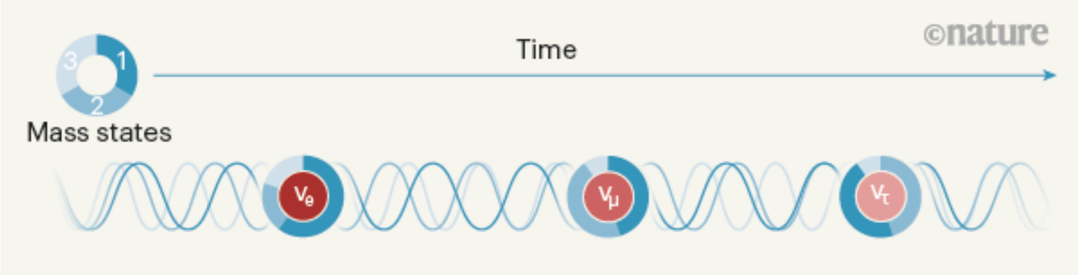
➡ The probability of finding a neutrino as a particular flavour "*oscillates*" as its mass states evolve



Neutrino Oscillations

- The oscillation probability depends on:
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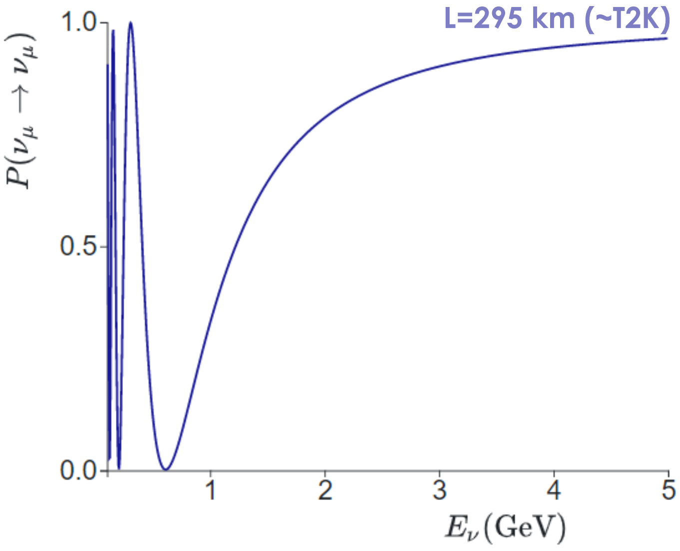

Two-flavour mixing

$$p_{\nu_\alpha \to \nu_\alpha} = 1 - \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 \boxed{L}}{\boxed{E_\nu}}\frac{[eV^2][km]}{[GeV]}\right)$$

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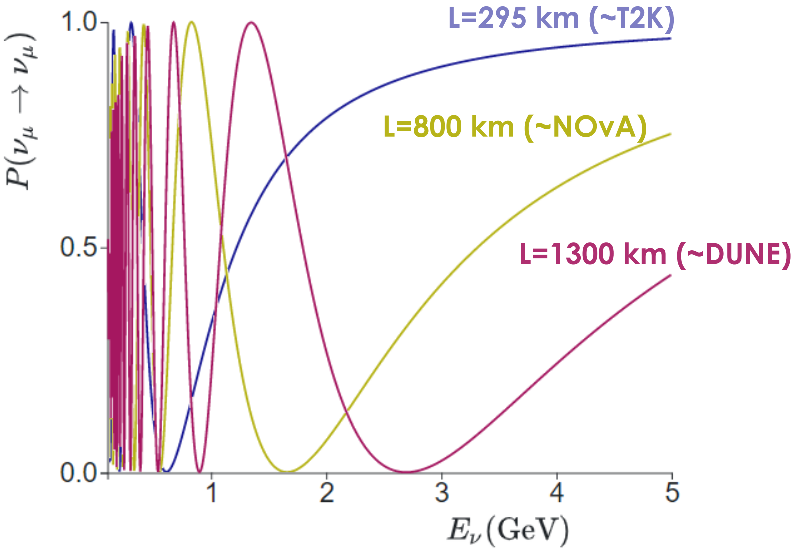

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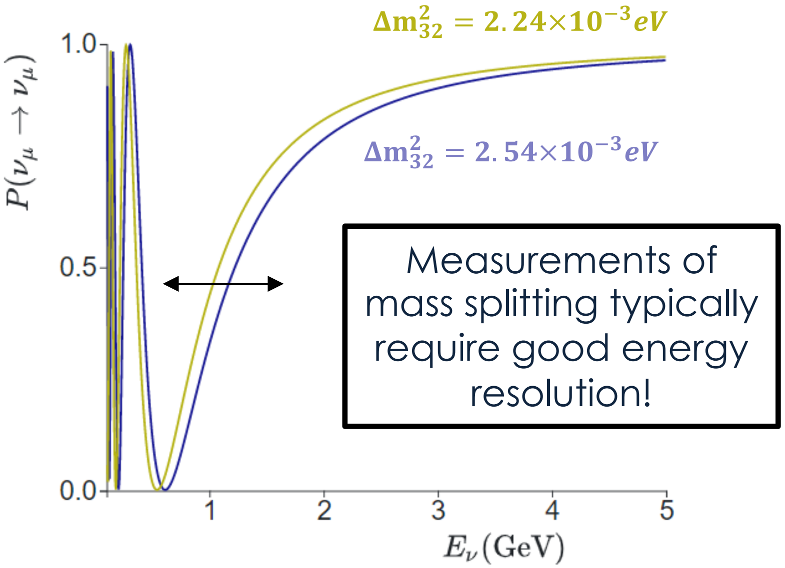

Measurements of mass splitting typically require good energy resolution!

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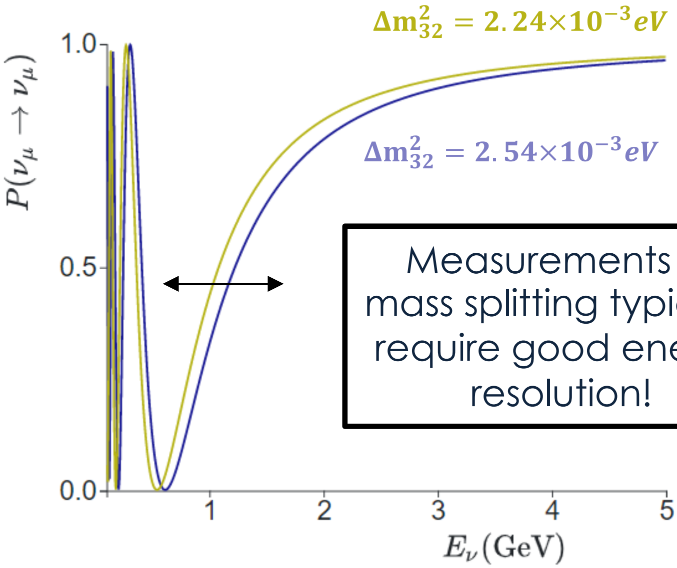

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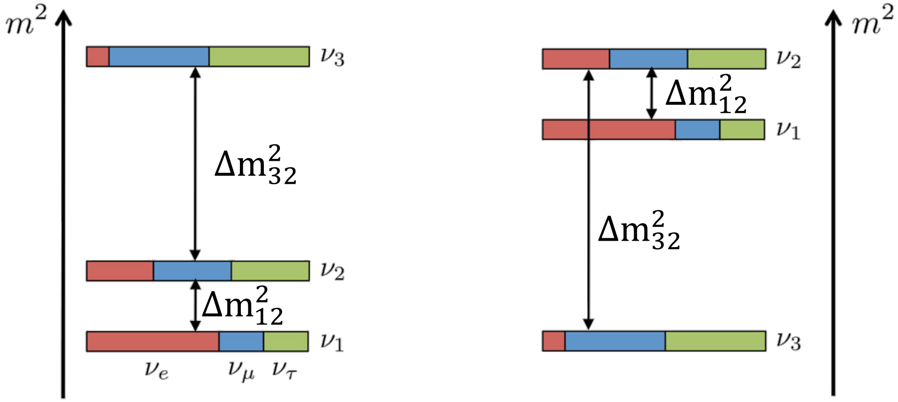
Normal Ordering (NO) **Inverted Ordering (NO)**



- Neutrino oscillations in a vacuum are, to first order, sensitive only to the square of the mass splittings.
- We don't yet know the right "ordering"

Neutrino Oscillations

- The oscillation probability depends on:
  - The neutrino energy
  - The travelled distance (“baseline”)
  - The difference in masses of ν_1, ν_2, ν_3
  - The mixing parameters

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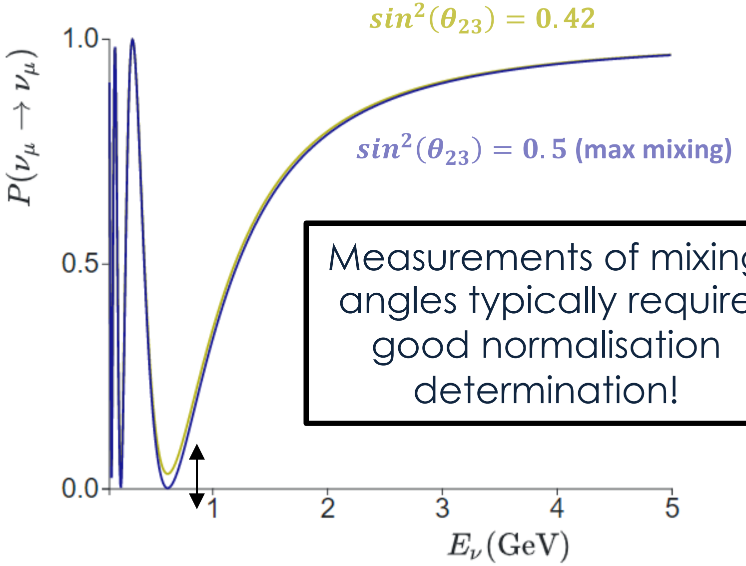
$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$



Measurements of mixing angles typically require good normalisation determination!

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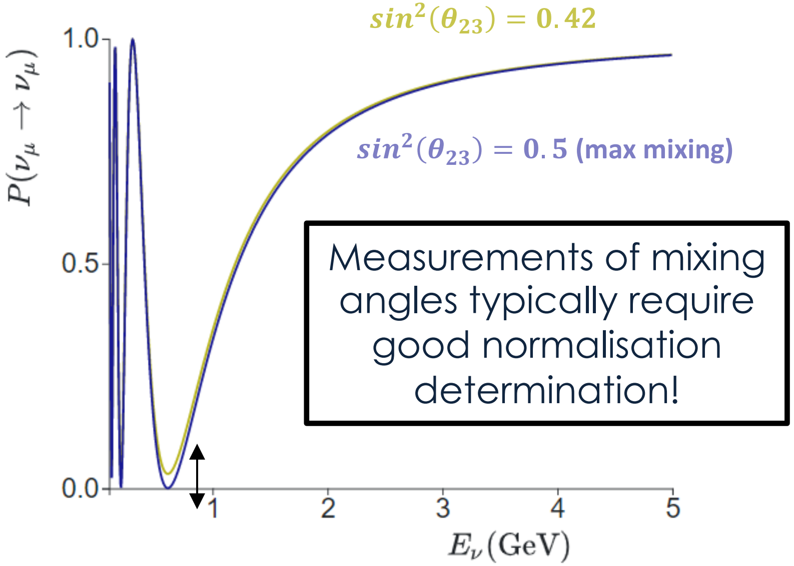

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Three-flavour mixing

$$P_{\alpha\rightarrow\beta} = |\langle \nu_\beta(t)|\nu_\alpha\rangle|^2 = \left|\sum_i \boxed{U^*_{\alpha i} U_{\beta i}} e^{-im_i^2 L/2E}\right|^2$$

$$U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

$s_{ij} = \sin \theta_{ij}$
$c_{ij} = \cos \theta_{ij}$

- Three mixing angles: $\theta_{12}, \theta_{13}, \theta_{23}$

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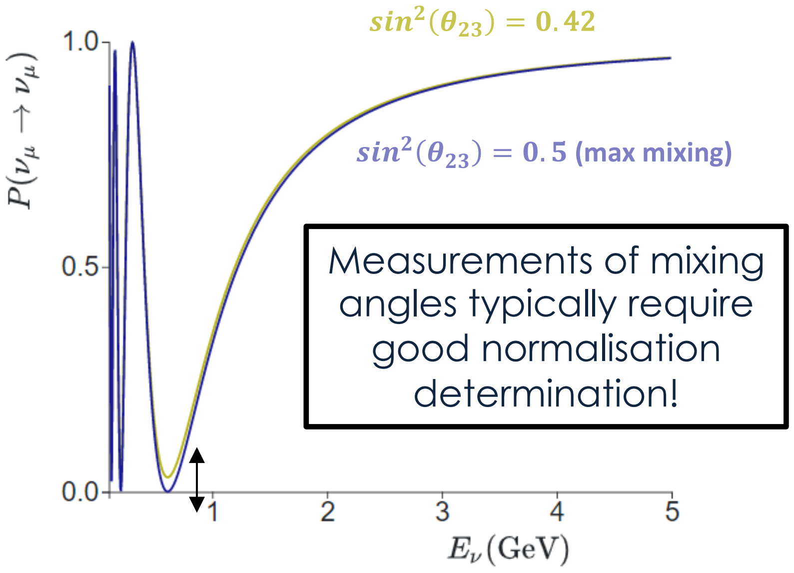

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Predominantly from KamLAND reactor neutrino experiment

From reactor experiments (e.g. Daya Bay) and from measuring $P(\nu_\mu \rightarrow \nu_e)$

Measuring $P(\nu_\mu \rightarrow \nu_\mu)$

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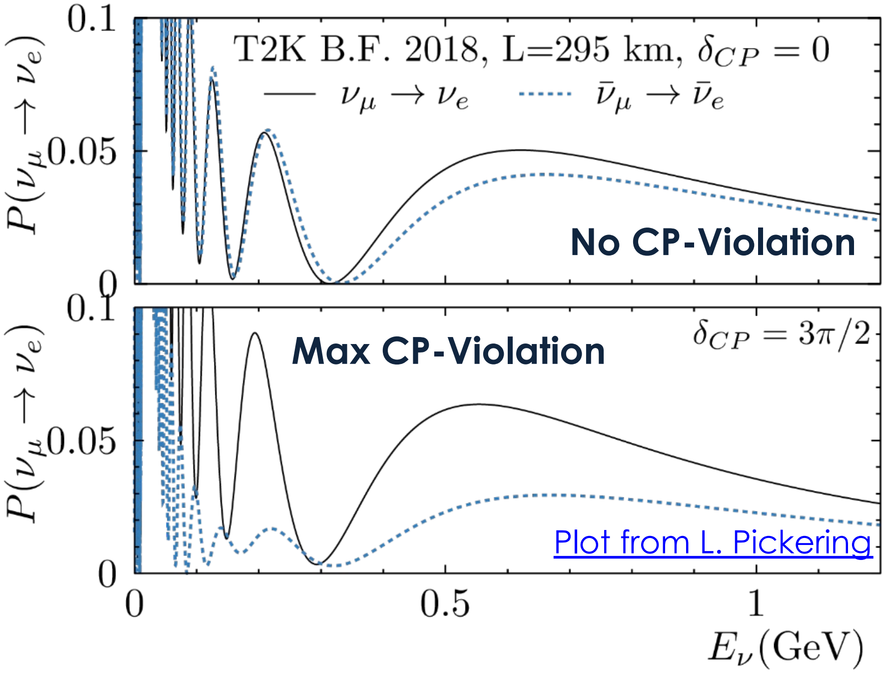

Plot from L. Pickering

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$s_{ij} = \sin \theta_{ij}$
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- Three mixing angles: $\theta_{12}, \theta_{13}, \theta_{23}$
- One CP-Violating phase: δ_{CP}

Required to have a difference between neutrino and anti-neutrino vacuum oscillations

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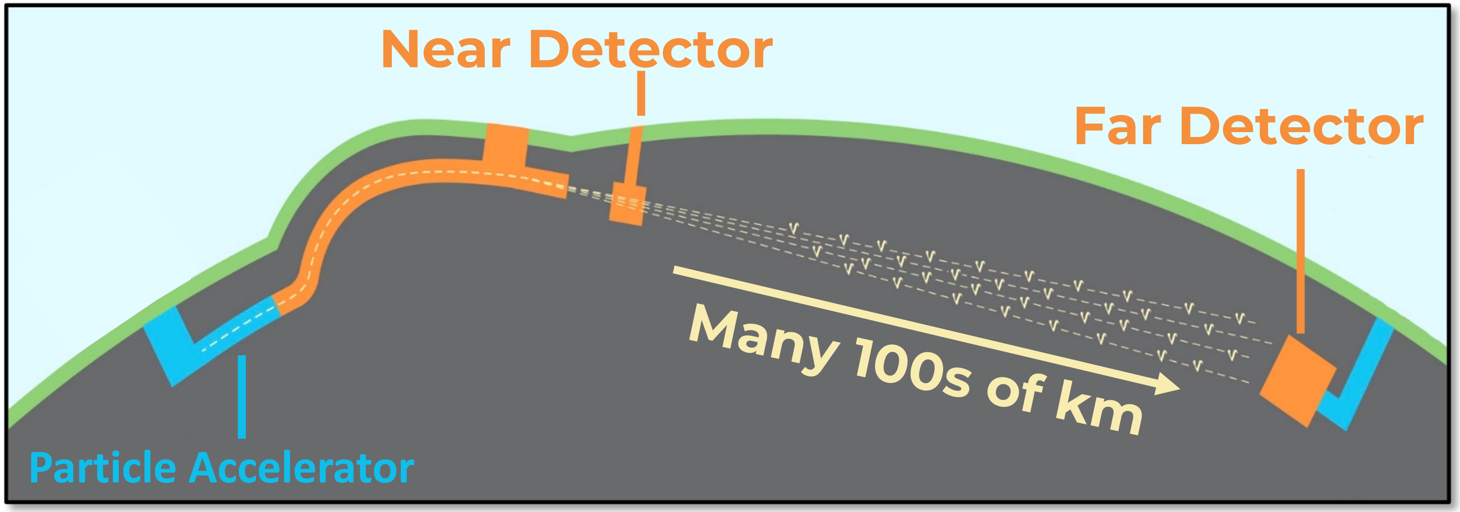
Accelerator-Based Experiments



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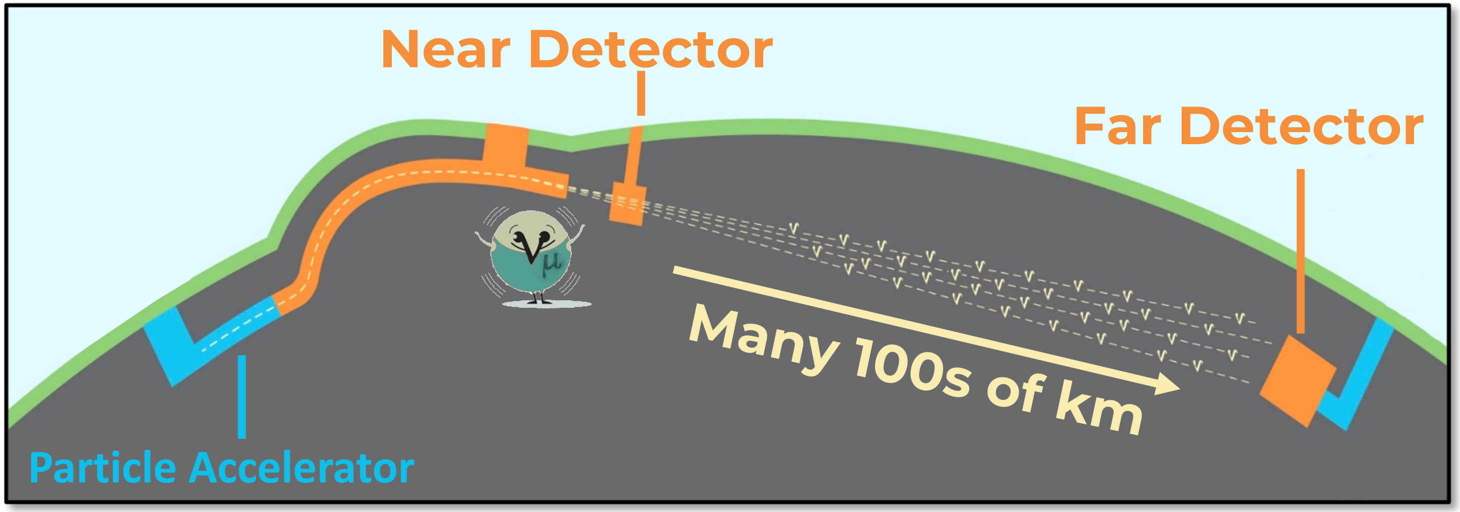

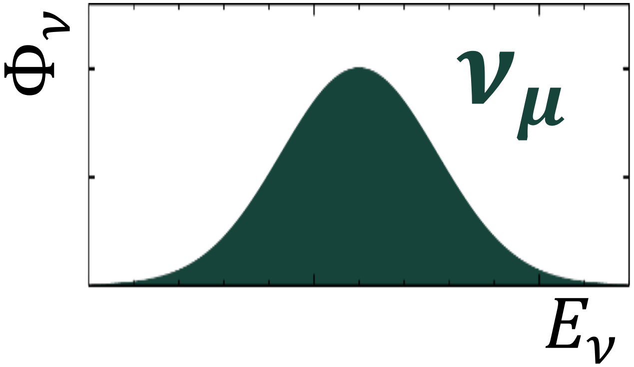

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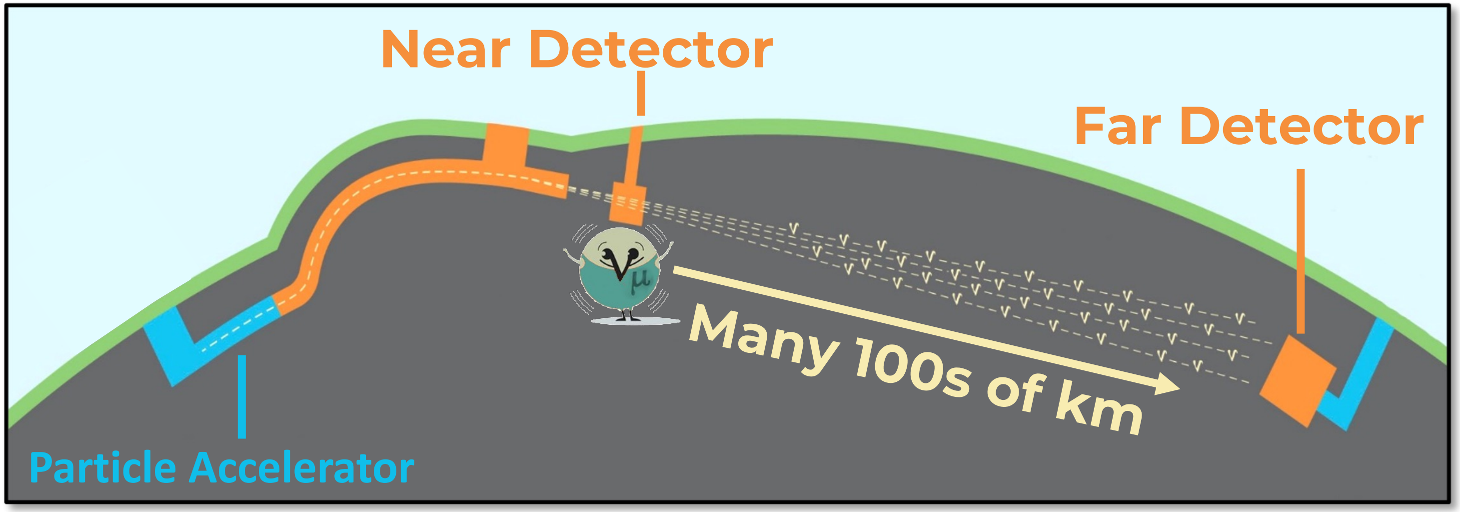
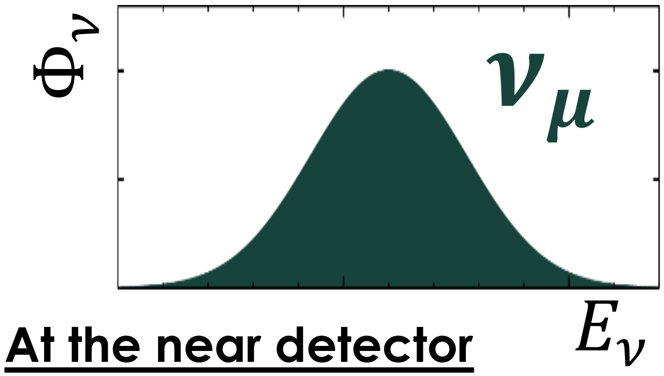
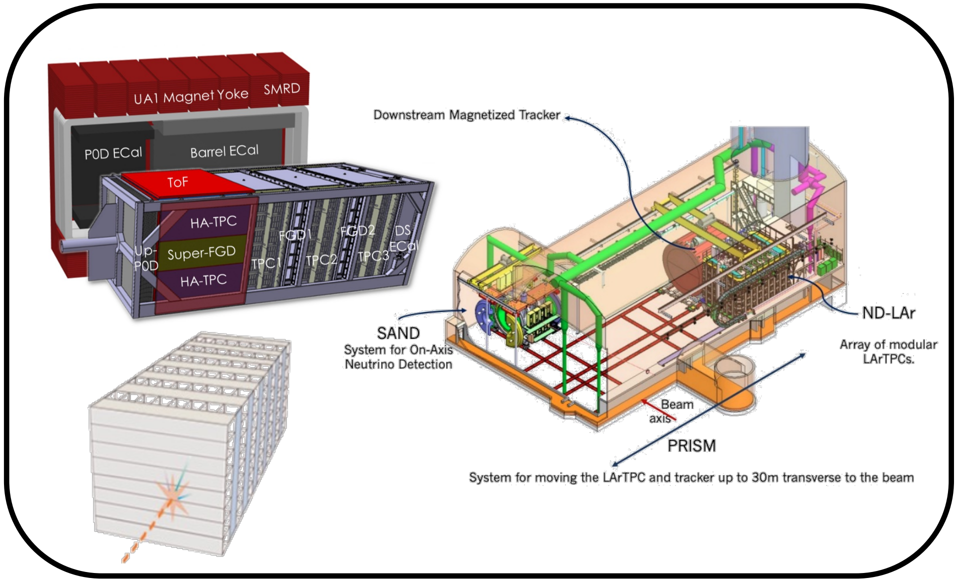






At the near detector

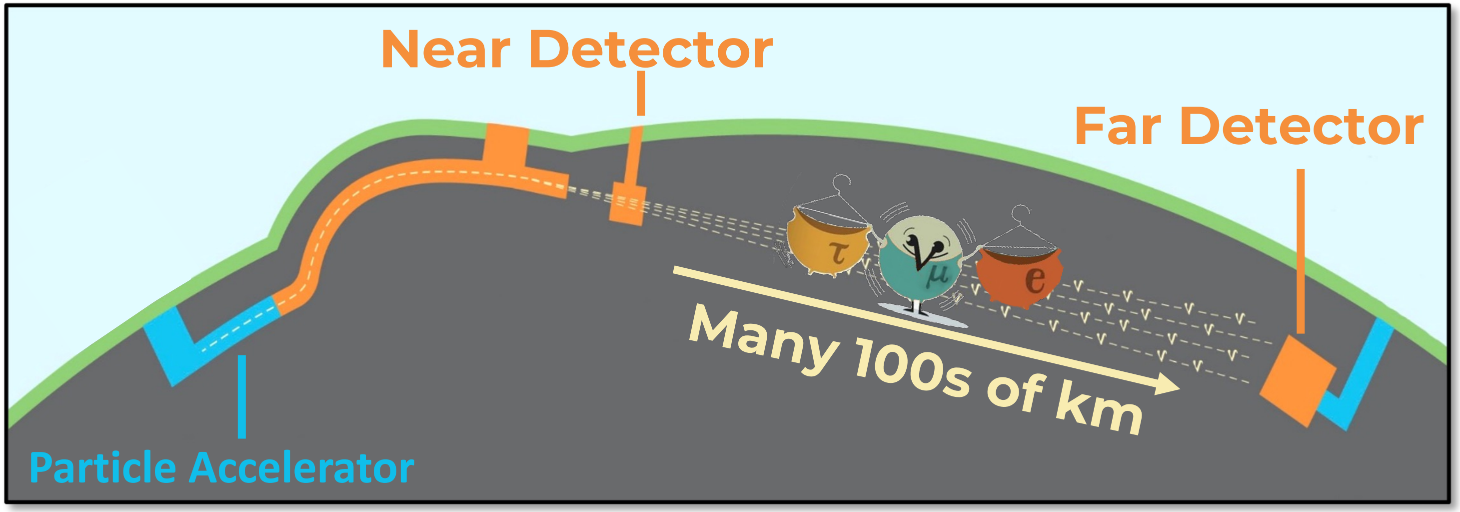
$$N_\mu(E_\nu) = \sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

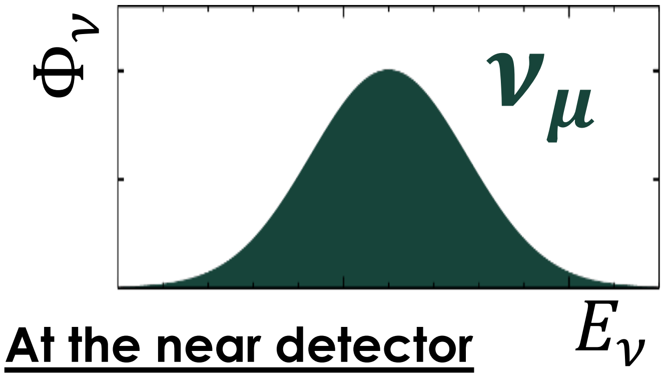
Interaction cross section

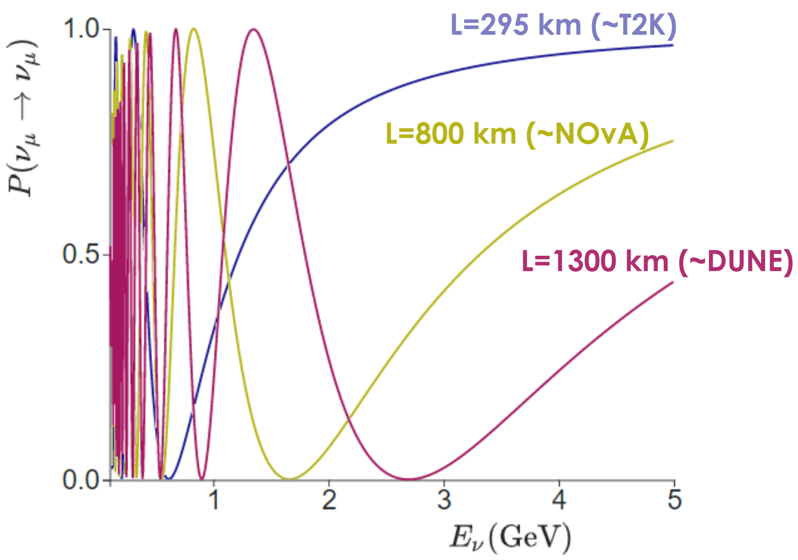
Neutrino flux

Detector effects

Accelerator-Based Experiments







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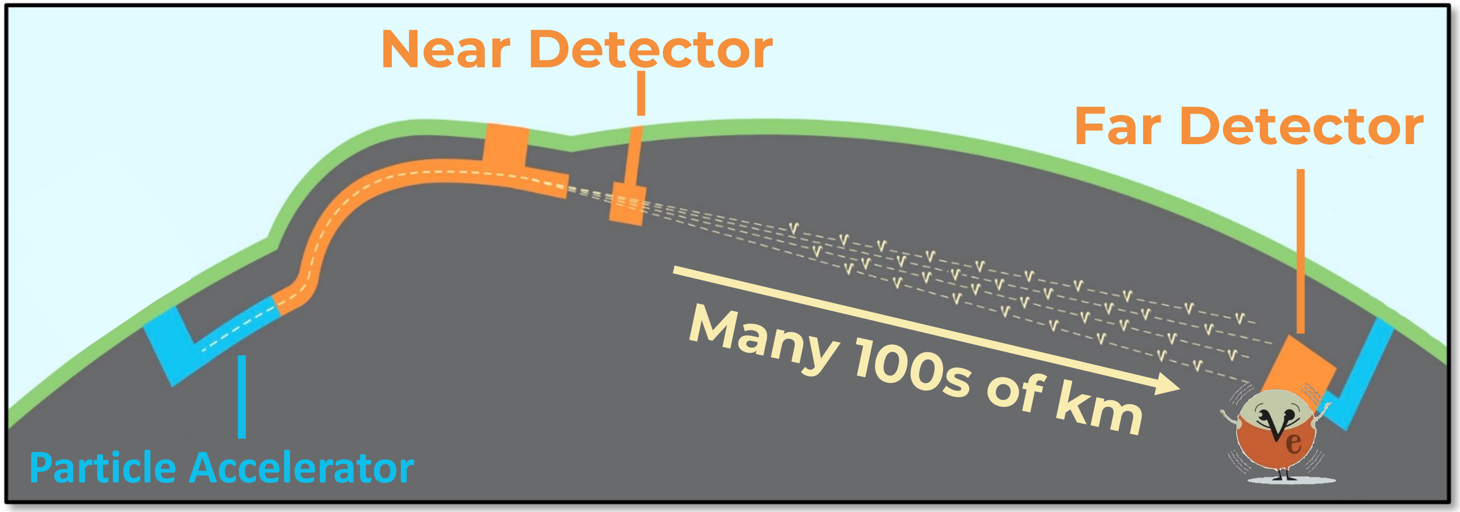

