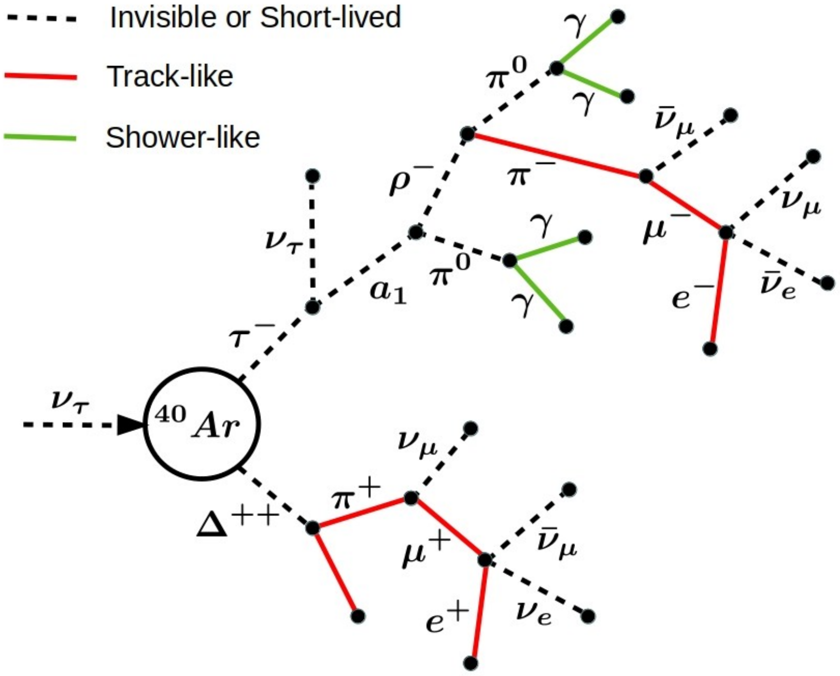
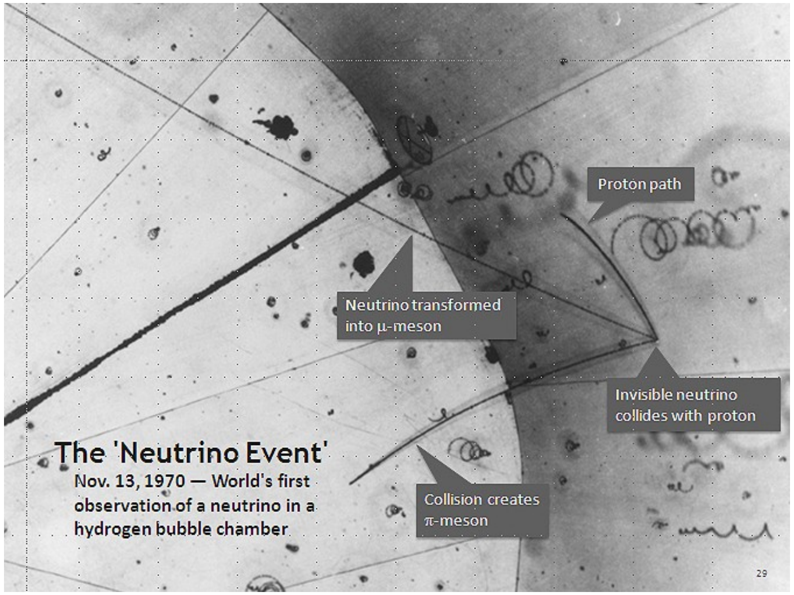
New Physics in Neutrino Oscillations




Proton path

Neutrino transformed into μ-meson

Invisible neutrino collides with proton

The 'Neutrino Event'

Nov. 13, 1970 — World's first observation of a neutrino in a hydrogen bubble chamber

Collision creates π-meson

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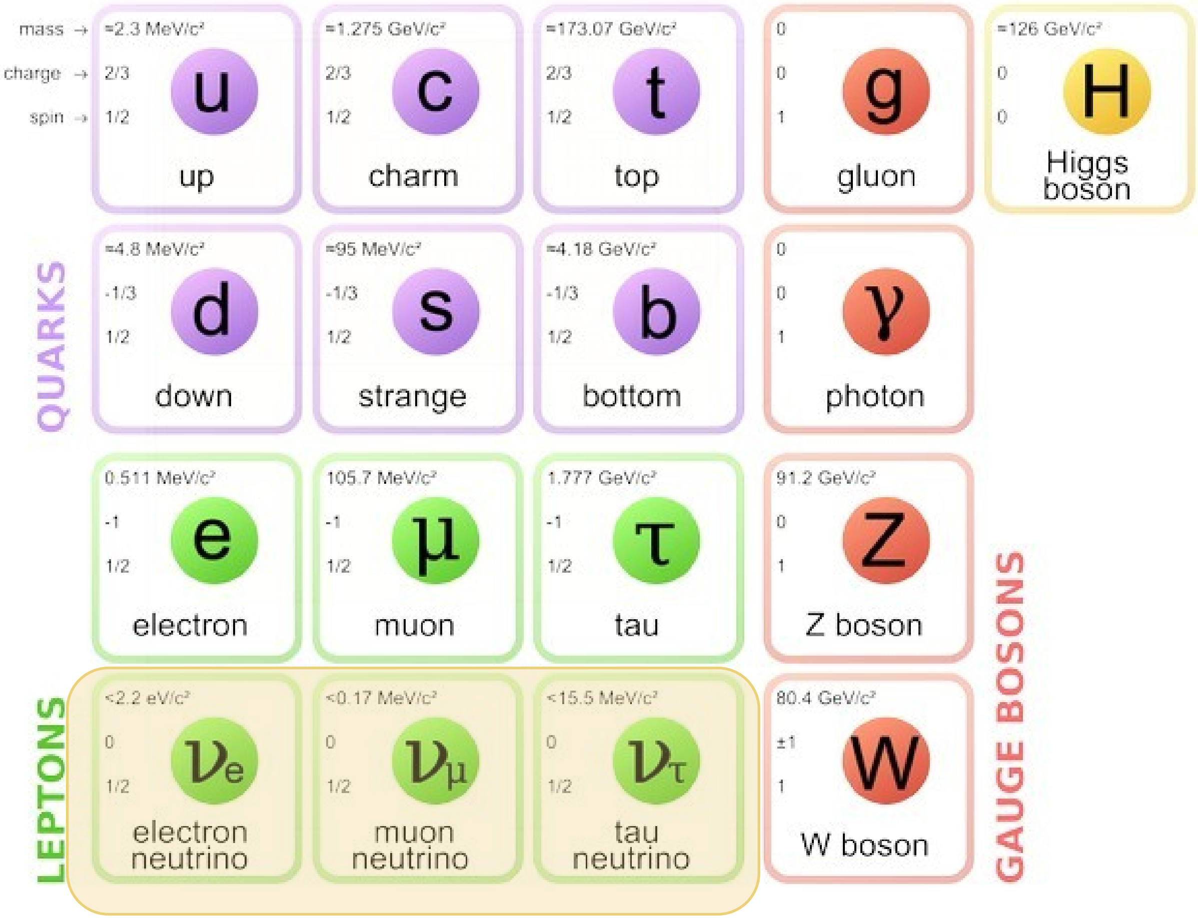
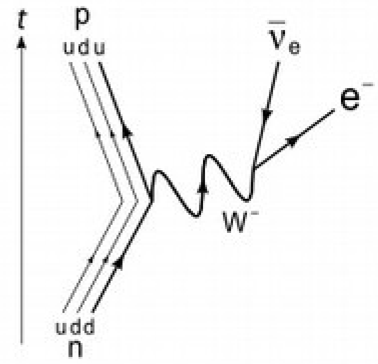
Adam Aurisano
University of Cincinnati

17th International Workshop on Tau Lepton Physics
Louisville, Kentucky
6 December 2023

