Impact of neutrino interaction uncertainties on oscillation measurements

Clarence Wret
June 12 2024
NuSTEC school, CERN

UNIVERSITY OF OXFORD

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Bias declarations:

T2K + (NOvA)

T2K + (Super K)

ex- DUNE, ex- MINERvA

NUISANCE

nuisance.hepforge.org

NEUT

Clarence Wret

University of Oxford

June 12 2024

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Structure

- Recap of neutrino oscillations
  - What are we looking for and how?
  - How big are the effects?
- The role of the near detector
- Energy estimators
- What else can go wrong?

Neutrino oscillations 101

Neutrino oscillations 101

- Neutrino flavour and mass eigenstates are separated

$$|\nu_i\rangle = \sum_{\alpha}^{n} U_{\alpha i} |\nu_\alpha\rangle$$

Mass state

Mixing matrix

Flavour state

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

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- Neutrinos propagate in **mass eigenstates**, but are born and detected in the **flavour eigenstate** via weak interaction

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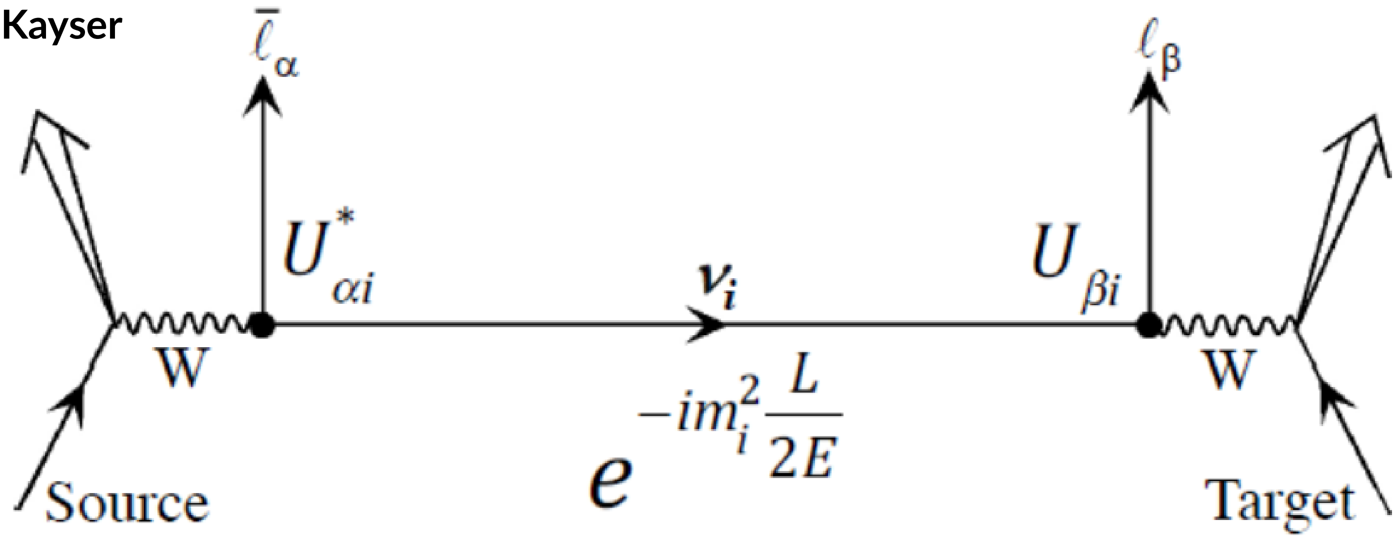
Mass state — Mixing matrix — Flavour state

- Neutrinos propagate in **mass eigenstates**, but are born and detected in the **flavour eigenstate** via weak interaction

B. Kayser



- Results in **oscillations** of the **detected flavour eigenstates**

Neutrino oscillations 101

- Express probability to detect a neutrino with flavour α and energy *E*, as flavour *β* after it's travelled distance *L*

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} Re\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin^2(\Delta m^2_{ij}\frac{L}{4E})$$

$$+ (-)2\sum_{i>j} Im\left(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j}\right)\sin(\Delta m^2_{ij}\frac{L}{2E})$$

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

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Mixing angles

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Mass² difference between eigenstate *i* and *j*

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Experiment design

Mixing angles

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Mixing angles

Mass² difference between eigenstate *i* and *j*

Experiment design

- Design of a neutrino oscillation experiment focusses on **L/E**
  - Determines sensitivity to mass squared splitting and mixing angles
  - Optimise L/E to match appearance/disappearance
  - Resolve neutrino energy adequately

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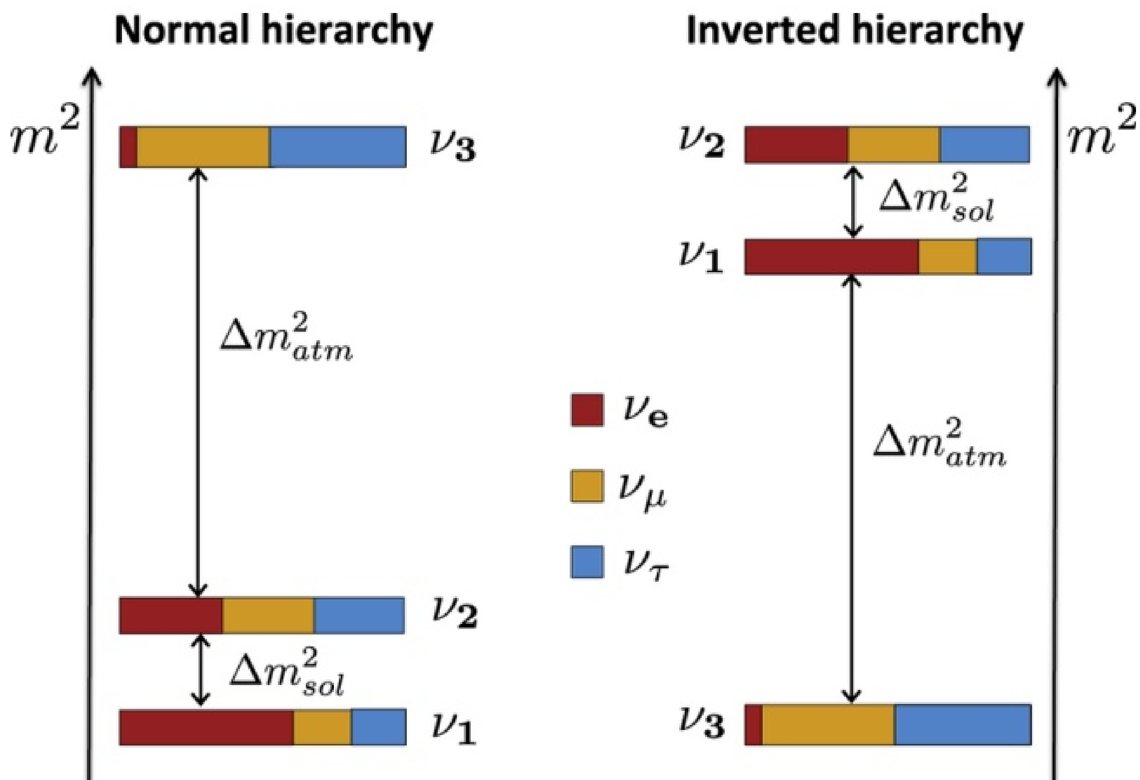

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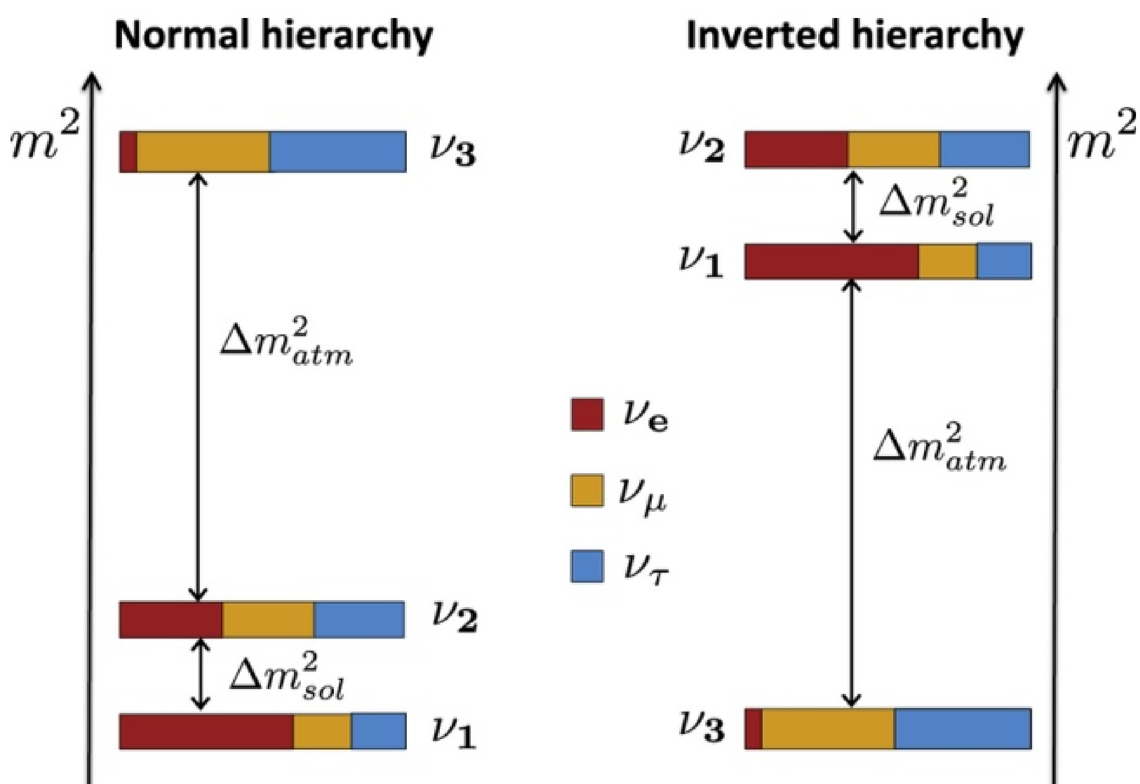
Dominant effect from **sin²:** to a unknown **mass ordering:** $\Delta m^2_{32}>0$?



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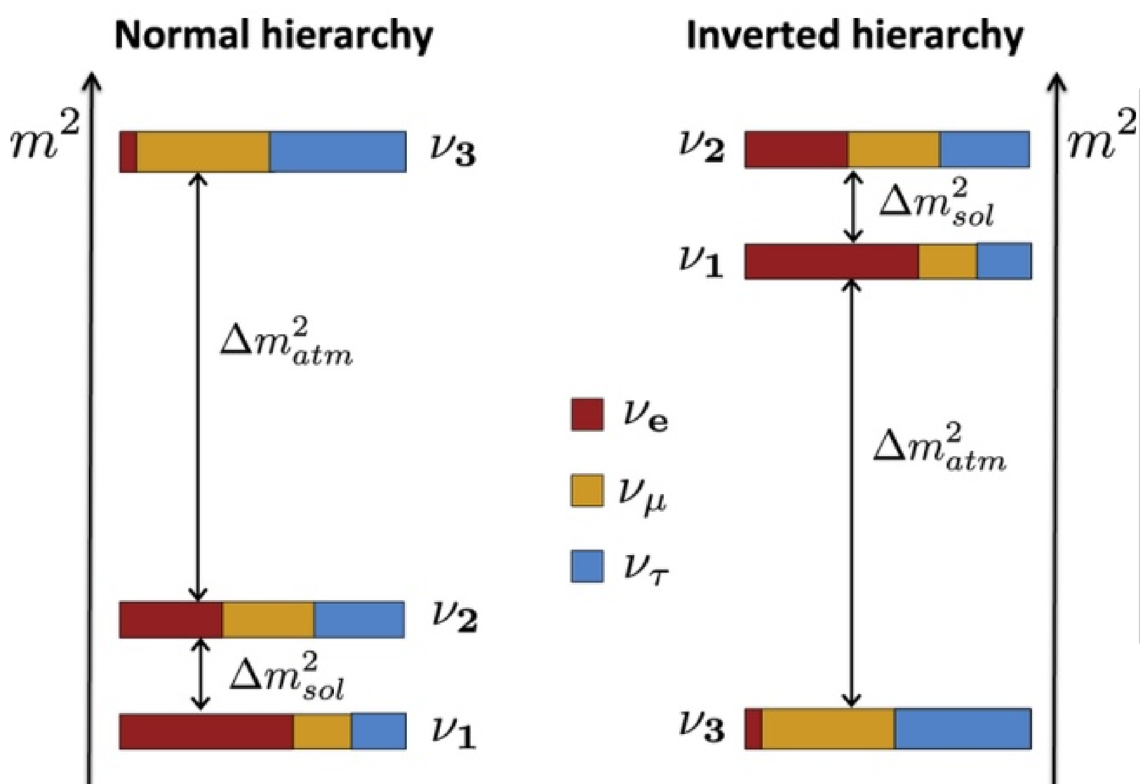

sin term resolves mass ordering, through second order

Know $\Delta m^2_{21}>0$ from SNO experiment

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Measure differences in $P(\nu_\mu \rightarrow \nu_e)$ and P(anti-$\nu_\mu \rightarrow$ anti-ν_e)
→ left with **single term**

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Measure differences in $P(\nu_\mu \to \nu_e)$ and $P(\text{anti-}\nu_\mu \to \text{anti-}\nu_e)$
→ left with **single term**

$$\Delta_{ij} \equiv \Delta m^2_{ij} L/4E$$

$$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = -16 J_{\alpha\beta}\sin\Delta_{12}\sin\Delta_{23}\sin\Delta_{31}$$

Sensitive to **CP violating phase**

Sensitive to **mass ordering**

$$J \equiv s_{12}c_{12}s_{23}c_{23}s_{13}c^2_{13}\sin\delta$$

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Neutrino oscillations 101

- But that was all in a **vacuum**!
- When **electron neutrinos** propagate through matter, they experience a different potential to the other flavours

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & \sin^2\theta_{23}\ \sin^2 2\theta_{13}\ \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2}\ \Delta_{31}^2 \\
& + \sin 2\theta_{23}\ \sin 2\theta_{13} \sin 2\theta_{12}\ \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \\
& \times \Delta_{31}\ \frac{\sin(aL)}{(aL)}\ \Delta_{21}\ \cos(\Delta_{31} + \delta) \\
& + \cos^2\theta_{23} \sin^2 2\theta_{12}\ \frac{\sin^2(aL)}{(aL)^2}\ \Delta_{21}^2,
\end{aligned}
$$

(leading order calculation)

$$a \equiv G_F N_e / \sqrt{2}$$

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- For electron anti-neutrinos: ***a*→-*a* and *δ*→-*δ***
- Matter effect produces a difference between P($\nu_\mu \to \nu_e$) and P(anti-$\nu_\mu \to$anti-ν_e) → **Same as CP violation signature**

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Neutrino oscillations

- The most general form of mixing matrix is seldom used; instead separate into three mixing matrices

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

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

Atomspheric or "2,3" sector

Reactor, or "1,3" sector

Solar, or "1,2" sector

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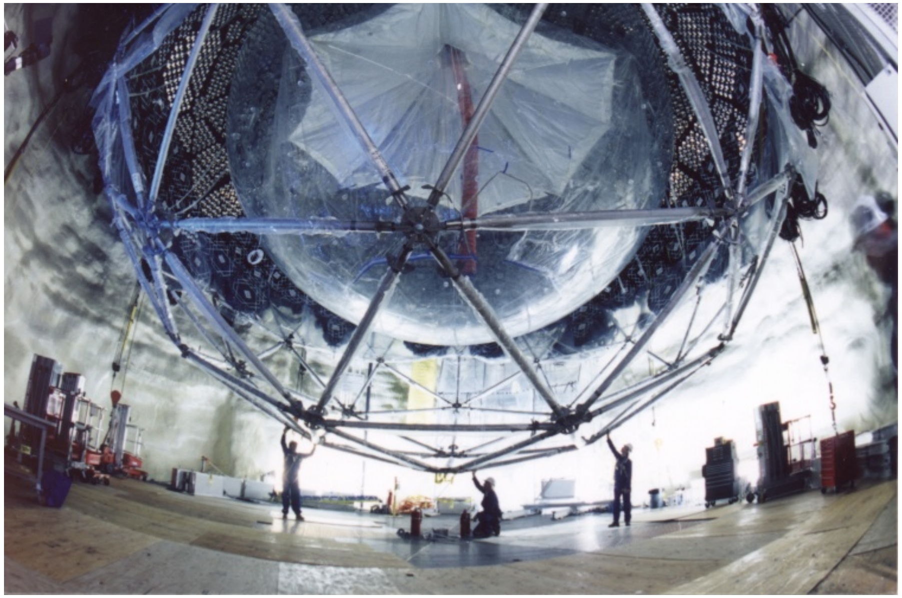
Atomspheric or “2,3” sector

Reactor, or “1,3” sector

Solar, or “1,2” sector

Solar experiments (SNO, SK) long baseline reactor experiments (KamLAND, JUNO)
L/E > 100km/MeV



From MIT

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Atomspheric or "2,3" sector

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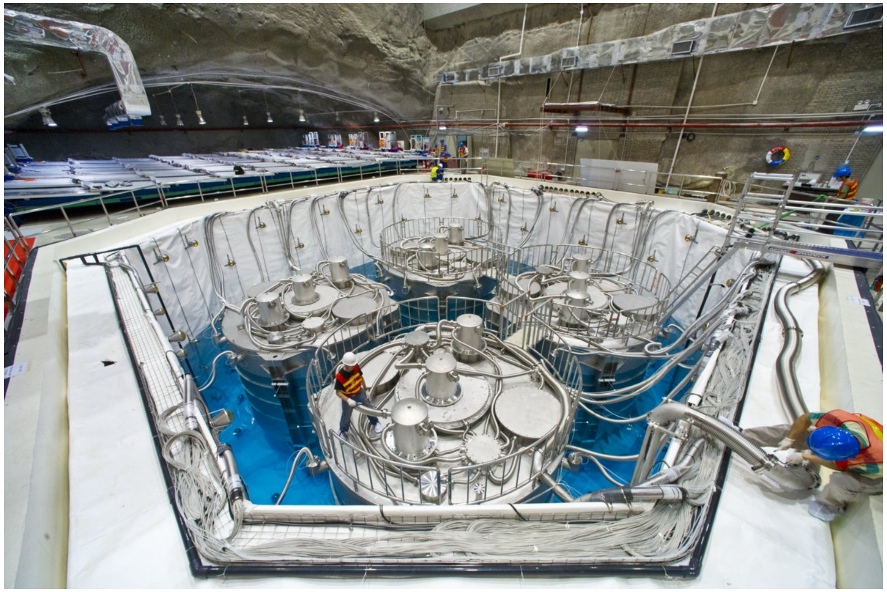
Reactor experiments (Daya Bay, RENO, Double Chooz)

L/E ~ 1km/MeV



From LBL

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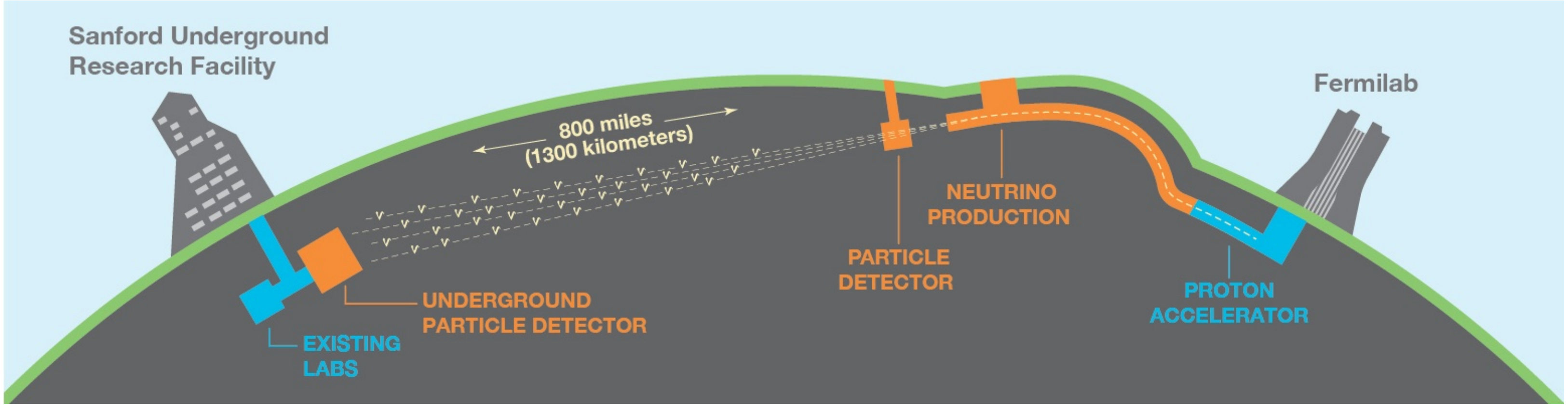
Reactor, or "1,3" sector

Solar, or "1,2" sector

Long baseline experiments (K2K, T2K, NOvA, MINOS, DUNE, HK), atmospheric experiments (SK, IceCube)

L/E ~ 400-500km/GeV



From DUNE

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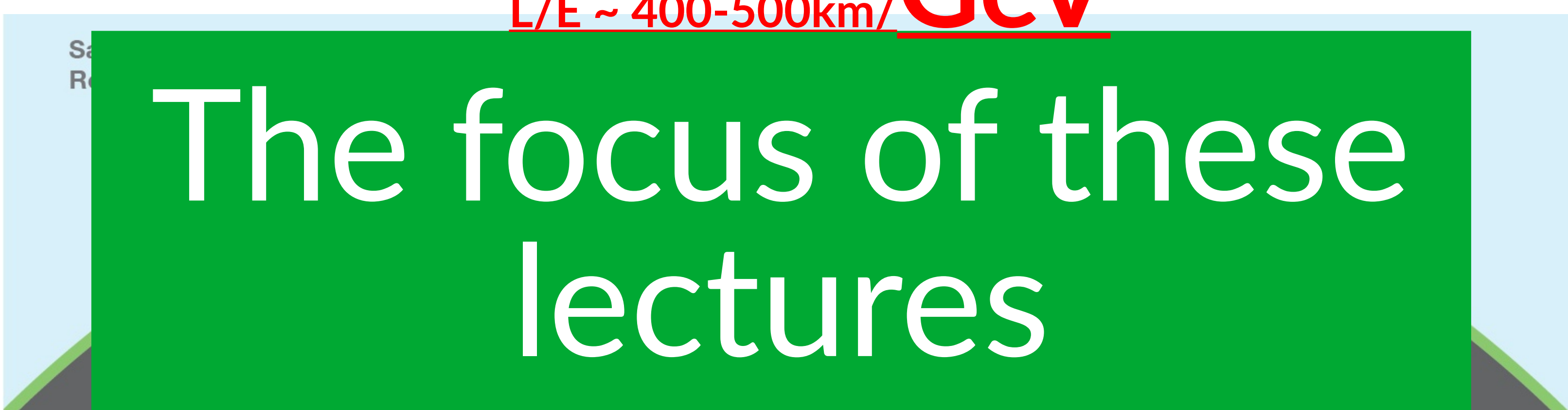
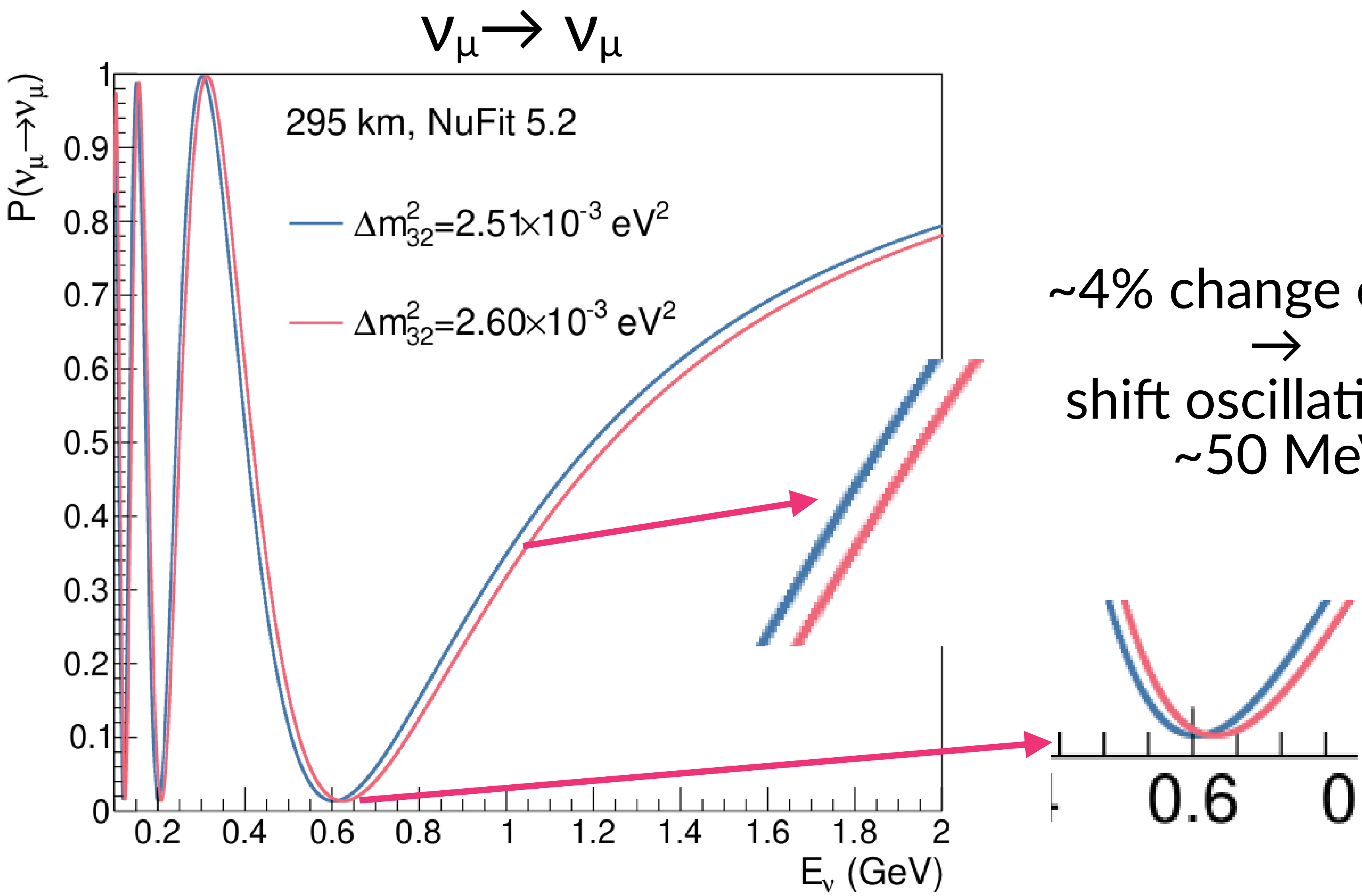


The focus of these lectures

From DUNE

How big are the effects?

- Varying **mass-squared splitting** to see impact on muon neutrino oscillation probability
- **Induces a shift in energy around the main oscillation dip**

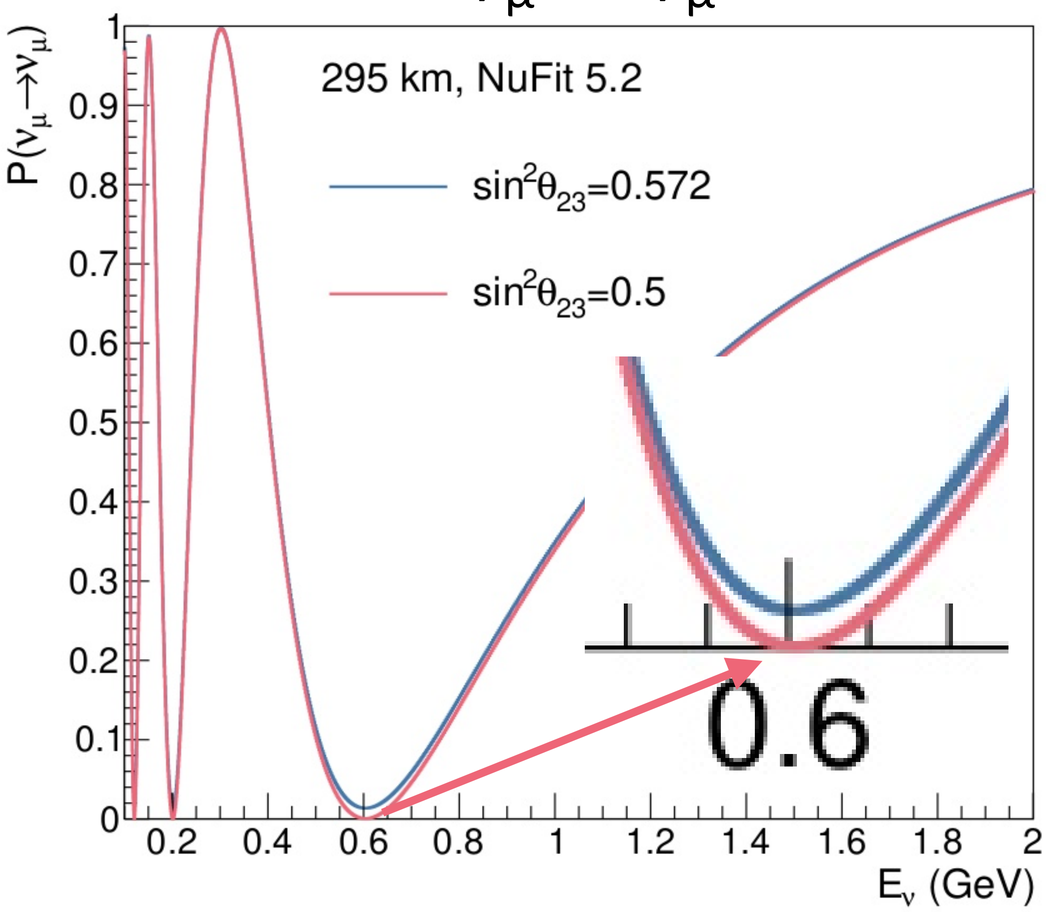


~4% change of Δm^2 → shift oscillation by ~50 MeV

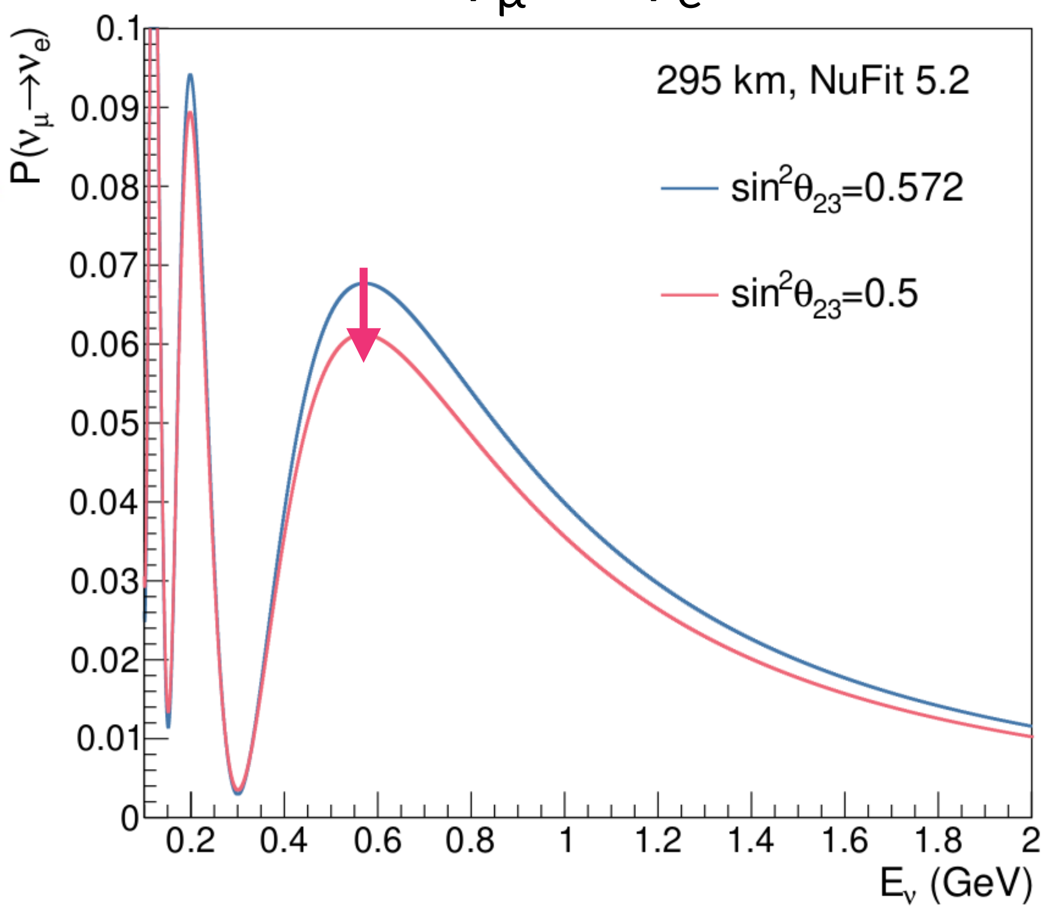
How big are the effects?

- Move from NuFit 5.2 to $\mathbf{sin^2\theta_{23}}$ = 0.5 → decrease probabilities for both flavours (increase $\nu_\mu \rightarrow \nu_\tau$ probability)
- **Overall decrease in normalisation, especially in dip region**

$\nu_\mu \rightarrow \nu_\mu$

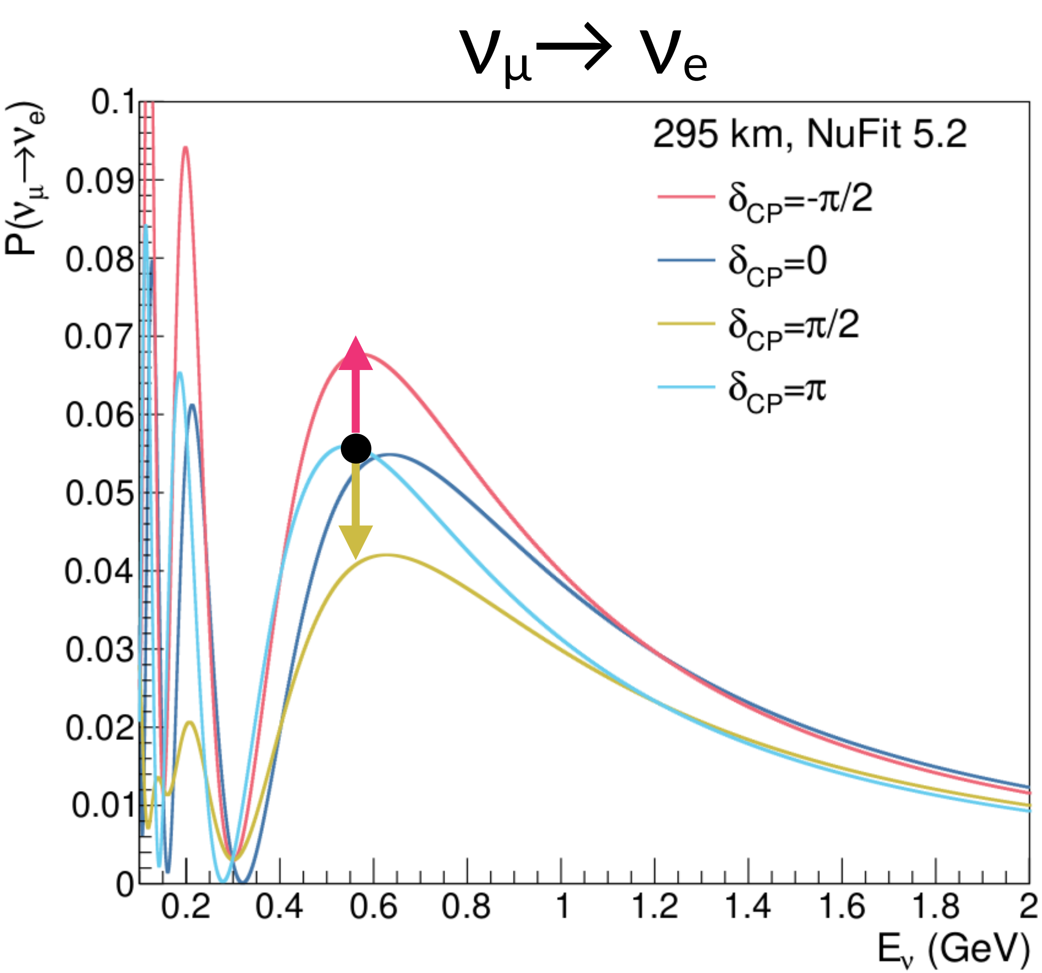


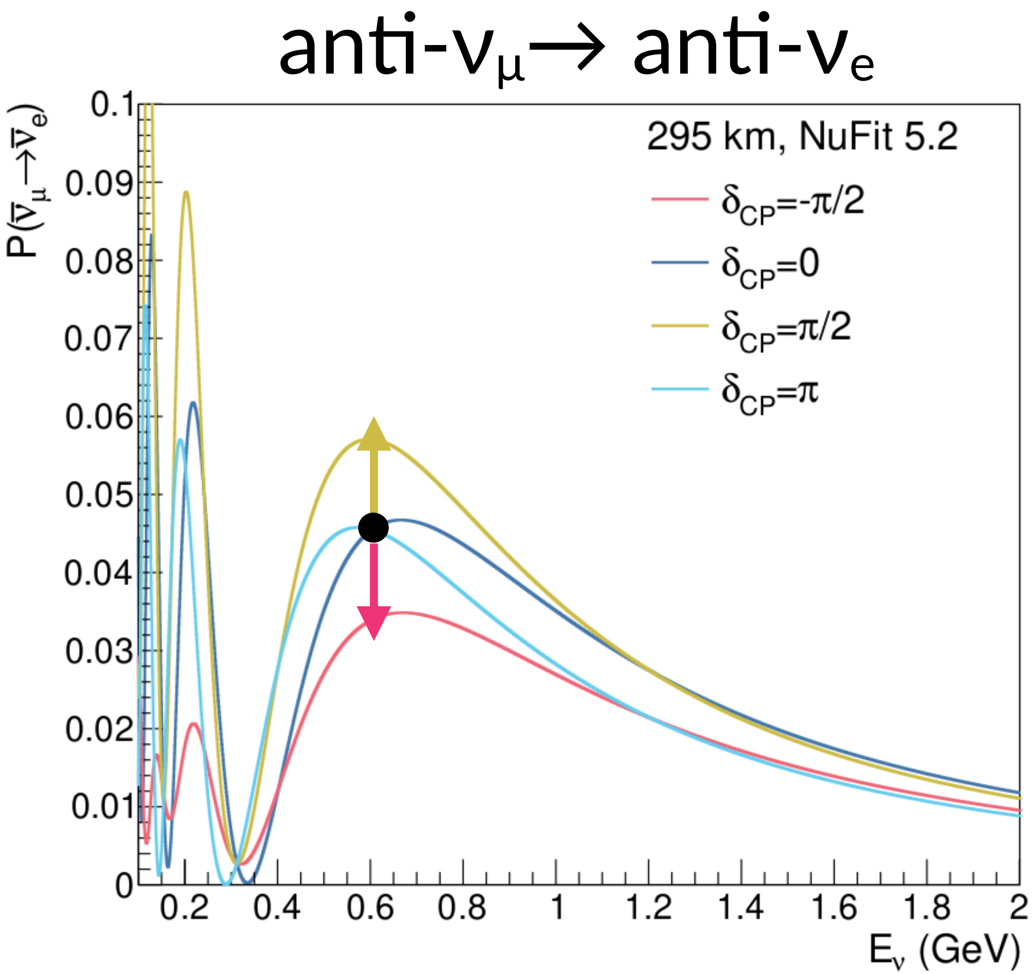
$\nu_\mu \rightarrow \nu_e$



How big are the effects?

- **Changing δ_{CP} cyclically** from maximum to minimum effect, through the two CP-conserving points $\delta_{CP}=0, \pi$
- **Opposite effect** for electron neutrinos and anti-neutrinos

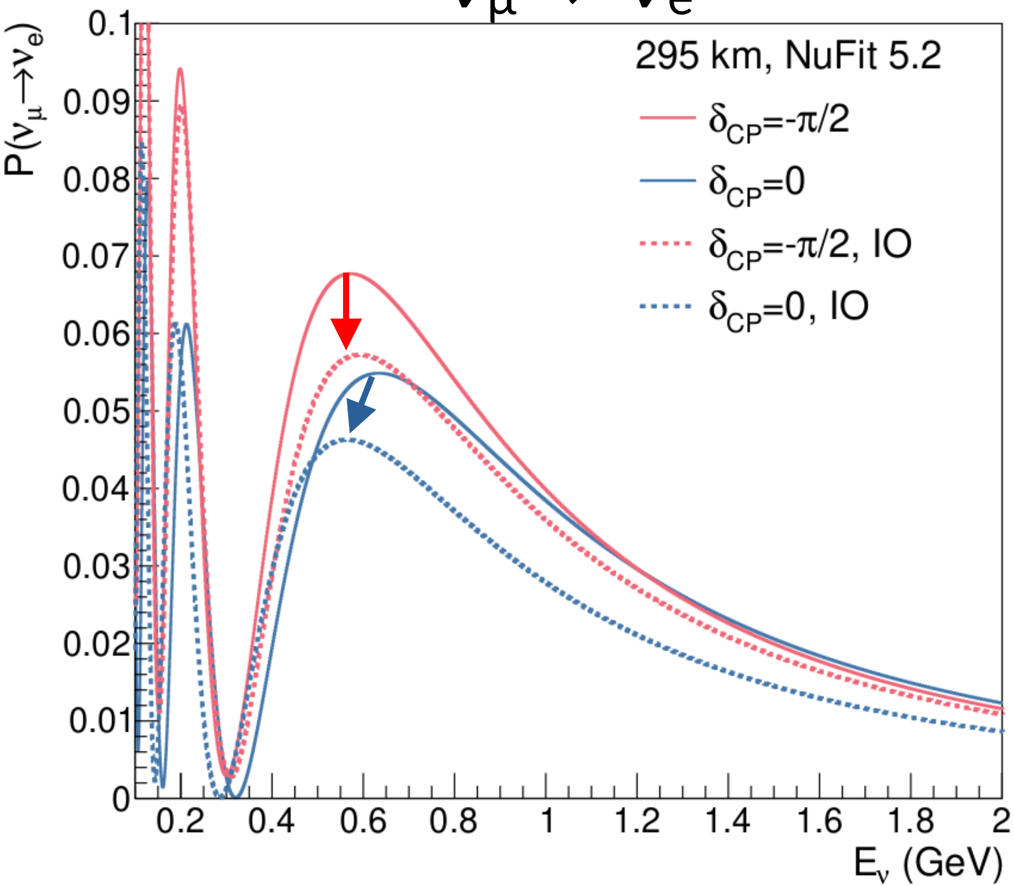




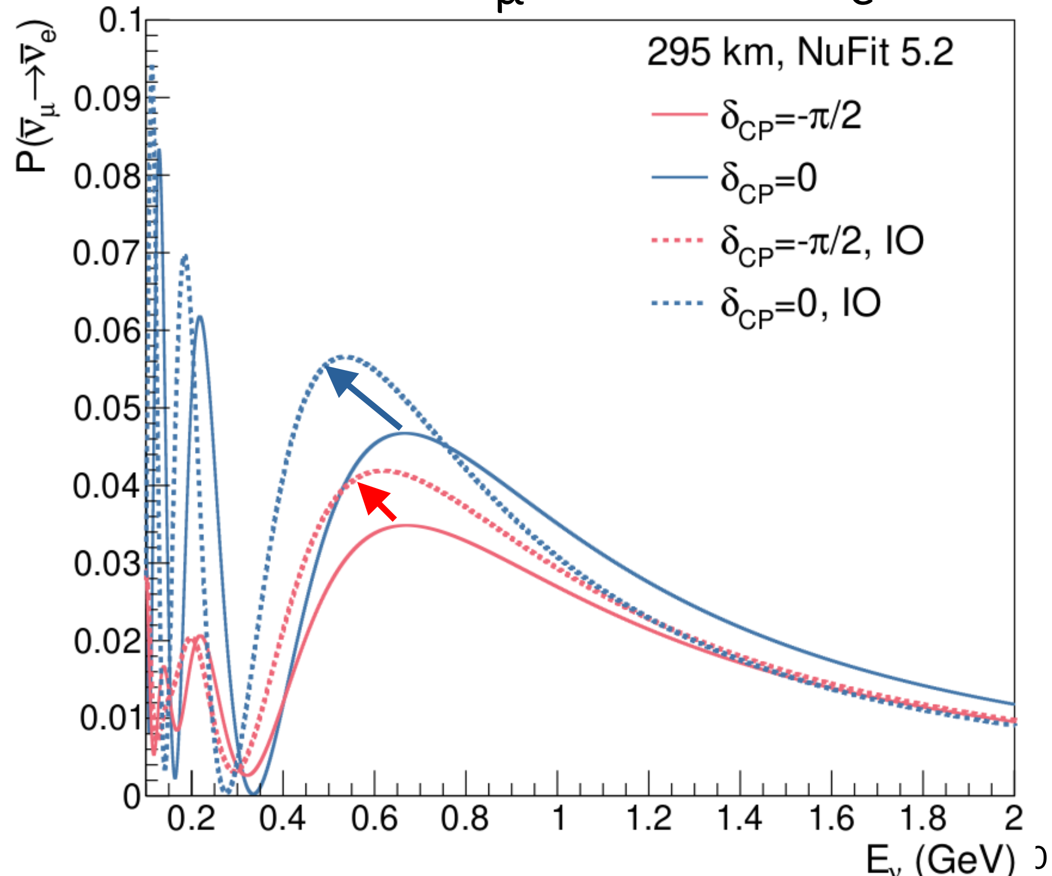
How big are the effects?

