Improving MicroBooNE's sterile neutrino sensitivity with PROfit

June Zey

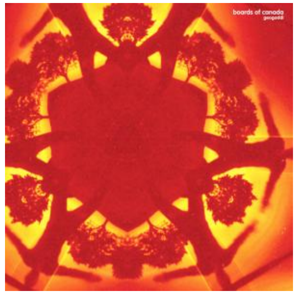
7/30/26

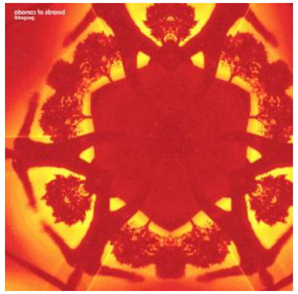
µBooNE

NEVIS LABORATORIES
COLUMBIA UNIVERSITY

U.S. National
Science Foundation

µBooNE





Neutrinos

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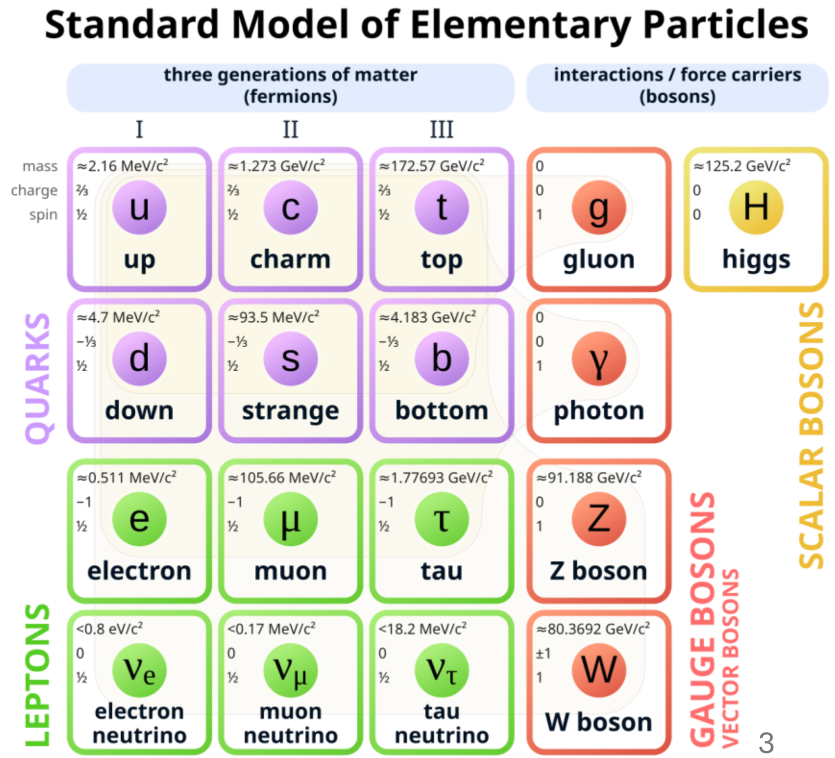
    - Neutrinos are $\frac{1}{2}$ spin fundamental particles.



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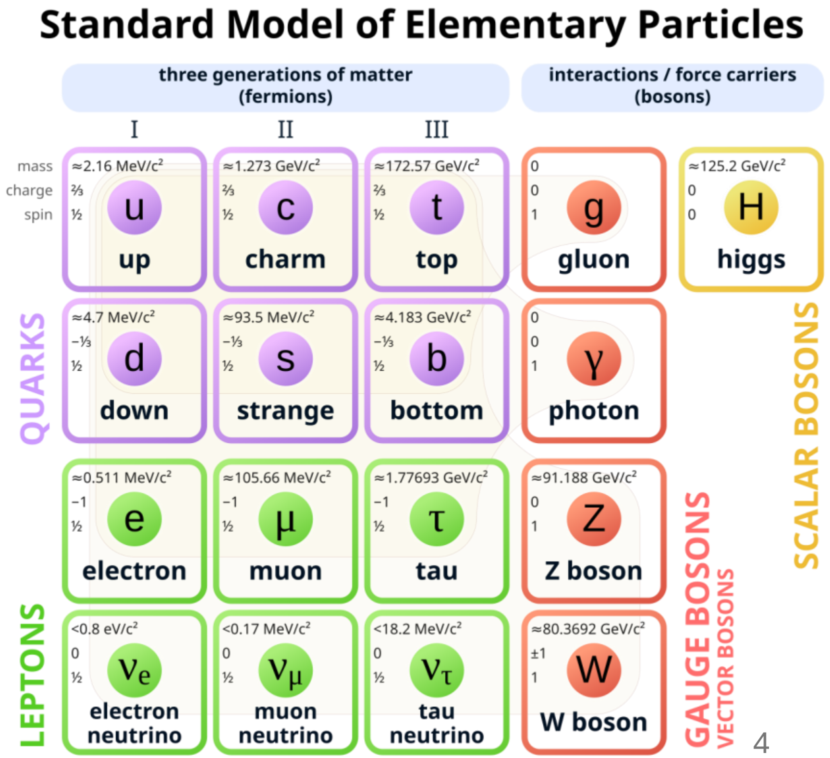

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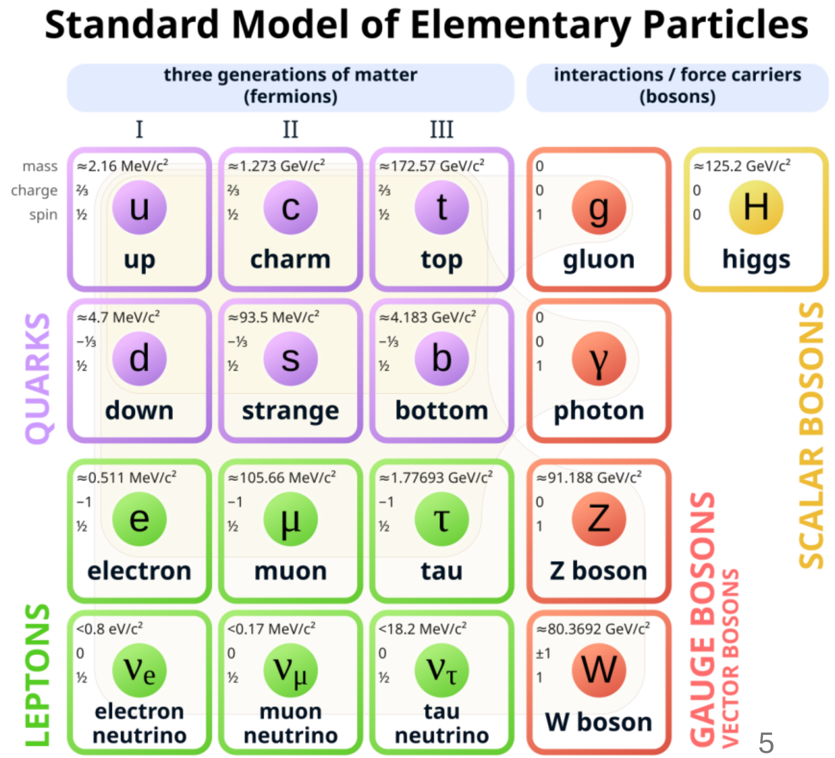

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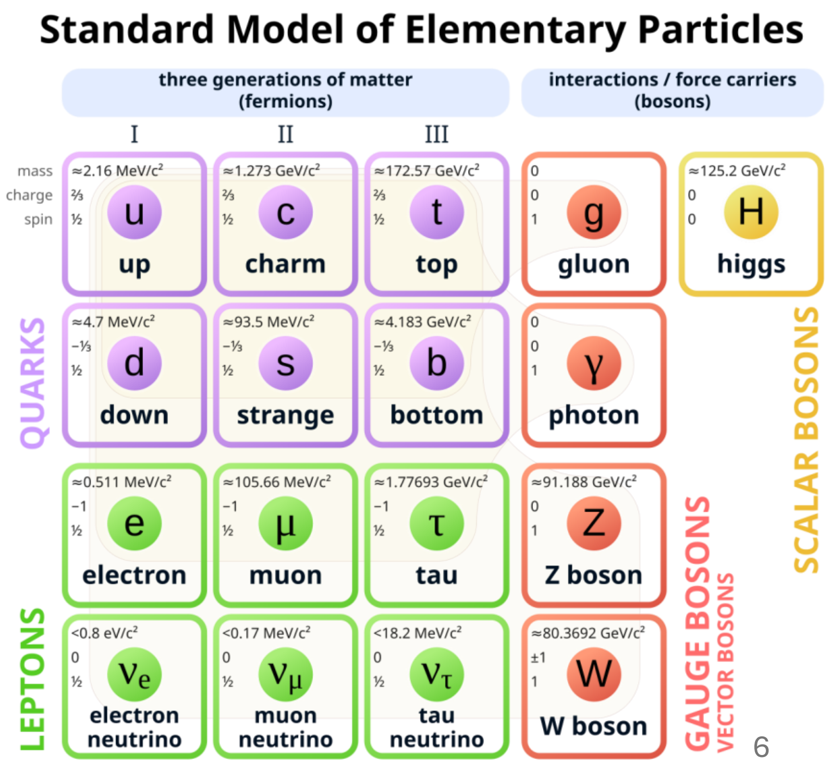

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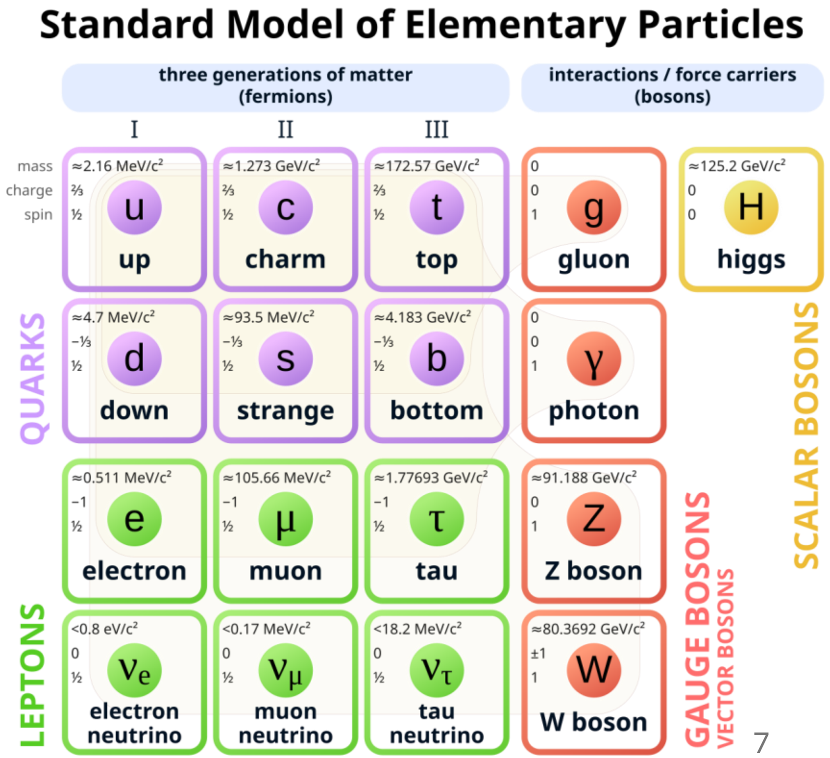

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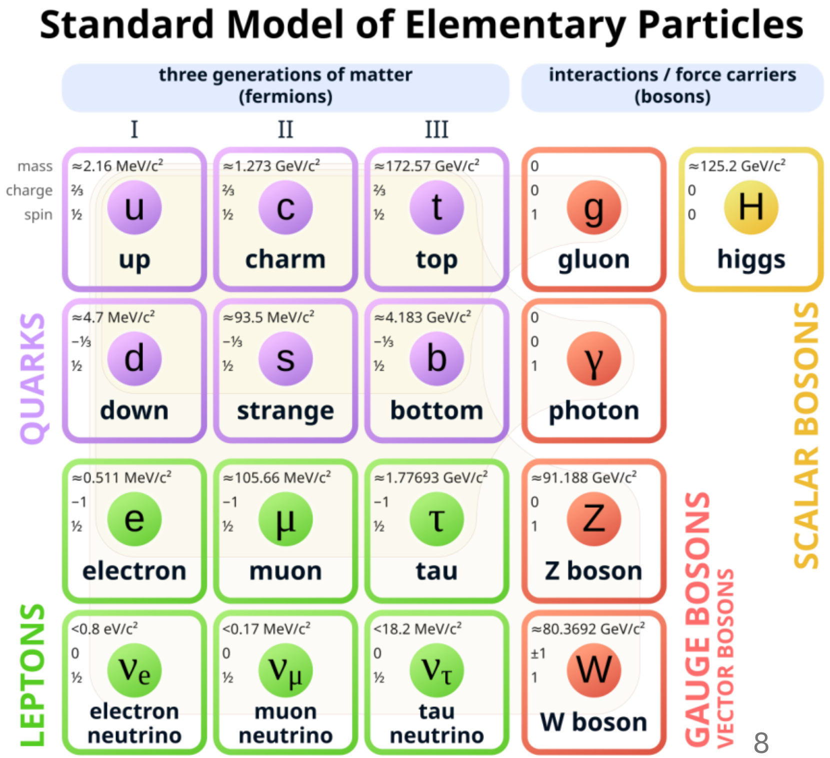
  - Explicitly break Standard model assumptions (Have non-zero masses)

(oscillated!)



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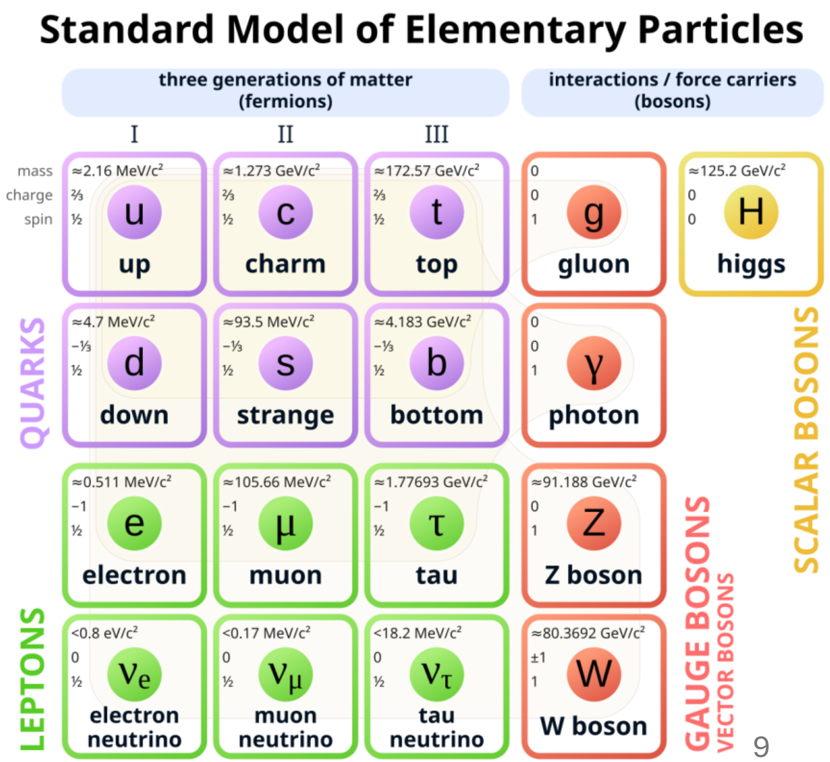

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  - Explicitly break Standard model assumptions (Have non-zero masses)
  - Potential portal to beyond standard model physics.
  - Ability to answer fundamental questions (baryogenesis, Dark matter, and Supernovae)

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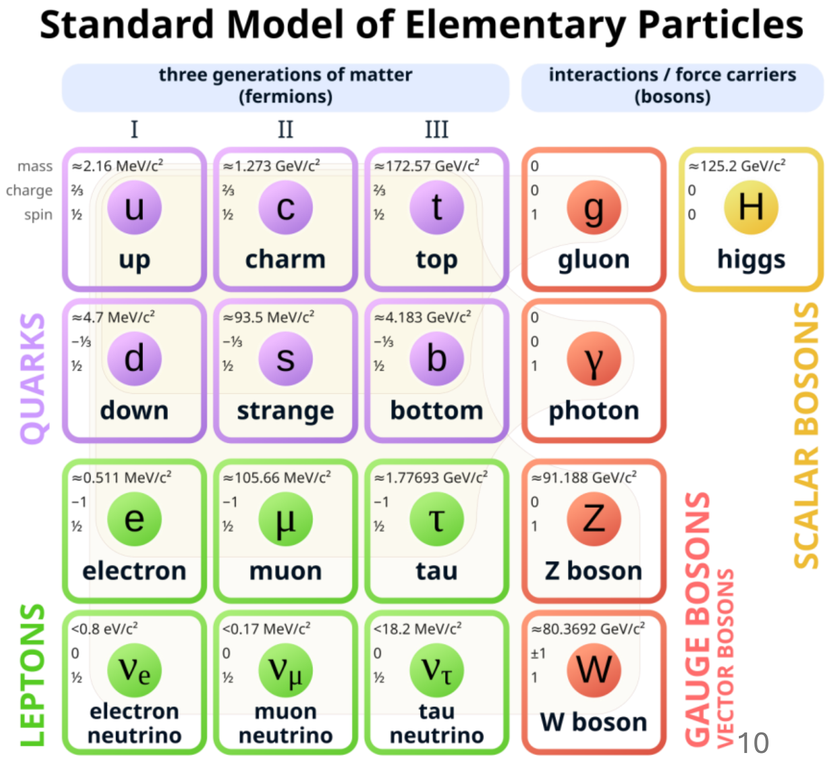

Neutrino oscillations

- Neutrinos Oscillate between flavors as they traverse space

Neutrino oscillations

- Neutrinos Oscillate between flavors as they traverse space
  - Mass eigenstates are transformed into flavor states by the PMNS matrix.

Flavor Eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}.$$

Mass eigenstates

$$\downarrow$$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Neutrino oscillations

- Neutrinos Oscillate between flavors as they traverse space
  - Mass eigenstates are transformed into flavor states by the PMNS matrix.
  - Probabilities are given by **constant** values experimentally acquired (Δm_{31}^2, θ_{13},θ_{23})

$$P\left(\nu_\mu \rightarrow \nu_e\right) \approx sin^2(\theta_{23}) sin^2(2\theta_{13}) sin^2(\frac{\Delta m_{31}^2 * E}{\mathrm{L}})$$

Neutrino oscillations

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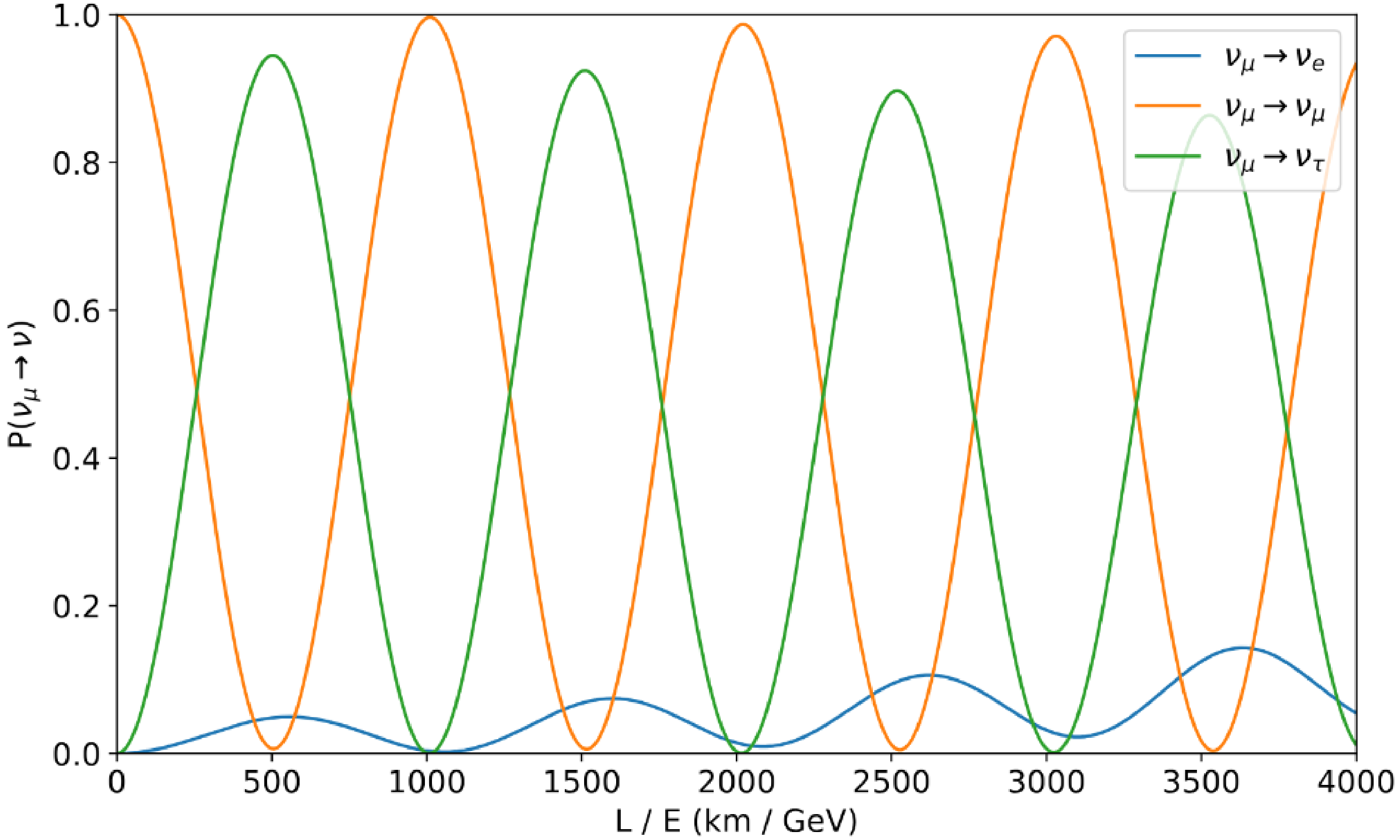
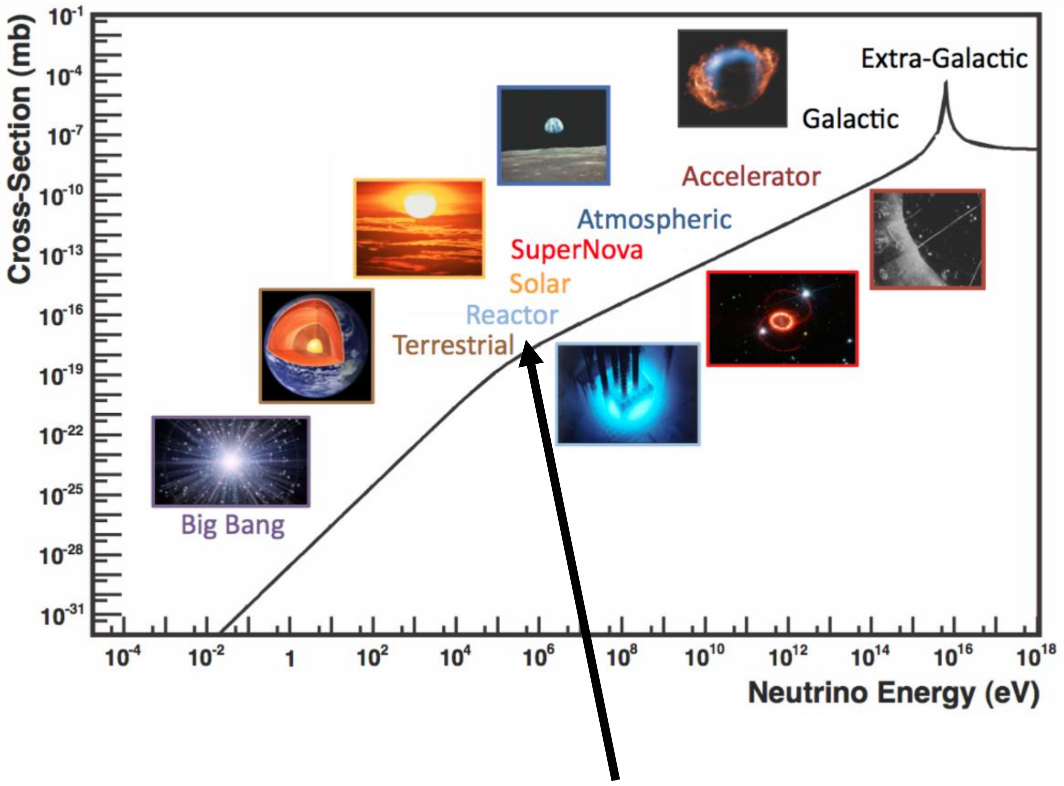


Neutrino experiments

- Experiments occupy different neutrino energy ranges, based on **sources**

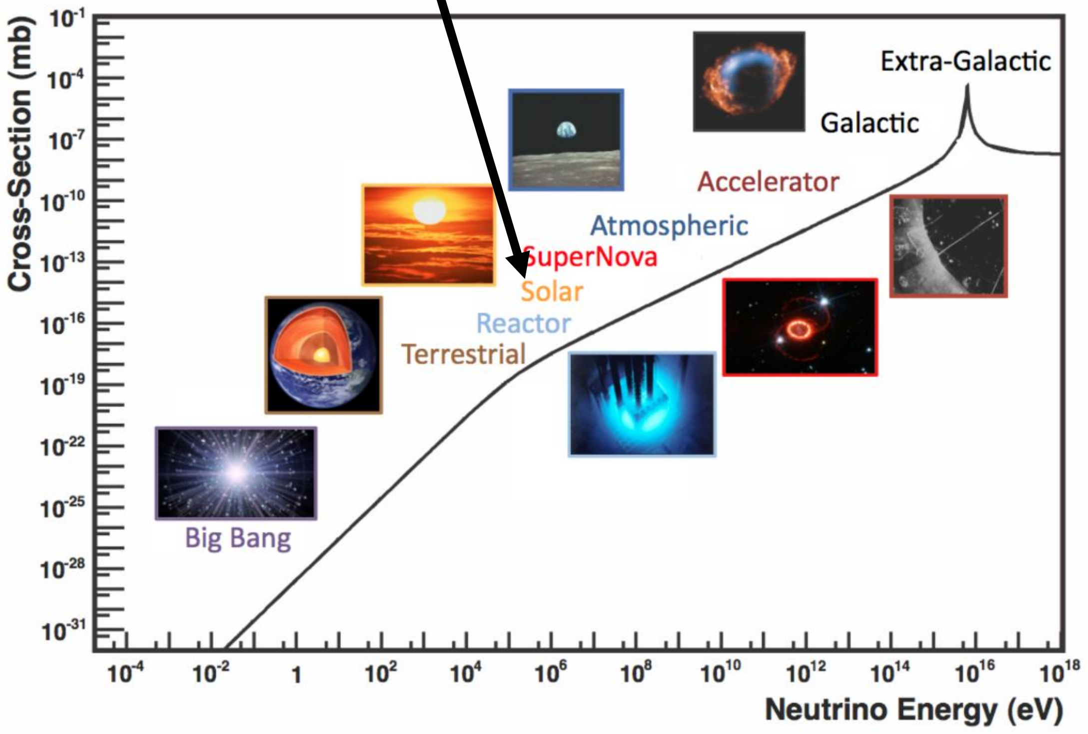
Neutrino experiments

- Reactor: Double chooz, KamLand
  Ricochet + many others.



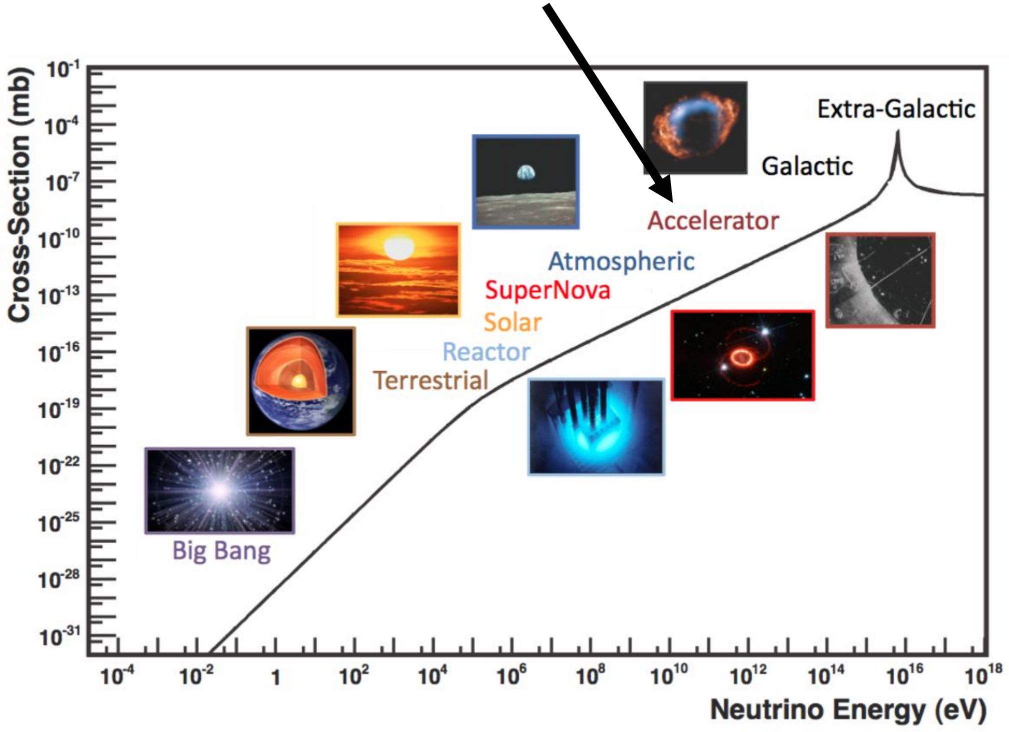
Neutrino experiments

- Solar: Super-K, SNO+, BOREXINO + many others.



