FERMILAB-SLIDES-23-352

THE UNIVERSITY of MISSISSIPPI

Search for CP-violating Neutrino Non-Standard Interactions with the NOvA Experiment

BSM 2023
Hurghada - Egypt

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On Behalf of the NOvA Collaboration

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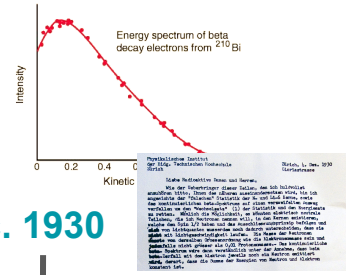
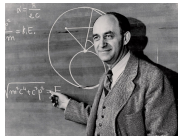
Neutrinos: an exciting timeline!

c. 1930

β decay issues



W. Pauli



E. Fermi

The neutrino is proposed

1956

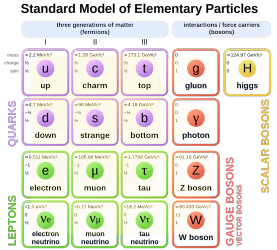
C. Cowan

F. Reines

Discovery! ν_e

1995

1962



ν_μ

1988

2000

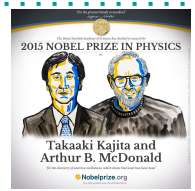
Solar ν

2002

ν_τ

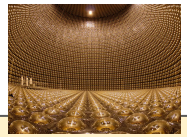
2000's

ν Oscillations



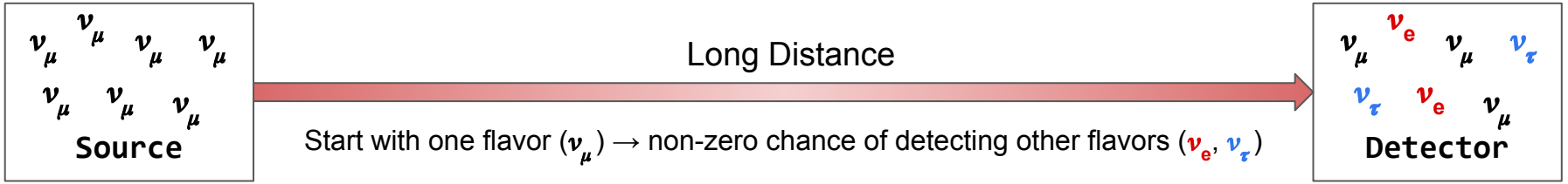
2015

Neutrino Era



..and **many** more!

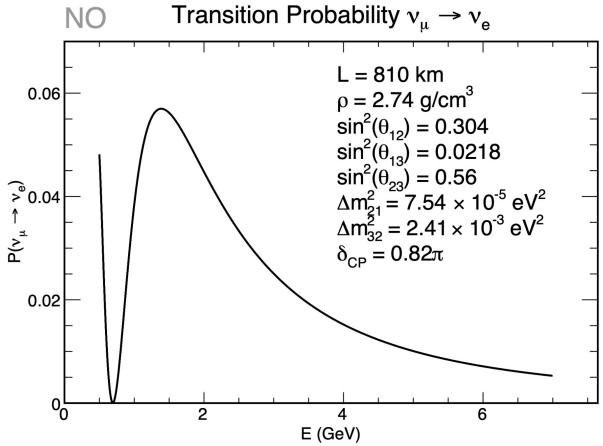
Neutrino Oscillations



flavor basis **mass basis**

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

$$P_{\nu_\mu \to \nu_e} \approx 4\cos^2(\theta_{13})\sin^2(\theta_{13})\sin^2(\theta_{23})\sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

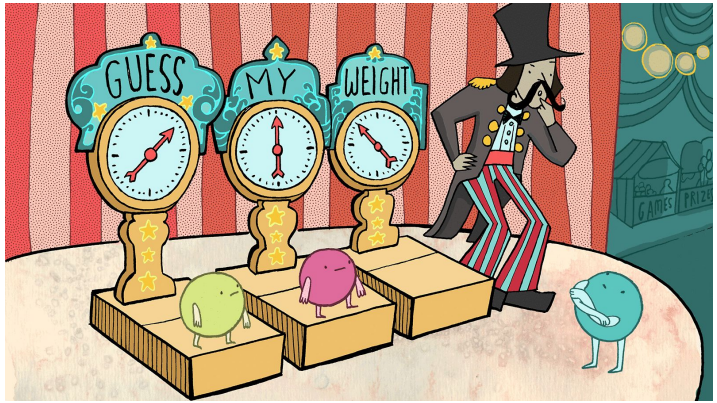


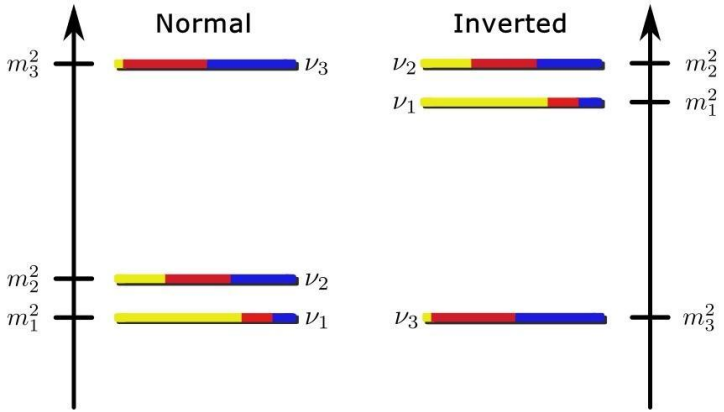
$\nu_\mu \longrightarrow \nu_e$ on NOvA

Outstanding Questions & This Talk

- **What is the mass ordering of neutrinos?**

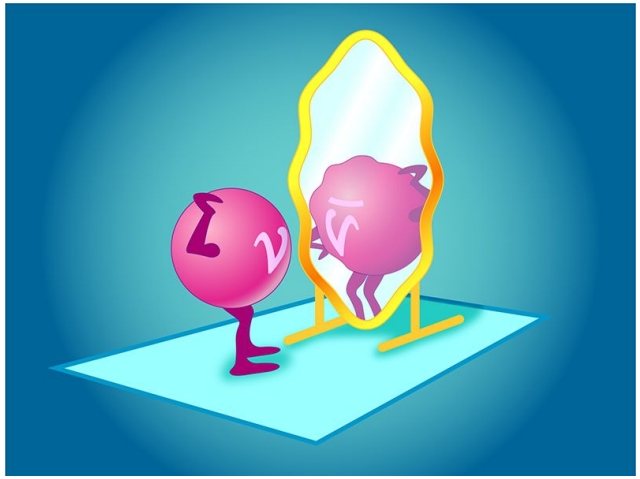
https://neutrinos.fnal.gov/mysteries/mass/





- **Is there CP-Violation in the Lepton sector?**

https://physics.aps.org/articles/v15/120

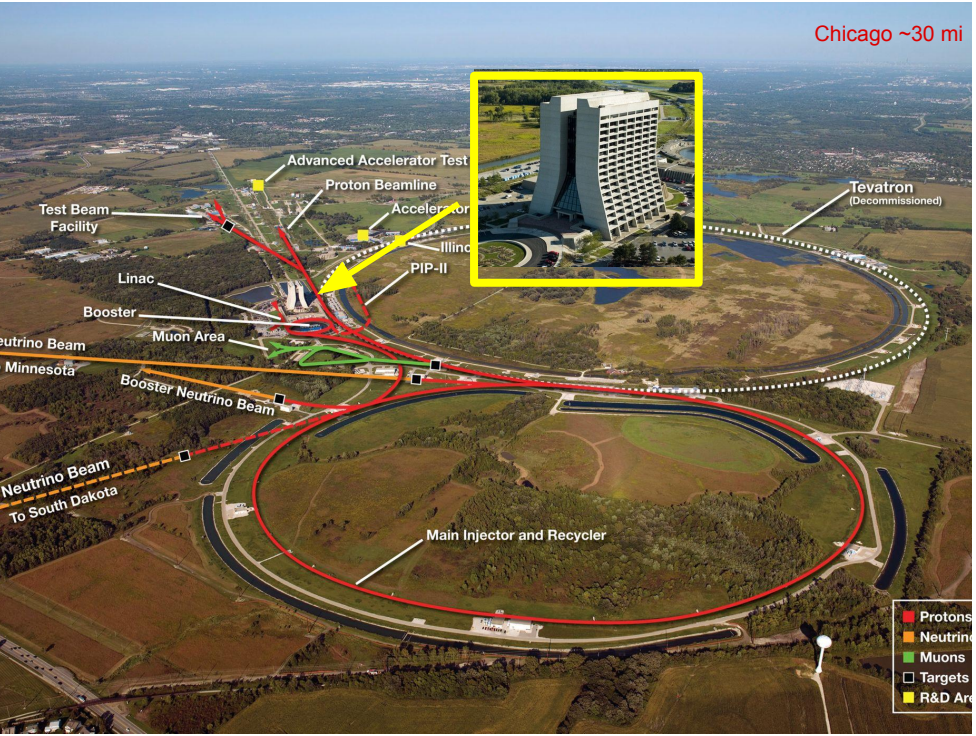


$$\Delta P \propto s_{13}c_{13}^2 s_{12}c_{12}s_{23}c_{23}\sin(\delta_{CP})$$

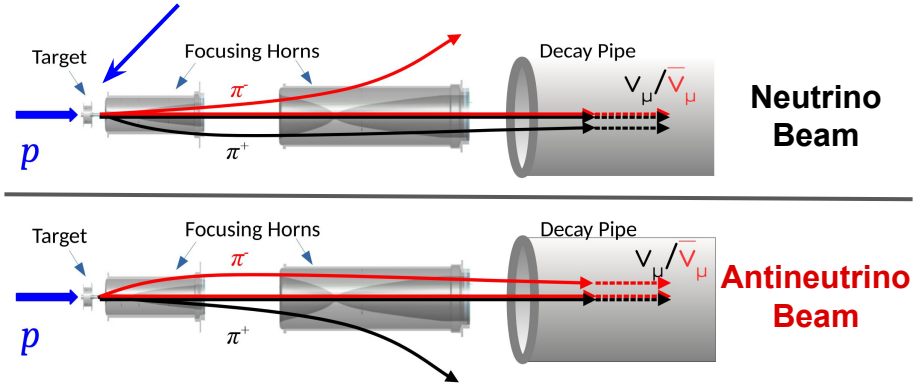
?

Making neutrinos at Fermilab

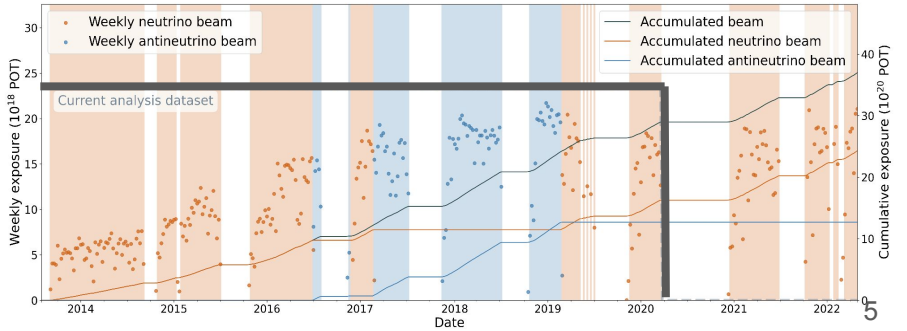
★ **Produce a 120 GeV proton beam**



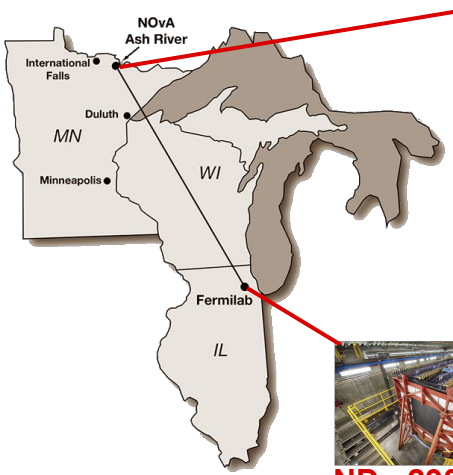
Collide protons with a fixed target

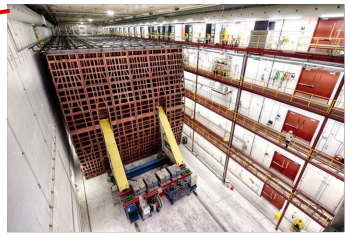


13.6 x 10^{20} POT ν **12.5 x 10^{20} POT $\bar{\nu}$**



The NOvA Experiment

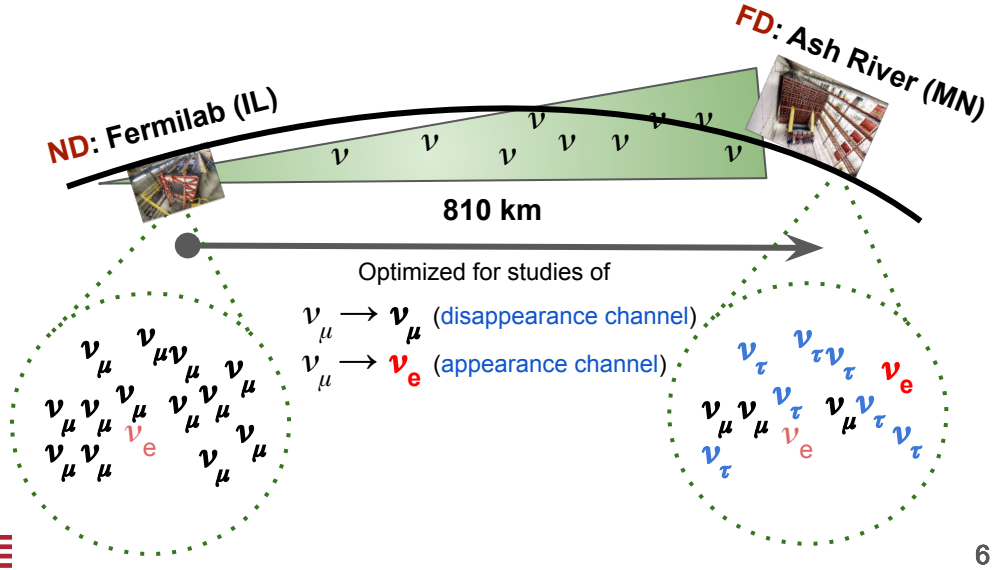




FD - 14kton

ND - 290 ton

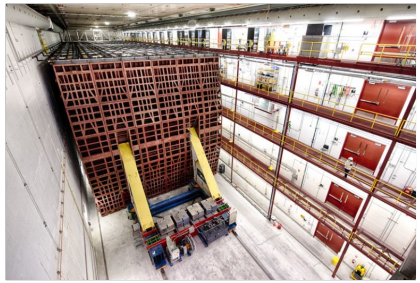
- ★ **2 detector long-baseline neutrino experiment using accelerator neutrinos produced at Fermilab**
- ➢ **Near Detector (ND)**: measures neutrino flux before oscillations
- ➢ **Far Detector (FD)**: measures oscillated neutrino flux



