

**Neutrino Theory in 10 Minutes,**

**Or,**

**Around the Theory Group in 10 Minutes**

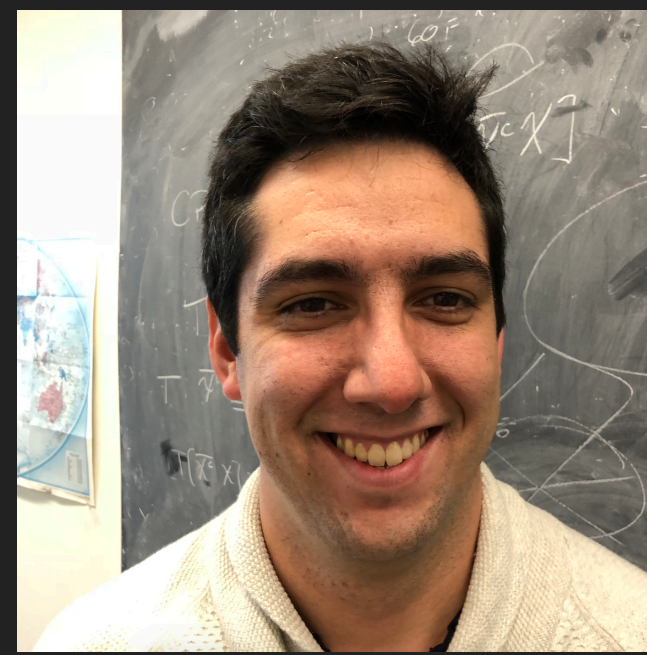
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Kevin Kelly, Fermilab

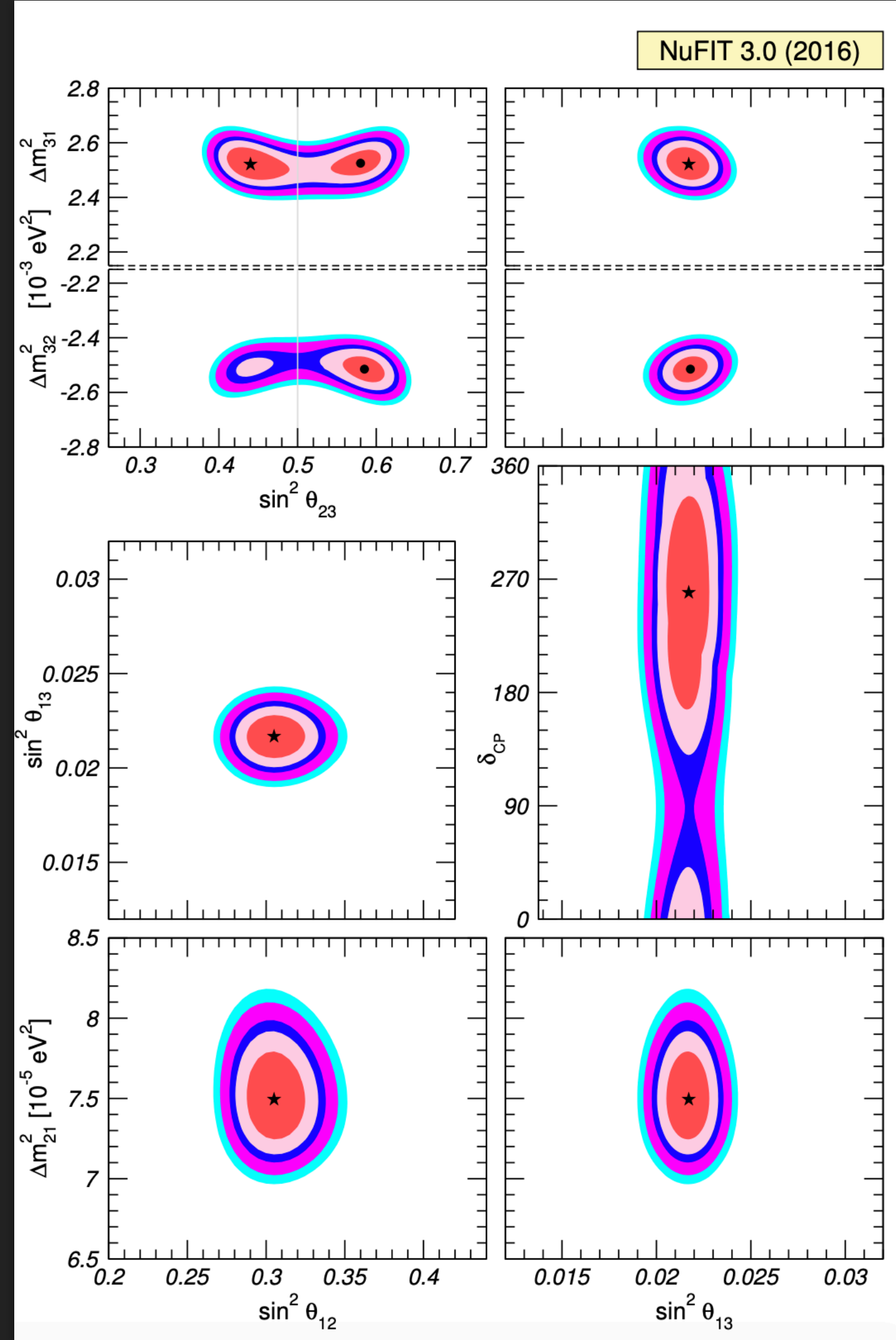
# Outline

- ▶ Neutrino masses and Neutrino Oscillations
- ▶ Consistency checks of the three-neutrino formalism
- ▶ Neutrino Cross Sections
- ▶ Rare neutrino scattering events
- ▶ Matter effects in long-baseline experiments
- ▶ New physics in long-baseline experiments
- ▶ Leptogenesis

# Neutrino Masses and Oscillations



Iván Martínez-Soler



Thanks to many, many, many experiments, we now know that neutrinos have mass and leptons mix.

Asking the question “how well do we know the neutrino mixing parameters” is nontrivial, especially when combining multiple experiments.

There are still many unknowns, many of which will be measured by the current/next generation of experiments.

- ▶ Neutrino Mass Ordering
- ▶ Whether CP is violated in the lepton sector
- ▶ The octant of the atmospheric mixing angle

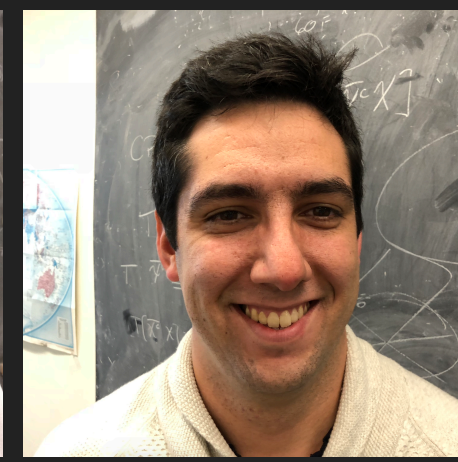
[1611.01514], <http://www.nu-fit.org/>

# Beyond the Three-Neutrino Paradigm

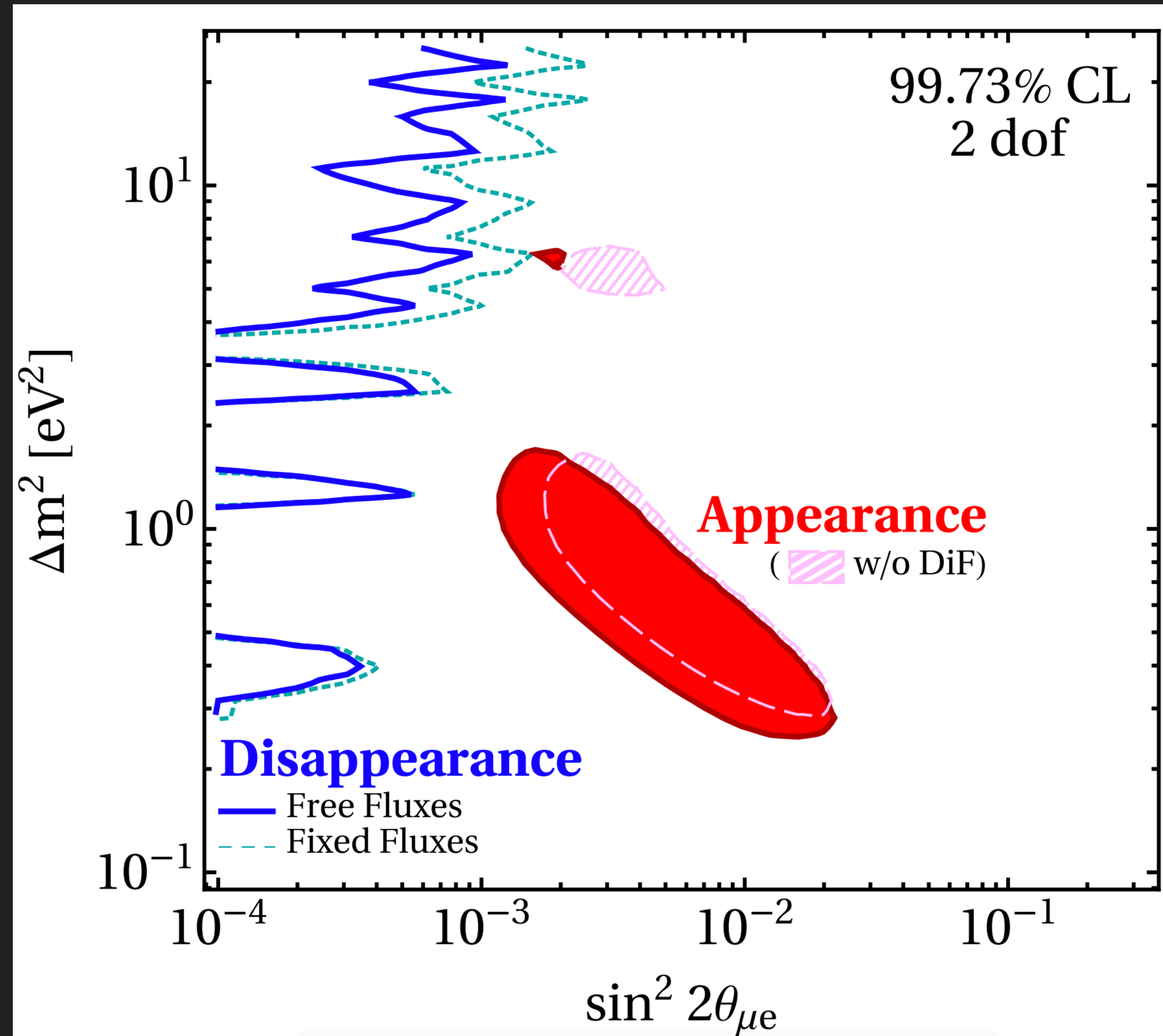
Well-known anomalies pointing towards new neutrino physics exist.  
Sterile neutrinos?



