Long Baseline Experiments - *a review of accelerator based neutrino physics*

Kendall Mahn (Michigan State University)

LEPTON PHOTON 2021 MAN

Thank you to the organizers for the opportunity to speak today!

Support from:

U.S. Department of Energy
award DE-SC0015903

Takeaways from today's talk:

Long baseline experiments are broad scientific programs with opportunities to test our understanding of the universe

The future is bright, with exciting long baseline results, starting with the current program, Tokai-to-Kamioka (T2K) and NuMI Off-axis ν_e Appearance (NOvA) experiments

Evidence of neutrino mass from neutrino oscillation experiments leads to important questions:

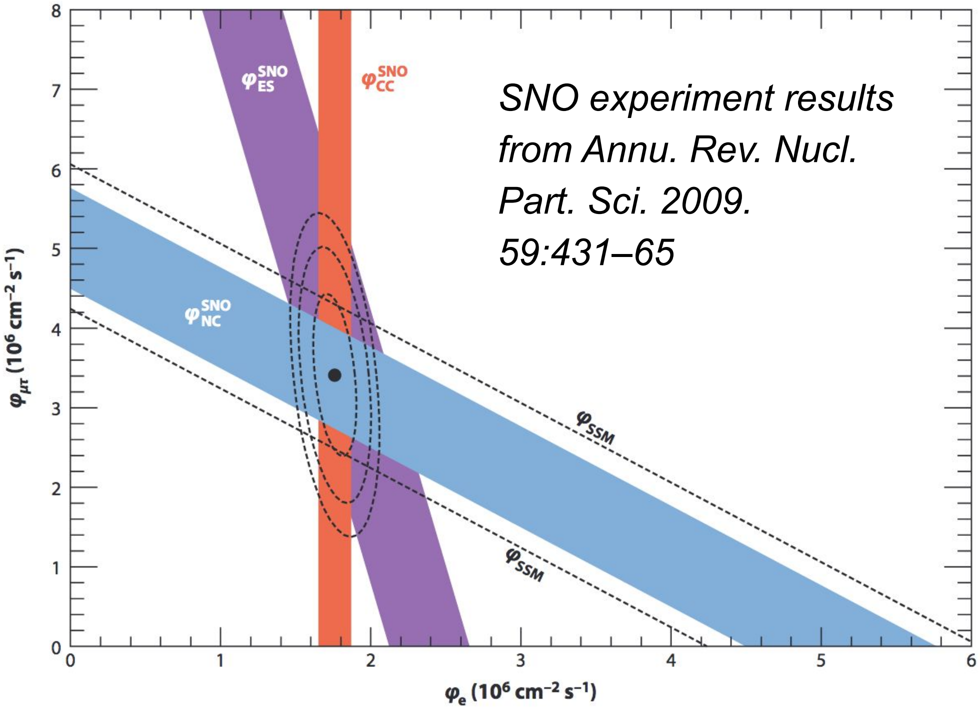
Is there new physics? CP violation in neutrinos?

What is the neutrino mass ordering?

Is our understanding complete? Are there sterile neutrinos? Non unitarity?

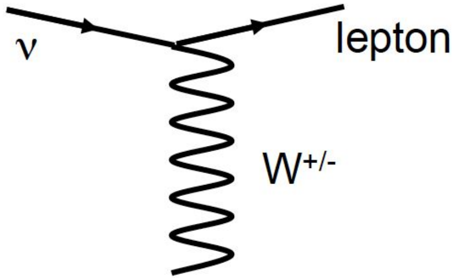
Evidence of neutrino mass from neutrino oscillation experiments:

- Electron neutrinos from the Sun



SNO experiment results from Annu. Rev. Nucl. Part. Sci. 2009. 59:431–65

Deficit in ν_e from charged current (CC):



$$\nu_e \longrightarrow e$$
$$\nu_\mu \longrightarrow \mu$$
$$\nu_\tau \longrightarrow \tau$$

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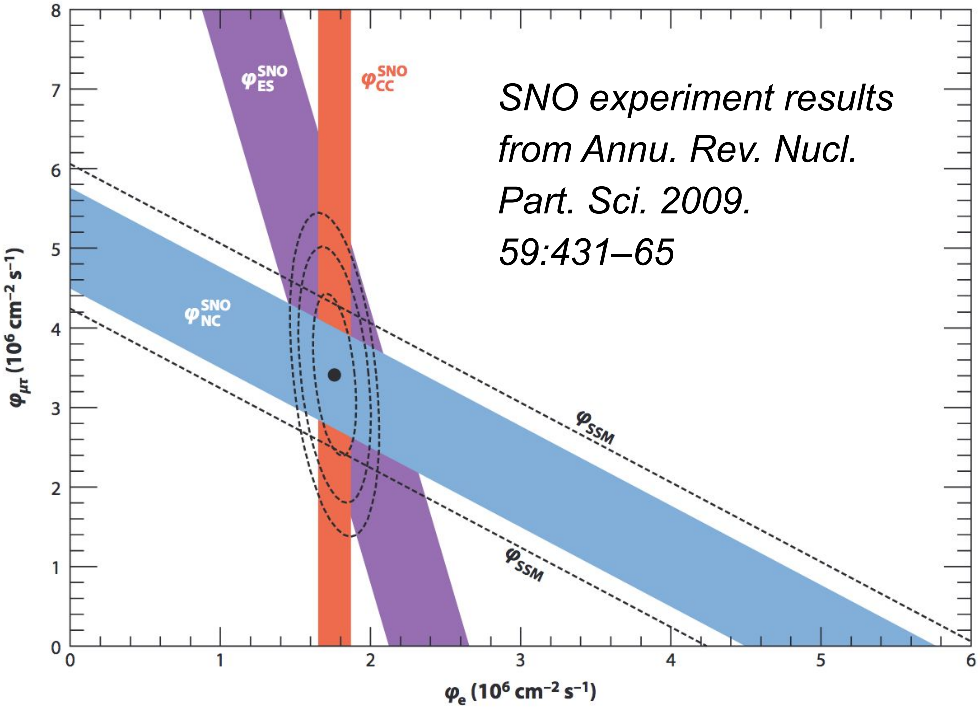

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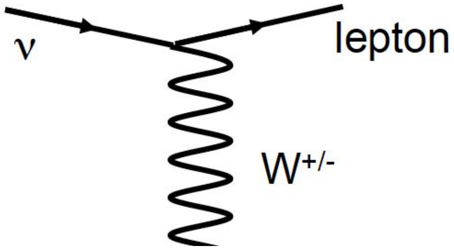
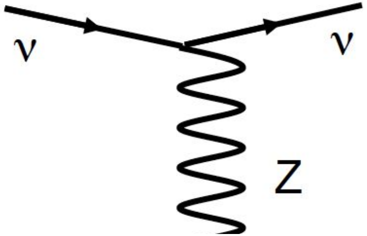


Total of all flavors matches expectation measured with neutral current (NC):



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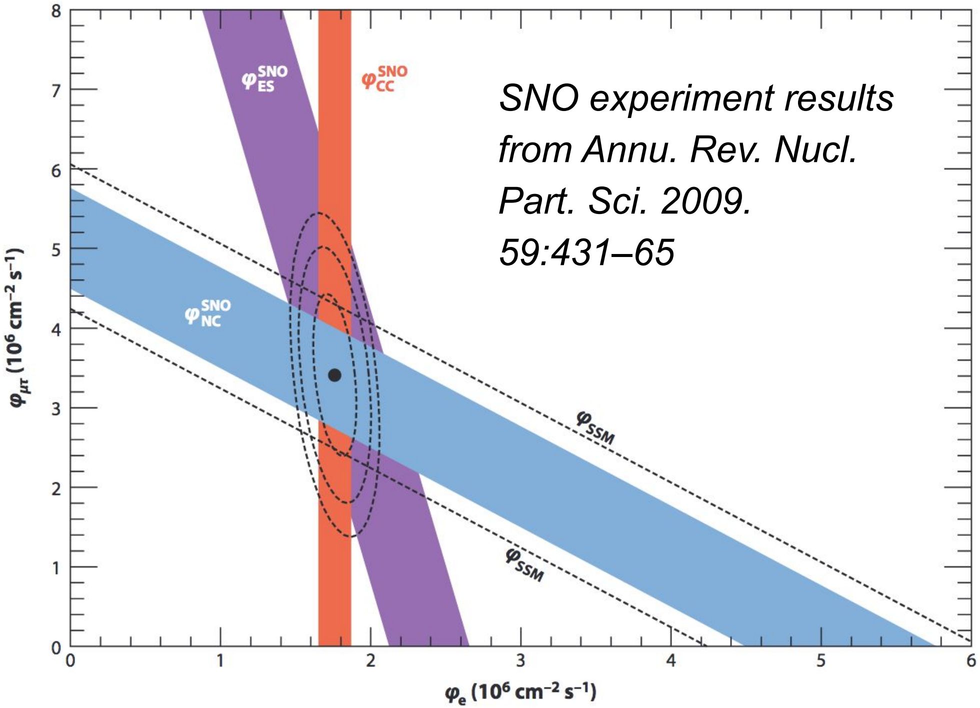


SNO experiment results from Annu. Rev. Nucl. Part. Sci. 2009. 59:431–65

Oscillation is the transition of one flavor to another

Here, electron neutrinos have oscillated into muon and tau flavors

Borexino latest results - see talk Thurs by A. Re

Evidence of neutrino mass from neutrino oscillation experiments:

- Muon neutrinos from an accelerator

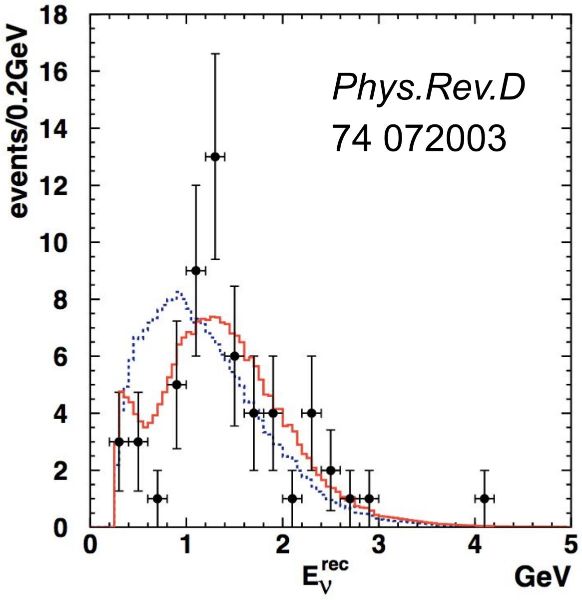
Example: KEK to Kamioka “Long baseline” experiment

250km from accelerator source to “far” detector

https://neutrino.kek.jp/intro/k2k.html

Evidence of neutrino mass from neutrino oscillation experiments:

- Muon neutrinos from an accelerator



Phys.Rev.D
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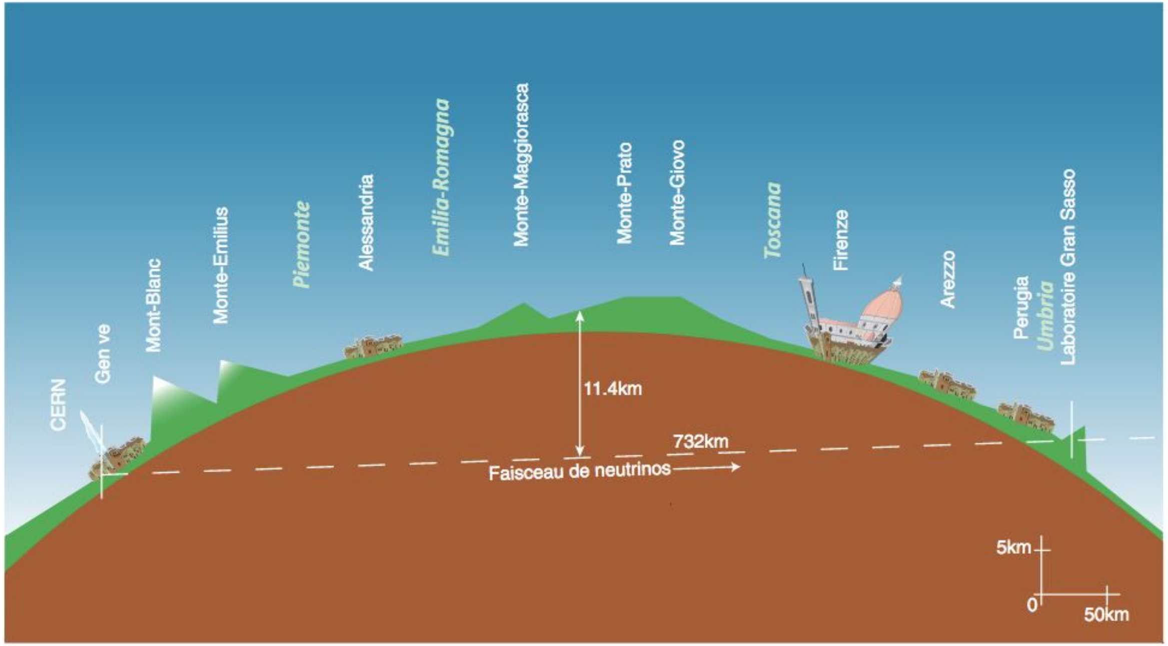
ν_μ "disappearance" into other flavors (ν_e, ν_τ)

- The spectrum is distorted and the rate reduced
- Oscillation depends on L (baseline) and E (energy of neutrinos)

Evidence of neutrino mass from neutrino oscillation experiments:

- Muon neutrinos from an accelerator



https://proj-cngs.web.cern.ch/

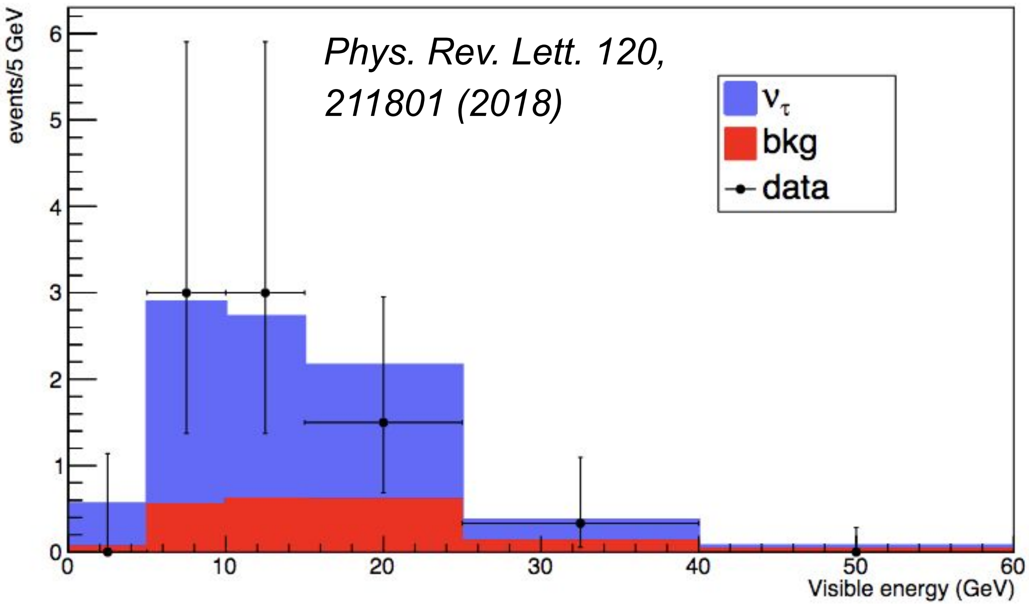
Example: OPERA experiment

Beam from CERN to Gran Sasso (732km)

Evidence of neutrino mass from neutrino oscillation experiments:

- Muon neutrinos from an accelerator

ν_τ "appearance" from predominantly muon neutrino flavor beam



Evidence of neutrino mass from neutrino oscillation experiments:

- Electron neutrinos from the Sun, and electron antineutrinos **from reactors**
- Muon (anti) neutrinos from accelerators **and atmosphere**

Atmospheric (and astrophysical neutrino) results - see talk Thurs by S. Klein

Future reactor results with JUNO - see parallel talk and E. Worcester plenary Friday

Evidence of neutrino mass from neutrino oscillation experiments:

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

Pontecorvo-Maki-Nakagawa-Sakata matrix (PMNS)

Assuming unitary matrix:

- Three mixing angles: θ_{12}, θ_{23}, θ_{13}
- CP violating phase: δ_{CP}
- Two Majorana phases - not accessible by osc experiments

see S. Mertens talk on 0n2b Thurs

Evidence of neutrino mass from neutrino oscillation experiments:

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Assuming unitary matrix:

- Three mixing angles: θ_{12}, θ_{23}, θ_{13}
- CP violating phase: δ_{CP}

Open questions:

- What is the CPV phase?
- Precision measurements of mixing angles (and U)
  - Is θ_{23} maximal? If not, what is the octant?
- Is our understanding complete?