Neutrino experiments

- Accelerator: DUNE, MiNoS+, NovA, T2K miniBooNE + many others.



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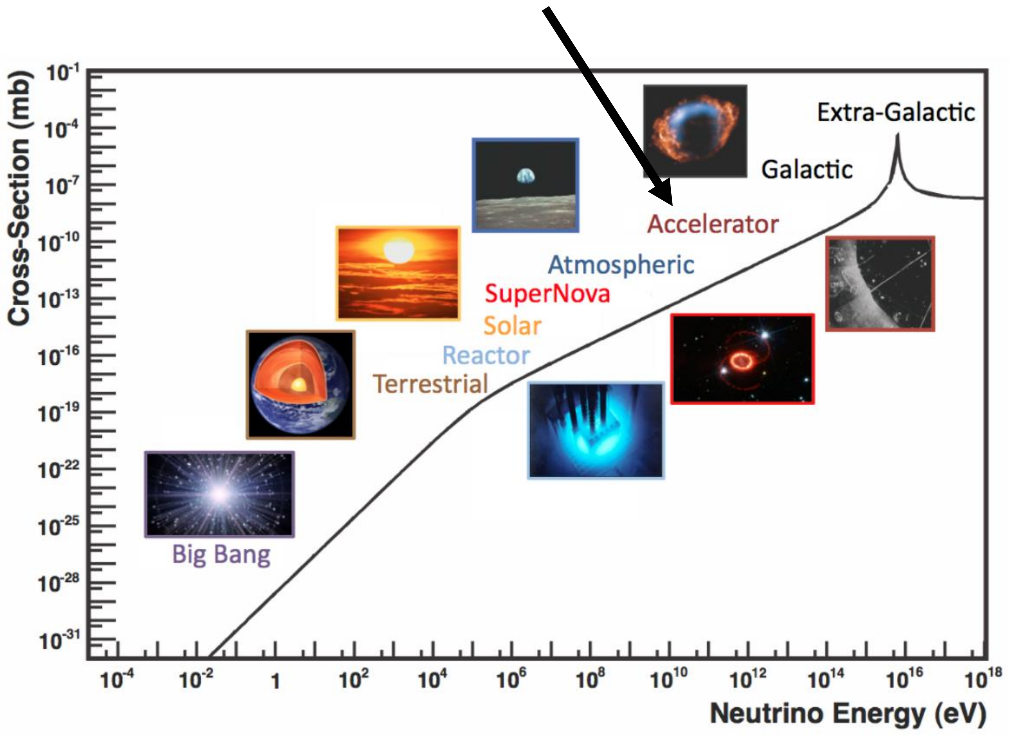
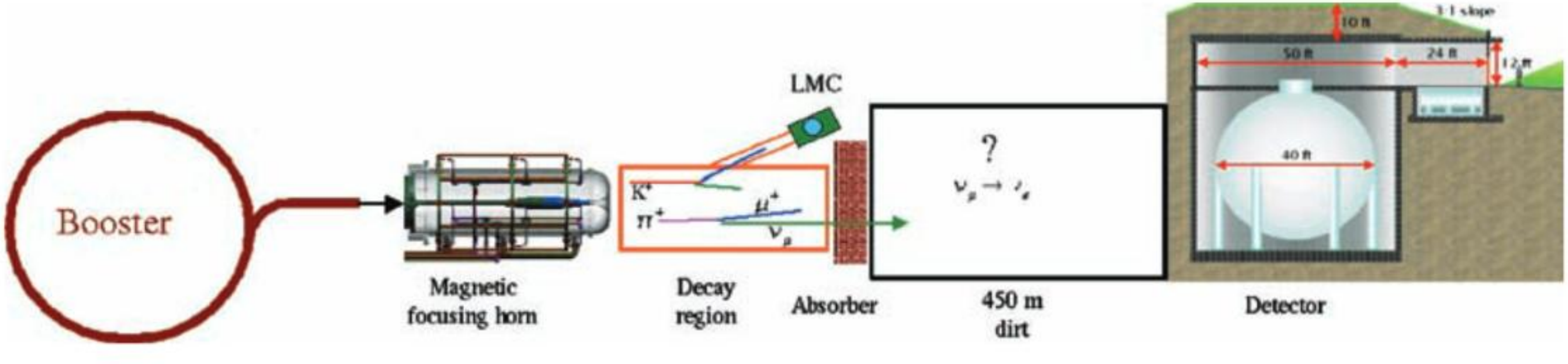


MiniBooNE

- MiniBooNE is a Cherenkov detector experiment at Fermilab designed to observe neutrino oscillations

- BooNE, stands for Booster Neutrino Experiment



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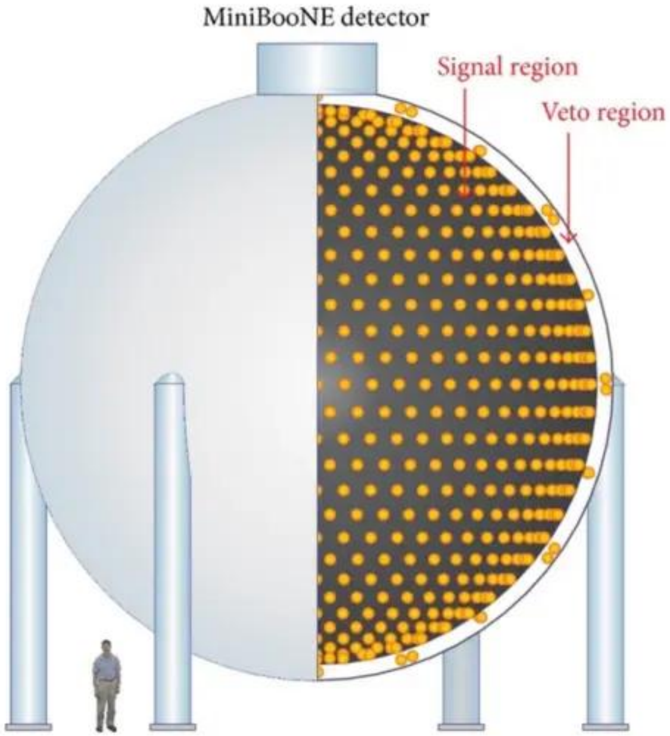

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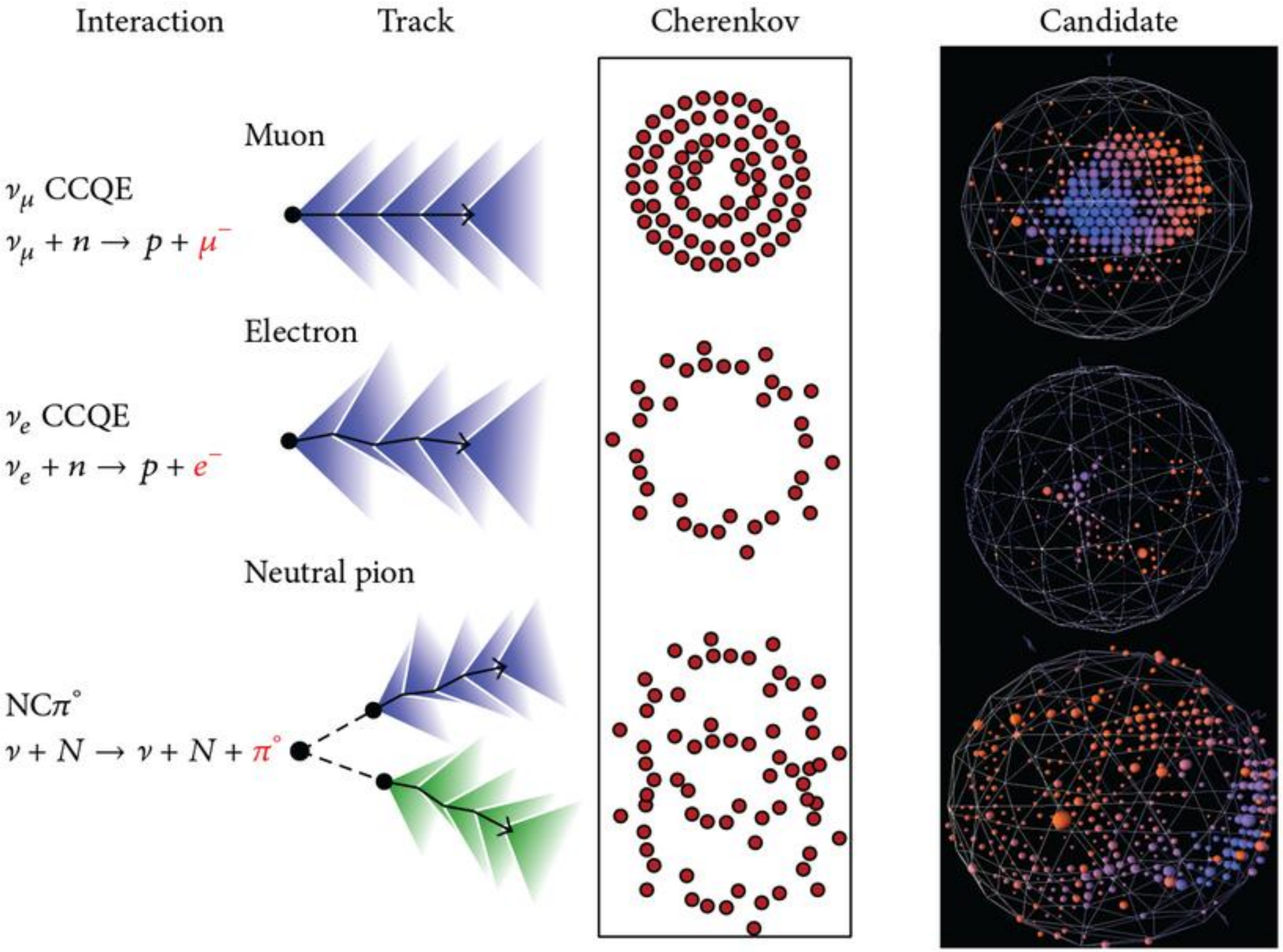

Interaction
Track
Cherenkov
Candidate
Muon
ν_μ CCQE
$\nu_\mu + n \rightarrow p + \mu^-$
Electron
ν_e CCQE
$\nu_e + n \rightarrow p + e^-$
Neutral pion
$NC\pi^\circ$
$\nu + N \rightarrow \nu + N + \pi^\circ$

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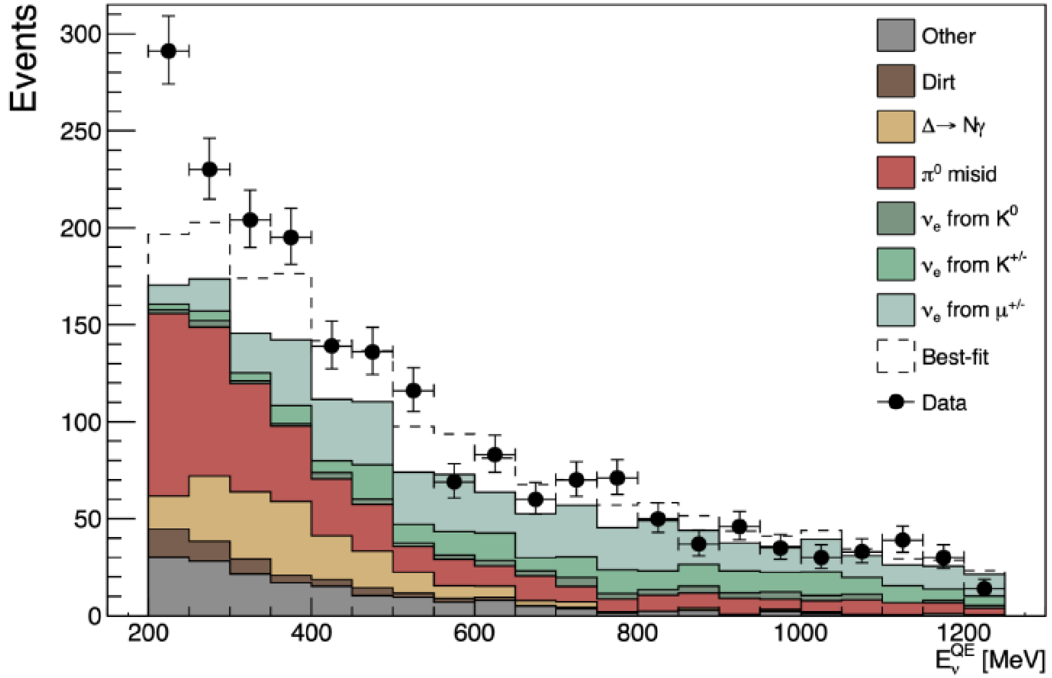
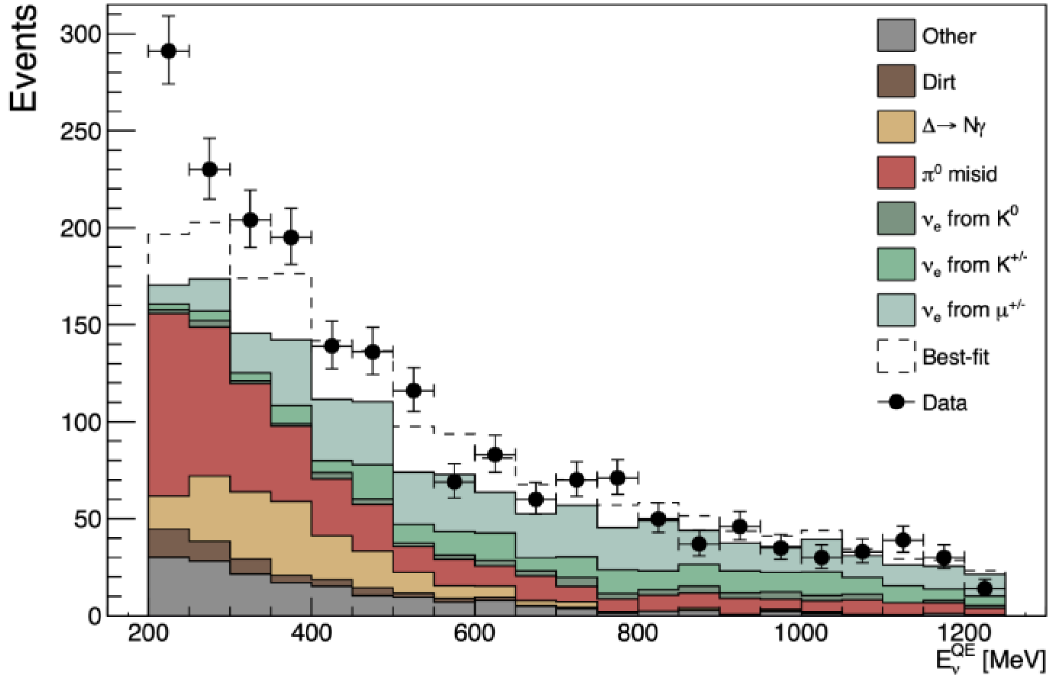
  - MiniBooNE saw an excess in low energy events.



MiniBooNE

- MiniBooNE is a Cherenkov detector experiment at Fermilab designed to observe neutrino oscillations
  - MiniBooNE saw an excess in low energy events.
  - **MiniBooNE did not have the capability to explain why.**



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- MicroBooNE is a large 170-ton liquid-argon time projection chamber (LArTPC) neutrino experiment located on the Booster neutrino beamline at Fermilab.

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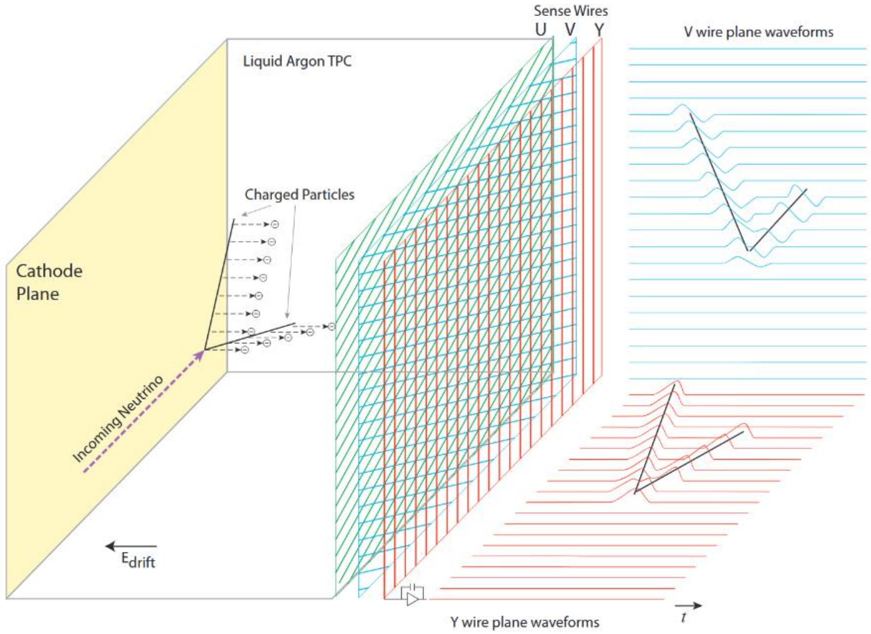


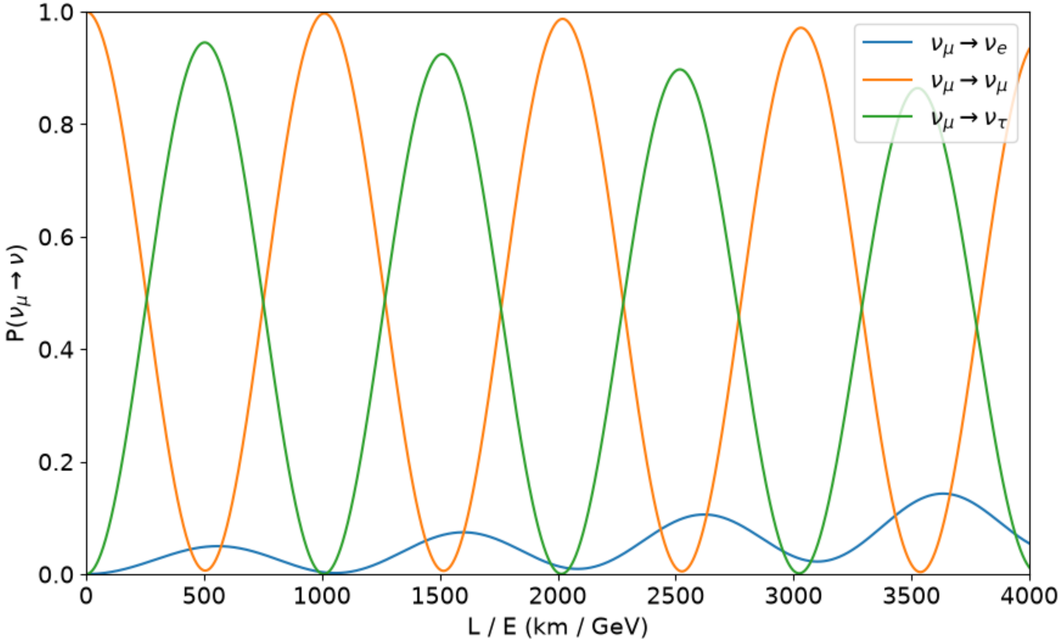
~~MiniBoone~~ MicroBooNE

- MicroBooNE is a large 170-ton liquid-argon time projection chamber (LArTPC) neutrino experiment located on the Booster neutrino beamline at Fermilab.
  - One of MicroBooNE's goals was to investigate the low energy event excess in MiniBooNE.
  - A possible explanation is the existence of a **fourth neutrino mass state** that doesn't interact **weakly.** This is referred to as a **sterile neutrino**.

Sterile Neutrinos

- Neutrinos Oscillation **changes** when a fourth flavor is introduced.

3 flavor oscillation model



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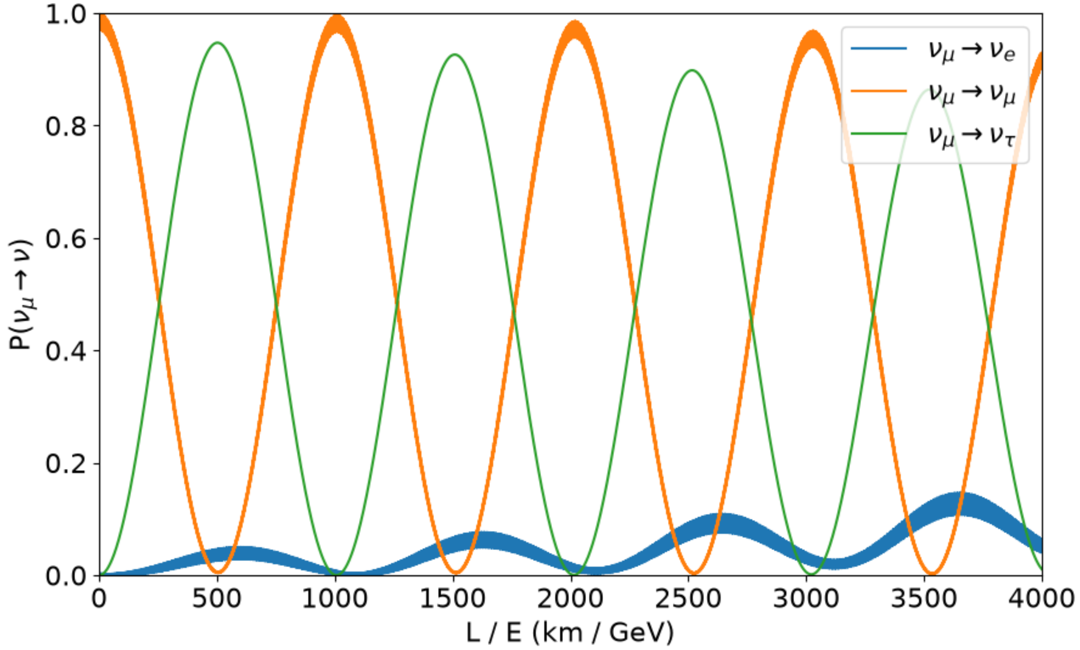
3+1 flavor oscillation model



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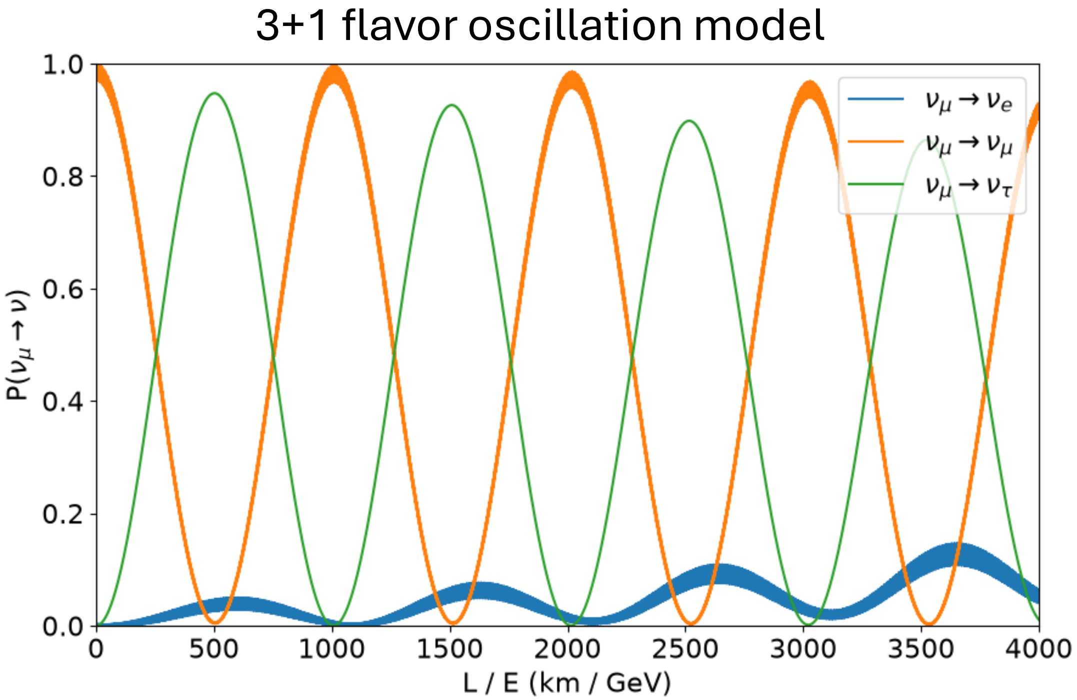

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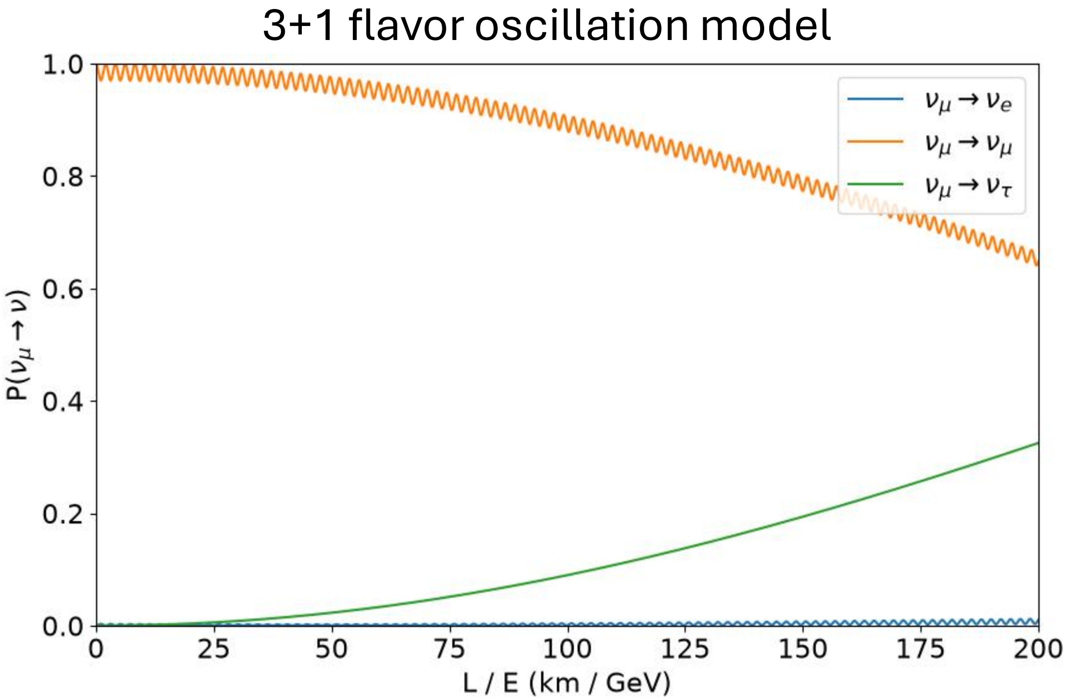

Sterile Neutrinos

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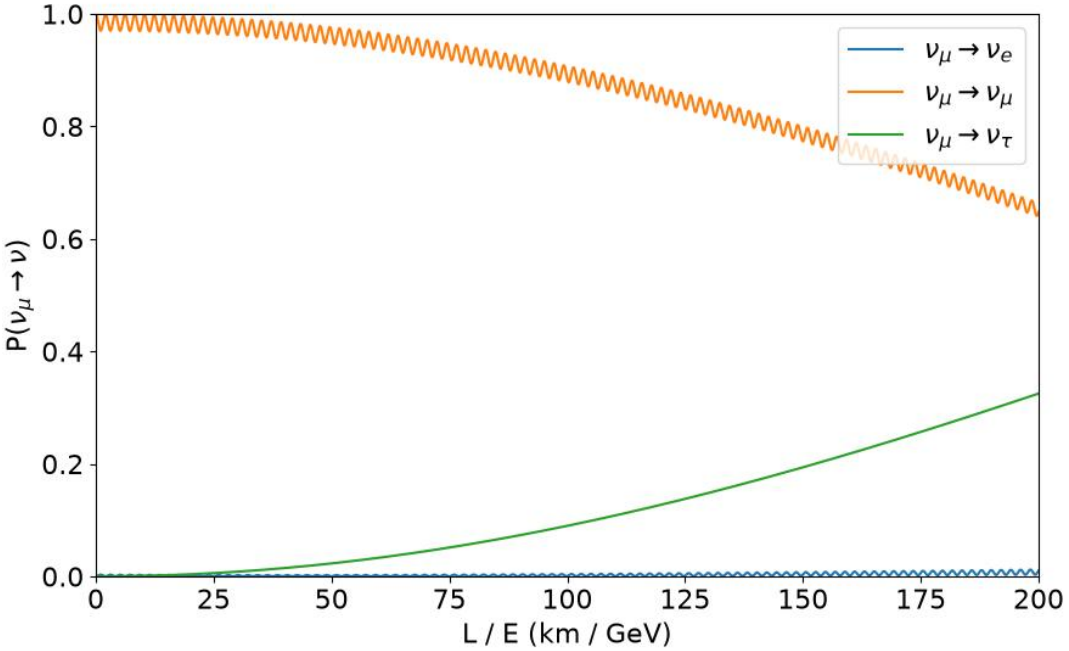
- MicroBooNE operates at $\frac{\mathrm{L}}{\mathrm{E}} \approx 0.5\ (\mathrm{km/GeV})$

3+1 flavor oscillation model



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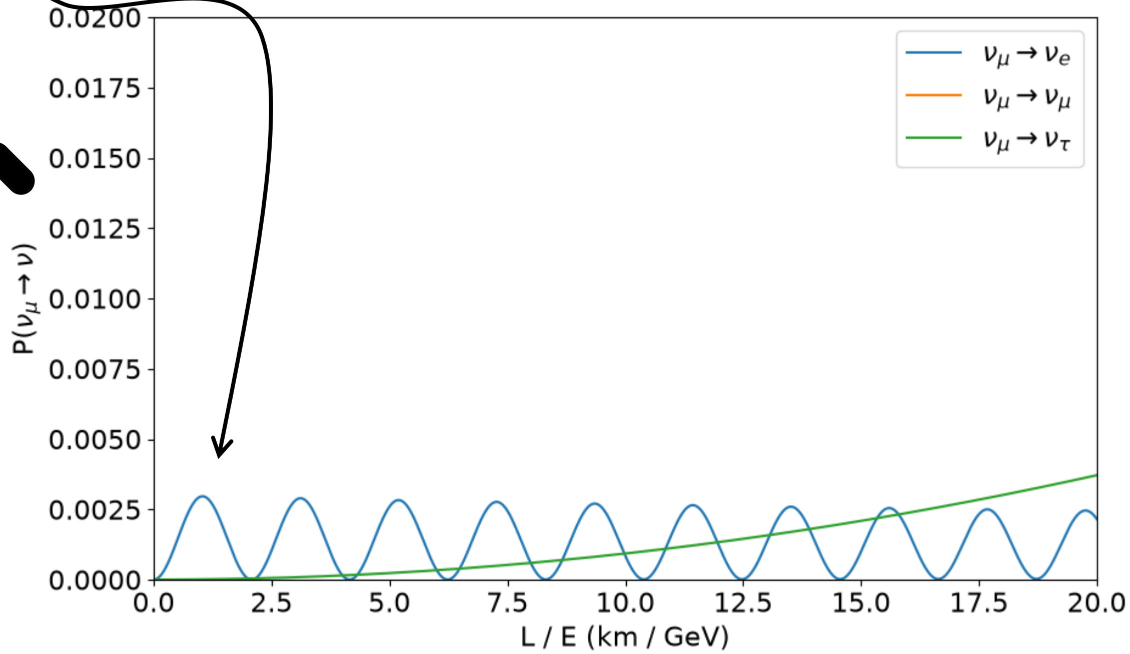

Sterile Neutrinos

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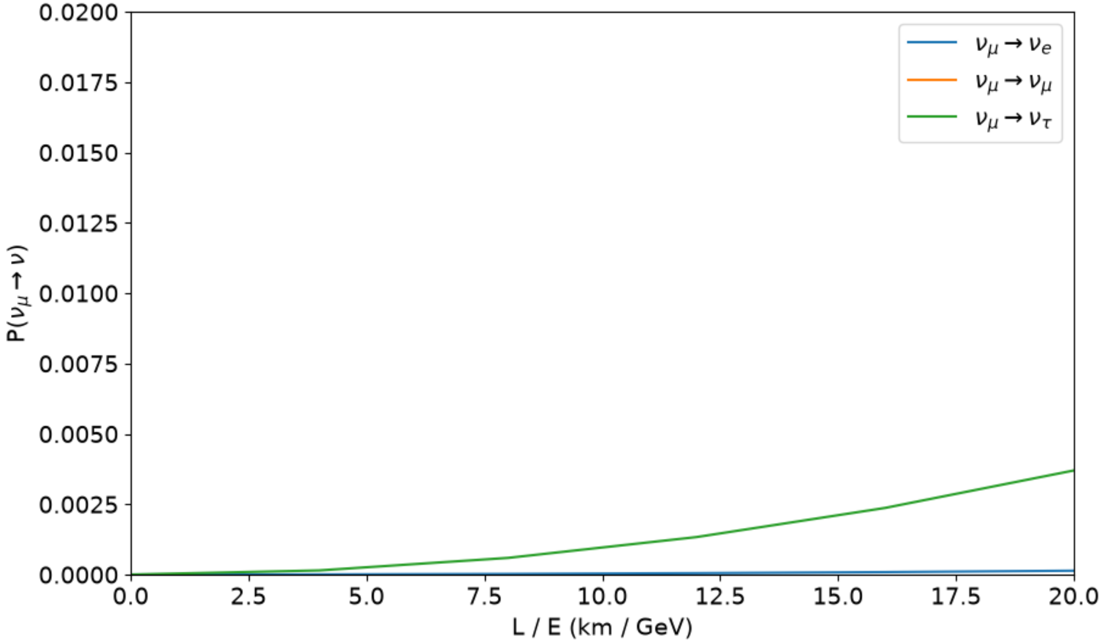
- Any Nue appearance **beyond background** is evidence for steriles!

