FERMILAB-SLIDES-23-352

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

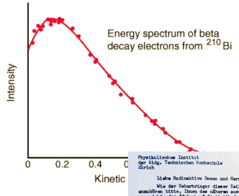
**BSM 2023**
**Hurghada - Egypt**

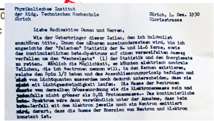
**Luiz R. Prais,**
**On Behalf of the NOvA Collaboration**

November 09, 2023

# Neutrinos: an exciting timeline!

$\beta$ decay issues





Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

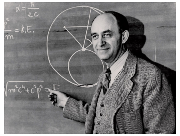
Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

c. 1930

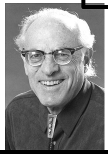
W. Pauli



E. Fermi

The neutrino is proposed

C. Cowan



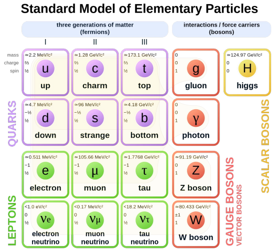
F. Reines

1956

Discovery!

$\nu_e$

1995




1962

$\nu_\mu$

1988

Solar

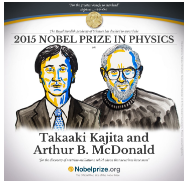
$\nu$

2002

2000

$\nu_\tau$

$\nu$ Oscillations

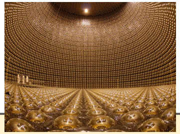


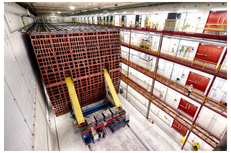

2000's

2015

Neutrino Era

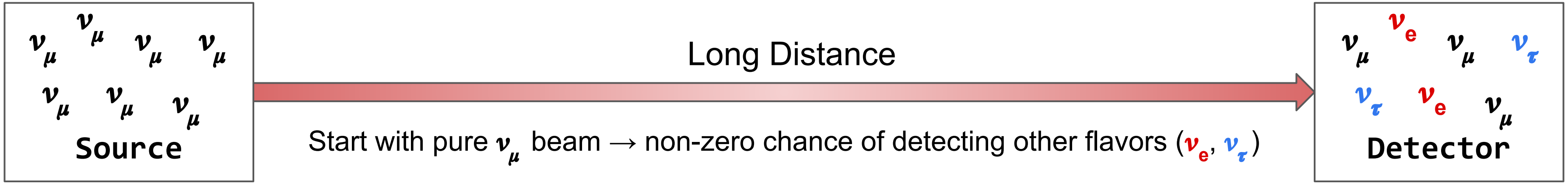
T2K





..and many **more**!

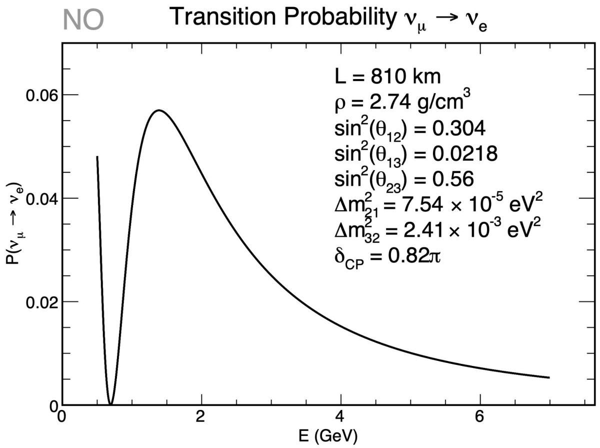
# Neutrino Oscillations




**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

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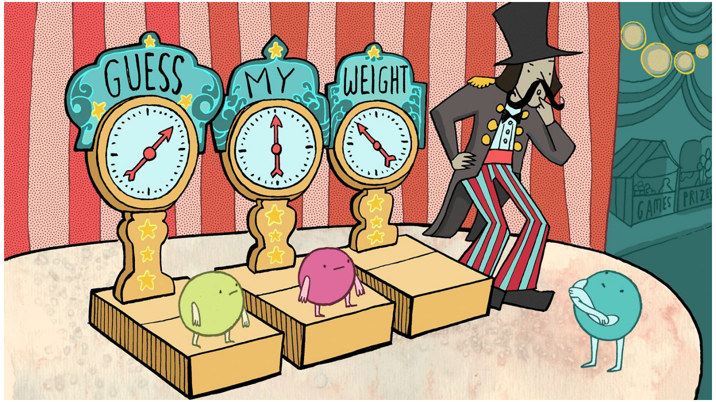
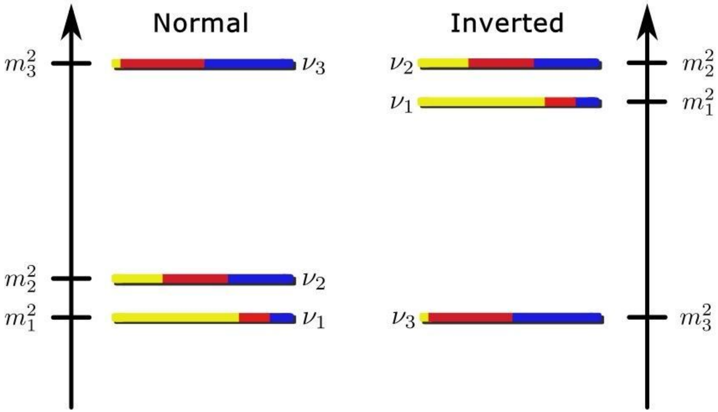
# Outstanding Questions & This Talk

NOvA

- What is the mass ordering of neutrinos?

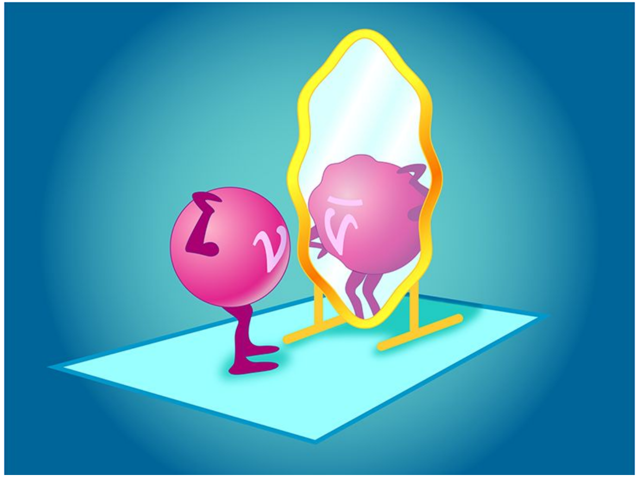
https://neutrinos.fnal.gov/mysteries/mass/




- Is there CP-Violation in the Lepton sector?

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




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

?

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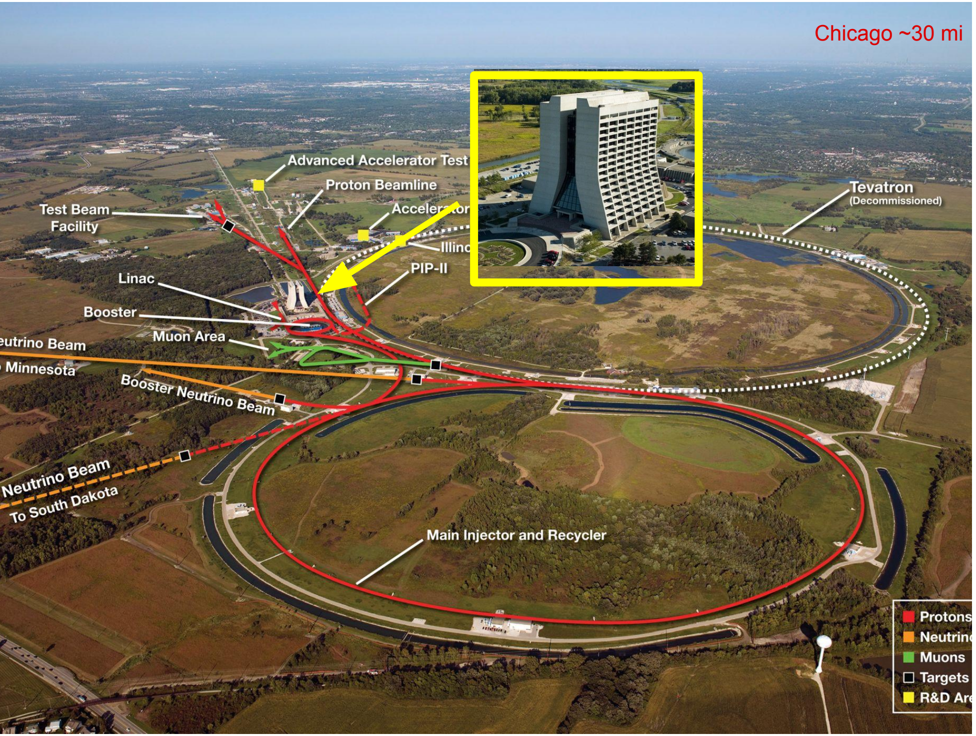
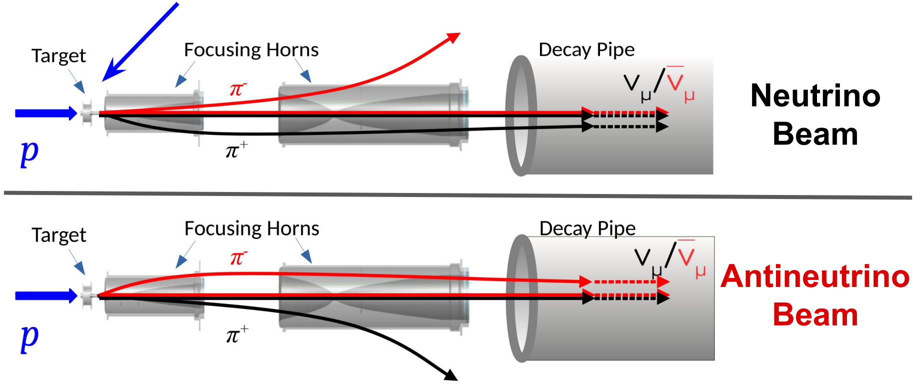
# Making neutrinos at Fermilab

NOvA

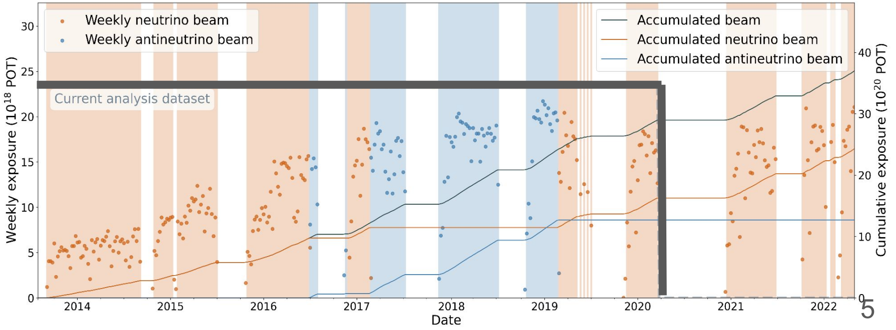
★ **Produce a 120 GeV proton beam**



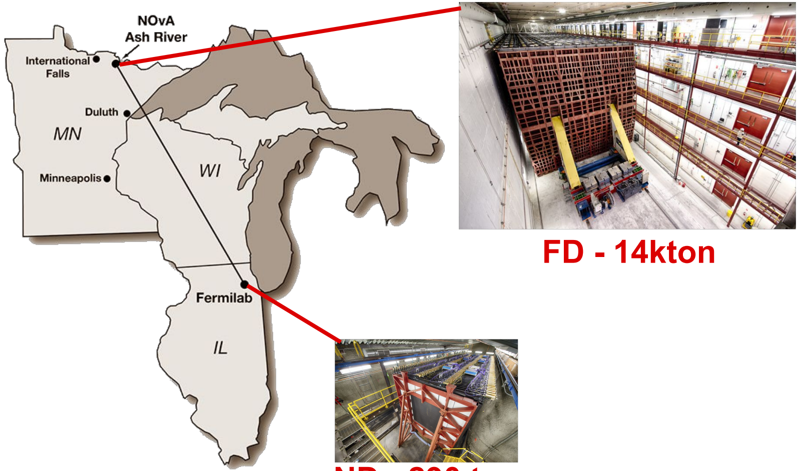

**Collide protons with a fixed target**




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



# The NOvA Experiment



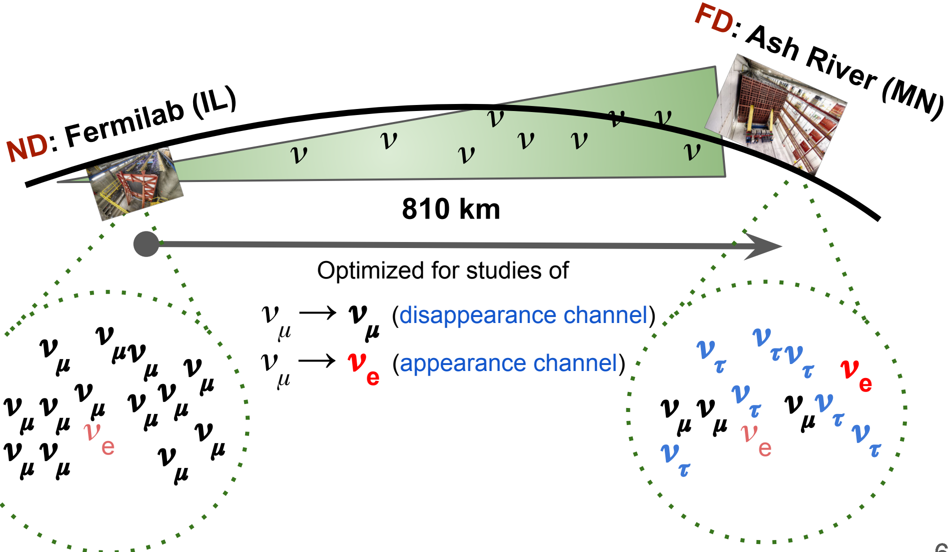

FD - 14kton

ND - 290 ton


★ **2 detector long-baseline neutrino experiment using accelerator neutrinos produced at Fermilab**

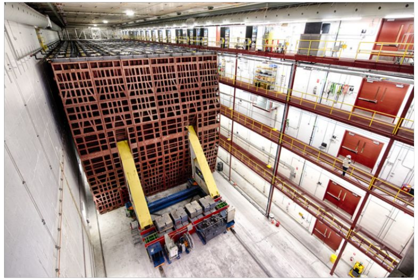
➢ **Near Detector (ND)**: measures neutrino flux before oscillations