See Thurs talks by P. Machado and J. Valle

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Three mass states, two mass splittings:

Evidence of neutrino mass from neutrino oscillation experiments:

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Δm^2_{21} is known to be positive from solar experiments

$\Delta m^2_{21} = m^2_2 - m^2_1$

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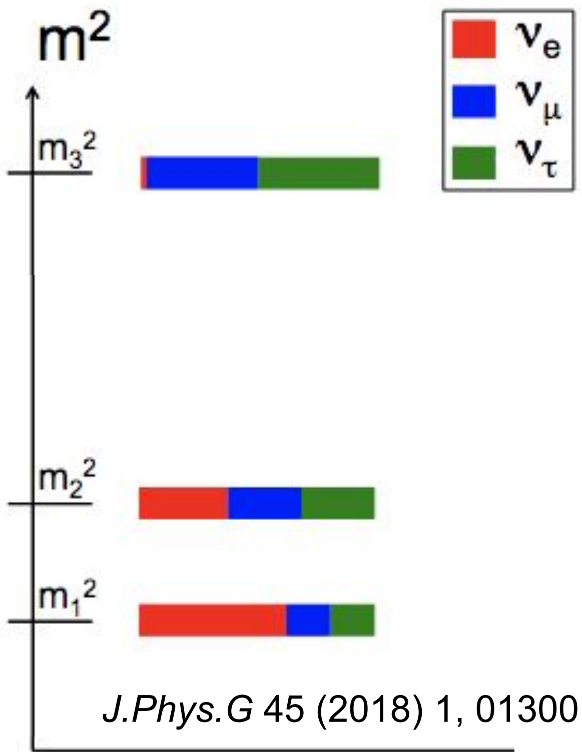
Is $\Delta m^2_{32} > 0$ ($m_3^2 > m_2^2$?)
"Normal ordering"



J.Phys.G 45 (2018) 1, 013001

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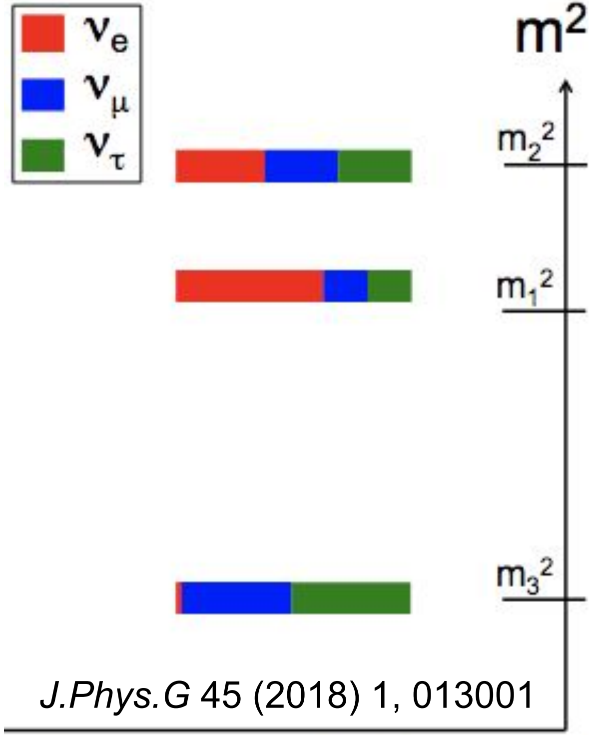
Or, is $\Delta m^2_{32} > 0$ ($m_3^2 > m_2^2$?)
"Inverted ordering"

What is the neutrino mass hierarchy?



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Measure elements of U via appearance and disappearance experiments:

What do we learn from long baseline experiments?

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$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}\left[U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j}\right] \sin^2\left(\frac{1.27\Delta m^2_{ij} L}{E}\right) + 2\sum_{i>j} \mathrm{Im}\left[U_{\beta i} U^*_{\alpha i} U^*_{\beta j} U_{\alpha j}\right] \sin\left(\frac{2.54\Delta m^2_{ij} L}{E}\right)$$

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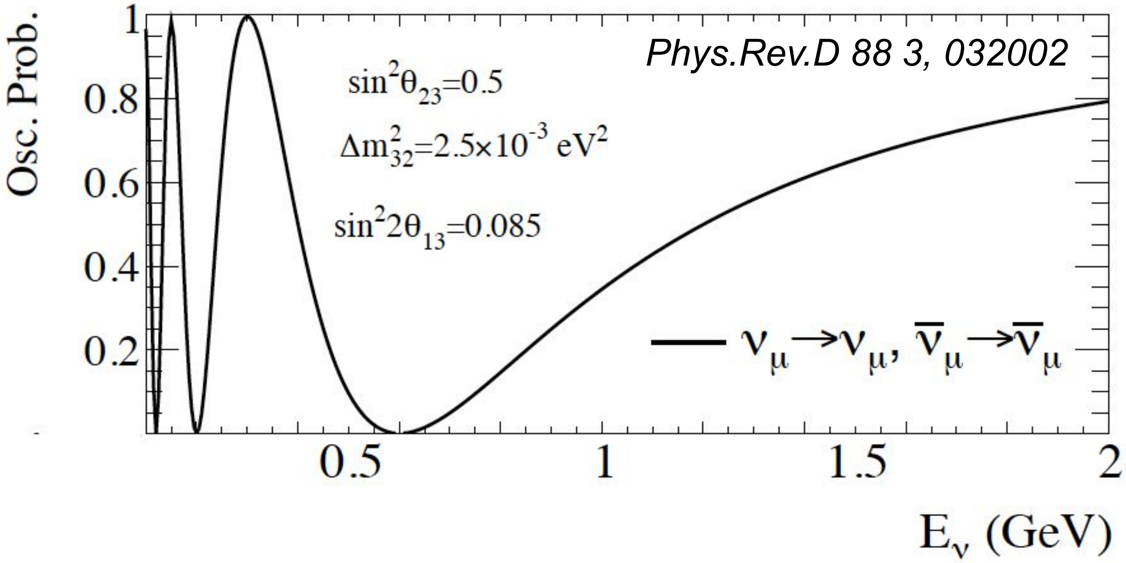
$$P(\nu_\mu \rightarrow \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\,\Delta m^2_{32} L}{E}\right) + \ldots$$

Muon neutrino and antineutrino disappearance



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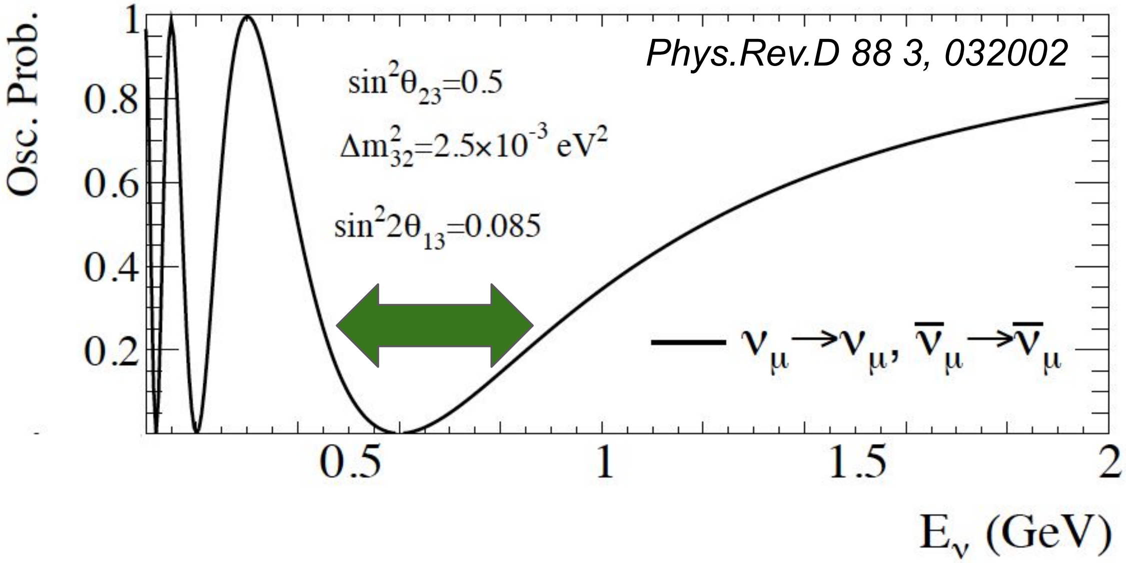
Muon neutrino and antineutrino disappearance

- Frequency determines mass splitting (Δm^2)



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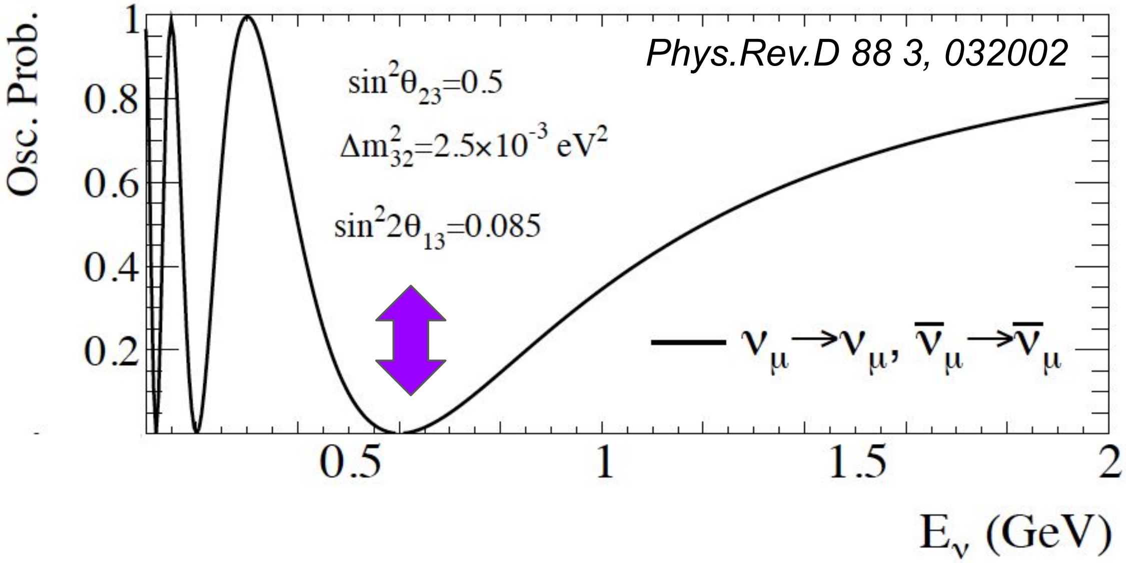
Muon neutrino and antineutrino disappearance

- Frequency determines mass splitting (Δm^2)
- Amplitude gives mixing angle (e.g. θ_{23})



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Electron neutrino and antineutrino appearance

- Sensitive to all oscillation parameters - include information from reactor, solar measurements, including δ_{CP} and mass hierarchy

$$P(\nu_\mu \rightarrow \nu_e)$$

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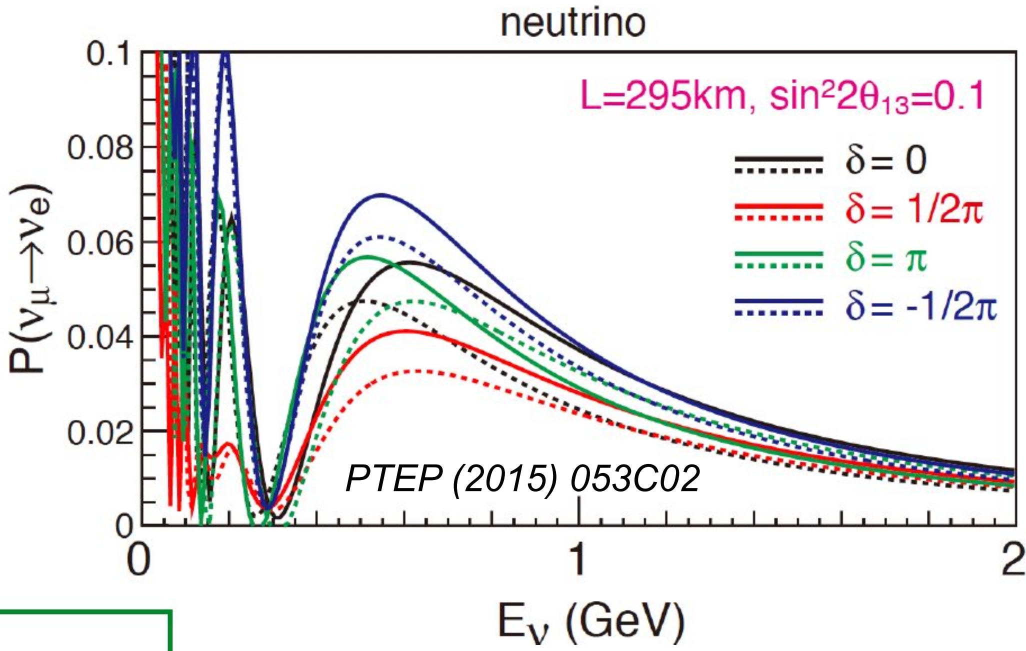
Changing δ_{CP} increases or decreases neutrino appearance



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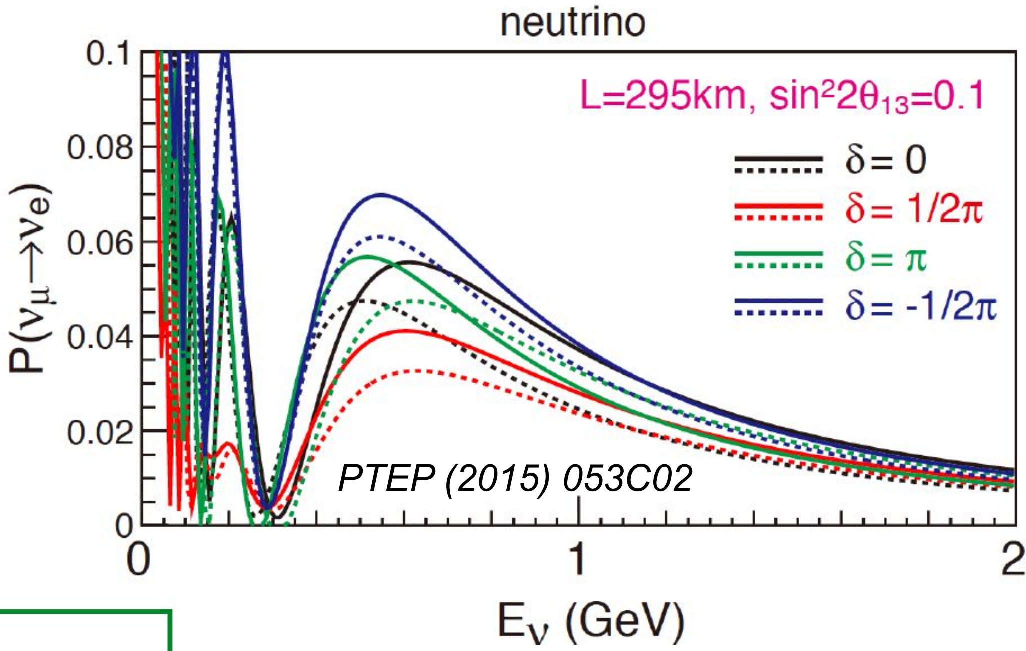
Electron neutrino and antineutrino appearance

- Sensitive to all oscillation parameters - include information from reactor, solar measurements, including δ_{CP} and mass hierarchy