3 flavor oscillation model



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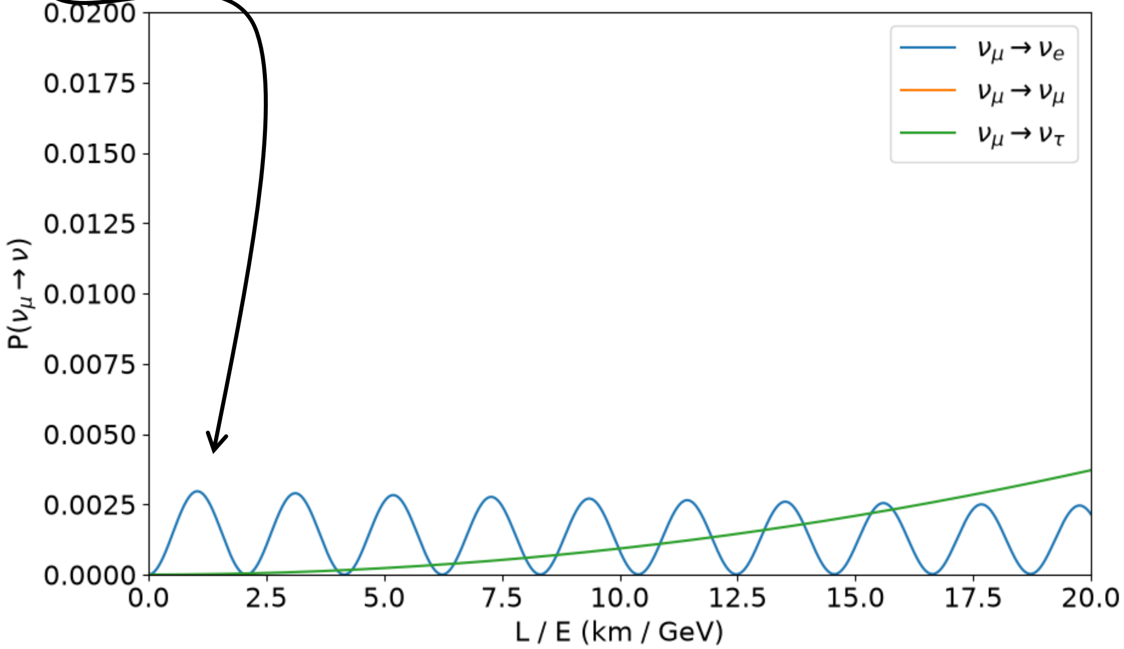
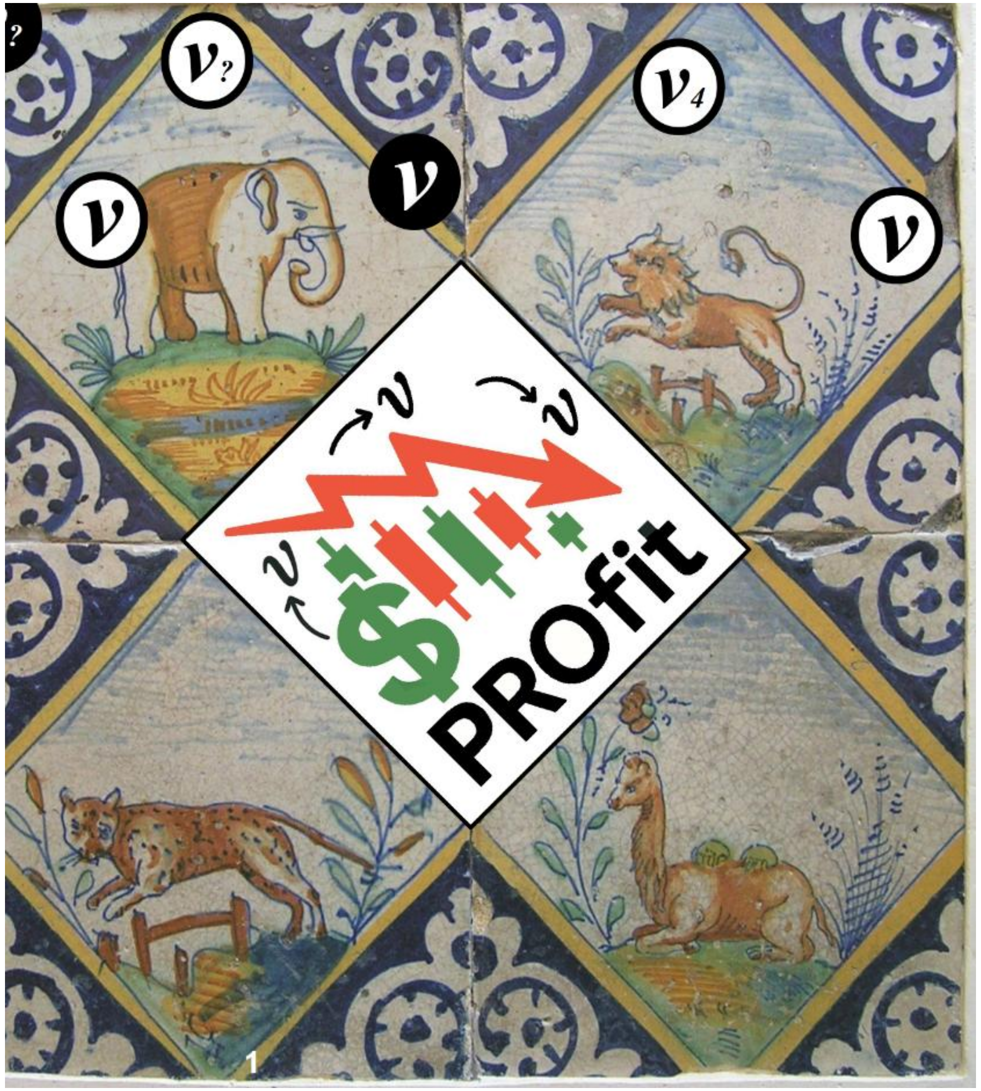


PROfit

- **PROfit** is a framework for fits of short-baseline neutrino oscillation and Beyond Standard model physics models.

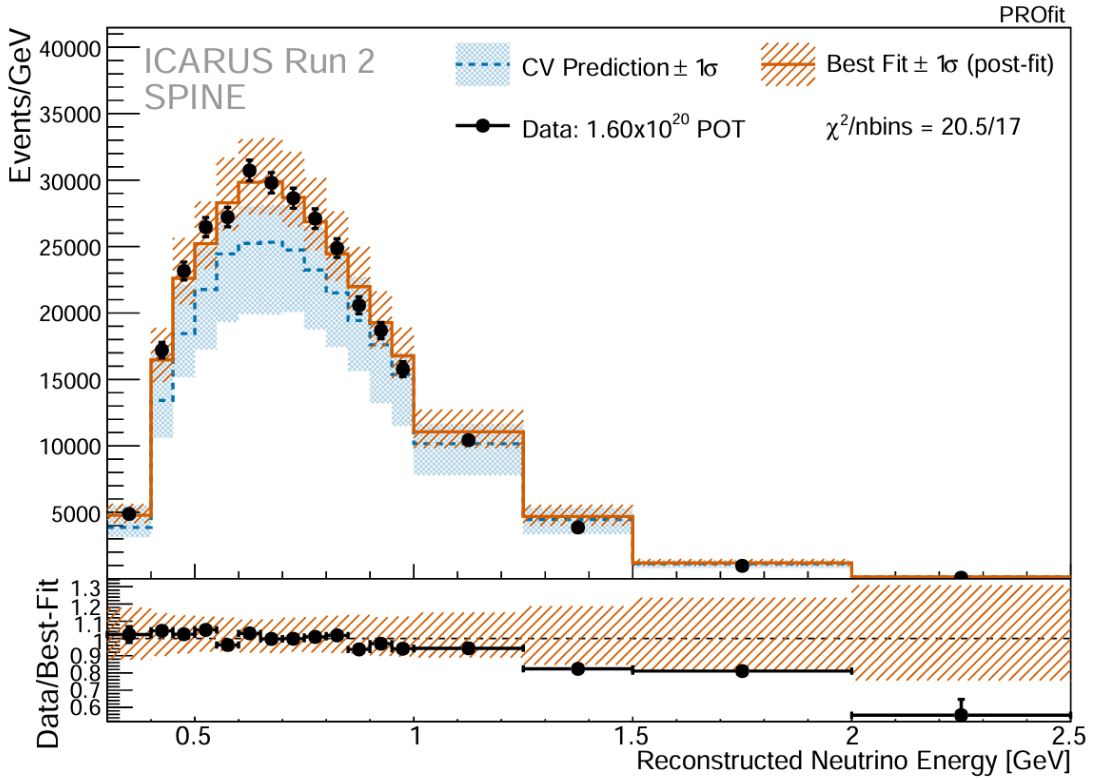
- Developed by Mark Ross-Lonergan and co.

- https://github.com/markrosslonergan/Elephant_Vanishes.git



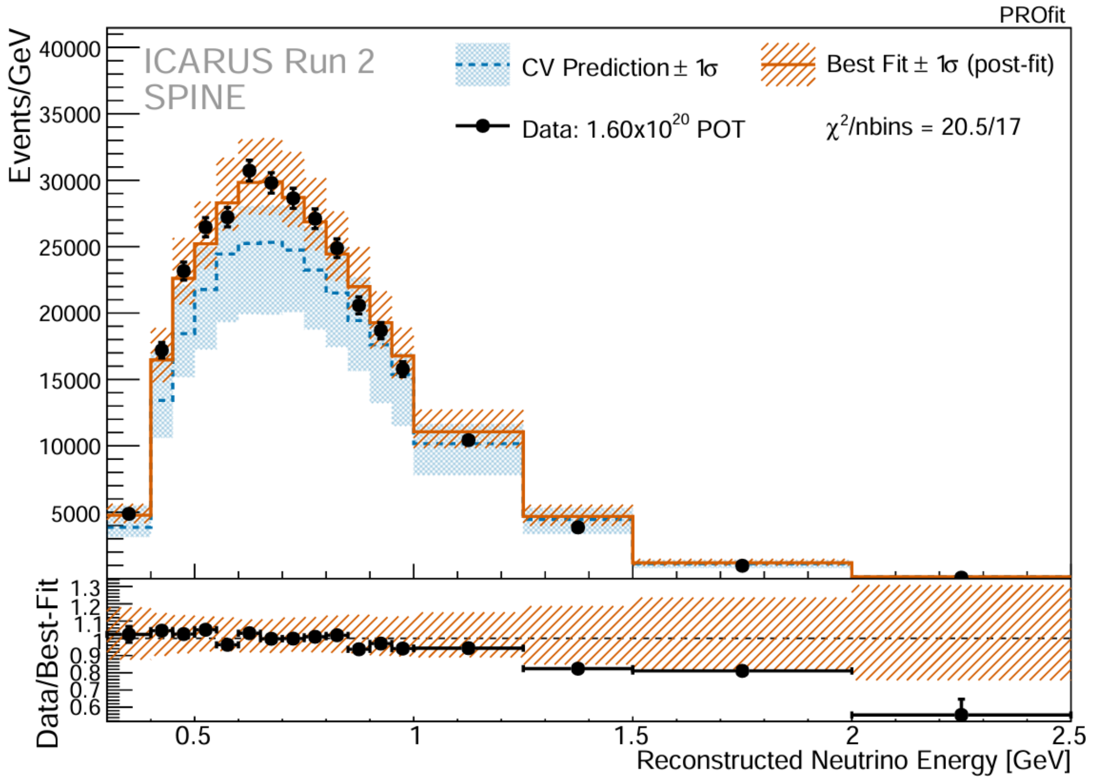
PROfit

- Takes in **processed** data and looks at the systematic uncertainty of our Monte-Carlo prediction.



PROfit

- How to fit a given physics model so we can understand what the data tells us about the model (within our systematic uncertainty!)



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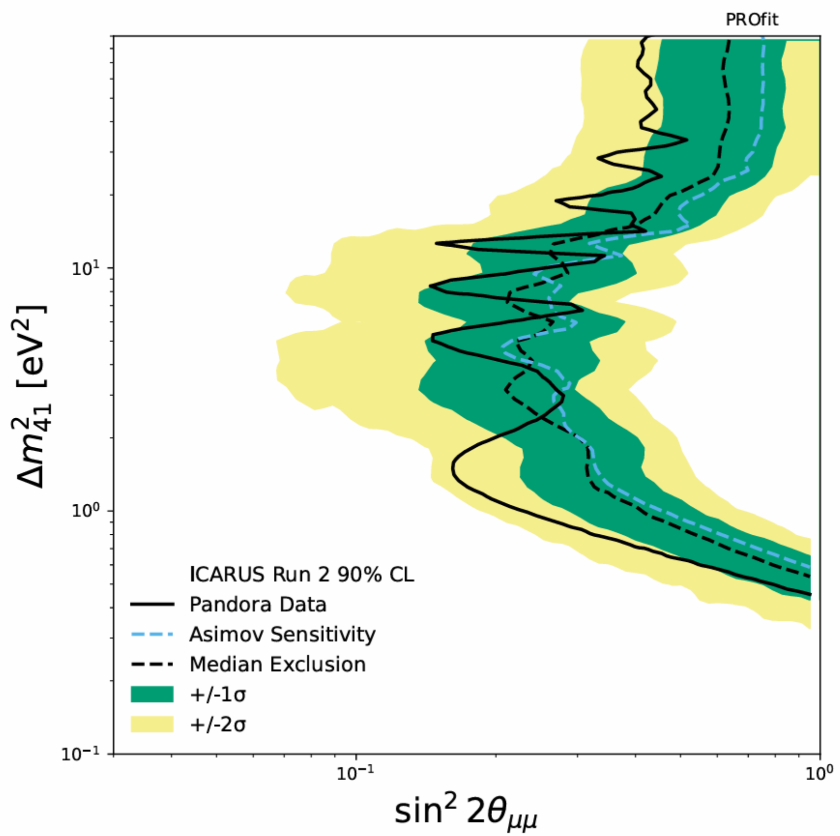
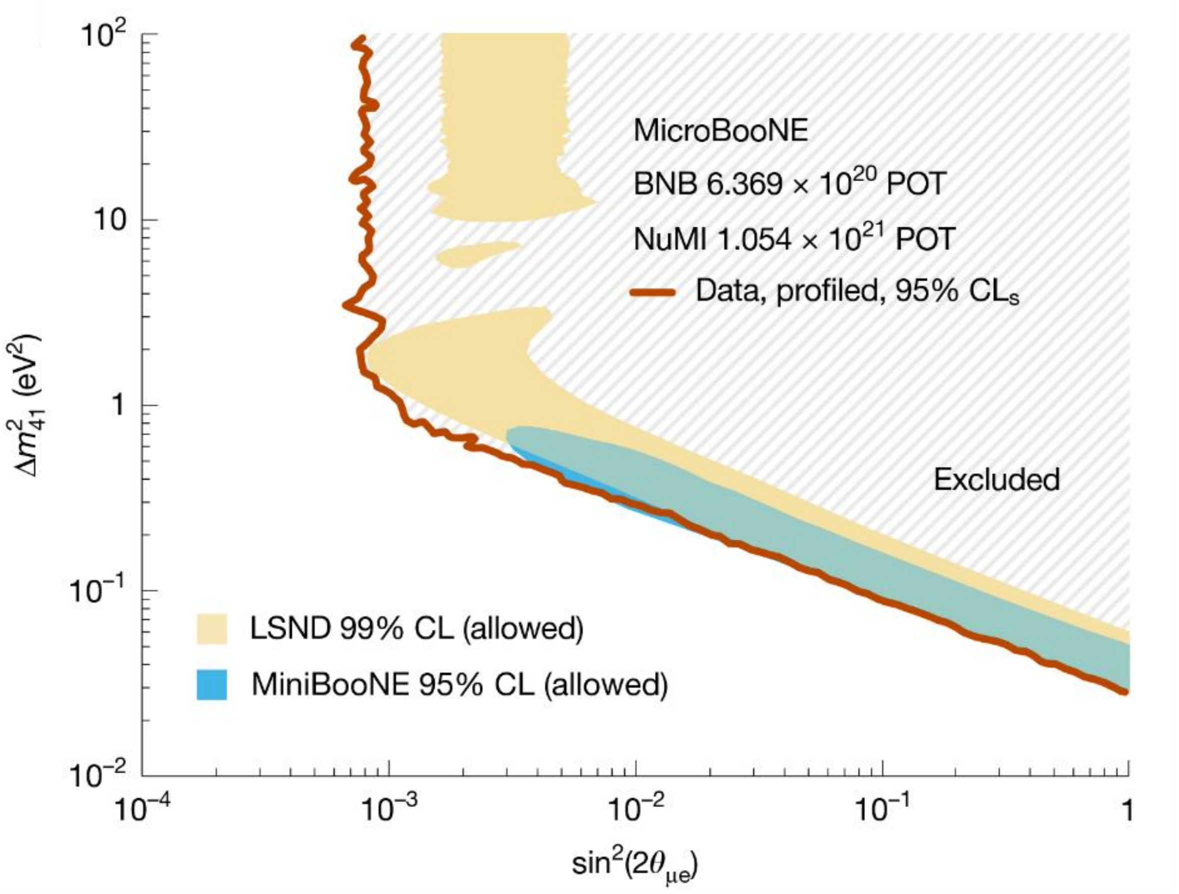


Exclusion plots

- Exclusion plots tell us the available **parameter** space for steriles.



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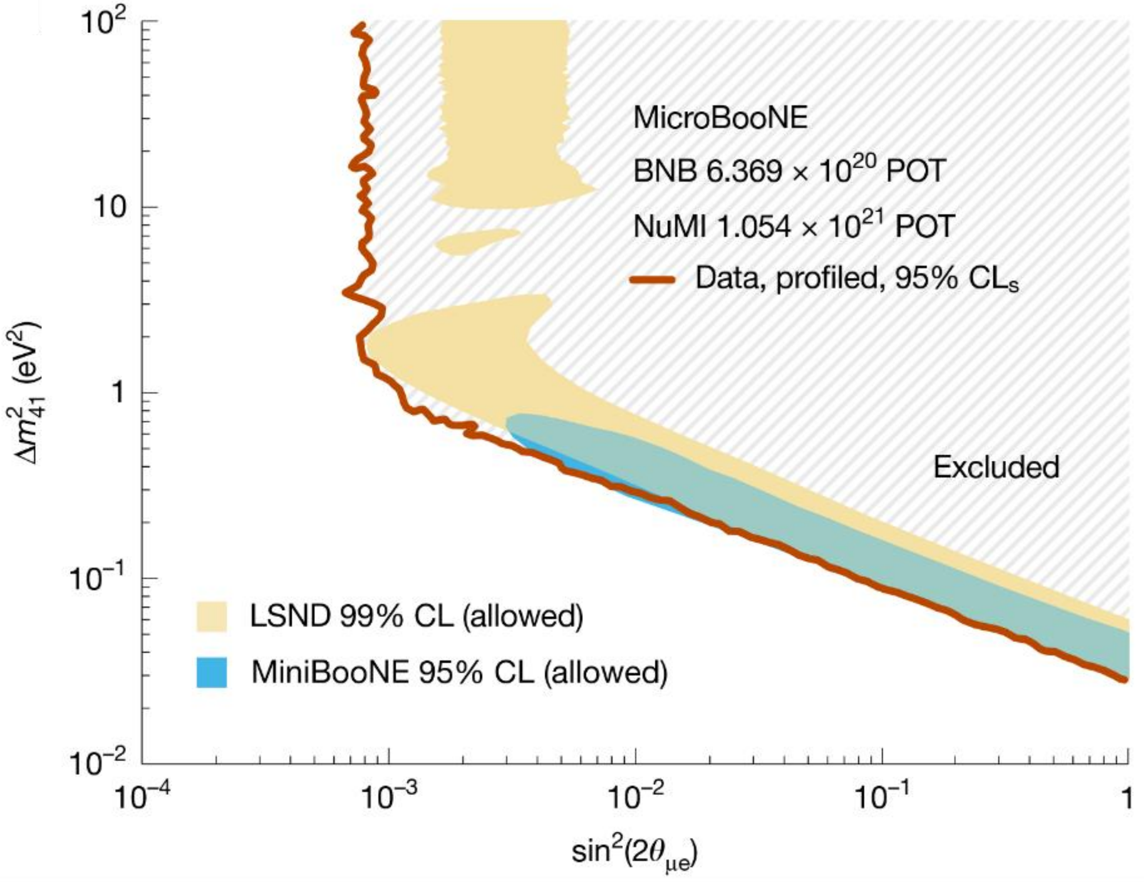

$$P(\nu_\mu \rightarrow \nu_e) \approx sin^2(2\theta_{\mu e}) sin^2(\frac{\Delta m^2_{41} * E}{\text{L}})$$

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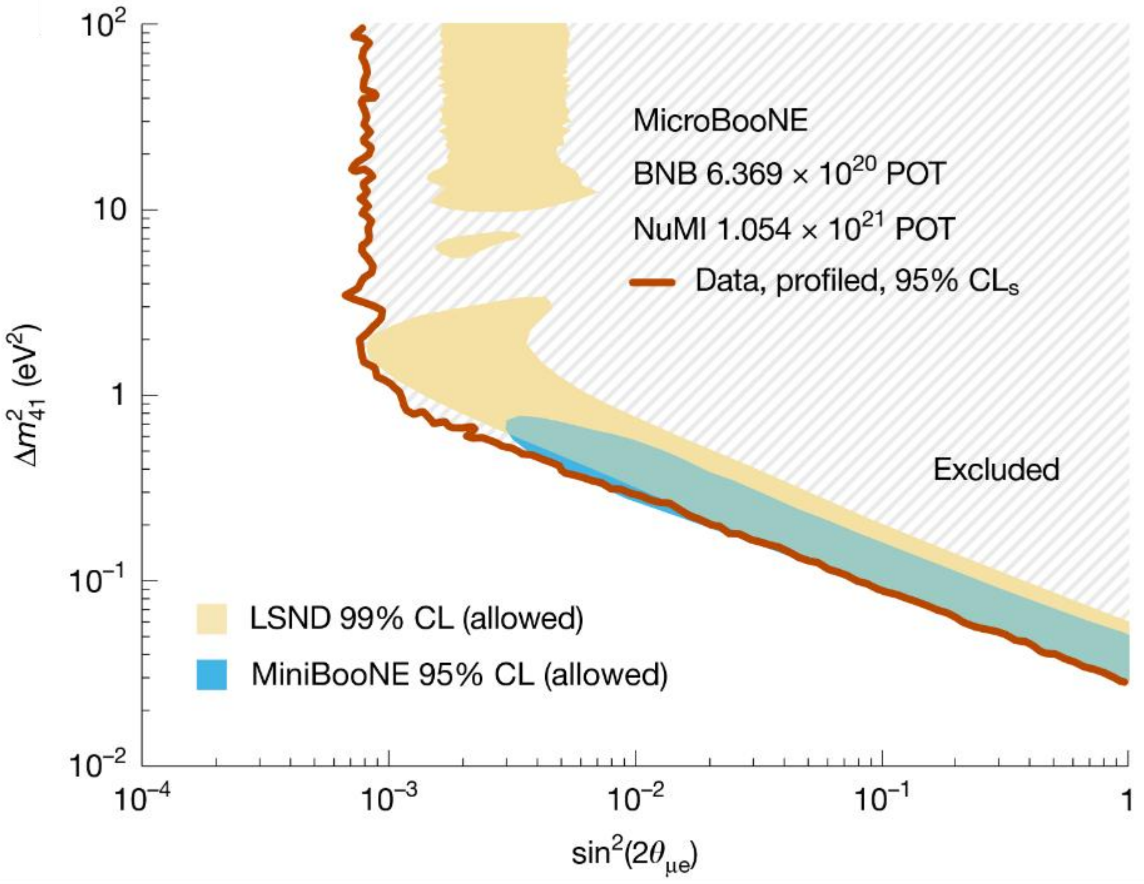

$\Delta m^2_{41} \approx$ Frequency

$sin^2(2\theta_{\mu e}) \approx$ Amplitude

$$P(\nu_\mu \rightarrow \nu_e) \approx sin^2(2\theta_{\mu e}) sin^2(\frac{\Delta m^2_{41} * E}{L})$$

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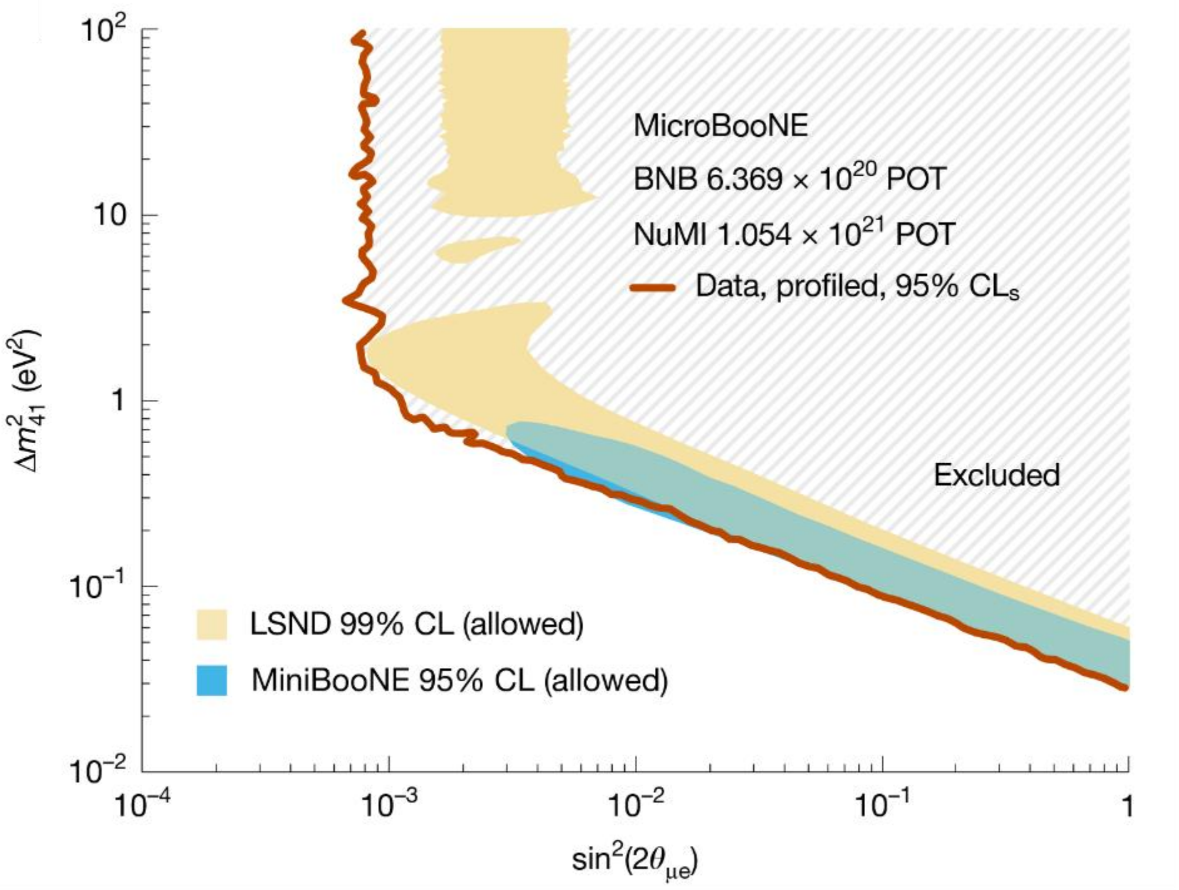

- Each point assumes that the truth value is given.