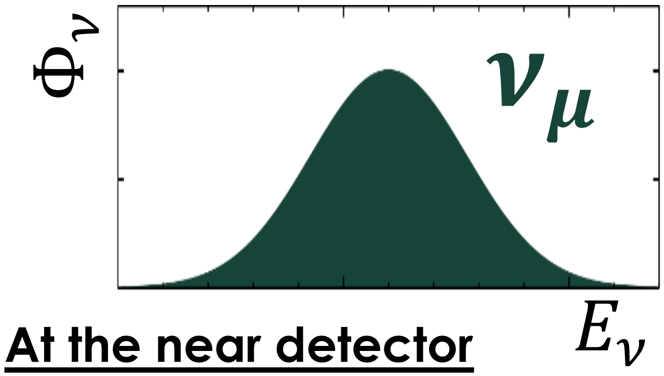

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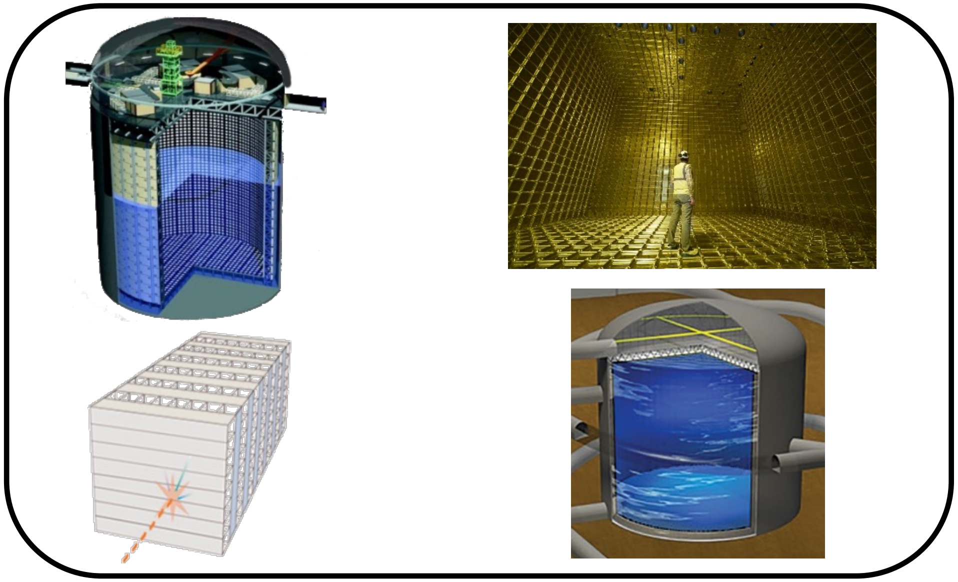

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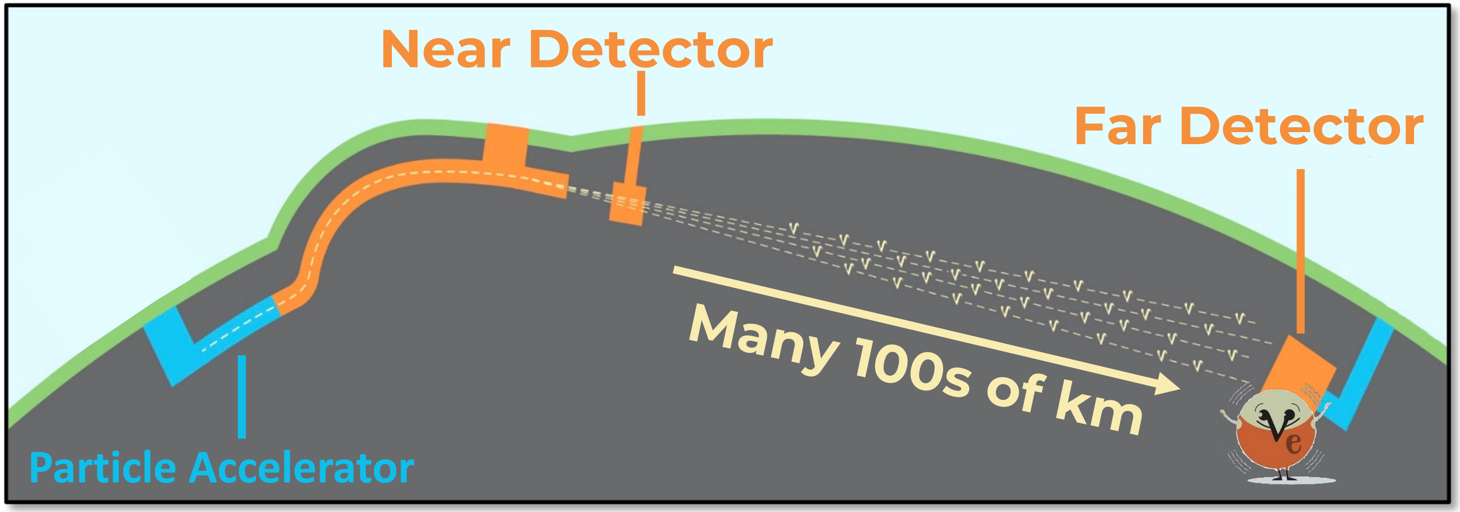

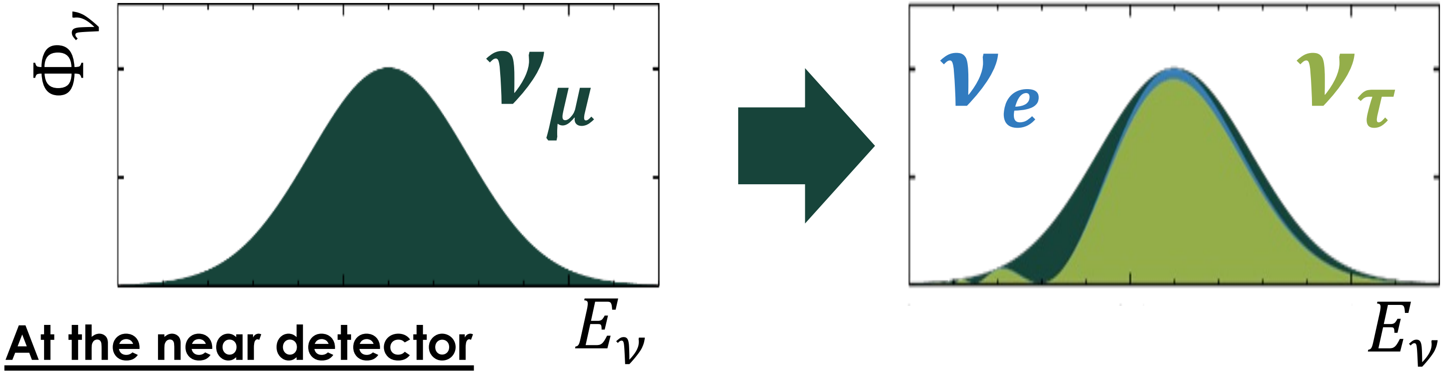

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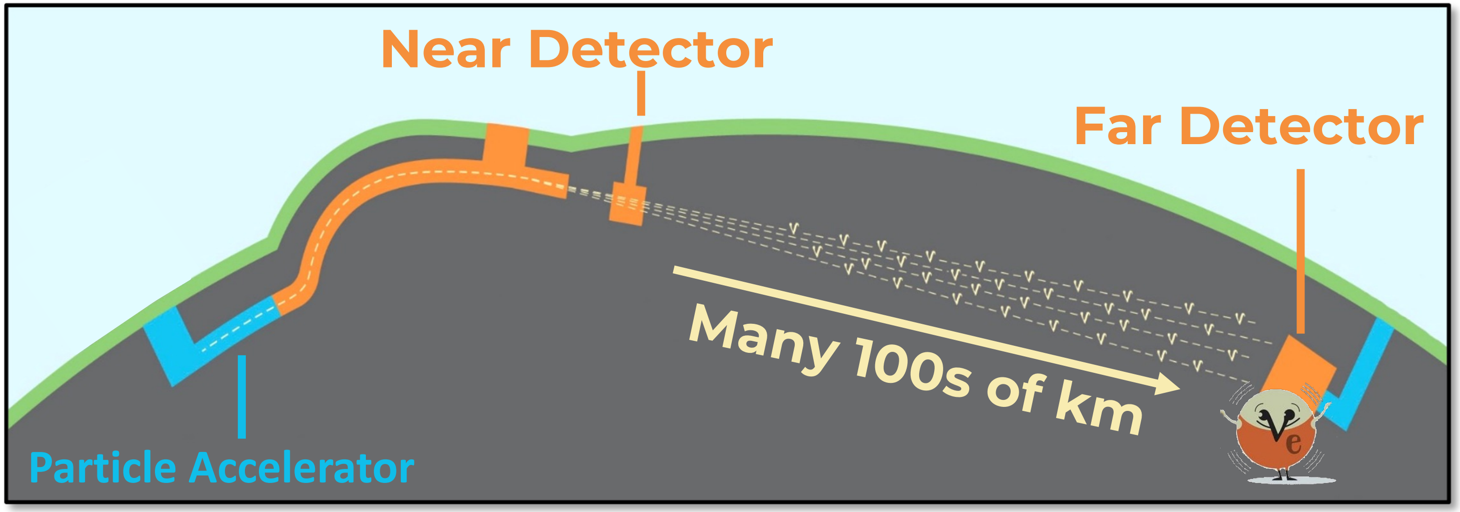

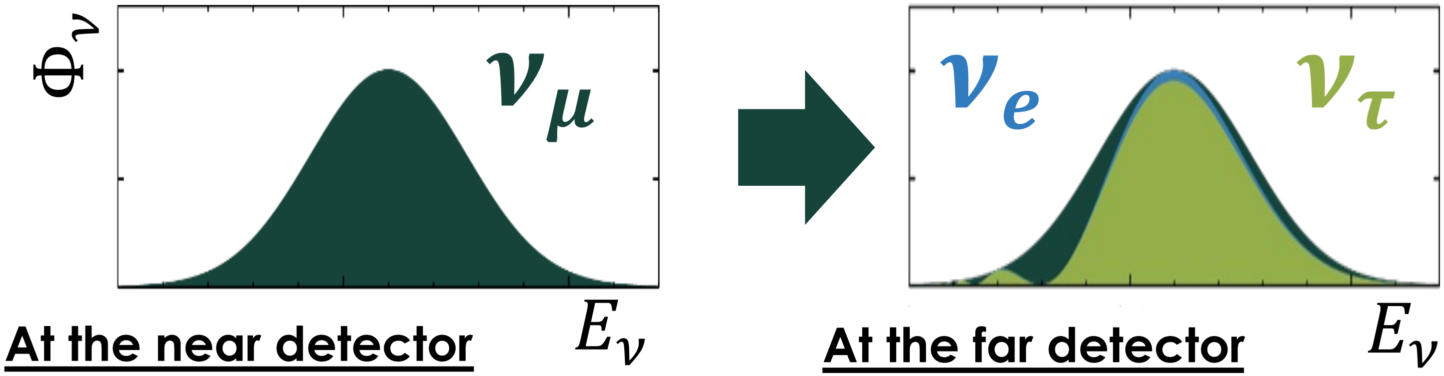

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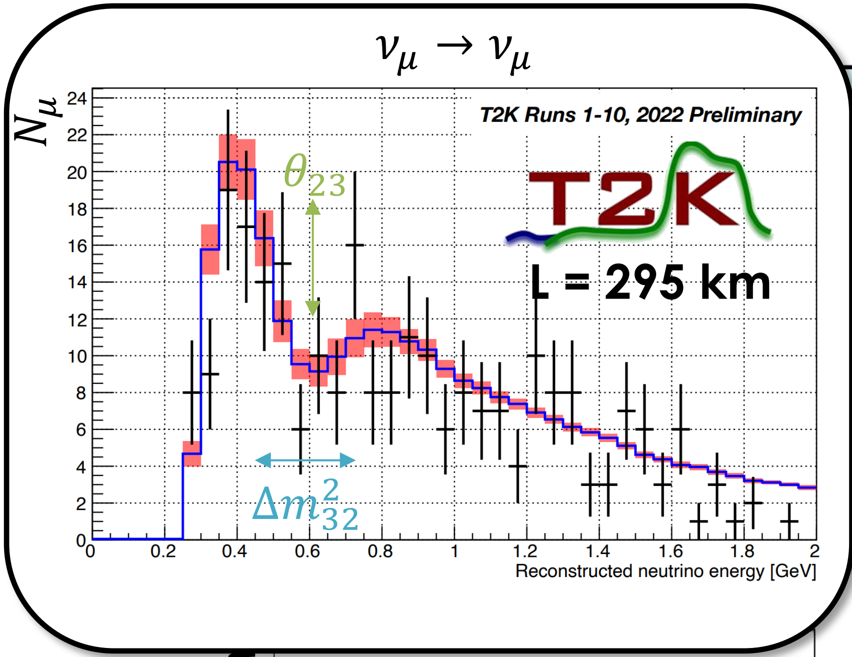
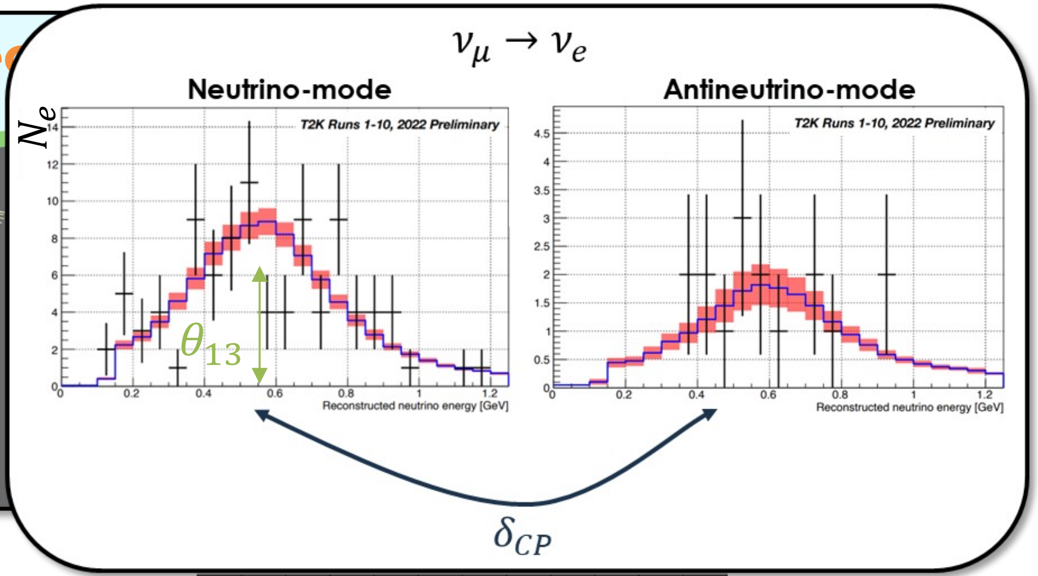
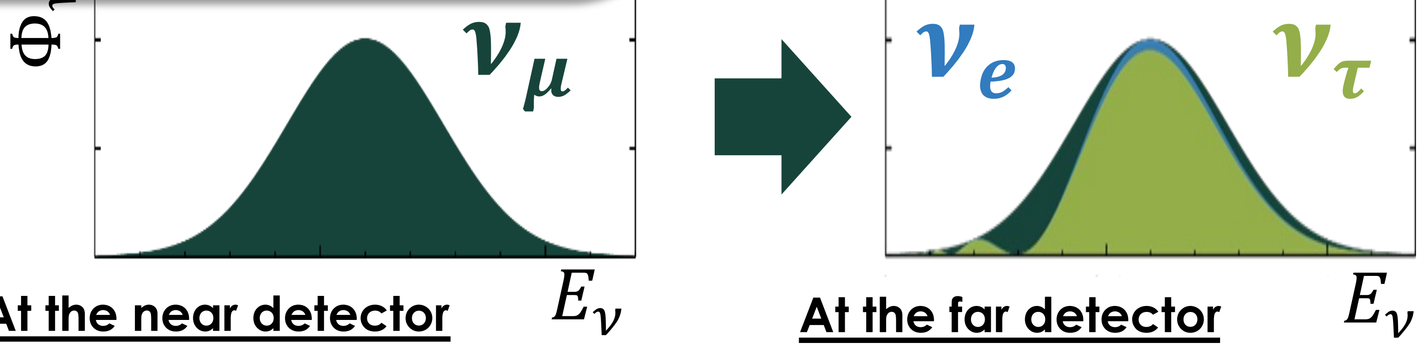
Oscillation probability

Accelerator-Based Experiments







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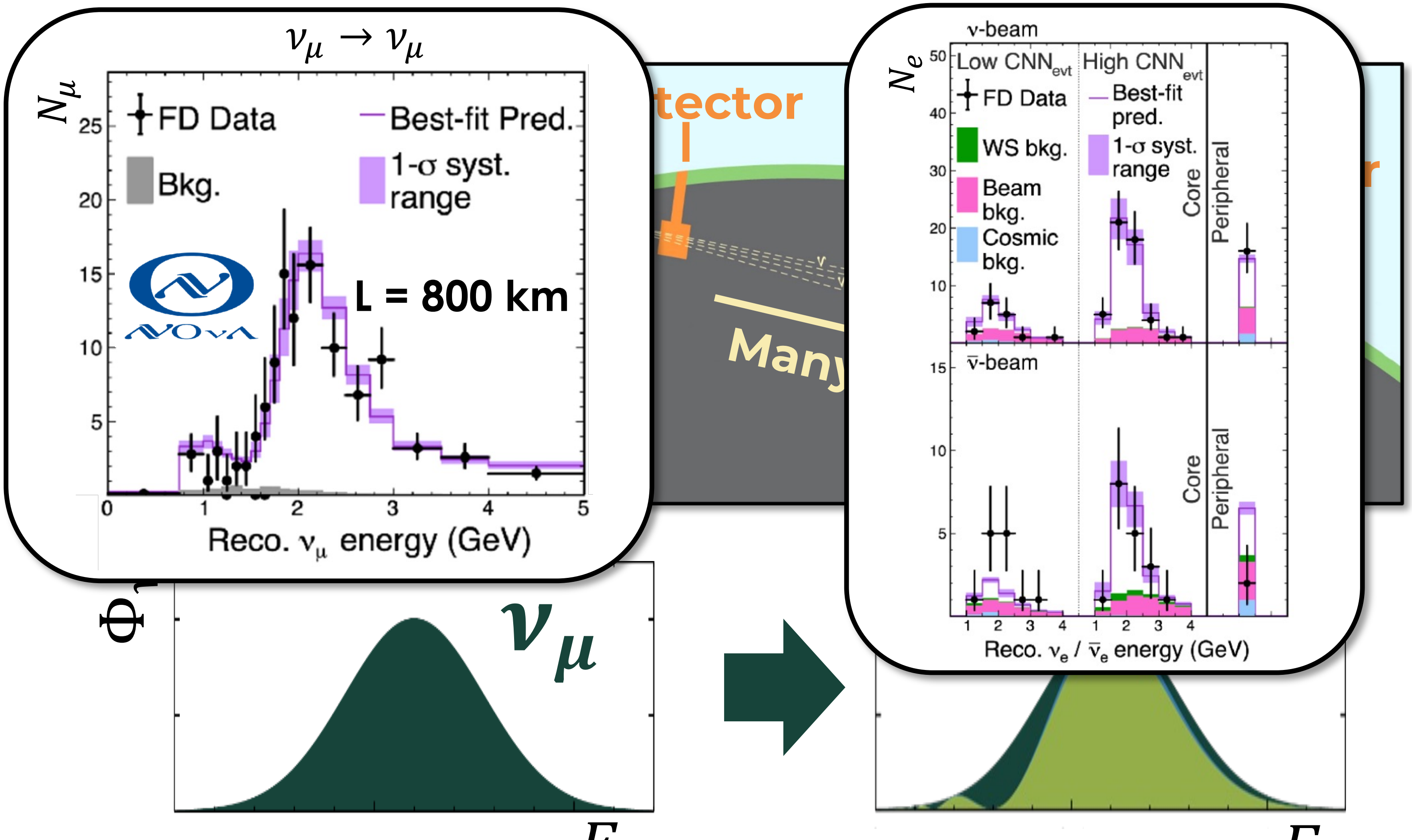

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Oscillation probability

How're we doing?

www.nu-fit.org

Parameter	Bestfit ±1σ	2016
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$\sim 4\%$
$\sin^2\theta_{23}$	$0.574^{+0.026}_{-0.144}$	$\sim 25\%$
$\sin^2\theta_{13}$	$0.02217^{+0.0013}_{-0.0010}$	$\sim 6\%$
δ_{CP} [°]	272^{+61}_{-64}	$\sim 63°$
Δm^2_{21} [10^{-5} eV^2]	$7.49^{+0.19}_{-0.17}$	$\sim 3\%$
$\Delta m^2_{3\ell}$ [10^{-3} eV^2]	$2.484^{+0.045}_{-0.048}$	$\sim 2\%$

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Parameter	Bestfit ±1σ	2016	2018
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$\sin^2\theta_{23}$	$0.538^{+0.033}_{-0.069}$	$\sim 25\%$	$\sim 13\%$
$\sin^2\theta_{13}$	$0.02206^{+0.00075}_{-0.00075}$	$\sim 6\%$	$\sim 3\%$
δ_{CP} [°]	234^{+43}_{-31}	$\sim 63°$	$\sim 37°$
Δm^2_{21} $[10^{-5}\ eV^2]$	$7.40^{+0.21}_{-0.20}$	$\sim 3\%$	$\sim 3\%$
$\Delta m^2_{3\ell}$ $[10^{-3}\ eV^2]$	$2.494^{+0.033}_{-0.031}$	$\sim 2\%$	$\sim 1\%$

How're we doing?

www.nu-fit.org

Parameter	Bestfit ±1σ	2016	2018	2022
$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.012}$	$\sim 4\%$	$\sim 4\%$	$\sim 4\%$
$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$\sim 25\%$	$\sim 13\%$	$\sim 3\%$
$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00059}$	$\sim 6\%$	$\sim 3\%$	$\sim 3\%$
δ_{CP} [°]	197^{+42}_{-25}	$\sim 63°$	$\sim 37°$	$\sim 34°$
Δm^2_{21} $[10^{-5}\ eV^2]$	$7.41^{+0.21}_{-0.20}$	$\sim 3\%$	$\sim 3\%$	$\sim 3\%$
$\Delta m^2_{3\ell}$ $[10^{-3}\ eV^2]$	$2.511^{+0.028}_{-0.027}$	$\sim 2\%$	$\sim 1\%$	$\sim 1\%$

Precision neutrino-oscillation physics!

Nature **580**, 339-344

Precision oscillation physics

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$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.012}$	$\sim 4\%$	$\sim 4\%$	$\sim 4\%$
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But still plenty more to find out:

- Maximal θ_{23} mixing? (flavour symmetries?)

Precision oscillation physics

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But still plenty more to find out:

- Maximal θ_{23} mixing?
- A new source of CP-violation? (implications for cosmology and leptogensis)

Precision oscillation physics

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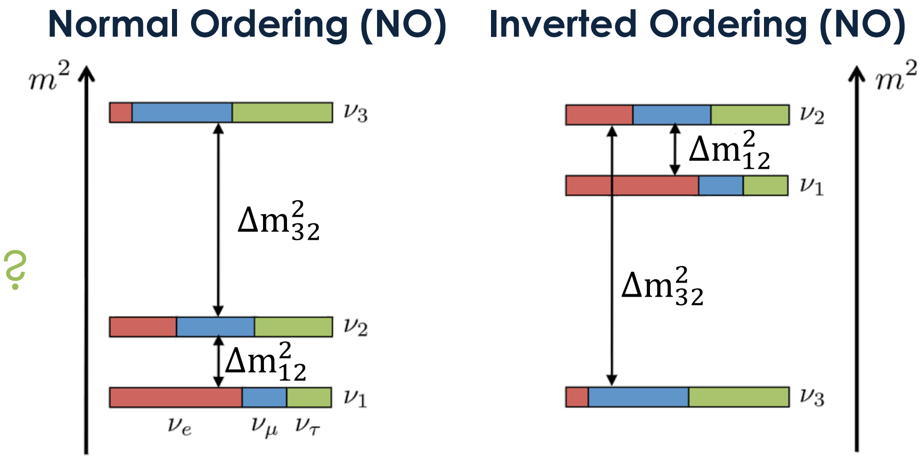
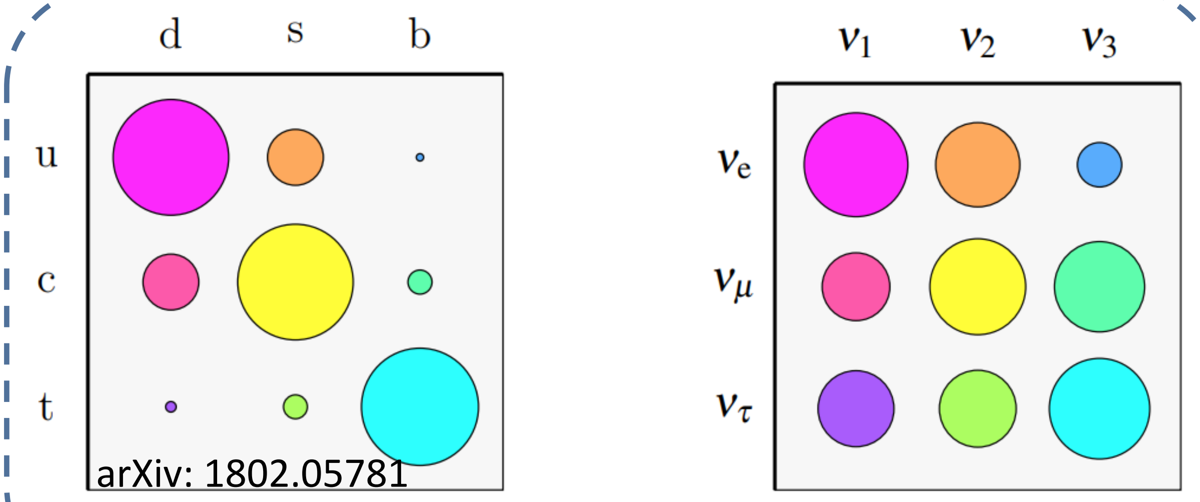


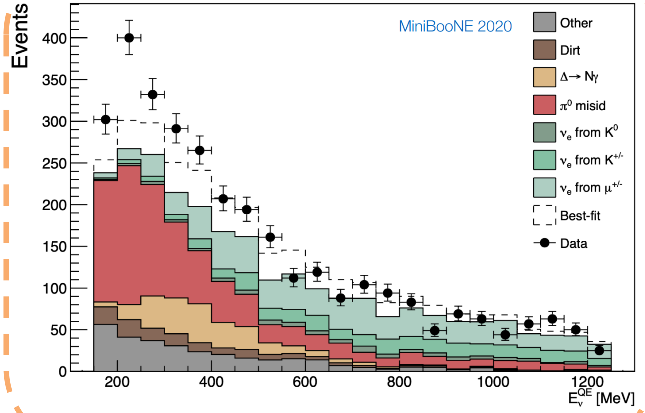
Precision oscillation physics



arXiv: 1802.05781

(a) Quark Mixing Elements.

(b) Lepton Mixing Elements.



MiniBooNE “low energy excess”

But still plenty more to find out:

- Maximal θ_{23} mixing?
- A new source of CP-violation?
- What’s the neutrino mass ordering?
- Physics beyond PMNS?

What's Next?

Hyper-Kamiokande

Baseline: 295 km
Beam: Narrow band, ~0.6 GeV
Far detector: Water Cherenkov
Far detector mass (FV): 187 kt
Expected N_e: ~2000

DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

Baseline: 1200 km
Beam: Wide band, ~3 GeV
Far detector: Liquid Argon TPC
Far detector mass (FV): 68 kt
Expected N_e: ~1500

But still plenty more to find out:

- Maximal θ_{23} mixing?
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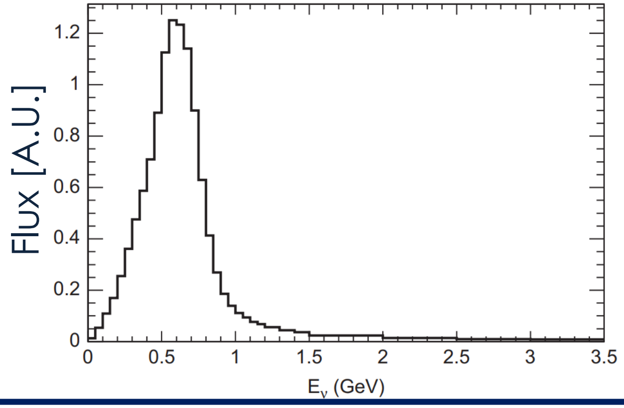
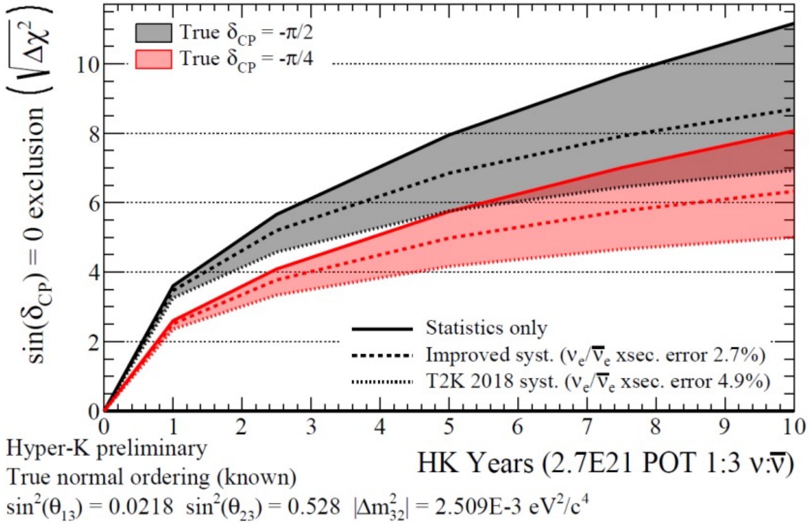
What's Next?

Hyper-Kamiokande





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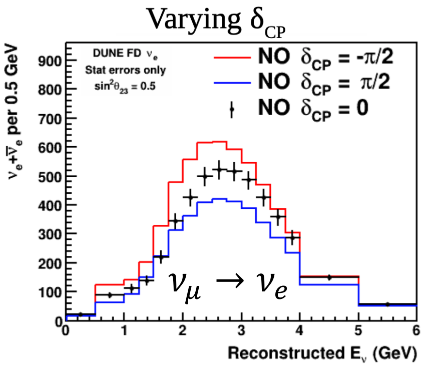
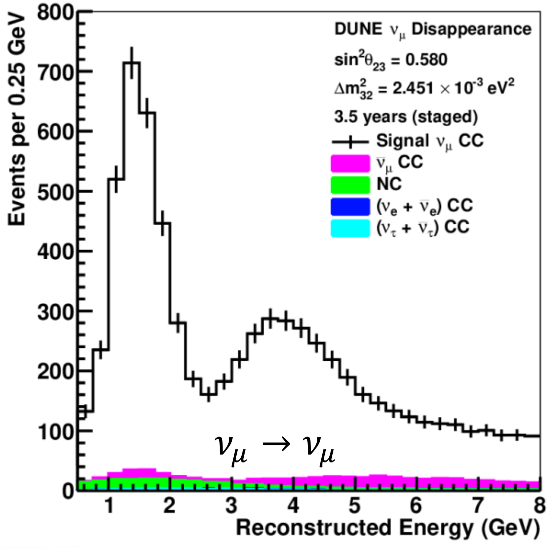
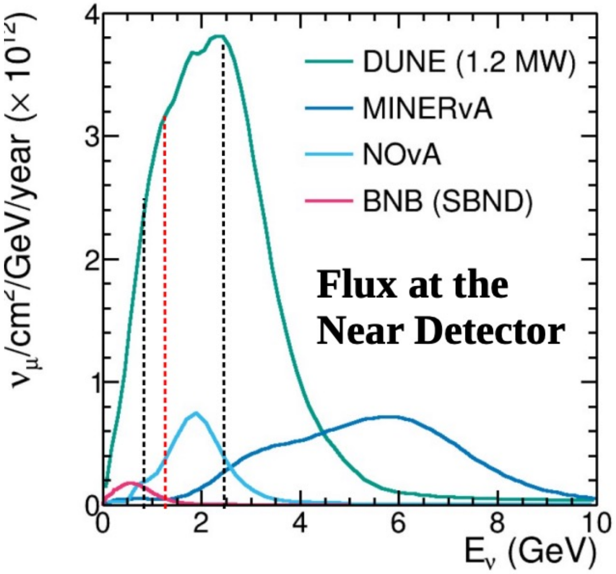
What’s Next?

