ν interactions, ν problem

nuSCOPE and the crucial role of neutrino interaction modelling in neutrino oscillation measurements

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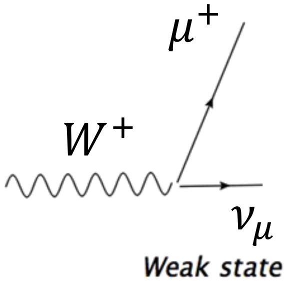
Overview

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

Neutrino Oscillations

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



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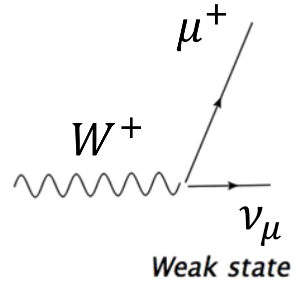

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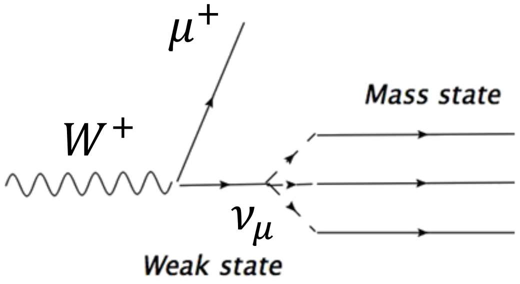

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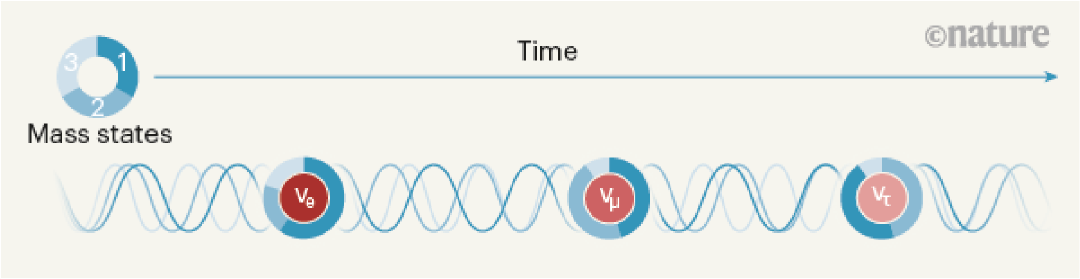

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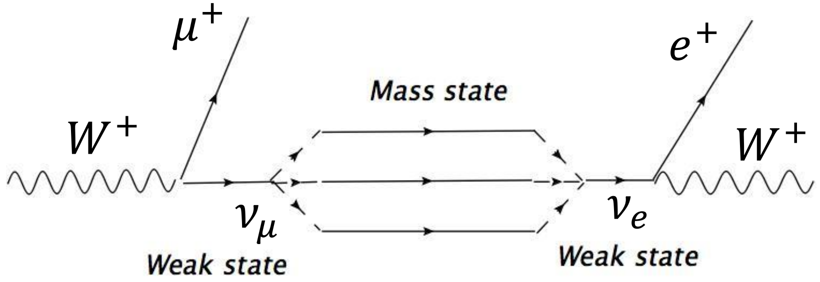

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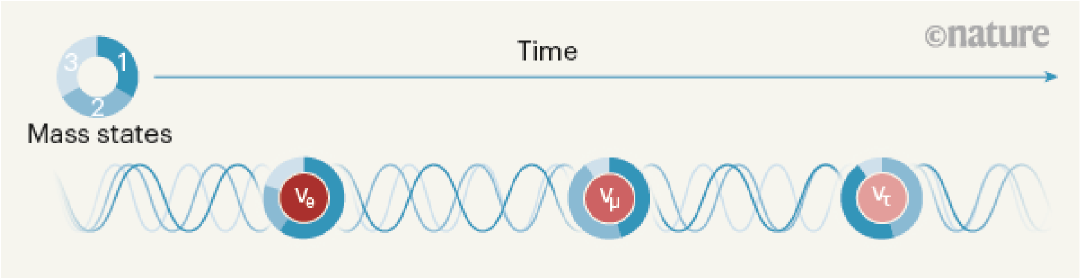

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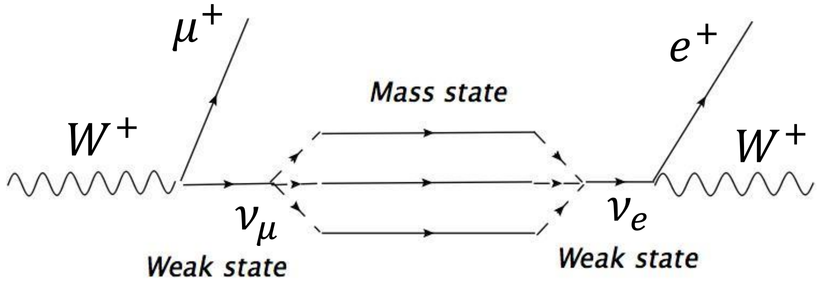

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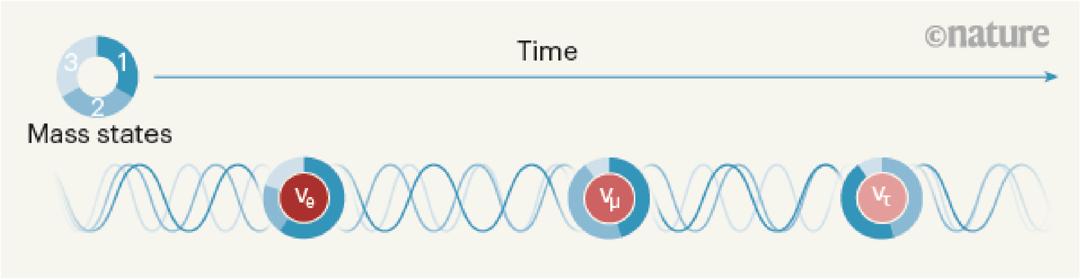
The probability of finding a neutrino as a particular flavour "*oscillates*" as its mass states evolve



Neutrino Oscillations

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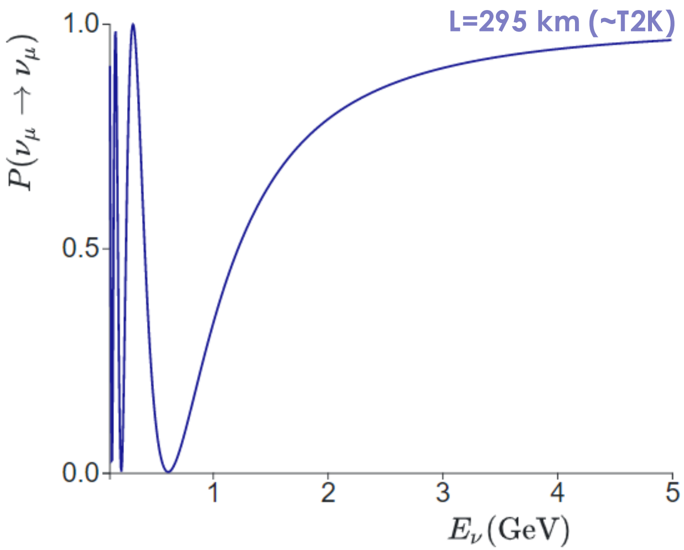

Two-flavour mixing

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

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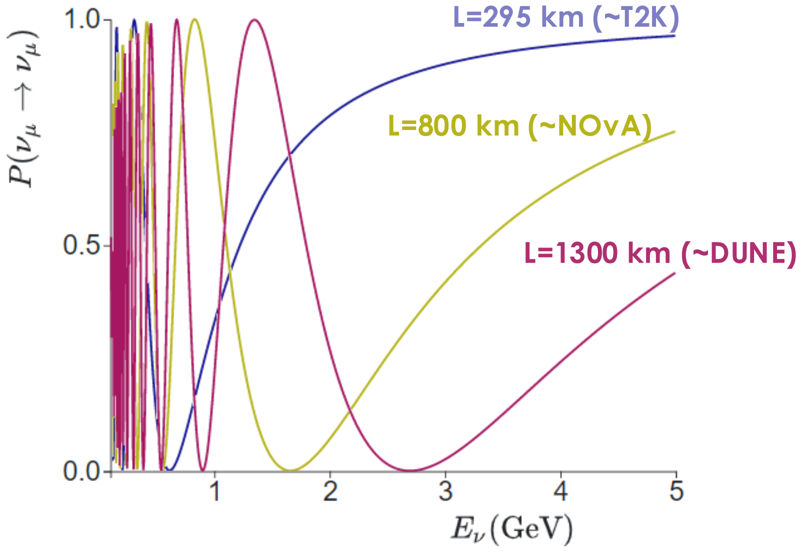

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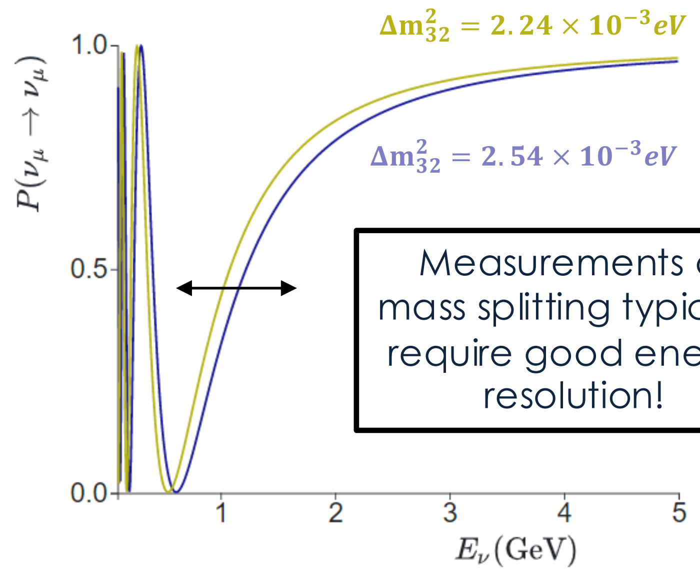

Measurements of mass splitting typically require good energy resolution!

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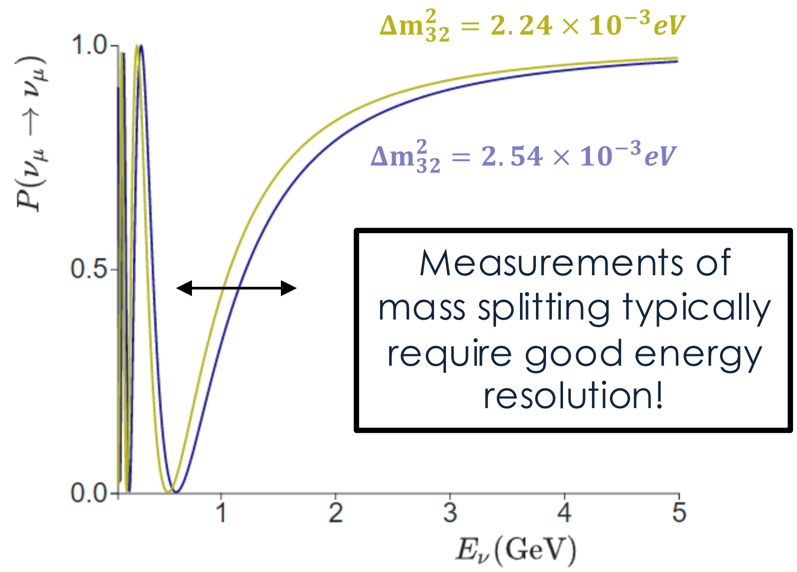

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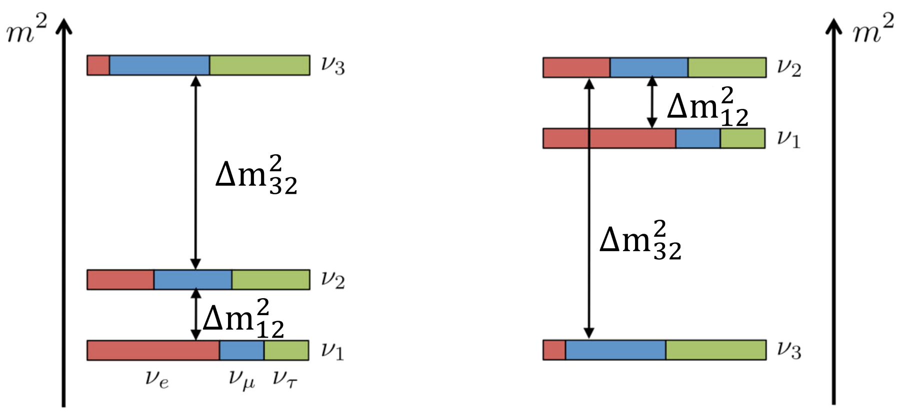
Normal Ordering (NO) **Inverted Ordering (NO)**

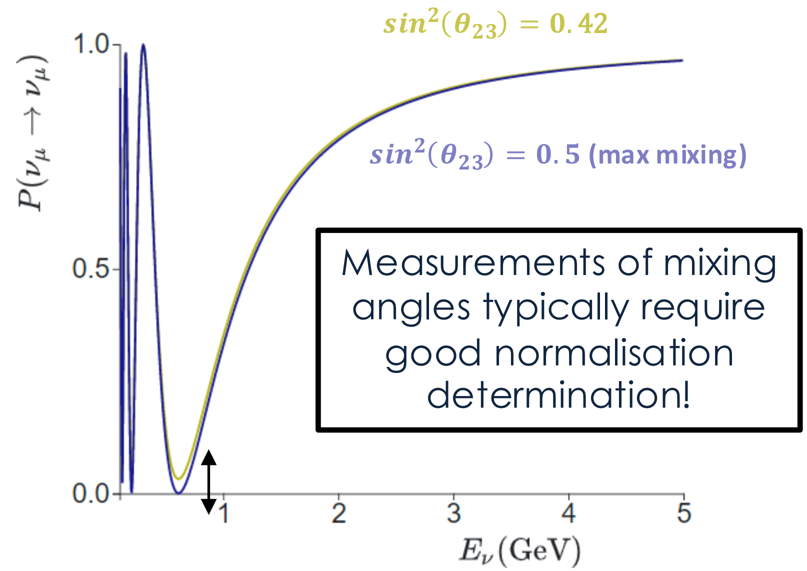


- Neutrino oscillations in a vacuum are, to first order, sensitive only to the square of the mass splittings.

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

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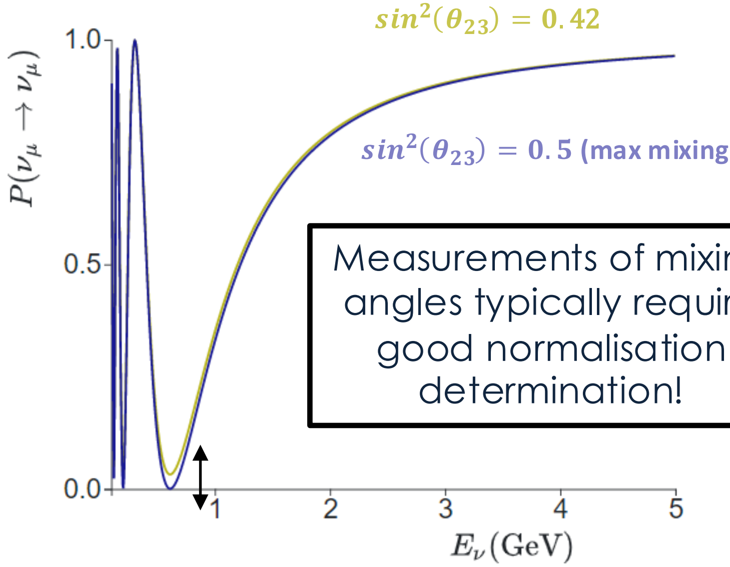

Measurements of mixing angles typically require good normalisation determination!

Three-flavour mixing

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

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

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

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

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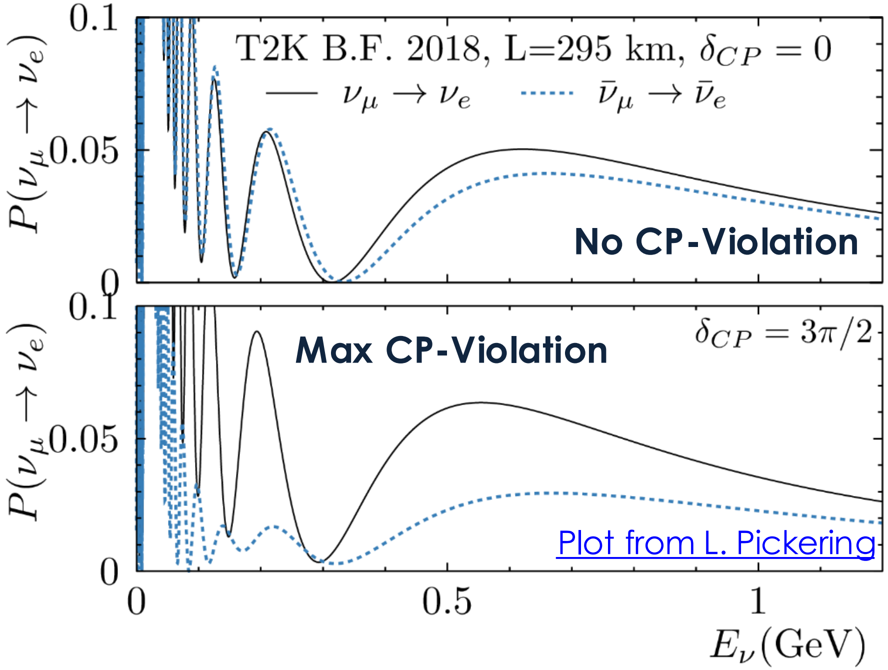

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$s_{ij} = \sin \theta_{ij}$
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- Three mixing angles: $\theta_{12}, \theta_{13}, \theta_{23}$
- One CP-Violating phase: δ_{CP}

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

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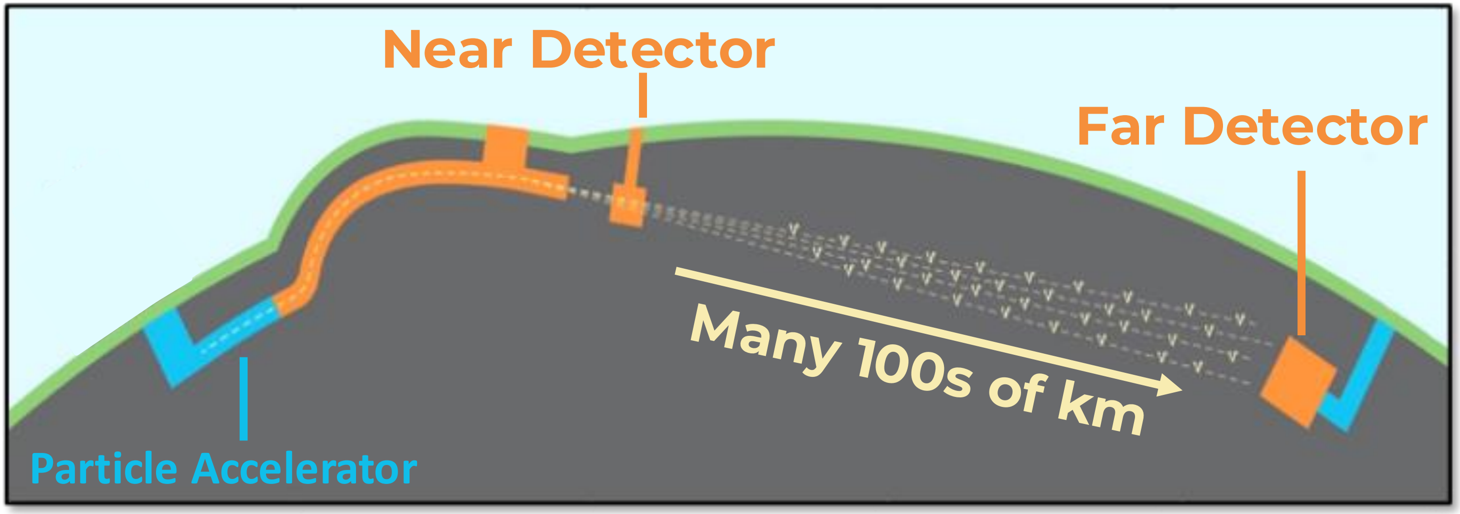
Accelerator-Based Experiments



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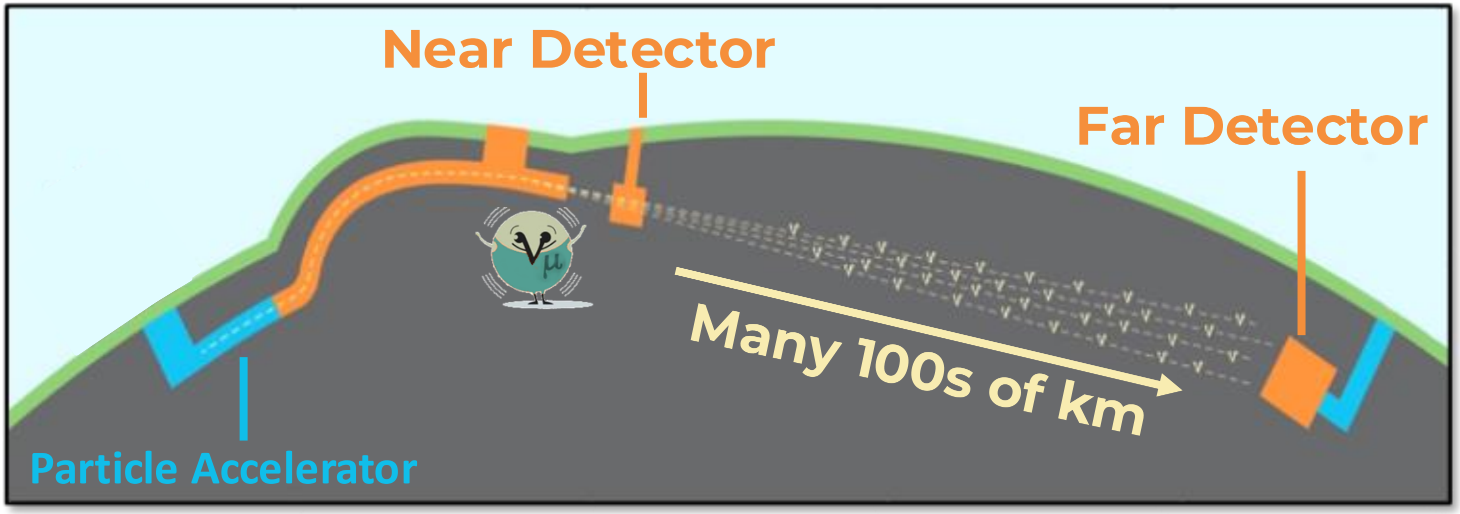

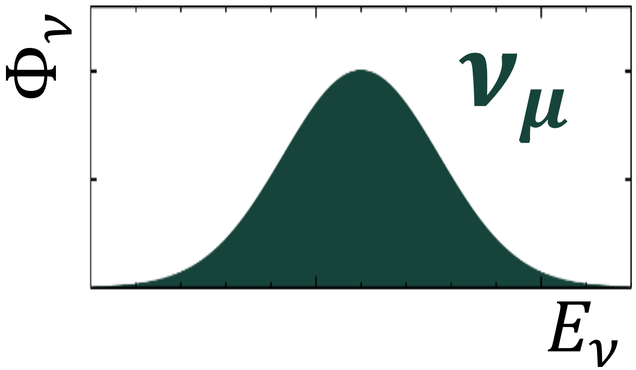

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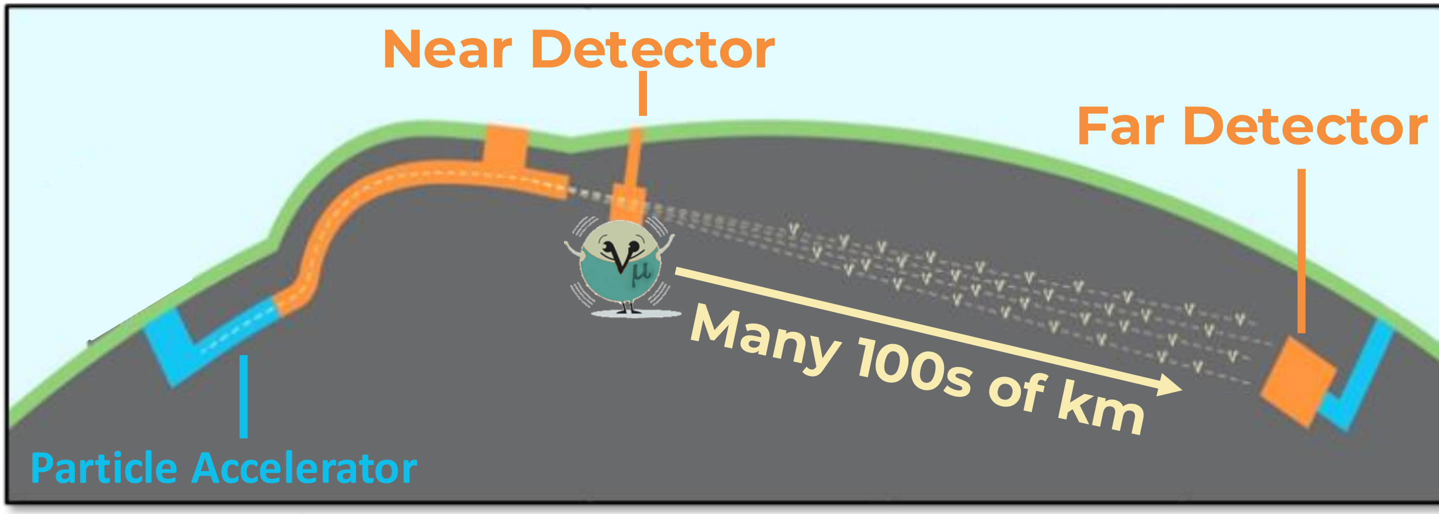
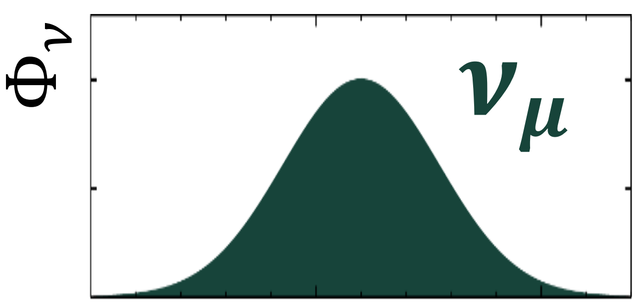




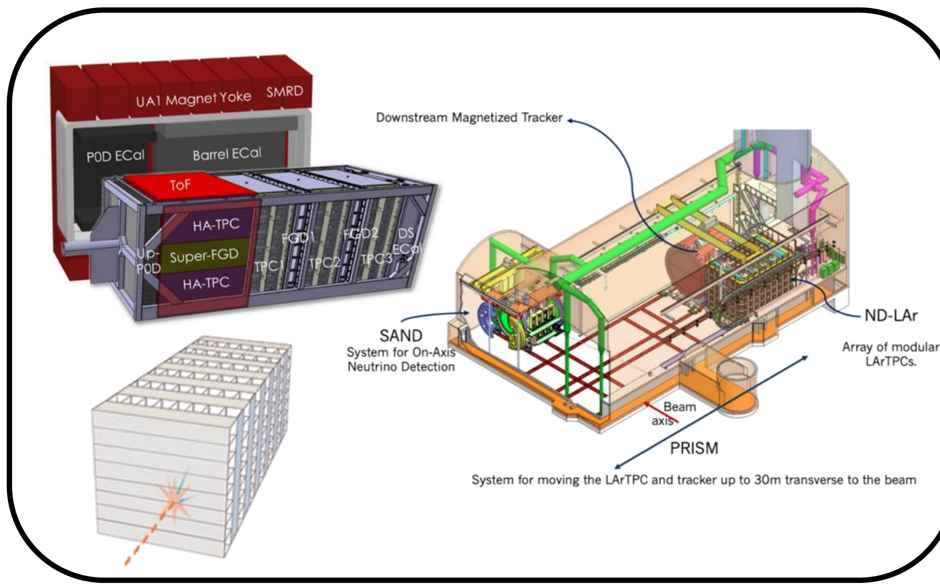
At the near detector

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

Interaction cross section

Neutrino flux

Detector effects



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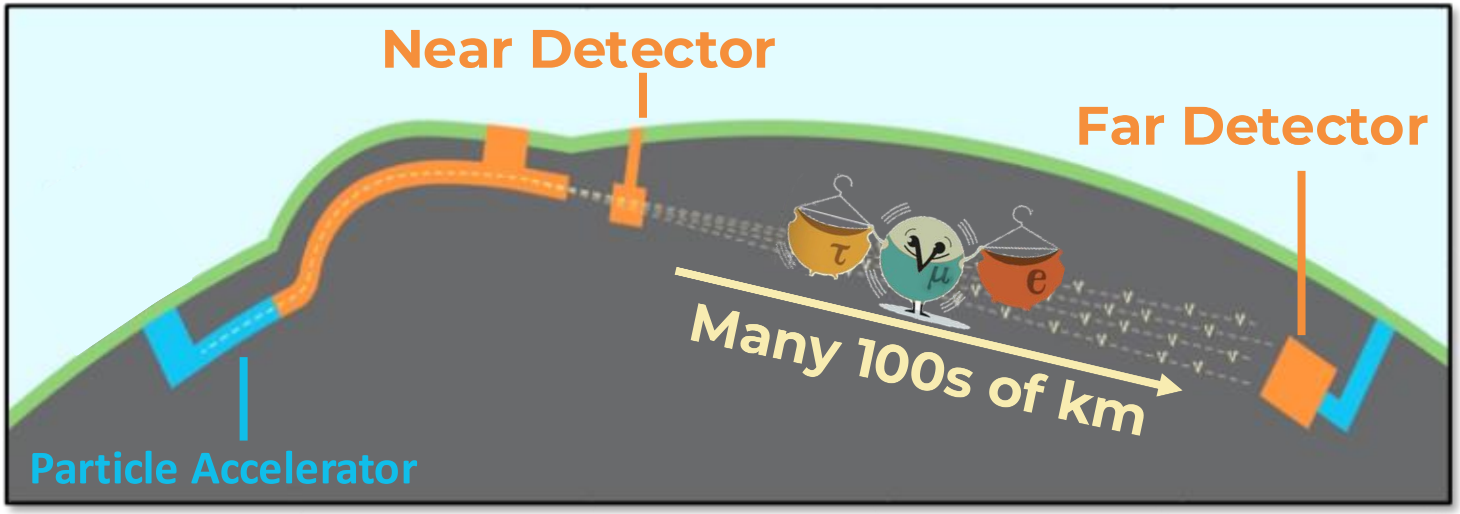

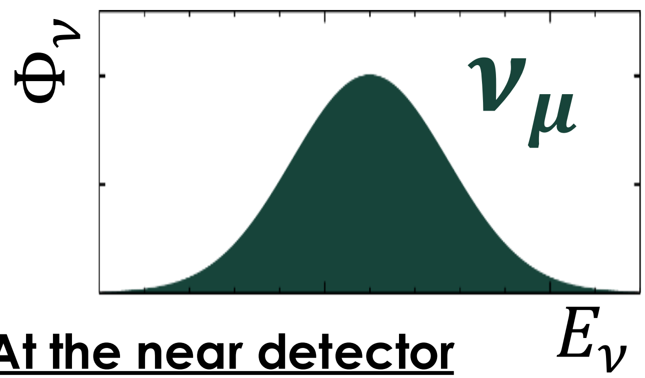

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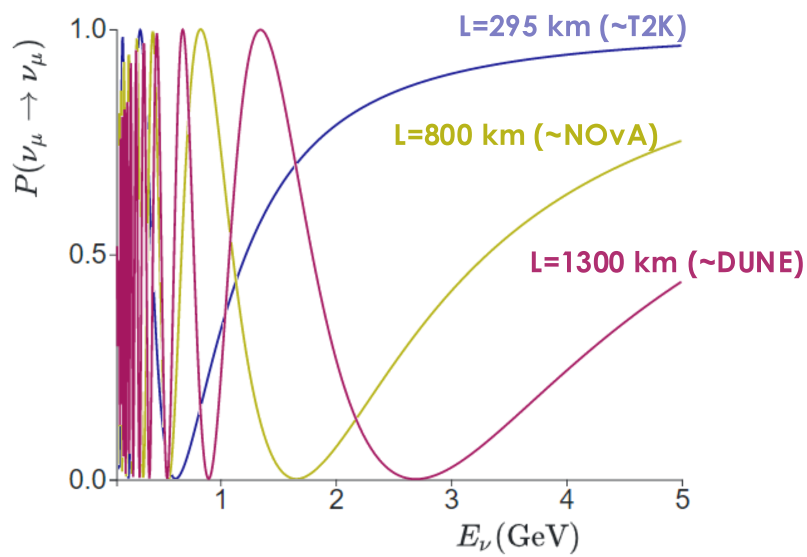

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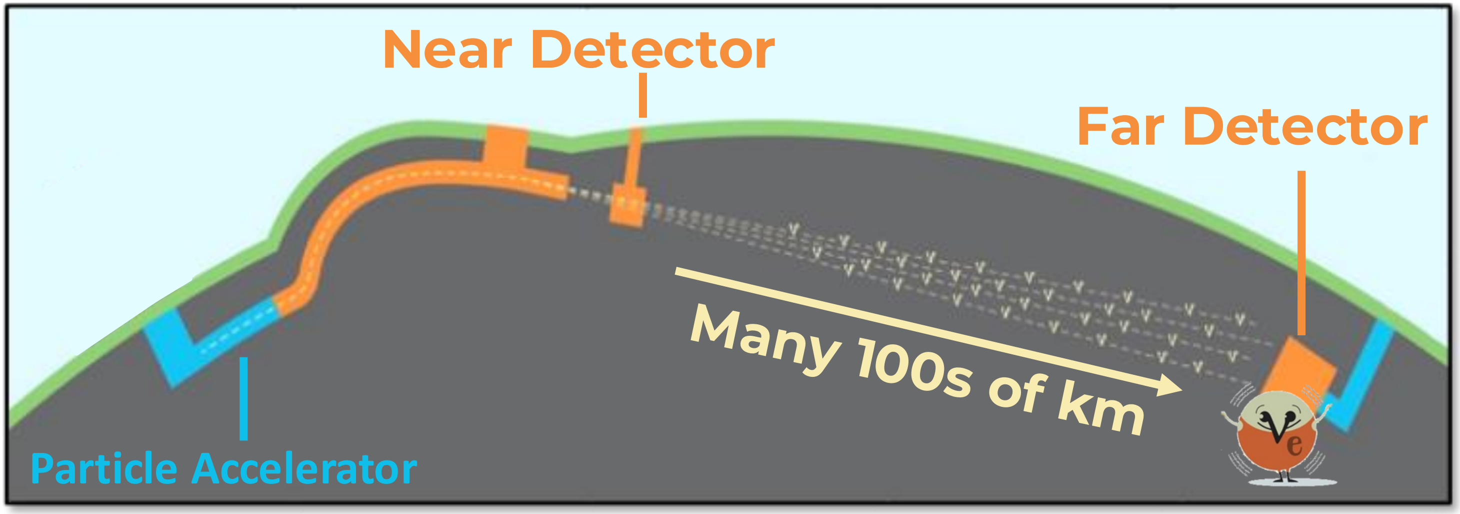