Pedro Machado



Iván Martínez-Soler



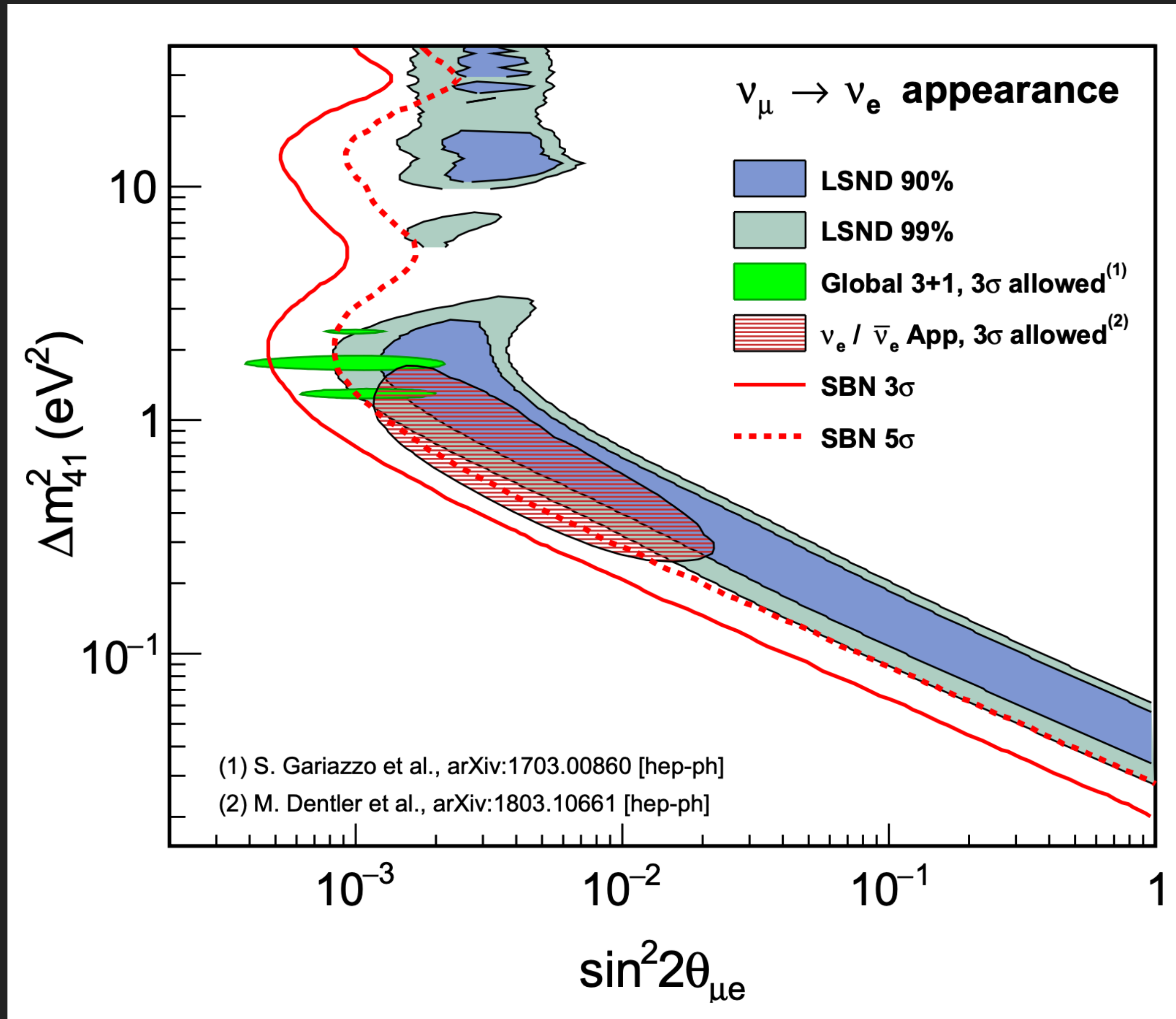
[1803.10661]

# Beyond the Three-Neutrino Paradigm



Pedro Machado

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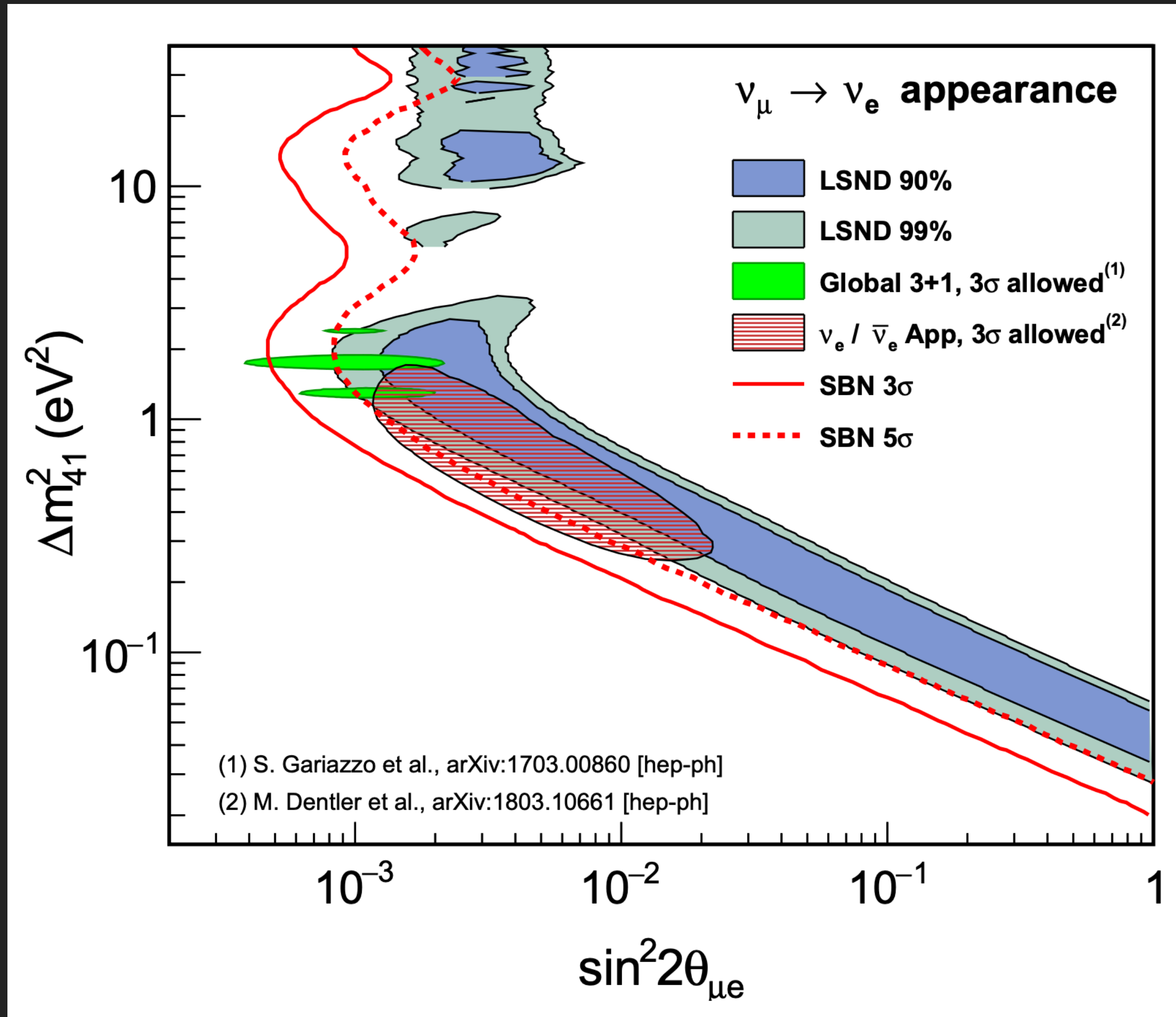
[1903.04608]