Changing δ_{CP} increases or decreases neutrino appearance

Changing from normal to inverted hierarchy decreases neutrino appearance



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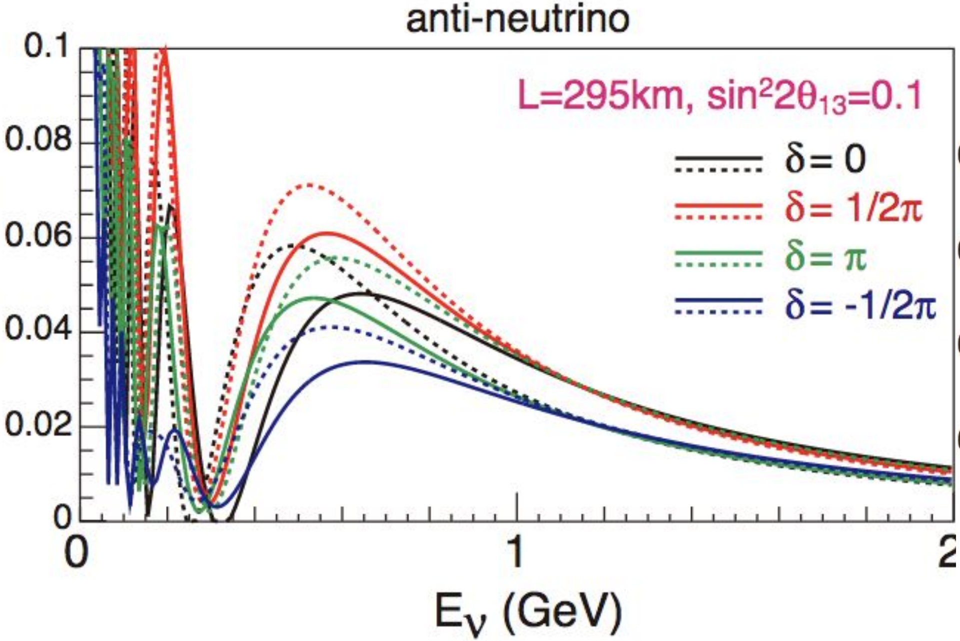

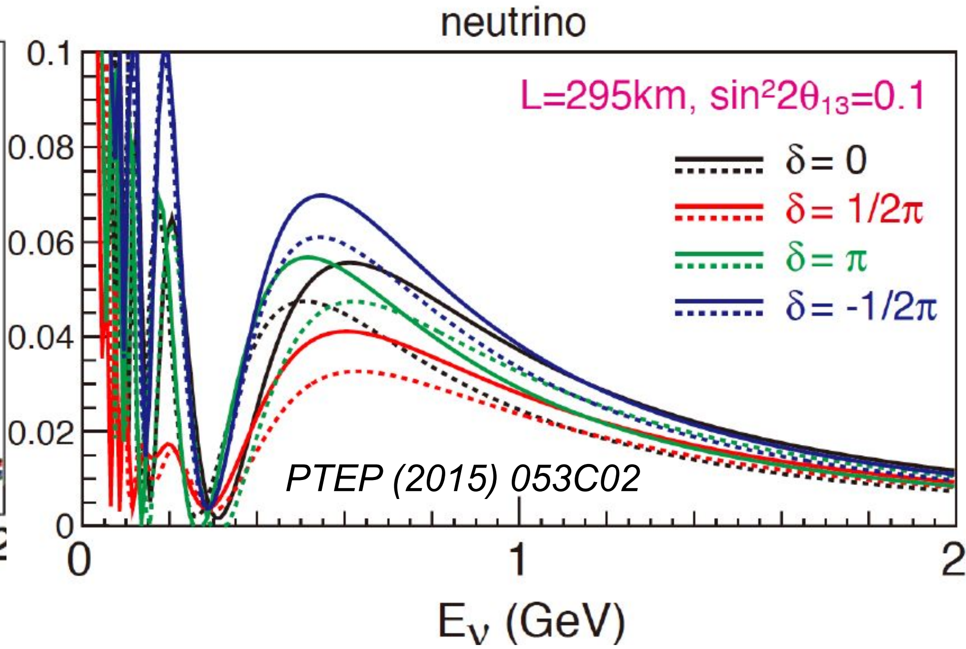

Changing δ_{CP} has an anticorrelated effect in neutrinos vs. antineutrinos

Infer oscillation parameters from event rates

Intense, accelerator-based neutrino flux (**Φ**)

Neutrino interaction cross section (**σ**)

Detection efficiency (**ϵ**)

$$N_{FD} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{FD} P(\nu_\mu \rightarrow \nu_e)$$

Near detector data improves event rate prediction through shared sources of systematic uncertainty

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Near detector data improves event rate prediction through shared sources of systematic uncertainty

Intense, accelerator-based neutrino flux (**Φ**)

Neutrino interaction cross section (**σ**)

Near (and far) detectors make valuable measurements of neutrino interactions

Detection efficiency (**ϵ**)

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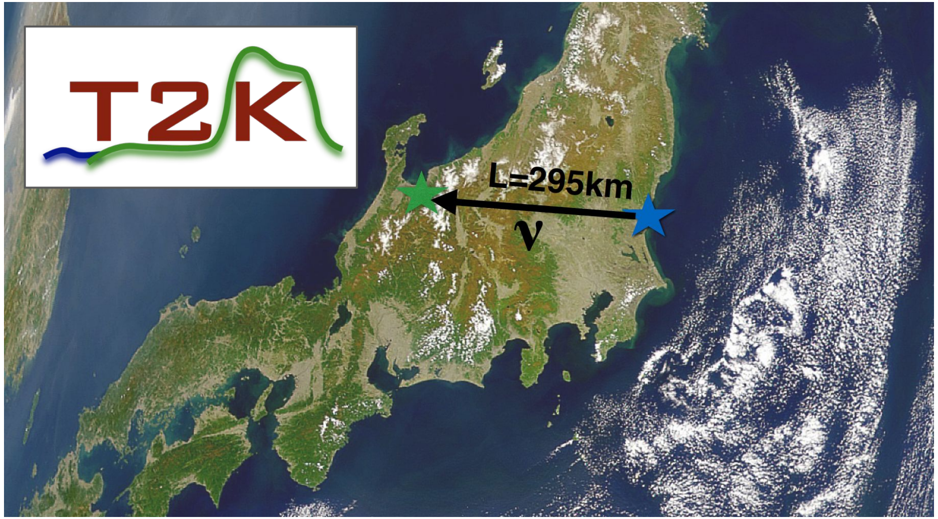
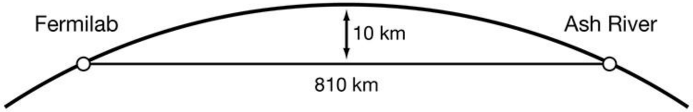
How a long baseline experiment works: examples from T2K and NOvA



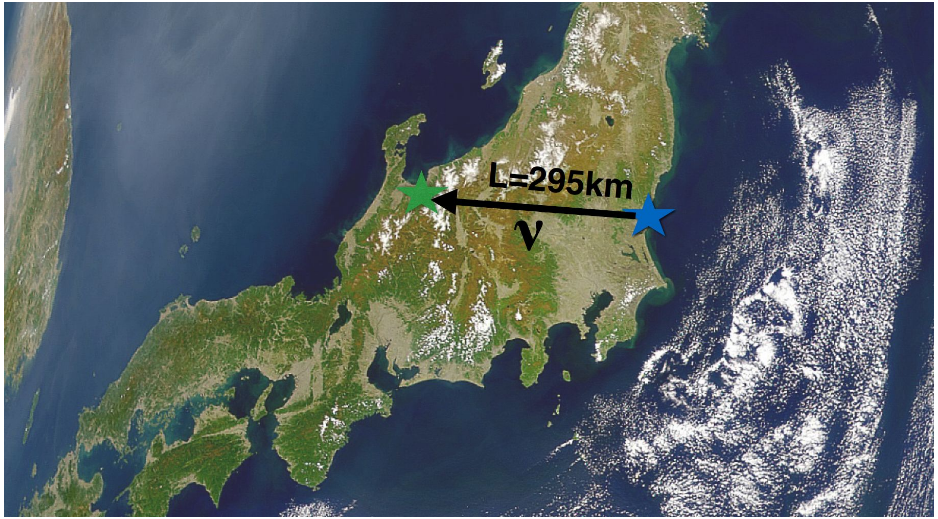
See T. Doyle talk on Tues, T2K status and plans



news.fnal.gov

See A. Sztuc talk on Tues, latest results from NOvA

How a long baseline experiment works: examples from **T2K** and NOvA



Intense, accelerator-based neutrino flux (**Φ**)

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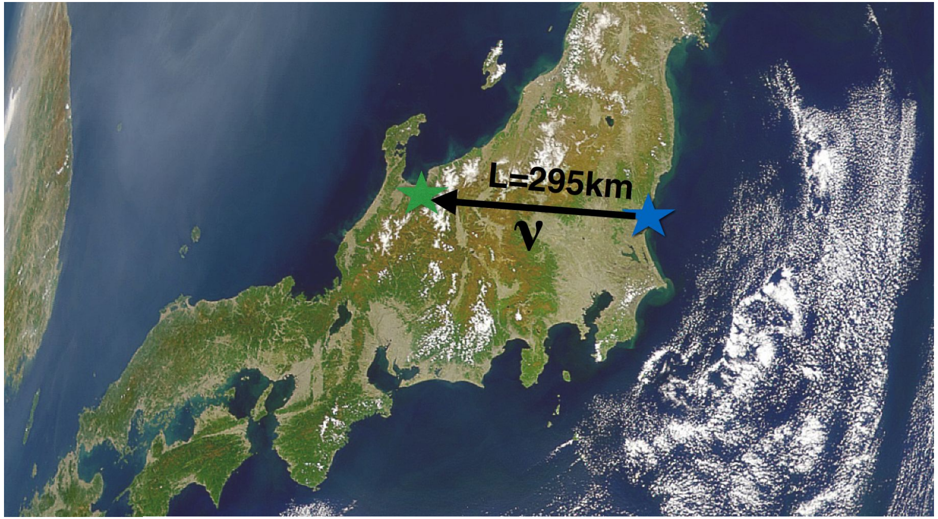
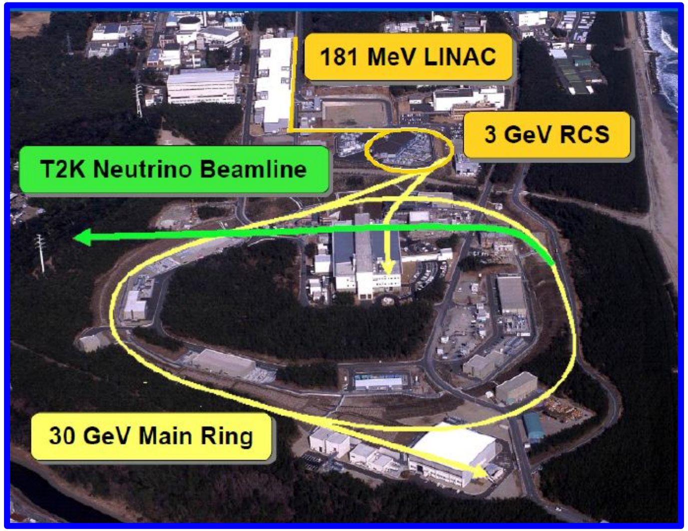
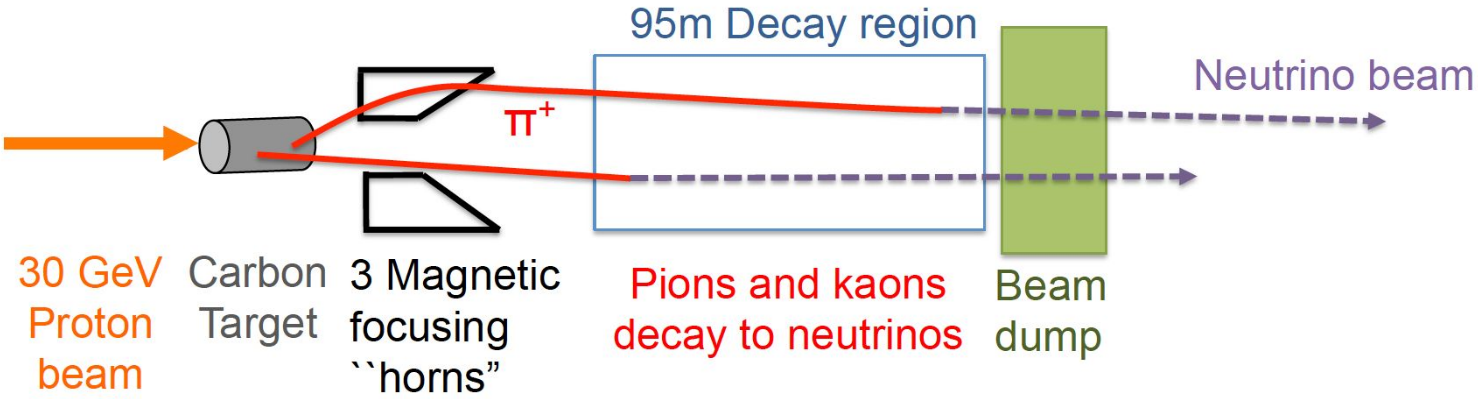
How a long baseline experiment works: accelerator based neutrino source



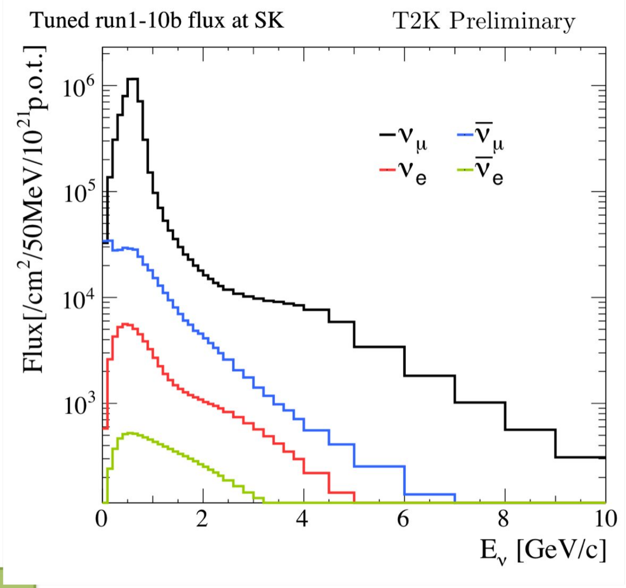


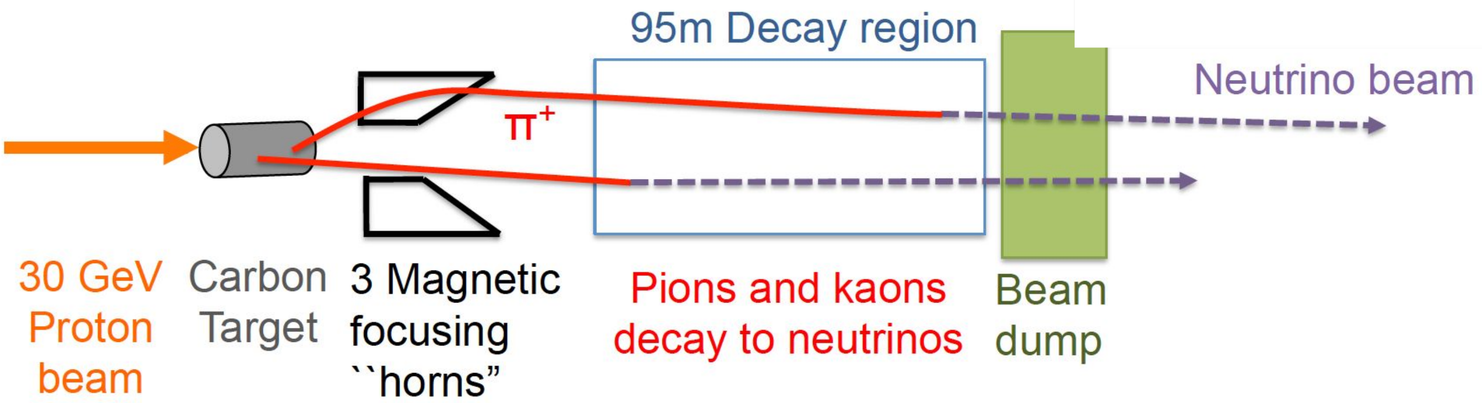


How a long baseline experiment works: accelerator based neutrino source

99% pure muon flavor

T2K flux prediction Phys. Rev. D 87, 012001 (2013)