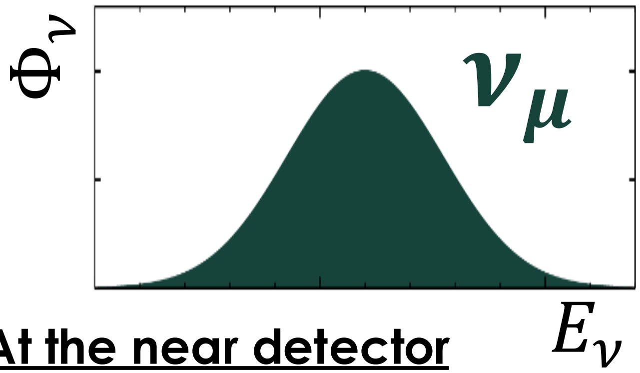

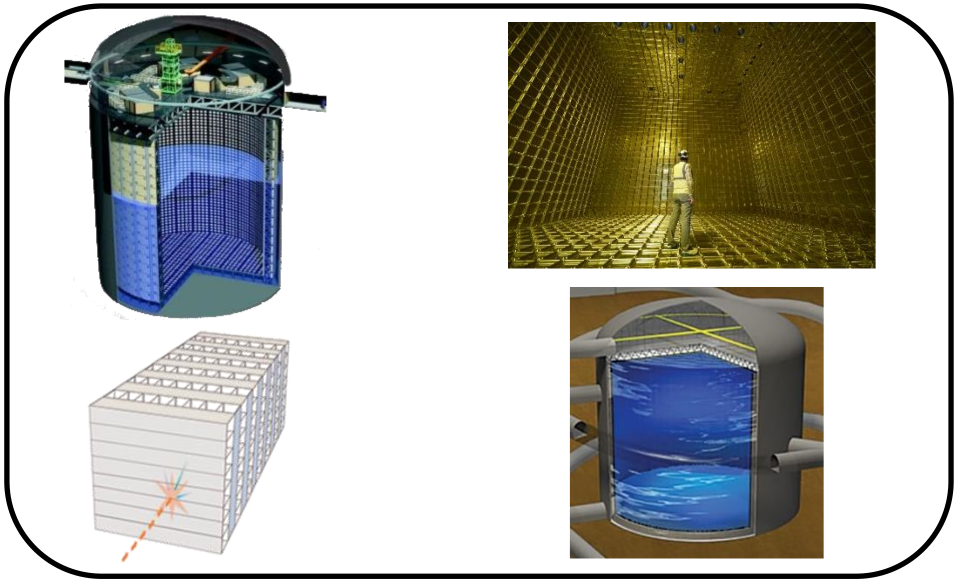

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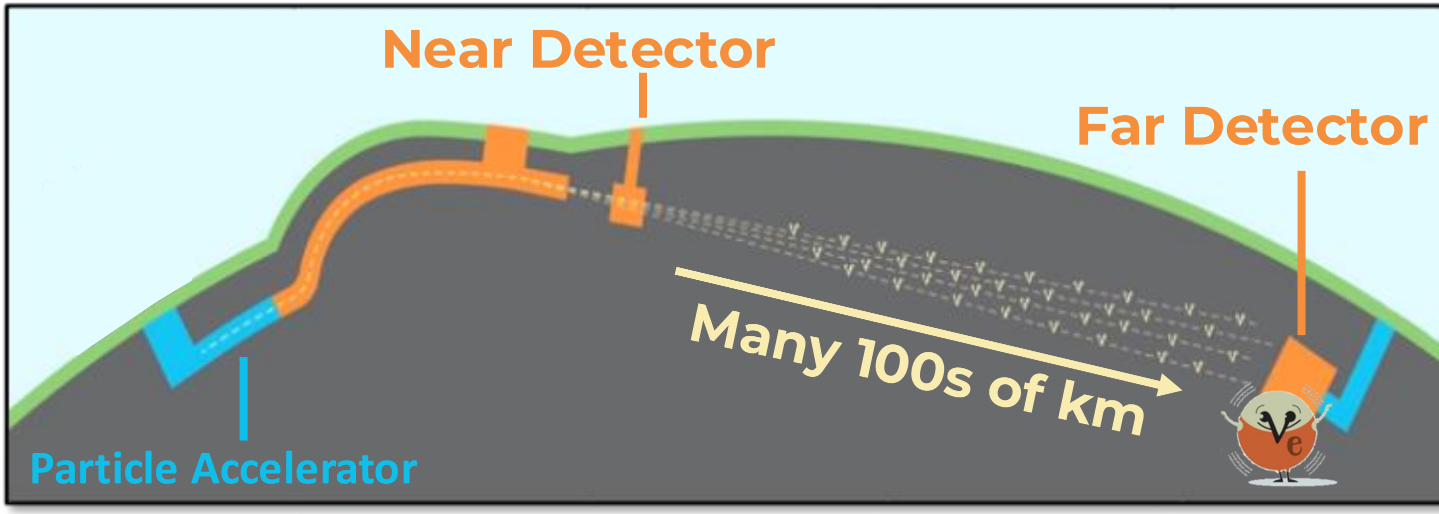

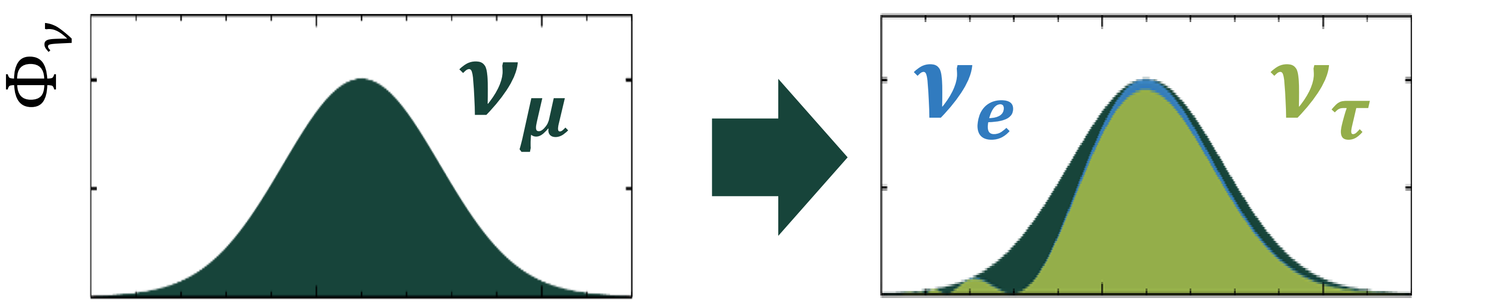

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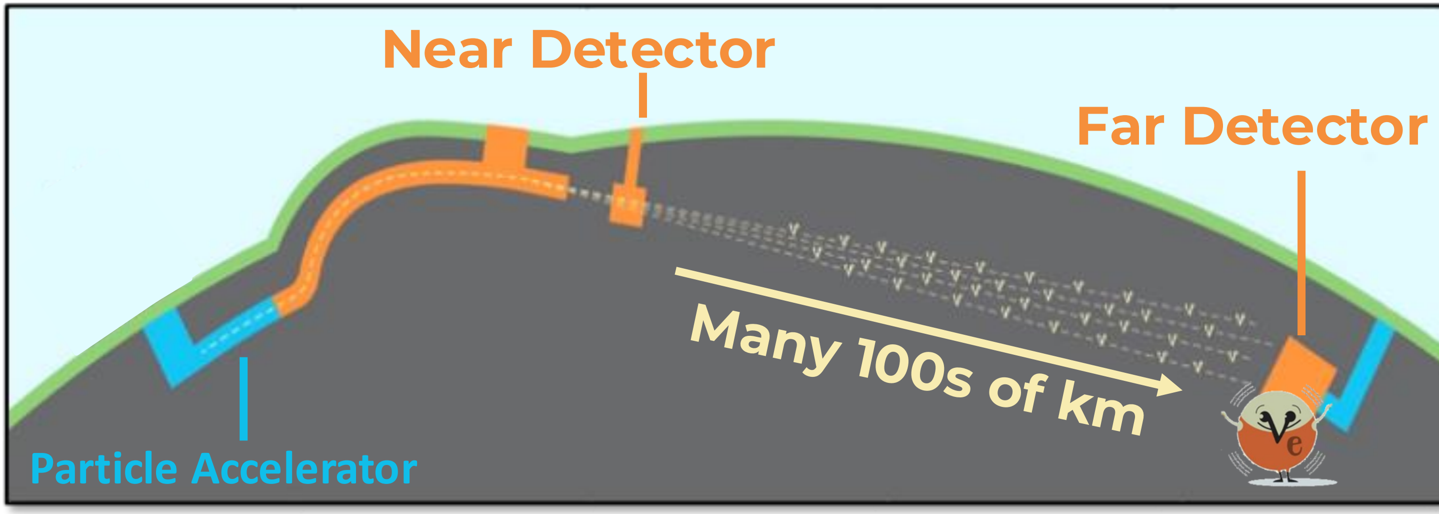

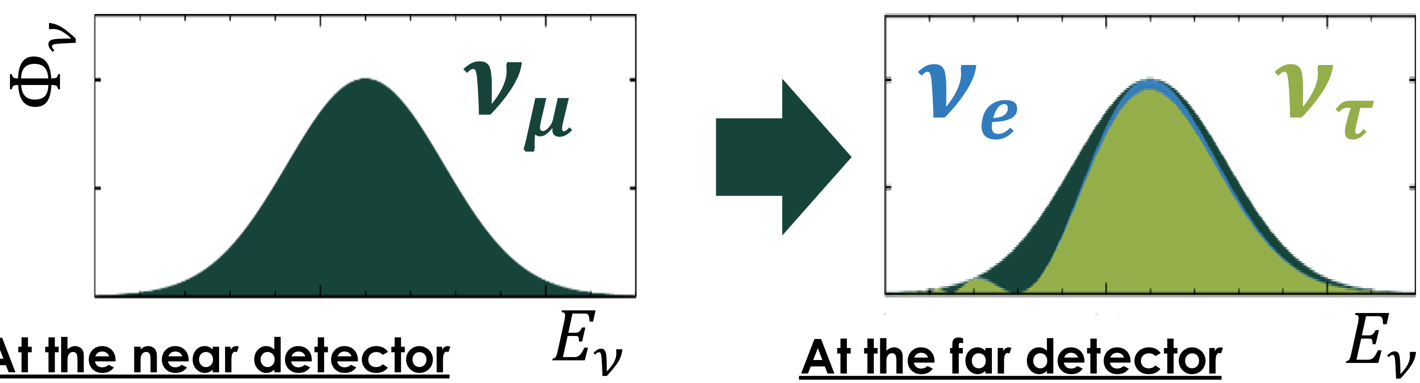

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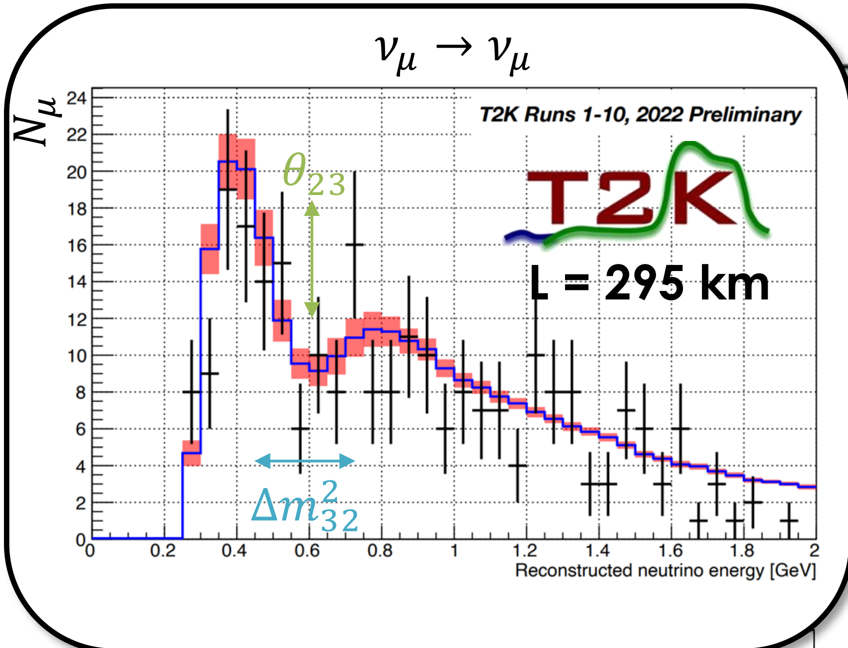
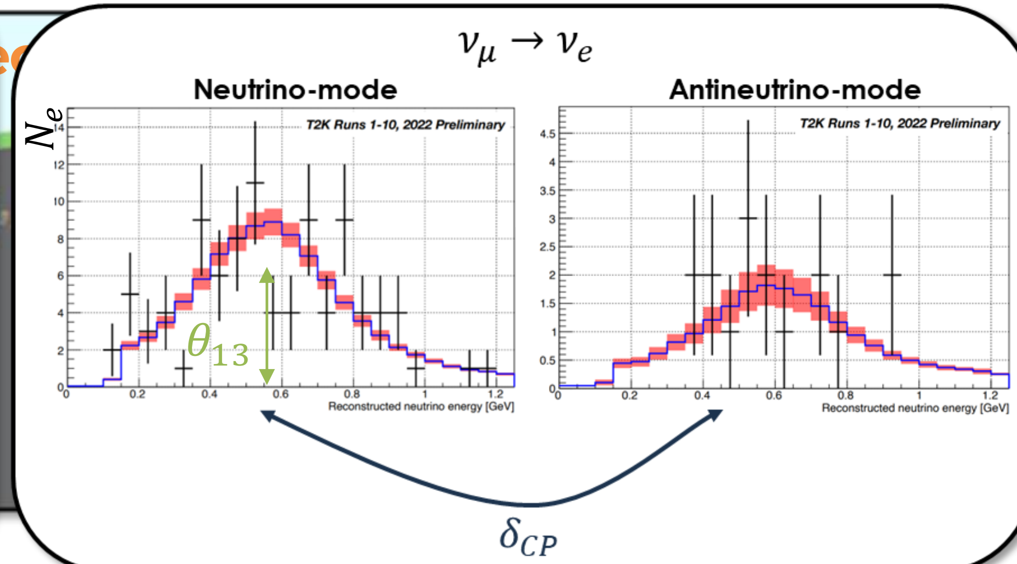
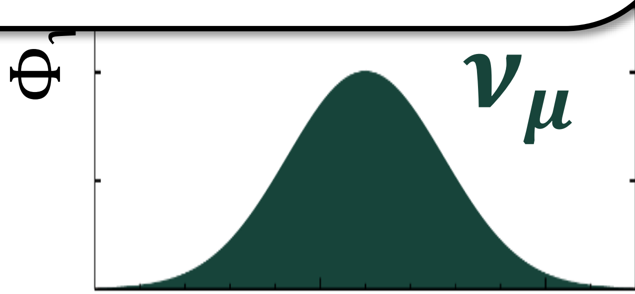
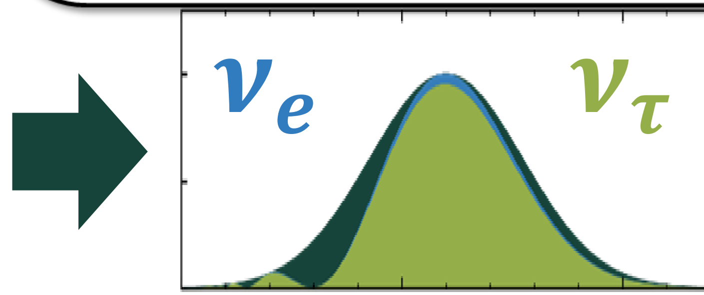
Oscillation probability

Accelerator-Based Experiments









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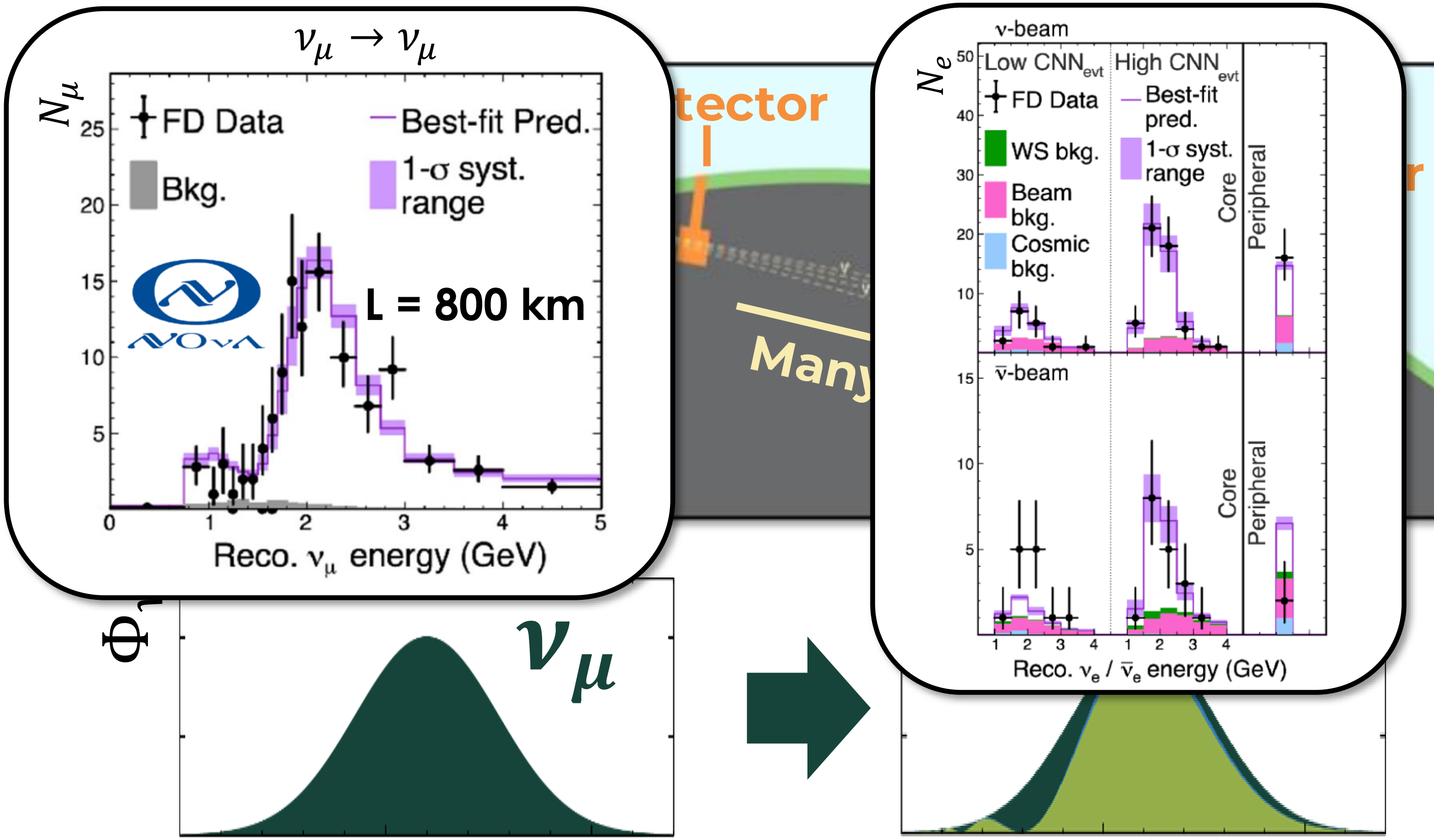

E_ν

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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]	$2.484^{+0.045}_{-0.048}$	$\sim 2\%$

How're we doing?

Parameter	Bestfit ±1σ	2016	2018
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$\sim4\%$	$\sim4\%$
$\sin^2\theta_{23}$	$0.538^{+0.033}_{-0.069}$	$\sim25\%$	$\sim13\%$
$\sin^2\theta_{13}$	$0.02206^{+0.00075}_{-0.00075}$	$\sim6\%$	$\sim3\%$
δ_{CP} [°]	234^{+43}_{-31}	$\sim63°$	$\sim37°$
Δm^2_{21} $[10^{-5}\ eV^2]$	$7.40^{+0.21}_{-0.20}$	$\sim3\%$	$\sim3\%$
$\Delta m^2_{3\ell}$ $[10^{-3}\ eV^2]$	$2.494^{+0.033}_{-0.031}$	$\sim2\%$	$\sim1\%$

How're we doing?

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Parameter	Bestfit ±1σ	2016	2018	2026
$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$\sim4\%$	$\sim4\%$	$\sim4\%$
$\sin^2\theta_{23}$	$0.561^{+0.012}_{-0.015}$	$\sim25\%$	$\sim13\%$	$\sim3\%$
$\sin^2\theta_{13}$	$0.02195^{+0.00054}_{-0.00058}$	$\sim6\%$	$\sim3\%$	$\sim3\%$
δ_{CP} [°]	177^{+19}_{-20}	$\sim63°$	$\sim37°$	$\sim20°$
Δm^2_{21} $[10^{-5}\ eV^2]$	$7.49^{+0.19}_{-0.20}$	$\sim3\%$	$\sim3\%$	$\sim3\%$
$\Delta m^2_{3\ell}$ $[10^{-3}\ eV^2]$	$2.459^{+0.025}_{-0.023}$	$\sim2\%$	$\sim1\%$	$\sim1\%$

Precision neutrino-oscillation physics!

Nature **580**, 339-344

Precision oscillation physics

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$\sin^2\theta_{23}$	$0.561^{+0.012}_{-0.015}$	$\sim 25\%$	$\sim 13\%$	$\sim 3\%$
$\sin^2\theta_{13}$	$0.02195^{+0.00054}_{-0.00058}$	$\sim 6\%$	$\sim 3\%$	$\sim 3\%$
δ_{CP} [°]	177^{+19}_{-20}	$\sim 63°$	$\sim 37°$	$\sim 20°$
Δm^2_{21} $[10^{-5}\ eV^2]$	$7.49^{+0.19}_{-0.20}$	$\sim 3\%$	$\sim 3\%$	$\sim 3\%$
$\Delta m^2_{3\ell}$ $[10^{-3}\ eV^2]$	$2.459^{+0.025}_{-0.023}$	$\sim 2\%$	$\sim 1\%$	$\sim 1\%$

But still plenty more to find out:

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

Precision oscillation physics

Parameter	Bestfit ±1σ	2016	2018	2026
$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$\sim 4\%$	$\sim 4\%$	$\sim 4\%$
$\sin^2\theta_{23}$	$0.561^{+0.012}_{-0.015}$	$\sim 25\%$	$\sim 13\%$	$\sim 3\%$
$\sin^2\theta_{13}$	$0.02195^{+0.00054}_{-0.00058}$	$\sim 6\%$	$\sim 3\%$	$\sim 3\%$
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$\Delta m^2_{3\ell}$ [$10^{-3}\ eV^2$]	$2.459^{+0.025}_{-0.023}$	$\sim 2\%$	$\sim 1\%$	$\sim 1\%$

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

Parameter	Bestfit ±1σ	2016	2018	2026
$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	~4%	~4%	~4%
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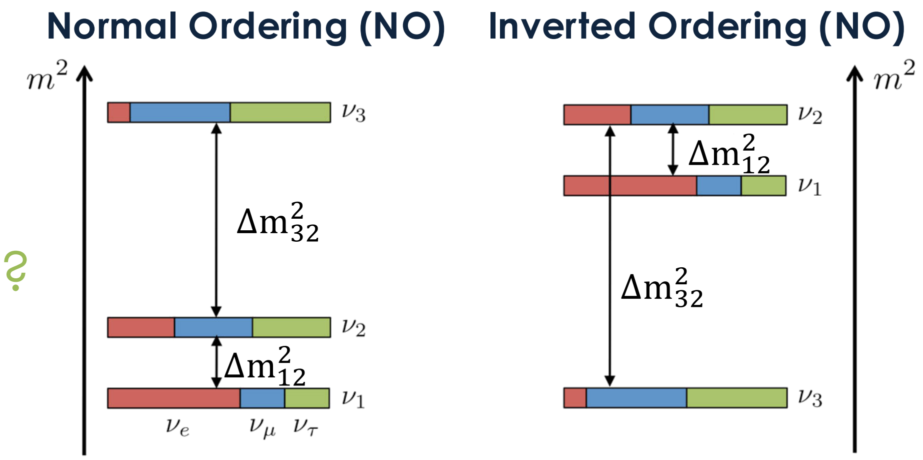
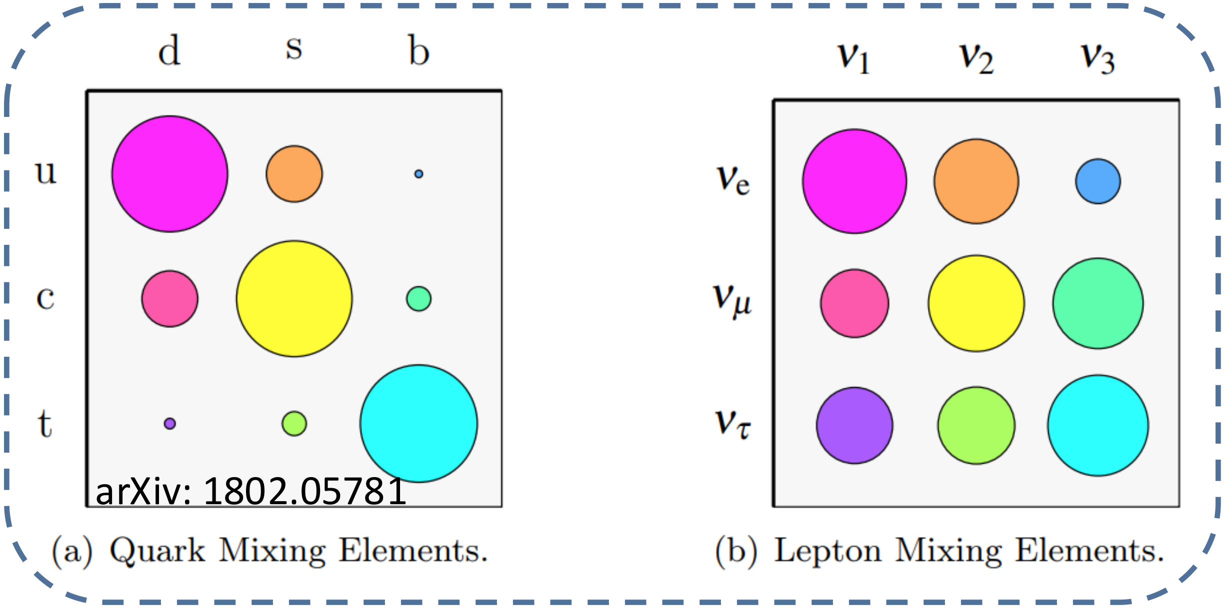
δ_{CP} [°]	177^{+19}_{-20}	~63°	~37°	~20°
Δm^2_{21} [10^{-5} eV^2]	$7.49^{+0.19}_{-0.20}$	~3%	~3%	~3%
$\Delta m^2_{3\ell}$ [10^{-3} eV^2]	$2.459^{+0.025}_{-0.023}$	~2%	~1%	~1%

But still plenty more to find out:

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



Precision oscillation physics



(a) Quark Mixing Elements. (b) Lepton Mixing Elements.

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

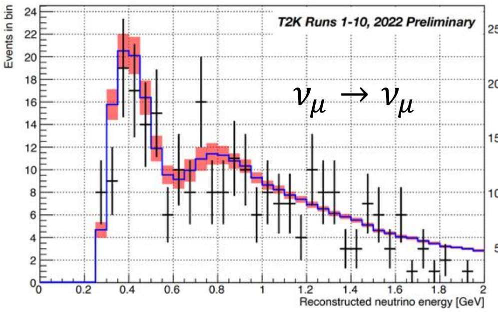
Baseline: 1200 km
Beam: Wide band, ~3 GeV
Far detector: Liquid Argon TPC
Far detector mass (FV): 68 kt
Expected N_e: ~1500

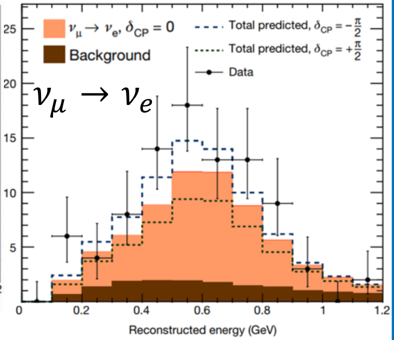
But still plenty more to find out:

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

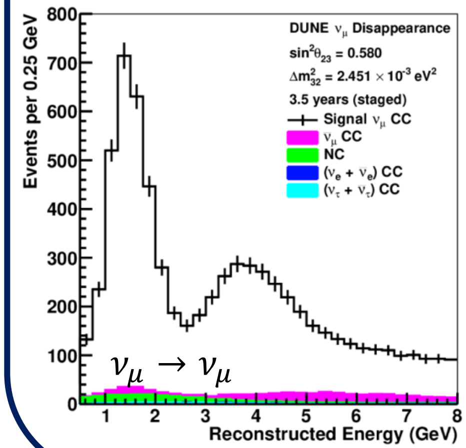
Beyond beyond the SM

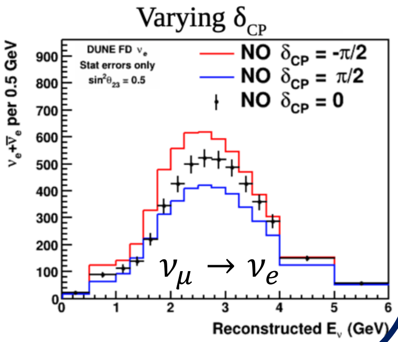
Present





Future





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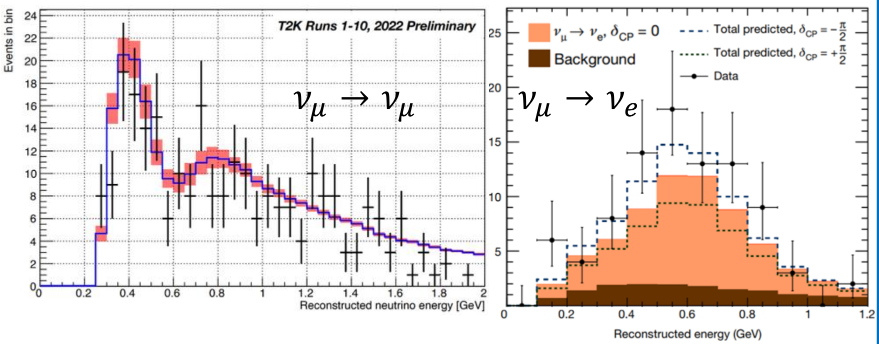
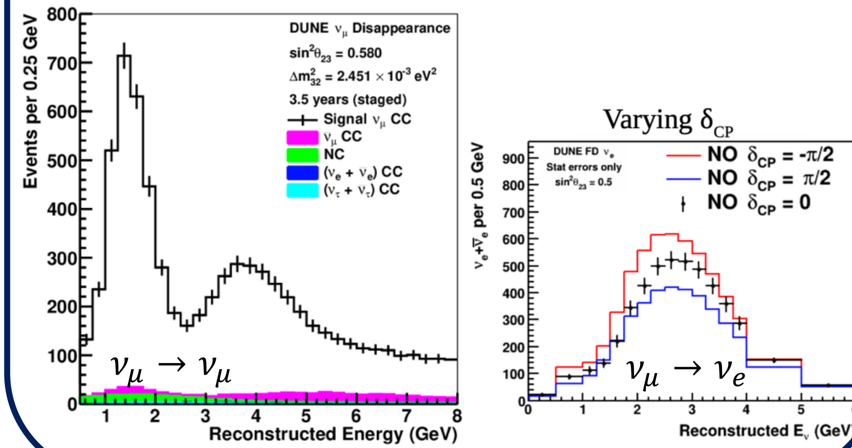


Future

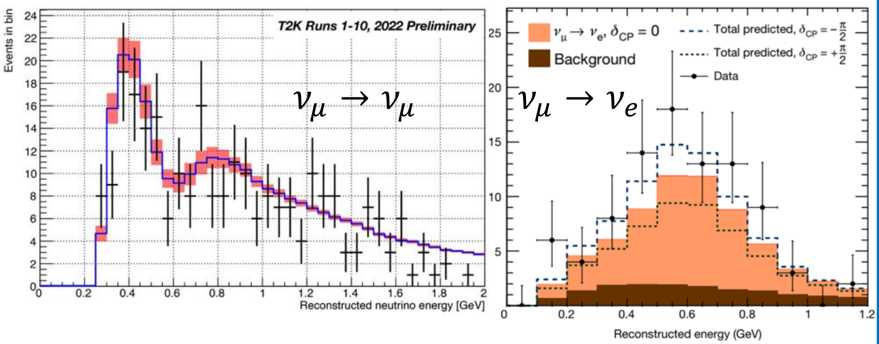


Facilities for exploring physics beyond the standard model + PMNS

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

Beyond beyond the SM

Present



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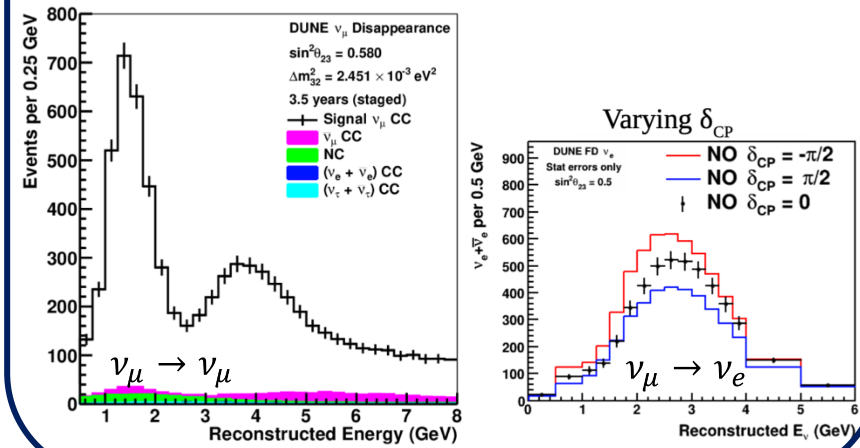