- Changing the **mass ordering** (NO, IO) and **δ_{CP} from 0 to -π/2**
- **Opposite effect** for electron neutrinos and anti-neutrinos
- <u>**Degeneracy:**</u> NO → IO decreases electron neutrino; increases electron anti-neutrino. But, <u>**shape of spectrum changes**</u>
- δ_{CP}=0, NO very similar to δ_{CP}=-π/2, IO for neutrinos

$\nu_\mu \rightarrow \nu_e$

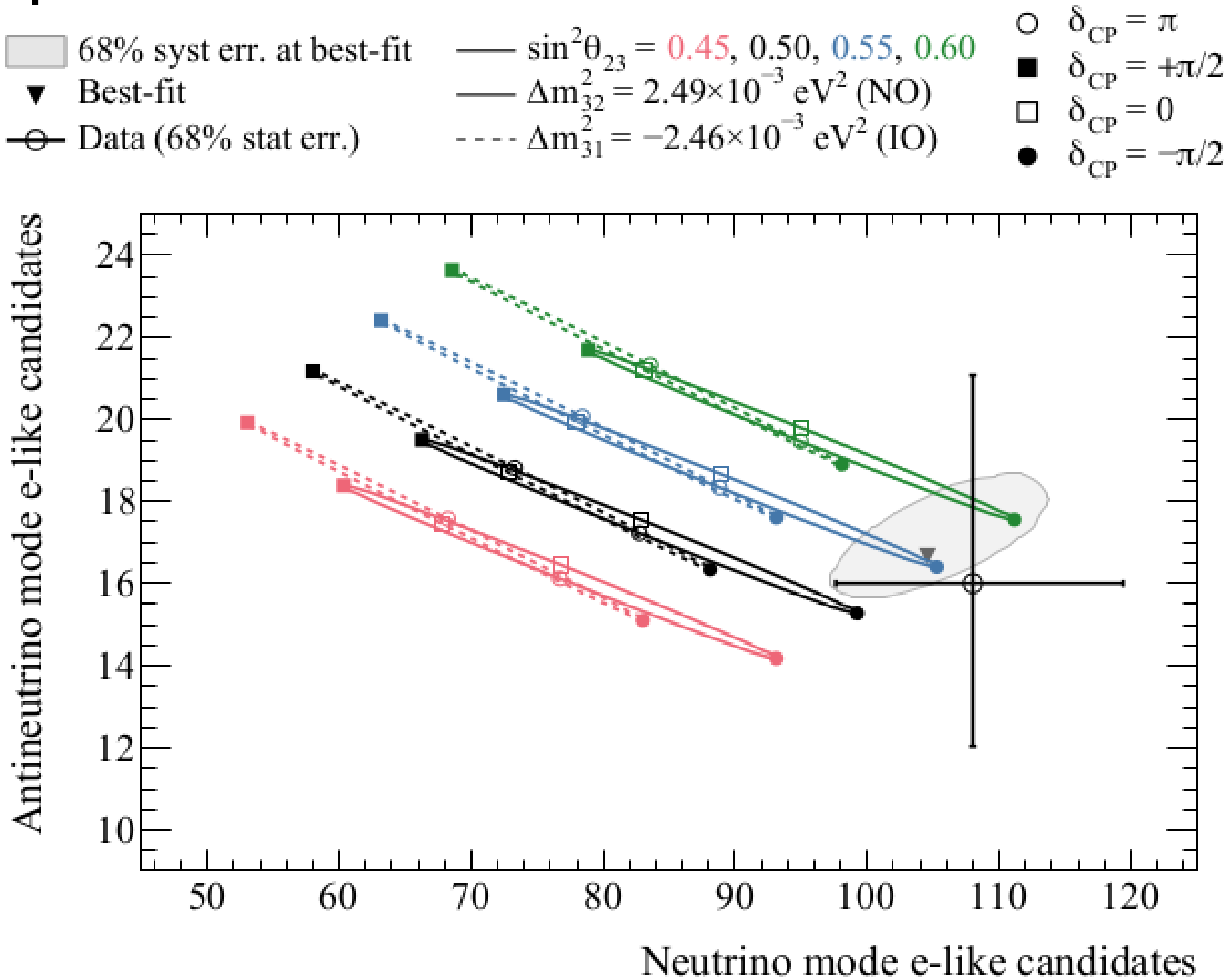


anti-$\nu_\mu \rightarrow$ anti-ν_e



Exploring the degeneracies

- The earlier features are often summarised in "bi-event plots"



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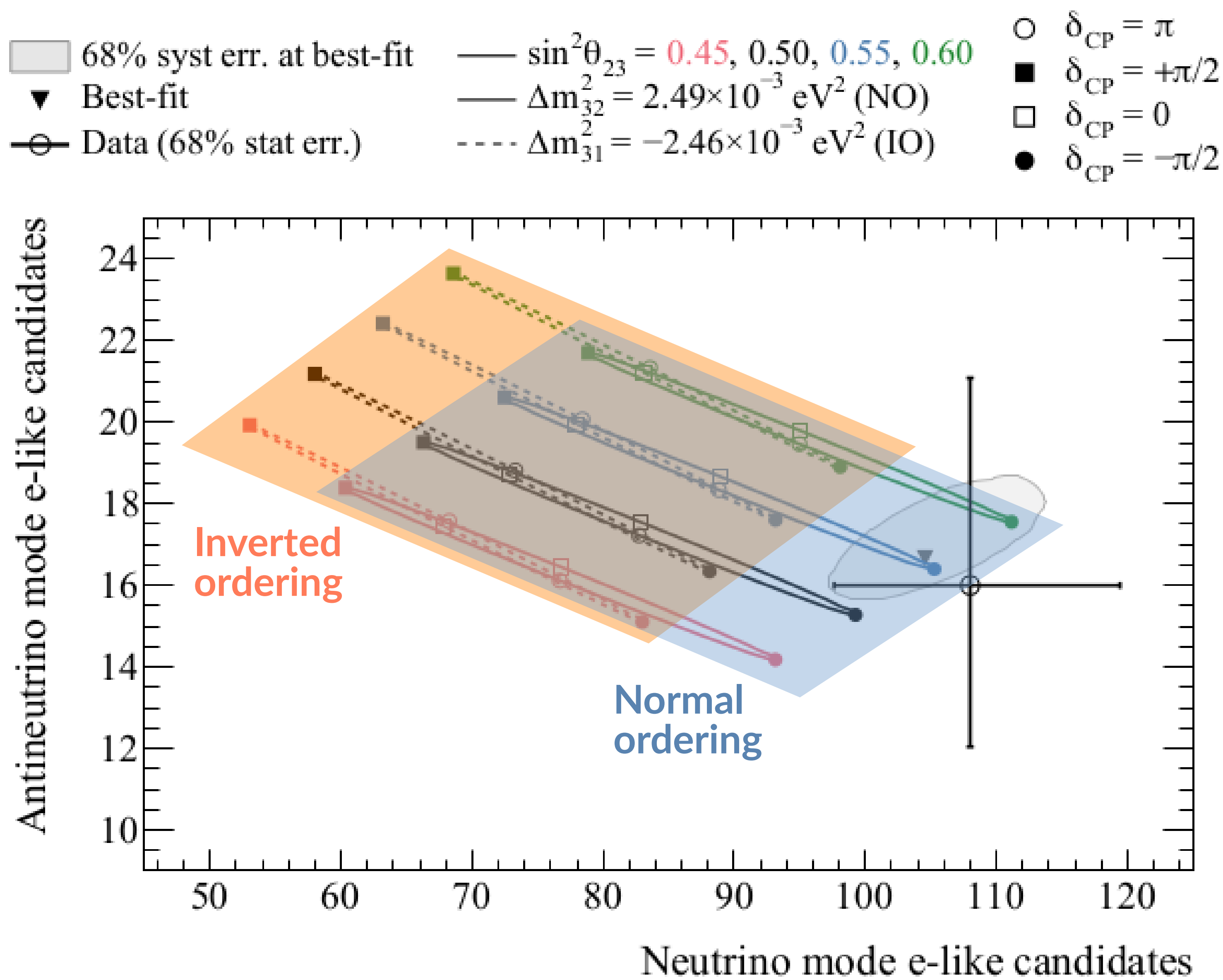
Exploring the degeneracies

- Separate by mass ordering scenarios



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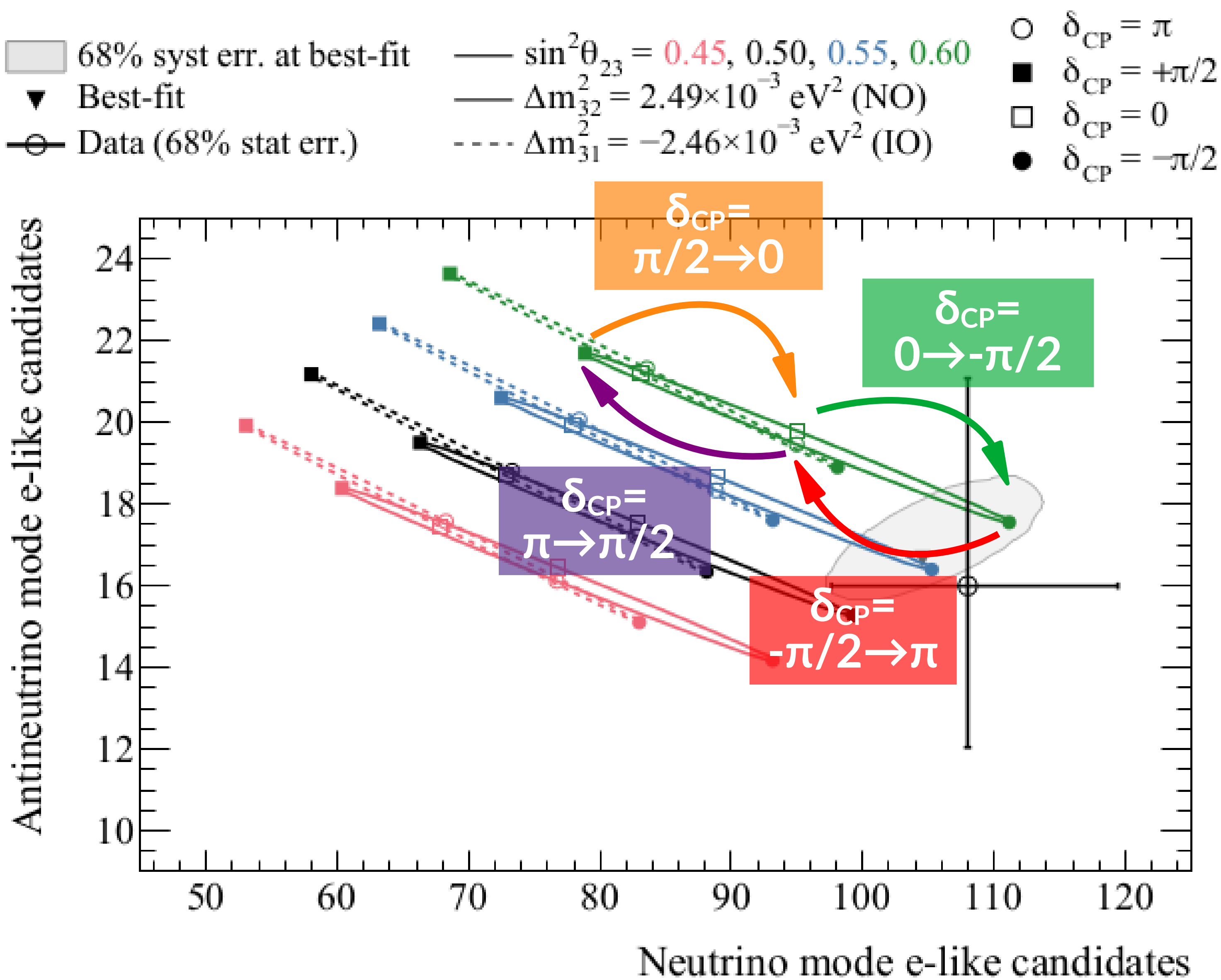
Exploring the degeneracies

- Separate by CP violating phase scenarios



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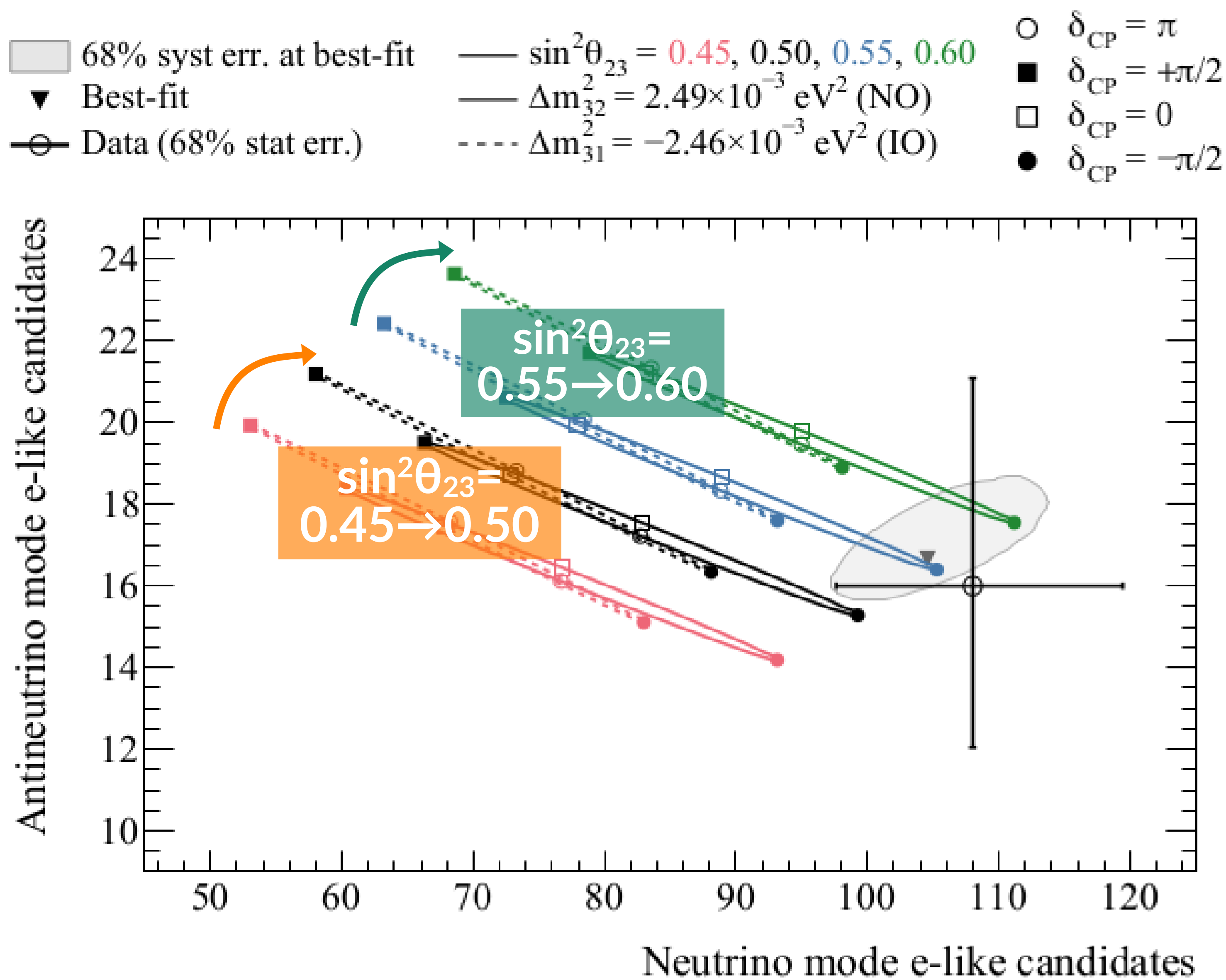
Exploring the degeneracies

- Separate by $\sin^2\theta_{23}$



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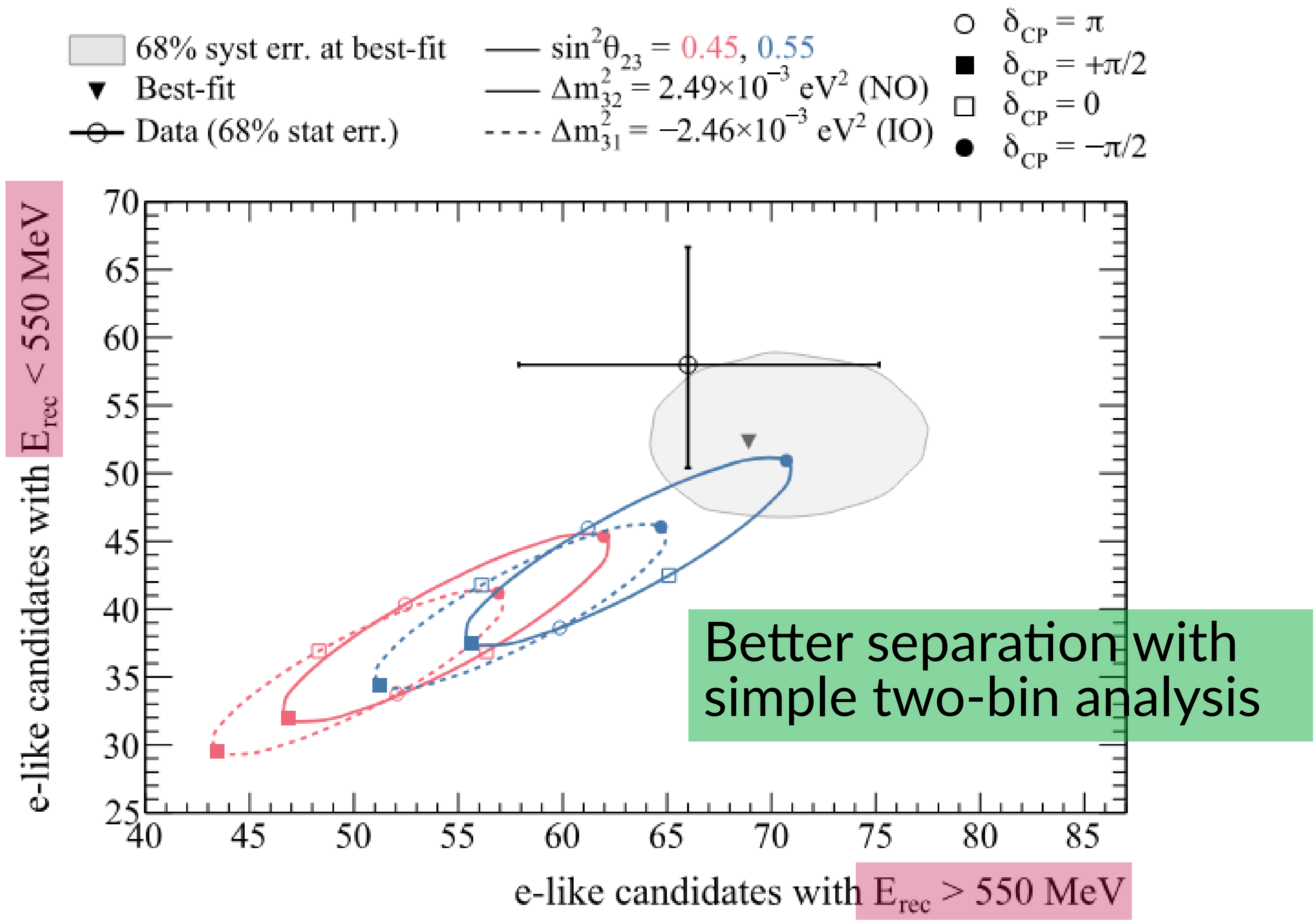
Exploring the degeneracies

- But, these don’t tell full story: **they ignore energy dependence** (simple counting experiment)

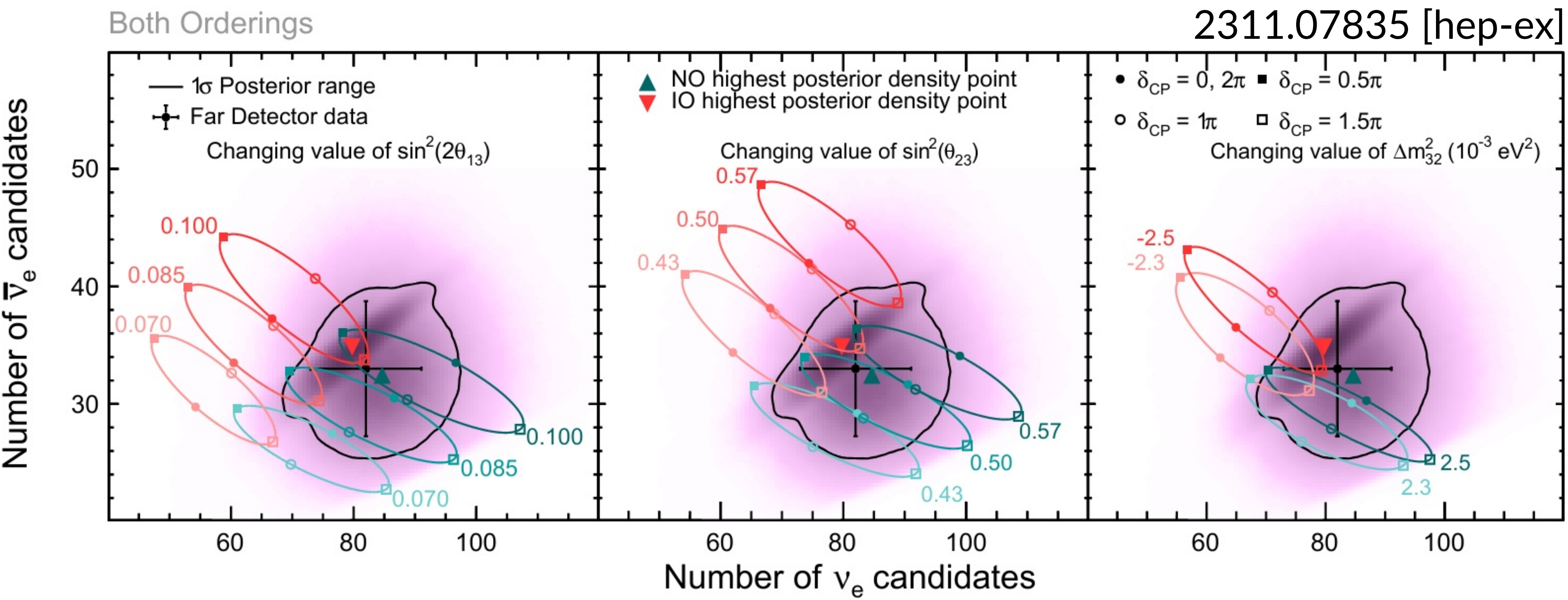


Eur. Phys. J. C 83, 782 (2023)

Exploring the degeneracies

- NOvA experiment has higher neutrino energy, and longer baseline compared to T2K
  - Stronger mass ordering sensitivity, weaker δ_{CP} sensitivity

2311.07835 [hep-ex]

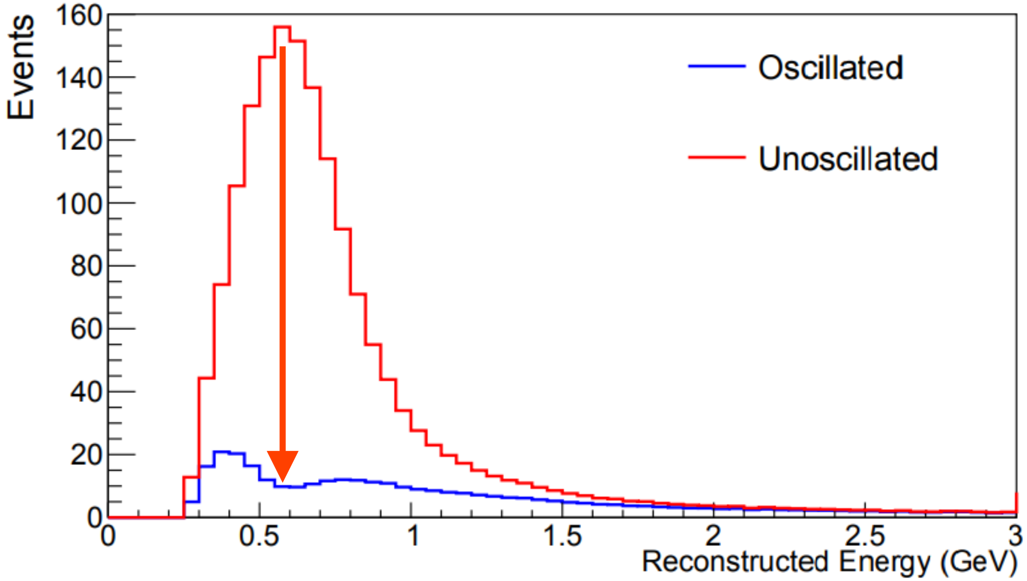


- Larger separation of δ_{CP} and mass ordering effects
- (the different sensitivity to δ_{CP} and MO makes joint T2K+NOvA fit very interesting, amongst other things)

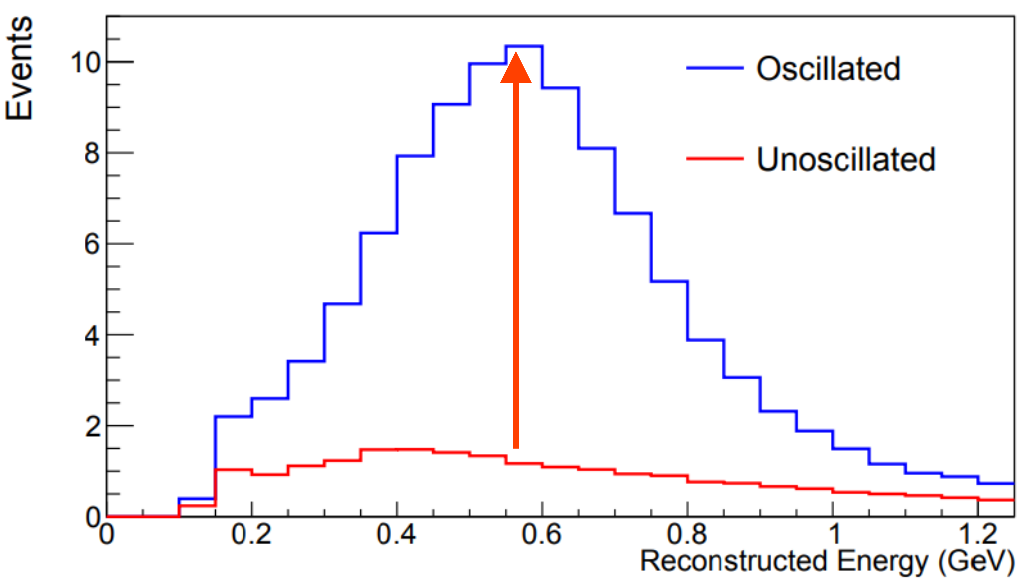
Introduction

- Oscillation parameters change the rate and shape of the appearing and disappearing neutrinos

T2K FHC 1Rμ



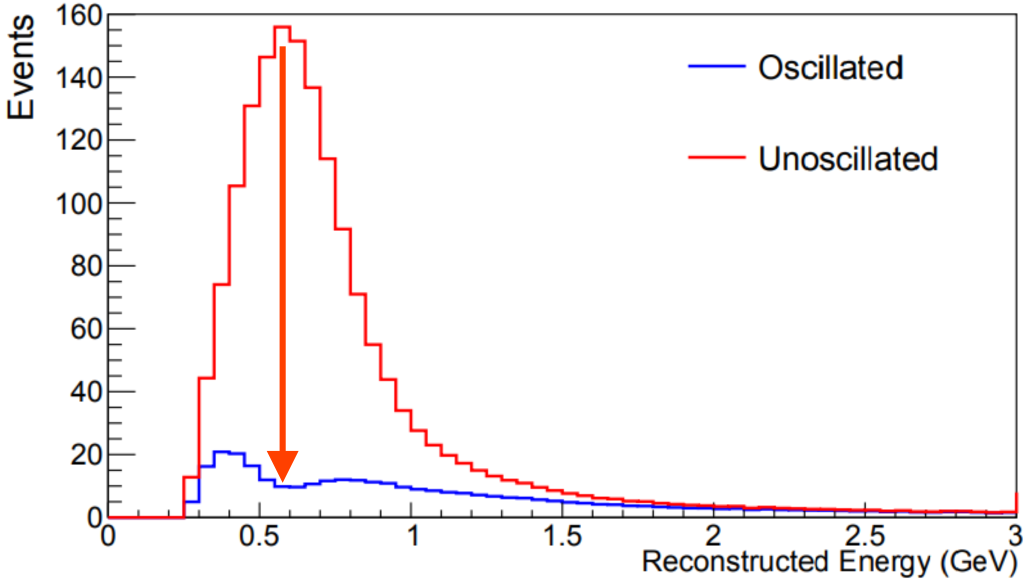
T2K FHC 1Re



Introduction

- Oscillation parameters change the rate and shape of the appearing and disappearing neutrinos

T2K FHC 1Rμ



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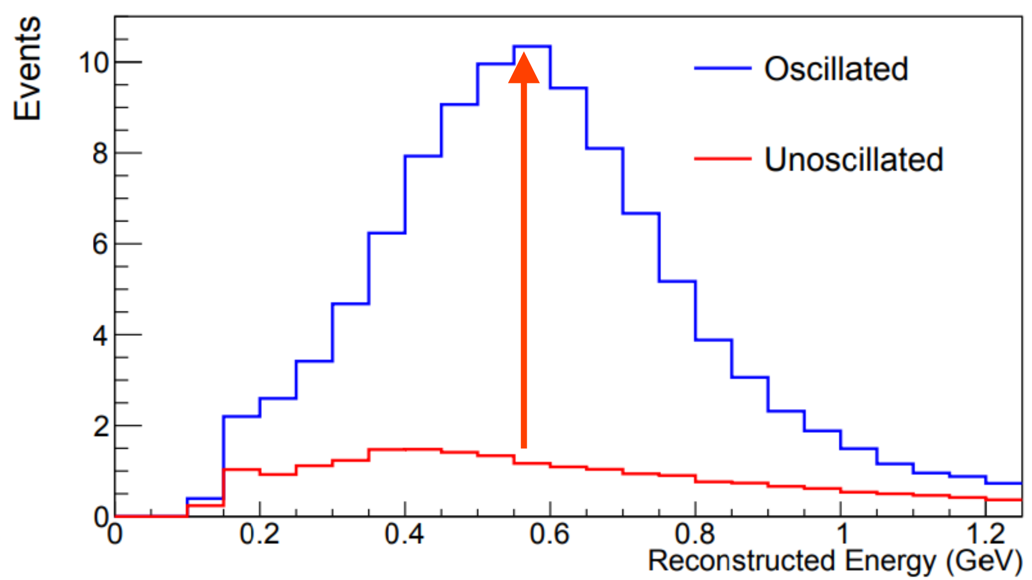
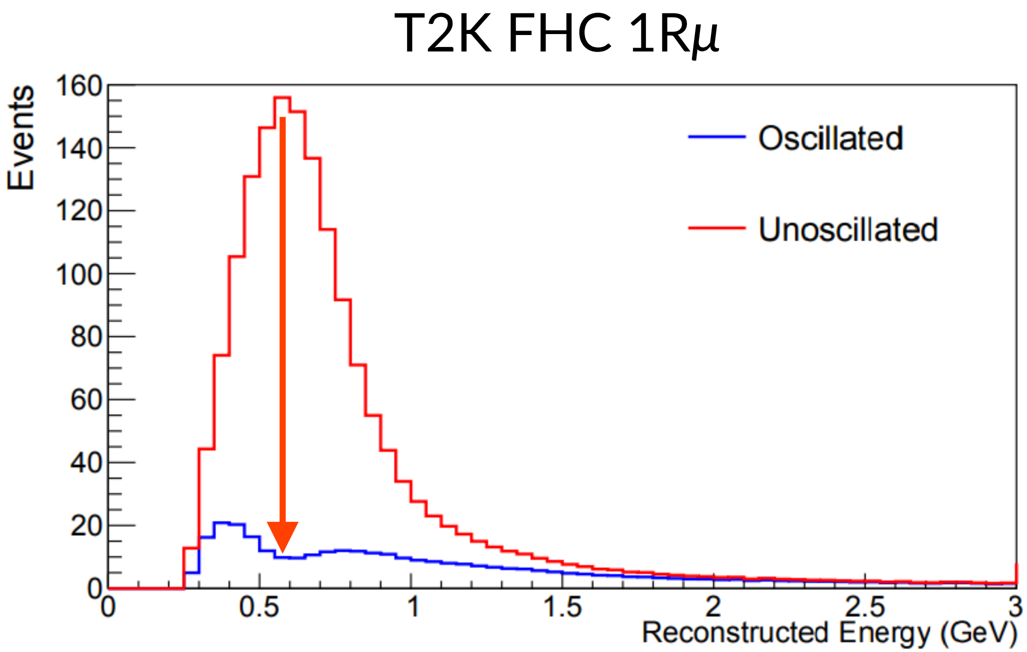
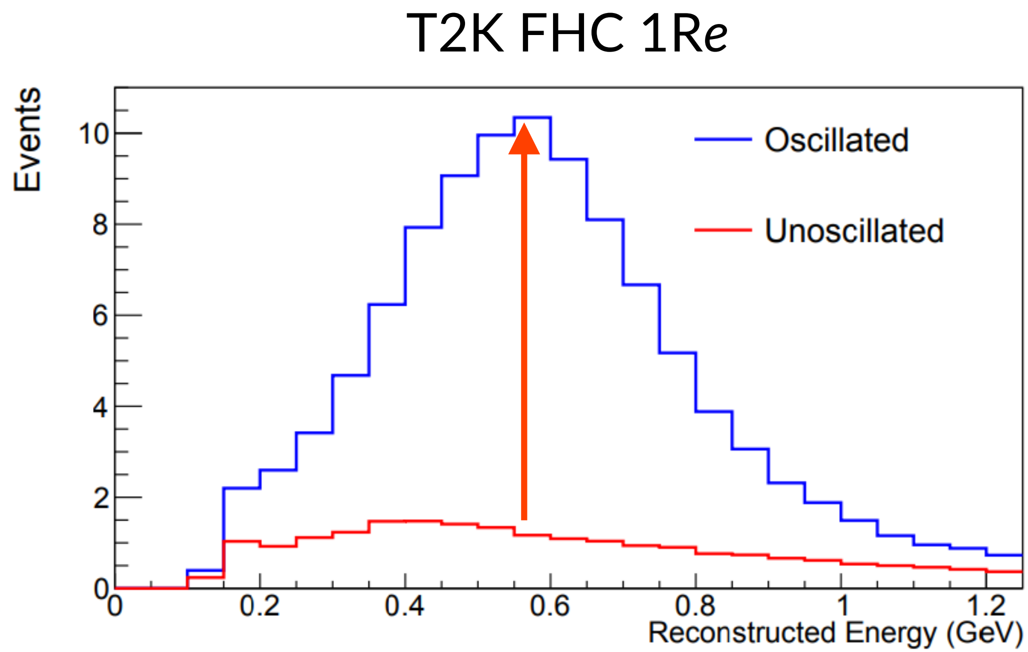


- Relies on the **model prediction** in the **absence of oscillations**
  - **Constrain this model → constrain your oscillation parameters!**

Introduction

- Oscillation parameters change the rate and shape of the appearing and disappearing neutrinos





- Relies on the **model prediction** in the **absence of oscillations**
  - **Constrain this model → constrain your oscillation parameters!**
- Finding cross-section effects which are degenerate with oscillation parameters is the **nightmare** scenario

Pause for air

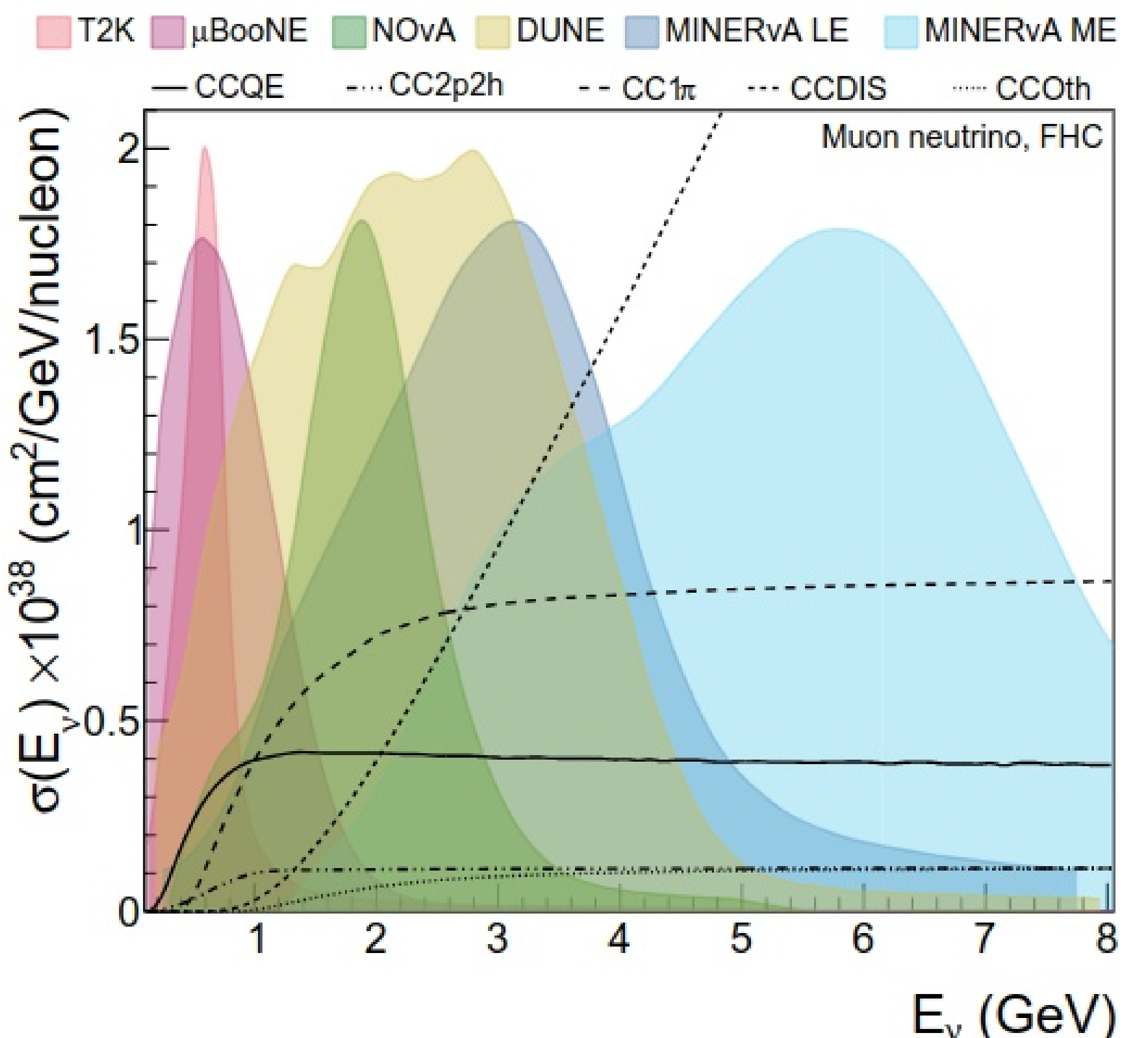
- **Muon** and **electron** (anti-)neutrinos respond differently to oscillation parameters
- **Electron (anti-)neutrinos** are the keys to unlocking $\boldsymbol{\delta_{CP}}$ and **mass ordering** measurements
  - Both cause an **asymmetry** between electron neutrino and anti-neutrino oscillations; **it's not just the CP violating phase!**
- **<u>The energy spectrum</u>** of the electron neutrinos is important when disentangling the degeneracies
  - This is not obvious in the bi-event plots, although they are illustrative
- The **degeneracy improves** for NOvA and DUNE, which have longer baselines (larger matter effects)
  - However, they are less sensitive to δ_{CP}
  - Less events at far detector because much further away

If you enjoy playing with oscillation calculations, consider **Prob3++**, **NuFast**, and many other calculators

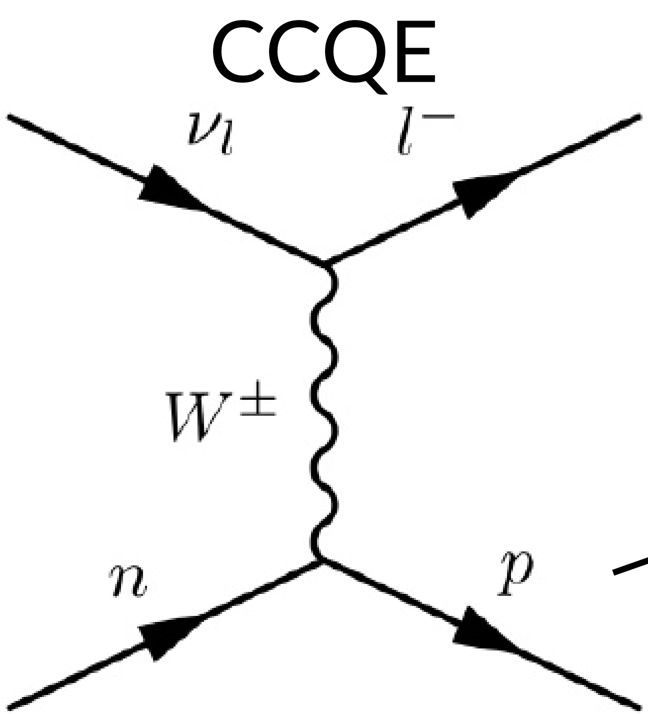
Experiments and how oscillations are measured

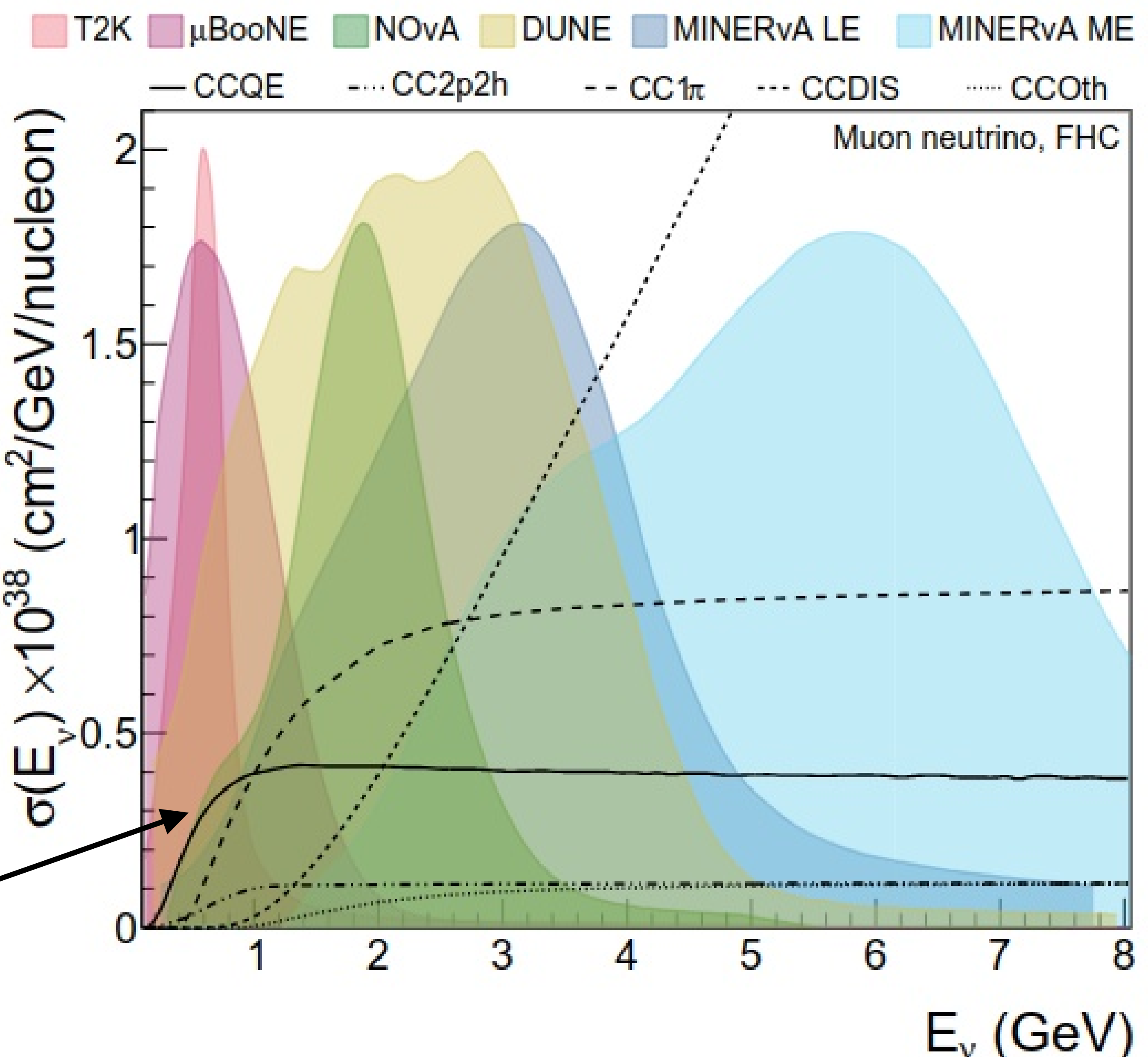
Neutrino fluxes from accelerators

- Accelerator neutrino oscillation experiments generally sit in the **0.5-5 GeV** region
  - Optimised for L/E ratio, matter effects, δ_{CP} sensitivity…
- The neutrino energy **is a key factor in dictating which interactions matter**
- Interaction mechanisms evolve differently in neutrino energy
- What matters for T2K, may not matter for NOvA, may not matter for DUNE
- Measurements from a cross-section experiment may not extrapolate well to oscillation experiment



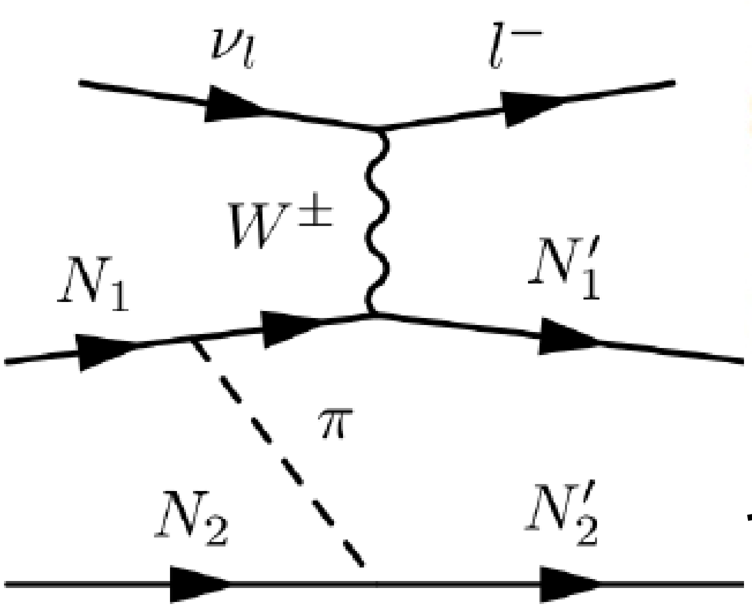
Neutrino fluxes from accelerators

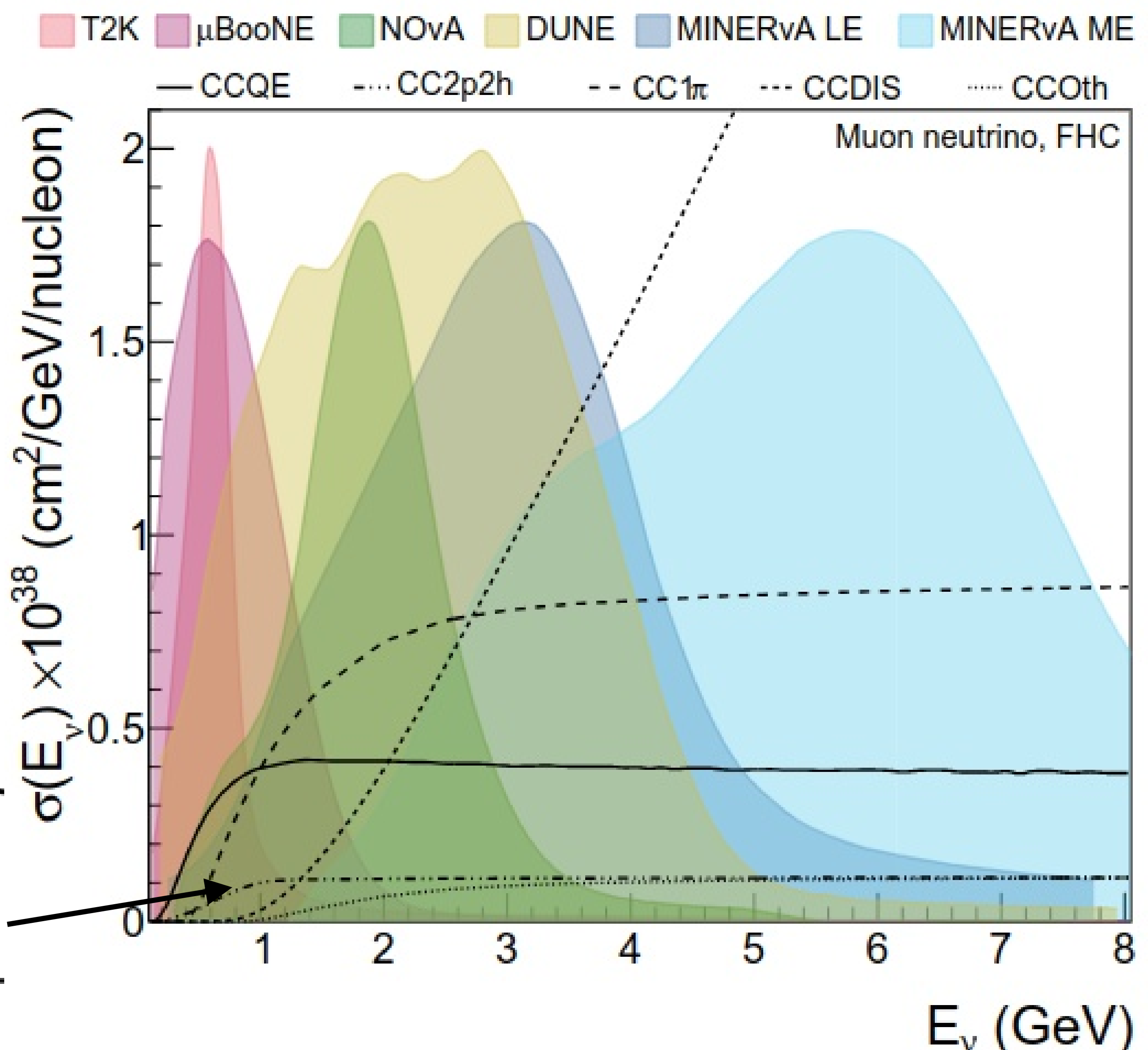




Neutrino fluxes from accelerators

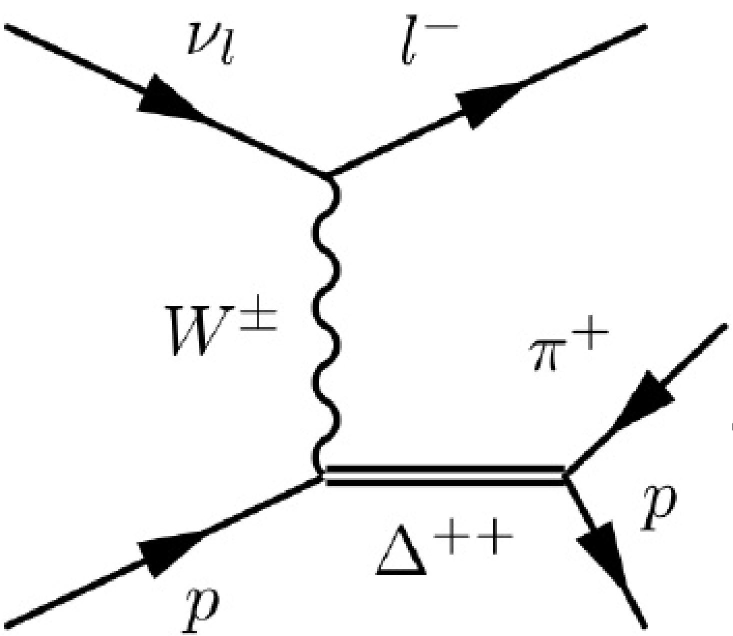
2p2h (one diagram)

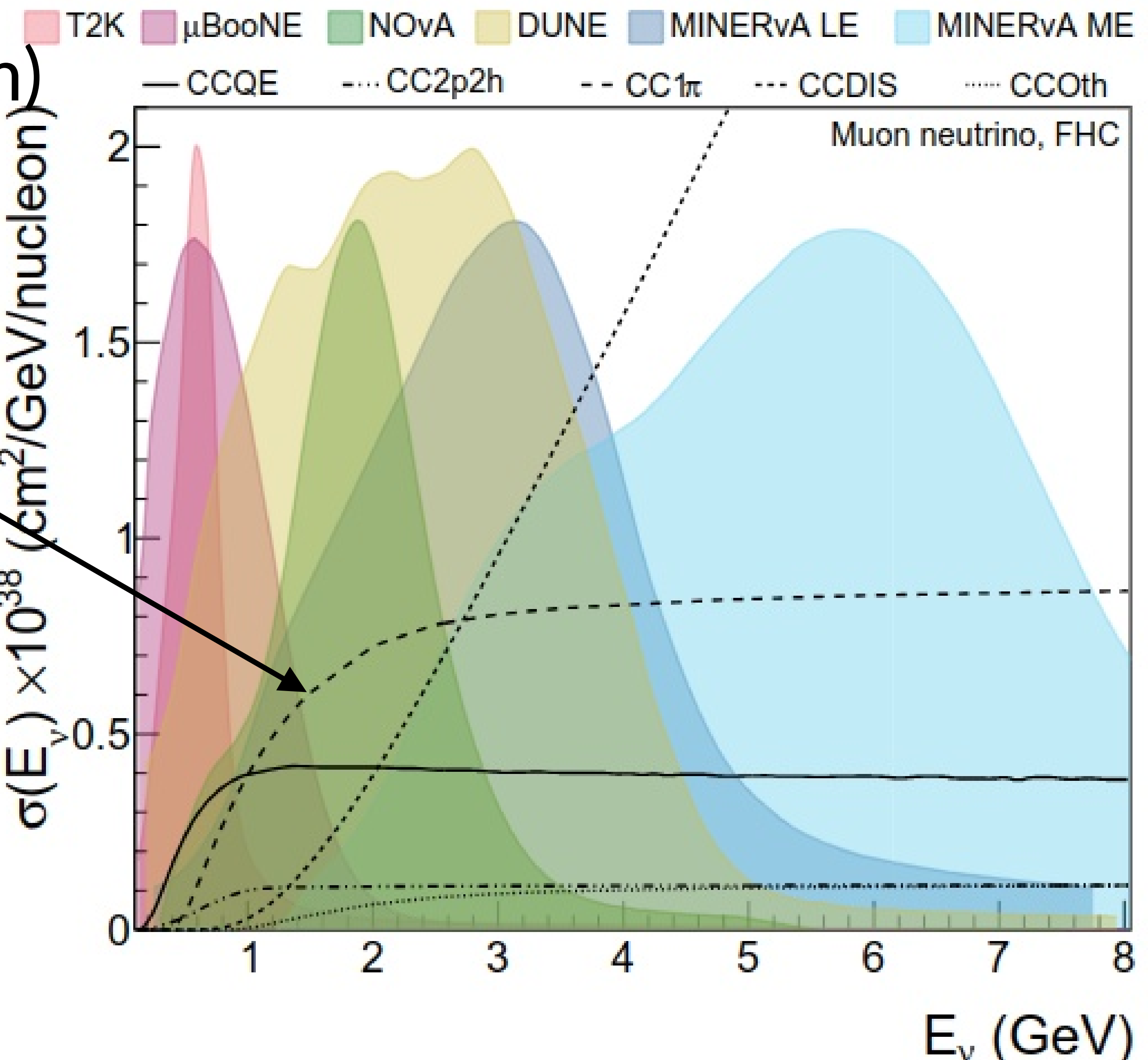




Neutrino fluxes from accelerators

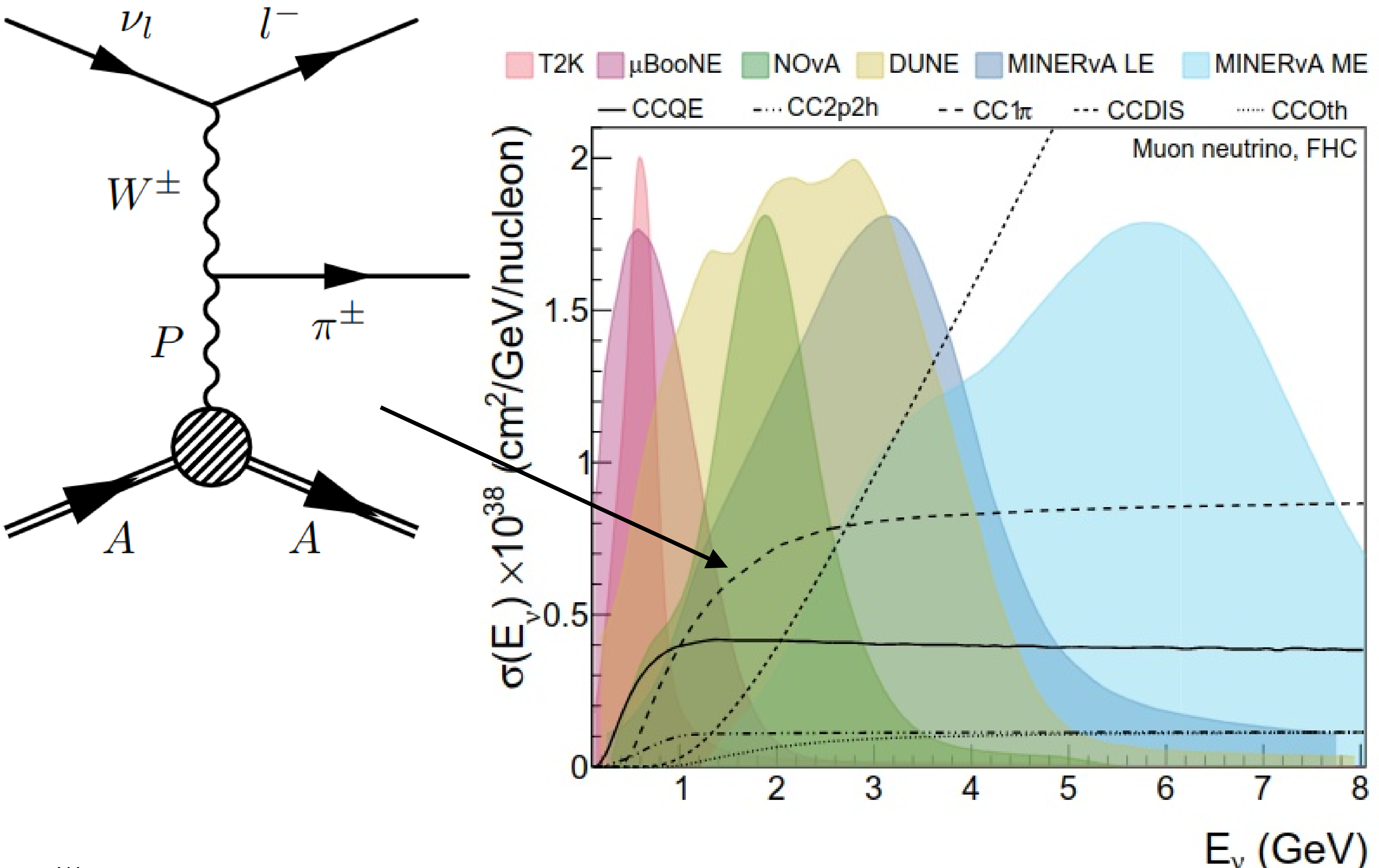
CC1π⁺ (one diagram)