➢ **Far Detector (FD)**: measures oscillated neutrino flux

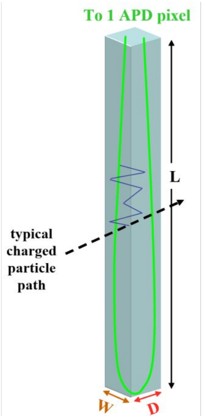


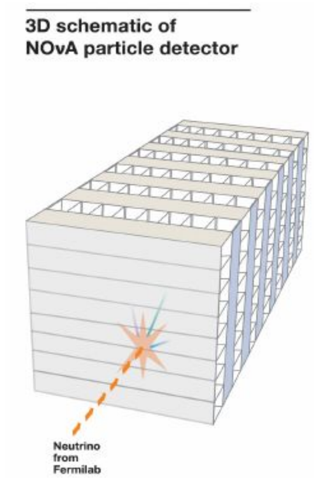
# The NOvA Experiment

Near Detector
**4m x 4m x 15.6 m**
underground



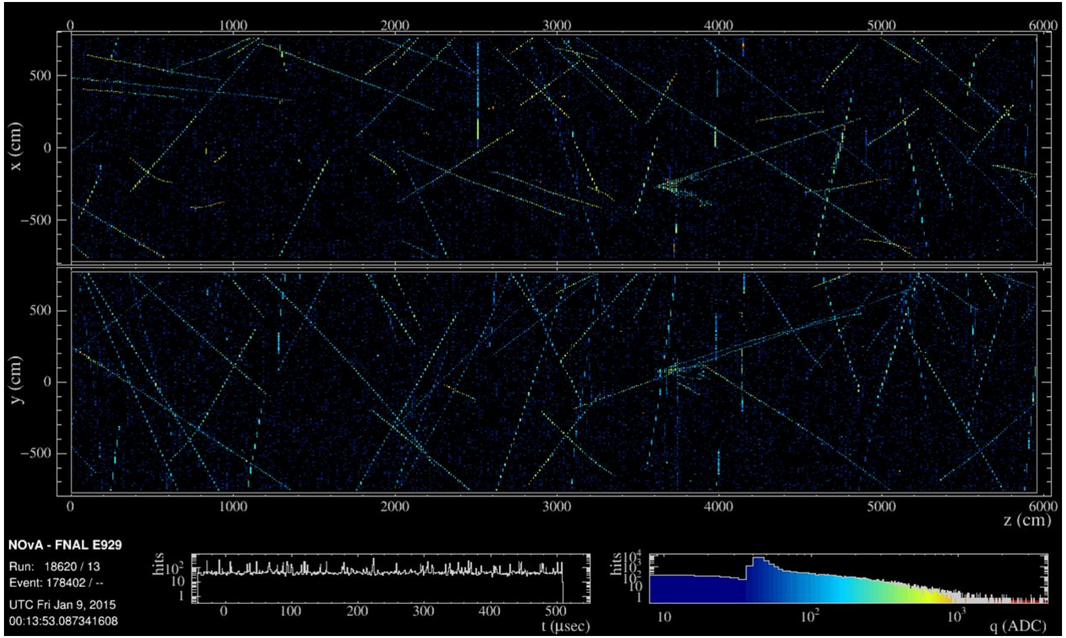
Far Detector
**15.5m x 15.5m x 60 m**
surface




each cell = 1 pixel

**Color denotes charge**



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Near Detector
**4m x 4m x 15.6 m**
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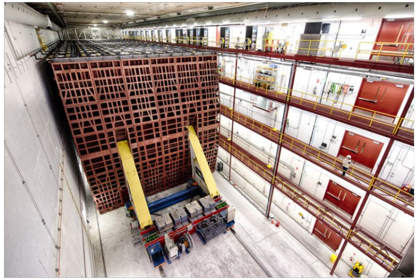

Far Detector
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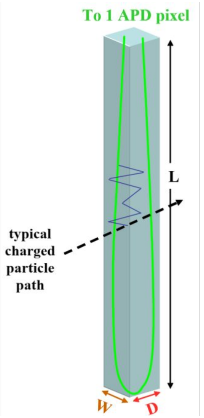
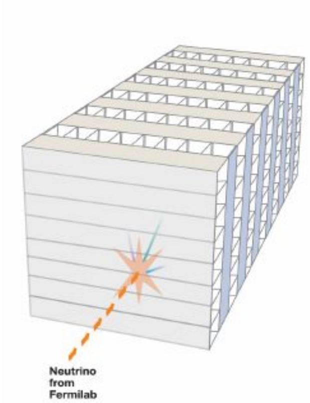
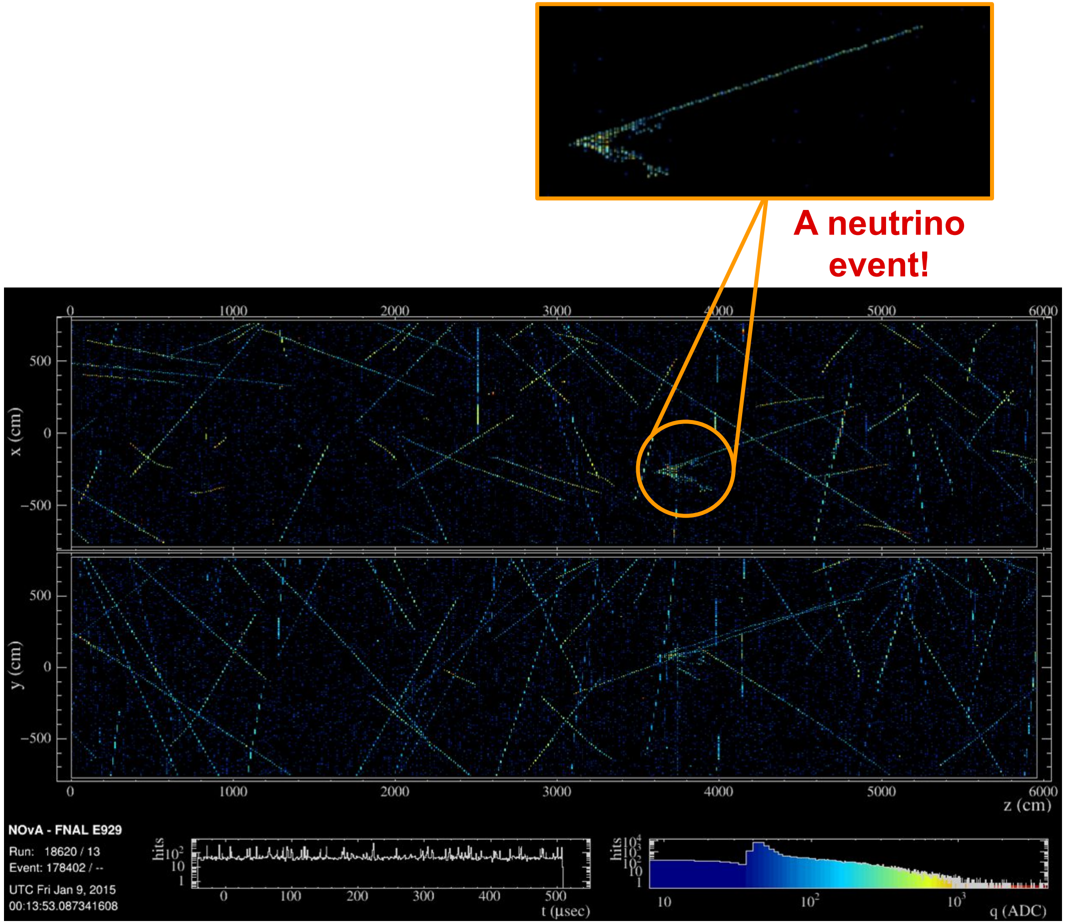



3D schematic of NOvA particle detector



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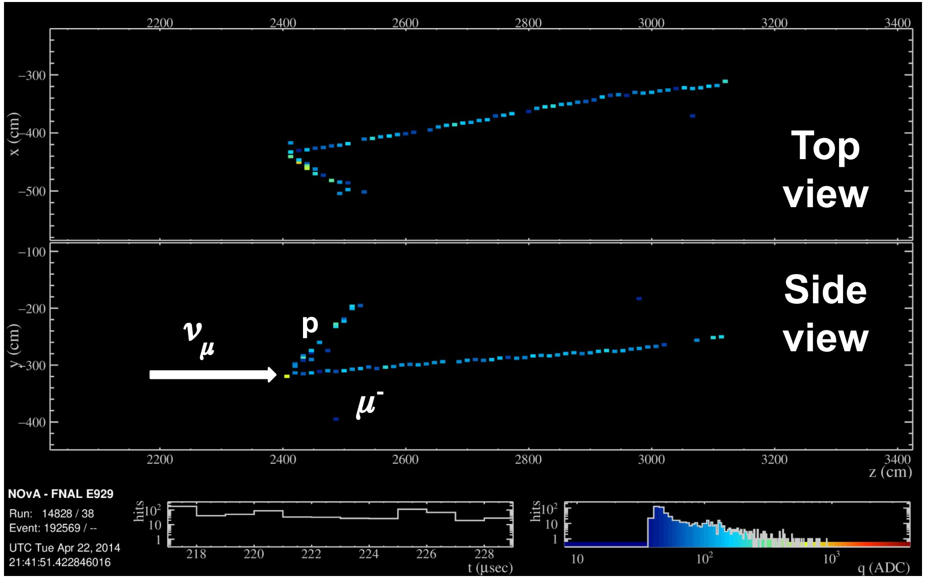
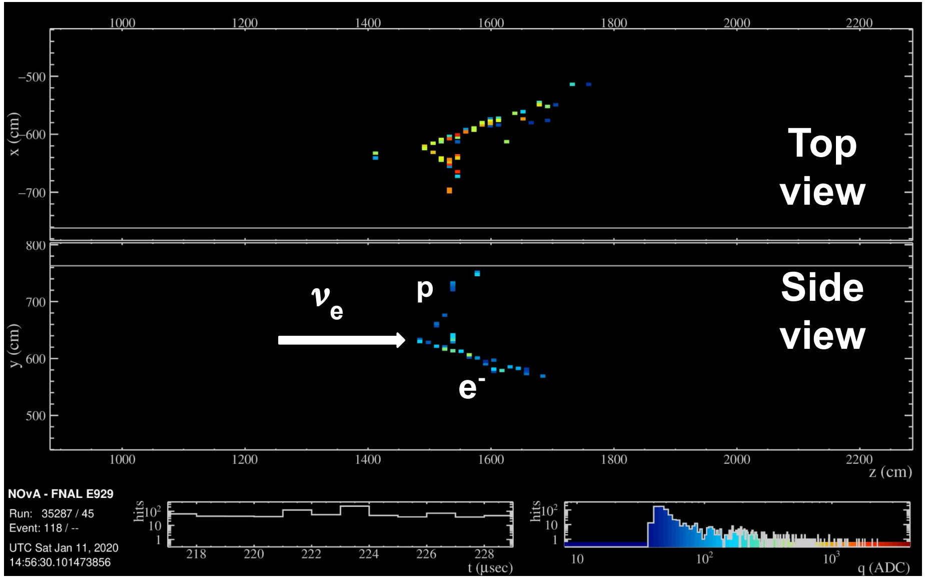
# Event Topologies

## Far Detector Event Displays




Muon neutrinos produce a characteristic long track



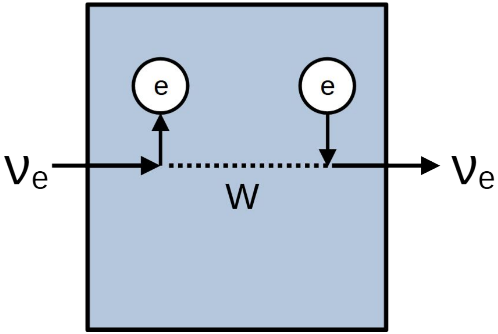

Electron neutrinos have shorter fuzzier tracks

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

# Non-Standard Interactions


https://www.particlezoo.net/

# First: Standard Matter Effect




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

$\nu_e$ different from $\nu_\mu$ and $\nu_\tau$ in matter

$\nu_e$ scatters coherently against matter's electron cloud

PHYSICAL REVIEW D VOLUME 17, NUMBER 9 1 MAY 1978

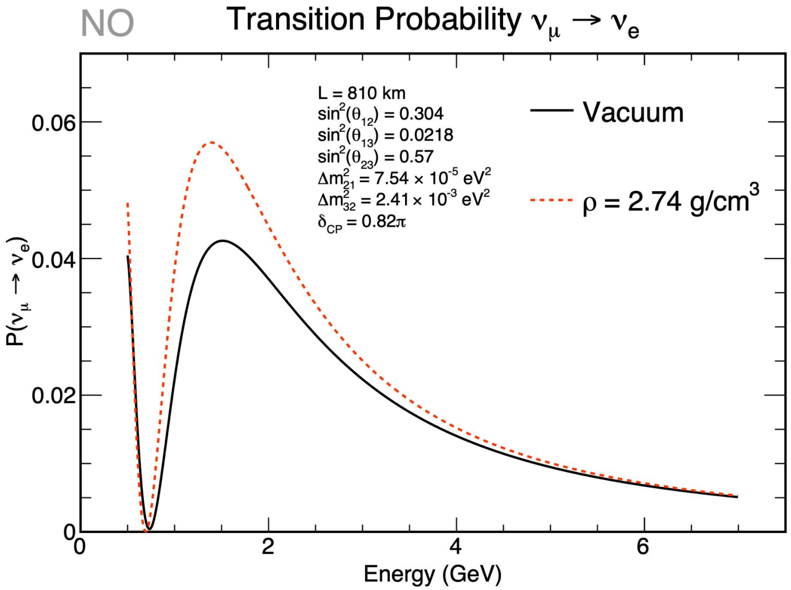
**Neutrino oscillations in matter**

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.

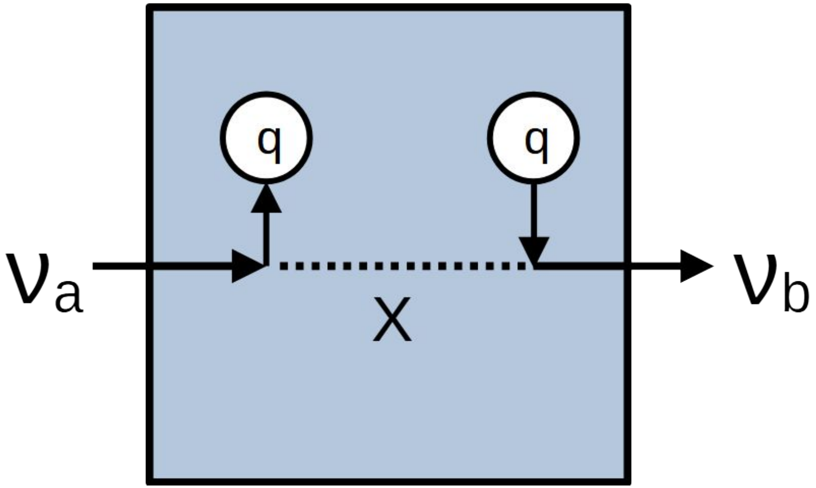



Important for our experiment's long baseline!