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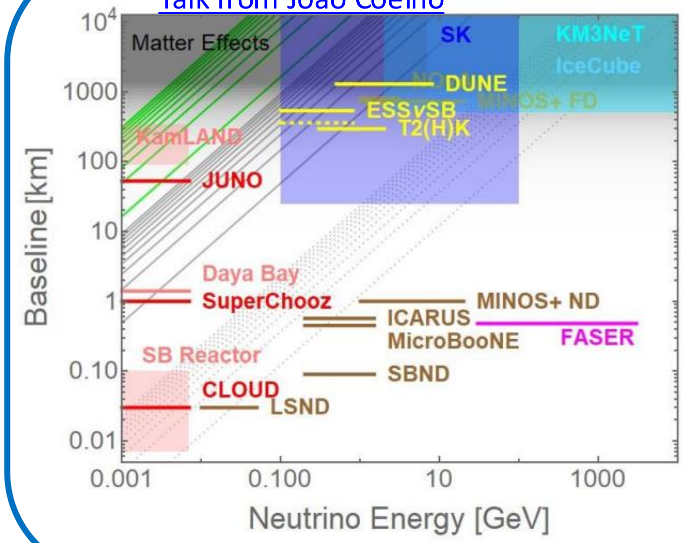
- DUNE and Hyper-K will offer a characterisation of neutrino oscillations with unprecedented precision (10-50 times more statistics)
- Opportunities to see new physics feeding down to create deviations from PMNS behaviour (e.g. "NSIs")

Beyond beyond the SM

Talk from João Coelho



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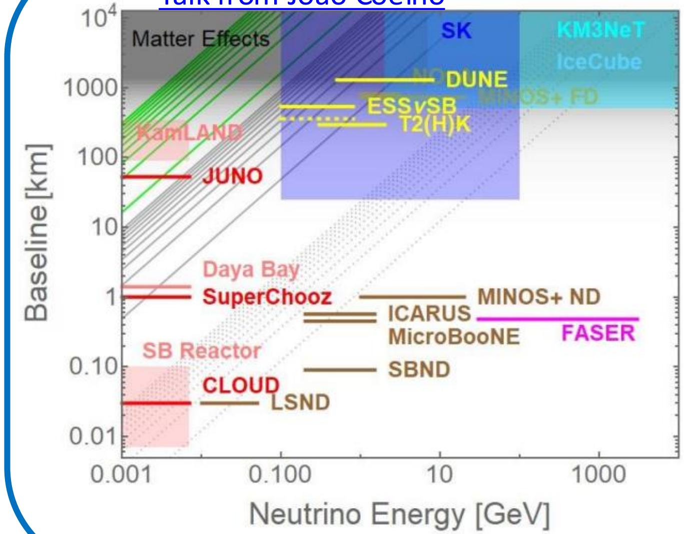

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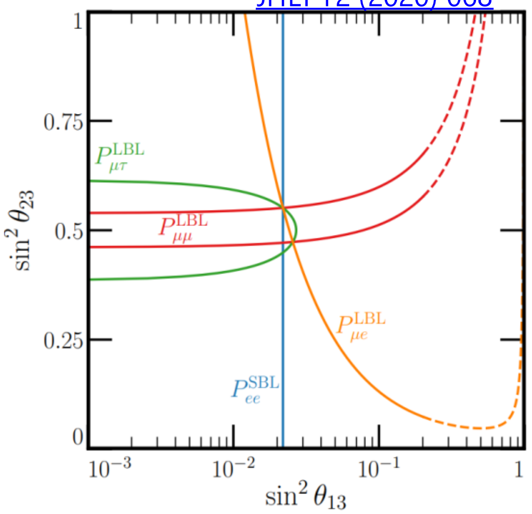

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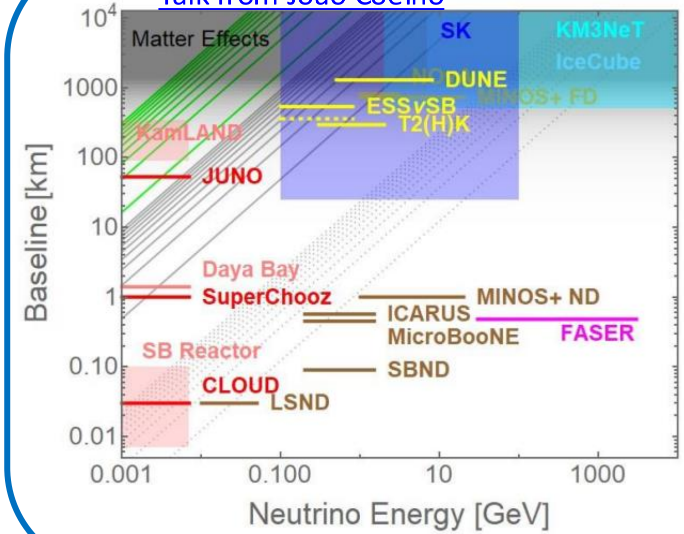
[Talk from João Coelho](#)



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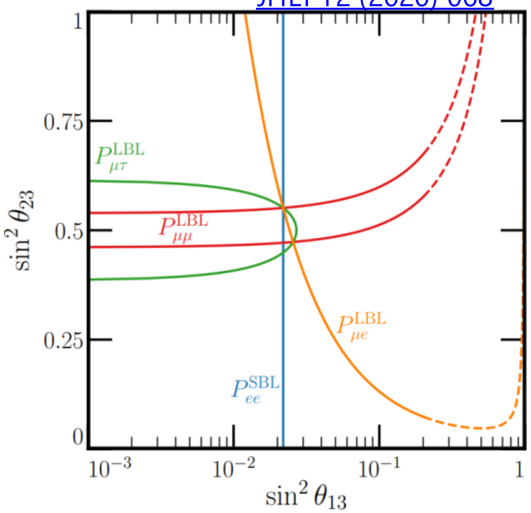

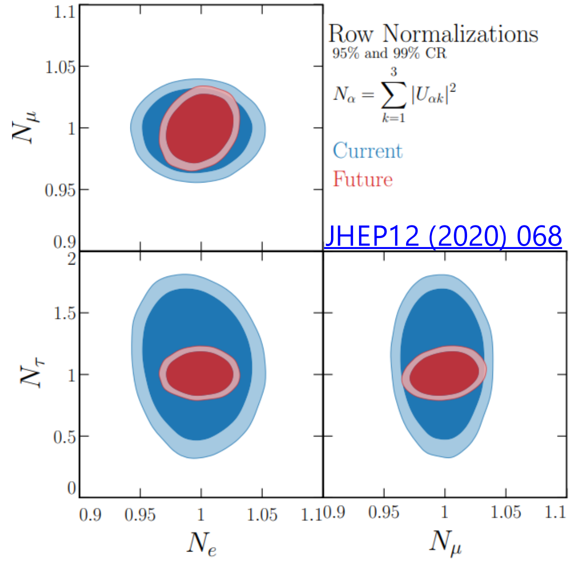

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Facilities for exploring physics beyond the standard model + PMNS

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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

NEUTRINO 2022

Source (T2K)	$N(\nu_e)$
Total Syst.	**5.2%**

At the far detector

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

Future uncertainties

Future long-baseline experiments

Coming 2027-2032

	HK	DUNE
	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

Current systematic uncertainties

NEUTRINO 2022

Source (T2K)	$N(\nu_e)$
Total Syst.	**5.2%**

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

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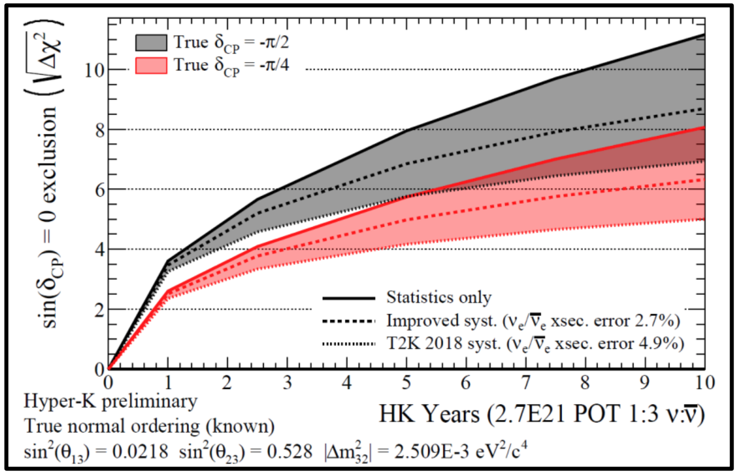
Approximate late-stage projections for reconstructed events in samples at the experiment's far detectors

Current systematic uncertainties

NEUTRINO 2022

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



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Future uncertainties

Future long-baseline experiments

Coming 2027-2032

HYPER-K DUNE

…002.03005

Baseline

N_μ^{rec} (ν-mode)	~10000	
N_e^{rec} (ν–mode)	~2000	~1500

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

Crucial to reduce uncertainties related to neutrino interaction cross sections

Current systematic uncertainties

NEUTRINO 2022

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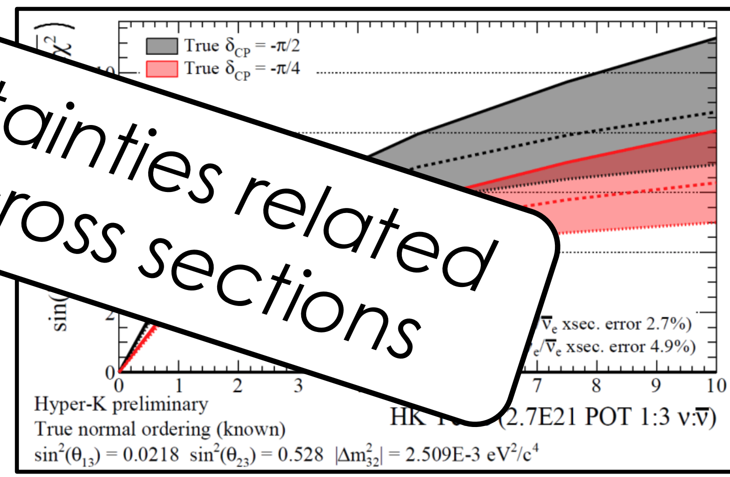

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Overview

- Neutrino Oscillations
- Accelerator-Based Experiments
- **ν Interactions for ν Oscillations**
- 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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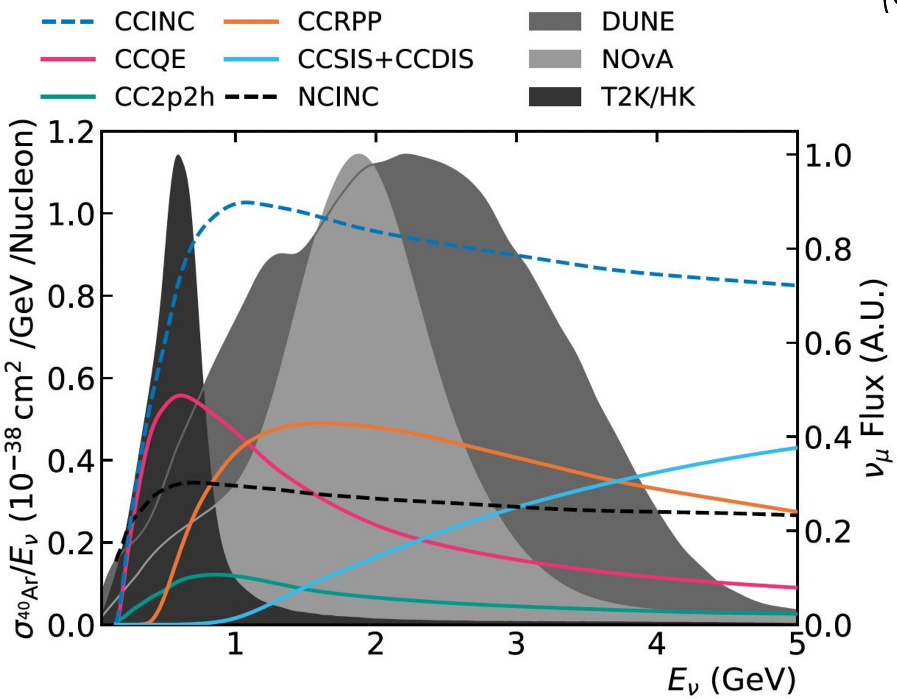
Neutrino-nucleus interactions

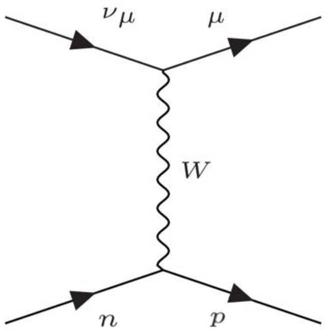


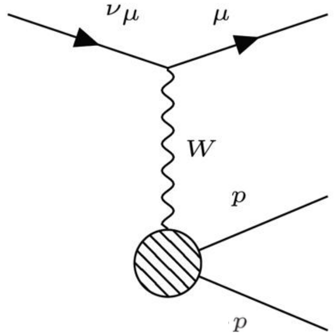
CCQE
(Charged-Current Quasi-Elastic)

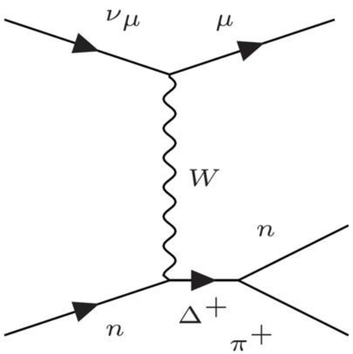
CC2p2h
(Two-Particle-Two-Hole)

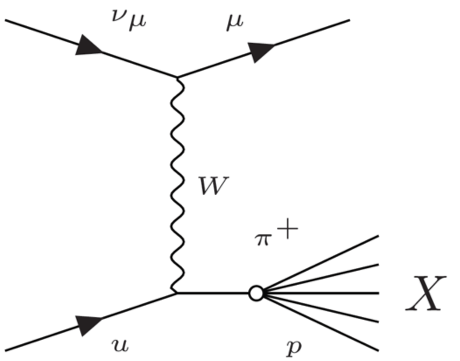
CCRPP
(Single Pion Production)

CCDIS
(Deep Inelastic Scattering)







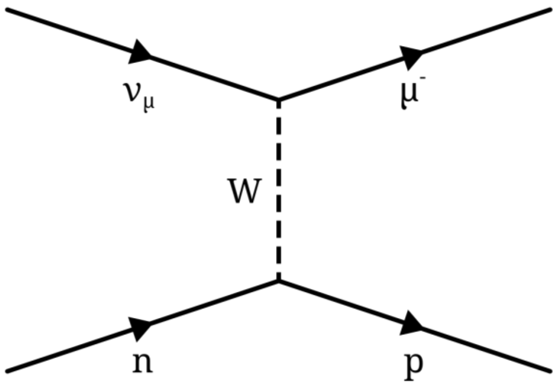


Neutrino-nucleus scattering

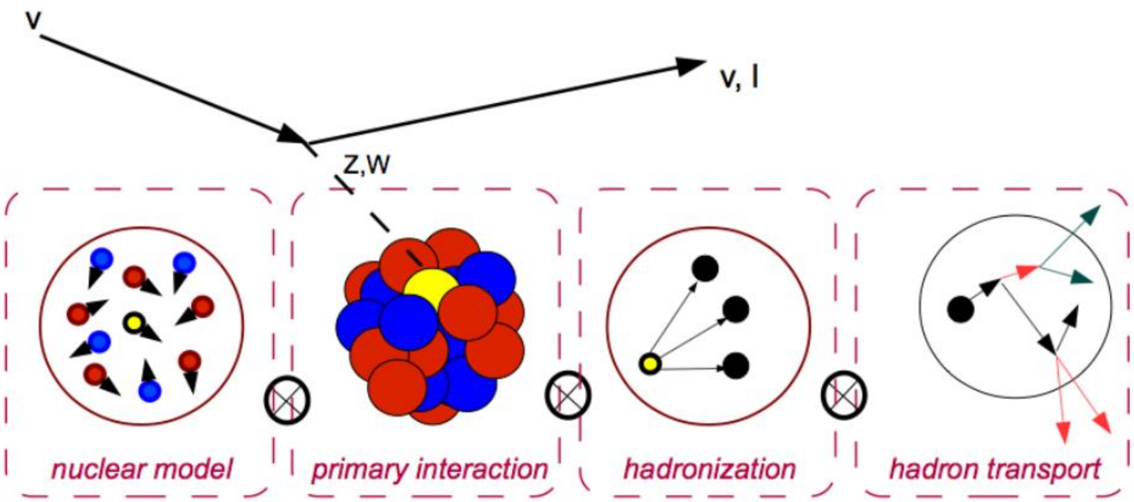
- Even the most simple "CCQE" interaction is hard to describe …

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

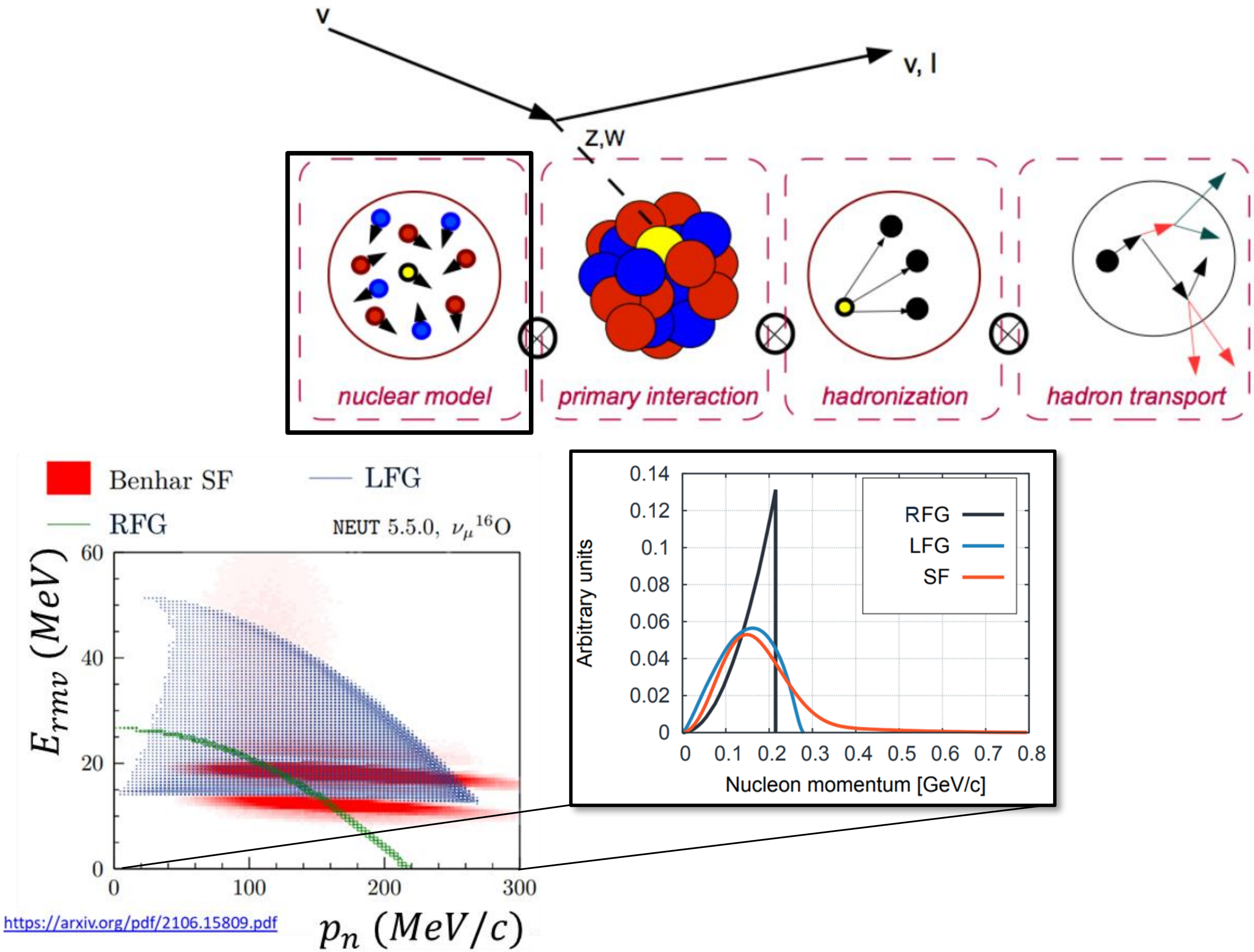
???



Neutrino-nucleus scattering

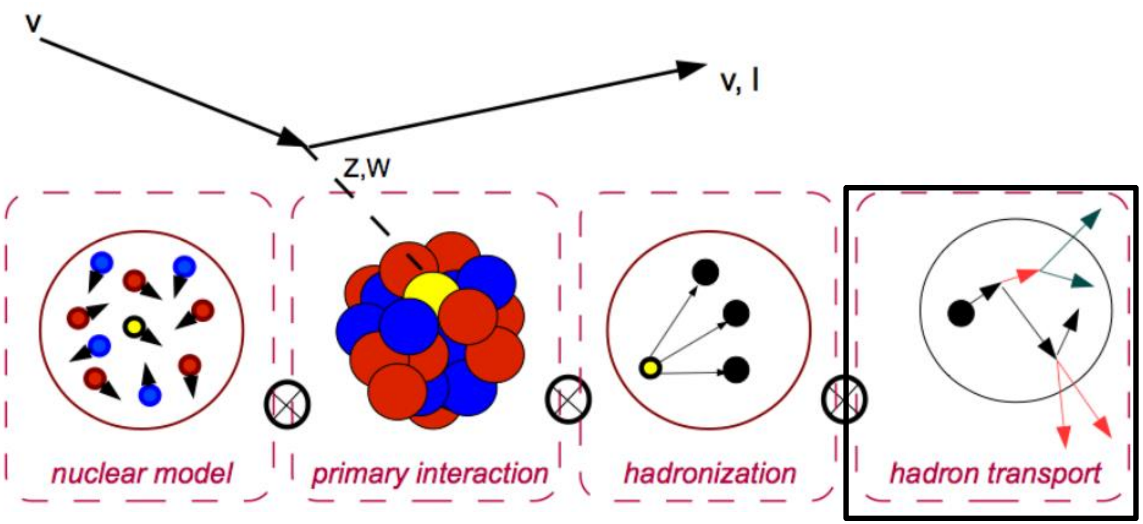


Neutrino-nucleus scattering

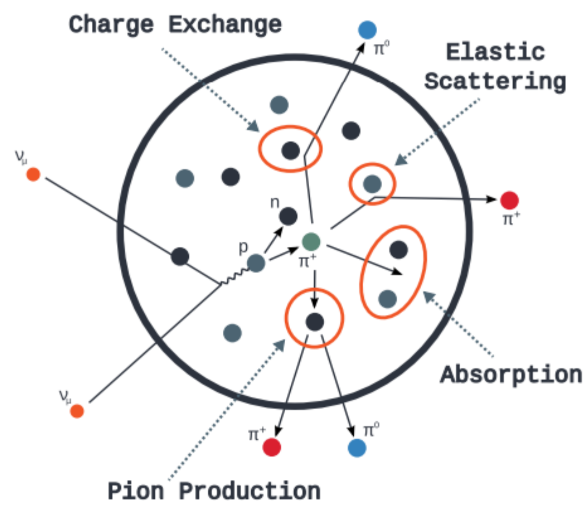


https://arxiv.org/pdf/2106.15809.pdf

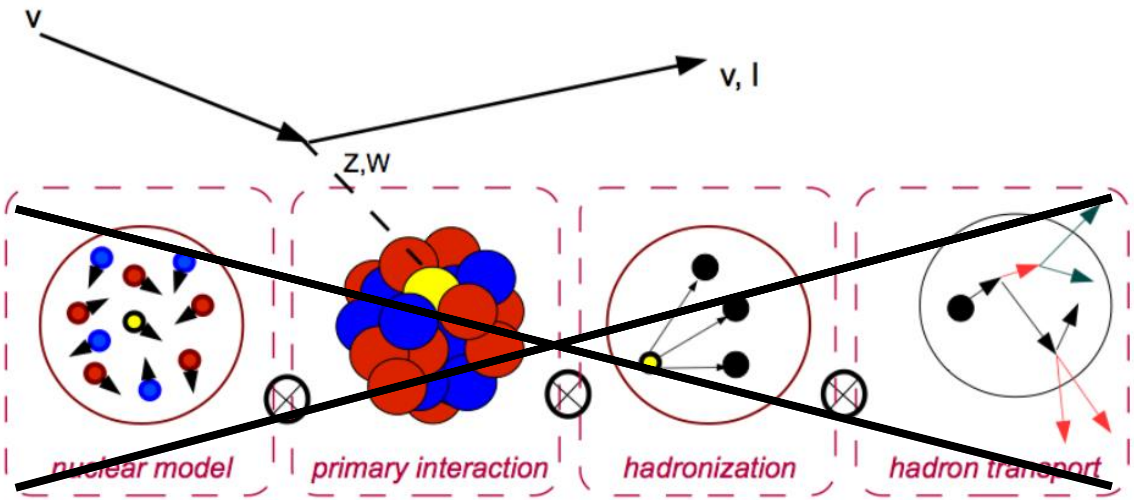
Neutrino-nucleus scattering



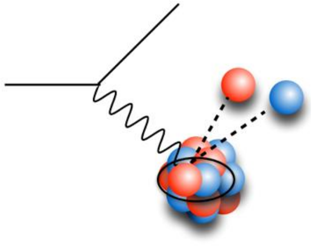
- Hadrons re-interact inside the nuclear medium: **Final State Interactions**
- Impractical to solve exactly, forced to use approximate methods



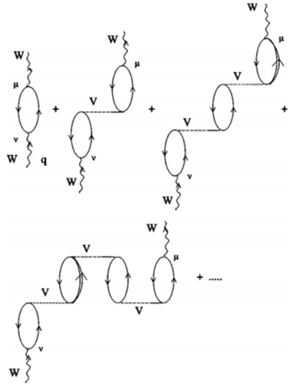
Neutrino-nucleus scattering



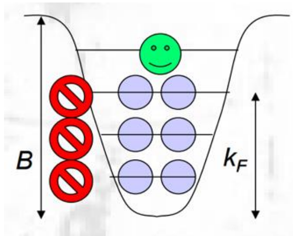
Multi-nucleon Interactions



Long range nuclear correlations



Pauli blocking



Where are we so far?

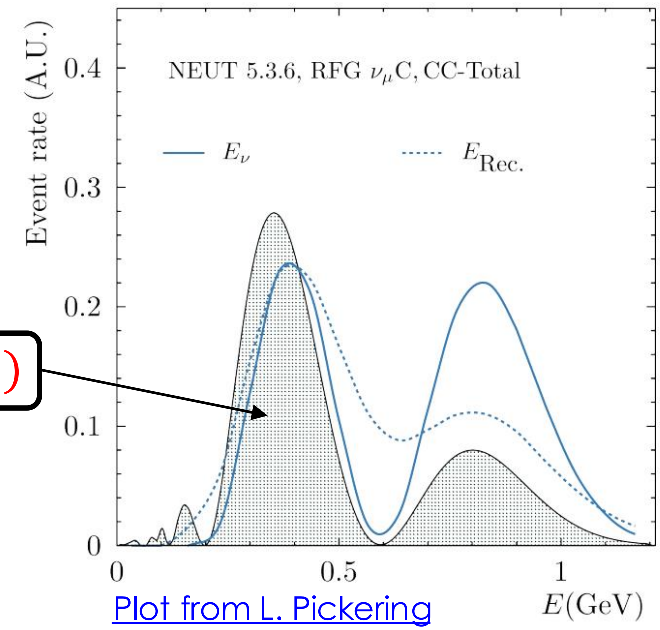
- Key questions:

    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

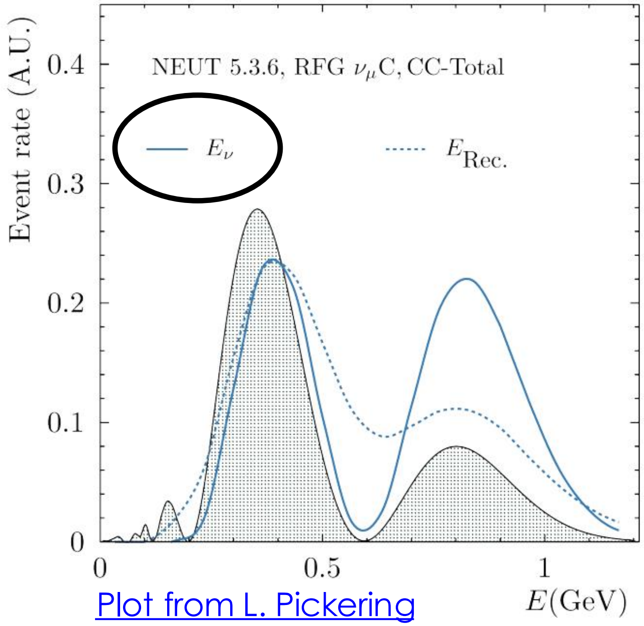
Our physics of interest

$P\left(\nu_\mu \rightarrow \nu_\ell\right)(E_\nu)\ \Phi_\nu(E_\nu)$



Plot from L. Pickering

Event rates to oscillation parameters



Plot from L. Pickering

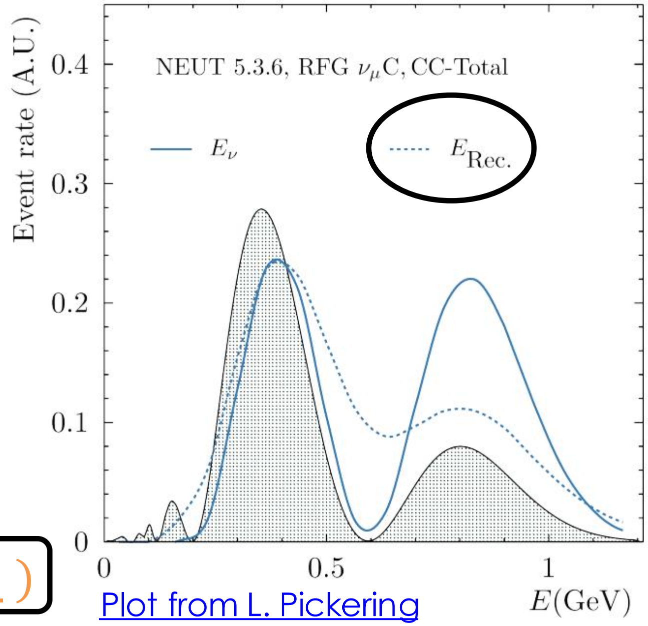
What we would like to measure

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

Event rates to oscillation parameters

What we can actually measure

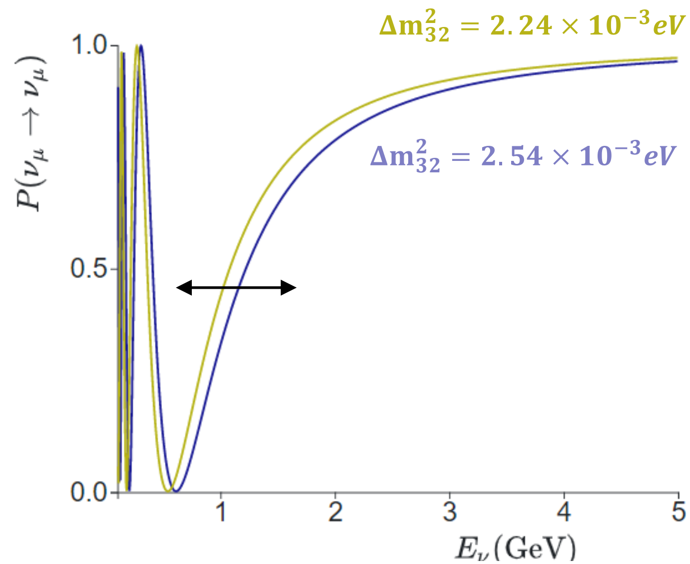
$$N_\ell(E_{Rec.}) = P(\nu_\mu \to \nu_\ell)(E_\nu)\ \sigma(E_\nu)\ \Phi_\nu(E_\nu)\ \epsilon(E_\nu)\ S(E_\nu, E_{Rec.})$$

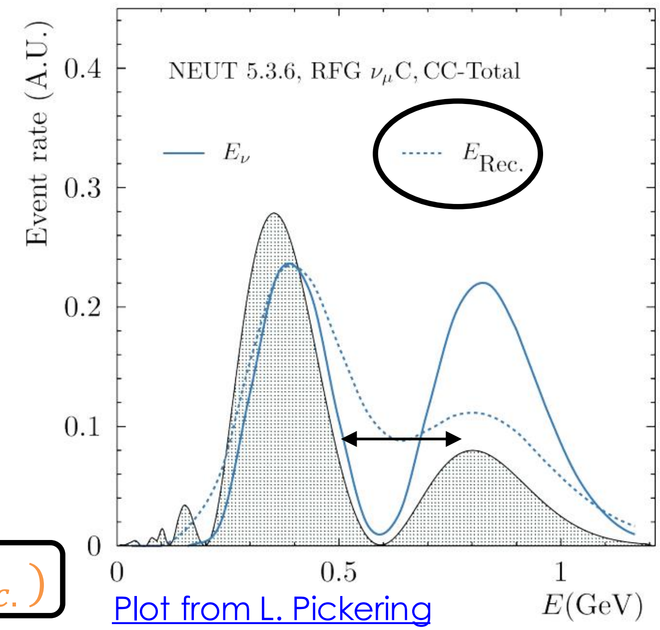


Plot from L. Pickering

Event rates to oscillation parameters

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





[Plot from L. Pickering]