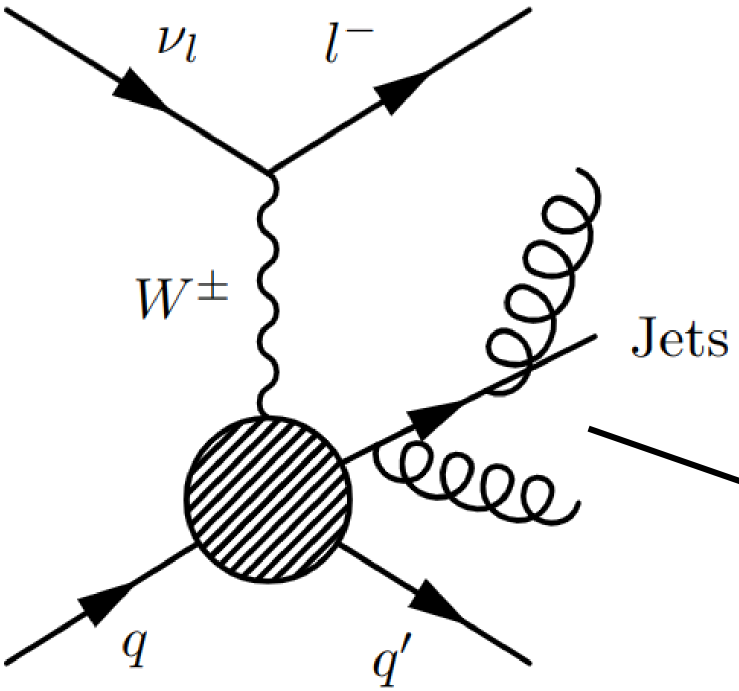


Neutrino fluxes from accelerators

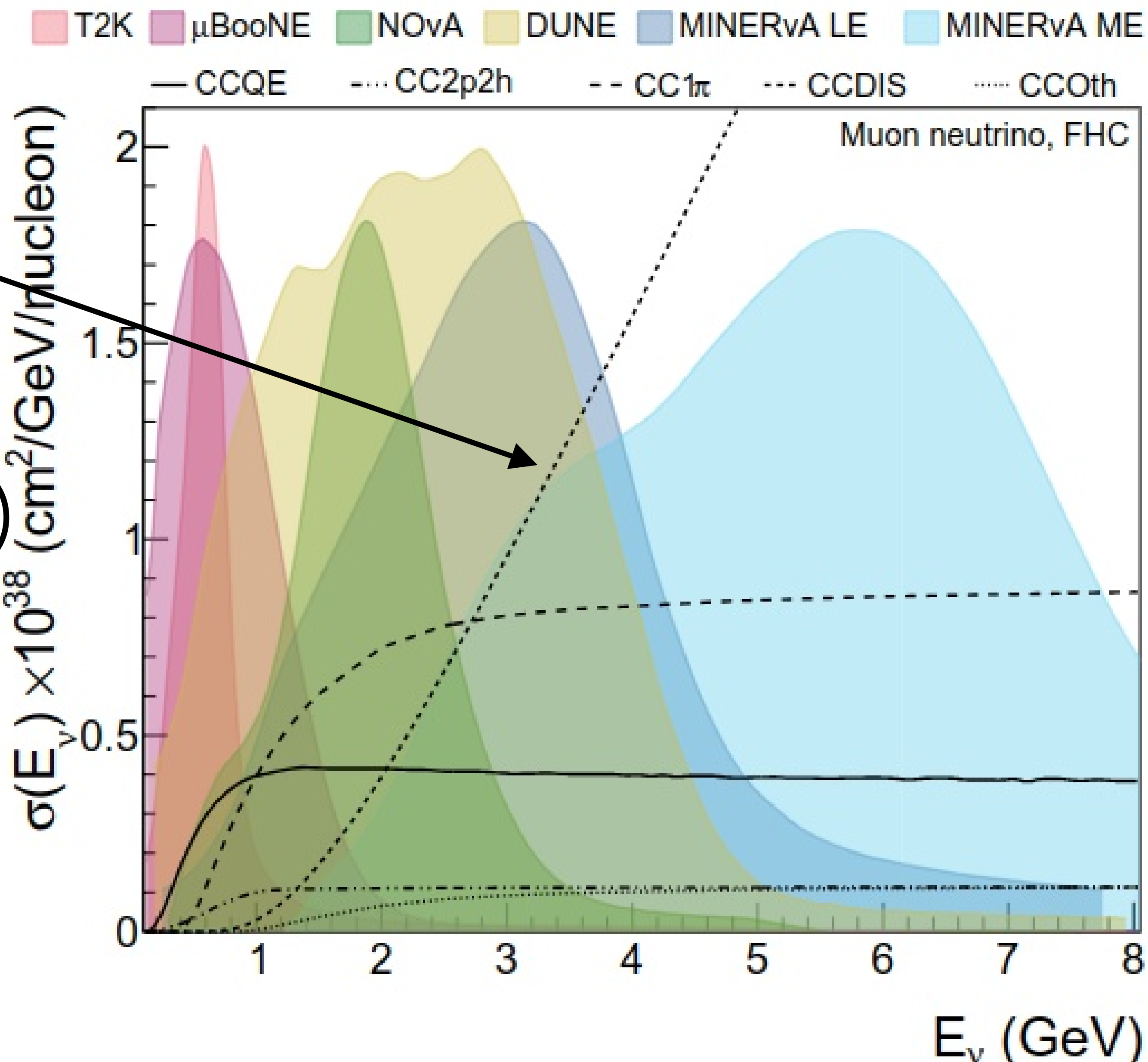
CC1π^+ coherent



Neutrino fluxes from accelerators

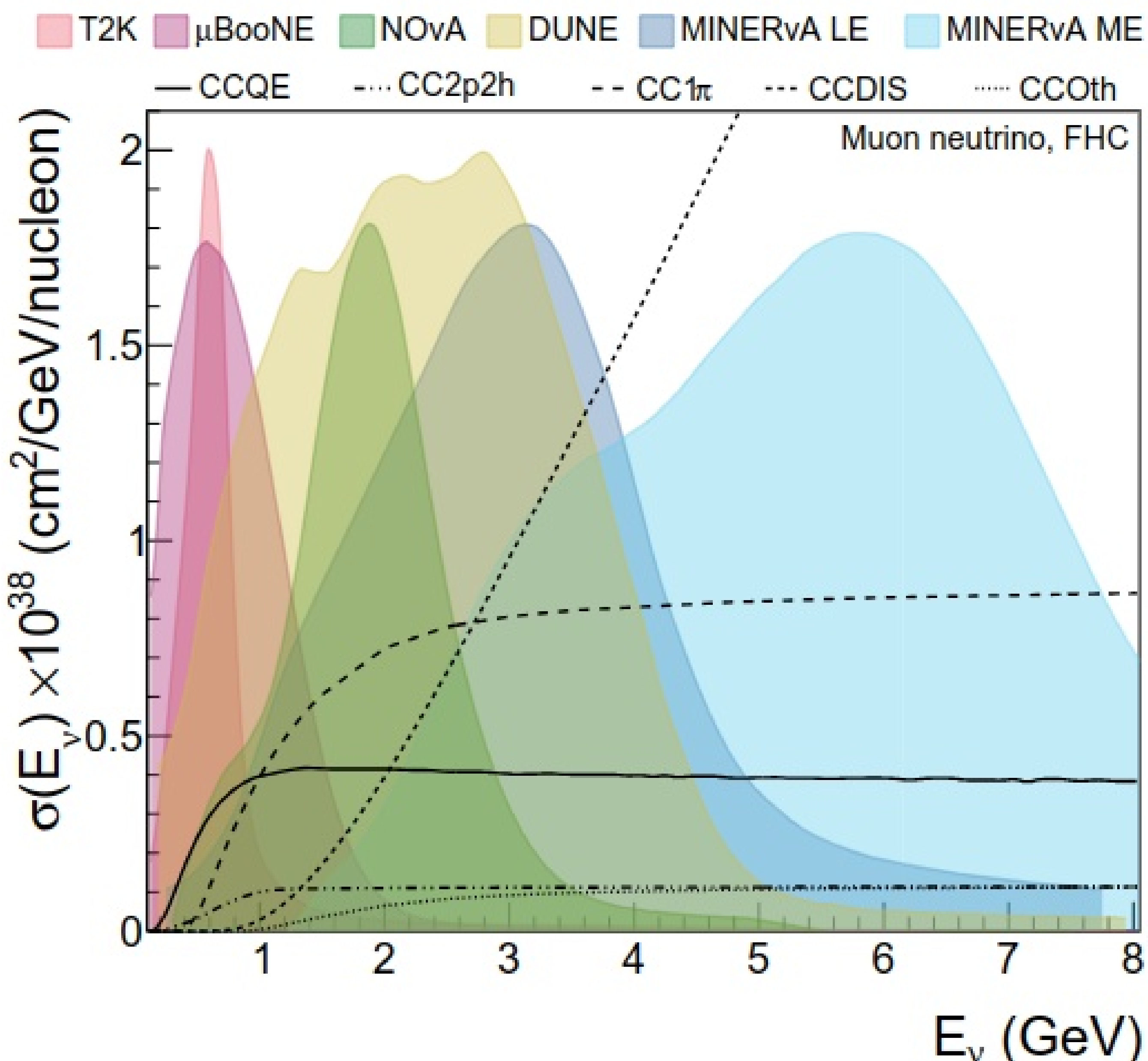


CCDIS (one diagram)



Neutrino fluxes from accelerators

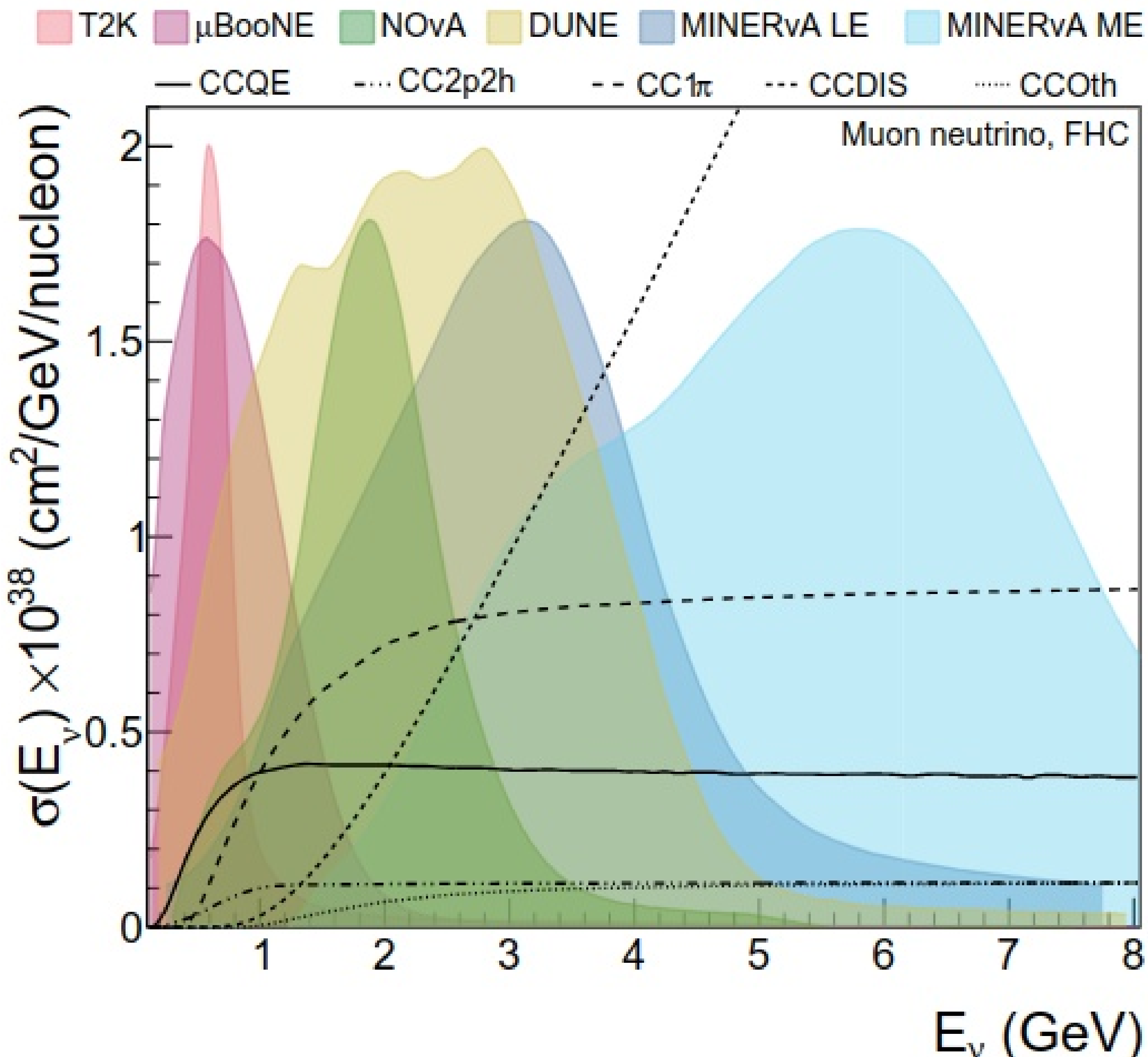
Which interactions do T2K need to worry about?



Neutrino fluxes from accelerators

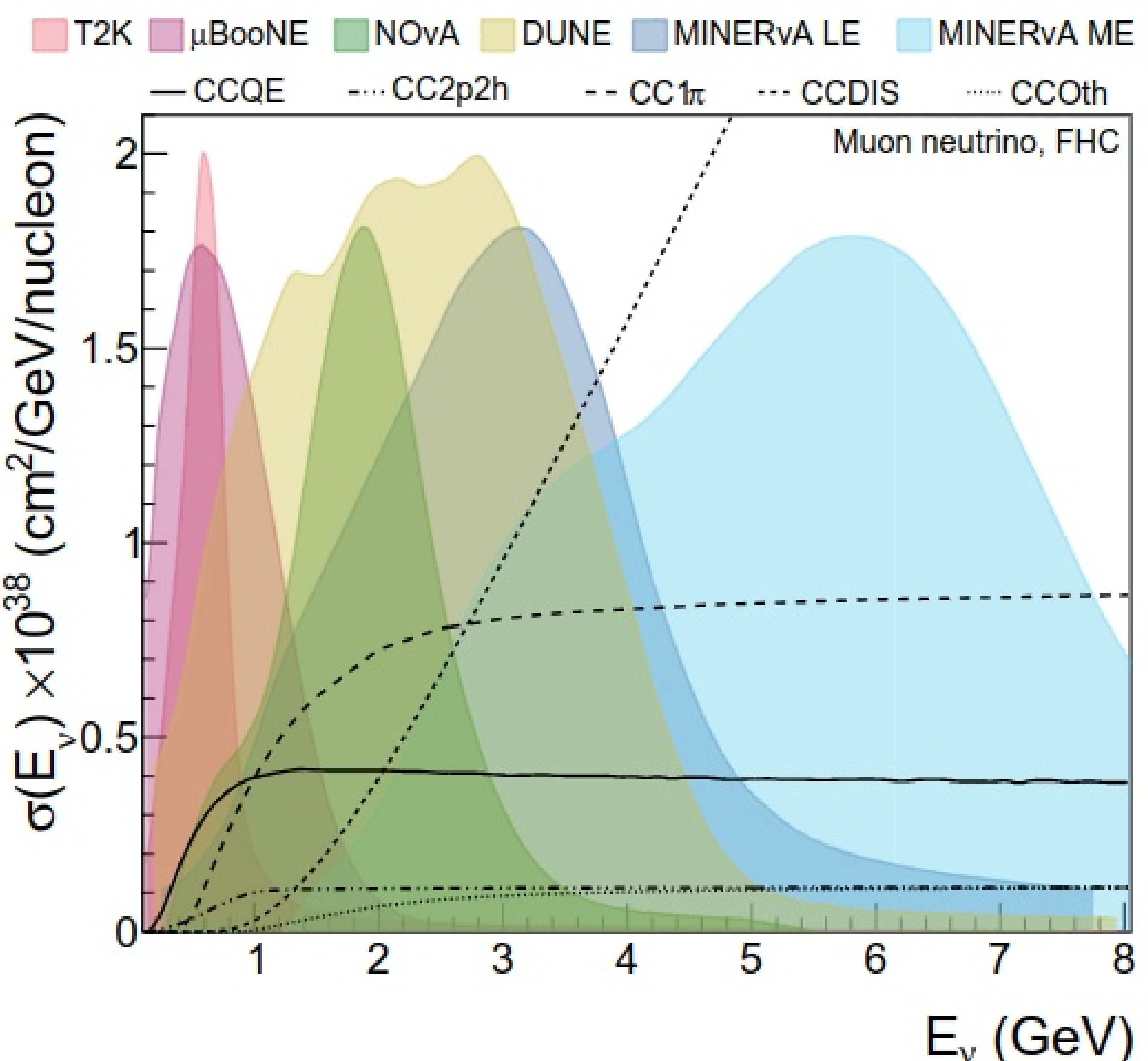
Which interactions do T2K need to worry about?

Are those shared with other experiments?

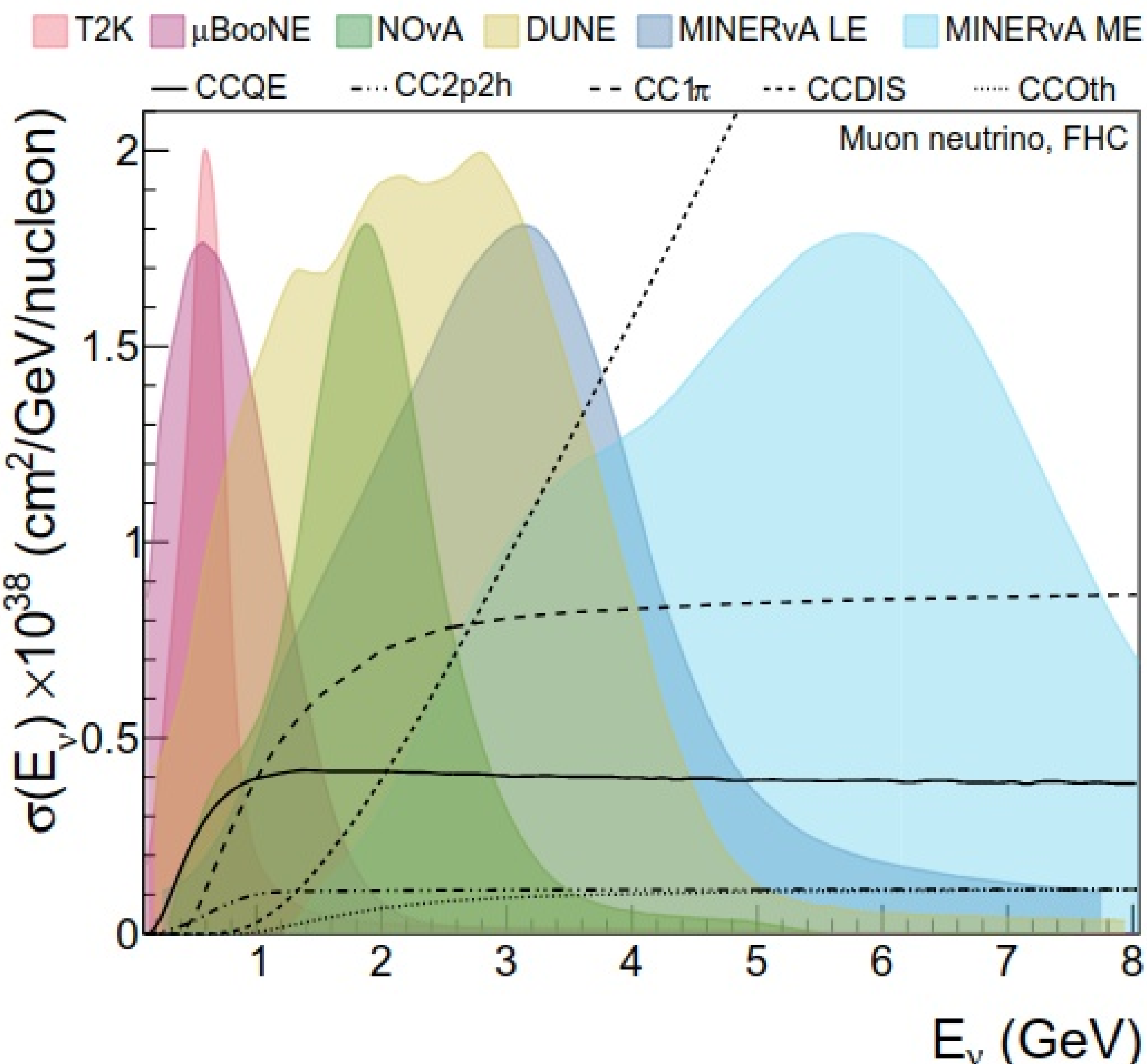


Neutrino fluxes from accelerators

What about NOvA?

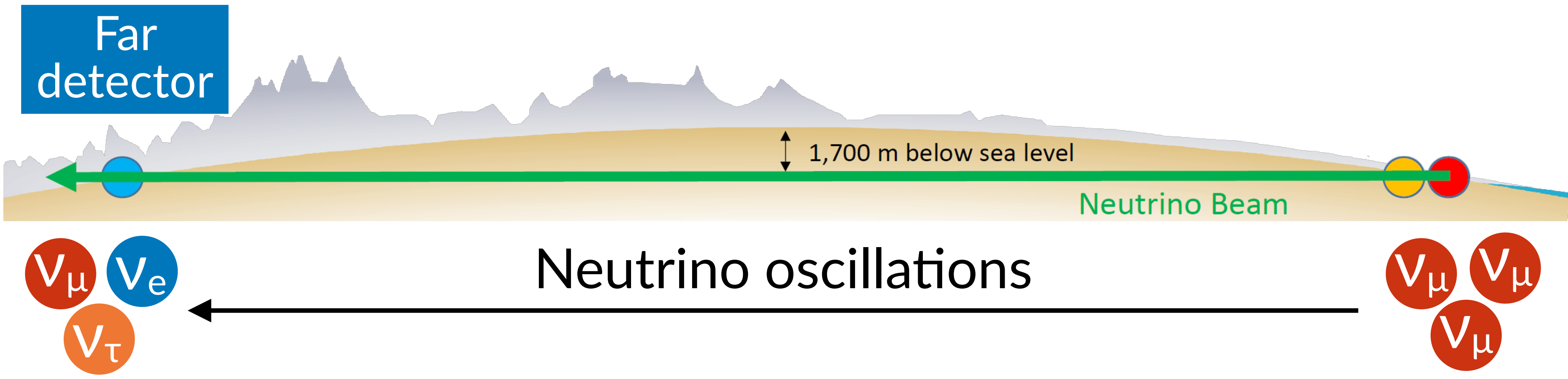


Neutrino fluxes from accelerators



And what about DUNE?

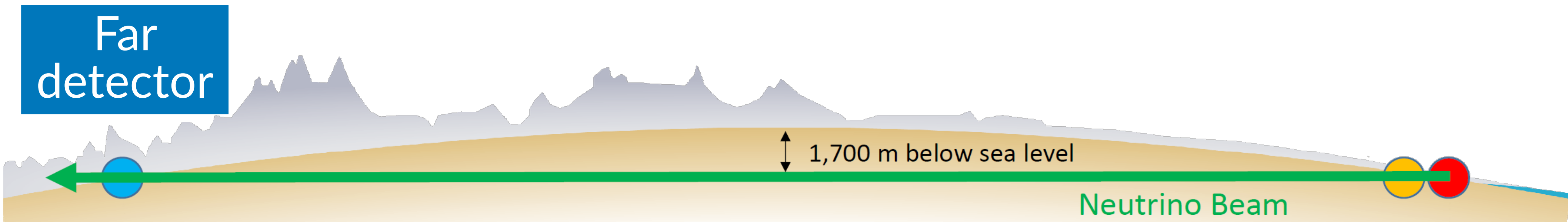
Observations at a far detector

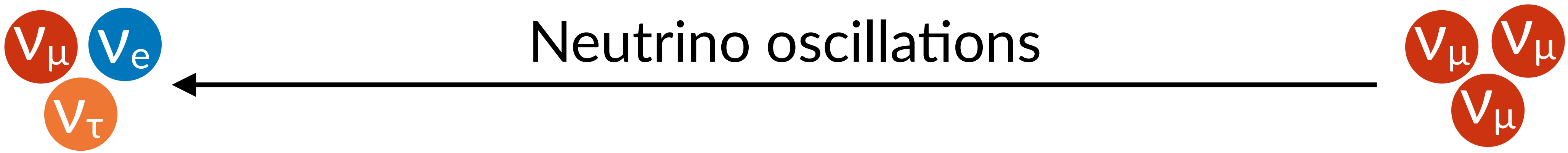


- Events observed at far detector depends on many factors

$$N^{\alpha}_{\mathrm{FD}}(\vec{x}) = P(\nu_\alpha \rightarrow \nu_\alpha) \times \Phi^{\alpha}(E_\nu) \times \sigma^{\alpha}(\vec{x}) \times \epsilon^{\alpha}_{\mathrm{FD}}(\vec{x})$$

Observations at a far detector





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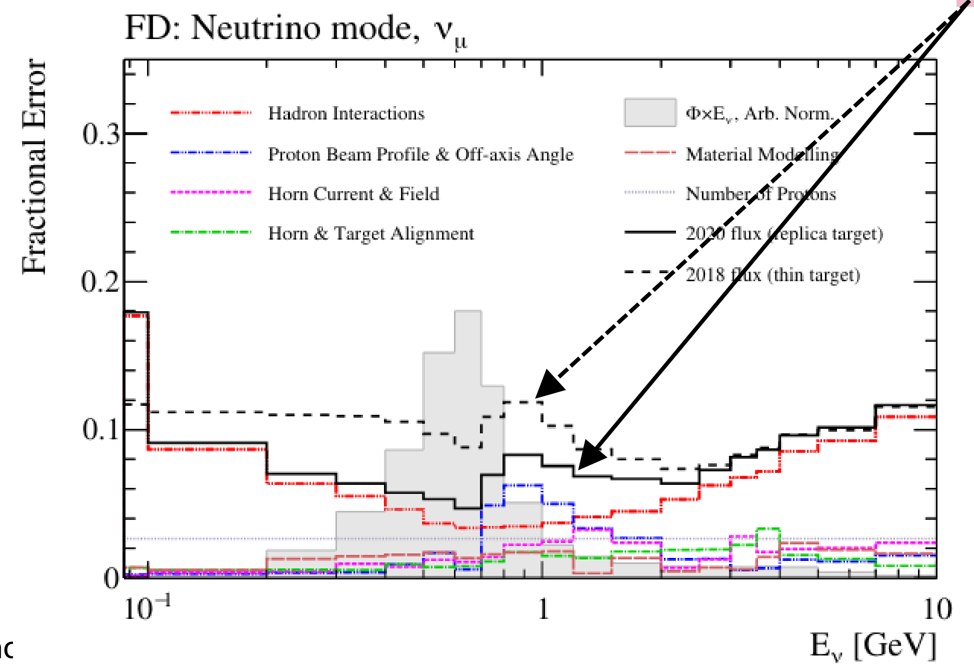

5-10% absolute uncertainties on the neutrino flux

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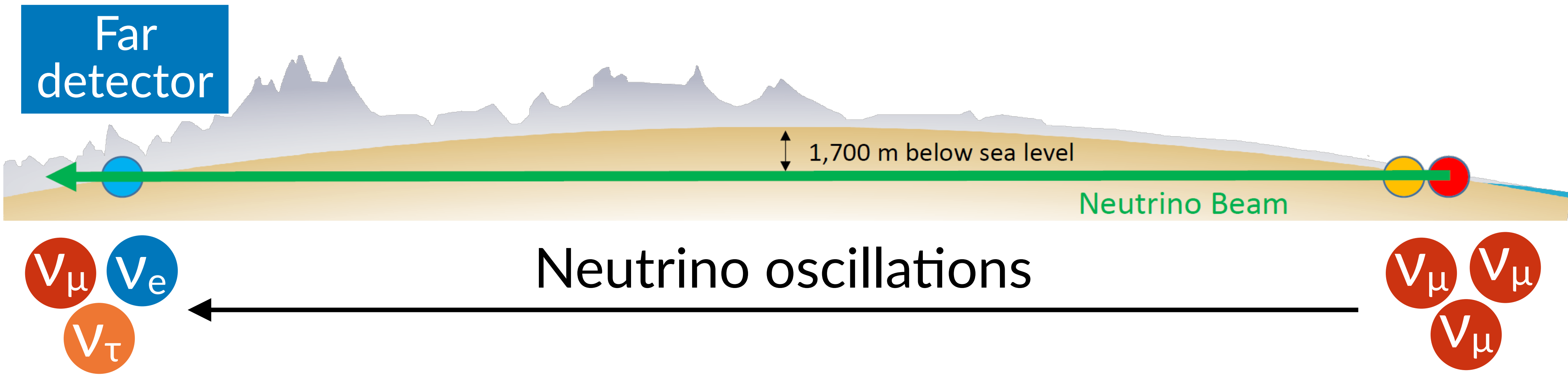
Observations at a far detector



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Sample	Interaction		
1Rμ	ν	3.1	(11.7)
	$\bar{\nu}$	3.0	(10.8)
1Re	ν	3.2	(12.6)
	$\bar{\nu}$	3.1	(11.1)
1Re1de	ν	4.2	(12.1)

Complicated energy-dependent and selection-dependent **cross-sections**

~10% uncertainties

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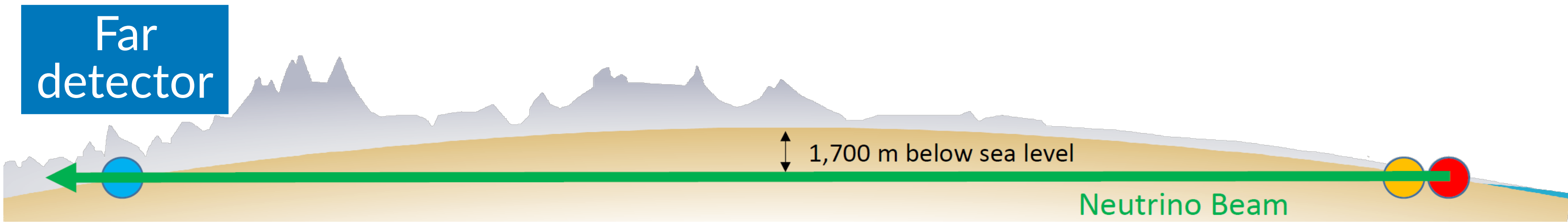
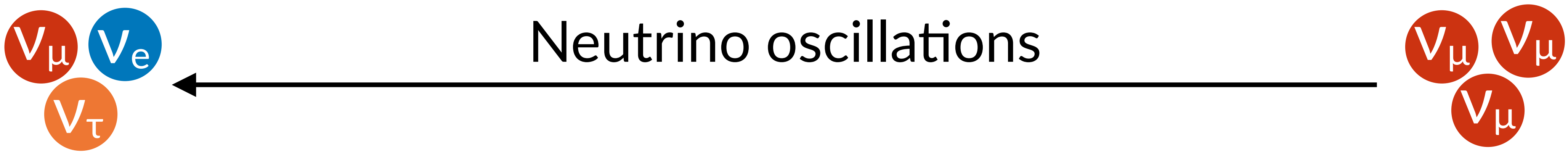
Observations at a far detector





- Events observed at far detector depends on many factors

$$N^{\alpha}_{\mathrm{FD}}(\vec{x}) = P(\nu_\alpha \rightarrow \nu_\alpha) \times \Phi^{\alpha}(E_\nu) \times \sigma^{\alpha}(\vec{x}) \times \epsilon^{\alpha}_{\mathrm{FD}}(\vec{x})$$

Sample		
1Rμ	ν	2.1 (2.7)
	$\bar{\nu}$	1.9 (2.3)
1Re	ν	3.1 (3.2)
	$\bar{\nu}$	3.9 (4.2)
1Re1de	ν	13.4 (13.4)

Particle acceptance may also depend on neutrino energy, and selection

3-15% uncertainty for T2K

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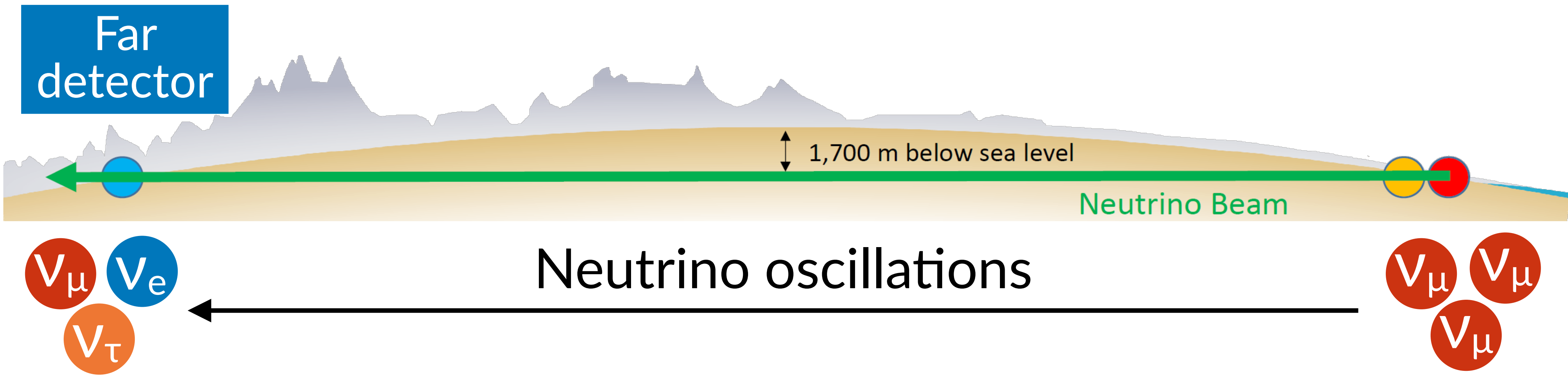
Observations at a far detector

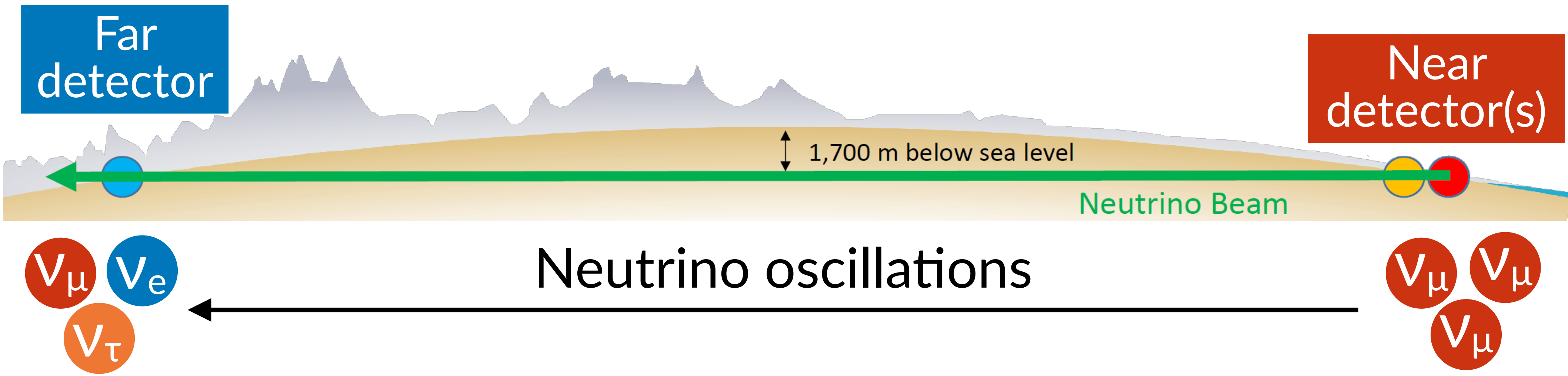


- Events observed at far detector depends on many factors

$$N_{\mathrm{FD}}^{\alpha}(\vec{x}) = P(\nu_\alpha \rightarrow \nu_\alpha) \times \Phi^{\alpha}(E_\nu) \times \sigma^{\alpha}(\vec{x}) \times \epsilon_{\mathrm{FD}}^{\alpha}(\vec{x})$$

- Difficult to accurately constraint **neutrino oscillations** with **many large uncertainties** getting in the way
  - Many effects **may mimic the oscillation signal**, especially if you only look at a single neutrino flavour

The near detector

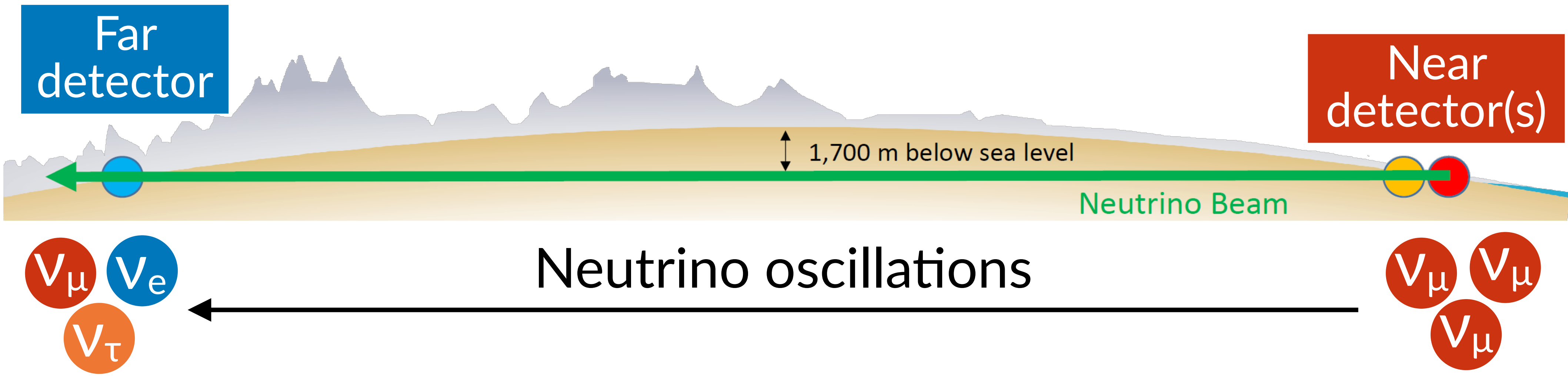


- But what if you have a **near detector**?

$$N^{\alpha}_{\mathrm{FD}}(\vec{x}) = P(\nu_\alpha \rightarrow \nu_\alpha) \times \Phi^{\alpha}(E_\nu) \times \sigma^{\alpha}(\vec{x}) \times \epsilon^{\alpha}_{\mathrm{FD}}(\vec{x})$$

$$N^{\alpha}_{\mathrm{ND}}(\vec{x}) = \Phi^{\alpha}(E_\nu) \times \sigma^{\alpha}(\vec{x}) \times \epsilon^{\alpha}_{\mathrm{ND}}(\vec{x})$$

The near detector



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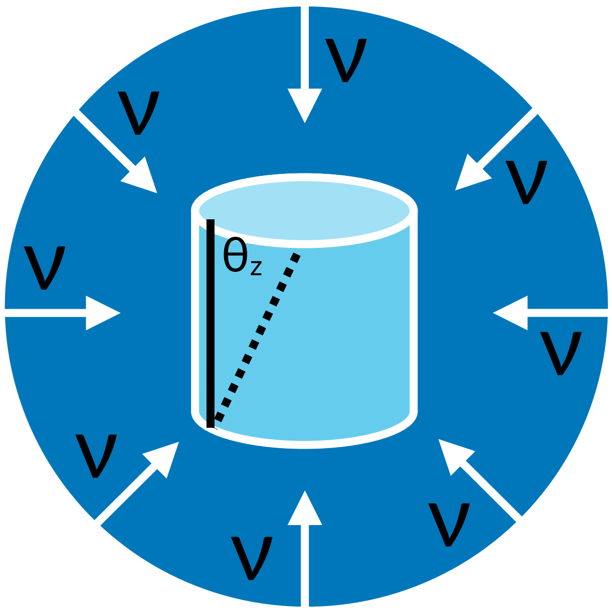
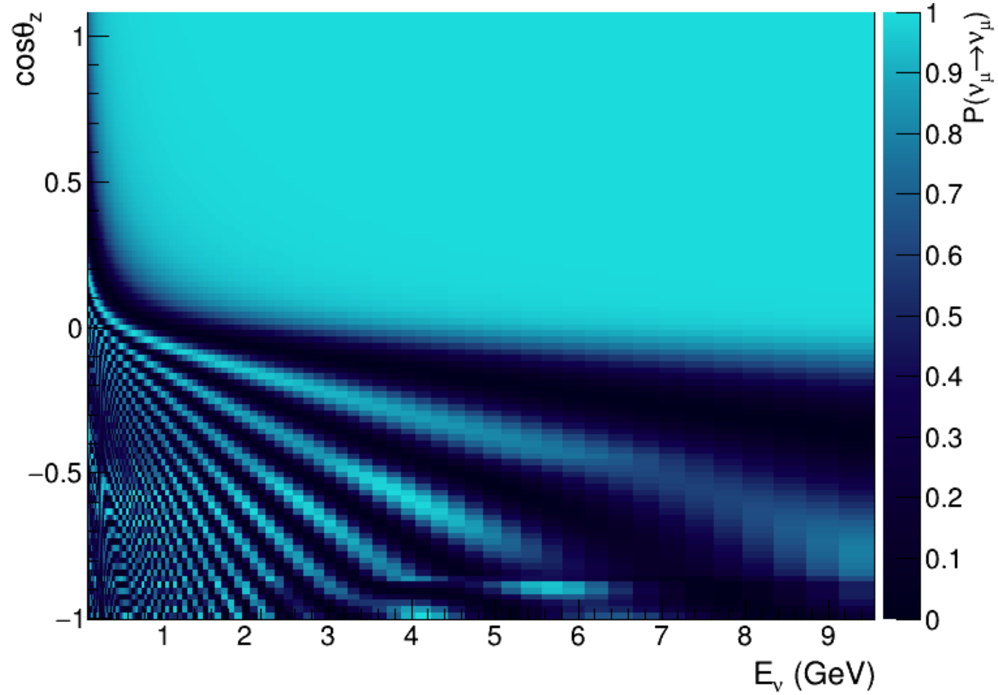
$$N^{\alpha}_{\mathrm{ND}}(\vec{x}) = \Phi^{\alpha}(E_\nu) \times \sigma^{\alpha}(\vec{x}) \times \epsilon^{\alpha}_{\mathrm{ND}}(\vec{x})$$

- Events observed at the far detector have many **shared uncertainties** with the near detector
  - Constrain **flux and interaction model** using near detector data
- **Characterise neutrinos** with **high-statistics near-detector samples** before long baseline oscillations
- **Mitigates many of the issues**, e.g. size of cross sections, flux normalisation...

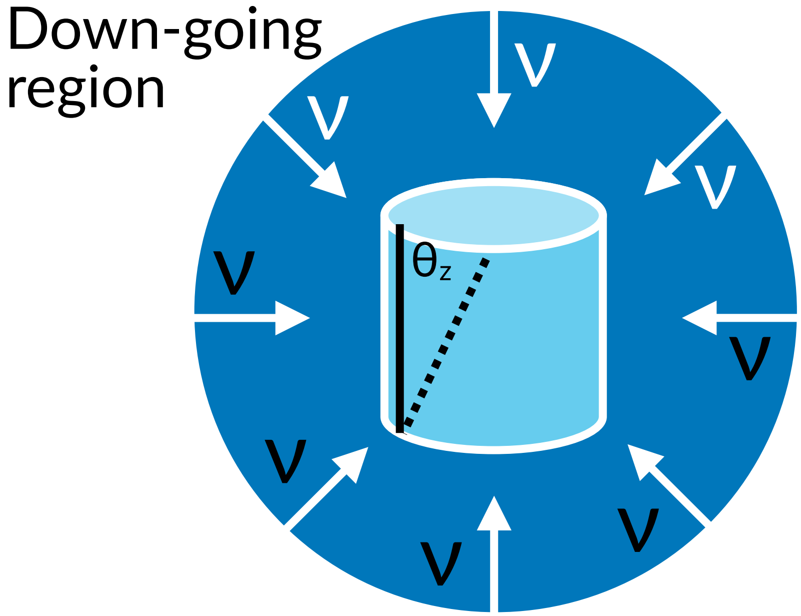
Aside: atmospheric near detector?

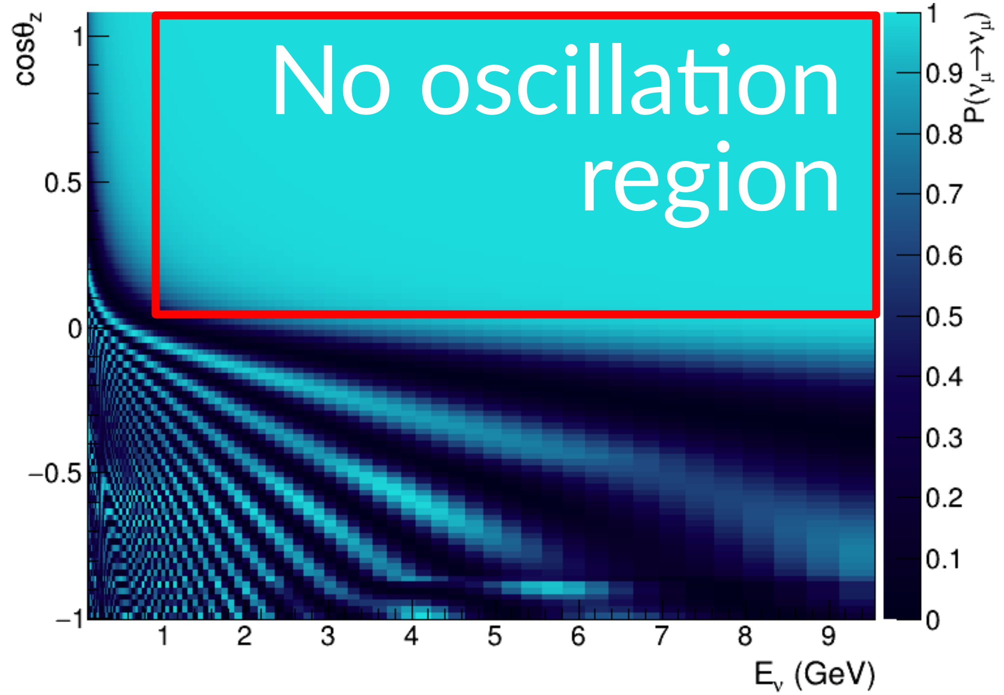




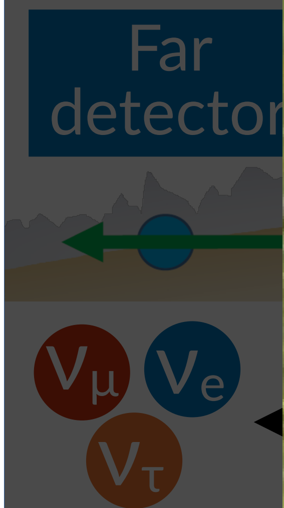
- For **atmospheric** neutrinos, **there is no near detector**

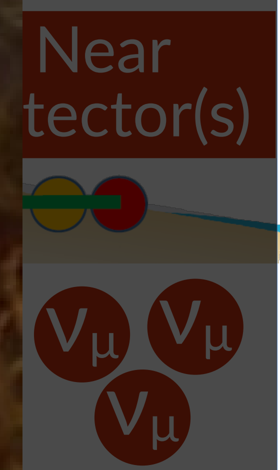
Aside: atmospheric near detector?