- Points to the right of the curve are excluded given MicroBooNE/fitting data(to a certain level).

- Points to the left are allowed (to a certain level)

Numu disappearance

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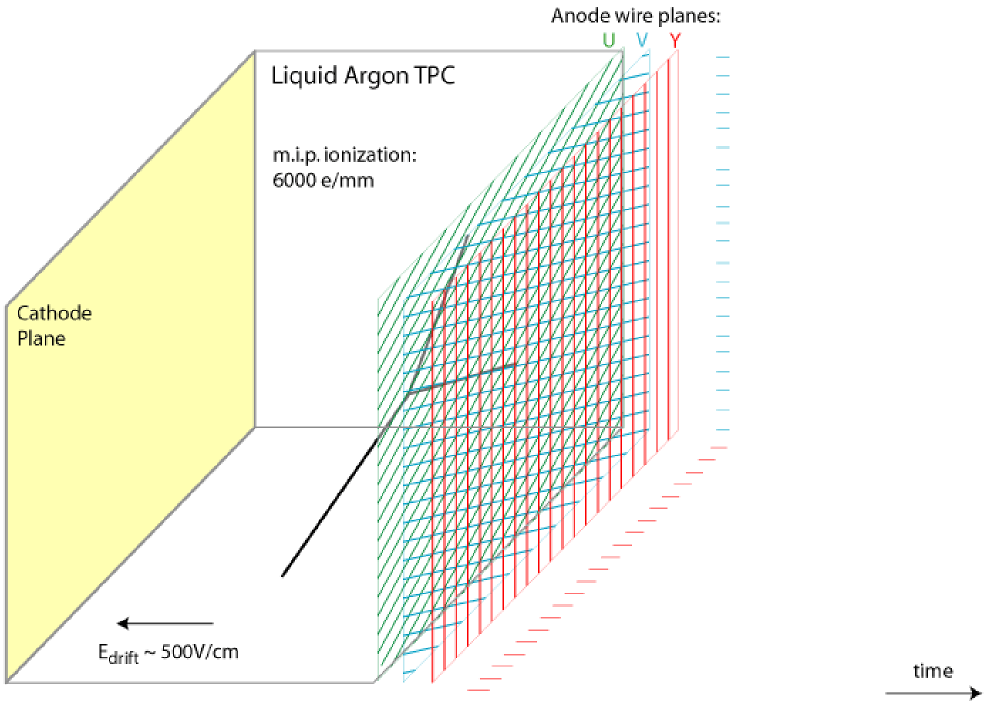
Wire-Cell

Numu disappearance

- Wire-Cell is a 3D event reconstruction package for liquid argon time projection chambers.



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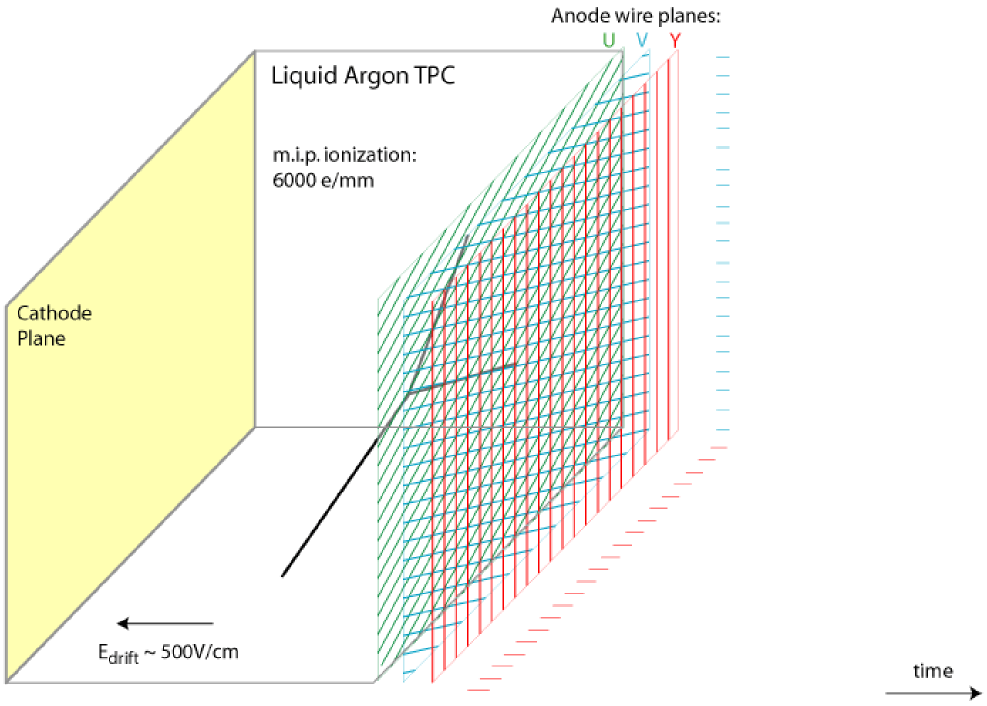

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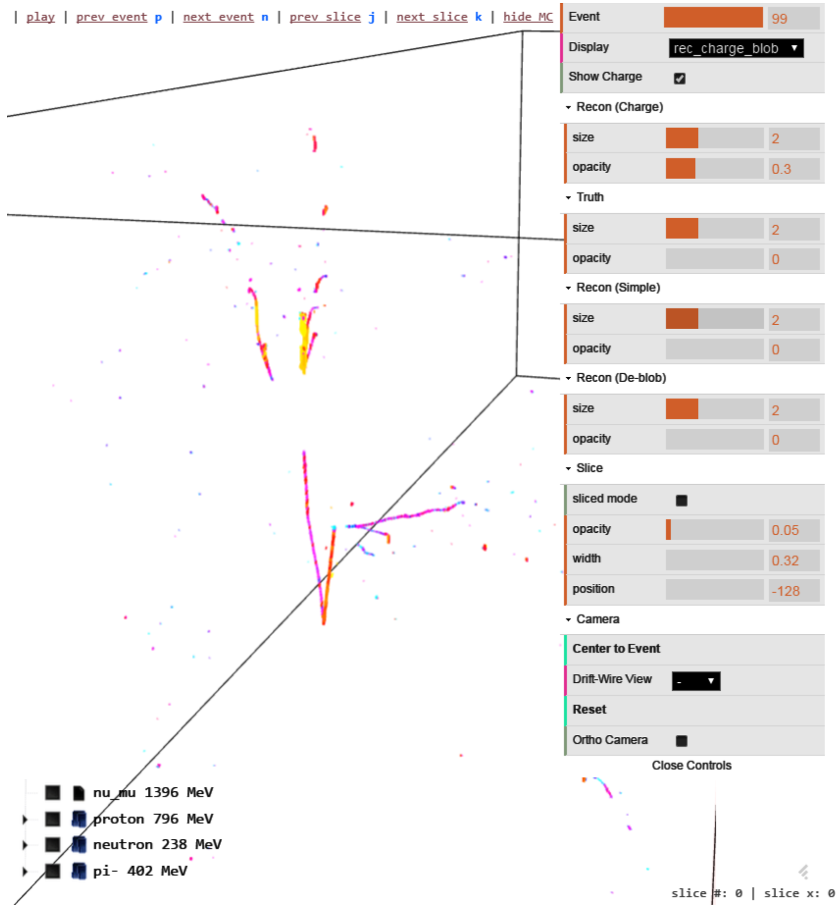
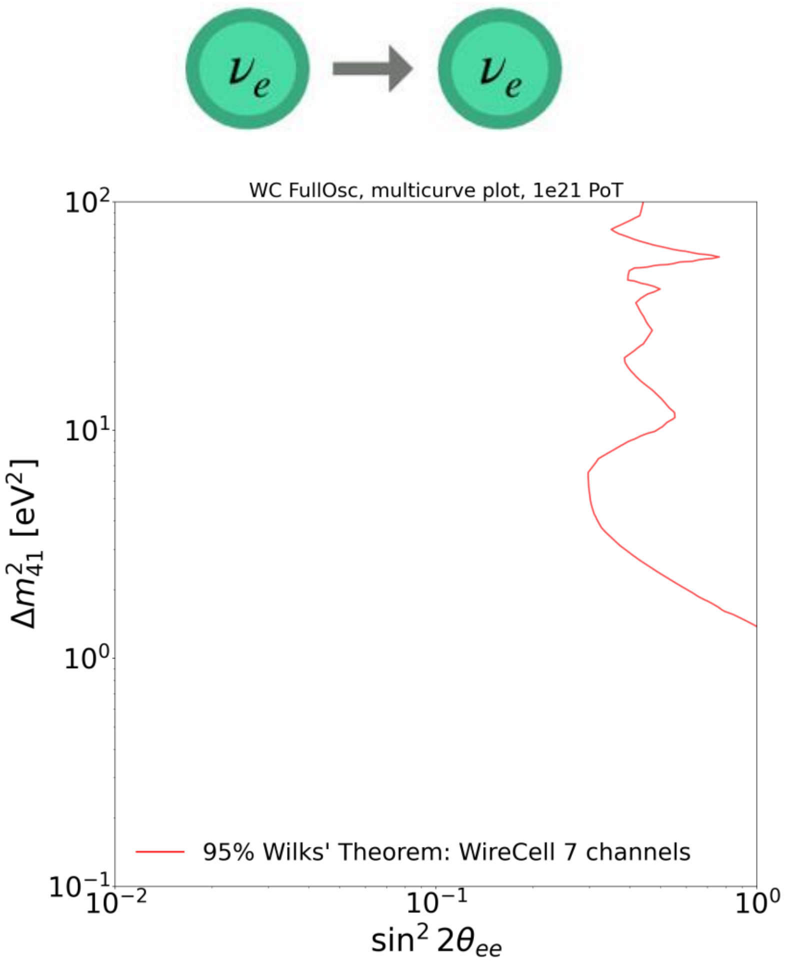


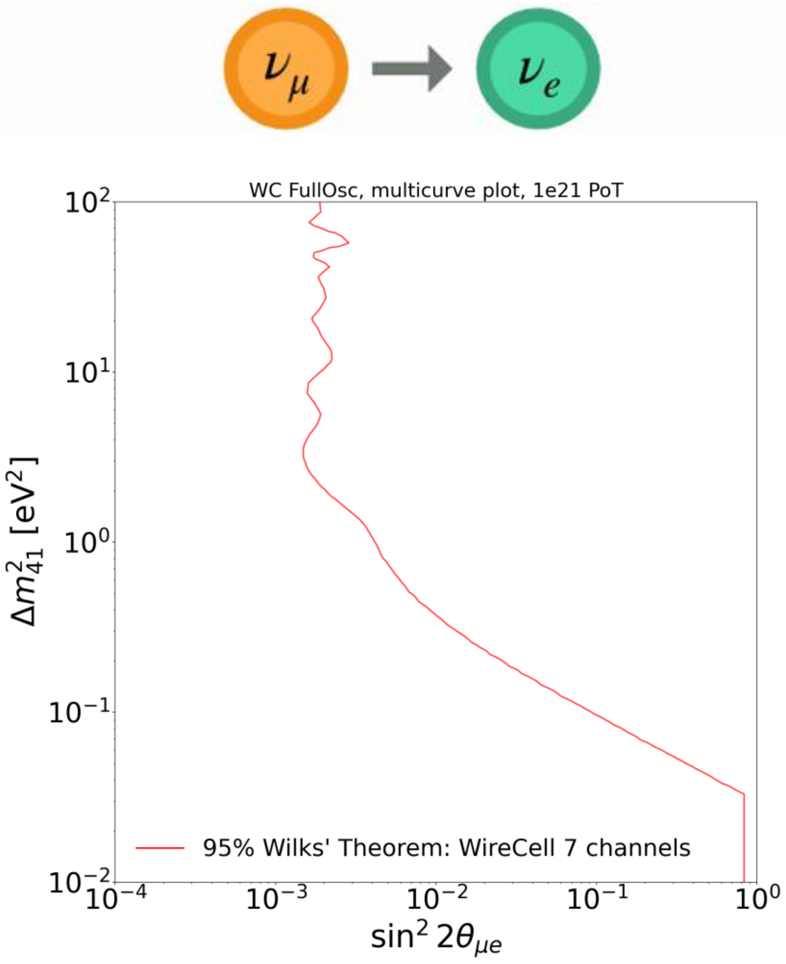
Numu disappearance

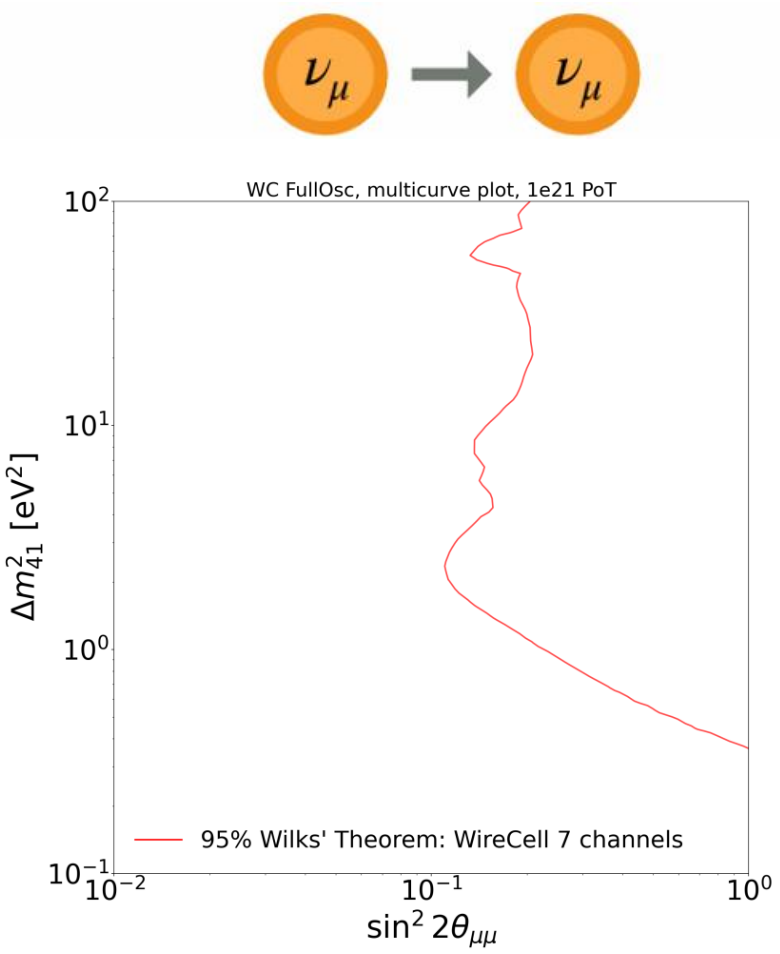
- BAGELS (**B**road **A**nalysis of **G**eneral **EL**ectromagnetic **S**howers) developed BDT(Boosted decision trees) event selections, with inputs from Wirecell and other reconstruction frameworks.

The goal

- The Wire Cell selections are the **standard** for further studies.

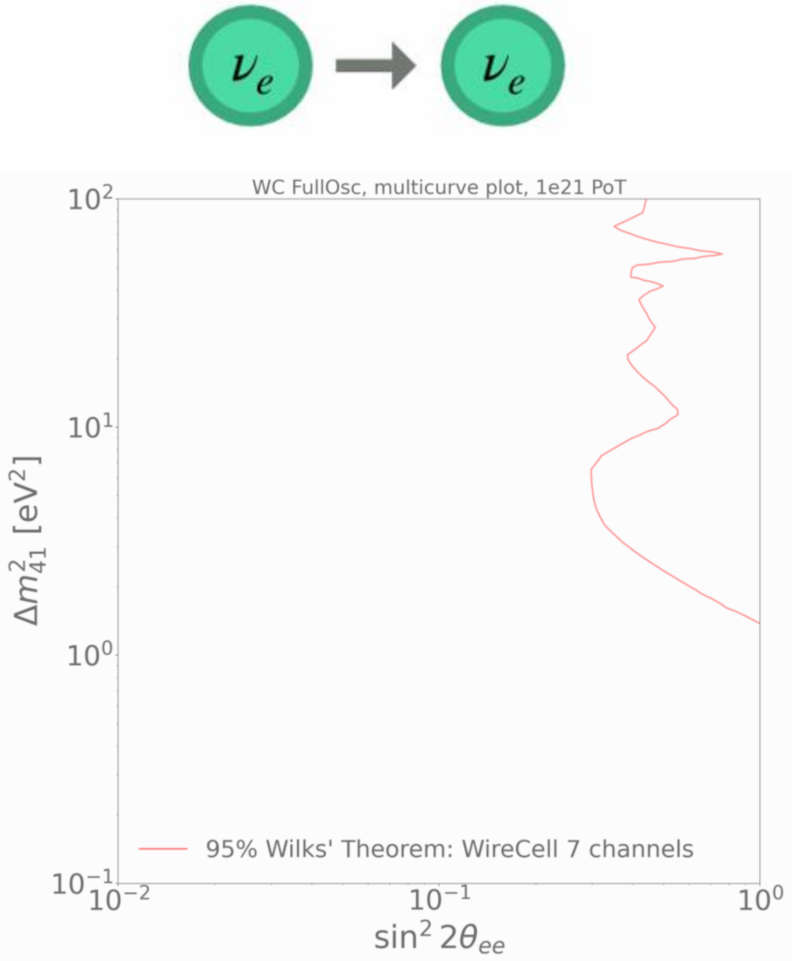


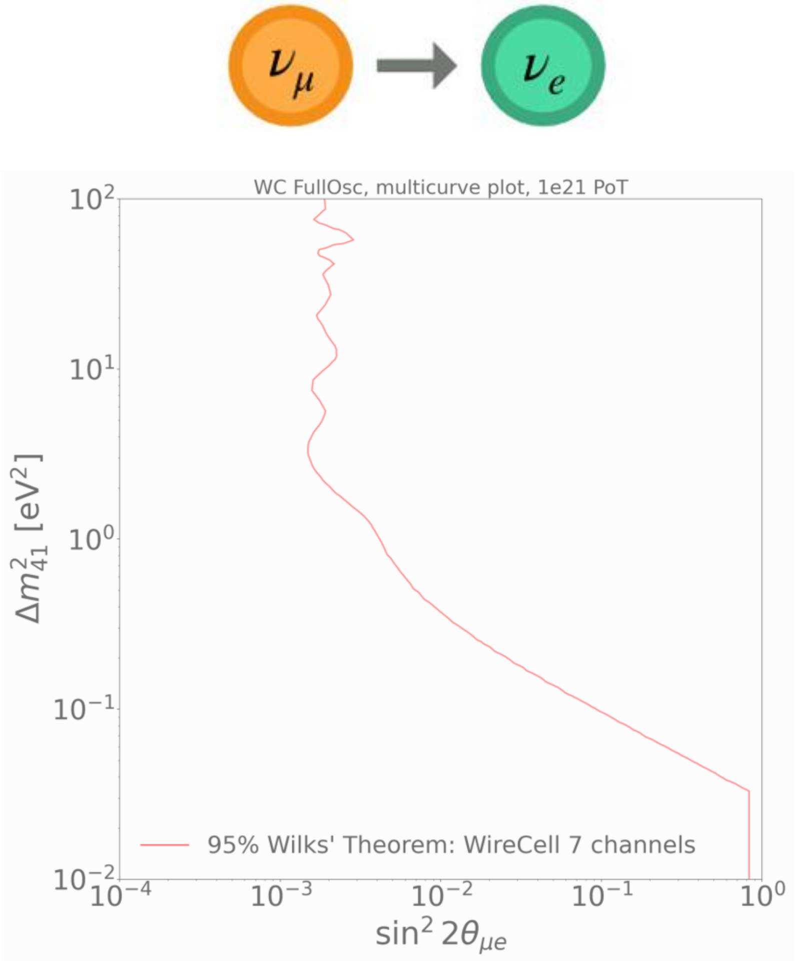


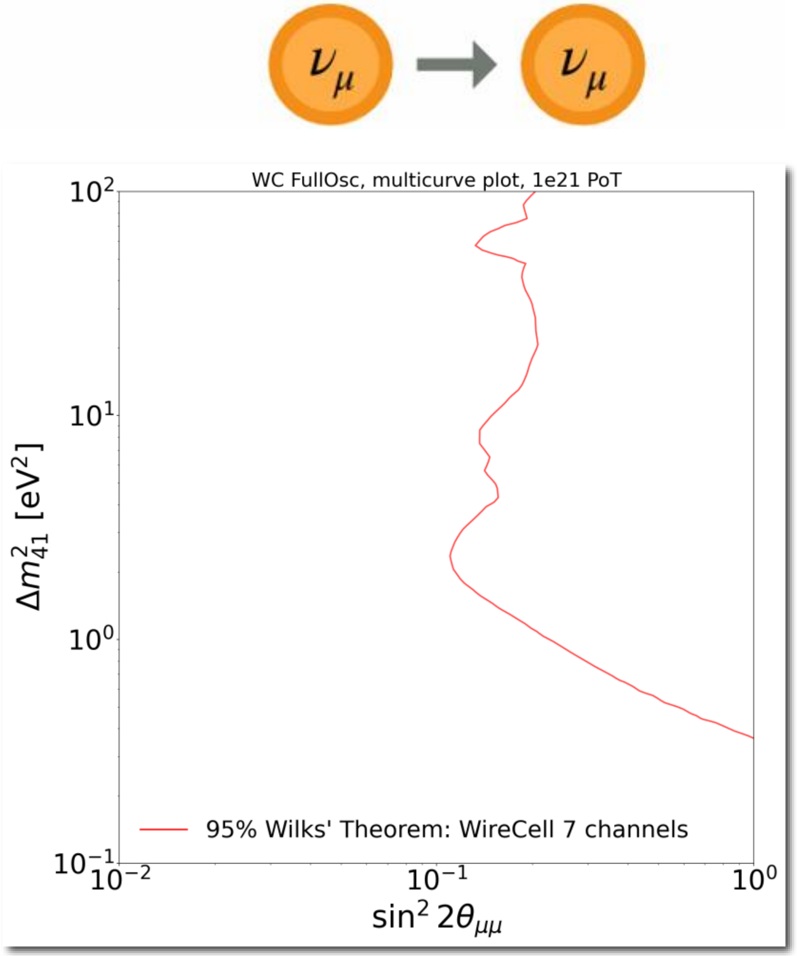


The goal

- I started by looking at **Numu disappearance**







Studies of PROfit channels

- There is a tree structure to the channels that we are looking at.

NumuCC events

Muon NeutrinoCharged Current

Xp

0 or N proton event

Xpi0

0 or N pi0 event

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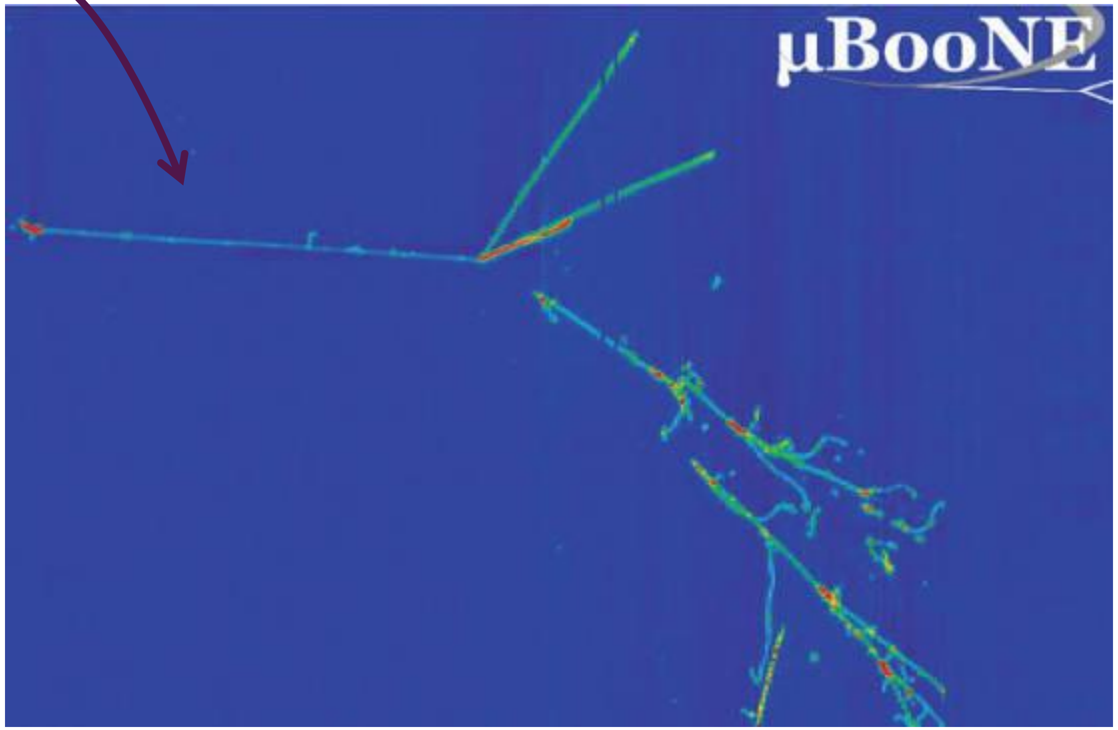

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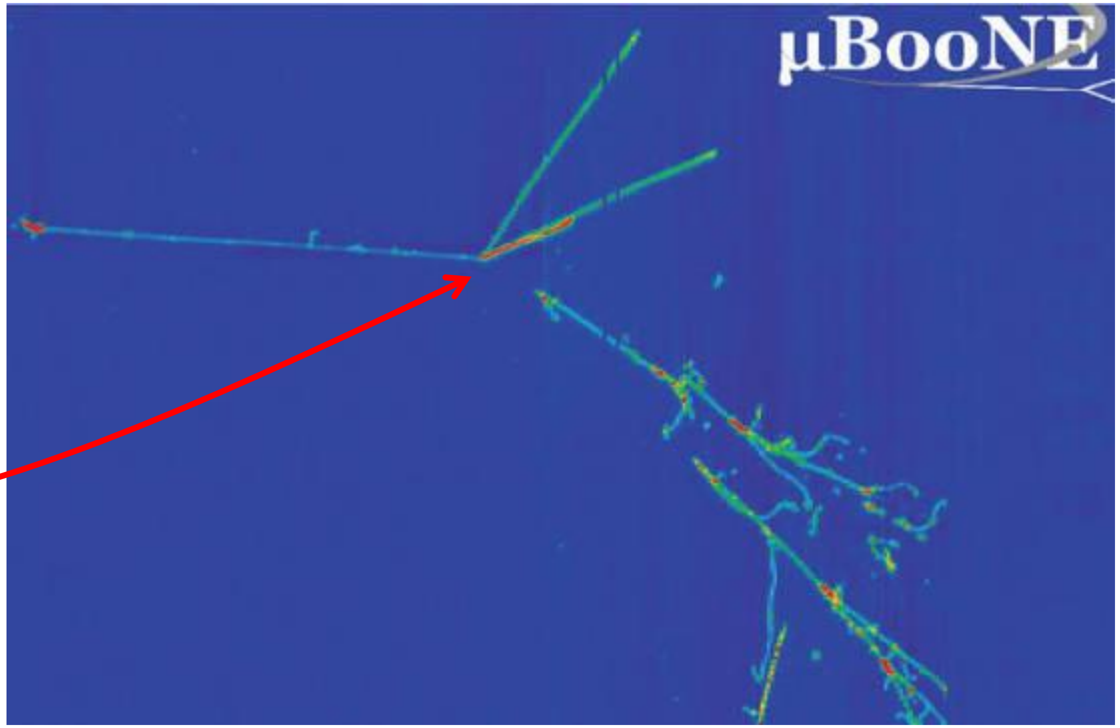