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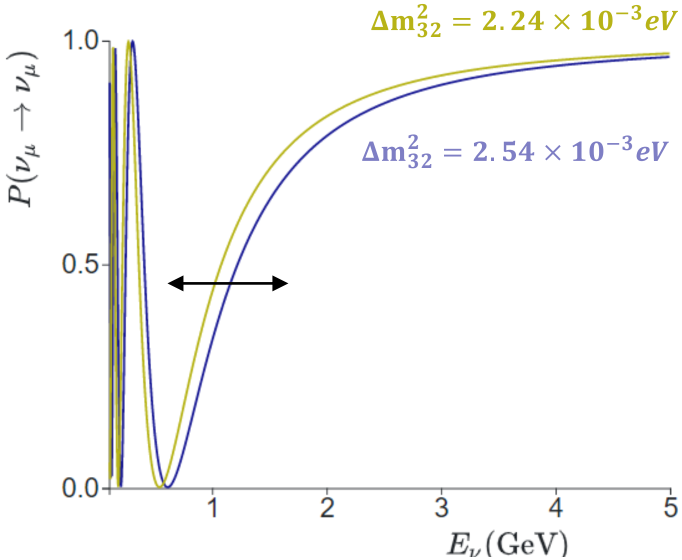
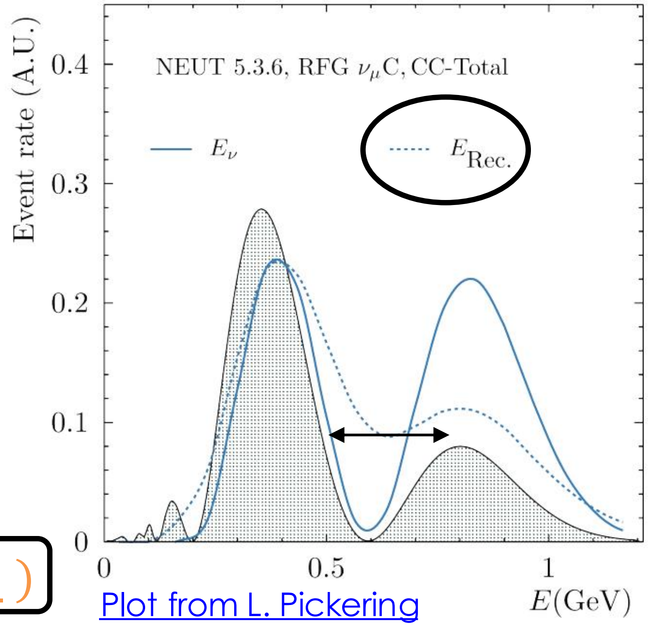
Event rates to oscillation parameters

- 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!**





Plot from L. Pickering

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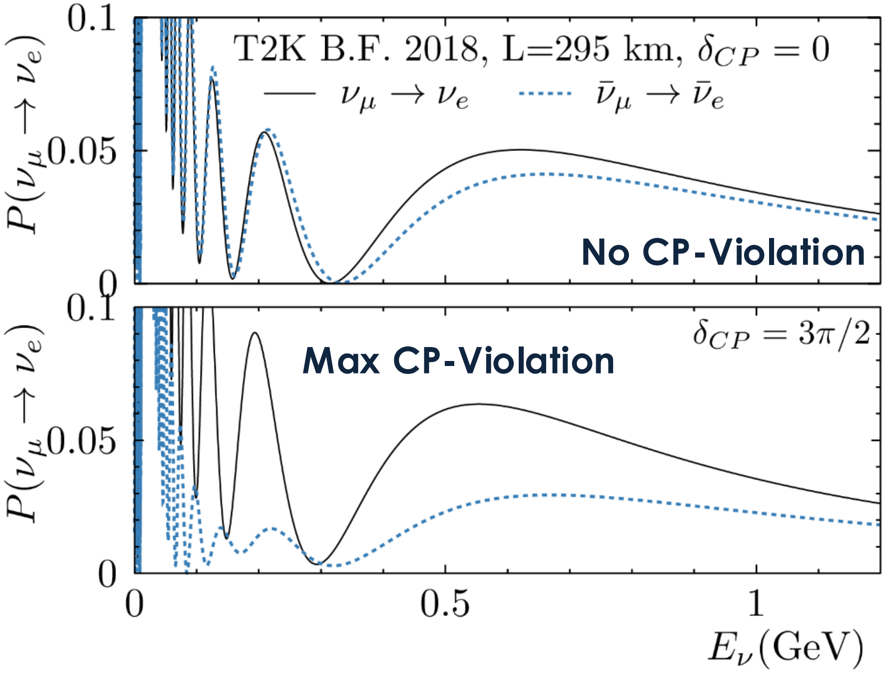
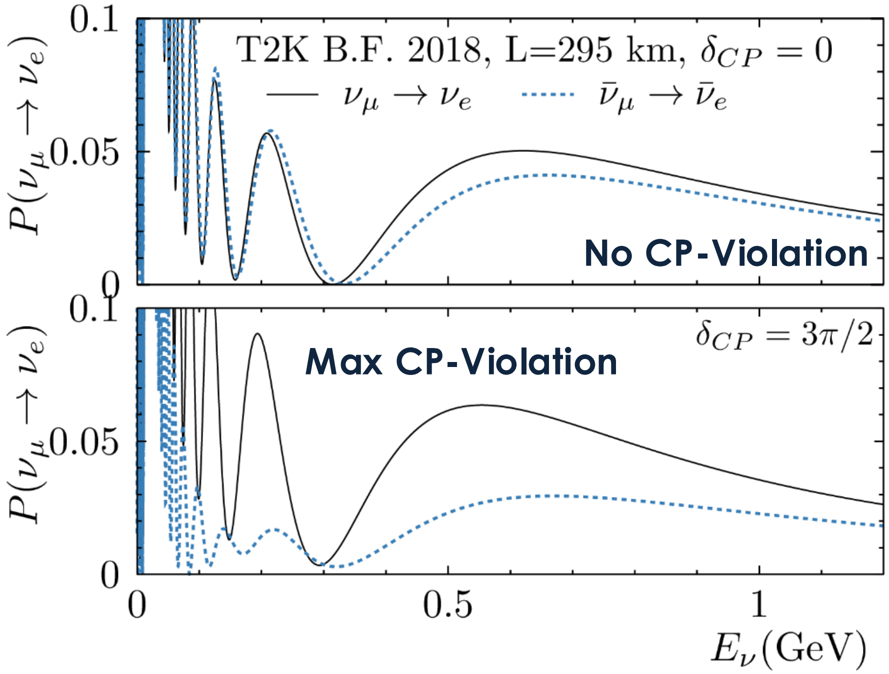
- Constraints on δ_{CP} rely on differences between electron neutrino and anti-neutrino appearance



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



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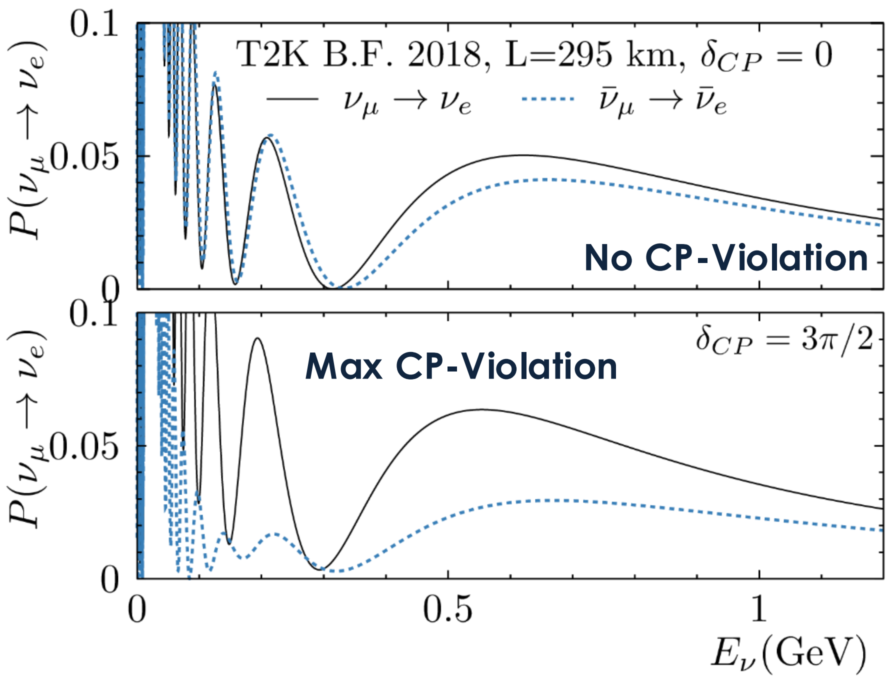
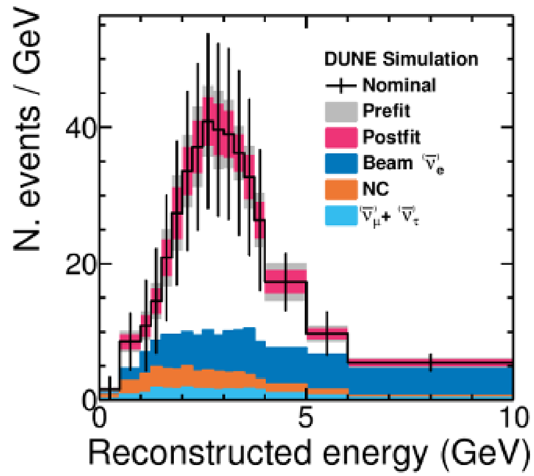
- **Require a good control over cross section energy dependence and energy reconstruction!**
- Constraints on δ_{CP} rely on differences between electron neutrino and anti-neutrino appearance
- But we mainly measure muon neutrino interactions at the near detector
- **A good modelling of ν_e/ν_μ and $\nu/\bar{\nu}$ cross section ratio is essential**



Event rates to oscillation parameters

- **Another challenge:** not all events are signal events



Experiment	Selection	NC	Wrong sign	Wrong flavour	Beam $\overset{(-)}{\nu}_e$	Total bkgd.
DUNE	$\nu_\mu \to \nu_\mu$	2.6%	6.7%	0.8%	N/A	10.1%
	$\bar{\nu}_\mu \to \bar{\nu}_\mu$	2.5%	36.2%	0.8%	N/A	39.5%
	$\nu_\mu \to \nu_e$	4.7%	0.8%	2.8%	12.8%	21.2%
	$\bar{\nu}_\mu \to \bar{\nu}_e$	8.4%	20.0%	5.9%	30.5%	64.8%
Hyper-K	$\nu_\mu \to \nu_\mu$	3.5%	5.3%	0.03%	N/A	8.8%
	$\bar{\nu}_\mu \to \bar{\nu}_\mu$	2.6%	34.3%	0.01%	N/A	36.9%
	$\nu_\mu \to \nu_e$ [1]	5.9%	0.5%	0.3%	12.2%	18.9%
	$\bar{\nu}_\mu \to \bar{\nu}_e$	9.8%	14.9%	0.6%	23.4%	48.6%

Four 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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Key question: how well do we know these?

Energy dependence

<u>We need to know:</u>

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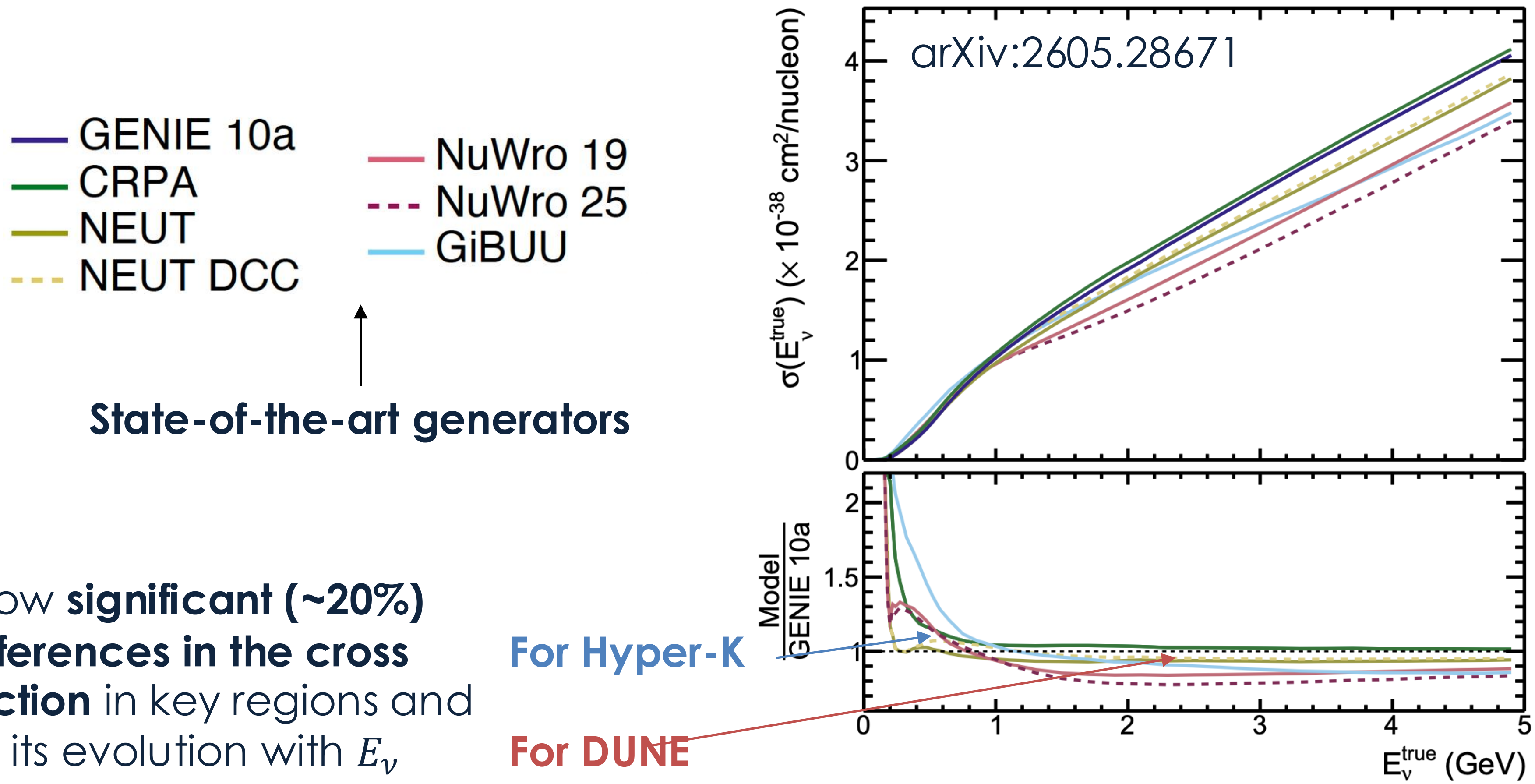
   - *So we know how to extrapolate from our near to far detectors*



State-of-the-art generators

Show **significant (~20%) differences in the cross section** in key regions and on its evolution with E_ν

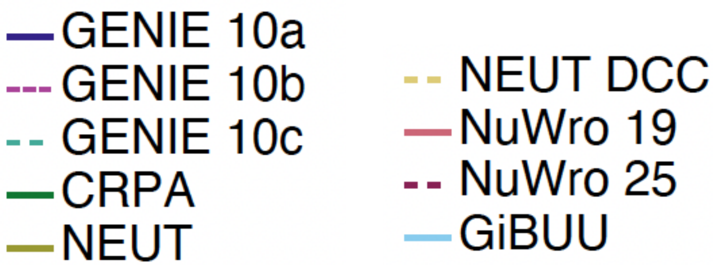
For Hyper-K

For DUNE

Neutrino energy reconstruction

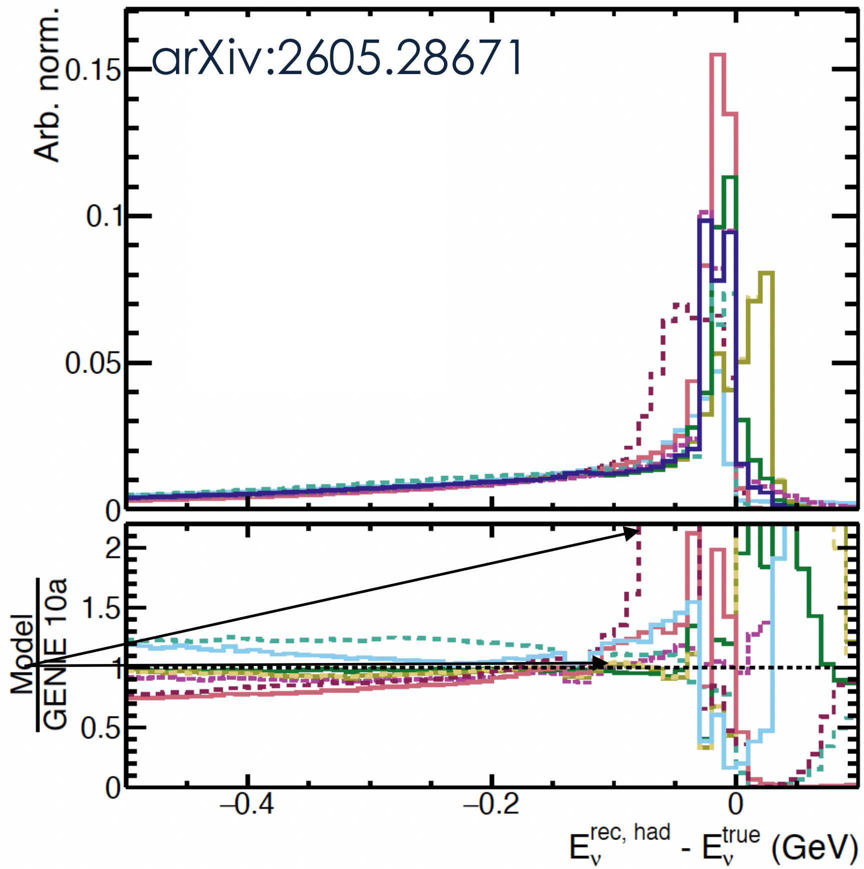
We need to know:

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



State-of-the-art generators

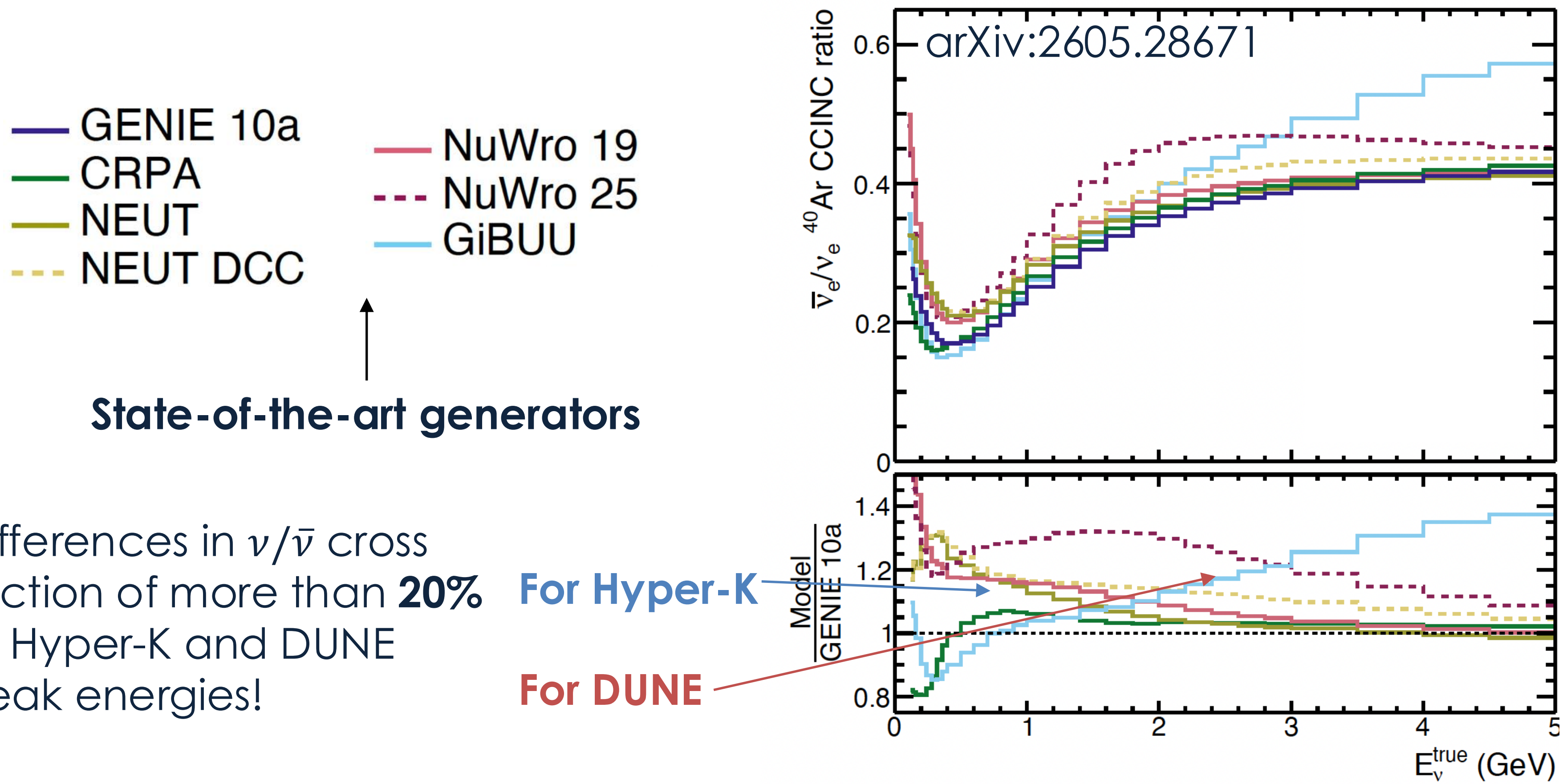
Proportion of E_ν reconstructed **within 200 MeV** of the true E_ν differs by **more than 100%**



$\nu/\bar{\nu}$ differences

<u>We need to know:</u>

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*

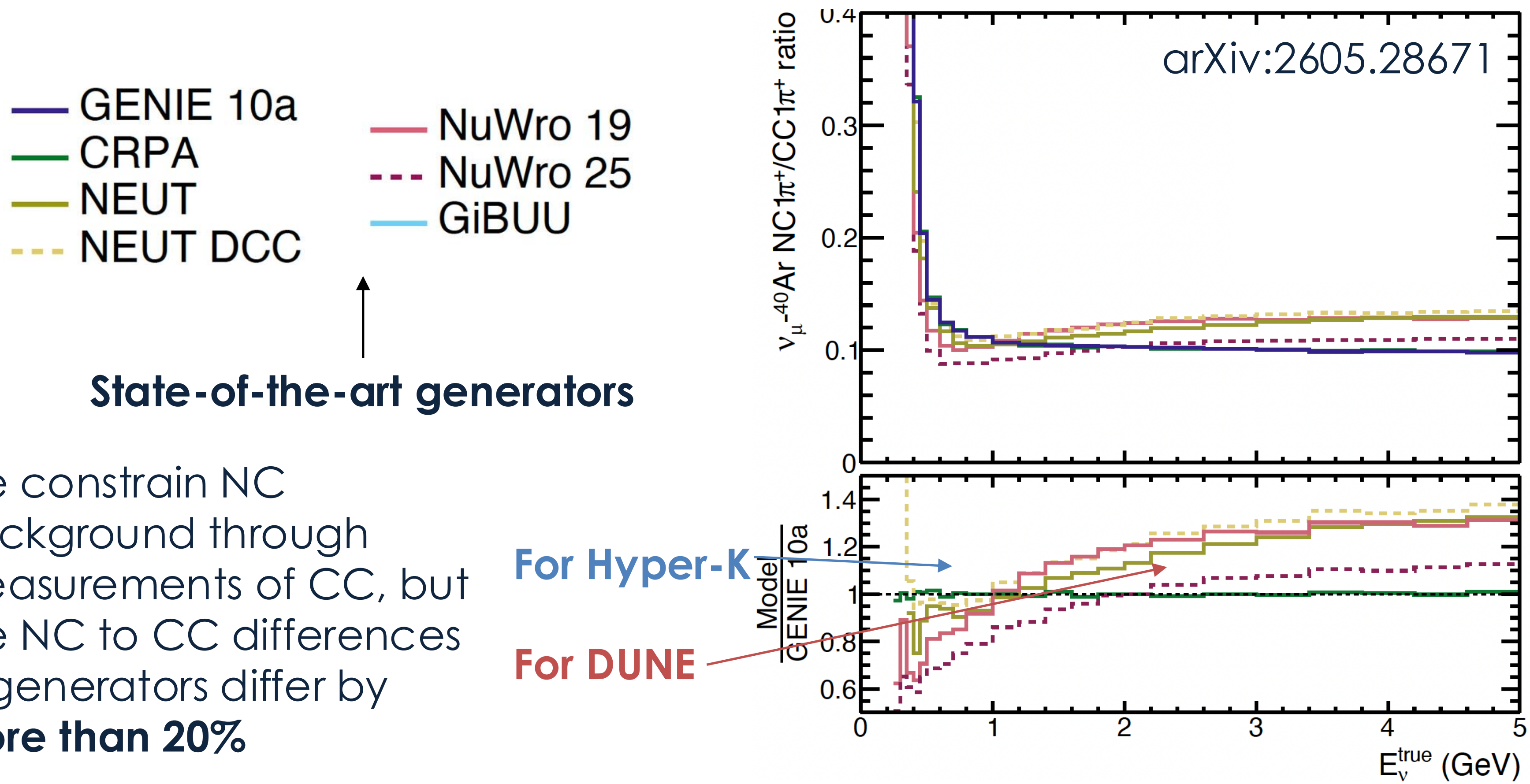


Differences in $\nu/\bar{\nu}$ cross section of more than **20%** at Hyper-K and DUNE peak energies!

$\nu/\bar{\nu}$ differences

We need to know:

4. Background contributions at the far detector
   - *So we can isolate the oscillation signal*



We constrain NC background through measurements of CC, but the NC to CC differences in generators differ by **more than 20%**

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*
4. Background contributions at the far detector
   - *So we can isolate the oscillation signal*

Key question: how well do we know these?
Answer: not well …

But surely cross-section measurements can help us…

Overview

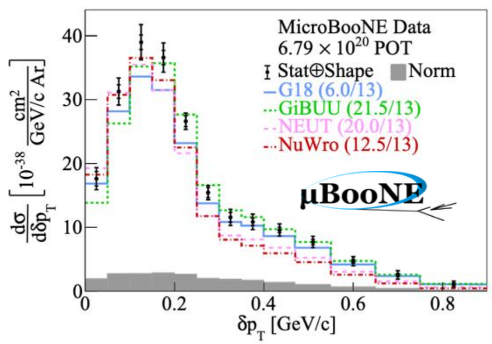
- Neutrino Oscillations
- Accelerator-Based Experiments
- $\boldsymbol{\nu}$ Interactions for $\boldsymbol{\nu}$ Oscillations
- **The Path to Precision Measurements**

Can’t we just measure neutrino cross sections?

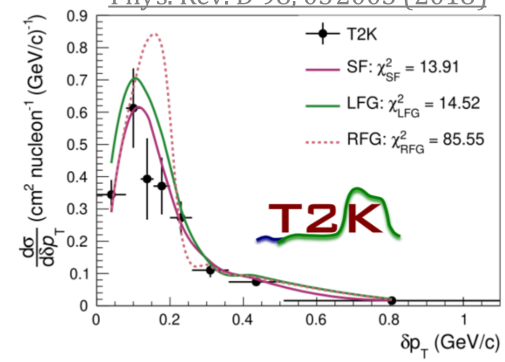
Can't we just measure neutrino cross sections?

We do, but…

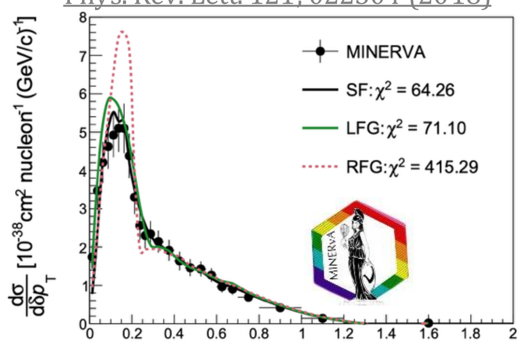
arXiv:2301.03700



Phys. Rev. D 98, 032003 (2018)

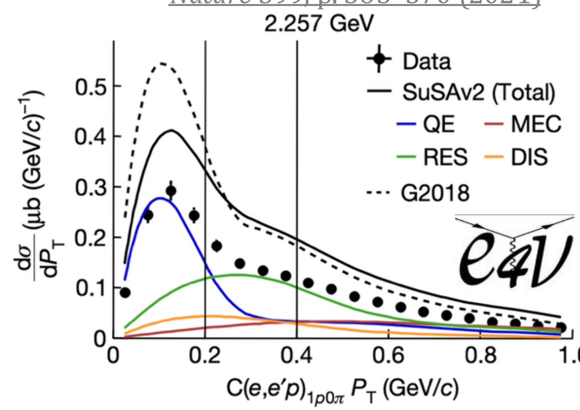


Phys. Rev. Lett. 121, 022504 (2018)



arXiv:2407.10962

Nature 599, p. 565–570 (2021)



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No model is able to describe global neutrino scattering measurements

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Phys. Rev. D 98, 032003 (2018)

***p*-values of model comparisons to measurements**
(red if excluded at <0.05)

arXiv:2407.10962

Measurement	N_{bins}	SF/SF*	LFG	RFG	More 2p2h	More FSI	Less FSI	More π abs.	Less π abs.
T2K $\delta\alpha_T$	8	0.01	0.00	0.00	0.00	0.00	0.02	0.06	0.02
T2K δp_T	8	0.08	0.69	0.00	0.00	0.02	0.07	0.00	0.18
MINERvA $\delta\alpha_T$	12	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00
MINERvA δp_T	24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MINERvA p_N	24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MicroBooNE $\delta\alpha_T$	7	0.02	0.45	0.62	0.07	0.18	0.00	0.02	0.01
MicroBooNE δp_T	13	0.12	0.42	0.00	0.33	0.23	0.02	0.13	0.10
MicroBooNE δp_T low $\delta\alpha_T$	11	0.26	0.23	0.14	0.37	0.44	0.10	0.28	0.24
MicroBooNE δp_T mid-low $\delta\alpha_T$	12	0.07	0.40	0.19	0.23	0.38	0.00	0.08	0.06
MicroBooNE δp_T mid-high $\delta\alpha_T$	13	0.04	0.23	0.02	0.16	0.22	0.01	0.05	0.04
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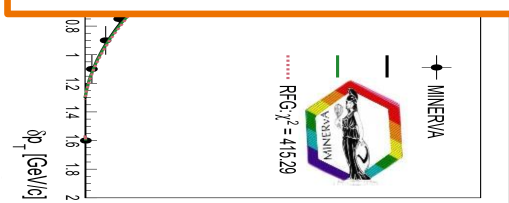

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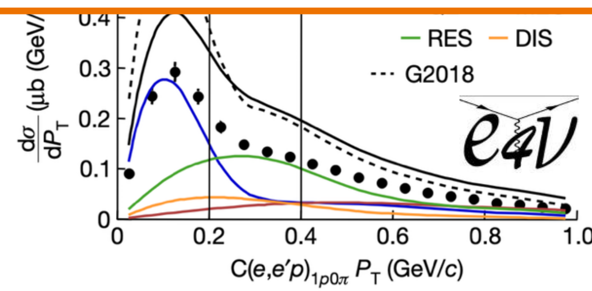


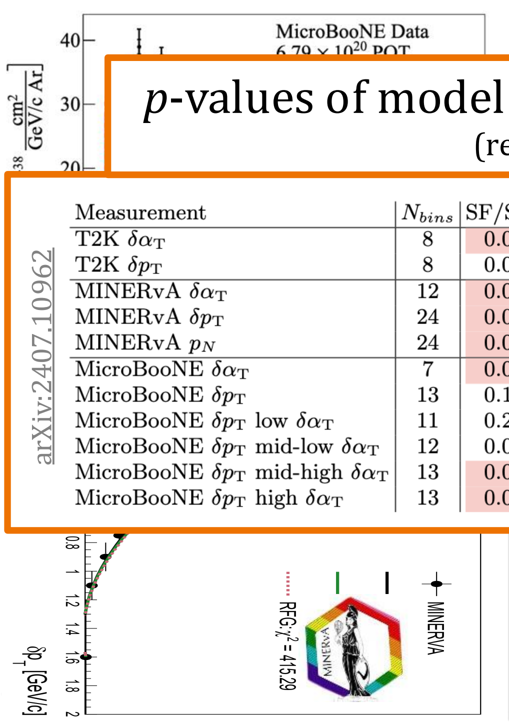
Can't we just measure neutrino cross sections?