# Beyond the Three-Neutrino Paradigm

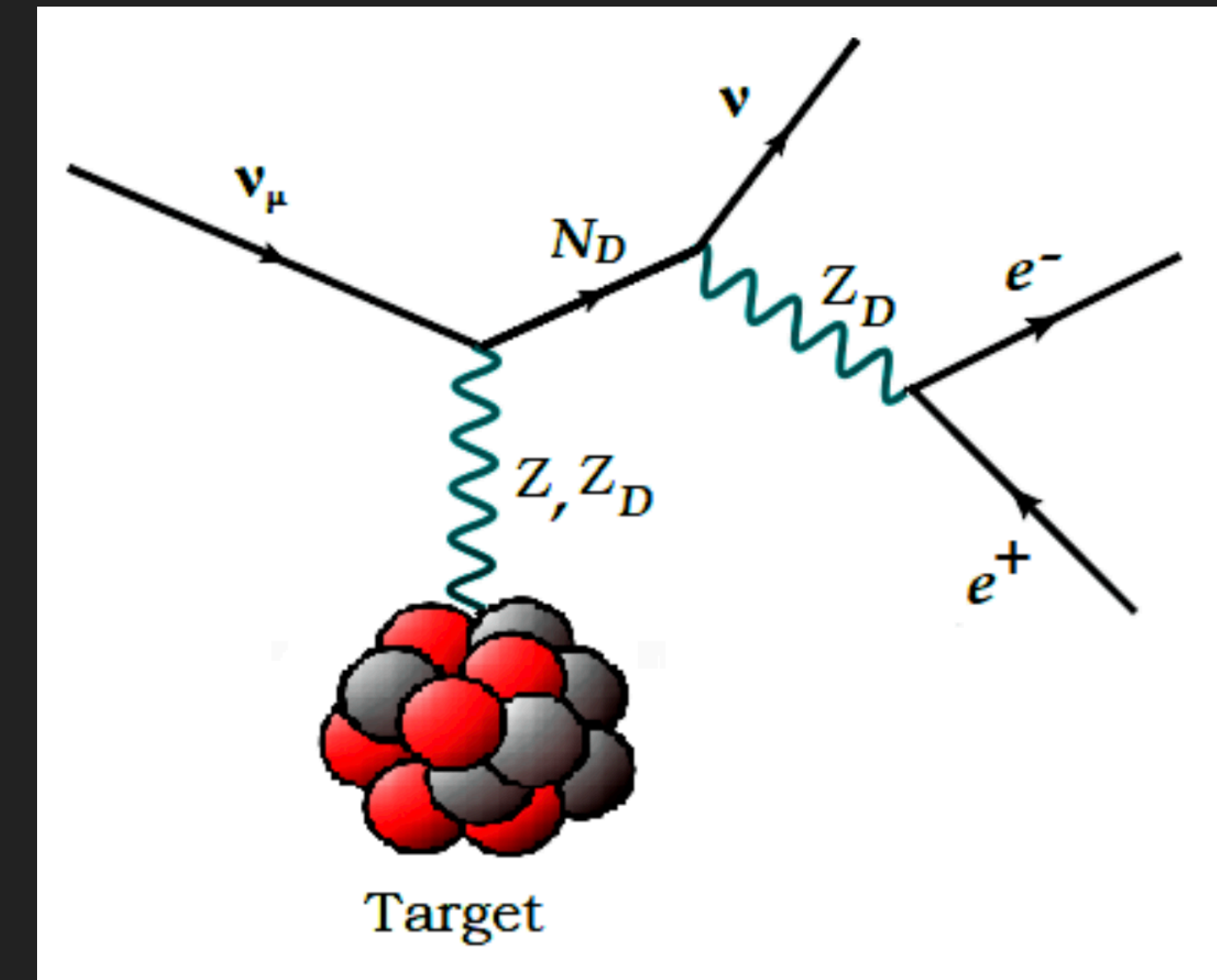


Pedro Machado

Well-known anomalies pointing towards new neutrino physics exist.  
Sterile neutrinos?



[1903.04608]

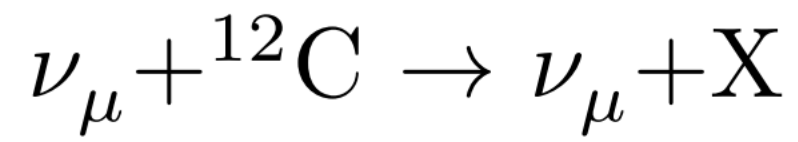


Possible alternate explanation?  
[1807.09877]

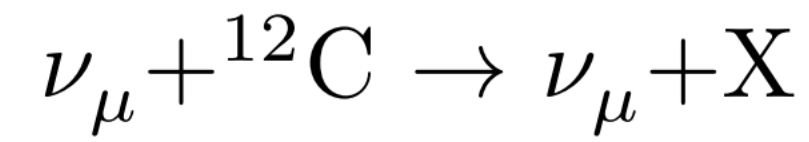
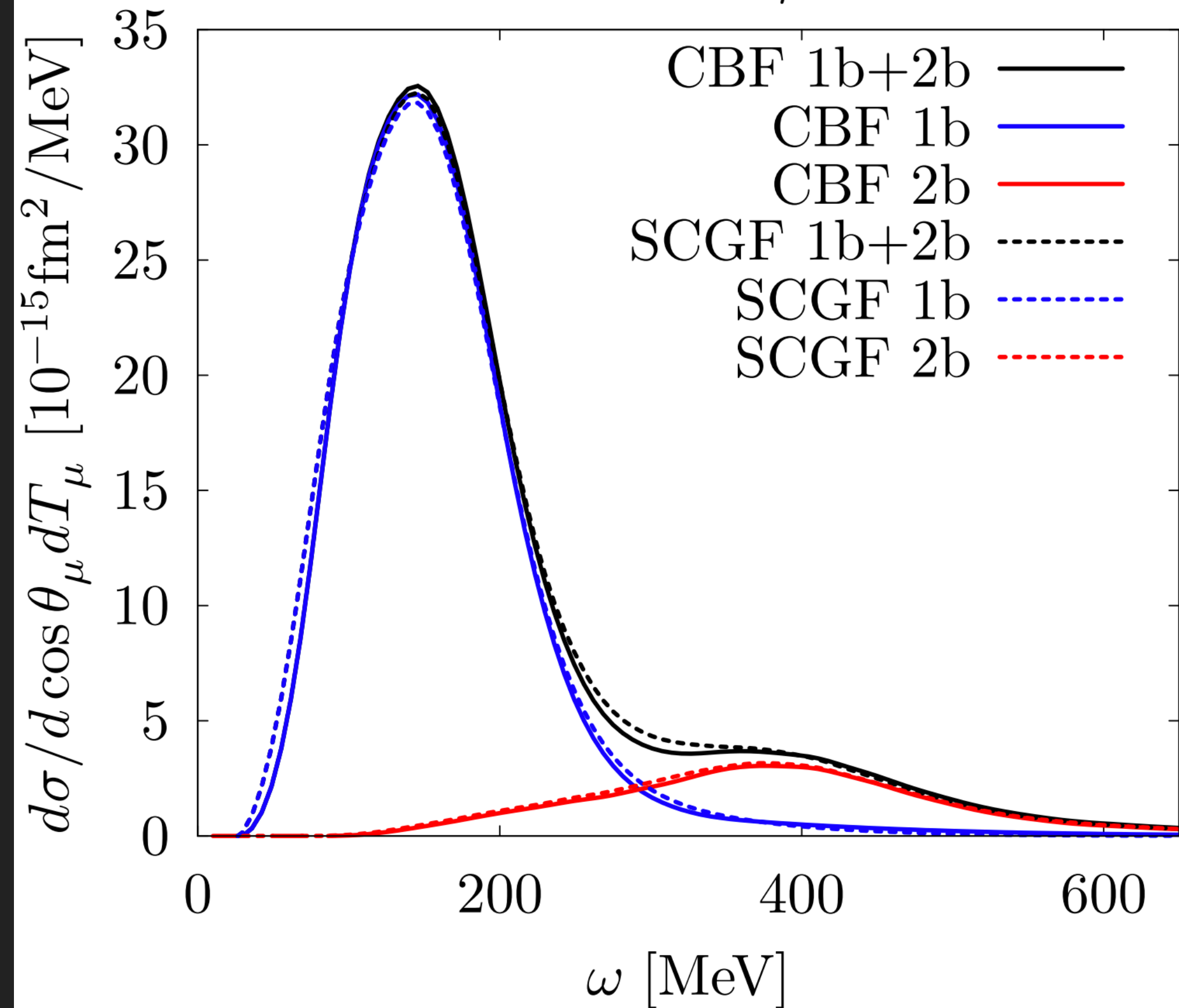
# Neutrino Cross Sections