Neutrinos in the Standard Model



1930: Wolfgang Pauli proposed neutrinos to make β decays conserve energy



1956: Cowan and Reines discovered the ν_e

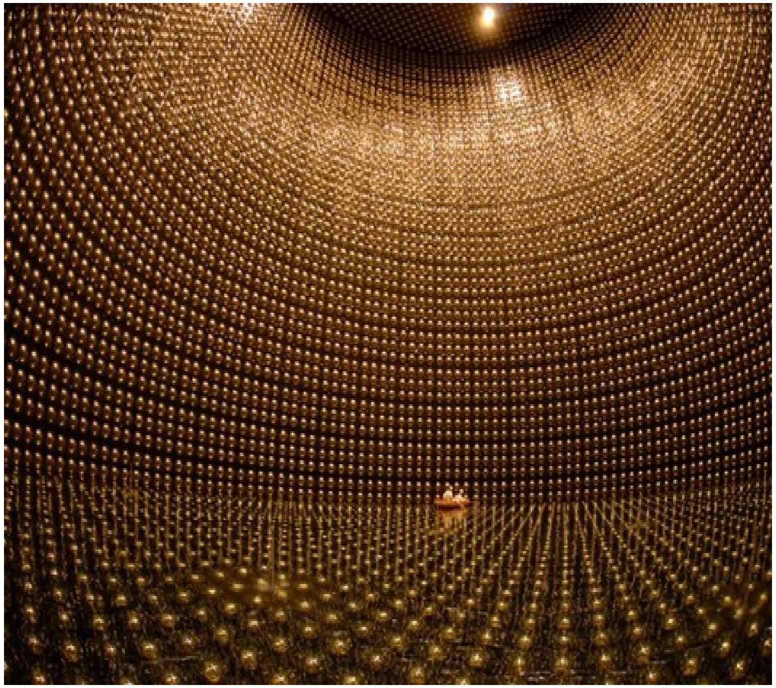
1962: Lederman, Schwartz, and Steinberger discovered the ν_μ

2000: DONUT collaboration discovered the ν_τ

Neutrinos only feel the weak force

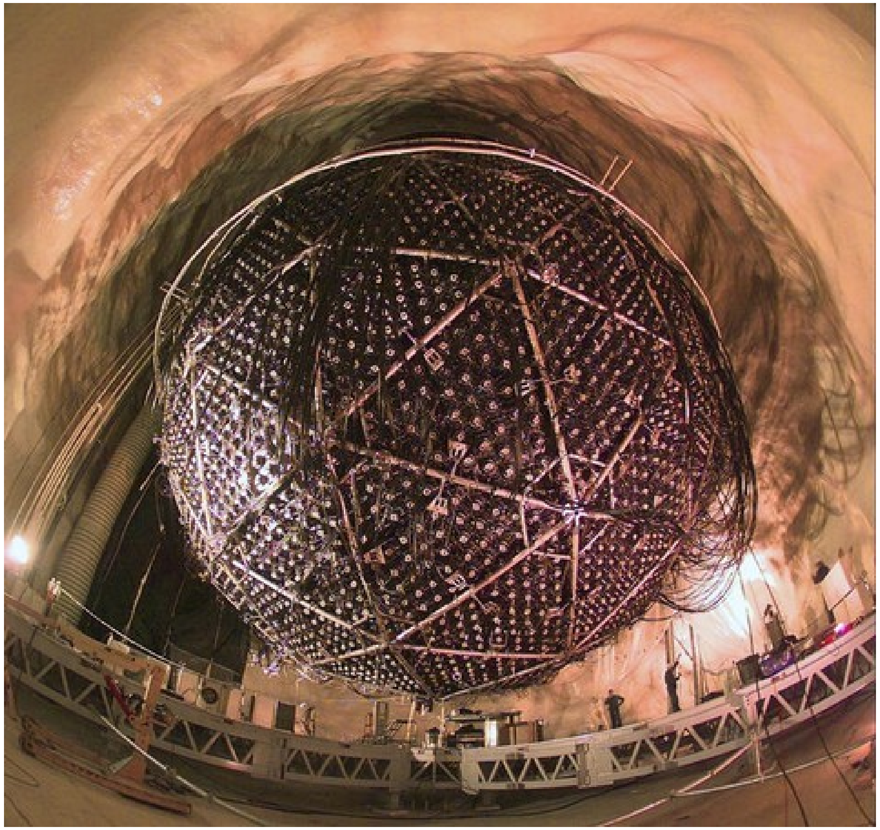
In the SM neutrinos are massless

Oscillations



- Super-Kamiokande
  - Looked for ν_μ produced in the atmosphere by cosmic rays
  - Deficit of ν_μ going up through the earth compared to those coming down from the sky.

- SNO
  - Showed that ν_e from the sun less than expected
  - Total number of neutrinos agreed with expectations