We do, but…

No model is able to describe global neutrino scattering measurements

Our ν measurements tell us that all the models are wrong ***but not why/where or how to fix them***

arXiv:2301.03700



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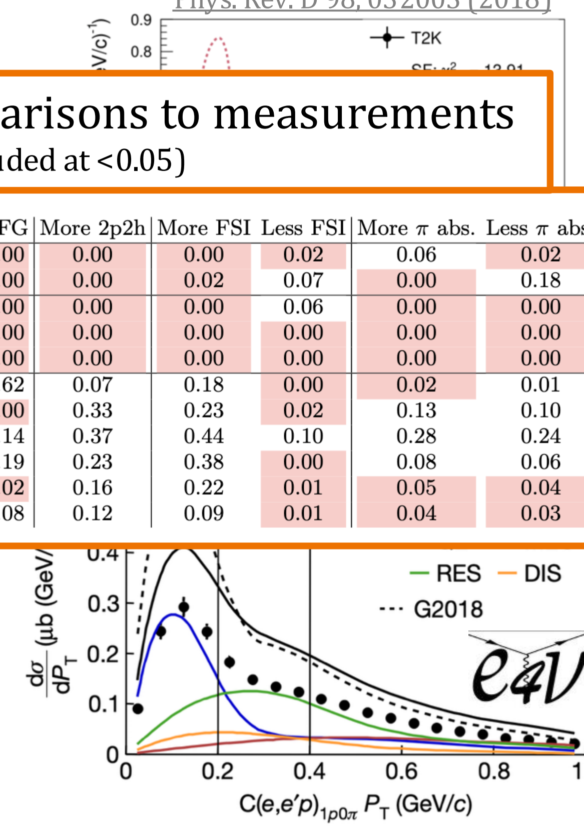

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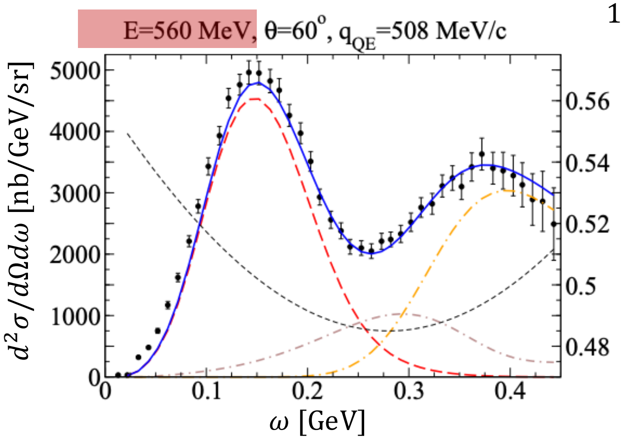
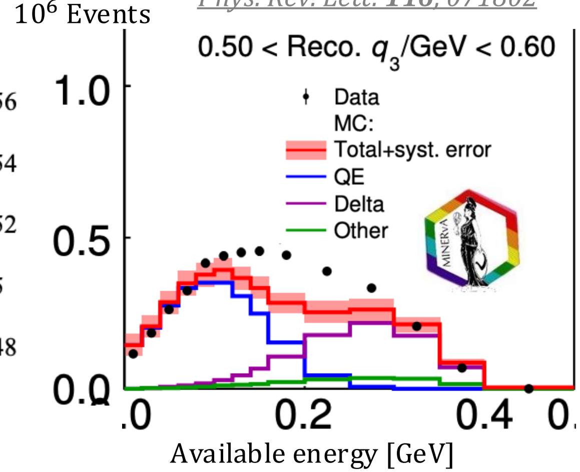
Why is it so difficult?

Electron scattering vs **neutrino** scattering



Phys. Rev. D 94, 013012 (2016)

Phys. Rev. Lett. ***116***, 071802

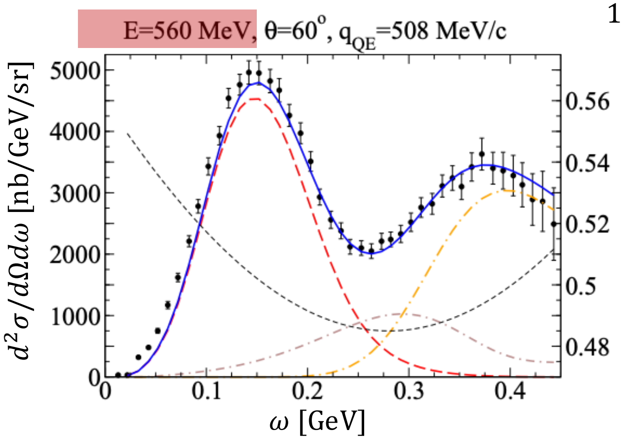


Monochromatic,
well-known flux

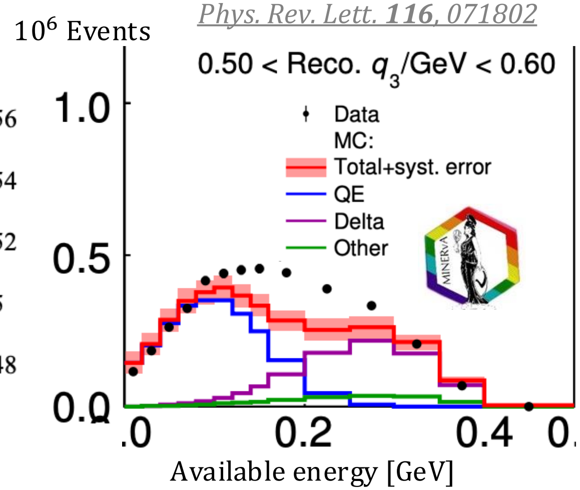
Broad-band,
poorly known flux

Why is it so difficult?

Electron scattering vs **neutrino** scattering



Phys. Rev. D 94, 013012 (2016)



Phys. Rev. Lett. **116**, 071802

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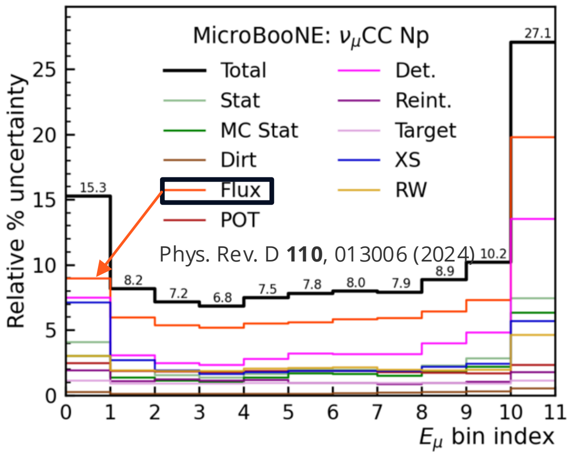
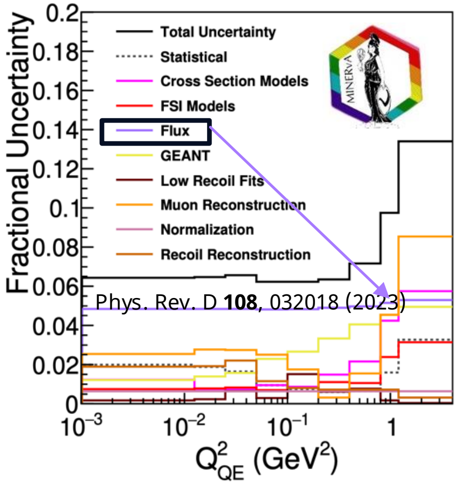
Broad-band, poorly known flux





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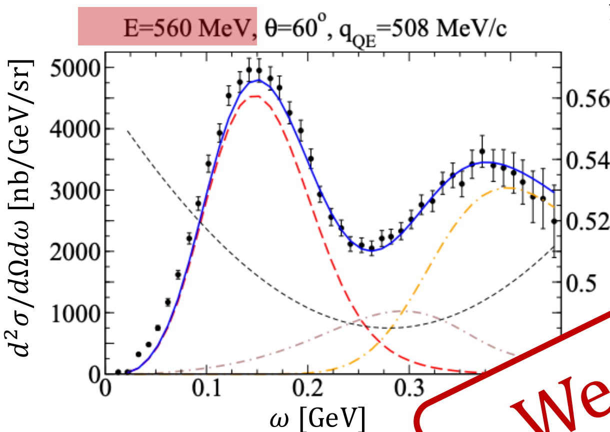
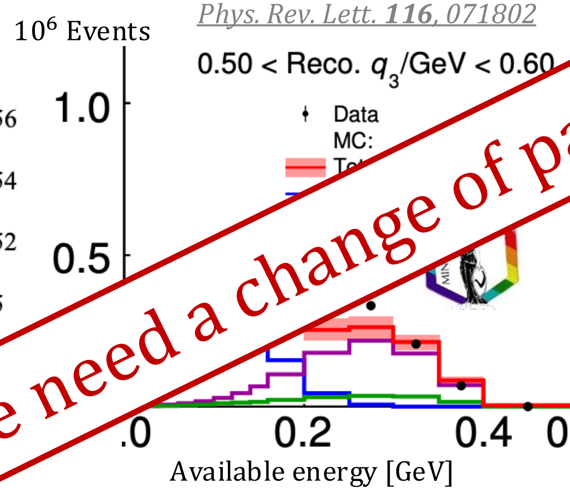
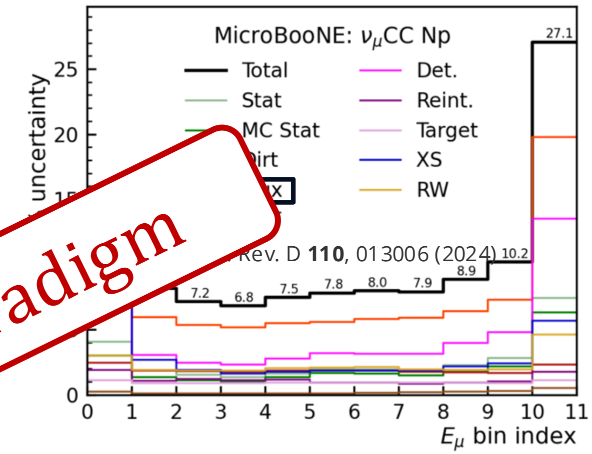
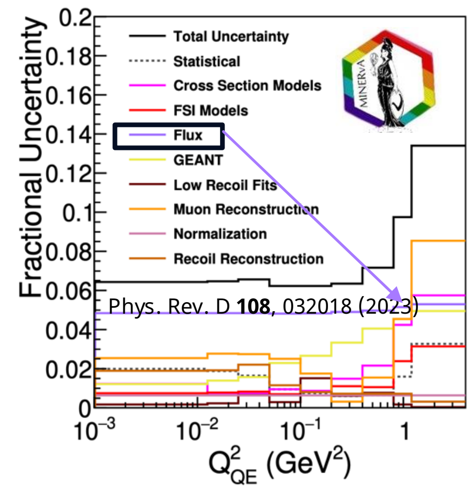


Phys. Rev. D 94, 013012 (2...







We need a change of paradigm

Monochromatic, well-known flux

Broad-band, poorly known flux

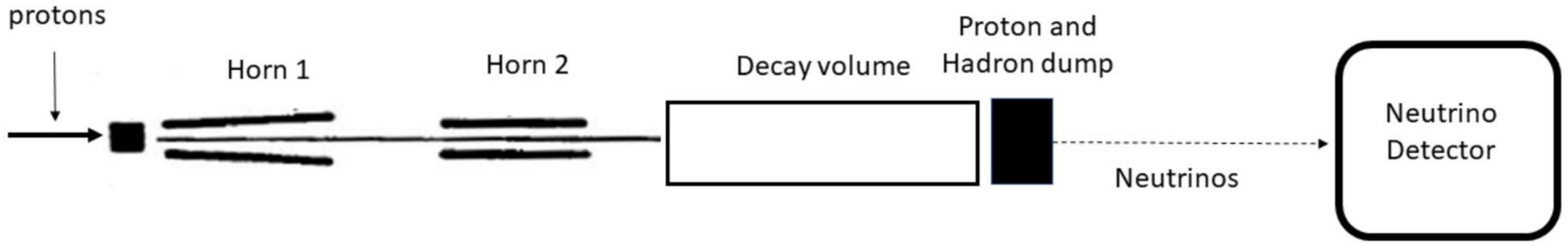
ν interactions, ν problems

ν interactions, ~~ν problems~~
ν SCOPE

Rethinking how to make a neutrino beam

Inspired by F. Terranova's seminar

Conventional neutrino beams



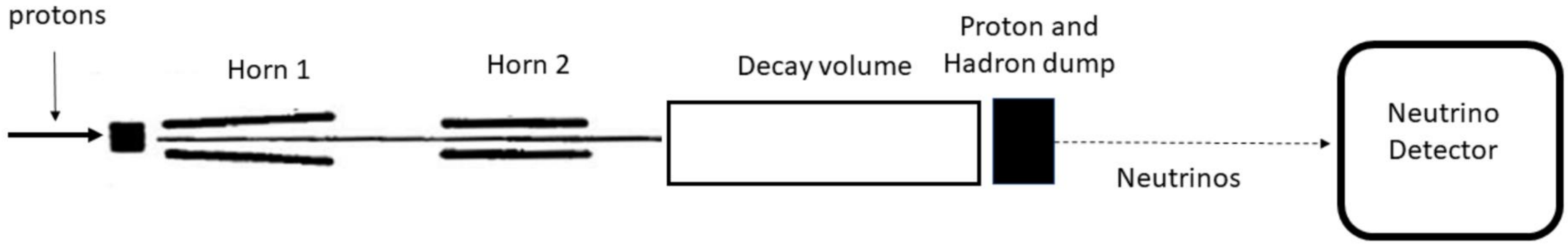
Appl. Sci. **2021**, *11*(4), 1644

Rethinking how to make a neutrino beam

Inspired by F. Terranova's seminar

Conventional neutrino beams

	"Employ the most intense proton accelerator at your disposal"	"Focus as many pions/kaons as possible"
Pros:		Large yield of pions per proton-on-target (pot)
Drawbacks:		Lack of control on neutrino energy



Appl. Sci. **2021**, *11*(4), 1644

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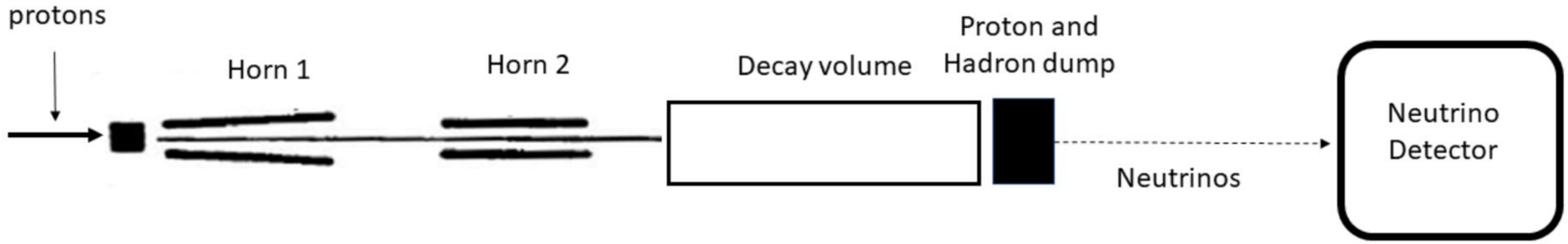
Pros:		Large yield of pions per proton-on-target (pot)	Large number of neutrinos from pion decay
Drawbacks:		Lack of control on neutrino energy	Coarse beam diagnostics



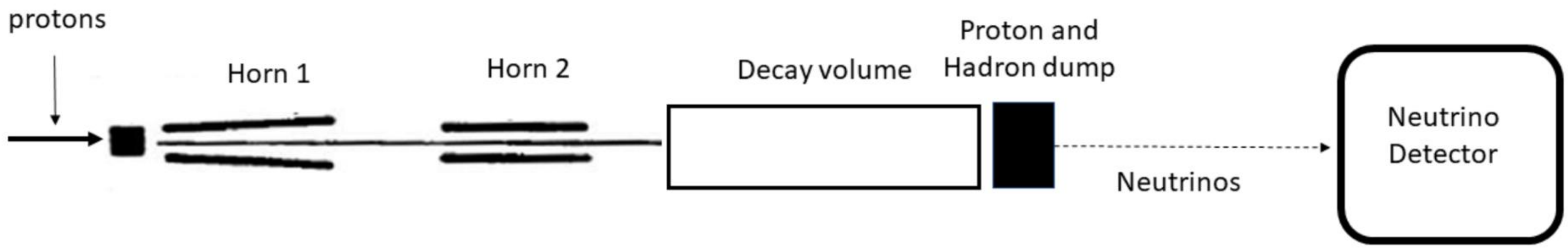
Appl. Sci. **2021**, *11*(4), 1644

Rethinking how to make a neutrino beam

Inspired by F. Terranova's seminar

Conventional neutrino beams

"Employ the most intense proton accelerator at your disposal"	"Focus as many pions/kaons as possible"	"Eliminate any material along the beamline in the decay tunnel"	"Build the largest possible neutrino detector"
Pros:	Large yield of pions per proton-on-target (pot)	Large number of neutrinos from pion decay	Large statistics of neutrino interaction events (CC and NC)
Drawbacks:	Lack of control on neutrino energy	Coarse beam diagnostics	Limited precision in the final state reconstruction



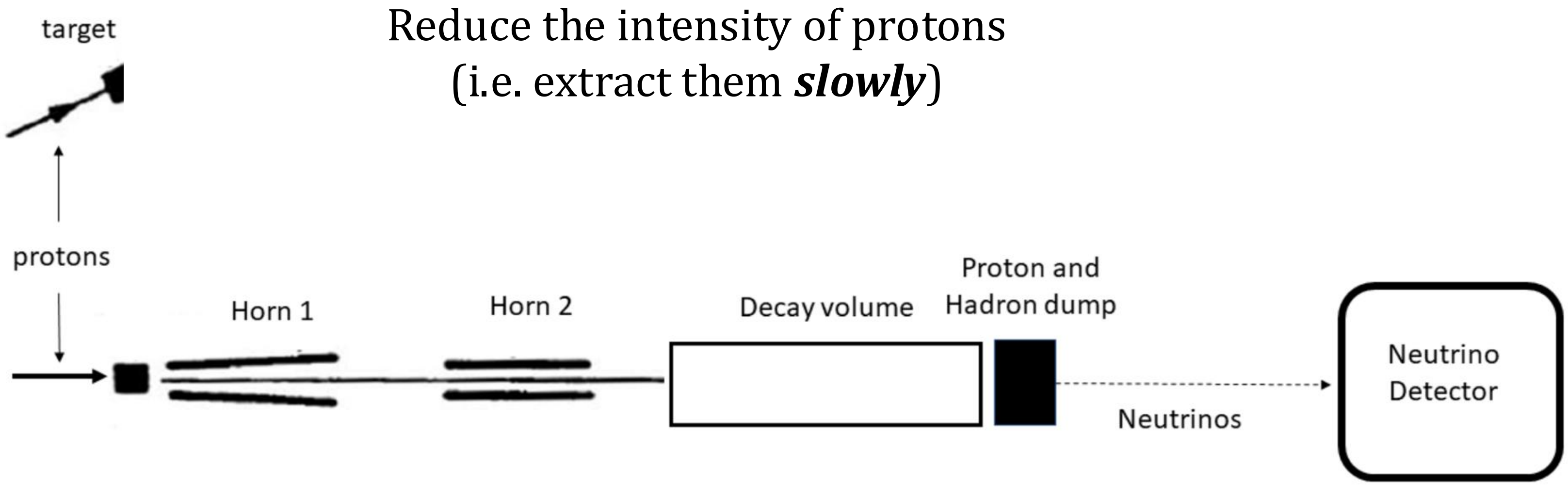
Appl. Sci. **2021**, *11*(4), 1644

Rethinking how to make a neutrino beam

Inspired by F. Terranova's seminar

A novel neutrino beam

Reduce the intensity of protons
(i.e. extract them ***slowly***)



Appl. Sci. **2021**, *11*(4), 1644

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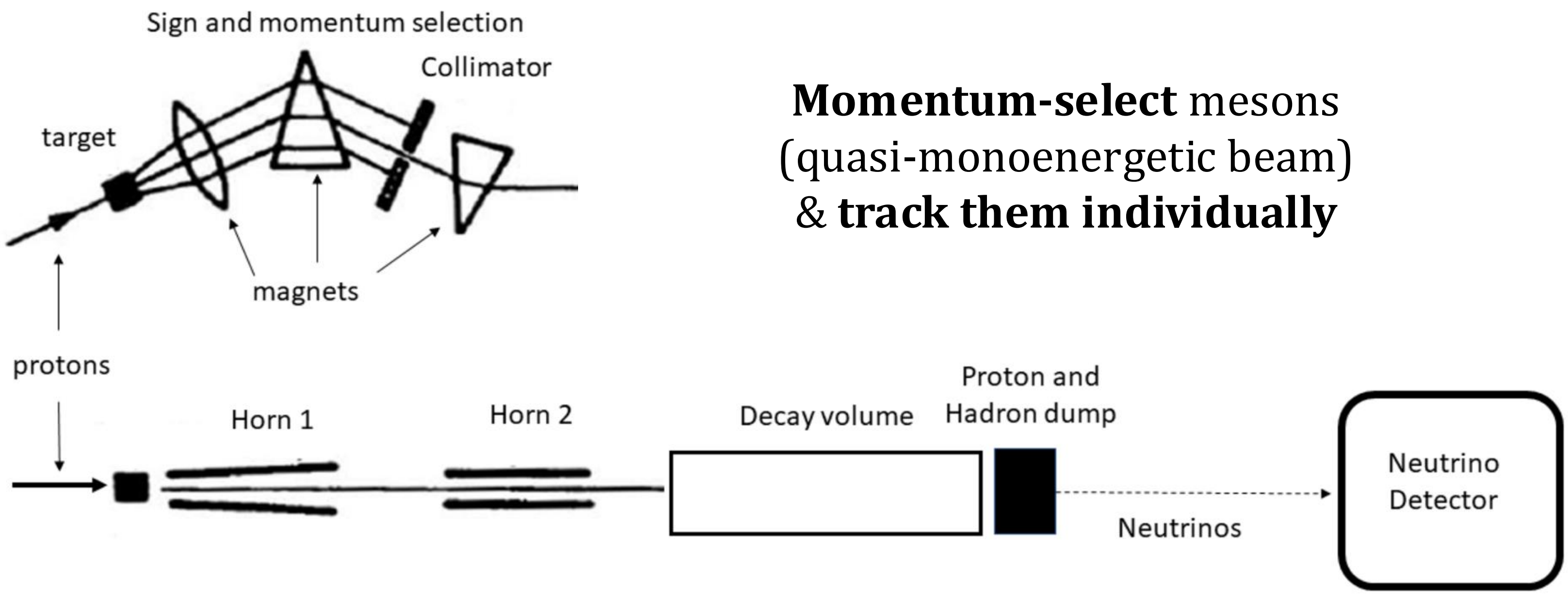
Inspired by F. Terranova's seminar

A novel neutrino beam



Momentum-select mesons
(quasi-monoenergetic beam)
& **track them individually**

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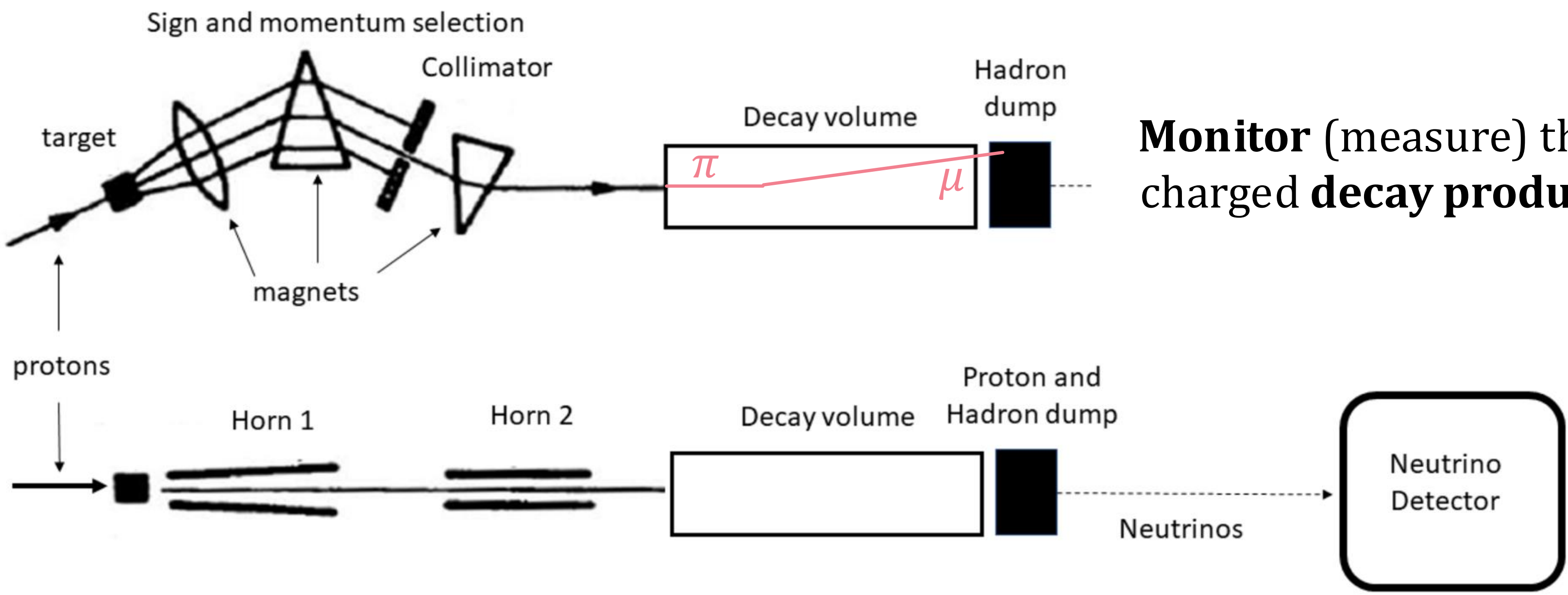
Rethinking how to make a neutrino beam

Inspired by F. Terranova's seminar

A novel neutrino beam



Monitor (measure) their charged **decay products**

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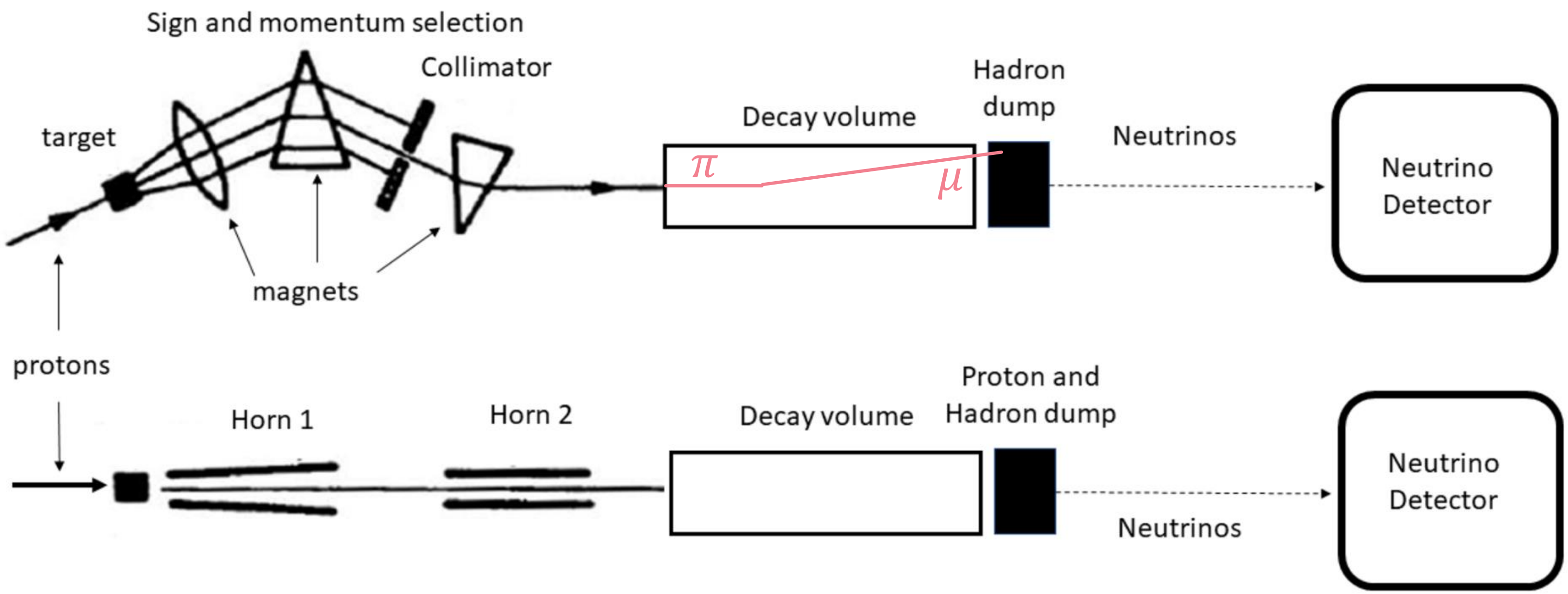
Rethinking how to make a neutrino beam

Inspired by F. Terranova's seminar

A novel neutrino beam **Measure neutrinos!**



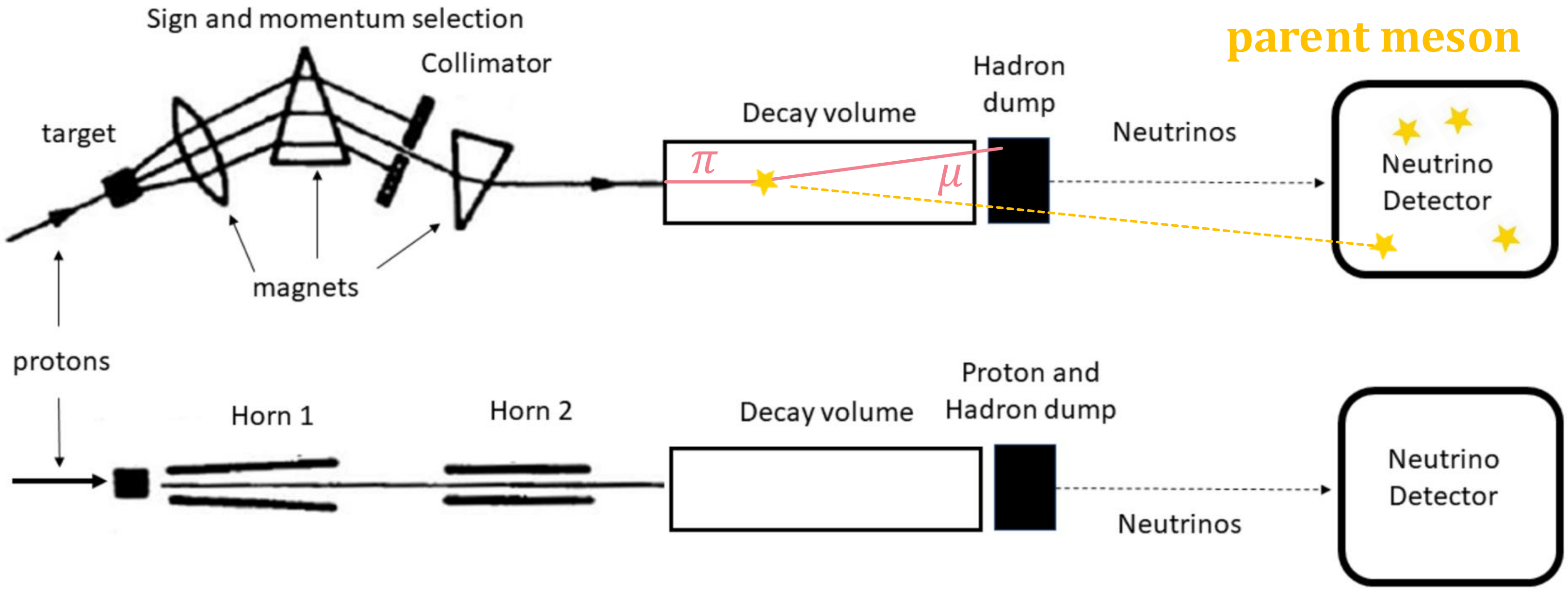
Appl. Sci. **2021**, *11*(4), 1644

Rethinking how to make a neutrino beam

Inspired by F. Terranova's seminar

A novel neutrino beam

Measure neutrinos!
AND relate them to their parent meson



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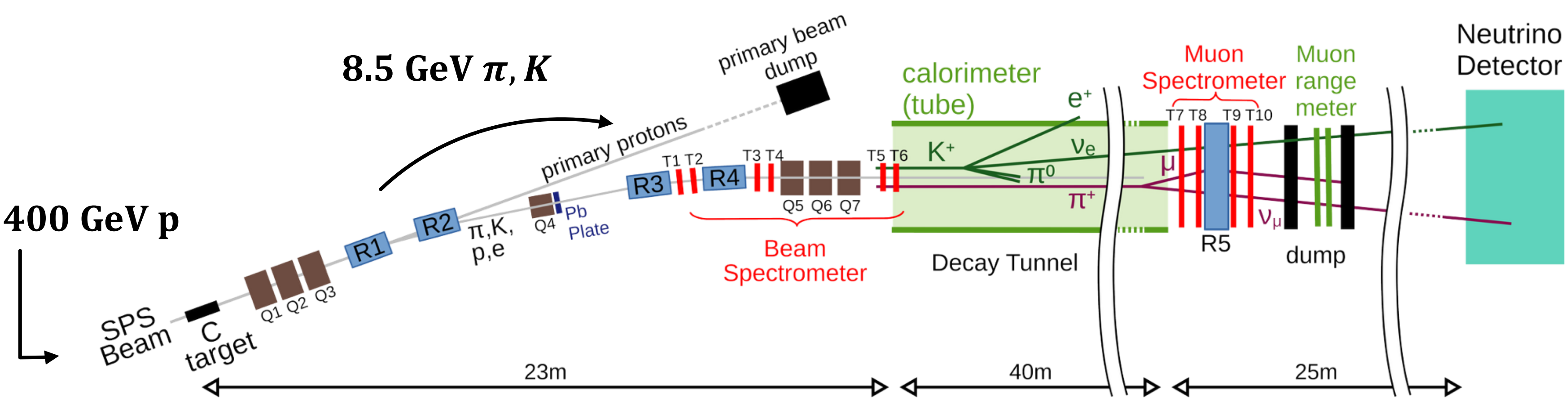
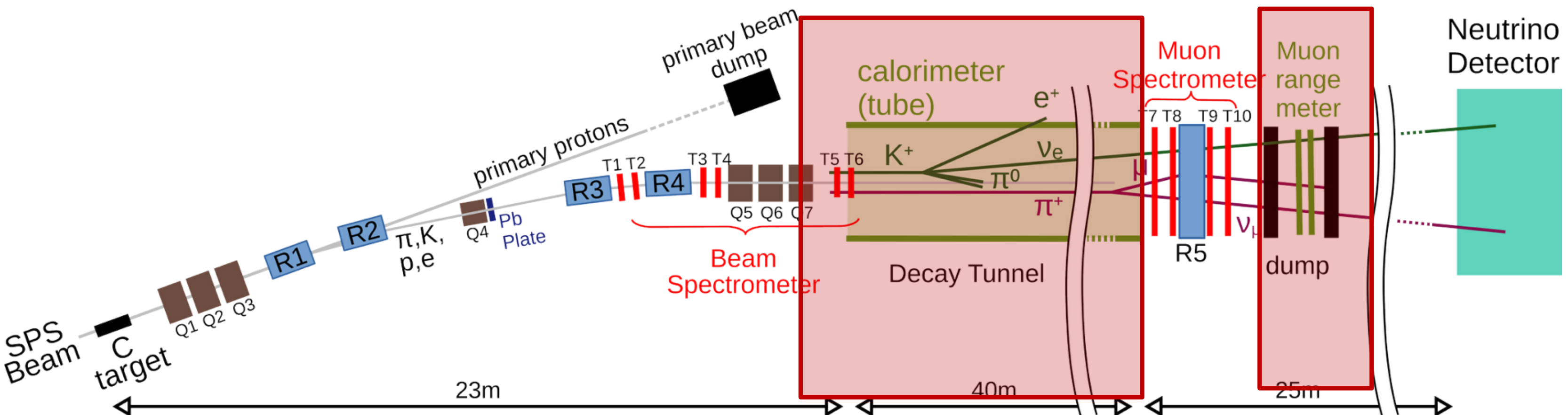
nuSCOPE (Neutrino SPS Complex for Precision Experiments)