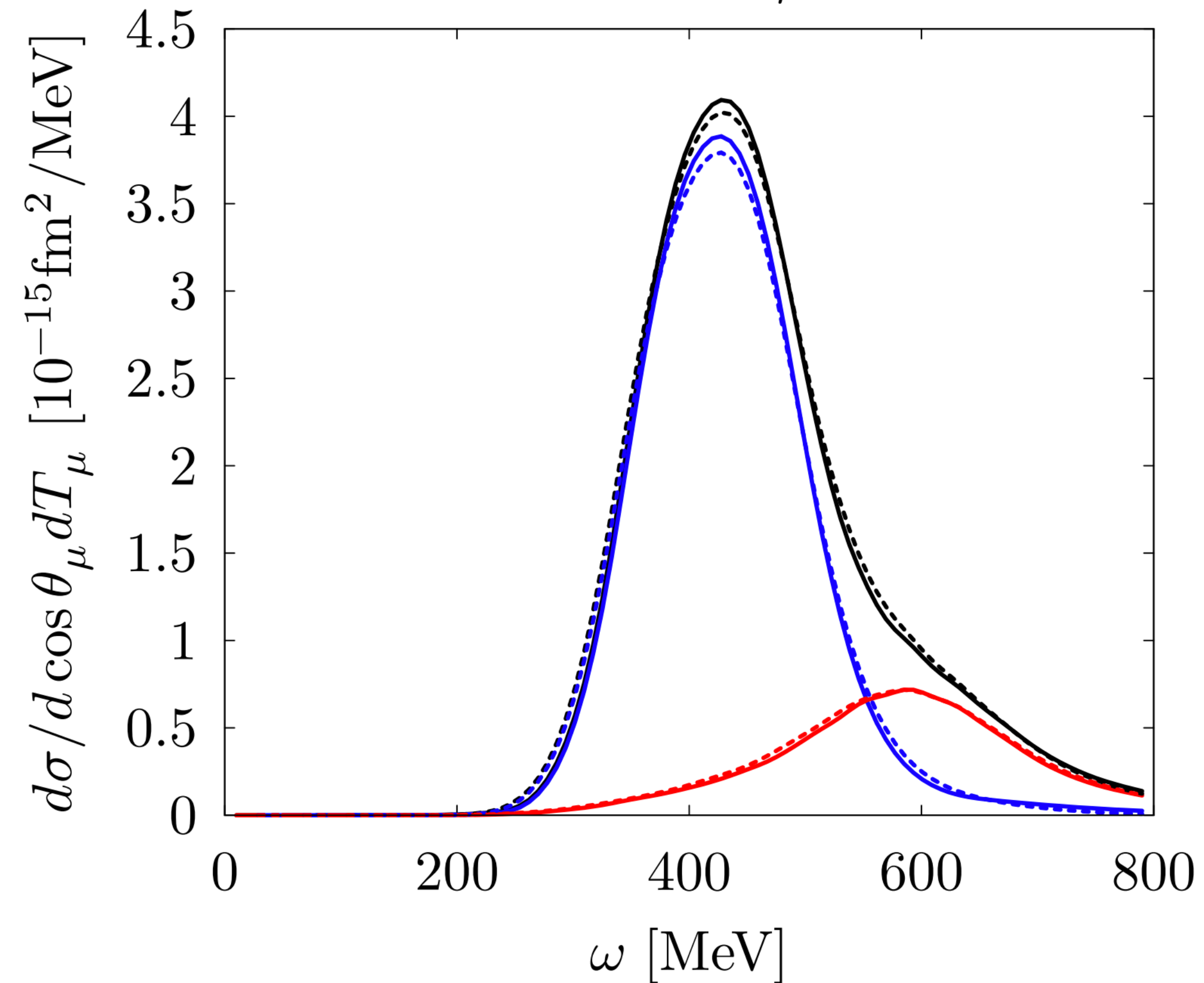
Noemi Rocco



$$E_\nu = 1 \text{ GeV}, \theta_\mu = 30^\circ$$



$$E_\nu = 1 \text{ GeV}, \theta_\mu = 70^\circ$$

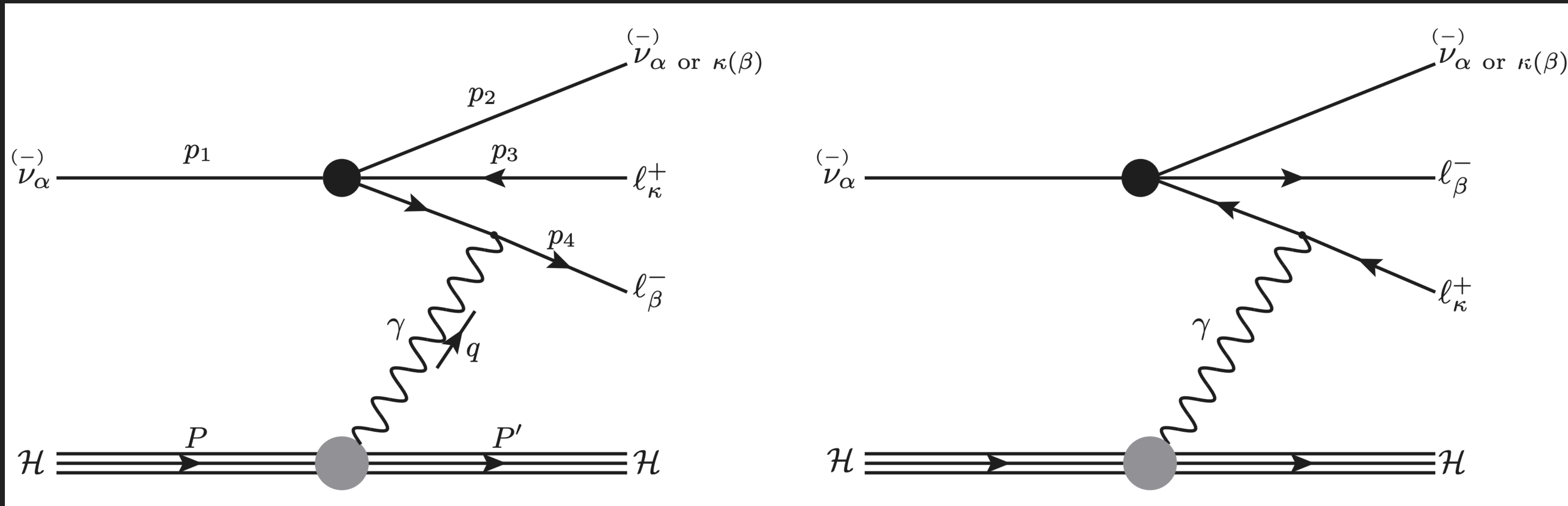


The future of neutrino experiments relies on scattering of neutrinos with heavier targets (argon). The larger the nucleus, the harder it is to calculate scattering cross sections!

# Can we learn anything from even rarer scattering processes?



Yuber Perez-Gonzalez



Neutrino Trident Scattering – to date, only the dimuon channel has been observed. Fermilab experiments, especially DUNE, should be able to measure all channels! [1807.10973]

