What's new about

Neutrino oscillations at NOvA

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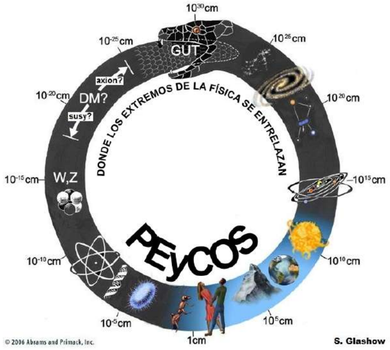
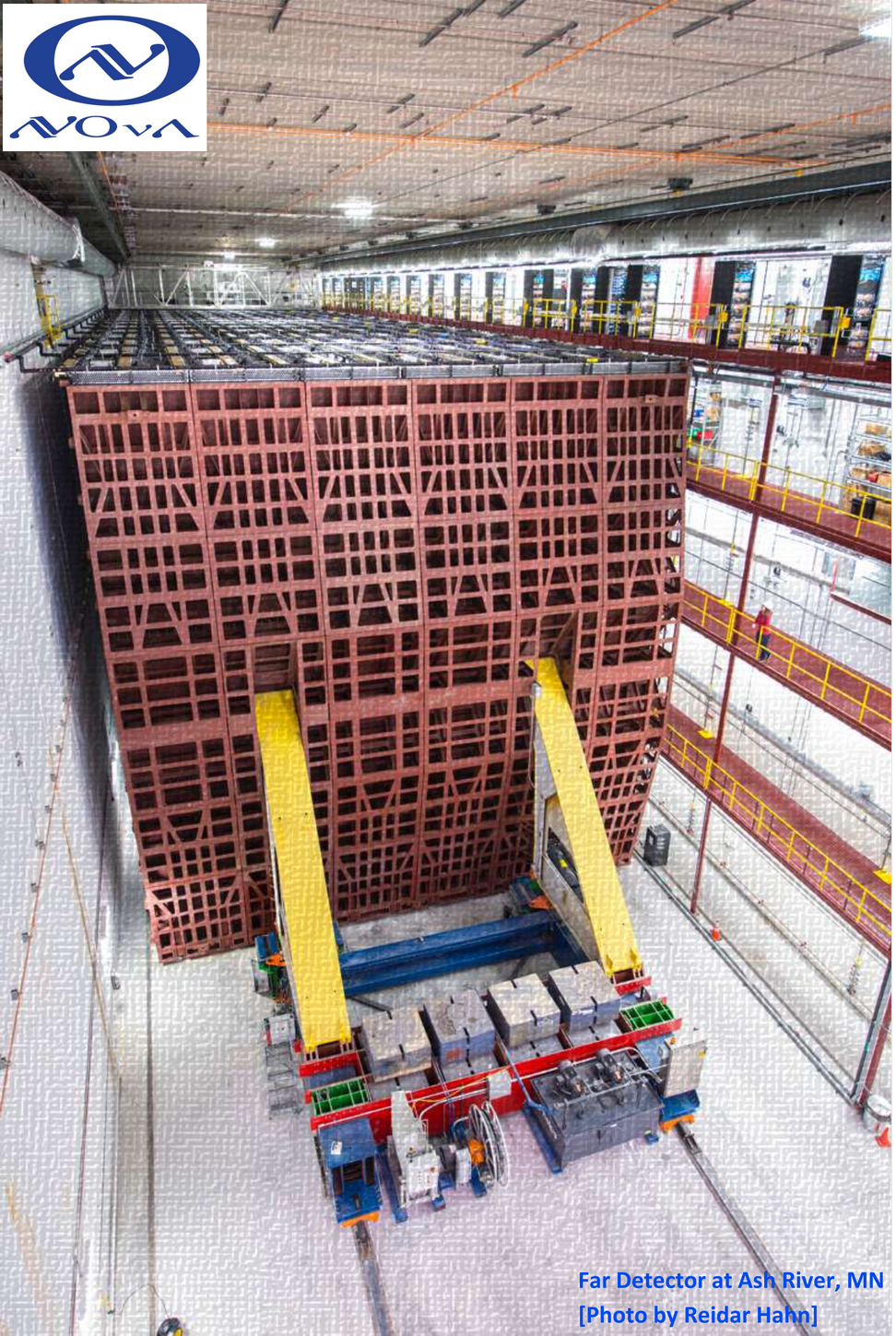
for the NOvA Collaboration

Seminario de Altas Energías, Instituto de Ciencias Nucleares, UNAM

21 de Octubre de 2020





Far Detector at Ash River, MN
[Photo by Reidar Hahn]

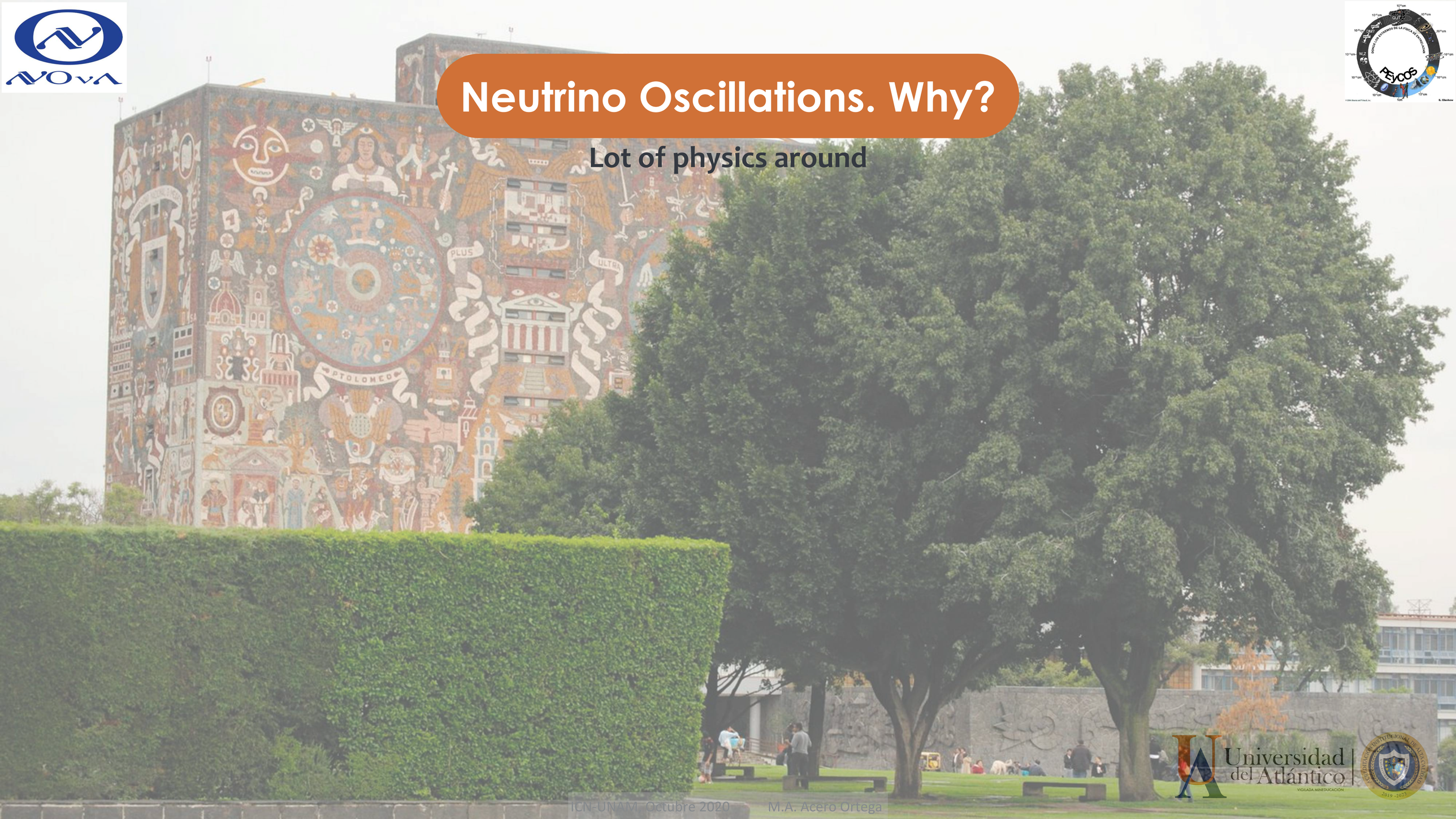
Outline

Focusing on latest oscillations results

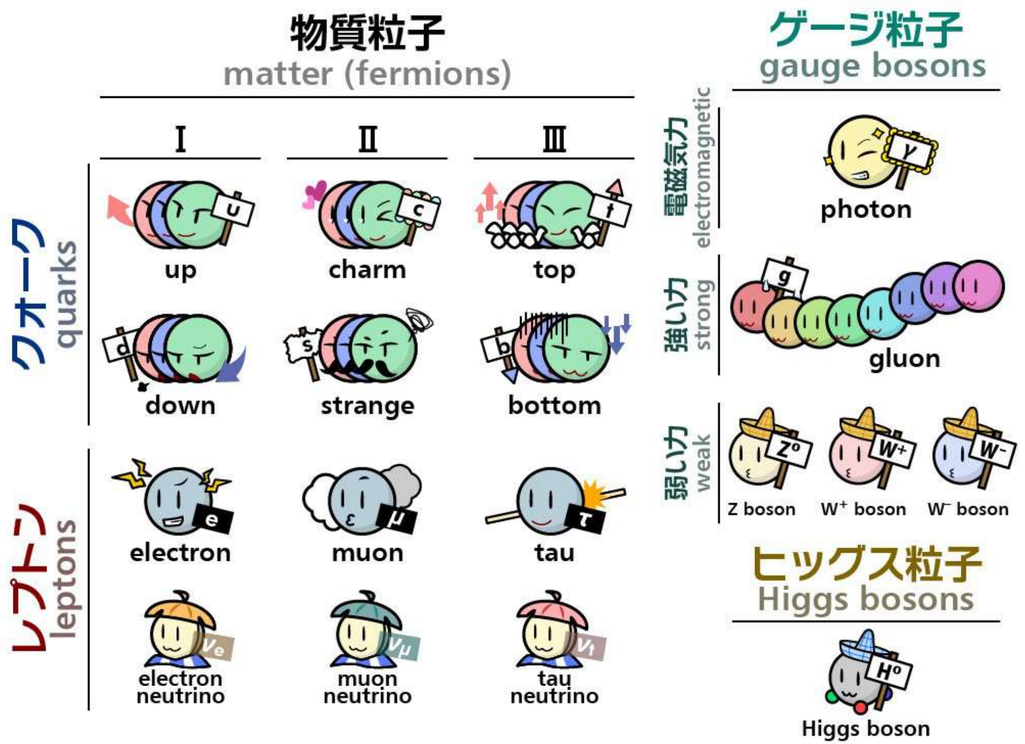
- Neutrino oscillations: why?
- NOvA, the experiment
- The results
- The future
- Conclusions

Neutrino Oscillations. Why?