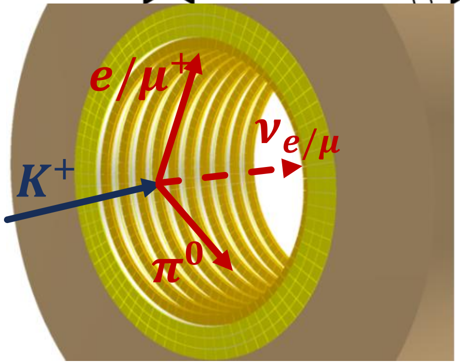
- Previous working name: SBN@CERN
- nuSCOPE is a result of the merge of the **ENUBET** and **NuTAG** collaborations
- Aim: investigate the physics we can probe with monitored and tagged neutrino beams at the SPS
- Input submitted to the ESPPU: https://arxiv.org/abs/2503.21589



A **monitored** and tagged neutrino beam

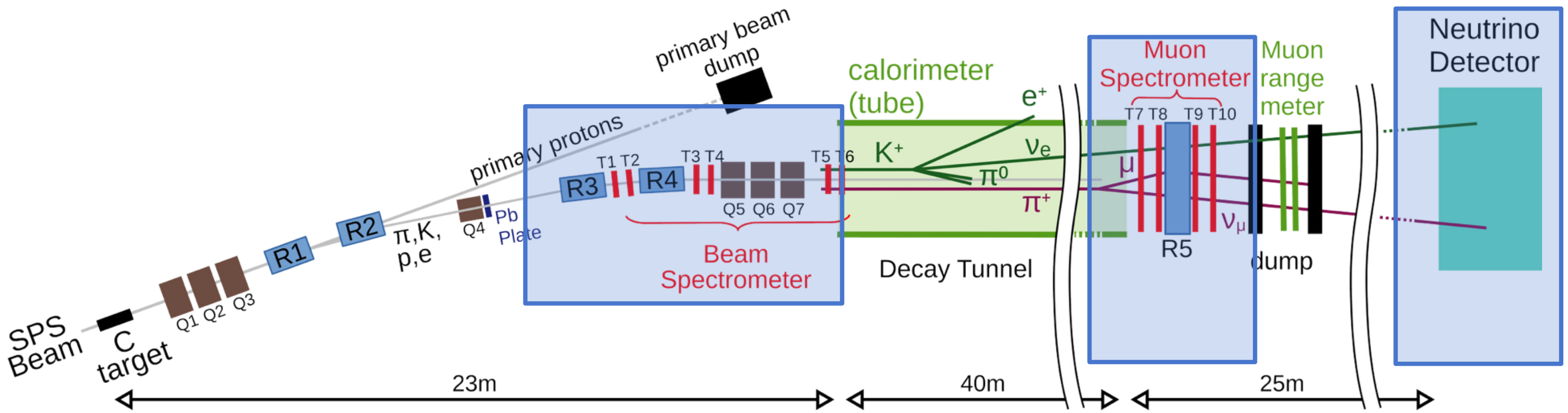


- Instrumented calorimeter decay tunnel & hadron dump
- Identifies the decay products of mesons producing neutrinos



Performance of a section of the decay tunnel tested at CERN T9 Test Beam facility under NP06/ENUBET
Eur. Phys. J. C **83**, 964 (2023)

A monitored and tagged neutrino beam



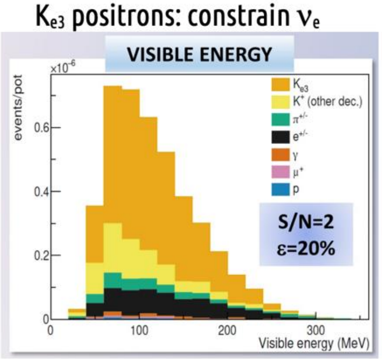
- State-of-the-art **silicon detectors** to track incoming mesons and outgoing muons
- **Unique association** between each neutrino interacting in the detector with its parents

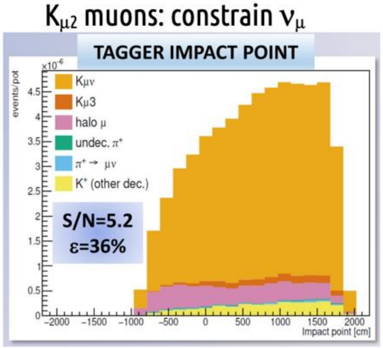
Phys.Lett.B 863 (2025) 139345

A first tagged neutrino candidate observed by NA62

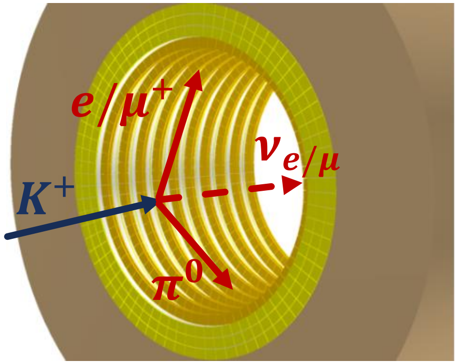
What does nuSCOPE bring to the table?

☑ Monitored beam: ~1% flux uncertainties





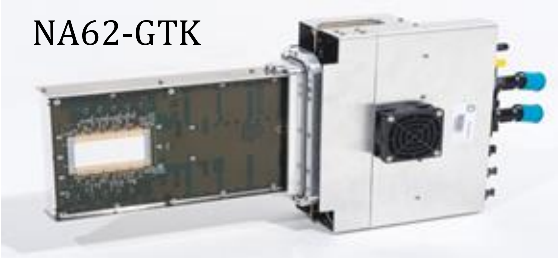
Lepton distributions from calorimeter and tagger (see slides from A. Longhin)



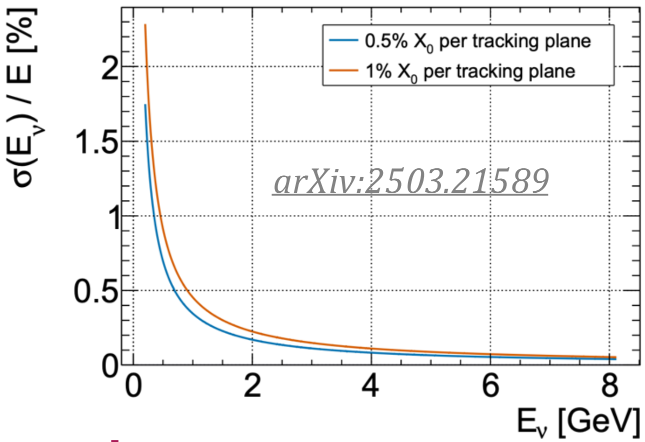
Performance of a section of the decay tunnel tested at CERN T9 Test Beam facility under NP06/ENUBET
Eur. Phys. J. C **83**, 964 (2023)

What does nuSCOPE bring to the table?

- ☑ Monitored beam: ~1% flux uncertainties
- ☑ Neutrino tagging: measure neutrino energy event-by-event



Phys.Lett.B 863 (2025) 139345



It is possible to measure neutrino energy event-by-event with <1% resolution

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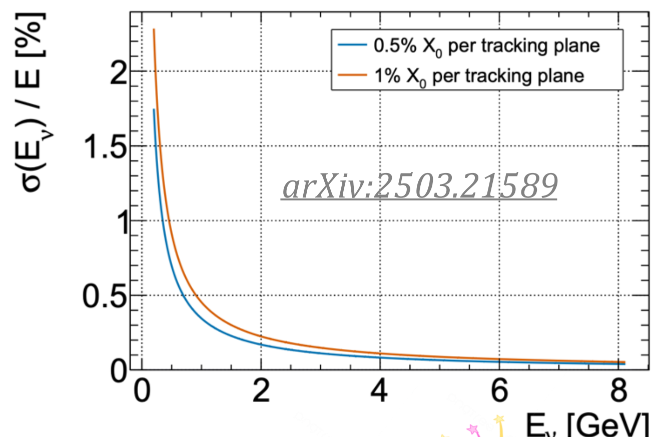
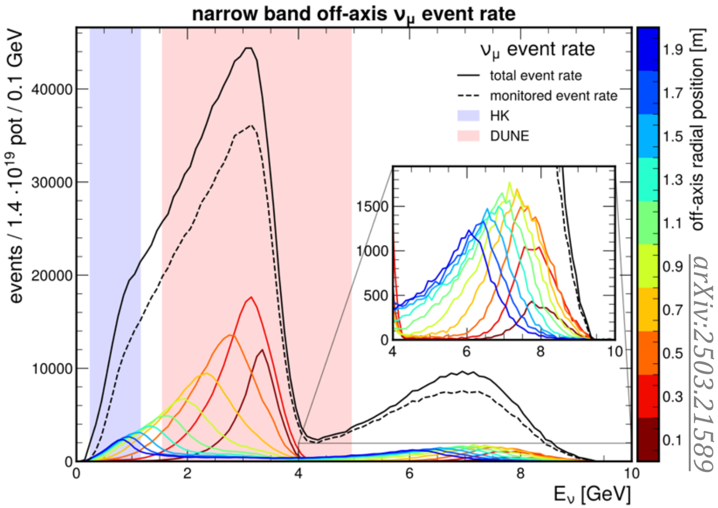
Phys.Lett.B 863 (2025) 139345



It is possible to measure neutrino energy event-by-event with <1% resolution

What does nuSCOPE bring to the table?

- ✓ Monitored beam: ~1% flux uncertainties
- ✓ Neutrino tagging: measure neutrino energy event-by-event
- ✓ Wide range of energies: covers both DUNE and HK regions of interest



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This relies on:

- Slow extraction beam, low intensity (10^{13} protons/9.6s spill)
- Large detectors – $O(1kt)$ – close to decay tunnel
- Excellent beamline ($O(10-100)$ps) and detector ($O(1)$ns) timing resolution

Examples of measurements nuSCOPE can make

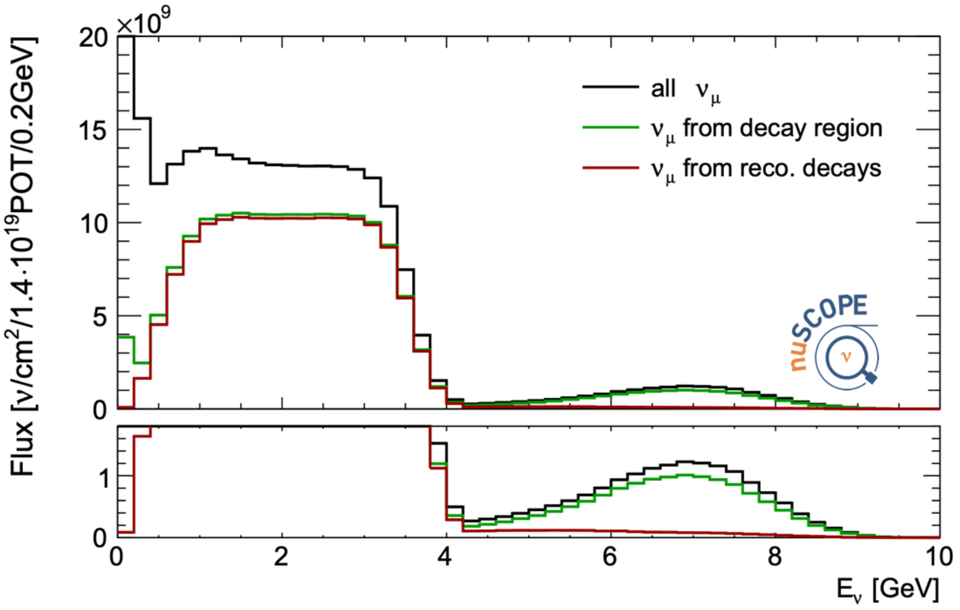
See arXiv:2503.21589 for more details

Studies done assuming 1.4×10^{19} *POT*

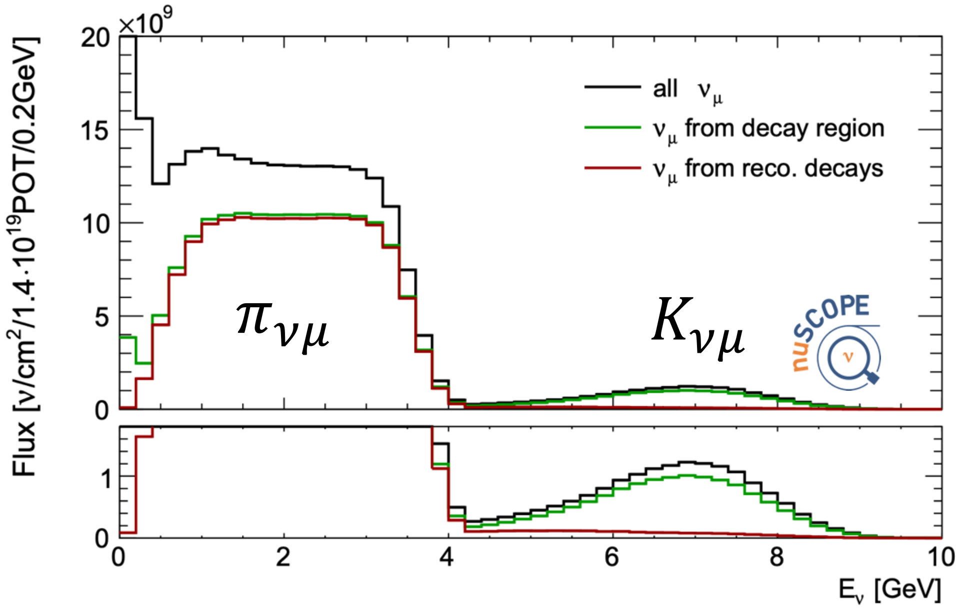
(5 years of running, POT to ensure compatibility with fixed target experiments e.g. SHiP)

Sensitivity studies led by **Filippo Bramati** (LAr), **Mara Pripon** (water)

Neutrino flux

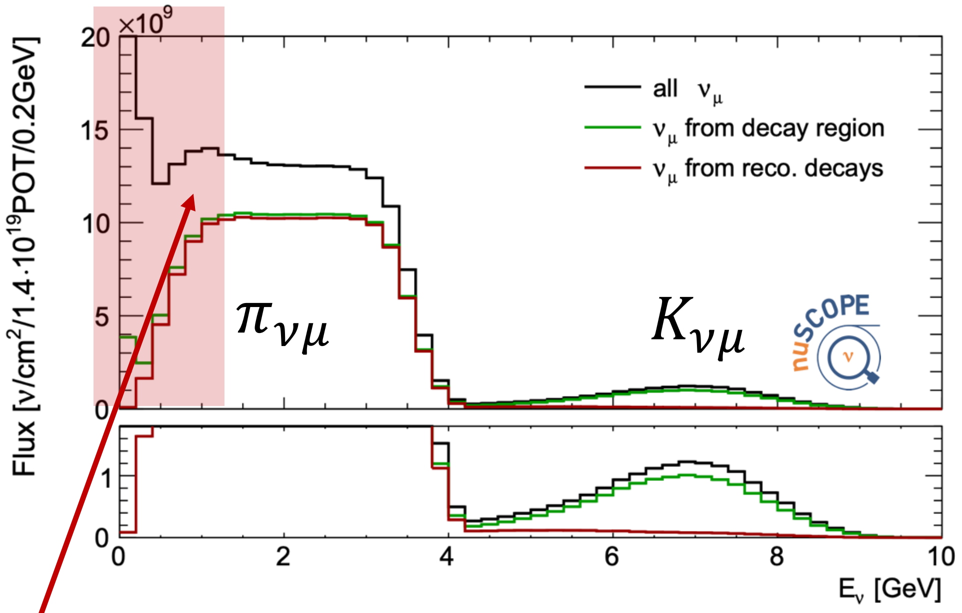


Neutrino flux



Kinematics of π and K decays with ~monoenergetic beam allow for a clear separation of the two contributions

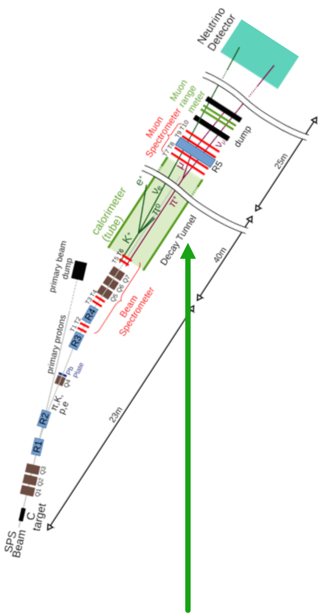
Neutrino flux

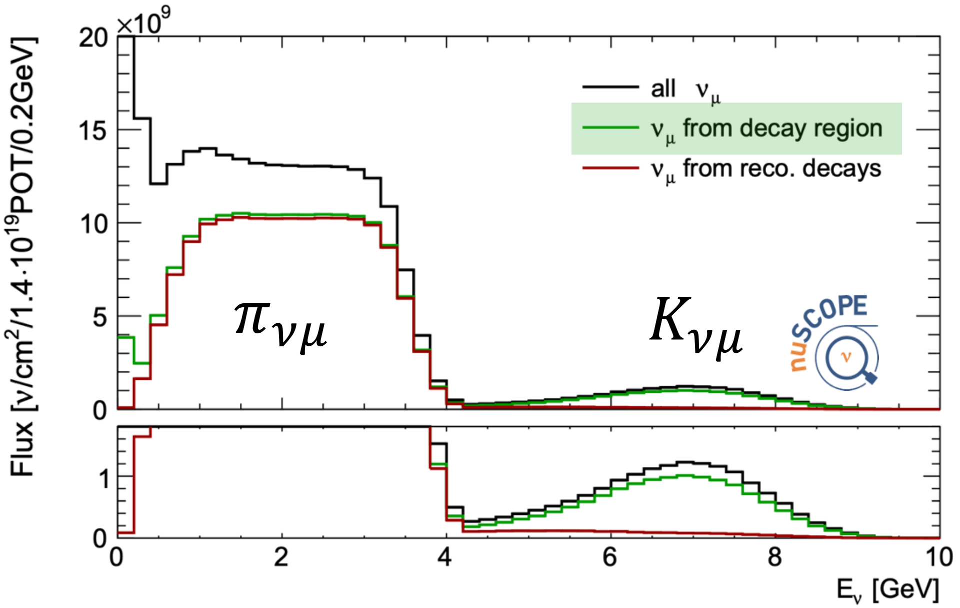


"Contamination" from low energy neutrinos produced from target region and proton dump

In practice it is heavily suppressed by the low cross-section

Neutrino flux

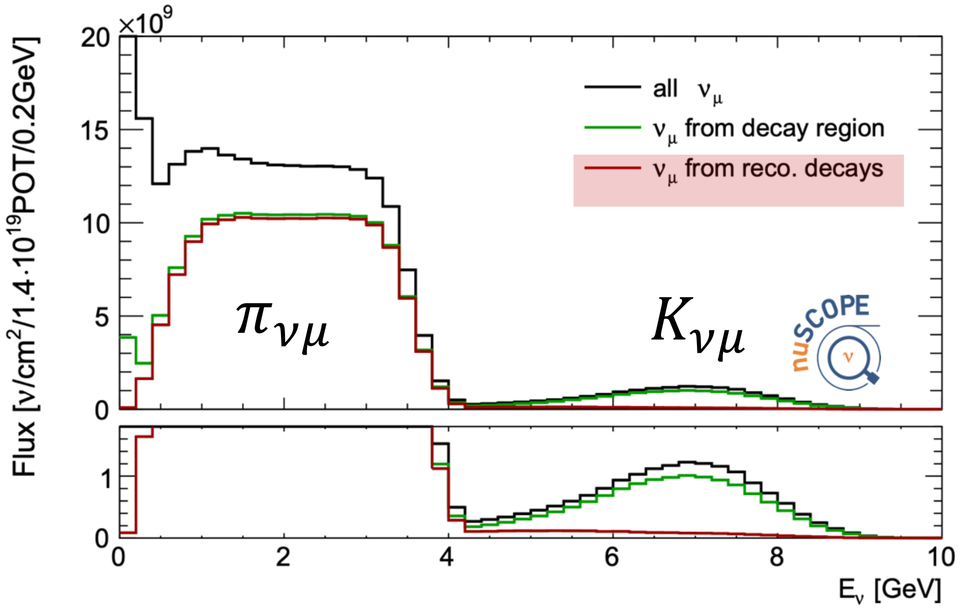


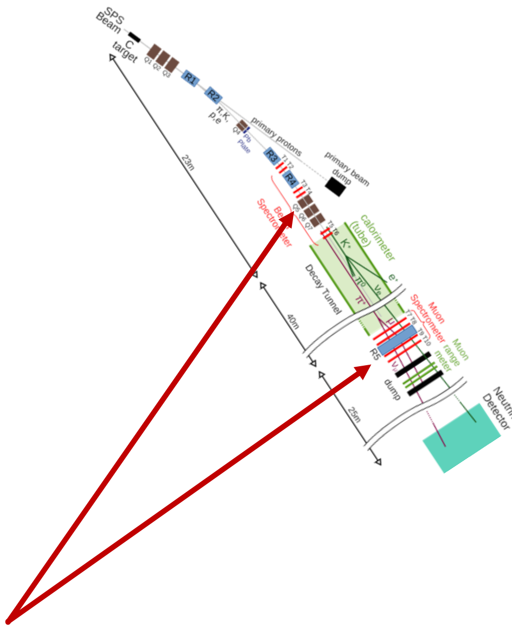


Monitored neutrinos (inside decay tunnel)

<1% flux uncertainties

Neutrino flux





Monitored neutrinos (inside decay tunnel)
<1% flux uncertainties

Tagged neutrinos (inside decay tunnel)
<1% resolution on neutrino energy event-by-event

Reference setup

Current preliminary studies performed assuming a simplistic detector design

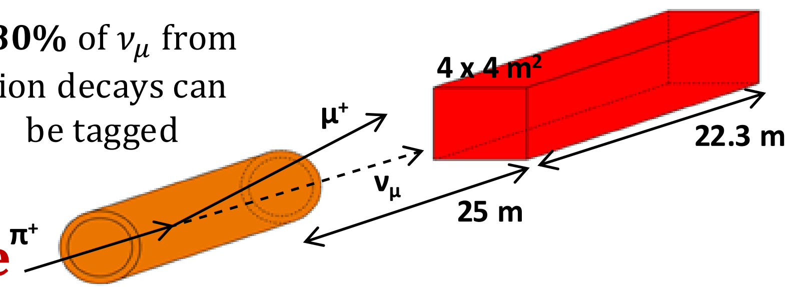
- Reference model is GENIE `AR23_20i_00_000`

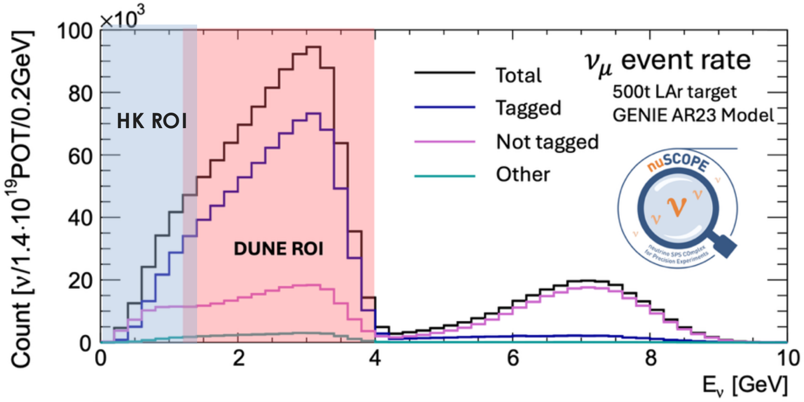
Low beam intensity compensated by **large detector size** and **proximity to beam**

- $\boldsymbol{O(1.0\times10^{6})/O(1.2\times10^{4})}$ monitored $\boldsymbol{\nu_\mu/\nu_e}$ CC events in both LAr and water
- **Tagging performance:**
  - $\boldsymbol{7.6\times10^{5}}$ tagged $\boldsymbol{\nu_\mu}$ **CC** events in LAr (500t)
  - $\boldsymbol{1.4\times10^{5}}$ tagged $\boldsymbol{\nu_\mu}$ **CC** events in water (100t)
    - Of which **52k** tagged $\boldsymbol{\nu_\mu}$ $\boldsymbol{CC0\pi}$ events

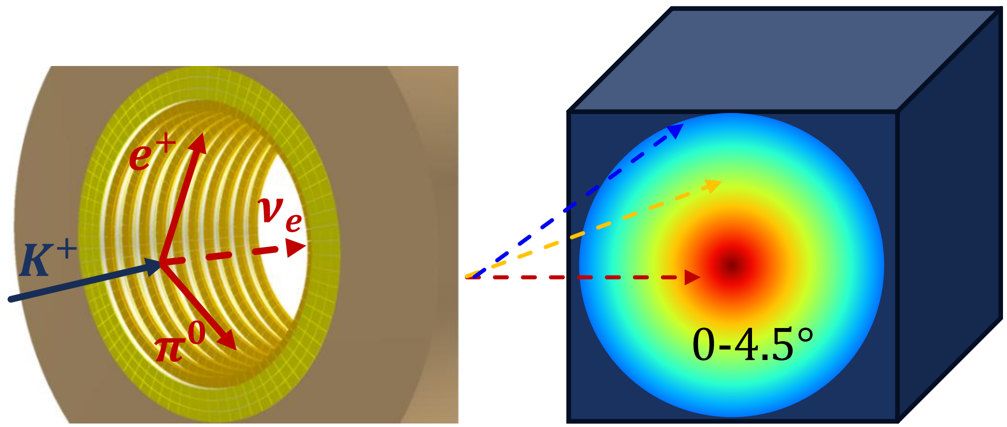
500t of LAr/100t of water

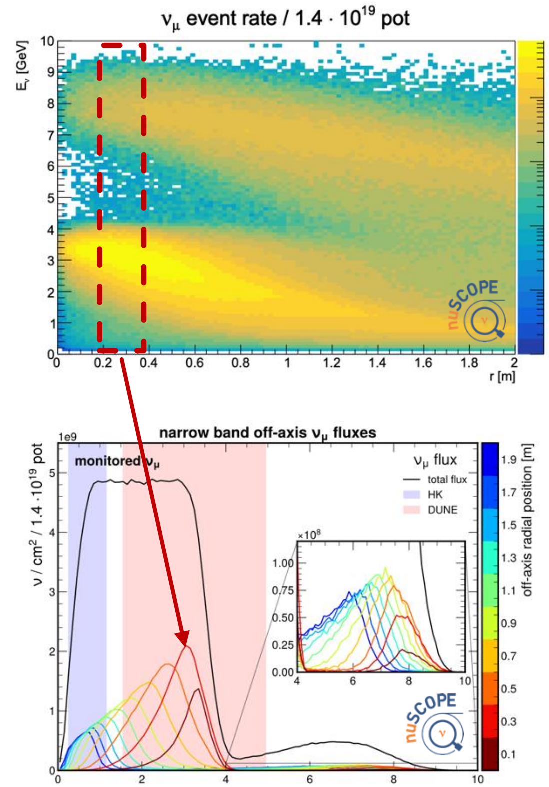
~80% of ν_μ from pion decays can be tagged





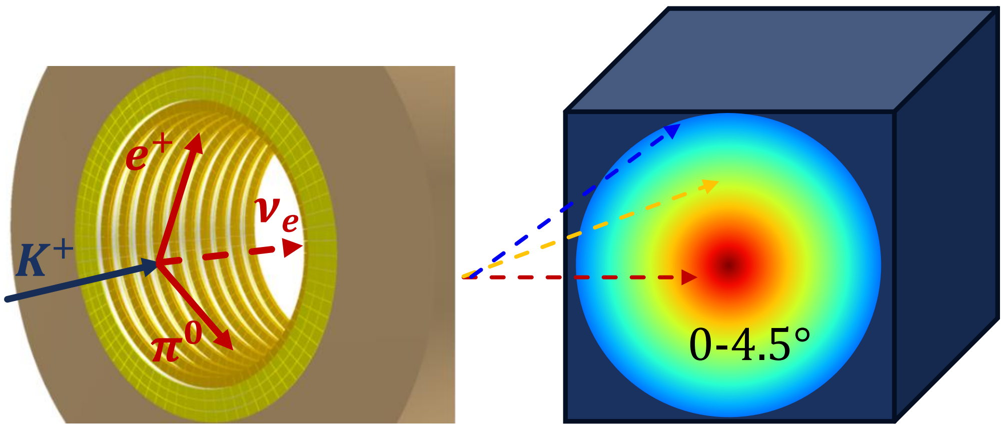
Energy dependence of the neutrino cross section





Exploit angular dependence of neutrino energy to obtain **narrow off-axis fluxes**

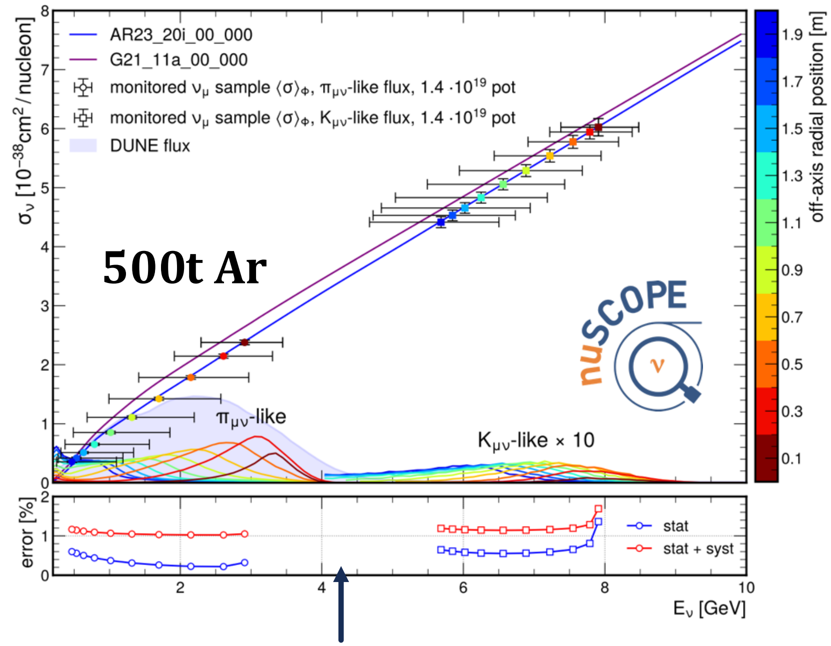
Energy dependence of the neutrino cross section



Exploit angular dependence of neutrino energy to obtain **narrow off-axis fluxes**