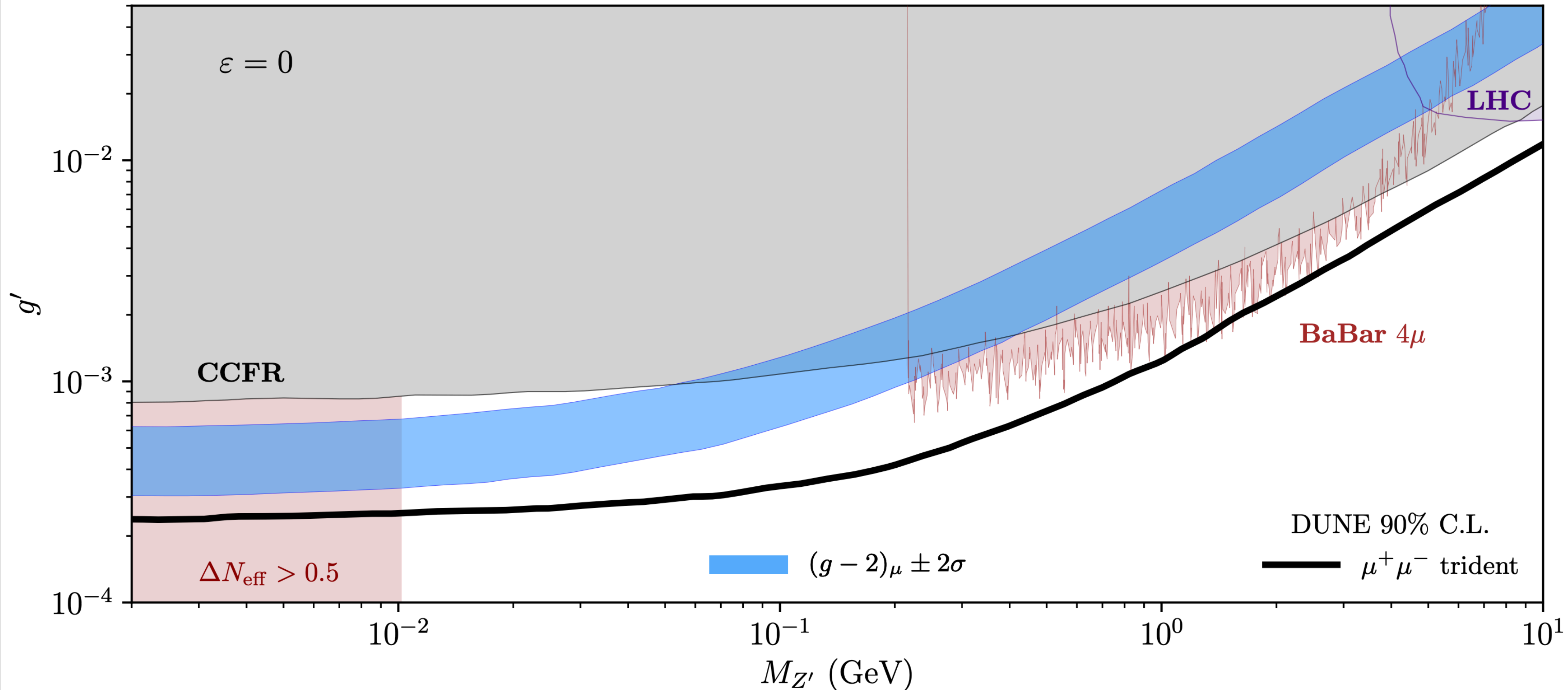


# Can we learn anything from even rarer scattering processes?



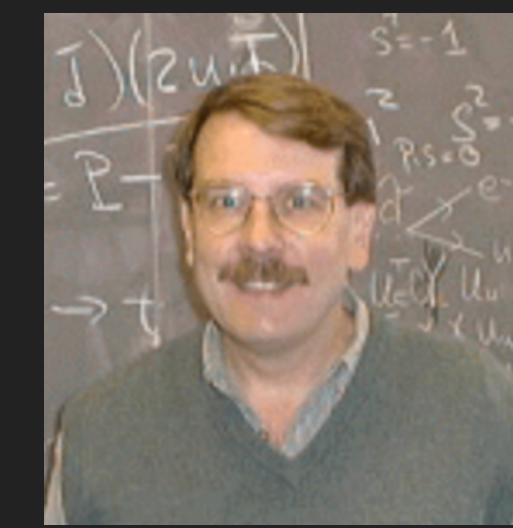
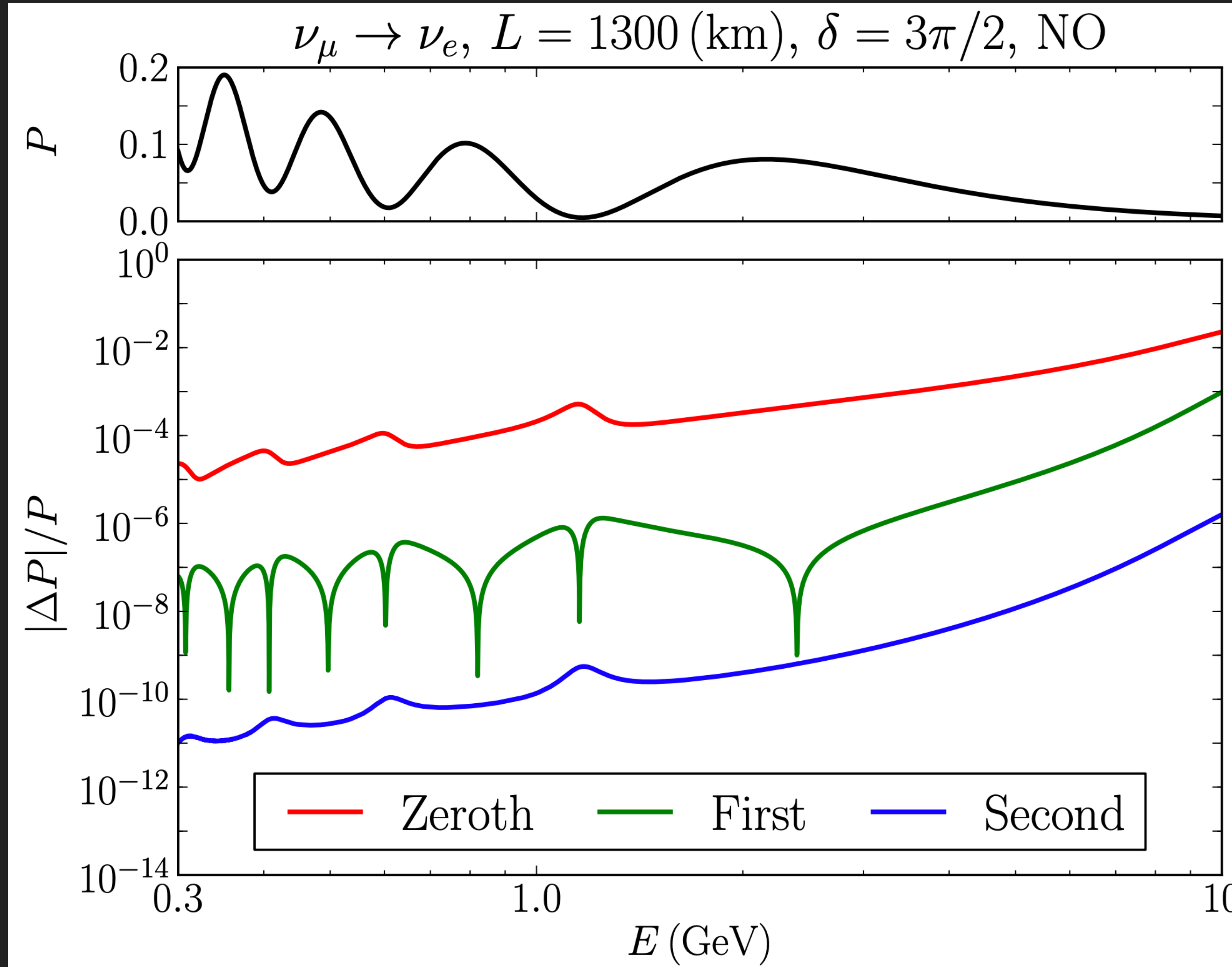
Yuber Perez-Gonzalez

$L_\mu - L_\tau$ , DUNE ND, 75 tonnes, 5 y  $\nu$ -mode + 5 y  $\bar{\nu}$ -mode, 120 GeV  $p^+$ ,  $\sigma_{\text{norm}} = 5\%$

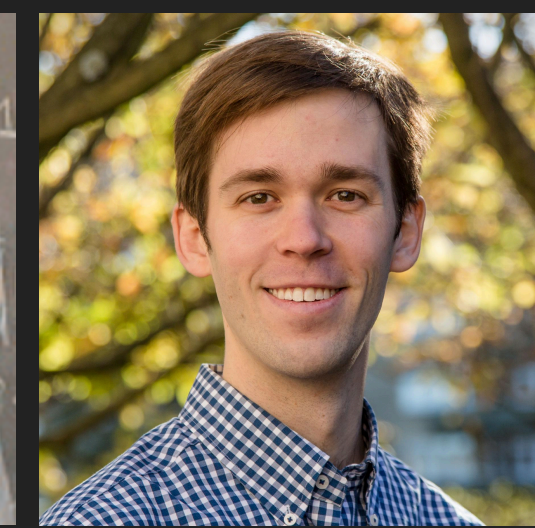


Measurement of trident events can constrain well-motivated new physics models [1902.08579]

# What do we need to worry about at Long-Baseline Distances?



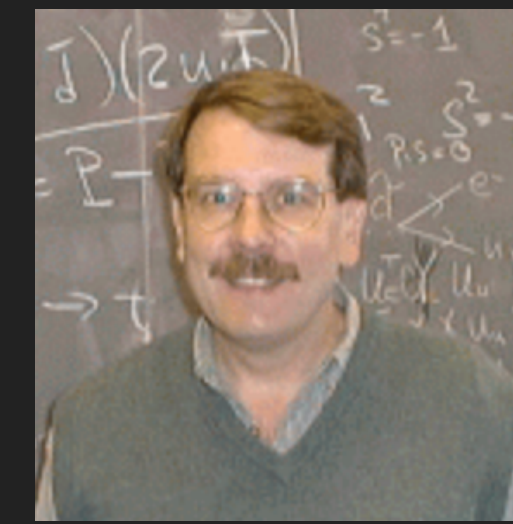
Stephen Parke



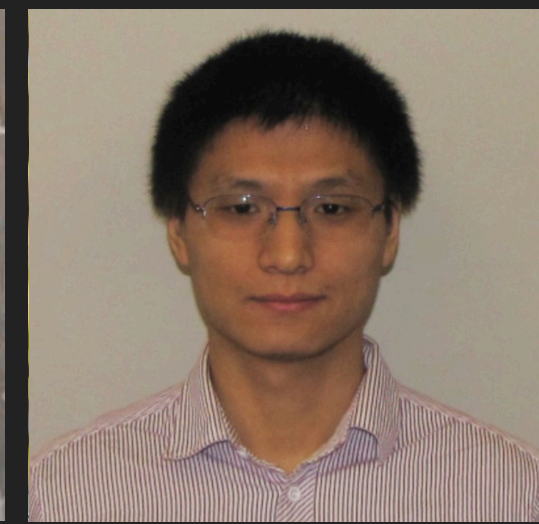
Peter Denton  
(Visiting for Summer)

Oscillation Probabilities get more complicated when matter is involved – Very fast, very accurate approximations developed in [1604.08167].