- For **atmospheric** neutrinos, **there is no near detector**
- Largely addressed by **down-going neutrinos**
  - Very small oscillation probability in region
  - **Effectively acts as a near-detector** constraint throughout a large neutrino energy range





- But wh

N

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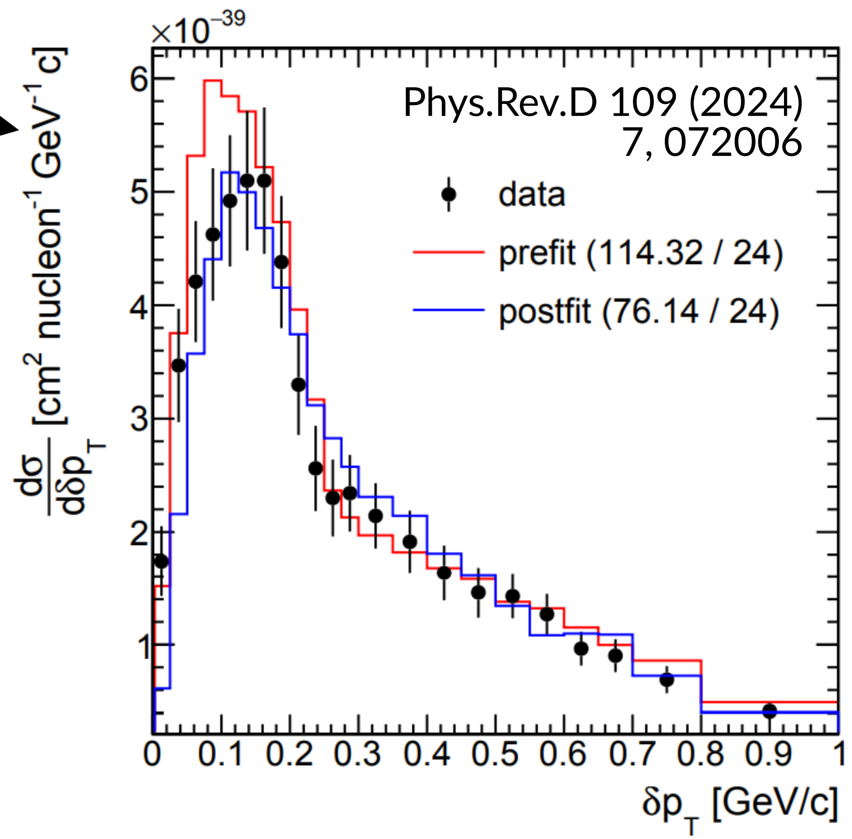
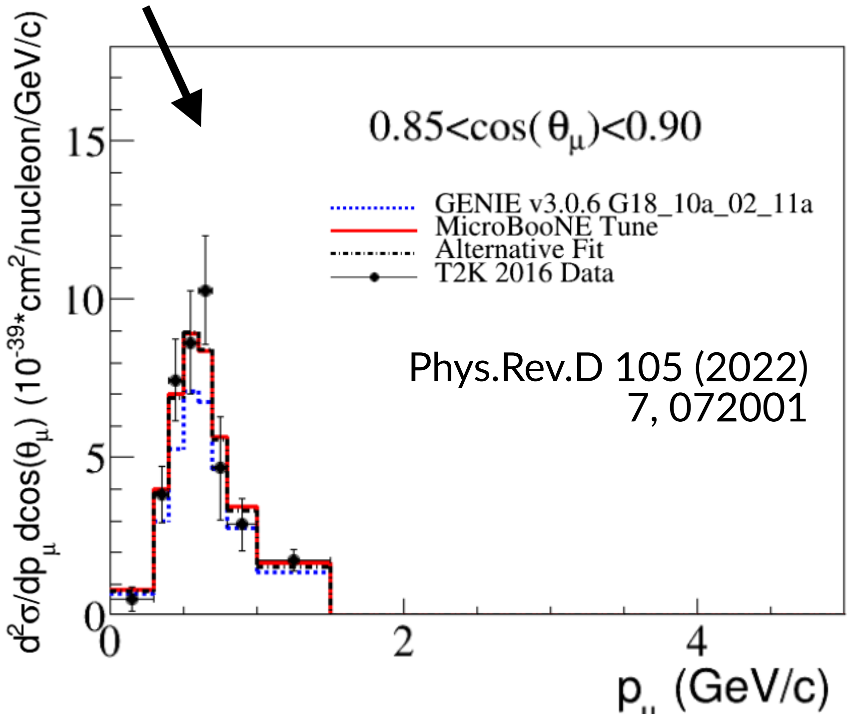
- Events ... with the near de
  - Co
- **Mitiga** ... sation...

Role of external data

- You might not have a near detector; what do you do?
- Or in some cases, data from the **near detector might not suffice**
  - e.g. you have an unmagnetised detector, but want to estimate NC1π^+ contribution to the background in ν_μ disappearance
- **External data** is often used to estimate **the cross section**, and prevent a **near-detector analysis from over-constraining** the model
  - T2K using MINERvA data
  - MicroBooNE using T2K data

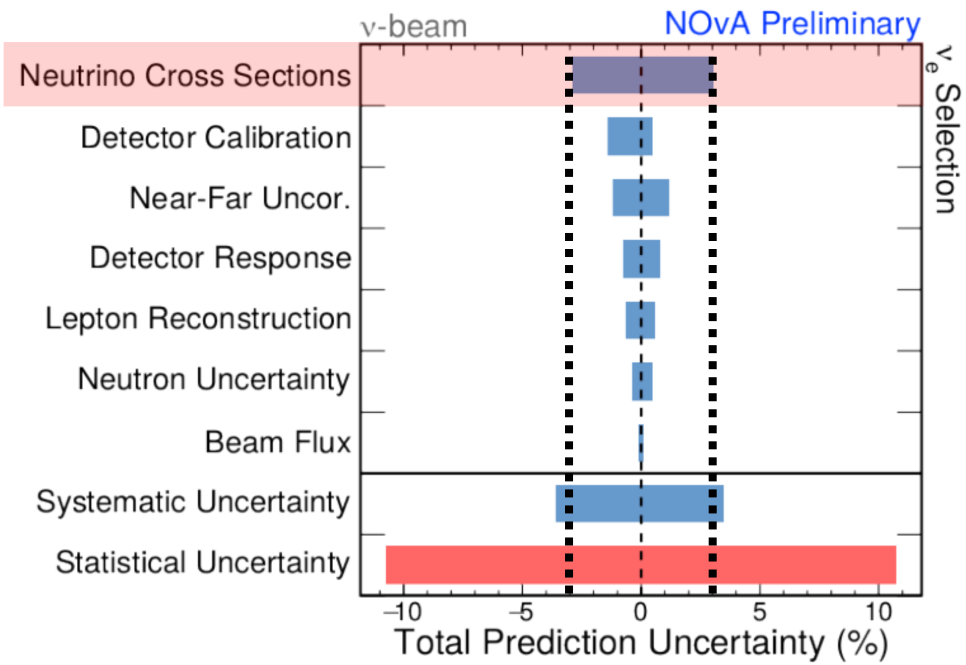




Impact of systematics at the FD

- Neutrino **cross-section uncertainties** contribute **~3%** to number of ν_e on **NOvA**

M. Elkins, T. Nosek, Neutrino 2020 poster



  - Dominant systematic amongst all systematics
  - But measurement significantly limited by statistics currently

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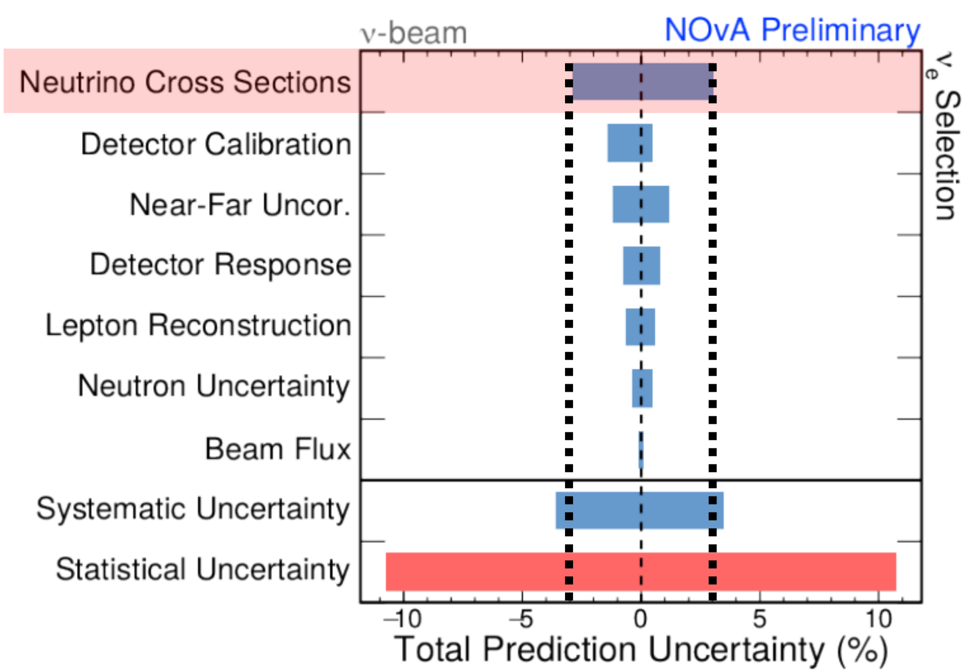

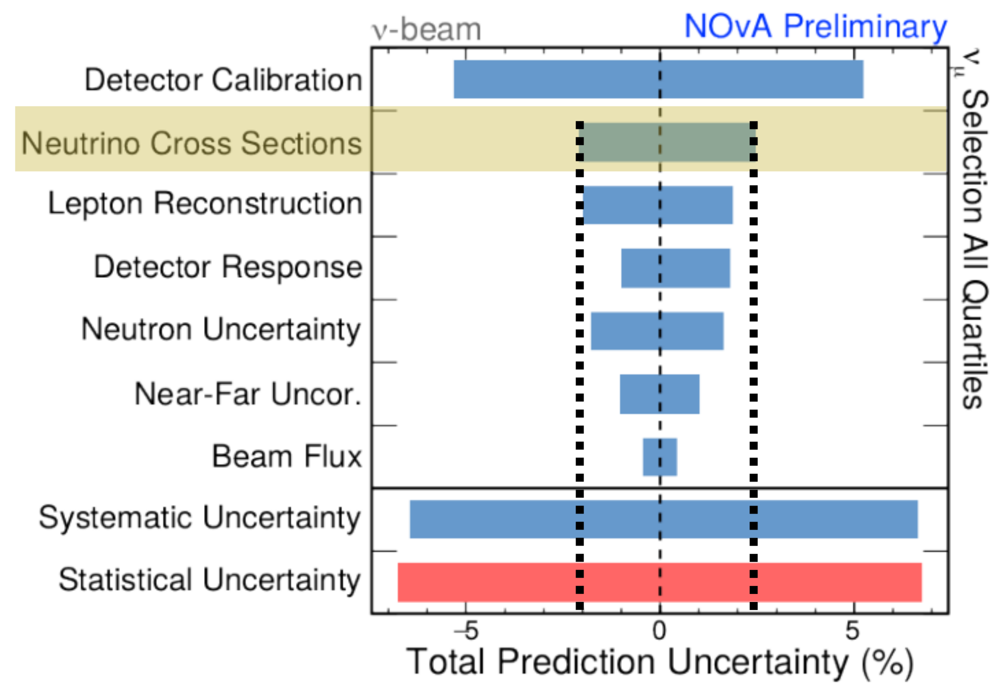

  - Dominant systematic amongst all systematics
  - But measurement significantly limited by statistics currently
- ν_μ roughly same systematic and statistical uncertainty!
  - Dominated by detector calibrations, followed by cross sections (~2% level)

Impact of systematics at the FD

- On **T2K**, cross-section uncertainties contribute **~3%** to $\boldsymbol{\nu_\mu}$ systematic uncertainty
  - In practice, slightly smaller because ND constrains convolution of flux * cross-section parameters

Sample		Uncertainty source (%) Flux	Interaction	FD + SI + PN	Flux⊗Interaction (%)	Total (%)
1Rμ	ν	2.9 (5.0)	3.1 (11.7)	2.1 (2.7)	2.2 (12.7)	3.0 (13.0)
	$\bar{\nu}$	2.8 (4.7)	3.0 (10.8)	1.9 (2.3)	3.4 (11.8)	4.0 (12.0)

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	$\bar{\nu}$	2.8 (4.7)	3.0 (10.8)	1.9 (2.3)	3.4 (11.8)	4.0 (12.0)
1Re	ν	2.8 (4.8)	3.2 (12.6)	3.1 (3.2)	3.6 (13.5)	4.7 (13.8)
	$\bar{\nu}$	2.9 (4.7)	3.1 (11.1)	3.9 (4.2)	4.3 (12.1)	5.9 (12.7)
1Re1de	ν	2.8 (4.9)	4.2 (12.1)	13.4 (13.4)	5.0 (13.1)	14.3 (18.7)

- ν_e samples see 3-5% contribution to the 5-14% total
  - Detector systematics on-par with cross-section systematics
  - Small statistics means current measurements not limited by systematics

- But… we'll come back to this later with "fake-data studies"

Event counts at the FDs

Sample	T2K	NOvA
N_μ^{rec} FHC	318	211
N_μ^{rec} RHC	137	105
N_e^{rec} FHC	108	82
N_e^{rec} RHC	16	33

- ν_e measurements, especially in RHC, are heavily limited by statistics in current experiments
  - ~10-25%
- ν_μ measurements at the ~5% statistics level

Event counts at the FDs

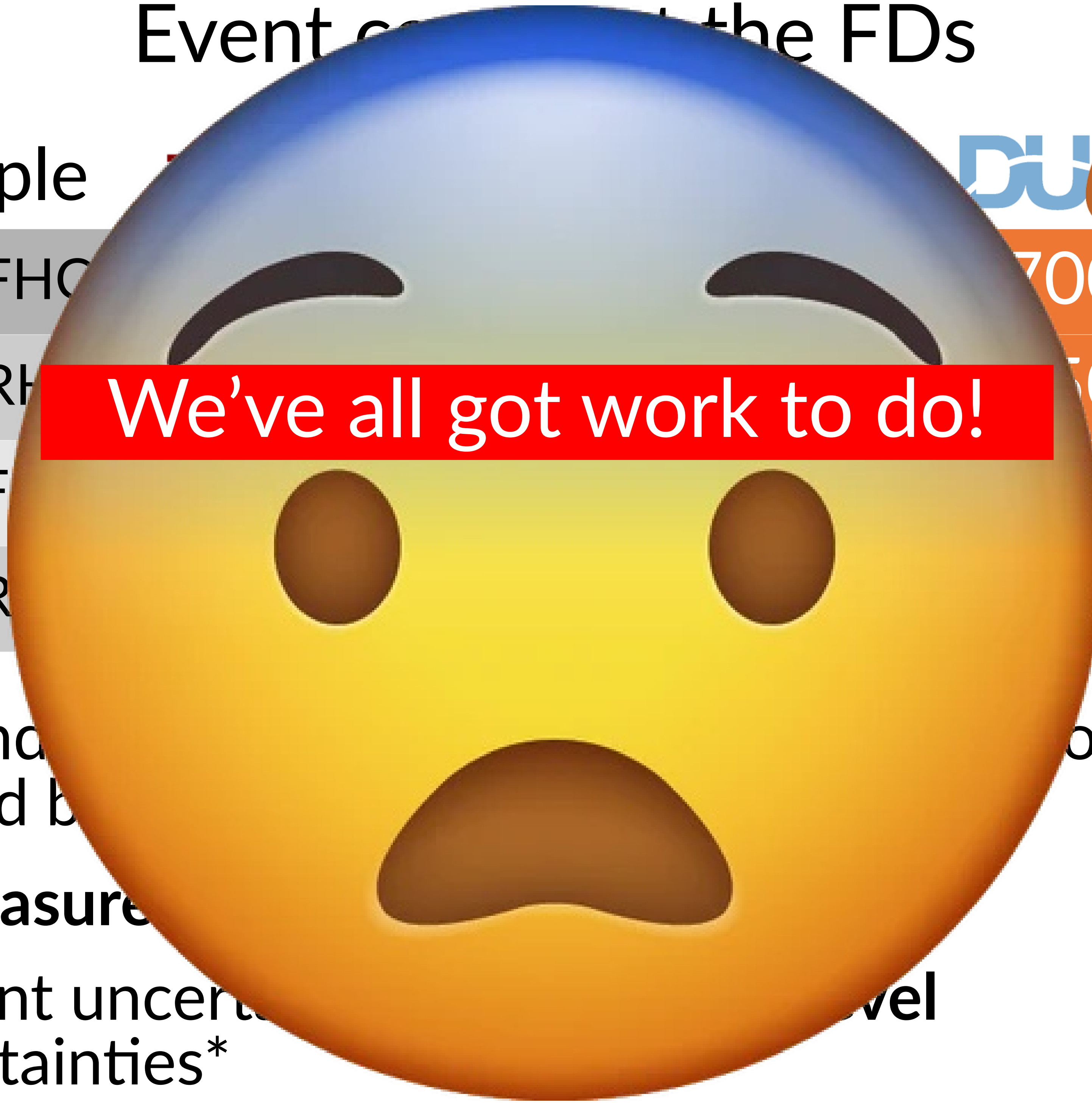
Sample	T2K	NOvA	Hyper-Kamiokande	DUNE
N_μ^{rec} FHC	318	211	10000	7000
N_μ^{rec} RHC	137	105	14000	3500
N_e^{rec} FHC	108	82	3000	1500
N_e^{rec} RHC	16	33	3000	500

- HK and DUNE will have **enough ν_e events** to be limited by the **~3% (anti-)ν_e uncertainty**
- **ν_μ measurements on the 1% scale**
- Current uncertainties at the **3-5% level** uncertainties*

*Exception of T2K's single-pion-below-threshold sample (10-15%)

Event c… the FDs

Sample		DUNE
N_{μ}^{rec} FHC		7000
N_{μ}^{rec} RH		500
N_{e}^{rec} F		00
N_{e}^{rec} R		0

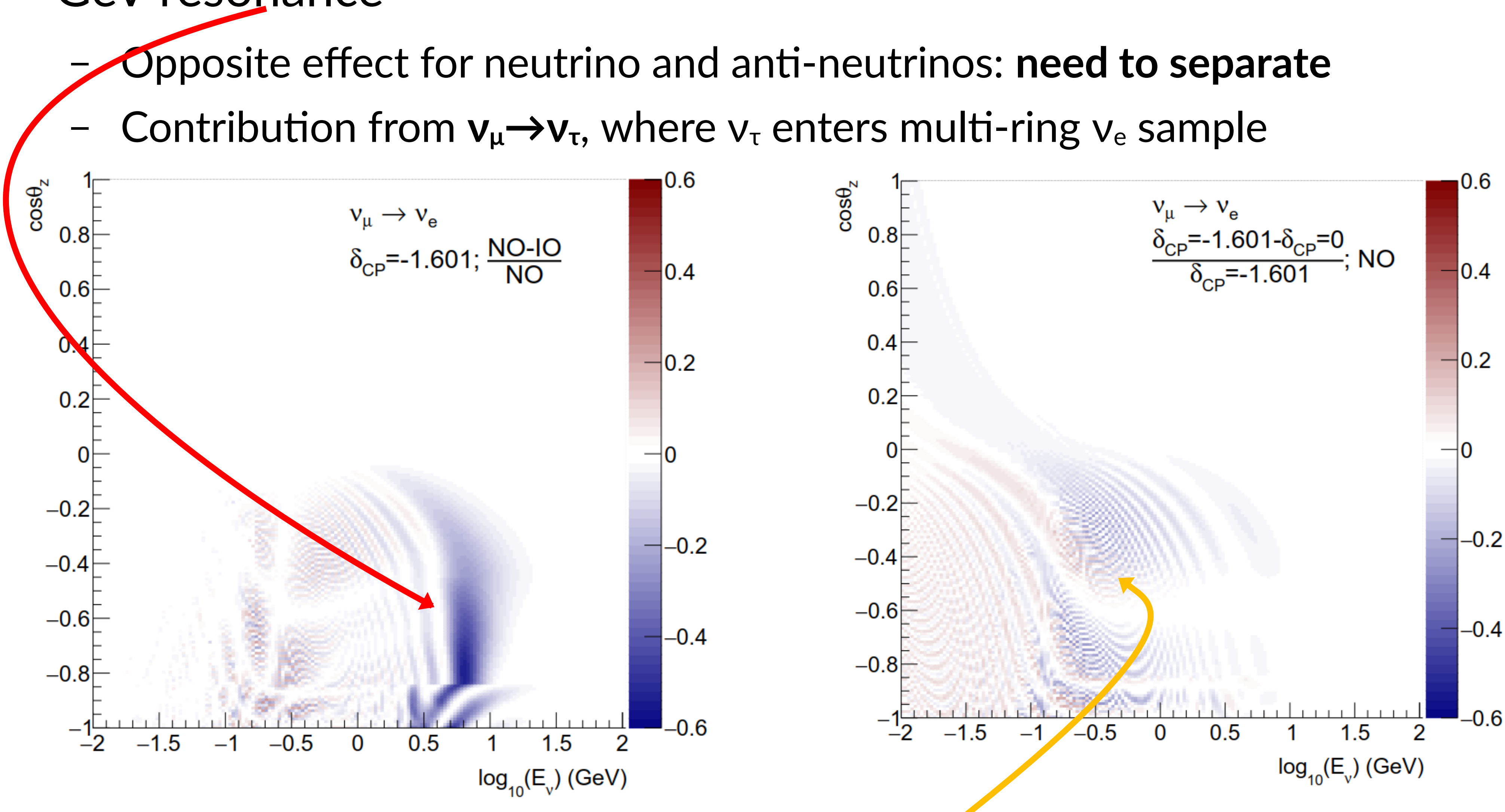


- HK and … o be limited b…
- **ν_{μ} measure…**
- Current uncert… **vel** uncertainties*

*Exception of T2K's single-pion-below-threshold sample (10-15%)

Atmospheric neutrinos

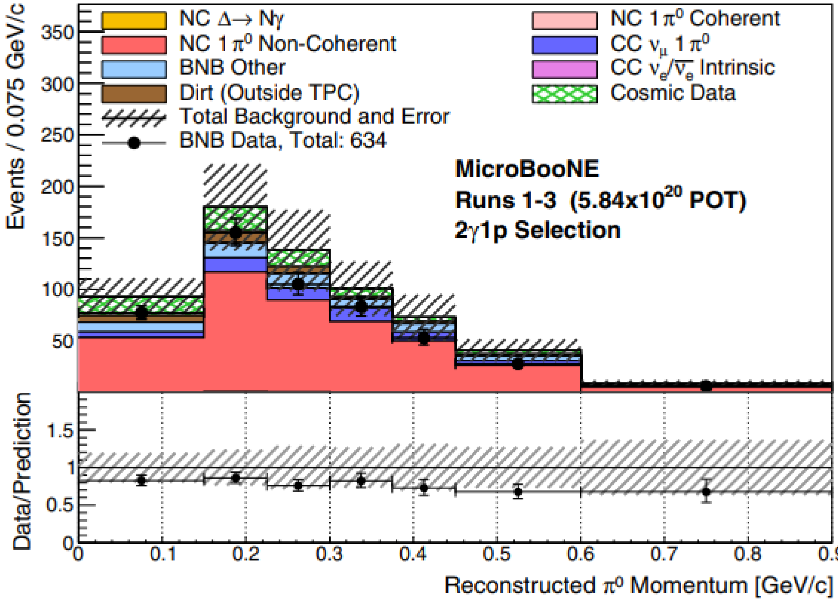
- Atmospheric neutrinos have sensitivity to mass ordering via 3-10 GeV resonance
  - Opposite effect for neutrino and anti-neutrinos: **need to separate**
  - Contribution from $\boldsymbol{\nu_\mu \to \nu_\tau}$, where ν_τ enters multi-ring ν_e sample



- δ_{CP} sensitivity from ν_e below 1 GeV → ν_e/ν_μ important
- **Neutrino flavour differences** also limiting atmospheric results

SBN

- For SBN programme and appearance searches, anything mimicking ν_e appearance is important
  - e.g. NC1γ, NC1π^0 DIS, NC1π^0 resonant, NC1π^0 coherent
  - Many constrained by dedicated measurements and sidebands



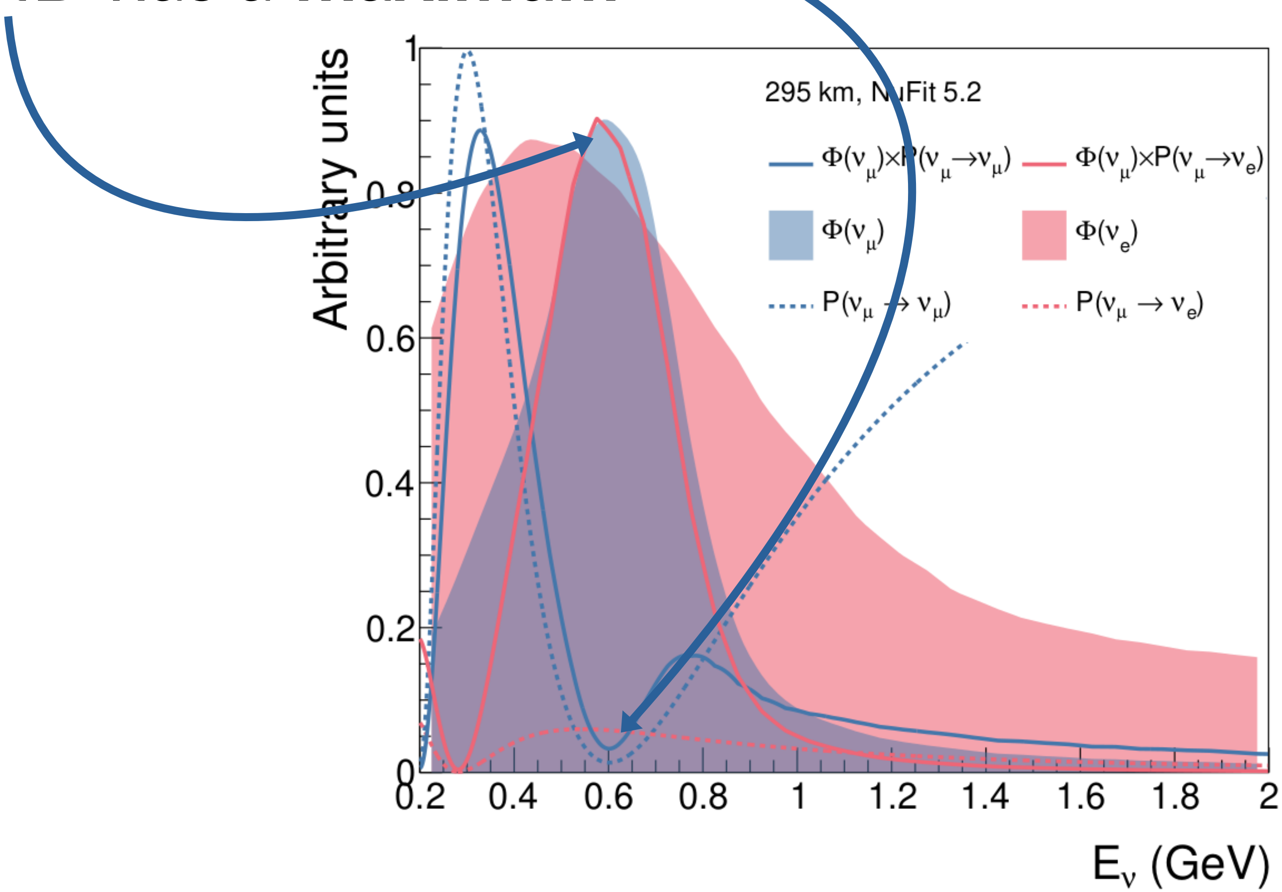
Phys. Rev. Lett. 128, 111801

- ν_e/ν_μ differences from nucleon and nuclear environment, especially considering ^{40}Ar
- Calorimetric energy reconstruction (see later)

Where does the model dependence enter?

Issues with the near detector

- The ν_μ **flux** at the **FD** has a **minimum** where the ν_μ **flux** at the **ND** has a **maximum**



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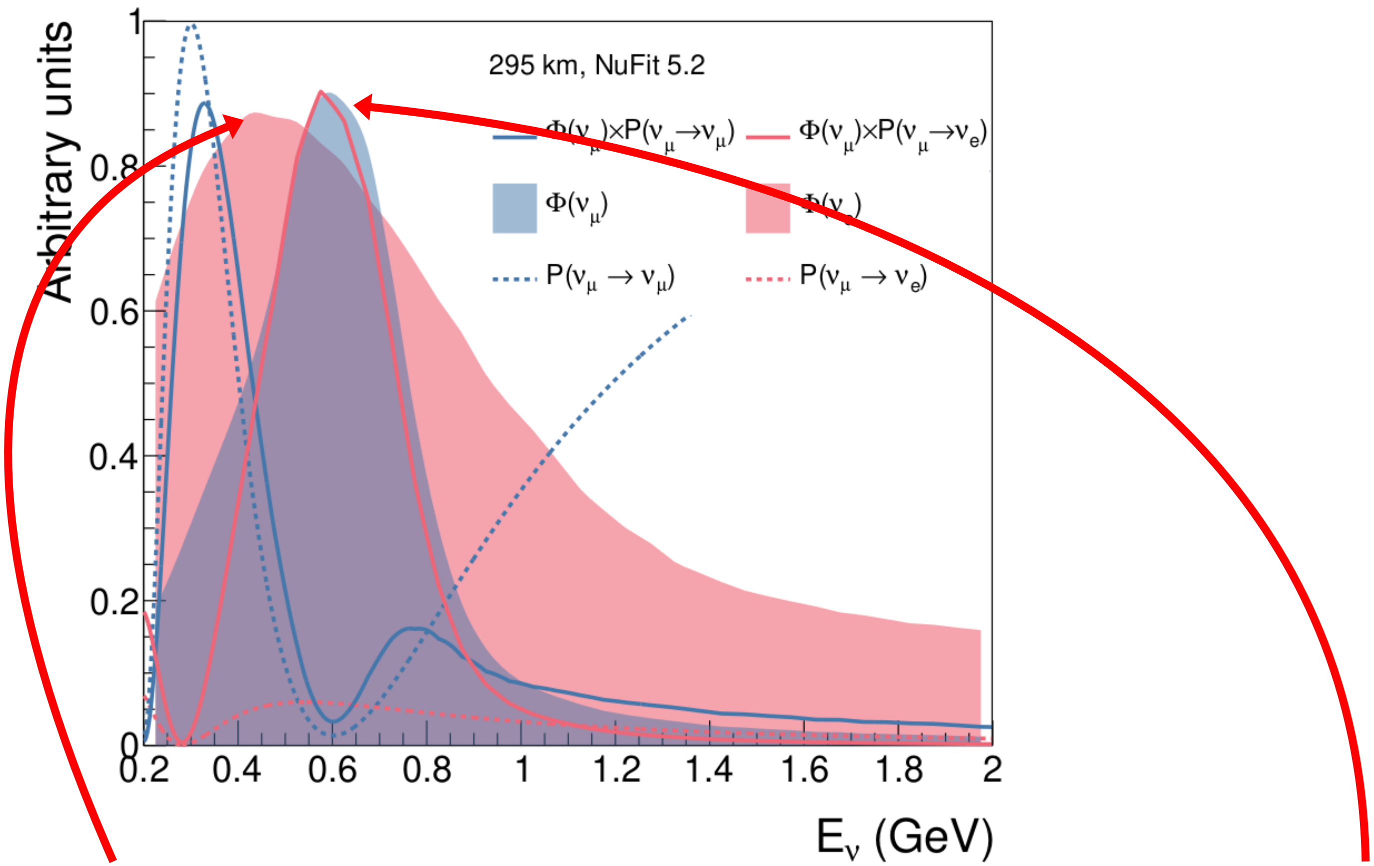

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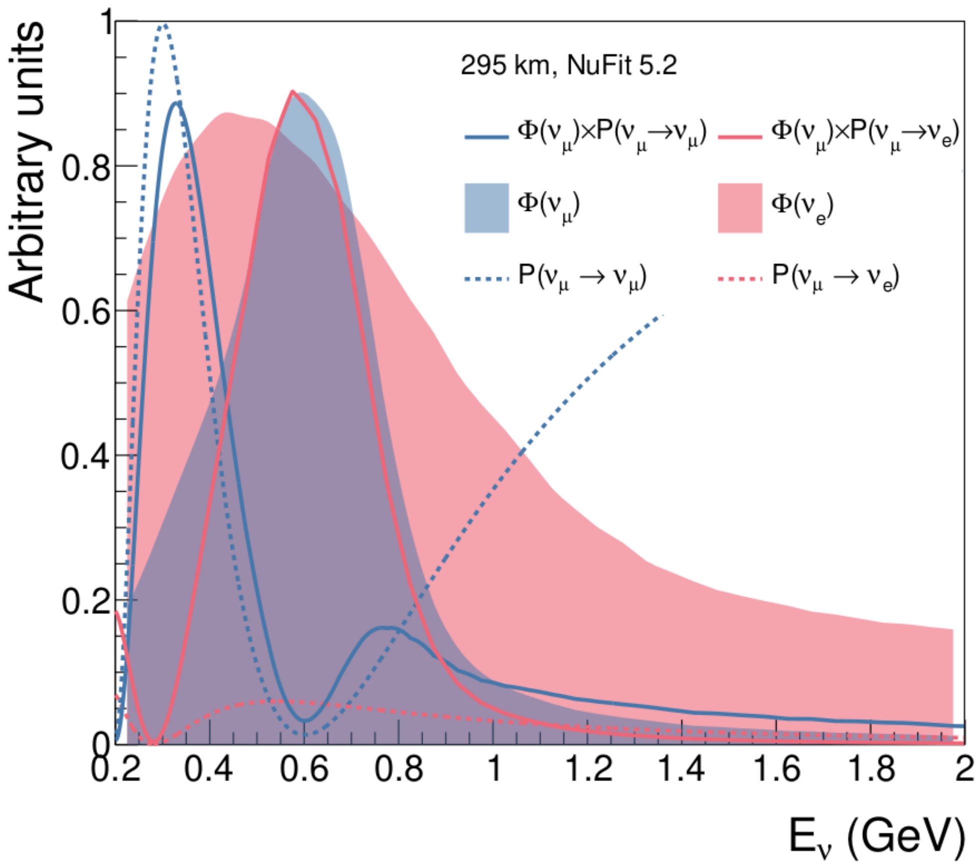

- Similarly, the ν_e **flux** at the ND does not match the ν_e **from** $\nu_\mu \rightarrow \nu_e$ **oscillations**
- **<u>Rely on model for extrapolating effects in neutrino energy</u>**, and **<u>ν_e at ND can't necessarily predict ν_e signal at FD</u>**

Electron/muon neutrino differences

- Appearing ν_e have different energy spectrum to ν_e at near detector

Electron/muon neutrino differences

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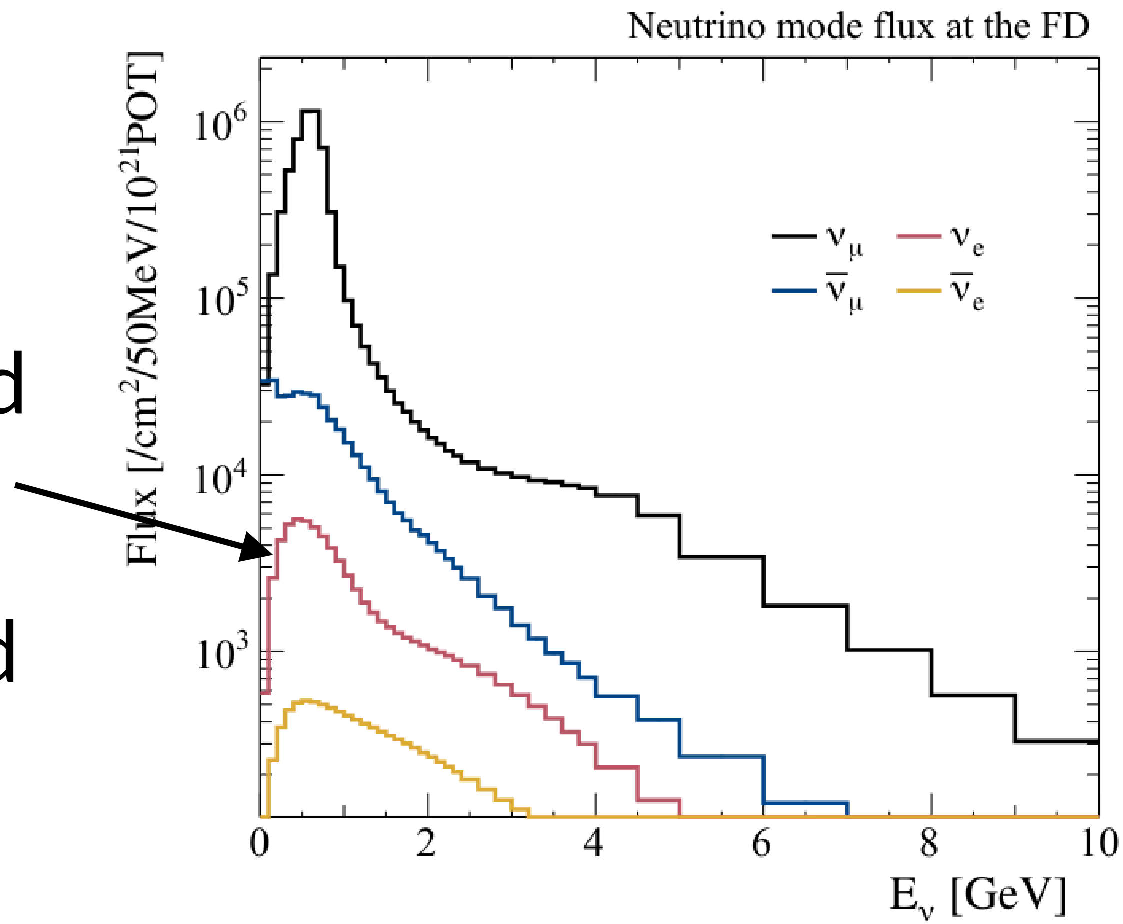
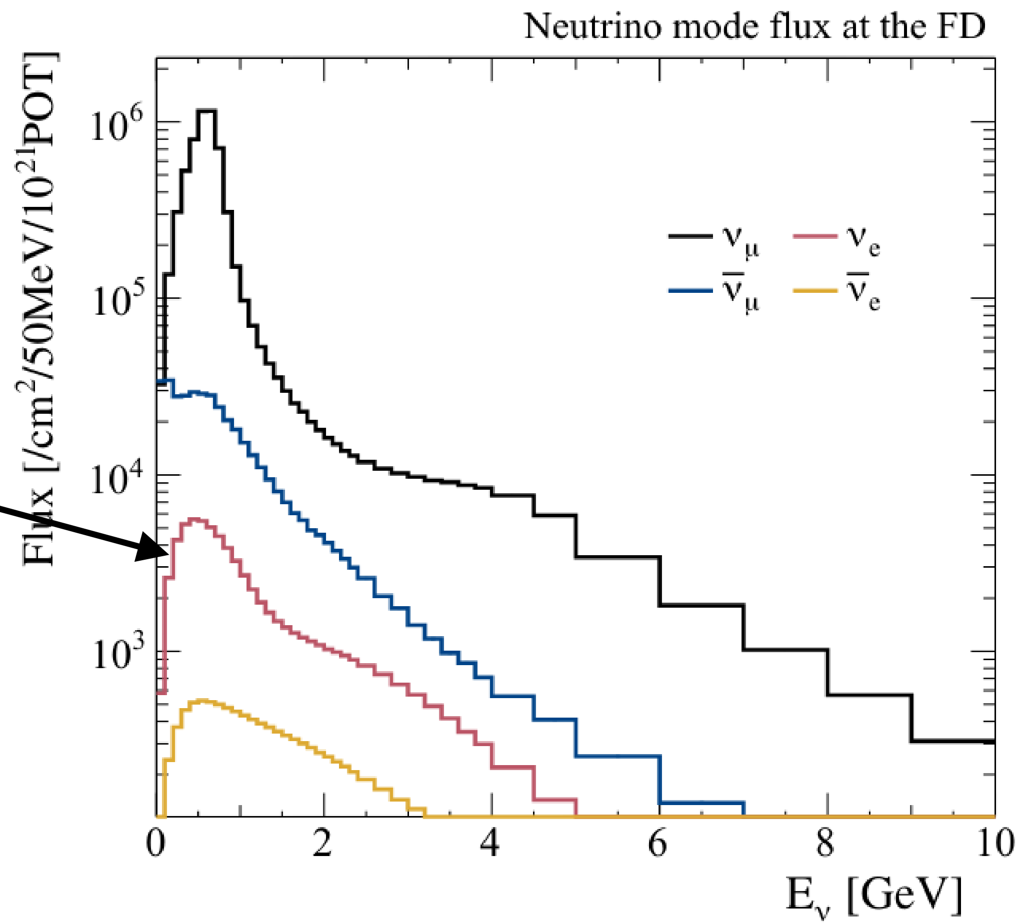
- ν_e at near detector used to understand **intrinsic** ν_e component in beam (irreducible background ν_e appearance)



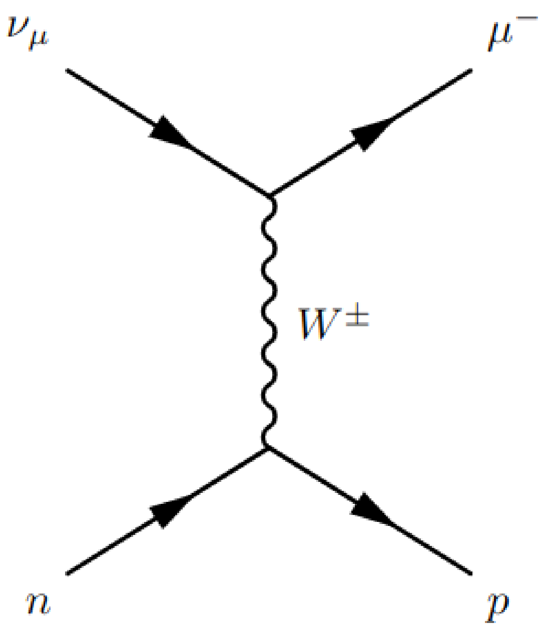
Electron/muon neutrino differences

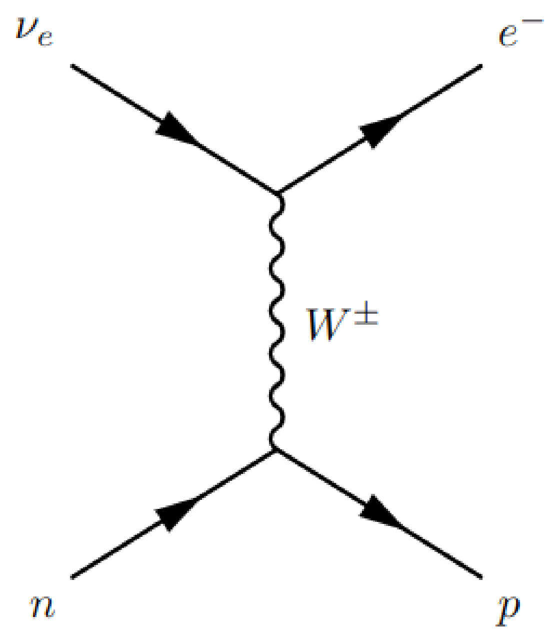
- Appearing ν_e have different energy spectrum to ν_e at near detector
- ν_e at near detector used to understand **intrinsic** ν_e component in beam (irreducible background ν_e appearance)
- ν_μ at near detector to constrain appearing ν_e (~same flux): **explicit dependence on muon-to-electron mapping**



Electron/muon neutrino differences

- On the nucleon-level, pretty simple?





Day, McFarland: Phys.Rev.D 86 (2012) 053003

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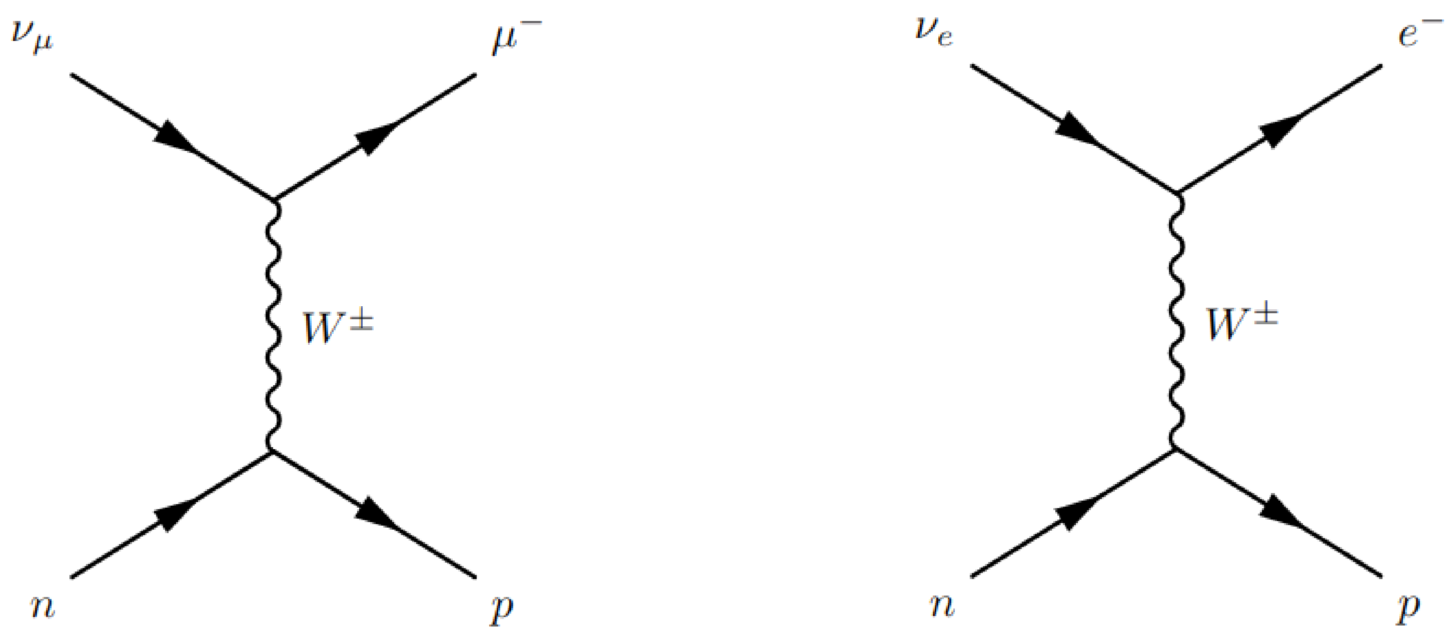

- Account for **lighter lepton mass**

Day, McFarland: Phys.Rev.D 86 (2012) 053003

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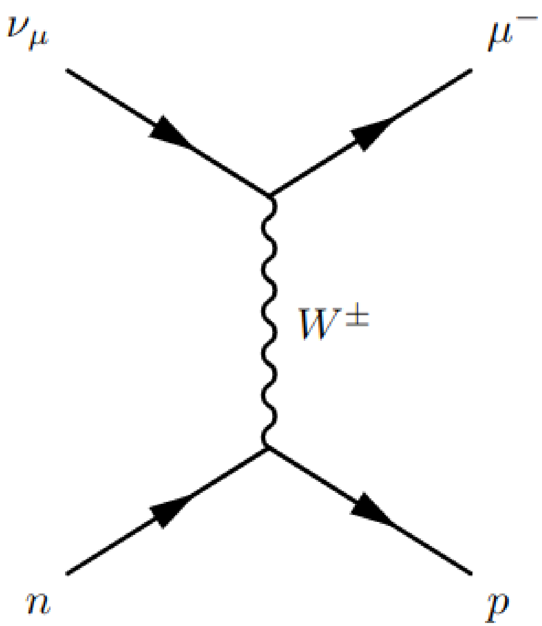

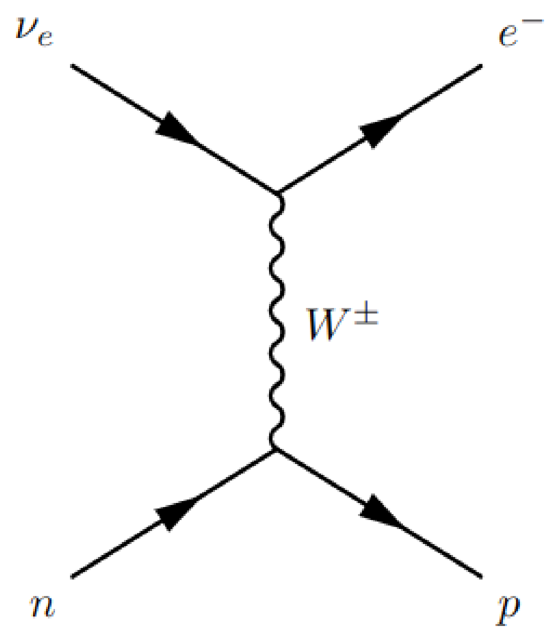

- Account for lighter lepton mass
- Maybe some **Coulomb repulsion**, shifts energy by ~MeV

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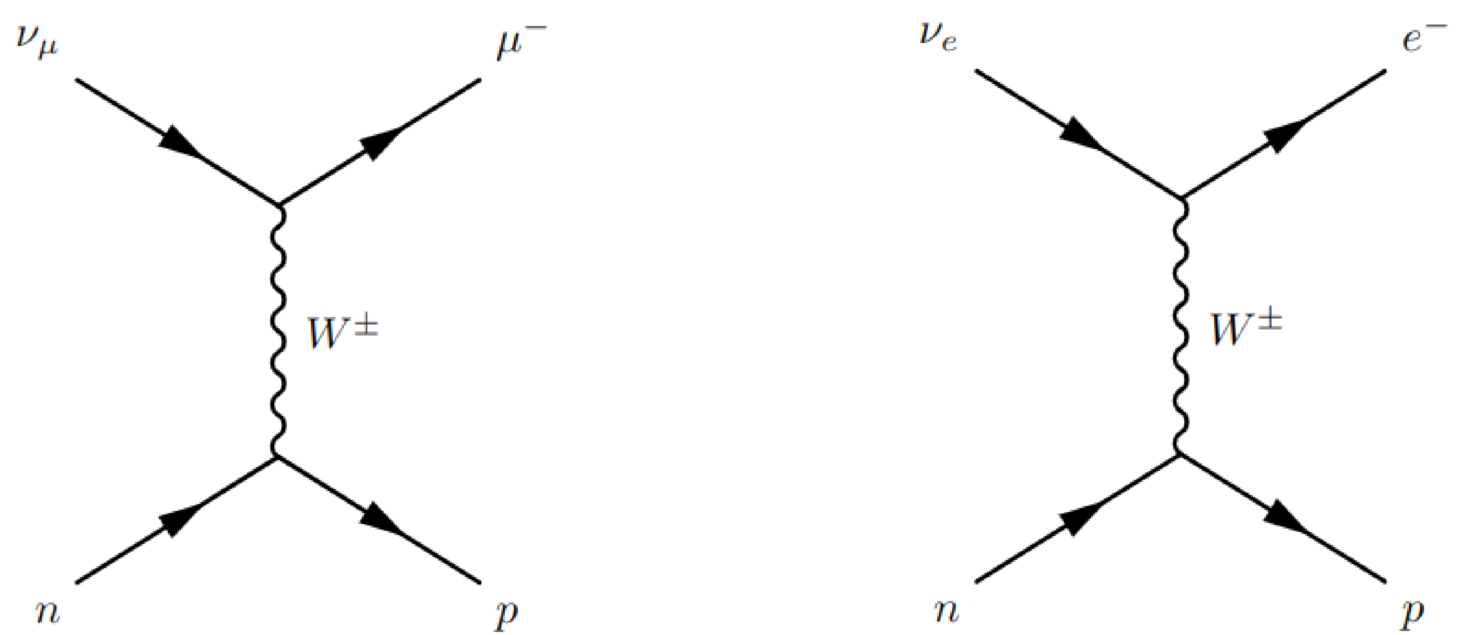


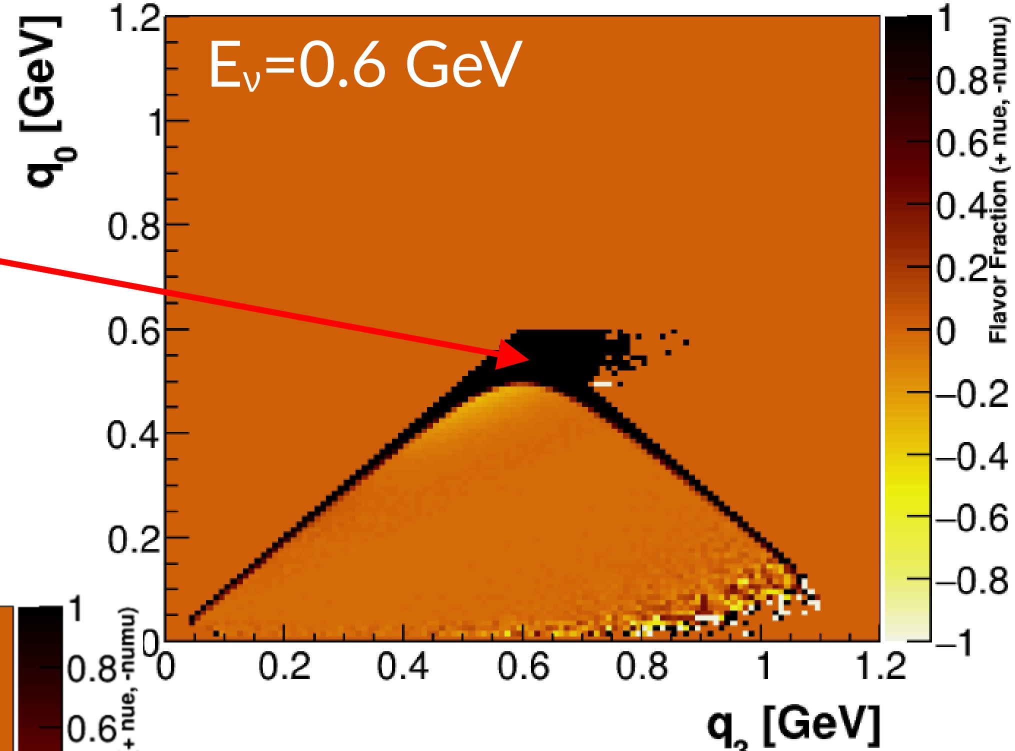
- Account for lighter lepton mass
- Maybe some Coulomb repulsion, shifts energy by ~MeV
- **Radiative corrections**, emitting collinear or virtual photon