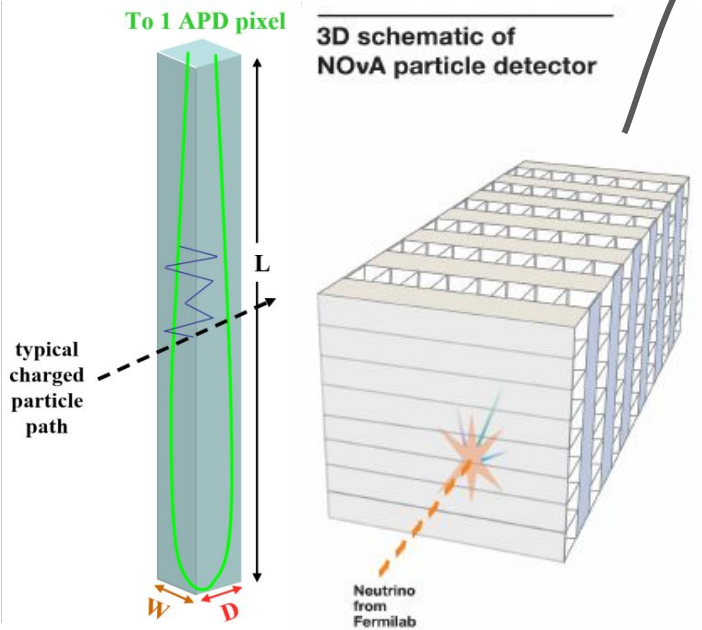
The NOvA Experiment

Two functionally identical tracking calorimeters

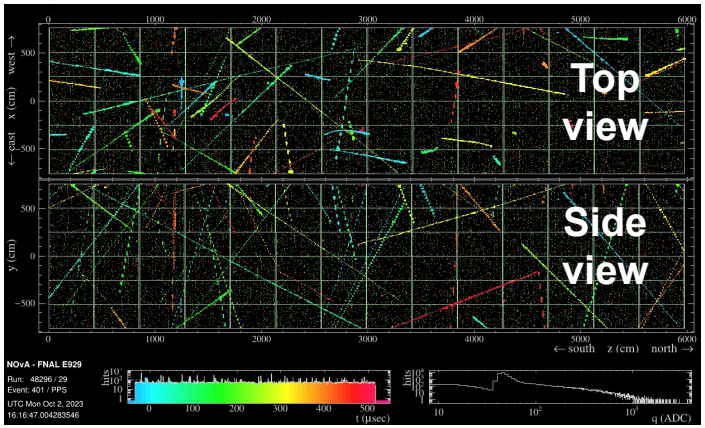
Near Detector
4m x 4m x 15.6 m
underground



Far Detector
15.5m x 15.5m x 60 m
surface

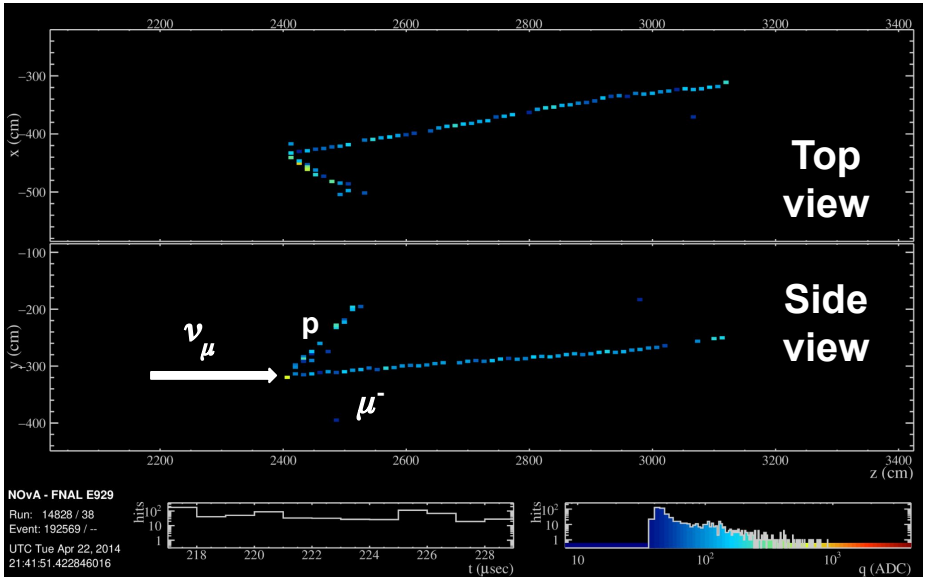


Each cell = 1 pixel of the Event Display

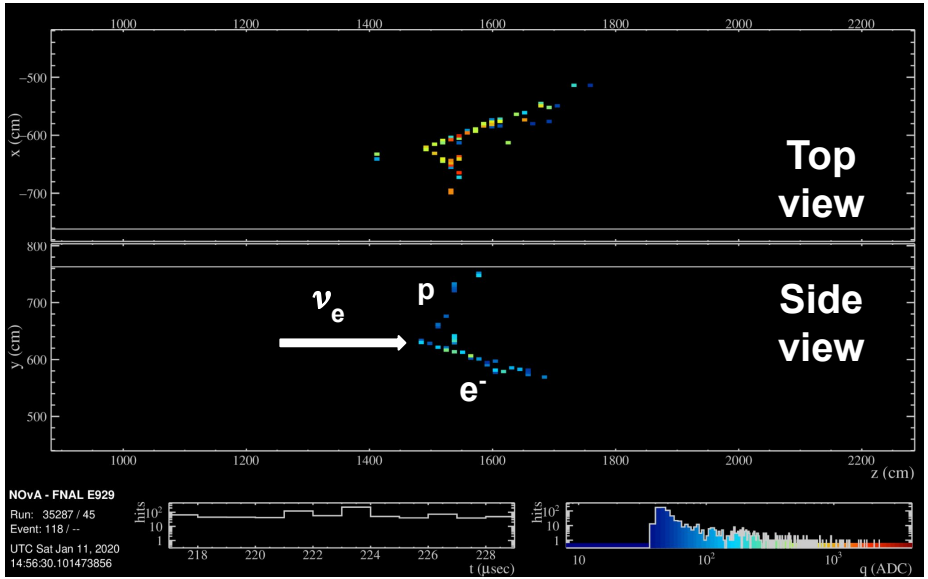


550 μs of data readout
color denotes time

Event Topologies



Muon neutrinos produce a characteristic long track



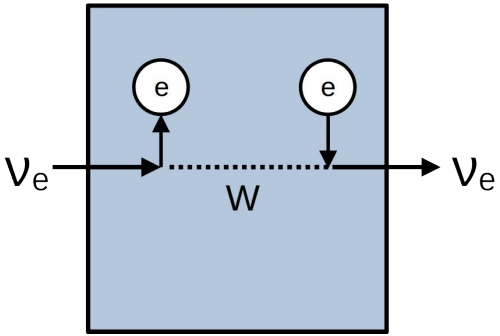
Electron neutrinos have shorter fuzzier tracks

By identifying the charged lepton, we infer the incoming neutrino flavor (CC)

Non-Standard Interactions

https://www.particlezoo.net/

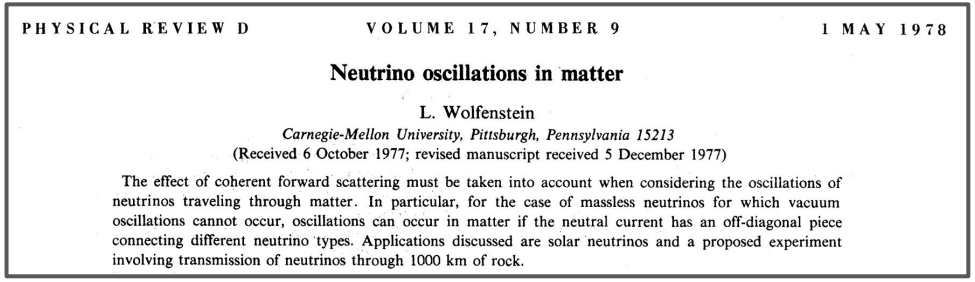
First: Standard Matter Effect



$$\mathcal{H} = U^{\dagger}\mathcal{H}_0 U + \mathcal{H}_{matter} \qquad \mathcal{H}_{matter} \doteq \pm V \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad V = \sqrt{2} G_F N_e$$

ν_e different from ν_μ and ν_τ in matter

ν_e scatters coherently against matter's electron cloud

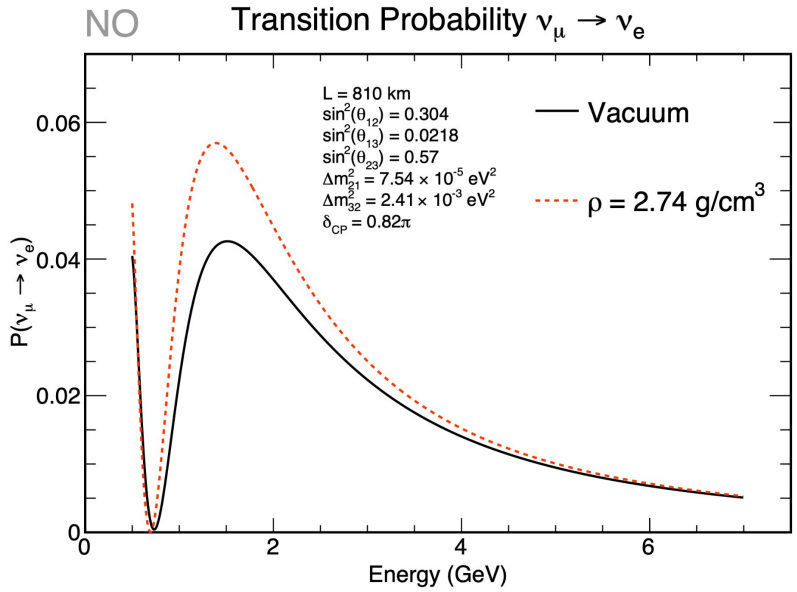


PHYSICAL REVIEW D VOLUME 17, NUMBER 9 1 MAY 1978

Neutrino oscillations in matter

L. Wolfenstein
Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213
(Received 6 October 1977; revised manuscript received 5 December 1977)

The effect of coherent forward scattering must be taken into account when considering the oscillations of neutrinos traveling through matter. In particular, for the case of massless neutrinos for which vacuum oscillations cannot occur, oscillations can occur in matter if the neutral current has an off-diagonal piece connecting different neutrino types. Applications discussed are solar neutrinos and a proposed experiment involving transmission of neutrinos through 1000 km of rock.

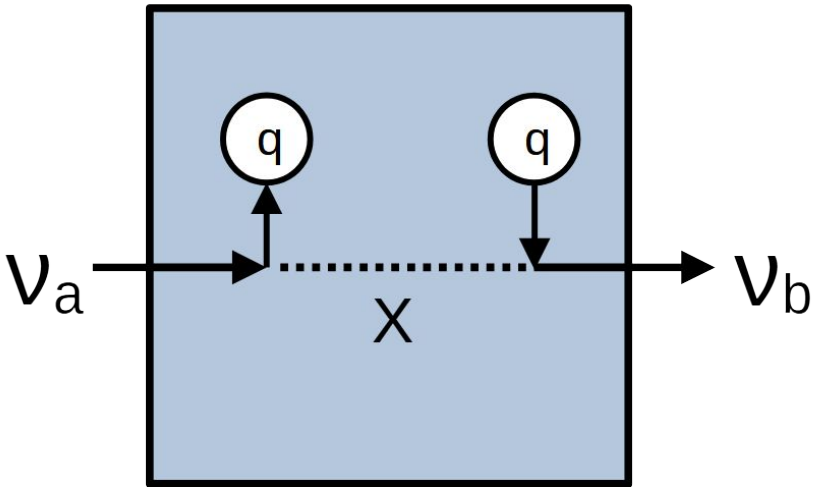


Important for our experiment's long baseline!

Non-Standard Interactions (NSI)

- NSI are a BSM extension of the standard matter effect
- Neutrinos might coherently scatter in ways that we don't know of yet

Flavor Changing



At the Hamiltonian level, add an interaction term

$$\mathcal{H}_{NSI} \doteq \pm\sqrt{2}G_F N_e \begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{\mu e} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{\tau e} & \varepsilon_{\tau\mu} & \varepsilon_{\tau\tau} \end{pmatrix}$$

ε can be seen as the strength of NSI

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NSI predicted by the same landmark paper

Non-Standard Interactions (NSI)

$$\mathcal{H}_{NSI} \doteq \pm\sqrt{2}G_F N_e \begin{pmatrix} \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{\mu e} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{\tau e} & \varepsilon_{\tau\mu} & \varepsilon_{\tau\tau} \end{pmatrix}$$

★ Sensitive to off-diagonal terms

★ focus on channels affecting ν_e neutrinos

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

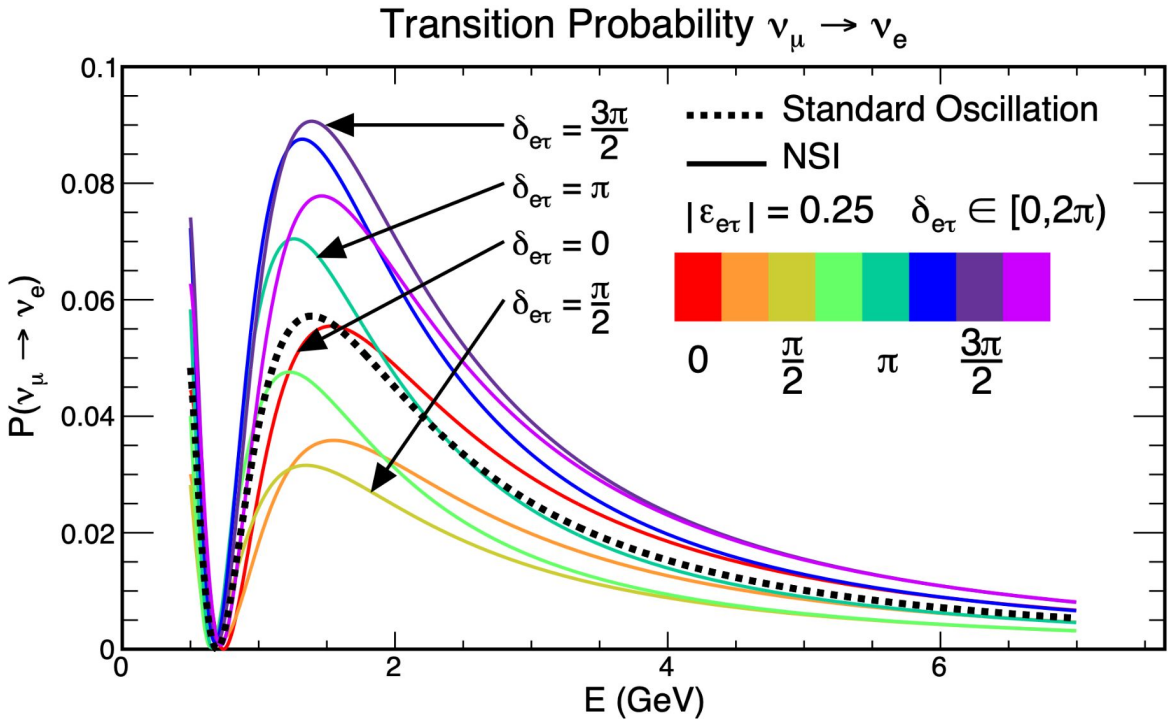
..including effects of new phases

Not looking for final states or mediators

Instead measure the effective ε's

If non-zero → NSI

Non-Standard Interactions (NSI)