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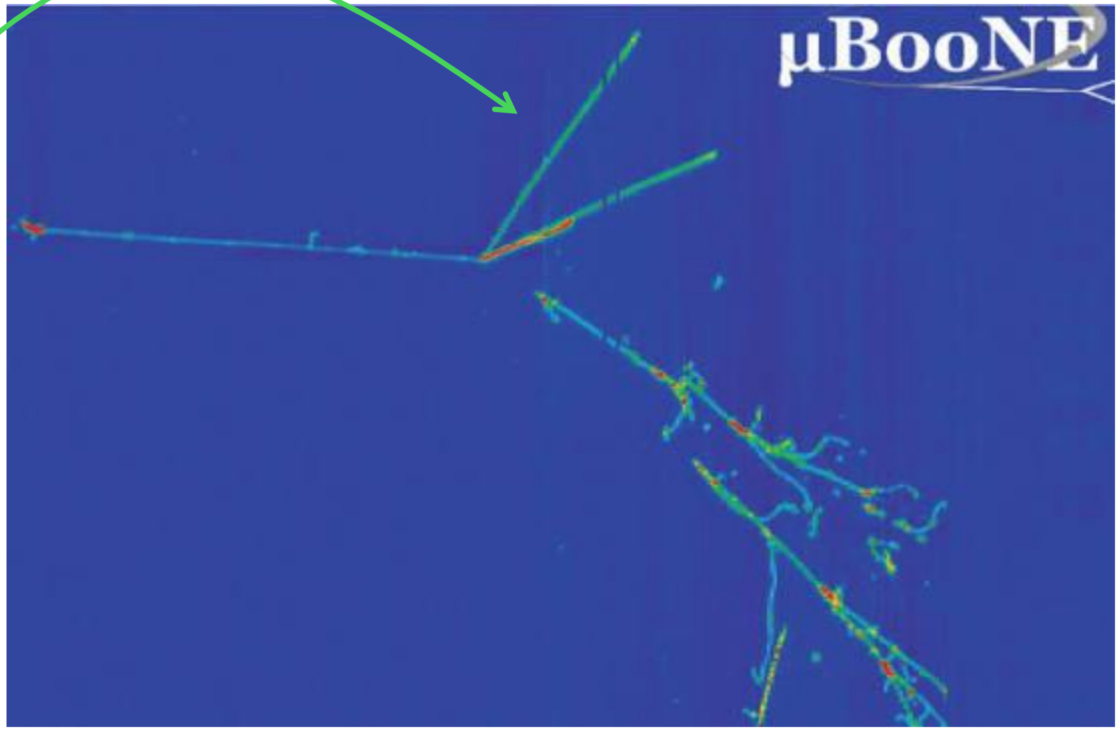
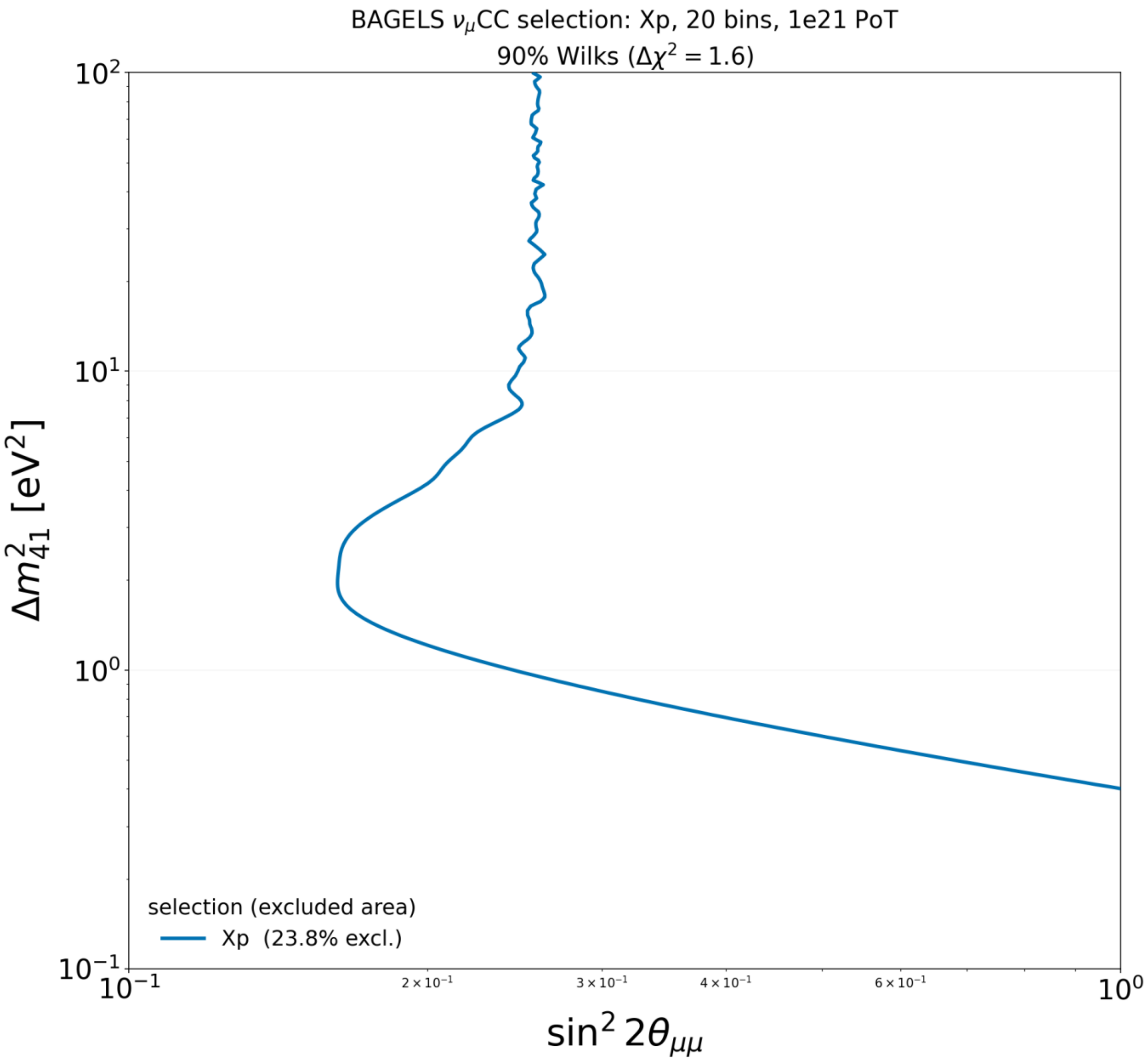


Studies of PROfit channels

- Numu Disappearance



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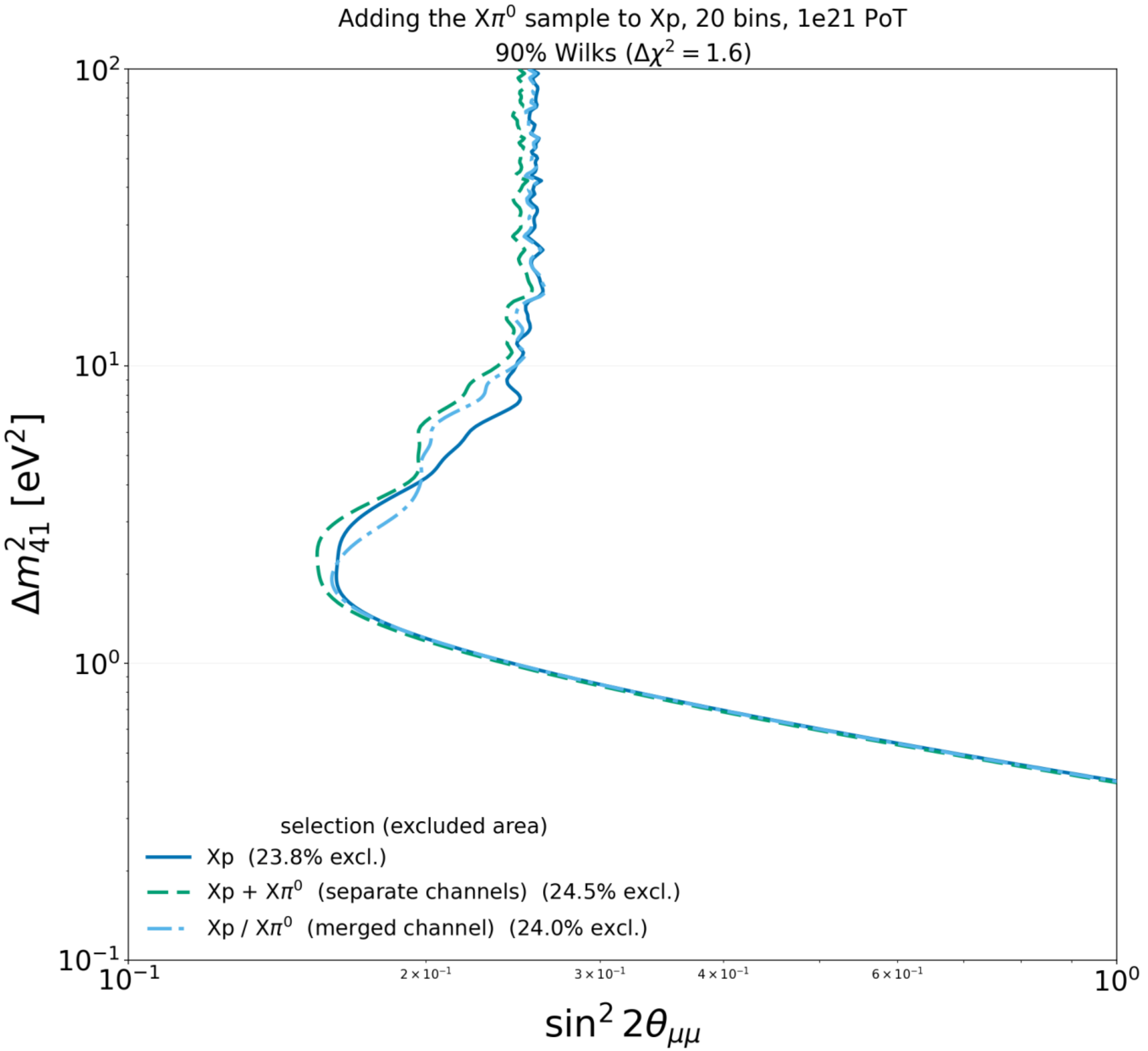

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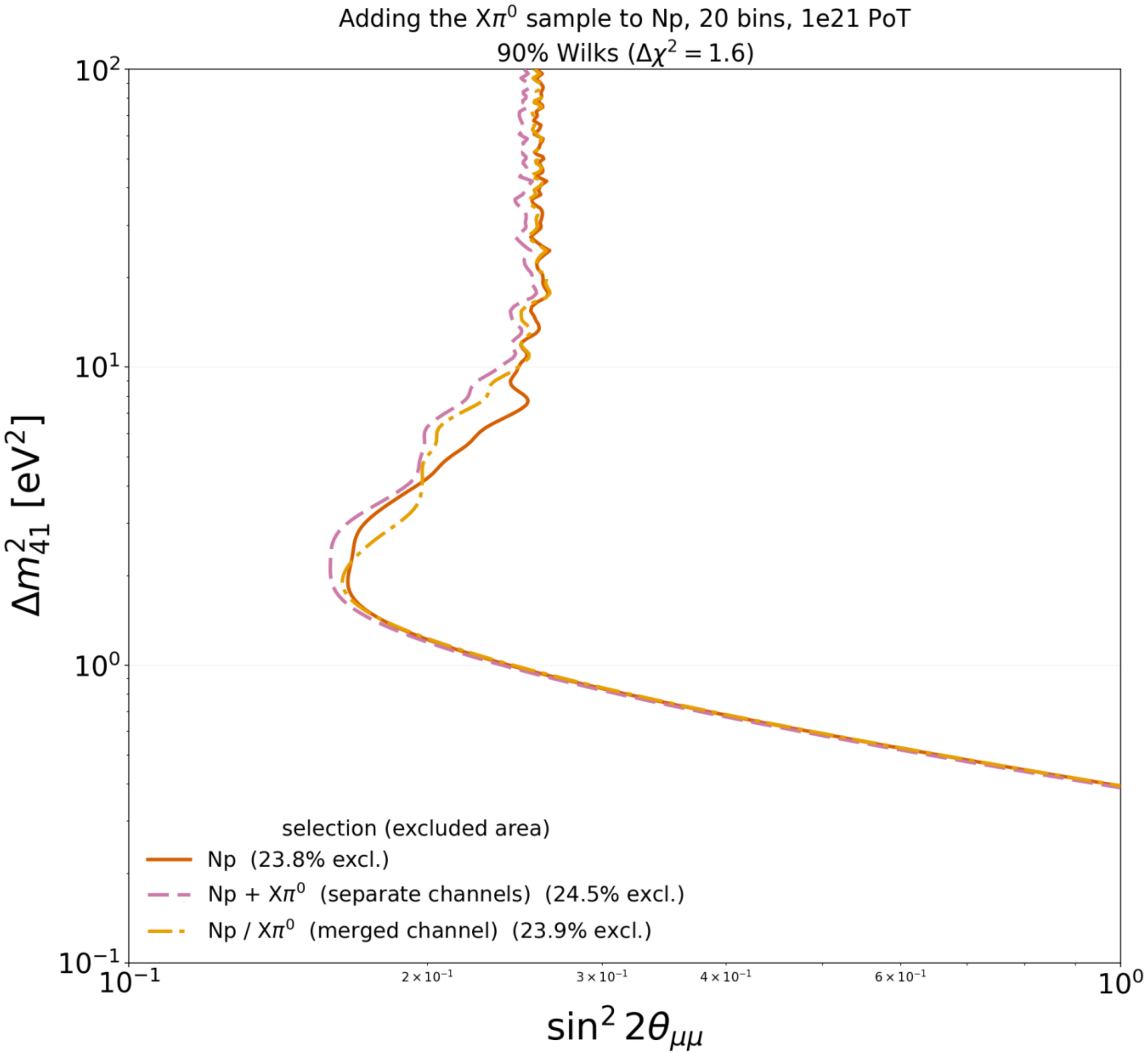


Studies of PROfit channels

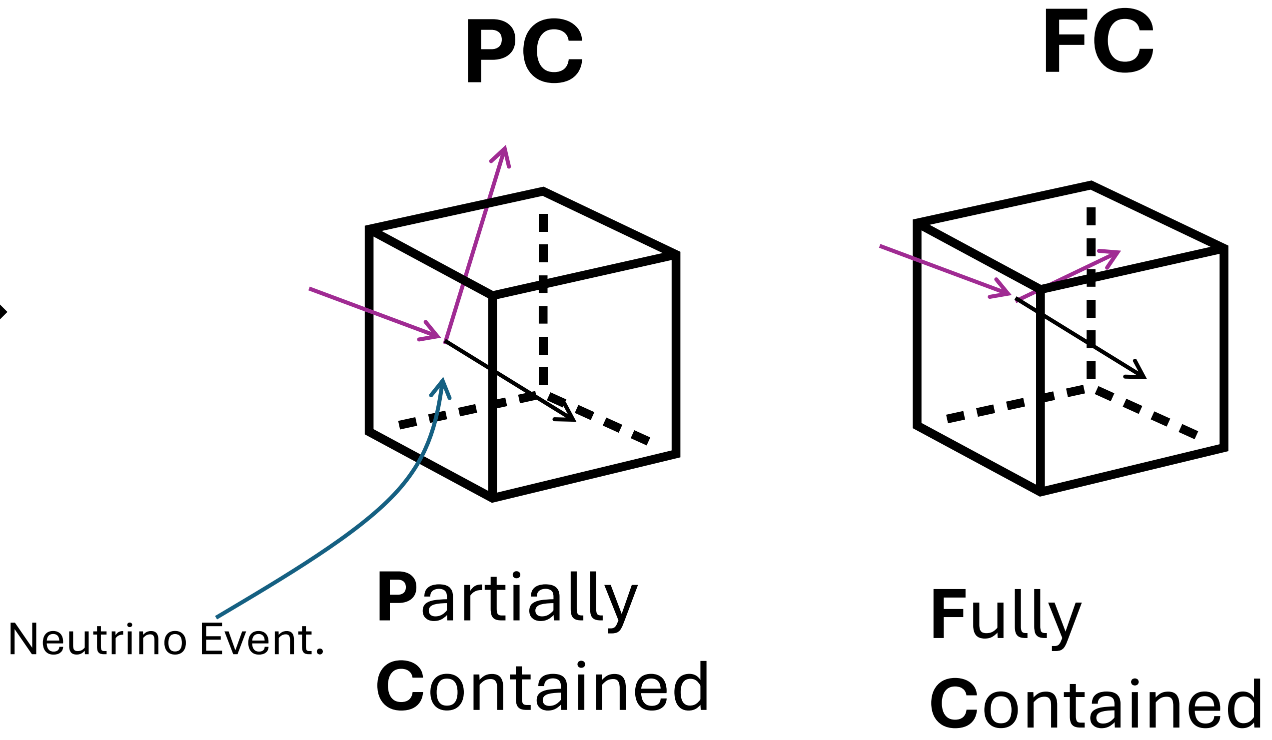
- Additional constraints:

Xpi0

0 or N pi0 event

Xp

0 or N proton event



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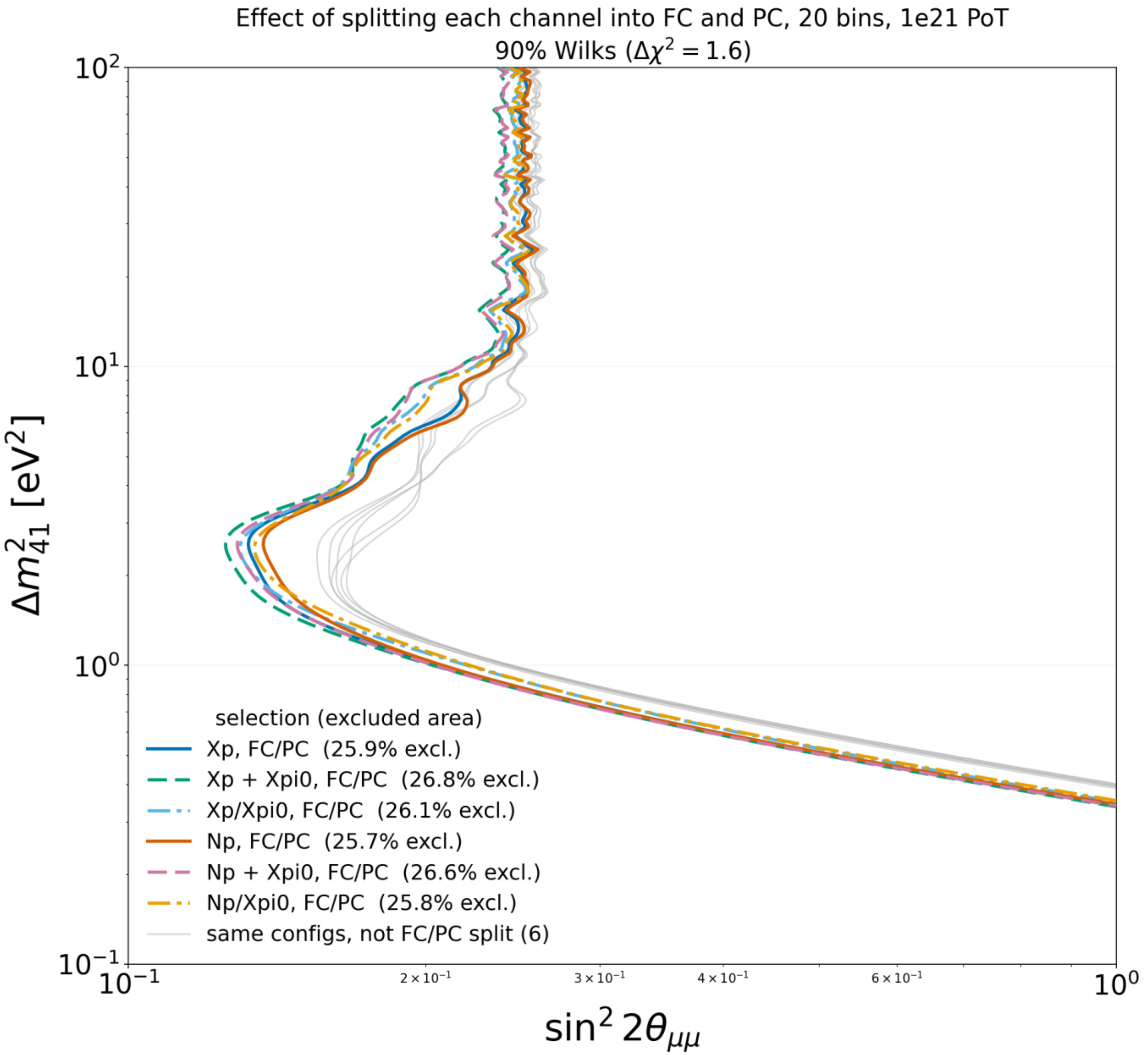

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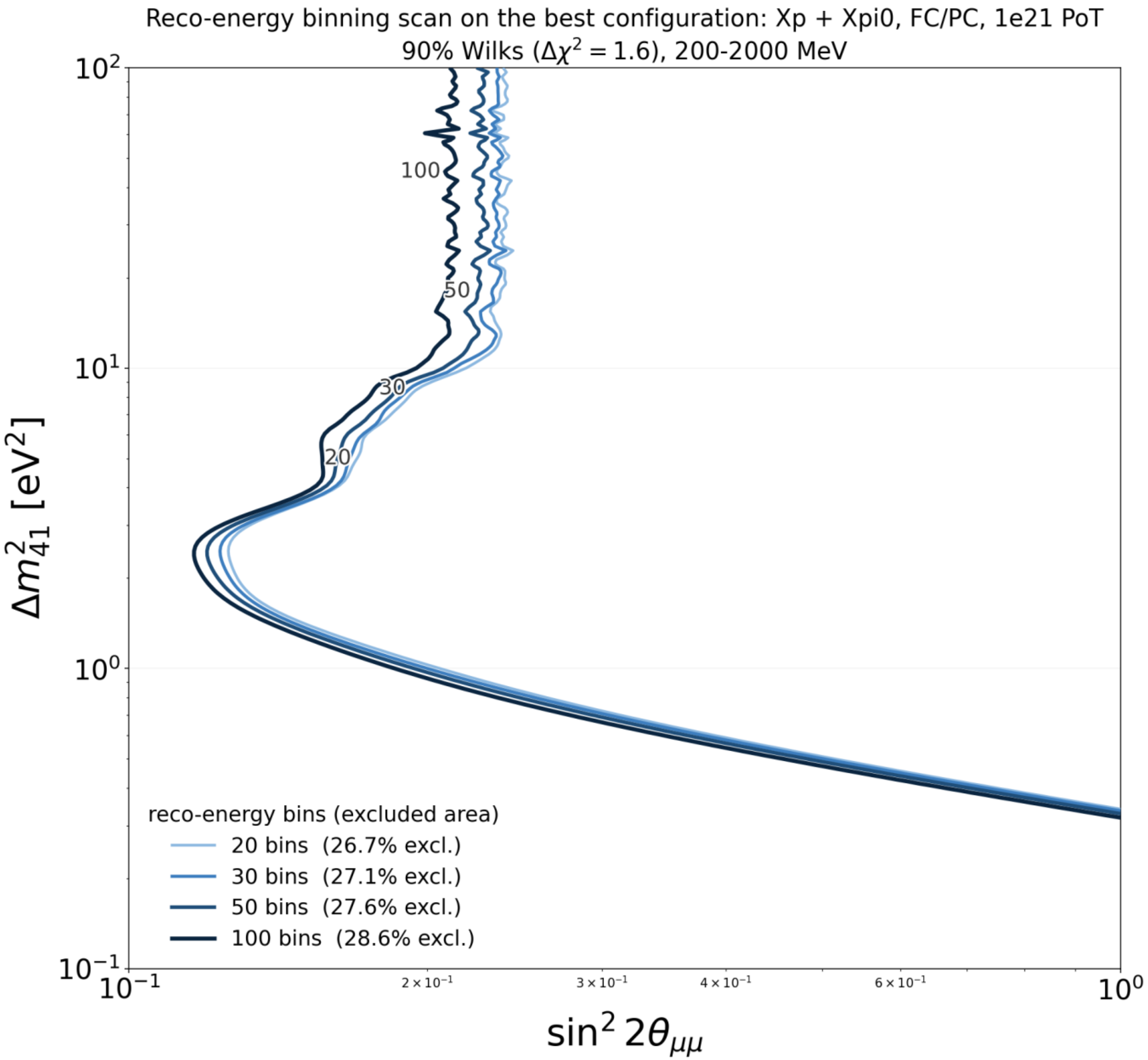

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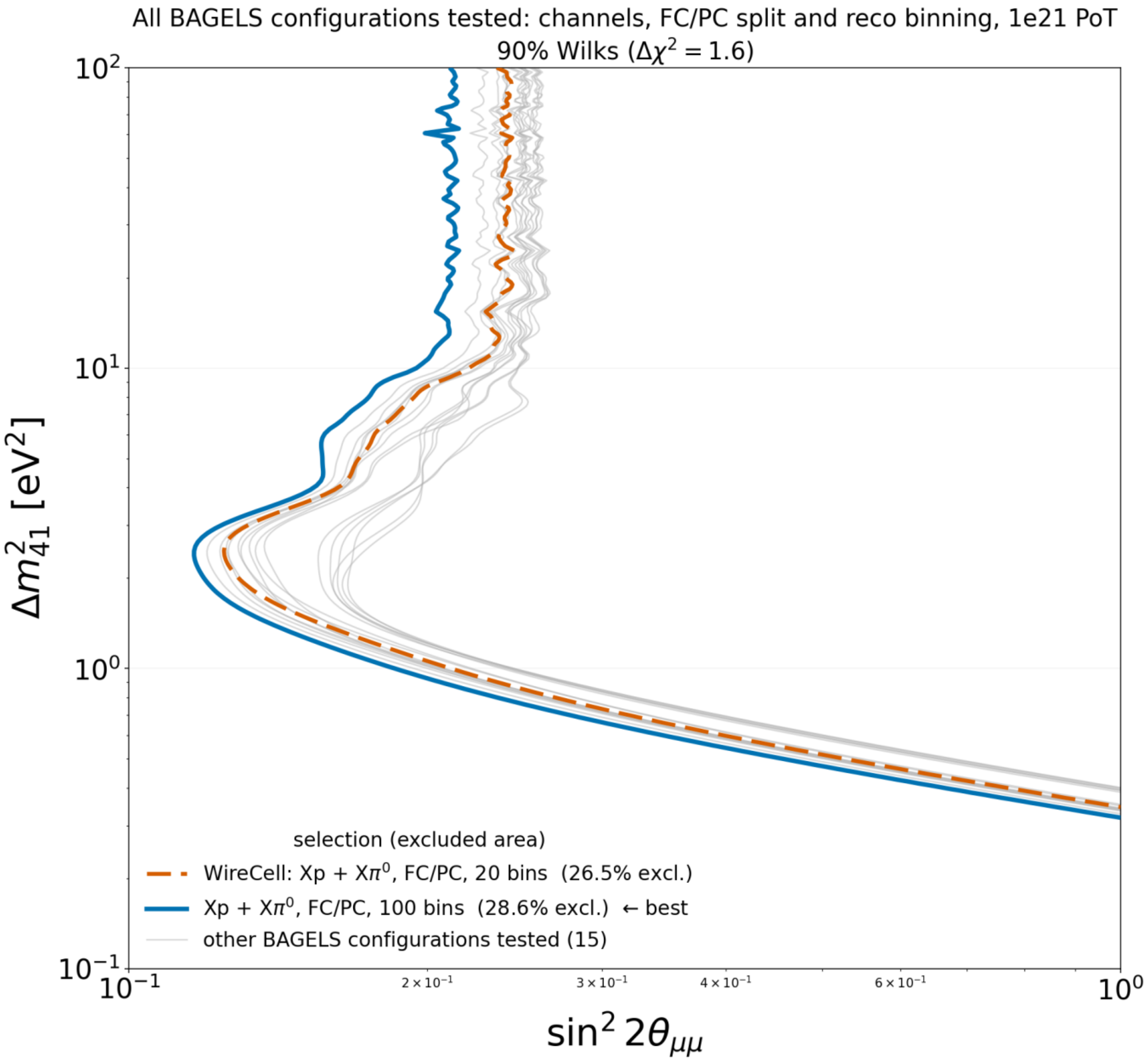
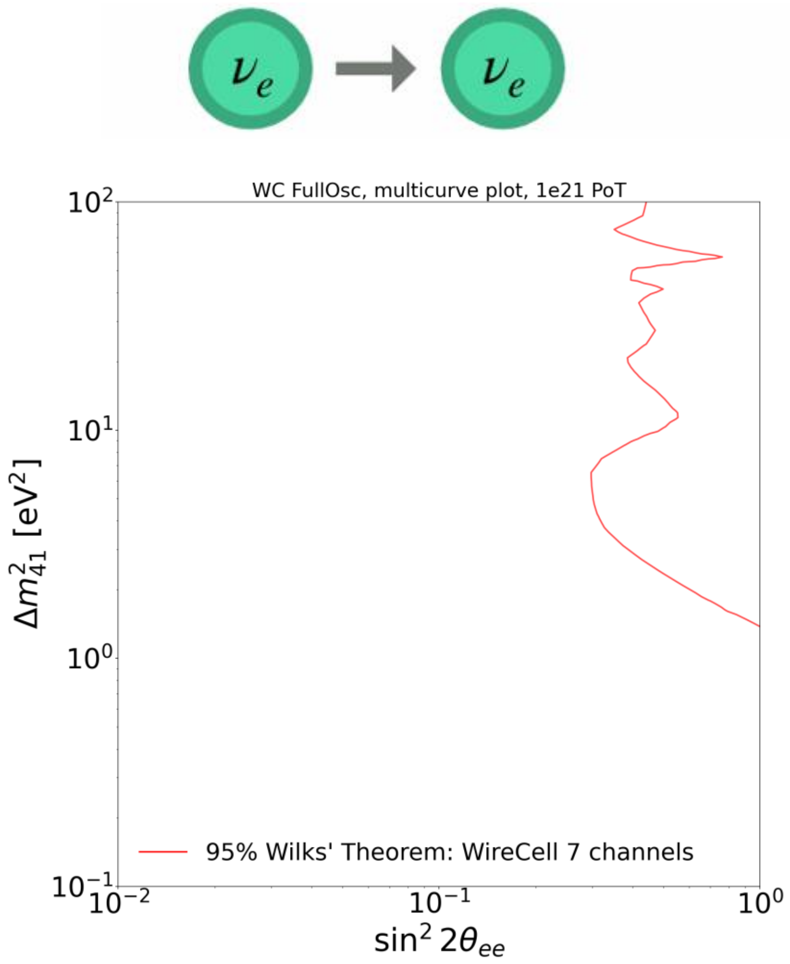
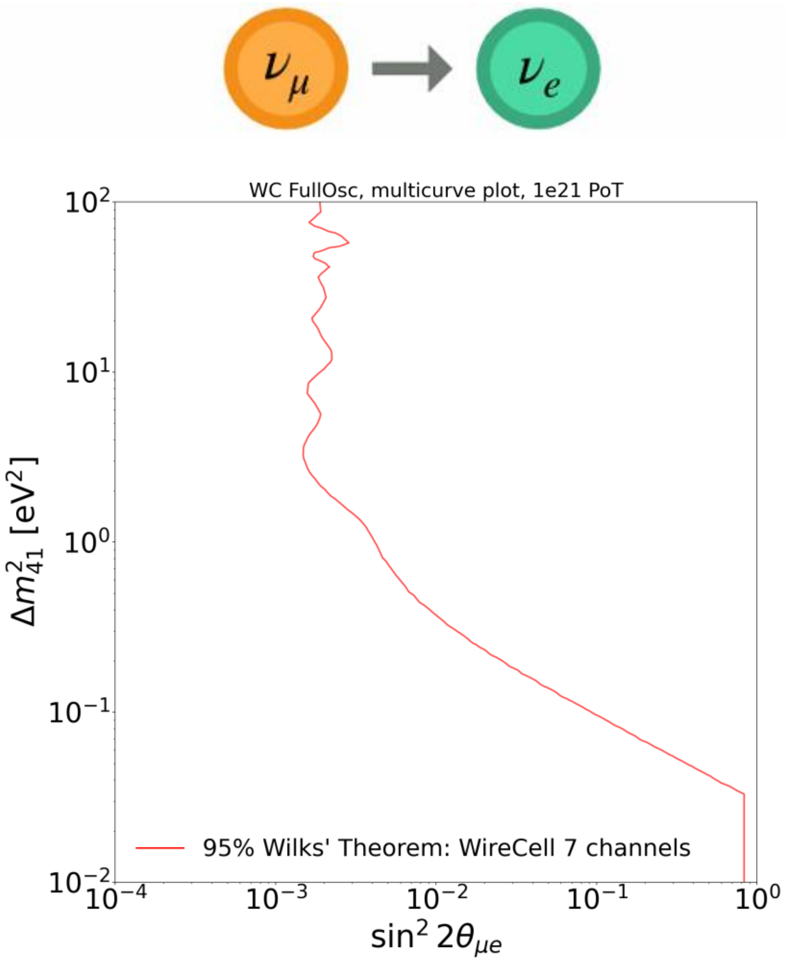
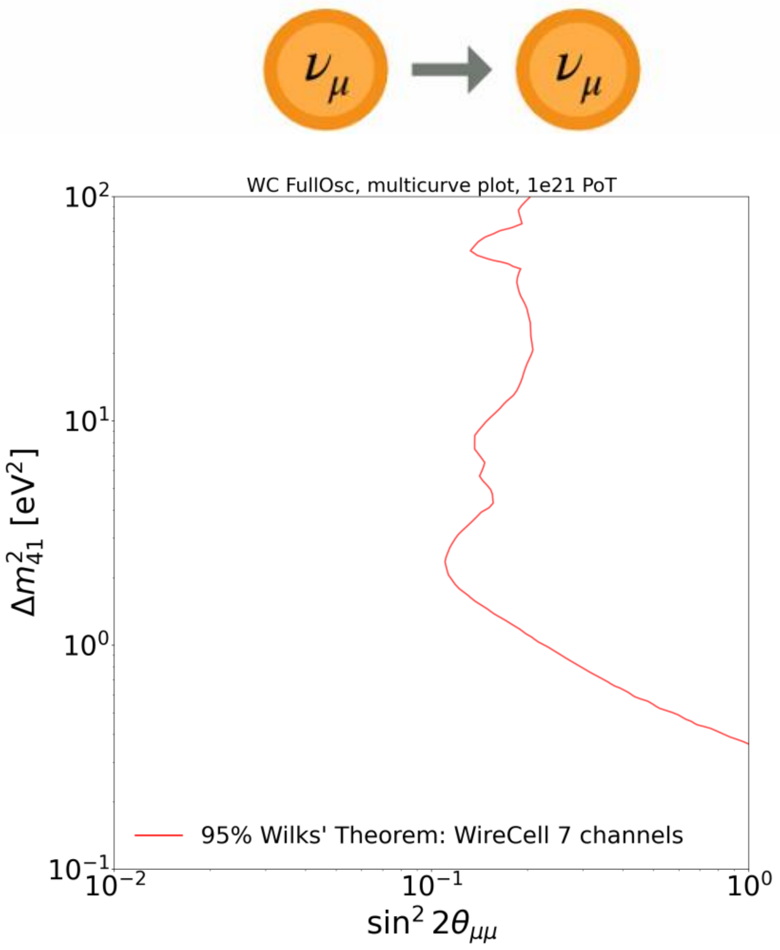