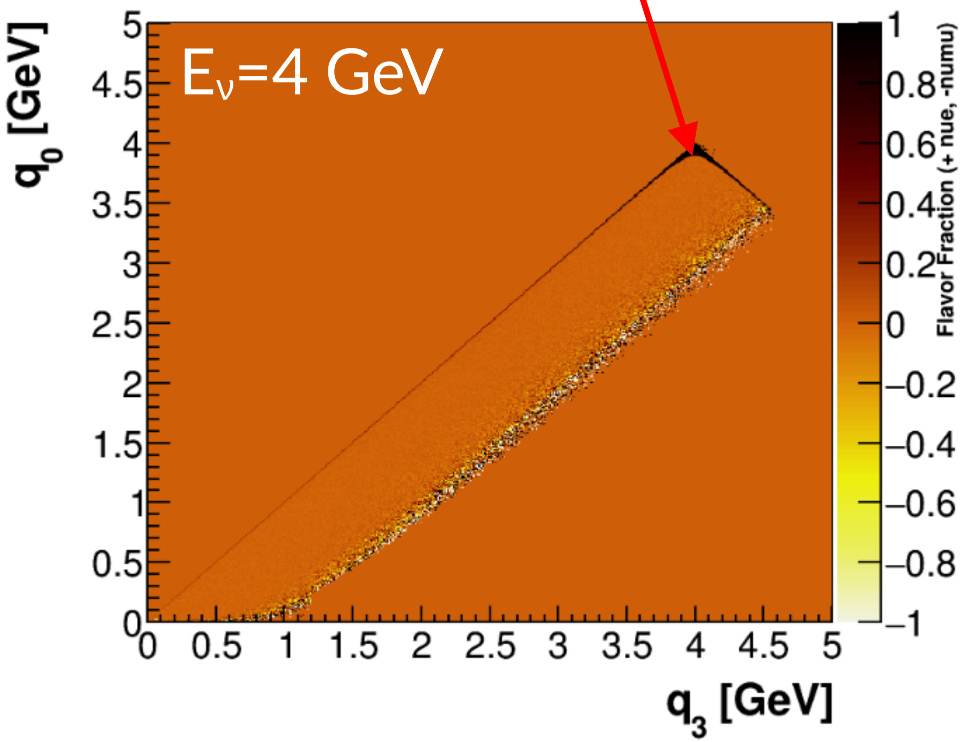
Tomalak et al. Phys.Rev.D 106 (2022) 9, 093006; Nature Commun. 13 (2022) 1, 5286

Electron/muon neutrino differences

- Due to lepton mass, access different (q_0, q_3) for a fixed neutrino (or lepton) energy

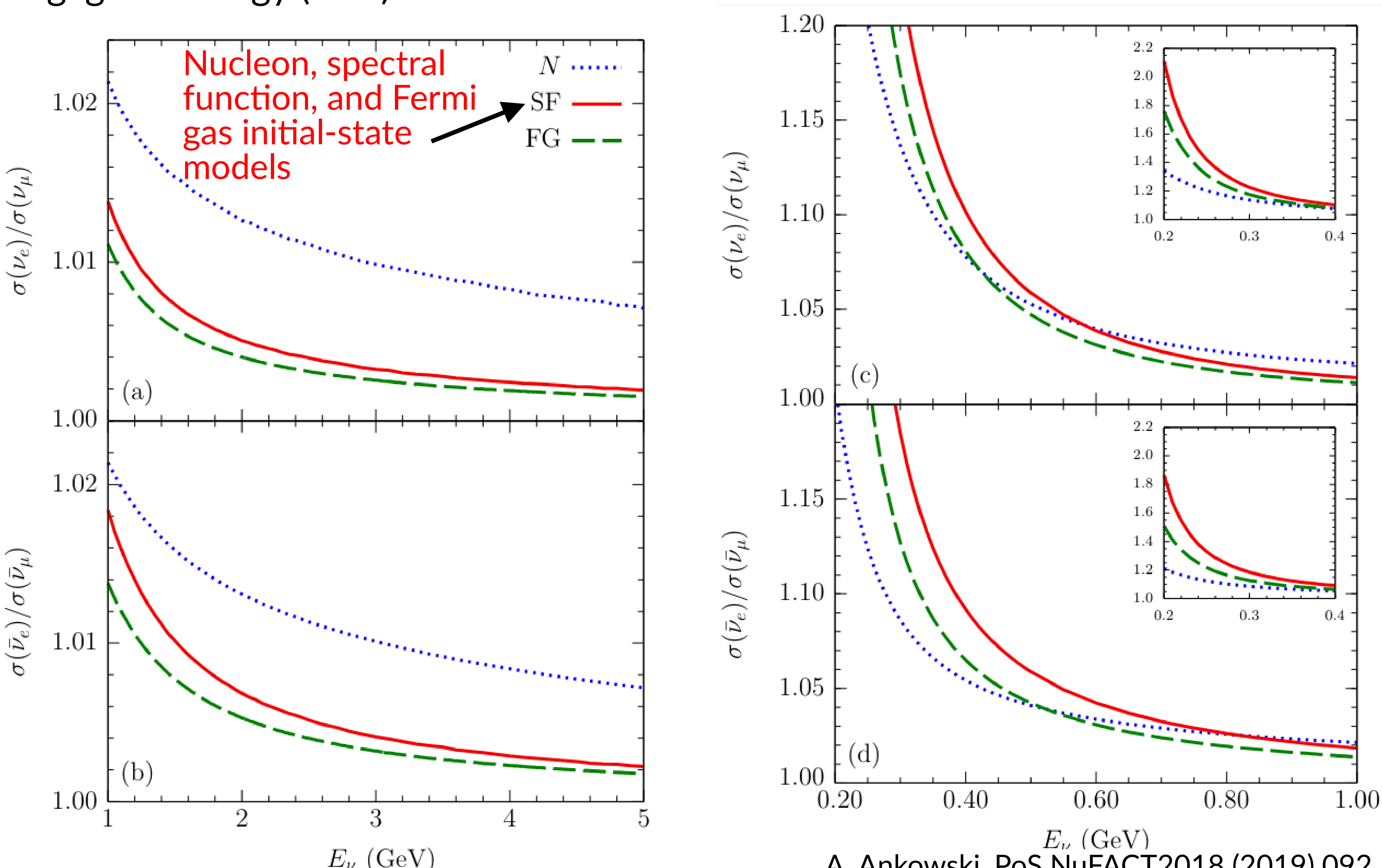
Region of events **only accessible with electron neutrinos**





Electron/muon neutrino differences

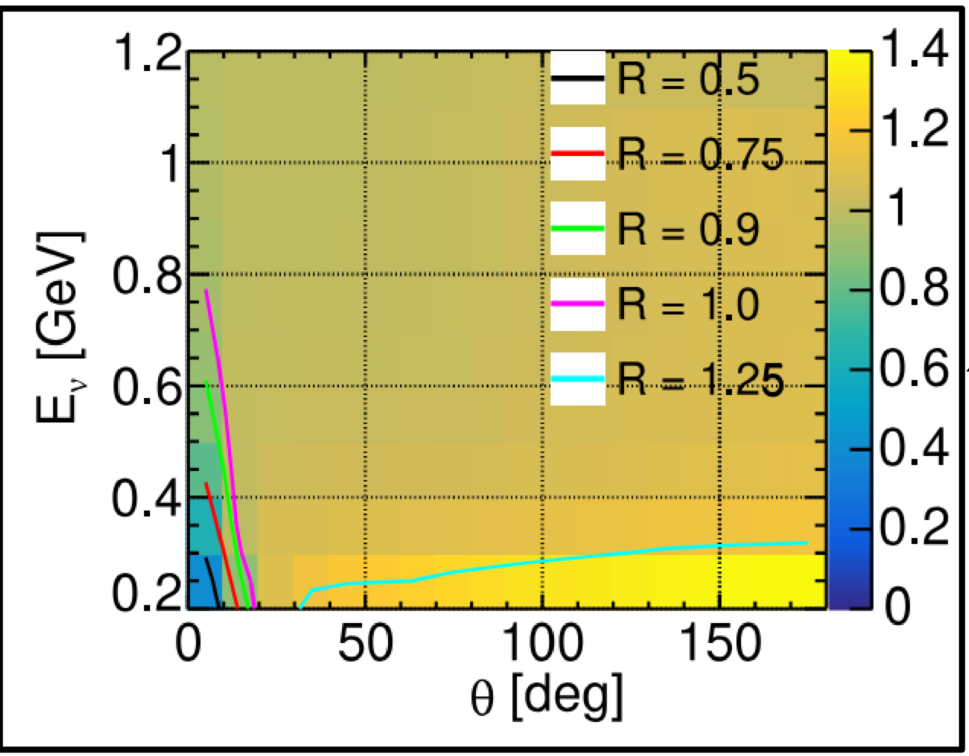
- Due to lepton mass, access different (q_0, q_3) for a fixed neutrino (or lepton) energy
- Especially bad when the cross-section rapidly rising, and lepton mass is non-negligible energy (T2K)

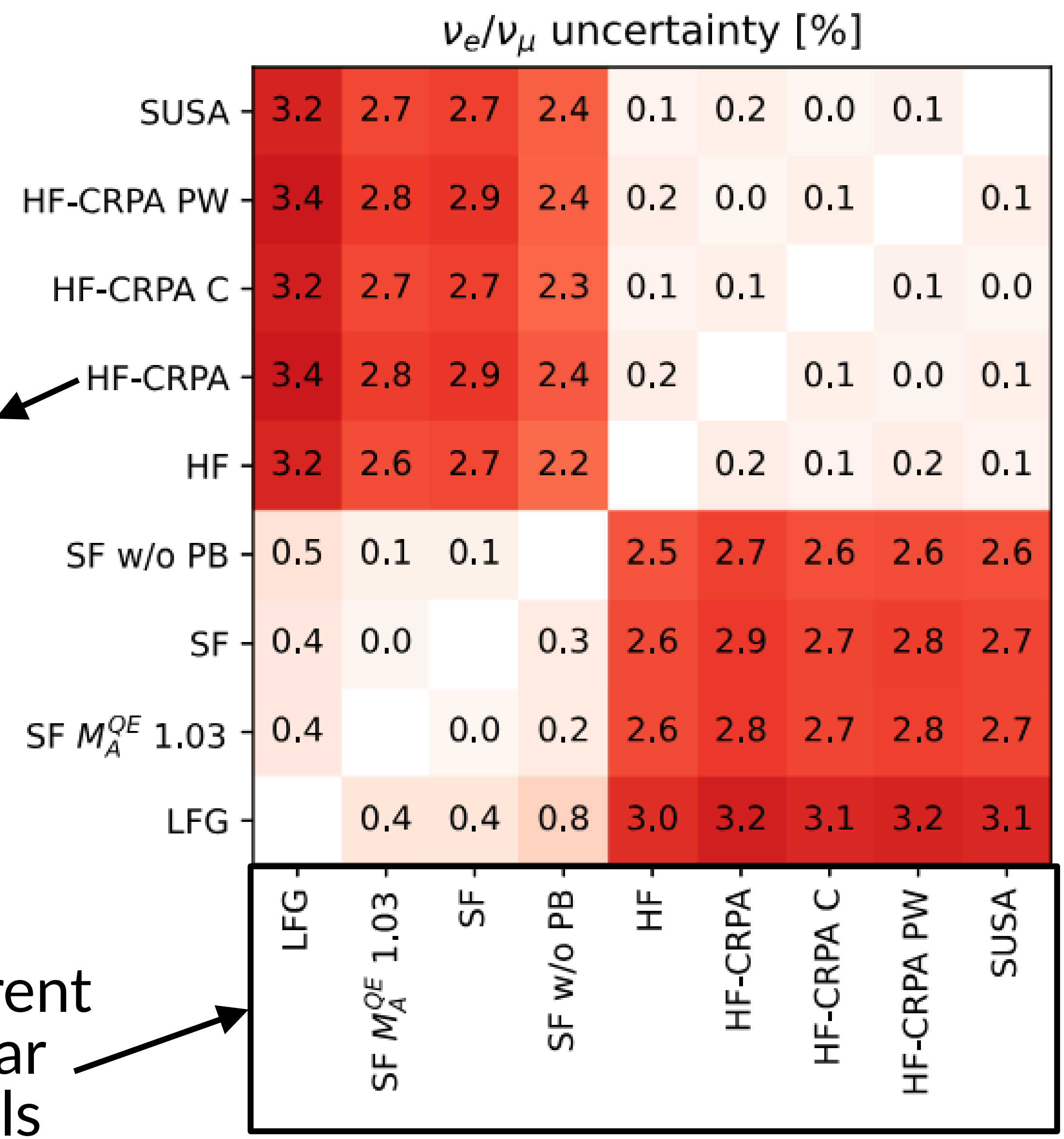


A. Ankowski, PoS NuFACT2018 (2019) 092

Electron/muon neutrino differences

- Extension of study, focussing on nuclear models and kinematics accessible in experiments, found similar effects, ~3-4% level



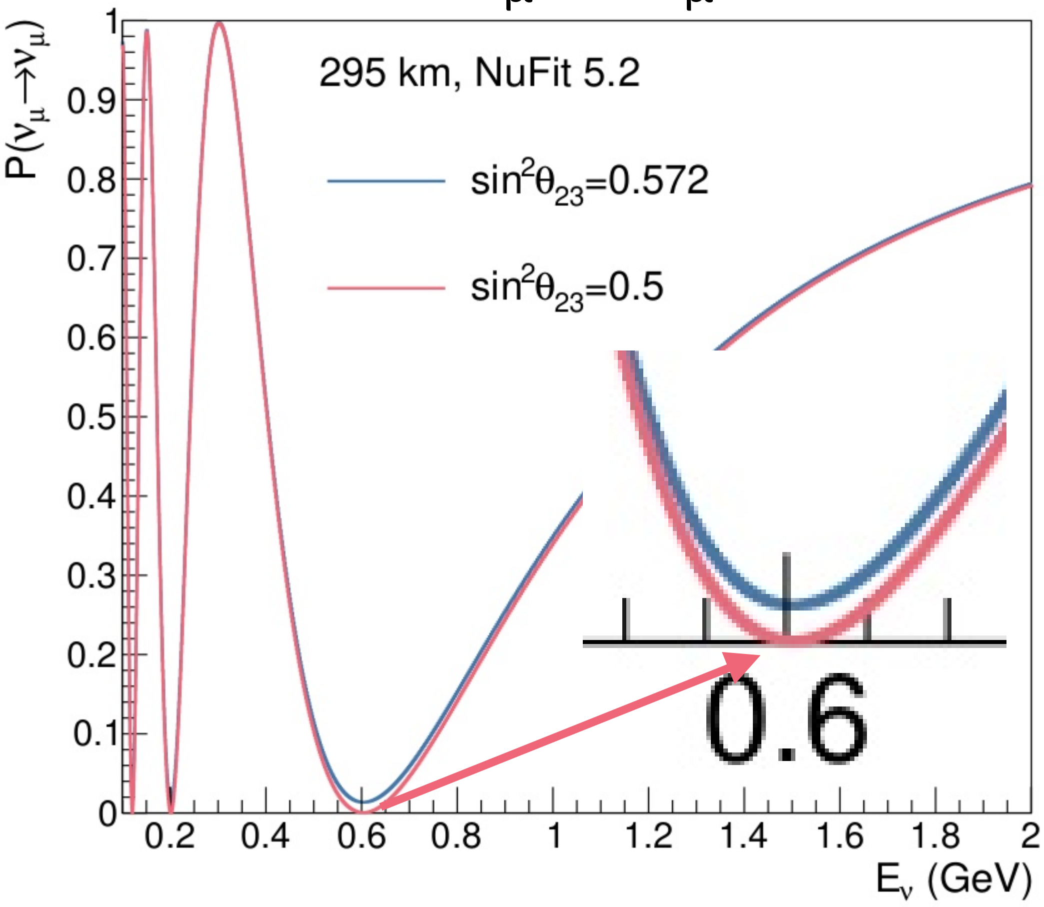


Different nuclear models

Issues with the near detector

- For accurate measurements of the dip (e.g. $\sin^2\theta_{23}$), the modelling of the few events in the dip becomes important

$\nu_\mu \rightarrow \nu_\mu$



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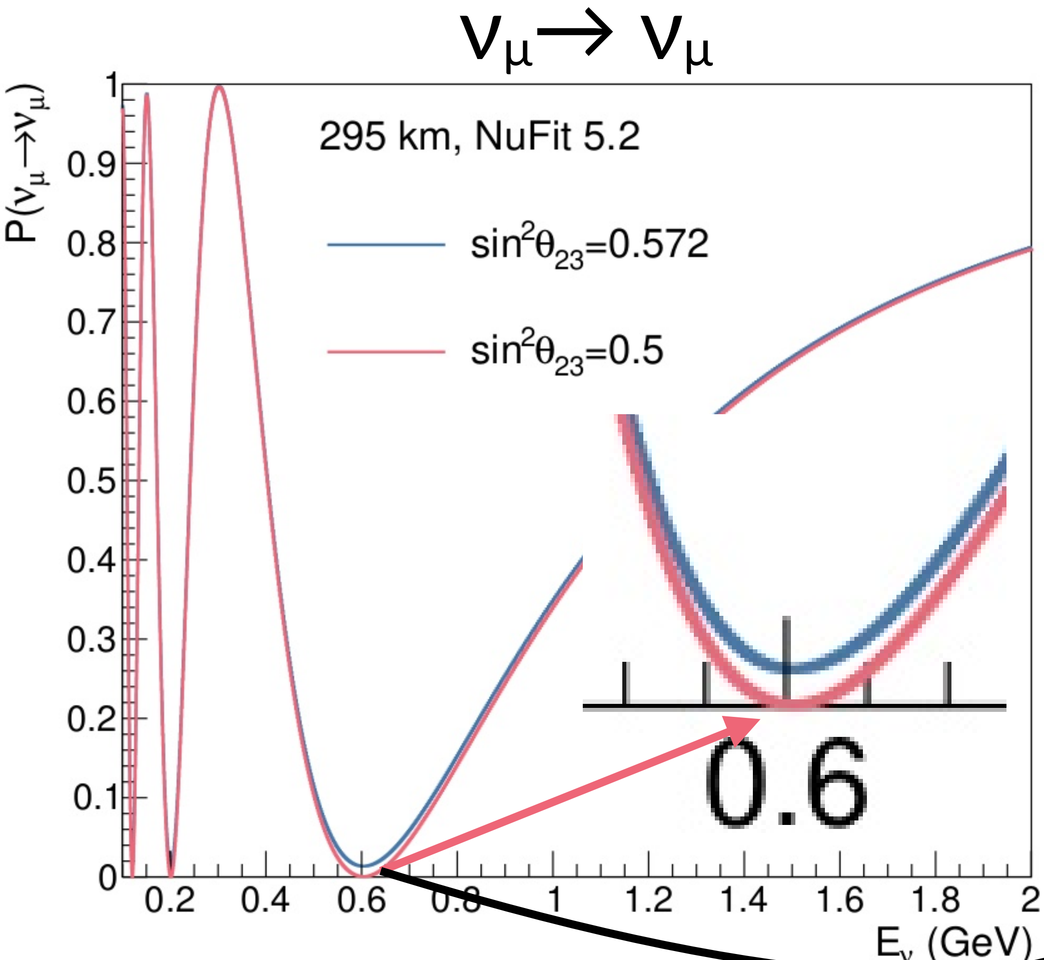
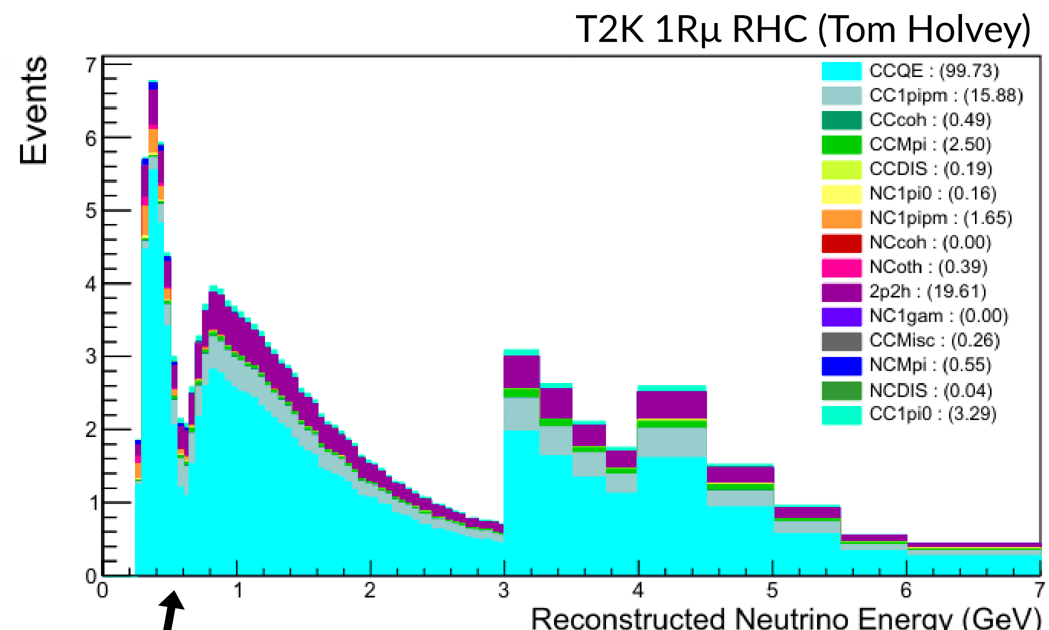


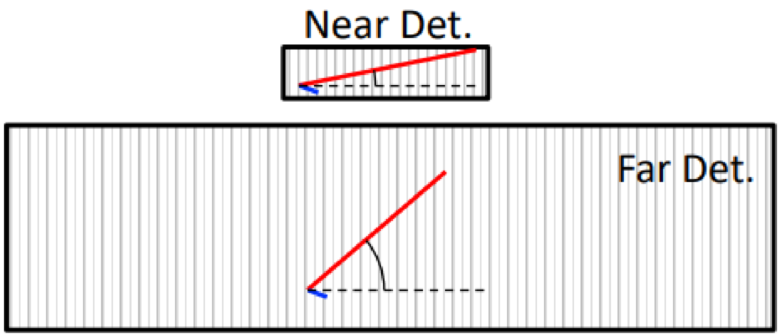


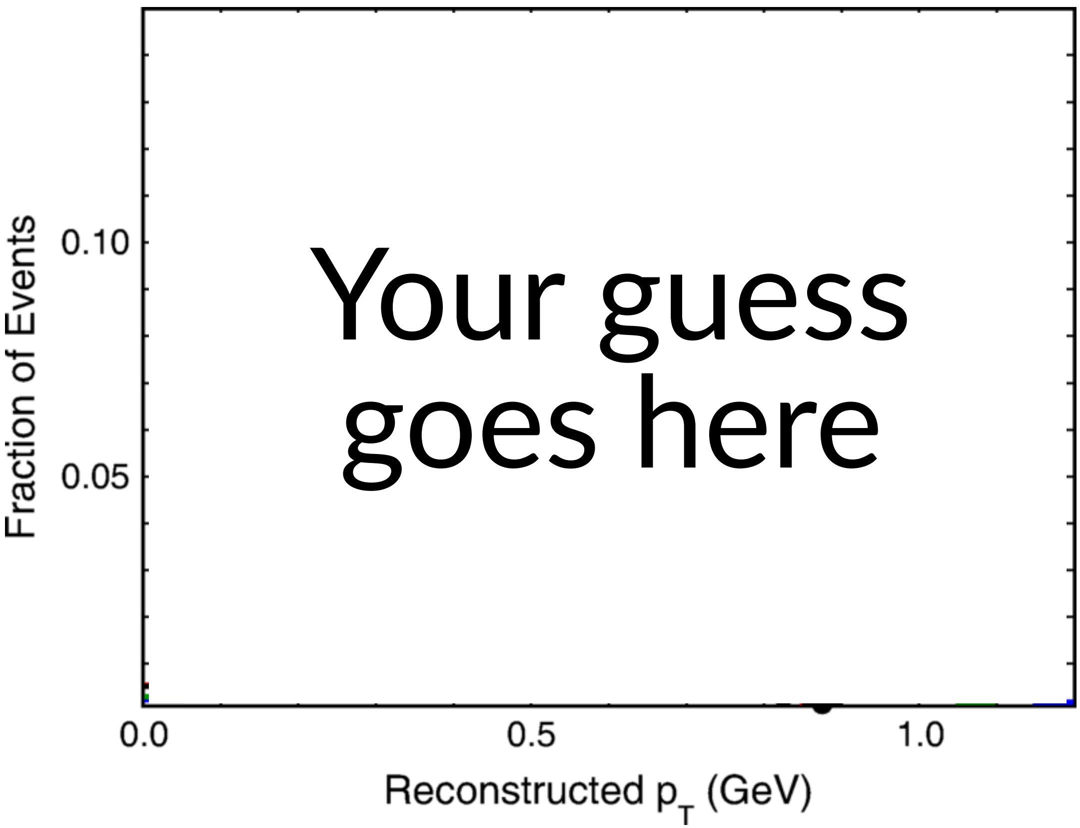
In reality, this minimum never reaches zero

Need to understand the backgrounds, and smearing in reco to true energy

Acceptance mismatch

- Acceptance differences from **differently sized detectors**





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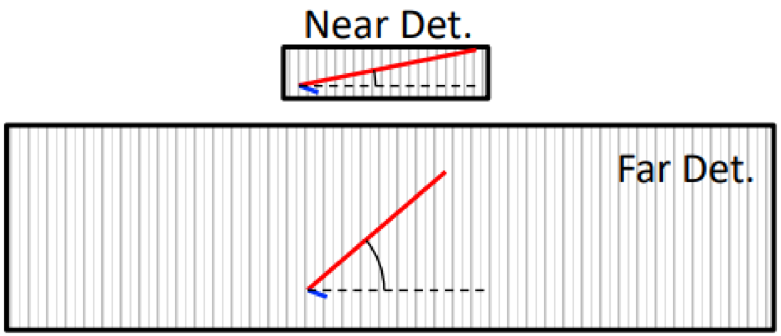

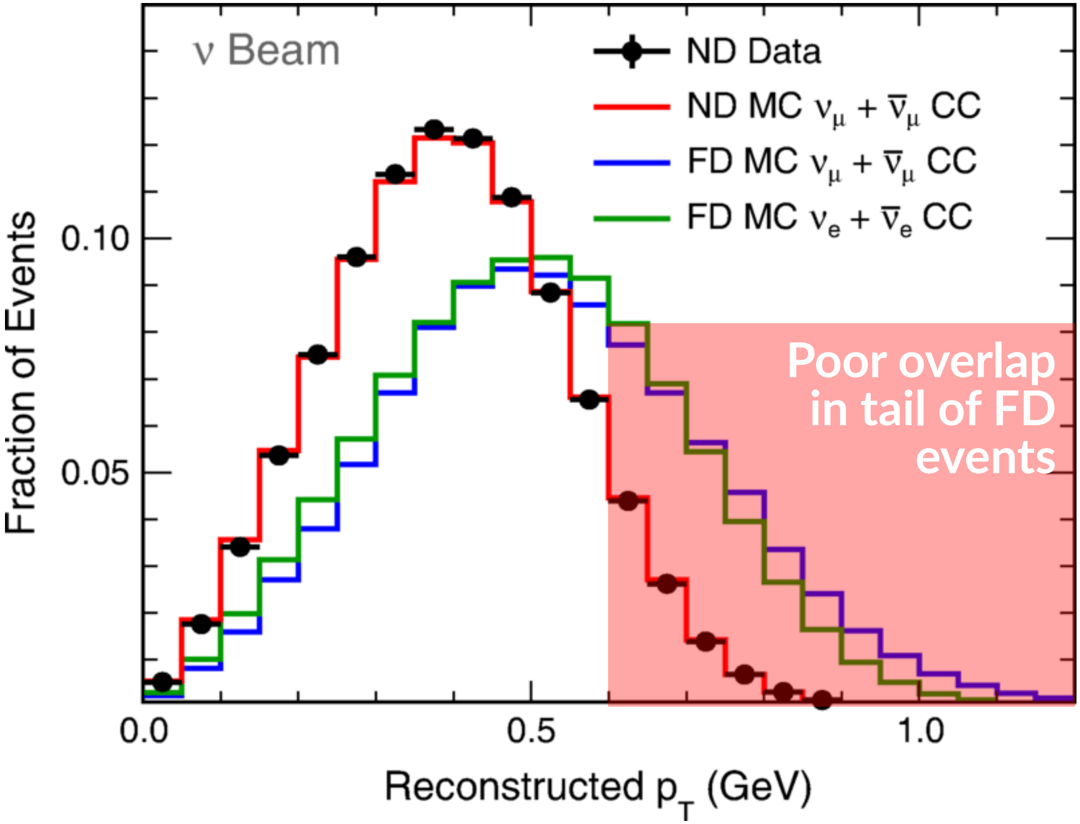

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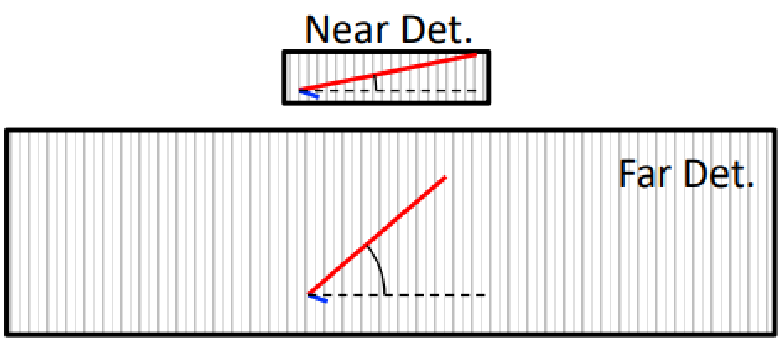
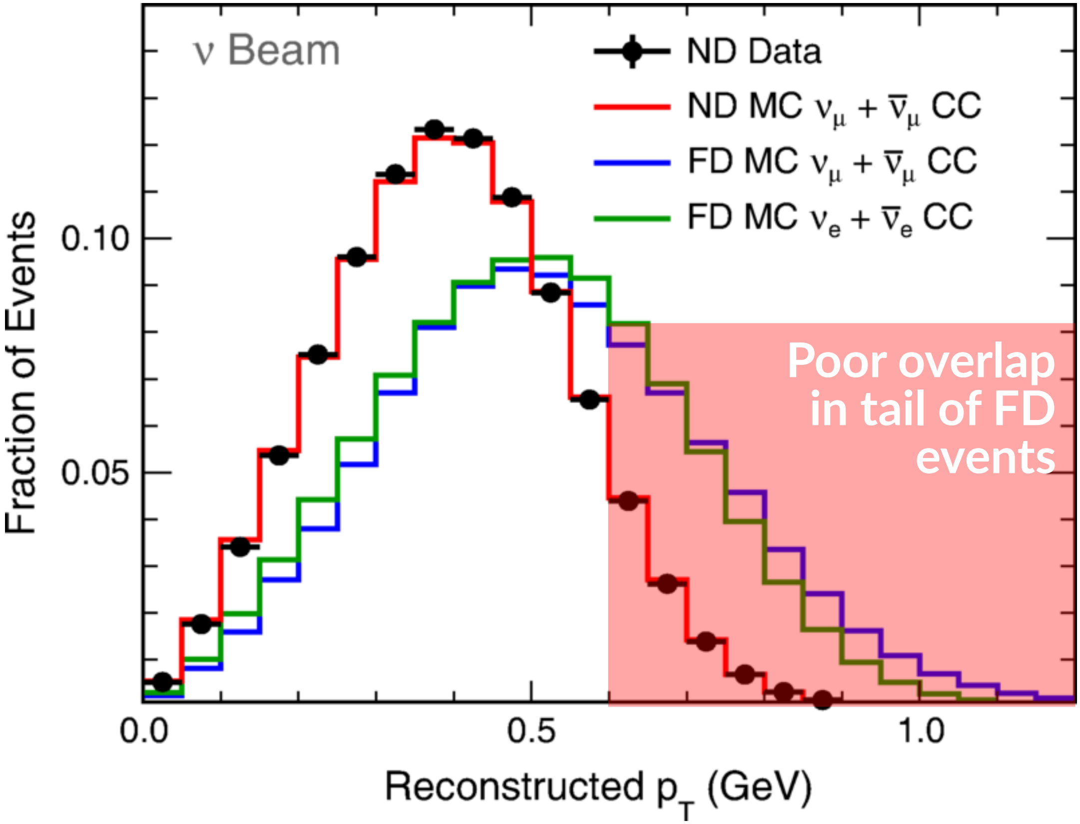
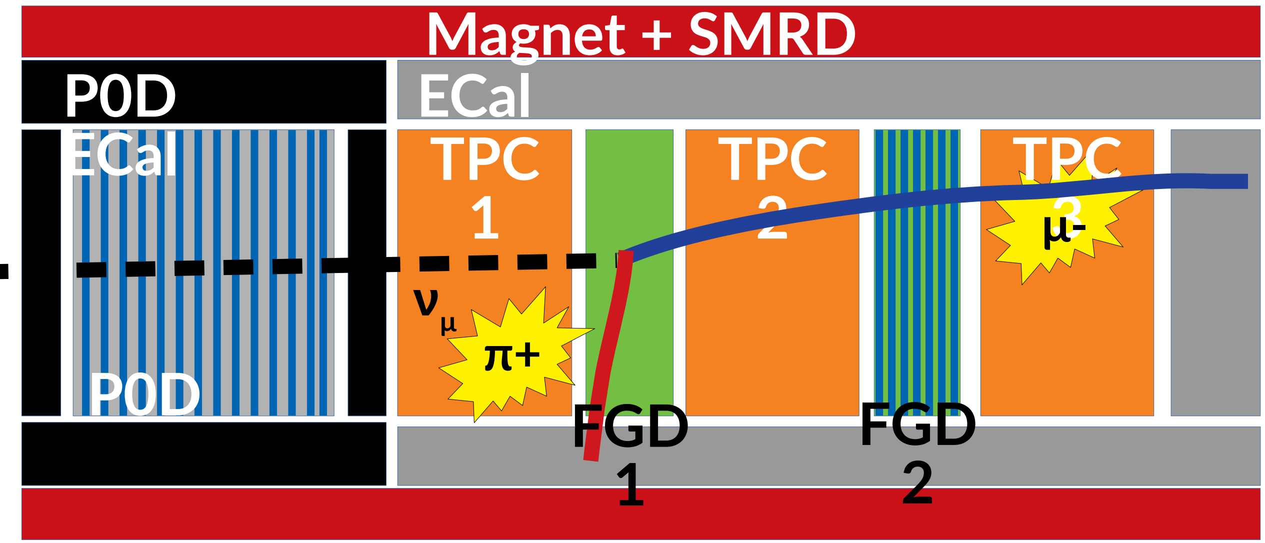




- **Different target material** and **detector design** means additional model dependence in $CH \rightarrow H_2O$
- **Different detector technologies** and **geometry** may mean **<u>different particle acceptance</u>**

Acceptance mismatch

- Issue is present in T2K too, potentially even larger
  - Near detector very forward-oriented
  - High-angle tracks challenging to reconstruct



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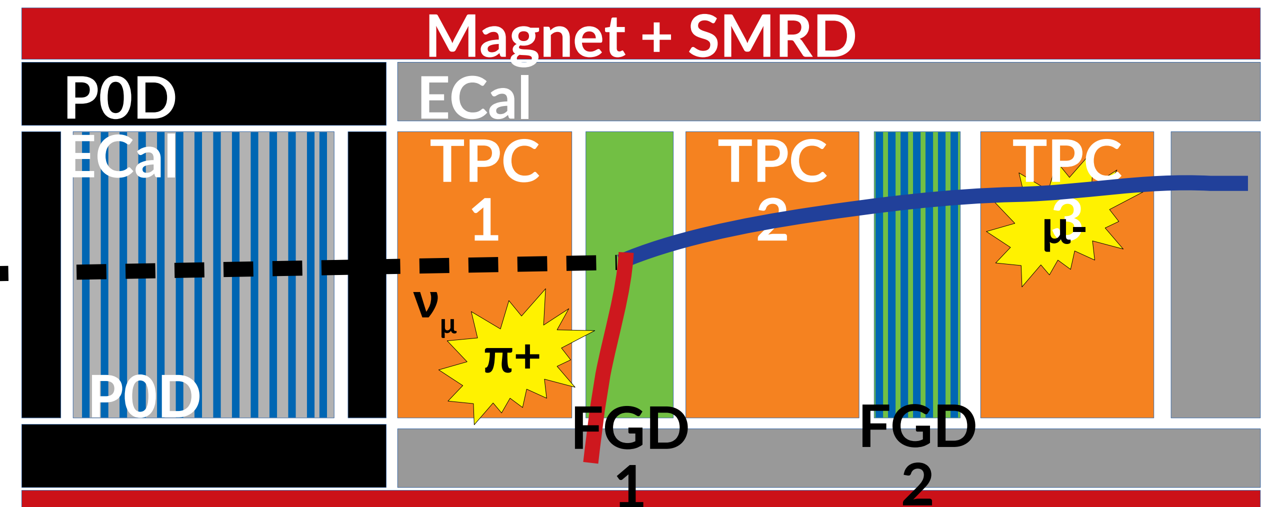

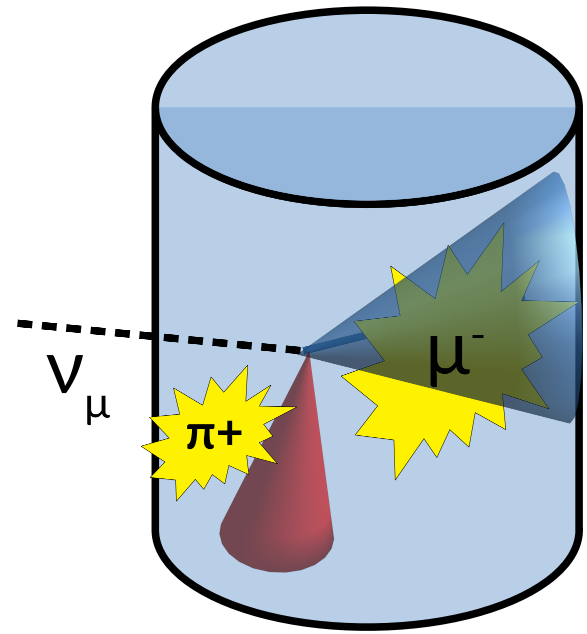

- SK is instead very symmetric and isotropic
  - Good acceptance forward, backward, upward and downward

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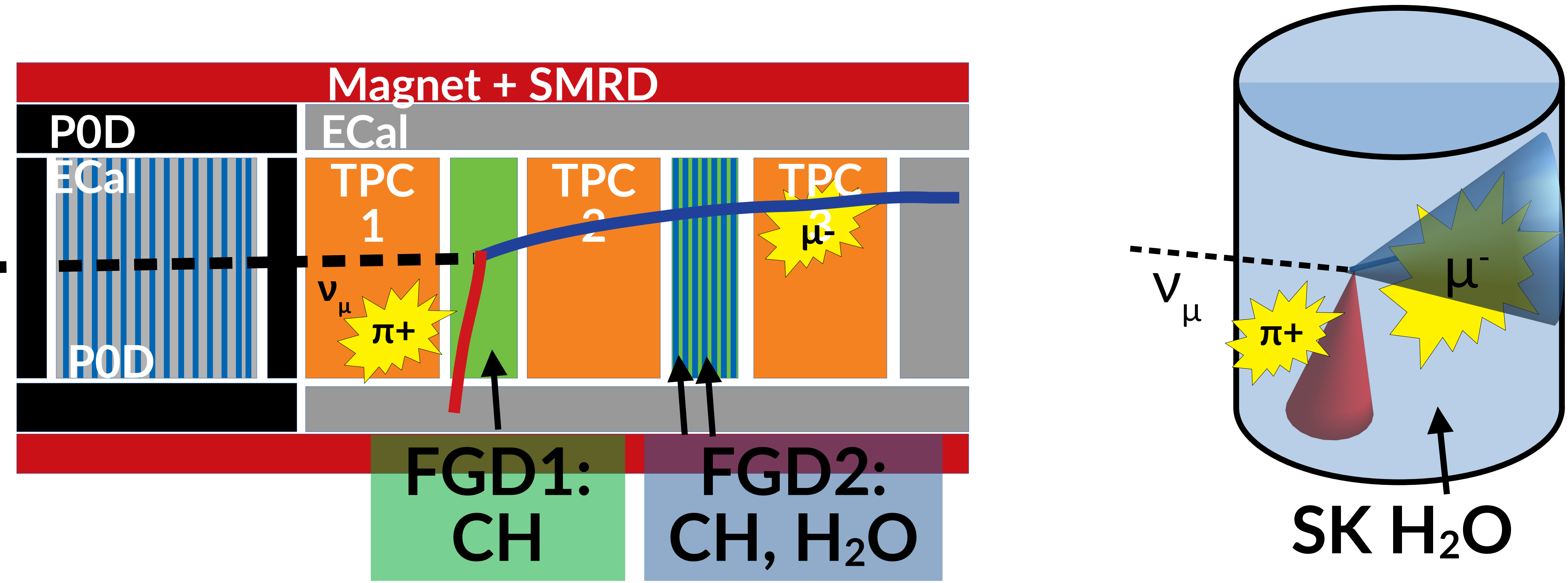

- SK is instead very symmetric and isotropic
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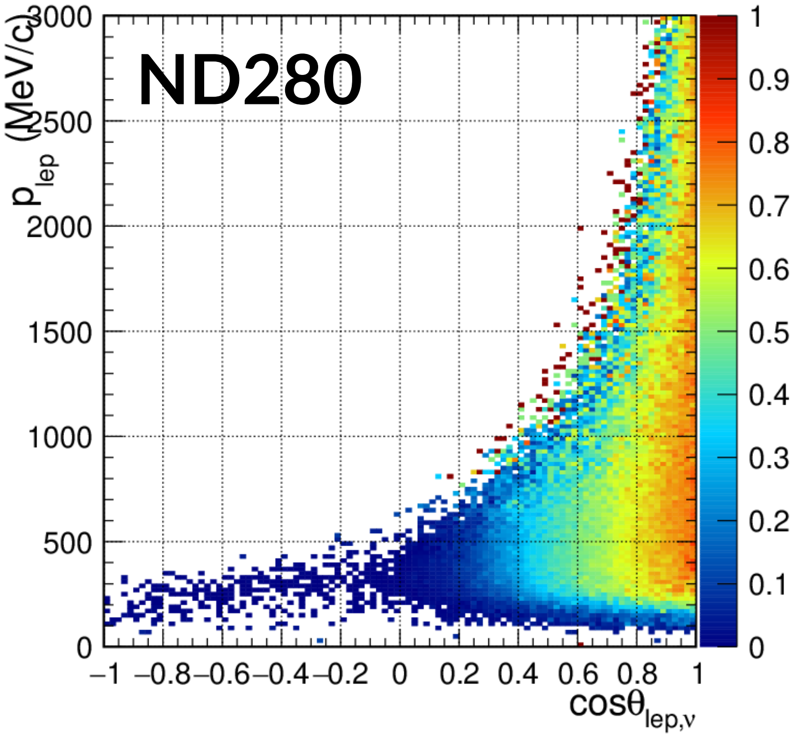

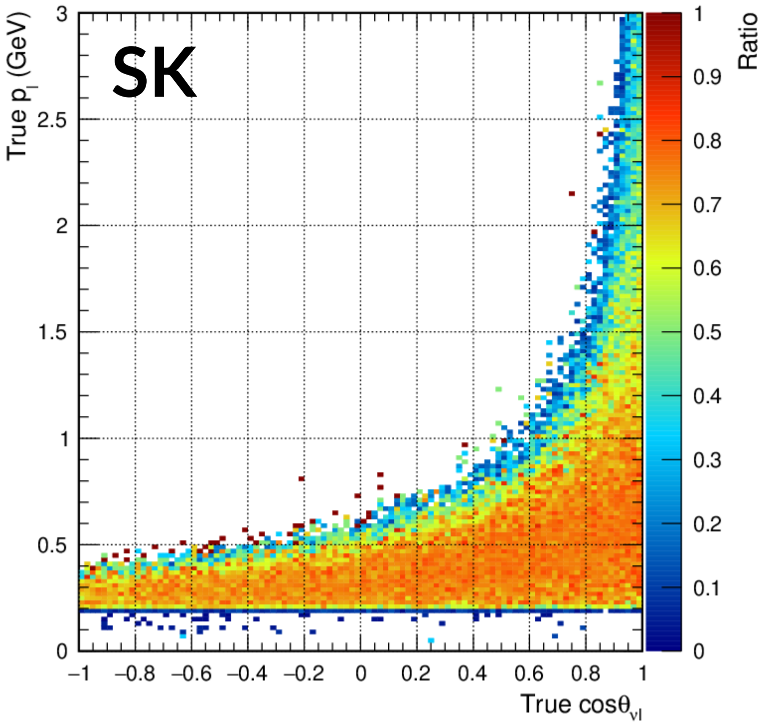

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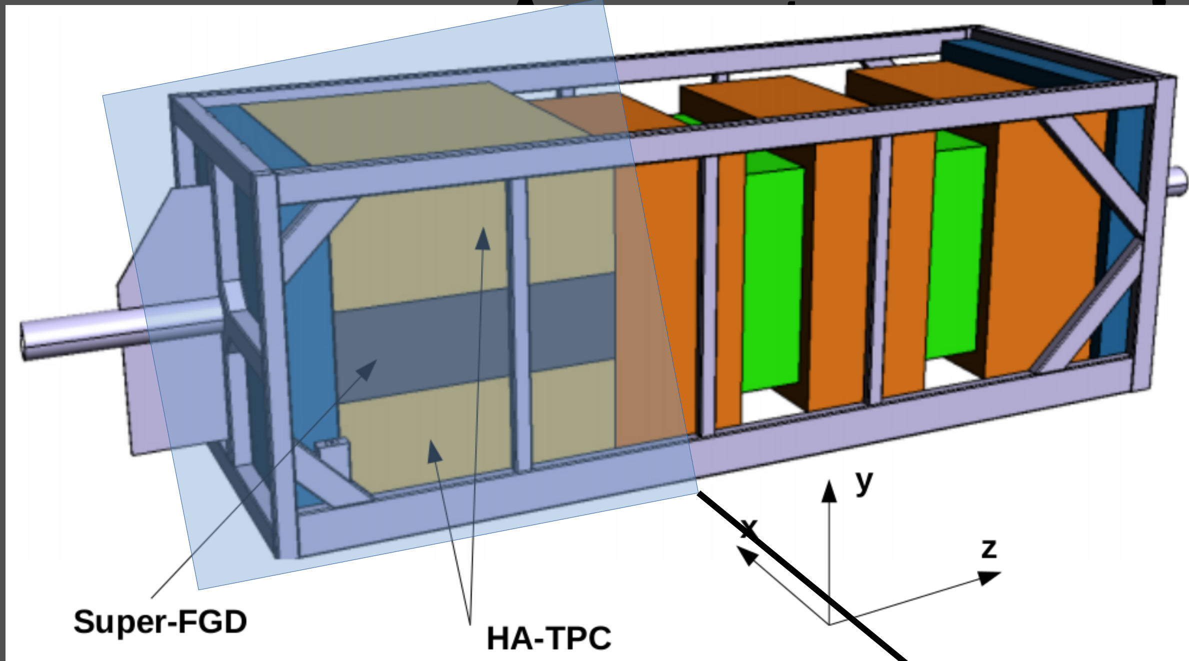
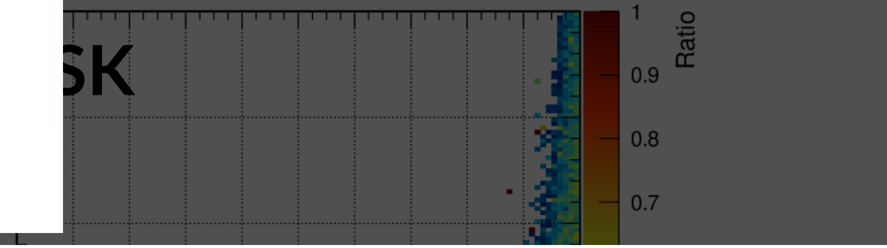
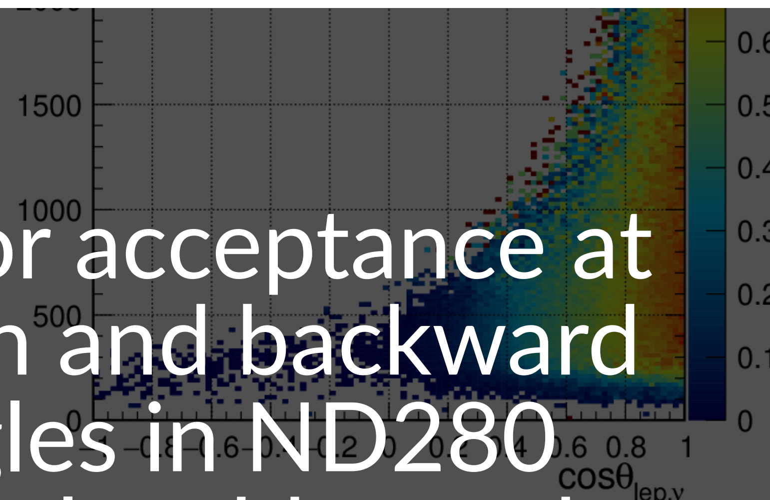
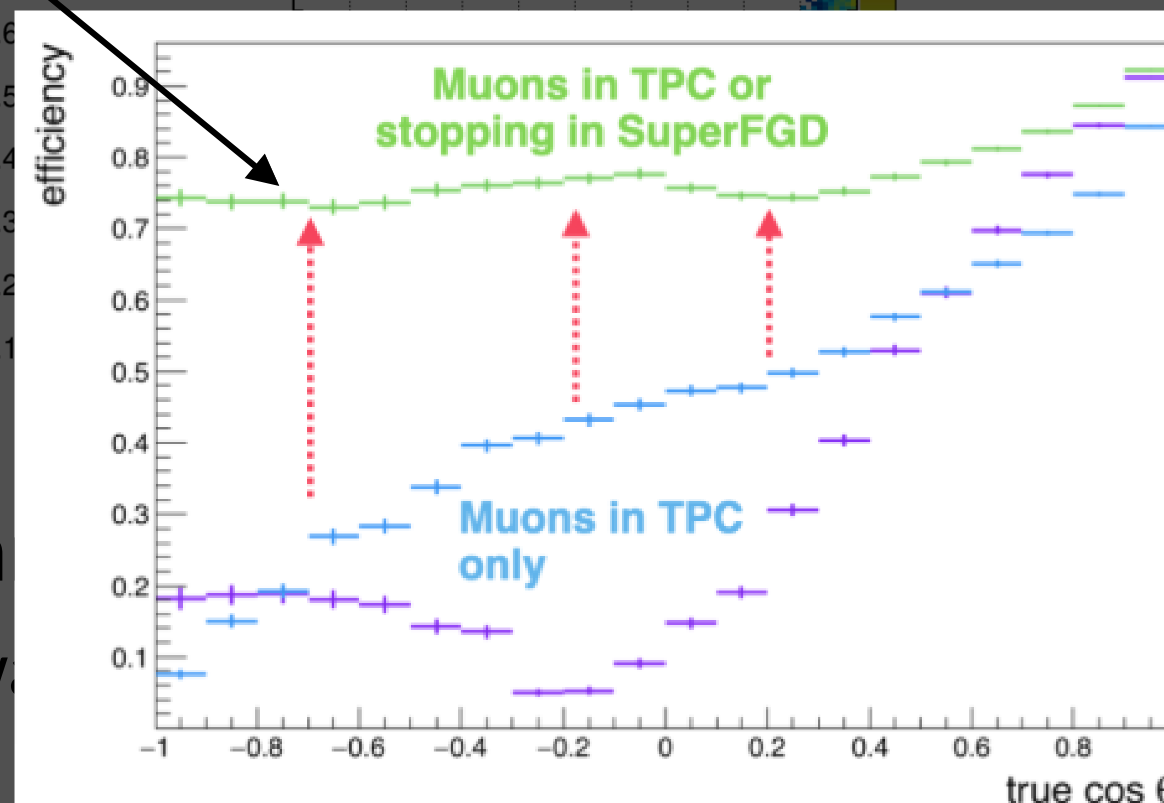
...smatch