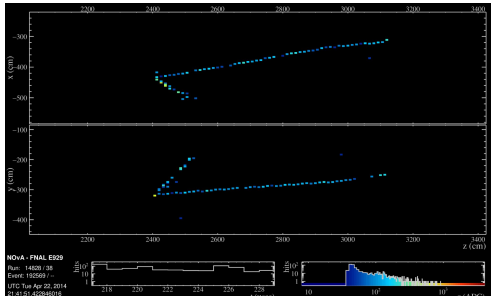
$$\varepsilon_{\alpha\beta} = |\varepsilon_{\alpha\beta}| \, e^{i\delta_{\alpha\beta}}$$

Expect strong impact from new CP-Violating Phases

Today's talk is an extension of a recent NOvA Standard Oscillation Analysis: **Phys. Rev. D 106, 032004**

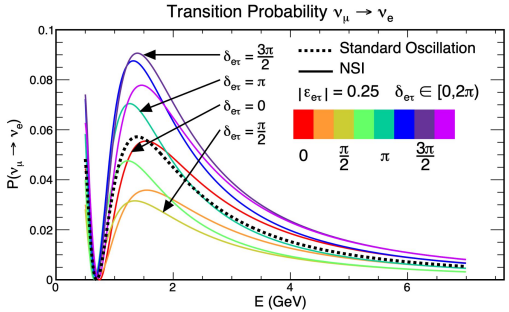
NSI Analysis: methodology

Data



ν_μ	211	ν_e	82
$\bar{\nu}_\mu$	105	$\bar{\nu}_e$	33

NSI Model



$\sin^2(\theta_{23})$, Δm^2_{32}, δ_{CP}

$|\varepsilon_{\alpha\beta}|$, $\delta_{\alpha\beta}$

Constraints and systematics

Δm^2_{21} (10^{-5}eV^2) = 7.54 ± 0.19

$\sin^2\theta_{12}$ = 0.304 ± 0.042

$\sin^2\theta_{13}$ = 0.0218 ± 0.0007

ρ (g/cm^3) = 2.74 ± 3.7%

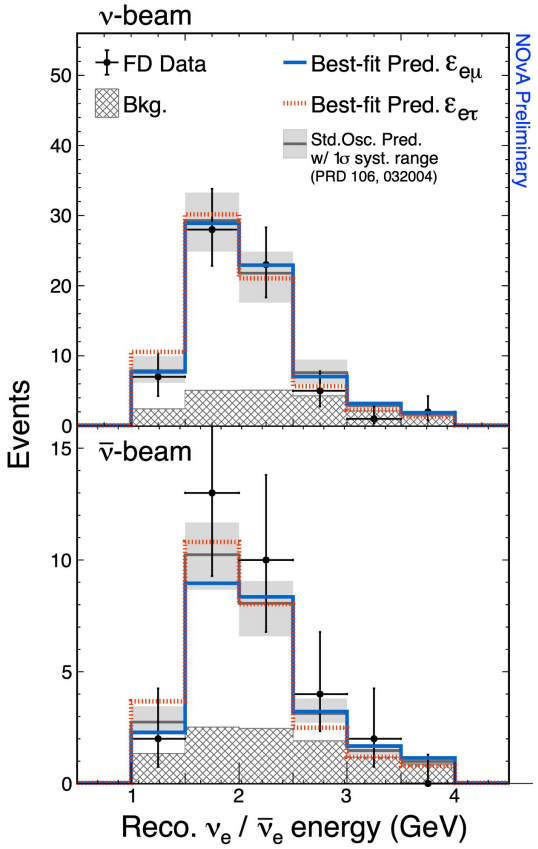
Systematic Pulls

$$\chi^2_{\lambda,P}\left(\text{data},\vec{\theta}\right) = 2\sum_{i=1}^{\text{bins}}\left[E_i\left(\vec{\theta}\right) - O_i + O_i \ln\frac{O_i}{E_i\left(\vec{\theta}\right)}\right]$$

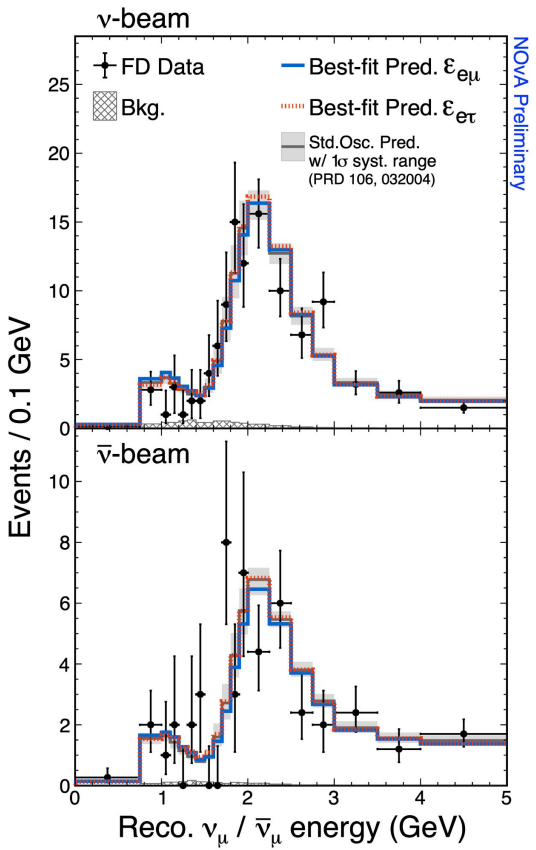
Results

https://www.pixelsquid.com/png/open-chest-2059422080763434711

Results



Electron (anti)neutrino events



Muon (anti)neutrino events

★ **Consistent with Std. Osc. within the 1-σ systematic uncertainty**

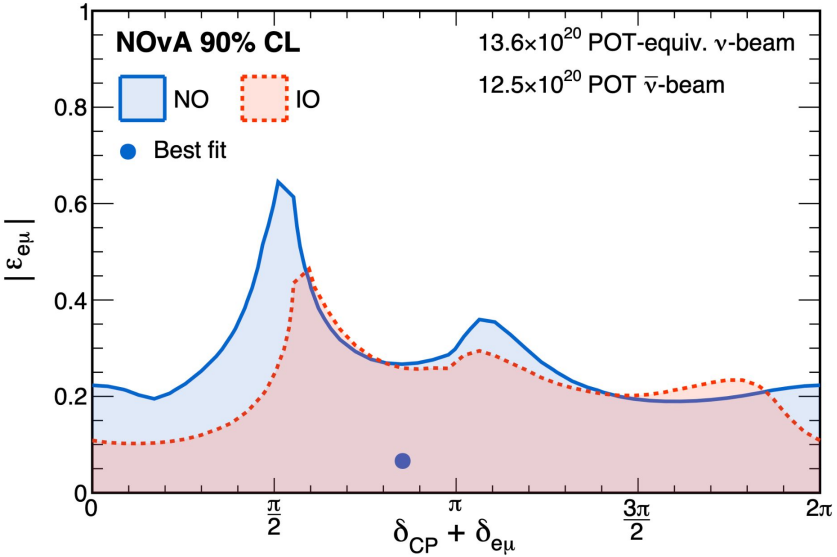
$\Delta\chi^2_{e\mu}$ = 173.3 (NO)

$\Delta\chi^2_{e\tau}$ = 172.9 (NO & IO)

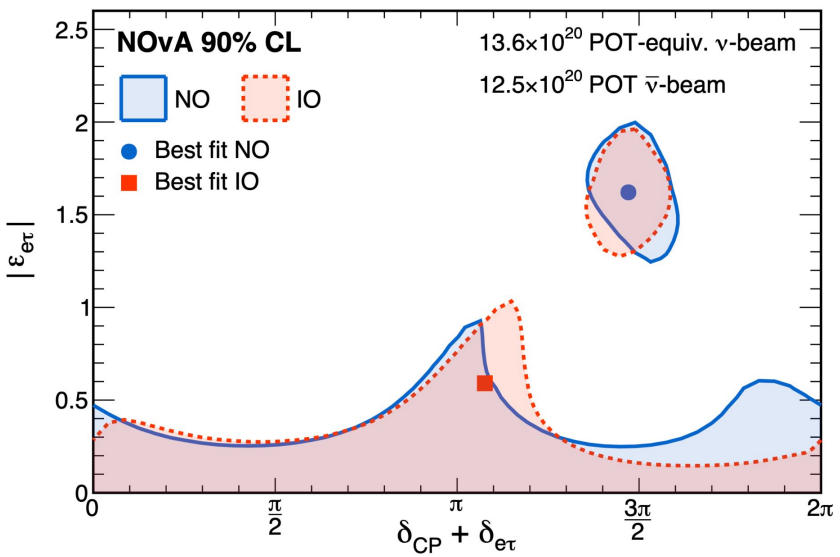
(loss of sensitivity to the ν Mass Ordering)

Results: NSI space

NOvA Preliminary



NOvA Preliminary



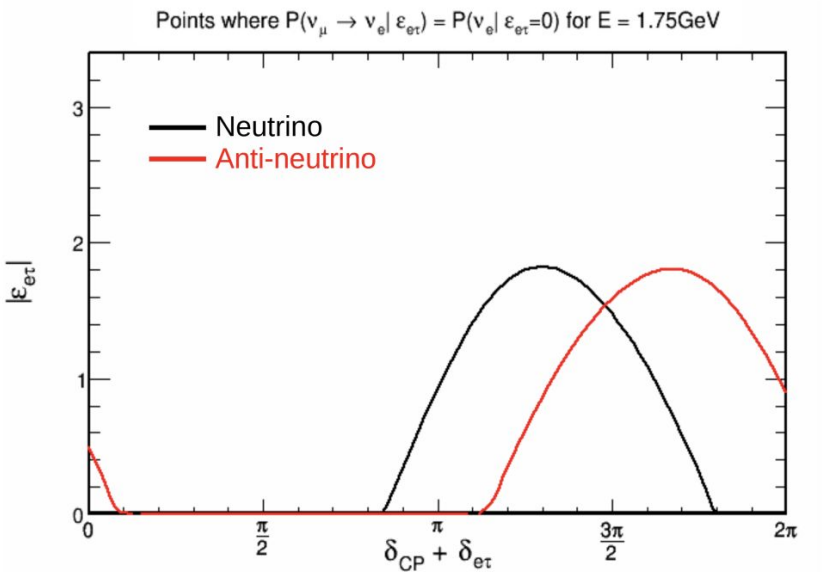
Construct an *NSI vs Effective Phase* space

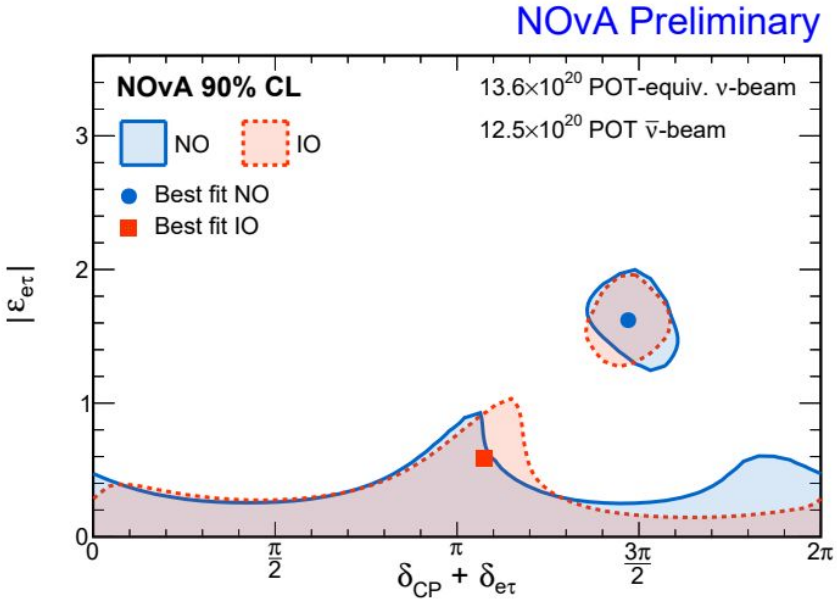
Rules out most of:

$|\varepsilon_{e\mu}| < \sim 0.3$

$|\varepsilon_{e\tau}| < \sim 0.4$

Degeneracy & large NSI

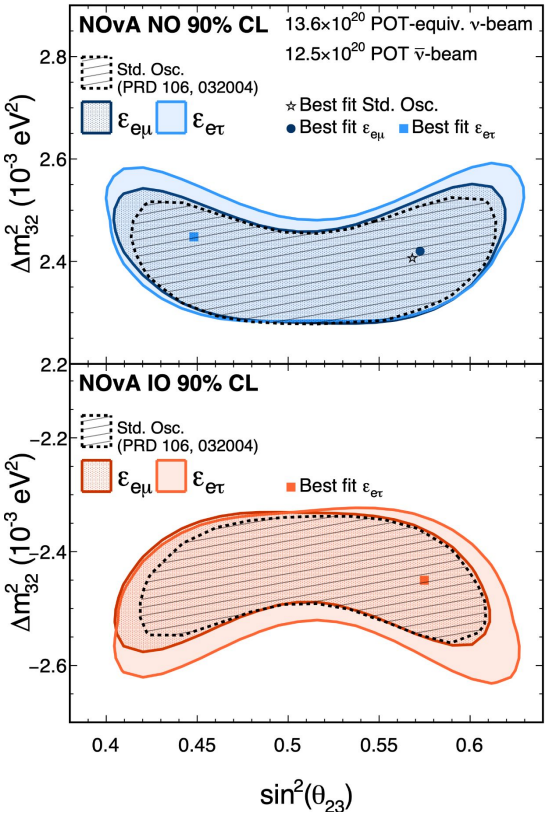




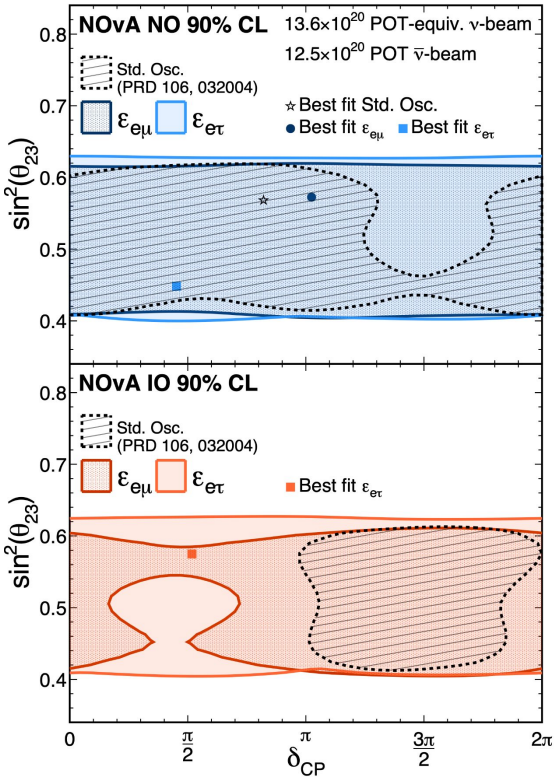
Loss of sensitivity for points where Standard Oscillation prediction equals the NSI prediction; leads to a degeneracy for *large* NSI

Results: impact of NSI on PMNS parameters

NOvA Preliminary



NOvA Preliminary



★ Inclusion of NSI seem to greatly impact our sensitivity to the standard CP-violating phase δ_{CP}

***Need* to further constrain NSI for a precise measurement of CP-violation in the neutrino sector**

THE UNIVERSITY of MISSISSIPPI

Summary

Study sponsored by
DOE Award DE-SC0021616

U.S. DEPARTMENT OF ENERGY

NOvA

Fermilab

- ★ NSI consistent with Standard Oscillations within uncertainty
  - However, must constrain NSI in order to study δ_{CP}
- ★ Degeneracy for large NSI in the $e\tau$ sector
  - plan to perform studies to enhance sensitivity
- ★ Constrain most of:
  - $|\varepsilon_{e\mu}| < \sim 0.3$
  - $|\varepsilon_{e\tau}| < \sim 0.4$

Watch particles
LIVE at **NOvA**!

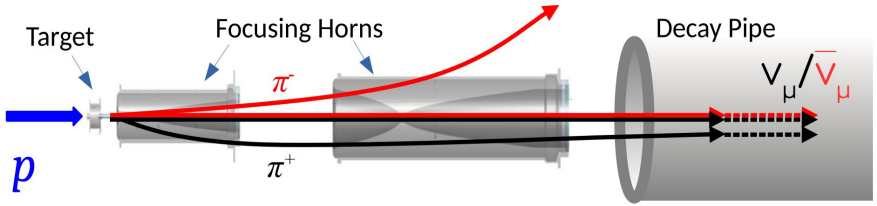
Thank you!

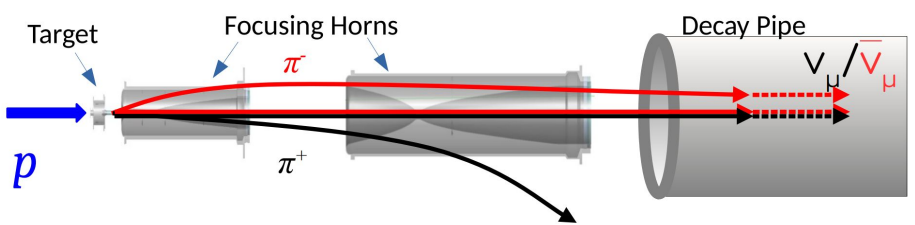
http://novaexperiment.fnal.gov

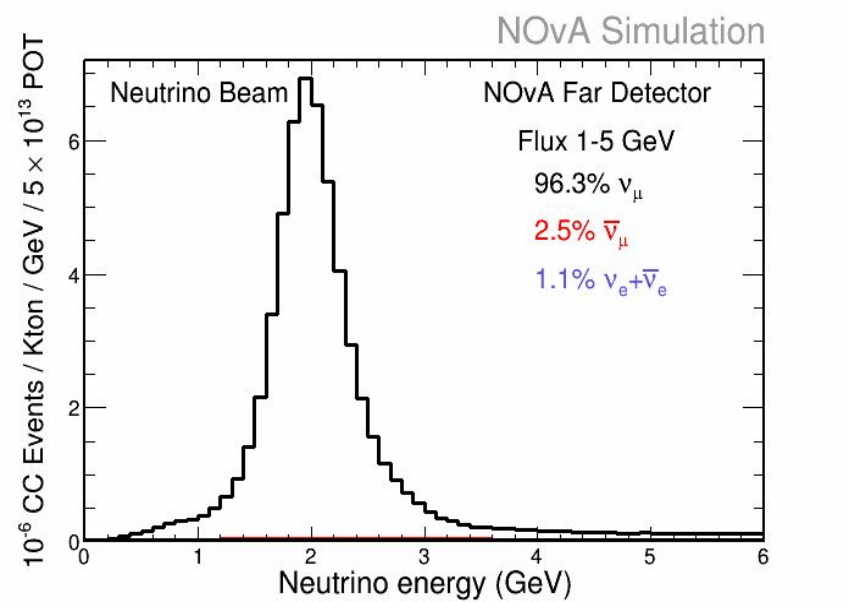
Backup

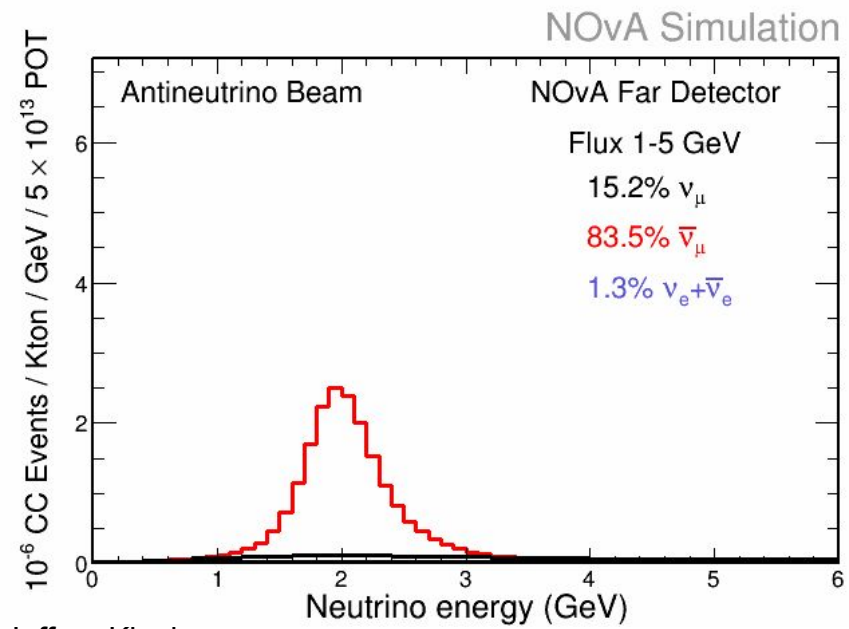
NOvA Experiment

Neutrinos or Antineutrinos



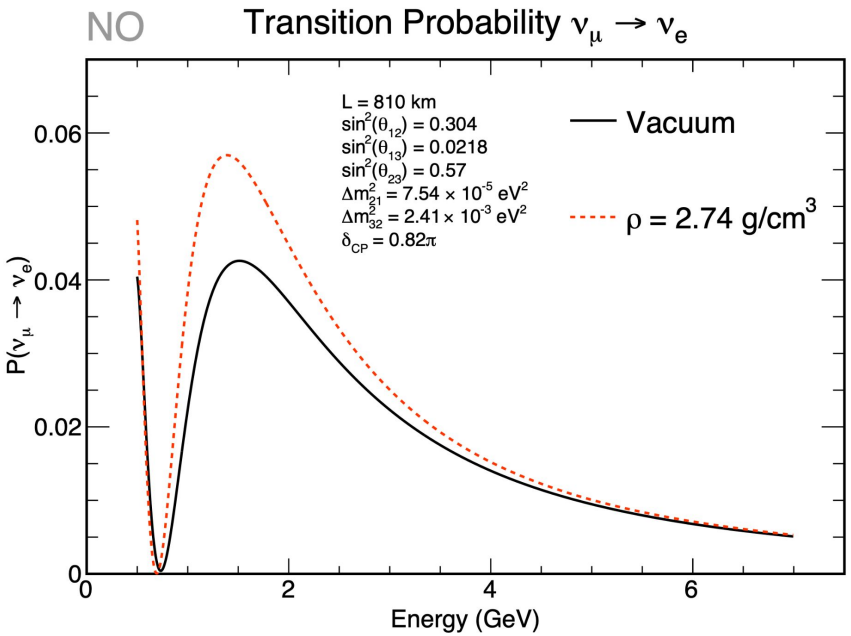


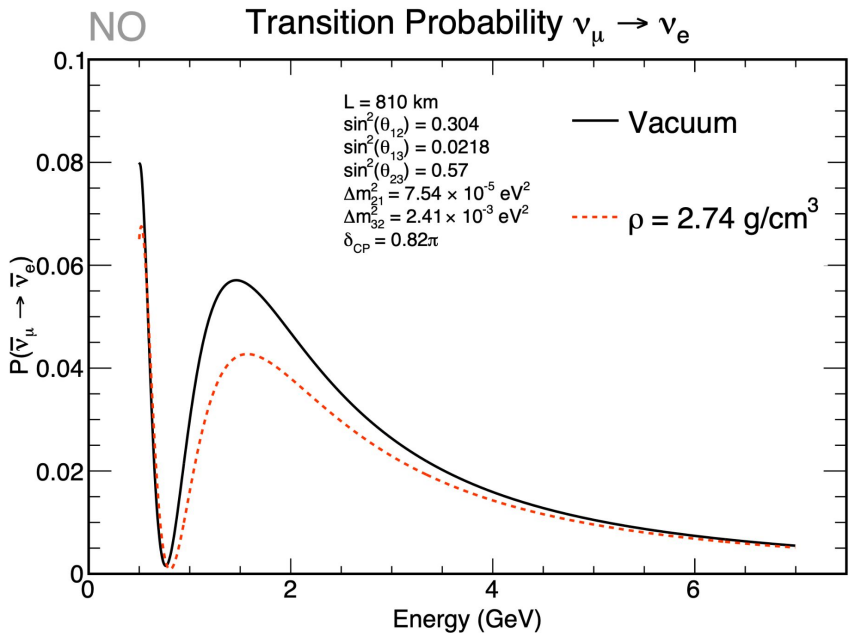




Slide courtesy of Jeffrey Kleykamp

Neutrinos or Antineutrinos



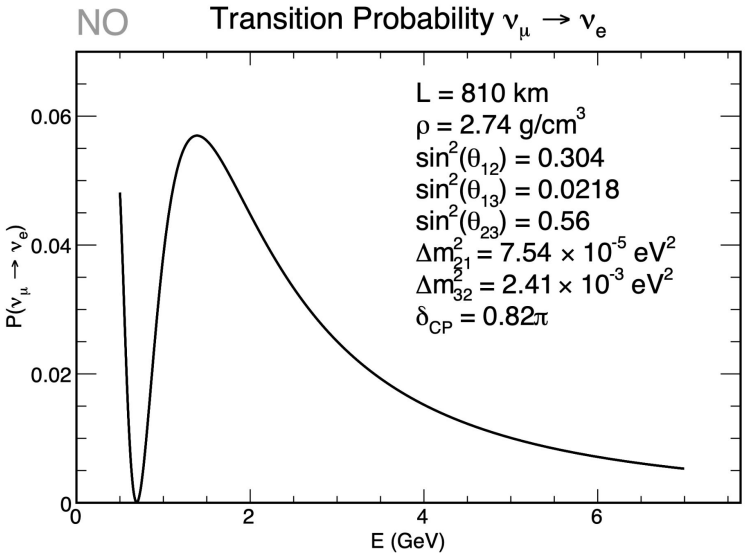


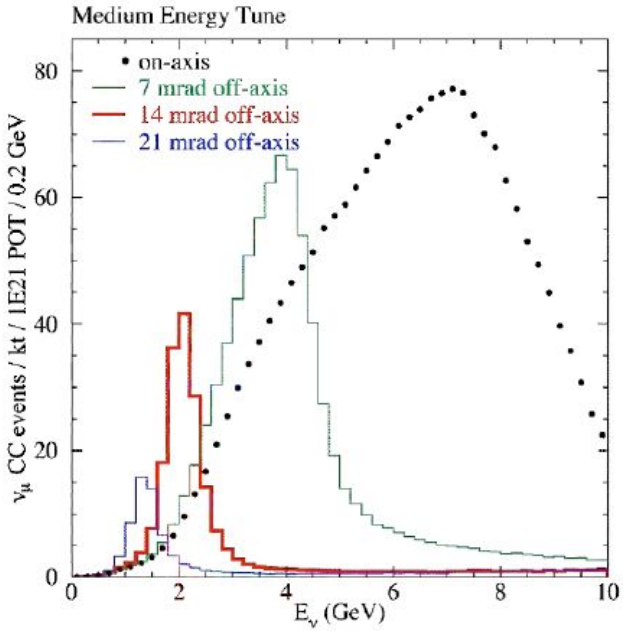
Matter affects neutrinos and antineutrinos differently