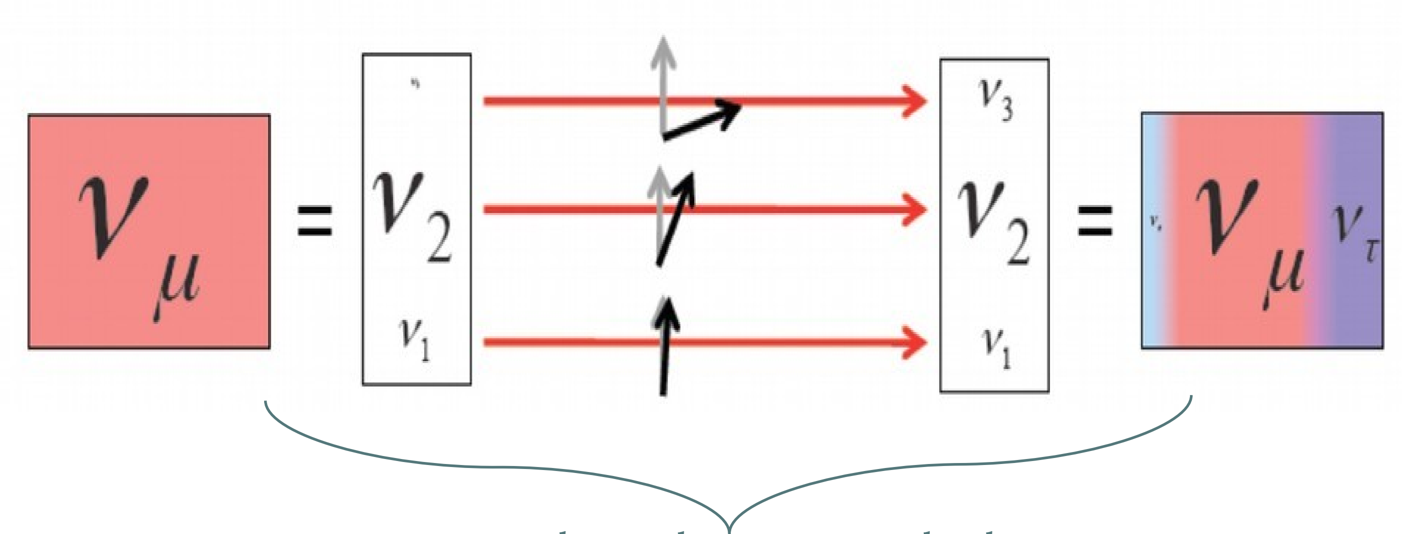


Neutrinos Have Mass

Neutrinos are produced with a definite flavor

They travel as a superposition of mass states

They interact with a definite flavor – maybe different than its starting flavor

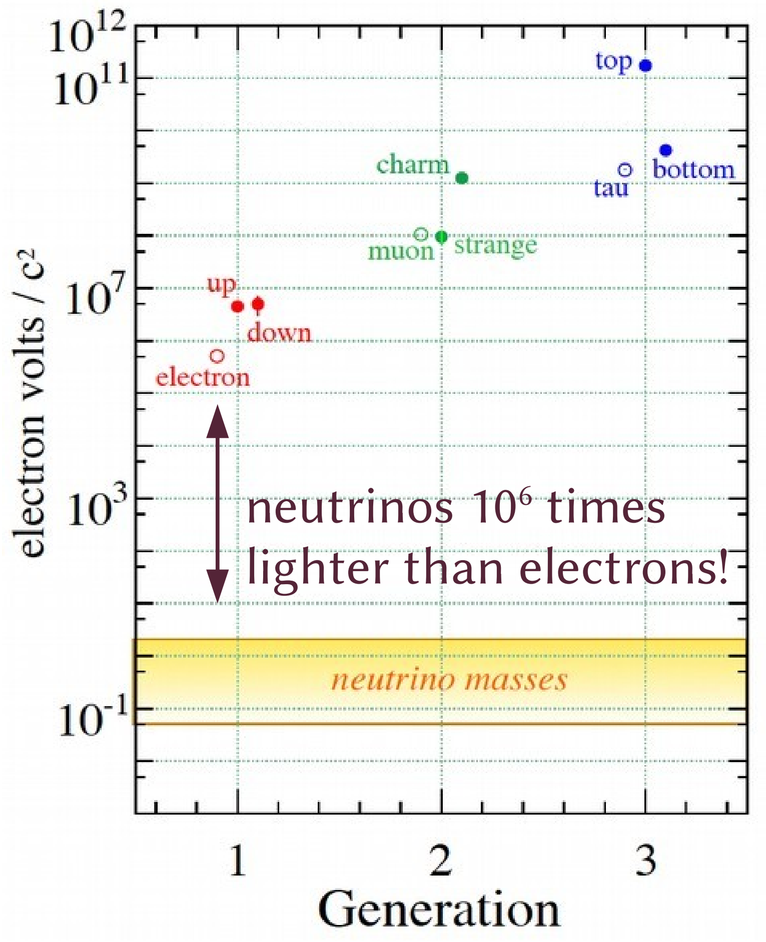


L = baseline traveled

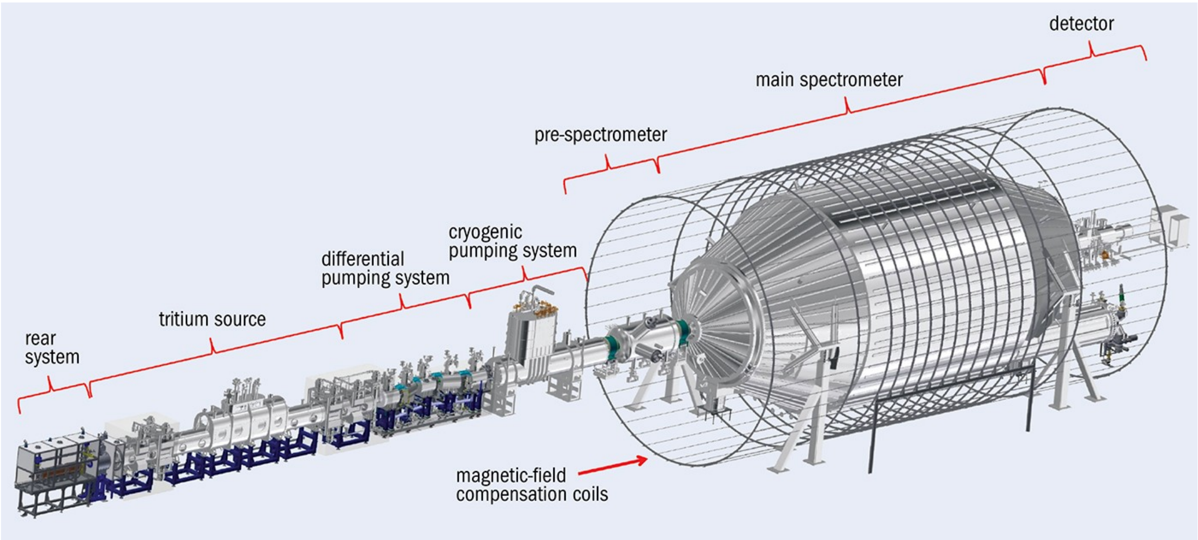
Neutrinos oscillations are only sensitive $\Delta m^2 = m_j^2 - m_i^2$

Not absolute masses!

Neutrino Masses are Very Small



- Best direct mass measurement from KATRIN experiment
- Upper limit set so far
  - $m_\nu < 0.8$ eV
    - Nat. Phys. 18 (2022) 160-166
- Neutrinos are at least six orders of magnitude lighter than electrons!

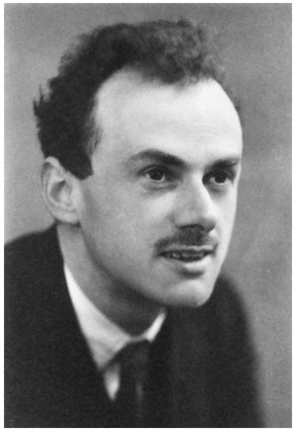


CERN Courier

Oscillations are New Physics

Dirac:

- All SM fermions get this type of mass
  - Generated by Higgs mechanism
- Requires right-handed neutrinos



- Small masses → very small Yukawa couplings
- Hard to naturally explain difference in scale between neutrinos and everything else
- Right-handed neutrinos couple to nothing except gravity → “sterile neutrinos”

Majorana:

- Couples particle to its antiparticle
- No fundamental particles are known to have this type of mass

- Higher dimension operators
- Introduces lepton number violation
- Implies scale of breakdown of SM

See-Saw Mechanism

- Add right-handed neutrinos and allow both types of masses
- See-saw mechanism allows for natural small neutrino masses.
  - Dirac mass ~ Electro-weak scale
  - Majorana mass ~ GUT scale
- Diagonalize mass matrix
  - One mostly active light neutrino (ν) and one mostly sterile heavy neutrino (N)

$$\mathcal{L}_{mass} = \begin{bmatrix} \nu_L & \nu_R \end{bmatrix} \begin{bmatrix} 0 & m_D \\ m_D & M \end{bmatrix} \begin{bmatrix} \nu_L \\ \nu_R \end{bmatrix}$$

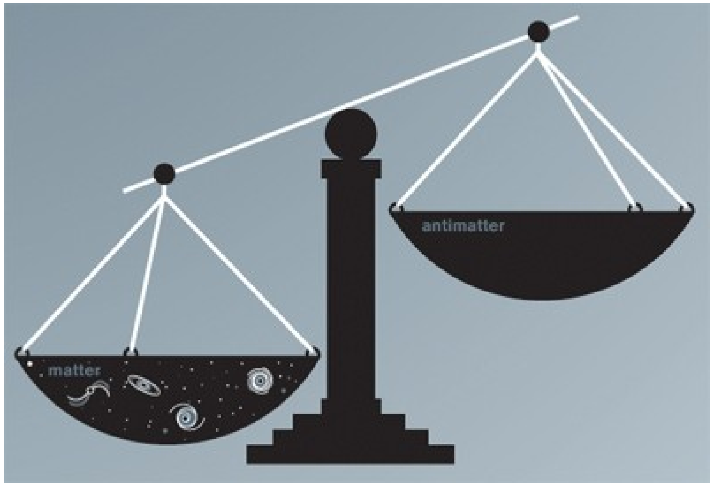
$$M \gg m_D$$

$$m_N \approx M \qquad m_\nu = \frac{m_D^2}{M}$$

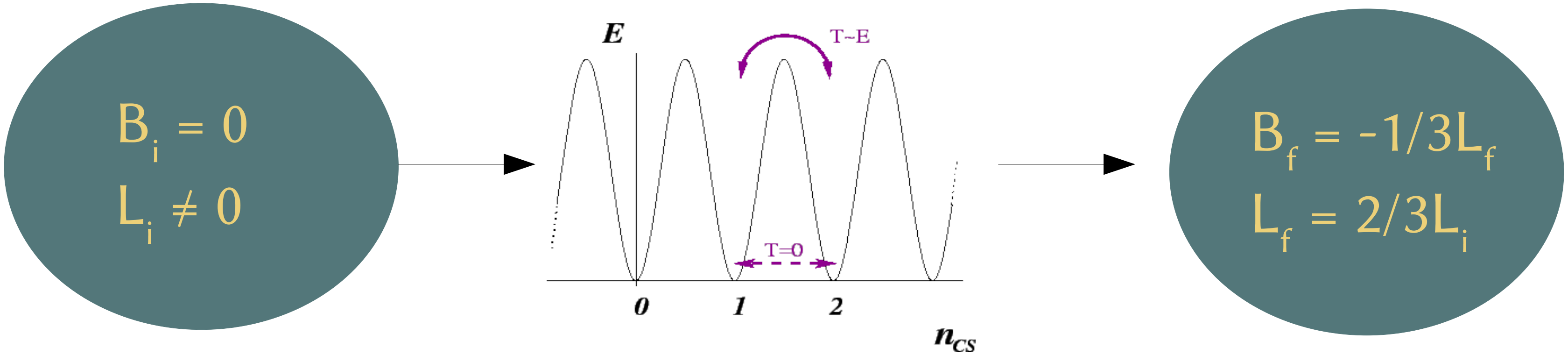
Yamagida; Gell-Mann, Ramond, Slansky
Minkowski; Mohapatra, Senjanovic

Matter-Antimatter Asymmetry

Symmetry



- Immediately after the big bang, expect equal amounts of matter and antimatter
- Now, matter dominates the universe
- Sakharov conditions
  - Baryon number violation
  - C and CP violation
  - Out of thermal equilibrium decays
- CP violation in quark sector not enough
- See-saw mechanism enables leptogenesis