Lot of physics around

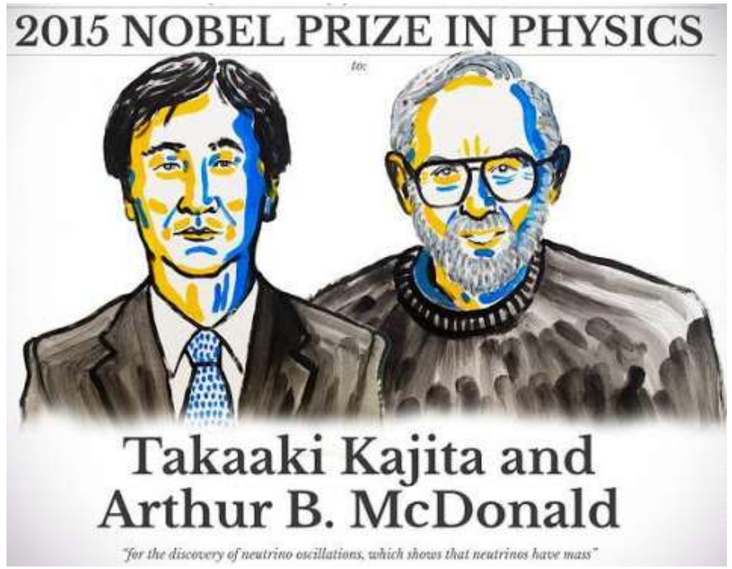


Neutrino oscillations: Why?



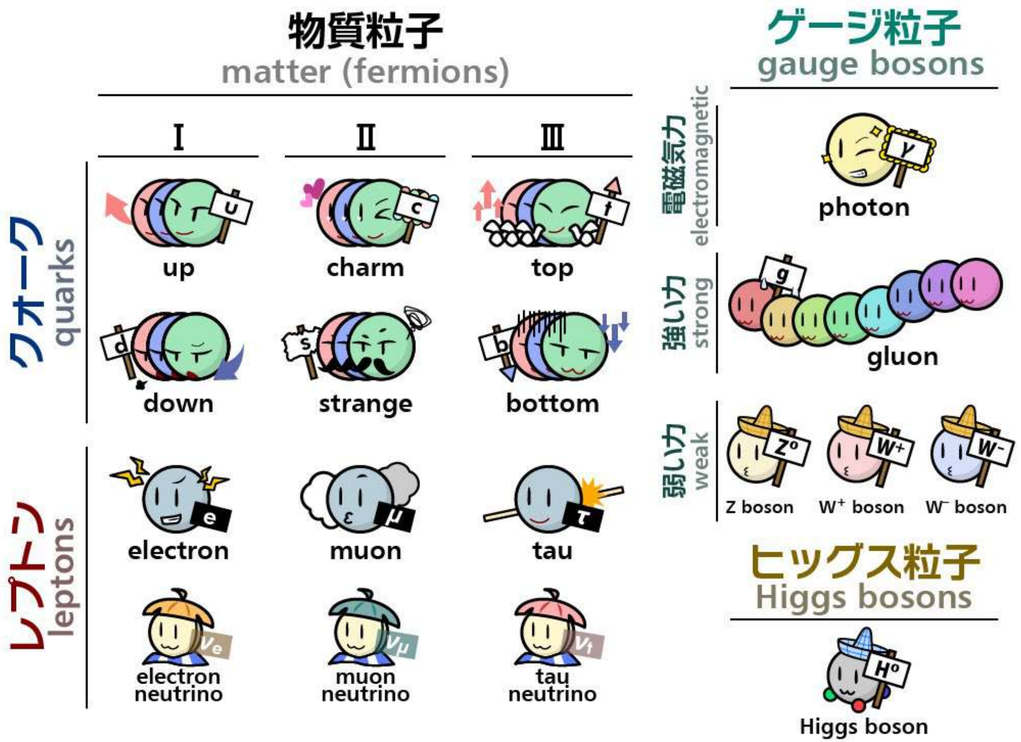
The Standard Model of Particle Physics

Such a successful theory and yet, so many questions yet to be answered



"For the discovery of neutrino oscillations, which shows that neutrinos have mass"

Neutrino oscillations: Why?



The Standard Model of Particle Physics

Such a successful theory and yet, so many questions yet to be answered

Questions addressed from the study of neutrino oscillations:

- Neutrino flavor mixing: predictable?
- Neutrino mass distribution: regular? similar to other fermions?
- Neutrinos vs. antineutrinos: the same oscillation pattern?
- Number of neutrinos: are there “only” three?

Neutrino Oscillations

[Teotihuacan]

Neutrino oscillations

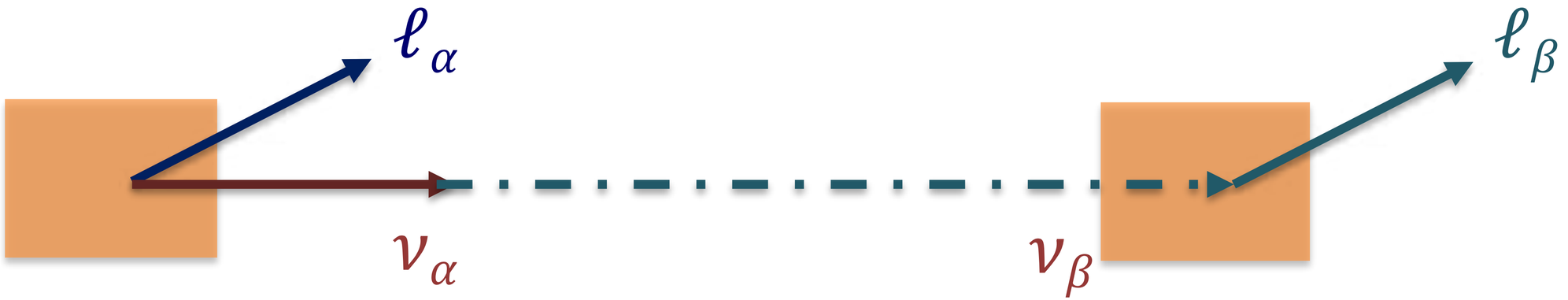
The neutrino of **flavor α** is the one created in W boson decay together with the charged lepton of flavor α.

And creates a charged lepton of **flavor α** when it undergoes a charged-current interaction.

[D. Schmitz, CTEQ Summer School 2011]

Neutrino oscillations

Flavor may change…



… if neutrinos have mass and mix

[D. Schmitz, CTEQ Summer School 2011]

Neutrino oscillations

- Neutrinos have mass and mix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U^\dagger \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Interactions (creation and detection)

Propagation

Neutrino oscillations

- Neutrinos have mass and mix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12})}_{\text{Mixing matrix}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$R(\theta_{23}) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

$$R(\theta_{12}) = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$R(\theta_{13}, \delta_{CP}) = \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}\, e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}\, e^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix}$$

Neutrino oscillations

- Neutrinos have mass and mix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12}) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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Atmospheric/Accelerators

Solar

Reactor

Neutrino oscillations

- Neutrinos have mass and mix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12}) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- The oscillation probability

$$P_{\nu_\alpha \to \nu_\beta} = \left| \sum_k U^*_{\beta k} \exp\left(-i \frac{m_k^2 L}{2E} \right) U_{\alpha k} \right|^2$$

Neutrino oscillations

- Neutrinos have mass and mix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12}) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- From Global fits…

$$\theta_{12} = 33.44^\circ$$

$$\theta_{13} = 8.57^\circ$$

$$\theta_{23} = 49.2^\circ$$

$$\Delta m^2_{31} = 2.5 \times 10^{-3}\ \mathrm{eV}^2$$

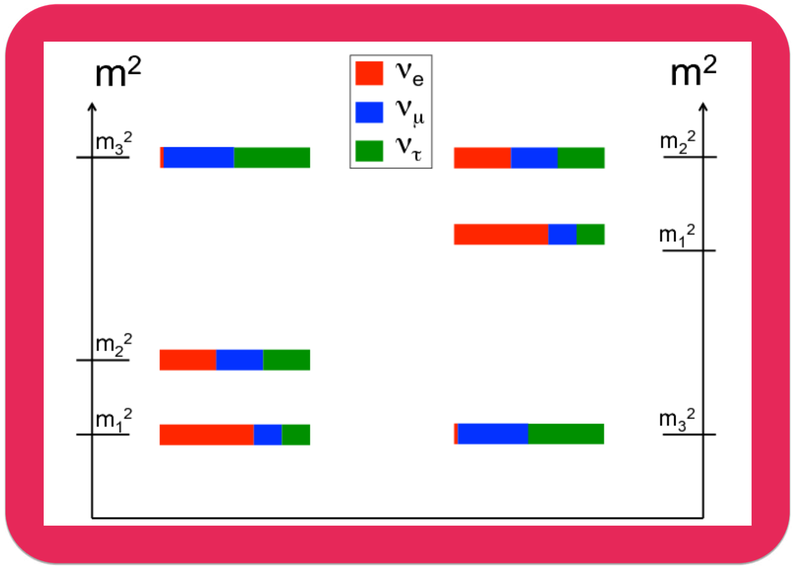
$$\Delta m^2_{21} = 7.4 \times 10^{-5}\ \mathrm{eV}^2$$

[I. Esteban et al., JHEP178 (2020)]
[NuFIT 5.0 (2020), http://www.nu-fit.org/]

Neutrino oscillations

- And the open questions…

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12}) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Neutrino oscillations

- And the open questions…

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12}) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Maximal mixing?