Off-axis configuration

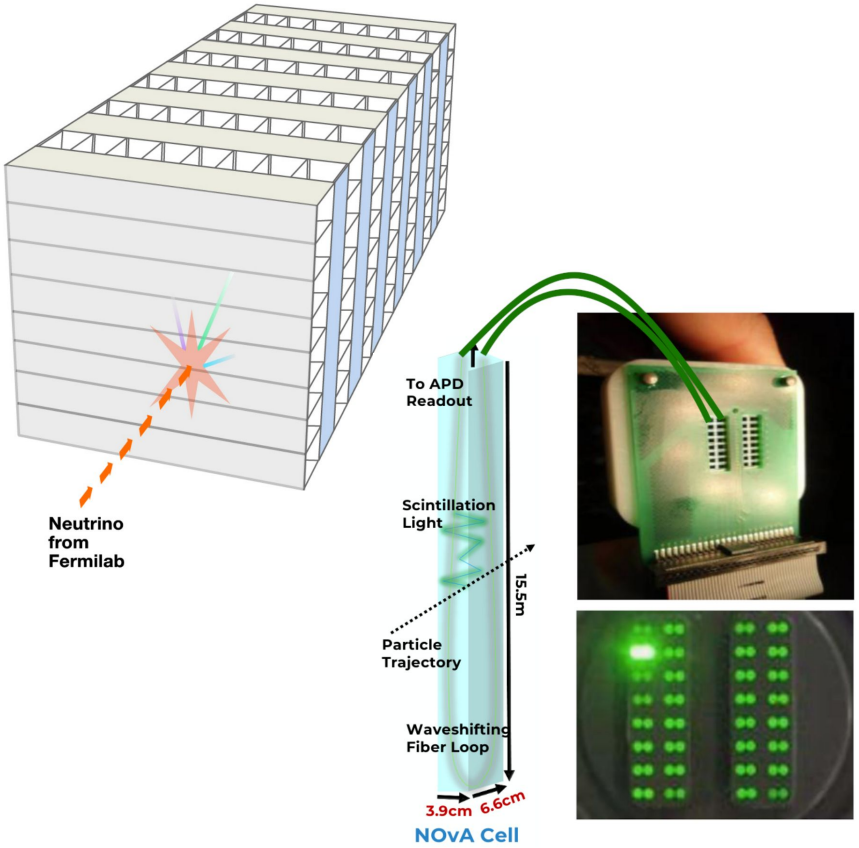
14 mrad off-axis:

E_ν around 2 GeV

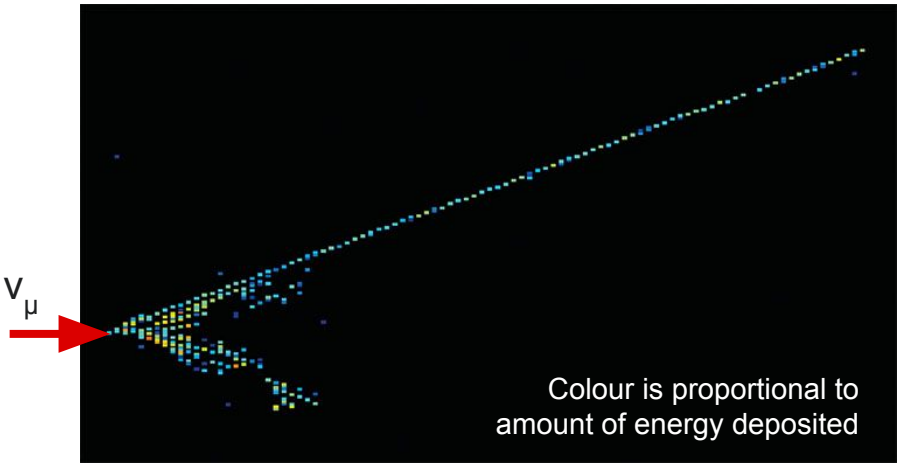




A Neutrino Camera



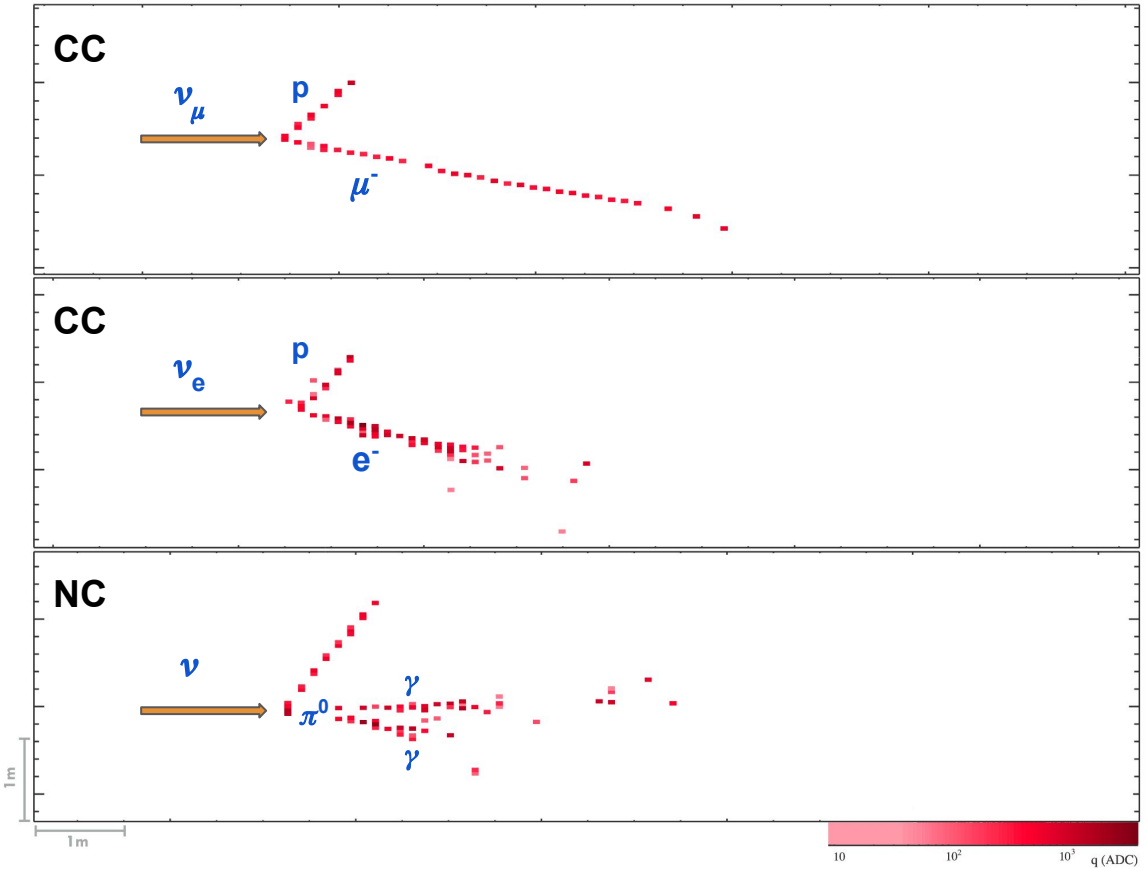
Snapshot of Neutrino Interaction



- The neutrino is invisible
- Measure the outgoing charged particles
  - Infer the neutrino energy and other properties

Slide courtesy of Jeffrey Kleykamp

Event Topologies



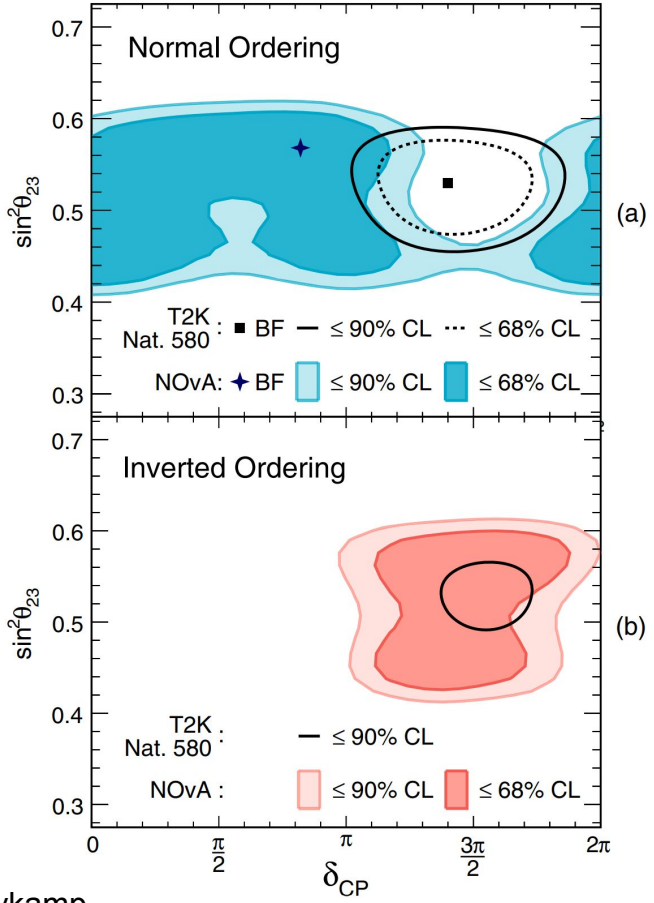
Muon neutrinos produce a characteristic long track

Electron neutrinos have shorter fuzzier tracks

Neutral Current events produce π^0
Background for ν_e events!

Recent Results from NOvA (Frequentist)

- Published August 1st, 2022
  - **Phys. Rev. D 106, 032004**
  - *Improved measurement of neutrino oscillation parameters by the NOvA experiment*
- Slight tension with other experiments
  - **δ_{CP} excluded ~ $3\pi/2$ at 90% C.L.**

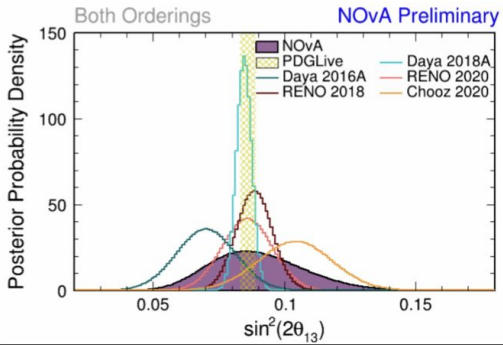


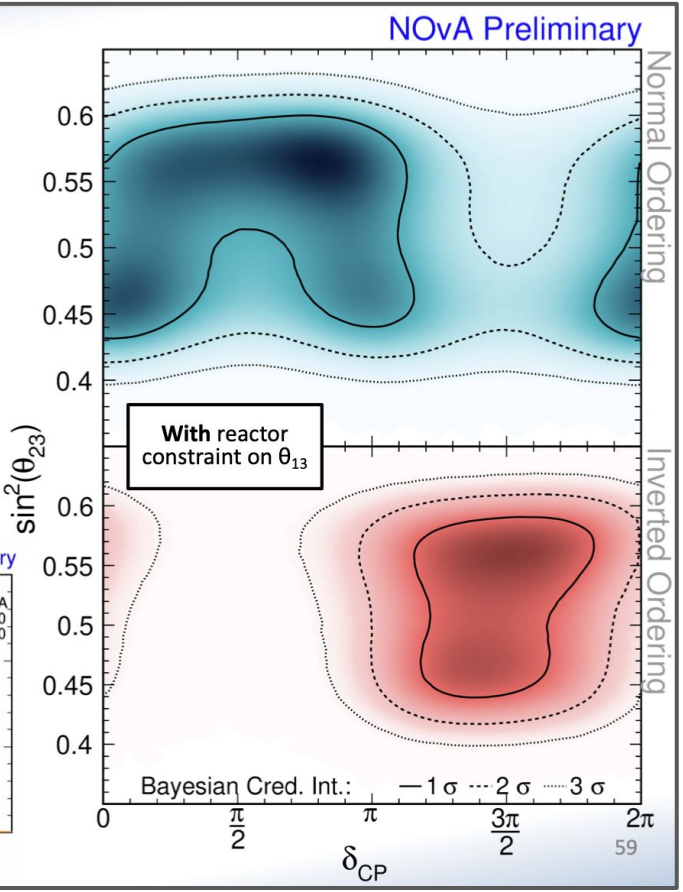
- **Today's results are an NSI extension of the previous measurement**

Slide courtesy of Jeffrey Kleykamp

Recent Results from NOvA (Bayesian)

- Disfavor ordering-δ combinations which generate large asymmetries.
  - NO, $\delta = 3\pi/2$ at $\sim 2\sigma$
  - IO, $\delta = \pi/2$ at $> 3\sigma$
  - Consistent with or without reactor θ_{13} constraint.
- Adding the reactor constraint gives $\sim 1\sigma$ preferences:
  - Upper Octant
  - Normal Ordering