DEEP UNDERGROUND NEUTRINO EXPERIMENT







But still plenty more to find out:

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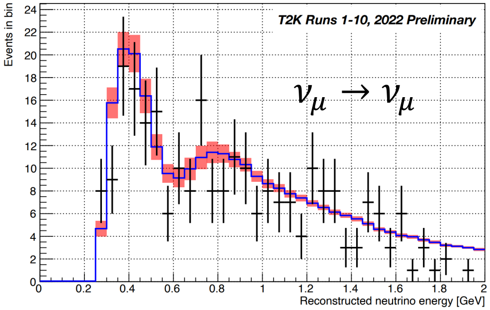
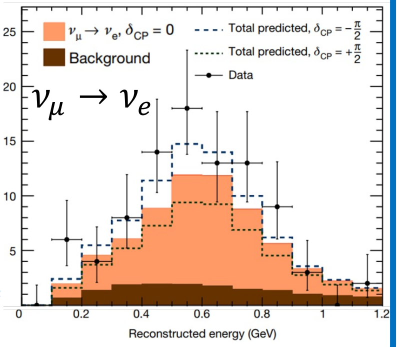
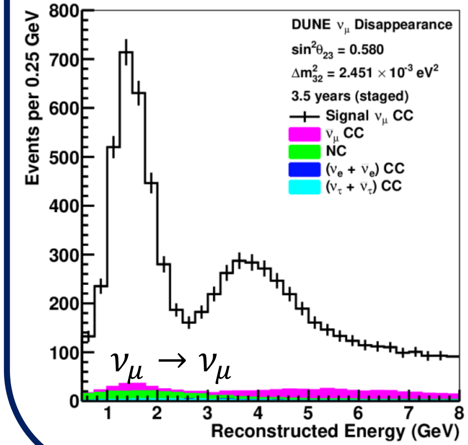
Beyond beyond the SM

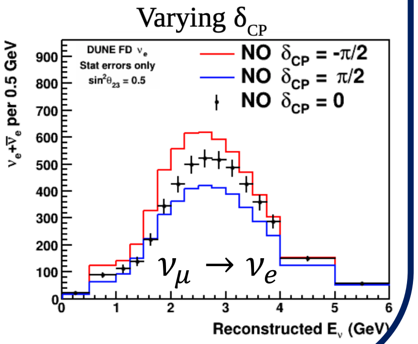
Present





Future





Beyond beyond the SM

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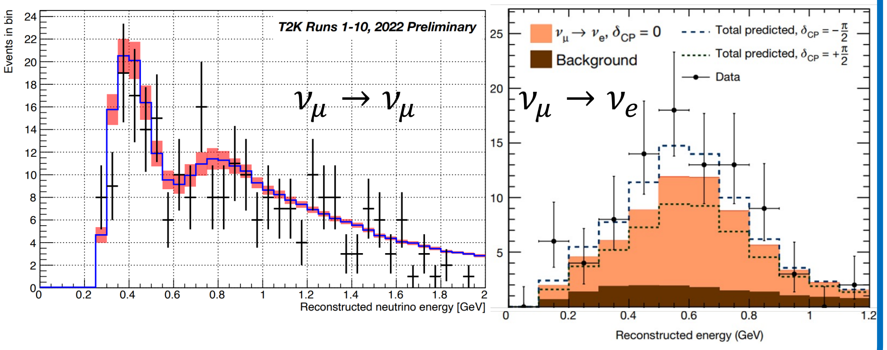

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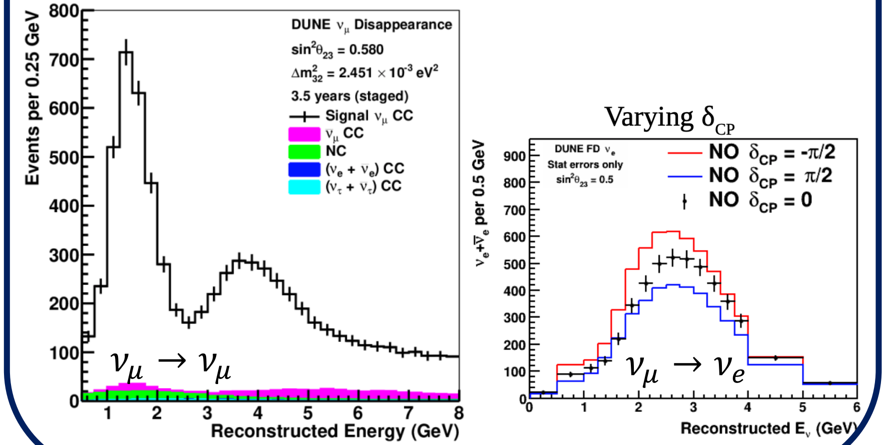

Facilities for exploring physics beyond the standard model + PMNS

- DUNE and Hyper-K will offer a characterisation of neutrino oscillations with unprecedented precision (10-50 times more statistics)

Beyond beyond the SM

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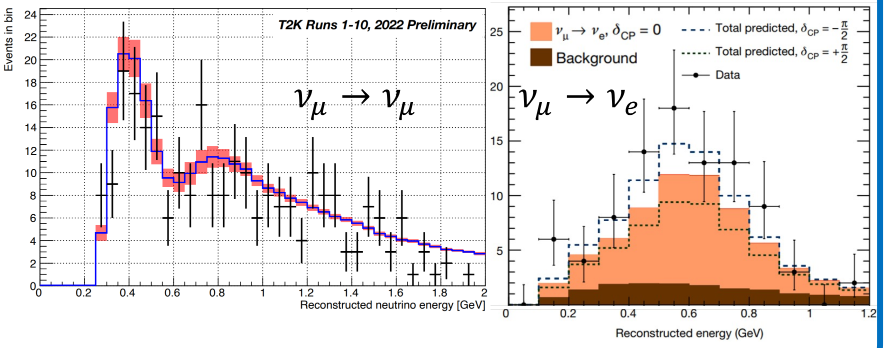

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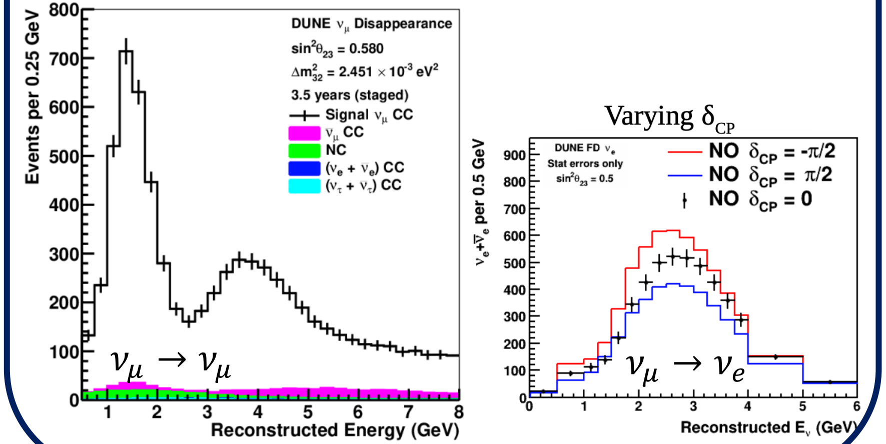

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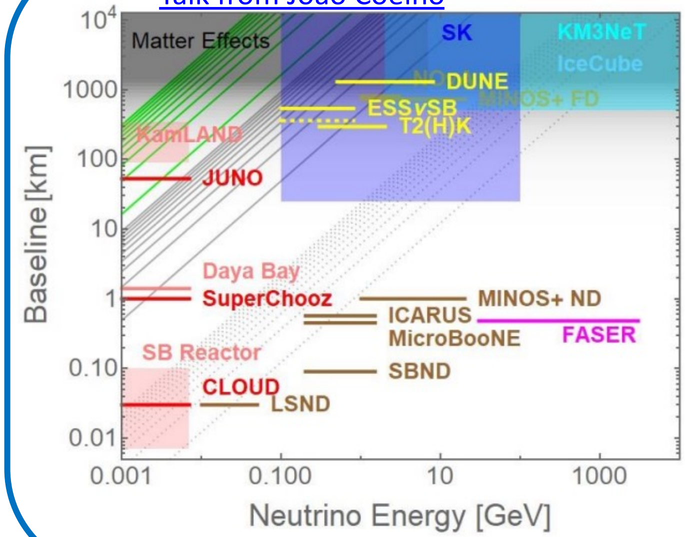
Beyond beyond the SM

Talk from João Coelho



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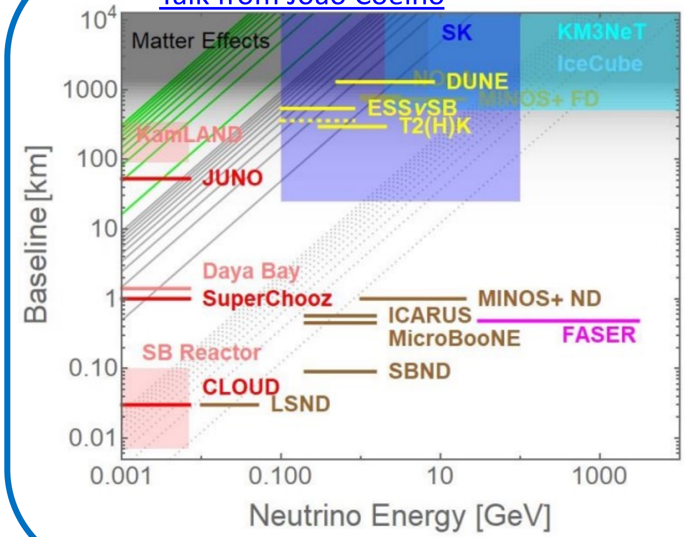
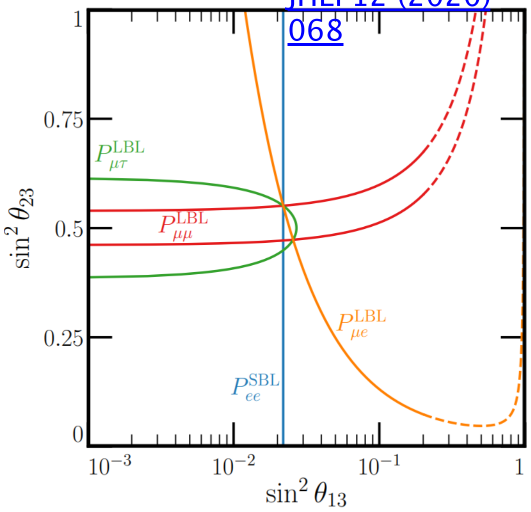


JHEP12 (2020) 068



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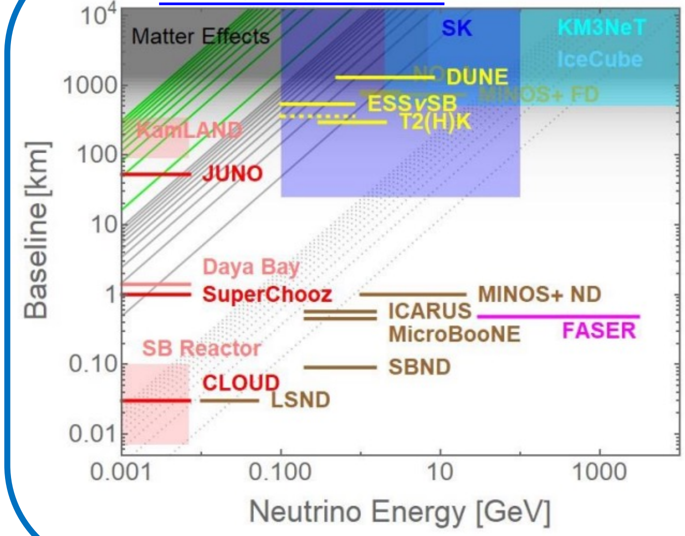

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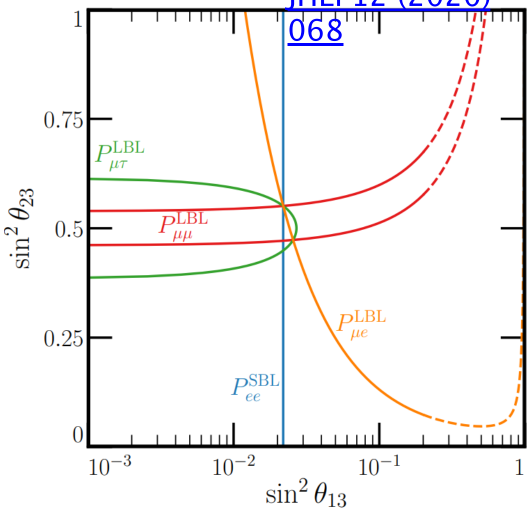

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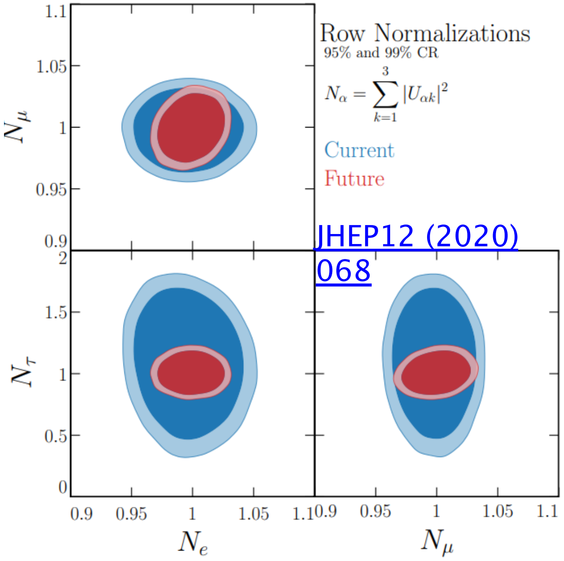

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Current uncertainties

Current long-baseline experiments

	T2K	NOvA
Baseline	295 km	800 km
N_{μ}^{rec} (ν-mode)	318	211
N_{e}^{rec} (ν−mode)	94	82

Reconstructed events in samples at the experiment's far detectors

Current systematic uncertainties

Source (T2K)	NEUTRINO 2022 XXX International Conference on Neutrino Physics and Astrophysics $N(\nu_e)$
Total Syst.	**5.2%**

At the far detector

$$N_{\mu}(E_{\nu}) = P(\nu_{\mu} \rightarrow \nu_{\mu})\sigma(E_{\nu})\Phi_{\nu}(E_{\nu})\epsilon(E_{\nu})$$
$$N_{e}(E_{\nu}) = P(\nu_{\mu} \rightarrow \nu_{e})\sigma(E_{\nu})\Phi_{\nu}(E_{\nu})\epsilon(E_{\nu})$$

Future uncertainties

Future long-baseline experiments

Coming 2027-2032

	arXiv:1805.04163	*arXiv:2002.03005*
Baseline	295 km	1300 km
N_μ^{rec} (ν-mode)	~10000	~7000
N_e^{rec} (ν−mode)	~2000	~1500

Approximate late-stage projections for reconstructed events in samples at the experiment's far detectors

Current systematic uncertainties

NEUTRINO 2022

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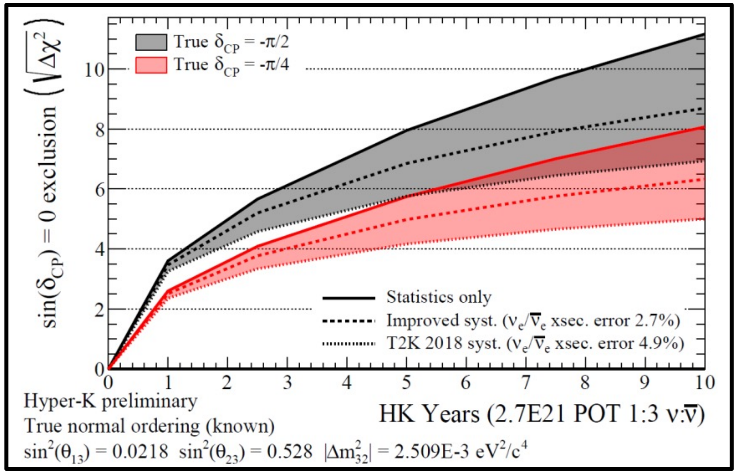
Current systematic uncertainties

Source (T2K)	NEUTRINO 2022 $N(\nu_e)$
Cross-section models	3.8%
Total Syst.	**5.2%**



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2002.03005

Baseline

N_μ^{rec} (ν-mode)	~10000	
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Crucial to reduce uncertainties related to neutrino interaction cross sections

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XXX International Conference on Neutrino Physics and Astrophysics

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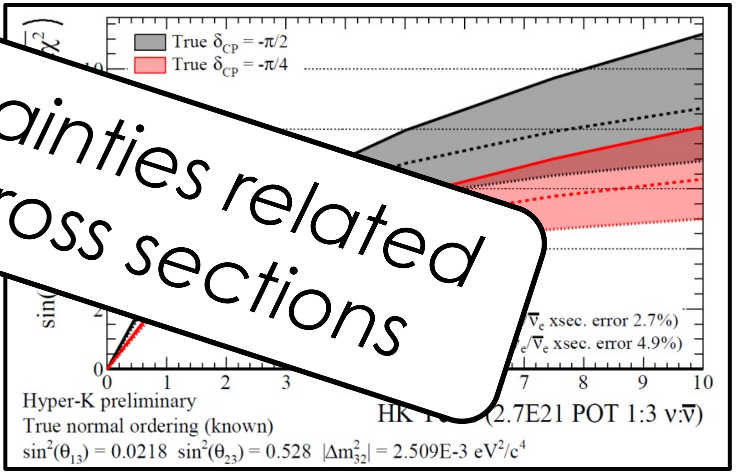

Hyper-K preliminary
True normal ordering (known)
$\sin^2(\theta_{13}) = 0.0218$ $\sin^2(\theta_{23}) = 0.528$ $|\Delta m^2_{32}| = 2.509\text{E-}3\ \text{eV}^2/\text{c}^4$

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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Overview

- Neutrino Oscillations
- Accelerator-Based Experiments
- **ν Interactions for ν Oscillations**
- Reconstructing Neutrino Energy
- The Path to Precision Measurements

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

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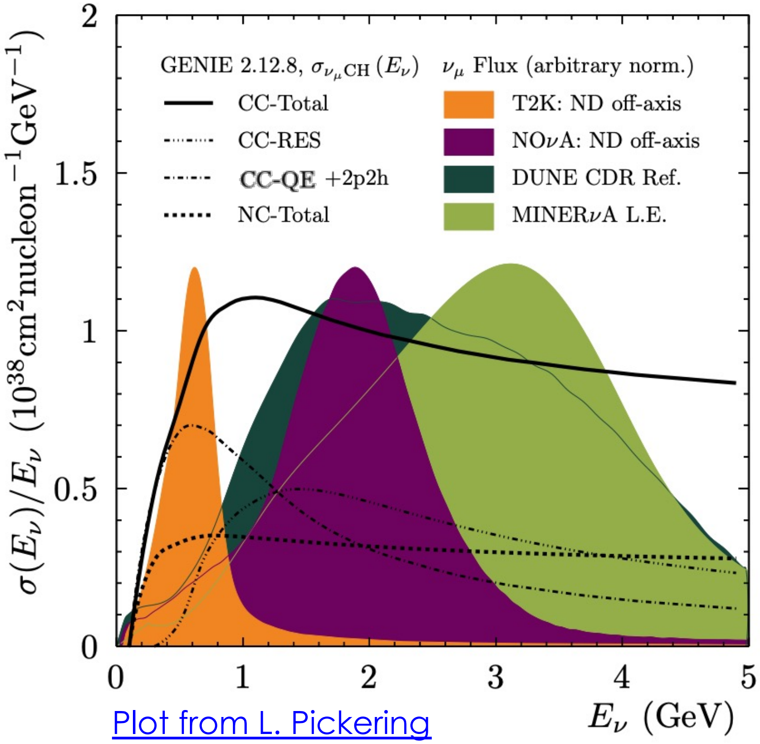
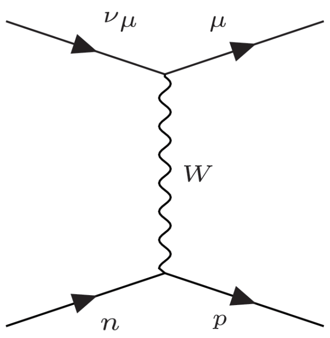
Neutrino-nucleus interactions



Plot from L. Pickering

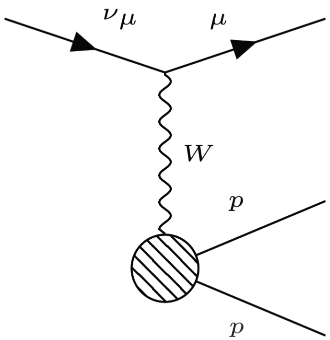
CC-QE

(Charged-Current Quasi-Elastic)



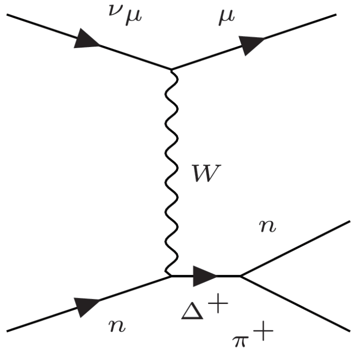
CC-2p2h

(Two-Particle-Two-Hole)



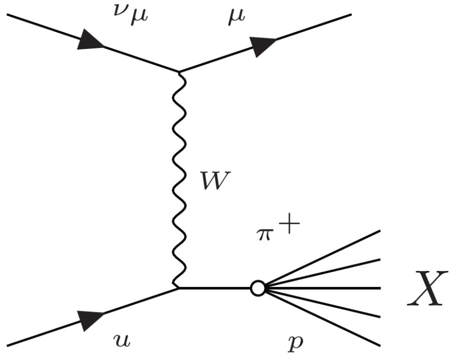
CC-SPP

(Single Pion Production)



CC-DIS

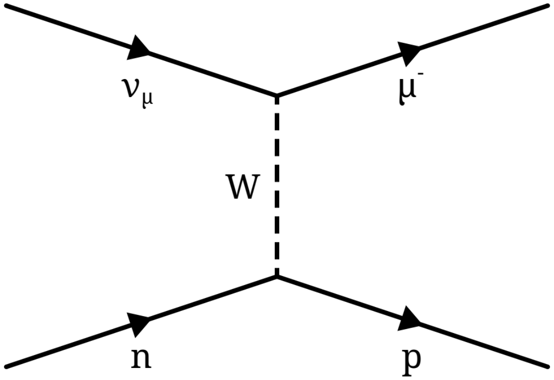
(Deep Inelastic Scattering)



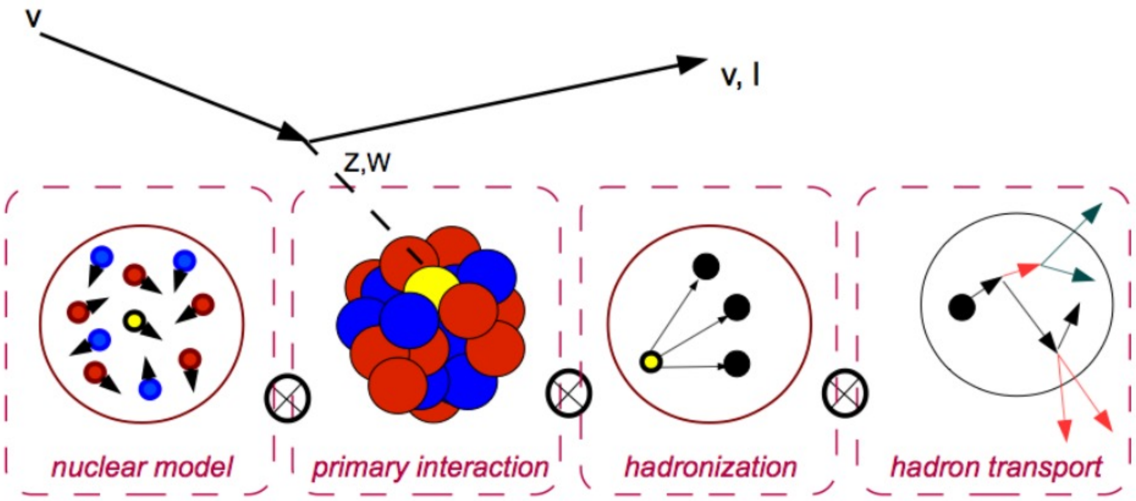
Neutrino-nucleus scattering

- Even the most simple "CCQE" interaction is hard to describe …

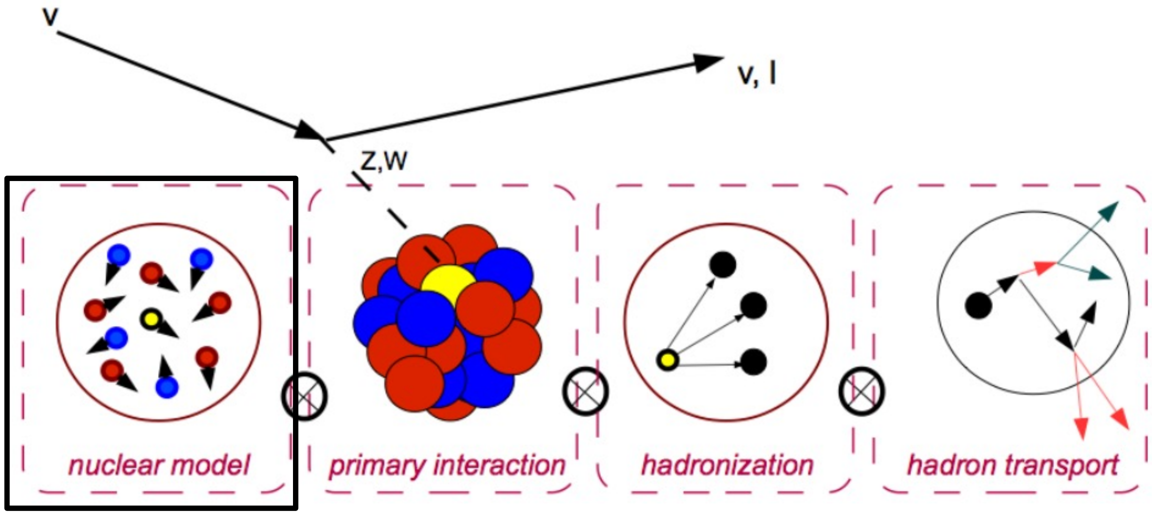
$$M \sim \frac{g_W^2}{8}\frac{1}{M_W^2}[\bar{u}_\mu \gamma_\mu (1-\gamma_5) u_\nu][\bar{u}_p \underset{\underset{???}{\uparrow}}{(\dots)} u_n]$$

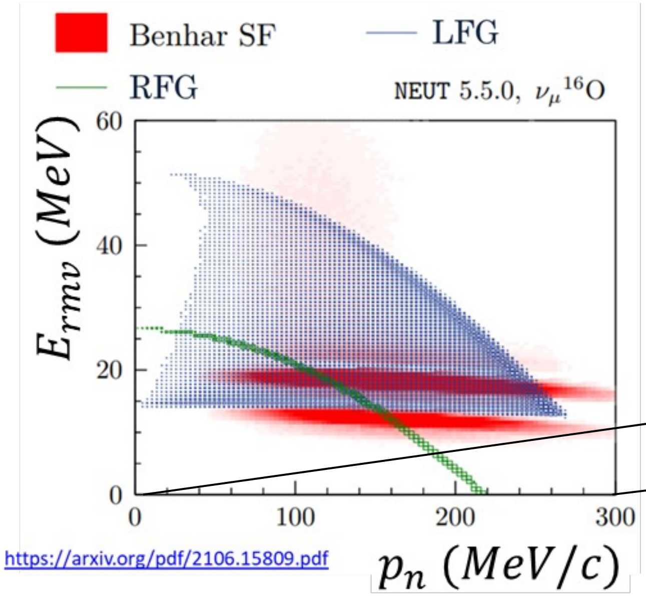


Neutrino-nucleus scattering

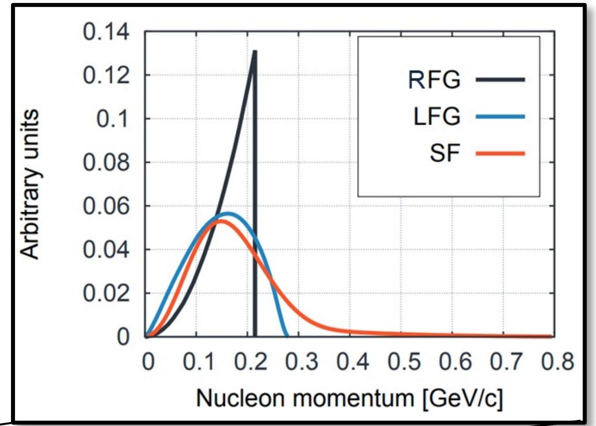


Neutrino-nucleus scattering

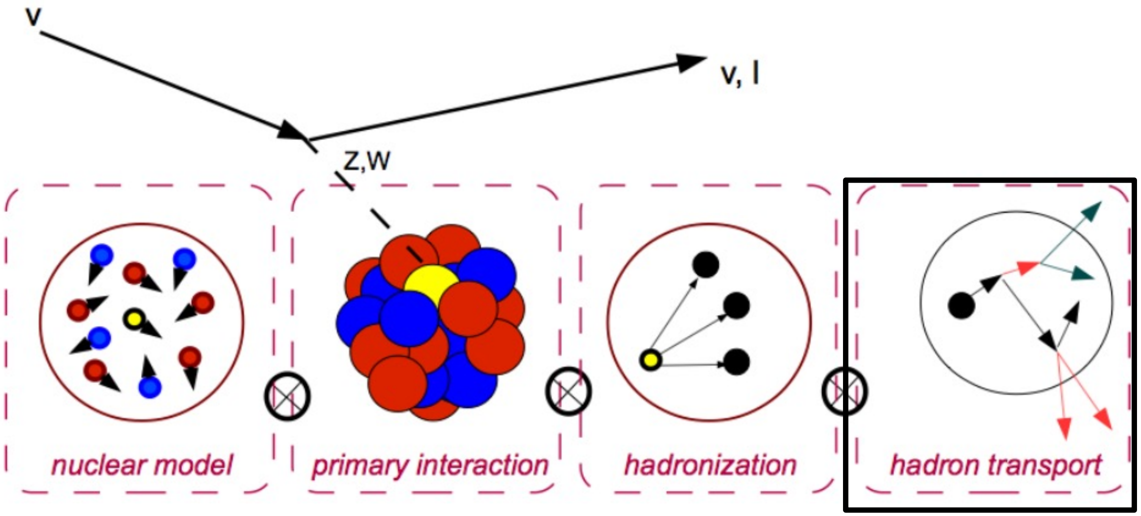




https://arxiv.org/pdf/2106.15809.pdf

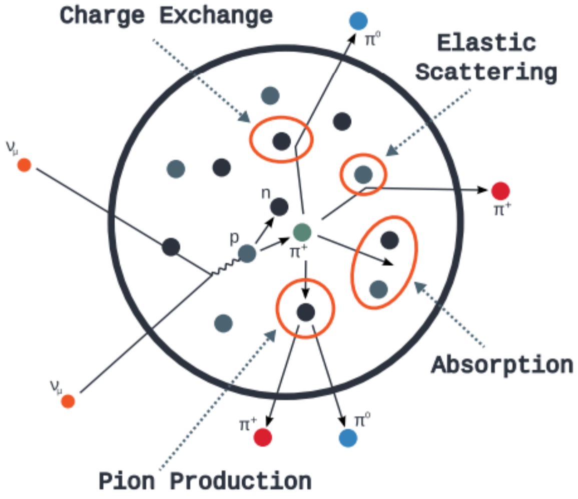


Neutrino-nucleus scattering

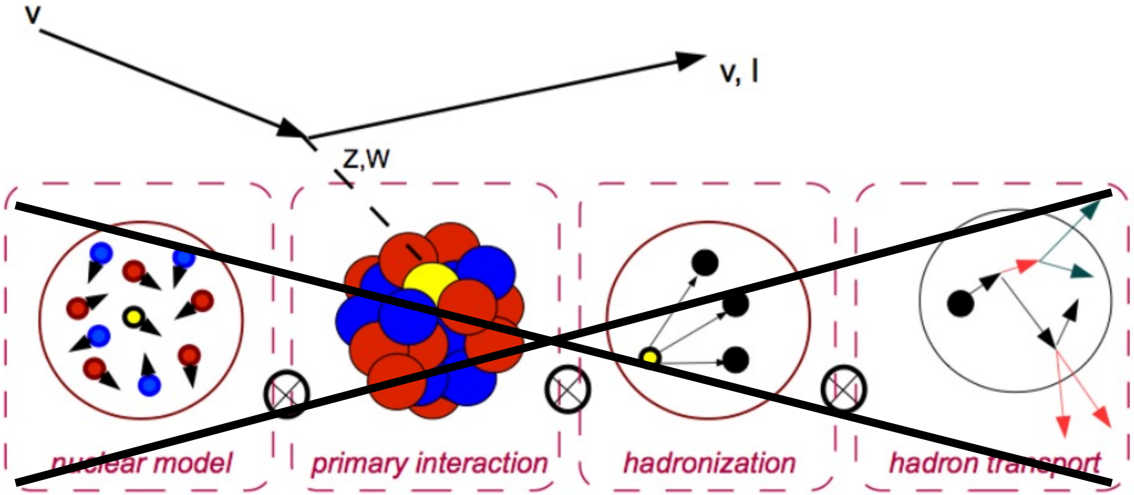


- Hadrons re-interact inside the nuclear medium: **Final State Interactions**

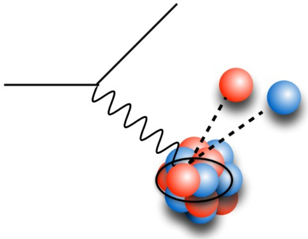
- Impractical to solve exactly, forced to use approximate methods



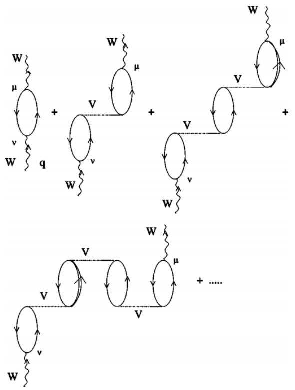
Neutrino-nucleus scattering



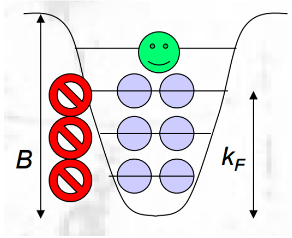
Multi-nucleon Interactions



Long range nuclear correlations

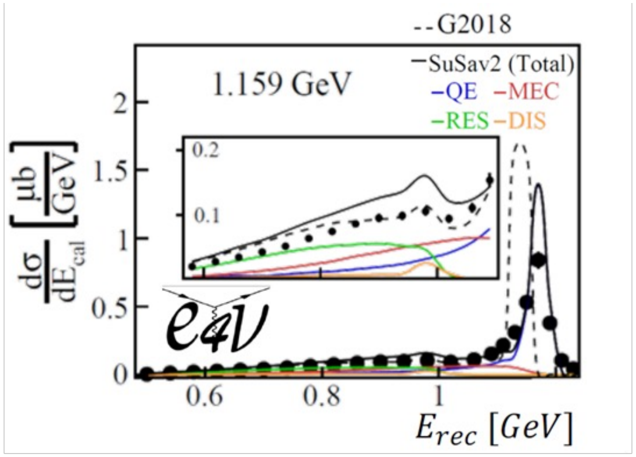


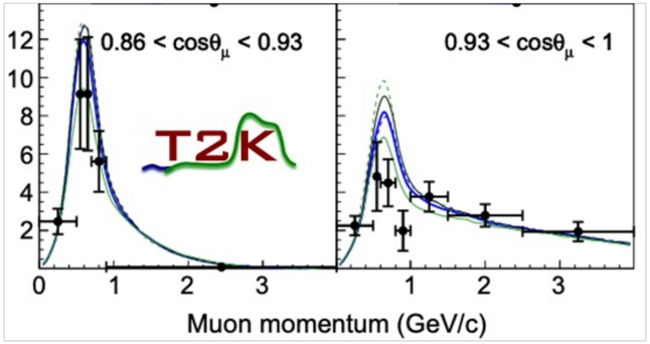
Pauli blocking

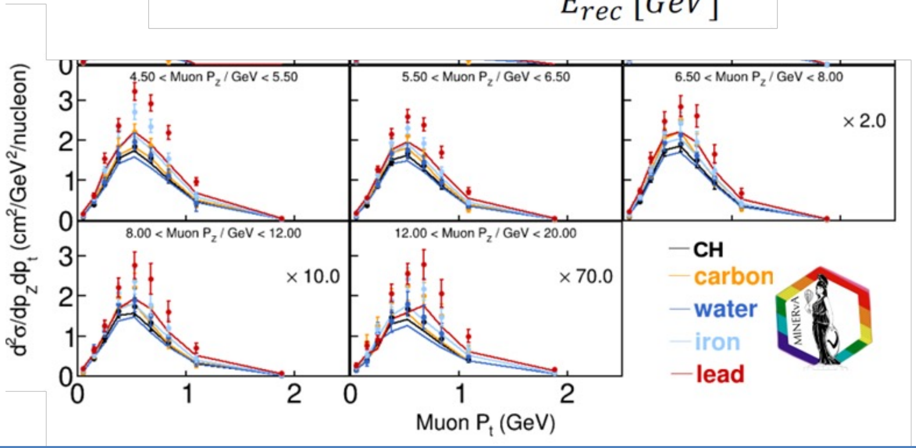


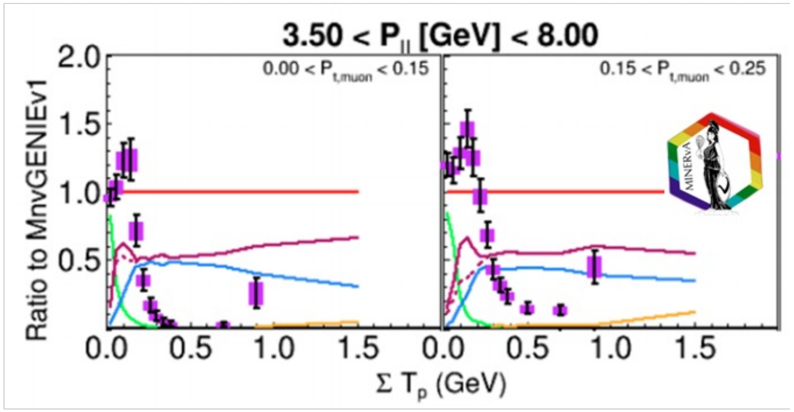
Comparisons to measurements

- Lepton-nucleus cross-section measurements provide a crucial means to benchmark interaction models
- In general, models are unable to describe modern measurements







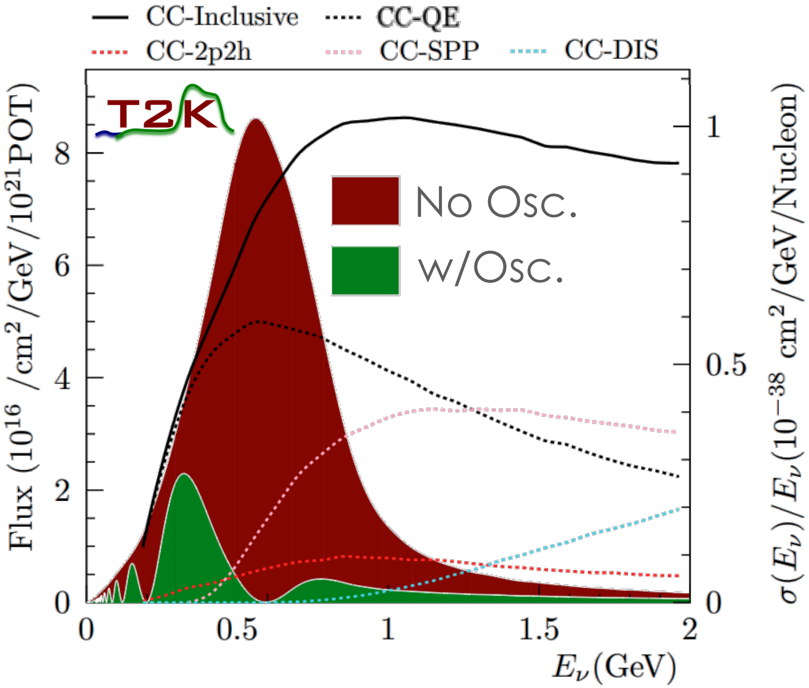


Where are we so far?