CP Violation?

② Is there a **symmetry** governing the ν_μ/ν_τ mixing into the 2nd and 3rd mass states?
i.e.: is θ_{23} "maximal" = 45°?

[J. Wolcott (2020), Fermilab W&C]

③ Is δ_{CP}/π non-integral?

If it is, neutrinos — and thus leptons — violate CP **symmetry**.
Related to wider matter/antimatter asymmetry in universe???

Neutrino oscillations

- And the open questions…

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12}) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

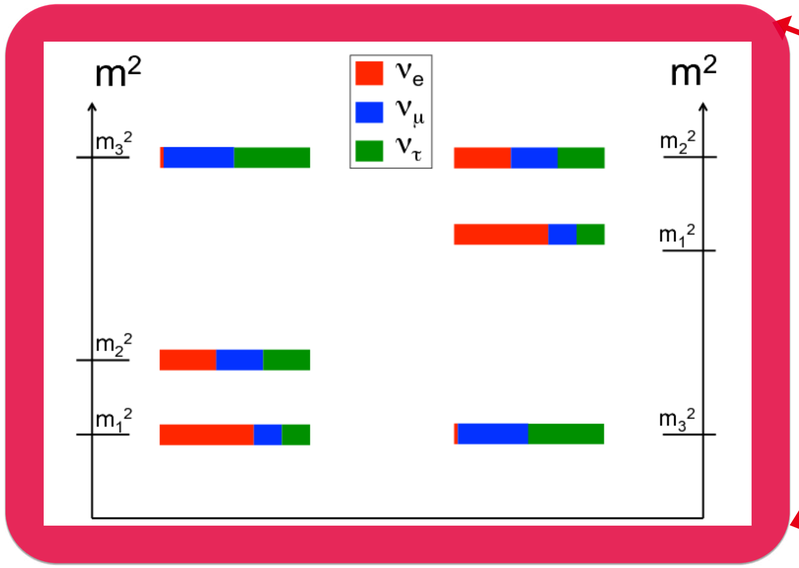
Maximal mixing?

CP Violation?

Mass ordering?

$$\Delta m^2_{32} > 0$$

$$\Delta m^2_{32} < 0$$



① Is there a symmetry governing the ordering of the lepton mass states?

Is the most electron-like state the lightest one, like with the charged leptons?

[J. Wolcott (2020), Fermilab W&C]

Neutrino oscillations

- And the open questions…

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12}) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Only 3 flavors?

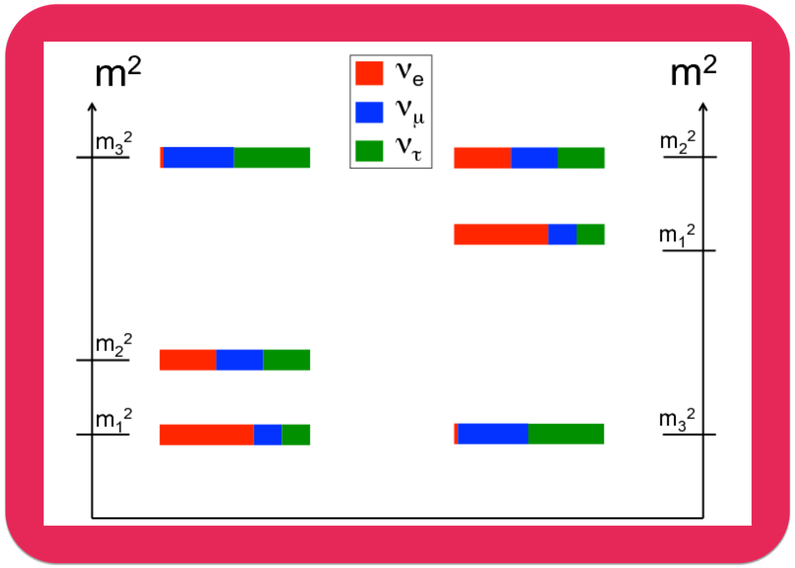
Maximal mixing?

CP Violation?

Mass ordering?

$$\Delta m^2_{32} > 0$$

$$\Delta m^2_{32} < 0$$



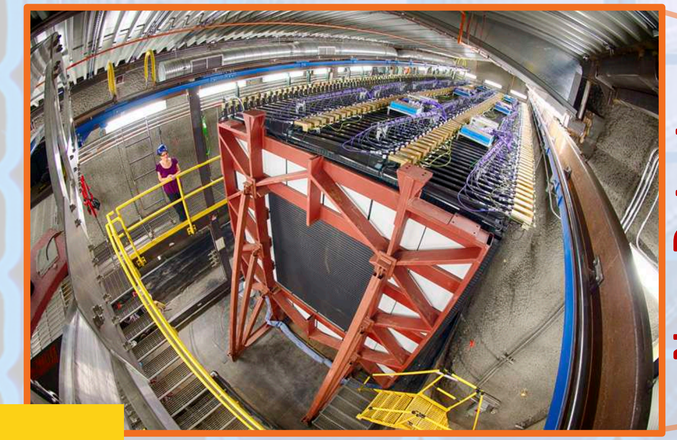
- Absolute neutrino mass?
- $\nu = \bar{\nu}$?