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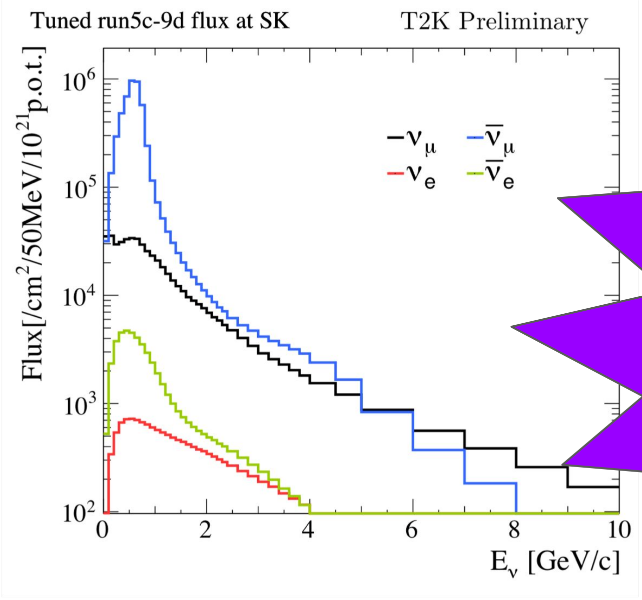
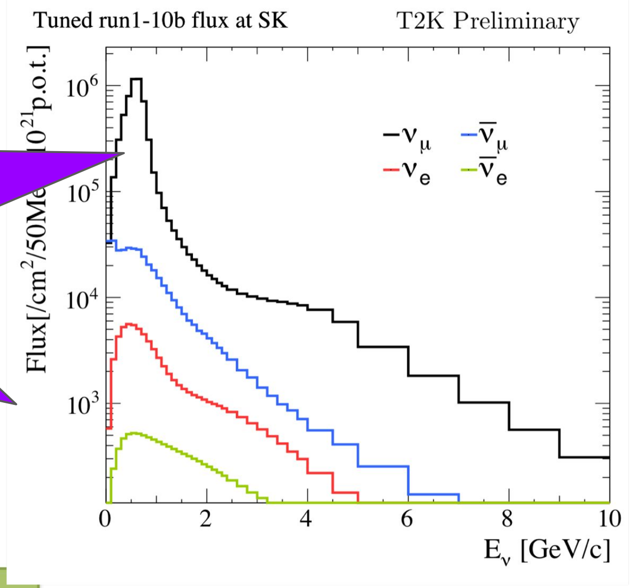
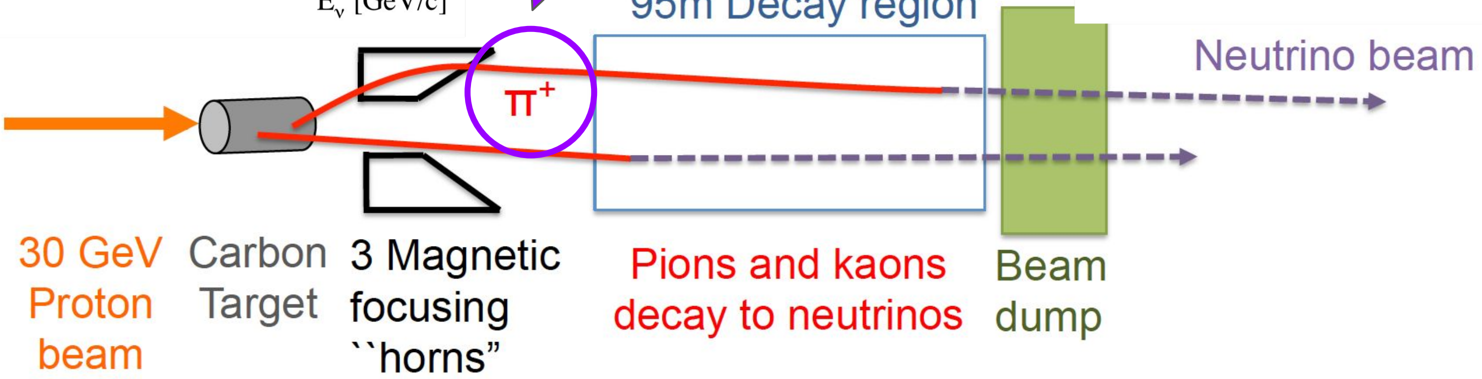


Select
neutrino or
antineutrino!





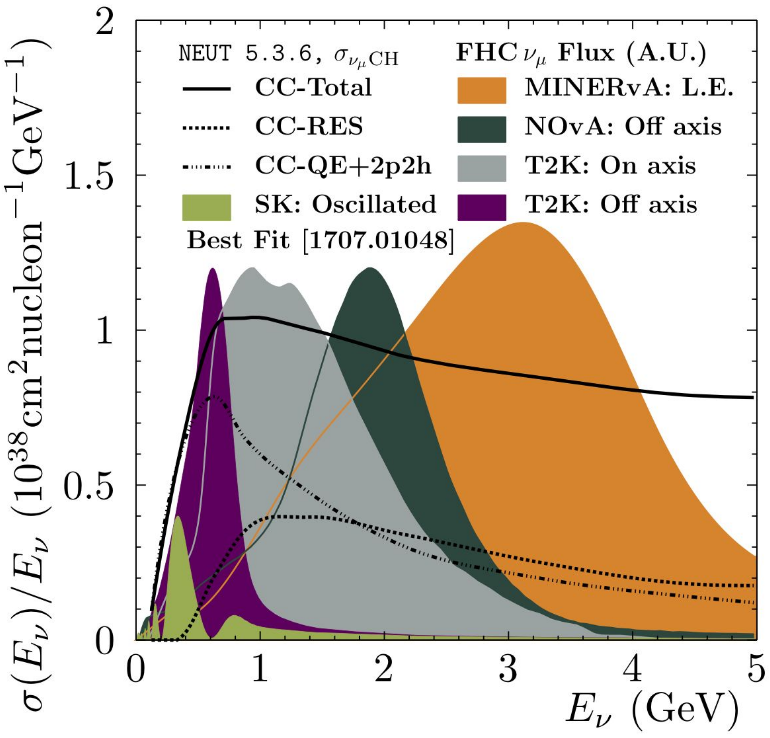
How a long baseline experiment works: accelerator based neutrino source

Tunable energy

T2K near detector flux (2.5degrees 'off-axis')

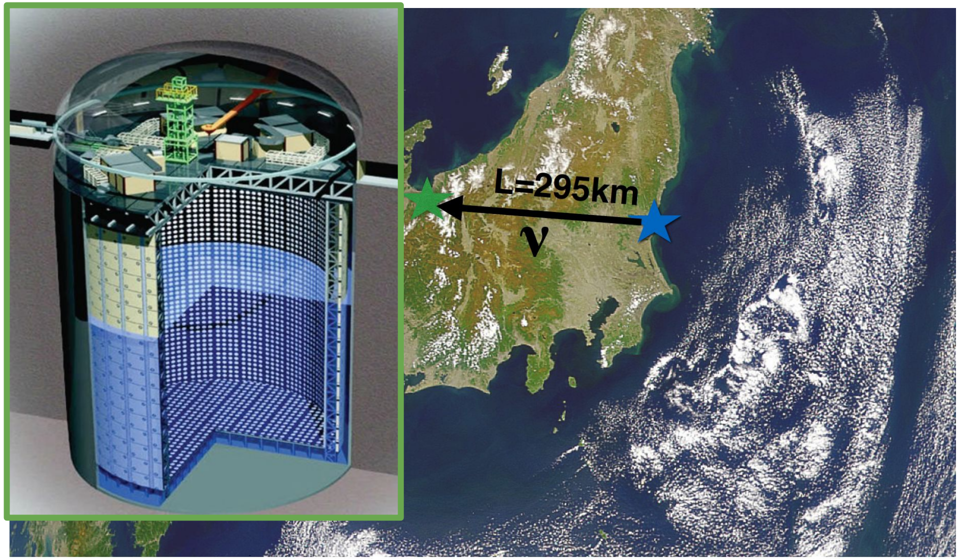
T2K near detector flux (off-axis)

30 GeV Proton beam



Credit: L. Pickering

How a long baseline experiment works: interactions in massive detectors



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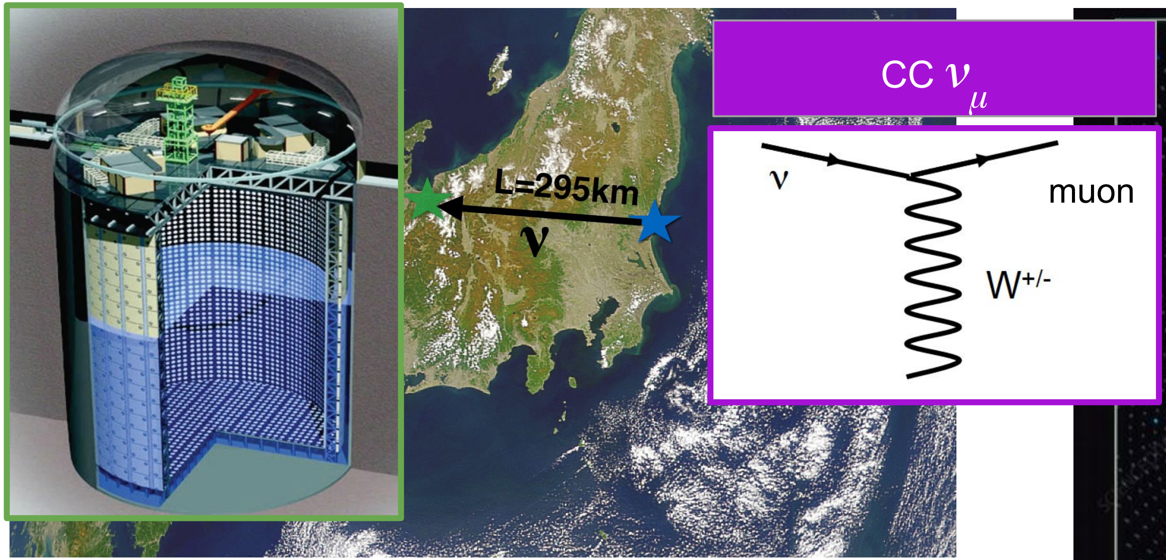
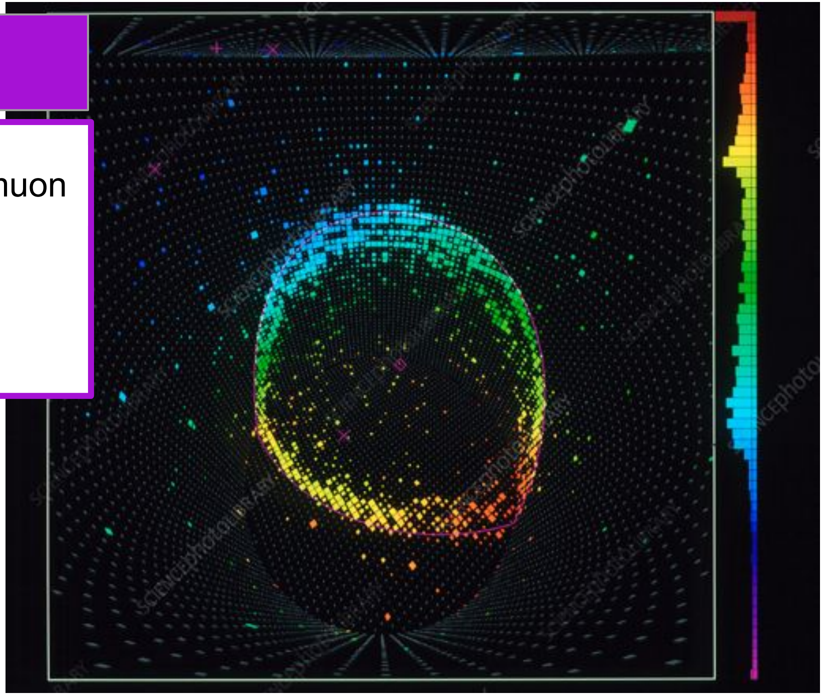
How a long baseline experiment works: interactions in massive detectors



See S. M. Lakshmi talk on Monday for selection details



Credit: Super-Kamiokande collaboration

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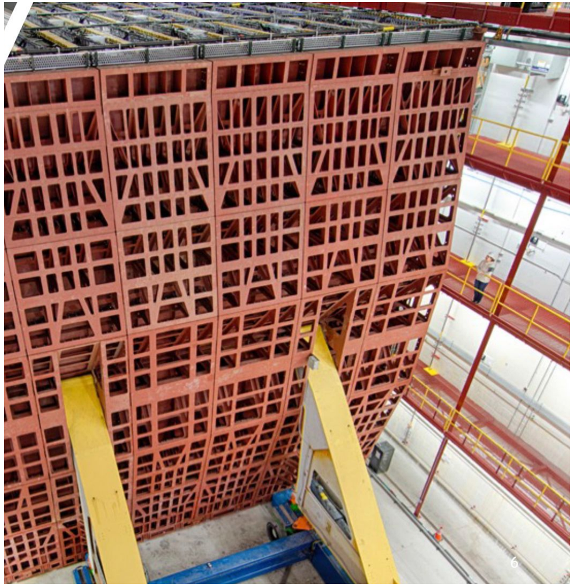

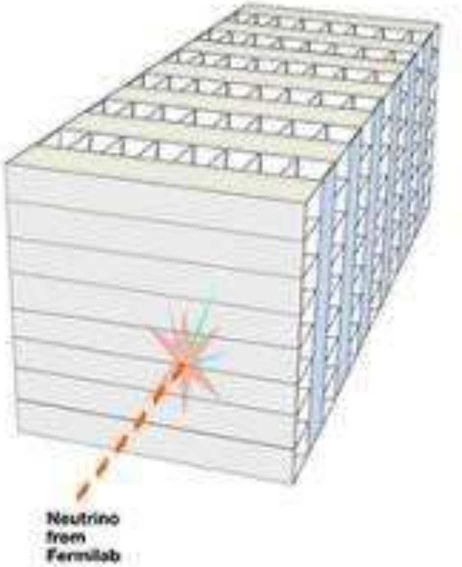

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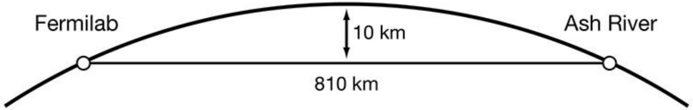

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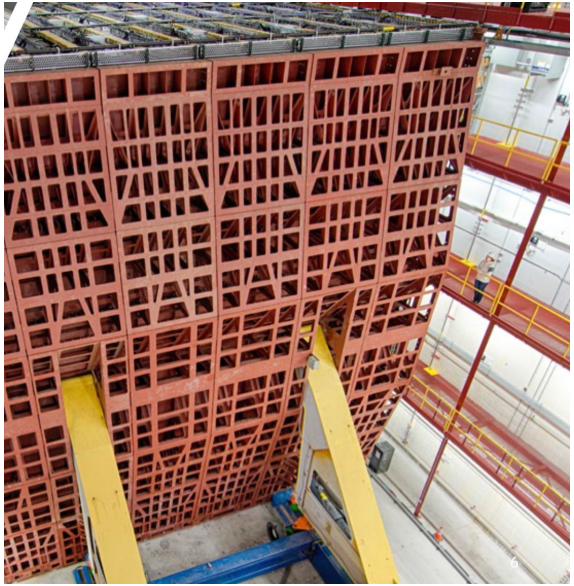