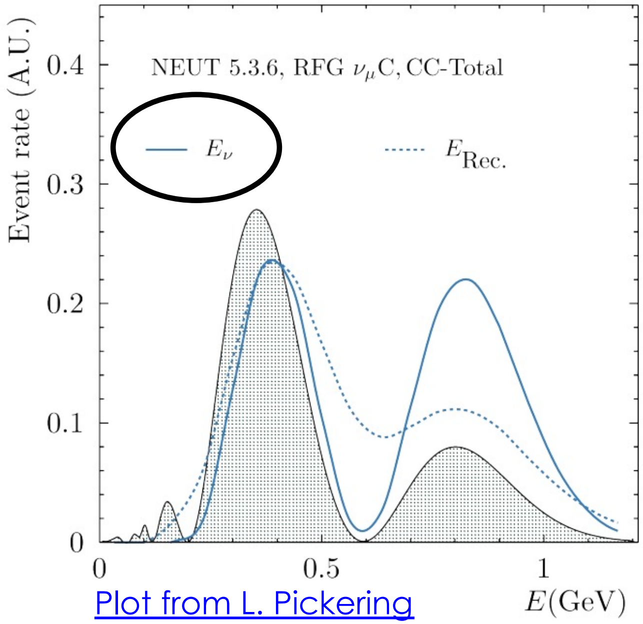
- Key questions:

  1. *Why is modelling neutrino interactions so difficult?*
  2. ***What exactly do we need to understand in order to reduce uncertainties on oscillation measurements?***

Event rates to oscillation parameters



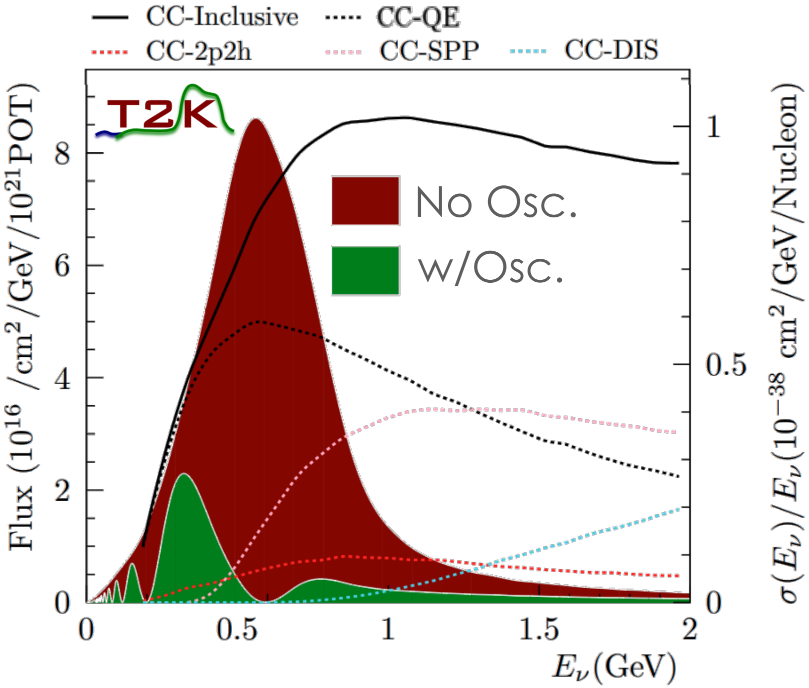
What we would like to measure



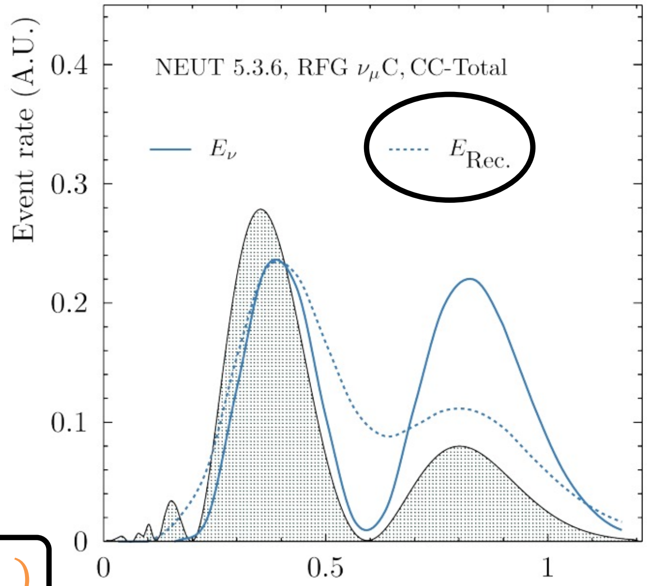
Plot from L. Pickering

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

Event rates to oscillation parameters



What we can actually measure



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

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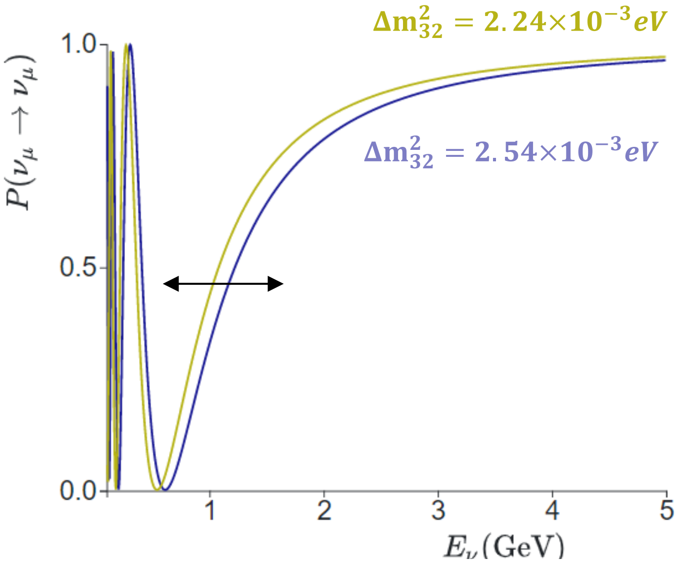
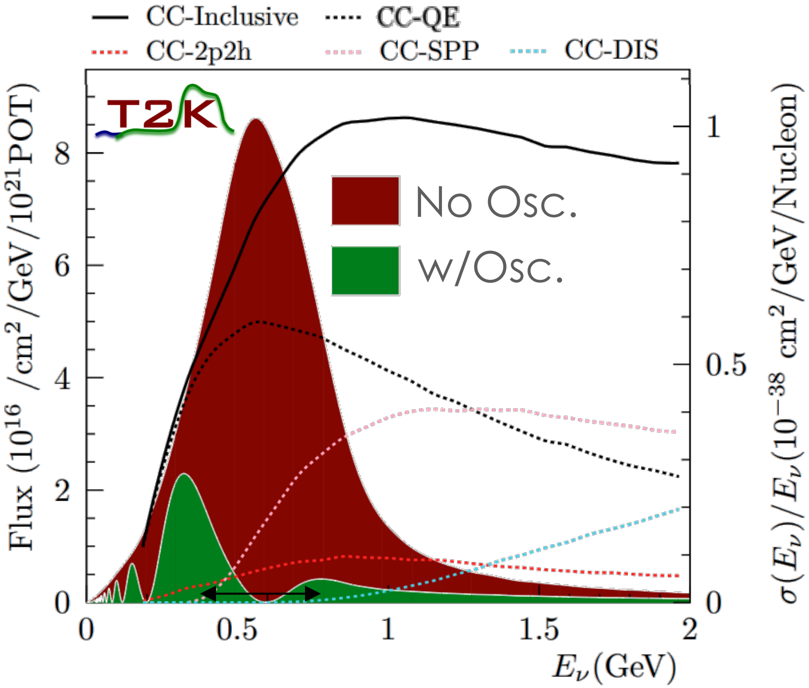
- For a precision probe of oscillation parameters, reconstructing the shape of the oscillated spectrum is crucial





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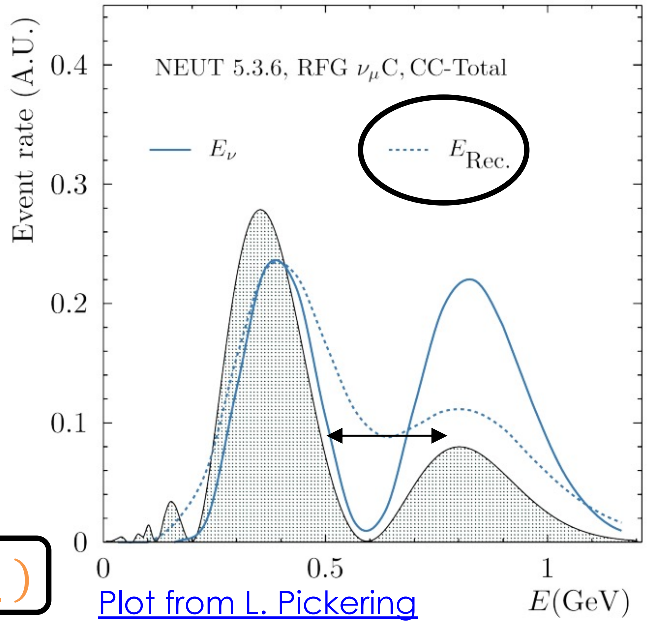

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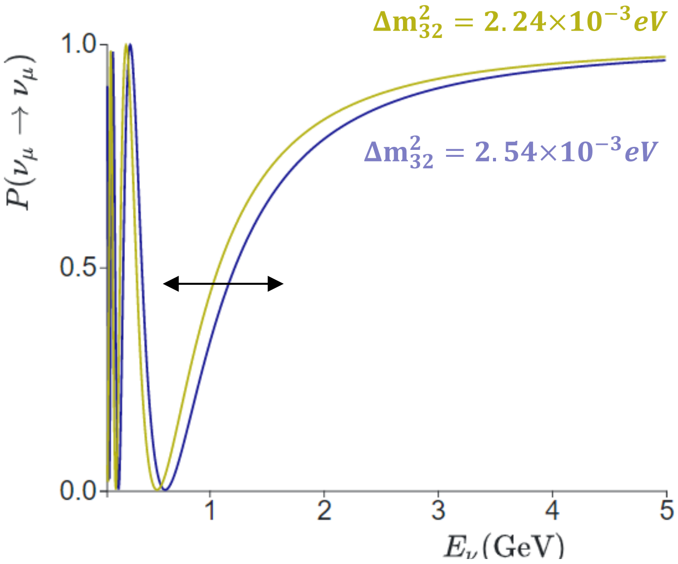

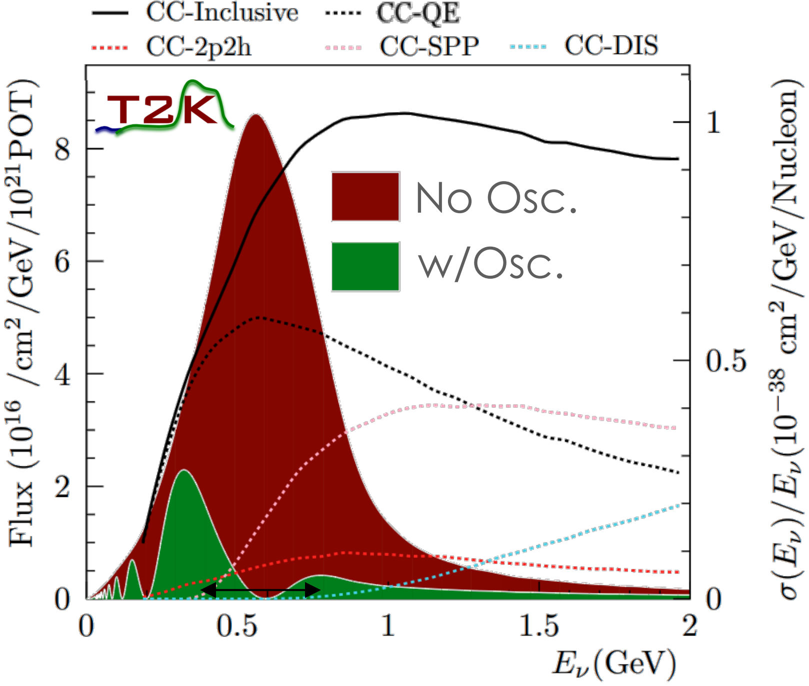

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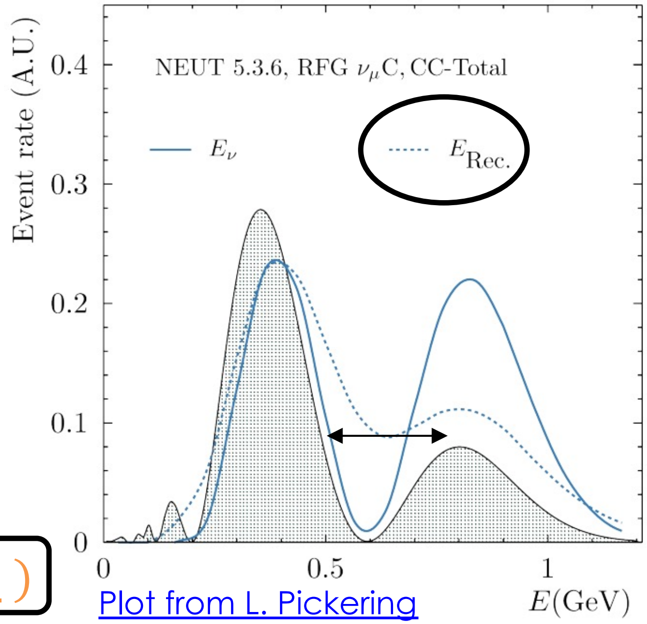

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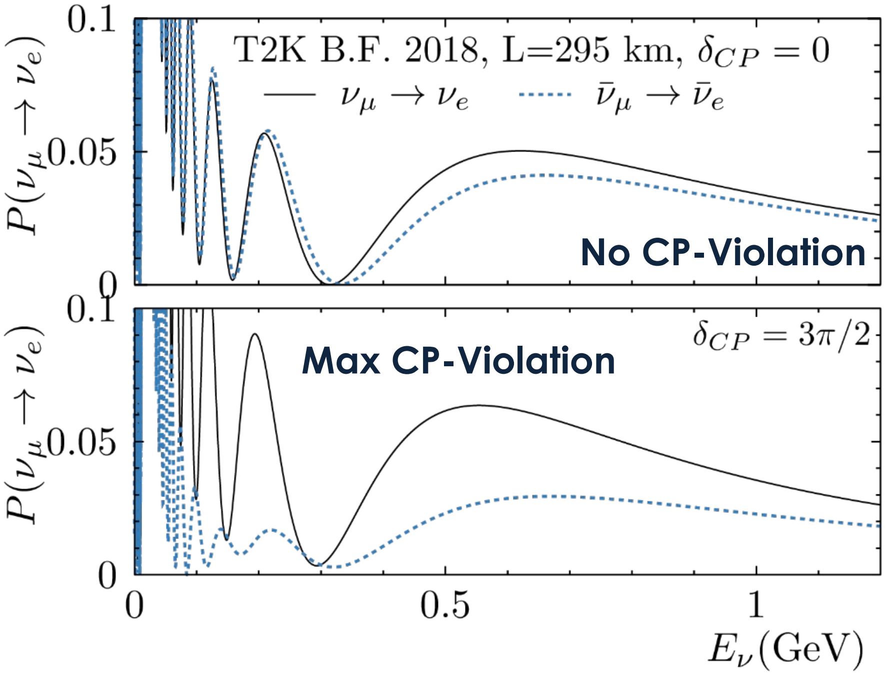

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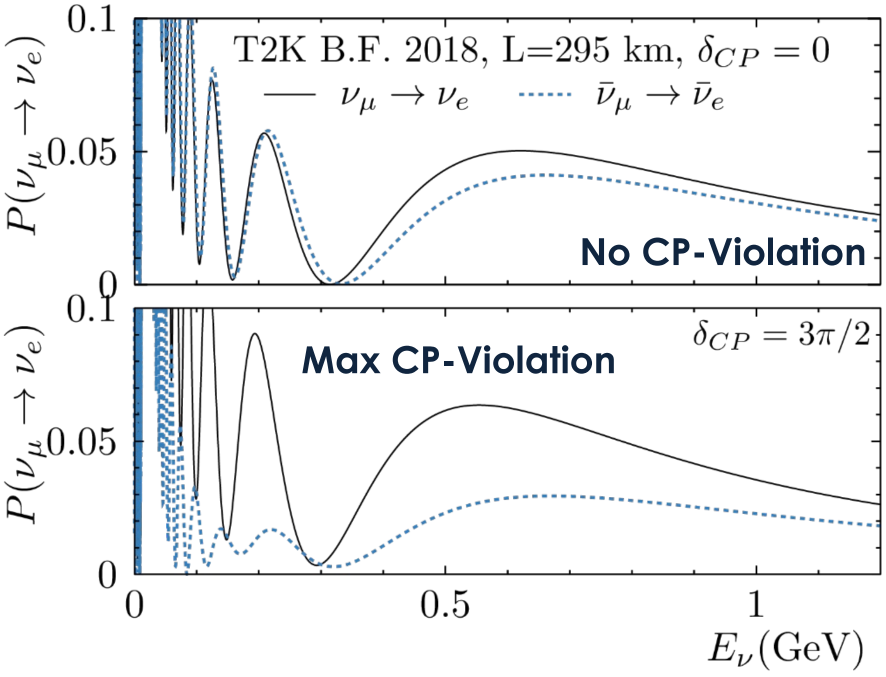

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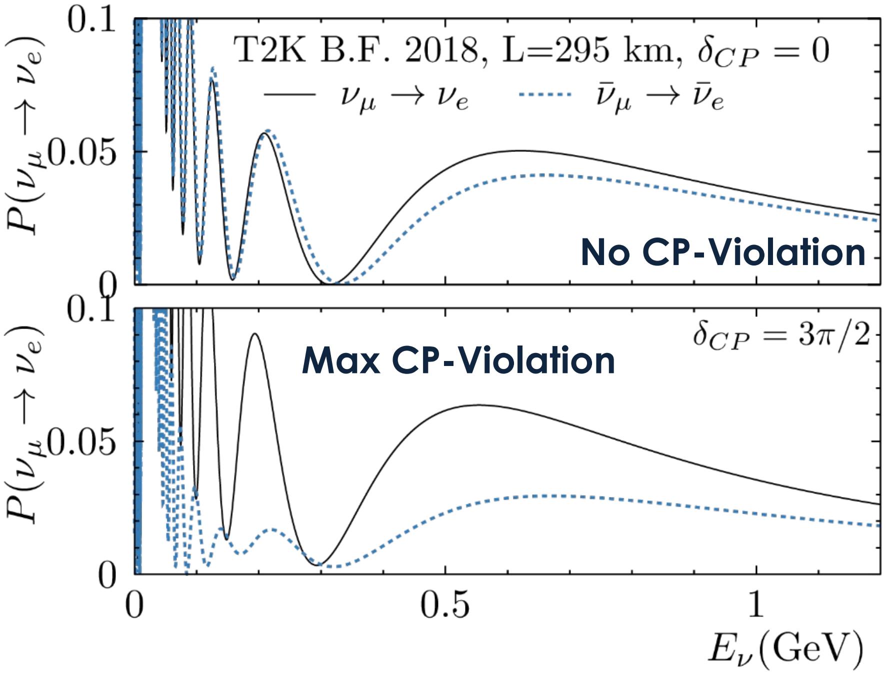
- But we mainly measure muon neutrino interactions at the near detector
- **A good modelling of ν_e/ν_μ cross section ratio is essential**



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*

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Reconstructing E_ν

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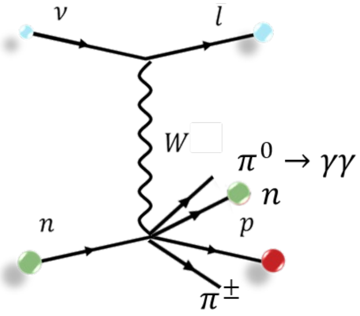
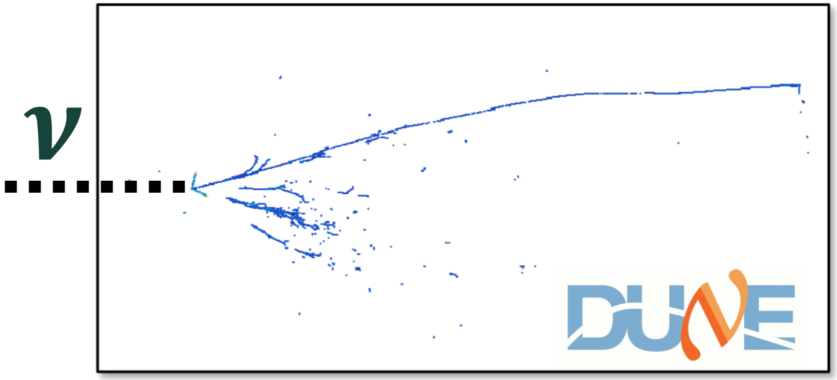
“Calorimetric method”

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

- 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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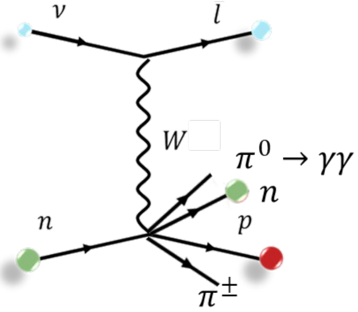
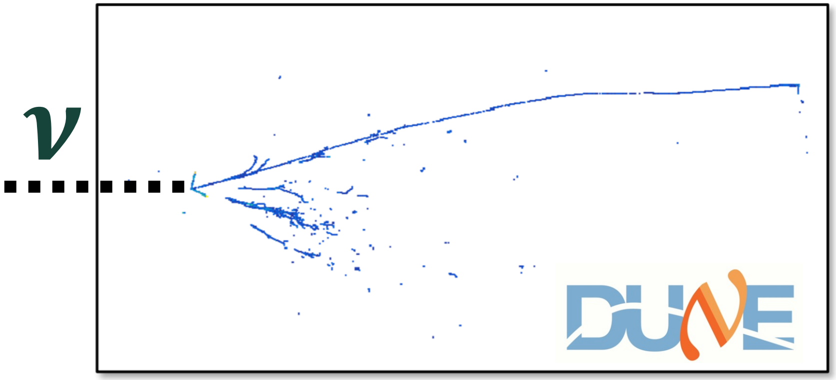
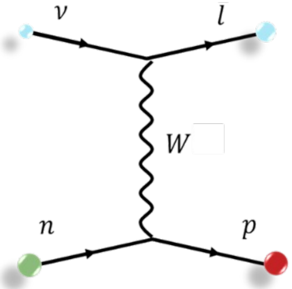


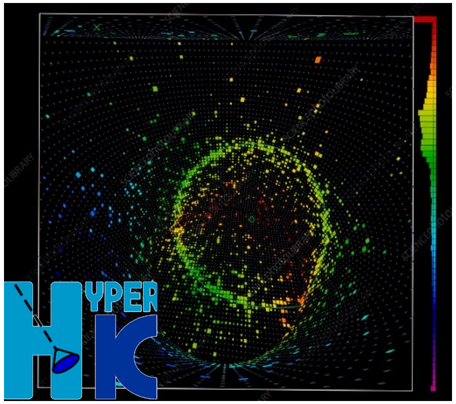


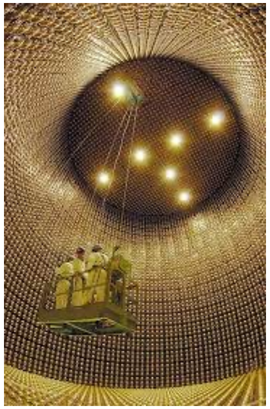
“Kinematic method”

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

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

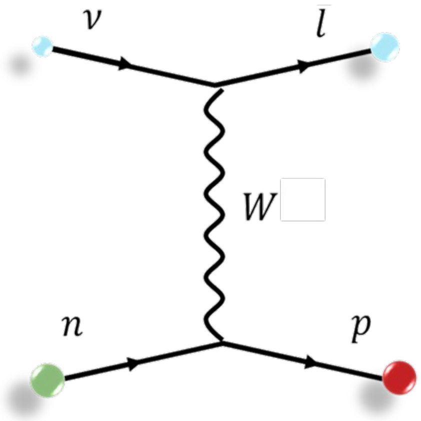


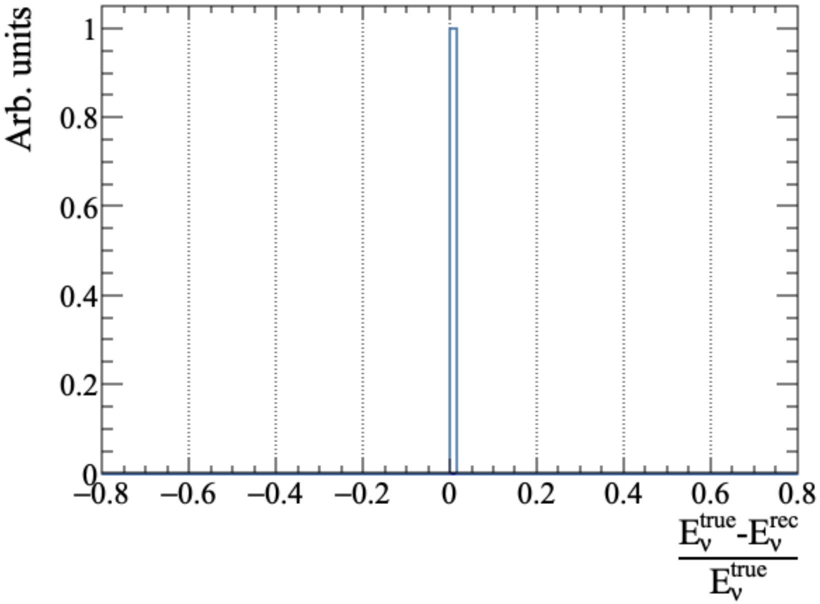




Nuclear effects and E_ν (T2K/HK)

CCQE (1p1h)





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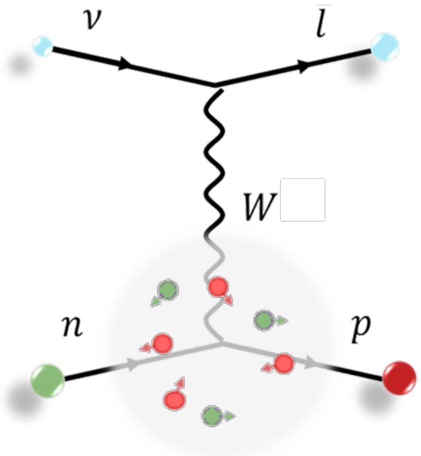
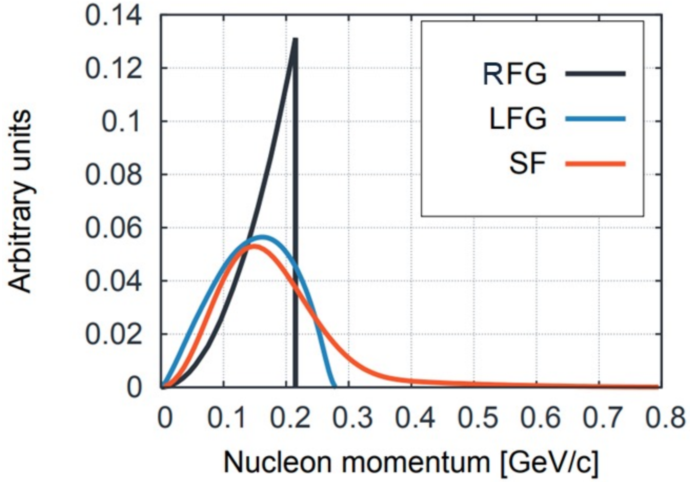
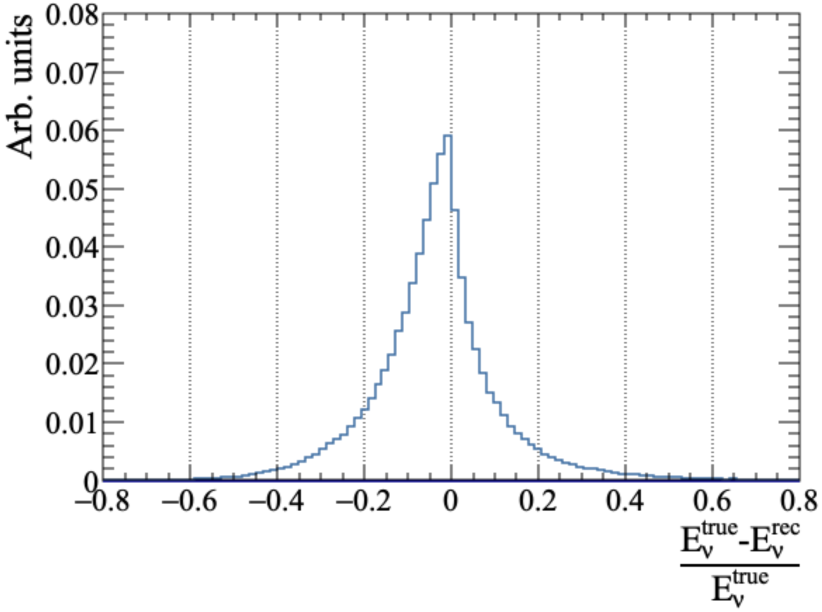
Proxy for E_ν from lepton kinematics is exact only for **CCQE elastic scattering** off a **stationary nucleon**

Nuclear effects and E_ν (T2K/HK)

CCQE (1p1h)







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The motion of the nucleons inside the nucleus (*Fermi motion*) causes a **smearing** on E_ν