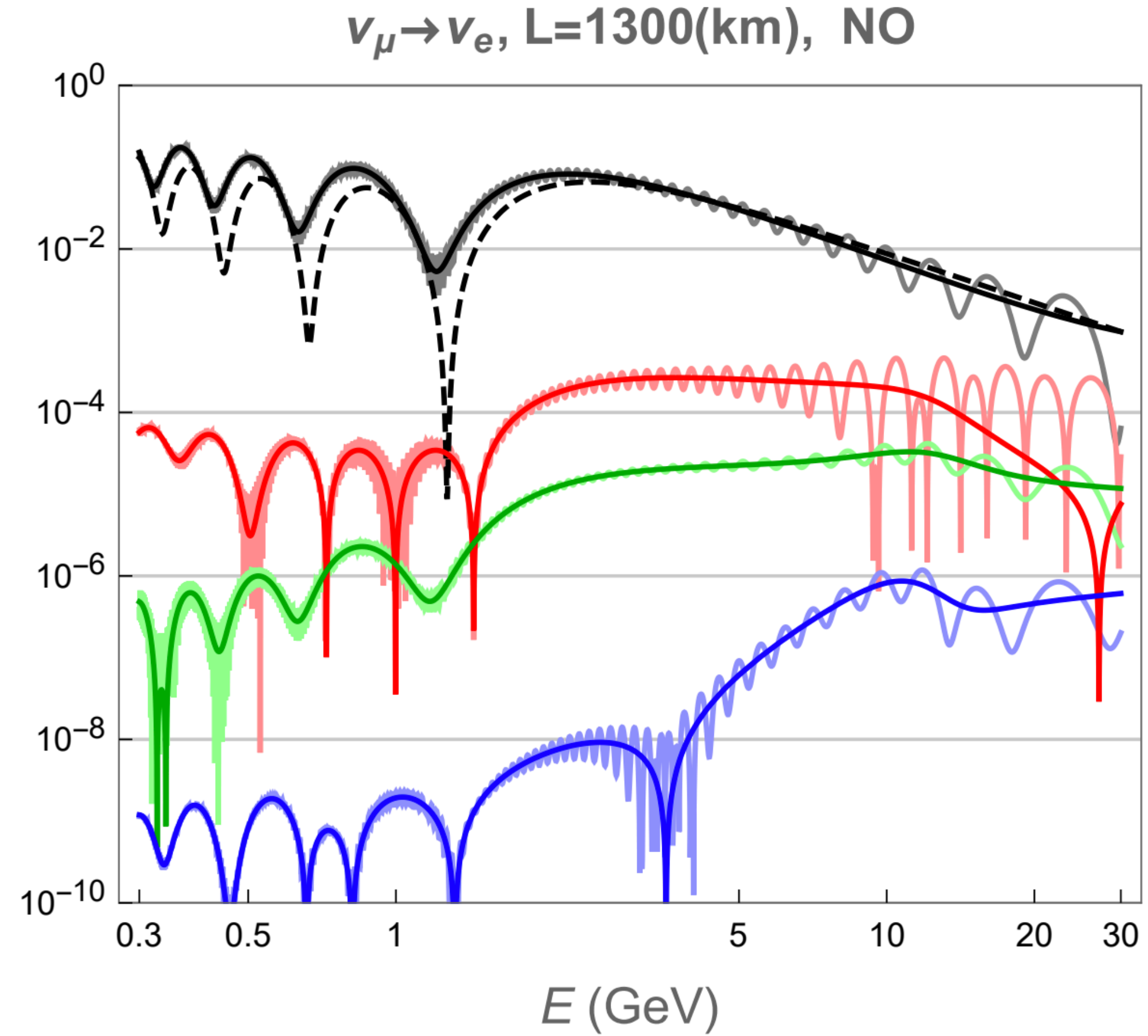
# What do we need to worry about at Long-Baseline Distances?



Stephen Parke



Xining Zhang



- - -  $P_{\nu\text{SM}}$   
 —  $P_{3+1}$   
 —  $|\Delta P_{3+1}^{(0)}|$   
 —  $|\Delta P_{3+1}^{(1)}|$   
 —  $|\Delta P_{3+1}^{(2)}|$

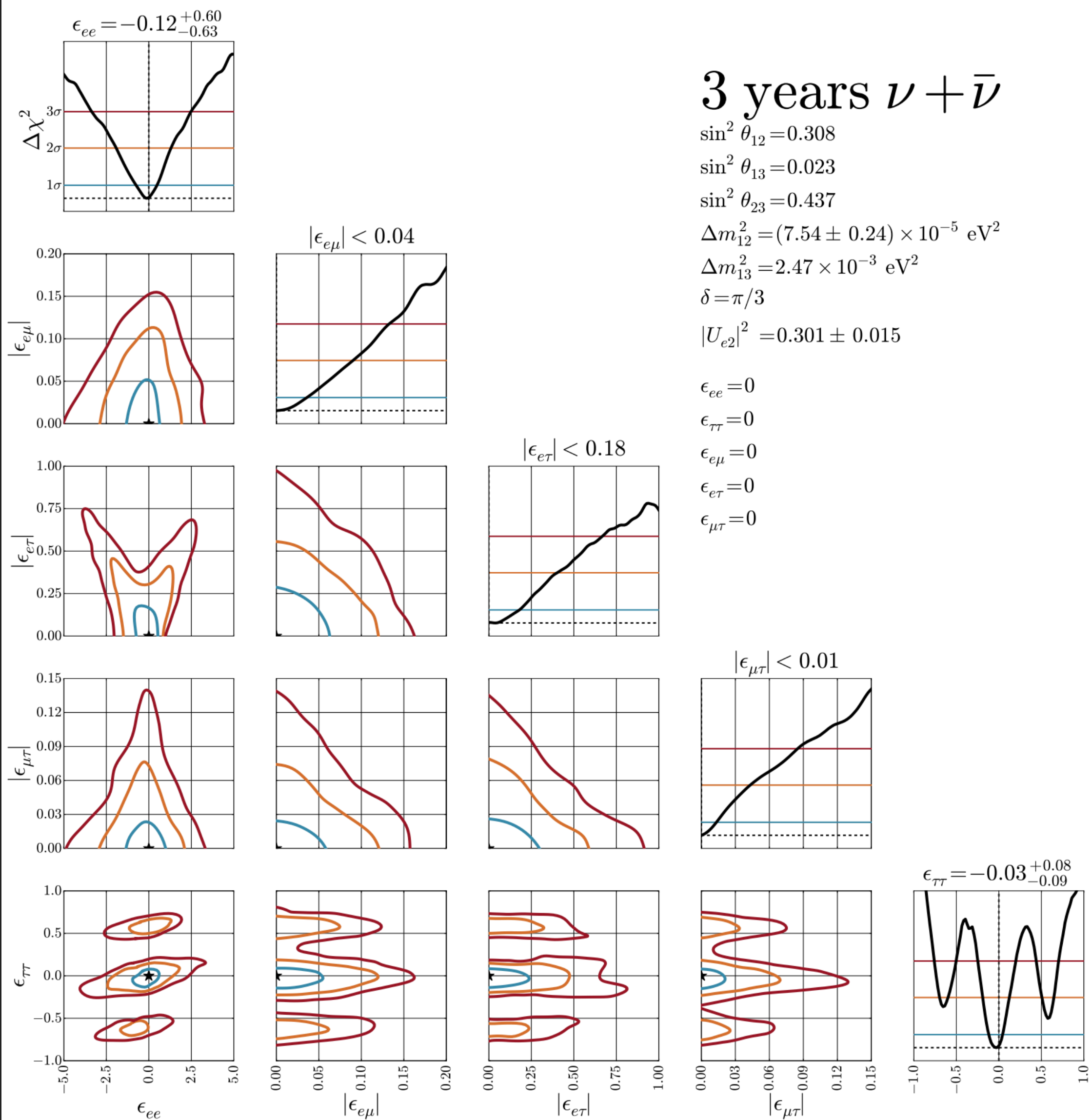
—  $\langle P_{3+1} \rangle$     —  $|\langle \Delta P_{3+1}^{(0)} \rangle|$     —  $|\langle \Delta P_{3+1}^{(1)} \rangle|$     —  $|\langle \Delta P_{3+1}^{(2)} \rangle|$

Extending this to four-neutrino oscillations [1905.01356]

# What can we Learn from DUNE?

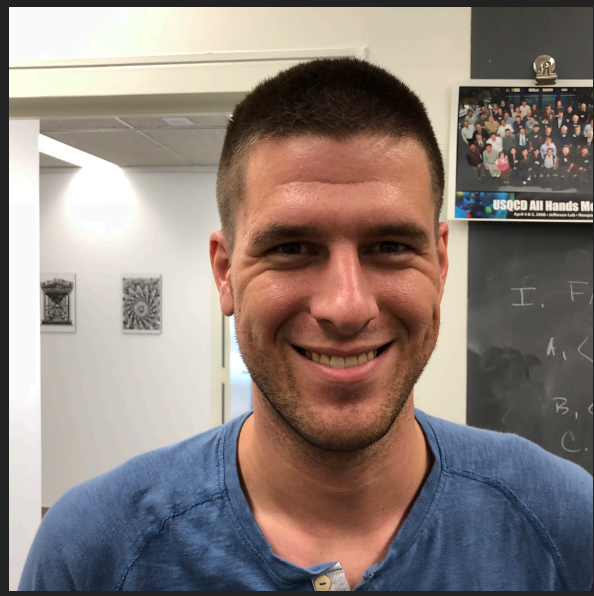


(Me)