# 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**

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

**$\varepsilon$ can be seen as the strength of NSI**

PHYSICAL REVIEW D VOLUME 17, NUMBER 9 1 MAY 1978

Neutrino oscillations in matter

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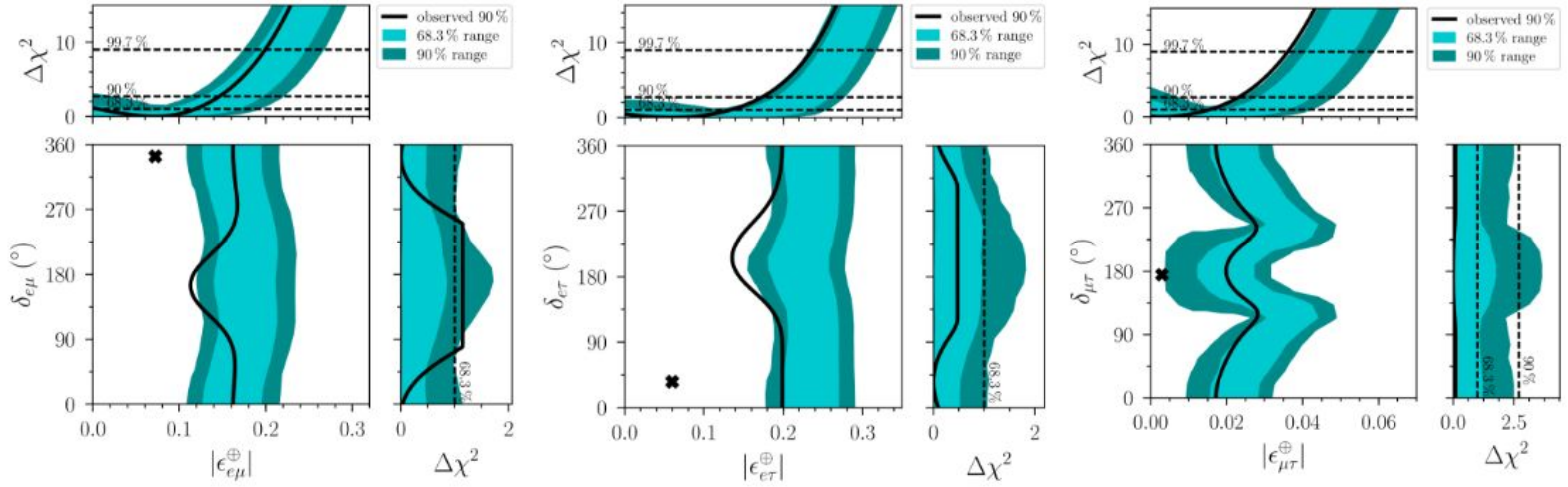
**NSI predicted by the same landmark paper**

# NSI: Recent Results from IceCube

- **IceCube (2021)**
- Tight constraints on NSI using atmospheric neutrinos
- Assumes $\delta_{CP} = 0$

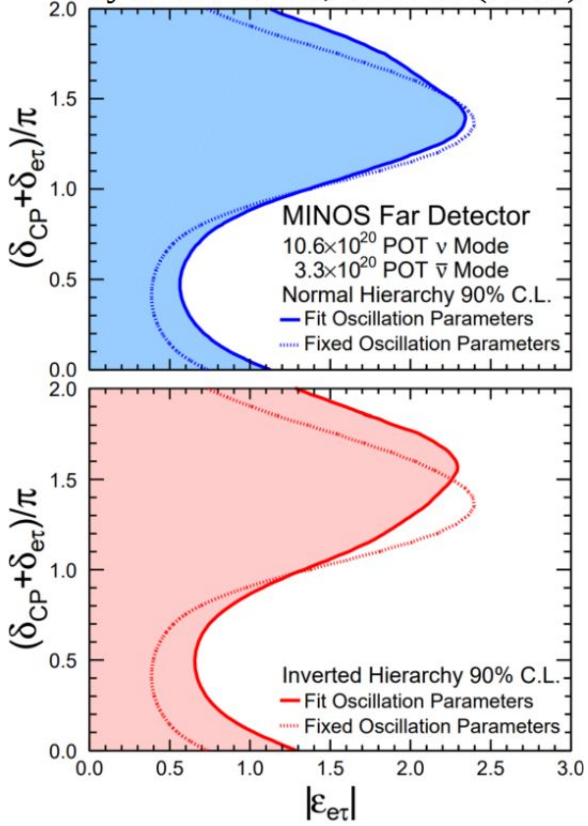
Phys. Rev. D104(Oct, 2021) 072006



# NSI: Recent Results from MINOS

- **MINOS (2017)**
- Investigate $\varepsilon_{e\tau}$ and it's effective phase ($\delta_{CP} + \delta_{e\tau}$)

Phys. Rev. D 95, 012005 (2017)



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# NSI at NOvA

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

- ★ Sensitive to off-diagonal terms
- ★ focus on channels affecting $\nu_e$ 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 $\varepsilon$'s**

**If non-zero → NSI**

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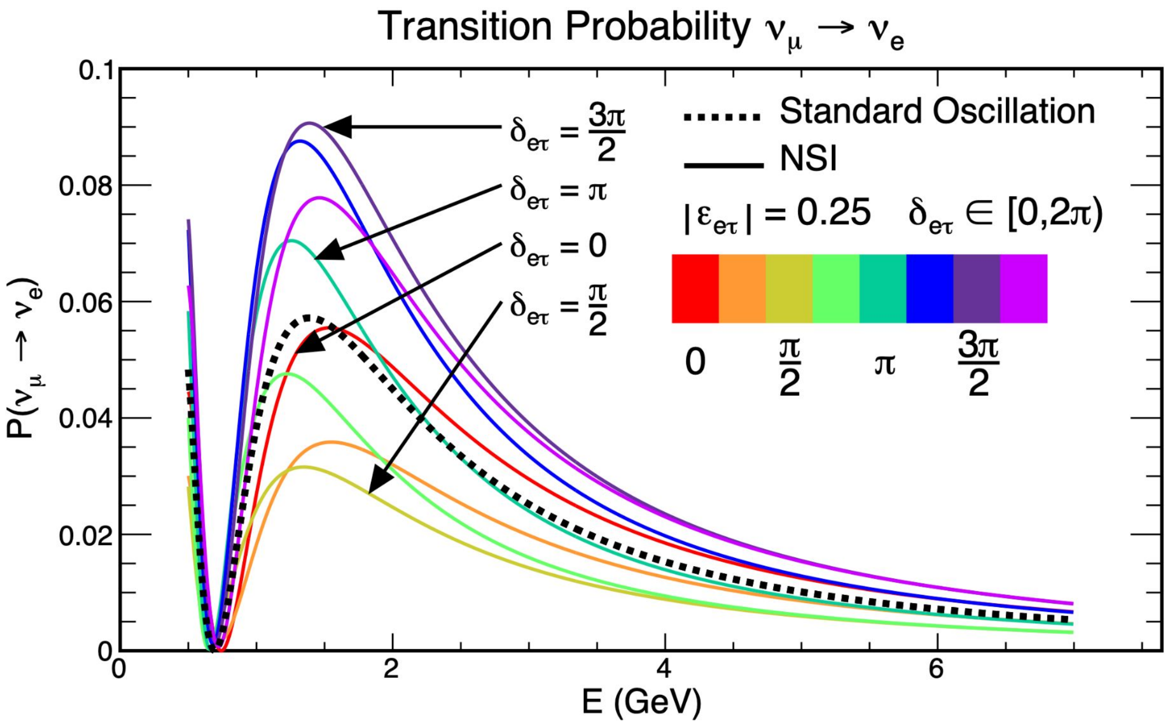
# Non-Standard Interactions (NSI)



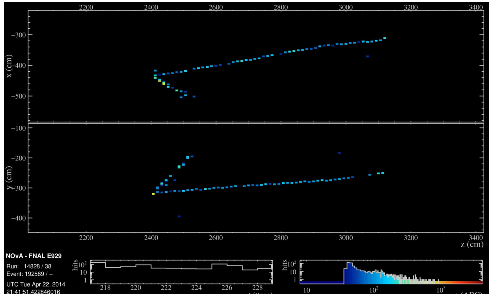

$$\varepsilon_{\alpha\beta} = |\varepsilon_{\alpha\beta}|\, e^{i\delta_{\alpha\beta}}$$

**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

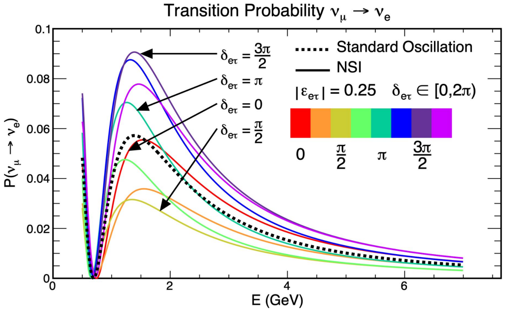
## Data




| | | | |
|---|---|---|---|
| $\nu_\mu$ | 211 | $\nu_e$ | 82 |
| $\bar{\nu}_\mu$ | 105 | $\bar{\nu}_e$ | 33 |

Phys. Rev. D 106, 032004

## NSI Model




$\sin^2(\theta_{23})$, $\Delta m^2_{32}$, $\delta_{CP}$

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

## Constraints and systematics

$\Delta m^2_{21}$ ($10^{-5}$eV$^2$) = 7.54 ± 0.19

$\sin^2\theta_{12}$ = 0.304 ± 0.042

$\sin^2\theta_{13}$ = 0.0218 ± 0.0007

$\rho$ (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

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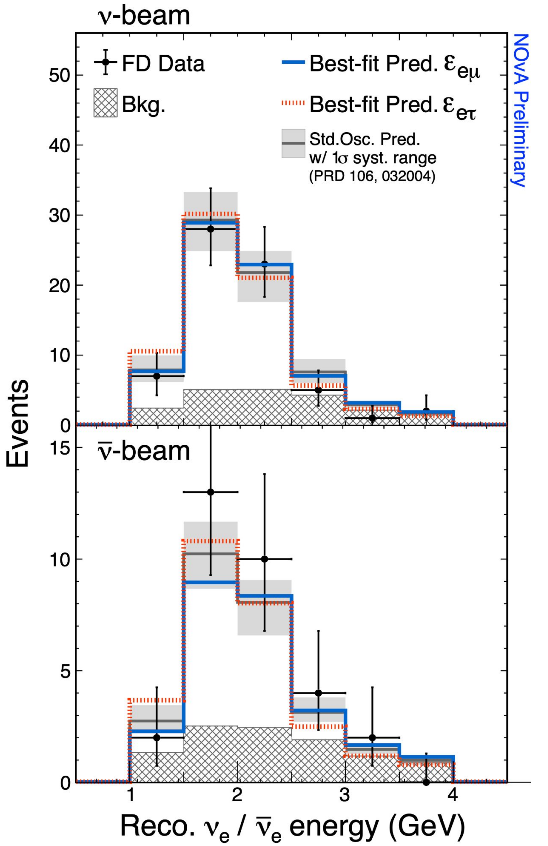
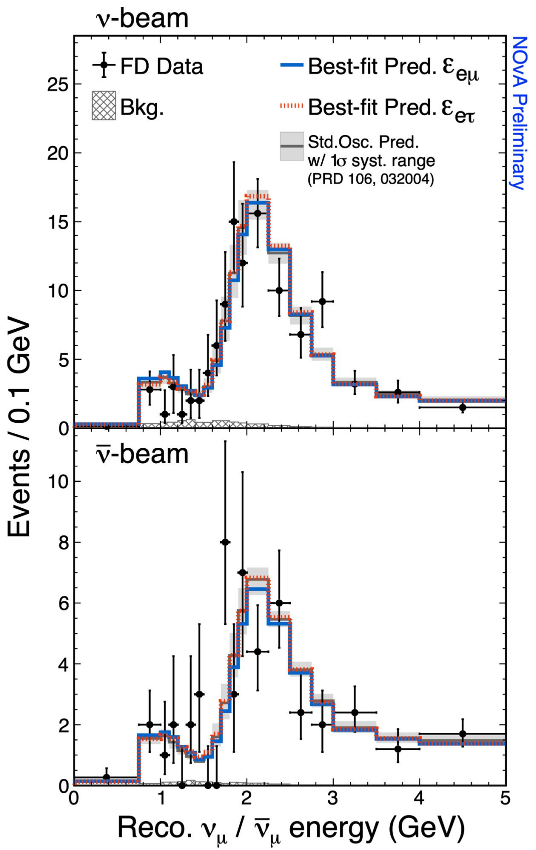
# Results




**Electron (anti)neutrino events**




**Muon (anti)neutrino events**

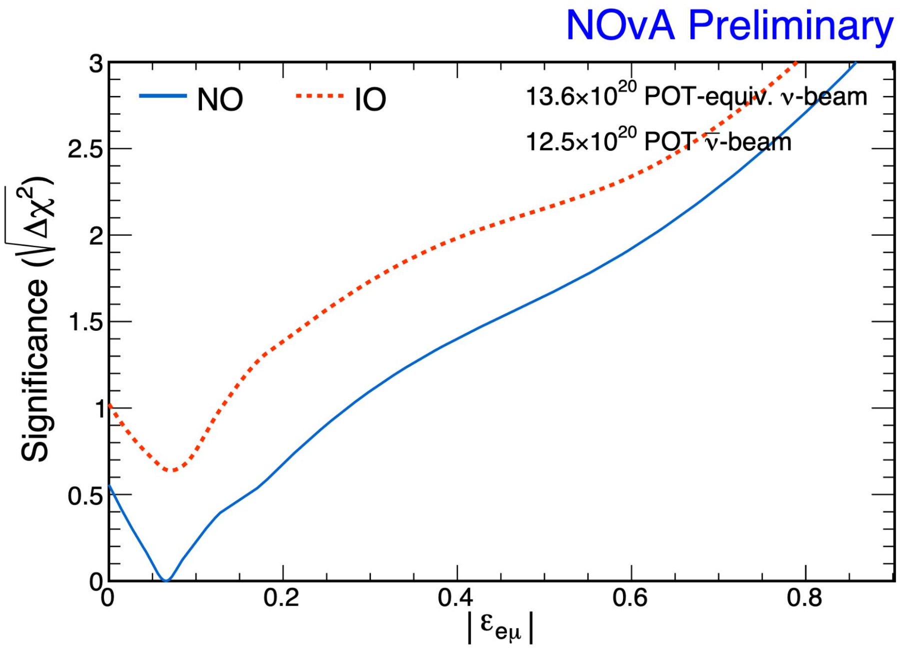
★ **Consistent with Std. Osc. within the 1-σ systematic uncertainty**

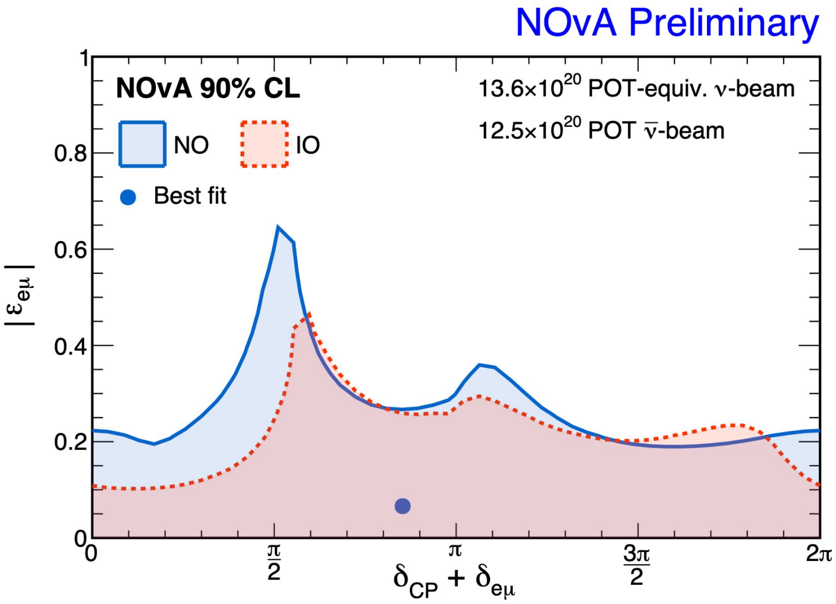
$\chi^2_{e\mu}$ = **173.3 (NO)**

$\chi^2_{e\tau}$ = **172.9 (NO & IO)**
**Degenerate best fit**

(loss of sensitivity to the ***ν*** Mass Ordering)