The goal

- We need to investigate this behavior for the other 2 modes.







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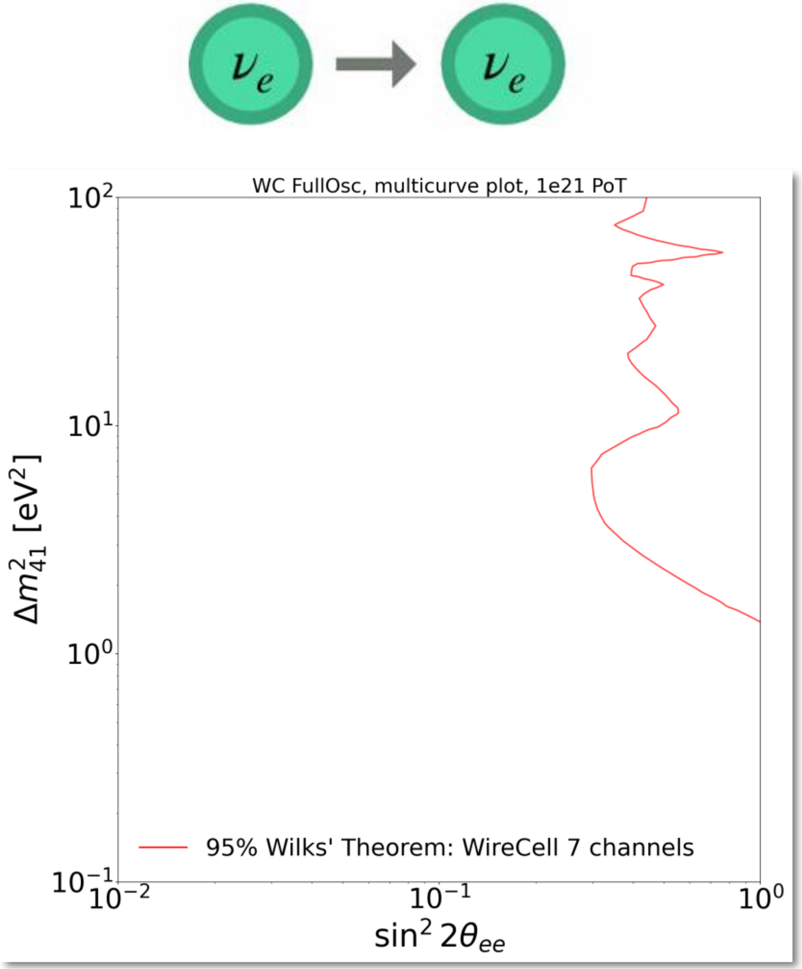

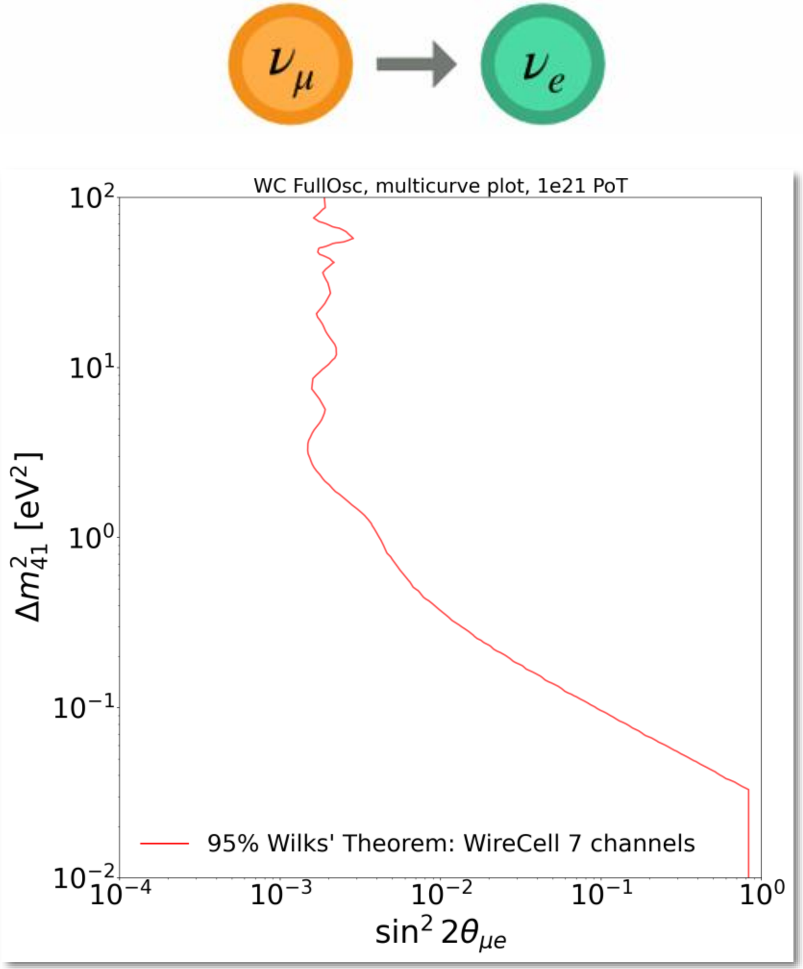

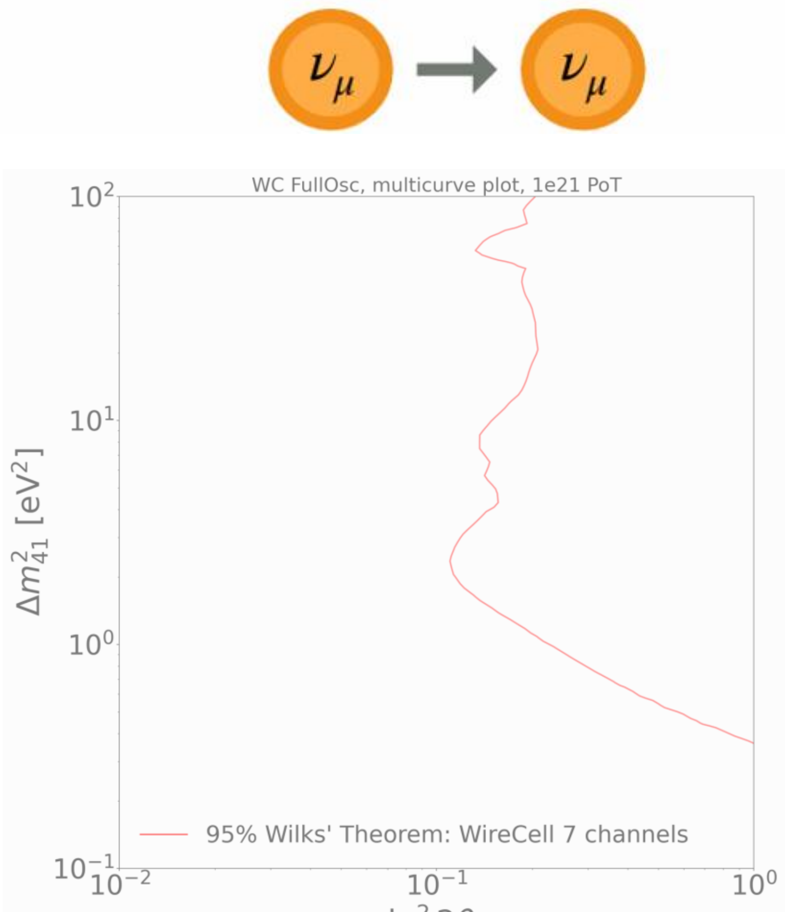

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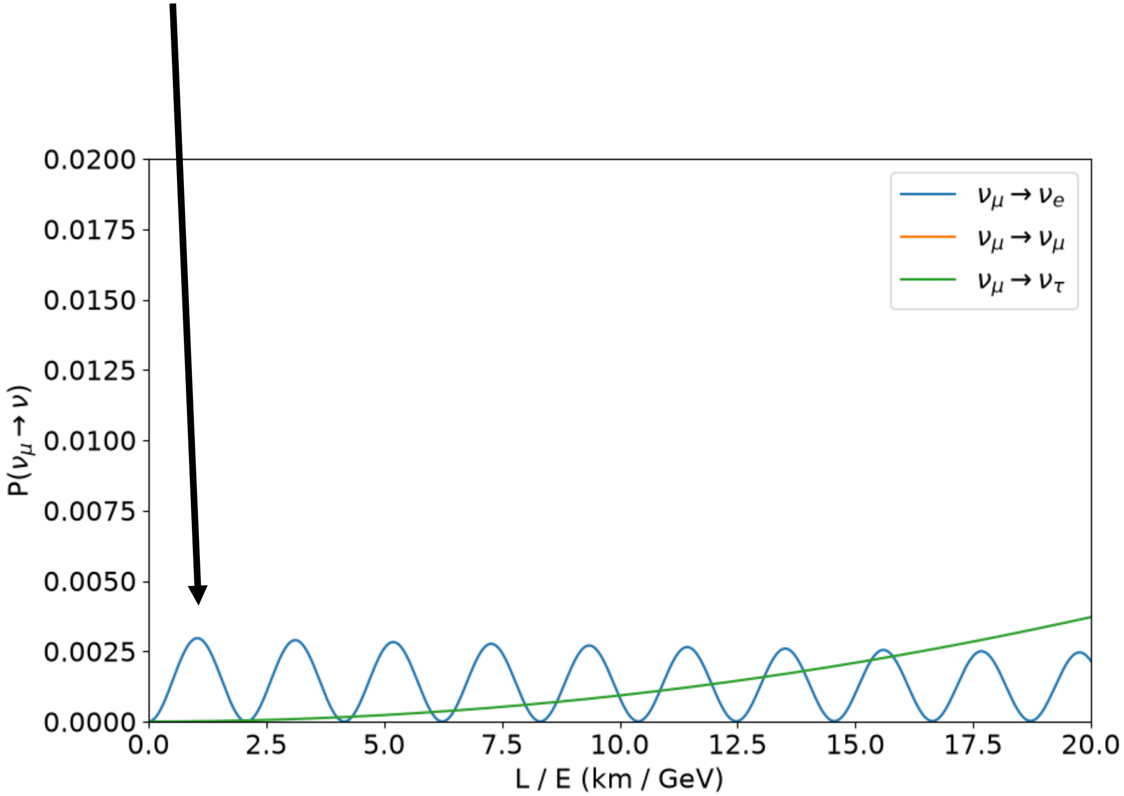

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- However to do a 3+1 model search, we need a **simulated fully oscillated numu to nue sample.**

- These take computational power, time, and resources to do.

- What if there was a way to approximate this **full osc sample?**

~~The Goal~~ The Task

- Generate a nue appearance sample from preexisting numu samples.

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- Generate a nue appearance sample from preexisting numu samples

1st

Nue Samples

ν_e ν_e ν_e

ν_μ ν_μ ν_μ ν_μ

Numu Samples

~~The Goal~~ The Task

- As the beam **started out in numu**, we have to **keep** the **flux systematics** from numu.

1st

Nue Samples

ν_e ν_e ν_e

ν_μ ν_μ ν_μ ν_μ

Numu Samples

2nd

Systematics: Detector, cross section

Nue Samples

Ex. 1.100, 1.1064, 1.23 :Gev

ν_e ν_e ν_e

This is a one-to-one matching

ν_μ ν_μ ν_μ

Ex. 1.105, 1.1082, 1.109 : Gev

Numu Samples

Systematics: Flux

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1st

Nue Samples

ν_e ν_e ν_e

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Numu Samples

2nd

Systematics: Detector, cross section

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ν_μ ν_μ ν_μ

Ex. 1.105, 1.1082, 1.109 : Gev

Numu Samples

Systematics: Flux

3rd

Nue Samples

+

Numu Samples

Fully oscillated Numu to nue samples (fullosc)

ν_e ν_e ν_e

~~The Goal~~ The Task

- Generate a nue appearance sample from preexisting numu samples

4th

First look at Fully oscillated
Sample.

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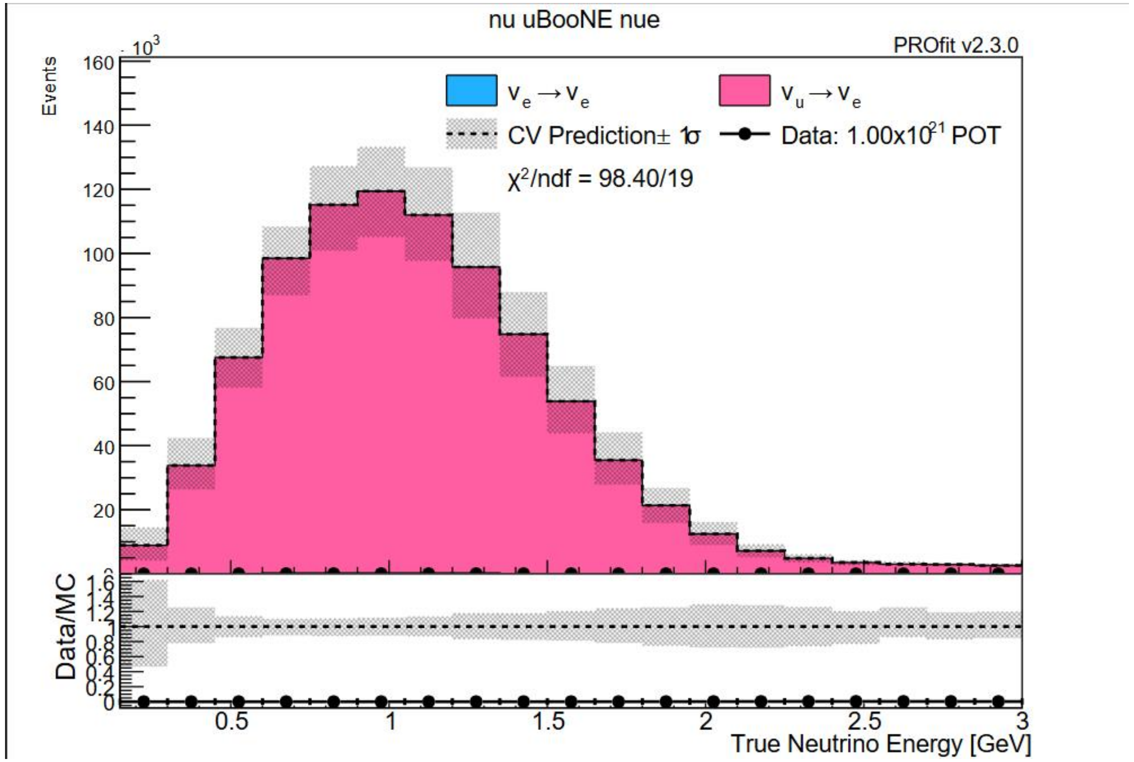

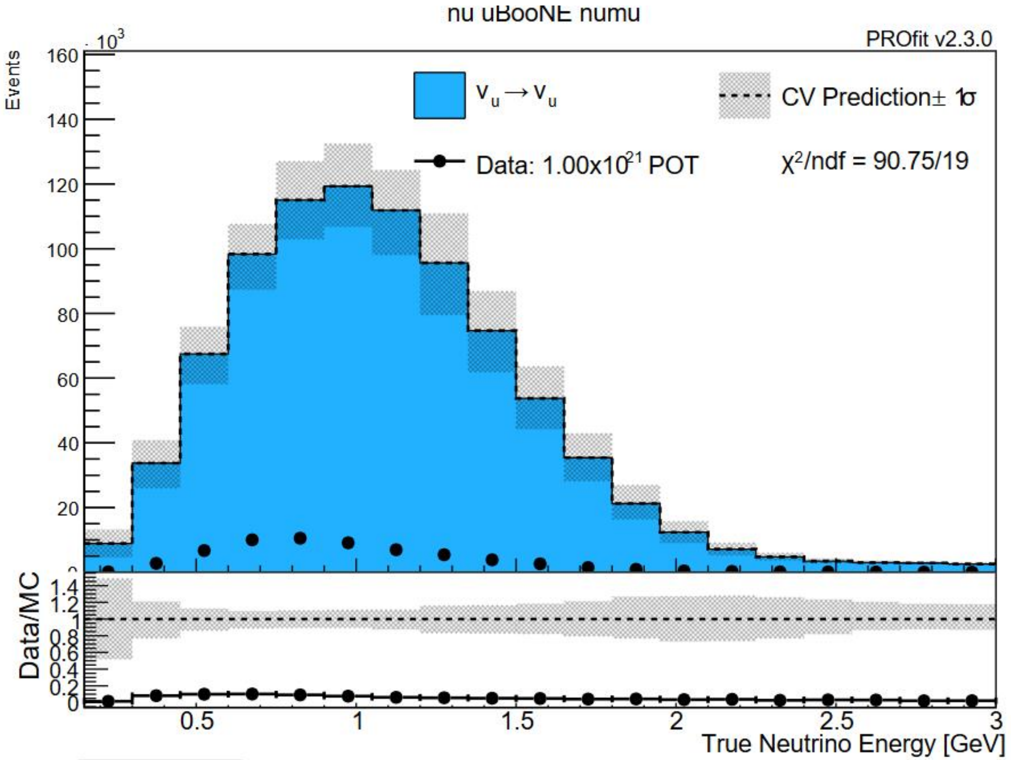

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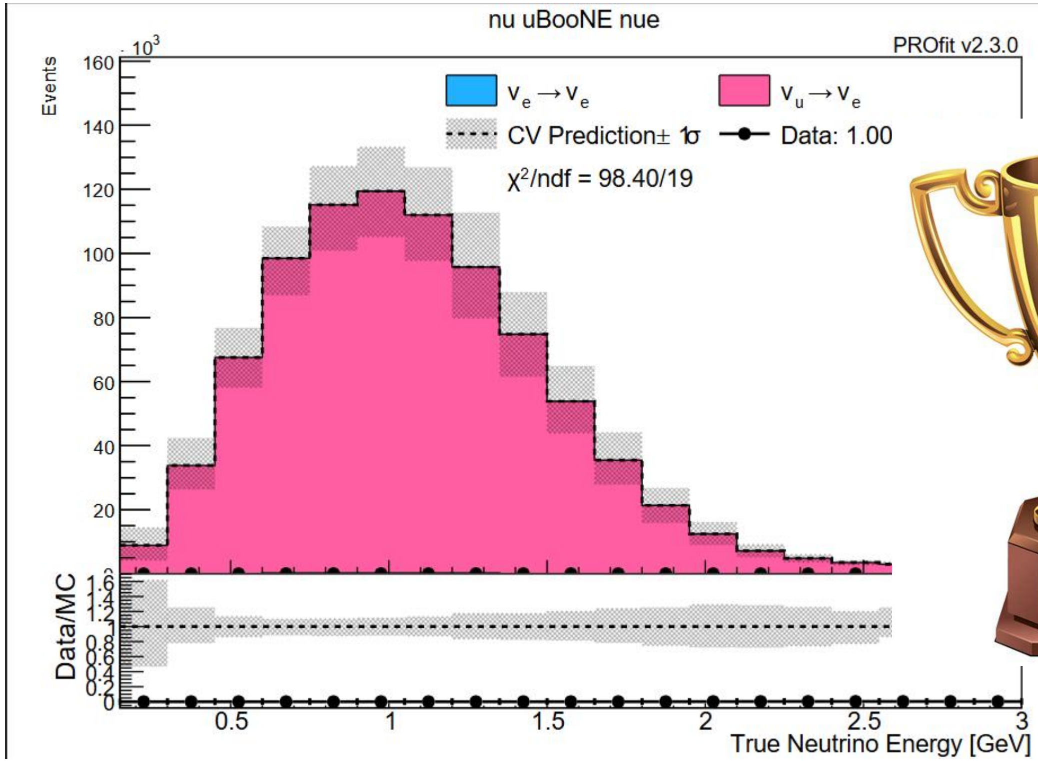

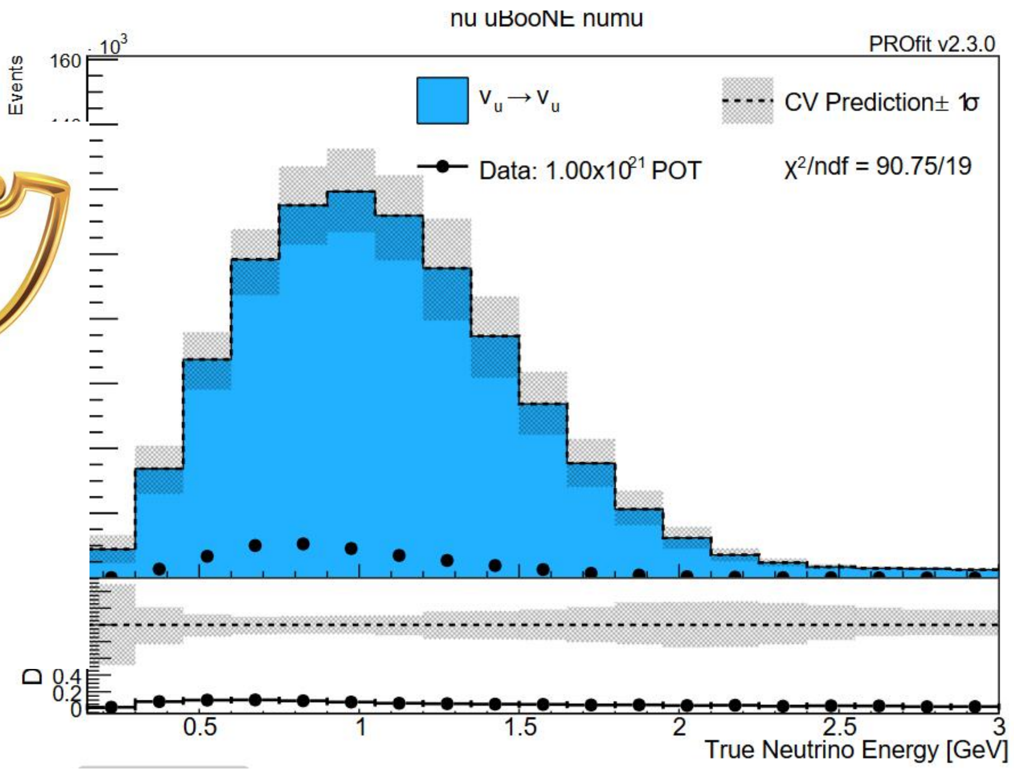

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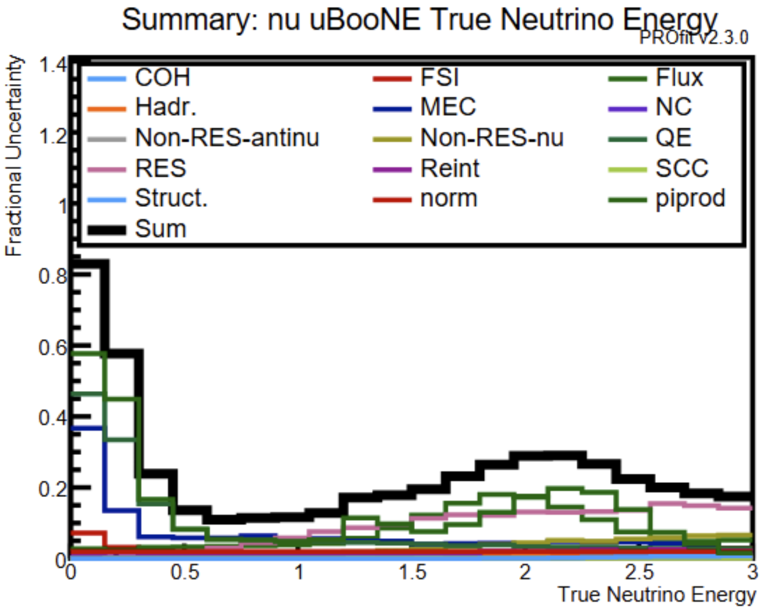
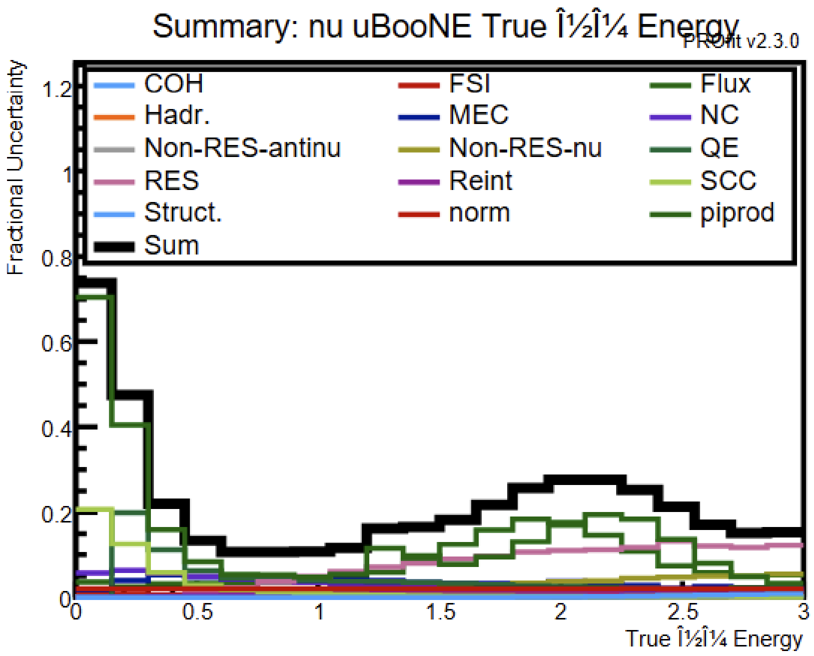
4th

First look at Fully oscillated Sample.