No answer from neutrino oscillations

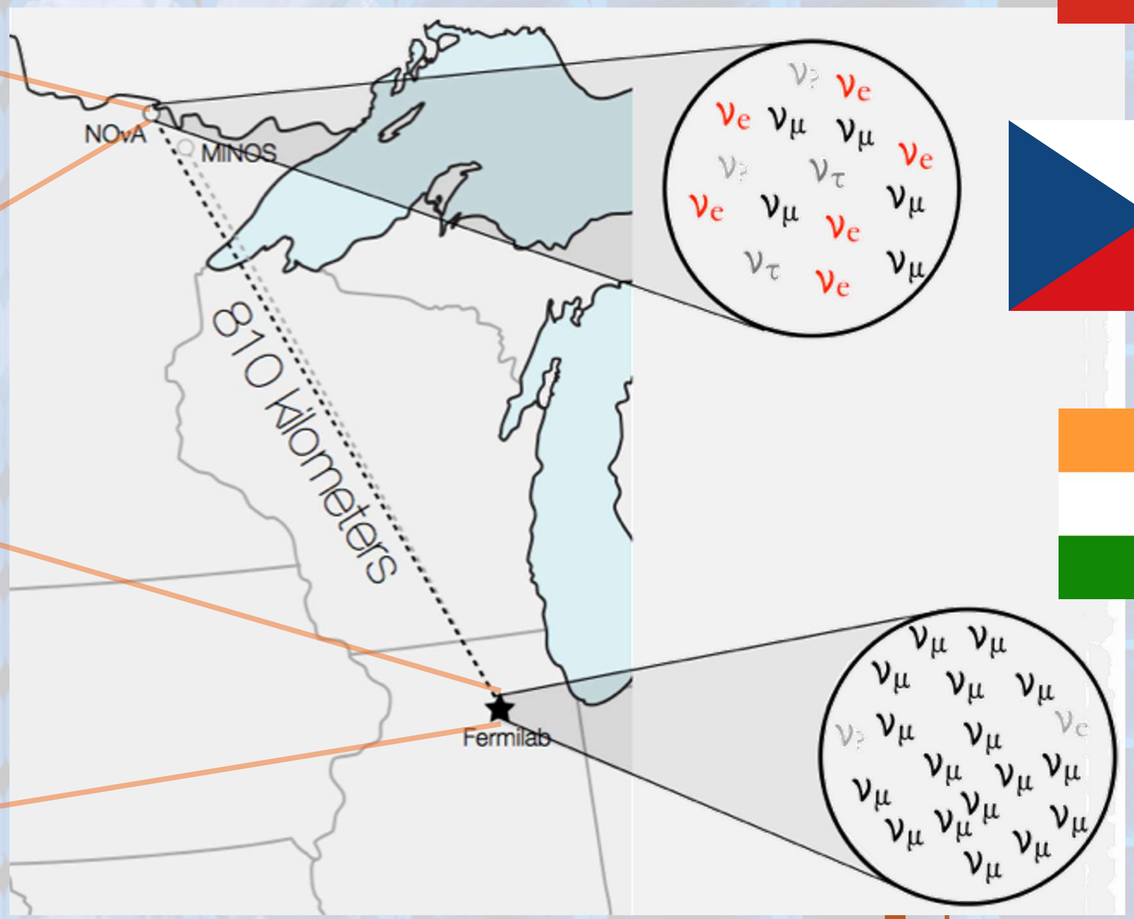
NOvA: The Experiment

NuMI Off-axis ν_e Appearance

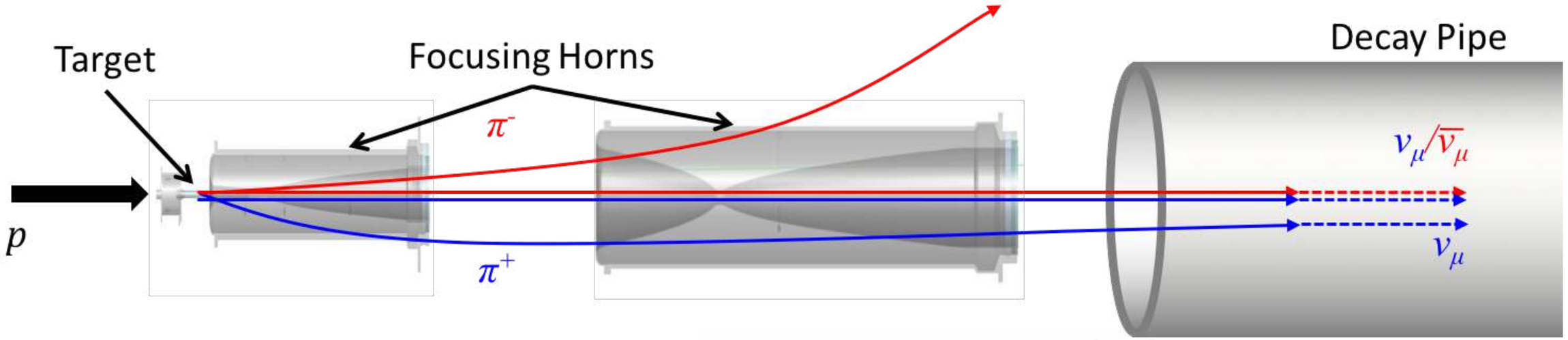
Far Detector



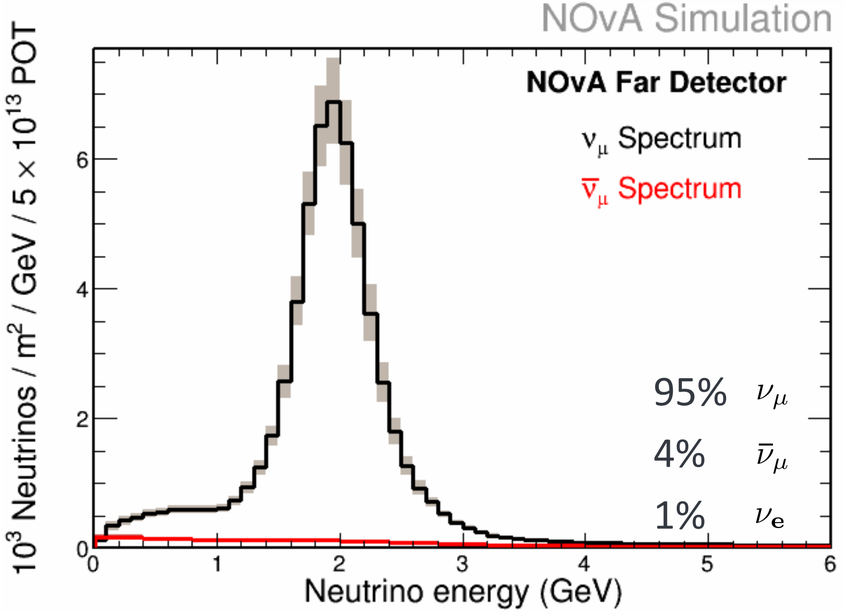
Near Detector



The Neutrino Beam



$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\downarrow$$
$$e^+ + \nu_e + \bar{\nu}_\mu$$



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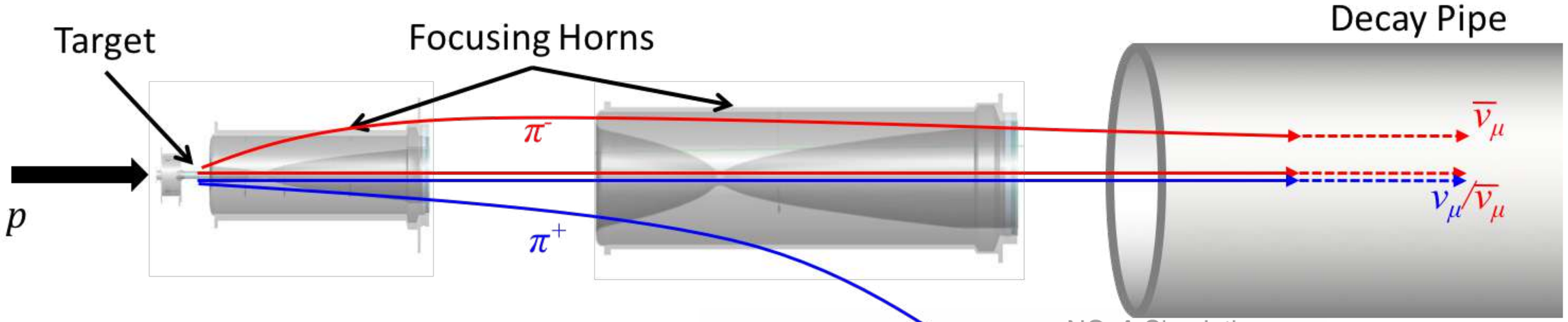
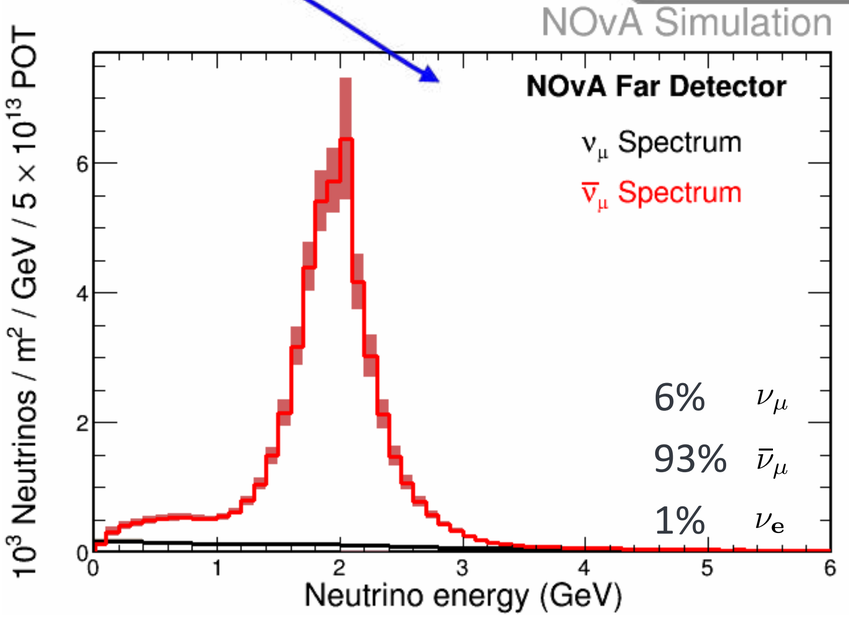


$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\downarrow$$
$$e^- + \bar{\nu}_e + \nu_\mu$$



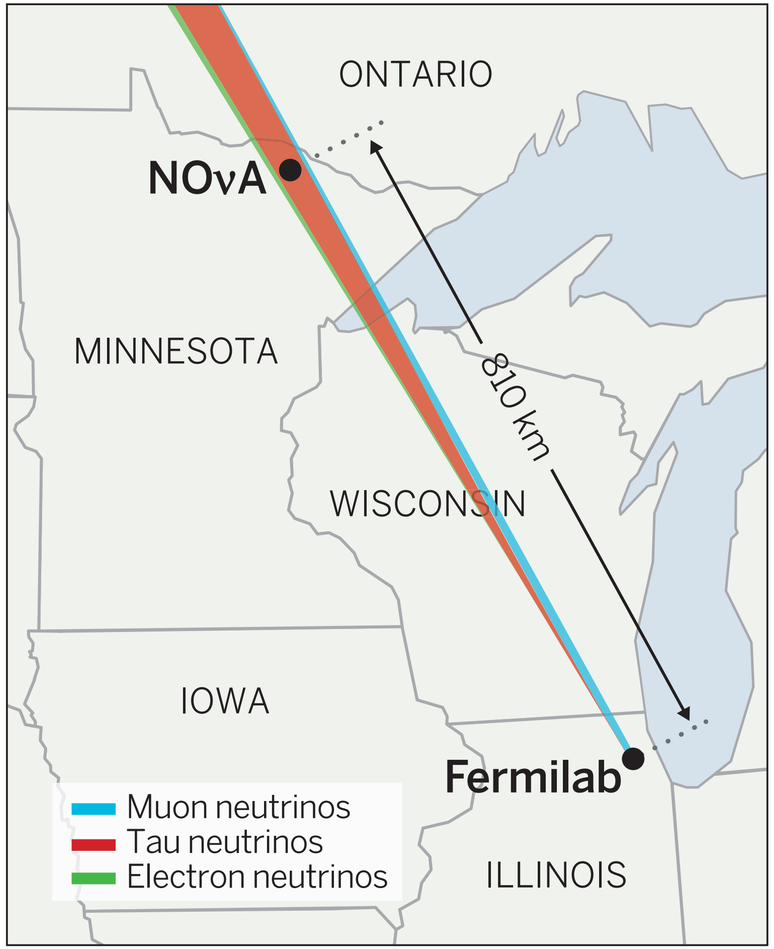
The NOvA Experiment

Scientific Goals

- Studying $\nu_\mu \rightarrow \nu_\mu \, (\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$
  - ✓Measurement of Δm^2_{32}
  - ✓Mixing angle θ_{23}