# Results: NSI space



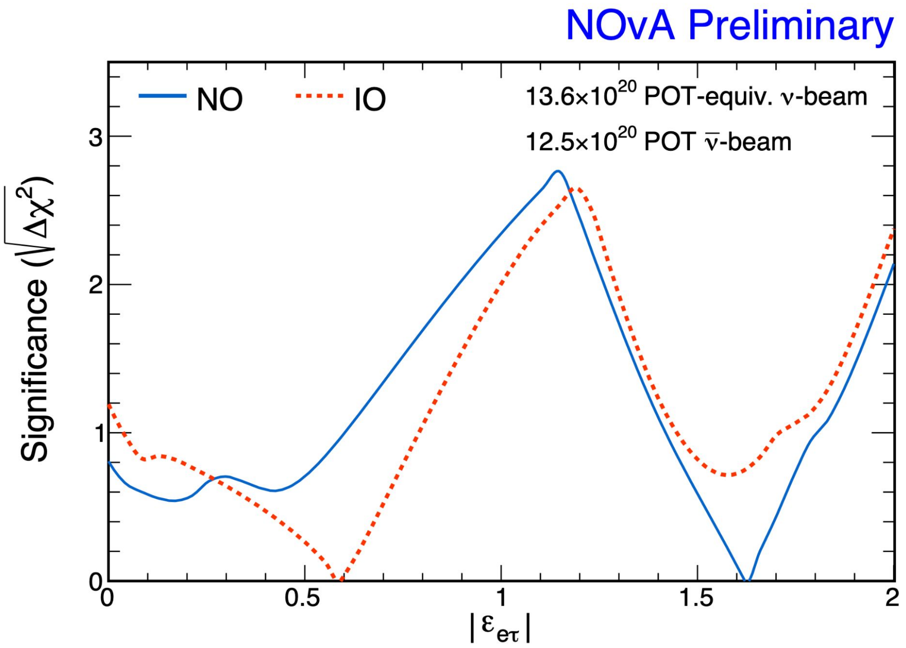



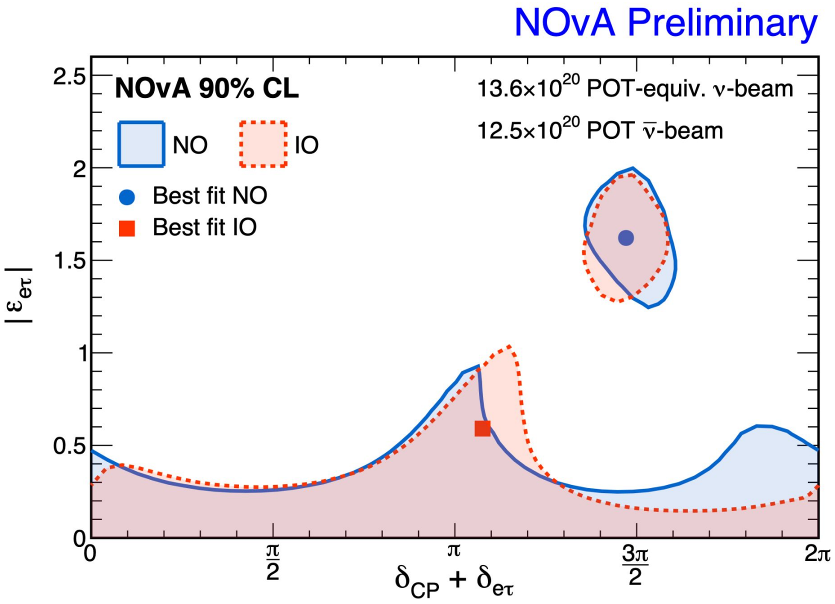

Construct an *NSI vs Effective Phase* space

**Rules out most of:**

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

# Results: NSI space



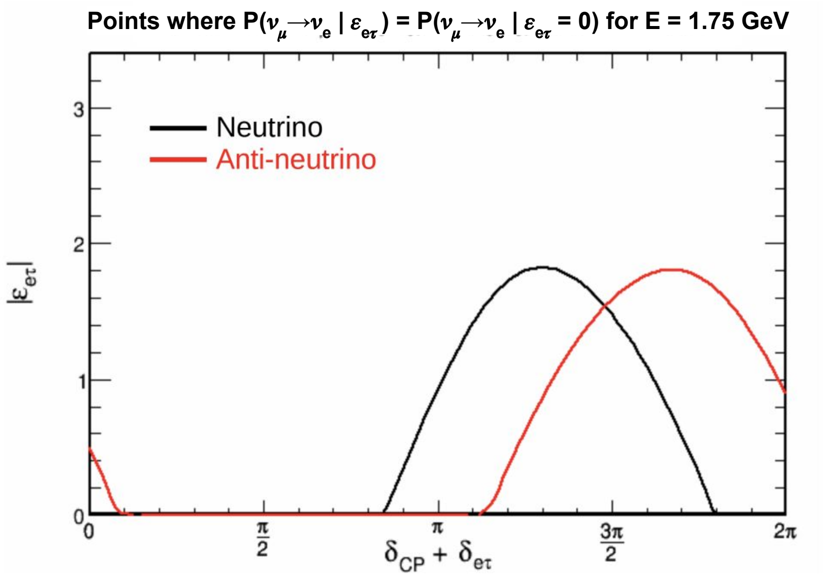



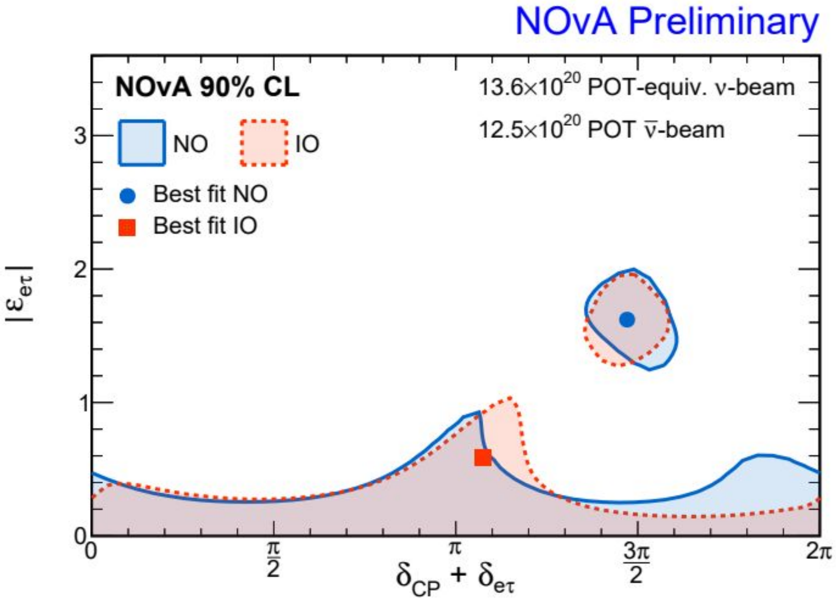

Construct an *NSI vs Effective Phase* space

**Rules out most of:**

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

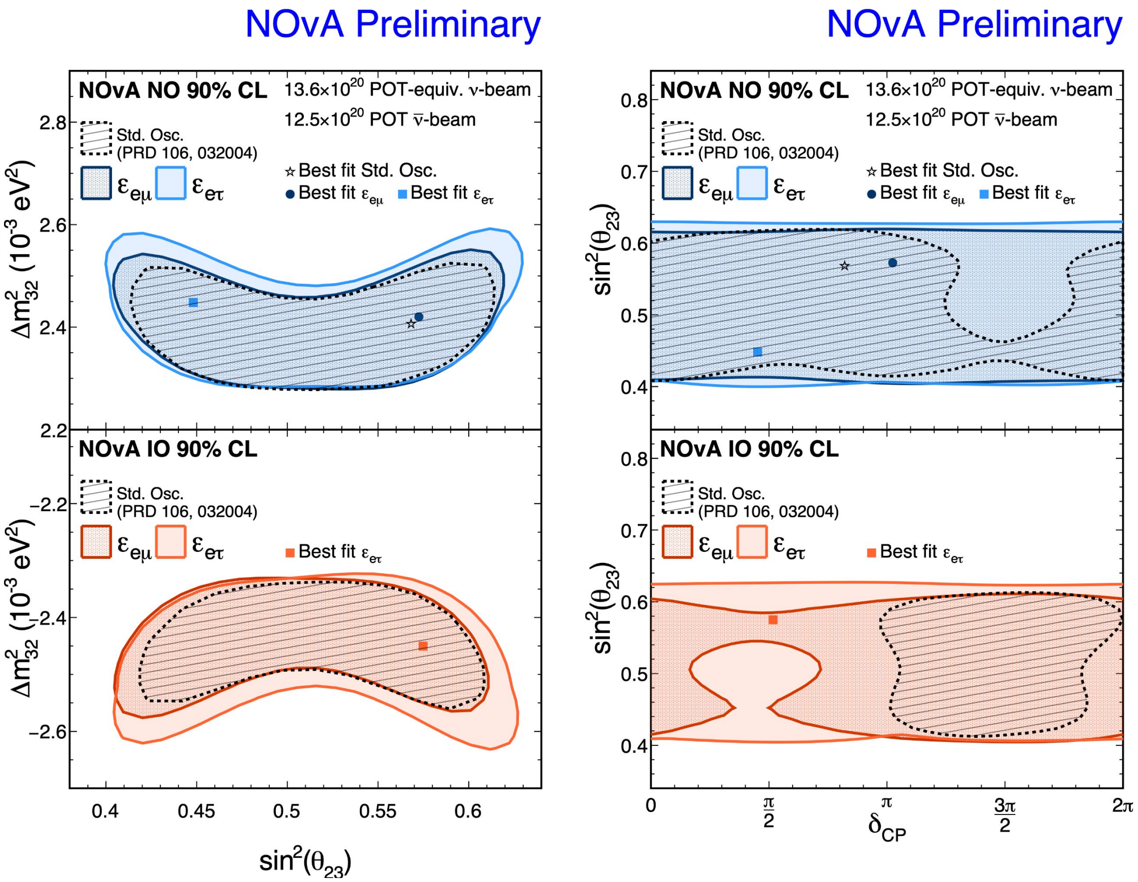
# Degeneracy & large NSI




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




★ Inclusion of NSI seem to impact our sensitivity to the standard CP-violating phase $\boldsymbol{\delta_{CP}}$

***Need* to further constrain NSI**

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# Summary

Study sponsored by
DOE Award DE-SC0021616

U.S. DEPARTMENT OF ENERGY

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

NOvA

Fermilab

Watch particles
LIVE at NOvA!

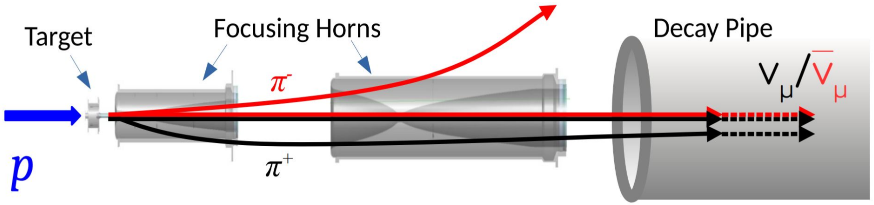
## Thank you!