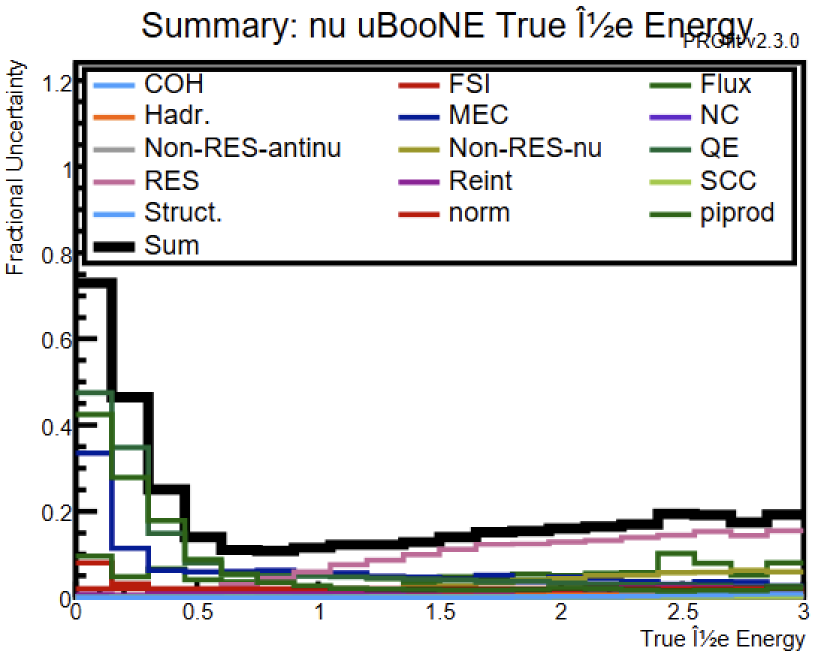
Fullosc sample



Numu sample



Nue sample



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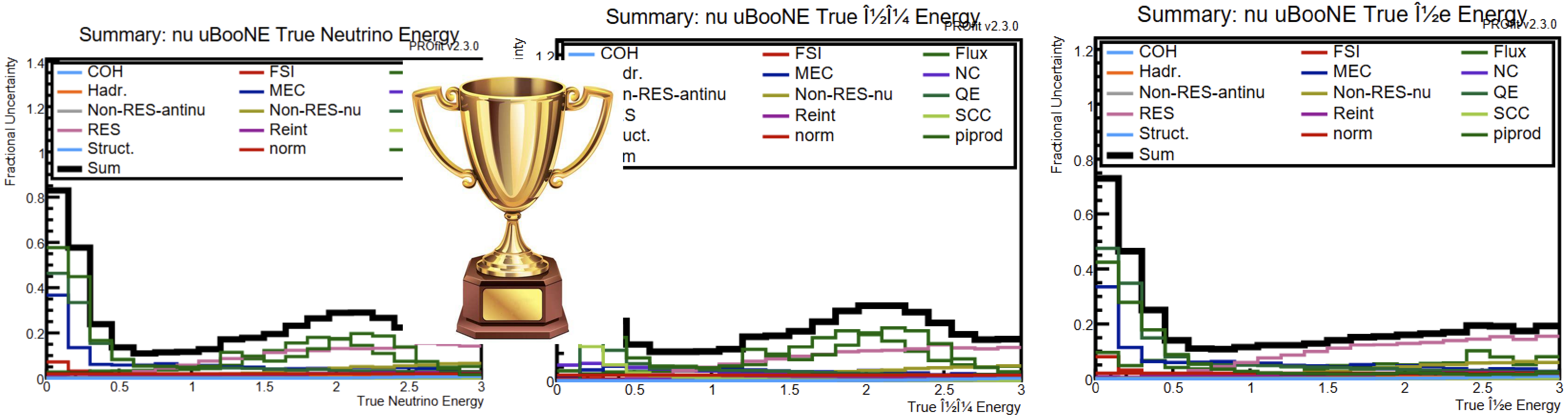
First look at Fully oscillated Sample.

Fullosc sample

Numu sample

Nue sample



3+1 model studies.

- First glimpse of a 3+1 model with a generated full osc sample.

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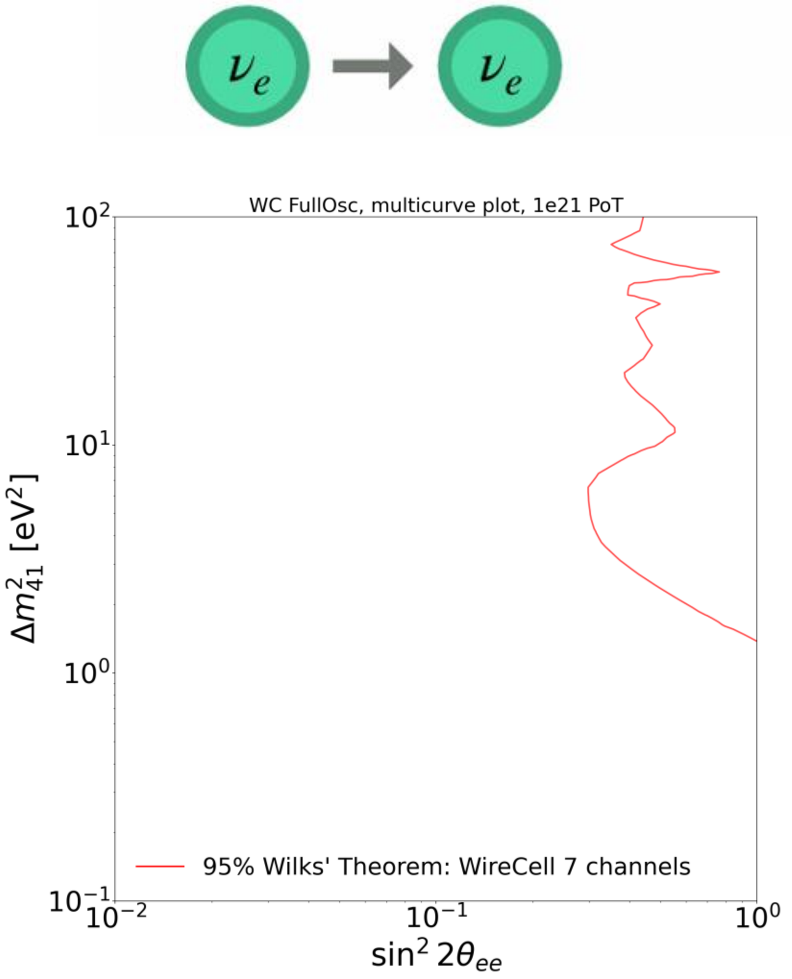
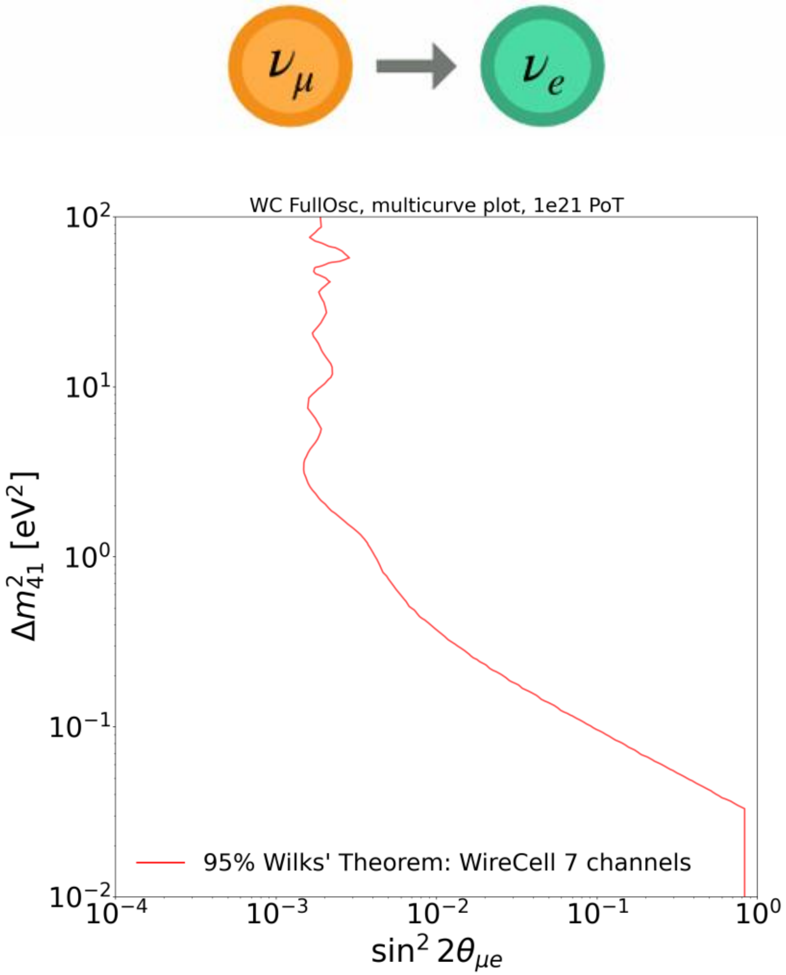
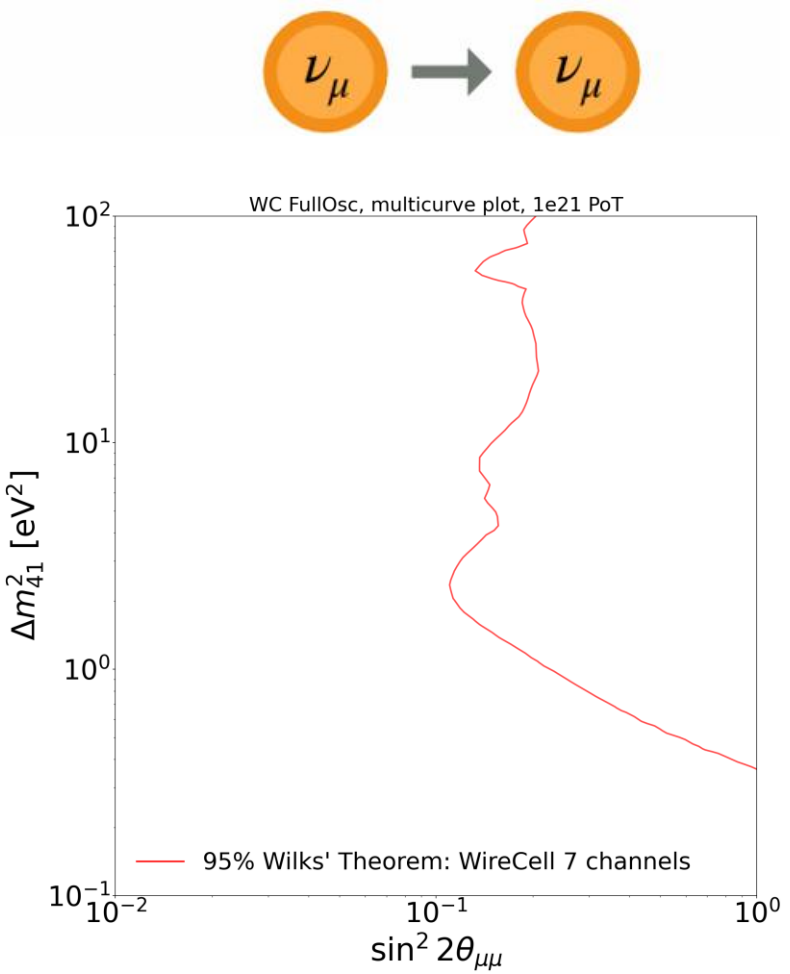






3+1 model studies.

- The Wire cell selection has a 7-channel section of

nueCCFC,

nueCCPC

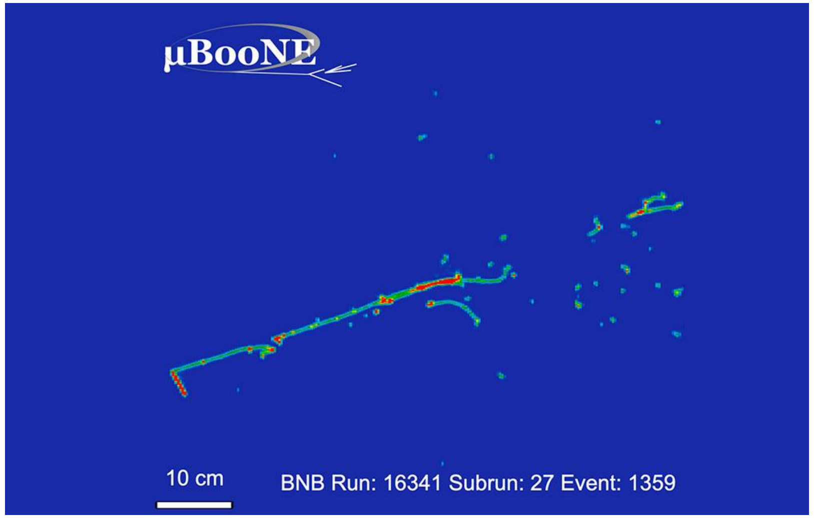
numuCC0pi0PC

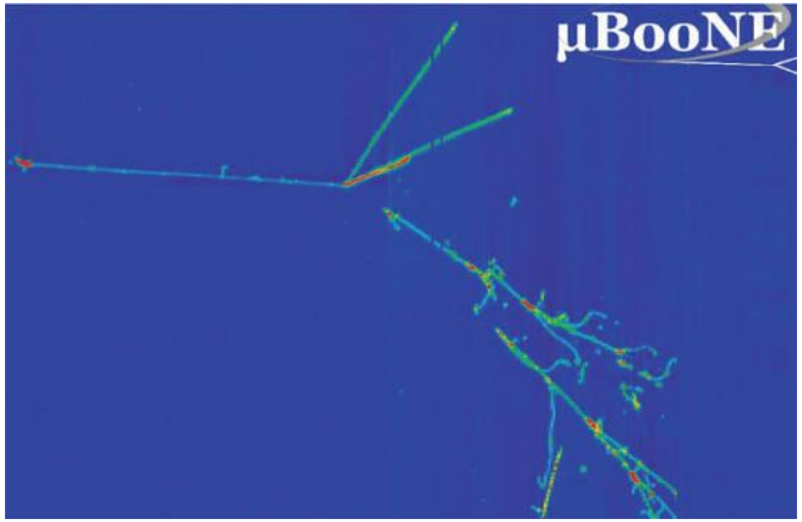
numuCC0pi0FC

numuCCpi0PC

numuCCpi0FC

NCpi0FCPC





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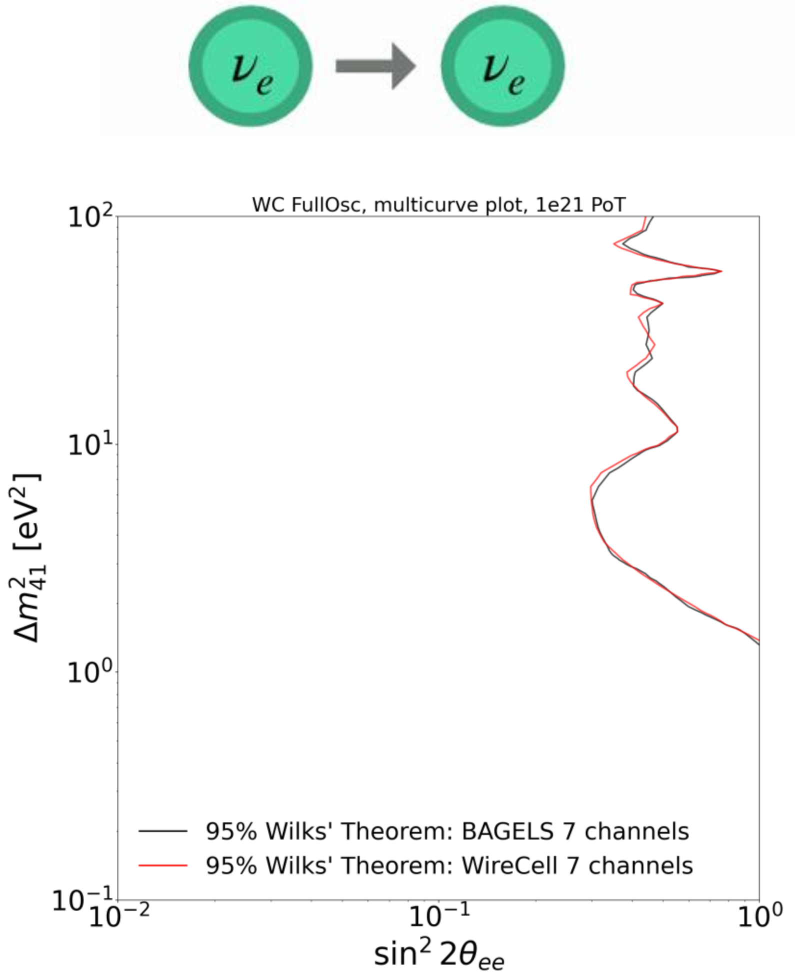

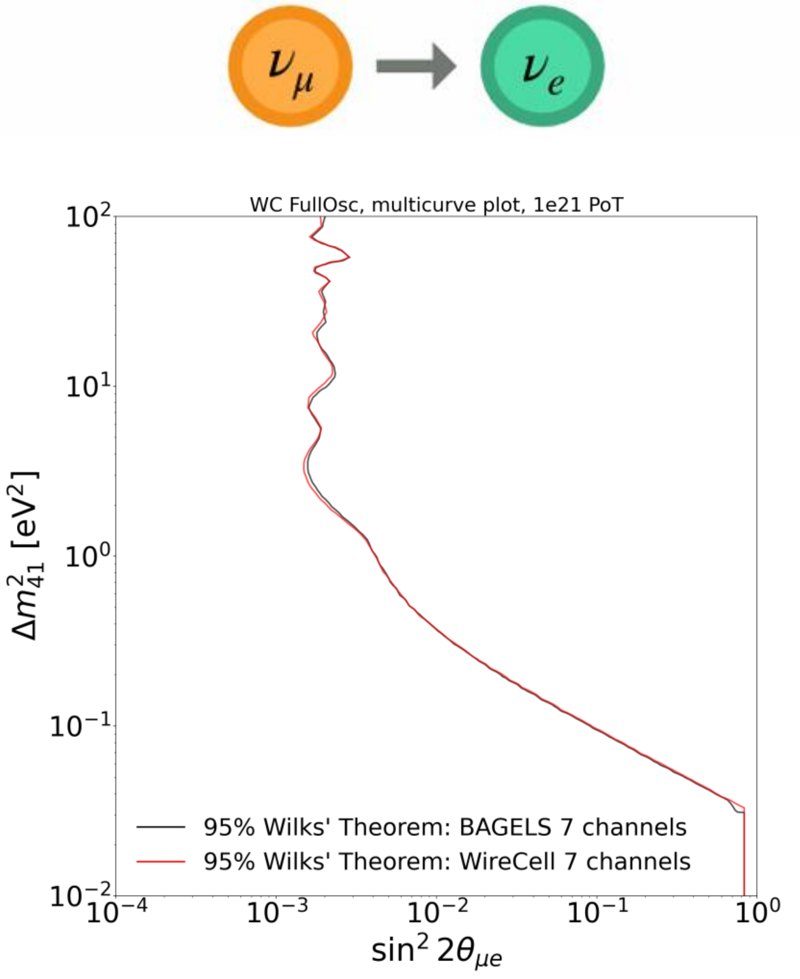

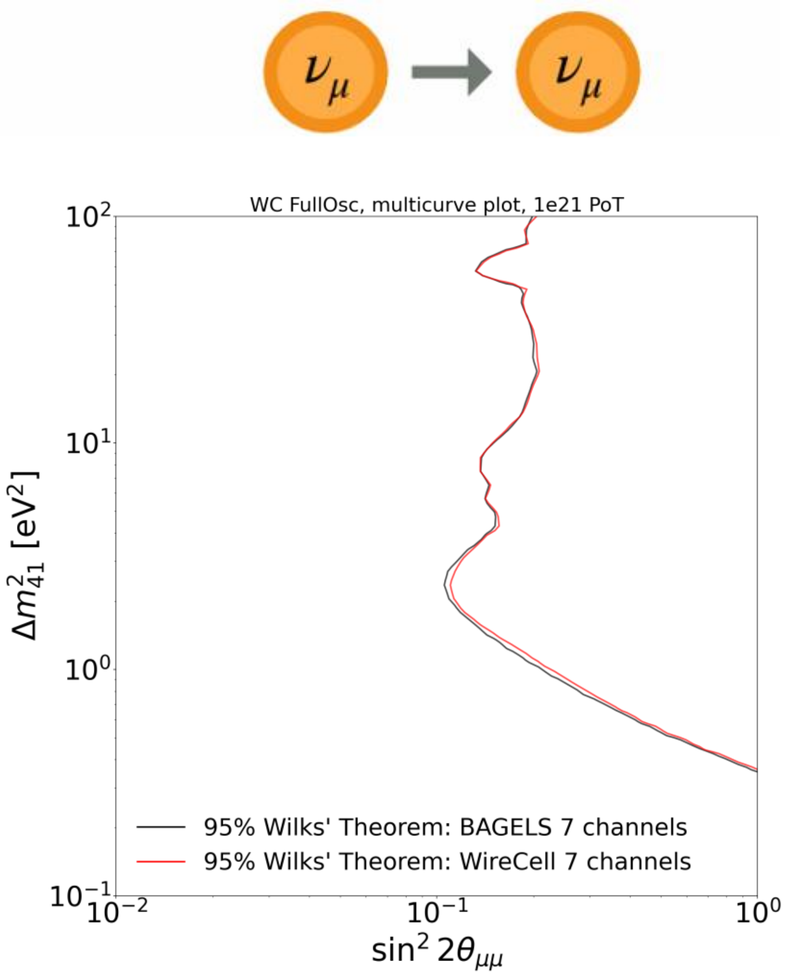

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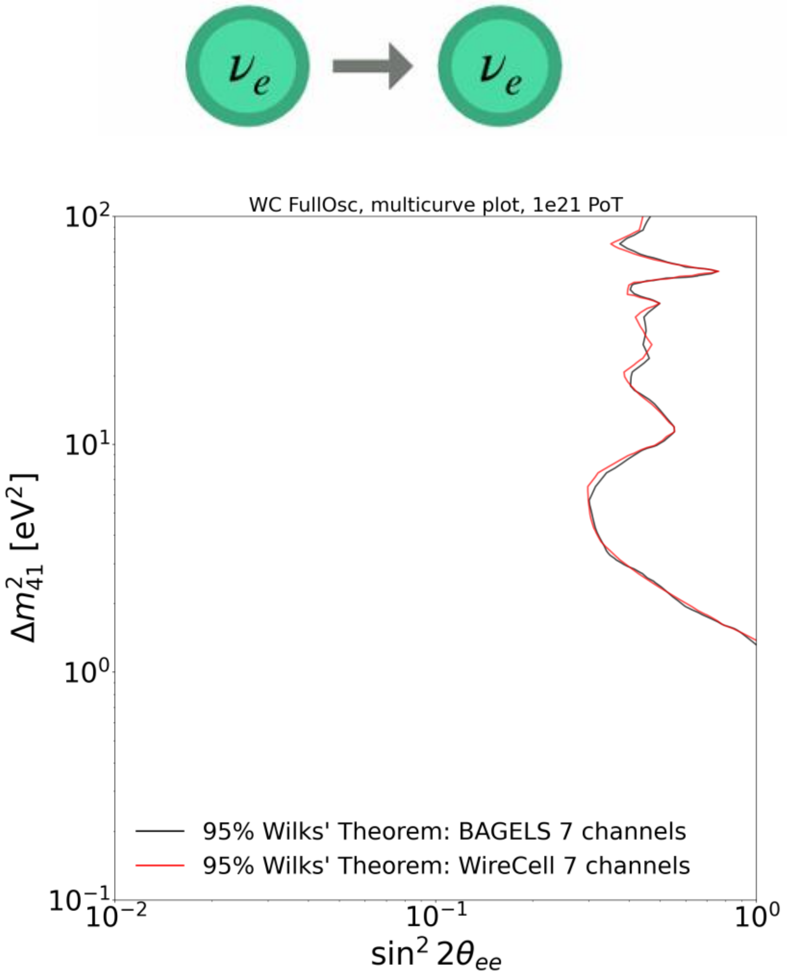

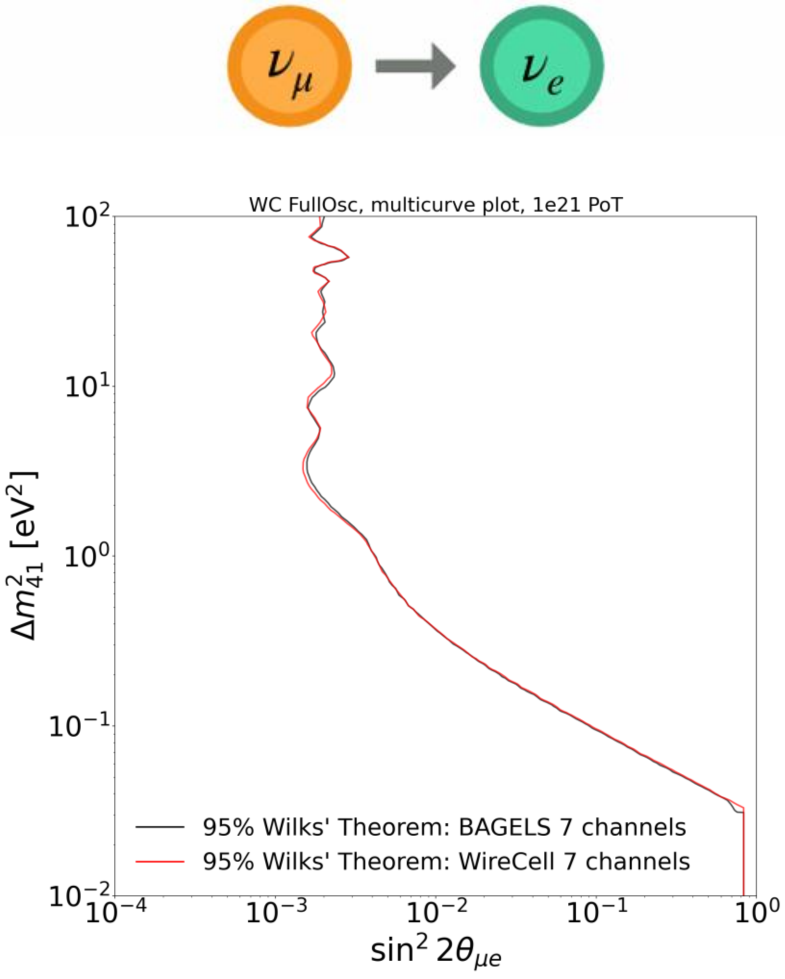

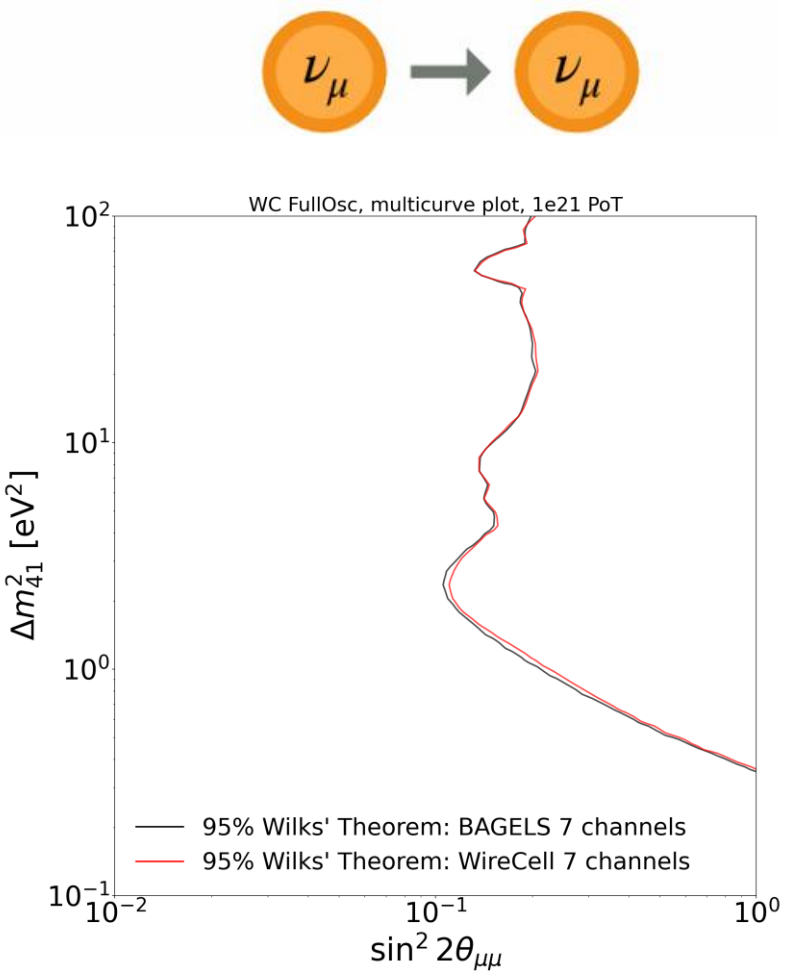

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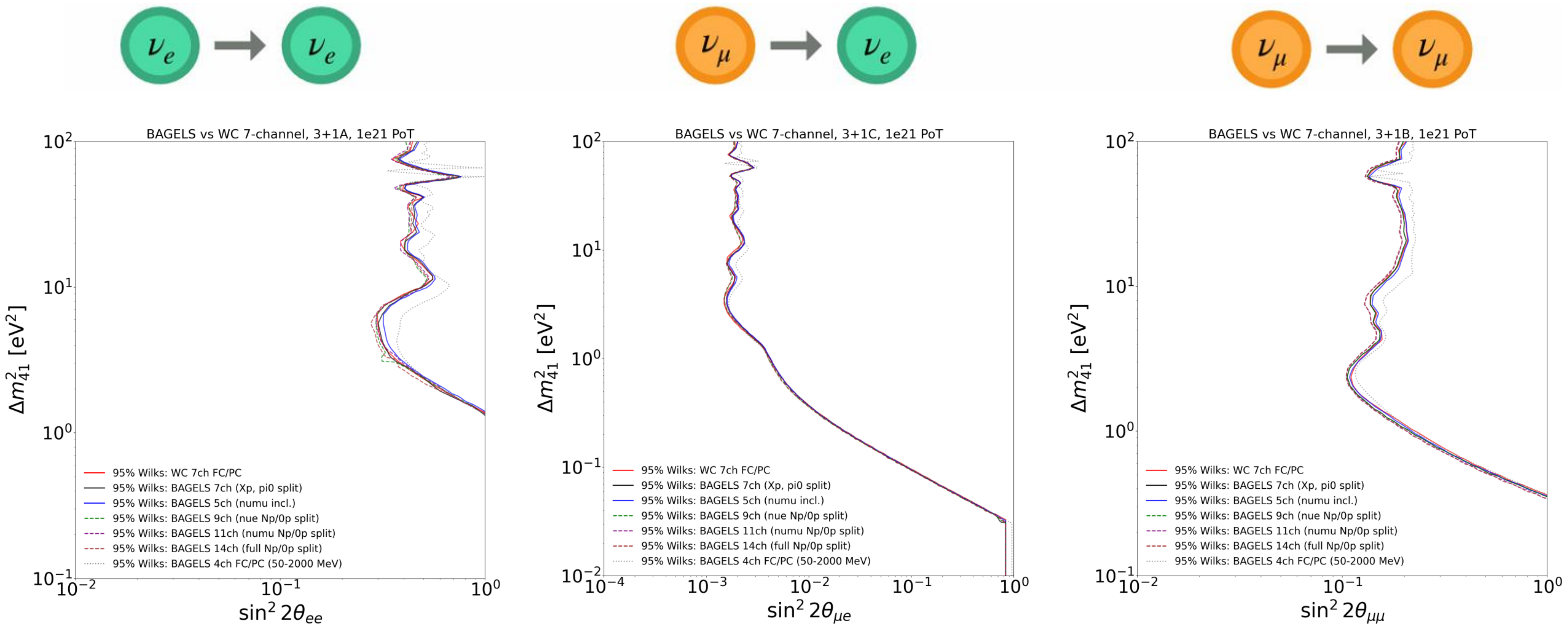

3+1 model studies.