- ...entially even larger
  - ...nted
  - ...reconstruct
  - ...SK









Poor acceptance at high and backward angles in ND280 largely addressed with **ND280 upgrade**

- SK is instead very sym...
  - Good acceptance forw... downward

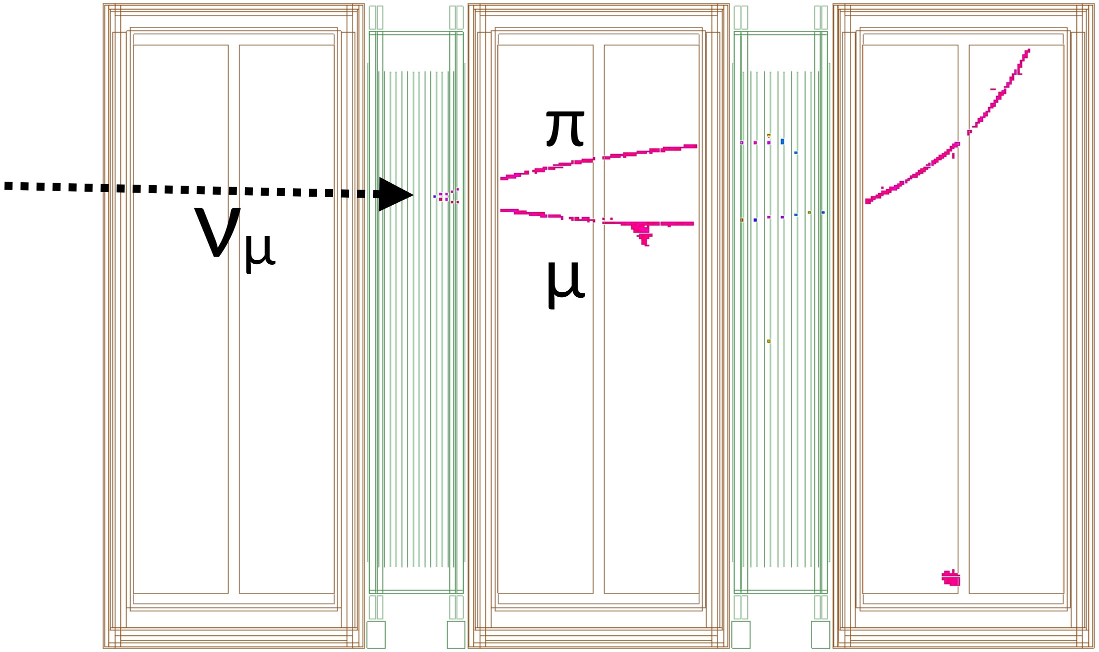
Acceptance mismatch

- Use forward-going events to model backward-going events
  - If this correlation is poorly modelled, issues!
- Similar argument goes for counting particles
  - If particles were emitted backwards in ND280, poorly reconstructed background

- DUNE's near and far detectors will have similar issues to NOvA
- Intermediate Water Cherenkov Detector (IWCD) addresses this on HK
  - Basically a small Super-K near detector

Energy reconstruction

- Energy reconstruction method is function of **selection** and **detector technology**
- Need to understanding mapping between **observed events** and the **not-observed neutrino energy**



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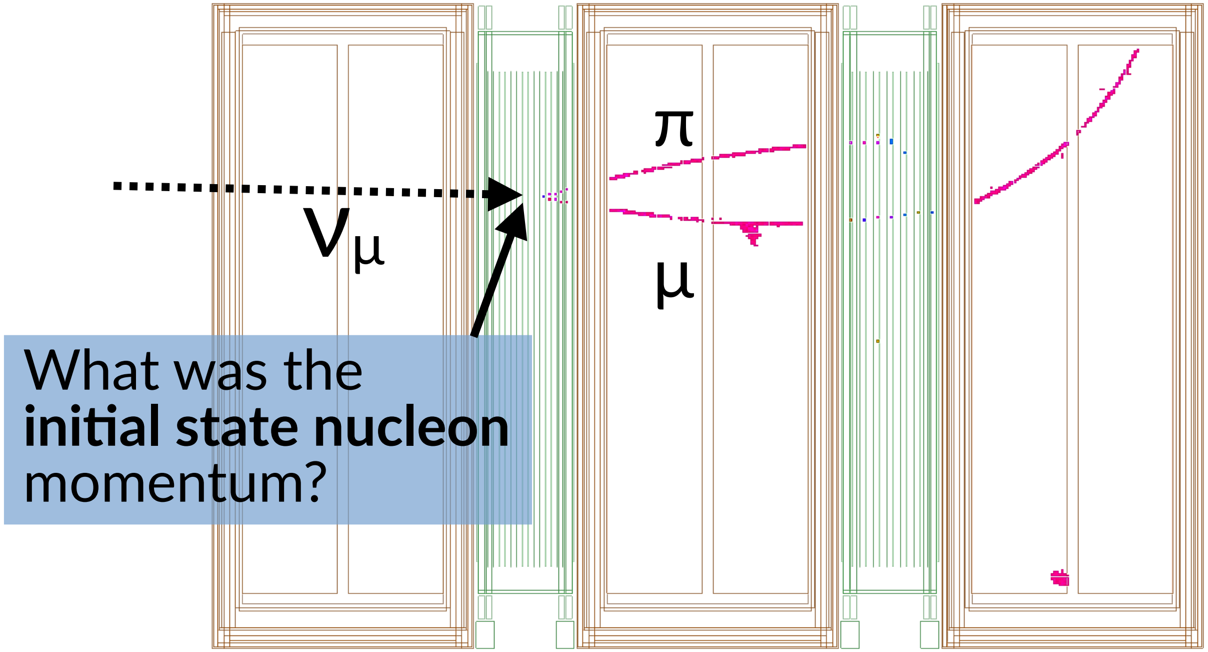

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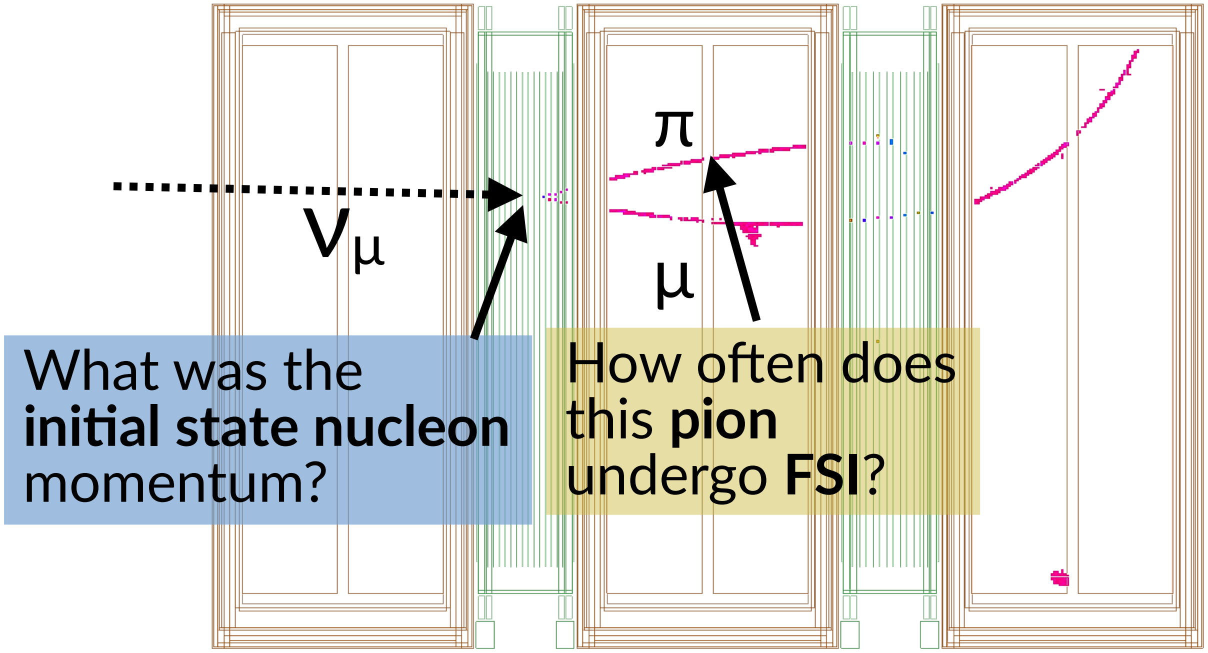

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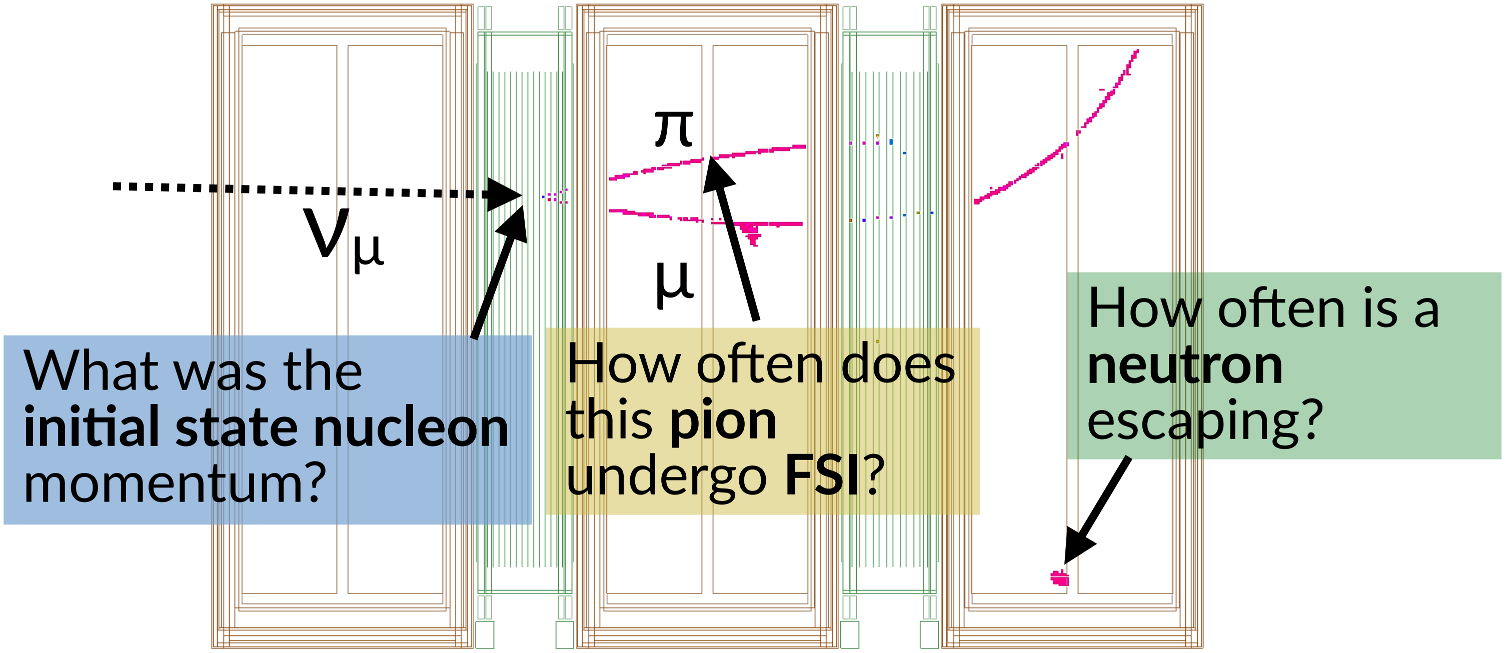

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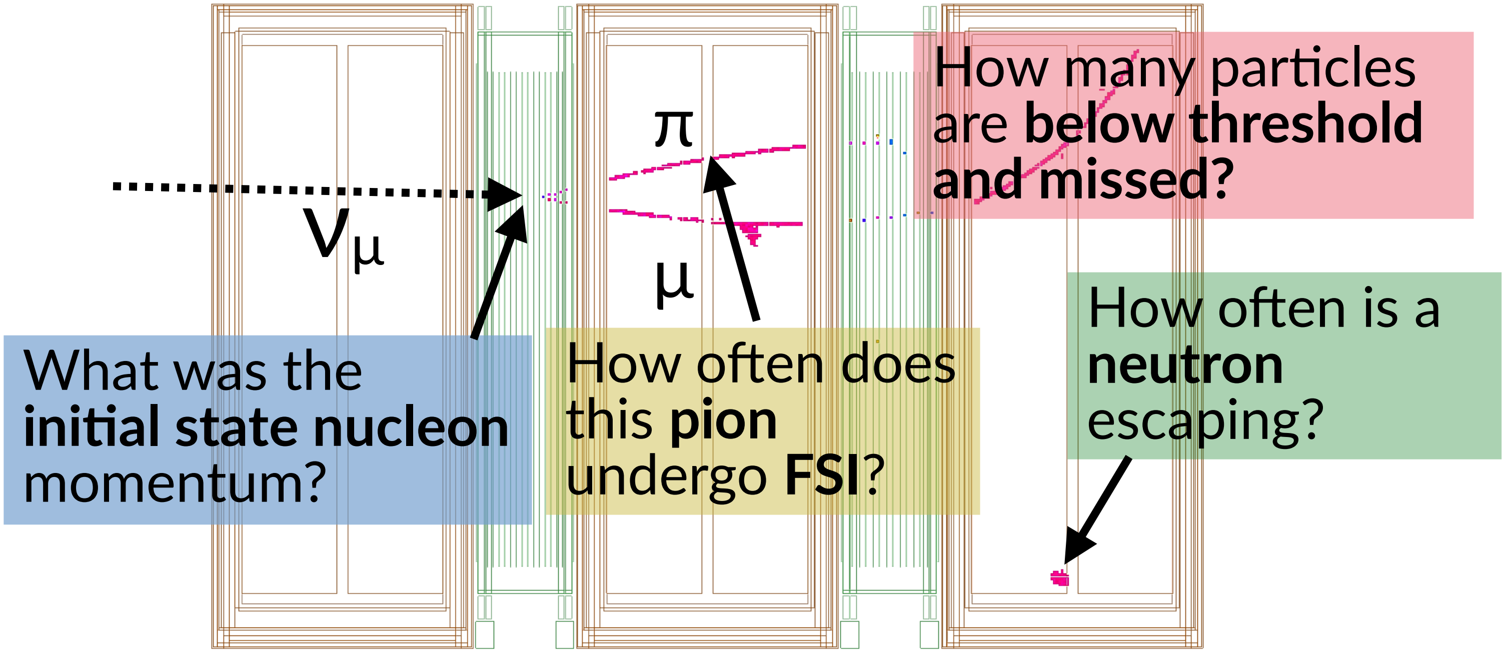

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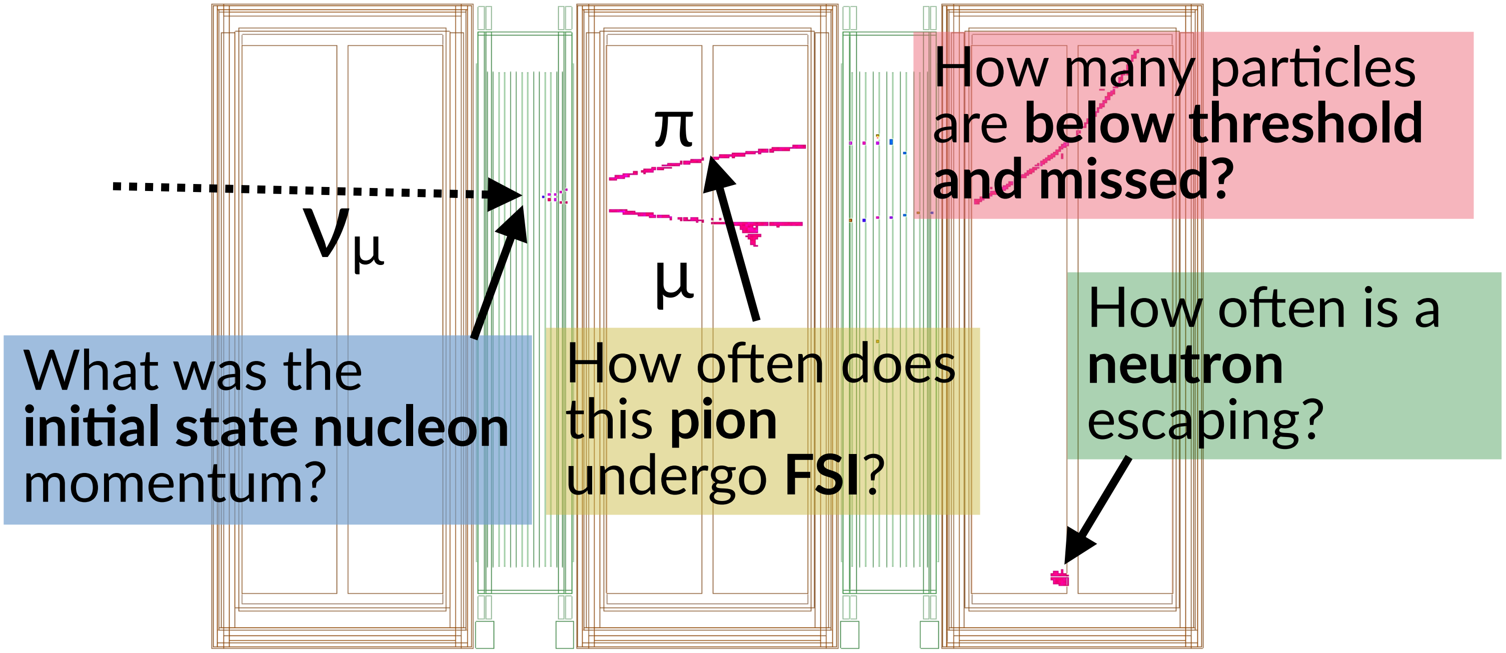
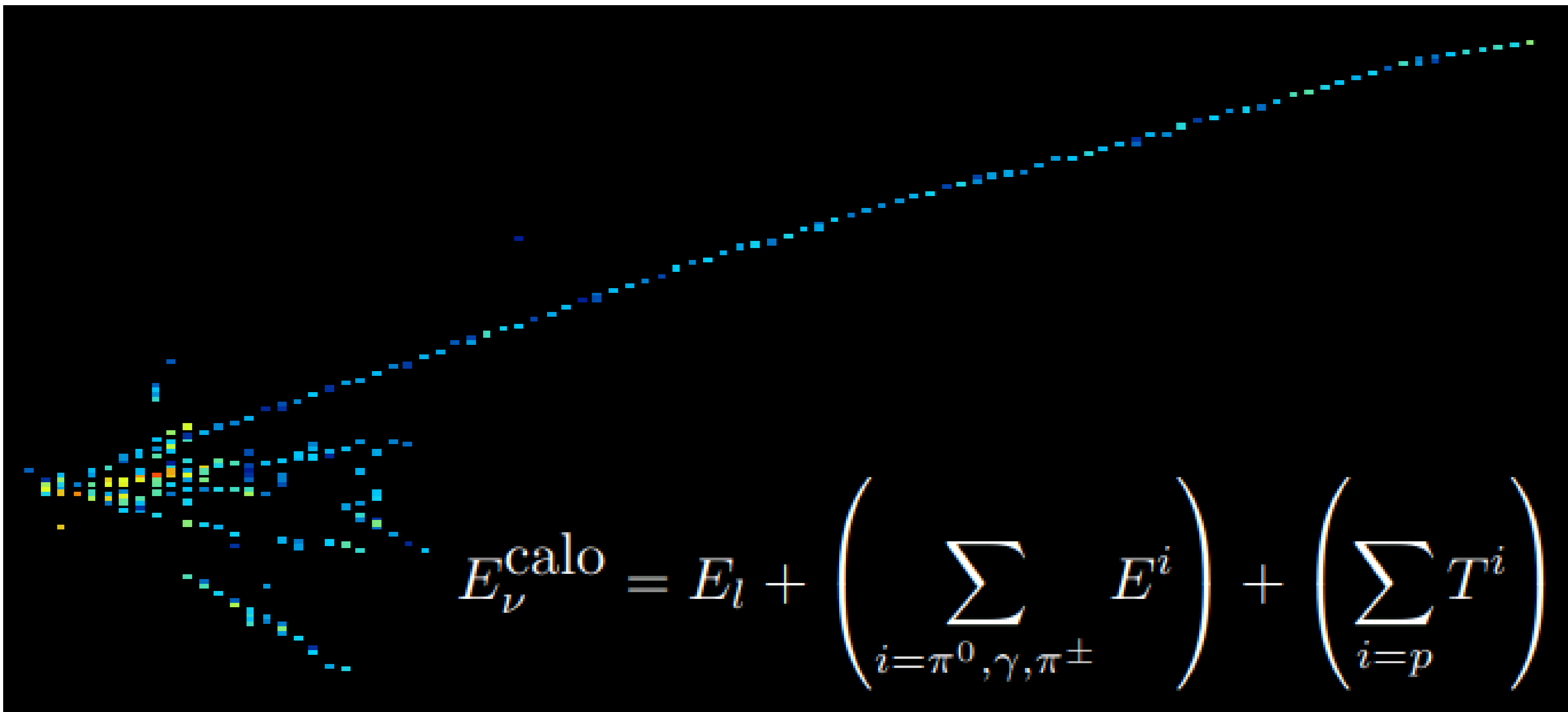


- <u>**All estimators are biased**</u>
  - Try to **reduce** the amount of bias
  - Understand the **uncertainty on the bias**

Calorimetric energy reconstruction

- NOvA, DUNE and SBN have **sampling calorimeters** and often **events with multiple tracks**
  - **CC-inclusive** selection
  - Energy estimator which **sums up energy deposits**



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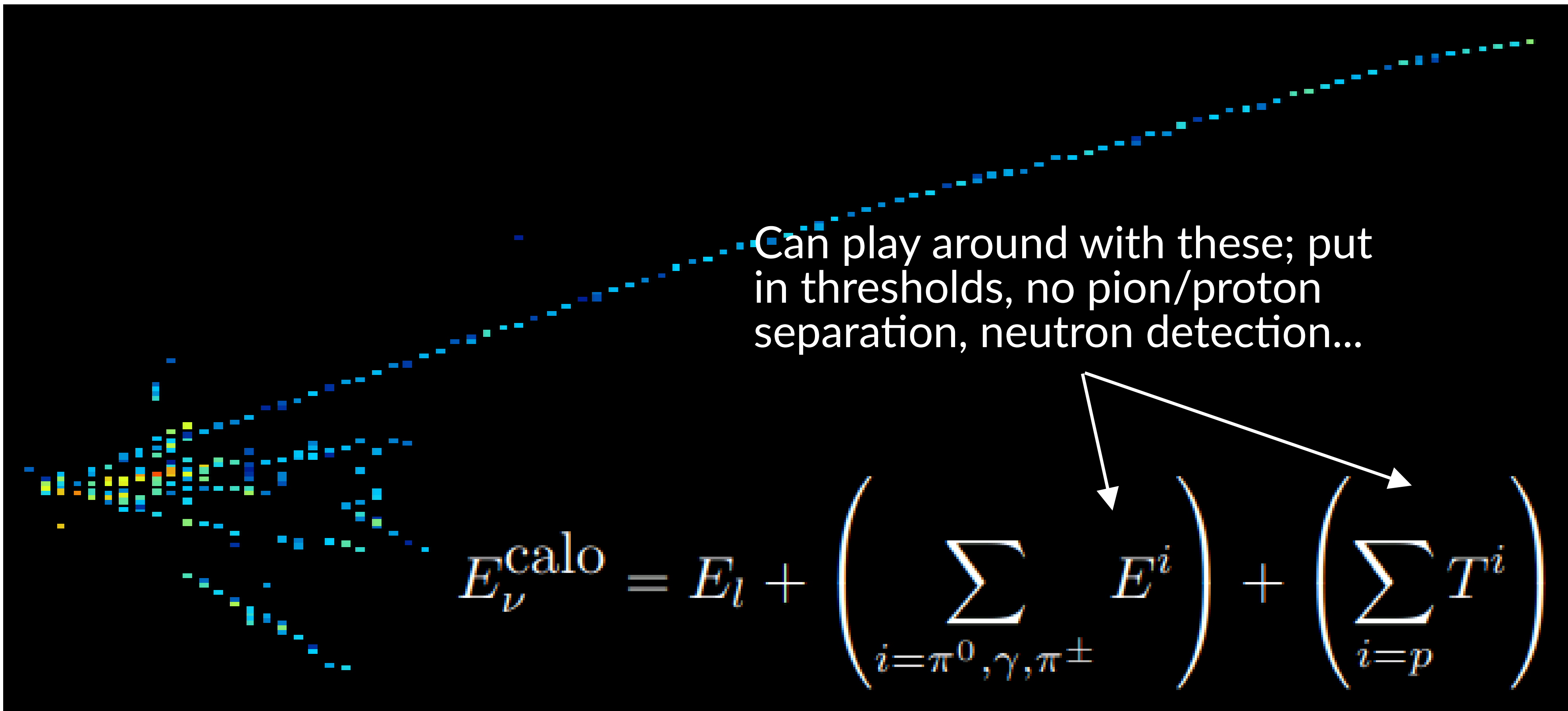
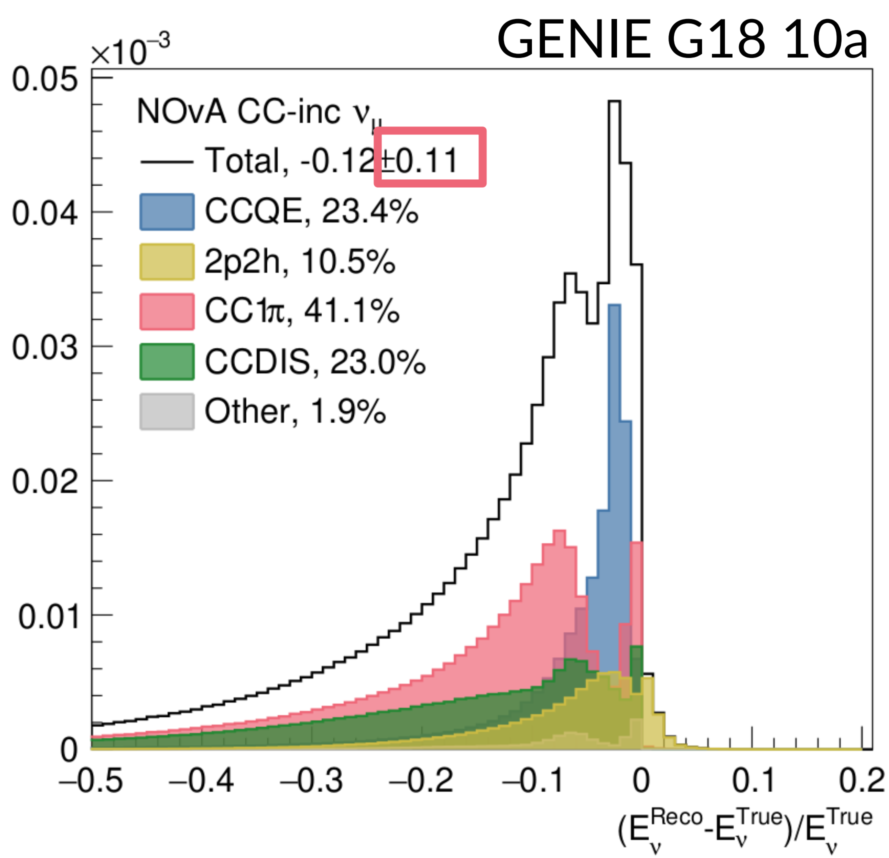
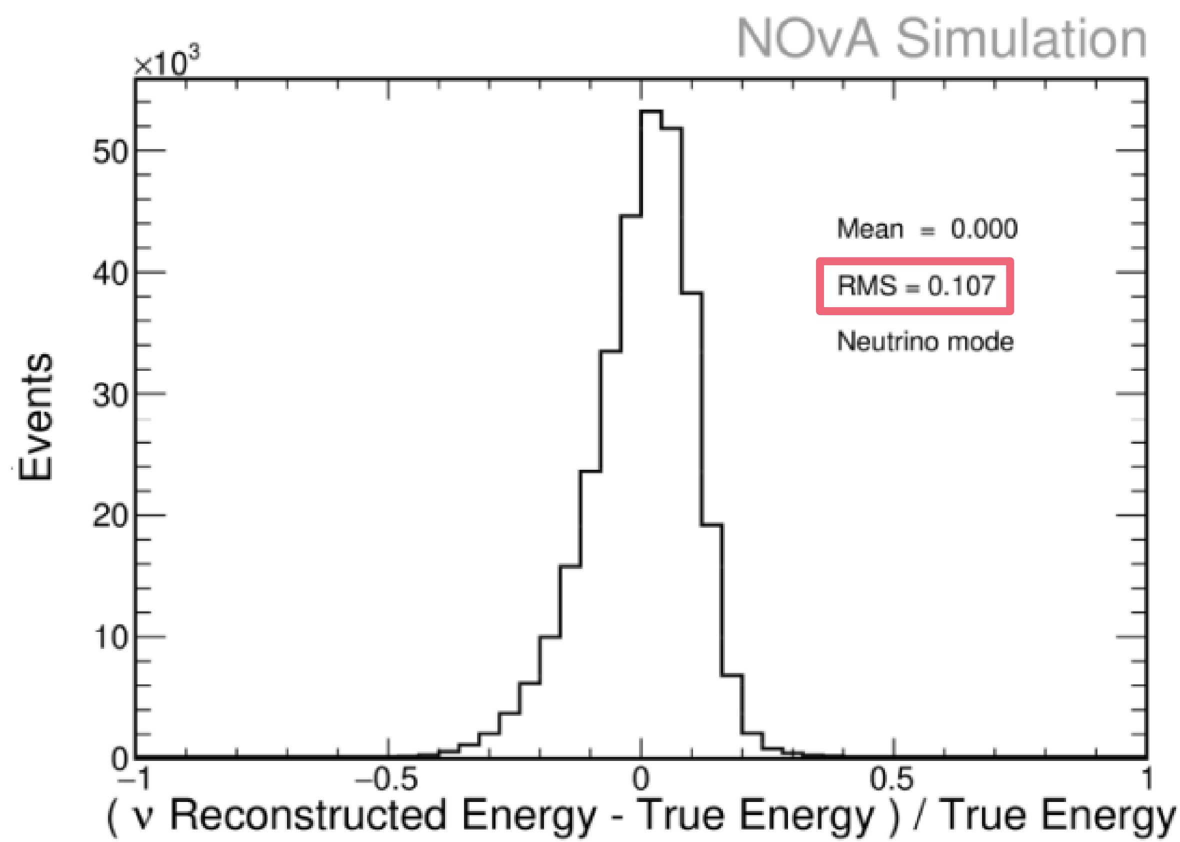


$$E_\nu^{\mathrm{calo}} = E_l + \left(\sum_{i=\pi^0,\gamma,\pi^\pm} E^i \right) + \left(\sum_{i=p} T^i \right)$$

Calorimetric energy reconstruction

- Simple simulation result agrees well with NOvA official figure: ~11% RMS





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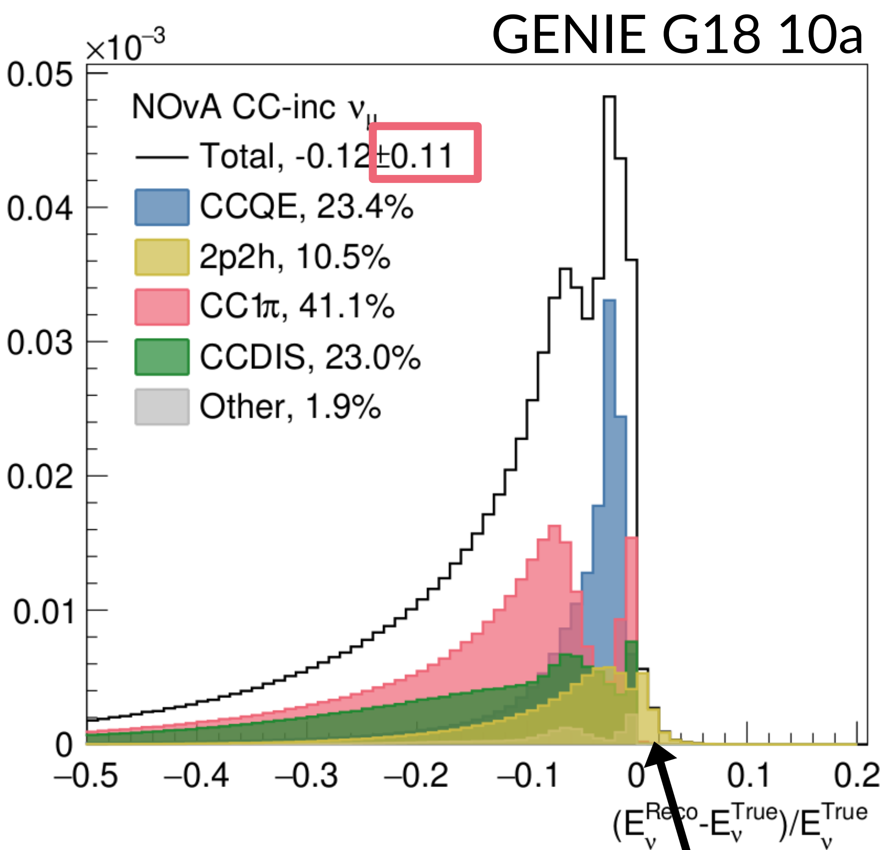
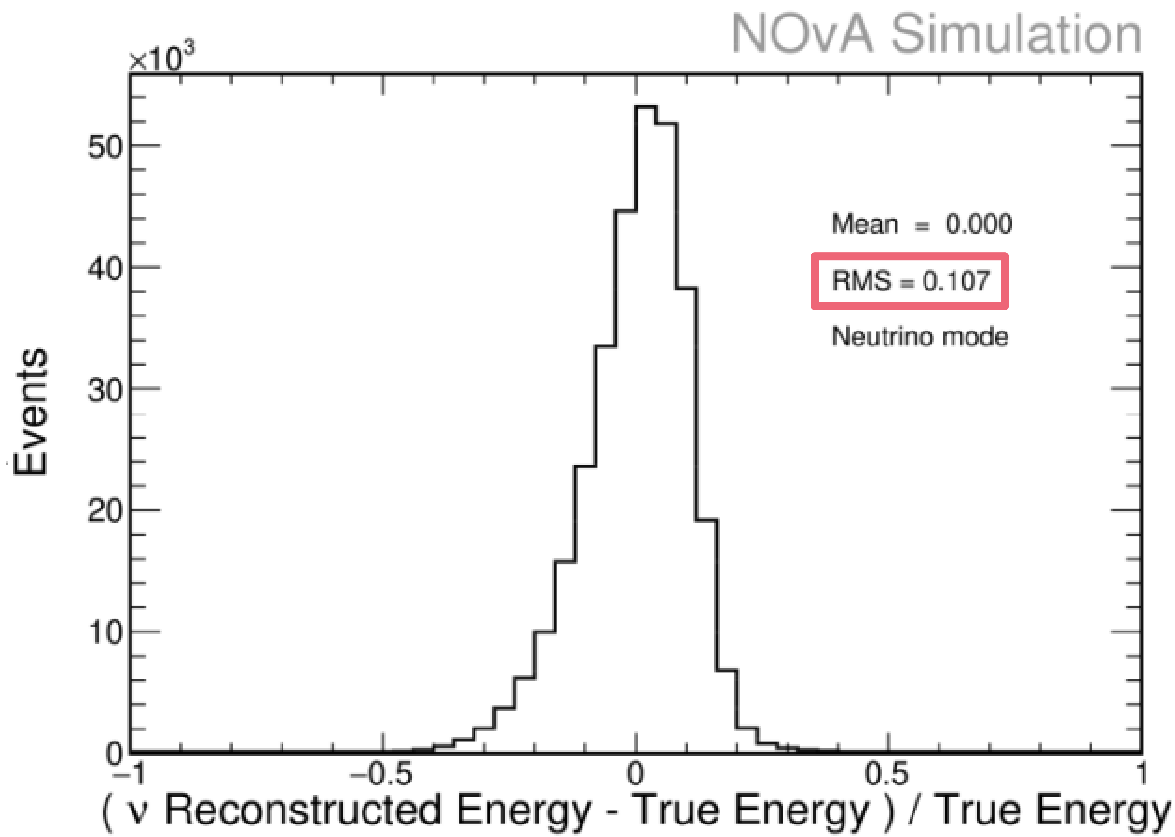


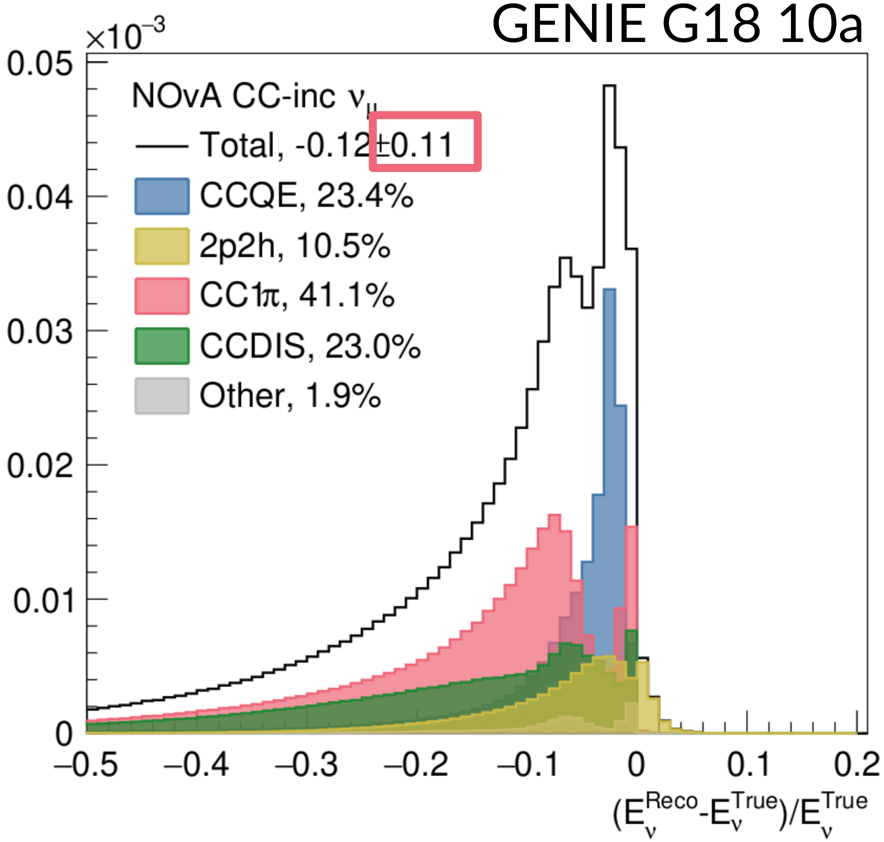


- Interaction modes bias differently, e.g. DIS has multiple neutrons and and pion that may undergo FSI

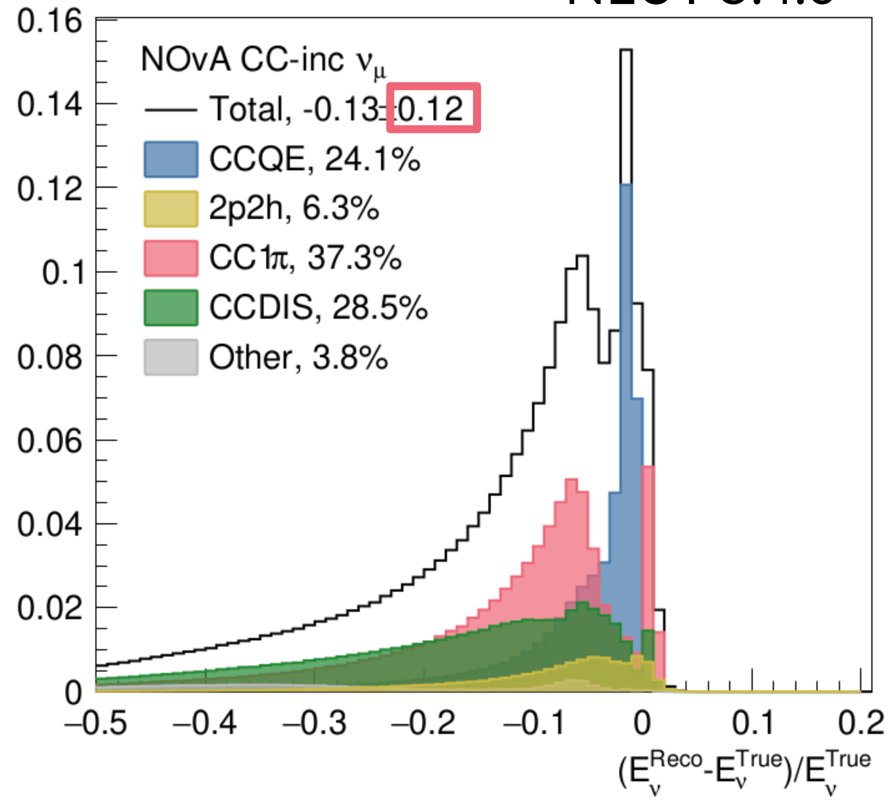
Calorimetric energy reconstruction

- Use a different generator (NEUT), approximately the same result as GENIE G18 10a

GENIE G18 10a



NEUT 5.4.0



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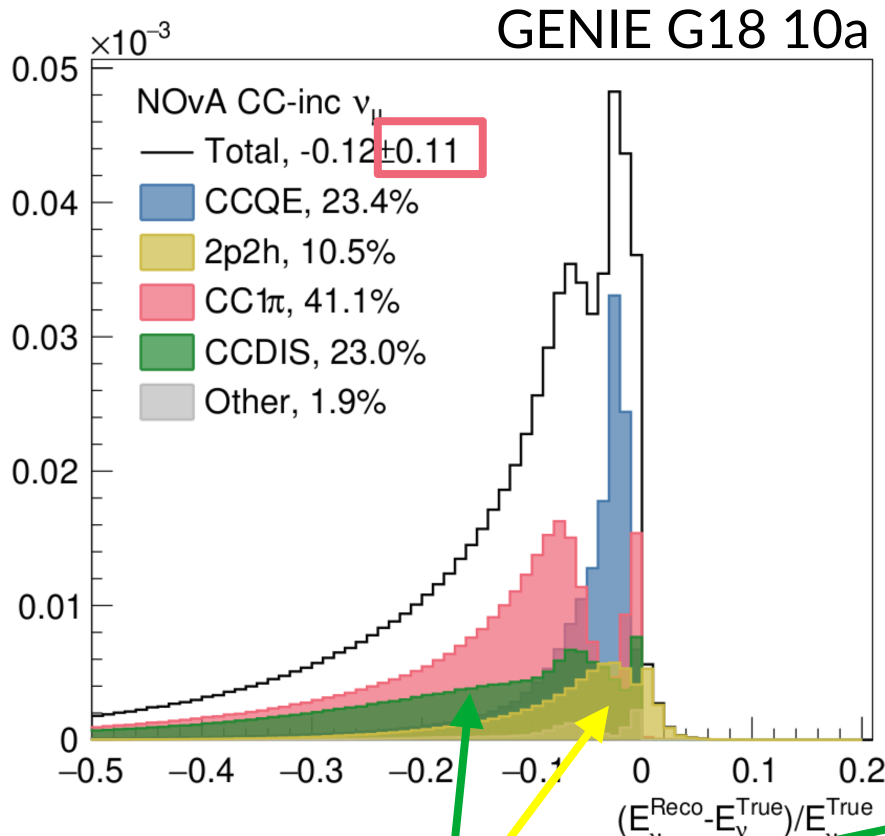
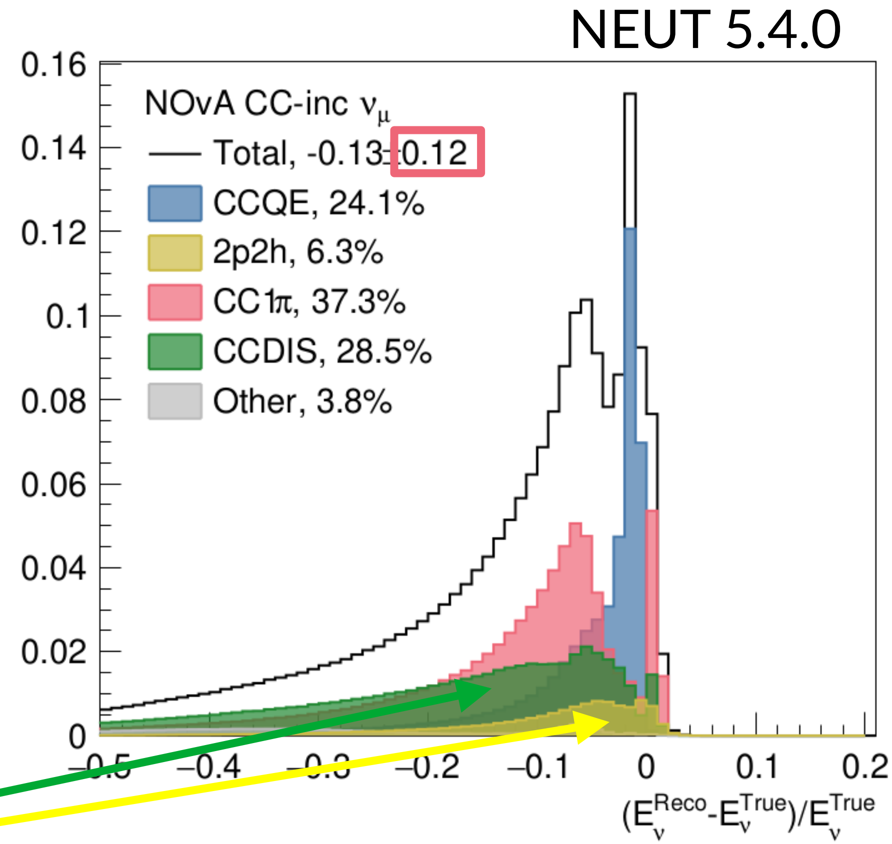




- Or… is it the same result?
  - Bias in the tail clearly different; source of uncertainty

Calorimetric energy reconstruction

- Generally **more precise energy estimate** than kinematic method (shown next)
- Susceptible to **missing neutrons** and other particles
- **Final-state interactions** directly bias the estimator
  - Absorption, charge exchange, nucleon knock-out, energy lost from rescattering
- Relies on **correct PID of every track**, otherwise risk bias by rest mass (e.g. mistake proton for pion)
- Will always have bias from **initial state motion**
  - Smaller impact at higher energies, e.g. NOvA and DUNE
- CC-inclusive selection means **complex contributions from multiple interaction modes**
  - Especially for DUNE and NOvA (many interaction modes)

Paraphrasing from Stephen:

"When we look at external data, the lepton kinematics are often OK. But the hadrons are a mess!"

General rule of thumb

Lepton kinematics
(except maybe at low energy transfers)

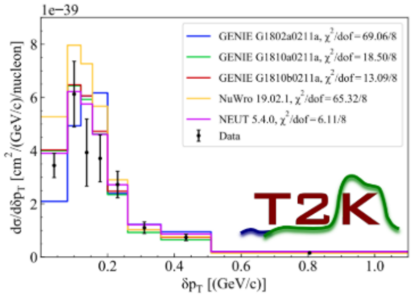
Lepton-hadron correlations

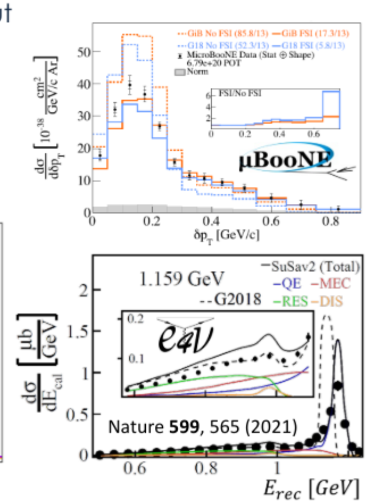
Generators vs data: a horror story

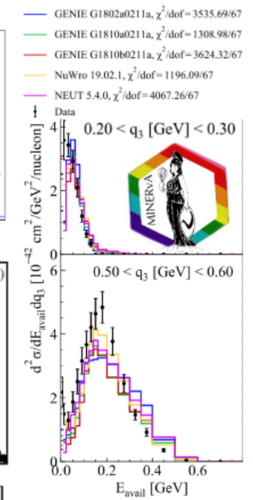
- No generator can come close to describing global data measuring lepton-hadron correlations
  - All models are "wrong", but they are each wrong in different ways

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

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

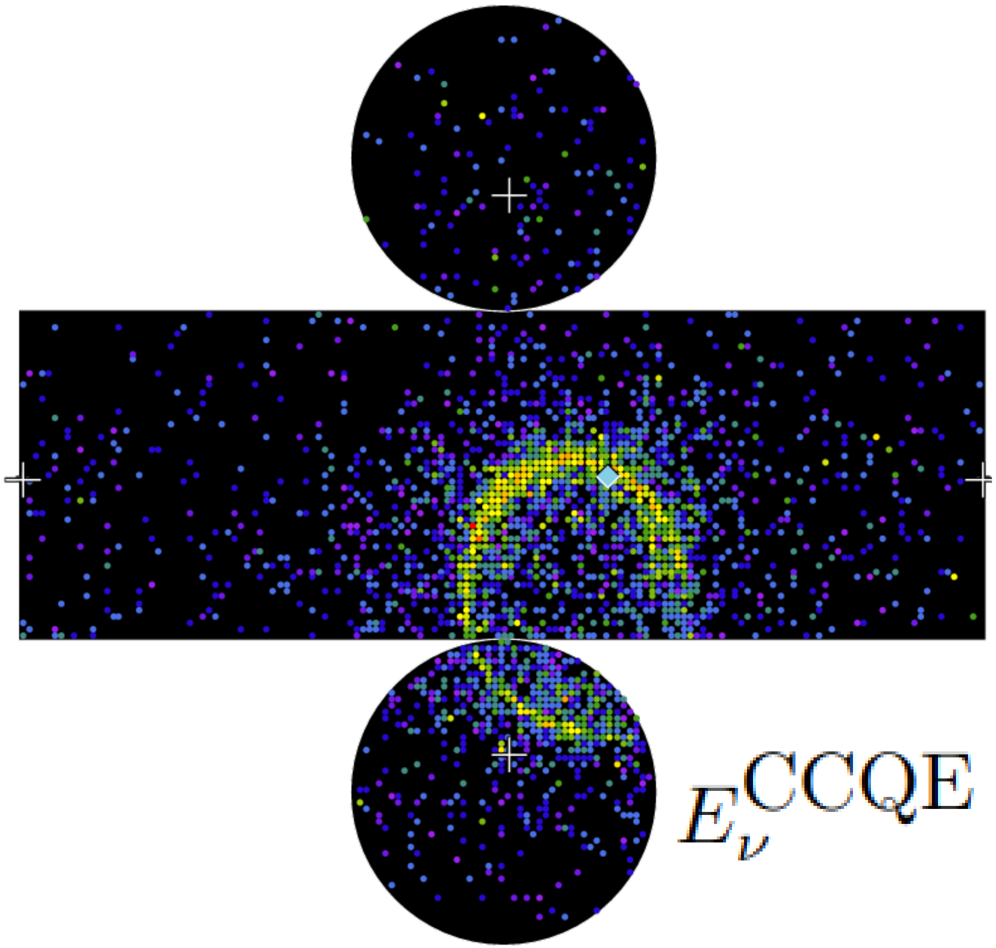






Kinematic energy reconstruction

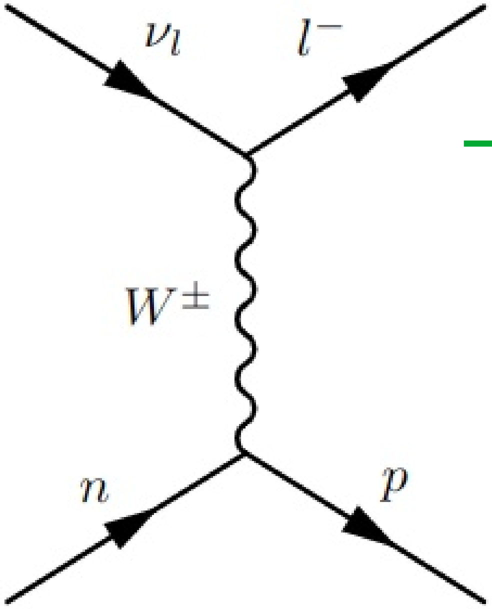
- Energy reconstruction method is function of **selection** and **detector technology**
- T2K and HK are dominated by **CC0π final state**, and Cherenkov threshold for proton is >1 GeV in H_2O



- **Single-track** events
- Kinematic reconstruction using **only lepton** information
- Assumes **4 legged CCQE** interaction, and **initial state nucleon at rest**

$$E_\nu^{\mathrm{CCQE}} = \frac{2m_N E_l - m_l^2 + m_{N'}^2 - m_N^2}{2\left(m_N - E_l + p_l \cos\theta_{\nu,l}\right)}$$

Kinematic energy reconstruction



Any interest in deriving this?