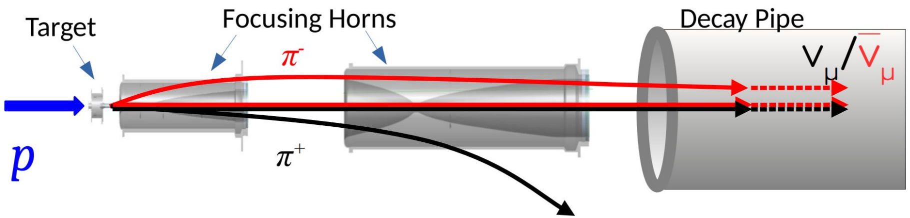
http://novaexperiment.fnal.gov

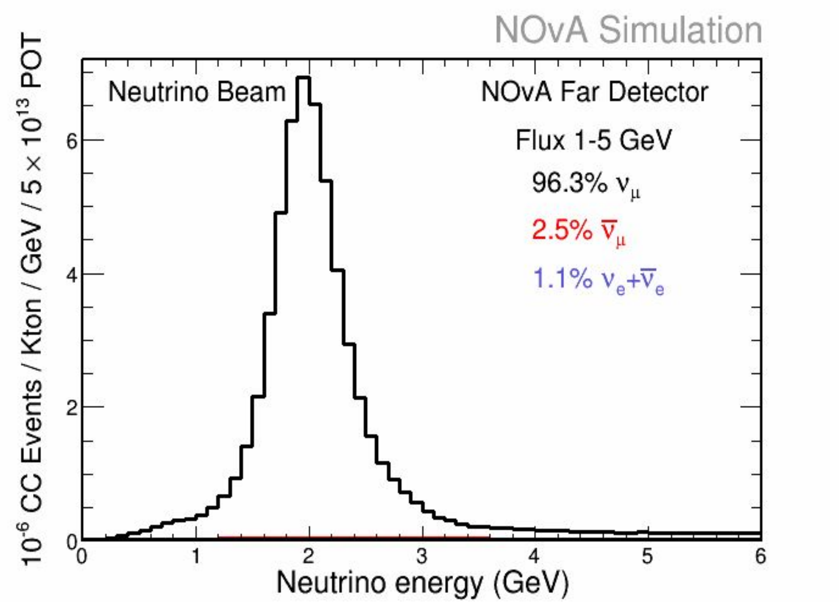
# Backup

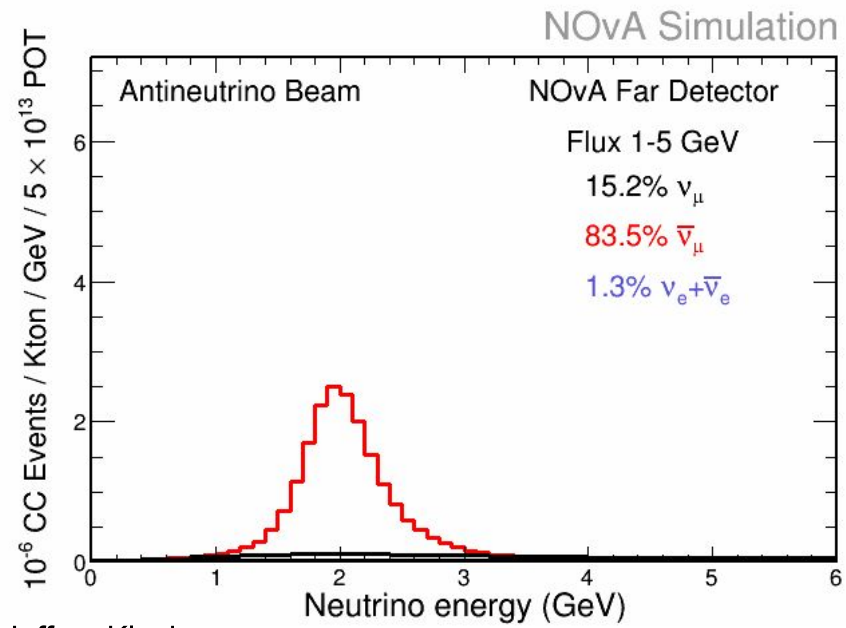
# NOvA Experiment

# Neutrinos or Antineutrinos



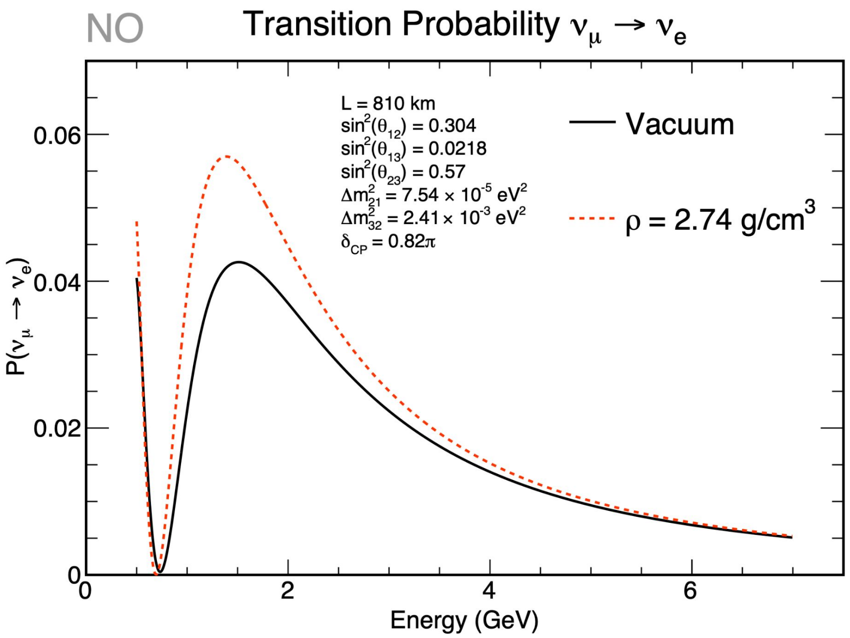



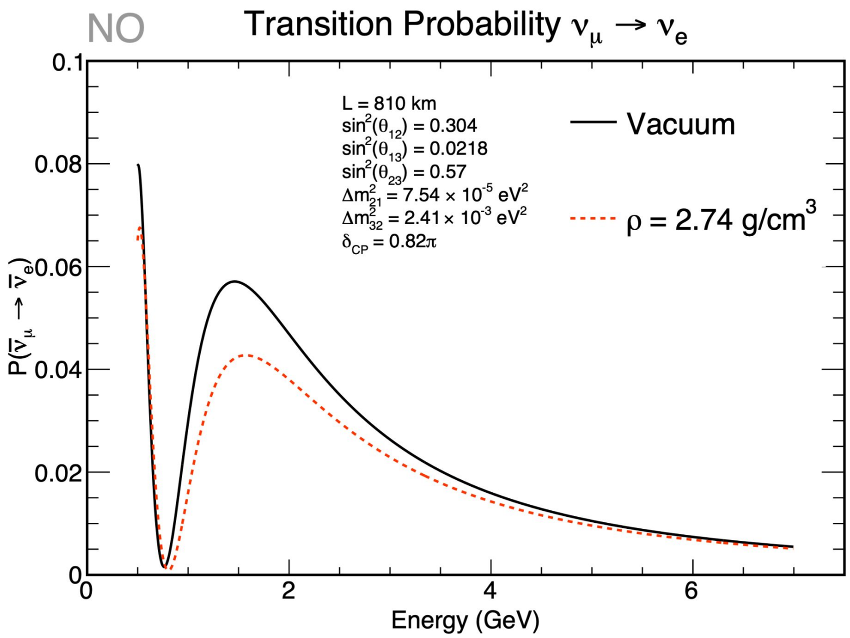




Slide courtesy of Jeffrey Kleykamp

# Neutrinos or Antineutrinos



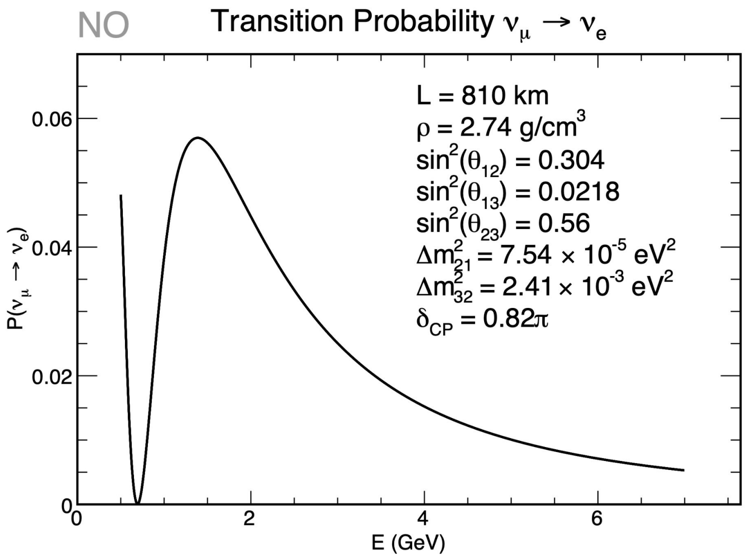



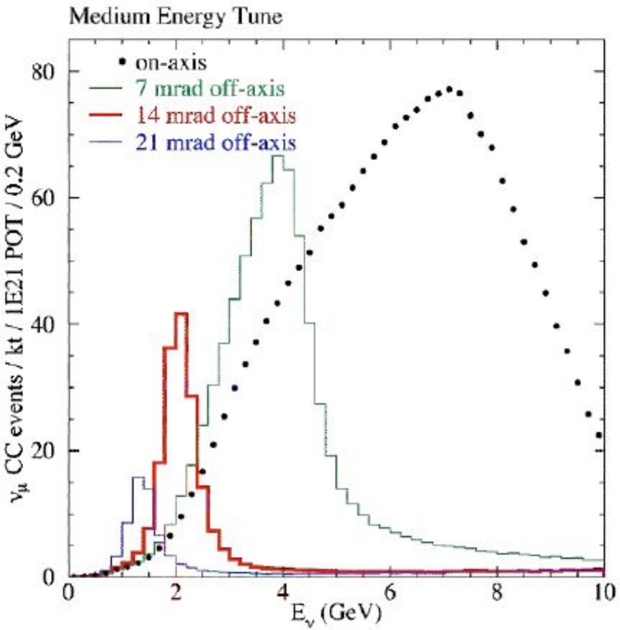

**Matter affects neutrinos and antineutrinos differently**

# Off-axis configuration

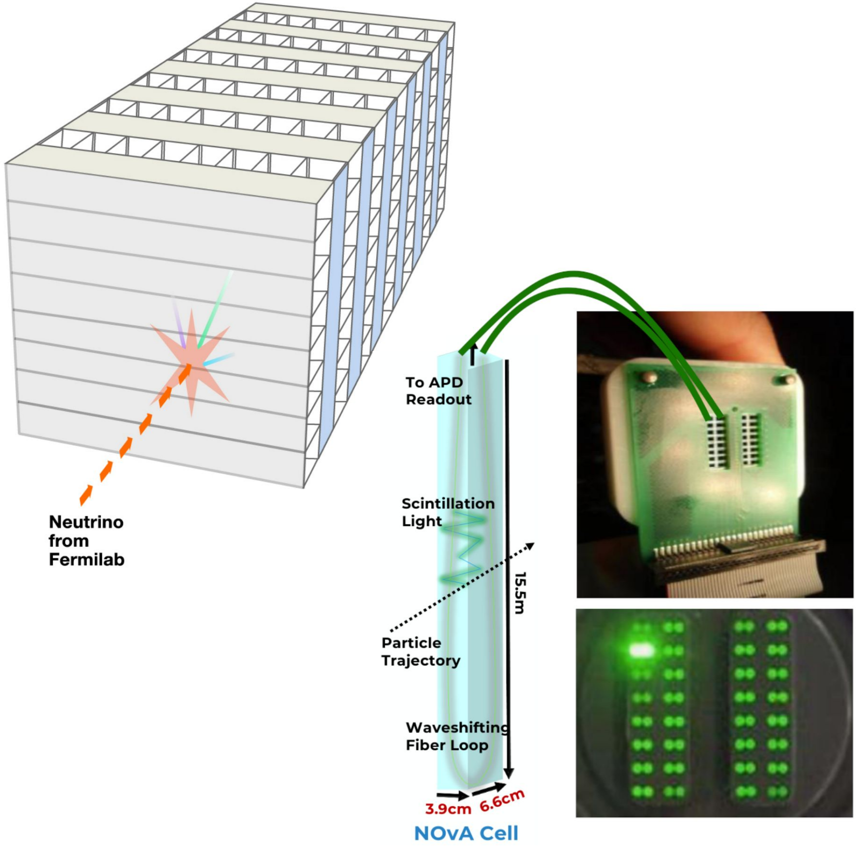
**14 mrad off-axis:**

**$E_\nu$ around 2 GeV**

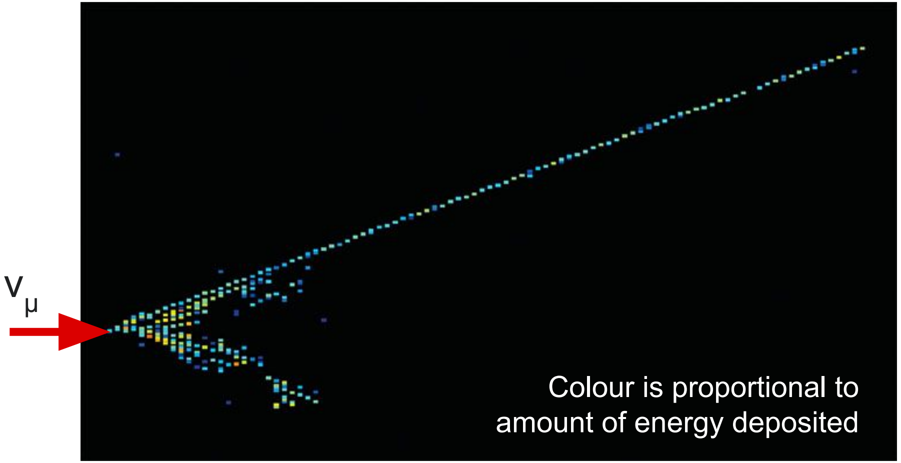


# A Neutrino Camera



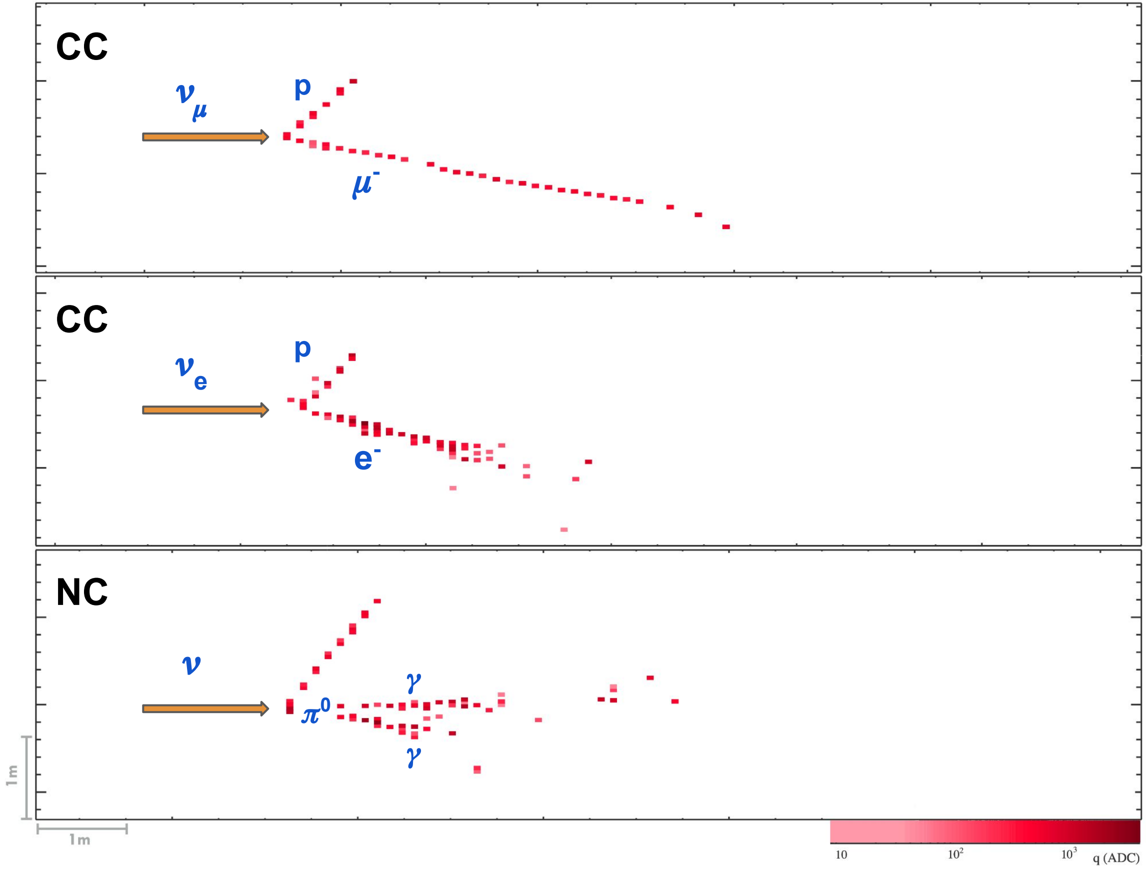

## Snapshot of Neutrino Interaction




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

Slide courtesy of Jeffrey Kleykamp

# Event Topologies



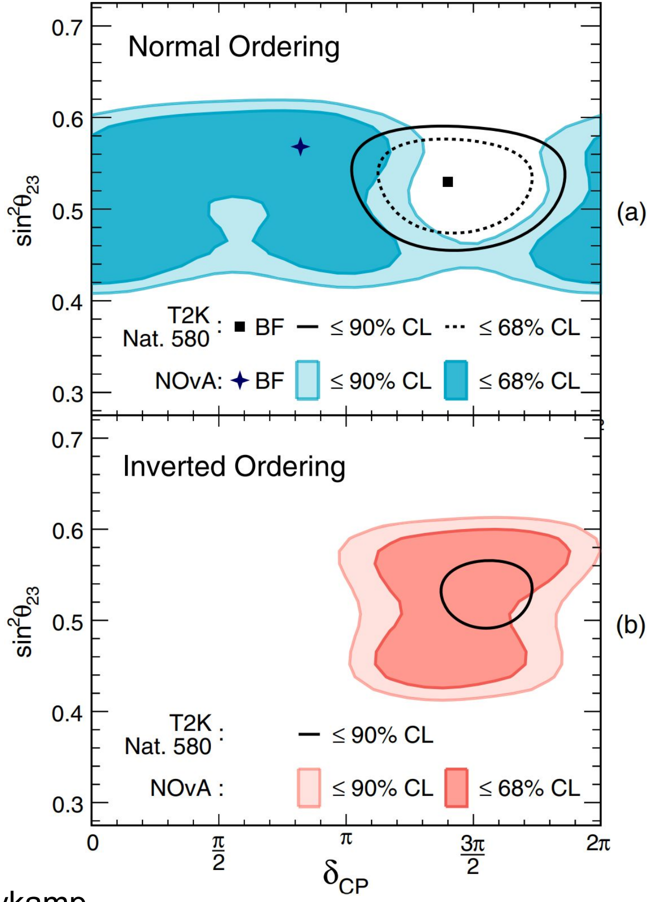

Muon neutrinos produce a characteristic long track

Electron neutrinos have shorter fuzzier tracks

Neutral Current events produce $\pi^0$
Background for $\nu_e$ 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
  - **$\delta_{CP}$ excluded ~ $3\pi/2$ at 90% C.L.**