Slide courtesy of Alex Himmel

NSI Model

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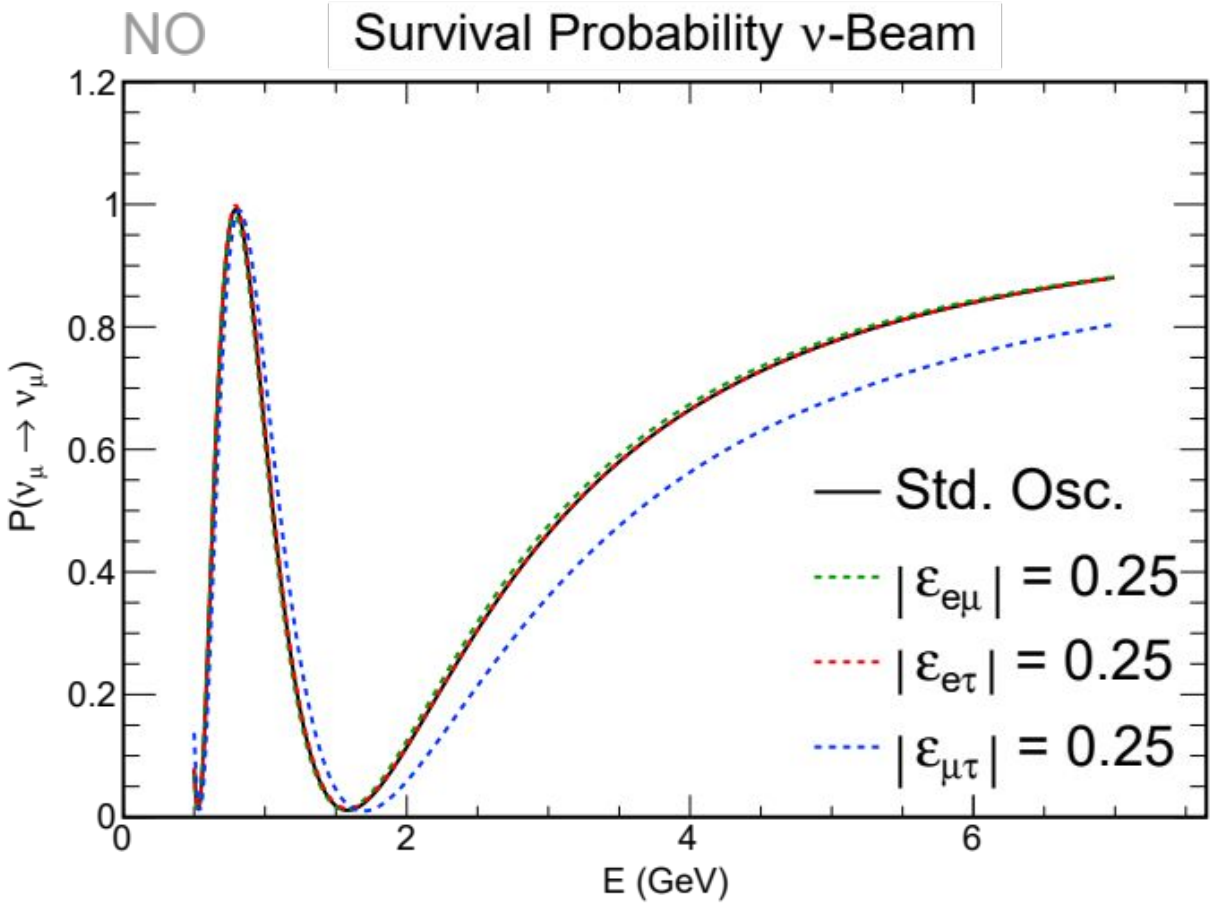
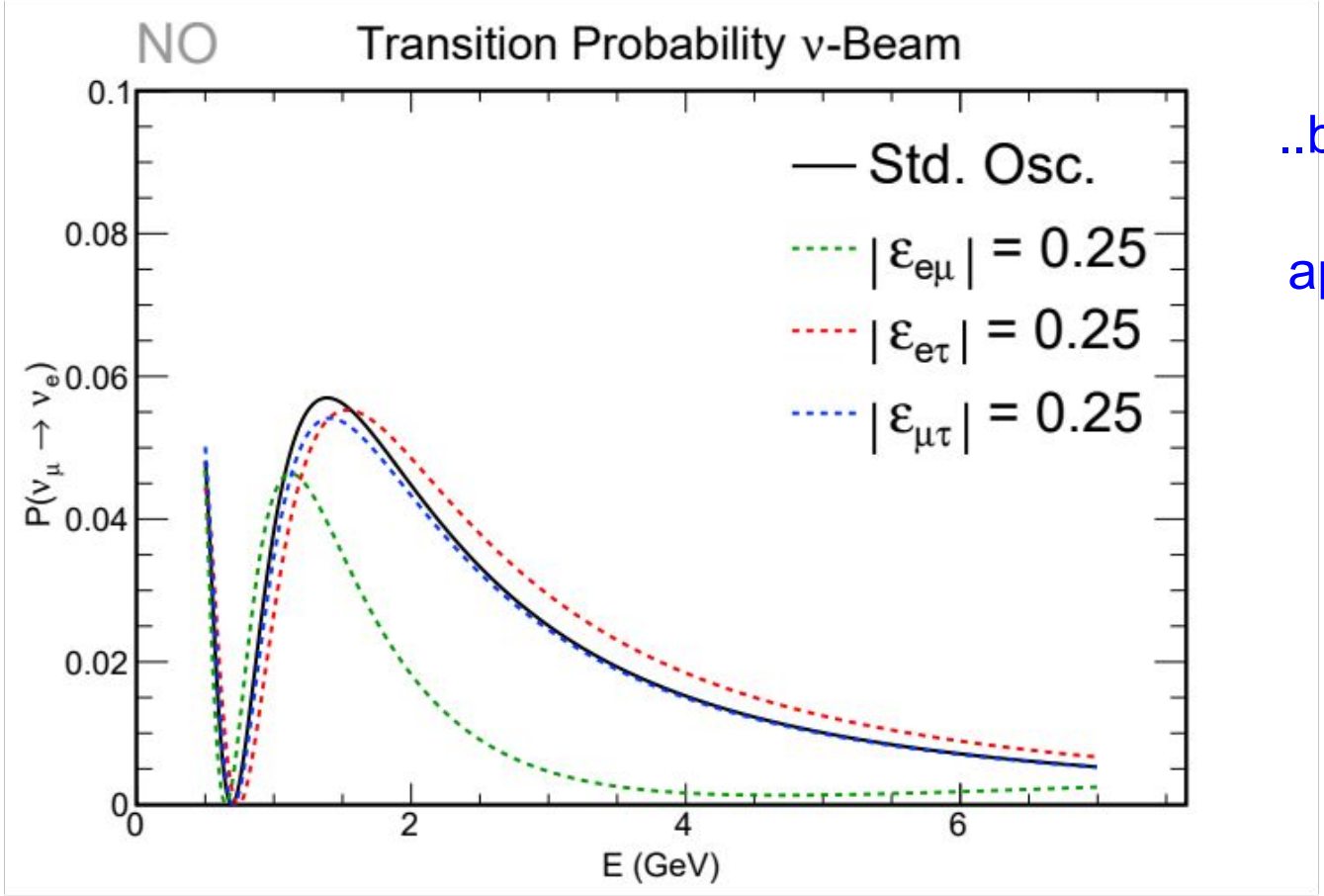
NSI Model



Effect of each parameter

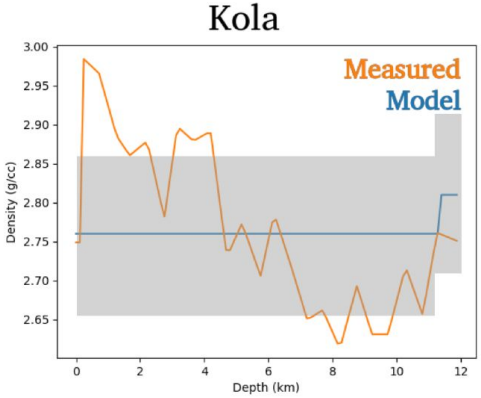
NSI Model

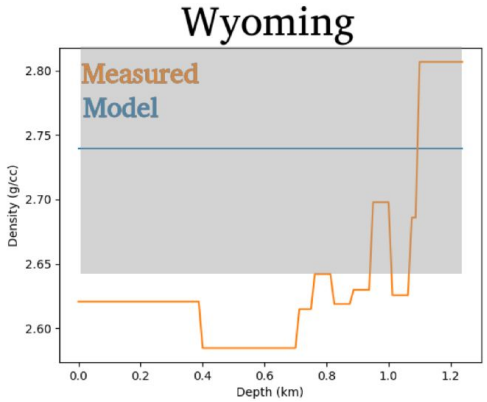


..but here for the ν_e appearance

ρ uncertainty

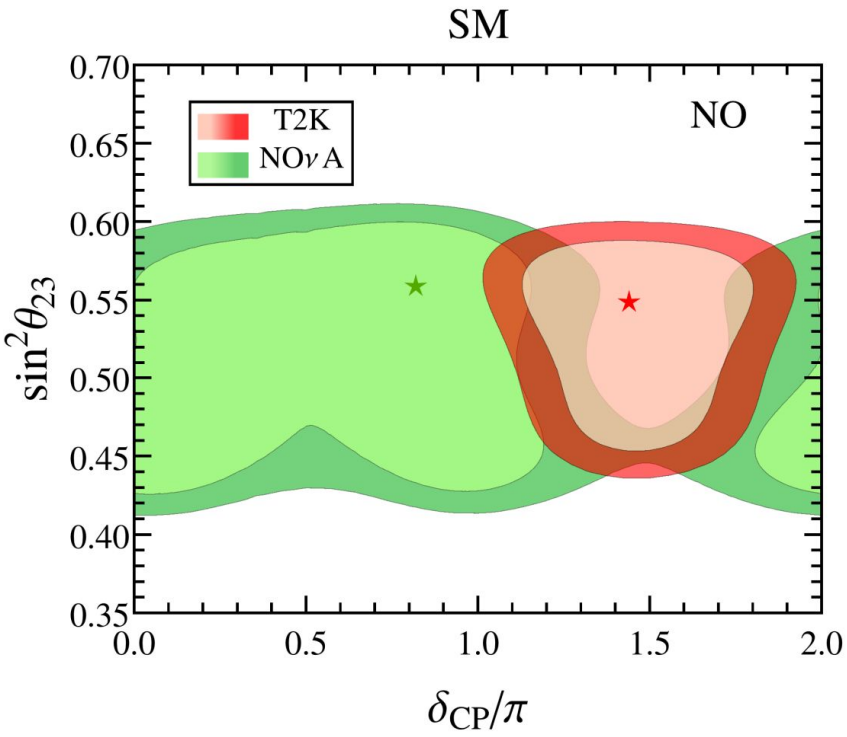
- Compare CRUST model to real data
- Kola bore – deepest bore
- Wyoming oil bore – geologically similar
- Also direct bores from the MINOS cave
- 3.7% uncertainty

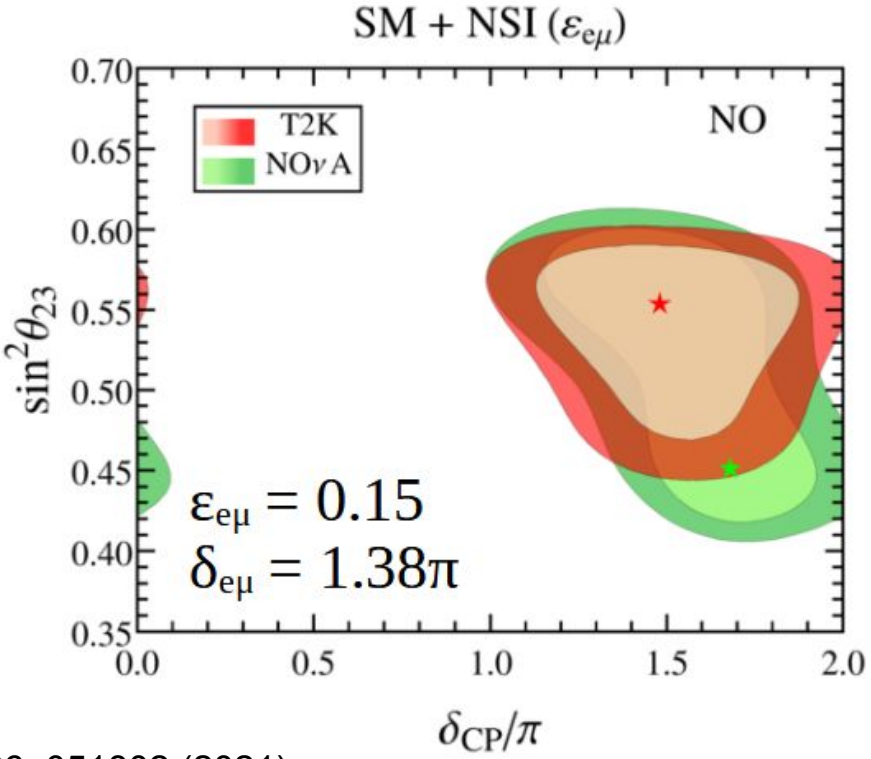




Kola Data: Acta Geodyn. Geomater., Vol. 11, No. 2 (174), 165–174, 20141

NOvA-T2K + NSI Motivation





Phys. Rev. Lett. 126, 051802 (2021)

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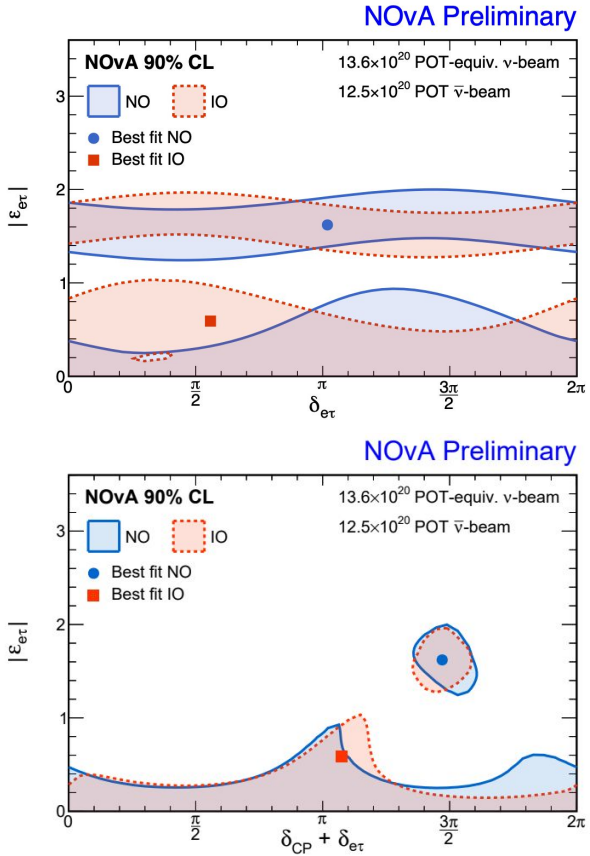
NSI & (δ_{cp} + $\delta_{e\tau}$)

- $P(\nu_\mu \rightarrow \nu_e)$
  - ~ sin δ_{CP} & cos δ_{CP} terms
  - ~ $\varepsilon_{e\tau}$ sin (δ_{CP} + $\delta_{e\tau}$), $\varepsilon_{e\tau}$ cos (δ_{CP} + $\delta_{e\tau}$)
- A $\varepsilon_{e\tau}$ grows, δ_{CP} + $\delta_{e\tau}$ terms become dominant effect
  - Largest terms are proportional to $\varepsilon_{e\tau}$ cos(δ_{cp}+$\delta_{e\tau}$)
  - Similar in $\varepsilon_{e\mu}$
- Measure vs δ_{cp}+$\delta_{e\tau}$