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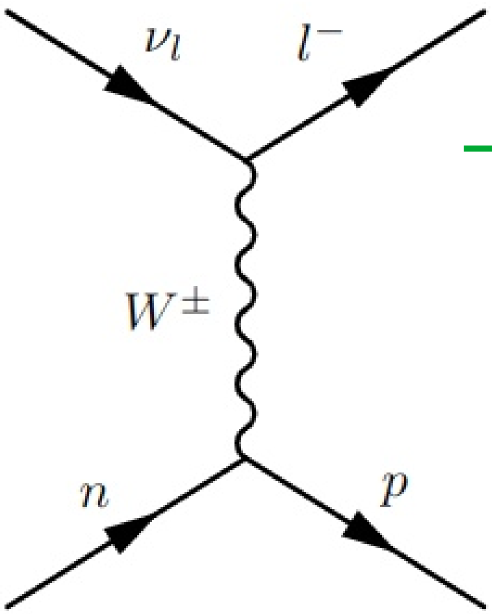

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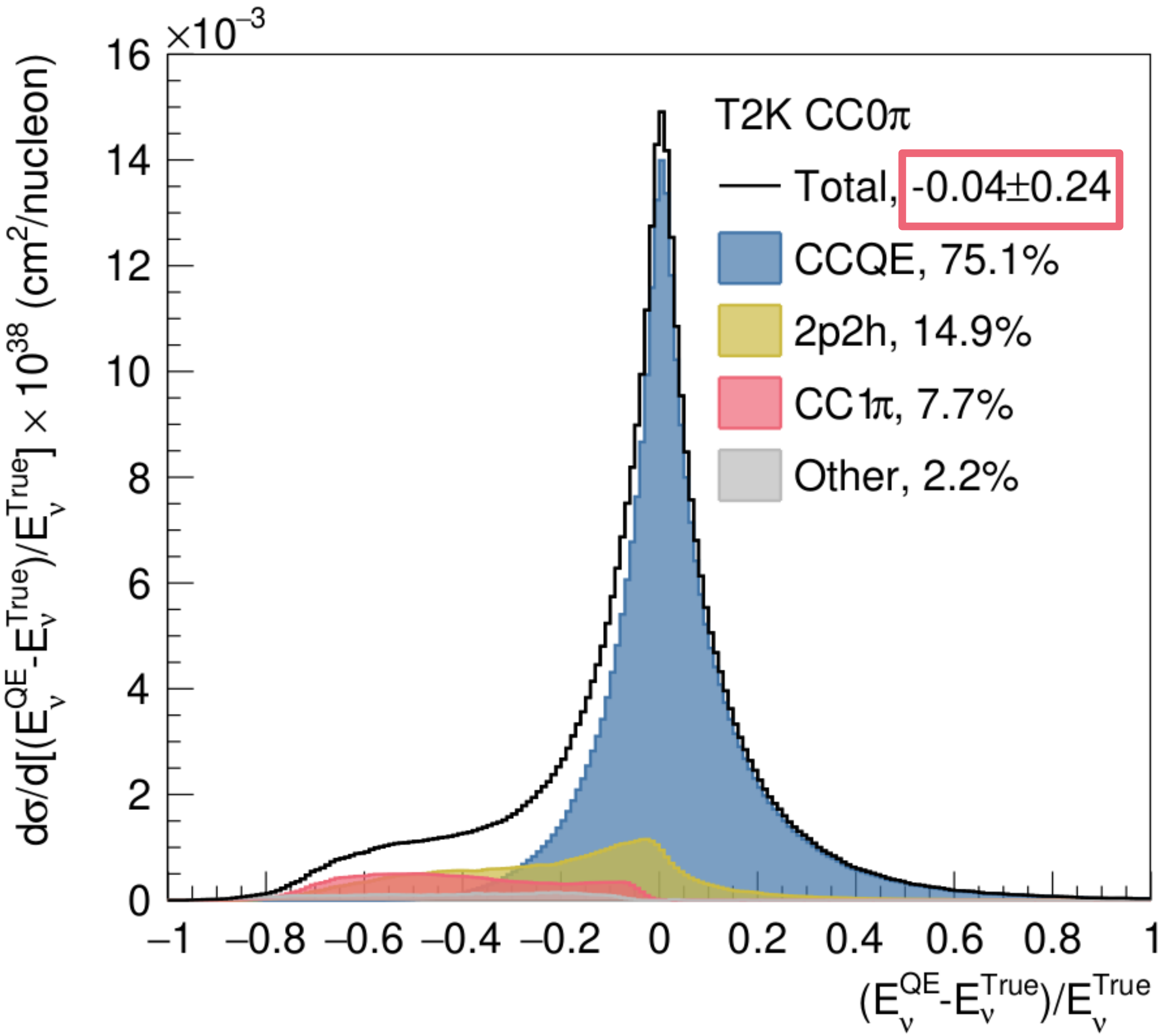
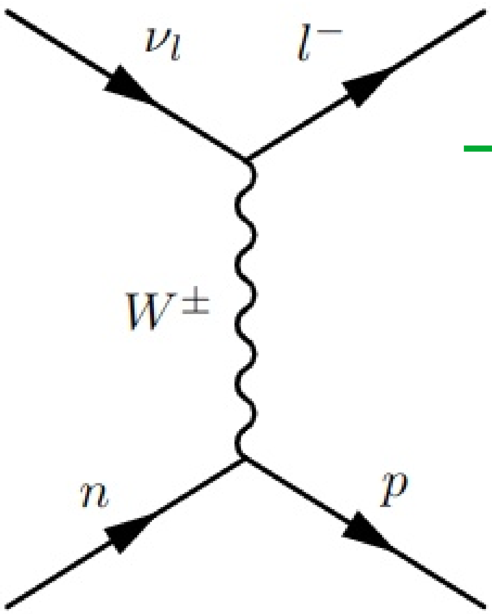


- **CCQE** contribution largely **unbiased**
- **20-25% RMS**
- CC1π+FSI and 2p2h contribution **less than 25%of total signal**

Kinematic energy reconstruction



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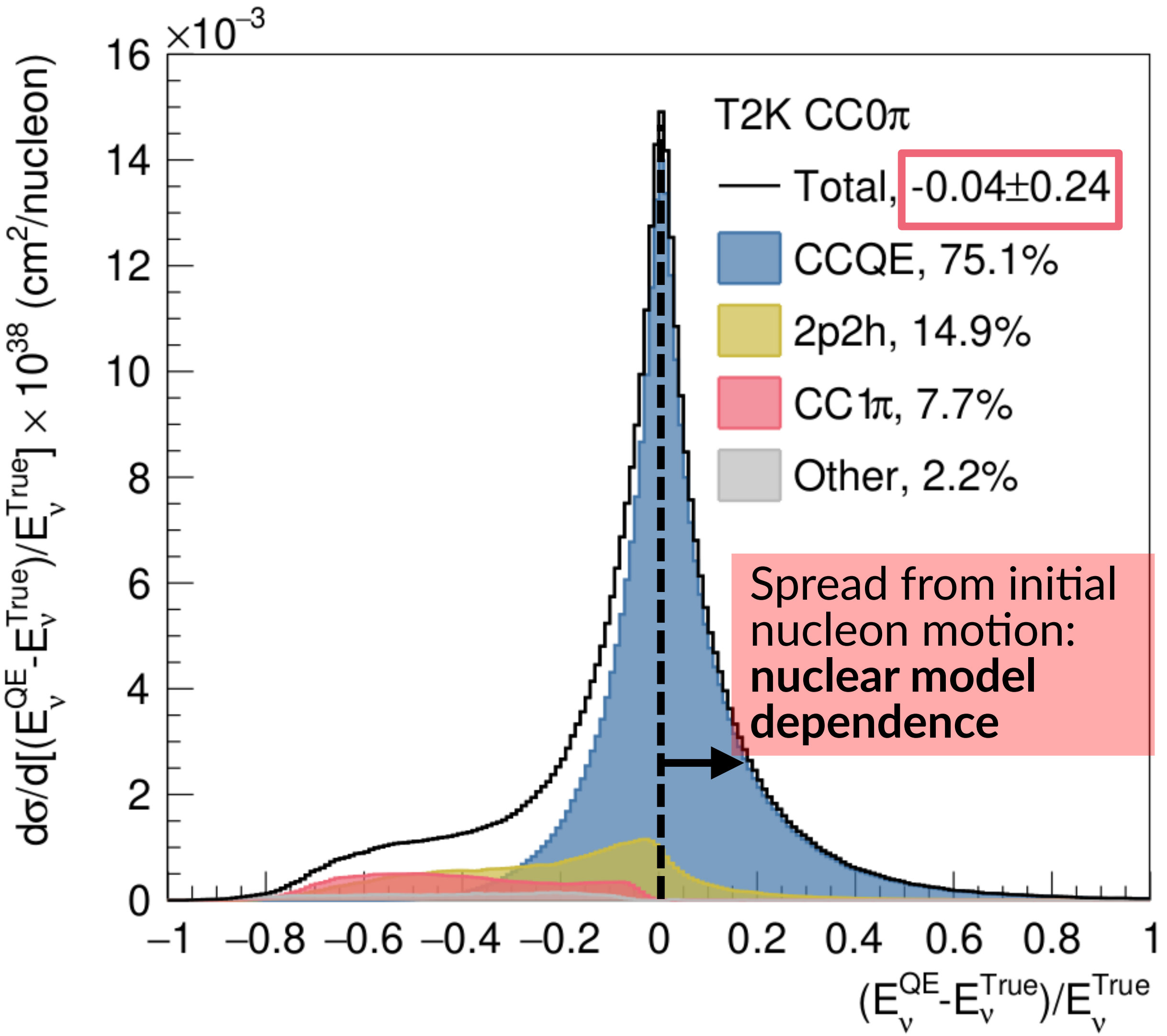

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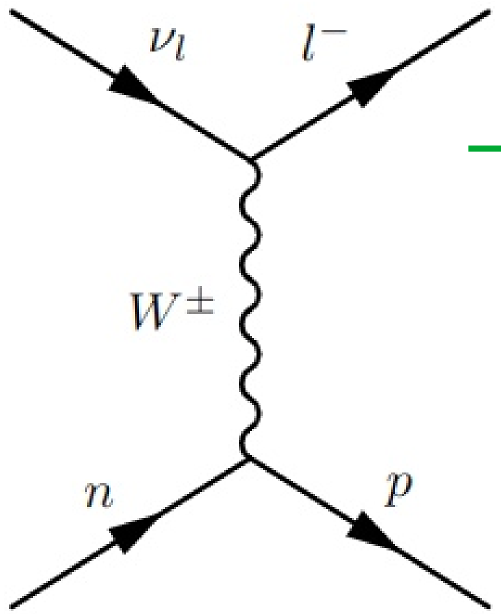

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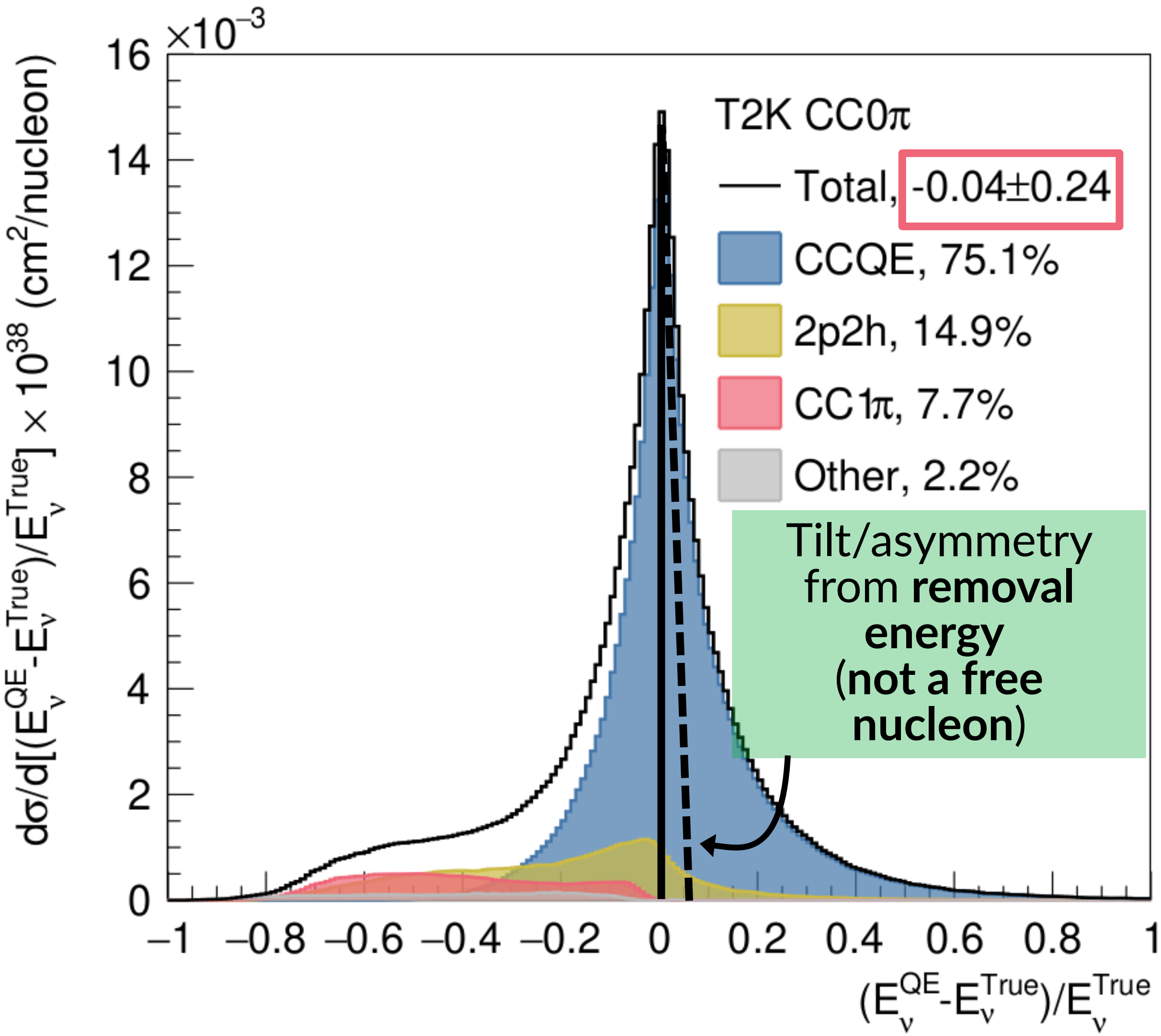

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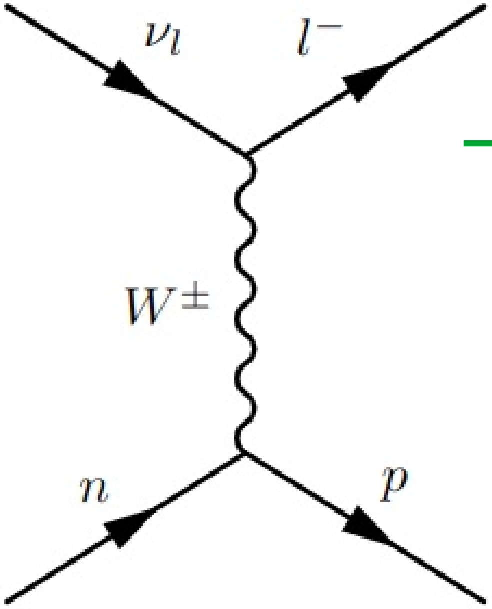

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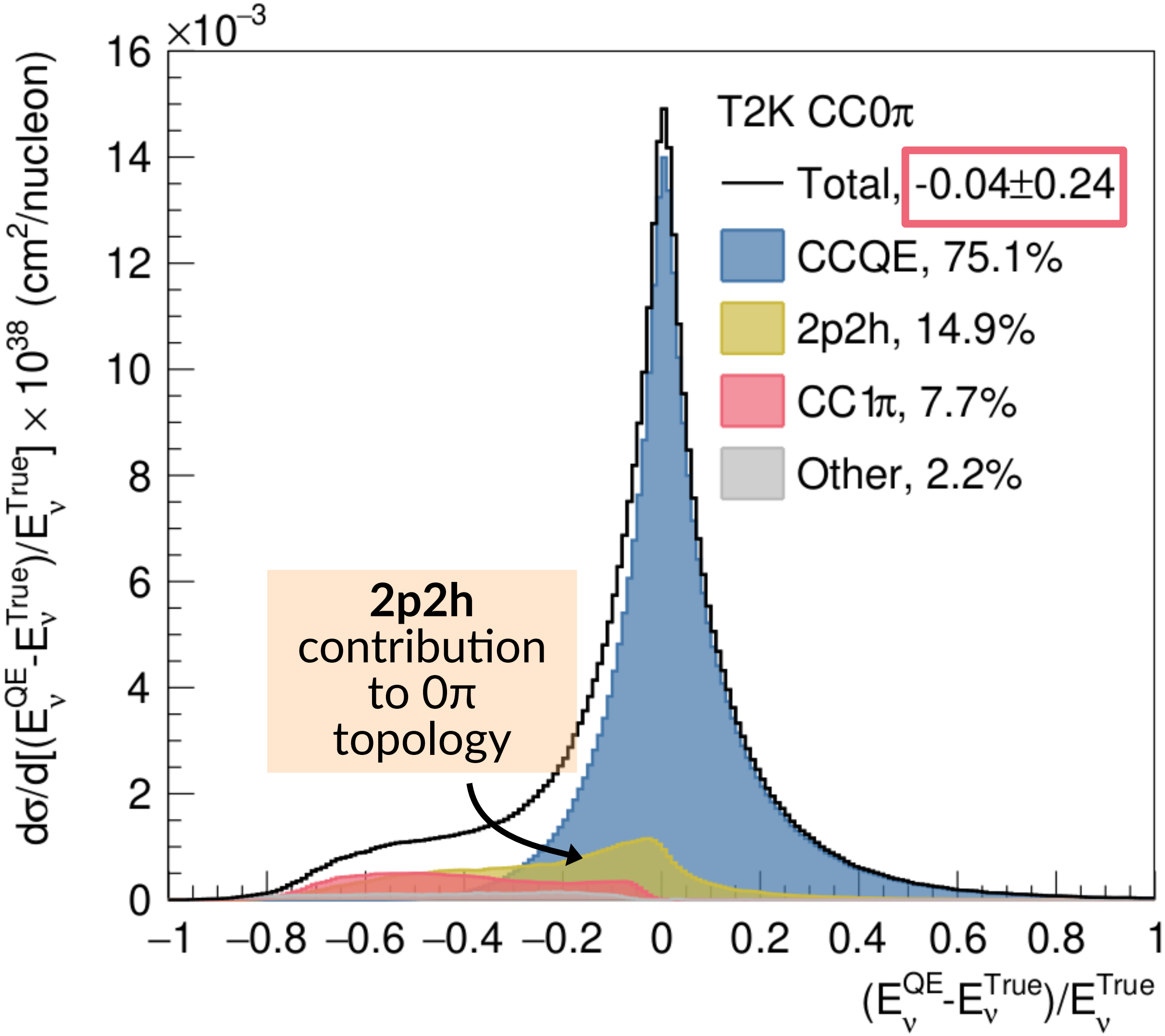

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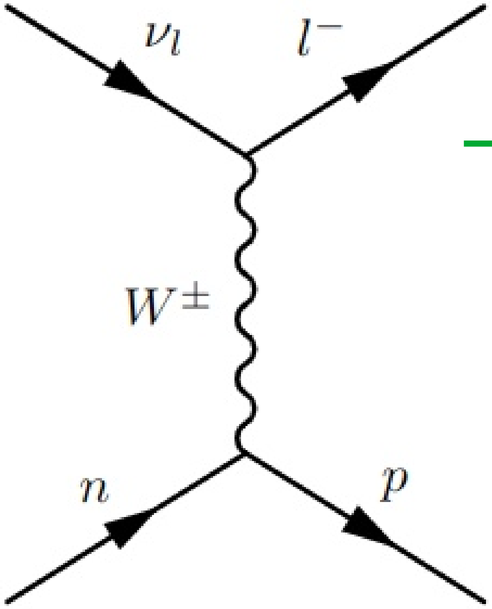

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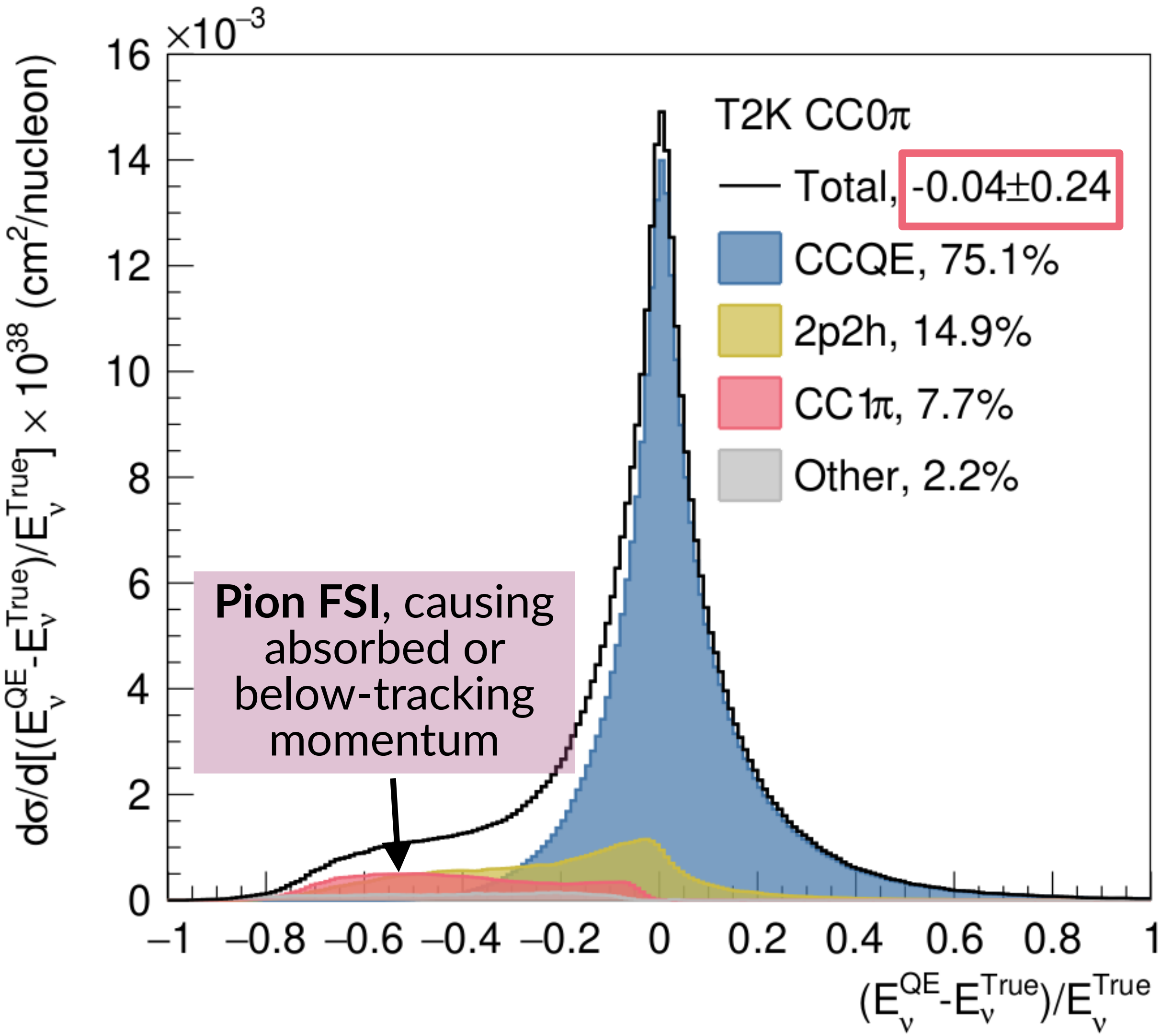

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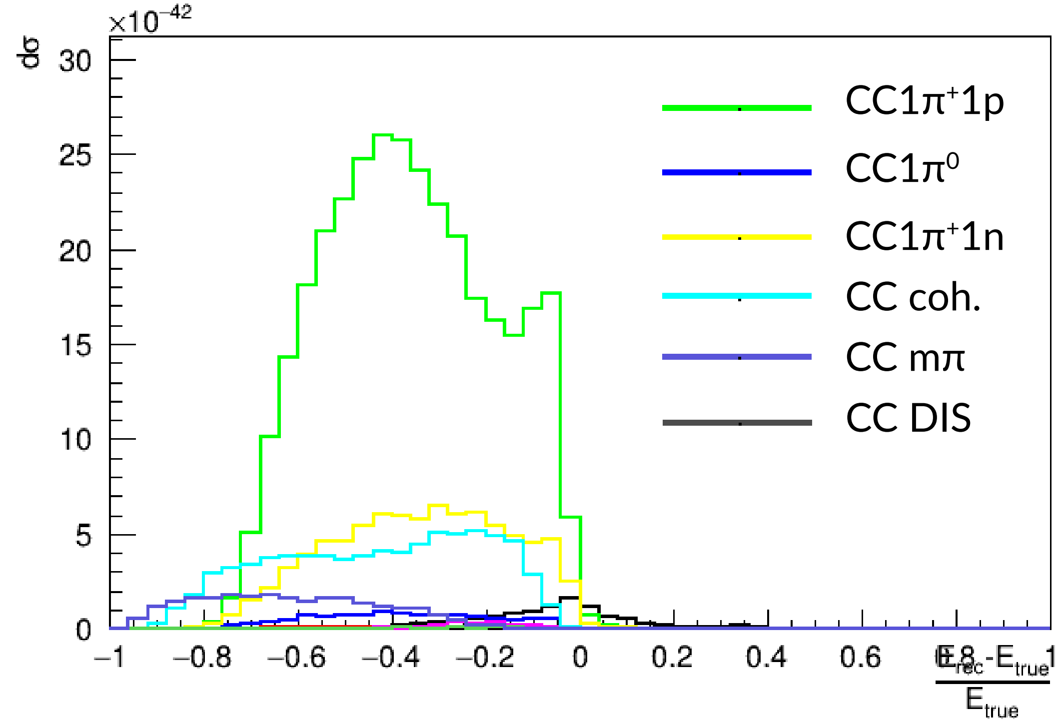
Kinematic energy reconstruction

- When applied to T2K's CC1π sample, we get a large bias
  - This is for CC1π events with a pion below 200 MeV/c momentum
- How can we improve?



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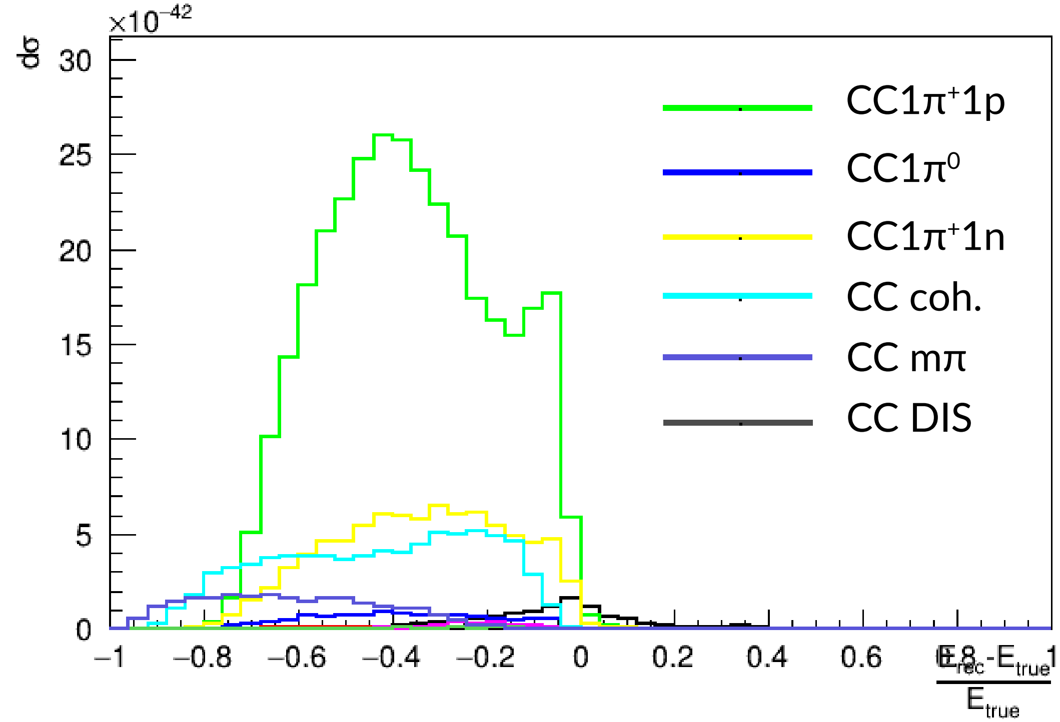
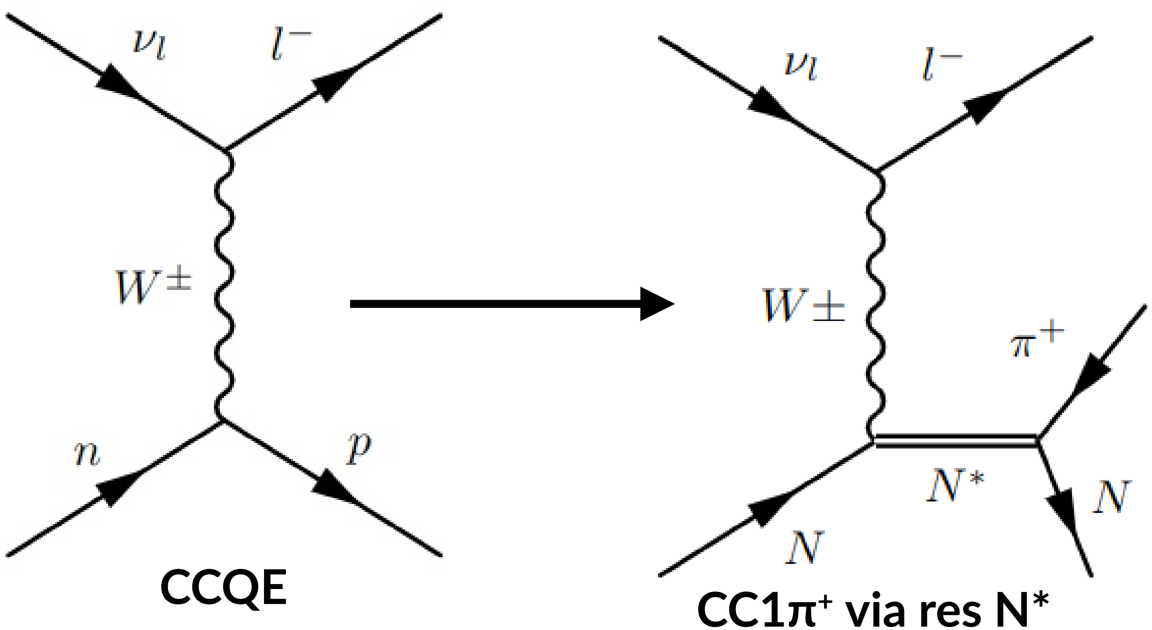


Clue:



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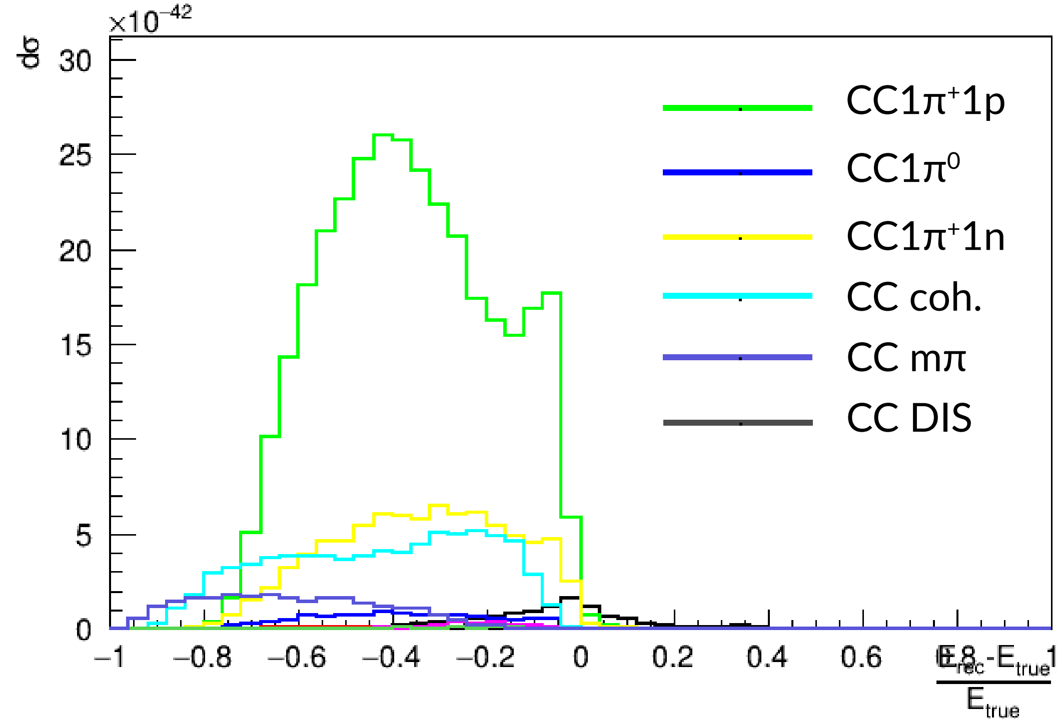

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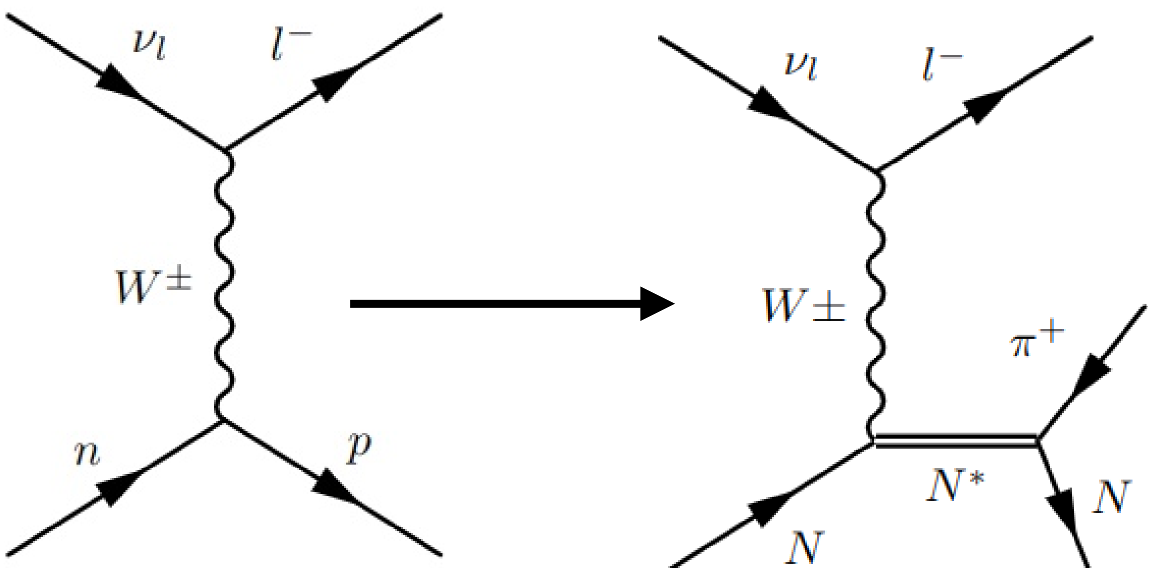
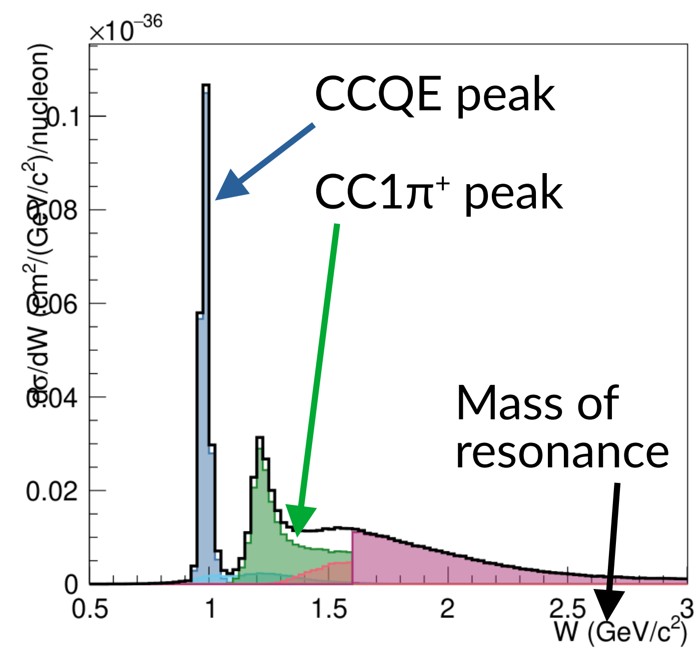


CCQE

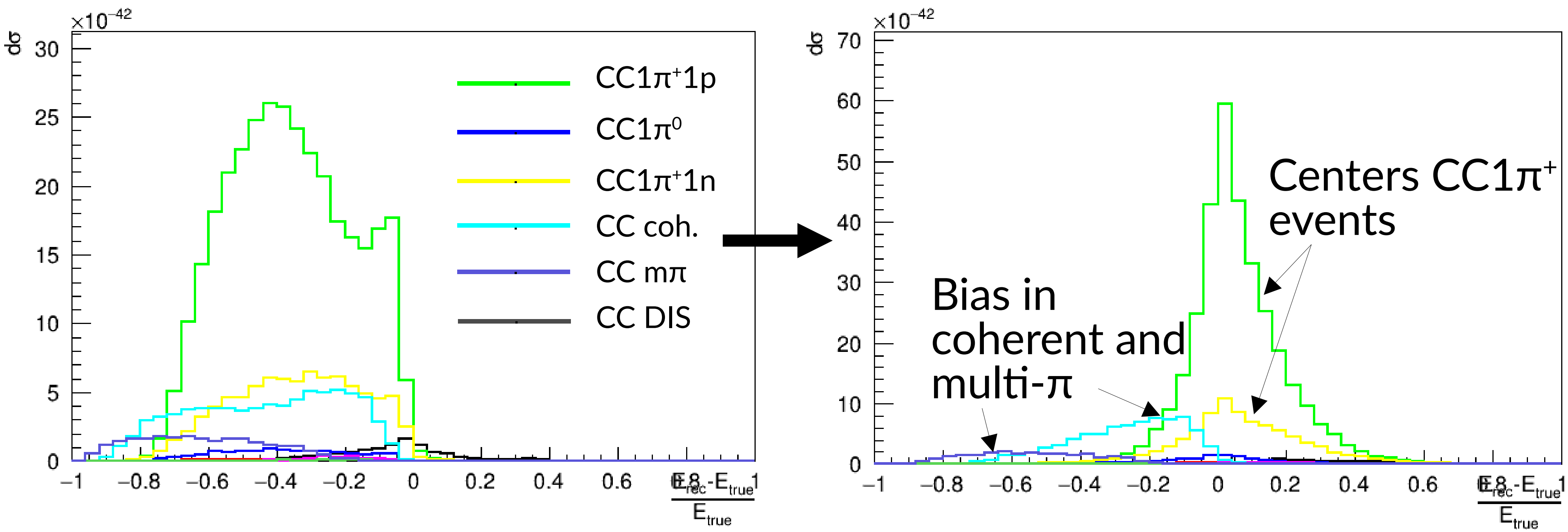
CC1π+ via res N*



Kinematic energy reconstruction

Replace $\boldsymbol{m_{N'}}$ (~0.938 GeV/c^2)
by $\boldsymbol{m_{\Delta}}$ (~1.232 GeV/c^2)

$$E_\nu^{\mathrm{CCQE}} = \frac{2m_N E_l - m_l^2 + m_{N'}^2 - m_N^2}{2\left(m_N - E_l + p_l \cos\theta_{\nu,l}\right)}$$

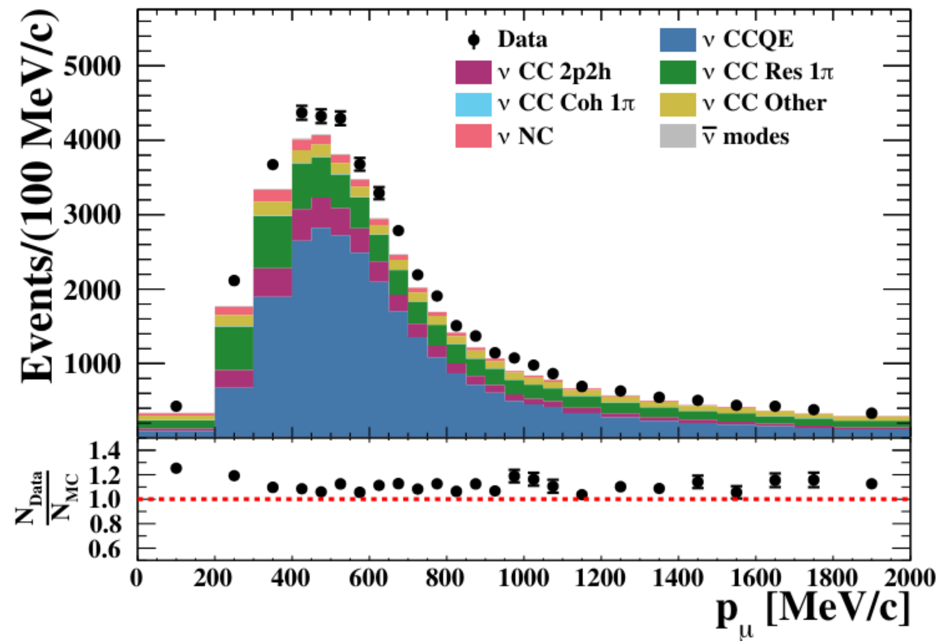


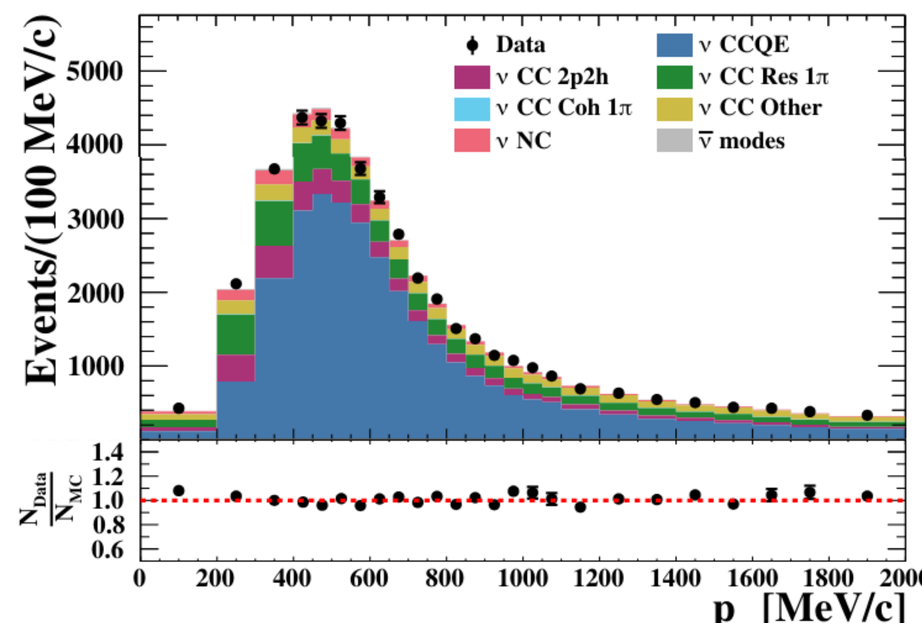
Kinematic energy reconstruction

- Important to get the **CCQE, 2p2h and CC1π contributions correct**
  - They bias the estimator differently: mistaking non-CCQE for CCQE imposes a bias
- Direct **dependence** on **nuclear initial-state model**
  - Relatively large contribution at E_ν=0.6 GeV
- Only dependent on **FSI in the absorption**
  - Proton may lose energy to nucleus; does not matter in estimator
  - Secondary dependence on FSI through **missing particles**: think it's four-limbed interaction when it was not
- **Small contribution** from higher W resonances, SIS and DIS contributions (if T2K energies!)