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

Slide courtesy of Jeffrey Kleykamp

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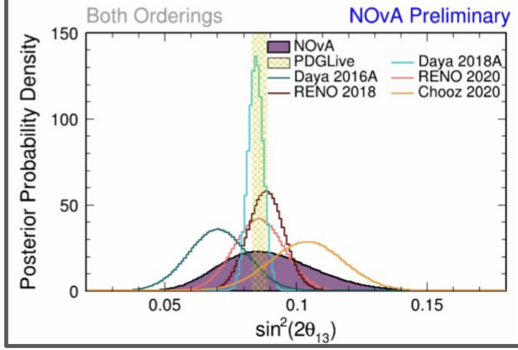
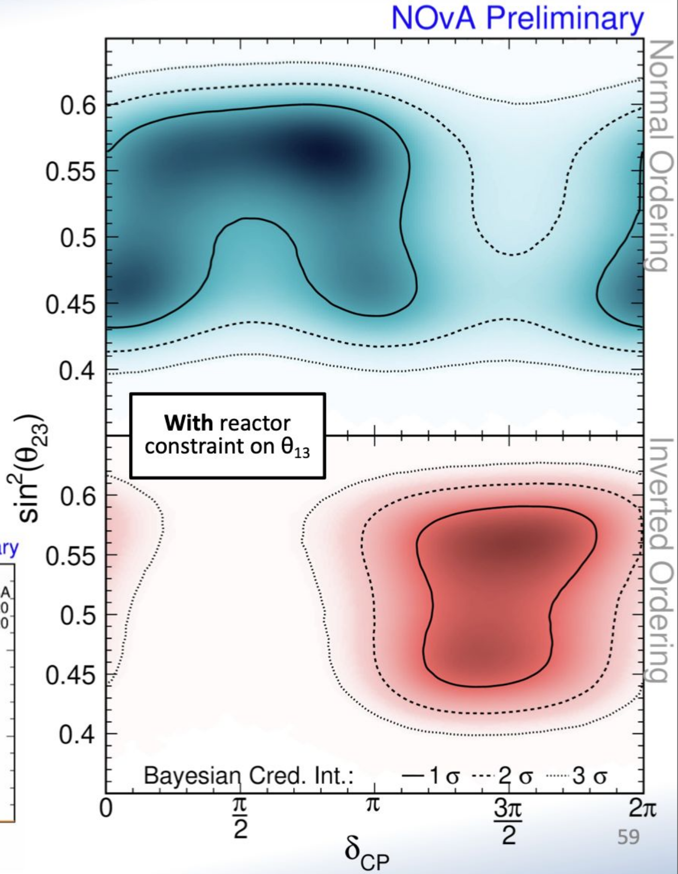
# Recent Results from NOvA (Bayesian)

- Disfavor ordering-$\delta$ 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 $\theta_{13}$ constraint.
- Adding the reactor constraint gives $\sim 1\sigma$ preferences:
  - Upper Octant
  - Normal Ordering

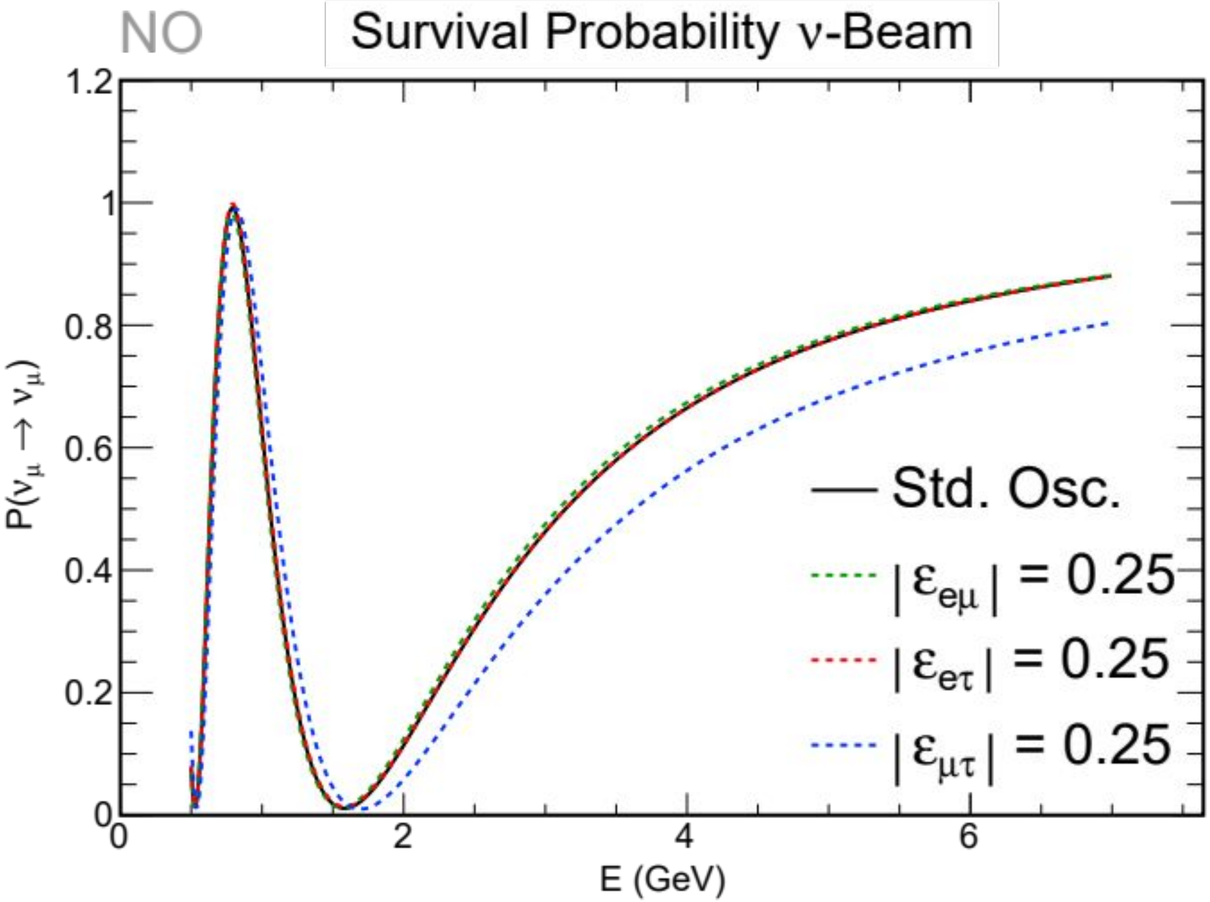



Slide courtesy of Alex Himmel

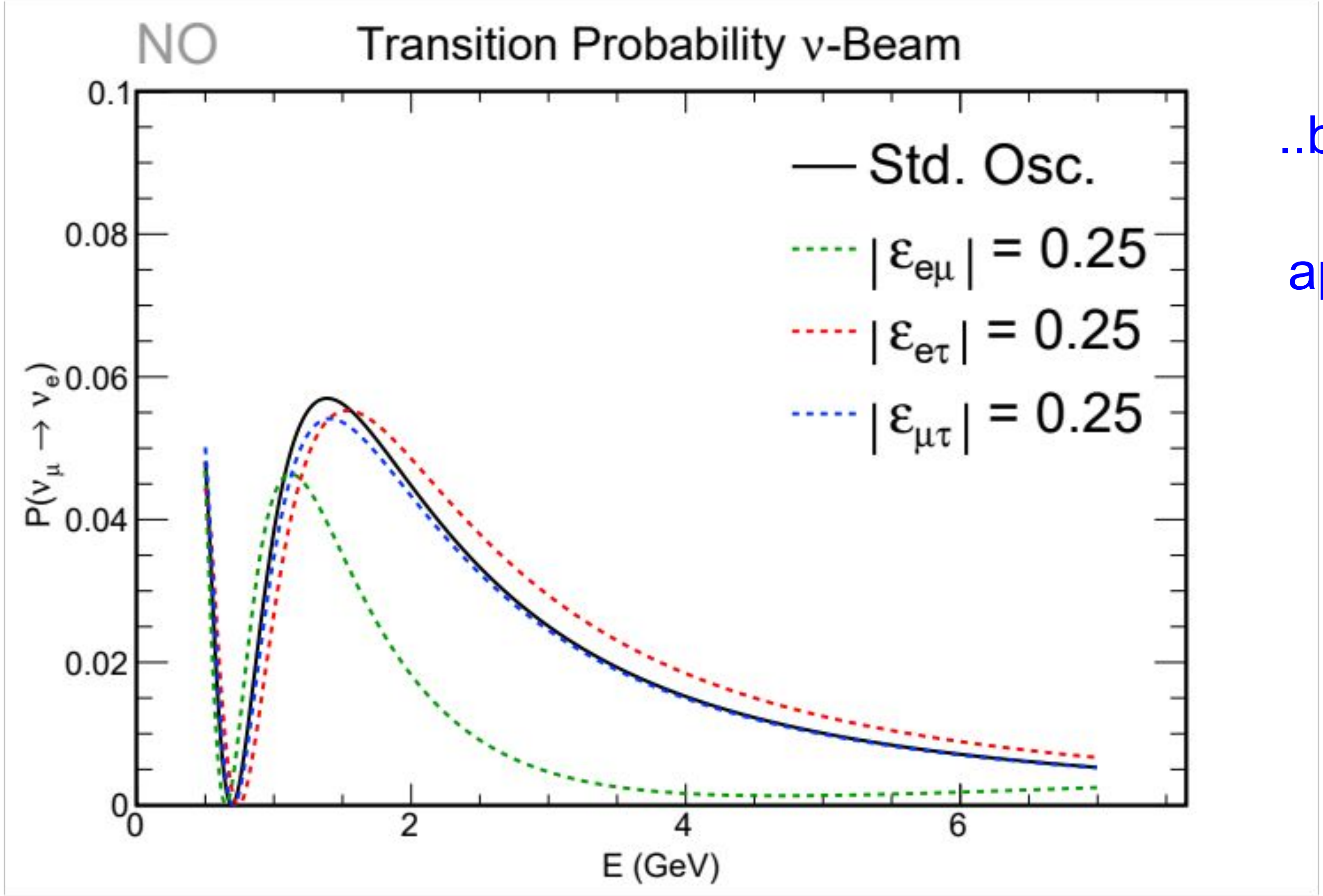
# NSI Model

# NSI Model




Effect of each parameter

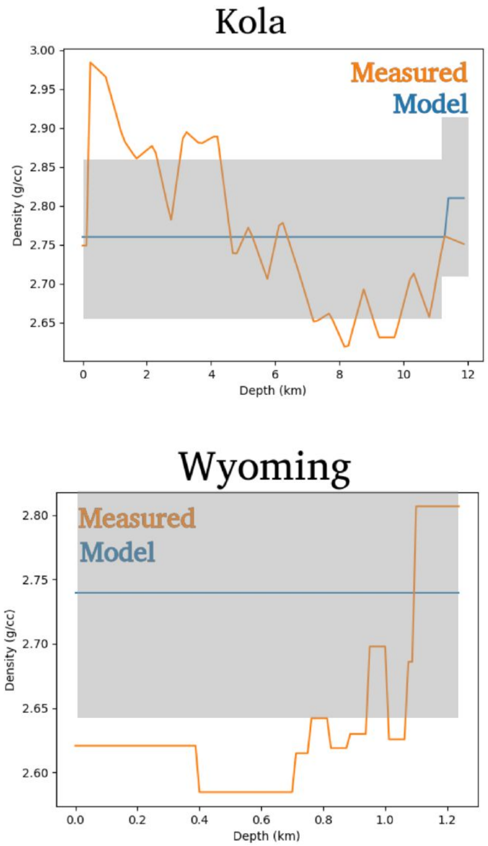
# NSI Model




..but here for the $\nu_e$ appearance

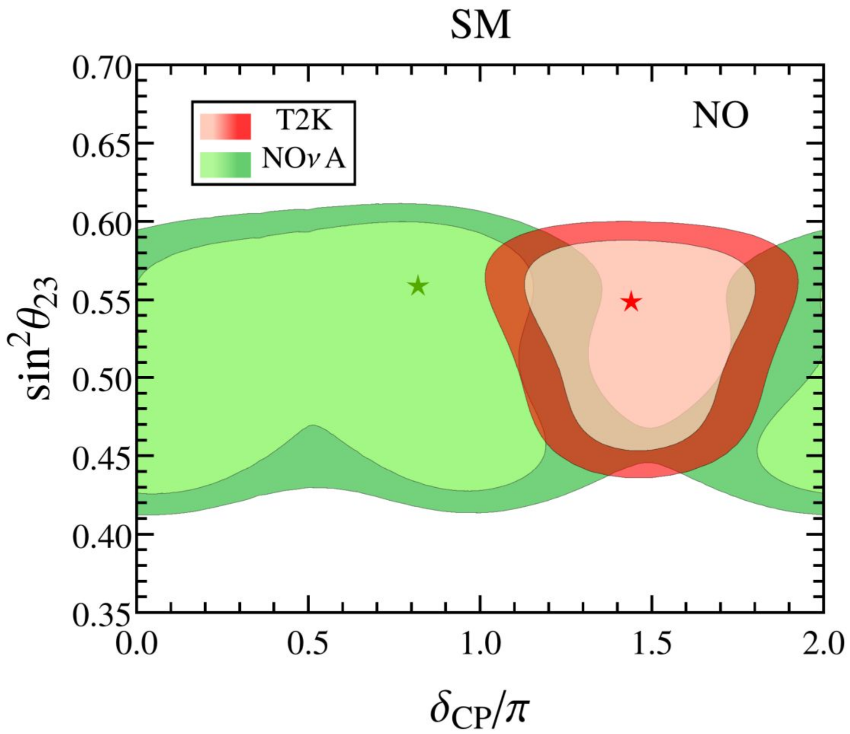
# ρ uncertainty

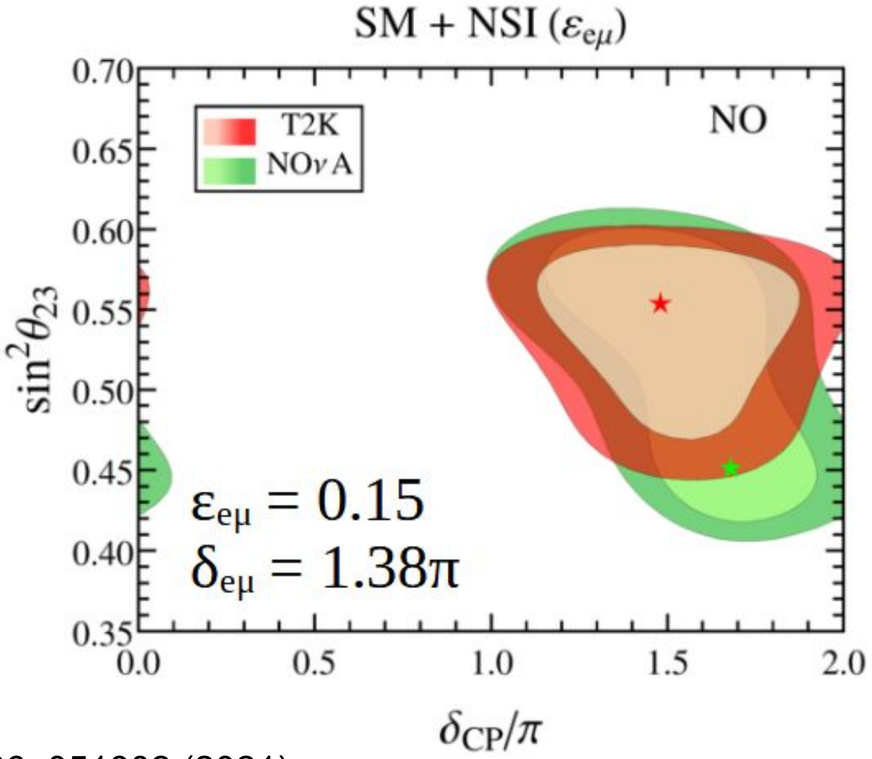
- Compare CRUST model to real data
- Kola bore – deepest bore
- Wyoming oil bore – geologically similar
- Also direct bores from the MINOS cave
- 3.7% uncertainty