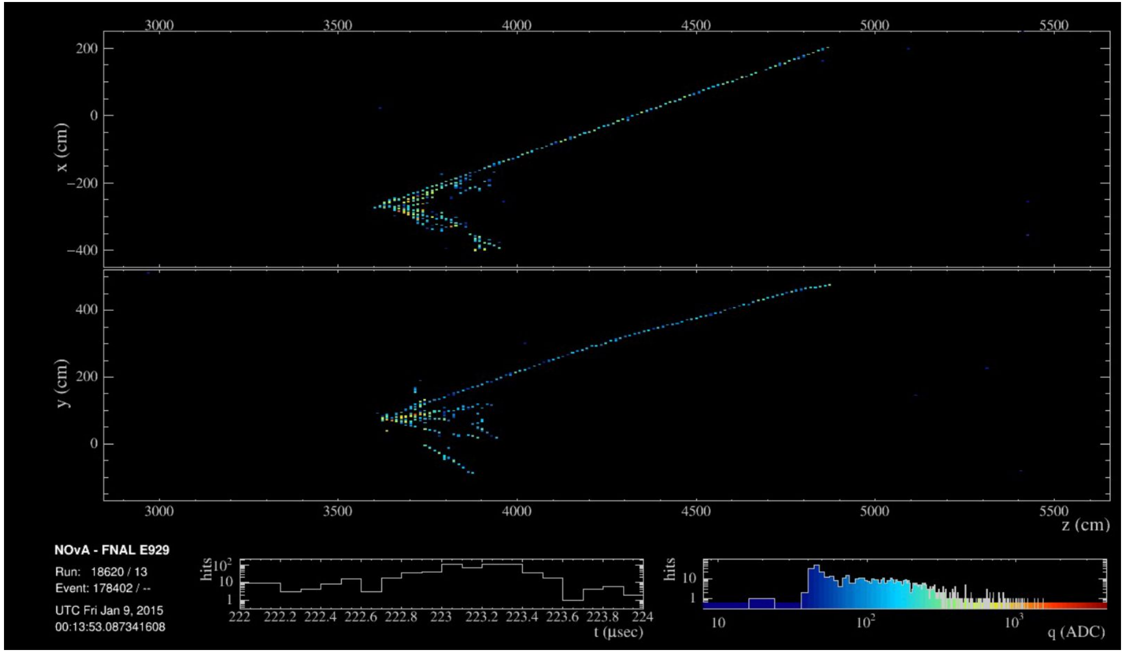

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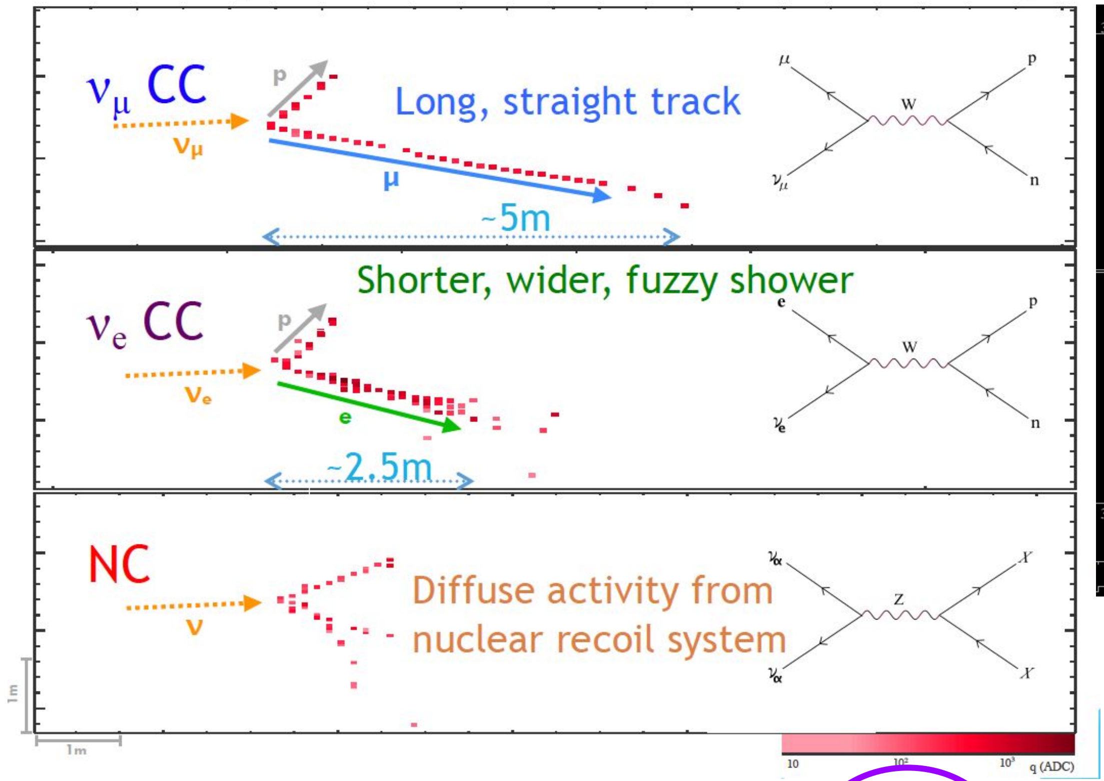
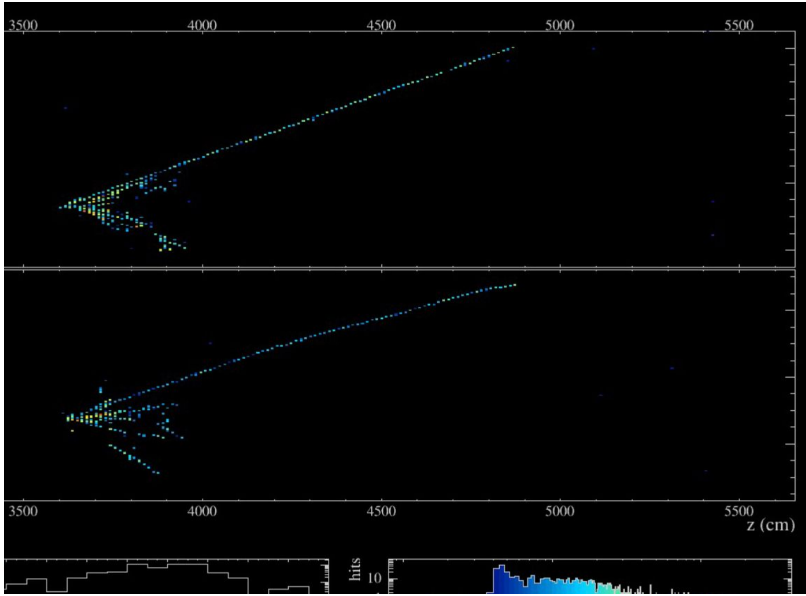
How a long baseline experiment works: interactions in massive detectors

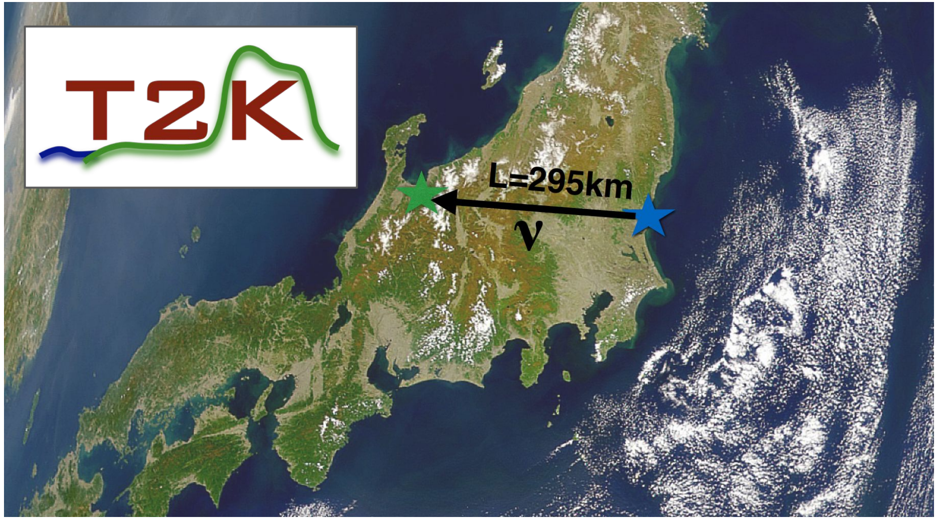




Credit: NOvA collaboration

$$N_{FD} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{FD}P(\nu_\mu \to \nu_e)$$

Recent results from T2K and NOvA

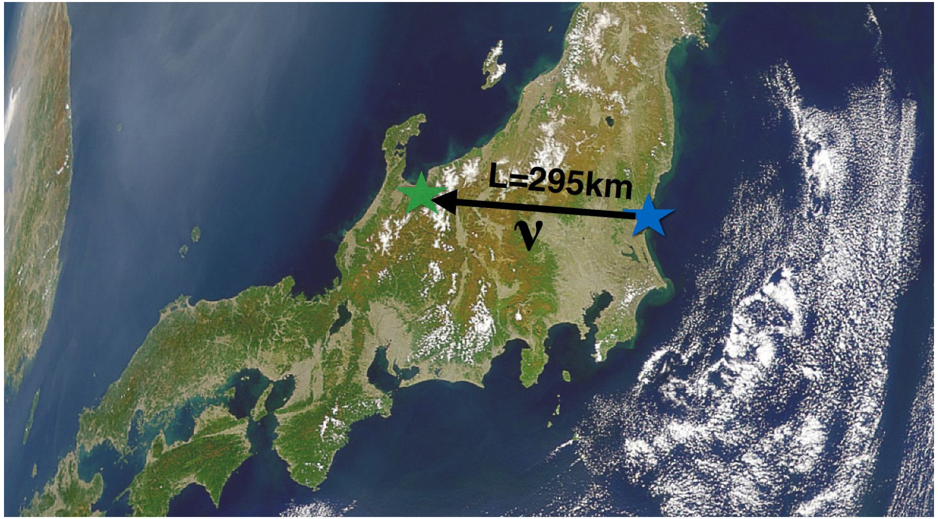


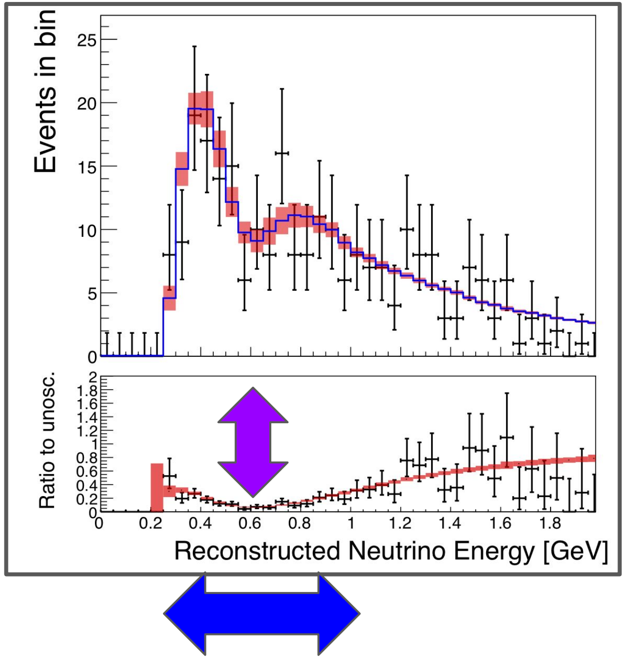
T2K preliminary 2020 results:
ν-mode POT: 1.851 x 10^{21}
$\bar{\nu}$-mode POT: 1.651 x 10^{21}

NOvA preliminary 2020 results:
ν-mode POT: 1.36 x 10^{21} (equivalent)
$\bar{\nu}$-mode POT 1.25 x 10^{21}

protons on target = POT

Recent results from T2K





$$P(\nu_\mu \to \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\,\Delta m_{32}^2 L}{E}\right) + \ldots$$

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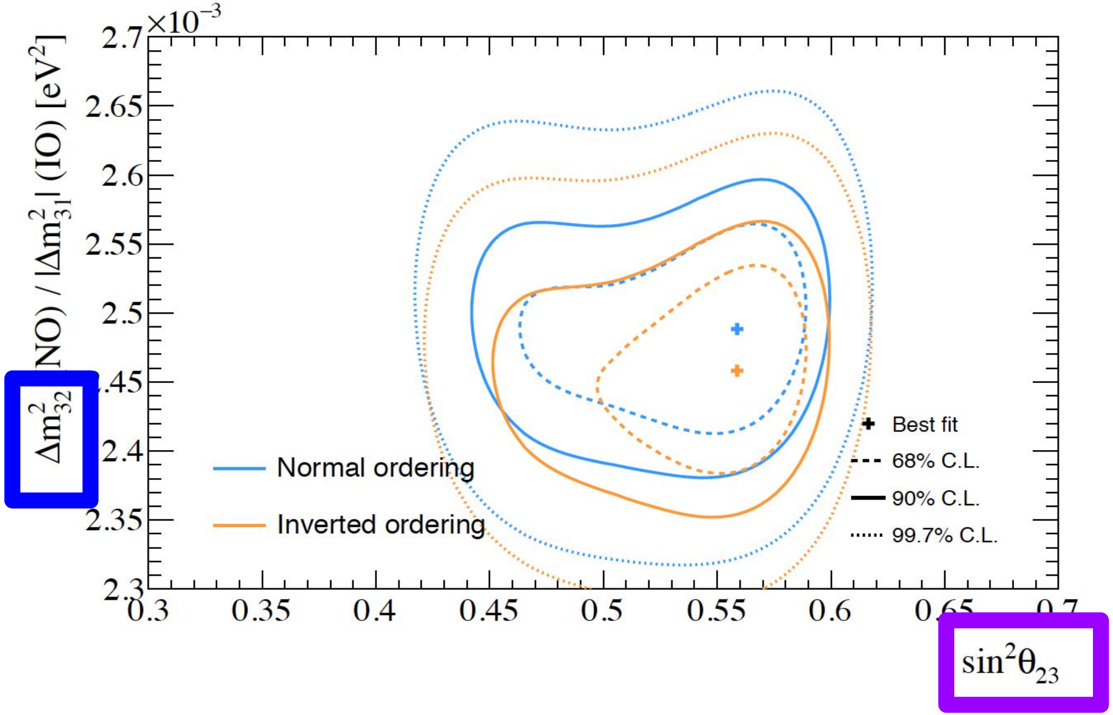