Using the near detector in analysis

- T2K builds prediction for data at the ND using model parameters
  - e.g. Nieves 2p2h normalisations, CCQE mean-field parameters, single pion production, final-state interactions…





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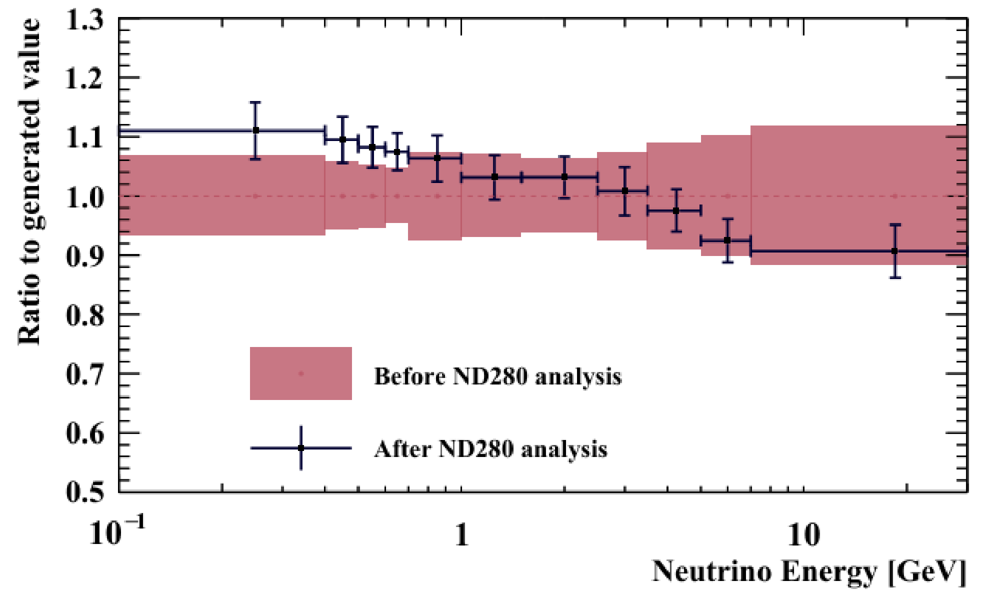

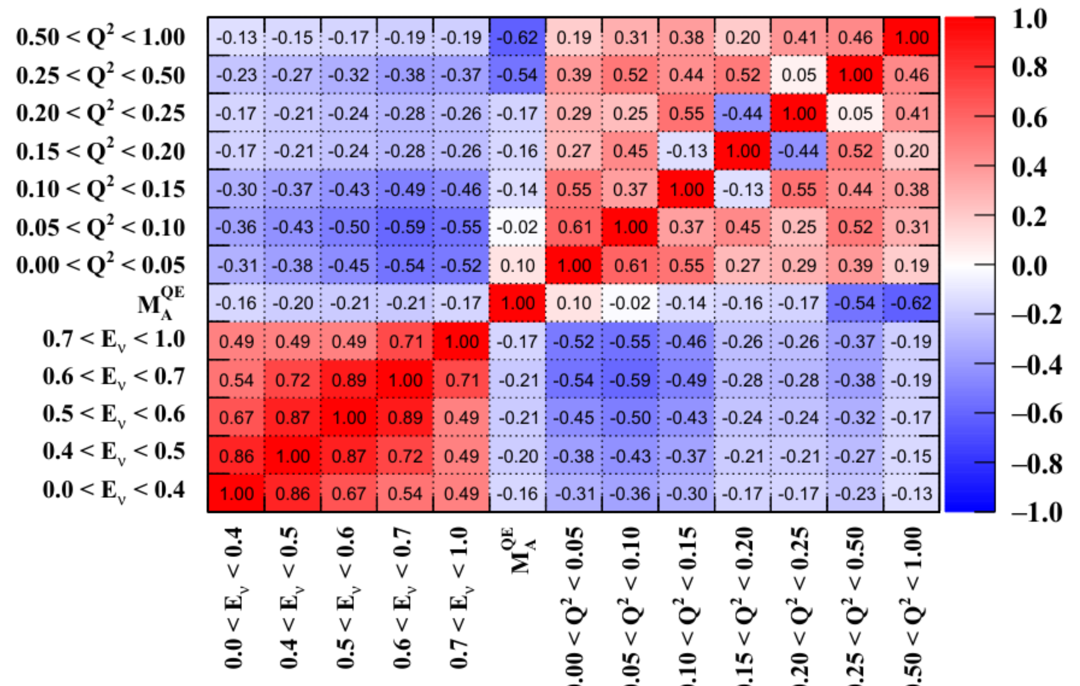

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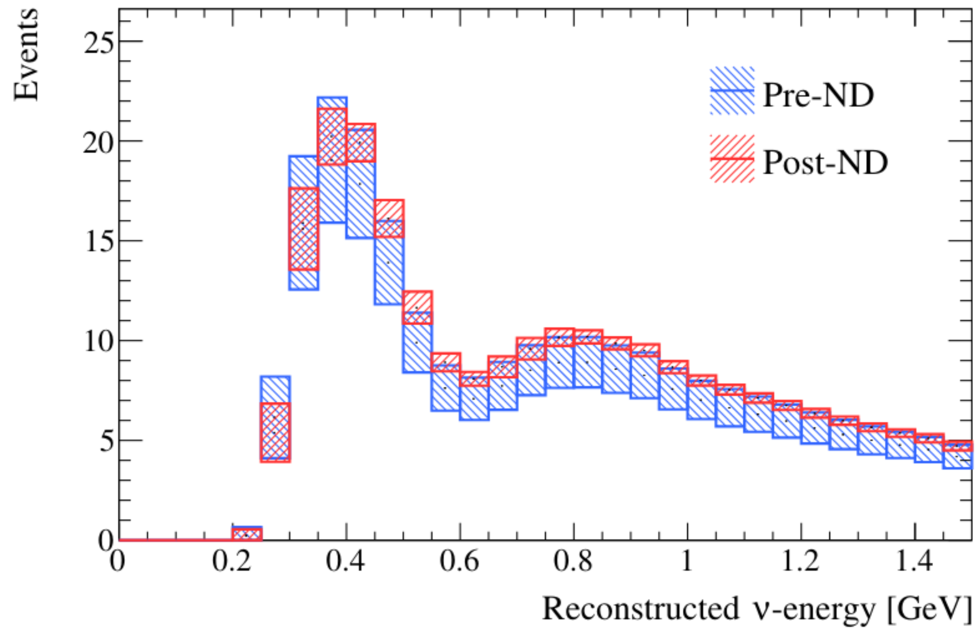
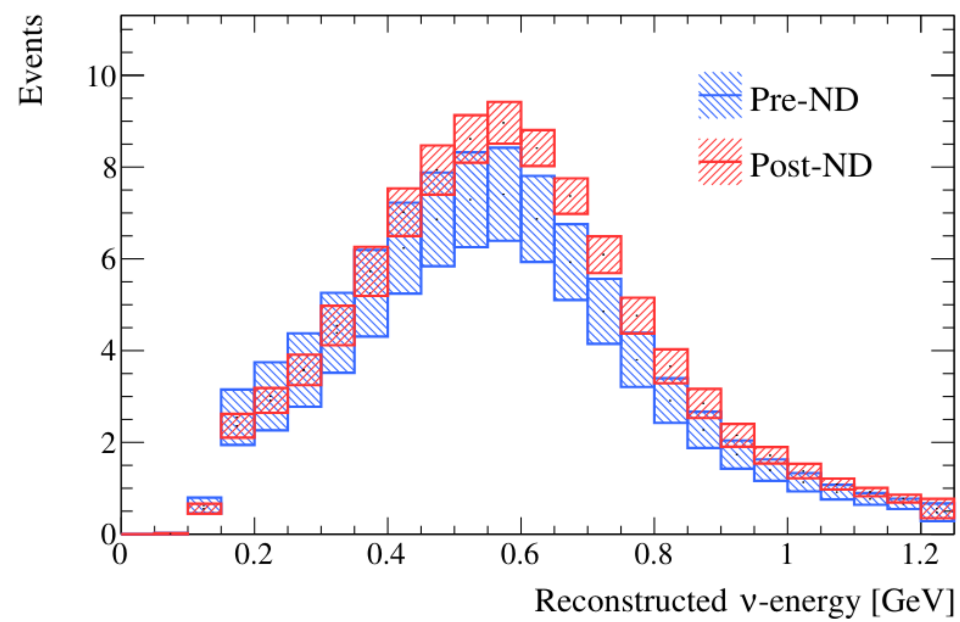
  - Using the adjusted model





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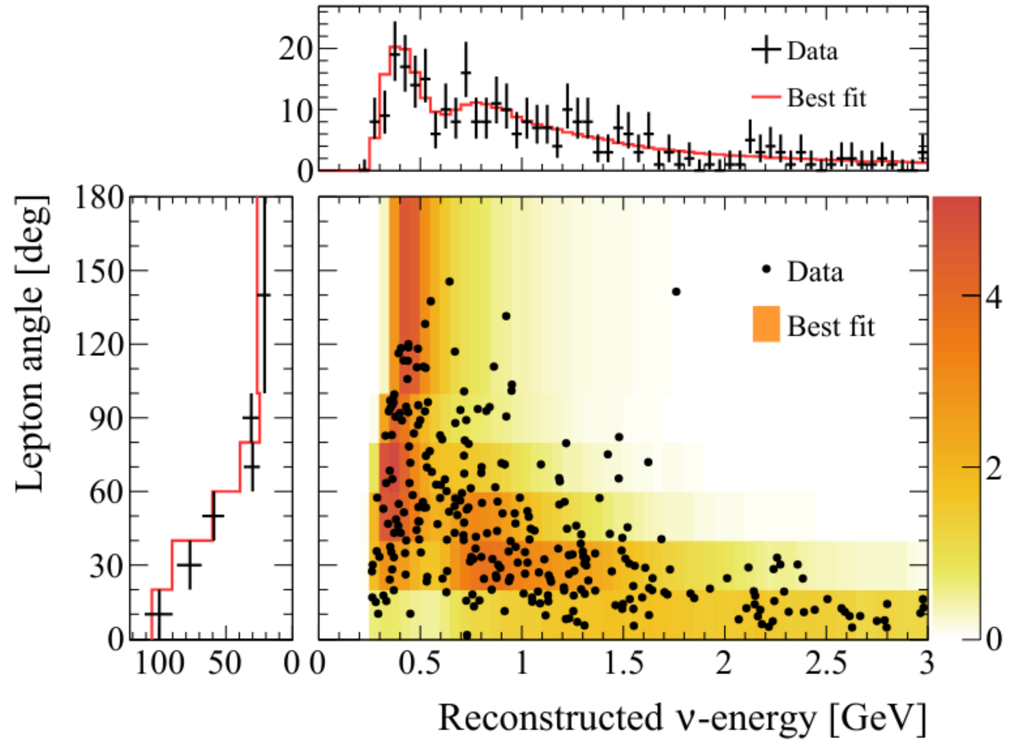
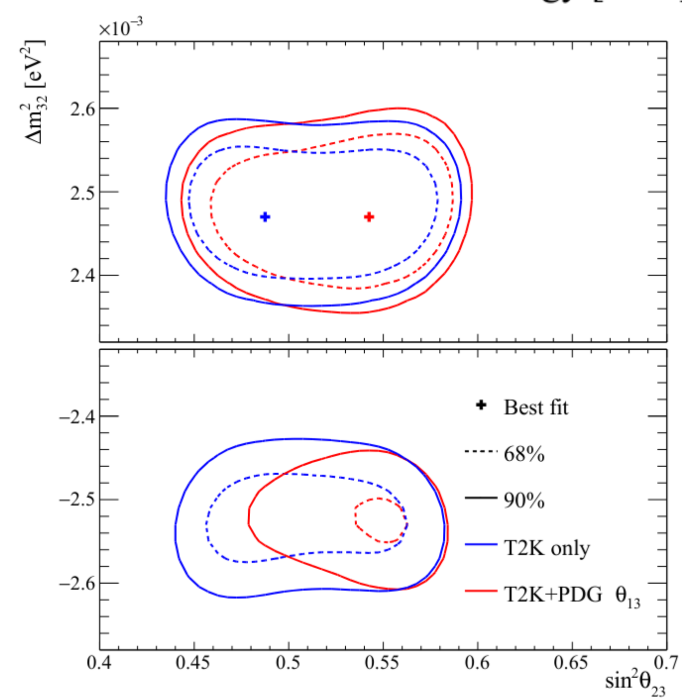
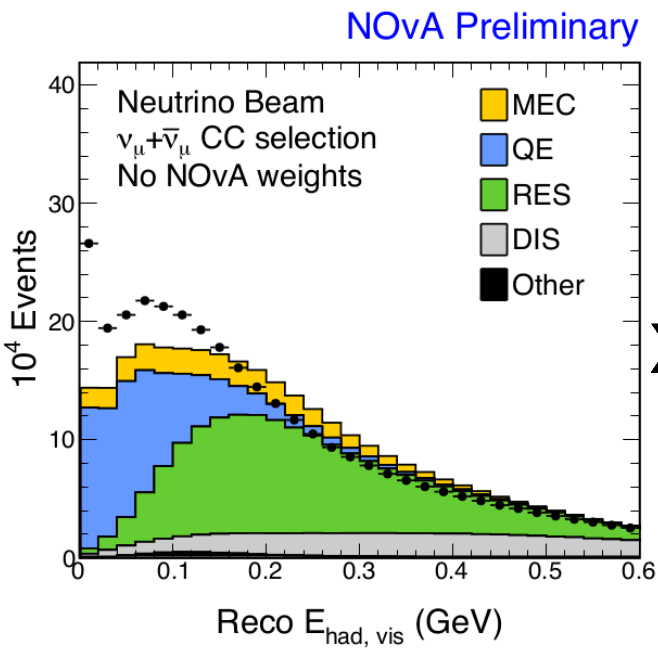
- Fit the oscillation parameters!





Using the near detector in analysis

- NOvA instead first tune **2p2h** model to **data** in **reconstructed hadronic** energy



X

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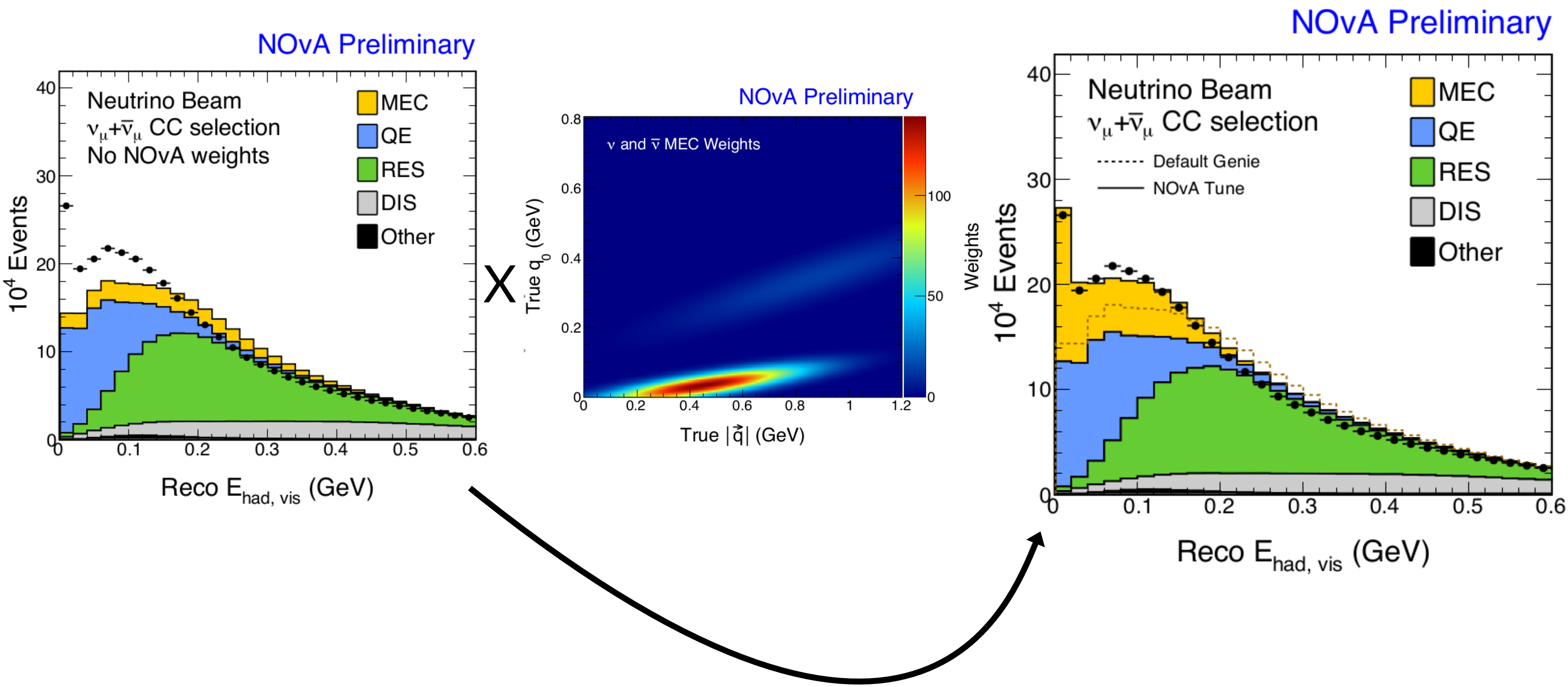

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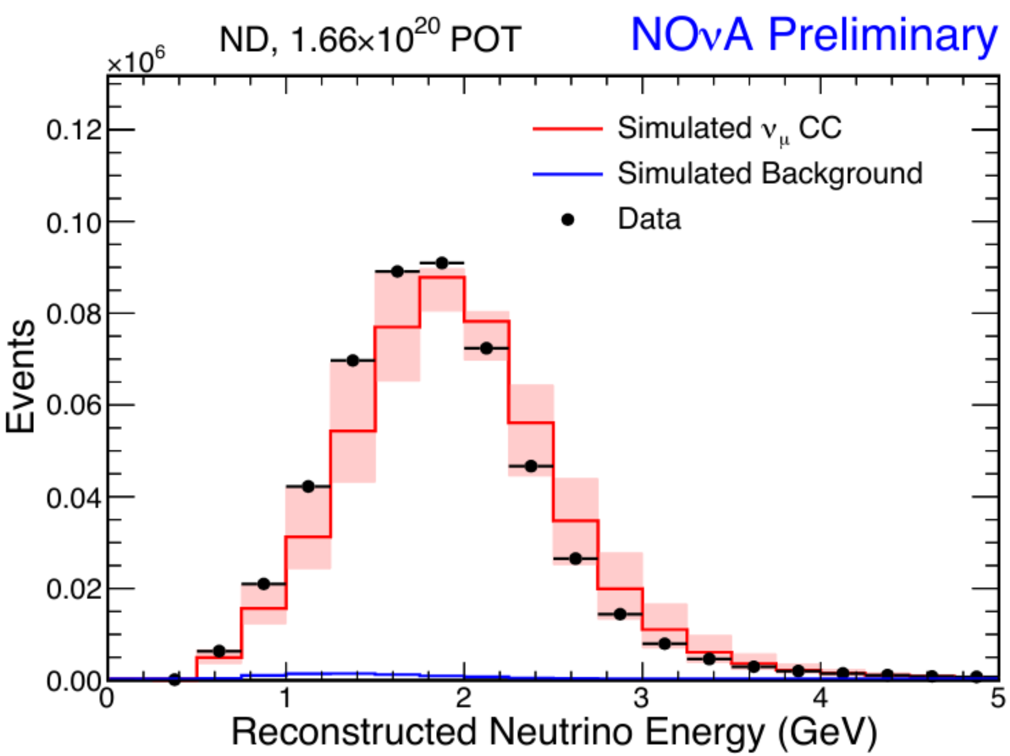
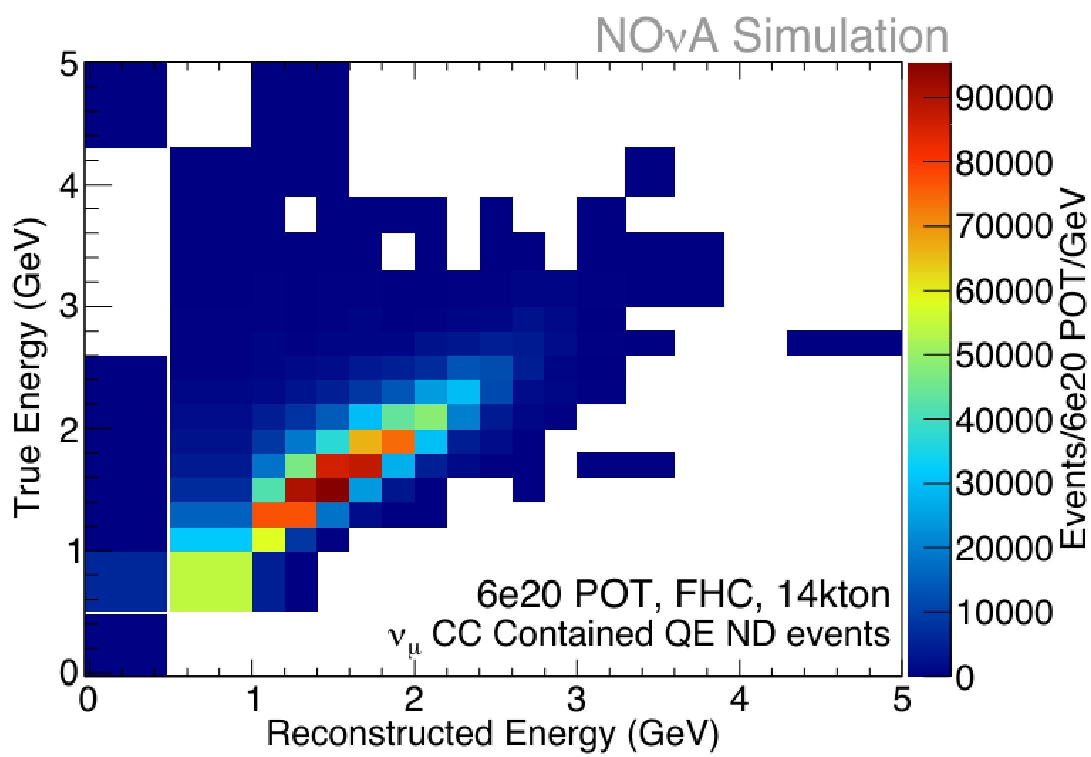
- NOvA instead first tune **2p2h** model to **data** in **reconstructed hadronic** energy
- Unfold **reco neutrino energy** to **true neutrino** energy via ND smearing matrix





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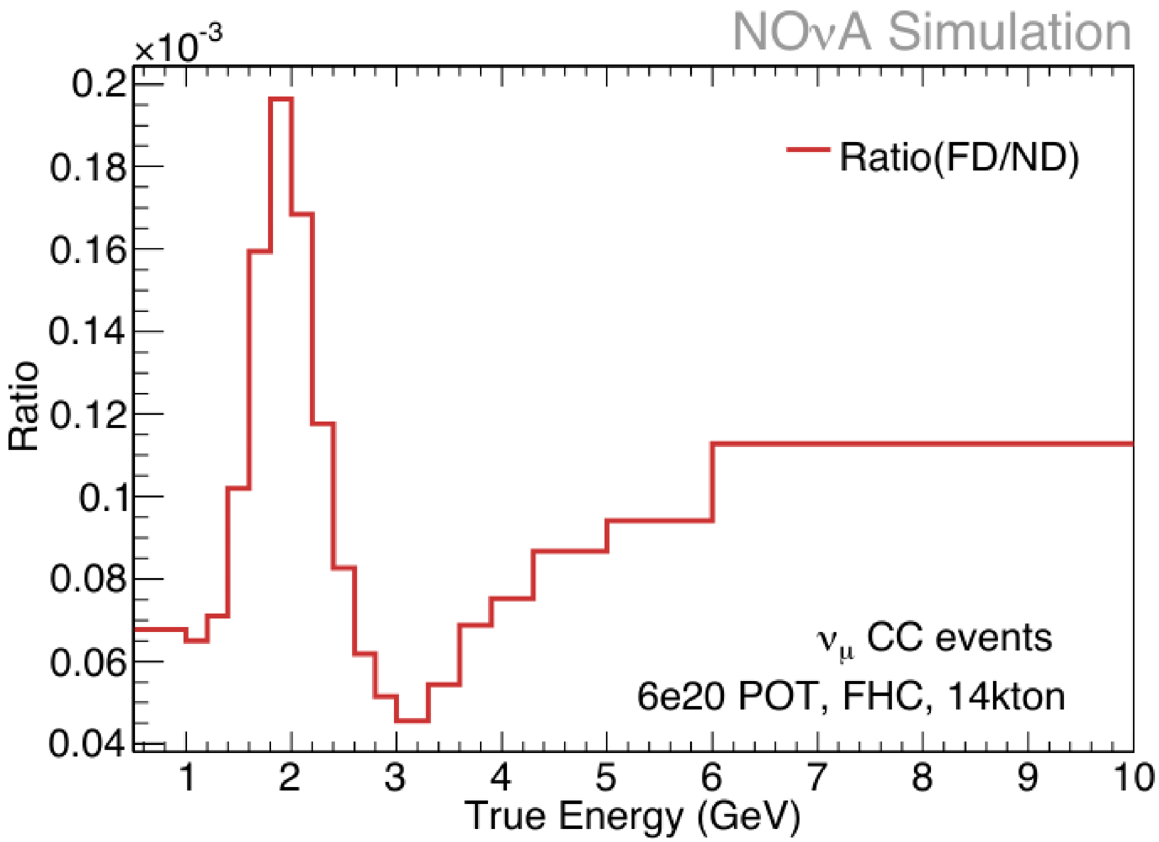

Using the near detector in analysis

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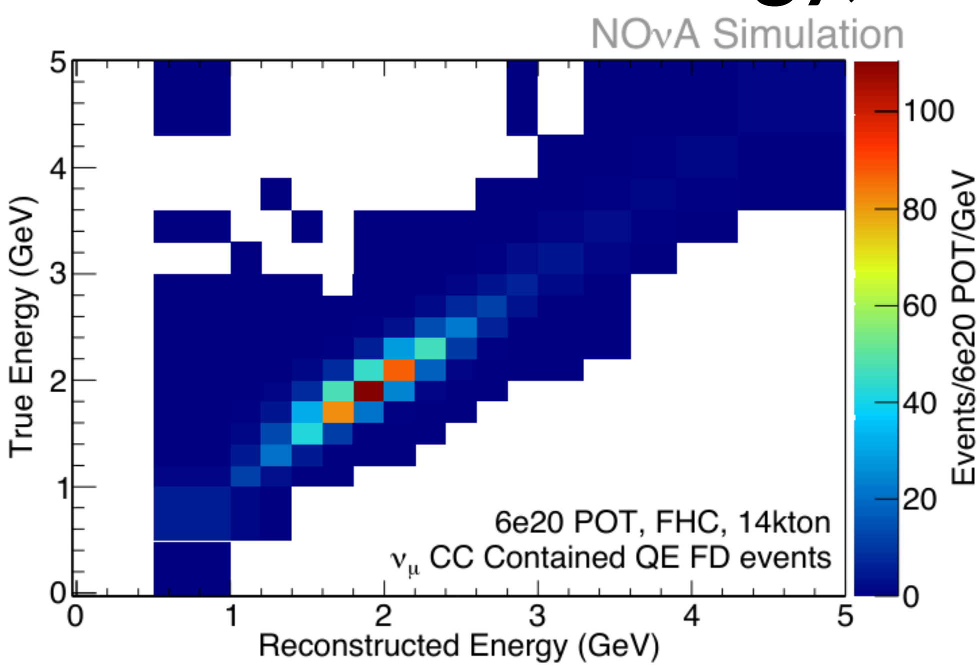
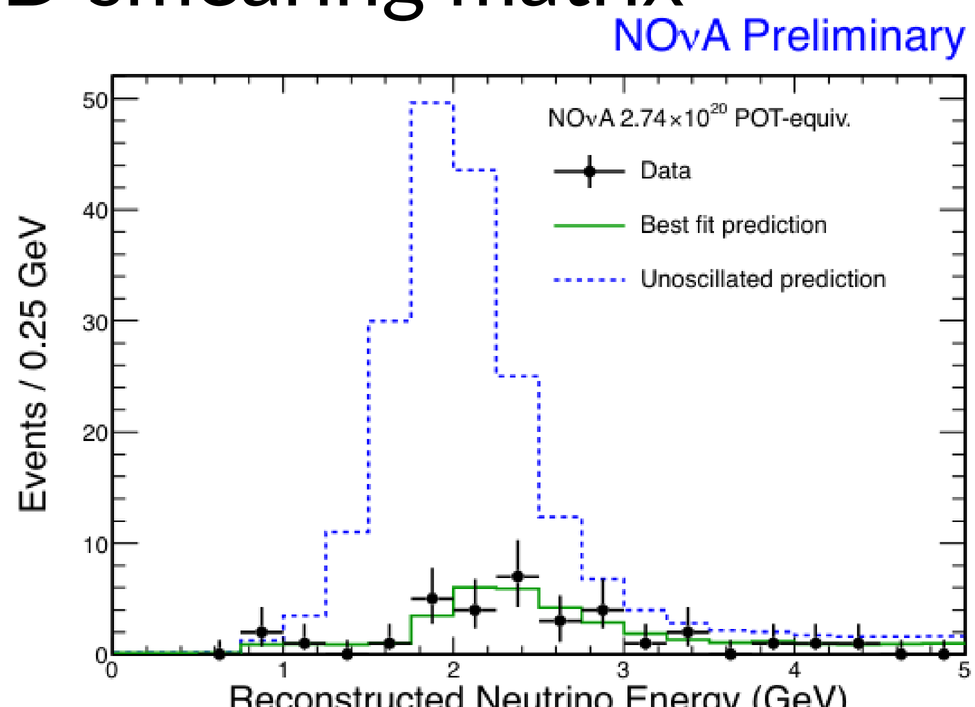
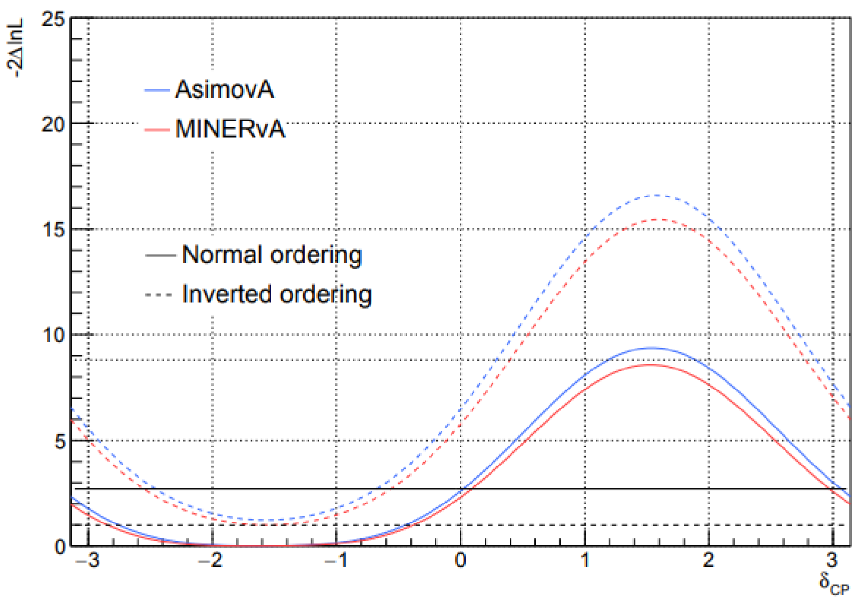
- Fold back into **reconstructed neutrino energy** from **true neutrino energy**, via FD smearing matrix

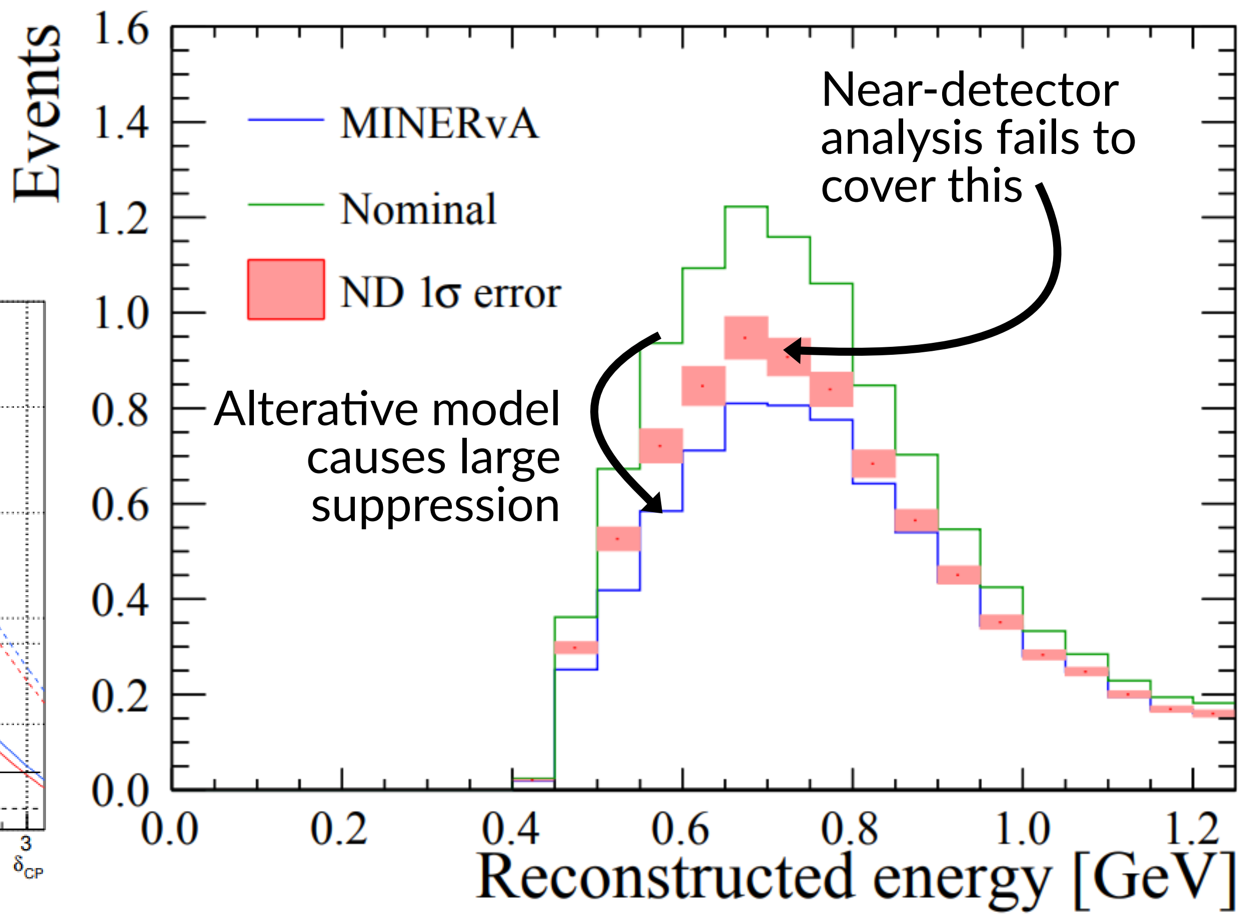




Fake-data studies

- Use an alternative model to make a prediction for near and far detectors
- Fit to the alternative model at the near detector
  - Set of parameters that best describe the alternative model
- Propagate result to far detector, perform oscillation analysis



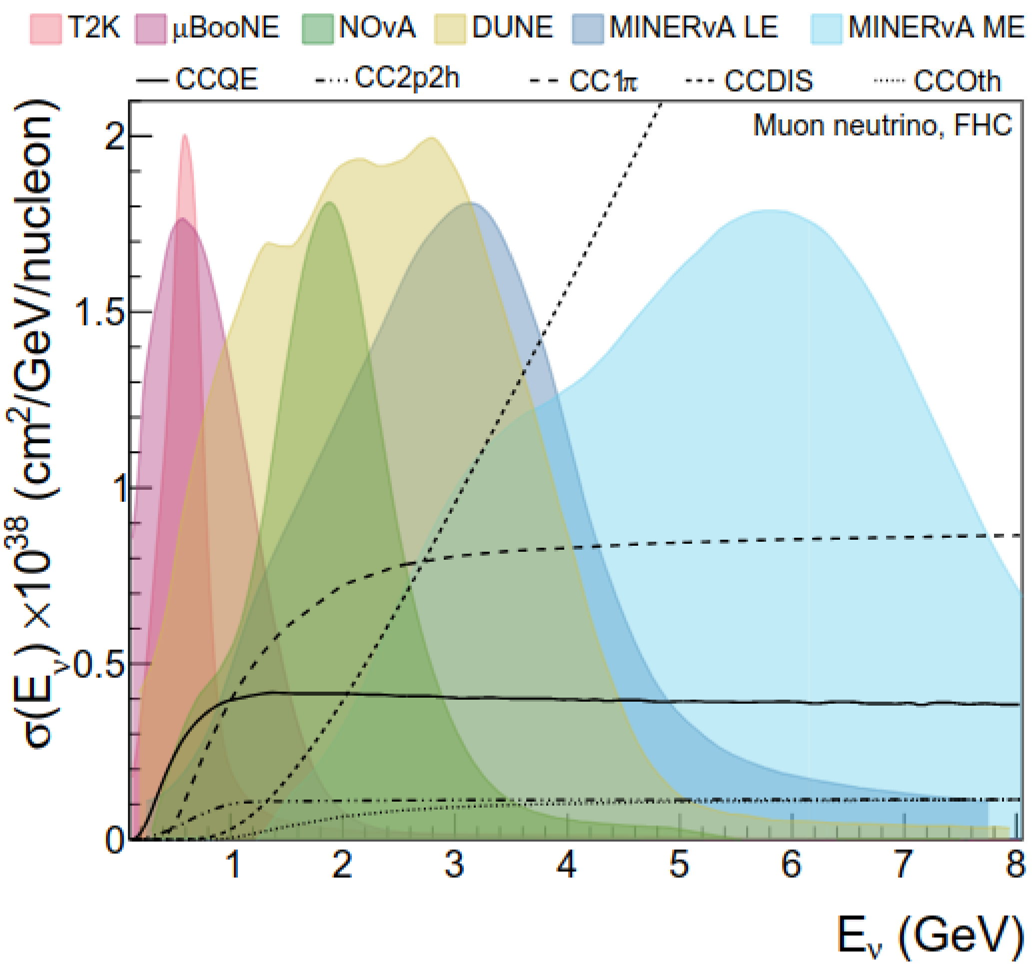


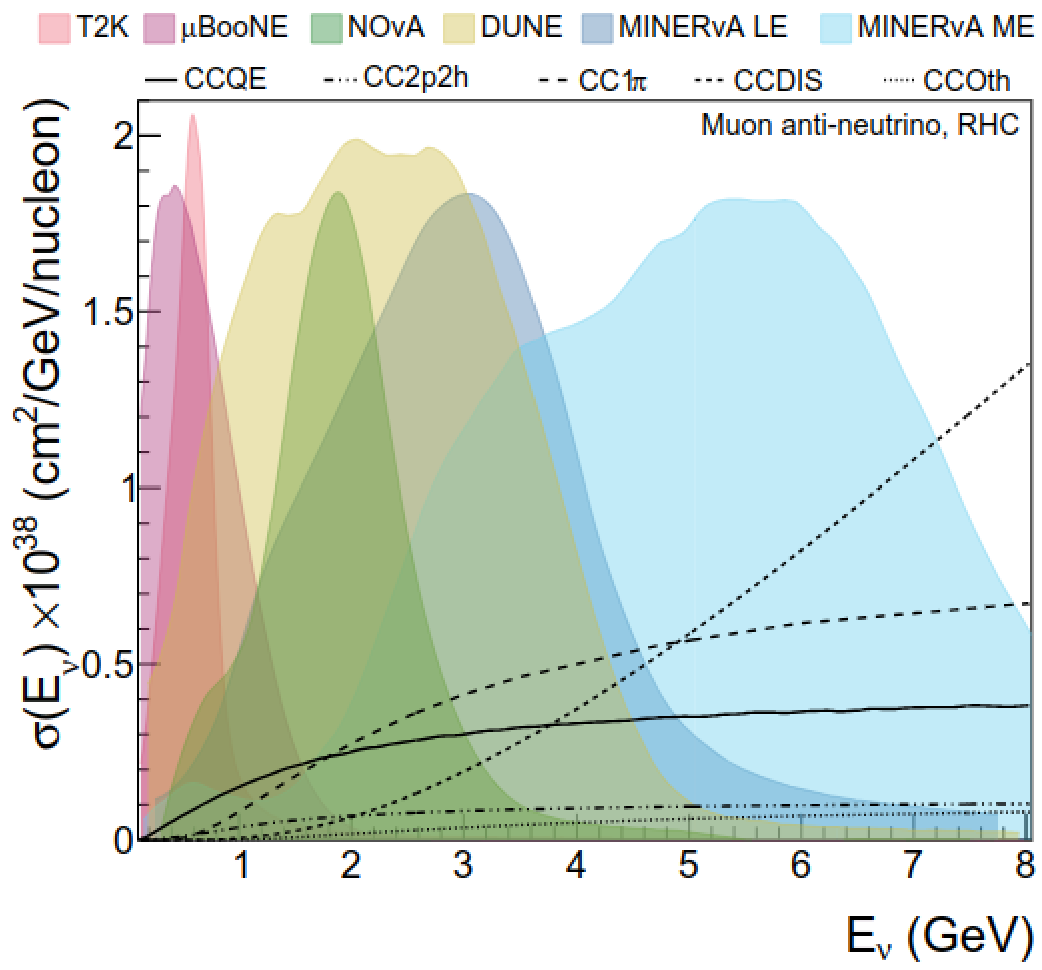
Concluding points

- We're in for a **statistical treat** with HK and DUNE, and the final results from NOvA and T2K!
- In the next 10 years, model uncertainties on neutrino interaction cross sections need to be reduced from **3-5%**, to **1-2%** level
  - Electron neutrino interaction cross sections
  - Carbon to Oxygen scaling (T2K)
  - Neutrino energy reconstruction, **hadrons**
  - Cross section evolution in neutrino energy
- Rich interaction physics contribute across the range
  - Initial state model, nuclear processes (e.g. FSI, in-medium corrections), transition between resonances and DIS…
  - What needs to be prioritised varies greatly between experiments
- Ongoing and upcoming experimental and theoretical programmes aim at addressing these
  - So speak to your new colleagues, and join in on the fun!

Backups

Neutrino fluxes





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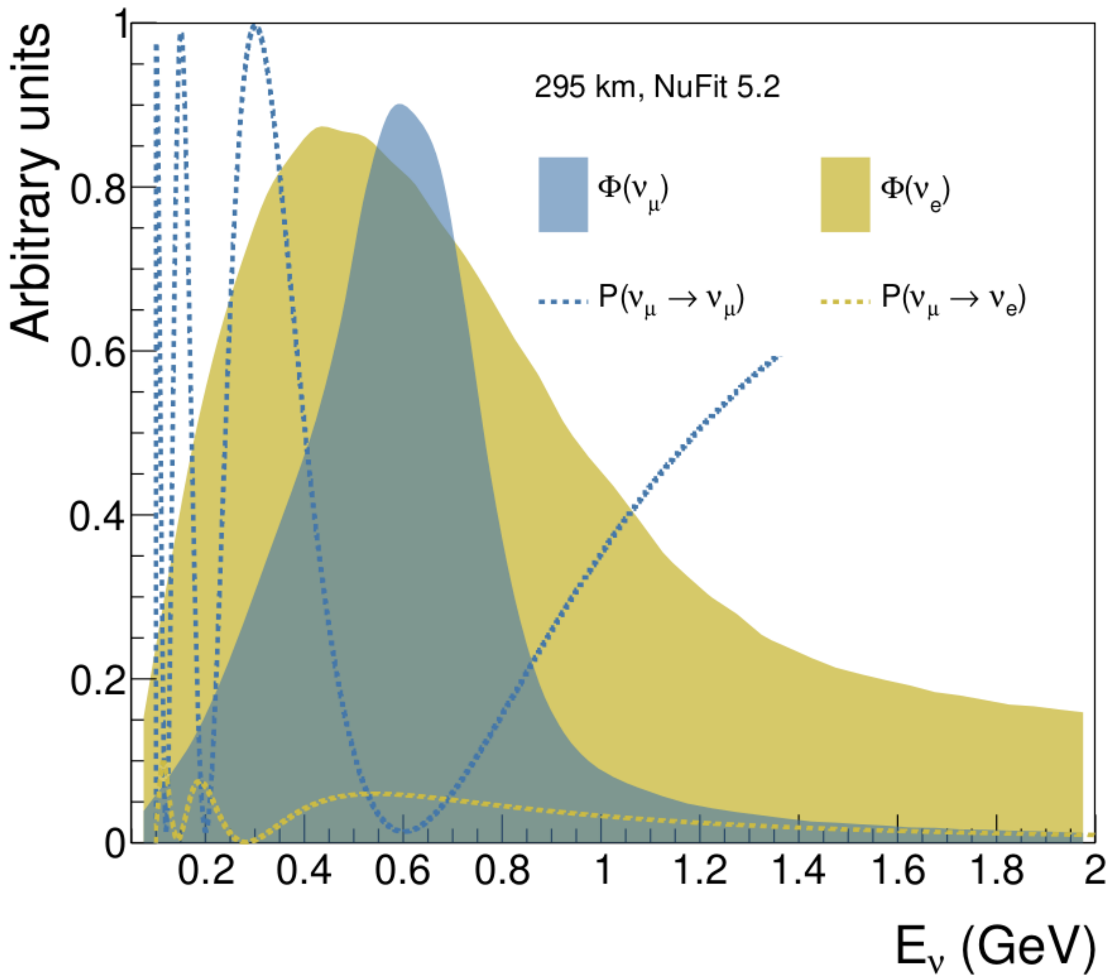
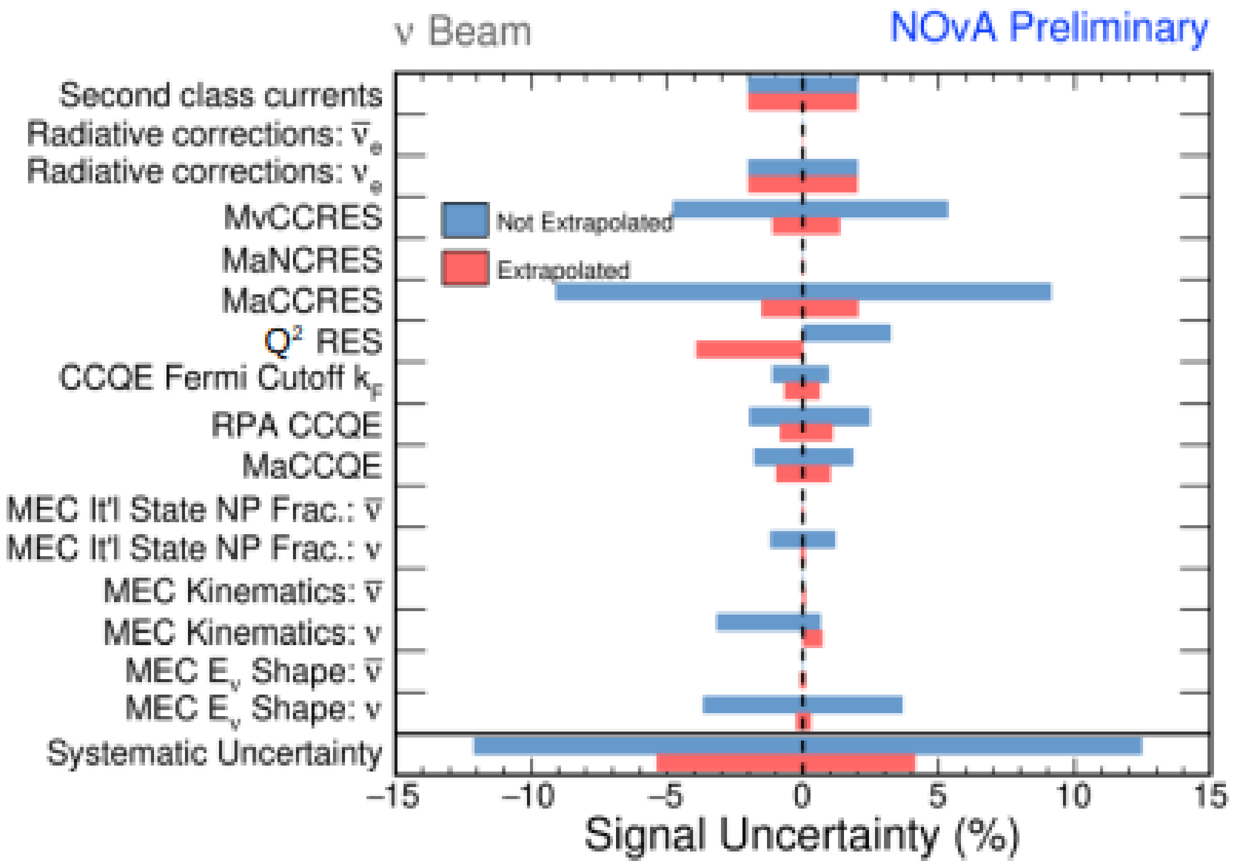


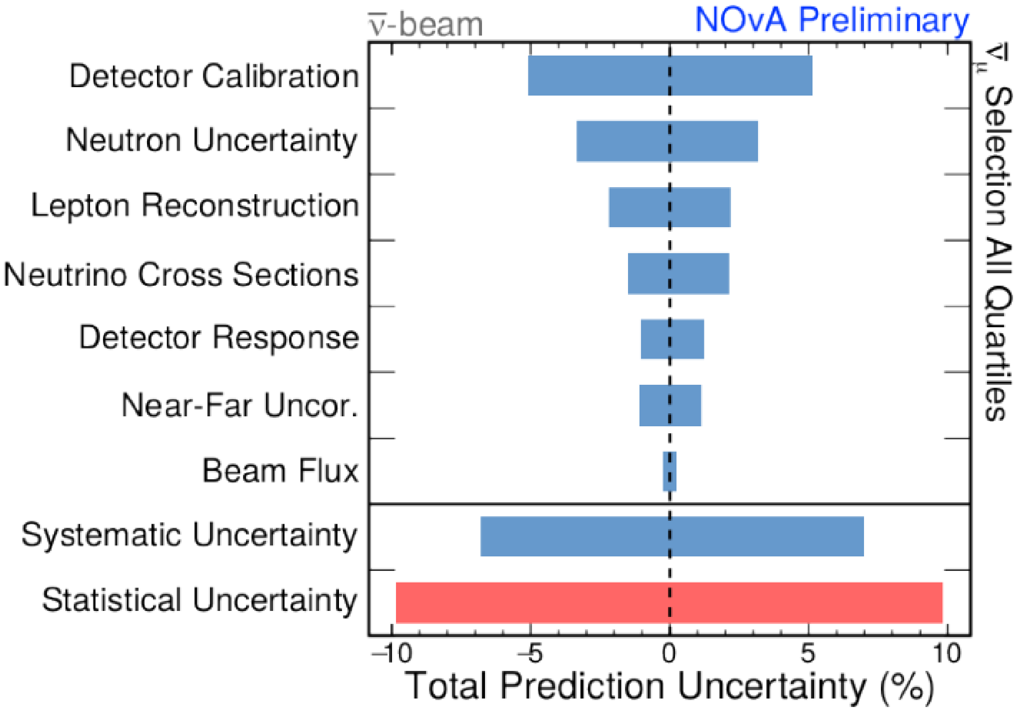
NOvA

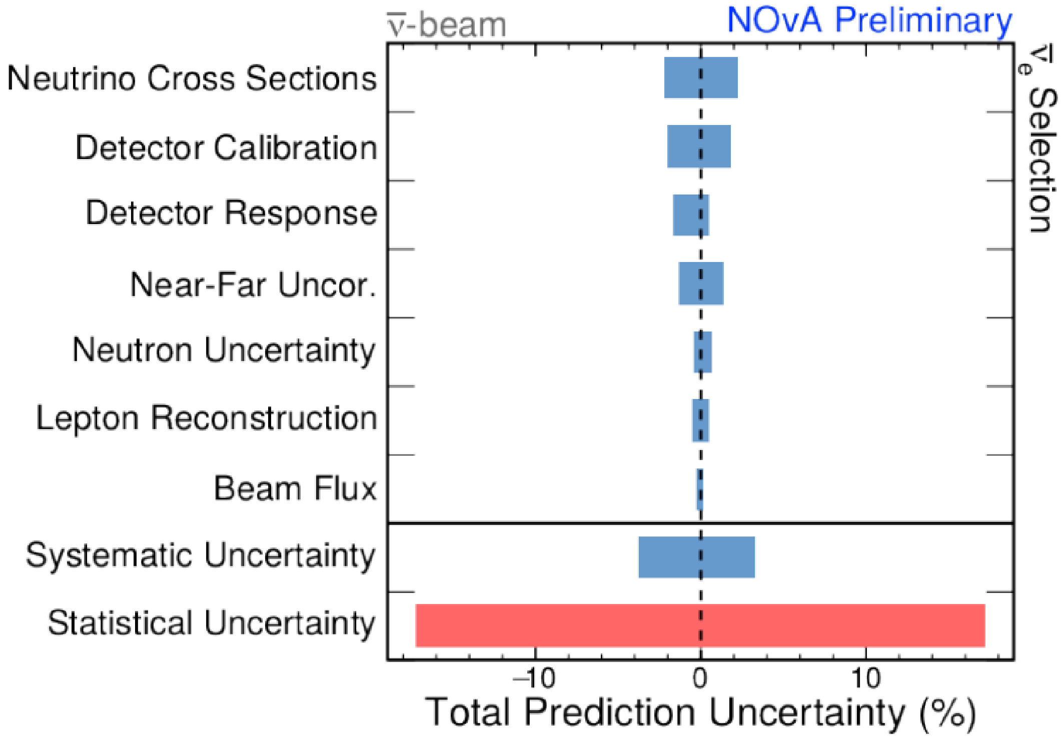
- Jeremy Wolcott, NuInt17



NOvA

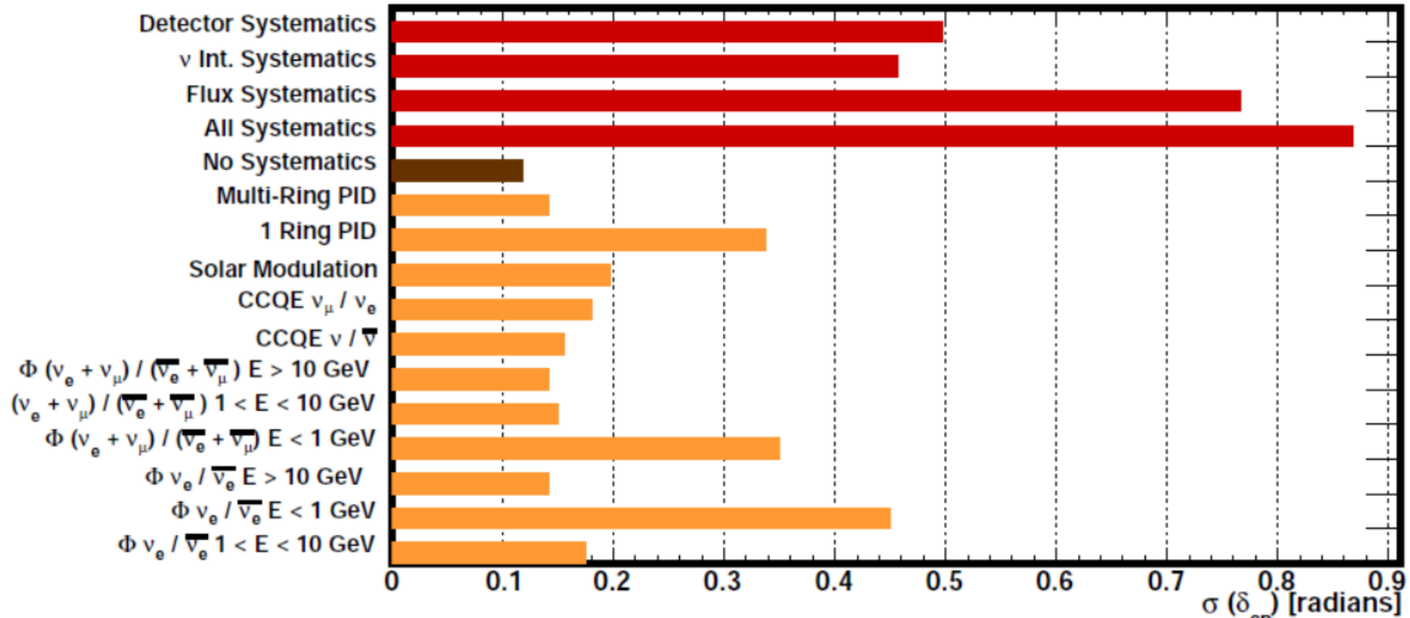
M. Elkins, T. Nosek, Neutrino 2020 poster





Atmospheric

Hyper-K's Sensitivity to δ_{cp} with Atmospheric neutrinos



Systematic Effect on Hierarchy Sensitivity at Super-K