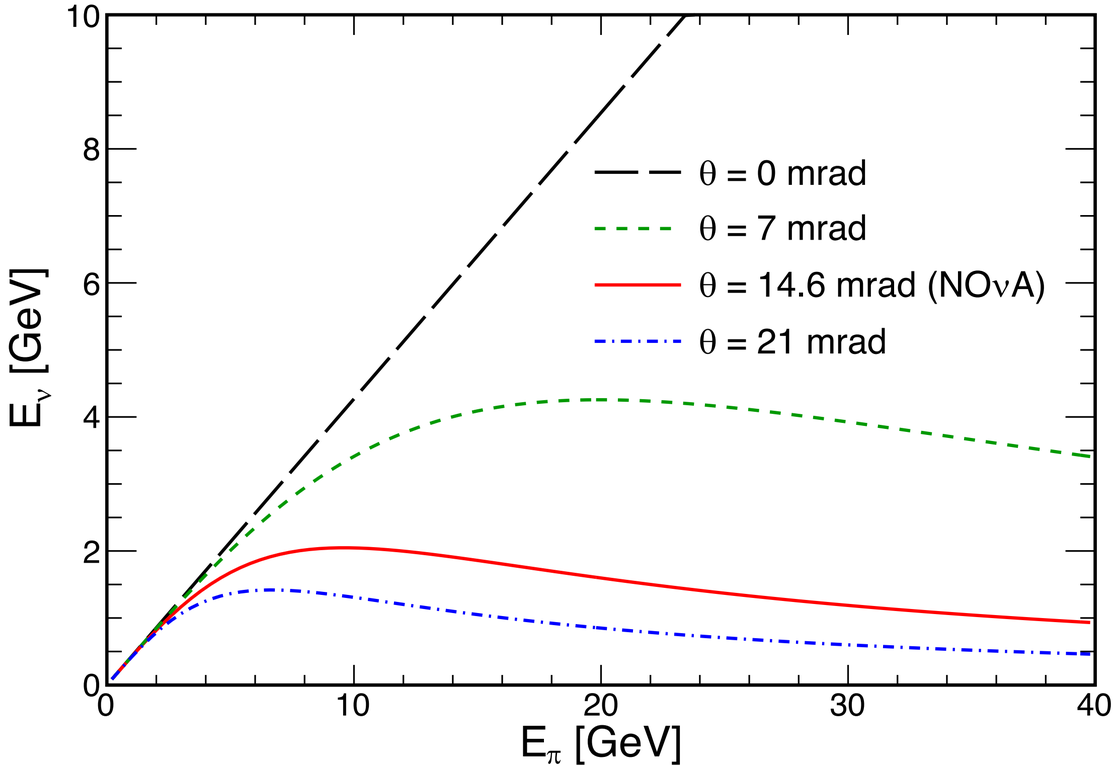
- Studying $\nu_\mu \rightarrow \nu_e \, (\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
  - ✓Mass hierarchy
  - ✓CP violation
  - ✓Mixing angle θ_{23}

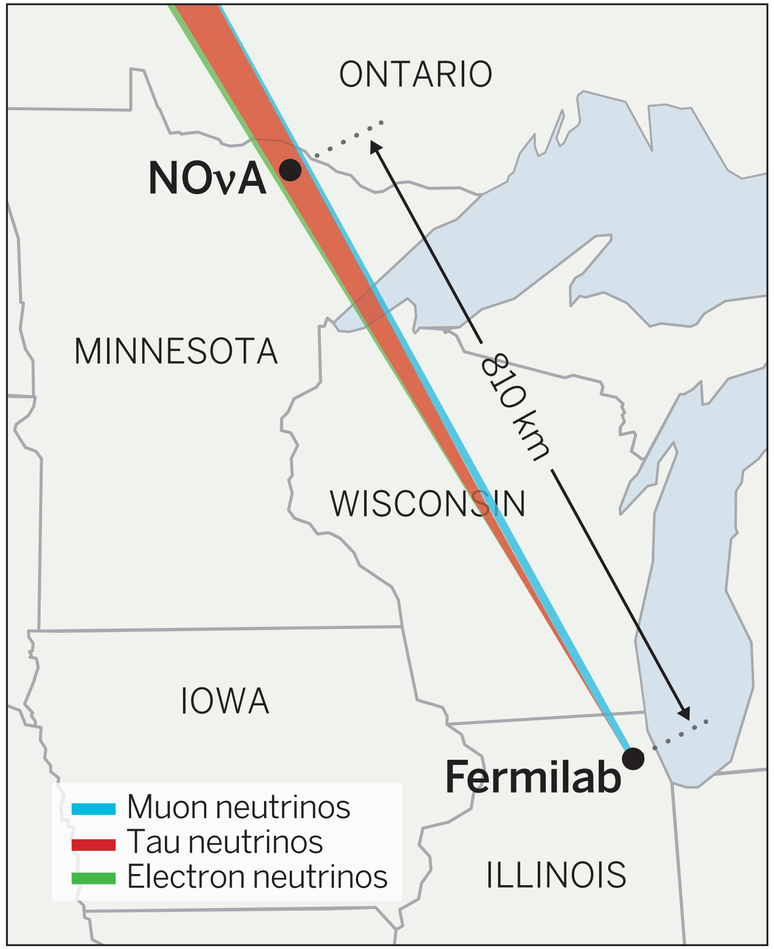
- Sterile neutrinos
- Neutrino cross sections
- Supernova neutrinos
- Cosmic ray physics
- More ‘exotic’ physics (monopoles, GW,…)



[A. Cho, Science 345, 6204 (2014)]

The NOvA Experiment

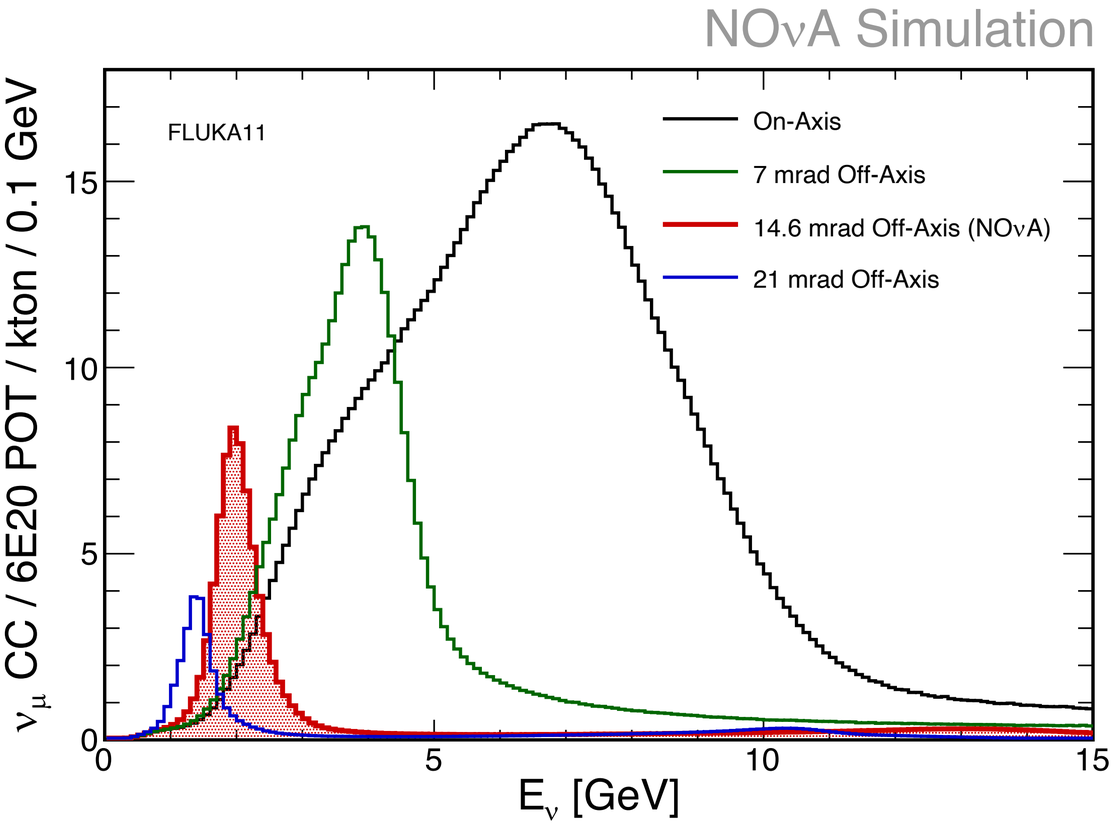


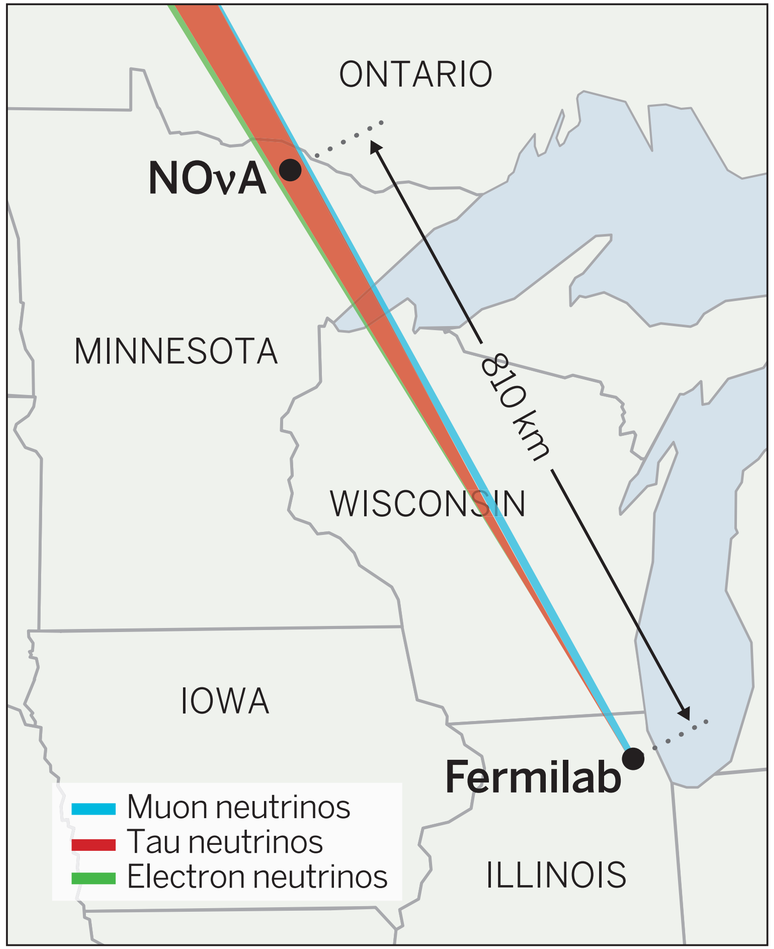


[A. Cho, Science 345, 6204 (2014)]