$B_i = 0$

$L_i \neq 0$

$B_f = -1/3L_f$

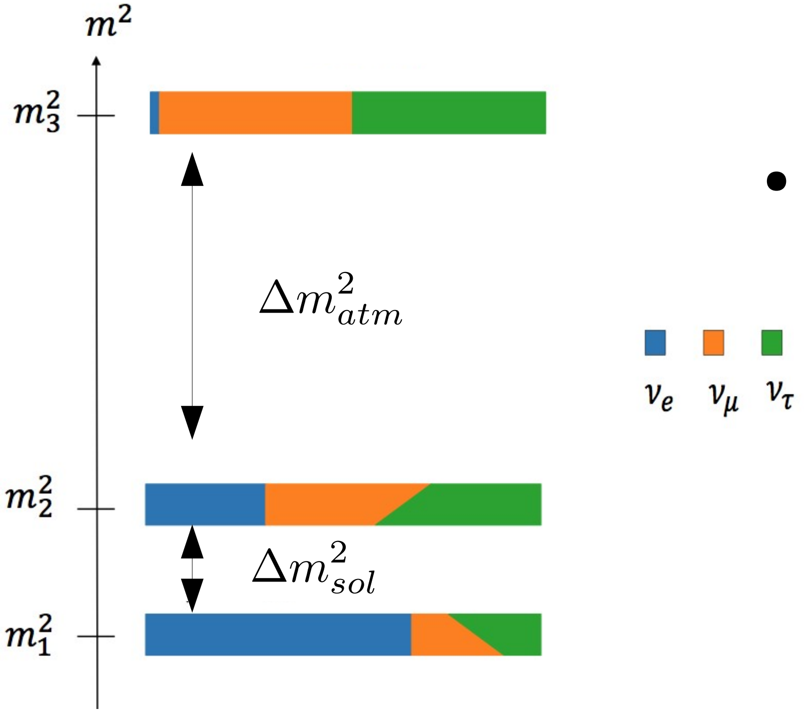
$L_f = 2/3L_i$

Three-Flavor Oscillations

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

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_j U_{\alpha j} U^*_{\beta j} e^{\frac{-i\Delta m^2_{j1} L}{2E}} \right|^2$$

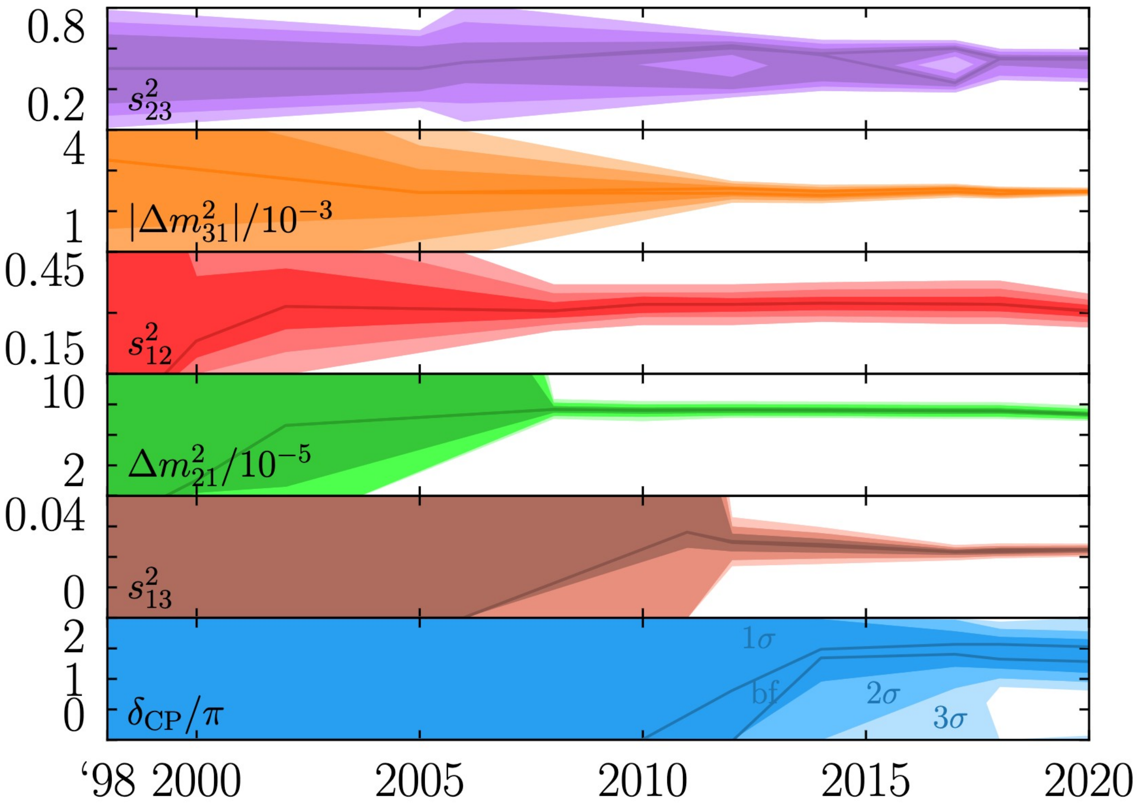


- 3-flavor oscillations parameterized by:
  - Three mixing angles (θ_{12}, θ_{13}, θ_{23})
  - One CP-violating phase (δ)
  - Two mass splittings (Δm^2_{sol} and Δm^2_{atm})

What We Know So Far

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

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix} \begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{bmatrix} \begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix} \begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

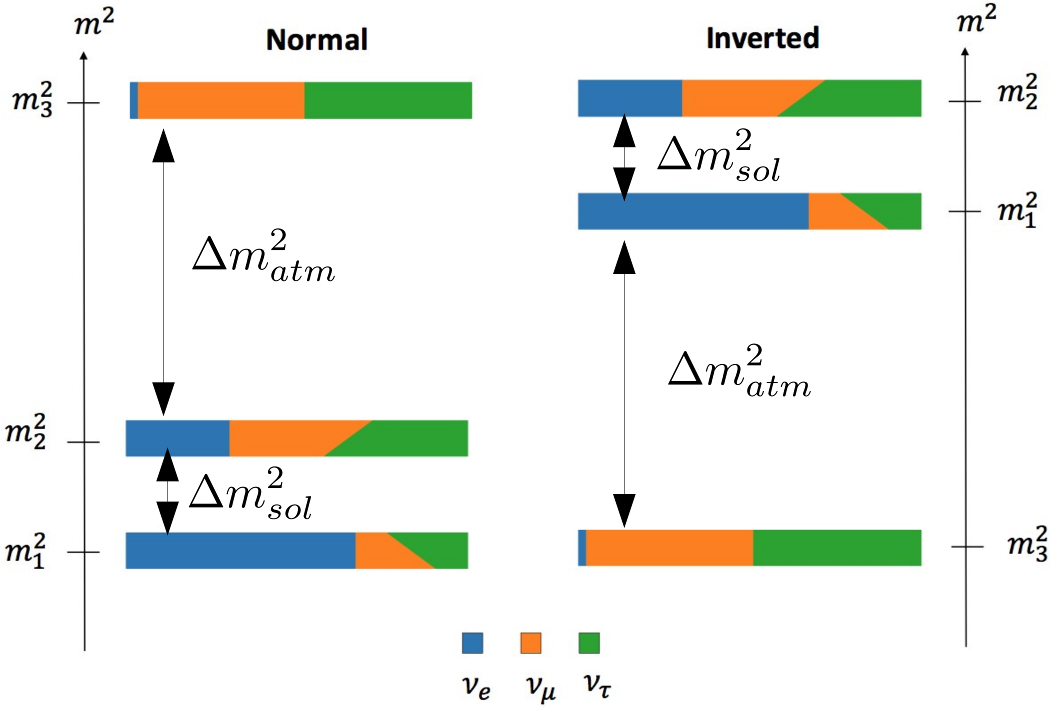


Denton et al. arXiv:2212.00809

Open Questions in Neutrino Oscillations

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

$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix} \begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{bmatrix} \begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix} \begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