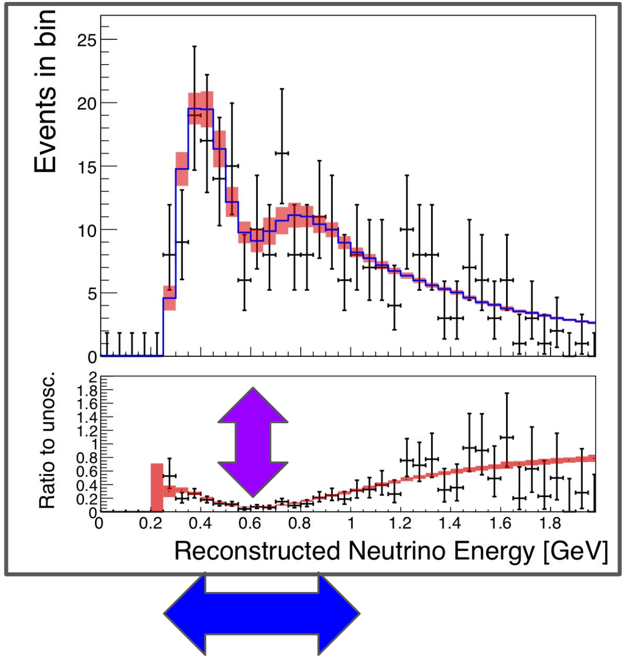

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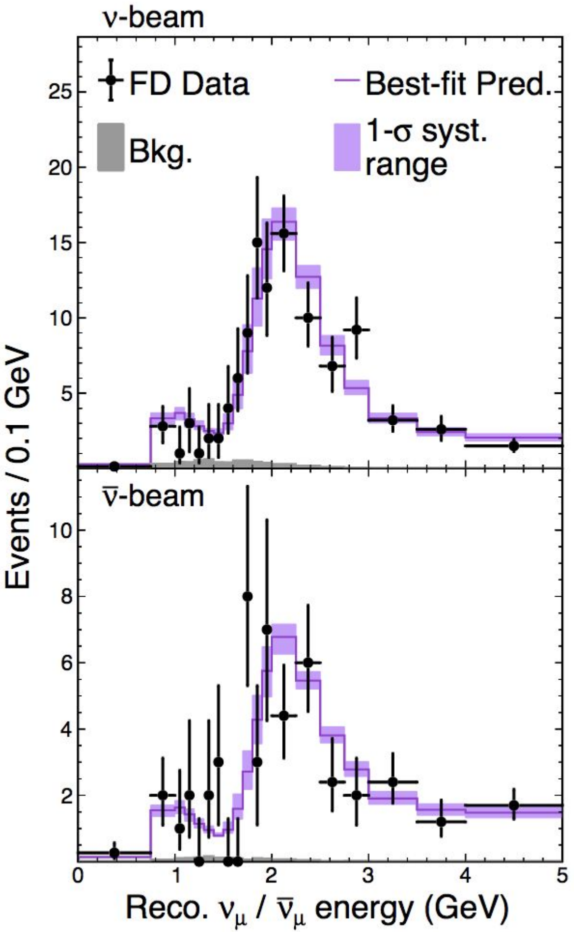
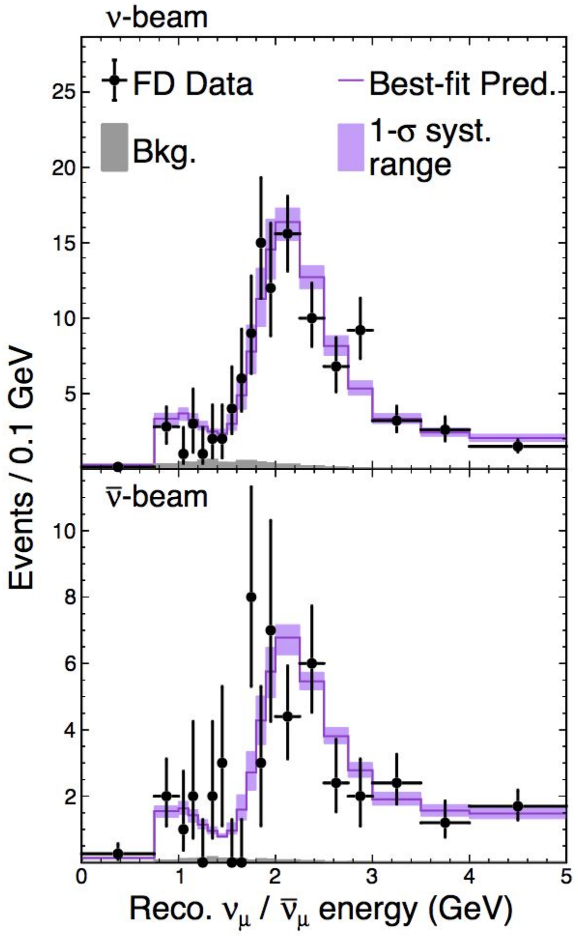
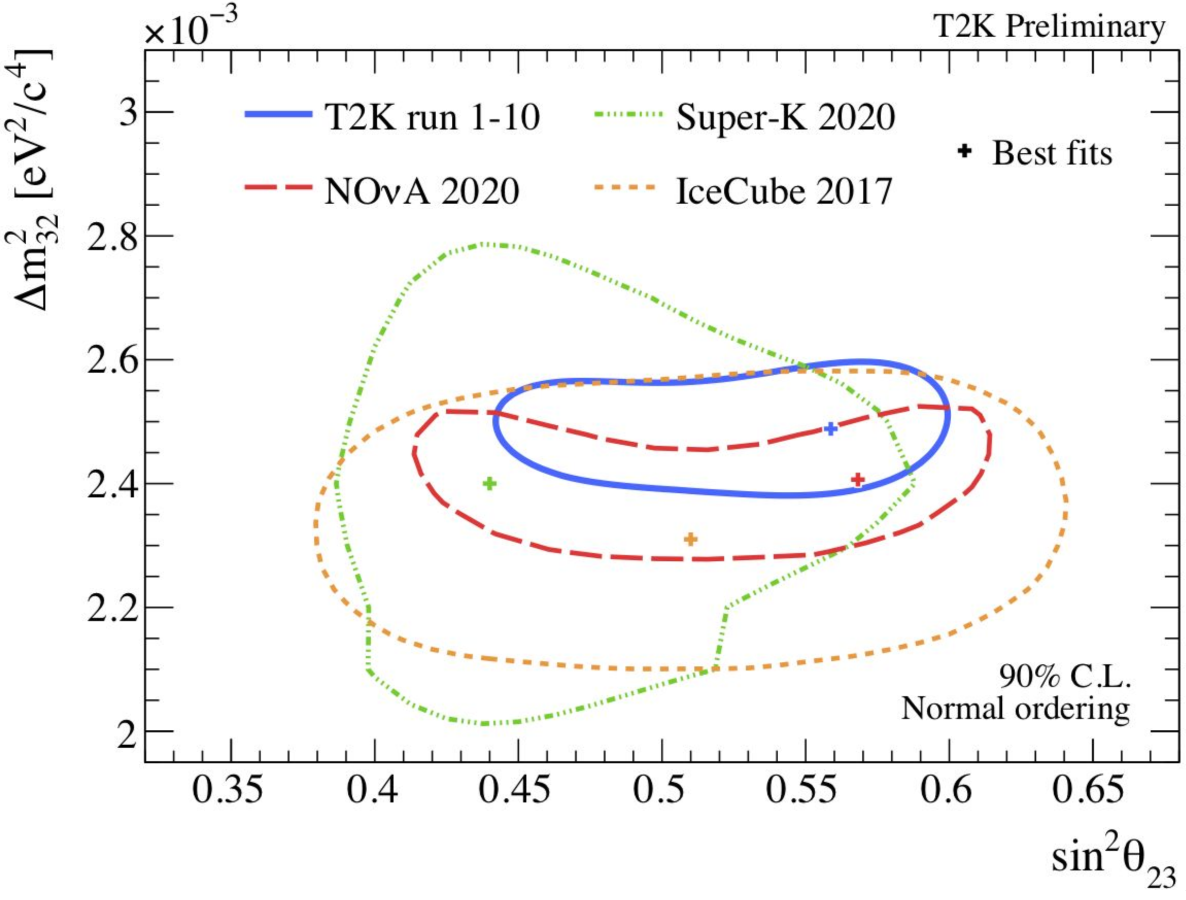
Recent results from NOvA



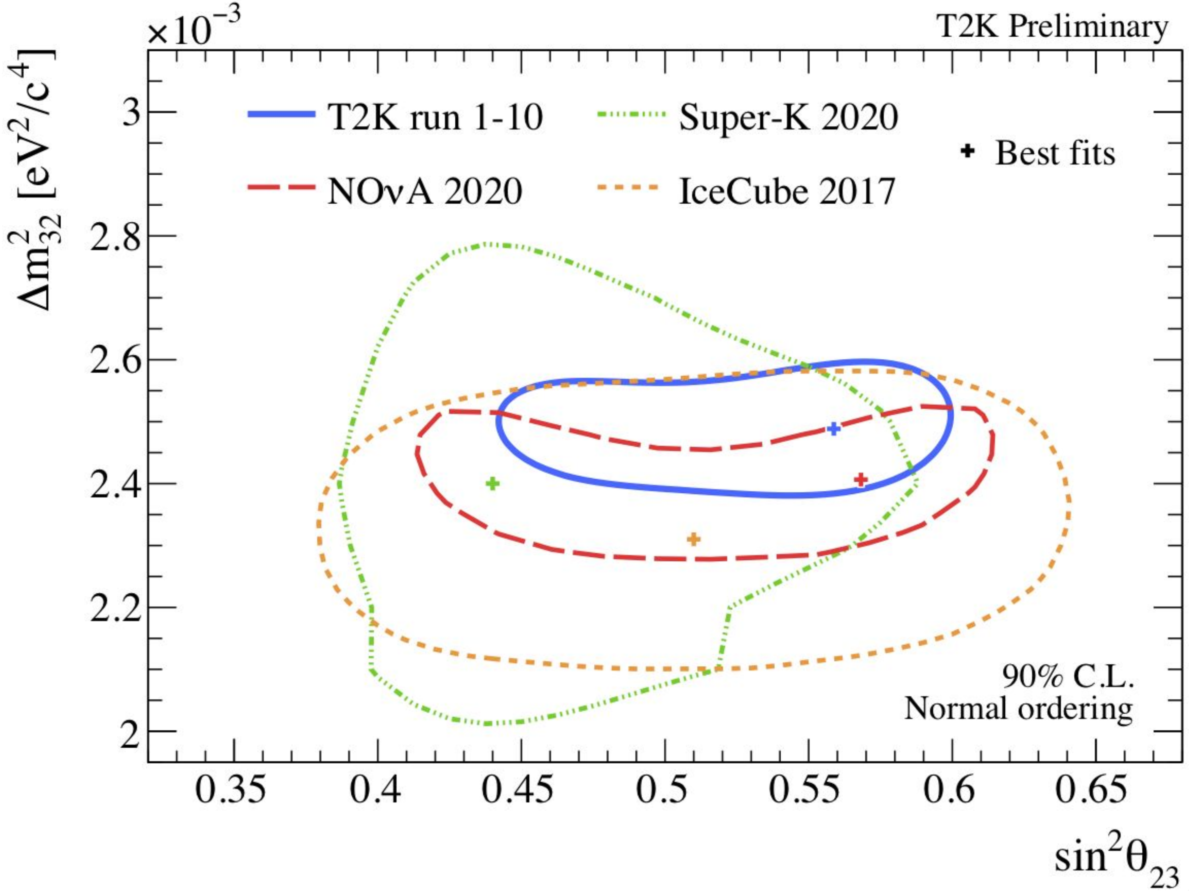
NOvA preprint: arxiv.org/abs/2108.08219

Recent results from NOvA





Recent results … in good agreement across beam, atmospheric data



Appearance results*

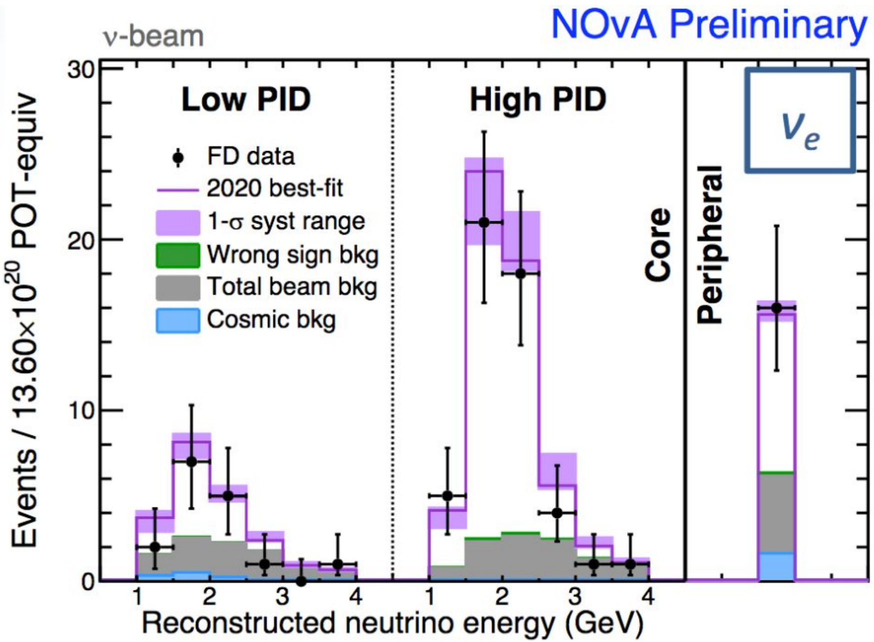
**Actually, we analyze disappearance and appearance samples together*

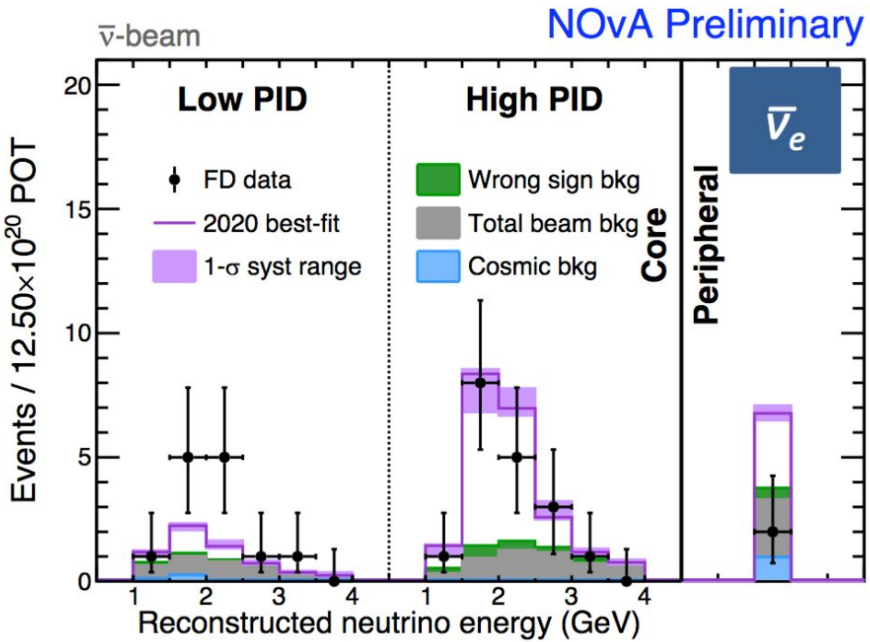
Recall the event rate depends on all oscillation parameters ($\boldsymbol{\delta}_{CP}$, $\boldsymbol{\theta}_{23}$, $\boldsymbol{\theta}_{13}$ Δm^2 and mass hierarchy)

$$N_{FD} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{FD} \boxed{P(\nu_\mu \rightarrow \nu_e)}$$

Appearance results - NOvA

Excellent signa/background separation





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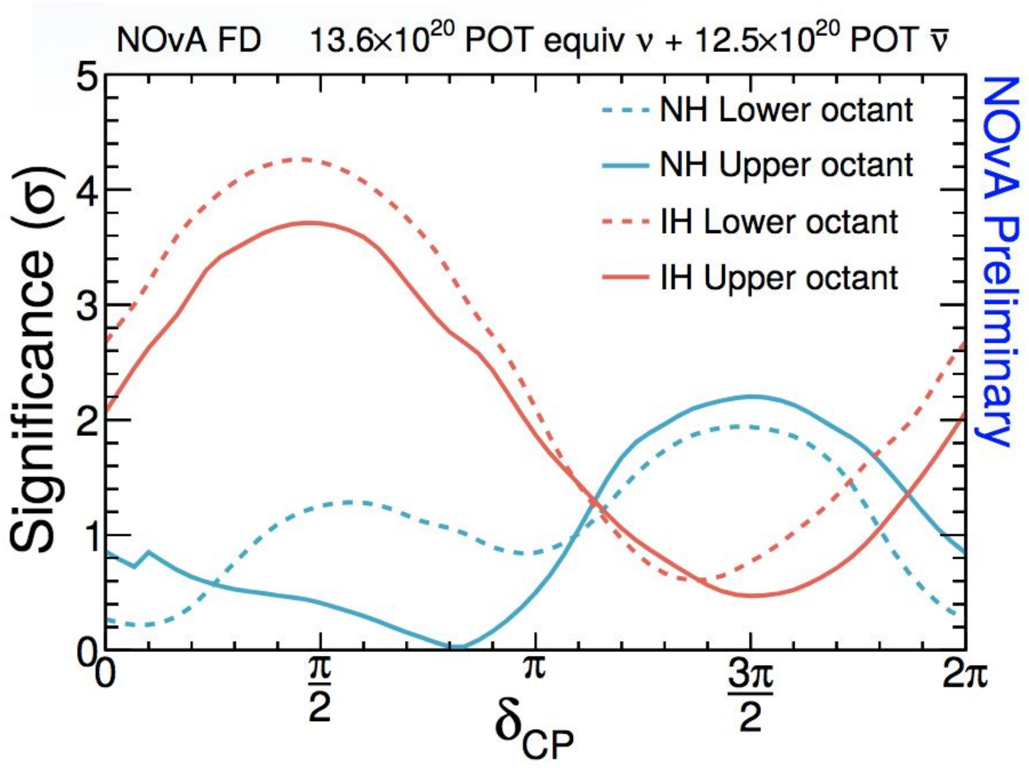
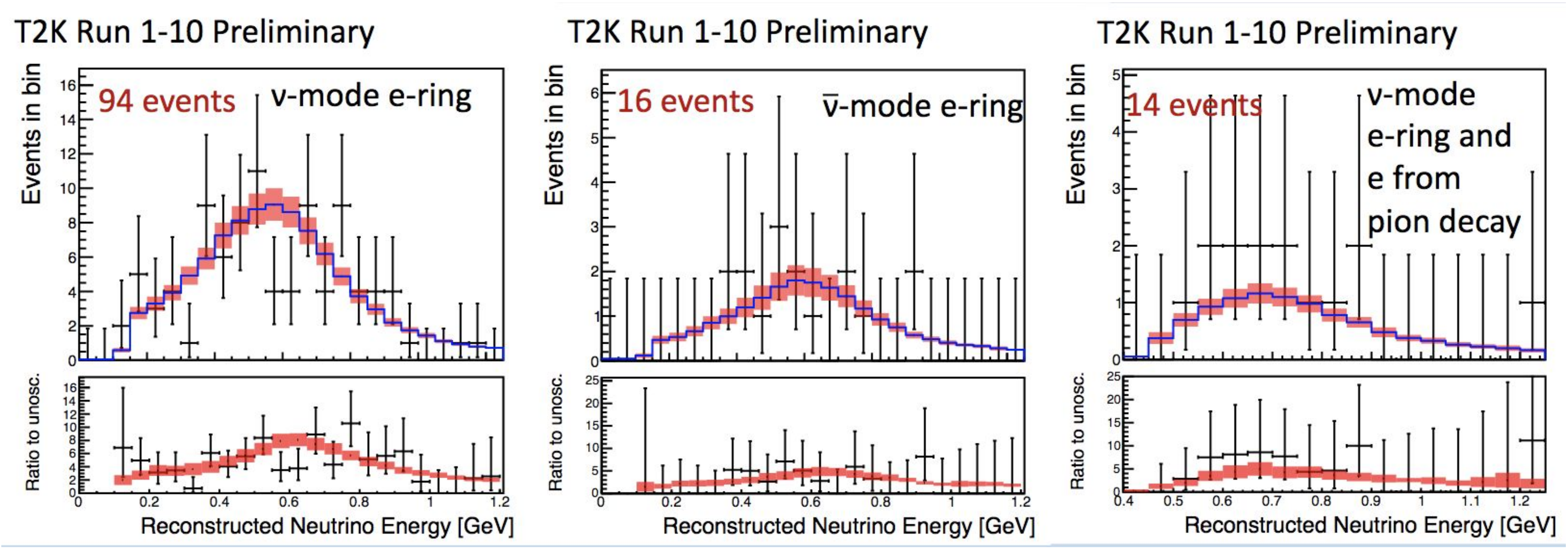
Appearance results - NOvA