- NOvA is 14 mrad off-axis (narrow band beam at 2 GeV)
- Enphasizes $\nu_\mu \rightarrow \nu_e$

The NOvA Experiment





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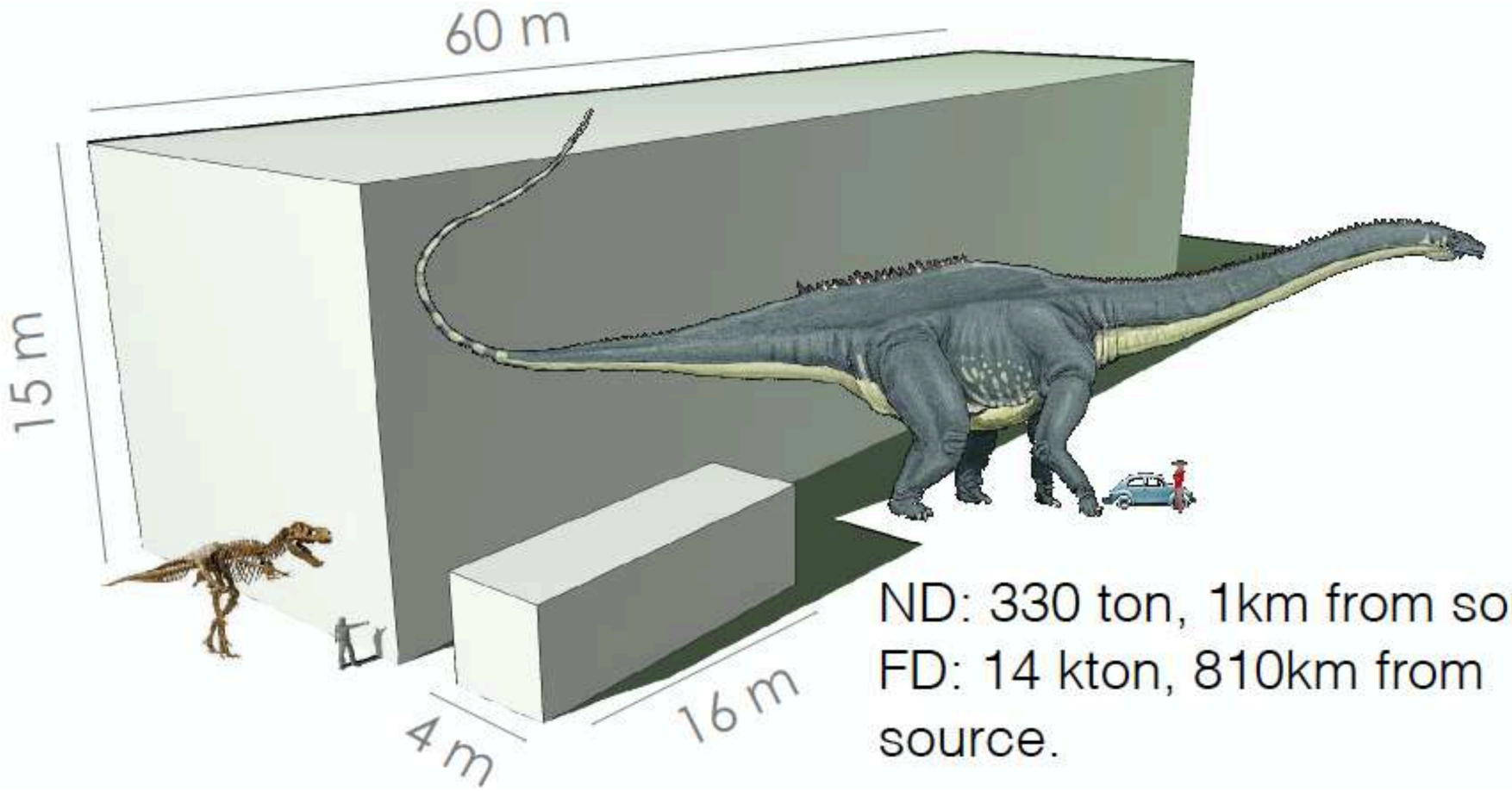
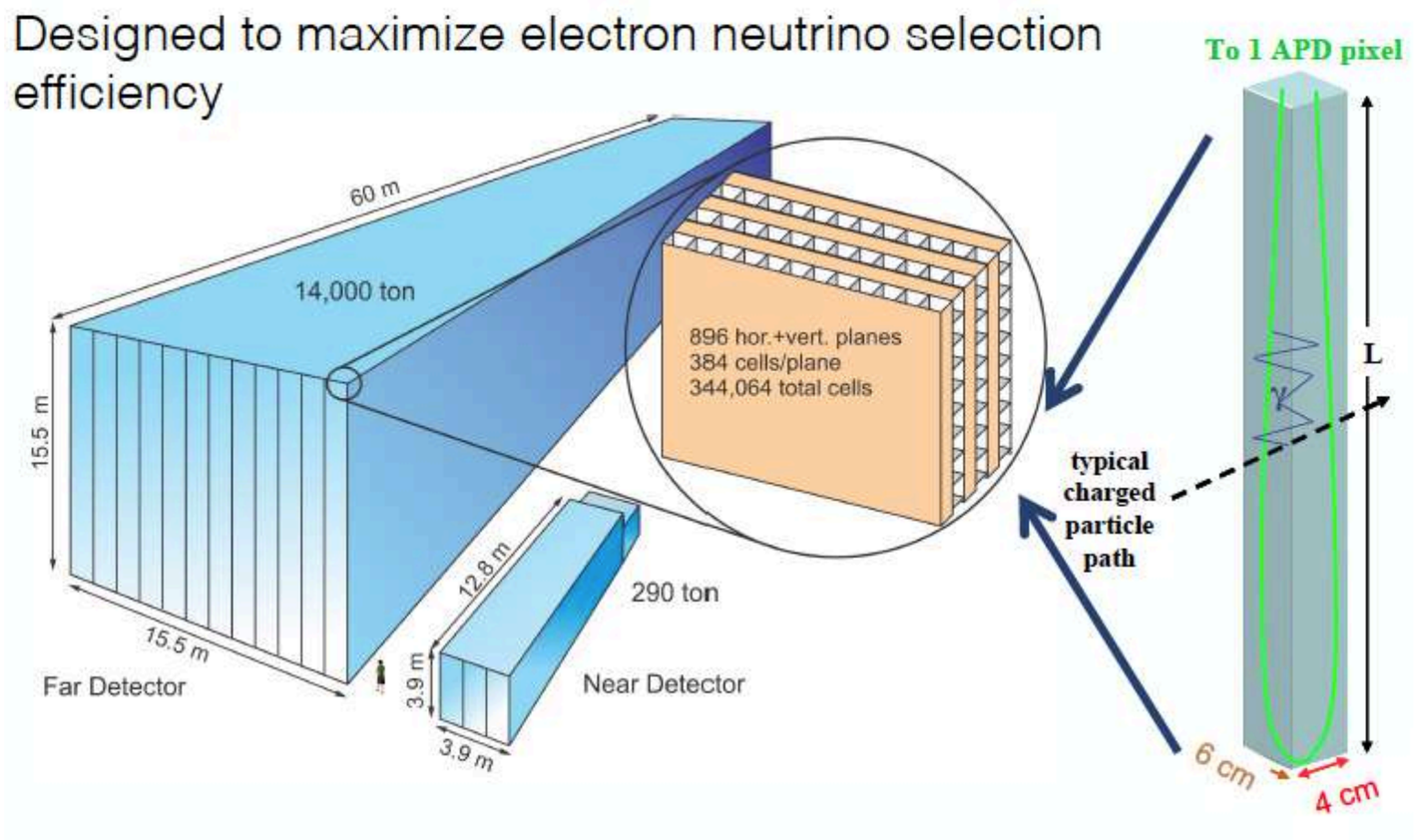


ND: 330 ton, 1km from source.
FD: 14 kton, 810km from source.