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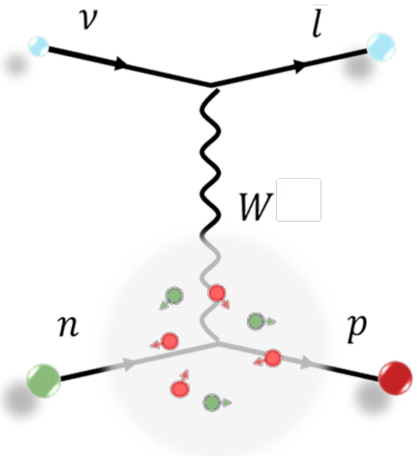
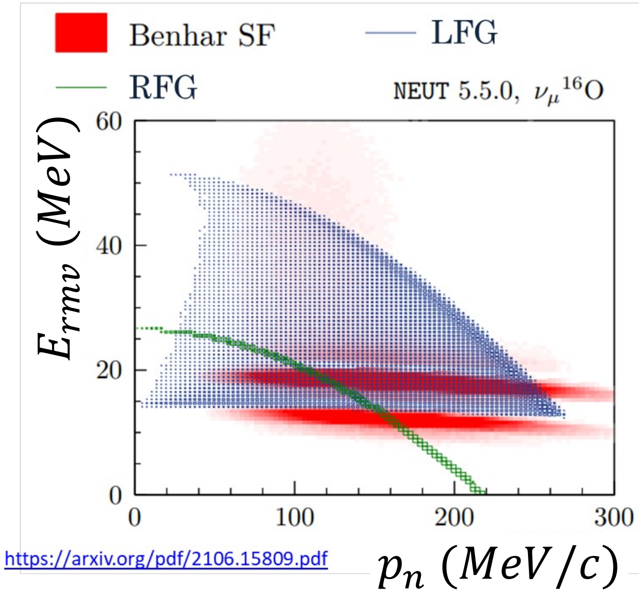
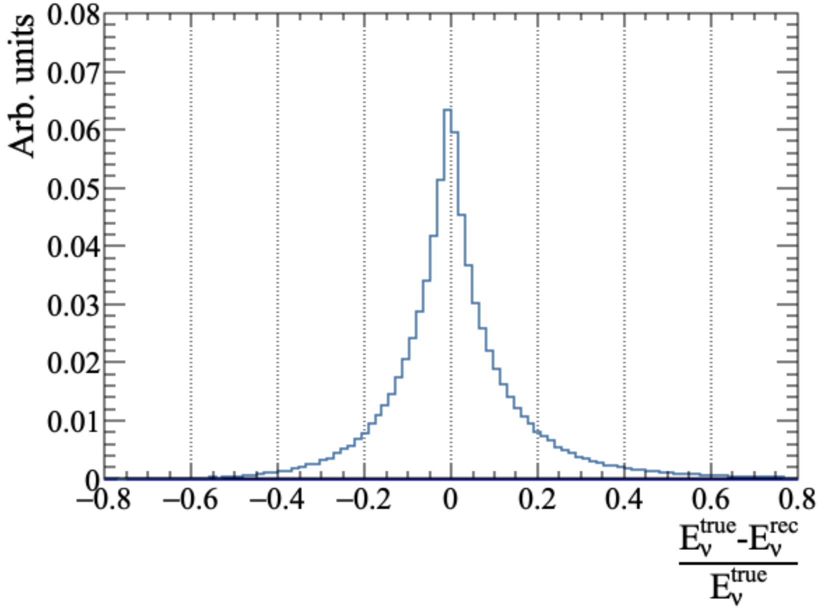




https://arxiv.org/pdf/2106.15809.pdf



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

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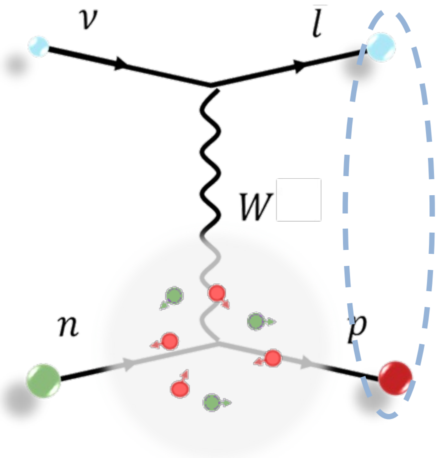
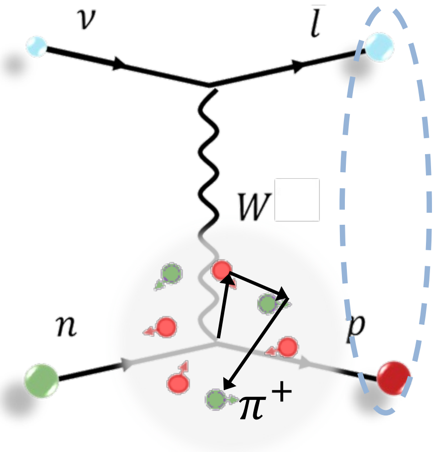
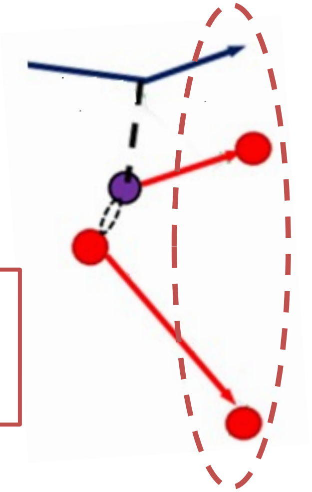


CCRES

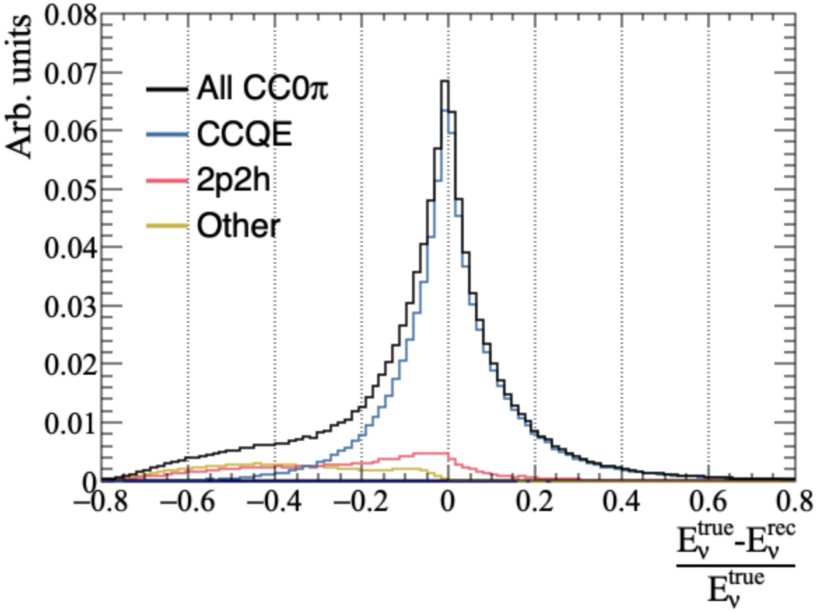


Final state interactions (FSI) can cause different interaction modes to have the same final state

2p2h



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



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

Nuclear effects and E_ν (T2K/HK)

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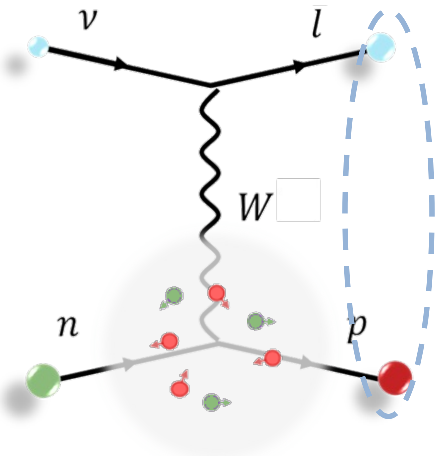

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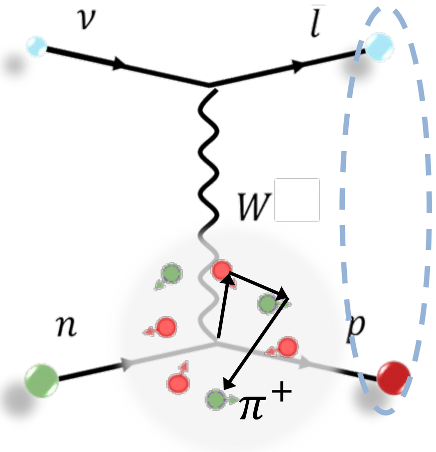

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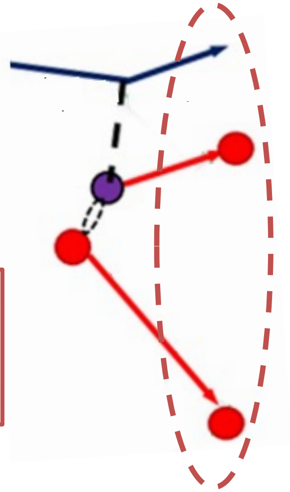

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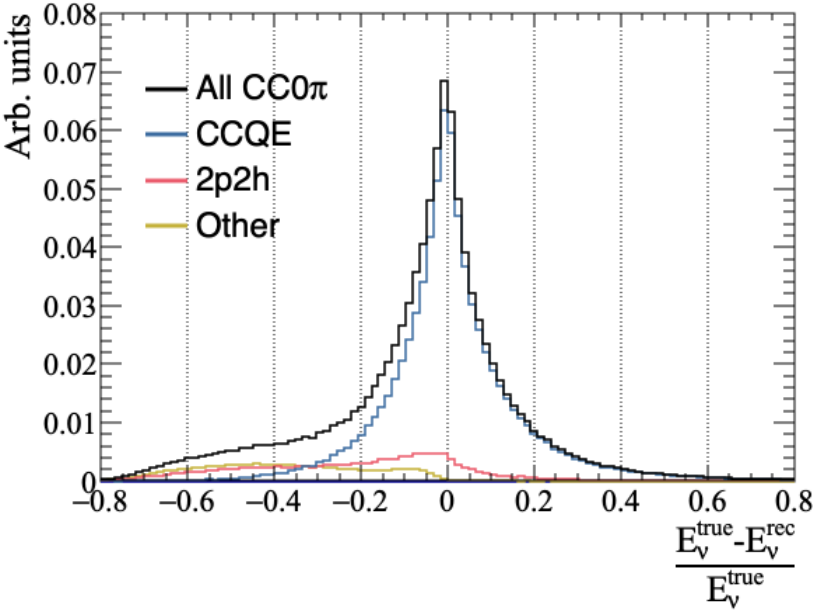

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First-order effects

Fermi motion causes a **smearing** on E_ν^{QE}

Nuclear removal energy effects introduce a **bias**

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

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

T2K/HK

(“kinematic” E_ν proxy)

Critical

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

- 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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DUNE/NOvA/SBN

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

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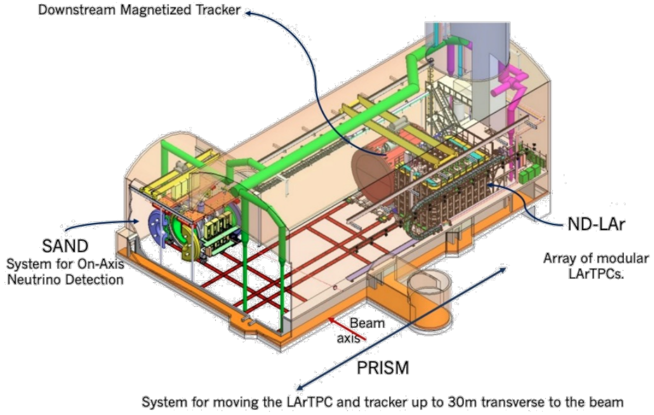
Path to Precision Measurements

Improved near detector capabilities



Engagement with the nuclear theory community

GiBUU

Genie

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

NuWro

Wroclaw Neutrino Event Generator

Dedicated lepton-nucleus cross-section measurement programs

SBN Program

MINERvA

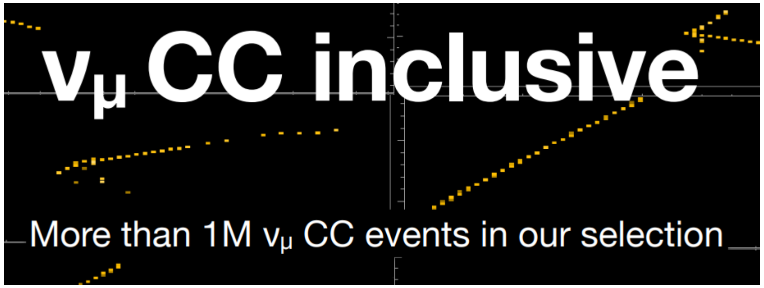
e4ν

Undetectable, you say?

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

Well, have I got *νs* for you!

L. Cremonesi NEUTRINO 2020



ν_μ CC inclusive

More than 1M ν_μ CC events in our selection

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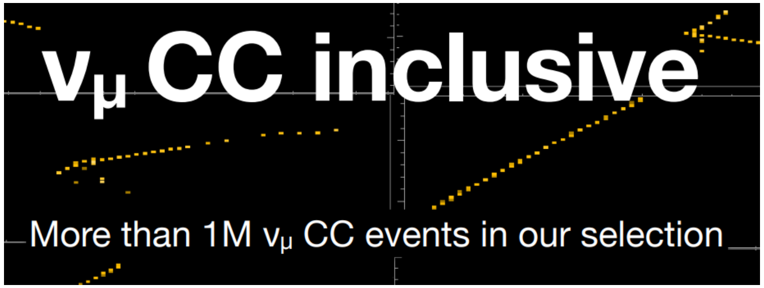

ν_μ CC inclusive

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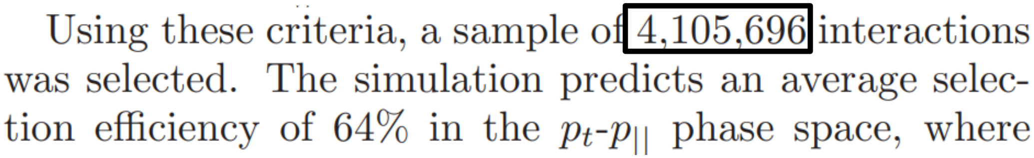
Phys. Rev. D **104**, 092007



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

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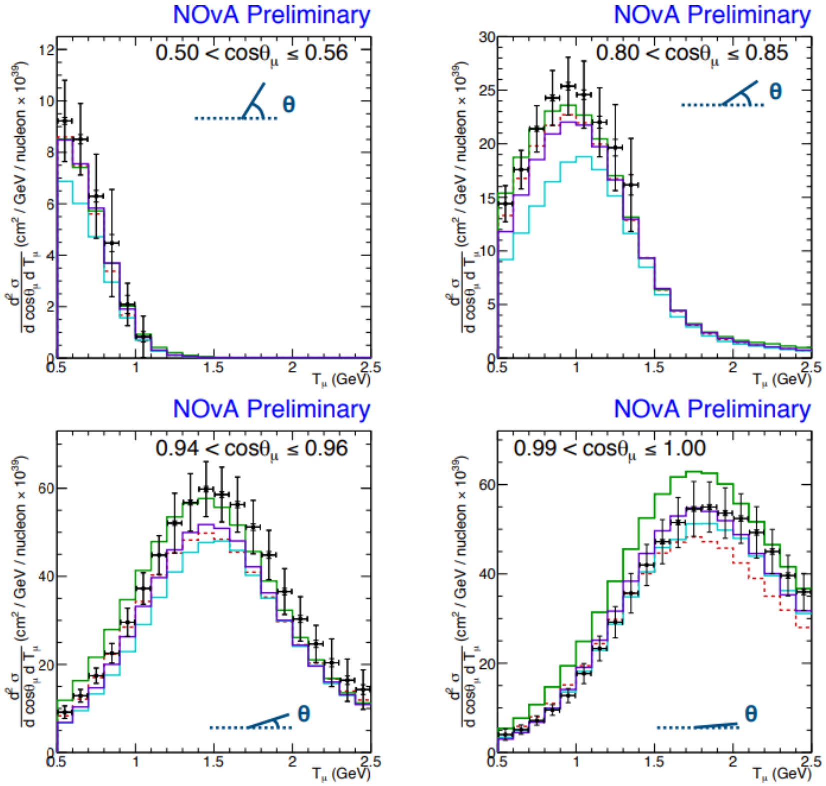
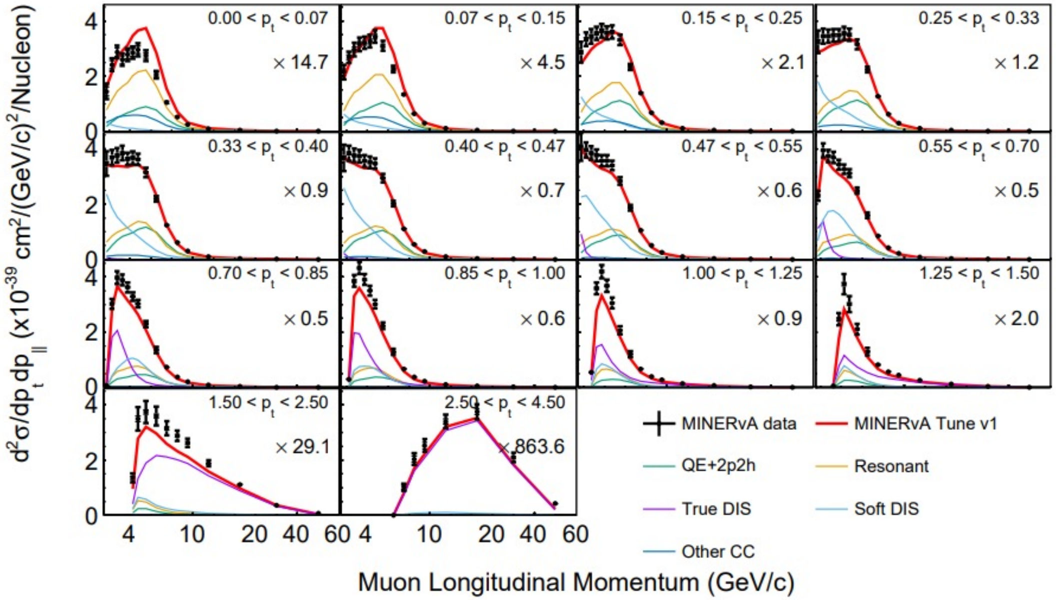
Well, have I got *νs* for you!

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

L. Cremonesi NEUTRINO 2020

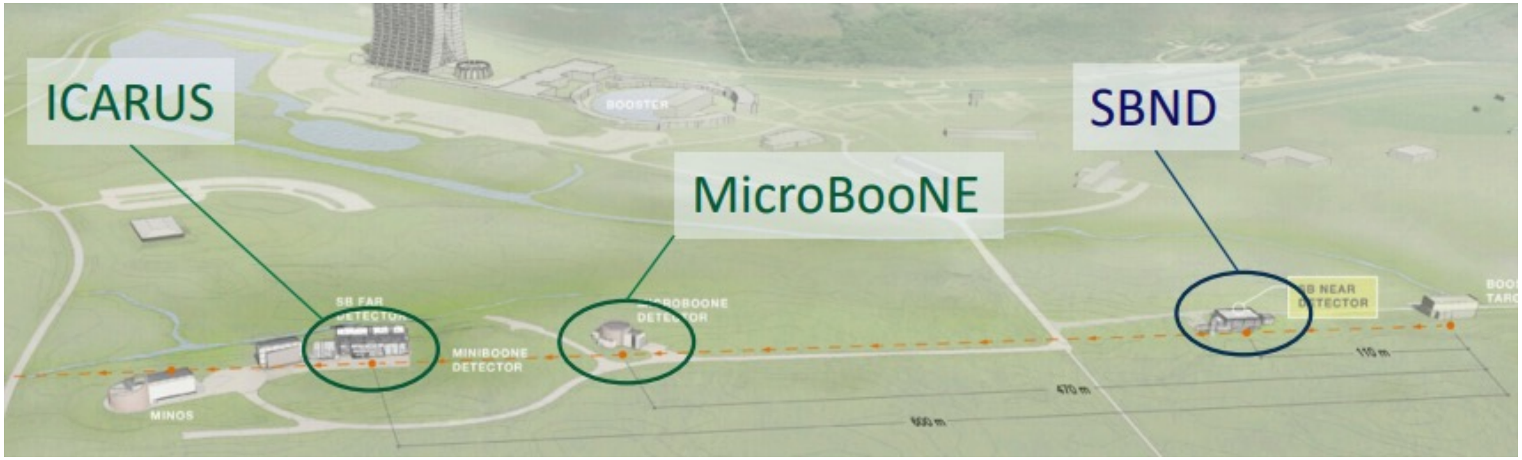
Phys. Rev. D **104**, 092007





A bright future for Argon

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



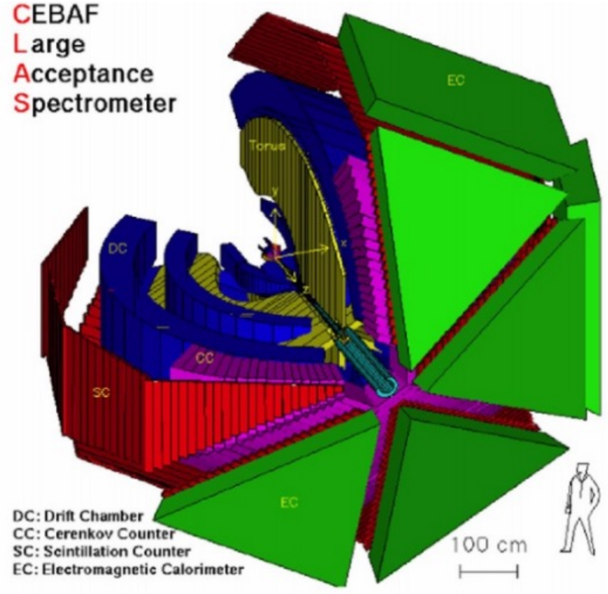
- **MicroBooNE**: already producing interesting results
- **ICARUS**: taking physics data
- **SBND:** enormous event rates coming soon (1M ν/y)

Beyond SBN:

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

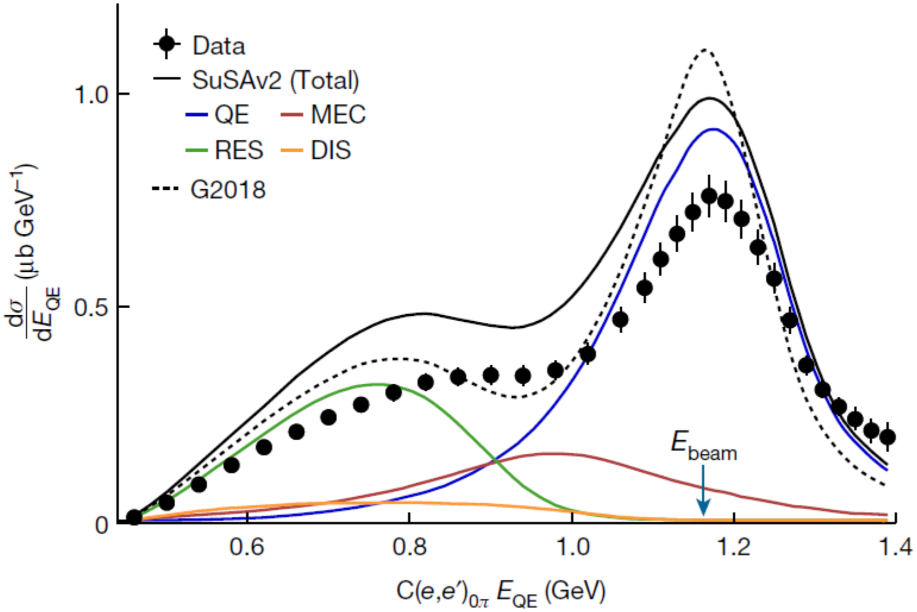
Tailored electron scattering

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



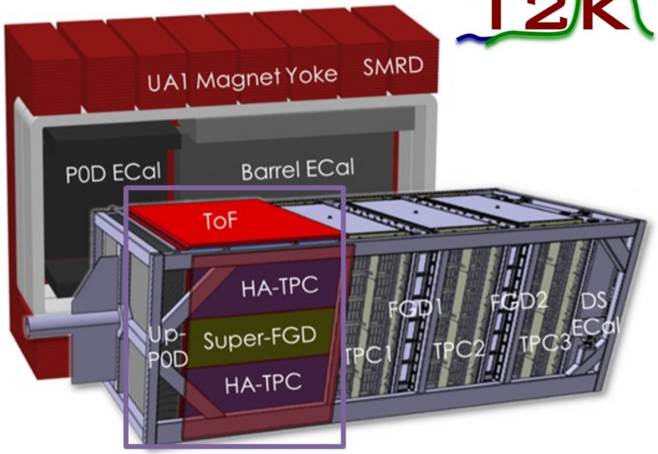
- Our models are becoming more able to make neutrino and electron scattering predictions in the same framework

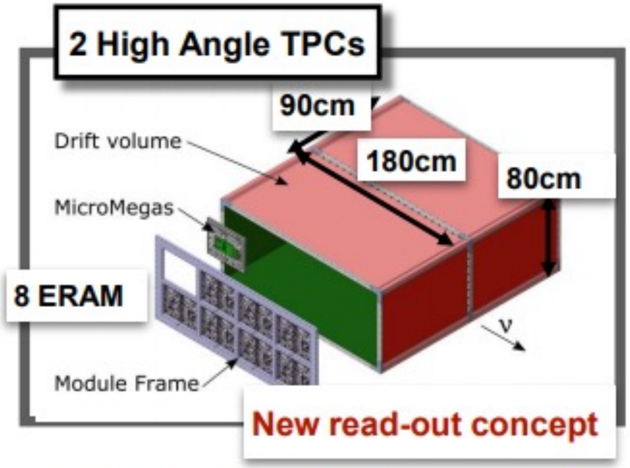
- New data from CLAS (e-scatting): specifically to help better understand neutrino scattering



arXiv:1901.03750

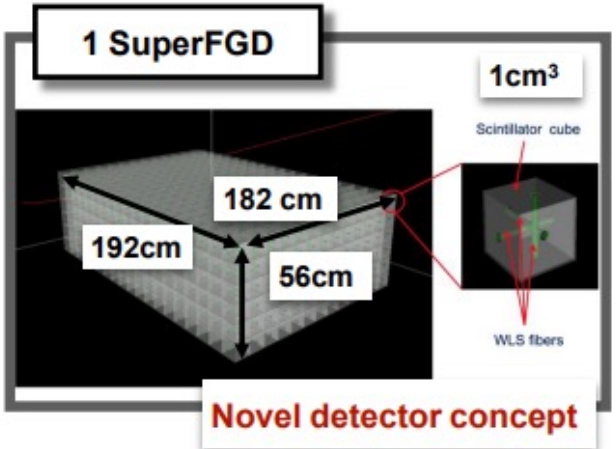
Improved near detectors




2 High Angle TPCs

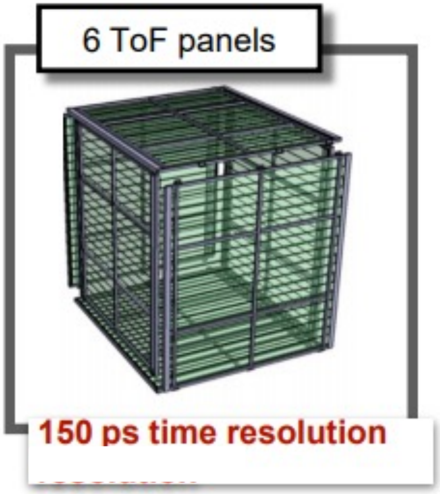
New read-out concept

NIM A 957 163286 (2020)


1 SuperFGD

Novel detector concept

JINST 13, P02006 (2018)
JINST 15 P12003 (2020)


6 ToF panels

150 ps time resolution

JPS Conf. Proc. 27, 011005 (2019)

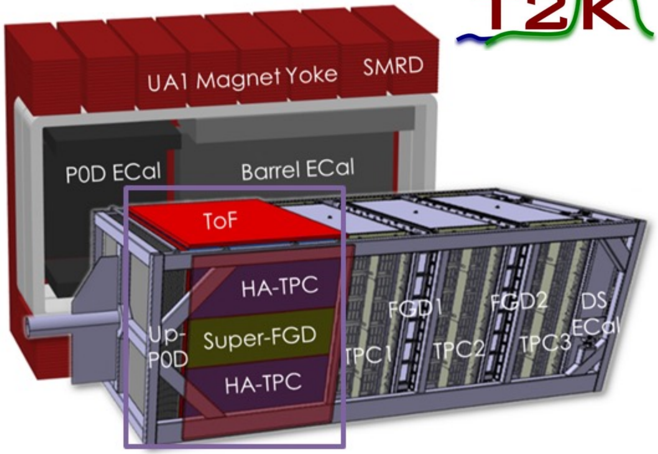
arXiv:1901.03750

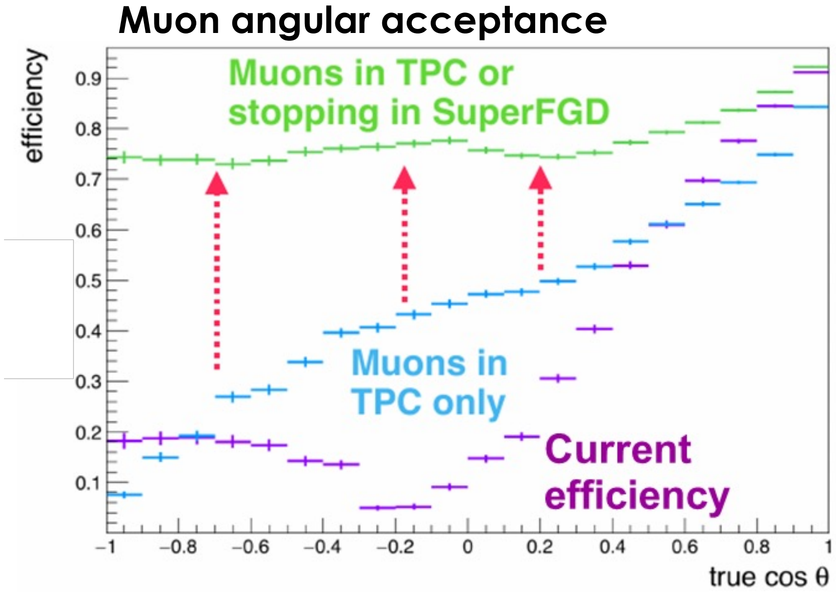
Improved near detectors

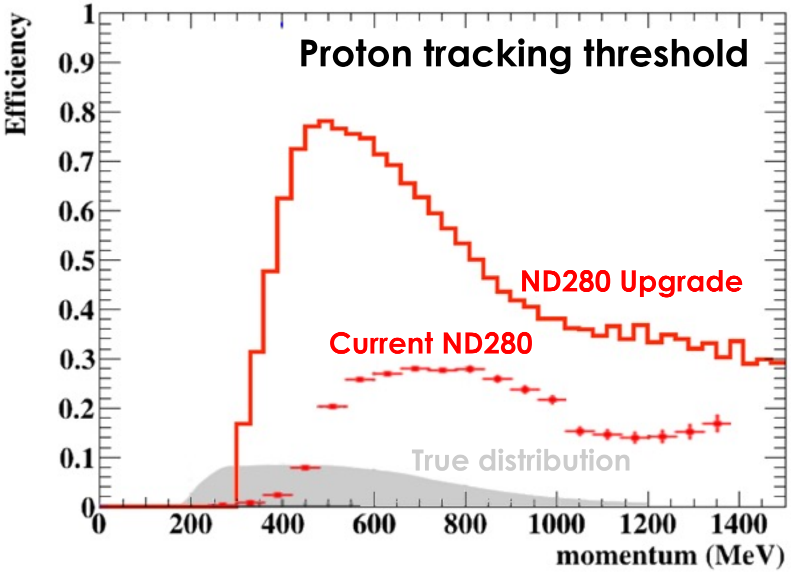
- 4π angular acceptance
- Lower tracking thresholds

$p_p^{thresh} \sim 300\ MeV/c$

$p_\mu^{thresh} < 100\ MeV/c$







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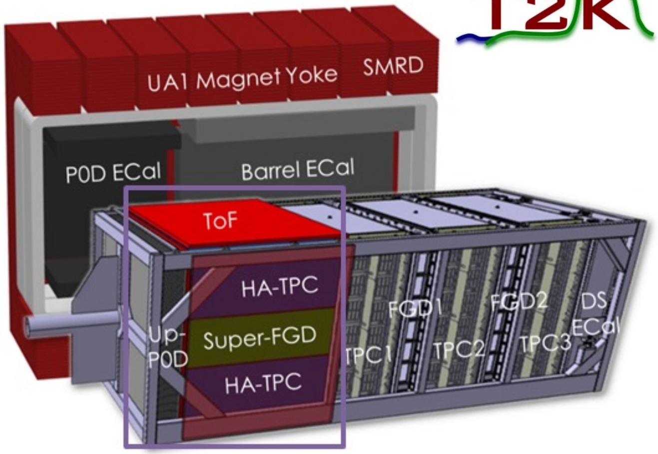
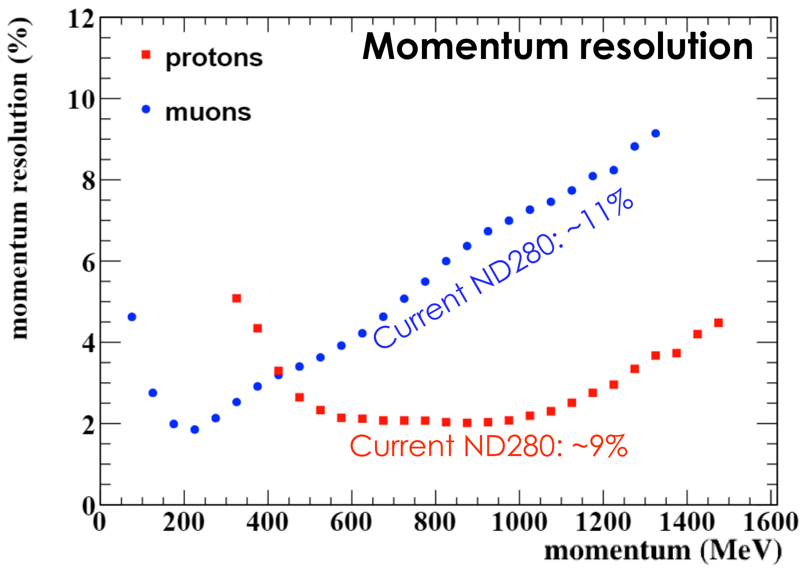
Improved near detectors

- 4π angular acceptance
- Lower tracking thresholds $p_p^{thresh} \sim 300\ MeV/c$ $p_\mu^{thresh} < 100\ MeV/c$
- Substantially improved resolutions $\Delta p_p / p_p < 5\%$





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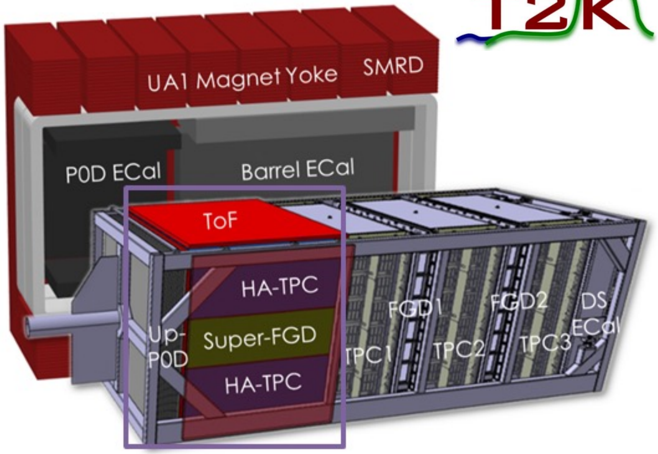
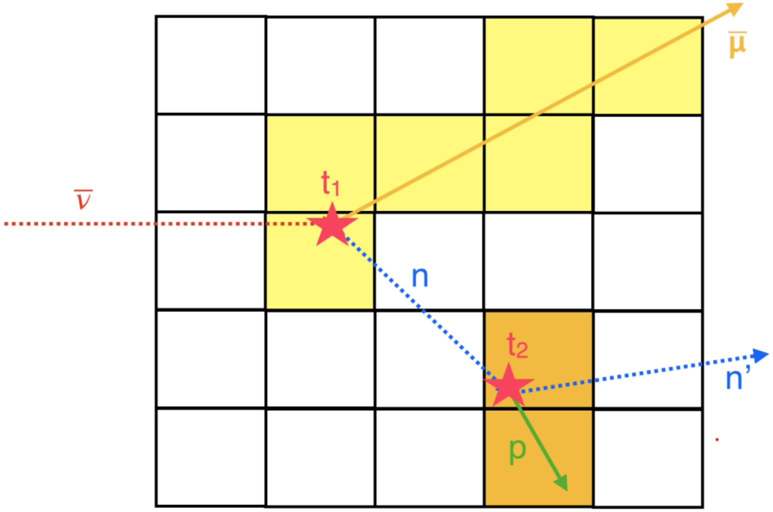
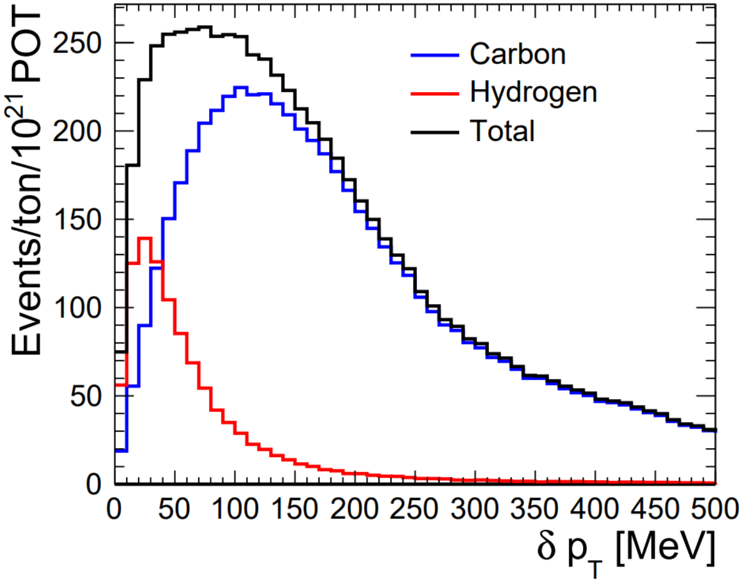
  Phys. Rev. D **105**, 032010
- Better timing resolution enables neutron energy measurements! $\Delta p_n / p_n < 30\%$

Phys. Rev. D **101**, 092003 (2020)
arXiv:2310.15633







Summary and outlook

- Neutrino oscillation measurements are entering **an era of precision measurements**
    - **Present:** few-% precision on most PMNS parameters, first significant constraints on δ_{CP}, closing in on the mass ordering
    - **Near future (~2030):** determination of mass ordering, exclusion of CP-conserving values of δ_{CP} (if δ_{CP} is large)
    - **Longer term:** physics beyond PMNS, tests of unitarity, a powerful complementary program ***to search for new physics***

Summary and outlook

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    - **Longer term:** physics beyond PMNS, tests of unitarity, a powerful complementary program ***to search for new physics***
- A detailed understanding of neutrino-nucleus interactions is **crucial for current and future experiments** to realise their extraordinary goals
- This is **challenging task** mismodelling of subtle nuclear processes can cause **leading-order biases** on measurements of oscillations
- We've made **enormous progress** in neutrino interaction physics over the last 10 years, but **still have some way to go**
- Expect plenty of **exciting new results** and a continued exponential growth of the field in the run up to DUNE & Hyper-K.