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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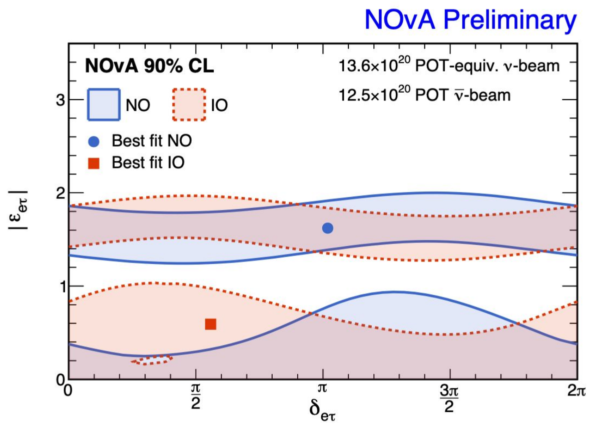
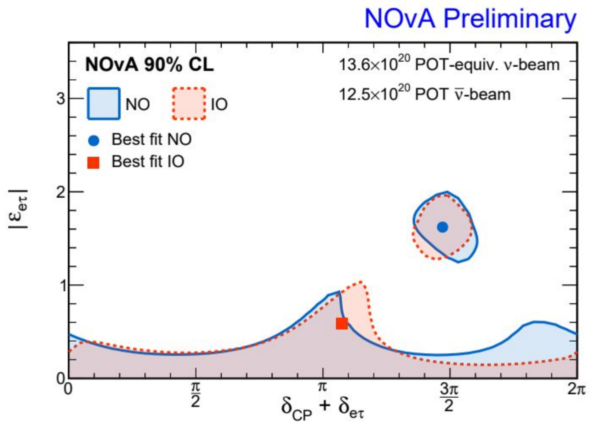
# NSI & ( $\delta_{cp} + \delta_{e\tau}$ )