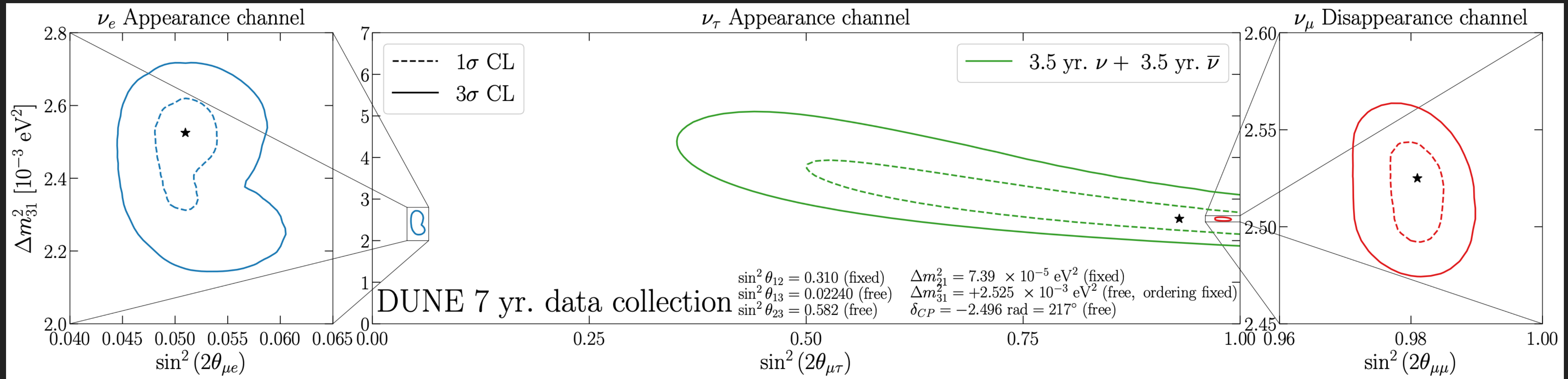


[1511.05562]

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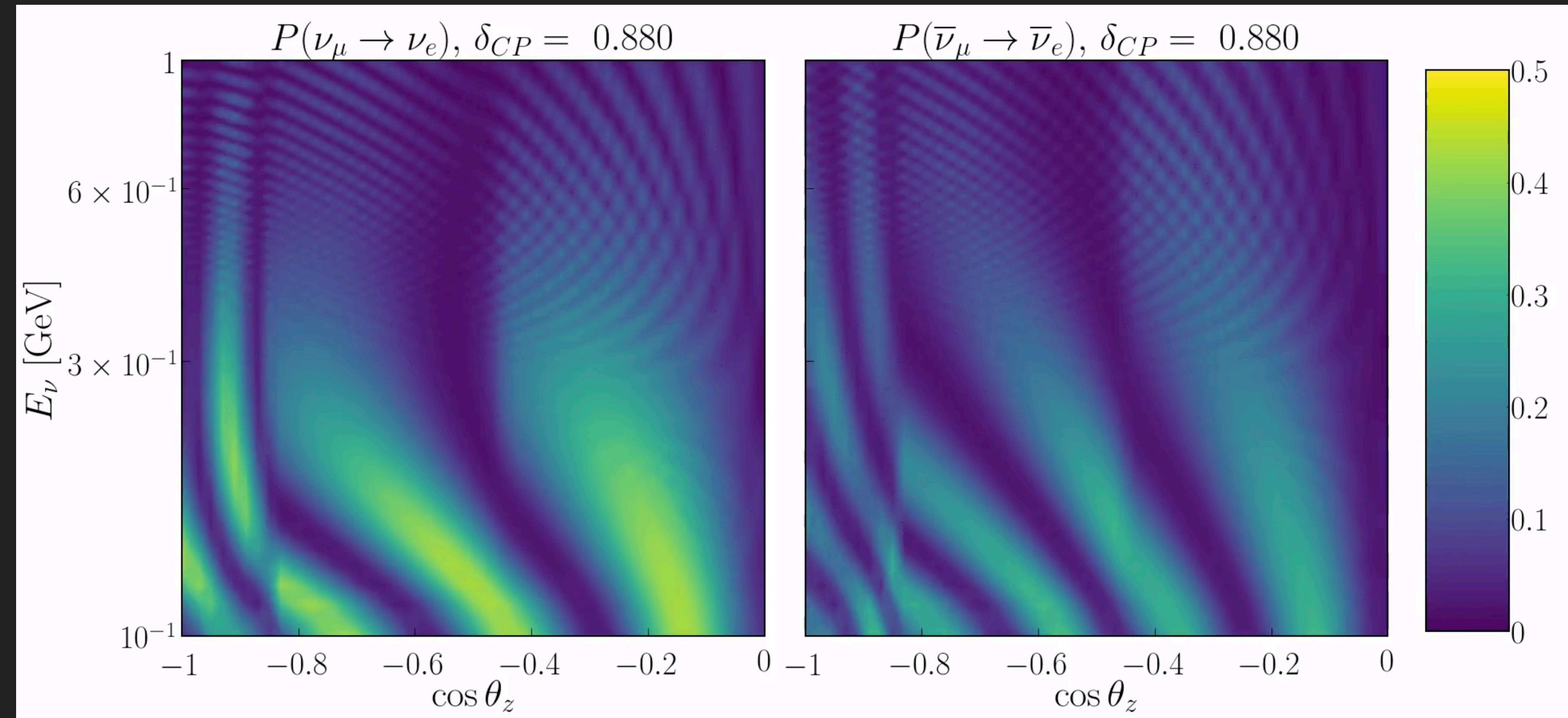
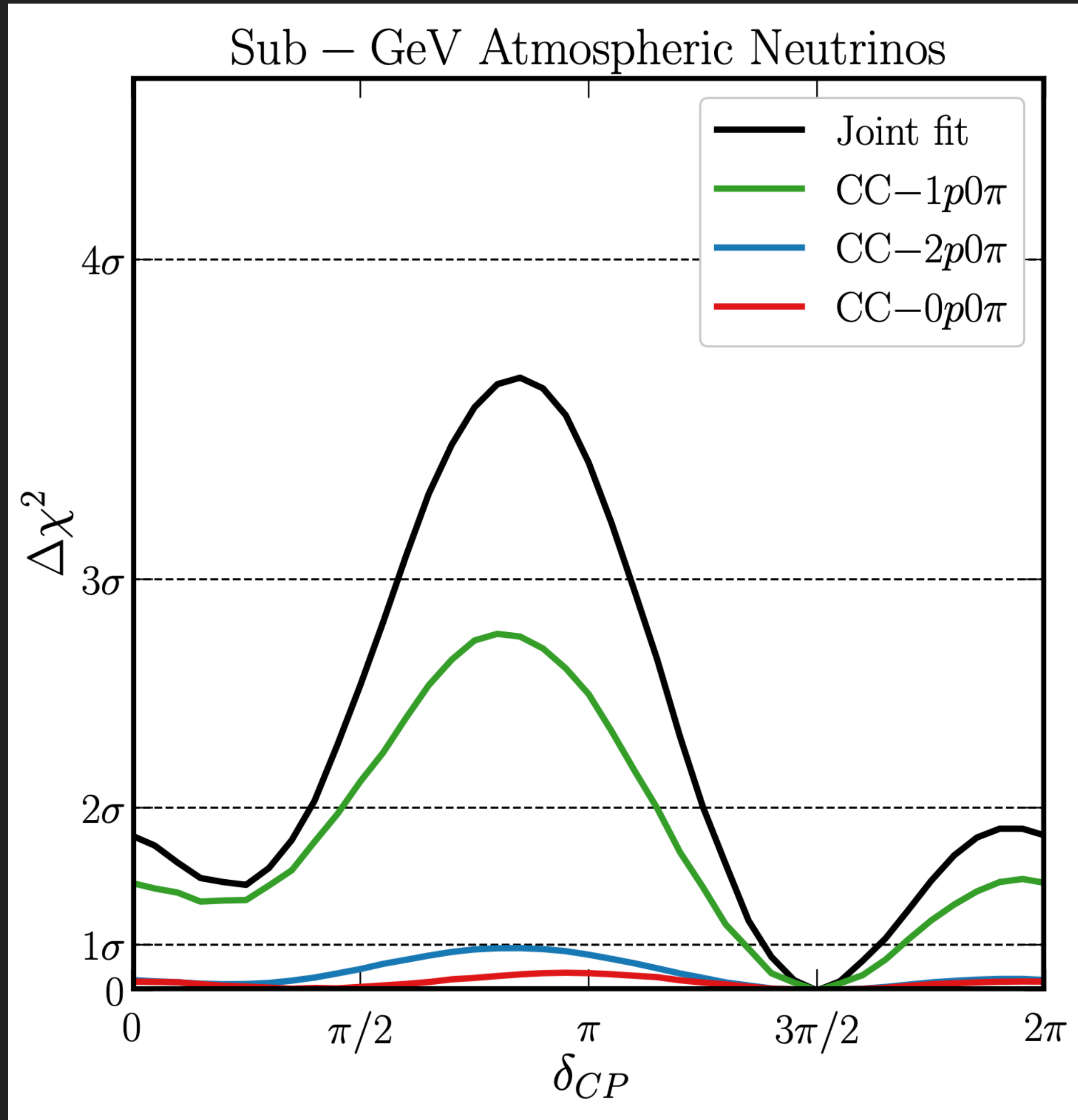