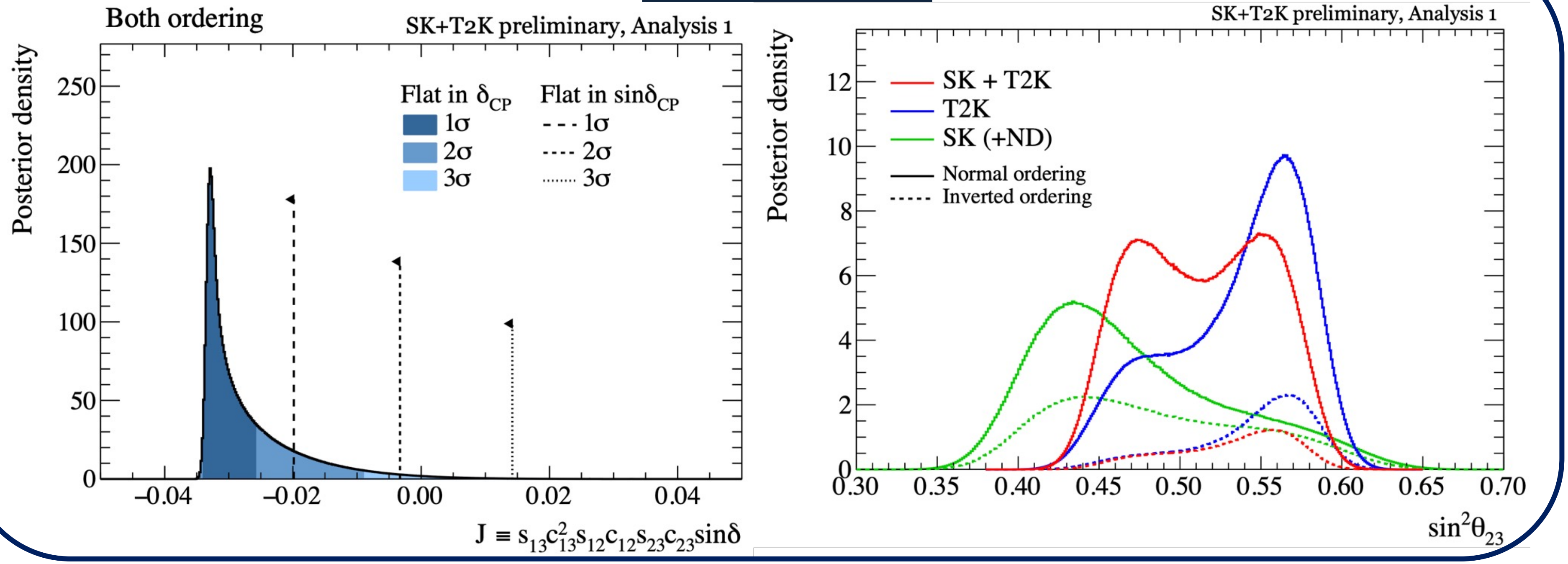
Backups

T2K+SK Joint Fit

- Stronger constraints w.r.t. T2K and SK naïve combinations
- CP-conservation (J=0) excluded at ~2σ
- Preference for normal mass ordering
    - ~90% posterior probability

HOT OFF THE PRESS!

T2K, NuTel 2023

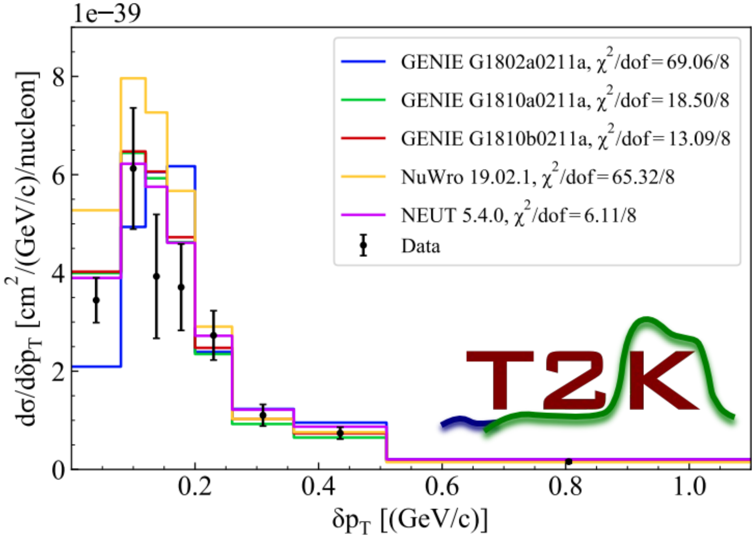


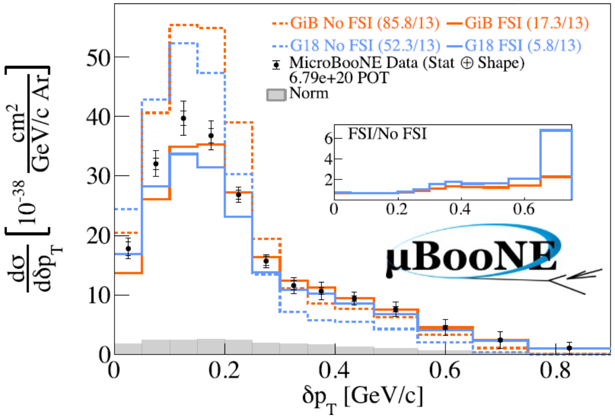
Generators vs data: a horror story

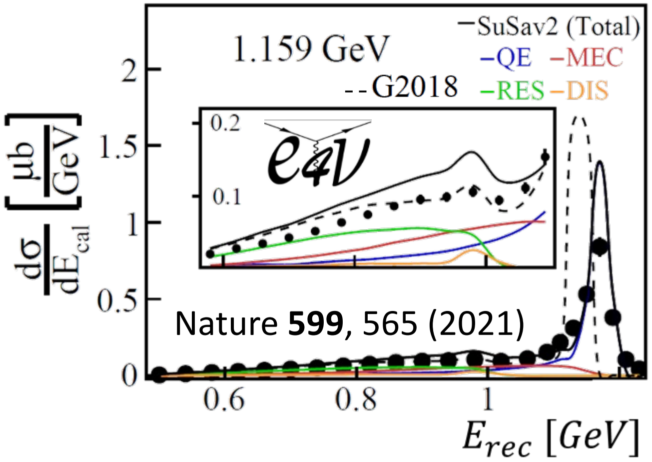
- No generator can come close to describing global lepton nucleus scattering data
  - All models are “wrong”, but they are each wrong in different ways

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

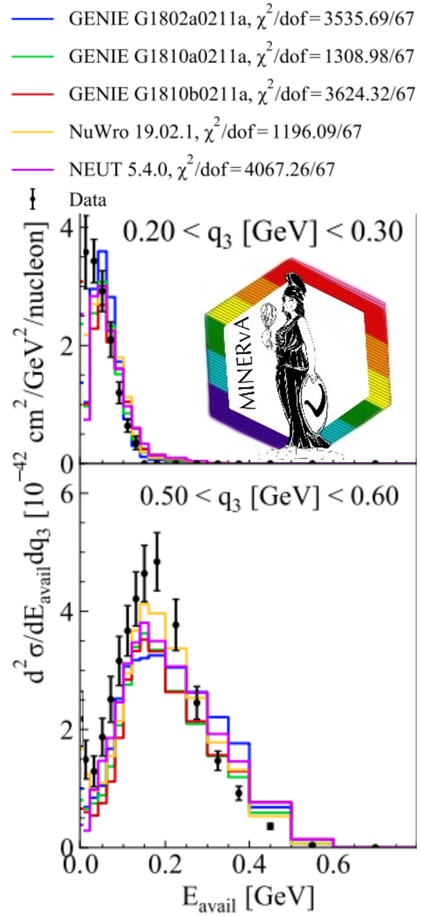
$$\chi^2_{allModels} \gg N_{bins}$$







Nature **599**, 565 (2021)



The hadronic current

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

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

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

f_{3V}, f_{3A} are "second class currents", typically set to 0 for cross-section calculations, ξ is the difference between proton and neutron anomalous magnetic moments

- The other f factors are the "form factors" (read "fudge factors")
- These give us a way of parameterising the fact that the nucleon we interact with in an extended object.
- It turns out that the Fourier transform of form factors are what represents a physical distribution
- A dipole form factor represents an exponential distribution

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

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- f_{1V}, f_{2V} (vector form factors) can be extracted from electron scattering experiments. f_p can be related to f_A ("Partially Conserved Axial Current Hypothesis")

- f_A, we guess the form of! Usually we take a dipole with one free parameter: the infamous nucleon axial mass (M_A)

- We constrain the axial form factor with bubble chamber neutrino-nucleon (or light nucleus) data.

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

Llewellyn-Smith CCQE

- Putting this all together gets us to the cross section

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

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

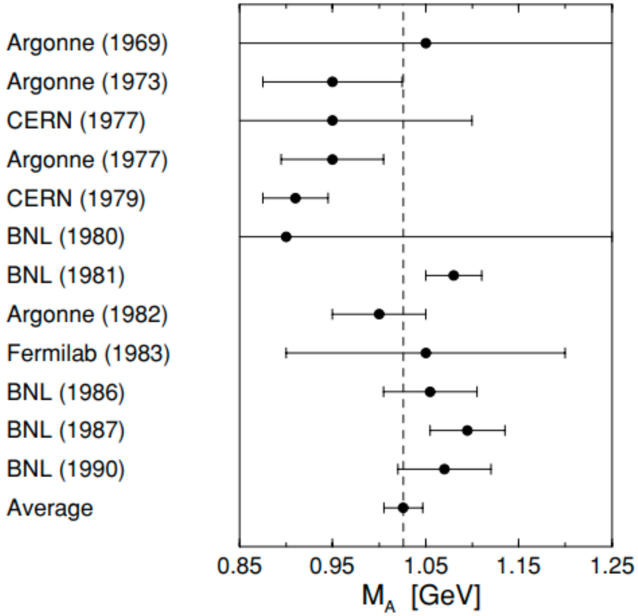
Neutrino reactions at accelerator energies, Llewellyn Smith, 1972

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

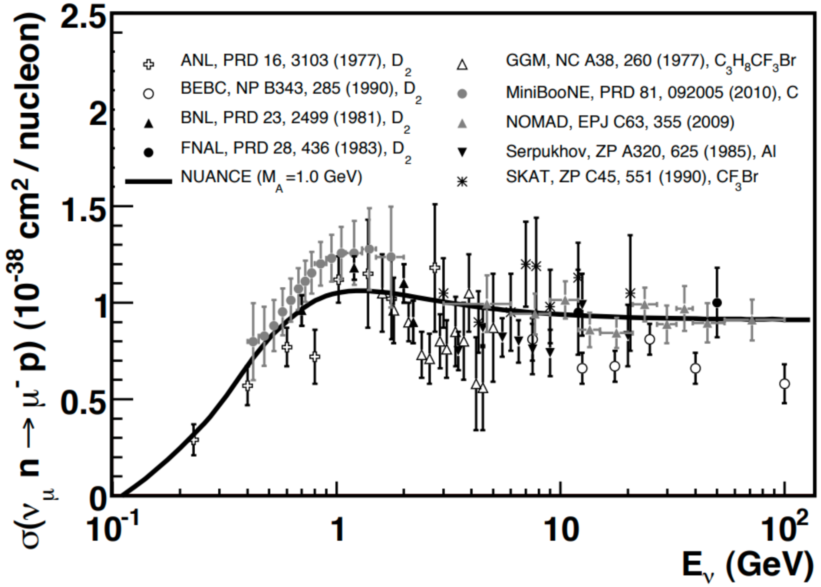
$$B\simeq\frac{1}{M^2}\left(\mathrm{Re}\left(f_{1V}f_A^*\right)+\xi\mathrm{Re}\left(f_{2V}f_A^*\right)\right)t\qquad C=\frac{1}{4}\left(|f_{1V}|^2+|f_A|^2-\frac{\xi^2|f_{2V}|^2}{4M^2}t\right)$$

The nucleon axial mass

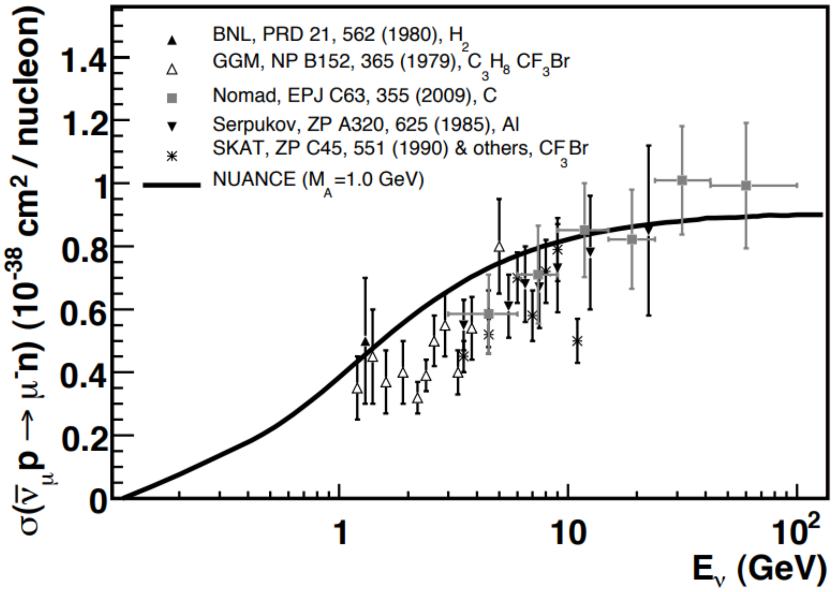
Journal of Physics G: Nuclear and Particle Physics, Volume 28, Number 1



- We constrain the axial form factor with bubble chamber neutrino-nucleon (or light nucleus) data.
- The results seem pretty consistent with $M_A \sim 1\ GeV$

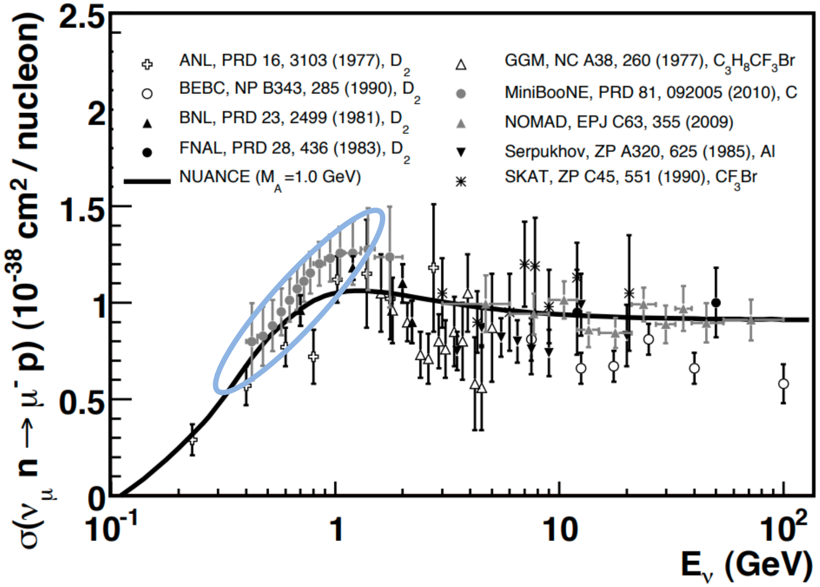


J. A. Formaggio and G. P. Zeller Rev. Mod. Phys. **84**, 1307



The nucleon axial mass “puzzle”

- Some heavier nuclear target experiments also try to measure M_A
- Now things don’t look so good
- We’ll come back to this …



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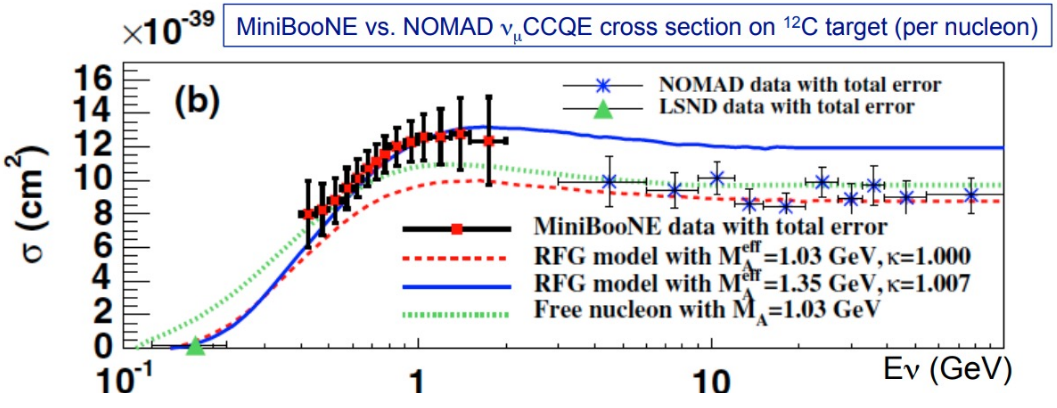
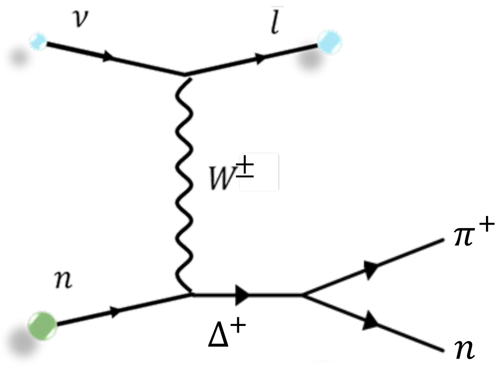


Resonant Pion Production

CCRES



CC Single Pion Production (SPP) final states

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

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

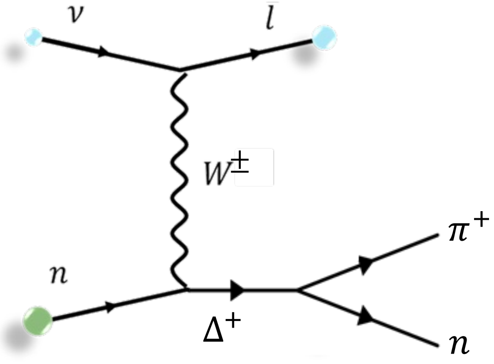
- Neutrinos can excite a nucleon into a resonance state, which then decays to give a nucleon + meson final state
- The dominant intermediate resonance is the $\Delta(1232)$ but others can contribute, as can non-resonant pion production
- And the contributions from each should have interference terms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

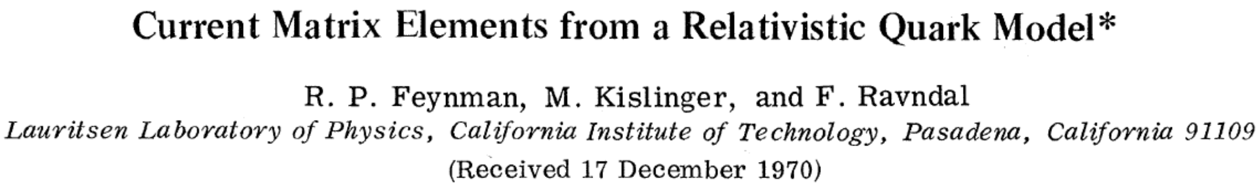
$$\frac{d\sigma}{dW\,dQ^2\,d\Omega_\pi}$$

Contains polar and azimuthal angle

Resonant Pion Production

CCRES



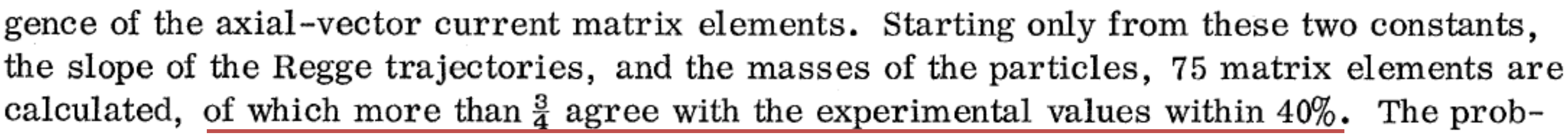

Current Matrix Elements from a Relativistic Quark Model*

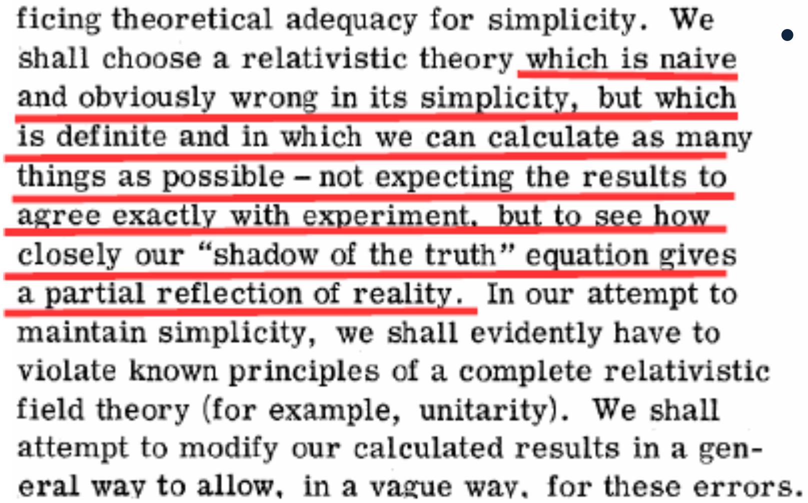
R. P. Feynman, M. Kislinger, and F. Ravndal

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

(Received 17 December 1970)

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


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


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

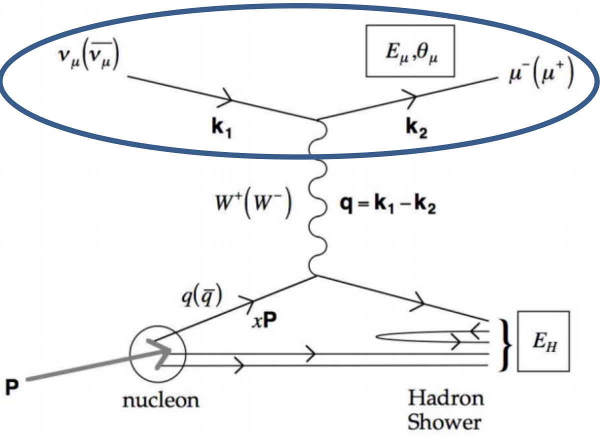
- The model includes its own form factors, including an axial part with an analogous M_A (and an additional uncertainty in the form factor numerator)

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

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

Deep inelastic scattering

CCDIS



- Given enough energy, neutrinos can resolve the quarks within a nucleon. This is deep inelastic scattering.

- At high energies, the *inclusive* (i.e. integrating over possible hadronic final states) cross-section is fairly well understood (perturbative QCD):

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

$$\begin{aligned} x &= \frac{Q^2}{2M\nu} = \frac{Q^2}{2ME_\nu y} \\ y &= E_{had}/E_\nu \\ Q^2 &= -m_\mu^2 + 2E_\nu(E_\mu - p_\mu\cos\theta_\mu) \end{aligned}$$

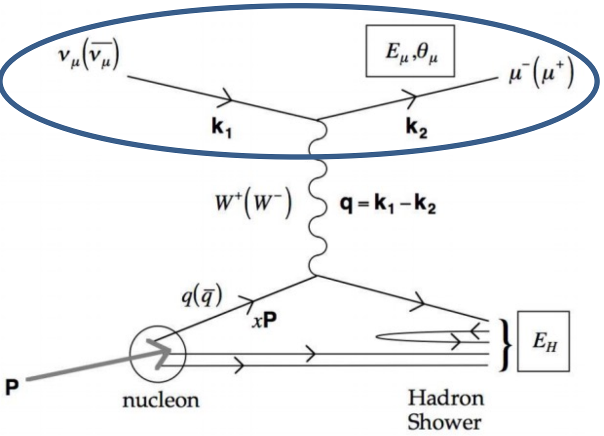
- The $F_i(x,Q^2)$ are nuclear structure functions, which are dimensionless and encompass the quark structure of nucleons

- The first two can be measured with e-scattering, the last one is from the weak VA interference term: only accessible with neutrinos!

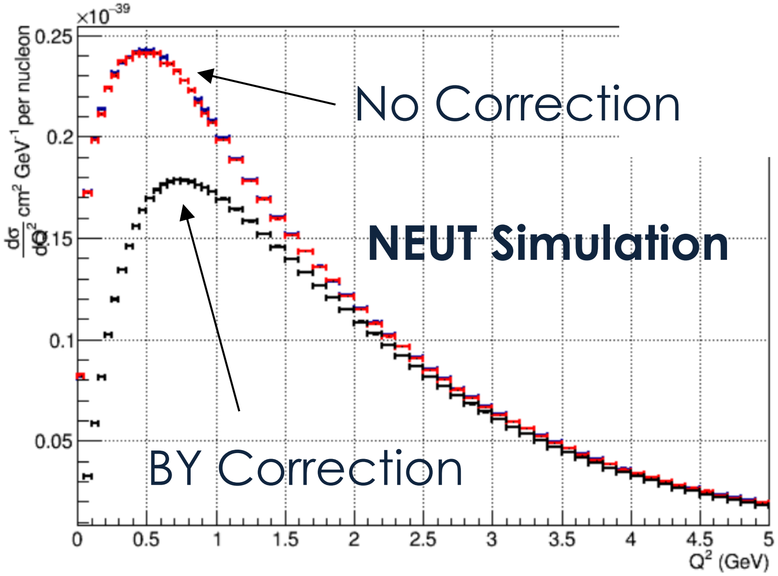
Deep inelastic scattering

https://arxiv.org/abs/1012.0261

CCDIS



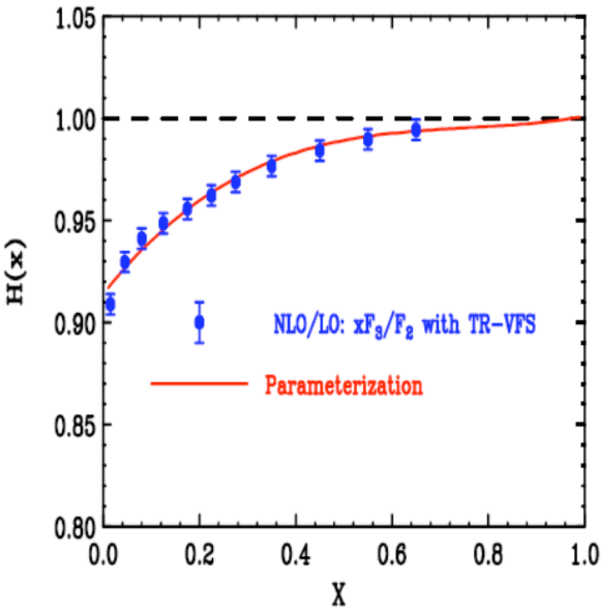
- At low energies (or actually low Q^2) QCD becomes non- perturbative.
- Bodek-Yang: extrapolate down to low Q^2 assuming some parametrised scaling. Fix the details with e-scatting, apply to ν- scattering
- But this is an empirical treatment that comes with uncertainties



No Correction

NEUT Simulation

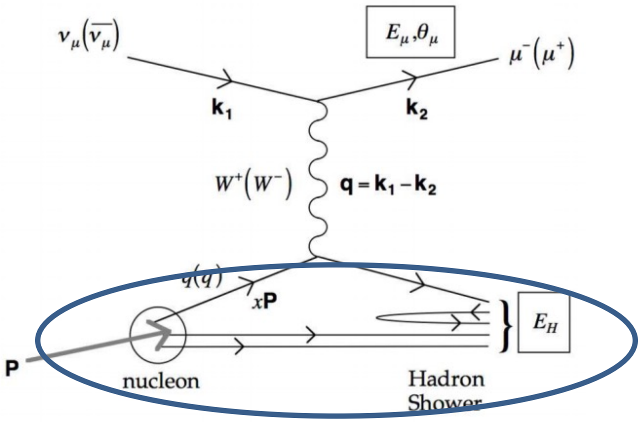
BY Correction



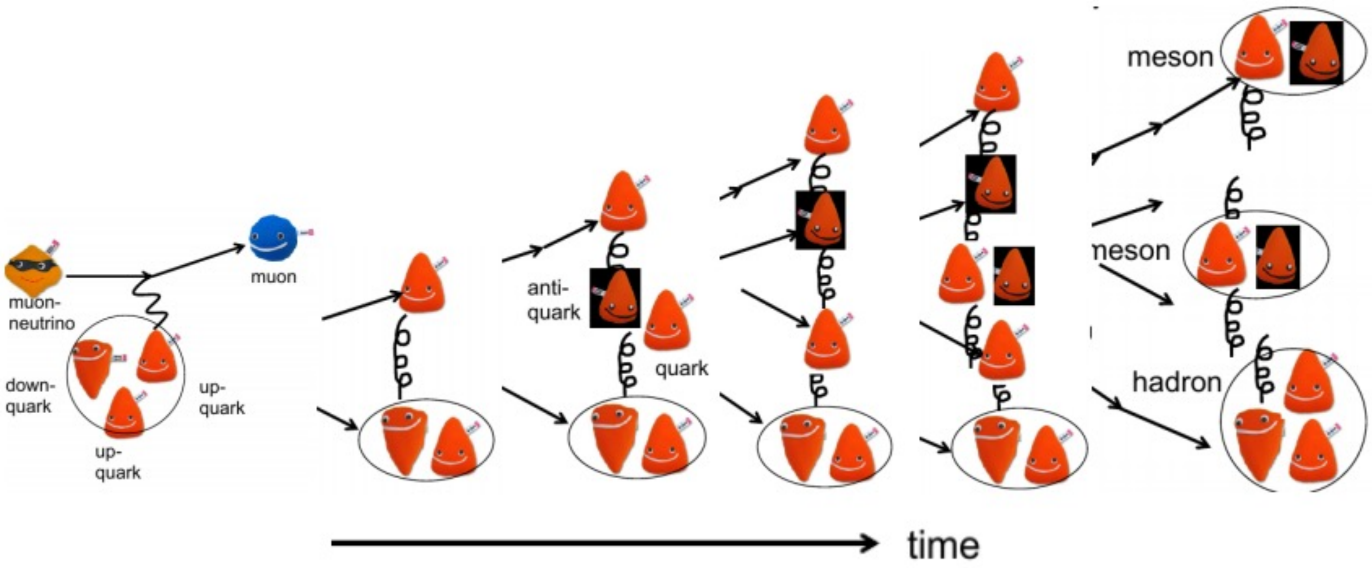
https://arxiv.org/abs/1012.0261

Deep inelastic scattering

CCDIS



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



T. Katori

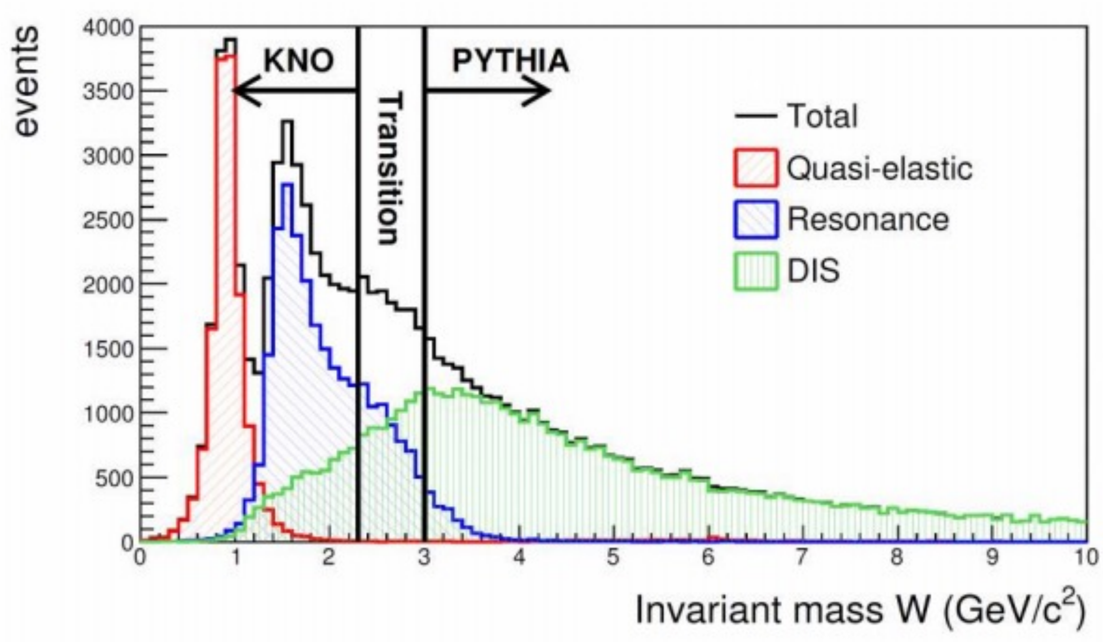
DIS-RES Transition Region

- 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)