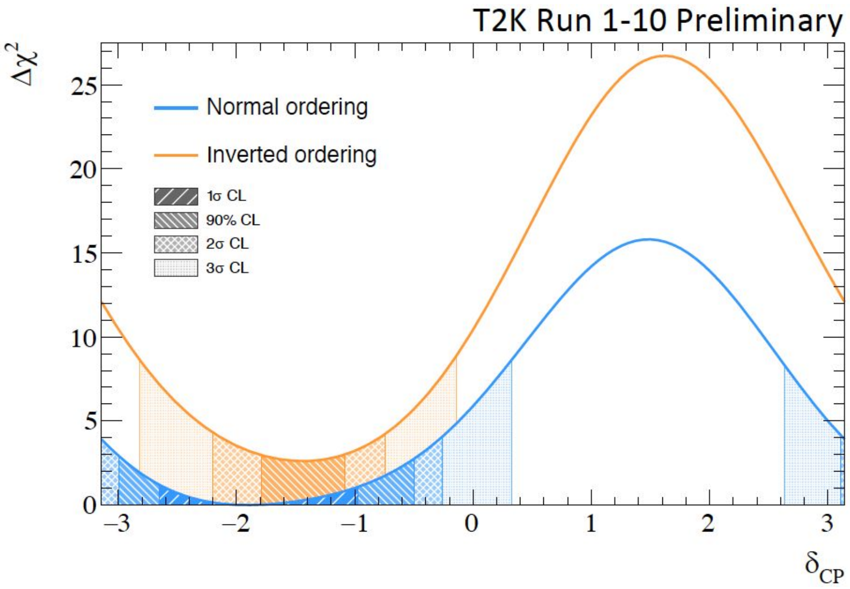
Best fit in normal ordering and θ_{23} upper octant

Appearance results - T2K



Data currently has an excess of electron neutrino events, and a deficit of electron antineutrino events

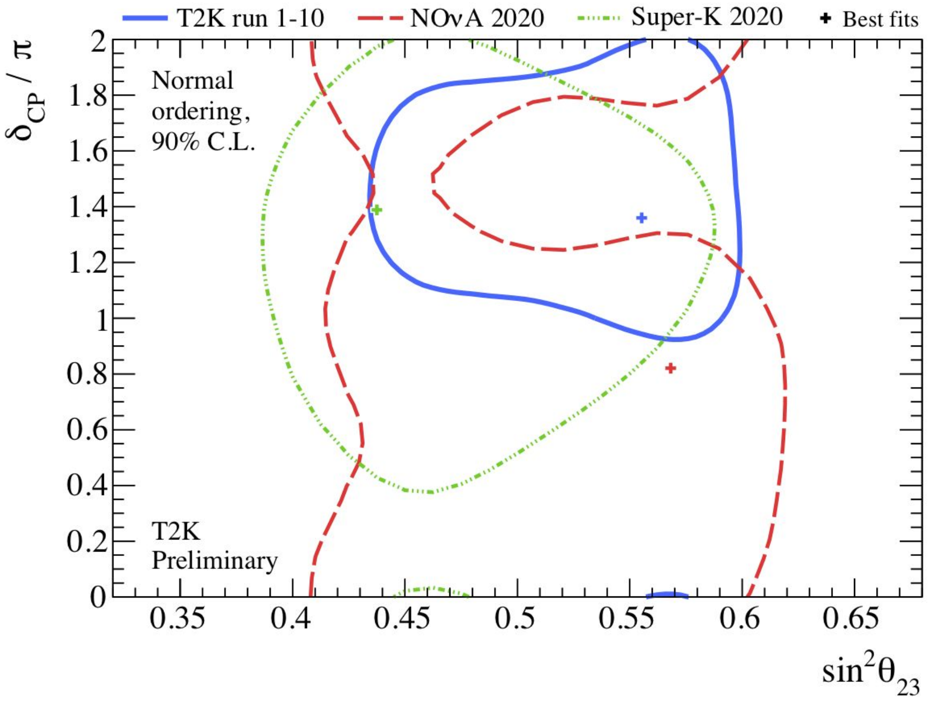
Appearance results - T2K

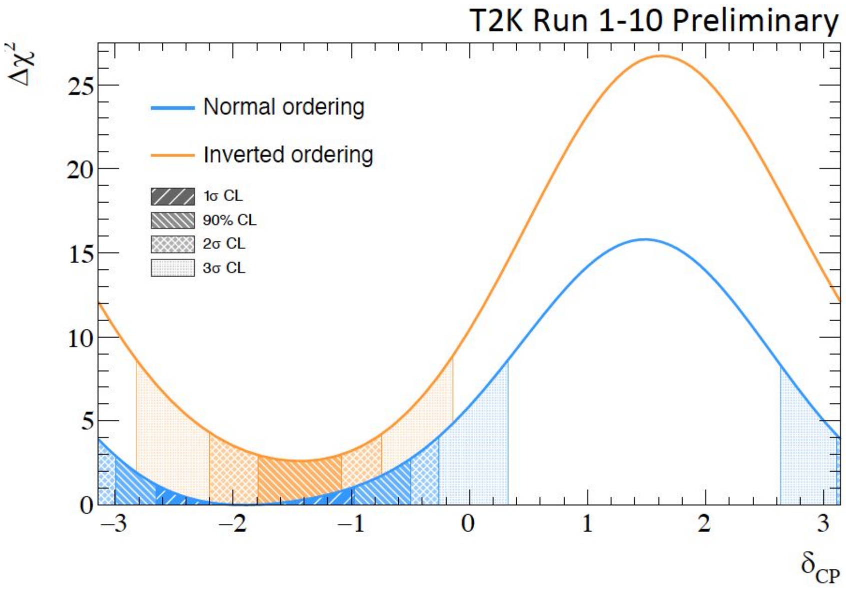


Preference for maximal CPV, normal ordering

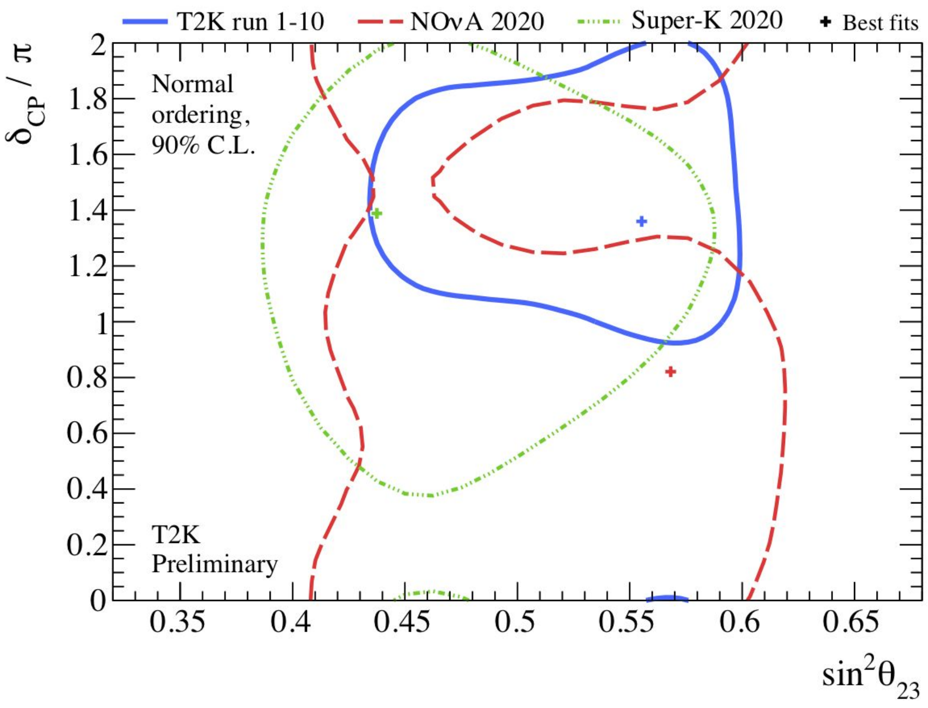
Exclude 35% of $\boldsymbol{\delta}_{CP}$ values at 3σ
(marginalized over both hierarchies)

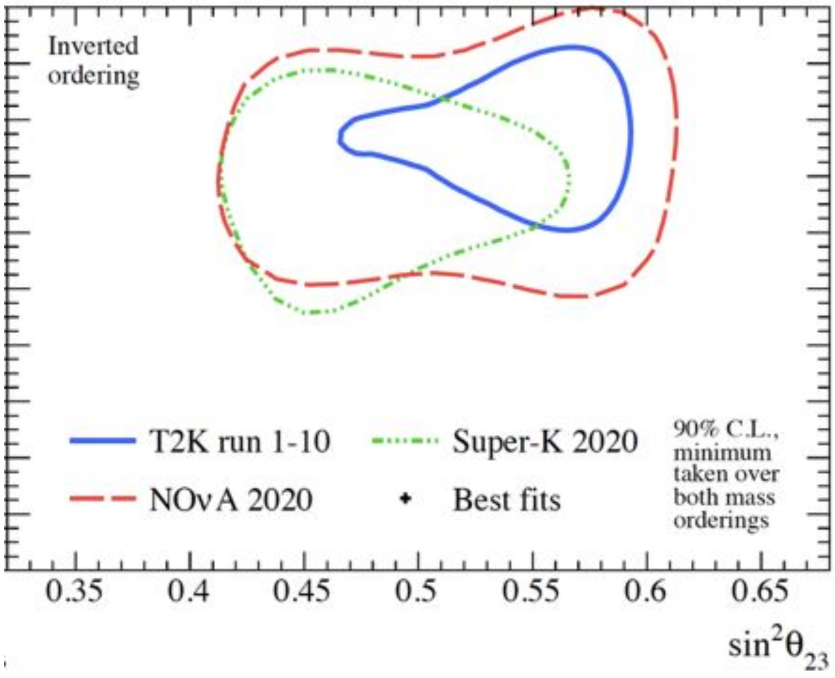
Appearance results - T2K





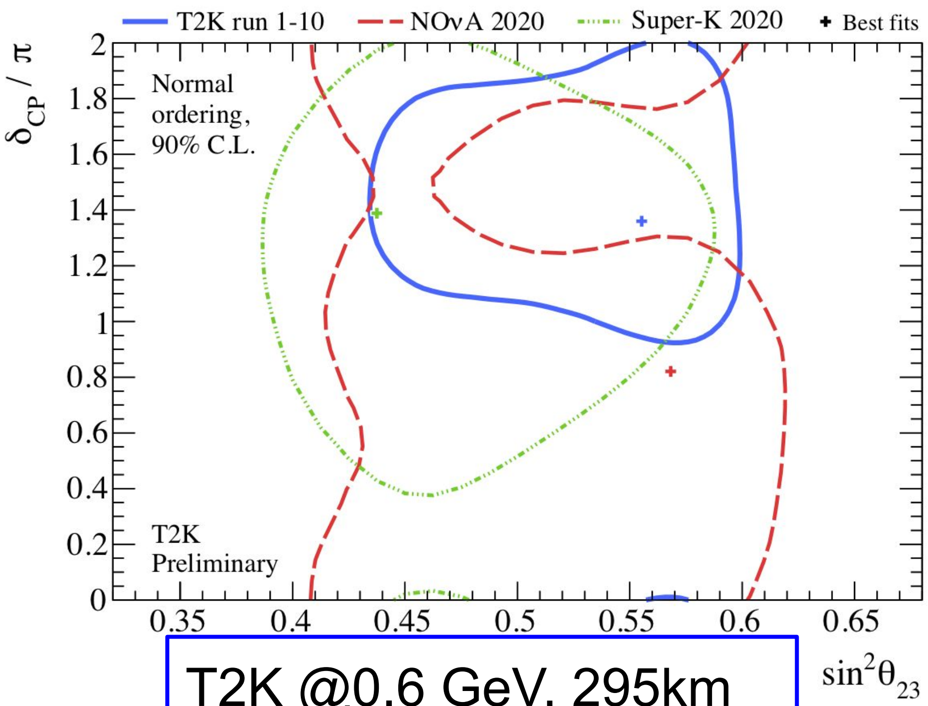
Global picture is complex - *these are statistics limited experiments!*

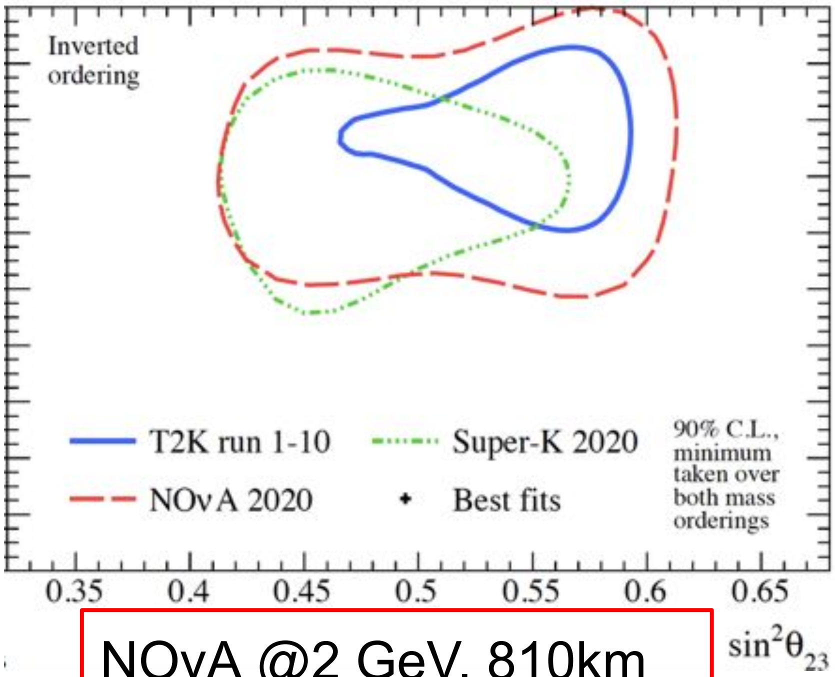




1σ contours have regions of overlap

Global picture is to be clarified with combined analysis of NOvA-T2K, T2K-SK





T2K @0.6 GeV, 295km
- *CP effect: 32%
- Matter effect: 9%

NOvA @2 GeV, 810km
- *CP effect: 22%
- Matter effect: 29%

*Credit: M. Hartz, *Minimum difference of sin(δcp)=0 and sin(δcp)=±1, neutrinos and antineutrinos*