Improves Sensitivity

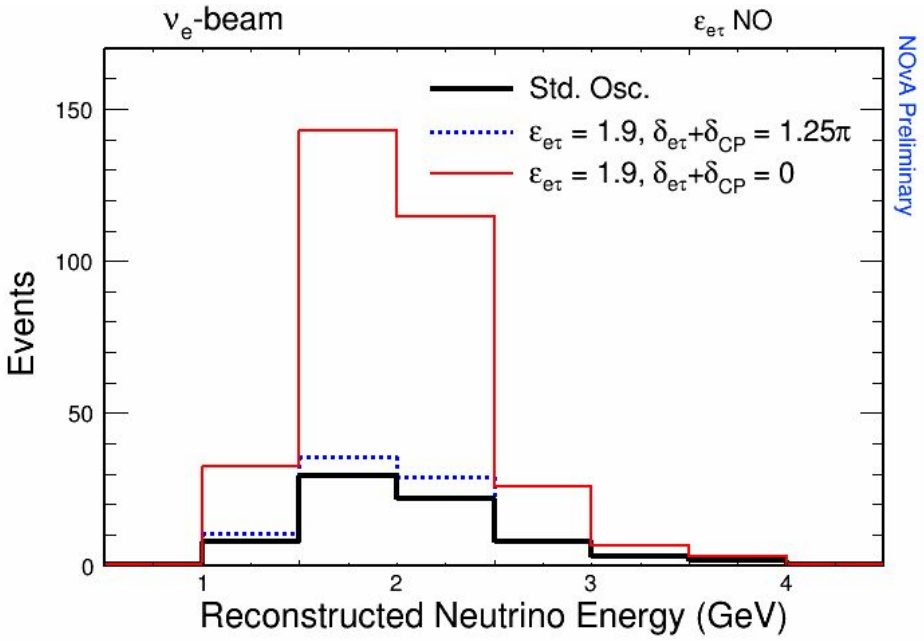


Slide courtesy of Jeffrey Kleykamp

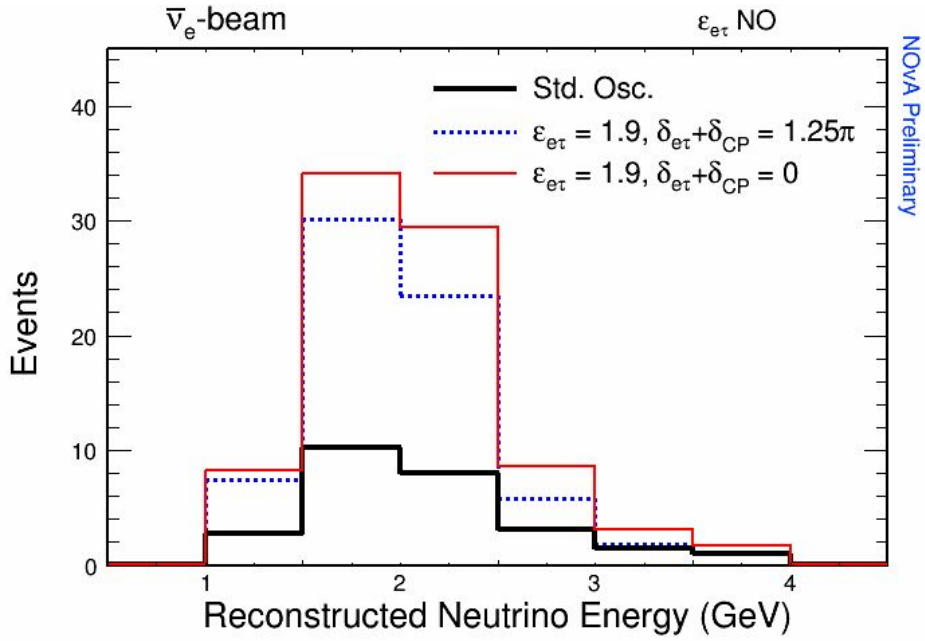
NSI Degeneracy

Degeneracy & large NSI

Neutrino Mode



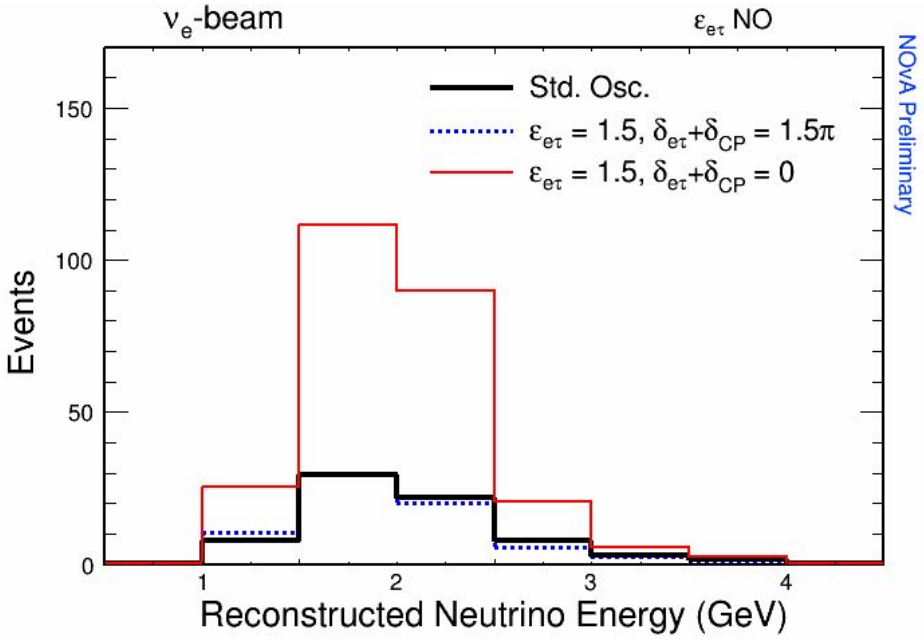
Antineutrino Mode



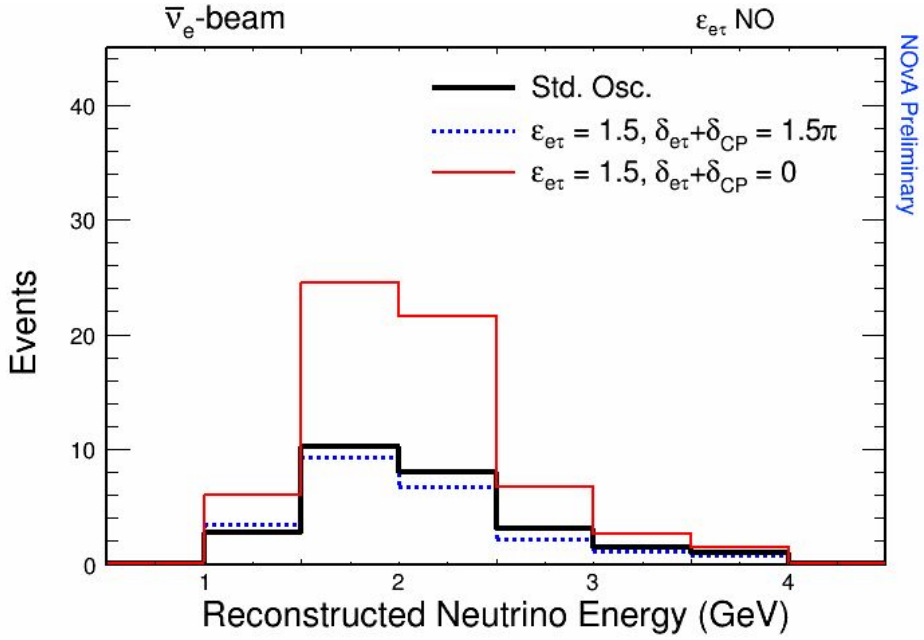
The joint neutrino-antineutrino fit breaks most of the degeneracies (Dashed blue curve of interest)

Degeneracy & large NSI

Neutrino Mode

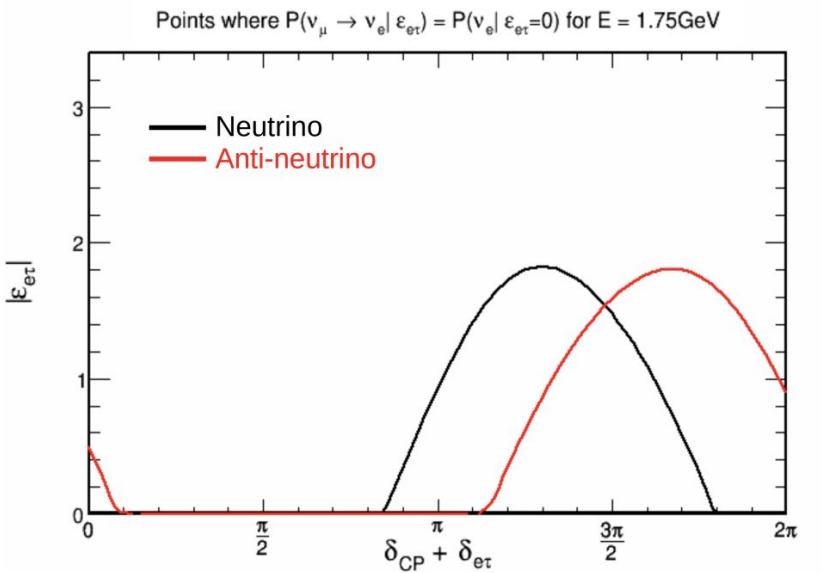


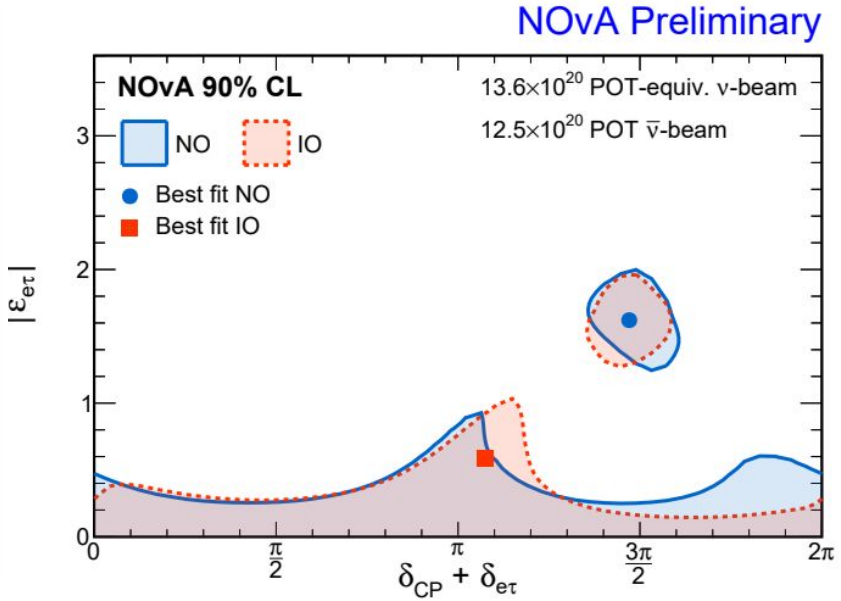
Antineutrino Mode



For a certain combination of parameters, NSI pred. ~ Std.Osc. pred (Dashed blue curve of interest)

Degeneracy & large NSI





Loss of sensitivity for points where Standard Oscillation prediction equals the NSI prediction; leads to a degeneracy for *large* NSI

NSI Results

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NSI Results

Parameter	Best Fit Value	
	Normal Ordering	Inverted Oredering
$\lvert\varepsilon_{e\mu}\rvert$	0.0659	0.0707
$\delta_{e\mu}\,(\pi)$	1.8288	0.0082
$\sin^2(\theta_{23})$	0.5725	0.4497
$\Delta m^2_{32}\,(\mathrm{eV}^2)$	2.4201	-2.4523
$\delta_{CP}\,(\pi)$	1.0242	1.4890
χ^2	173.2472	173.6535

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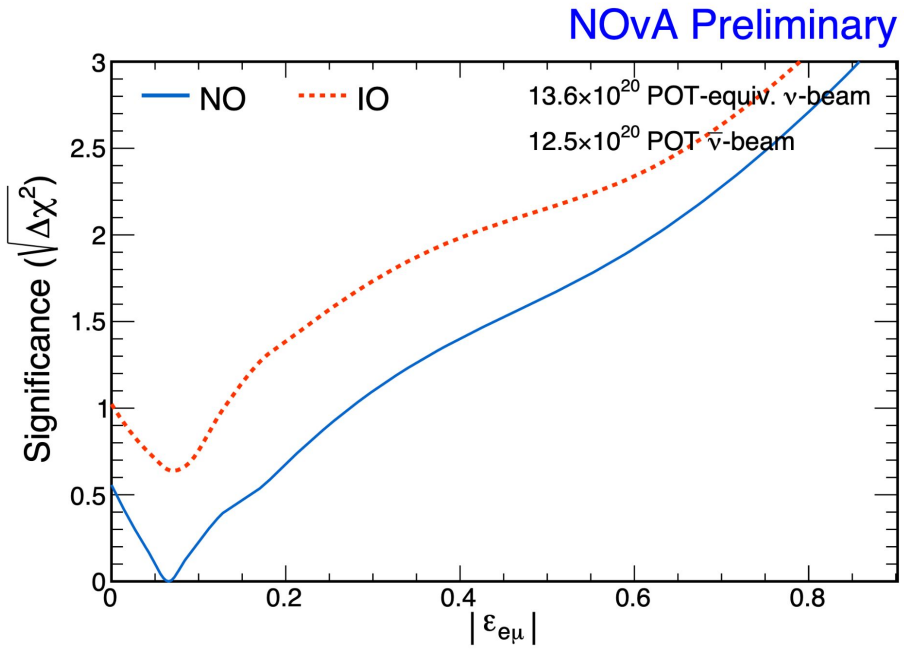
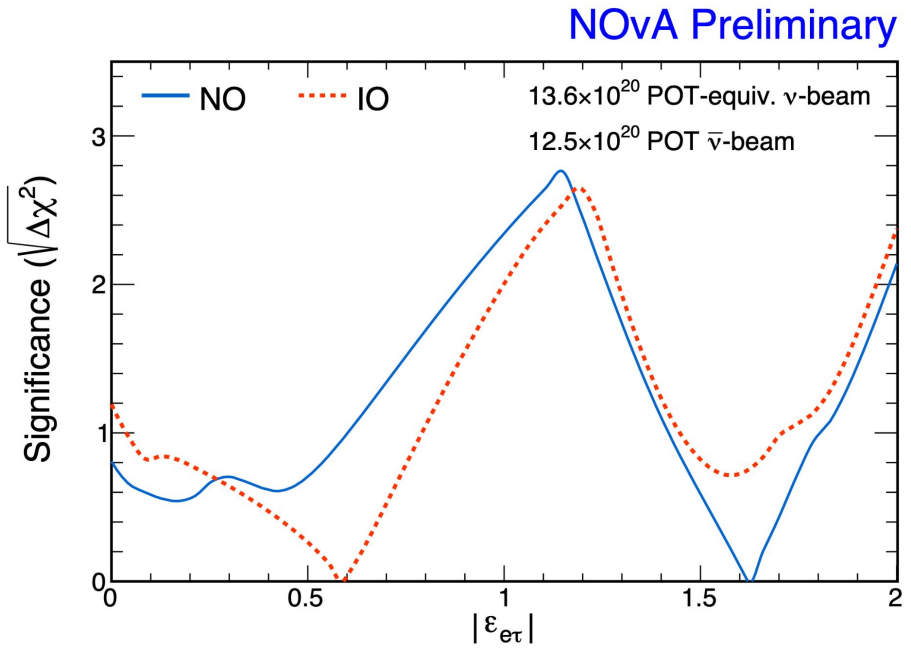
NSI Results

Parameter	Best Fit Value	
	Normal Ordering	Inverted Oredering
$\lvert\varepsilon_{e\tau}\rvert$	1.6208	0.5908
$\delta_{e\tau}\,(\pi)$	1.0185	0.5580
$\sin^2(\theta_{23})$	0.4481	0.5748
$\Delta m^2_{32}\,(\mathrm{eV}^2)$	2.4480	-2.4503
$\delta_{CP}\,(\pi)$	0.4522	0.5173
χ^2	172.9054	172.8716