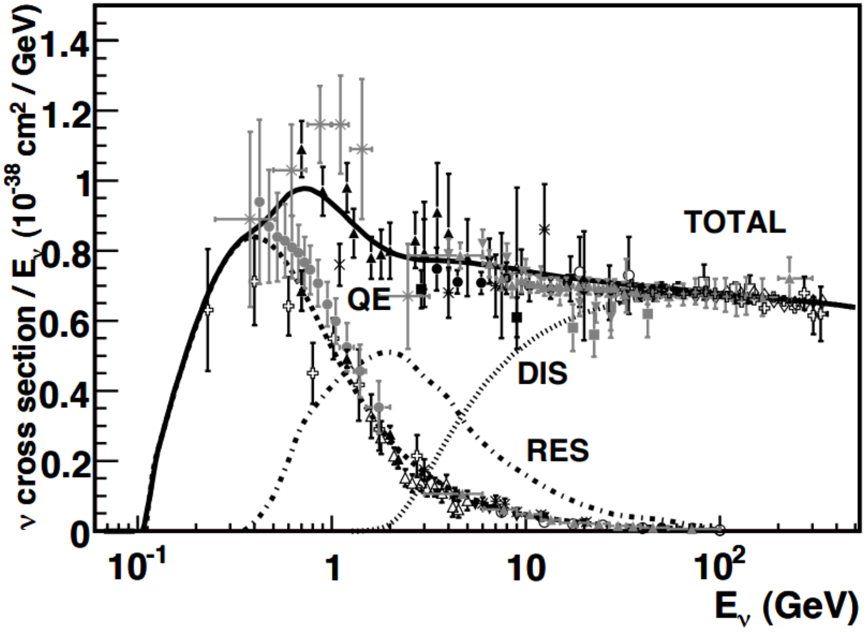
W = interaction invariant mass

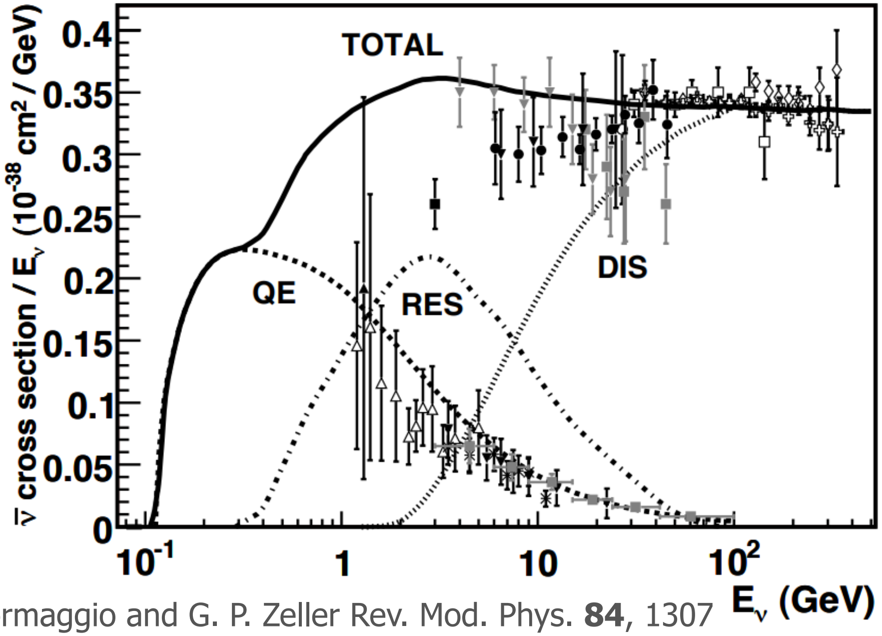
- But this is an imprecise method applied to a region that will be important for DUNE



Neutrino-nucleon cross sections

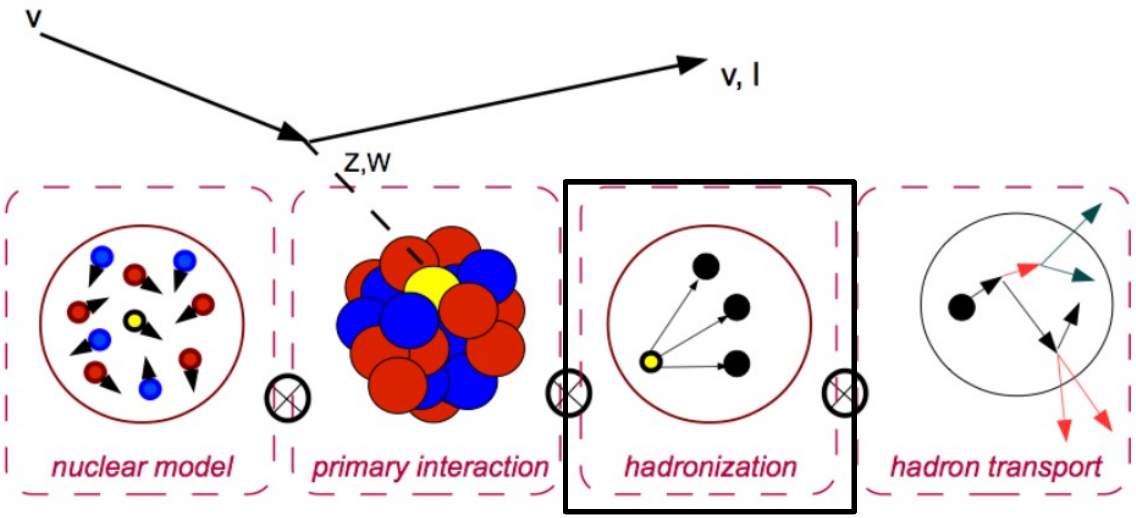
- Discussed neutrino-nucleon interactions
- But it’s been a long time since we’ve measured this process!
- Almost all modern experiments use nuclear targets

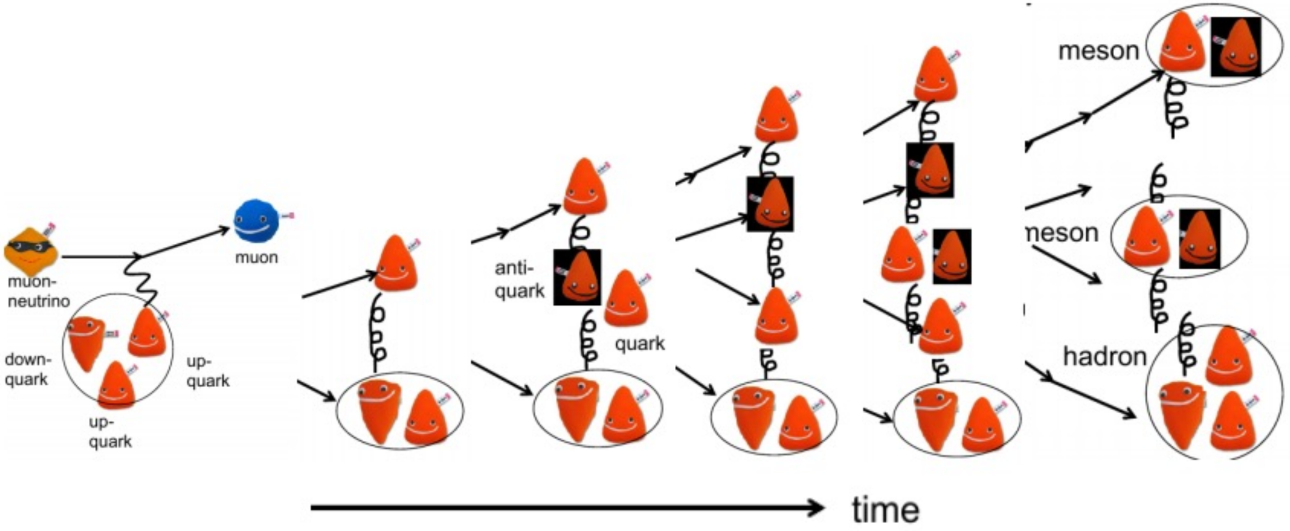




J. A. Formaggio and G. P. Zeller Rev. Mod. Phys. **84**, 1307

Neutrino-nucleus scattering





T. Katori

Where are we so far?

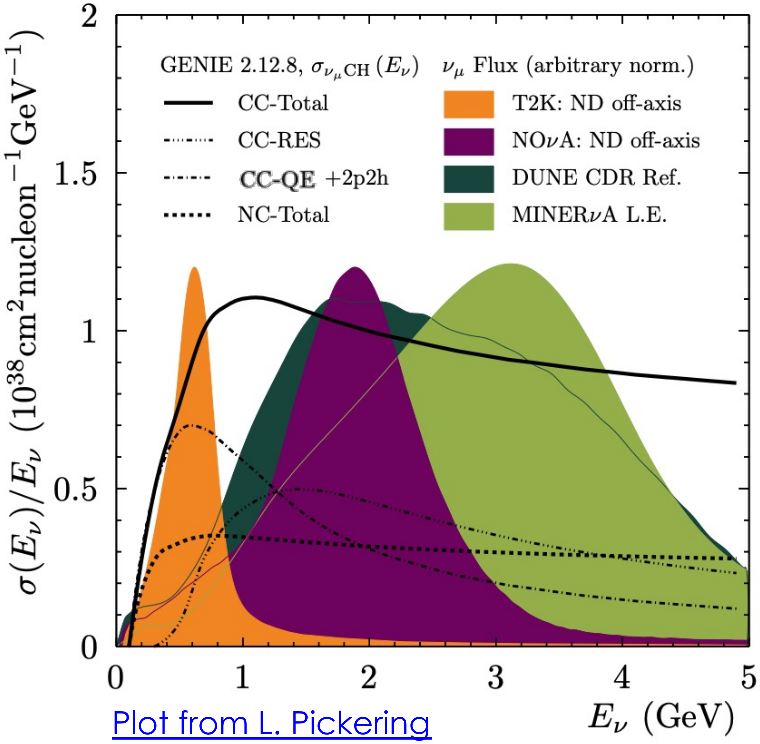
- Key questions:

  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?*

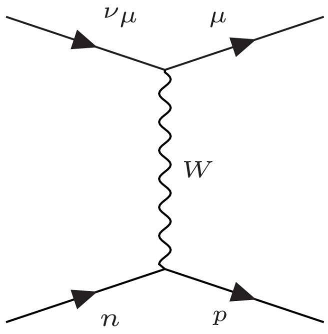
Neutrino-nucleus cross sections



Plot from L. Pickering

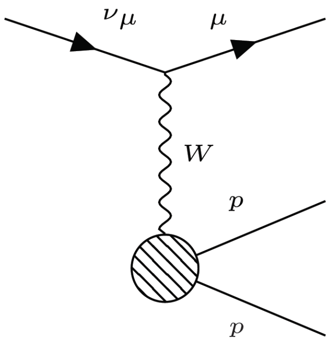
CC-QE

(Charged-Current Quasi-Elastic)



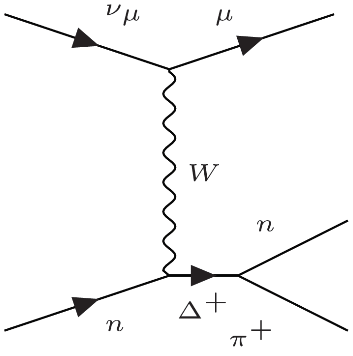
CC-2p2h

(Two-Particle-Two-Hole)



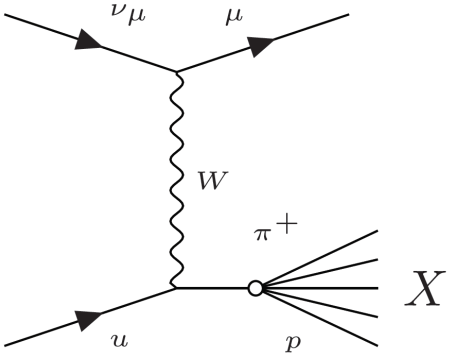
CC-SPP

(Single Pion Production)

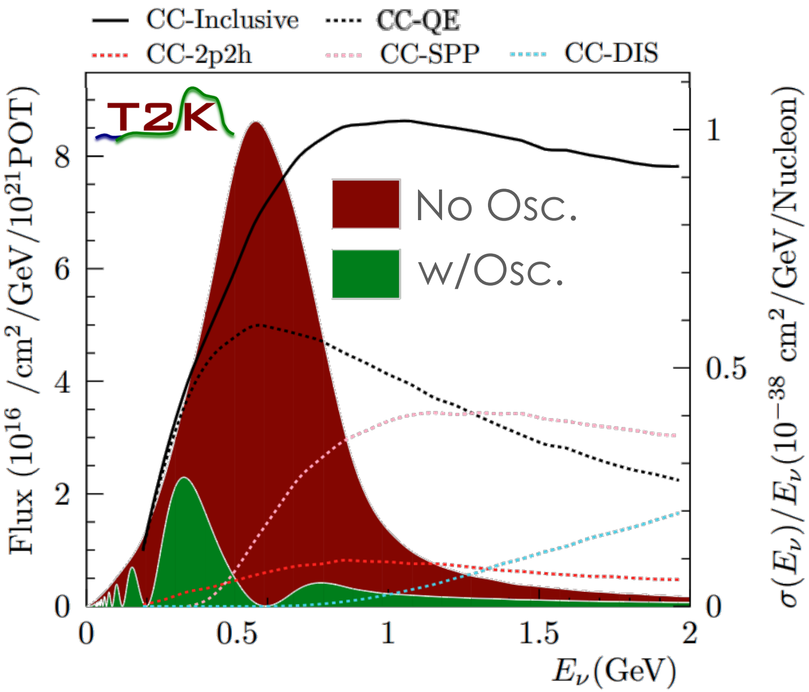


CC-DIS

(Deep Inelastic Scattering)

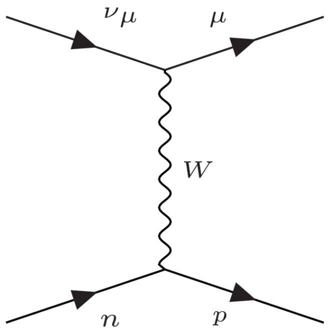


Neutrino-nucleus cross sections



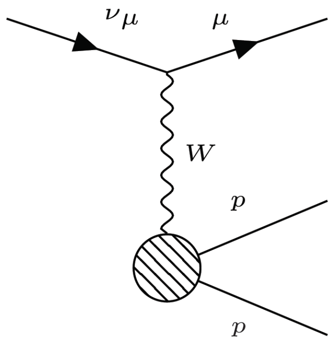
CC-QE

(Charged-Current Quasi-Elastic)



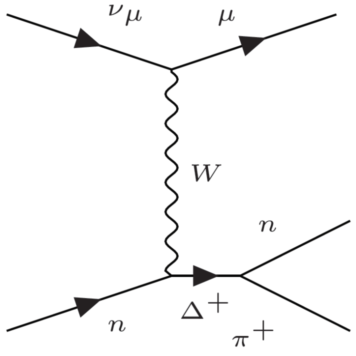
CC-2p2h

(Two-Particle-Two-Hole)



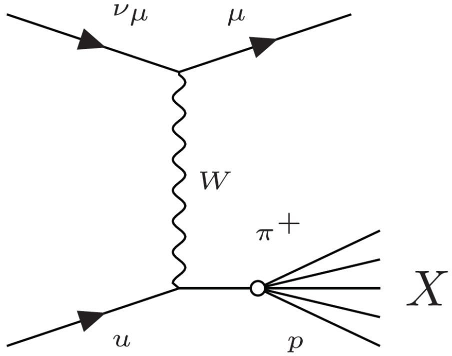
CC-SPP

(Single Pion Production)

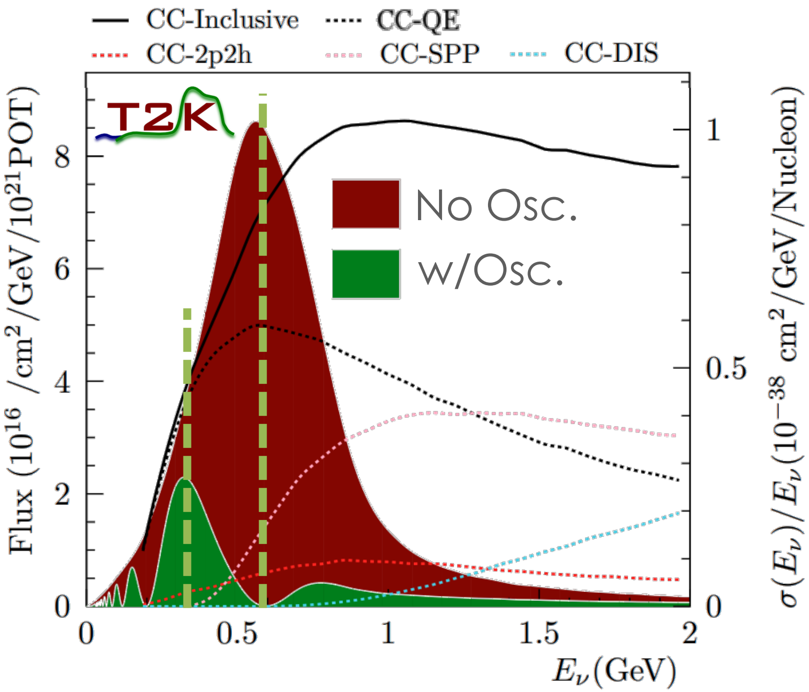


CC-DIS

(Deep Inelastic Scattering)

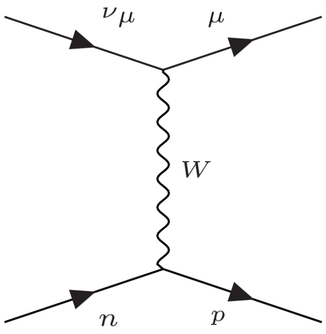


Event rates to oscillation parameters



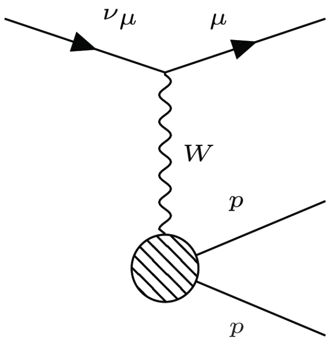
CC-QE

(Charged-Current Quasi-Elastic)



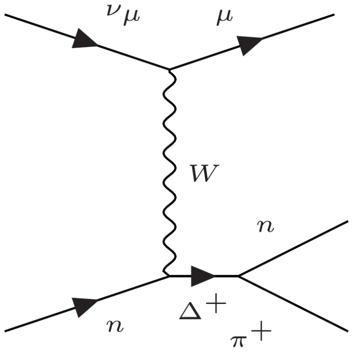
CC-2p2h

(Two-Particle-Two-Hole)



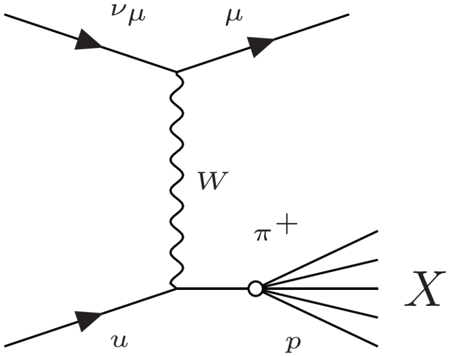
CC-SPP

(Single Pion Production)

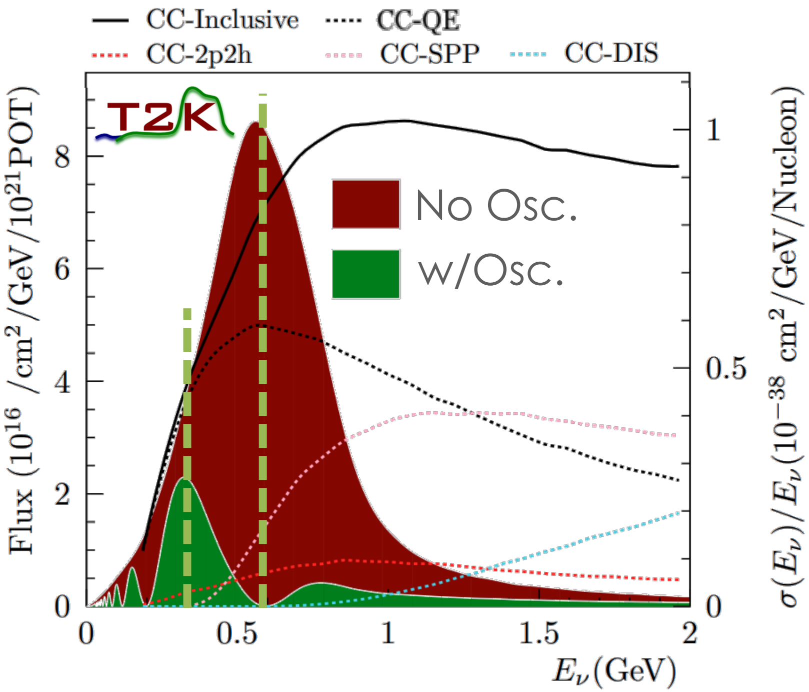


CC-DIS

(Deep Inelastic Scattering)



Event rates to oscillation parameters



- Near / far ratios don't fully cancel systematics:
  - Dramatic change in E_ν distribution due to oscillations
  - ν_μ at ND vs ν_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

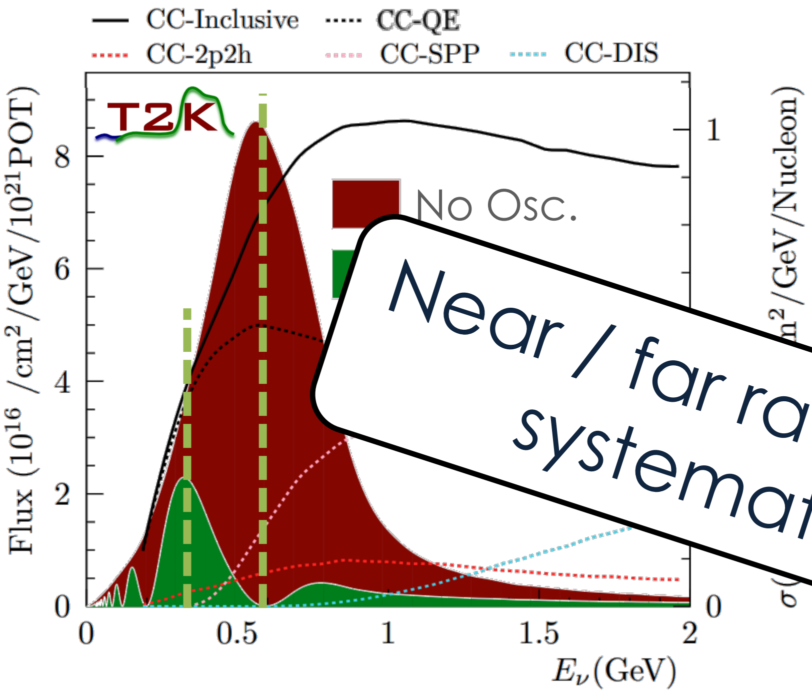
At the far detector

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

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

Oscillation probability

Event rates to oscillation parameters



- Near / far ratios don't fully cancel systematics:
  - Dramatic change in E_ν distribution due to oscillations
  - ν_μ at ND vs ν_e at FD (for
    arance)
  - design,

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

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

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

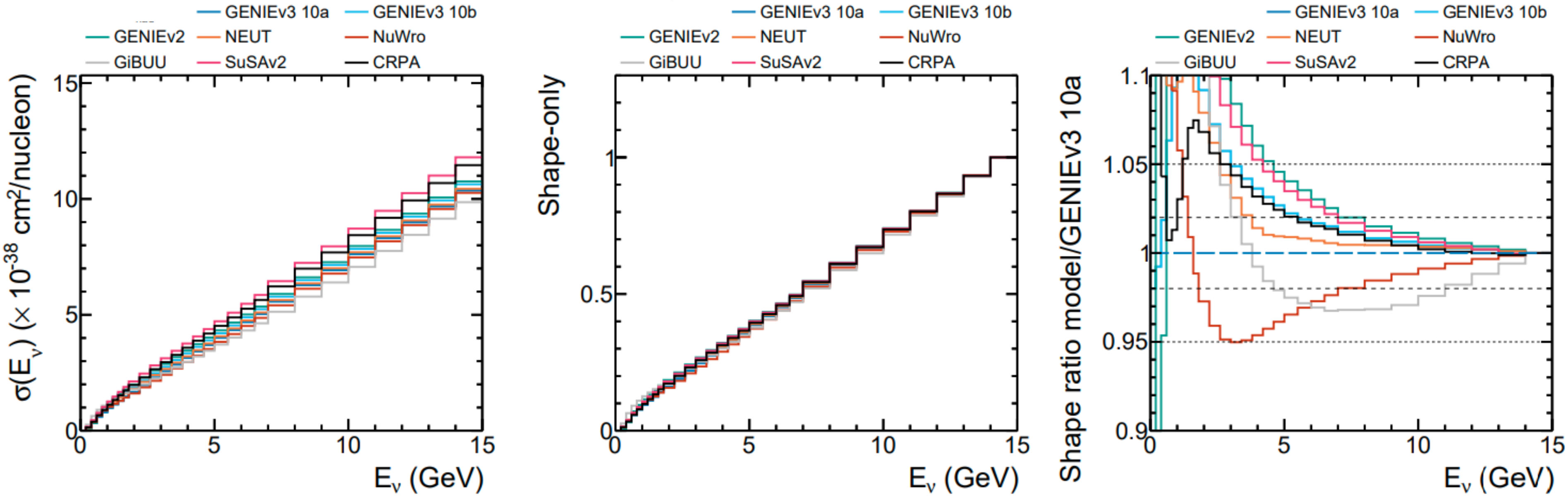
$$N_e(E_\nu) = P(\nu_\mu \to \nu_e)\sigma(E_\nu)\Phi_\nu(E_\nu)\epsilon(E_\nu)$$

Oscillation probability

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

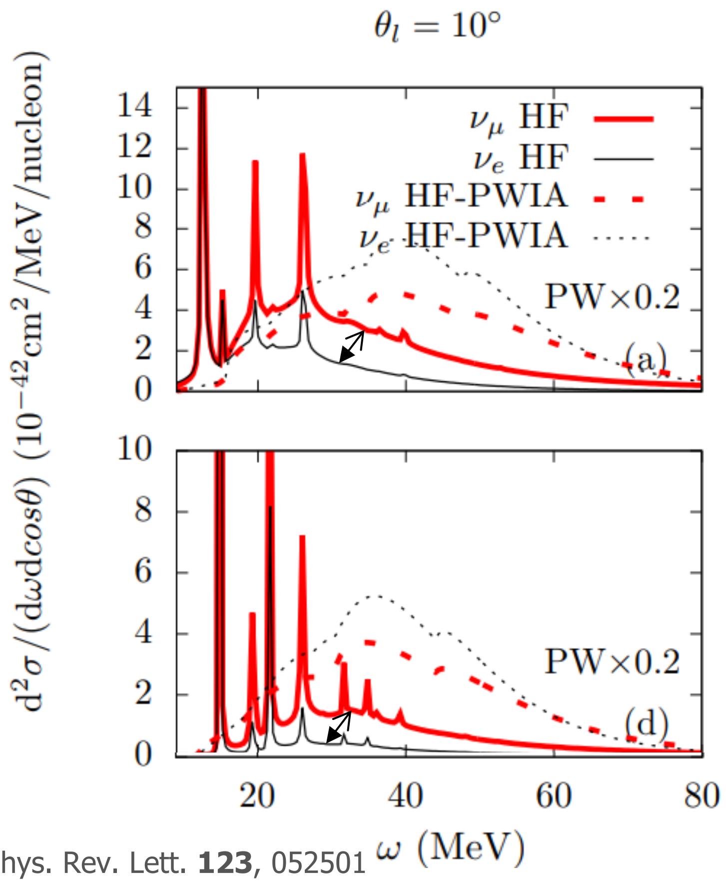
- What matters ND→FD extrapolation is the shape of total cross section as a function of E_ν
- Models differ by 5-10% in the region of interest for DUNE and Hyper-K
- Given expected statistics (~1000 ν_e, ~6000 ν_μ), this may be concerning
- Mitigation by direct measurements of cross section energy dependence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



Nuclear effects and $\sigma(\nu_e)/\sigma(\nu_\mu)$

- Ratio of ν_e to ν_μ critical for future oscillation analyses
  - Measure ν_μ at ND but need to know about ν_e to measure δ_{CP}

- This is also subject to subtleties in the nuclear physics…



Phys. Rev. Lett. **123**, 052501

- If the outgoing nucleon exits the nucleus as a "plane wave" (no FSI): $\sigma(\nu_e) > \sigma(\nu_\mu)$

- If the outgoing nucleon is distorted by the nuclear potential (FSI): $\sigma(\nu_e) < \sigma(\nu_\mu)$

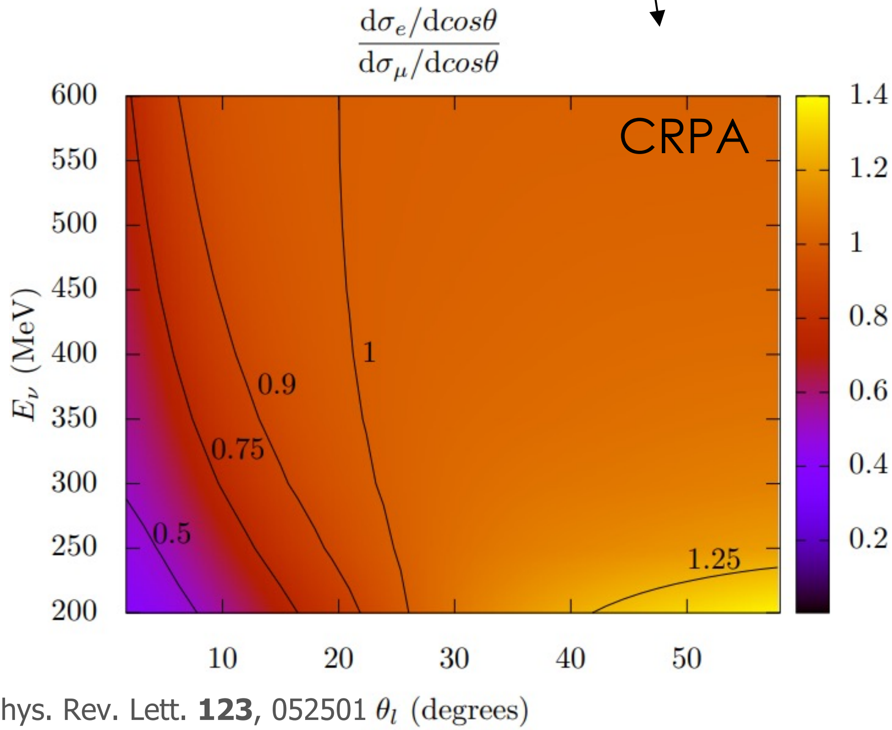
Nuclear effects and $\sigma(\nu_e)/\sigma(\nu_\mu)$

- Different models can predict quite different cross section ratios!
- Important for T2K/HK?

$$\frac{d\sigma_e/d\cos\theta}{d\sigma_\mu/d\cos\theta}$$

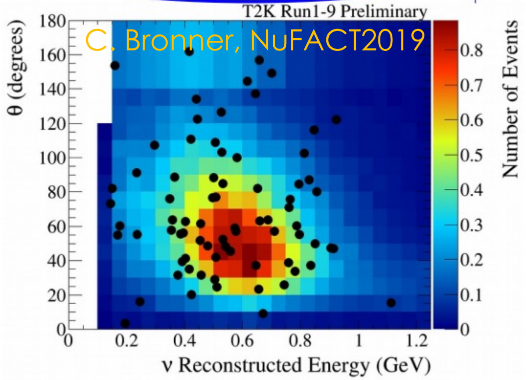
	$E_\nu = 200\ MeV$		$E_\nu = 600\ MeV$	
Model	5°	60°	5°	60°
RFG (w/PB)	0.64	1.61	0.97	1.03
SF (full)	1.41	1.92	1.04	1.03
CRPA	~0.5	~1.4	~0.9	~1.0

Tabulated from Phys. Rev. C **96**, 035501 and the left figure



Phys. Rev. Lett. **123**, 052501

These differences are predicted in regions that are relevant to T2K/HK oscillation analyses