Multiple **flux-averaged measurements of total cross-section**

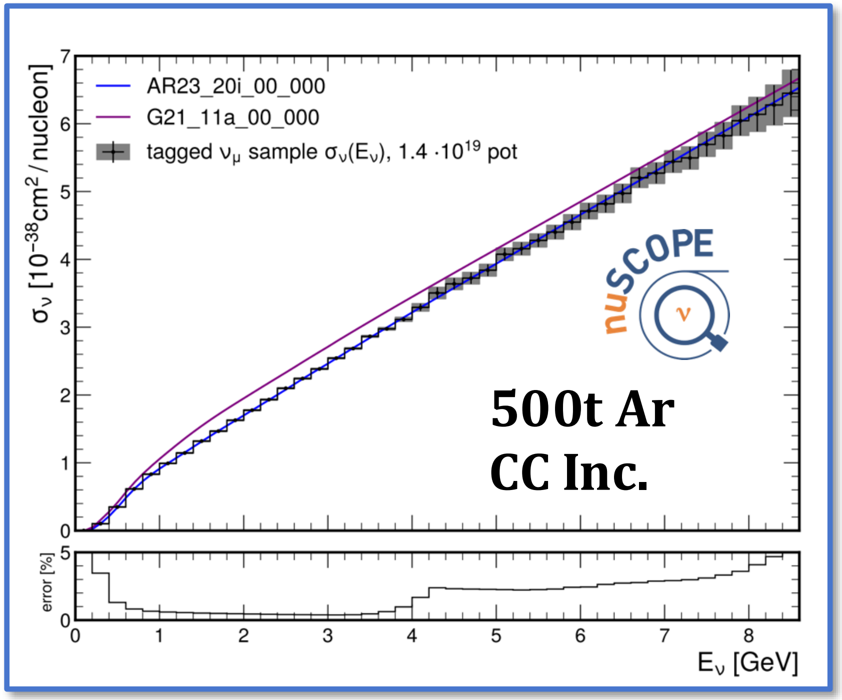
By monitoring

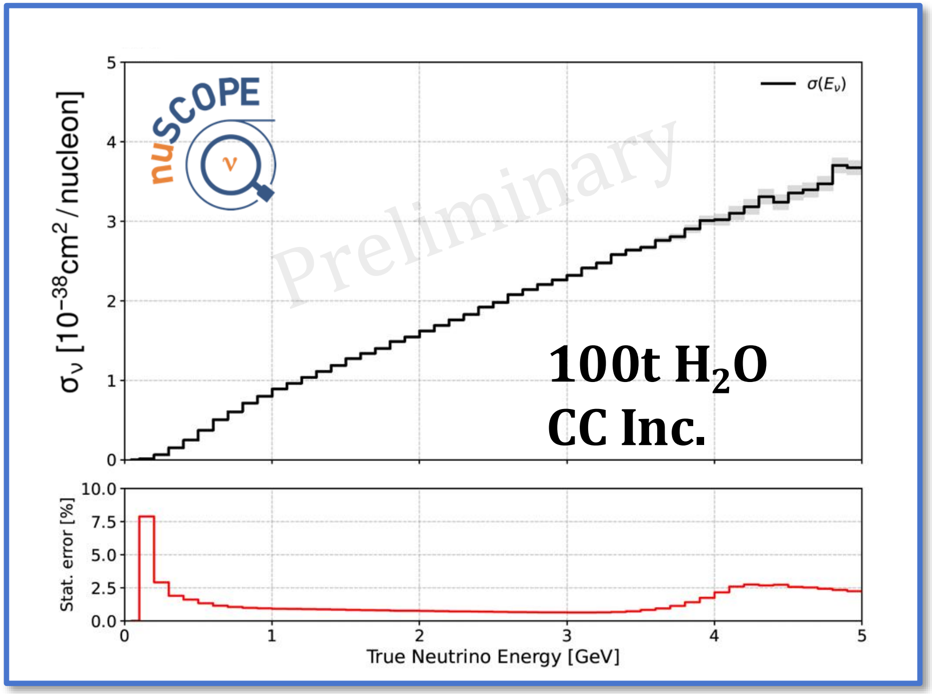


<1% systematic error on flux

Energy dependence of the neutrino cross section

By tagging





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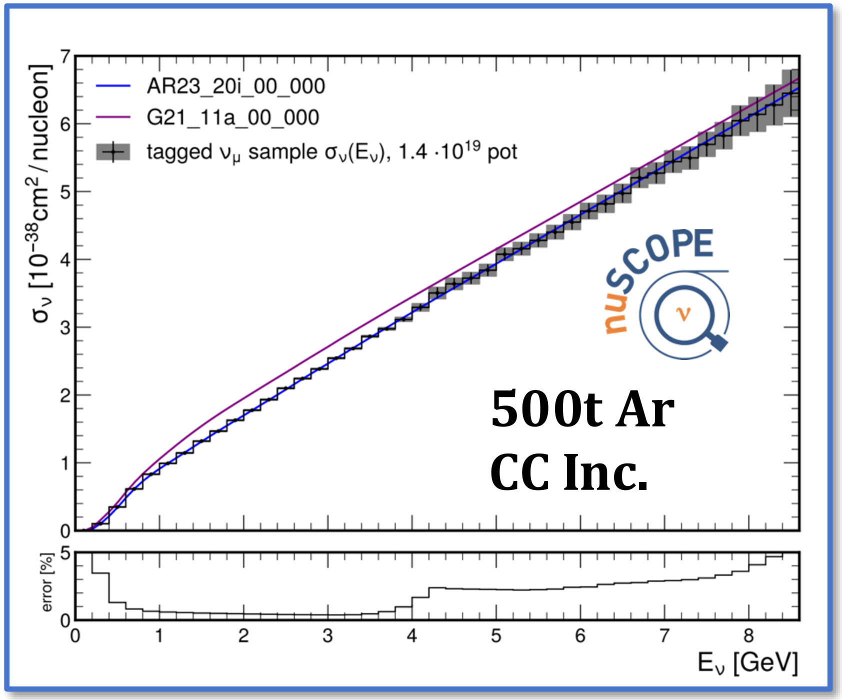

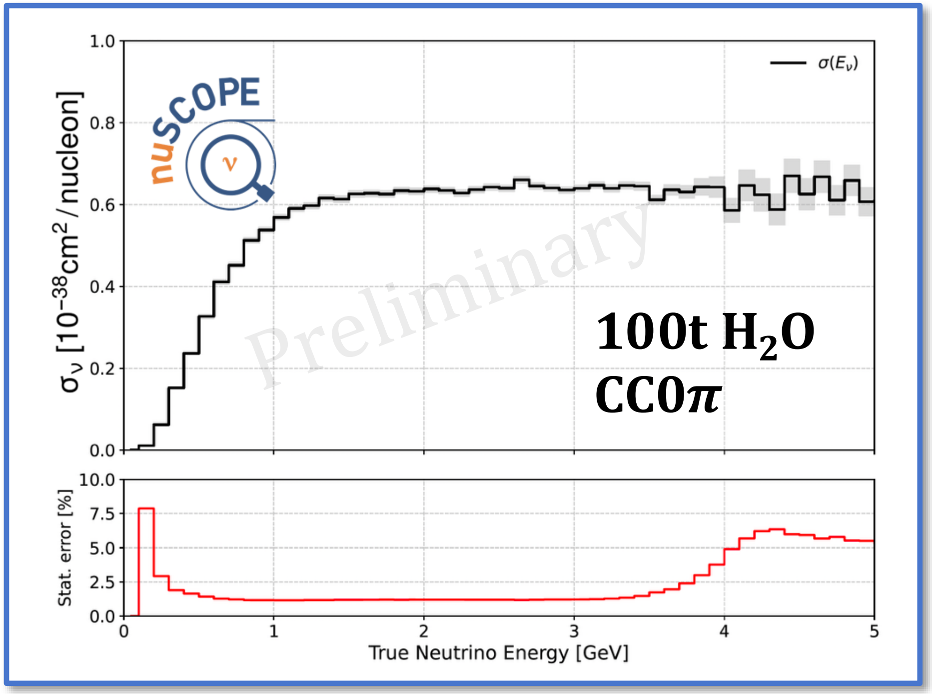

What do we need to know about ν interactions?

(non-exhaustive list focused on LBL experiments)

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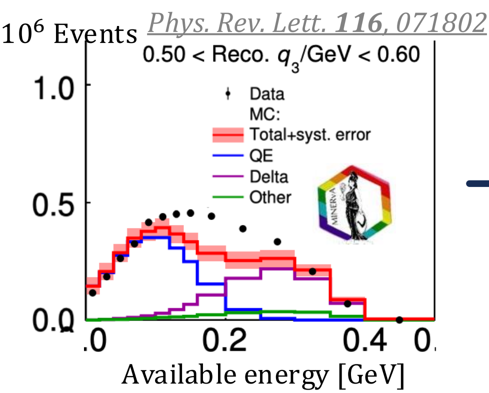
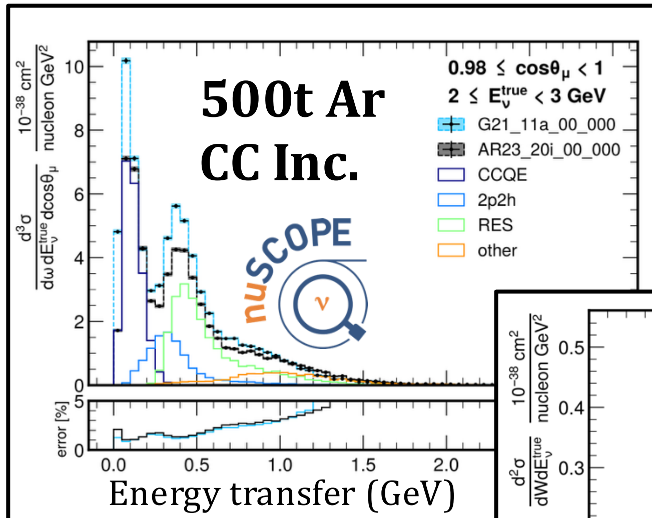
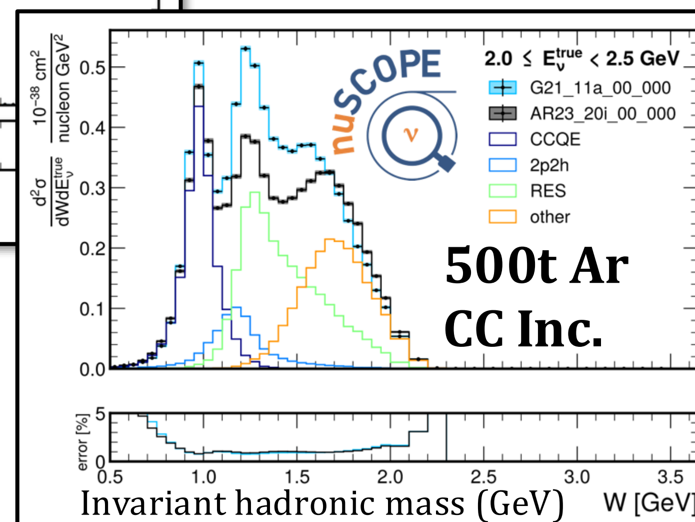
Studies for water in progress

Electron scattering-like measurements with neutrinos







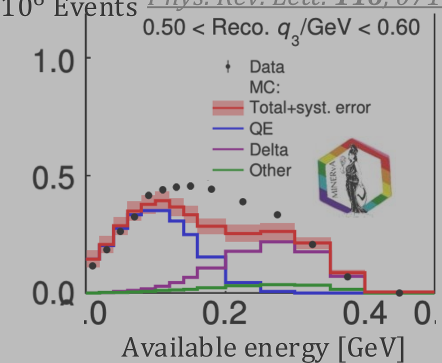
Large model disagreement

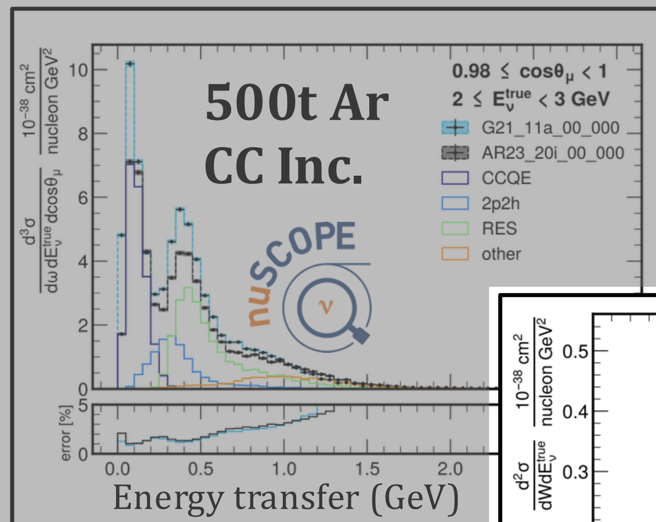
Gives access to fundamental nuclear physics processes

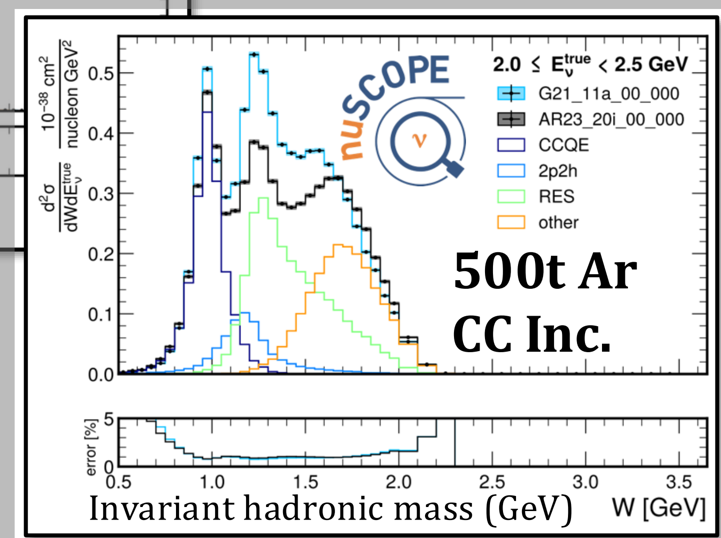
Studies for water in progress

Electron scattering-like measurements with neutrinos

Phys. Rev. Lett. **116**, 071802







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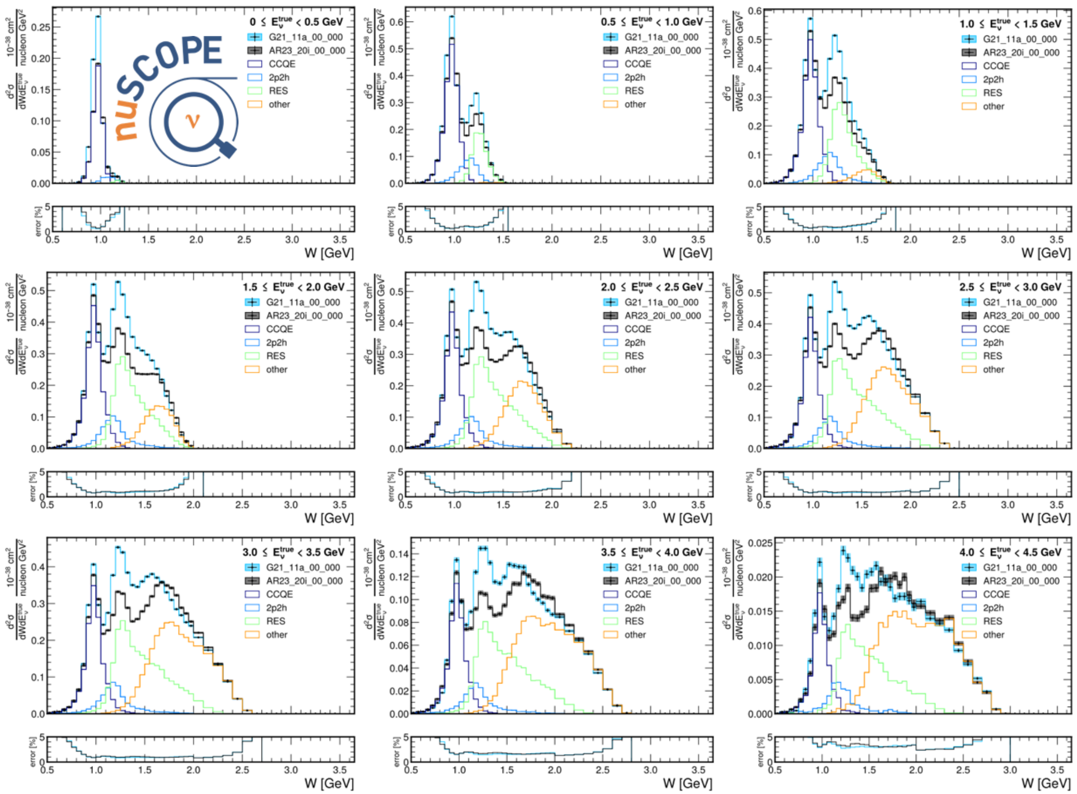

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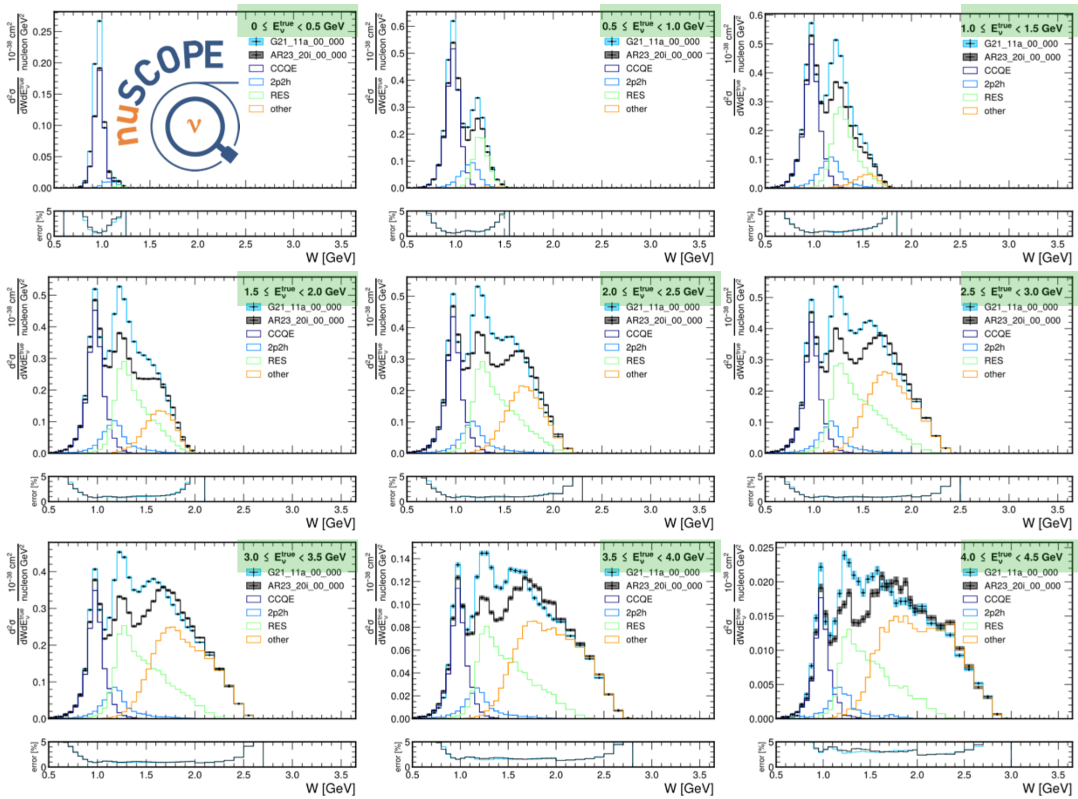

High statistics for **multi-differential measurements** (here as a function of E_ν)

Studies for water in progress

Electron scattering-like measurements with neutrinos

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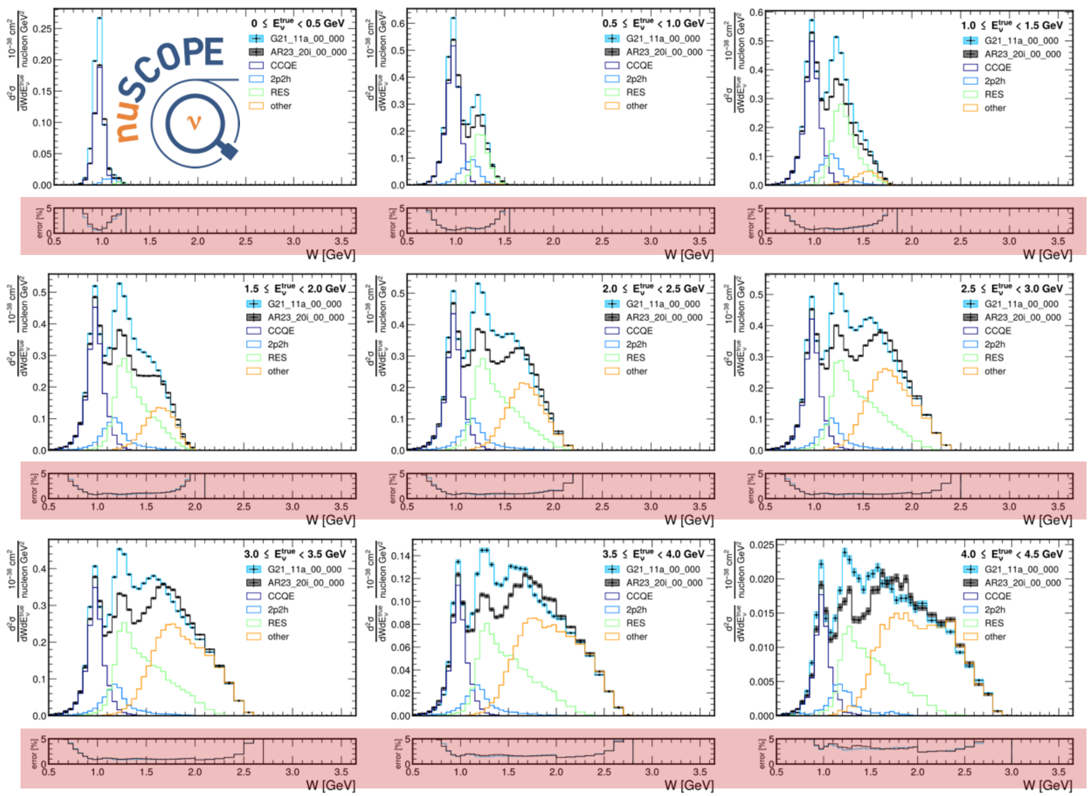
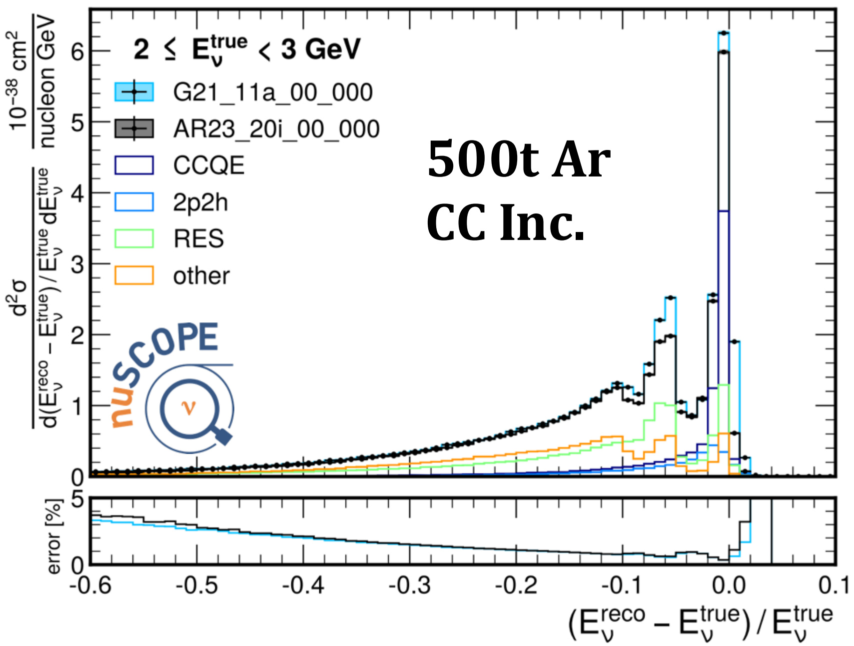


(<)1% level statistical uncertainties

Calibration of detector energy response



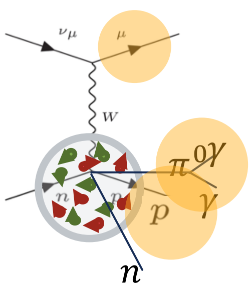
Can measure the **difference between true and reconstructed neutrino energy**

$$E_\nu^{\mathrm{reco}} = E_\mu + \sum_{i=\pi^\pm,p} T_i + \sum_{i=\pi^0,\gamma} E_i$$

“visible” energy using calorimetric method (like DUNE, NOvA, MINERvA)

Measures the amount of invisble energy carried away by neutrons and neutrinos

Calibrate out nuclear effects



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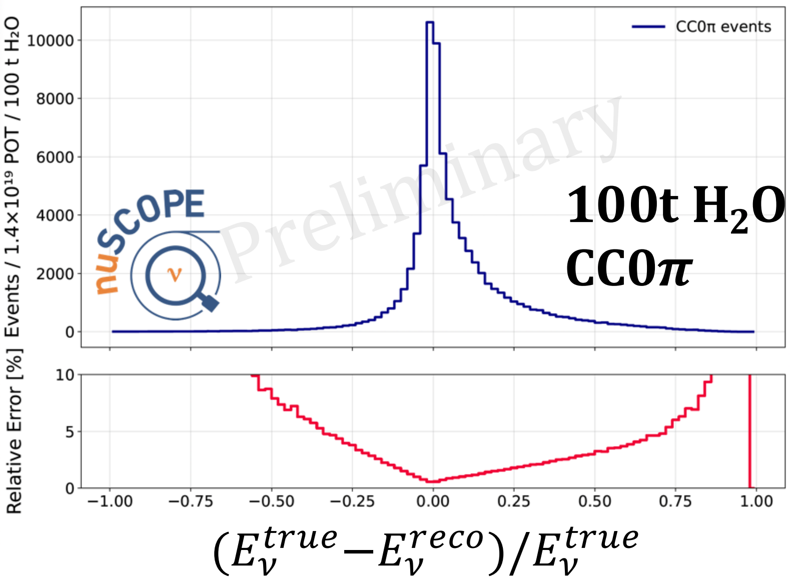

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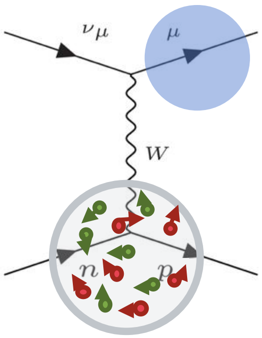
$$E_\nu^{QE} = \frac{1}{2}\frac{m_\ell^2 + (m_N^{eff})^2 - m_{N'}^2 - 2E_\mu m_N^{eff}}{E_\ell - |\vec{p_\ell}|\cos\theta_\ell - m_N^{eff}},$$

$$m_N^{eff} = m_N - E_b,$$

"QE" energy using kinematic reconstruction (T2K/SK/HK)

Measures the neutrino energy bias due to Fermi motion, npnh, FSI…

Calibrate out nuclear effects



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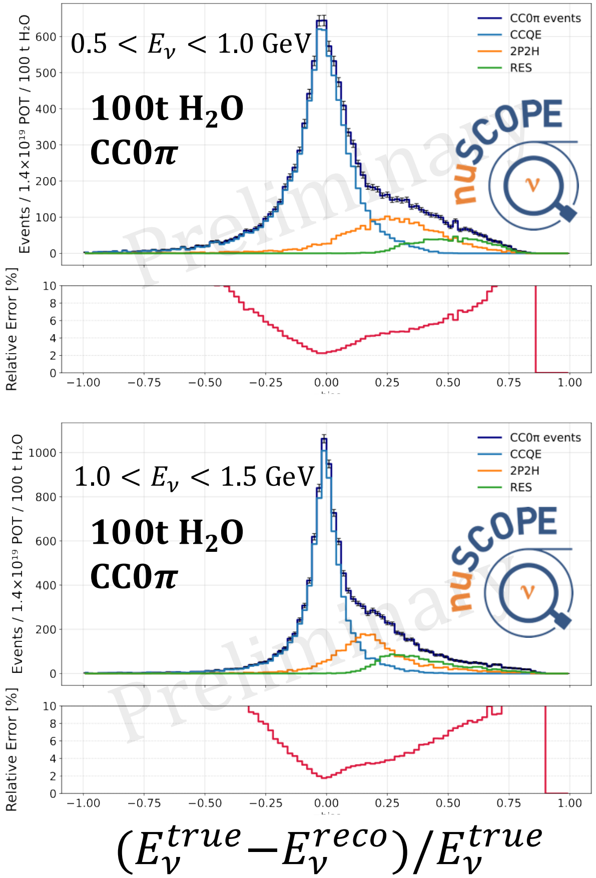

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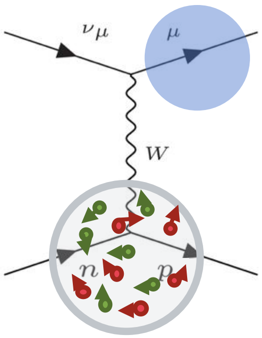

Calibrate out nuclear effects

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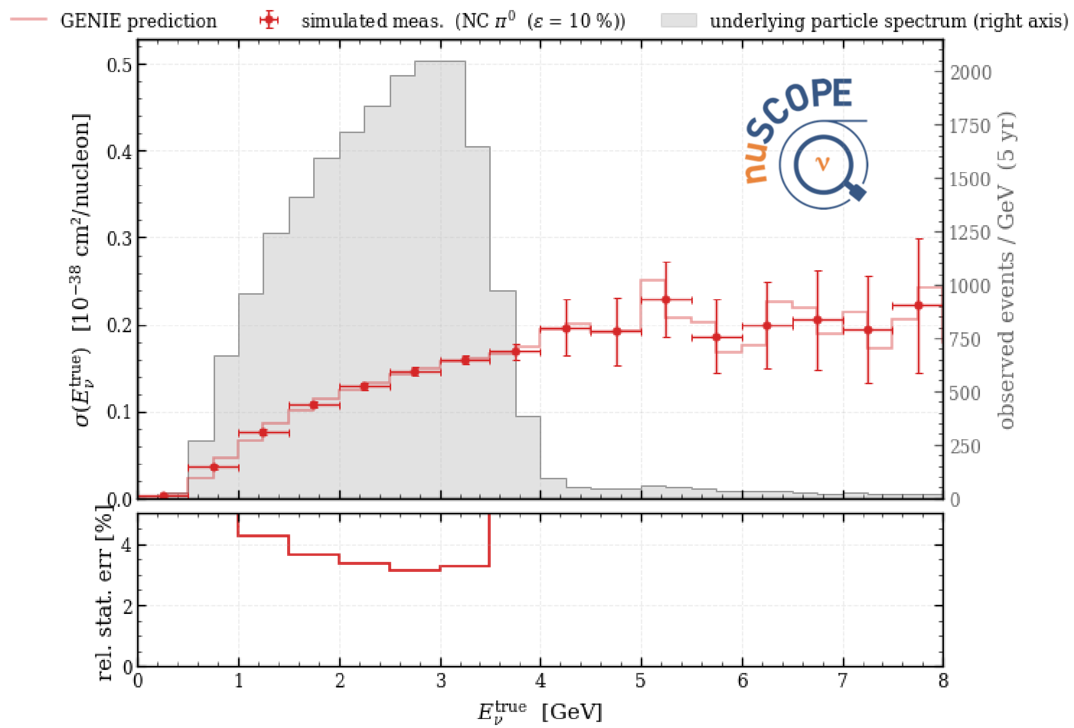
Constraining the NCπ^0 cross section



The tagging technique can be applied to measure the NCπ^0 cross section

(background for oscillation searches)

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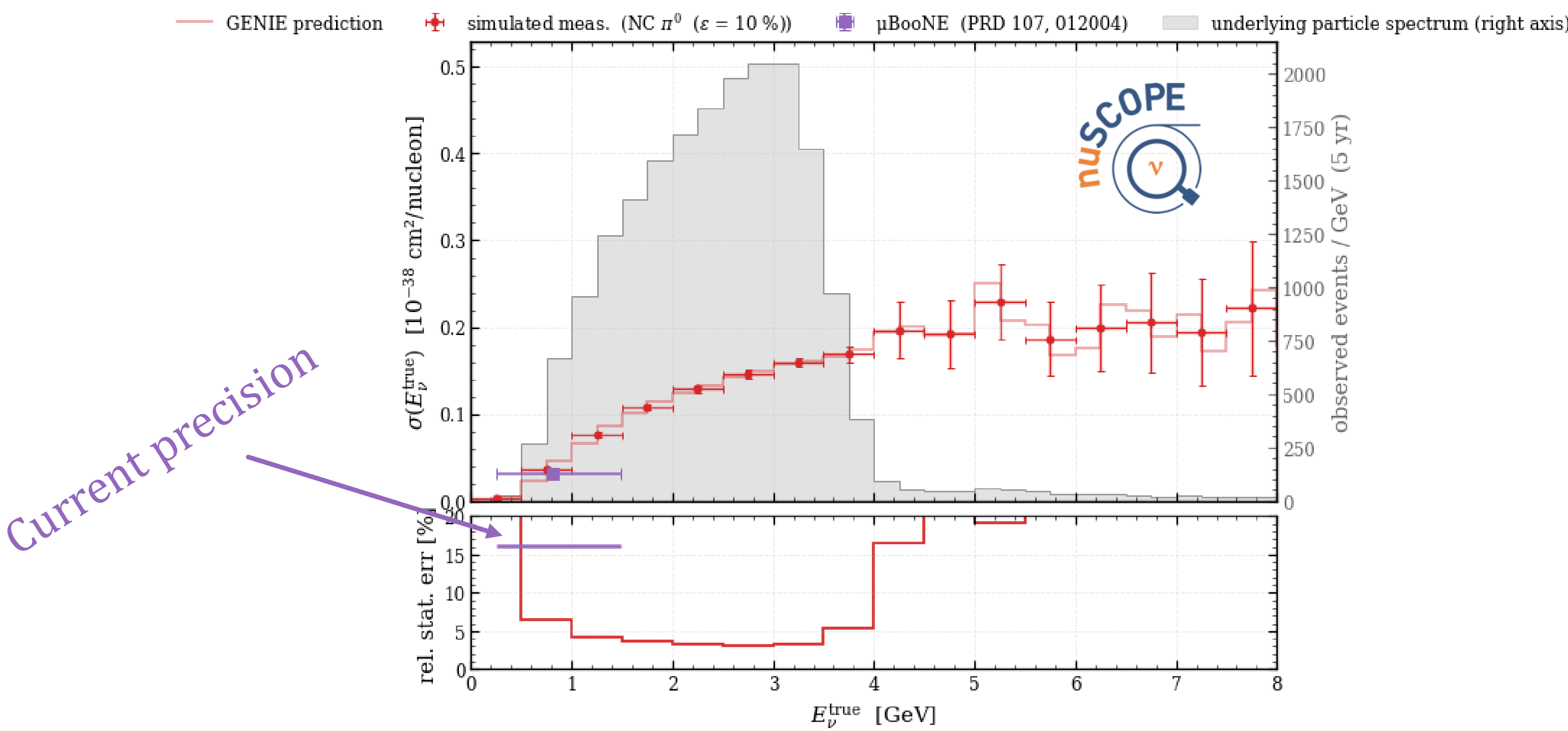