(Me)



[1904.07265]

# Squeezing every ounce of physics out of DUNE



Extra sensitivity to CP violation for free with low-energy atmospheric neutrinos [1904.02751], <https://imgur.com/HoWUniu>

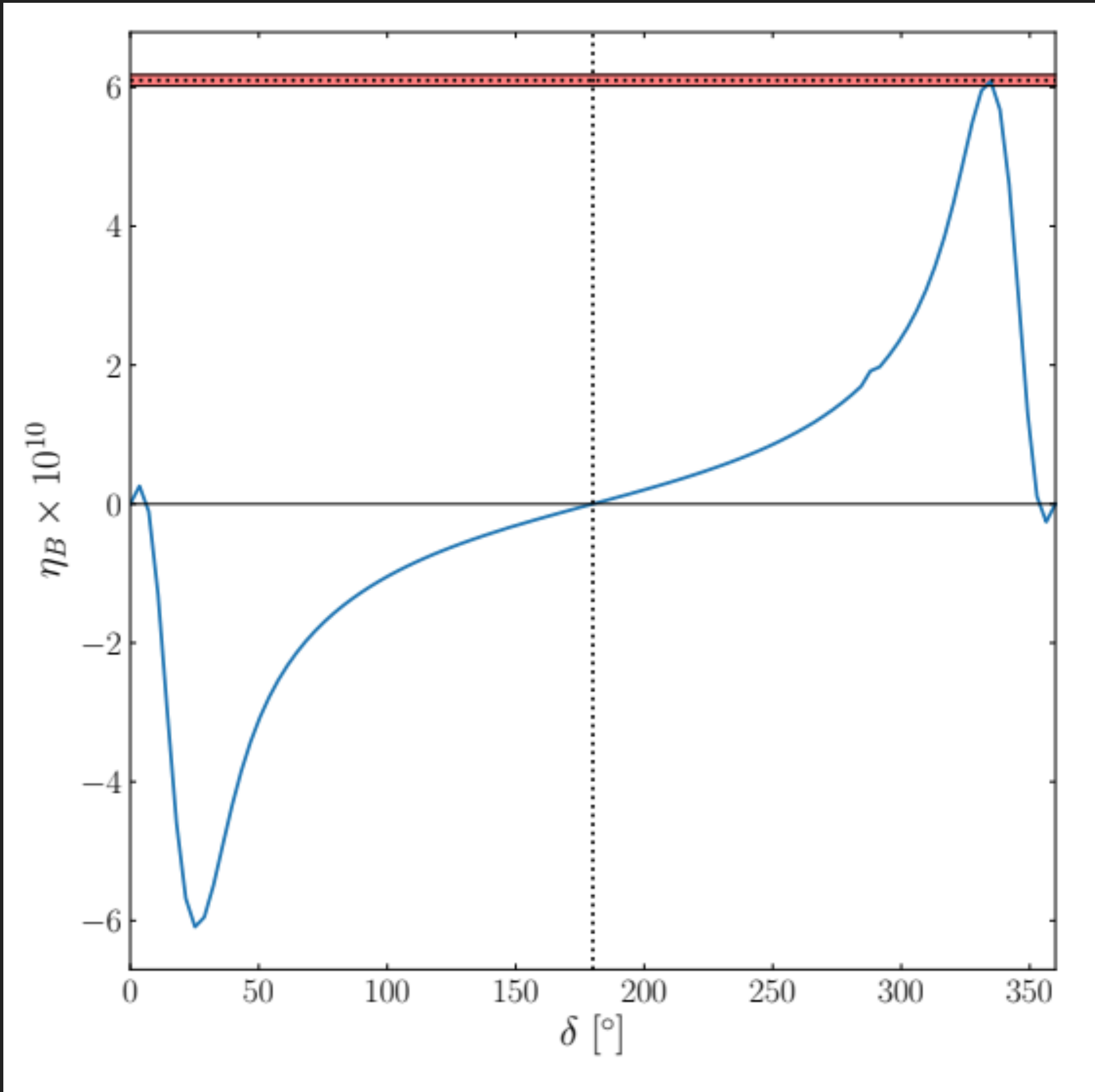
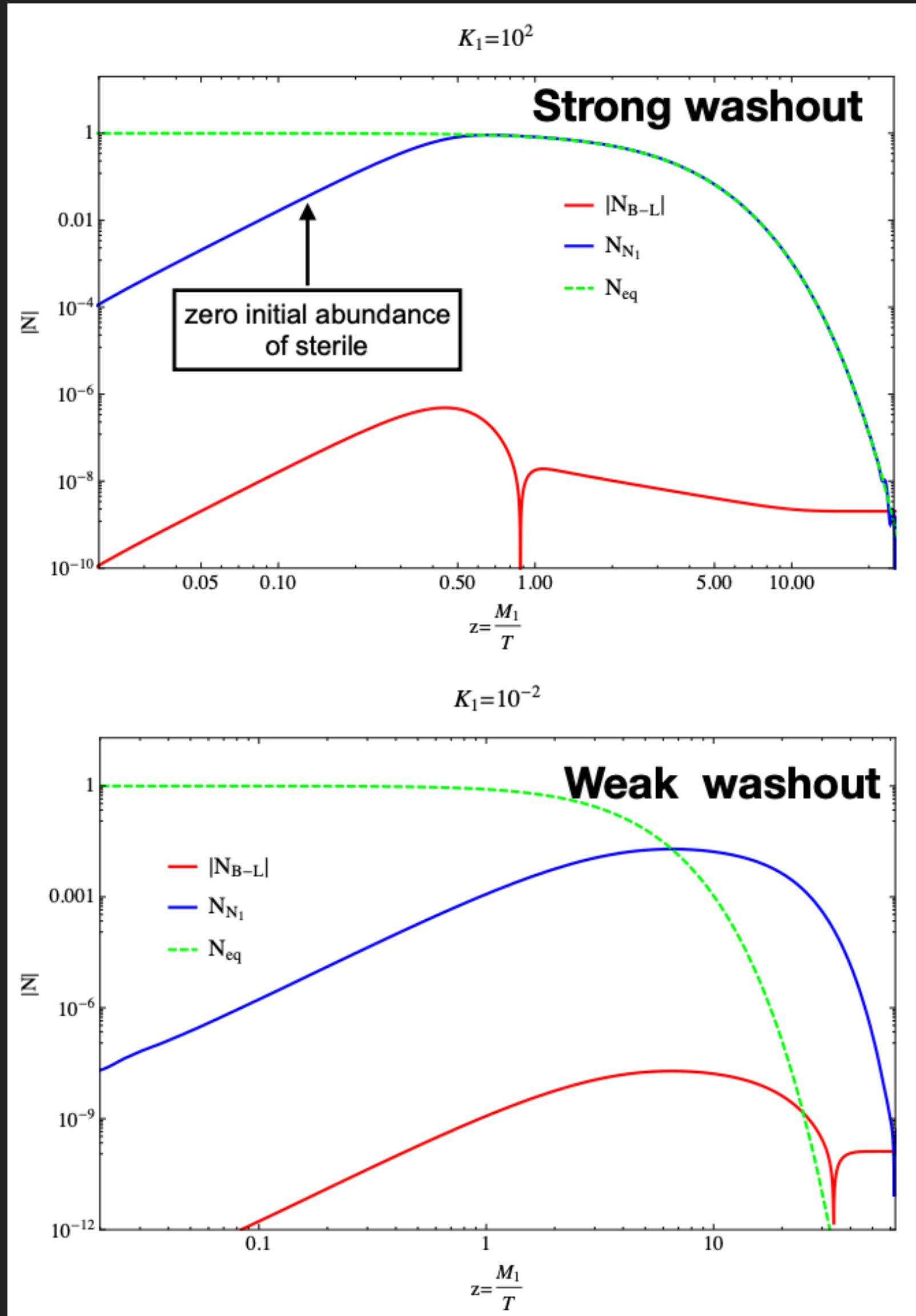
# Leptogenesis

## 1. Search for the origin of matter

DUNE scientists will look at the differences in behavior between neutrinos and antineutrinos, aiming to find out whether neutrinos are the reason the universe is made of matter.



Jessica Turner



[1809.08251]

# Conclusions

- ▶ A great deal of work is being done regarding neutrino theory, on the third floor of Fermilab and beyond.
- ▶ We still have a lot to do when it comes to three-neutrino oscillations, and current/future experiments will answer a lot of the remaining questions.
- ▶ The theory group members who specialize in neutrino physics have a wide range of interests, from cross sections to BSM physics to leptogenesis.
- ▶ Many ideas regarding new physics are being explored. If you want to hear more, we're happy to discuss!