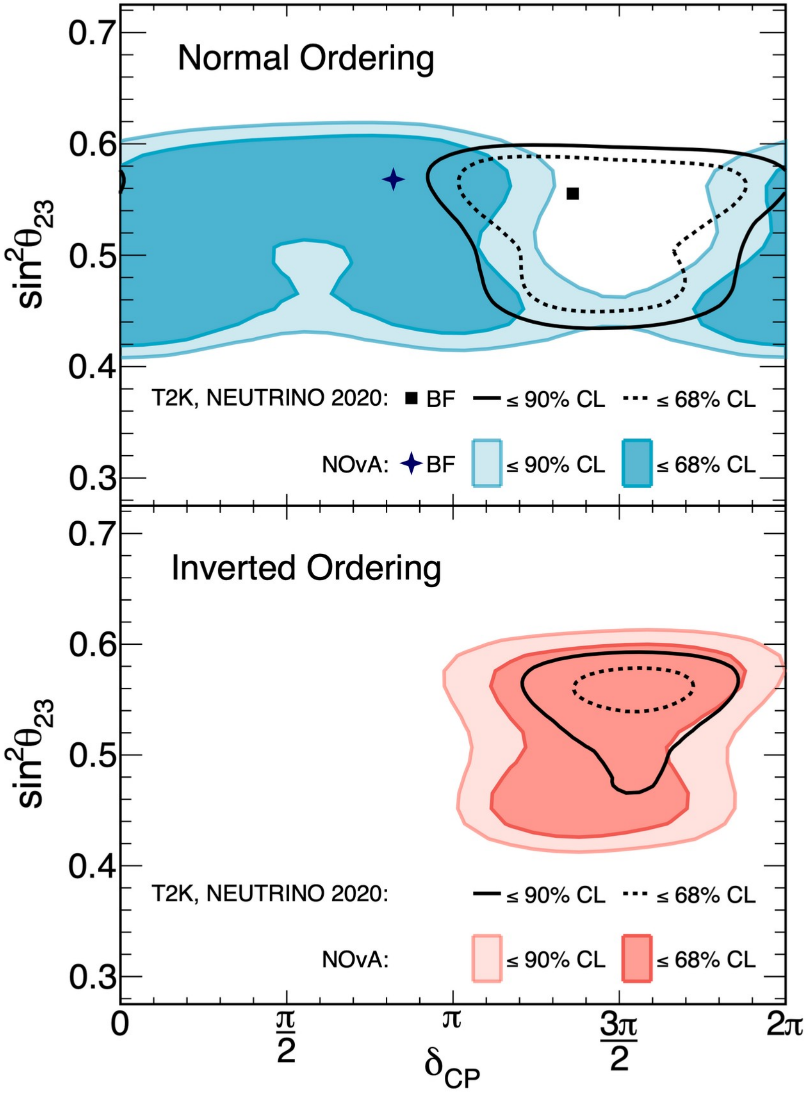


- Is θ_{23} exactly 45°?
- Is ν_3 the heaviest or lightest neutrino?
- What is the value of sin δ?
- Is this the whole picture?

Non-Standard Interactions

NOvA and T2K

- NOvA and T2K both measure ν_e appearance and ν_μ disappearance
  - Designed to study the mass ordering and CP violation
- Both experiments are designed to have similar L/E
  - NOvA: E ~2 GeV, L = 810 km
  - T2K: E ~600 MeV, L = 295 km
- Recent results broadly compatible, but with qualitative differences
- If tension were to increase in future, what could it mean?



Non-Standard Interactions

Non-standard interactions (NSI) modify standard three flavor neutrino oscillations by introducing anomalous interactions between neutrinos and matter, in addition to the standard MSW effect

$$\mathcal{H} = \frac{1}{2E}\left[U_{\text{PMNS}}\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta^2_{21} & 0\\ 0 & 0 & \Delta^2_{31}\end{pmatrix}U^\dagger_{\text{PMNS}} + a\begin{pmatrix}1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau}\\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}\\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau}\end{pmatrix}\right]$$

$$a = 2\sqrt{2}G_F N_e E$$

$$\epsilon_{\alpha\beta} = |\epsilon_{\alpha\beta}|e^{i\delta_{\alpha\beta}}$$

Wolfenstein matter potential

Introduces 9 new parameters:

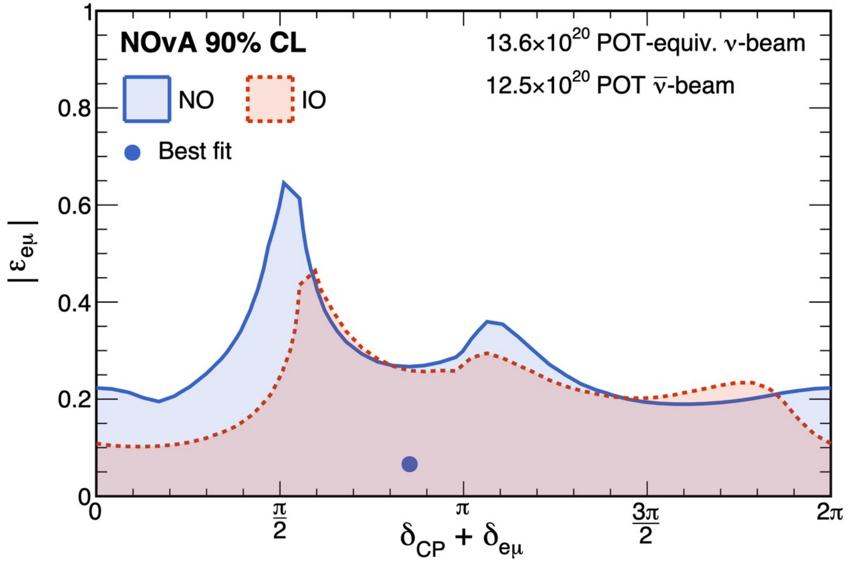
On-diagonal: NSI-induced mass squared splittings (real valued)

Off-diagonal: NSI-induced mixing angles (complex)

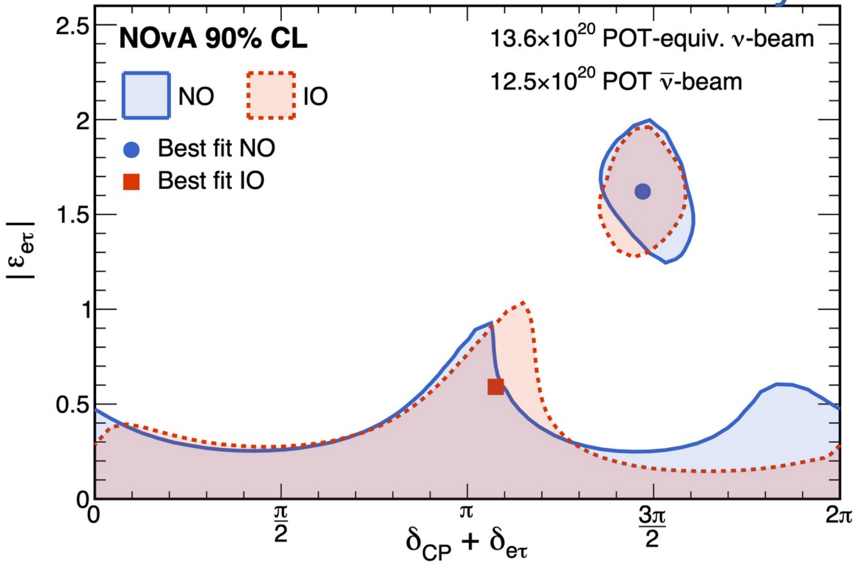
NOvA Search for NSI

- NSI, in general, has many parameters
- NOvA investigated effect of $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$ terms
- Prefers standard oscillations
- Strength of result would be improved through combining results from experiments with different matter effects

NOvA Preliminary



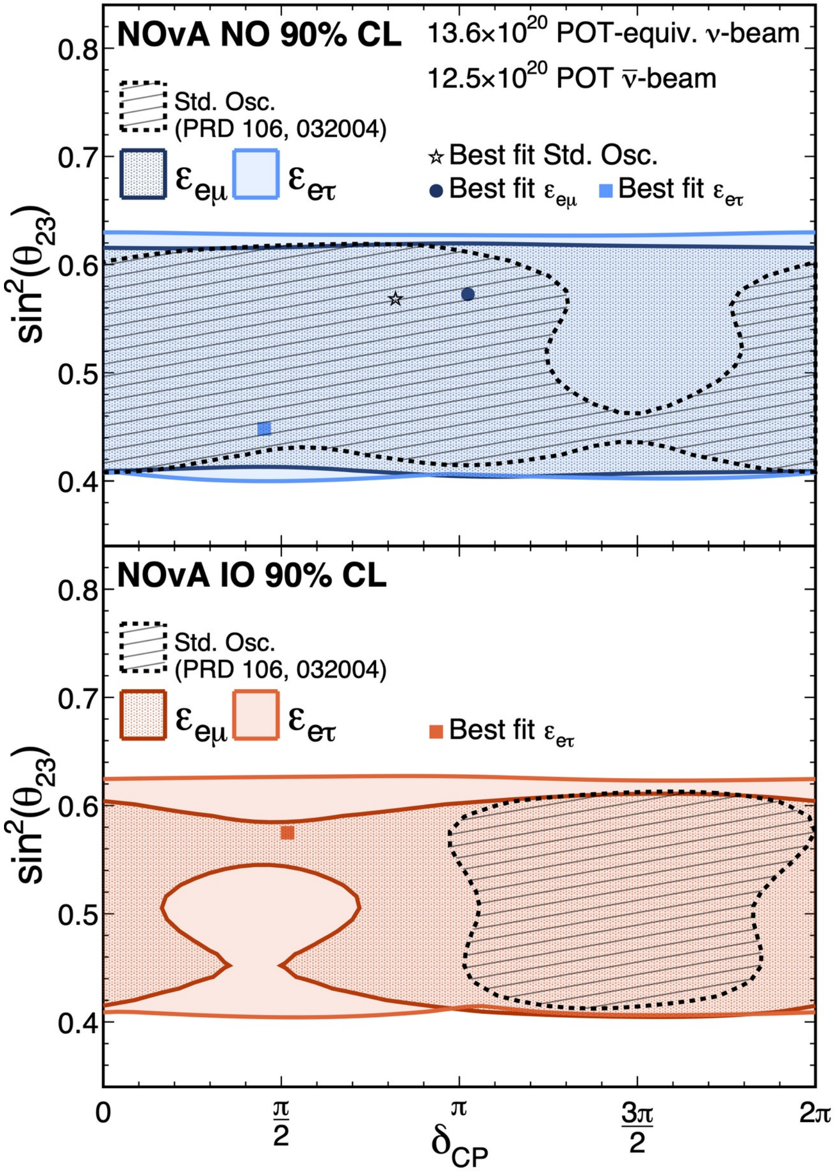
NOvA Preliminary



Effect on Three Flavor Measurements

- Introducing NSI into three flavor oscillations profoundly affects sensitivity to CP violation
- Much sensitivity to δ_{CP} in the three flavor interpretation is lost when introducing NSI, due to degeneracy with CP-violating phases of oscillation parameters