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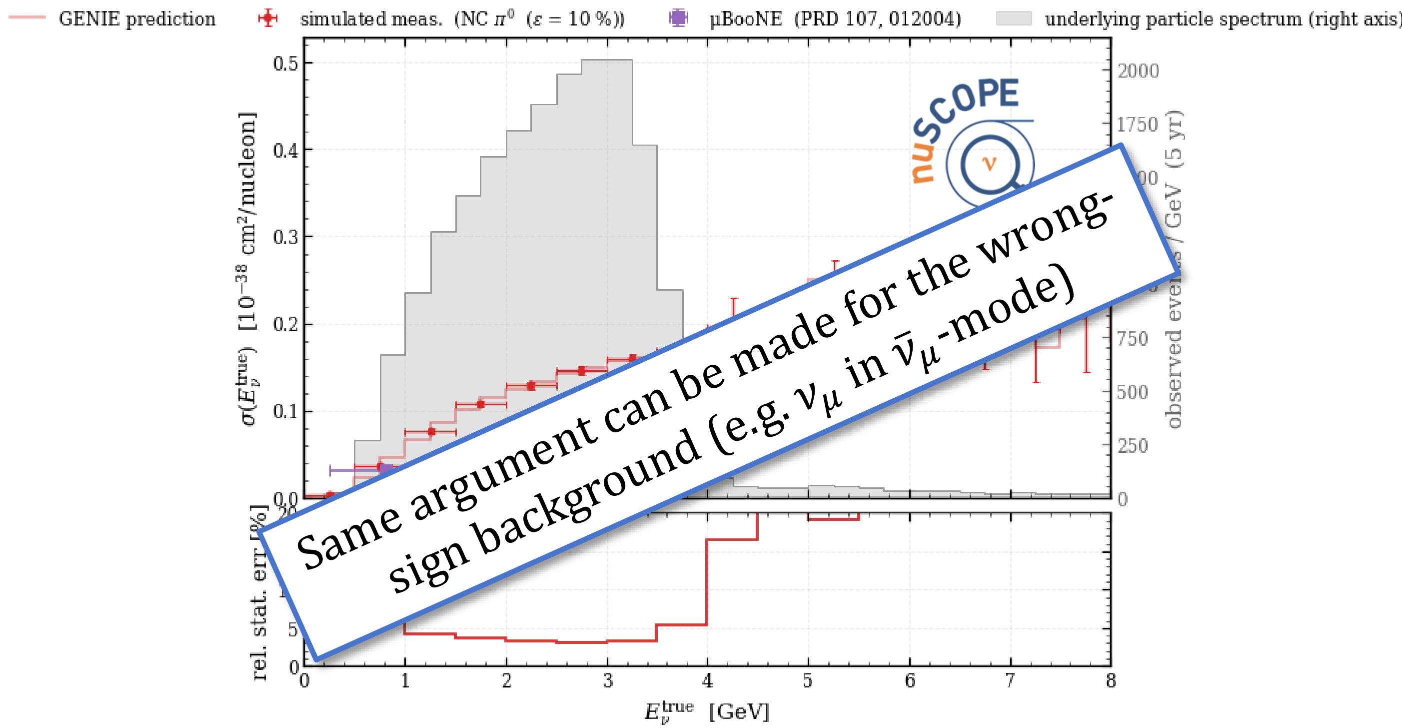

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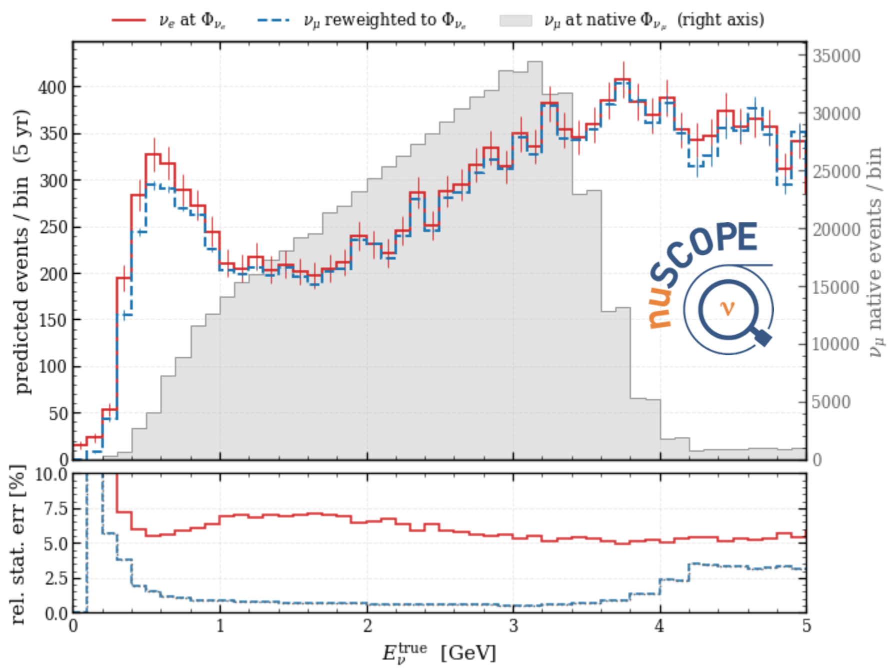
Constraining the ν_μ/ν_e cross section ratio



$$\frac{\sigma_{\nu_\mu}}{\sigma_{\nu_e}} = 0.971 \pm 0.0078 \quad (\mathbf{0.801}\,\%)$$

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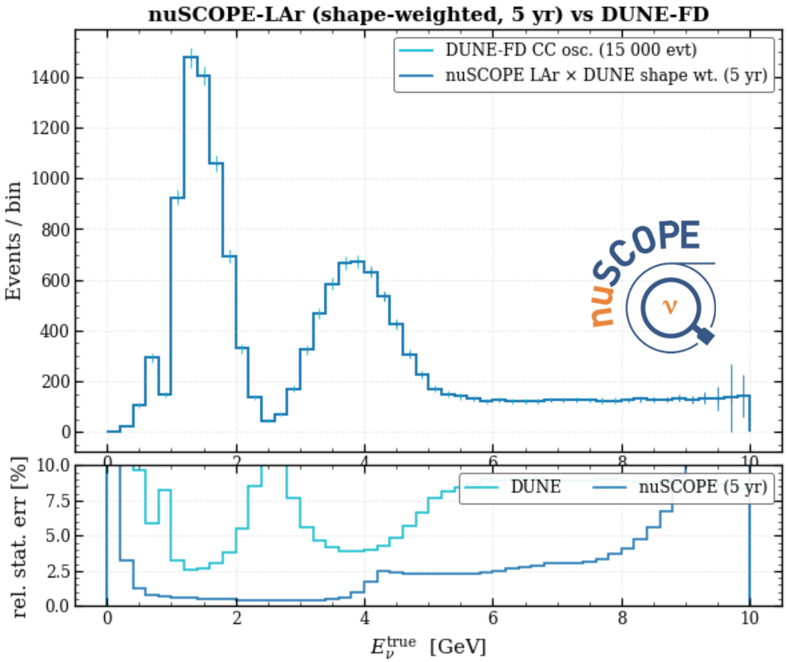
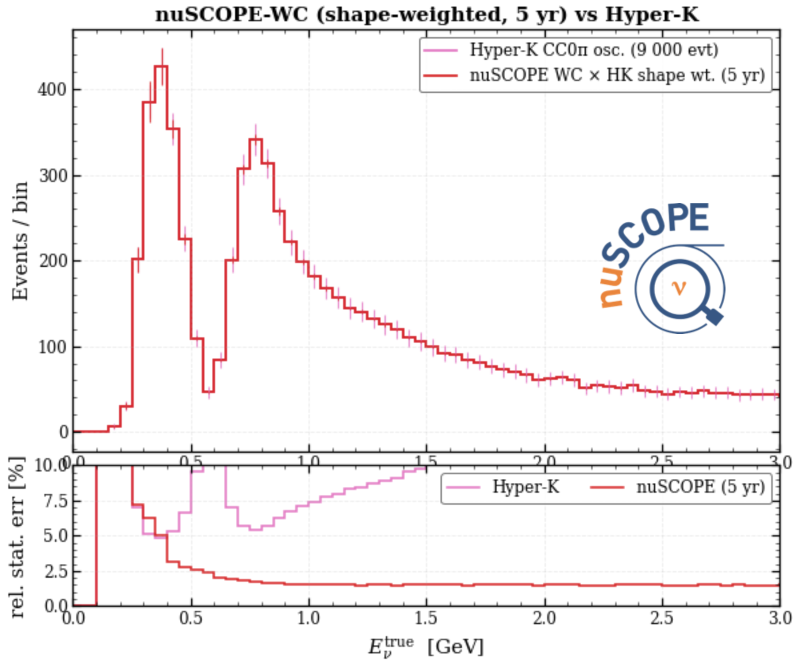
How long would this take nuSCOPE?

Numbers correspond to approx. 10 years of DUNE FD and Hyper-K

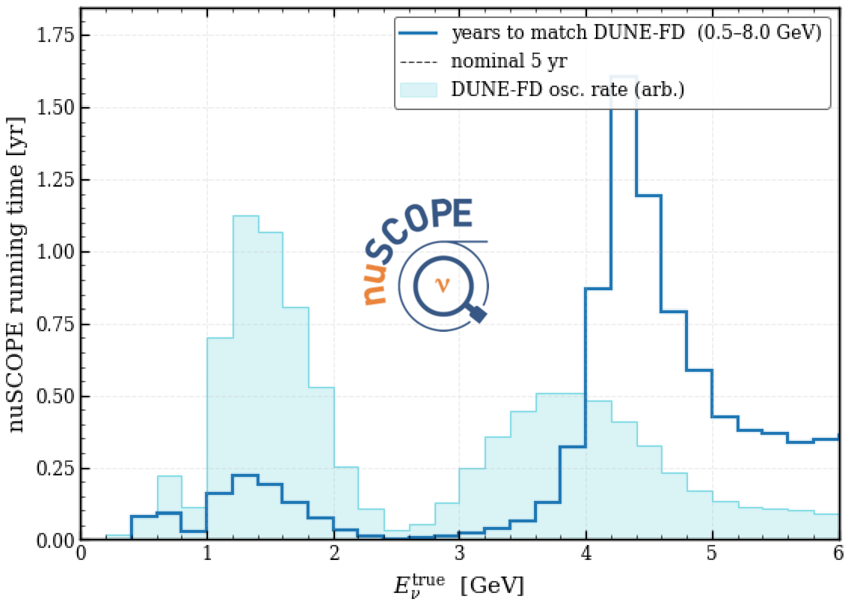




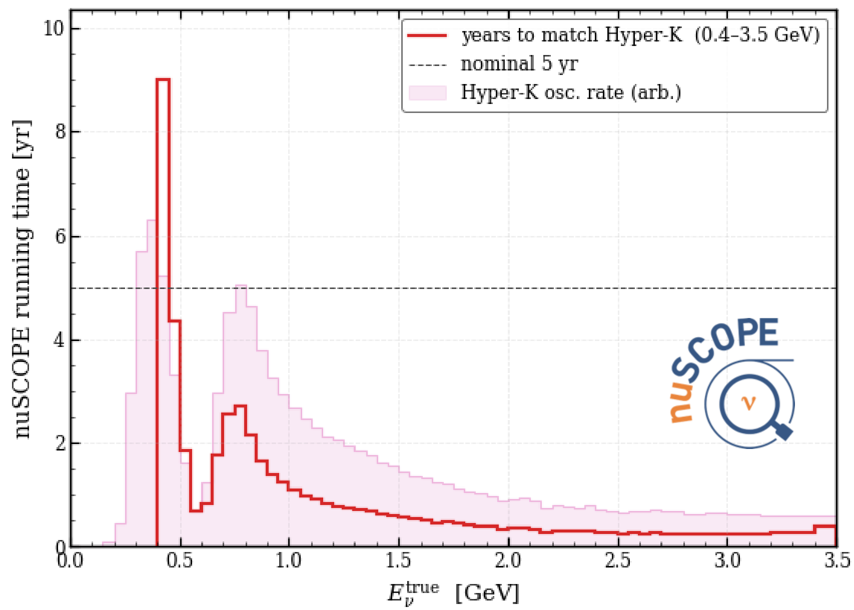
Statistical power of nuSCOPE 5 years (1.4×10^{19} POT) data taking reweighted to DUNE and Hyper-K predicted oscillated event rates after ~10 years

How long would this take nuSCOPE?

Numbers correspond to approx. 10 years of DUNE FD and Hyper-K



Can provide informative constraints in the region of the oscillation maxima of DUNE **almost immediately** once operation starts



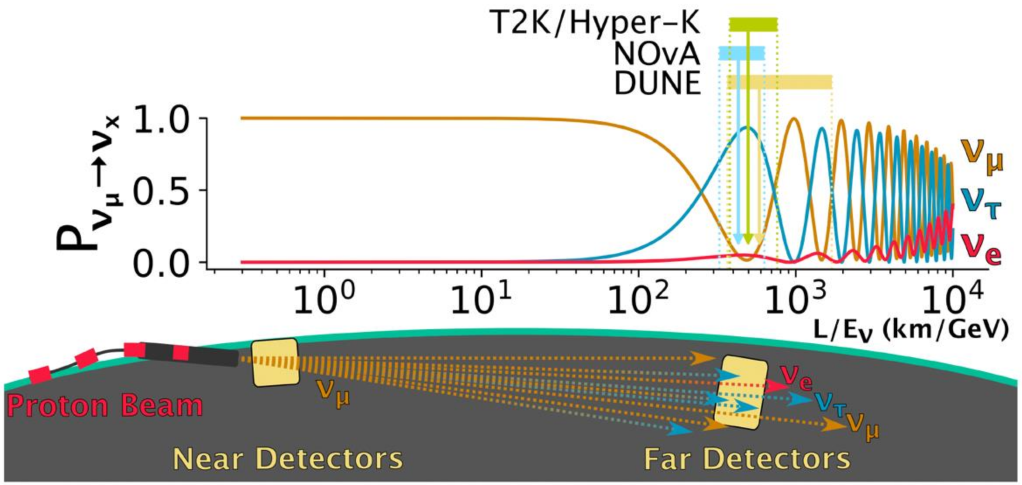
Can provide informative constraints in the region of the oscillation maximum of Hyper-K **within ~1 year** once operation starts

Beyond neutrino cross section measurements

Studies done assuming 1.4×10^{19} *POT*

(5 years of running, POT to ensure compatibility with fixed target experiments e.g. SHiP)

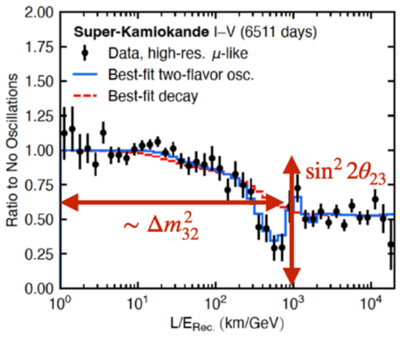
Short-baseline neutrino oscillations



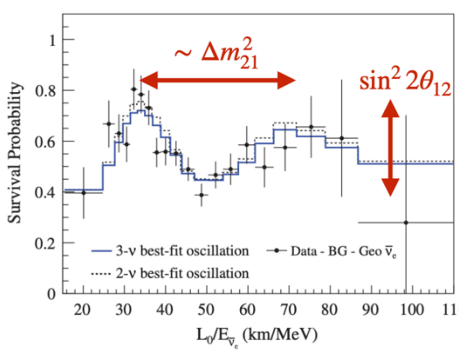
$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\ \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Very challenging to measure L/E directly with accelerator neutrinos because of **large uncertainty on neutrino energy**

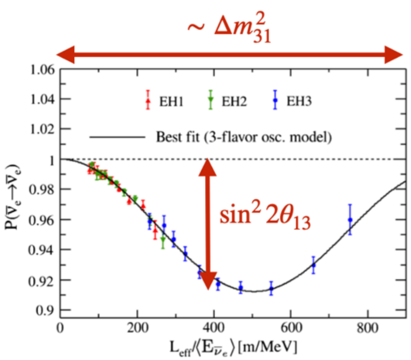
L/E dependency plots are rare!



Super-K with atmospheric neutrinos [link]

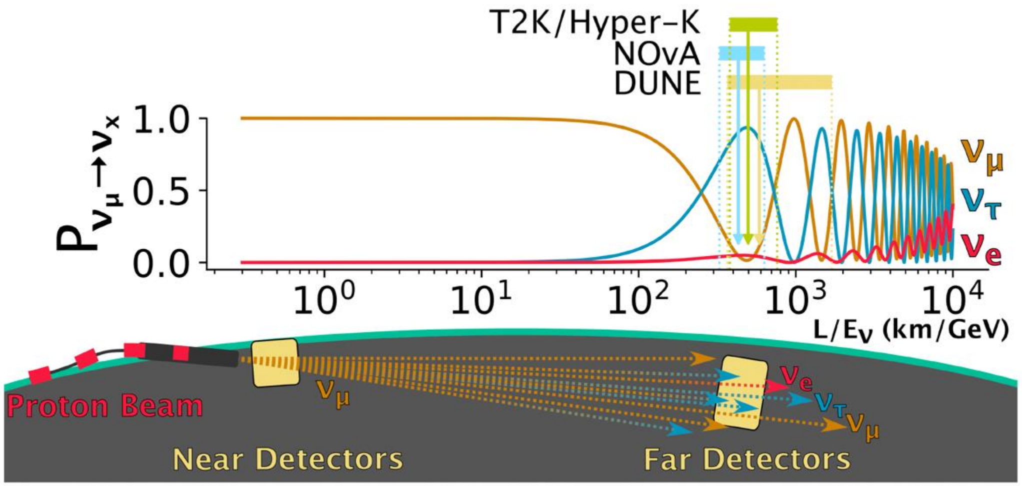


KamLAND with reactor antineutrinos [link]



DayaBay with reactor antineutrinos [link]

Short-baseline neutrino oscillations

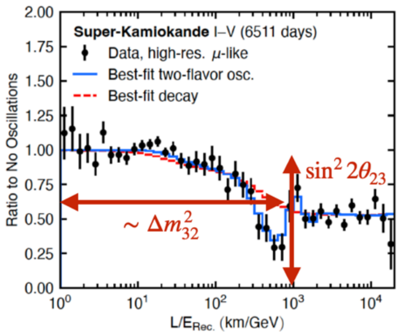


$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\,\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

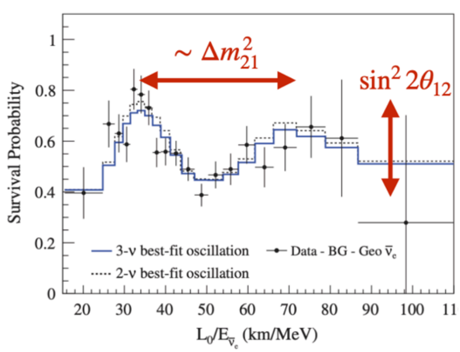
Very challenging to measure L/E directly with accelerator neutrinos because of **large uncertainty on neutrino energy**

But not for

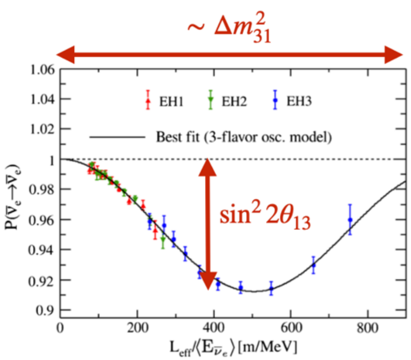
L/E dependency plots are rare!



Super-K with atmospheric neutrinos [link]



KamLAND with reactor antineutrinos [link]

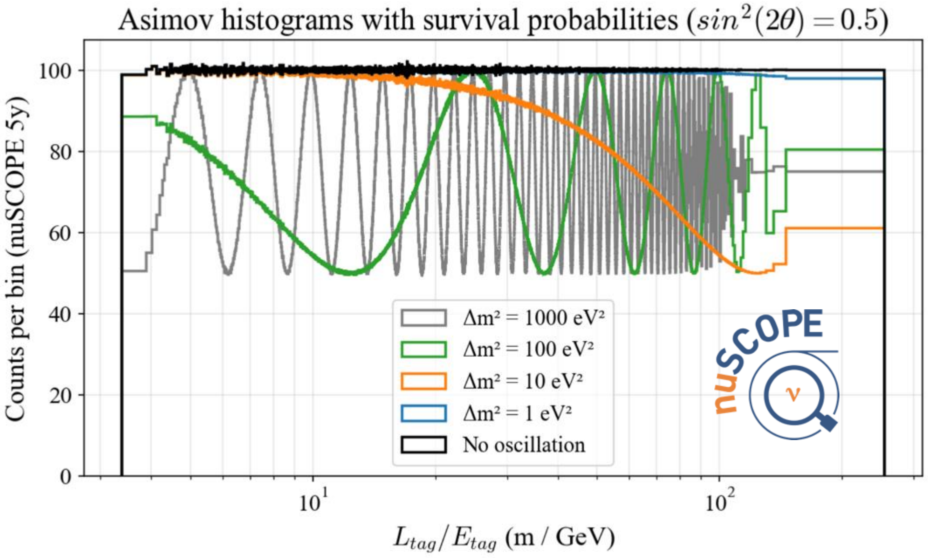


DayaBay with reactor antineutrinos [link]

Short-baseline neutrino oscillations

✓ **Neutrino energy** known with **<1%** uncertainty event-by-event
✓ **Precise** neutrino detector (~mm) to determine L

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{24})\sin^2(1.267\Delta m^2_{41}L_{true}/E_{true})$$



Short-baseline neutrino oscillations

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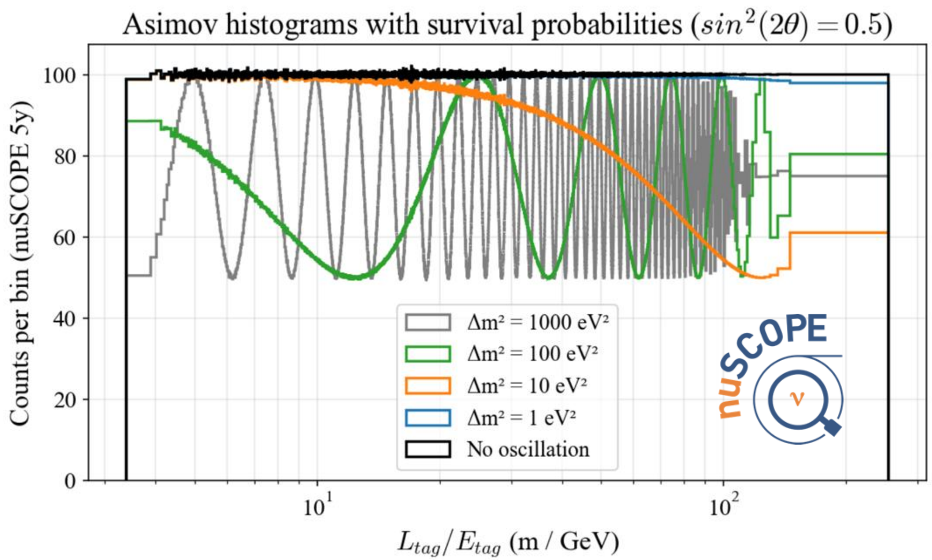
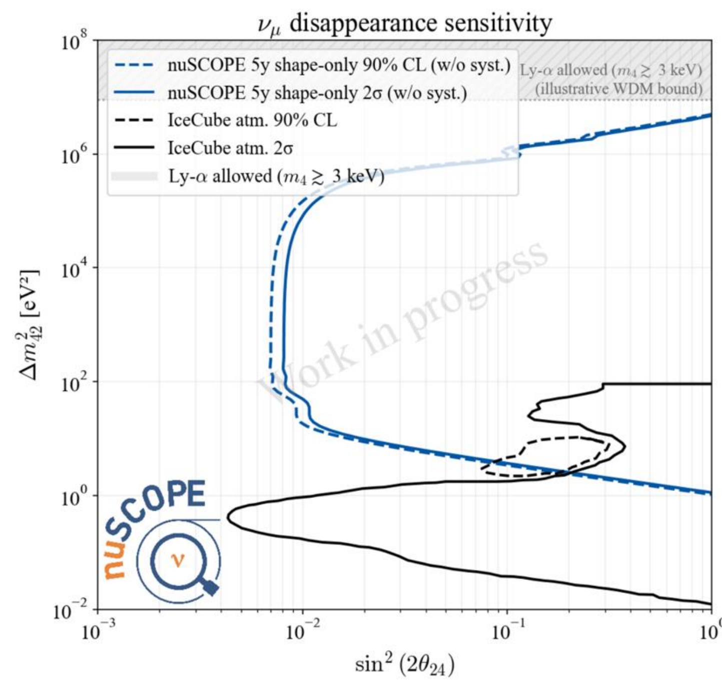
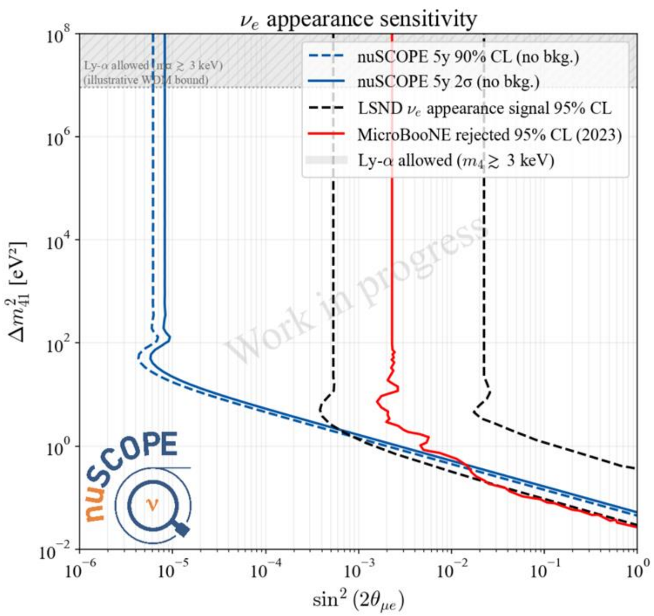
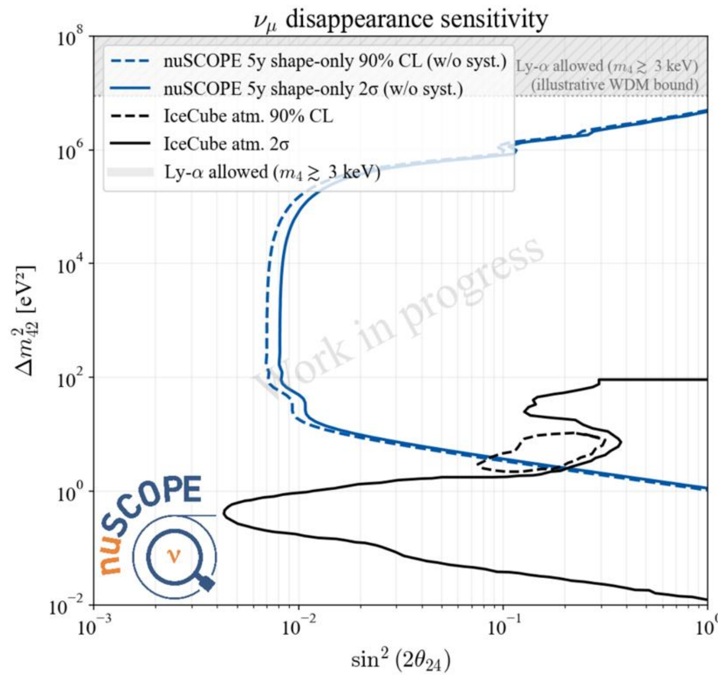




Short-baseline neutrino oscillations

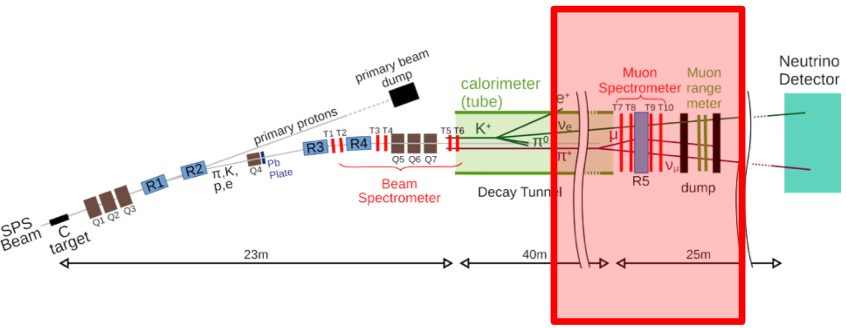
- ✓ **Neutrino energy** known with **<1%** uncertainty event-by-event
- ✓ **Precise** neutrino detector (~mm) to determine L
- ✓ Known neutrino **flavor**

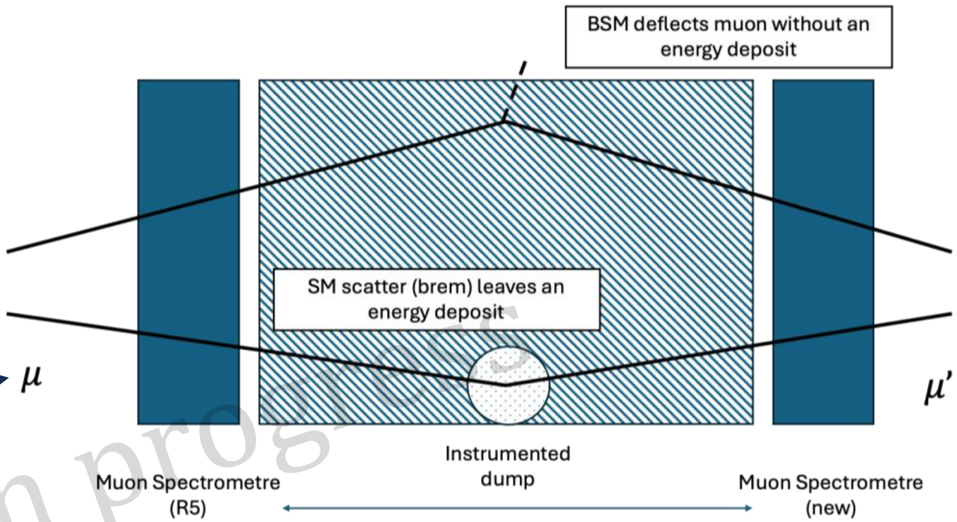




nuSCOPE→μSCOPE?

Idea proposed by R. Plestid & Y. Soreq (CERN Theory Department)





Muon used to tag neutrino
→ energy known with <1% uncertainty
Expect $O(10^{16})$ **tagged** muons

Figure from S. Dolan

Studies in progress

Thanks to its silicon trackers and high muon flux, nuSCOPE can serve as **a high precision** muon experiment
(searches for dark matter, other exotic processes…)

There might be more!

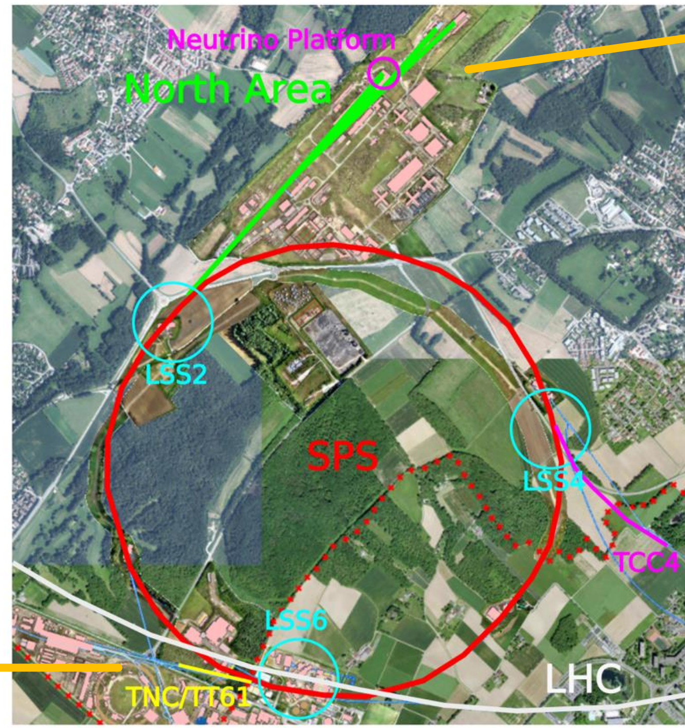
- nuSCOPE proposes a **unique facility** which may be suited for other physics searches
  - E.g. very large kaon and pion flux (which is well known!), missing energy searches in neutrino detector, beam dump facility, QCD measurements etc..
- If you have any ideas, please get in touch!

Implementation at CERN and next steps

Possible implementation at CERN

- ☑ Feasibility studies conducted by CERN Accelerator & Technology Sector – **2 sites identified**
- ☑ Proton sharing is compatible with other fixed target experiments (e.g. SHiP)

Meyrin (LSS6)



North Area (ECN4)

Feasibility studies ongoing under the umbrella of **Physics Beyond Colliders**

Status and next steps

- In 2024-2025 we submitted an input to the ESPPU process (and now feature in the Physics Briefing Book!)
  - Focused on beamline design and preliminary physics sensitivities, mainly cross-section measurements
- We held a successful workshop & kick-off collaboration meeting at CERN in Oct. 2025 and a proto-collaboration meeting in May 2026
  - Focused on neutrino detector design, physics studies & inputs for EoI
- We are preparing a more sophisticated simulation and reconstruction framework and exploring further physics studies
- Plan to submit a EoI to CERN SPSC before end of the year

Synergies: why should you care?

Comprehensive effort with **lots of opportunities**

- Accelerator studies
- Beamline detectors/instrumentation
  - E.g. **Silicon trackers** taking inspiration from LHCb-VELO & new R&D for HiLumi LHC
  - Need to cope with event rates of 20 GHz!
- Neutrino detector
  - We need a **fast** neutrino detector !
  - High coverage **photo-detection system**
  - **Containment** and design optimization
- Collaboration with **nuclear theory** community

Synergies: why should you care?

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- Accelera
- Beamlin
  - E.g. **Sil**
    VELO &
  - Need t
- Neutrin
  - We nee
  - High co
  - **Containment** and design optimization
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Budimir Kliček

Leon Halić

Already enlisted for our cause

(keeps you forever young)

Summary

- Future oscillation experiments will be severley limited by uncertainties related to neutrino-nucleus interactions
- Cross-section measurements are limited by poorly understood neutrino beams
- nuSCOPE proposed a paradigm change for artificial neutrino beams
  - Flux uncertainties <1%
  - Neutrino energy event-by-event with <1% uncertainty
- Range of measurements include:
  - Neutrino cross-section measurements
  - Nuclear physics measurements
  - BSM searches
- Studies ongoing to expand the physics case

Visit our website

Thank you for your attention!

Please get in touch if you'd like to get involved!