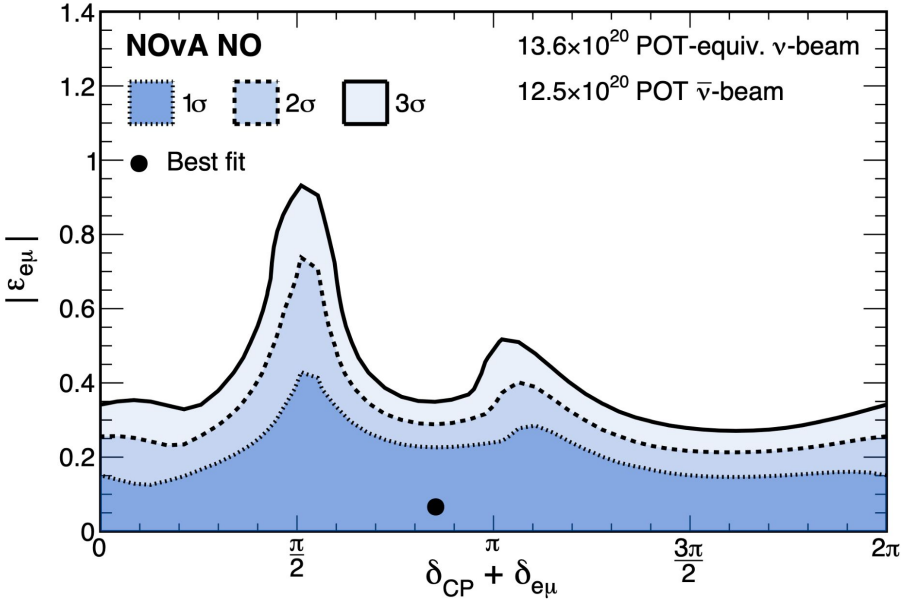
NSI Results


NOvA Preliminary
NO
IO
13.6×10^20 POT-equiv. ν-beam
12.5×10^20 POT ν̄-beam
Significance ($|\sqrt{\Delta\chi^2}|$)
$|\varepsilon_{e\mu}|$

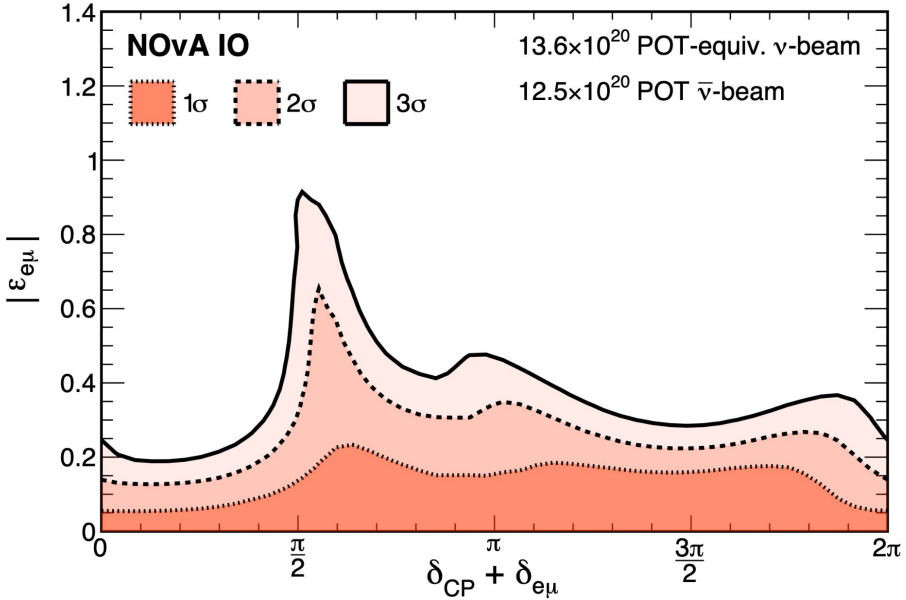

NOvA Preliminary
NO
IO
13.6×10^20 POT-equiv. ν-beam
12.5×10^20 POT ν̄-beam
Significance ($|\sqrt{\Delta\chi^2}|$)
$|\varepsilon_{e\tau}|$

NSI Results

NOvA Preliminary

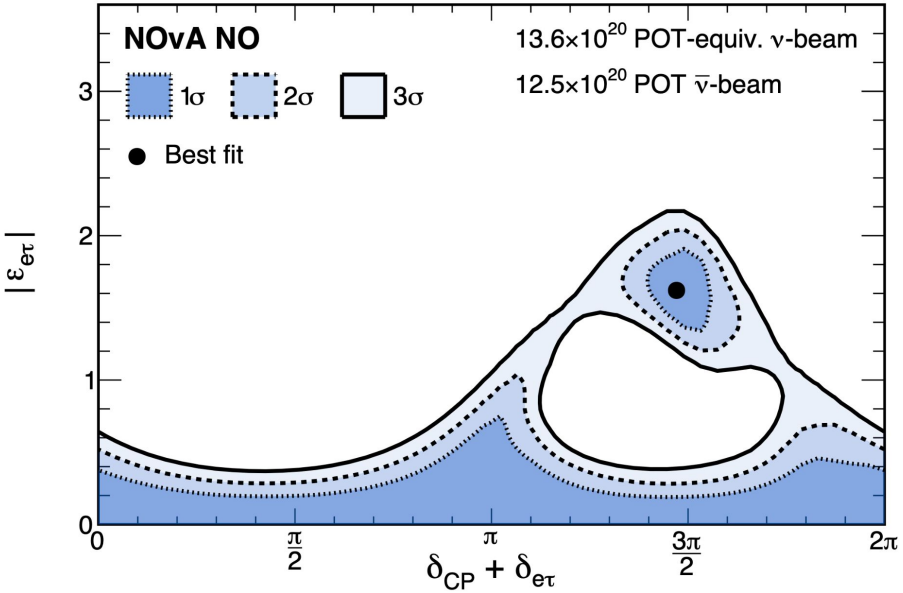


NOvA Preliminary

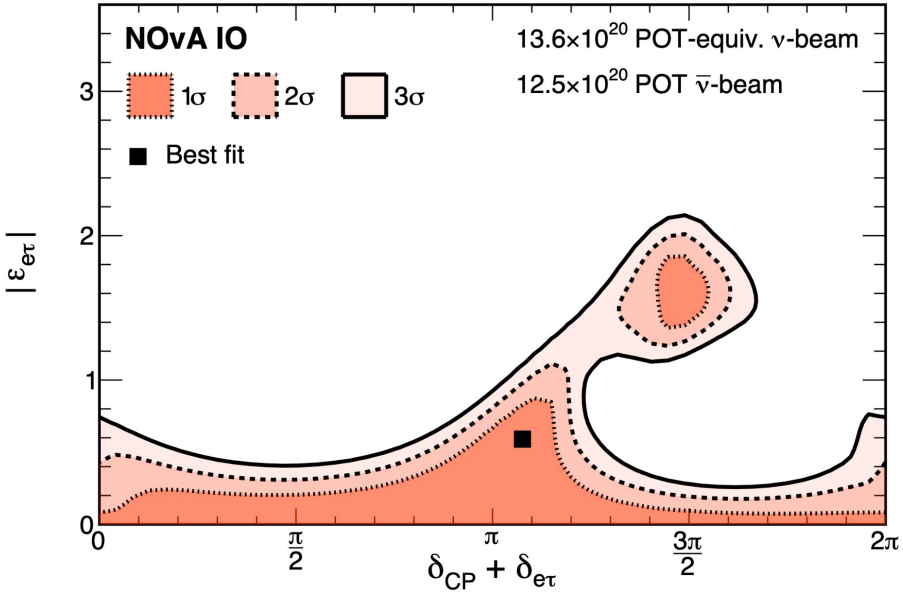


NSI Results

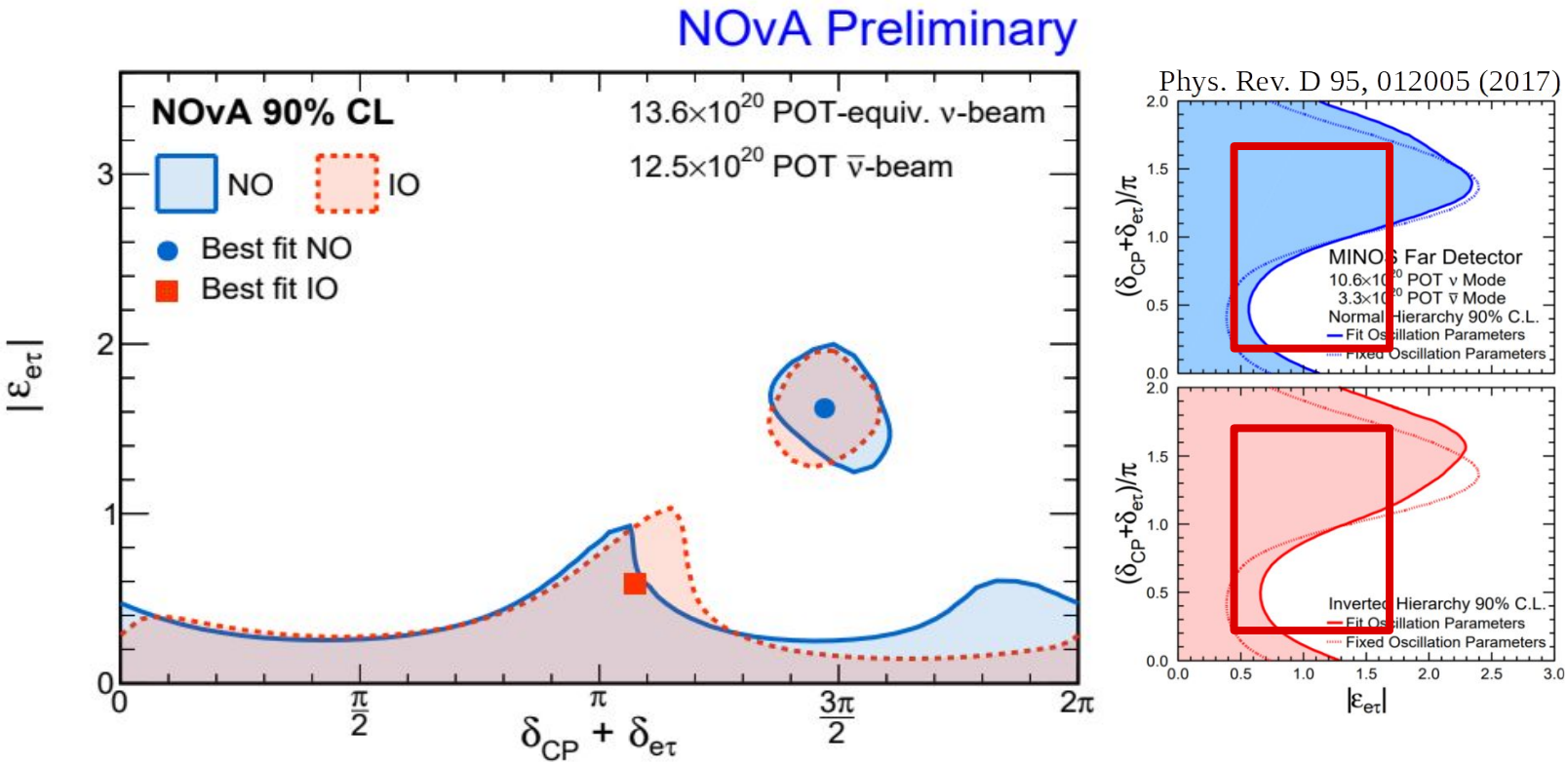
NOvA Preliminary



NOvA Preliminary

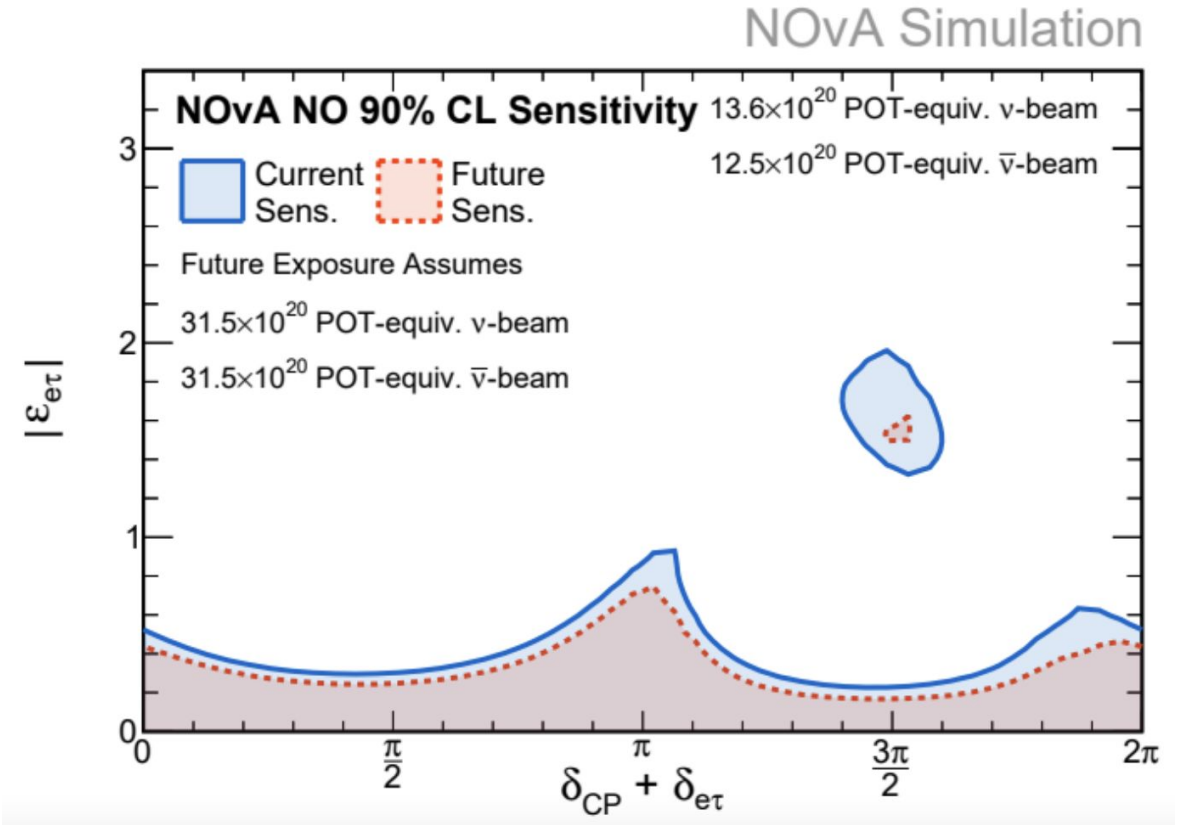


Results: comparison to MINOS



Complementary to previous measurements from the MINOS Experiment

Future Sensitivity



Addition of statistics is not enough to resolve the degeneracy.

Exploring improvements for the next NSI analysis!