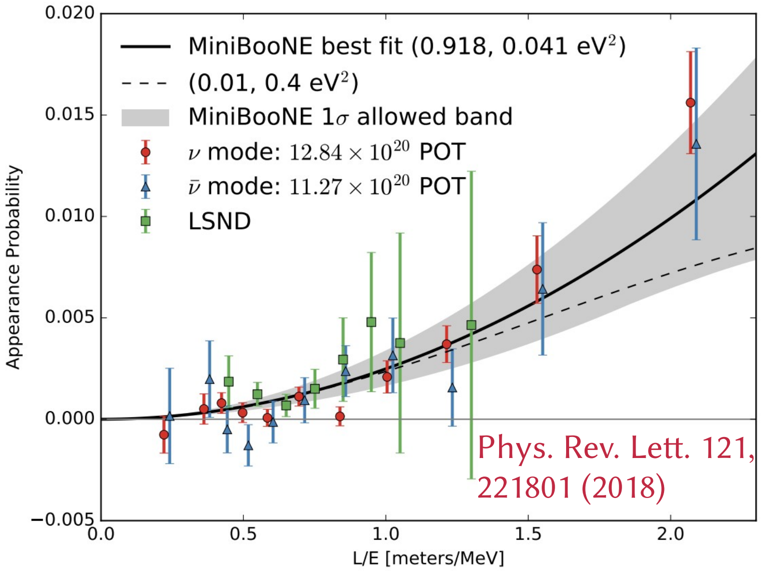
NOvA Preliminary



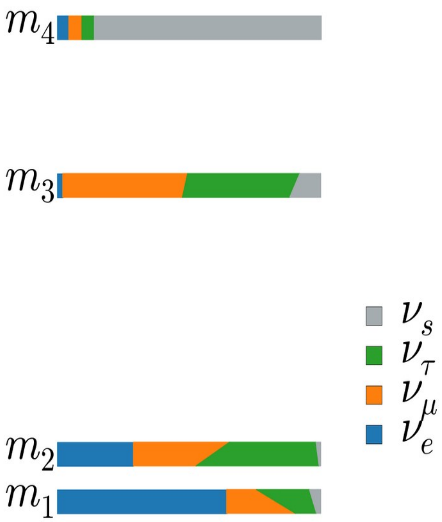
Light Sterile Neutrinos

Light Sterile Neutrinos

- Short-baseline experiments (LSND, MiniBooNE) observed anomalous excesses of ν_e ($\bar{\nu}_e$) in ν_μ ($\bar{\nu}_\mu$) beams
- BEST observed anomalous deficit in ν_e from a ^{51}Cr neutrino source over short baselines
- Anomalies could all be explained by oscillations driven by a mass splitting $\Delta m^2 \sim 1$ eV^2
  - Not consistent with three known active flavors
- Simplest model adds one new mass state and one new, sterile flavor state
  - 3+1 model contains 6 new parameters

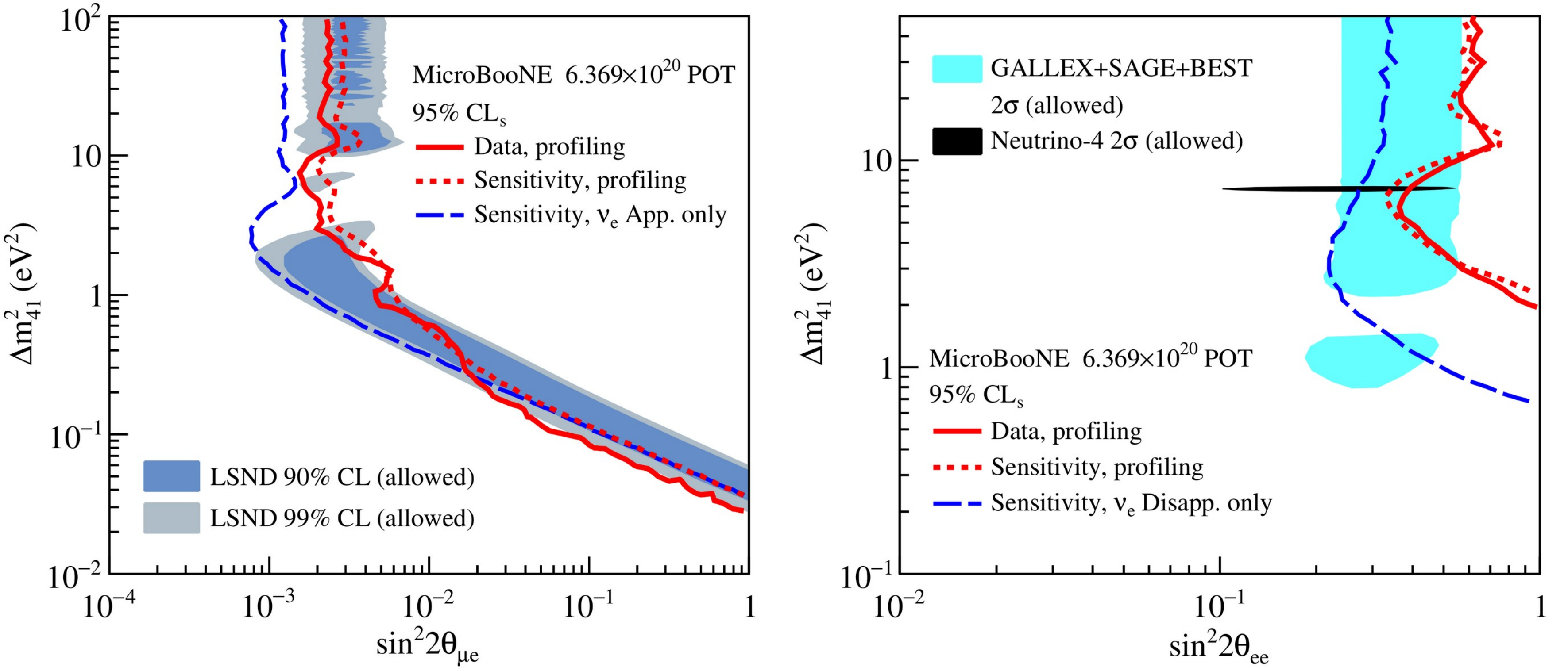


Phys. Rev. Lett. 121, 221801 (2018)



MicroBooNE Results

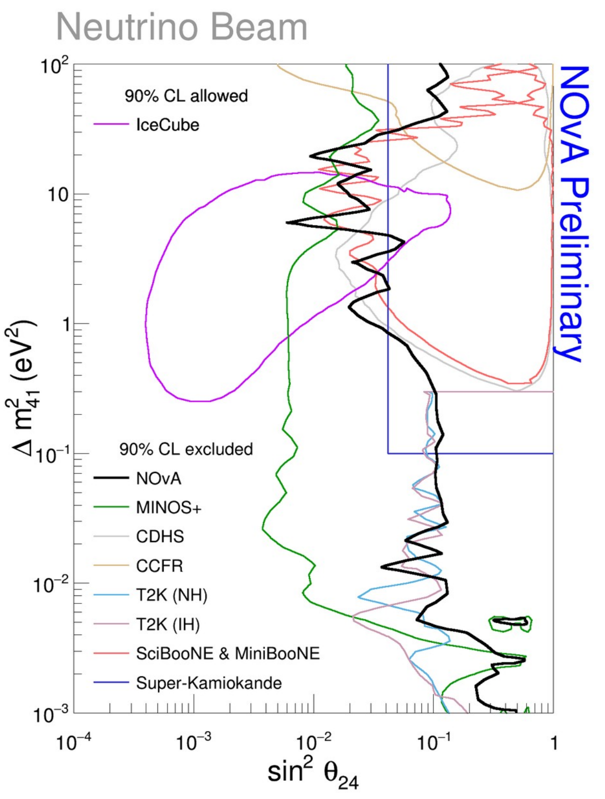
- MicroBooNE recently searched for sterile-driven oscillations at short baselines in the ν_e channel
- Considered oscillations involving $\nu_\mu \rightarrow \nu_e$ and $\nu_e \rightarrow \nu_s$
- Set limits on effective mixing parameters
  - Encroaching on allowed regions from anomalous results