- Bagels differ **fundamentally** from **wireCell** in the way channels are constructed.

3+1 model studies.

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nueCC Probability

numuCC Proability

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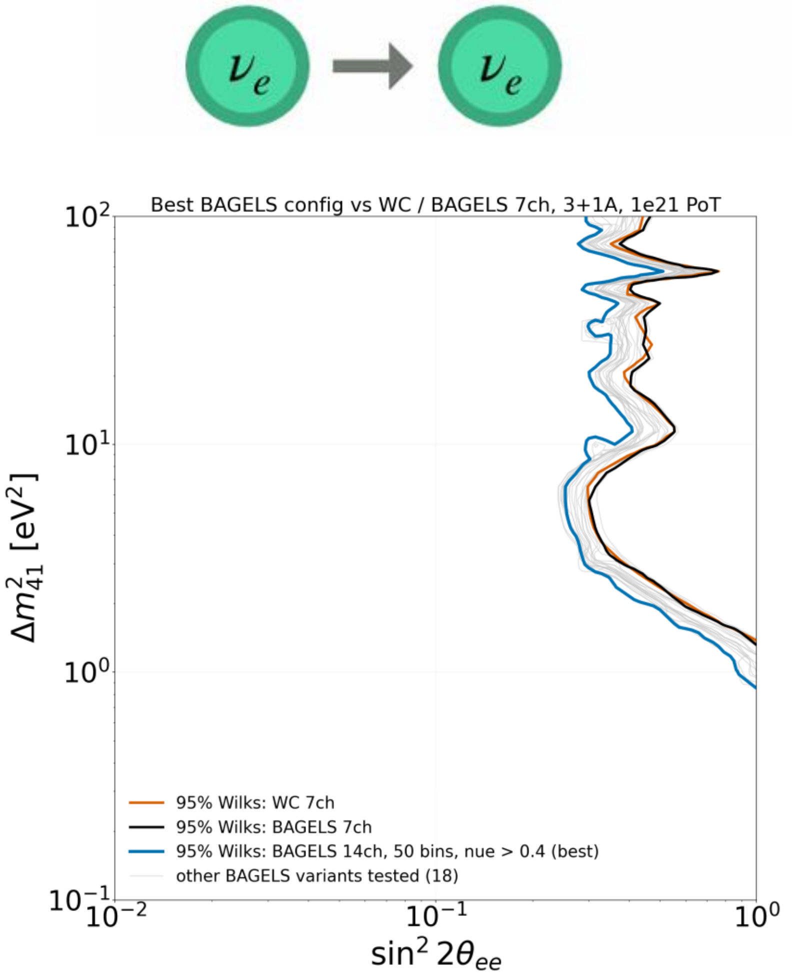
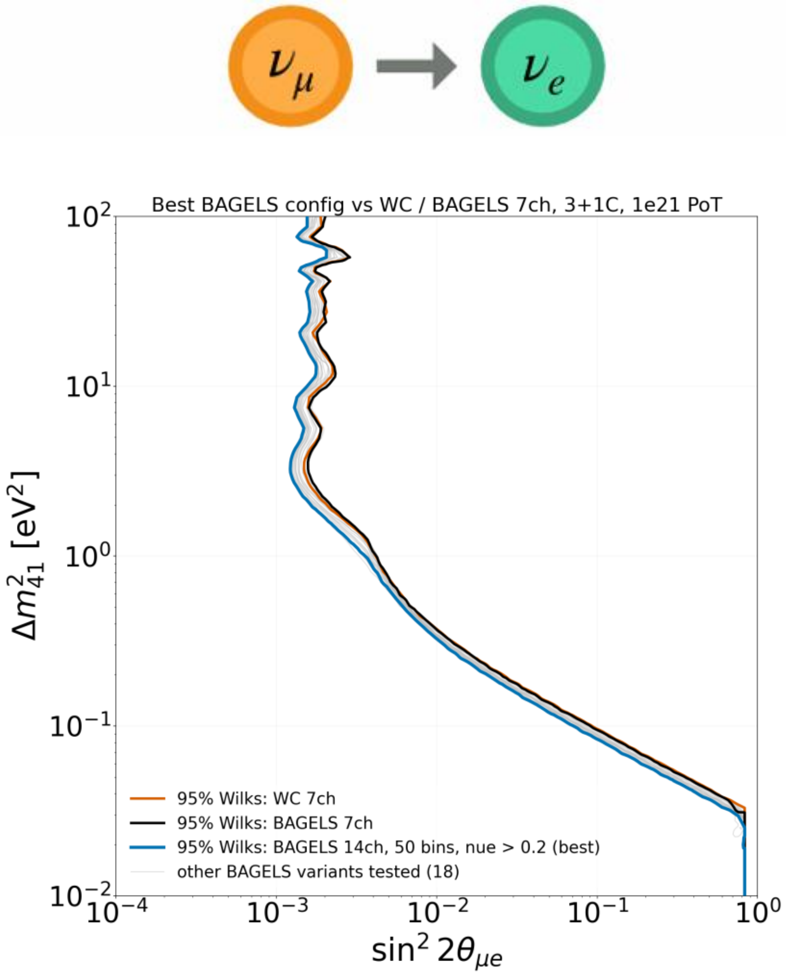
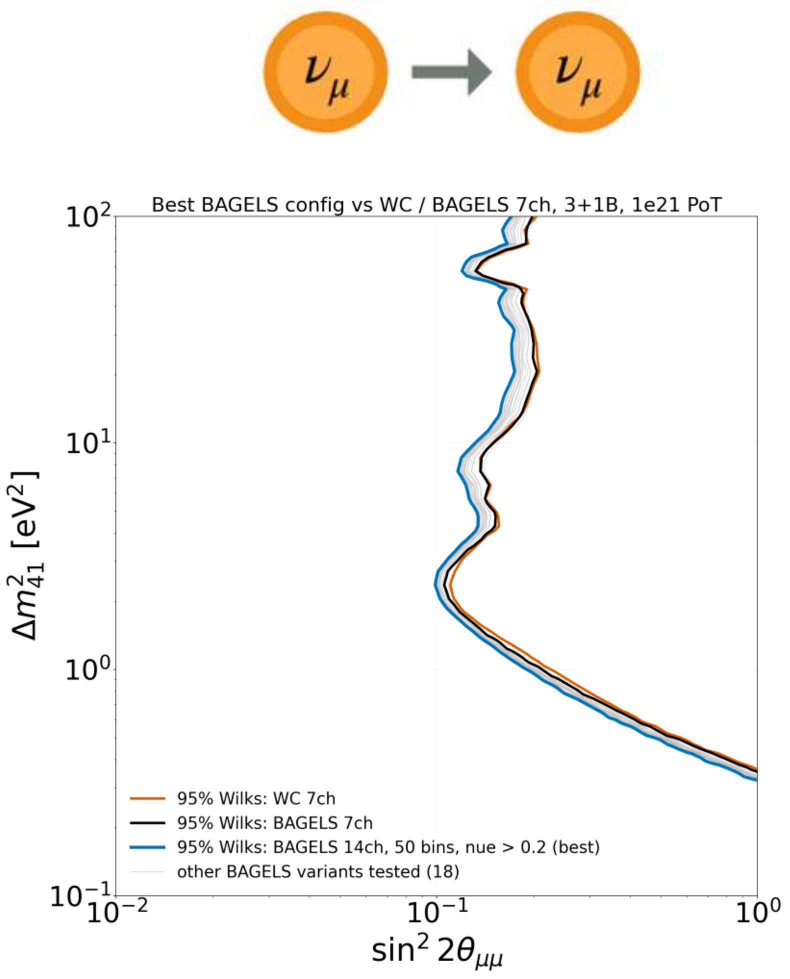






Future plans

- Fully Validate the Full Osc sample(compare with completed dedicated simulation).

- Include numu to nue cross section ratio weighting (already completed, need to implement).

- Include NuMI (higher energy neutrino source), to the full osc sample.

- Expanding to different oscillation models, such as 3+2.

Acknowledgements

I'd like to personally thank Dr. Lee Hagaman, and Professor Mark Ross-Lonergan for their endless patience with me and my questions.

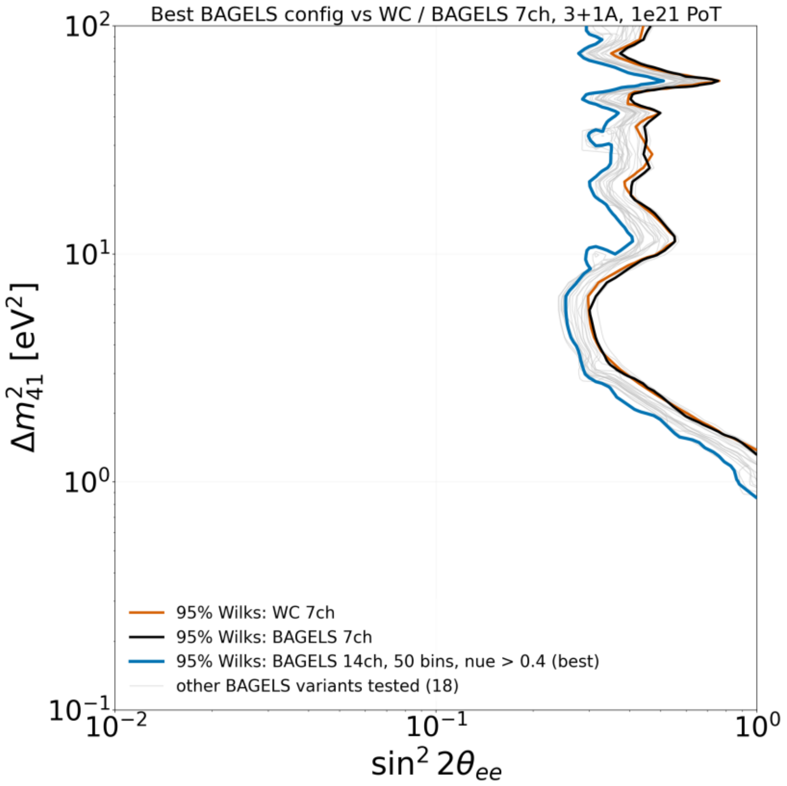
NEVIS LABORATORIES
COLUMBIA UNIVERSITY

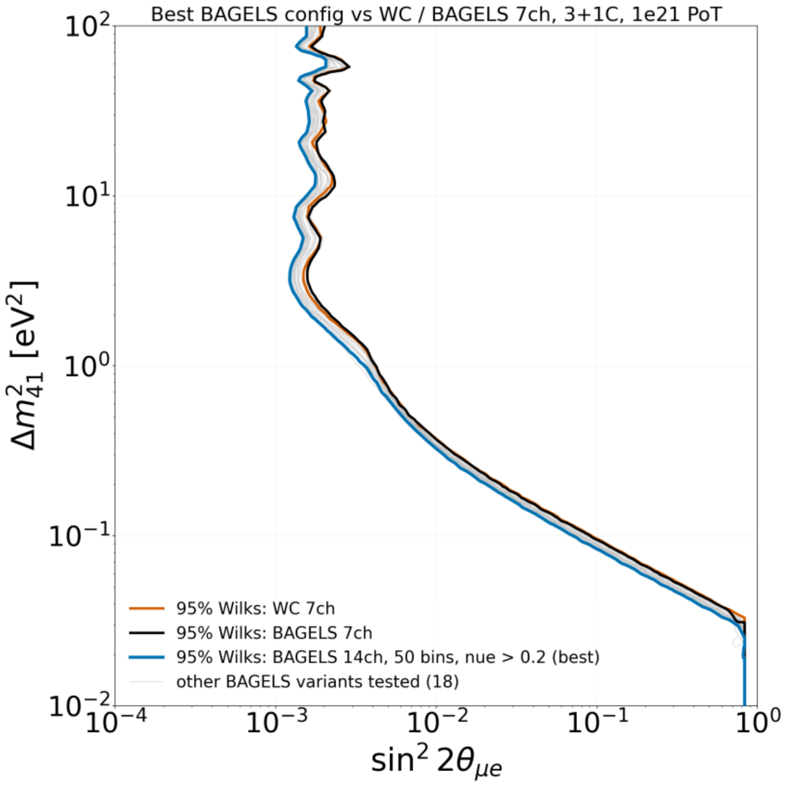
NSF U.S. National Science Foundation

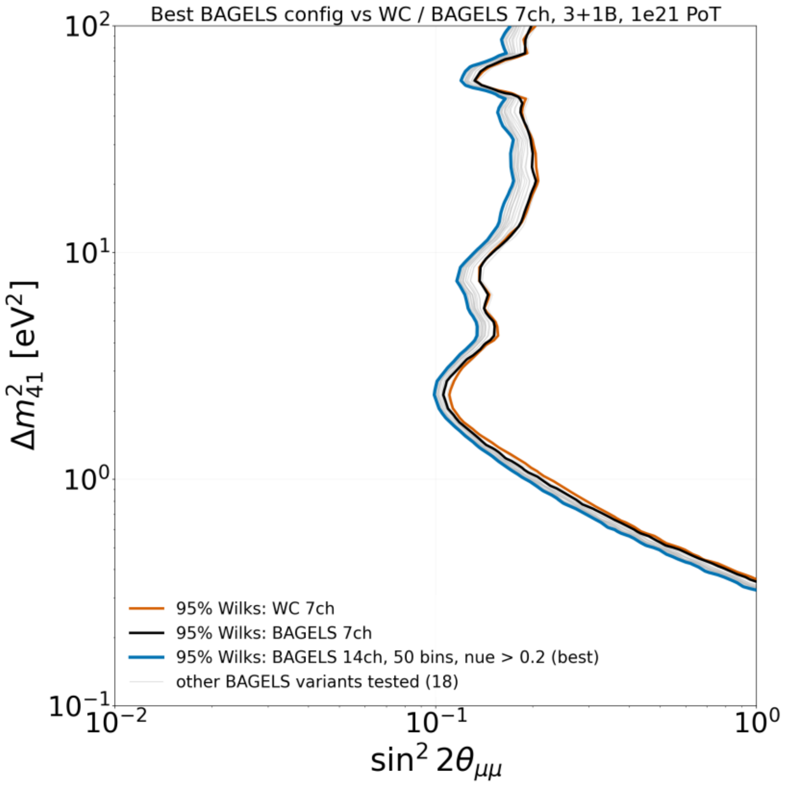
Conclusion.

U.S. National
Science Foundation

This material is based upon work supported by the National Science
Foundation under Grant No. PHY-2349438.



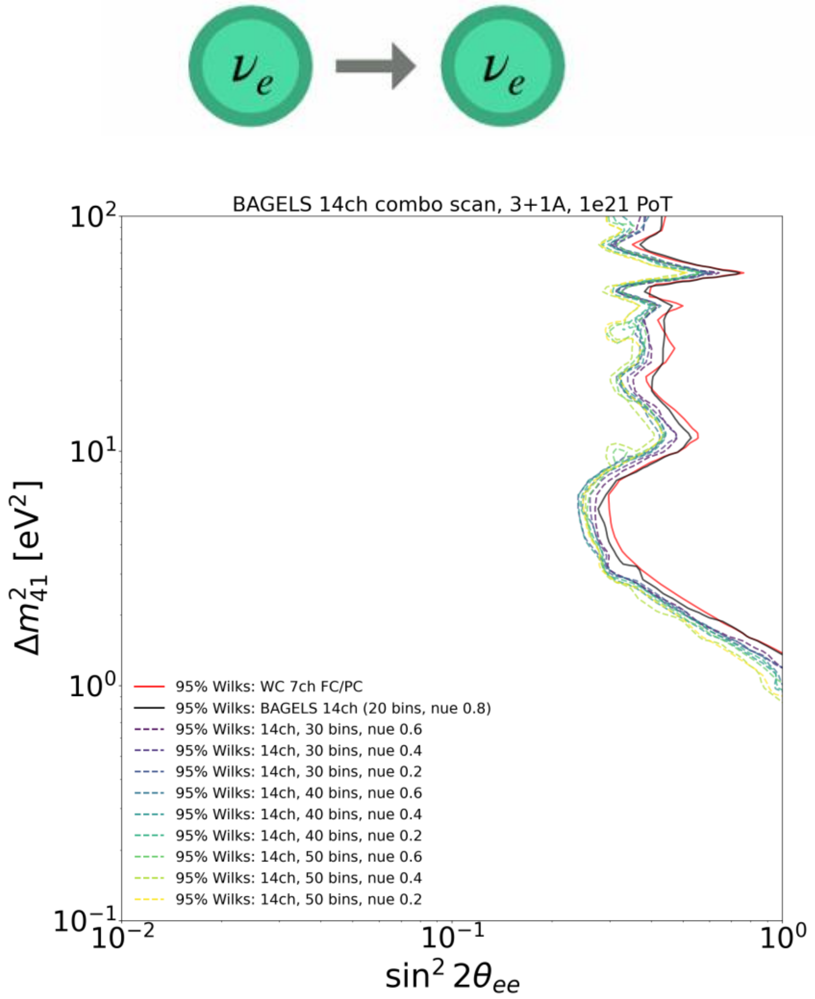


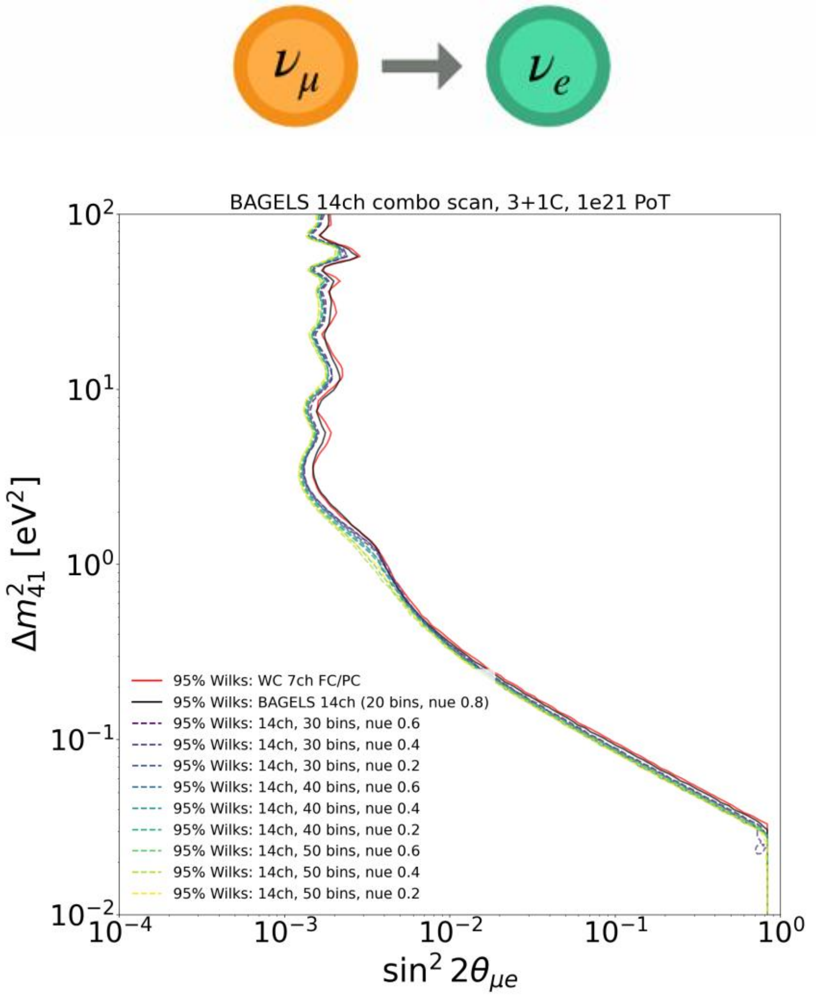


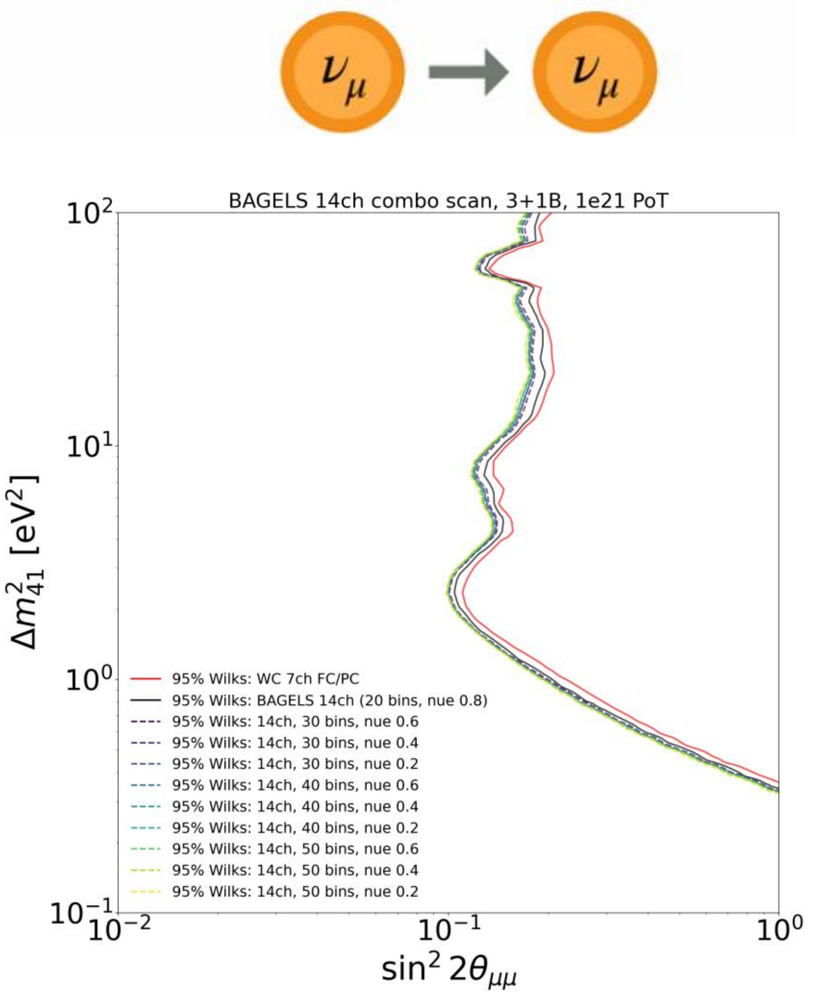
backup

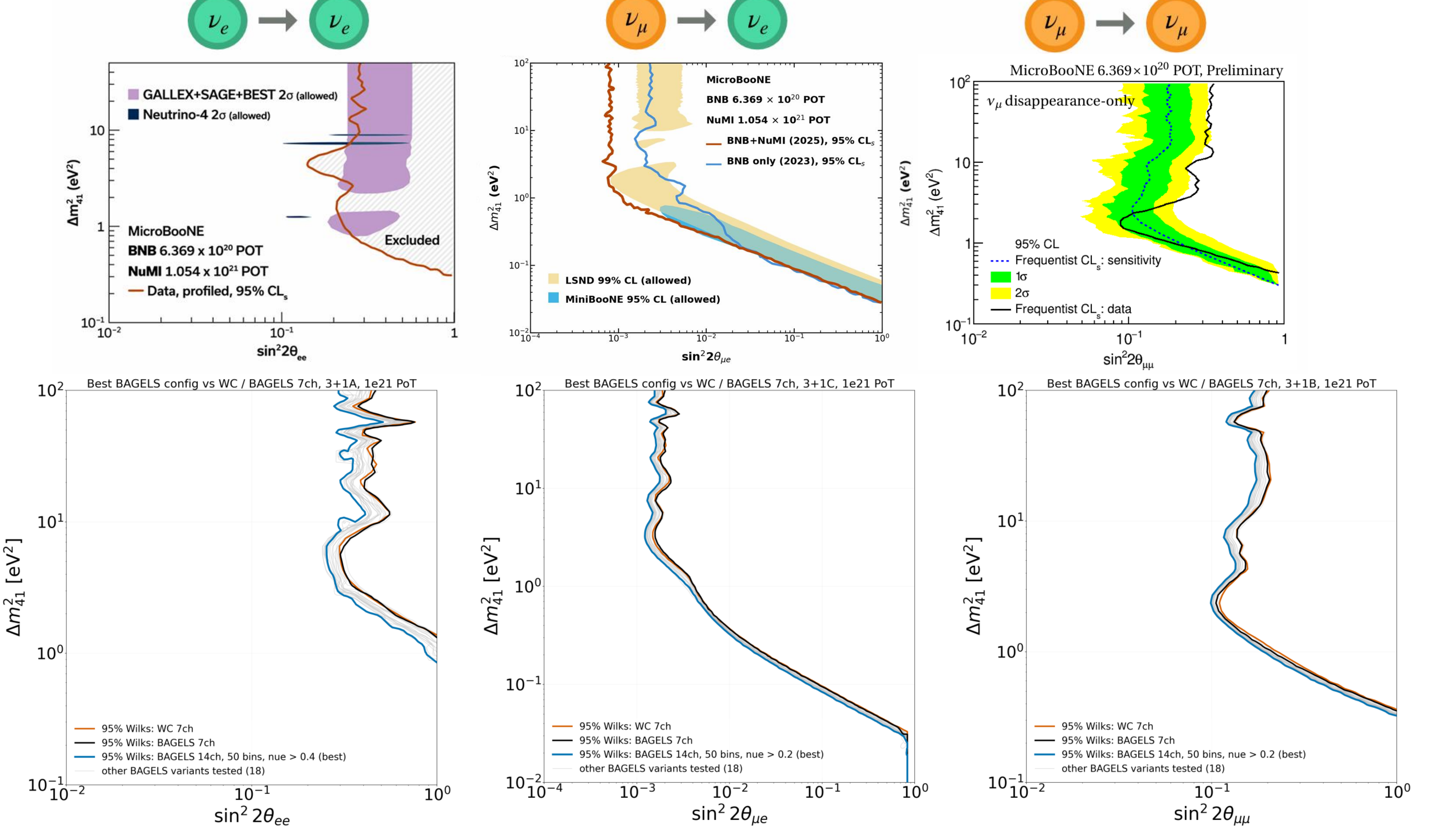
3+1 model studies.

- Plot Mania









νe → νe
νμ → νe
νμ → νμ
GALLEX+SAGE+BEST 2σ (allowed)
Neutrino-4 2σ (allowed)
MicroBooNE
BNB 6.369 x 10^20 POT
NuMI 1.054 x 10^21 POT
Data, profiled, 95% CLs
Excluded
Δm²41 (eV²)
sin²2θee
MicroBooNE
BNB 6.369 × 10^20 POT
NuMI 1.054 × 10^21 POT
BNB+NuMI (2025), 95% CLs
BNB only (2023), 95% CLs
LSND 99% CL (allowed)
MiniBooNE 95% CL (allowed)
sin²2θμe
MicroBooNE 6.369×10^20 POT, Preliminary
νμ disappearance-only
95% CL
Frequentist CLs : sensitivity
1σ
2σ
Frequentist CLs : data
sin²2θμμ
Best BAGELS config vs WC / BAGELS 7ch, 3+1A, 1e21 PoT
95% Wilks: WC 7ch
95% Wilks: BAGELS 7ch
95% Wilks: BAGELS 14ch, 50 bins, nue > 0.4 (best)
other BAGELS variants tested (18)
Δm²41 [eV²]
sin² 2θee
Best BAGELS config vs WC / BAGELS 7ch, 3+1C, 1e21 PoT
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