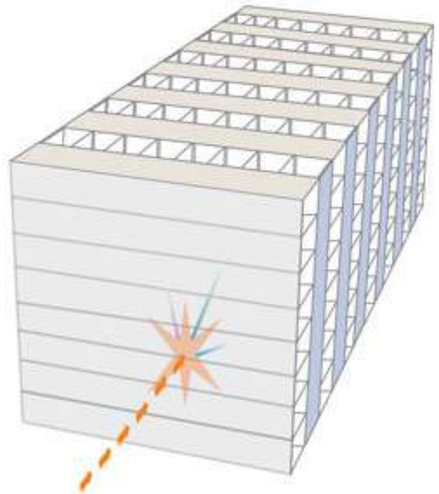
Near Detector
100 m underground, 20K channels

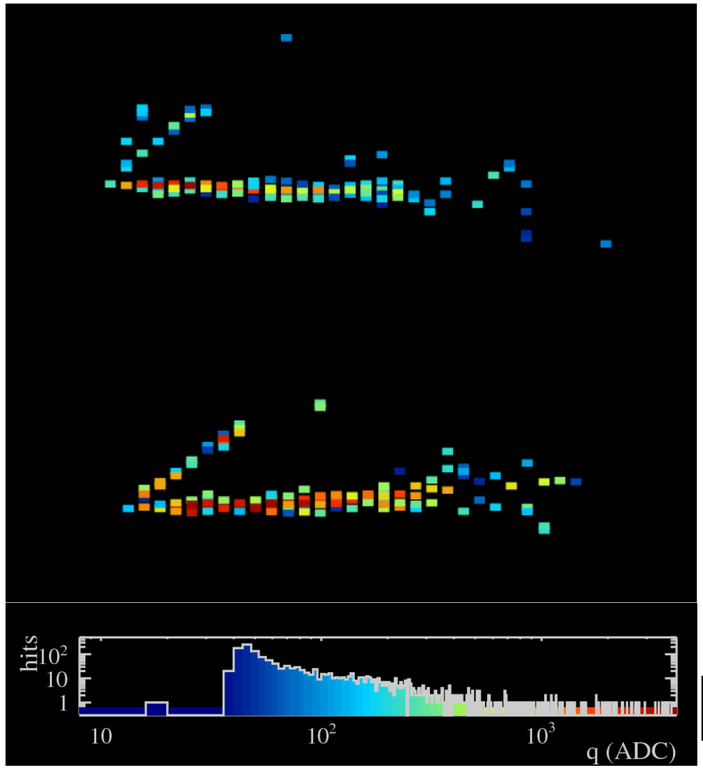
Far Detector
On the surface, 344K channels

The NOvA Experiment



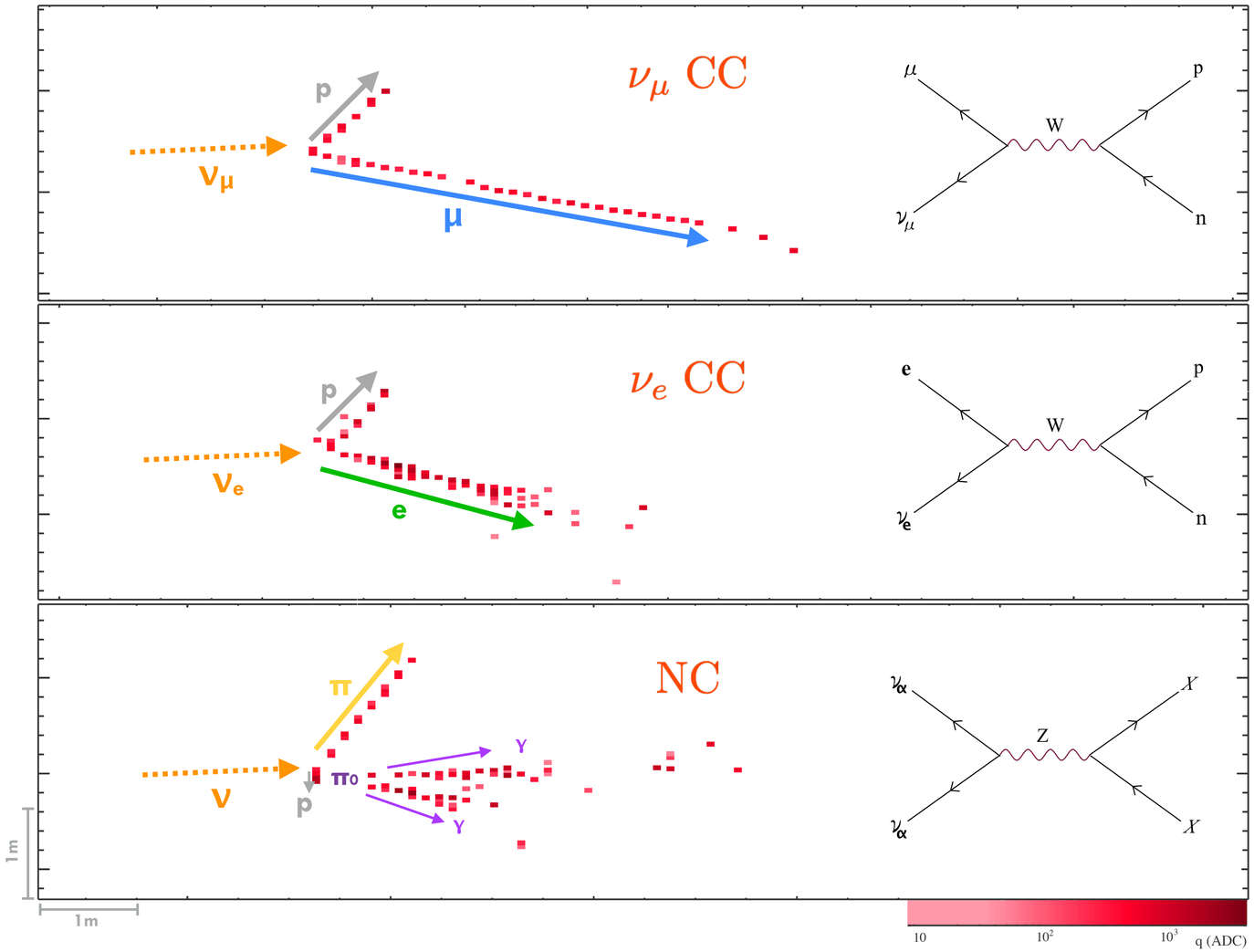
The detectors are functionally identical





Data event from the FD

Event topology



Near Detector Event Topologies

NOvA uses computer vision and deep learning techniques for **event selection**

Convolutional Visual Networks (CVN)

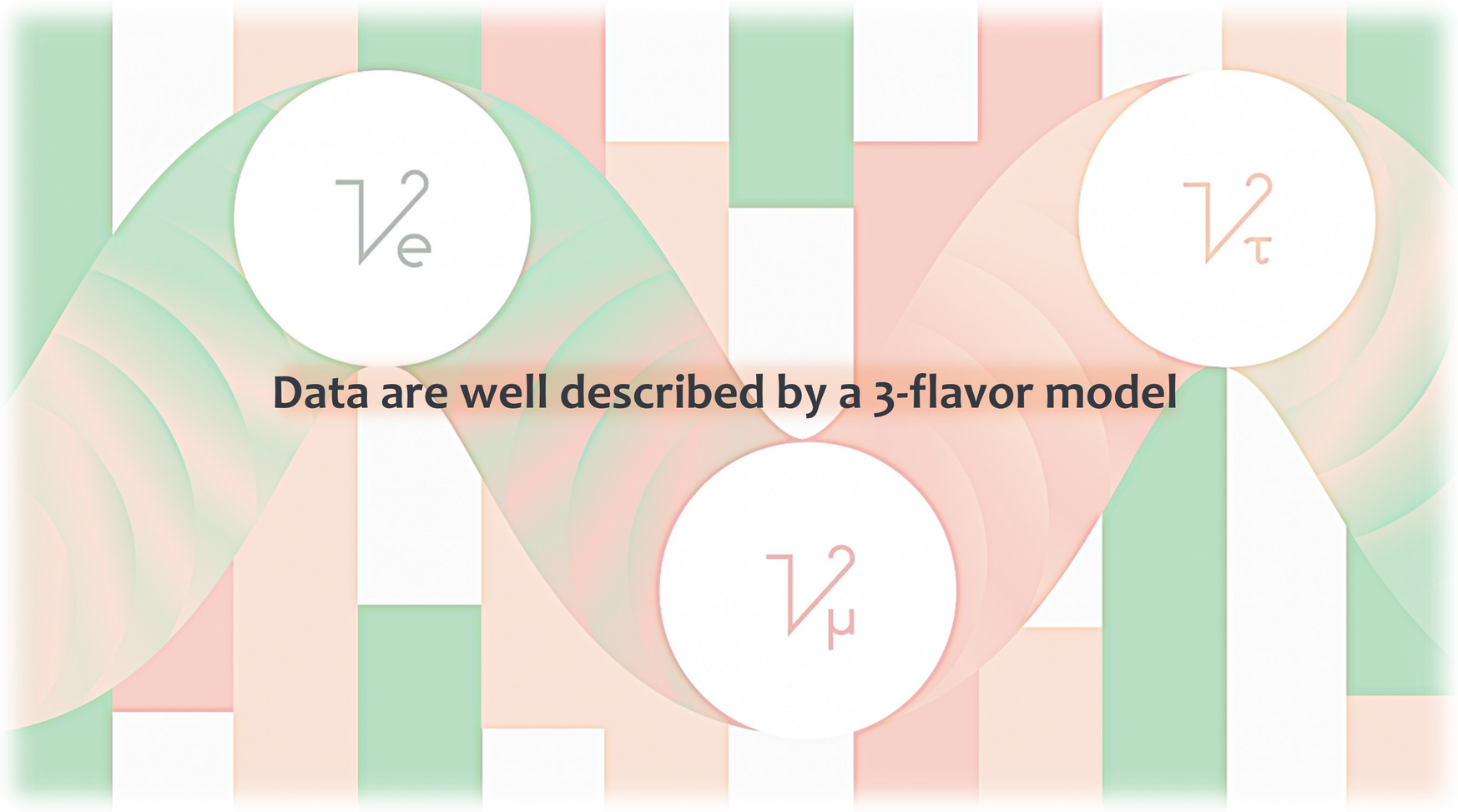
[A. Aurisiano et al., JINST11 (2016), arXiv:1604.01444]