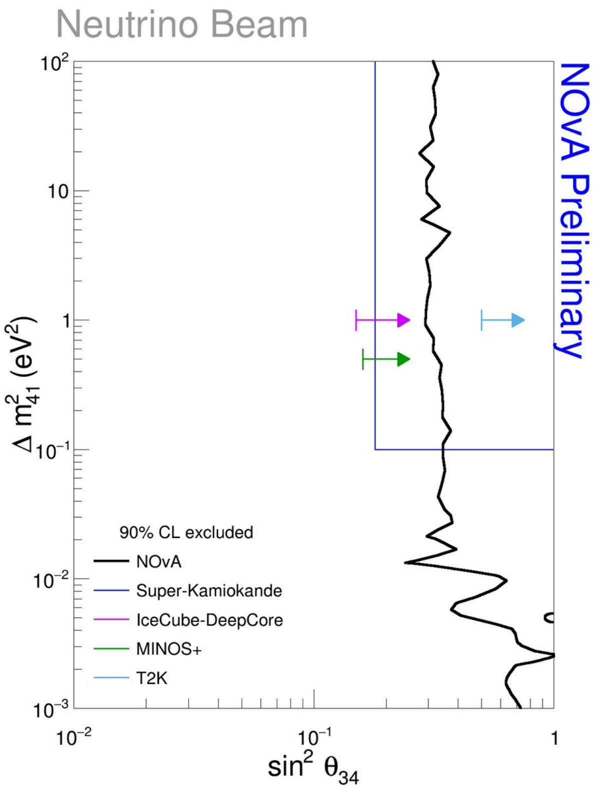


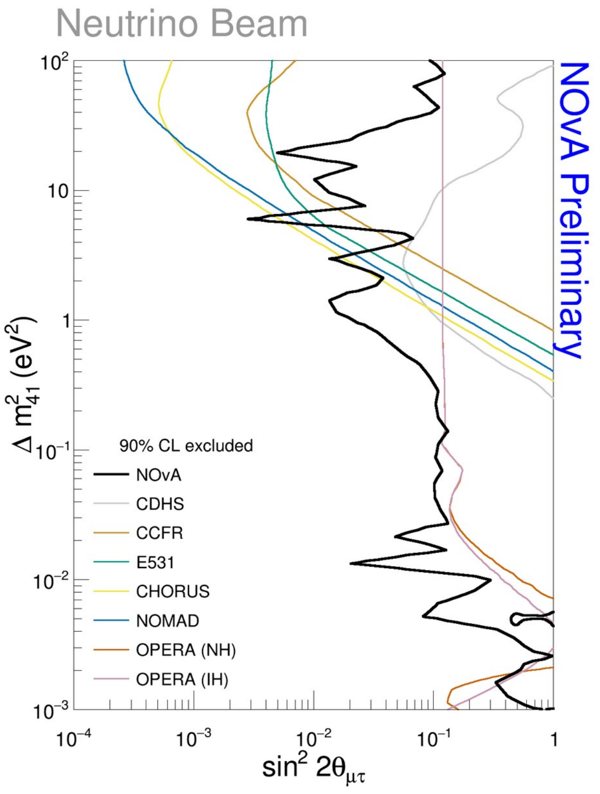
PRL 130 (2023) 011801

NOvA Results

- NOvA recently searched for sterile-driven oscillations using a joint short and long baseline analysis
- Considered both ν_μ disappearance and NC disappearance
- Set limits on $\sin^2\theta_{24}$ and $\sin^2\theta_{34}$
  - Limits can be combined to set limits on effective mixing parameter controlling anomalous $\nu_\mu \rightarrow \nu_\tau$ appearance



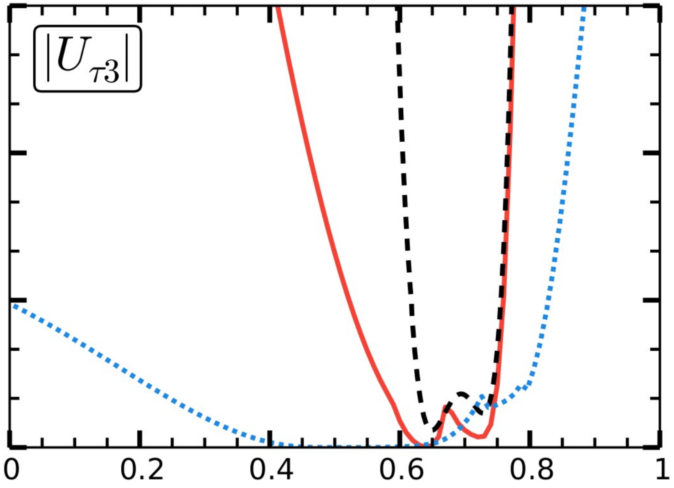


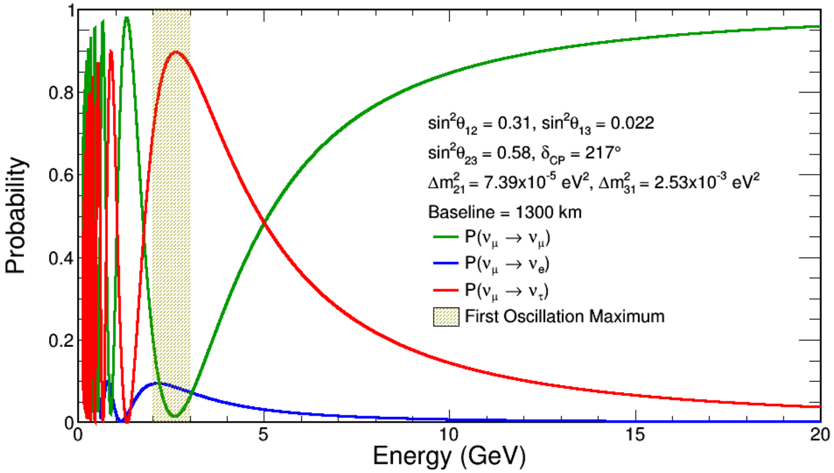


Non-Unitary Mixing

Unitarity and Tau Neutrinos

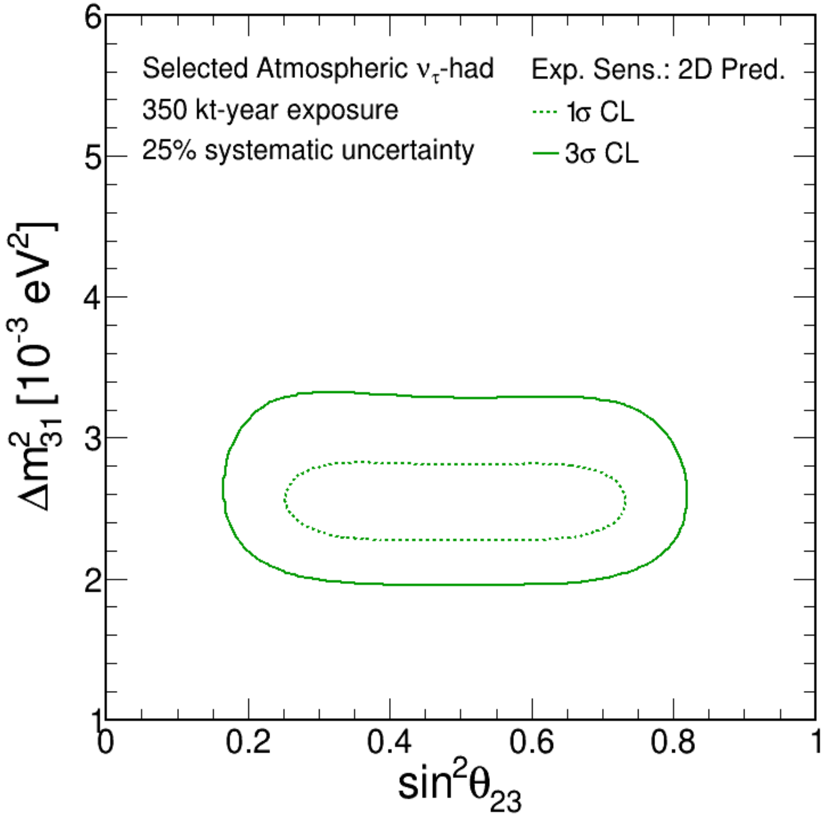
PRD 93, 1103009 (2016)