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



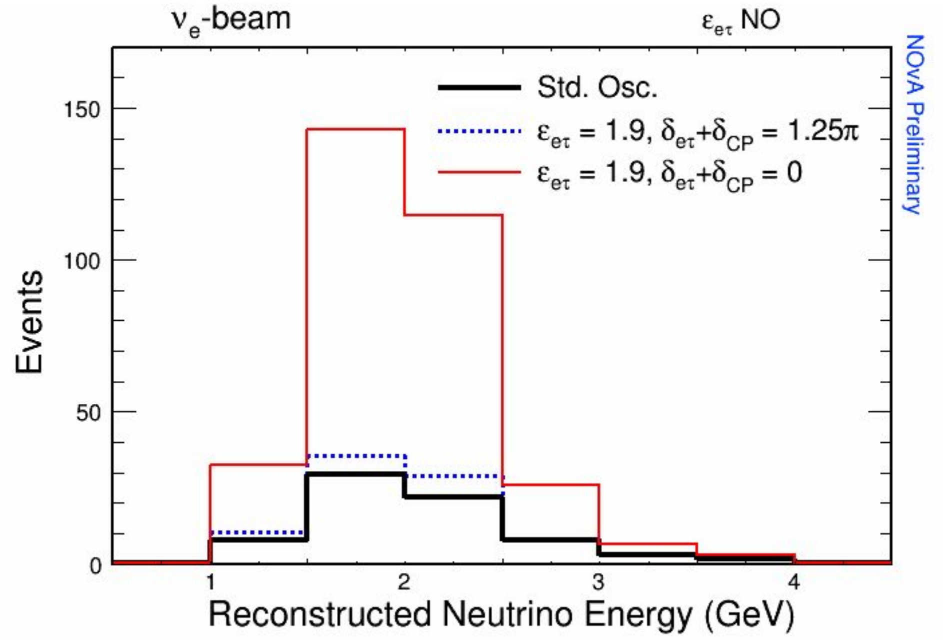




Slide courtesy of Jeffrey Kleykamp

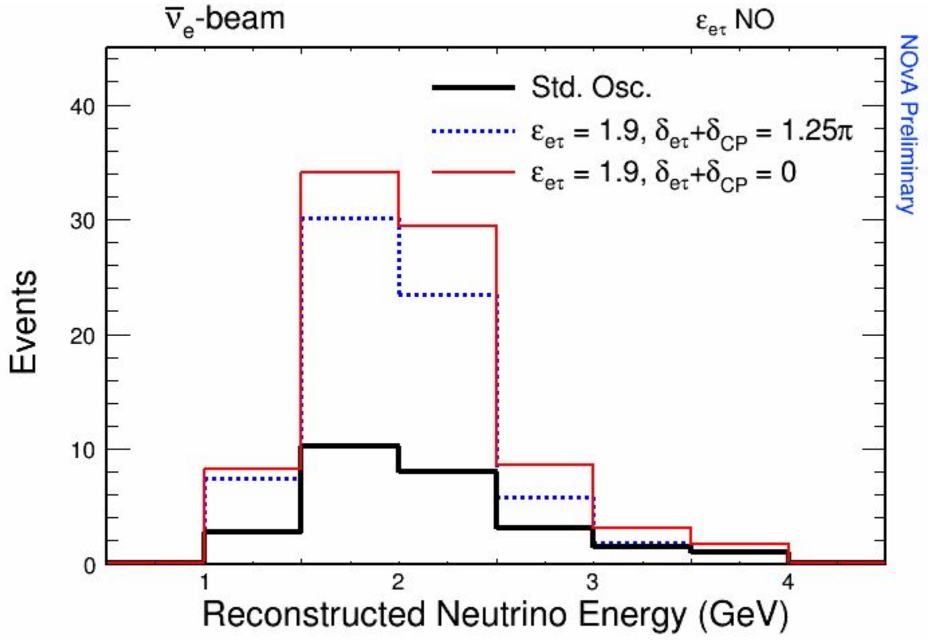
# NSI Degeneracy

# Degeneracy & large NSI

## Neutrino Mode



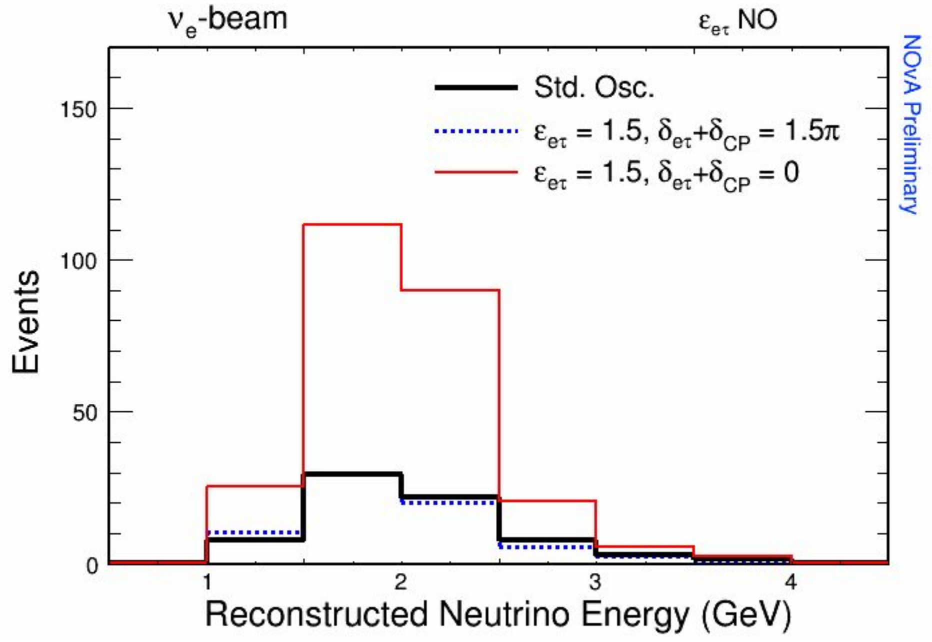

## Antineutrino Mode



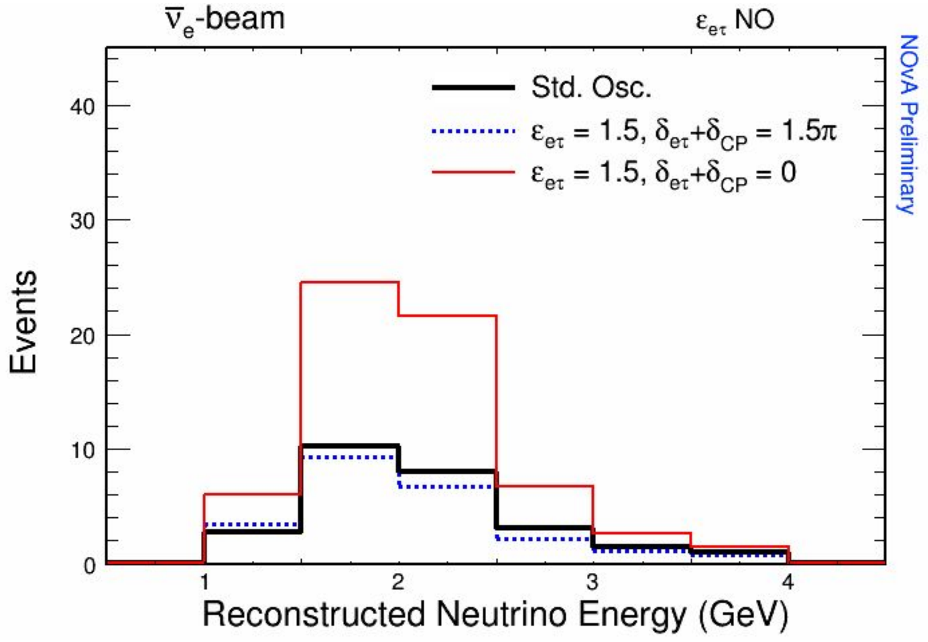

**The joint neutrino-antineutrino fit breaks most of the degeneracies (Dashed blue curve of interest)**

# Degeneracy & large NSI

## Neutrino Mode



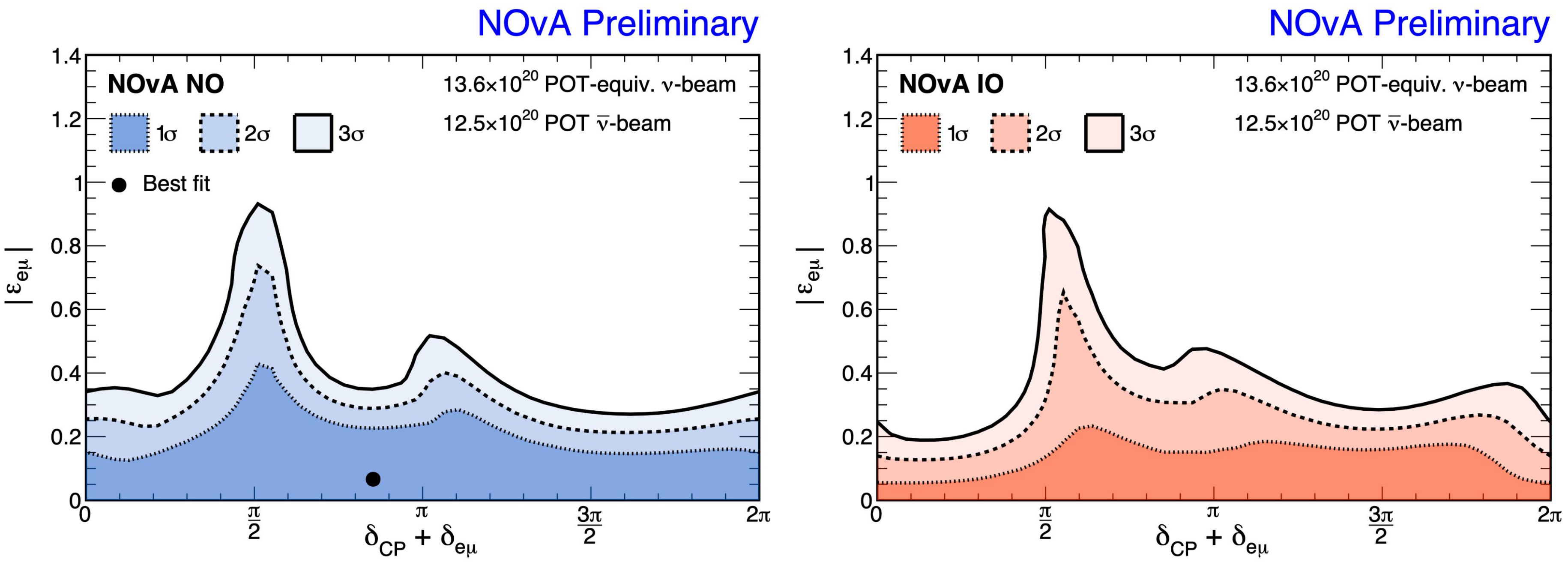

## Antineutrino Mode




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

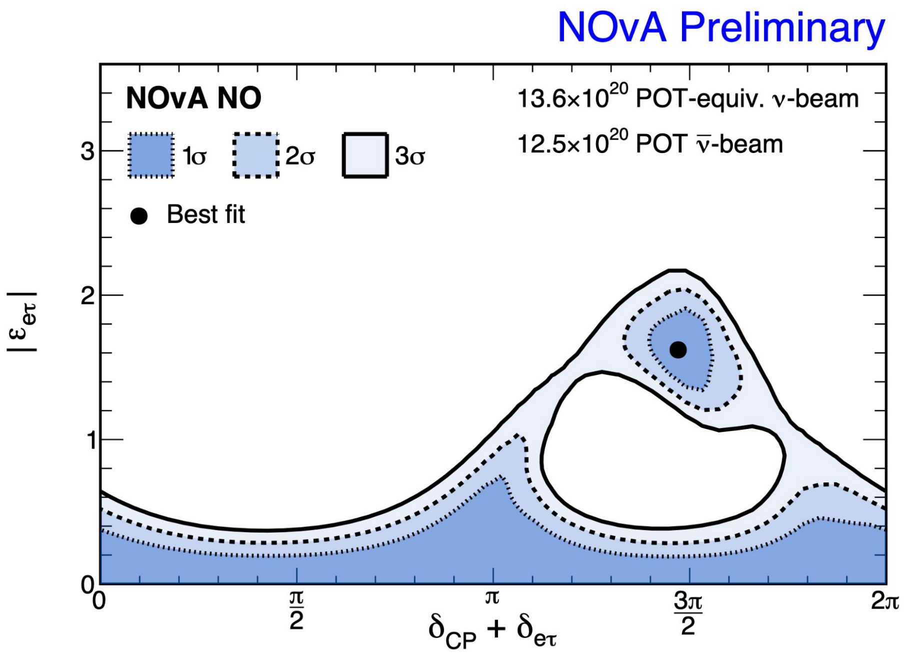
# NSI Results

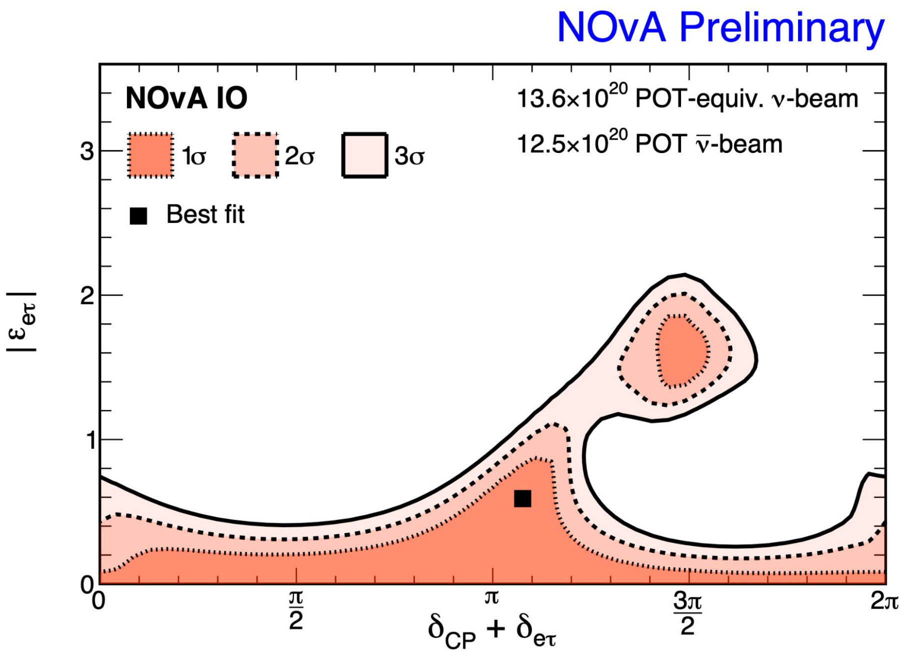
# NSI Results



NOvA Preliminary
NOvA NO
13.6×10^20 POT-equiv. ν-beam
12.5×10^20 POT ν̄-beam
1σ
2σ
3σ
Best fit
|ε_eμ|
δ_CP + δ_eμ
0
π/2
π
3π/2
2π
0.2
0.4
0.6
0.8
1
1.2
1.4
NOvA Preliminary
NOvA IO
13.6×10^20 POT-equiv. ν-beam
12.5×10^20 POT ν̄-beam
1σ
2σ
3σ
|ε_eμ|
δ_CP + δ_eμ

# NSI Results


NOvA Preliminary
NOvA NO
$13.6\times10^{20}$ POT-equiv. ν-beam
$12.5\times10^{20}$ POT $\bar{\nu}$-beam
1σ
2σ
3σ
Best fit
$|\epsilon_{e\tau}|$
$\delta_{CP} + \delta_{e\tau}$
0
1
2
3
π/2
π
3π/2
2π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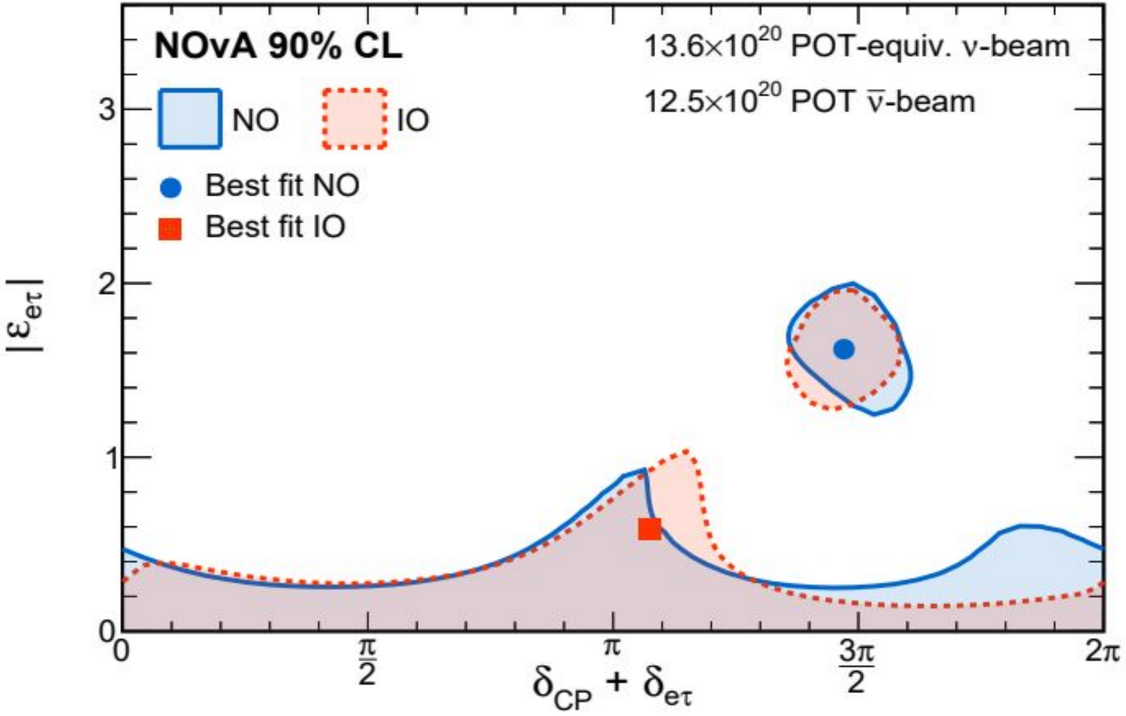
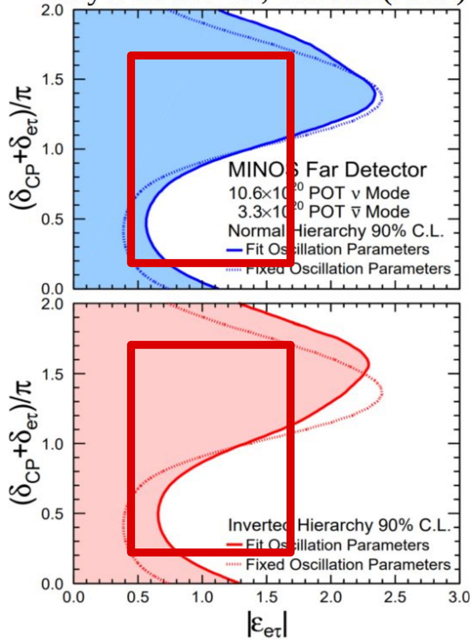
1σ
2σ
3σ
Best fit
$|\epsilon_{e\tau}|$
$\delta_{CP} + \delta_{e\tau}$
0
1
2
3
π/2
π
3π/2
2π

# Results: comparison to MINOS

NOvA Preliminary

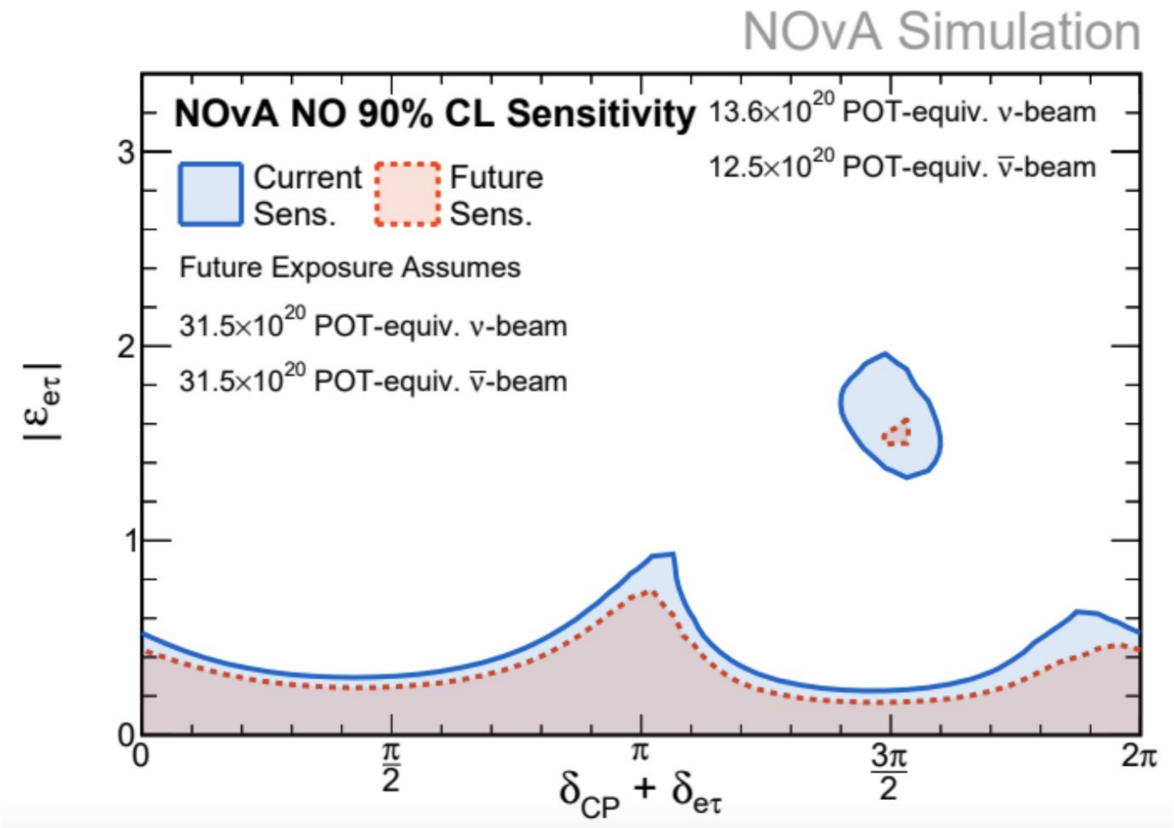



Phys. Rev. D 95, 012005 (2017)




Complementary to previous measurements from the MINOS Experiment

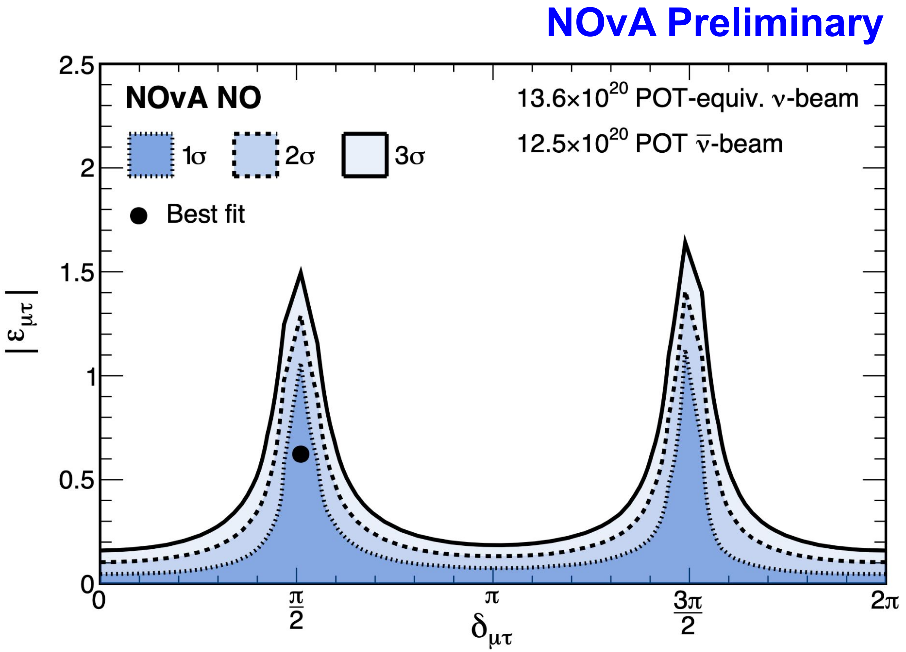
# Future Sensitivity

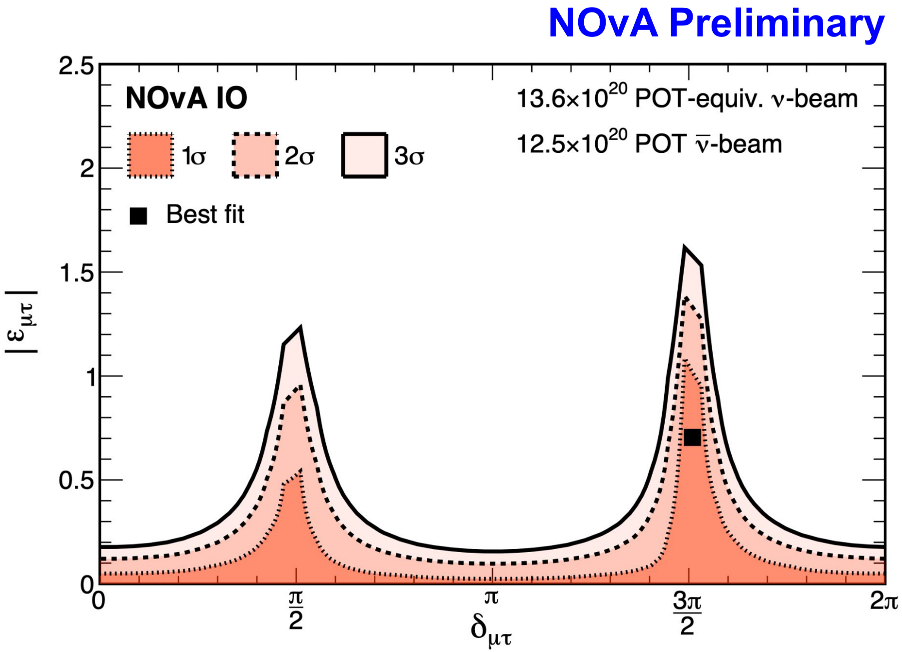



Addition of statistics is not enough to resolve the degeneracy.

Exploring improvements for the next NSI analysis!

# NSI Results


NOvA Preliminary
NOvA NO
13.6×10^20 POT-equiv. ν-beam
12.5×10^20 POT ν̄-beam
1σ
2σ
3σ
Best fit
|ε_μτ|
δ_μτ
0
0.5
1
1.5
2
2.5
π/2
π
3π/2
2π


NOvA Preliminary
NOvA IO
13.6×10^20 POT-equiv. ν-beam
12.5×10^20 POT ν̄-beam
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2σ
3σ
Best fit
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δ_μτ
0
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2
2.5
π/2
π
3π/2
2π