C. Bronner, NuFACT2019

Nuclear effects and $\sigma(\nu_e)/\sigma(\nu_\mu)$

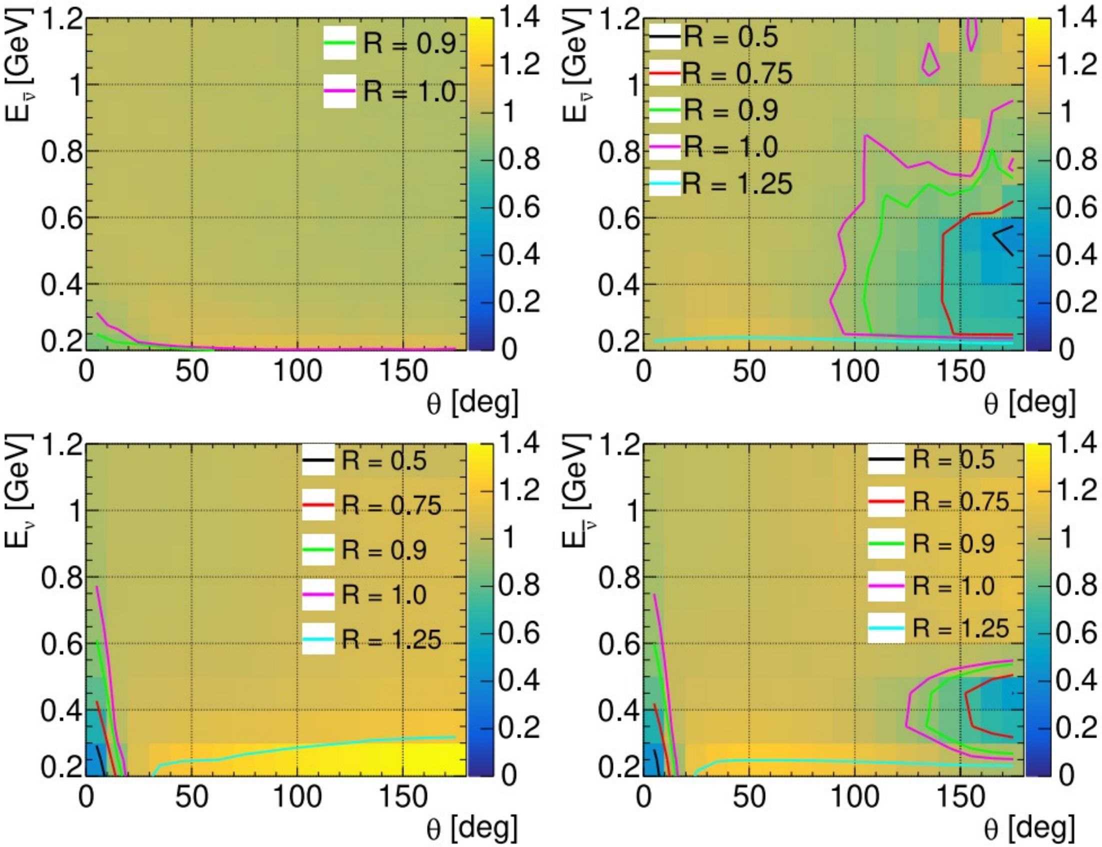
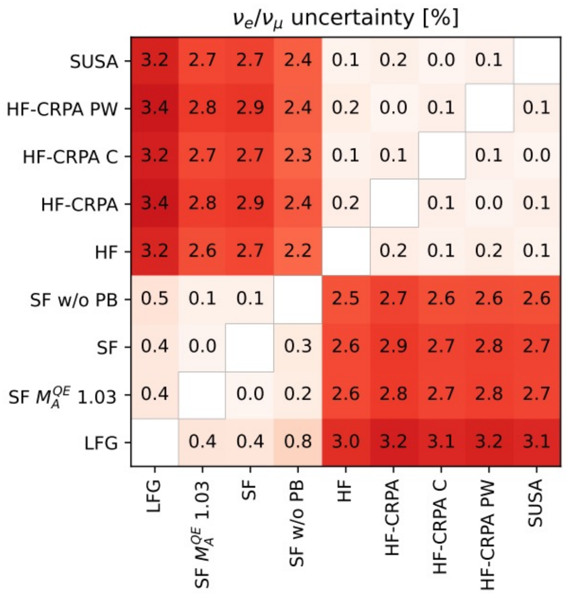


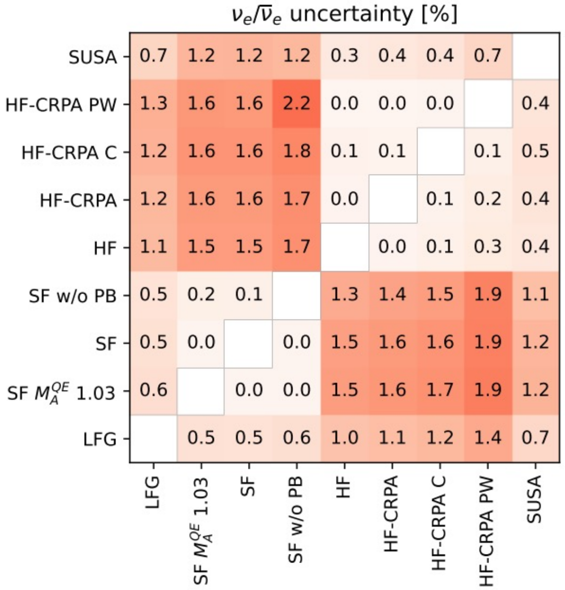
FIG. 1: $R^{\mathrm{SF}}_{\nu_e/\nu_\mu}$ (top-left), $R^{\mathrm{HF\text{-}CRPA}}_{\nu_e/\nu_\mu}$ (bottom left), $R^{\mathrm{SF}}_{\bar\nu_e/\bar\nu_\mu}$ (top-right) and $R^{\mathrm{HF\text{-}CRPA}}_{\bar\nu_e/\bar\nu_\mu}$ (bottom-right) are shown as a function of outgoing lepton angle and the neutrino energy. The contour lines highlight the regions where the ratio significantly deviates from unity.



ν_e/ν_μ uncertainty [%]

	LFG	SF M_A^{QE} 1.03	SF	SF w/o PB	HF	HF-CRPA	HF-CRPA C	HF-CRPA PW	SUSA
SUSA	3.2	2.7	2.7	2.4	0.1	0.2	0.0	0.1	
HF-CRPA PW	3.4	2.8	2.9	2.4	0.2	0.0	0.1		0.1
HF-CRPA C	3.2	2.7	2.7	2.3	0.1	0.1		0.1	0.0
HF-CRPA	3.4	2.8	2.9	2.4	0.2		0.1	0.0	0.1
HF	3.2	2.6	2.7	2.2		0.2	0.1	0.2	0.1
SF w/o PB	0.5	0.1	0.1		2.5	2.7	2.6	2.6	2.6
SF	0.4	0.0		0.3	2.6	2.9	2.7	2.8	2.7
SF M_A^{QE} 1.03	0.4		0.0	0.2	2.6	2.8	2.7	2.8	2.7
LFG		0.4	0.4	0.8	3.0	3.2	3.1	3.2	3.1

arXiv:2301.08065

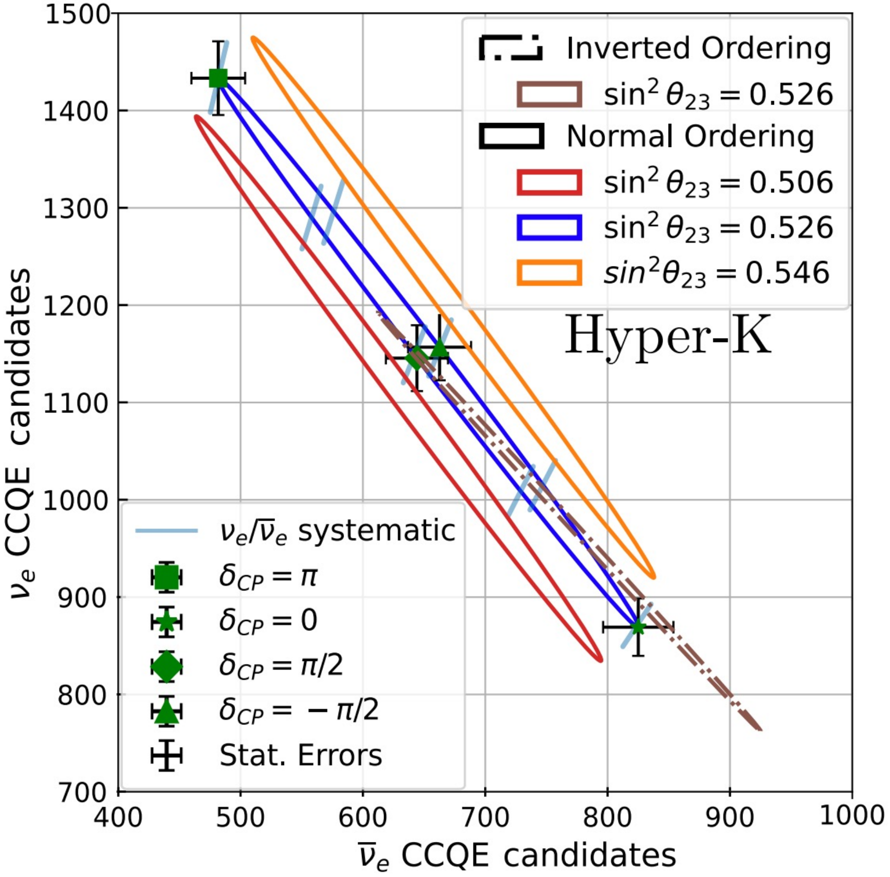


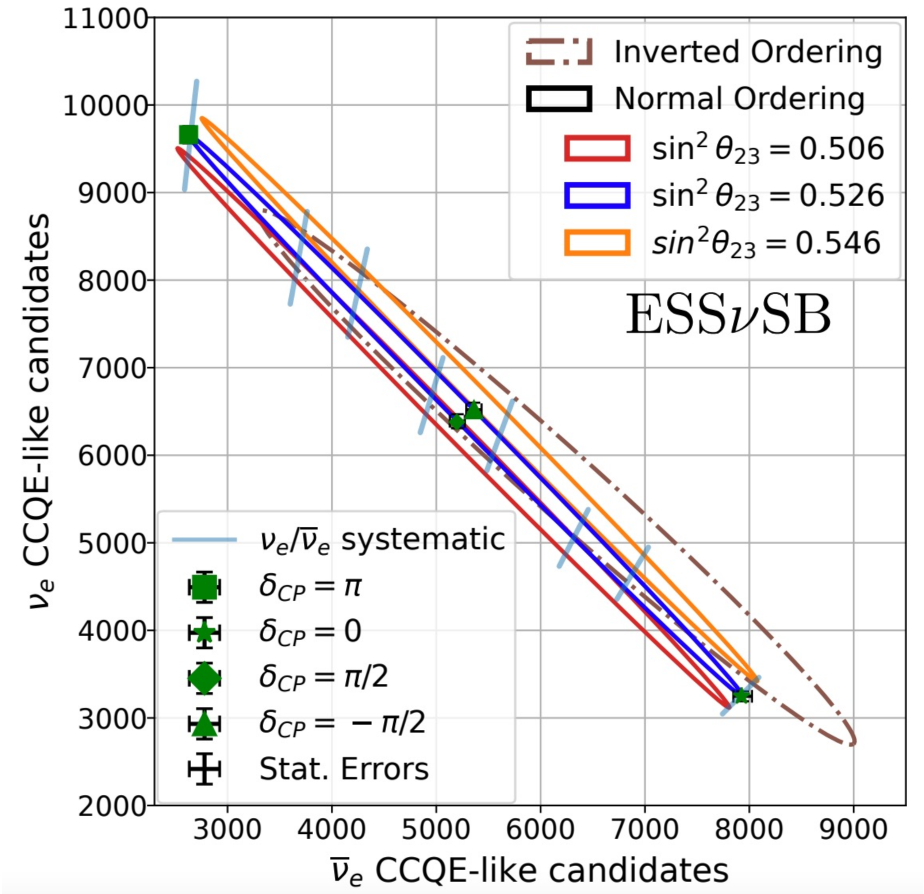
$\nu_e/\bar\nu_e$ uncertainty [%]

	LFG	SF M_A^{QE} 1.03	SF	SF w/o PB	HF	HF-CRPA	HF-CRPA C	HF-CRPA PW	SUSA
SUSA	0.7	1.2	1.2	1.2	0.3	0.4	0.4	0.7	
HF-CRPA PW	1.3	1.6	1.6	2.2	0.0	0.0	0.0		0.4
HF-CRPA C	1.2	1.6	1.6	1.8	0.1	0.1		0.1	0.5
HF-CRPA	1.2	1.6	1.6	1.7	0.0		0.1	0.2	0.4
HF	1.1	1.5	1.5	1.7		0.0	0.1	0.3	0.4
SF w/o PB	0.5	0.2	0.1		1.3	1.4	1.5	1.9	1.1
SF	0.5	0.0		0.0	1.5	1.6	1.6	1.9	1.2
SF M_A^{QE} 1.03	0.6		0.0	0.0	1.5	1.6	1.7	1.9	1.2
LFG		0.5	0.5	0.6	1.0	1.1	1.2	1.4	0.7

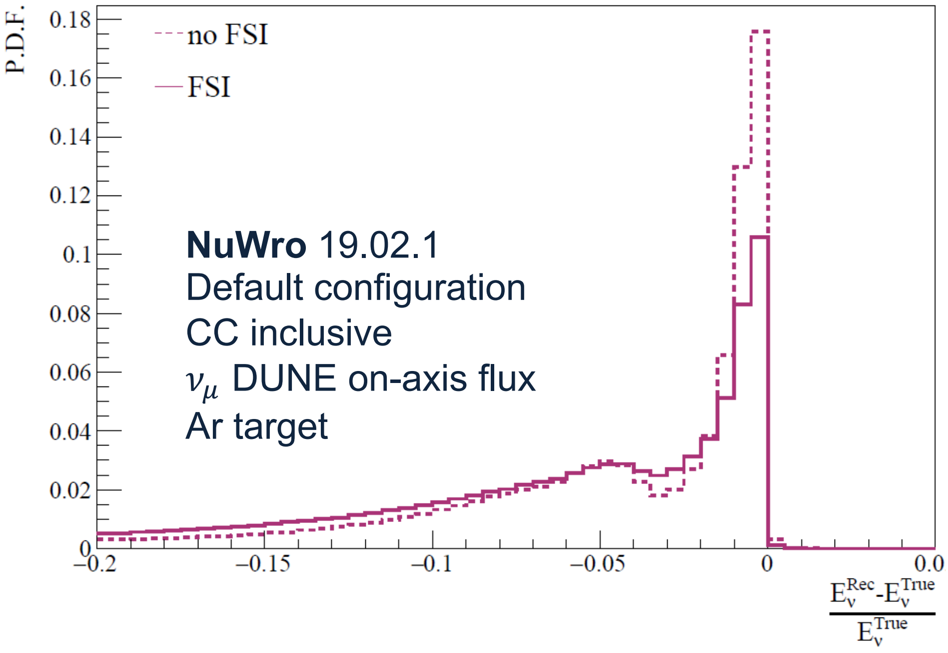
Nuclear effects and $\sigma(\nu_e)/\sigma(\nu_\mu)$

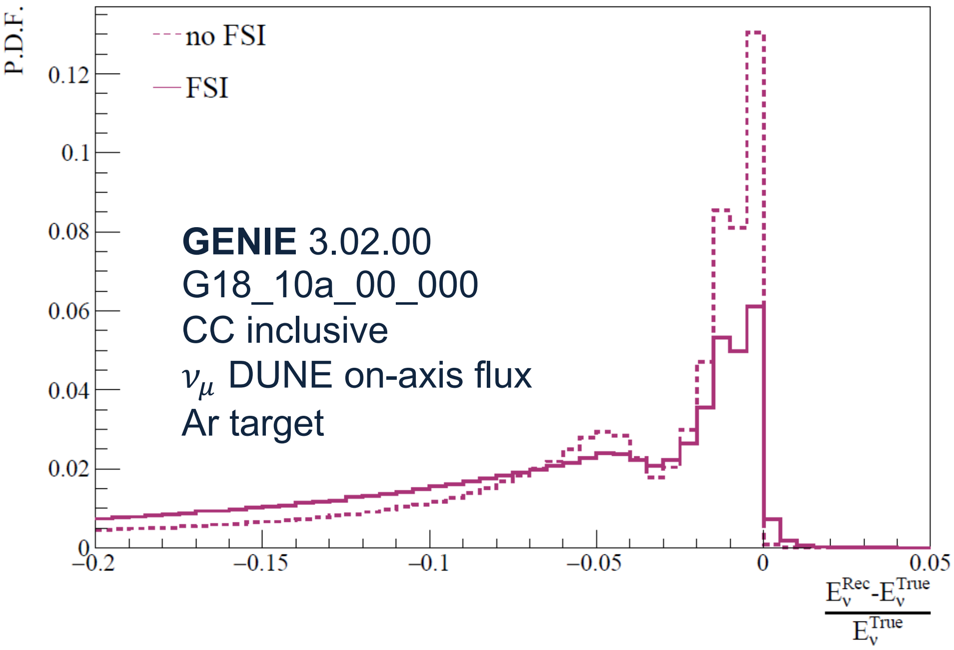
arXiv:2301.08065





FSI and neutrino energy reconstruction

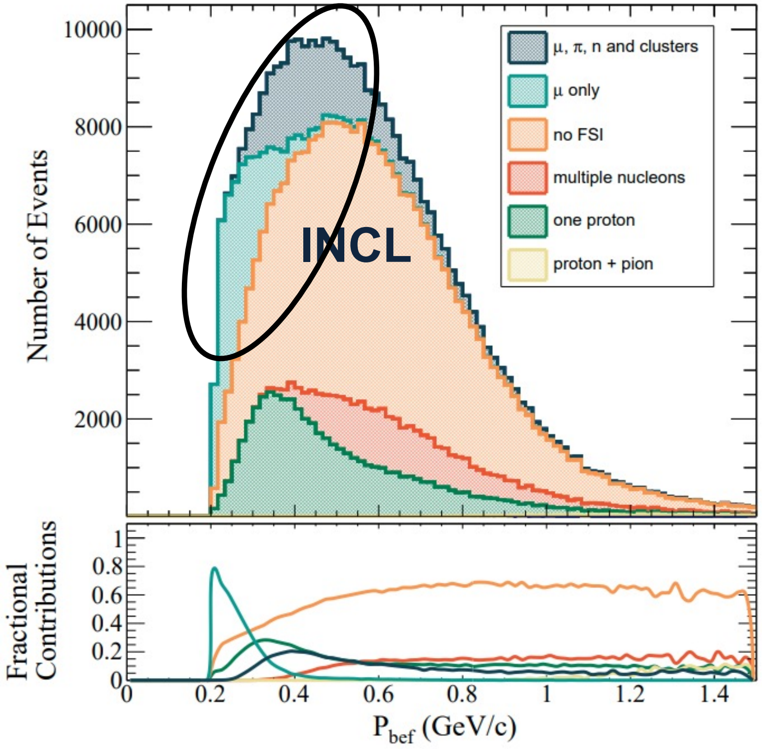


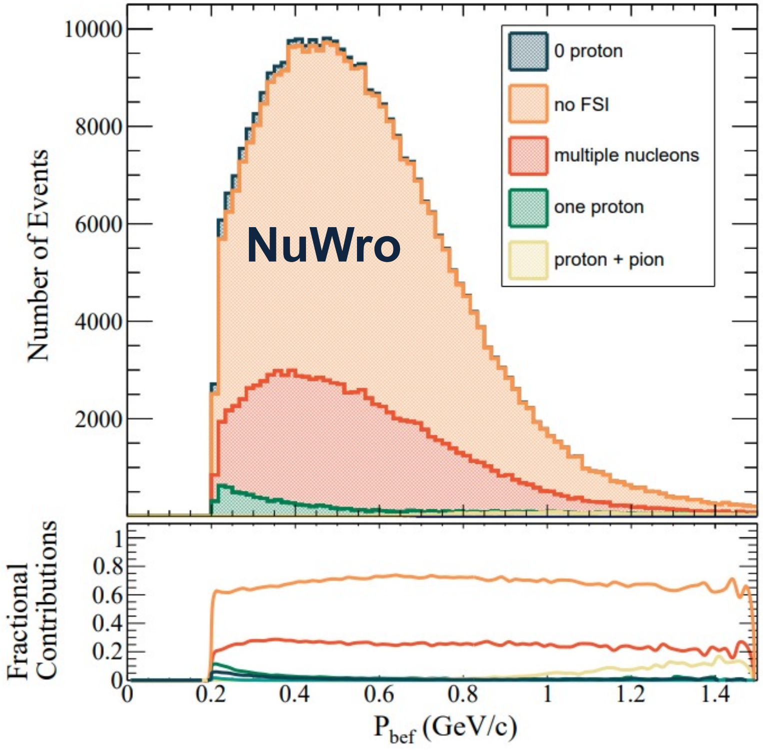


Advanced FSI cascades

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)
- 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

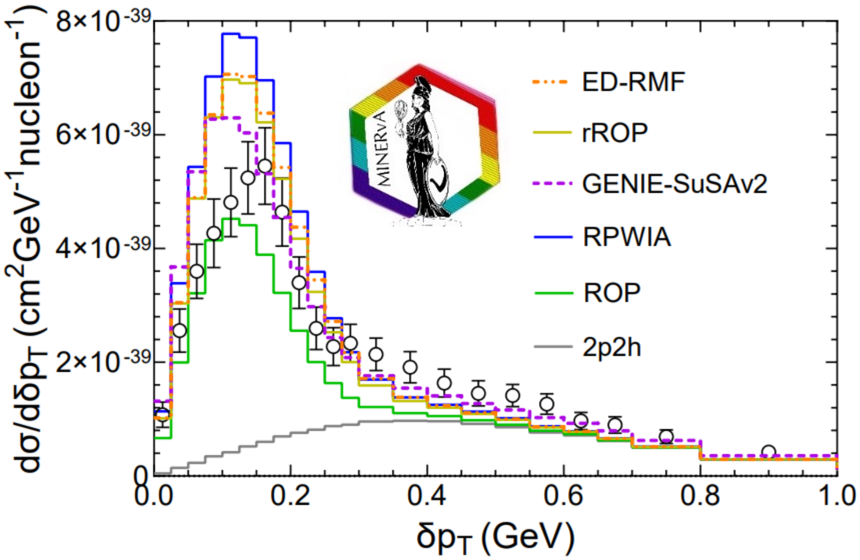
Plots from:
Franco-Patino et al.,
arXiv:2207.02086

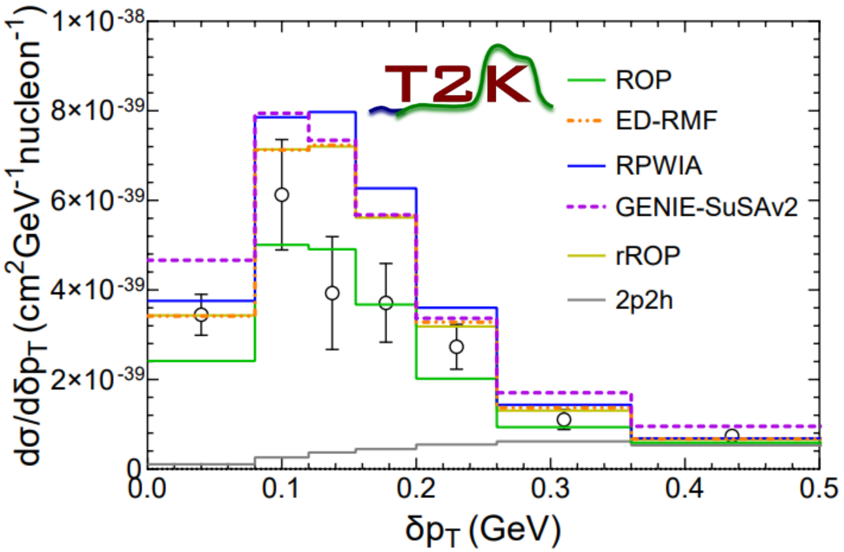
See also:
Nikolakopoulos et al.,
Phys. Rev. C **105**, 054603

- 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
  - Example below: missing transverse momentum
  - In general: high δp_T → more missing hadronic energy → 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

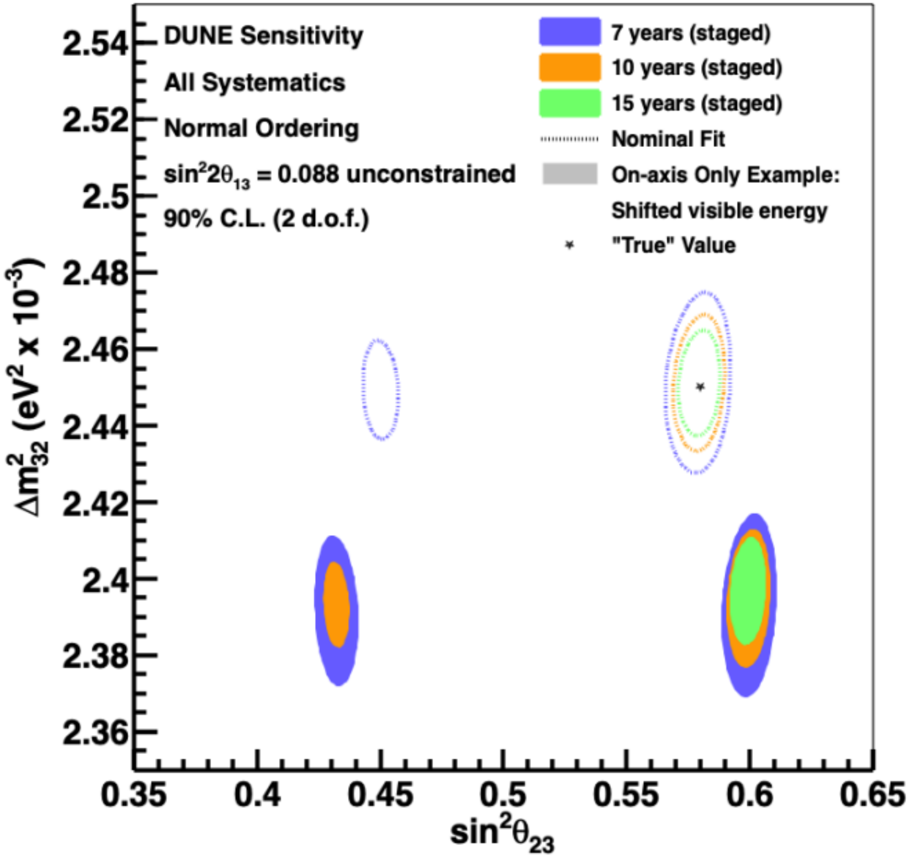
Plot from:
DUNE physics TDR,
arXiv:2002.03005

- 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**

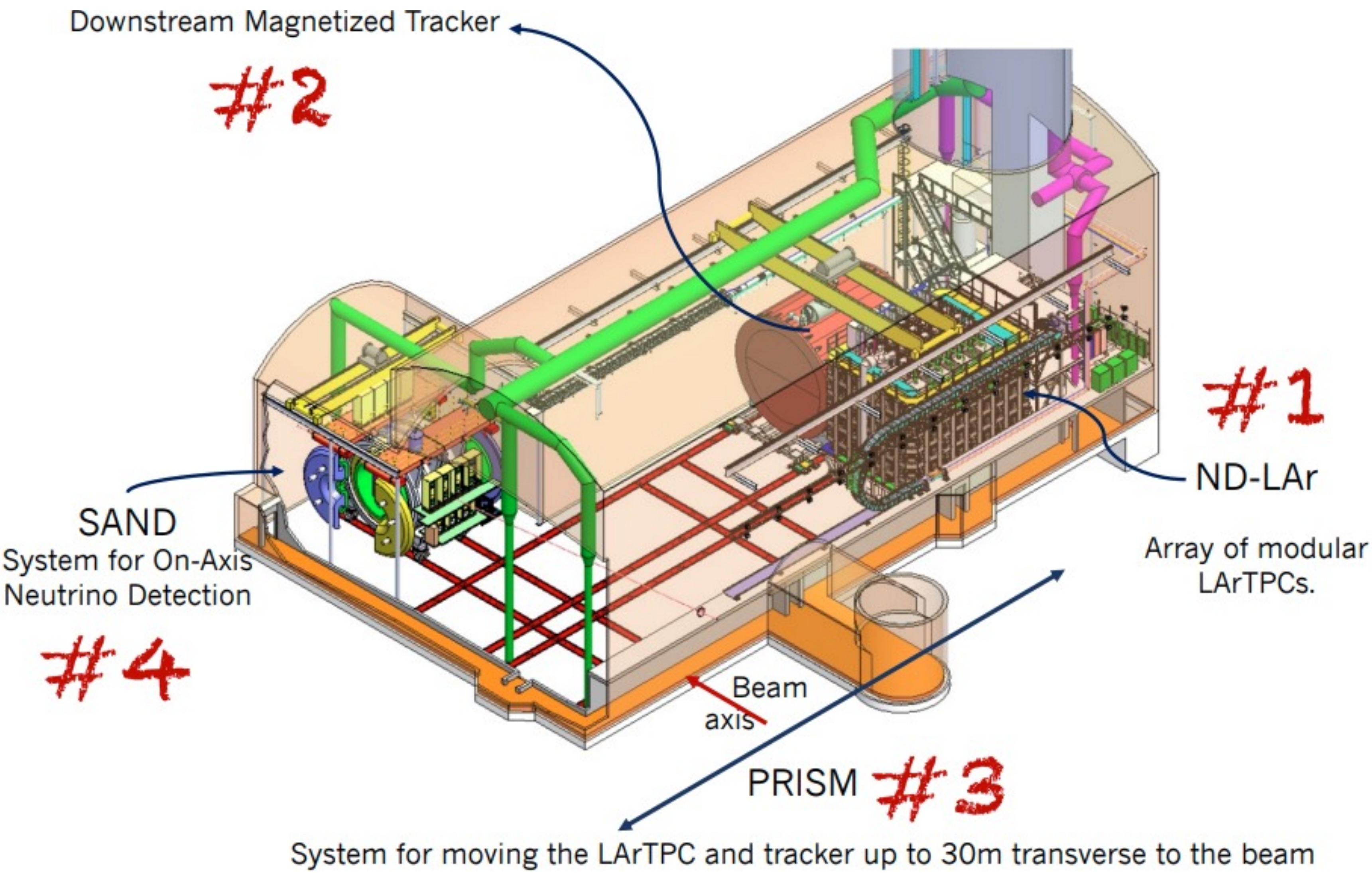
- At the same time, the cross section is altered to leave the proton momentum distribution unchanged
  - Another plausible change to the cross section model

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

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



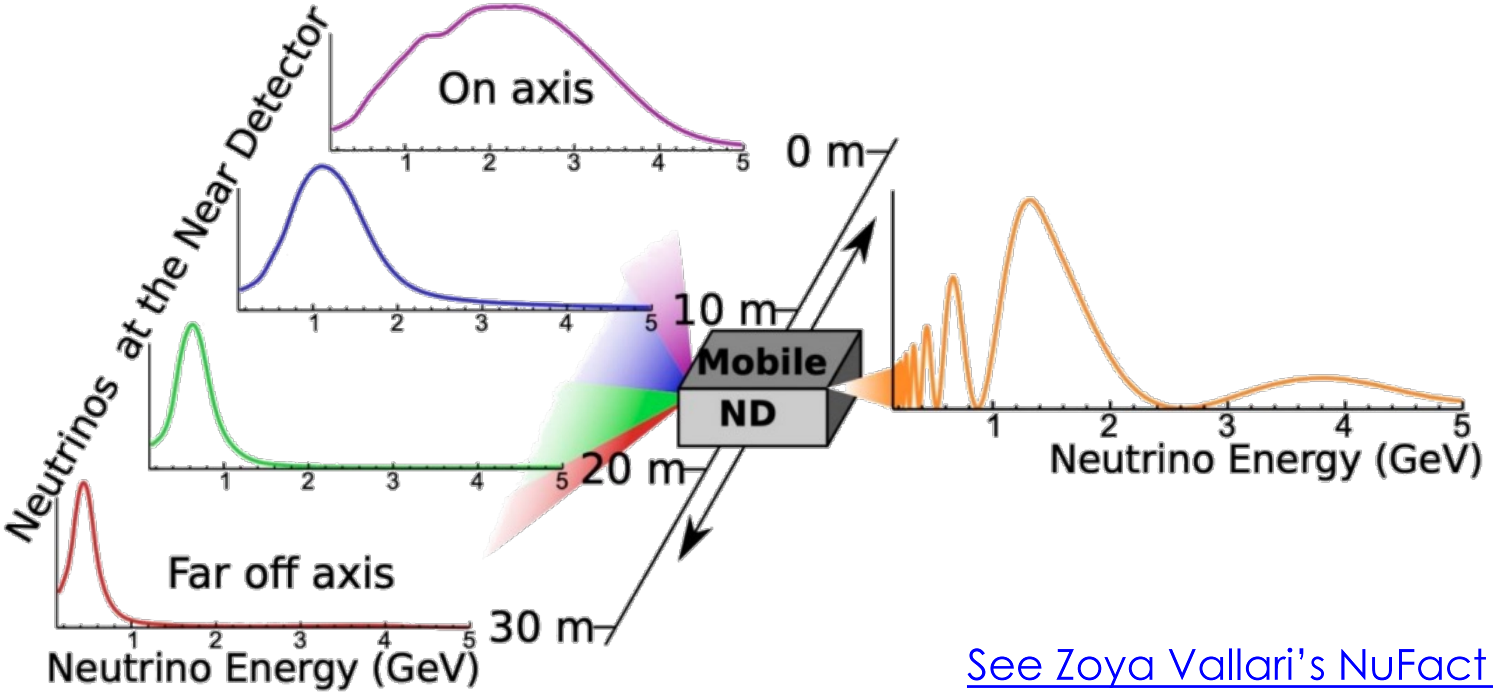
Improved near detectors



System for moving the LArTPC and tracker up to 30m transverse to the beam

DUNE PRISM

- A mobile 50 t liquid argon detector with a downstream spectrometer
  - ~59 M neutrino interactions per year!
- Moving the detector **changes the neutrino flux** in a predictable way, taking linear combinations of measurements at different positions allows a **construction of the oscillated spectrum at the near detector**
  - Better cancellation of uncertainties in oscillation measurements



See Zoya Vallari's NuFact 2022 talk