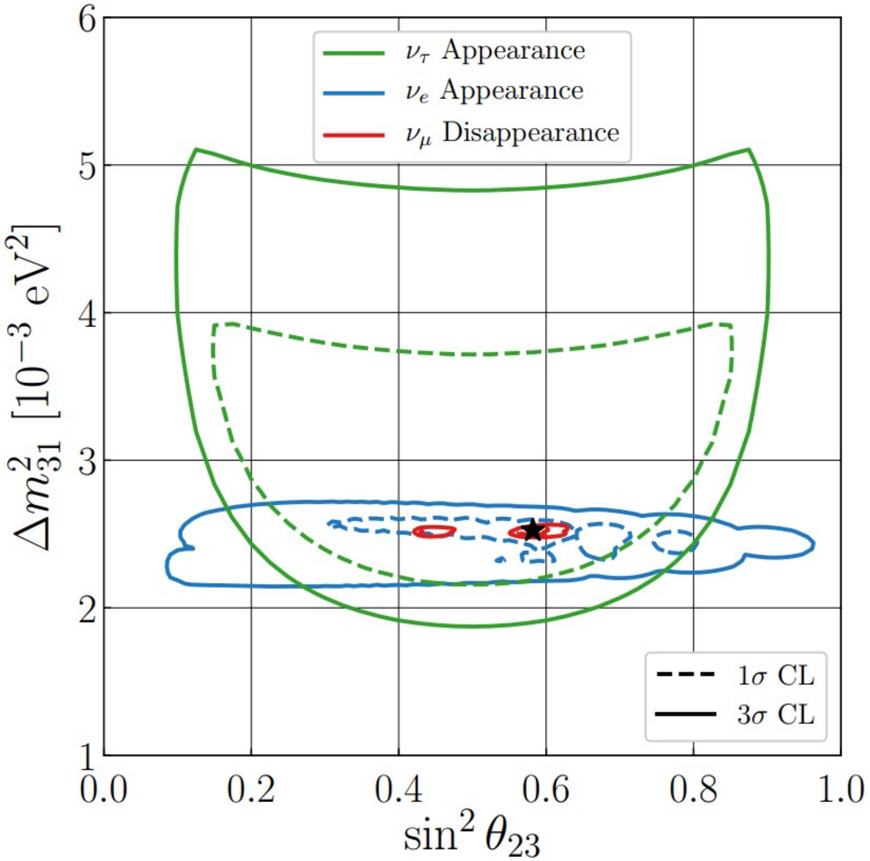


- Current experiments NOvA and T2K are making huge strides in understanding standard neutrino oscillations
- Is this model complete?
- Almost all knowledge of ν_τ sector is based on assumption of PMNS unitarity
- Almost all ν_μ disappear at oscillation maximum
  - Assumed oscillating into ν_τ
  - Only 10 high-purity, oscillated, ν_τ candidates have ever been observed
- DUNE will be the only experiment able to directly observe tau neutrinos appearing
  - High statistics samples both from beam and atmospherics

Atmospheric Parameters with Tau Neutrinos



de Gouvea, Kelly, Stenico, Pasquini, PRD 100, 016004 (2019)



Atmospheric sample - expected counts

~**1** ν_τ per kton-year
~**40** ν_τ per year, with all modules

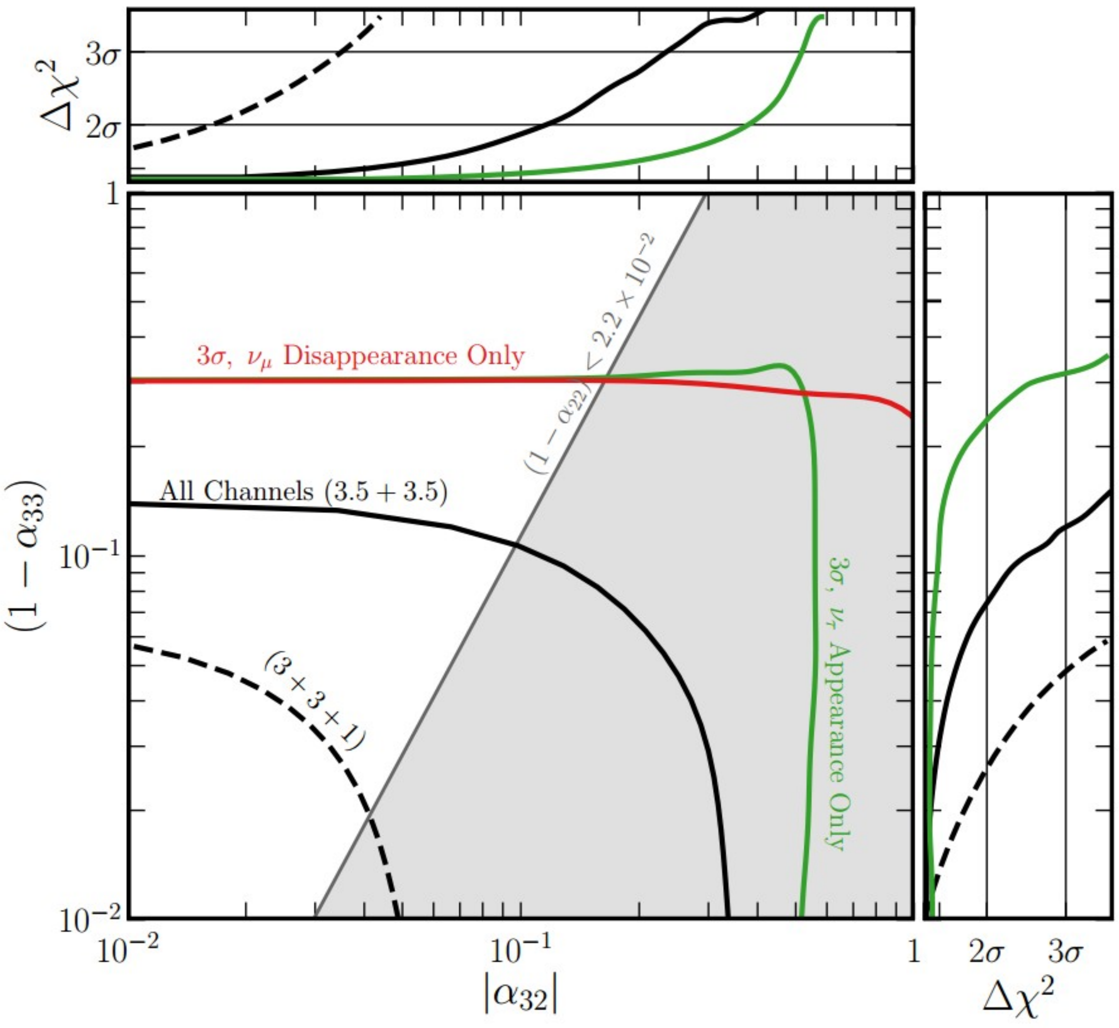
Beam sample - expected counts/year:

~**130** ν_τ in low-energy neutrino mode
~**30** $\bar{\nu}_\tau$ in low-energy antineutrino mode
~**800** ν_τ in high-energy neutrino mode

Non-Unitary Oscillations

- In type I see-saw models, number of neutrino states goes from 3 ⟶ n
- Three states correspond to observed light neutrinos, rest are heavy sterile neutrinos
- Unitary PMNS matrix becomes: $U^{n\times n} = \begin{pmatrix} N & S \\ V & T \end{pmatrix}$
- N is the 3x3 matrix describing mixing between the light states
  - Observed PMNS matrix
- Apparent non-unitarity of 3x3 submatrix provides a way to detect existence of sterile states too heavy to directly access

Constraining Parameterized Non-Unitarity



de Gouvea, Kelly, Stenico, Pasquini, PRD 100, 016004 (2019)

$$U \to NU = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$

- Can constrain non-unitarity using α parameters
- Tau neutrino data, in addition to other channels, improves bounds on α_{33}
- Only considers DUNE beam samples
    - Alternate high energy beam mode is particularly powerful

Summary

- Even standard, three-flavor neutrino oscillations are beyond the Standard Model physics
- Mass generation may be related to physics at very high scales
- Current generation of neutrino experiments are making good progress at measuring standard mixing parameters
- Next generation of experiments will definitely measure standard mixing parameters
- It is critical that we broaden our focus to try understand the consistency between measurements from a broad range of baselines, energies, and sources to determine if three flavor mixing fully describes the data