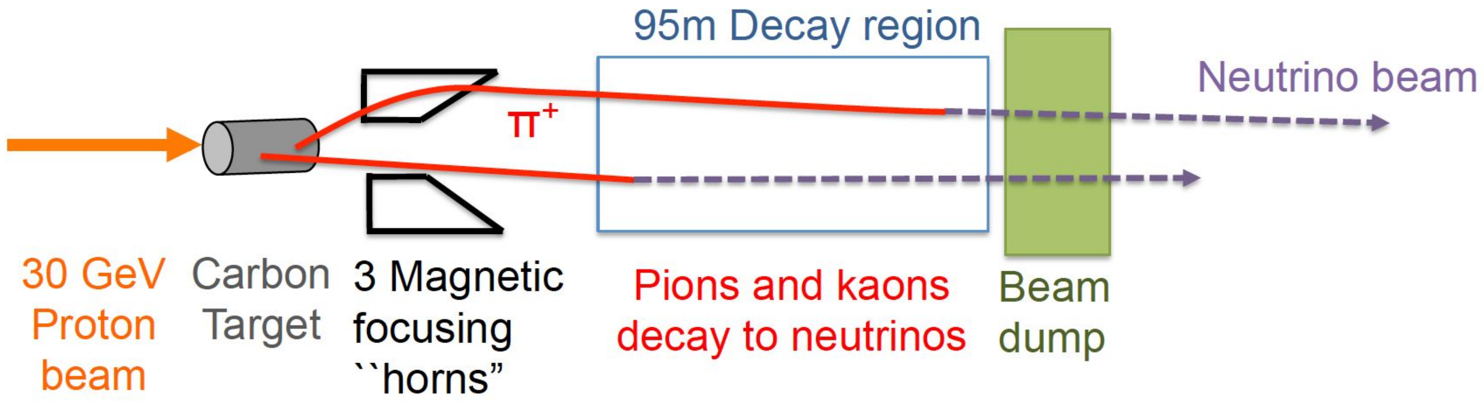
Future plans of T2K and NOvA - *operate through 2026*

Significant improvements to T2K underway:

- Gd doping at far detector
- New near detectors (“ND upgrade”) *TDR: arXiv:1901.03750*
- Upgraded beamline *TDR: arXiv:1908.05141*

NOvA will reduce largest systematics with results from test beam program

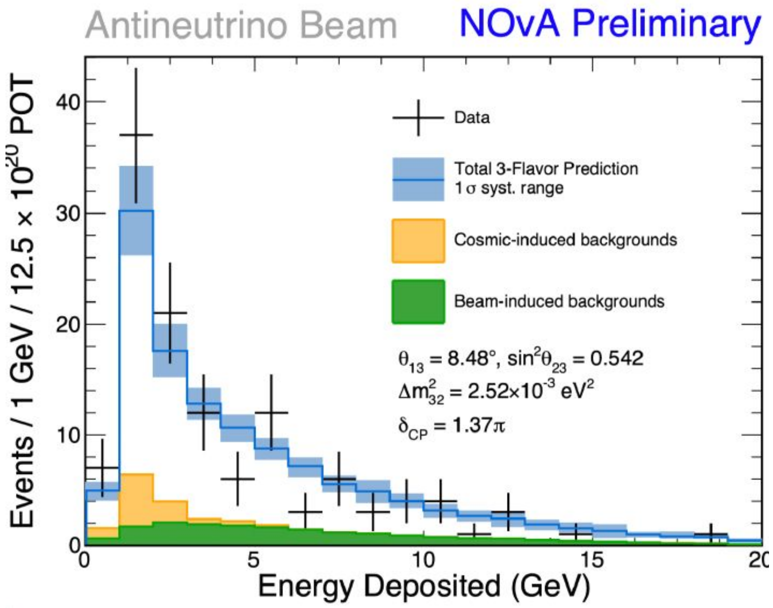
Not just long baseline physics: exotic physics tests



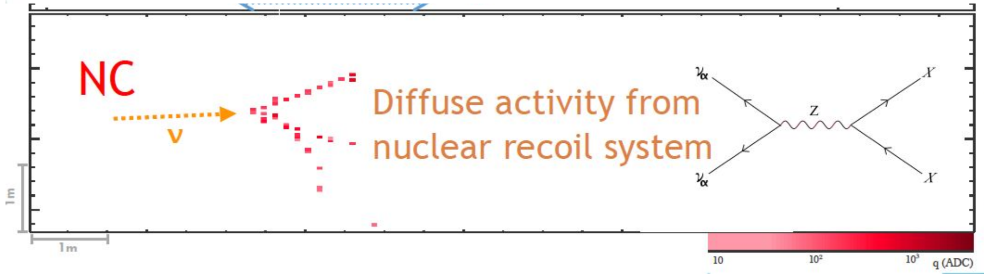
- Intense neutrino source x multiple detectors = searches for new physics!
  - Light dark matter
  - Sterile neutrinos - *MINOS, MINOS+, T2K, NOvA*
  - Heavy neutral leptons - *T2K*
  - Lorentz violation - *MINOS, T2K*
  - Large extra dimensions - *MINOS+*

See MicroBooNE talks, D. Caratelli for short baseline program

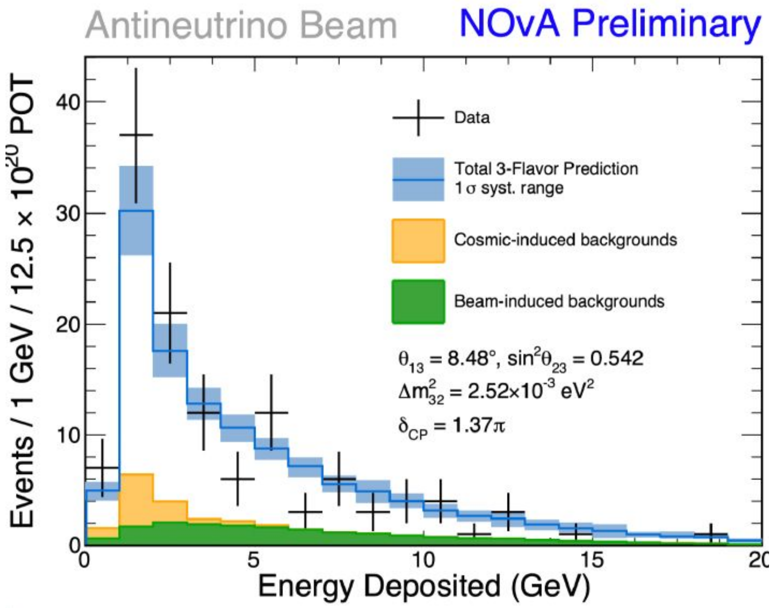
Sterile neutrinos with NOvA

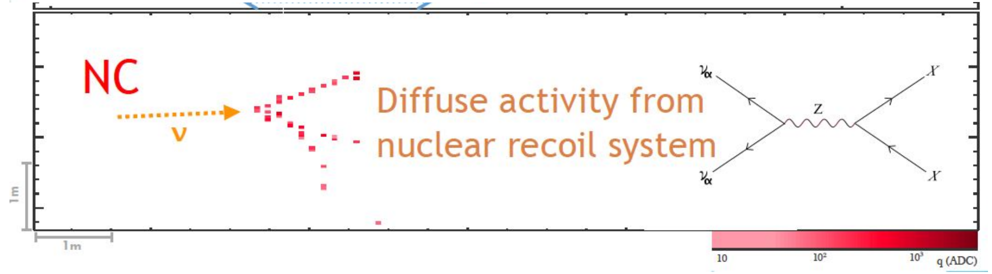


Phys. Rev. Lett. 127, 201801



Sterile neutrinos with NOvA





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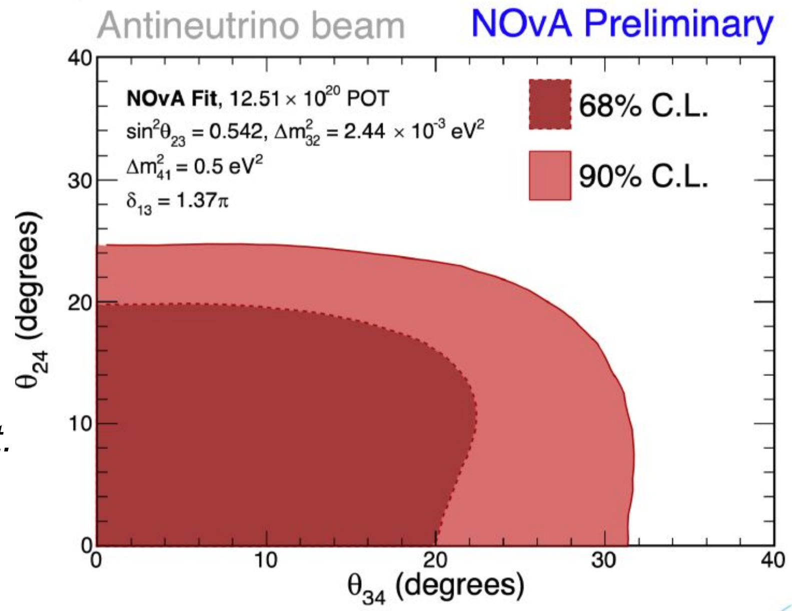
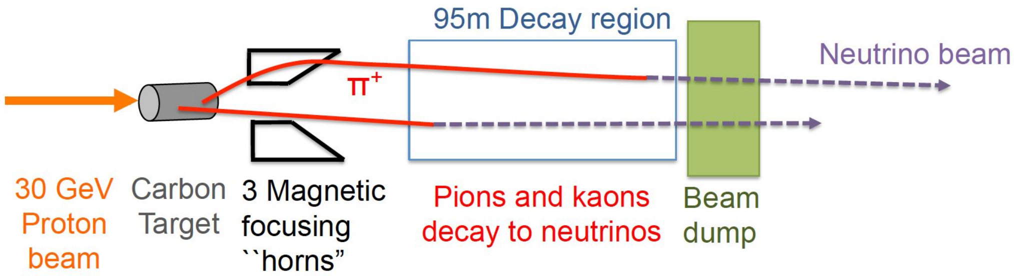


No significant suppression of NC rate due to sterile mixing

Heavy neutral lepton search on T2K



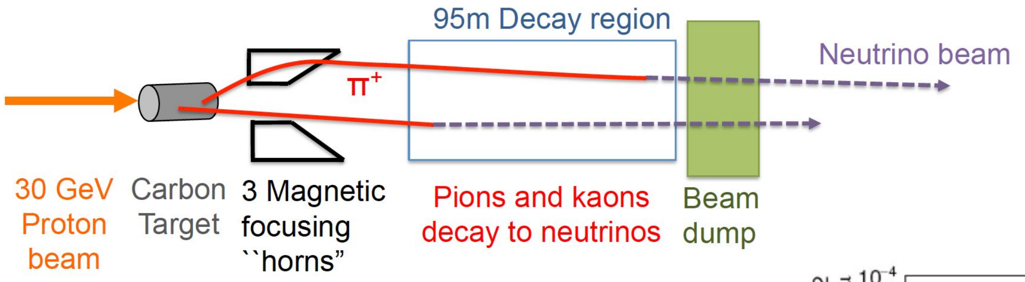
$$K^+ \to \ell^+ N$$

$$N \to \ell^\pm \pi^\mp, \ell^\pm \ell^\mp \nu$$

Production of heavy neutral leptons (N) from kaon decay

- Use large volume, low mass TPCs to identify signal

Heavy neutral lepton search on T2K

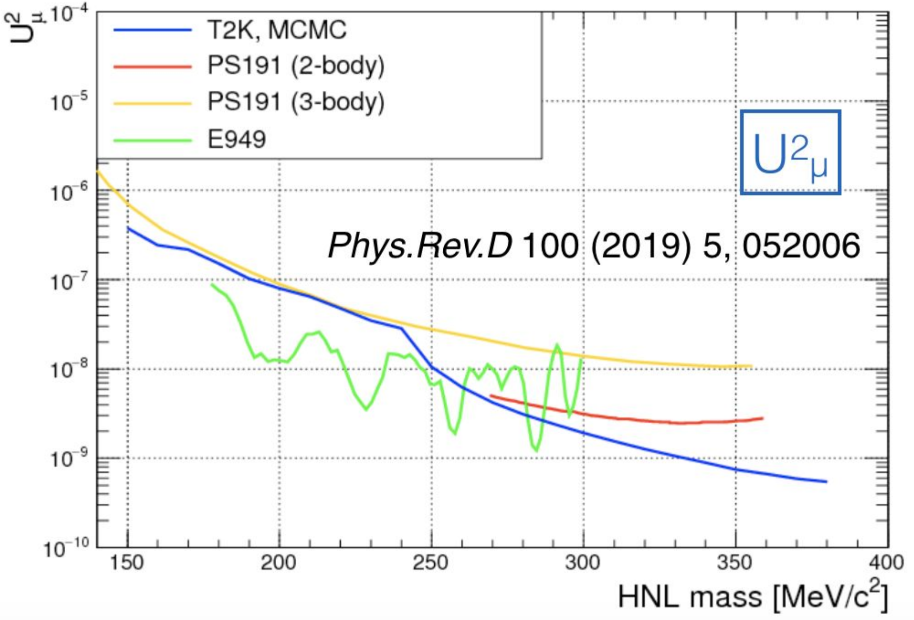


$$K^+ \to \ell^+ N$$

$$N \to \ell^\pm \pi^\mp, \ell^\pm \ell^\mp \nu$$

Production of heavy neutral leptons (N) from kaon decay

- Competitive high mass limits on coupling N to from μ, e
- Complementary search to dedicated measurements - *see talk Tues, R. Wanke*



Long baseline experiments are broad scientific programs with opportunities to test our understanding of the universe

- Neutrino oscillation open questions: mass hierarchy, CPV and θ_{23} octant
- Searches for exotic physics phenomena, neutrino interaction physics

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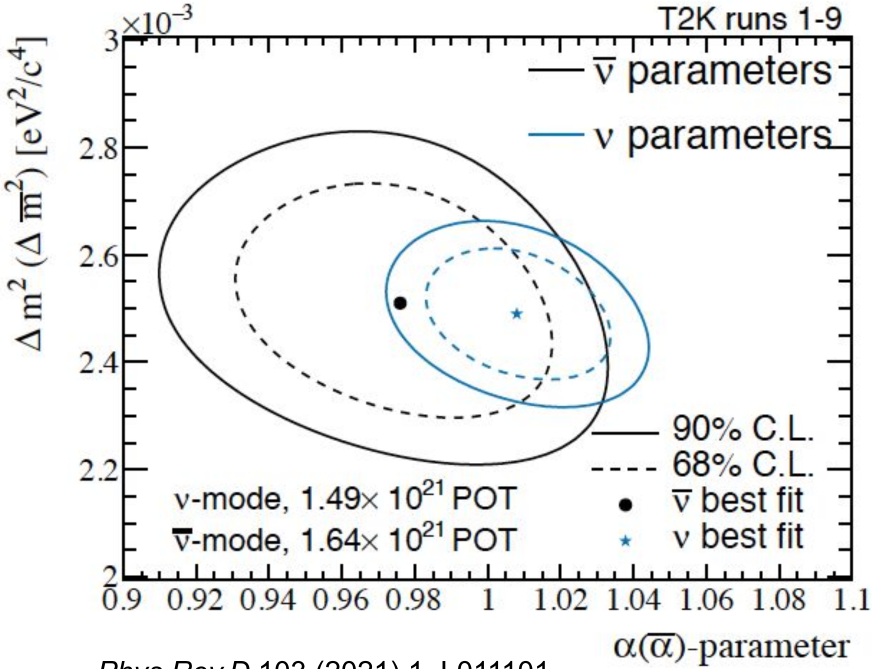
The future will be exciting with new long baseline results:

- Combined analysis of NOvA, T2K and atmospheric (Super-K) data sets exploits complementary information
- T2K and NOvA are statistics limited - *both plan to continue running*
- Beyond that, DUNE and HK will make precision measurements of oscillation physics, and more - *see E. Worcester talk on future experiments on Friday*

Backup

Results: deficit in disappearance spectra

1) Overall rate is underpredicted: 318 1Rmu in data, ~346 predicted
2) Deficit is covered by uncertainties, but this question has motivated model scrutiny:
   a) Example: HE process is overpredicted, then post oscillation, there is a MC excess over data.
3) Postfit spectrum is acceptable; fit to 2 flavor case where $\sin^2 2\theta_{23}$ is allowed to go larger than 1 (α>1, unphysical) includes PMNS (α <1) space.



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