The Data

And its interpretation

[Nevado de Toluca]

The Data



Data are well described by a 3-flavor model

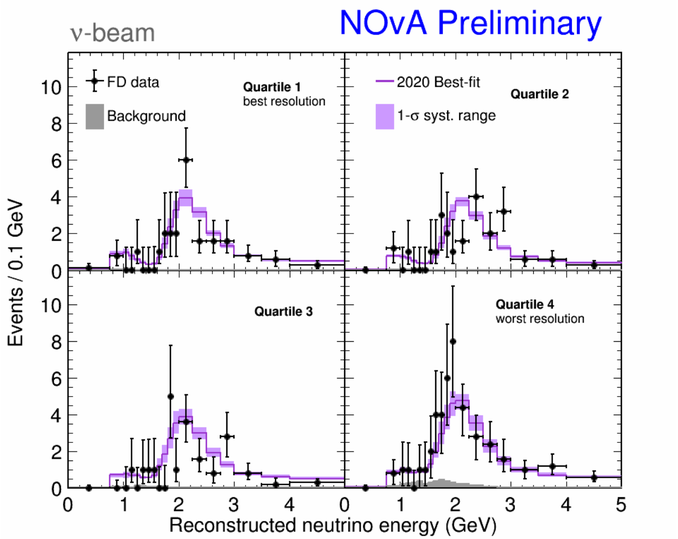
[www.sanfordlab.org/]

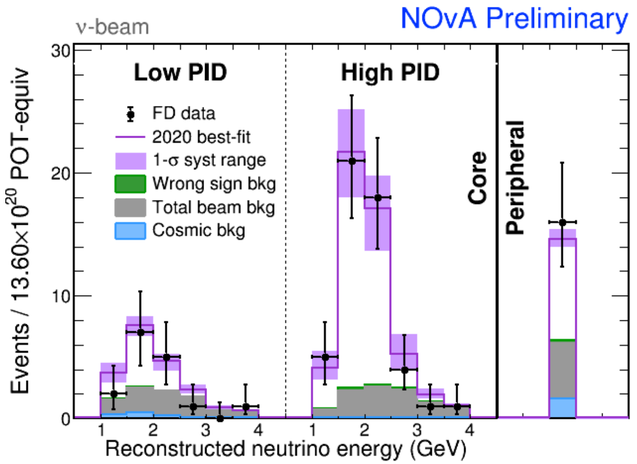
The Data

ν_μ

Events: 211

Bkgd: 8.2





ν_e

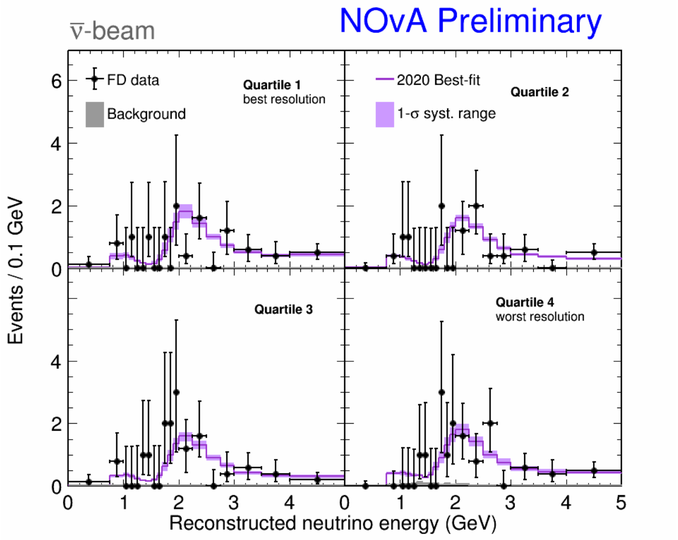
Events: 82

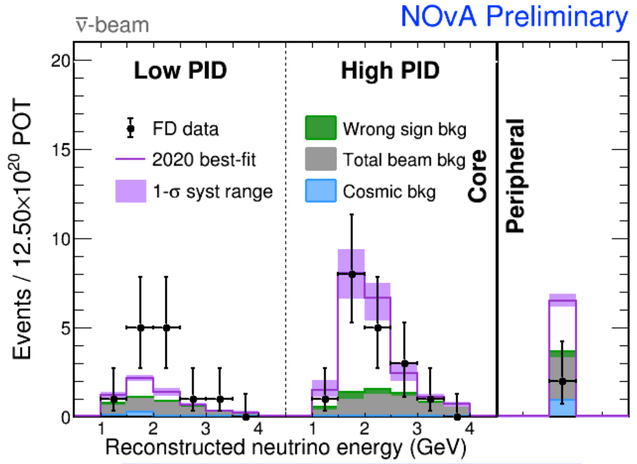
Bkgd: 23.8

$\bar{\nu}_\mu$

Events: 105

Bkgd: 2.1





$\bar{\nu}_e$

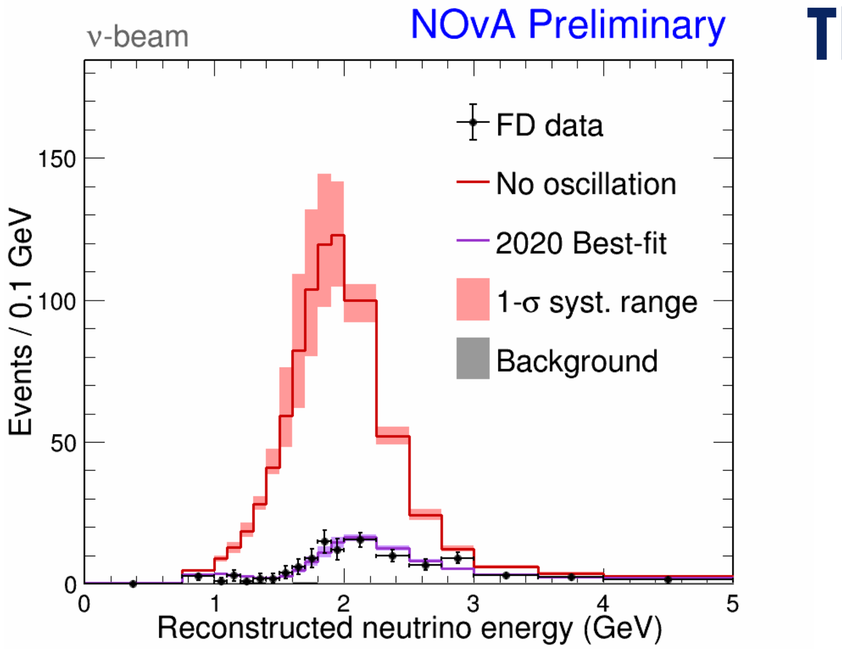
Events: 33

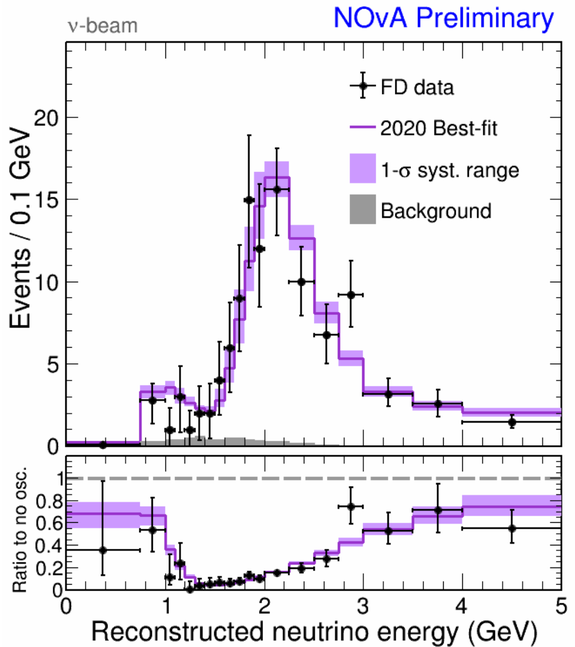
Bkgd: 14.1

$> 4\sigma\ \bar{\nu}_e$ appearance

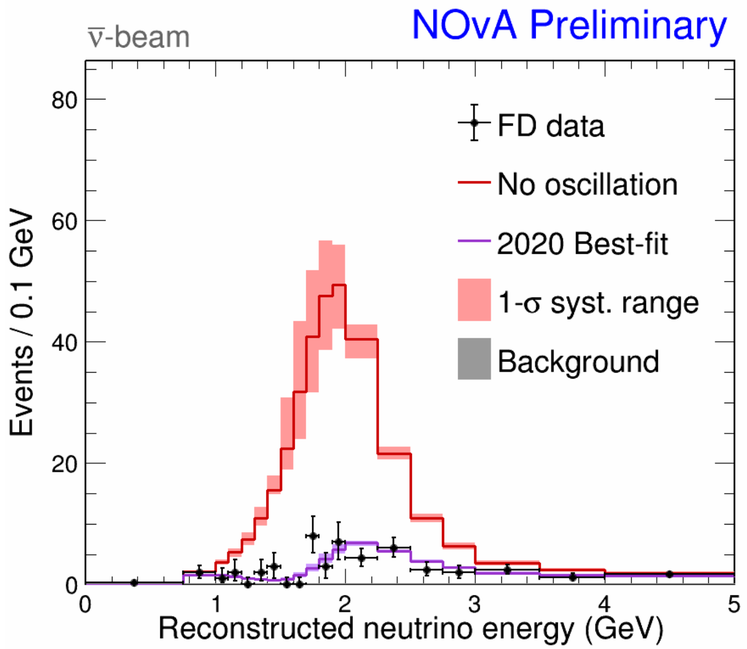
The Data

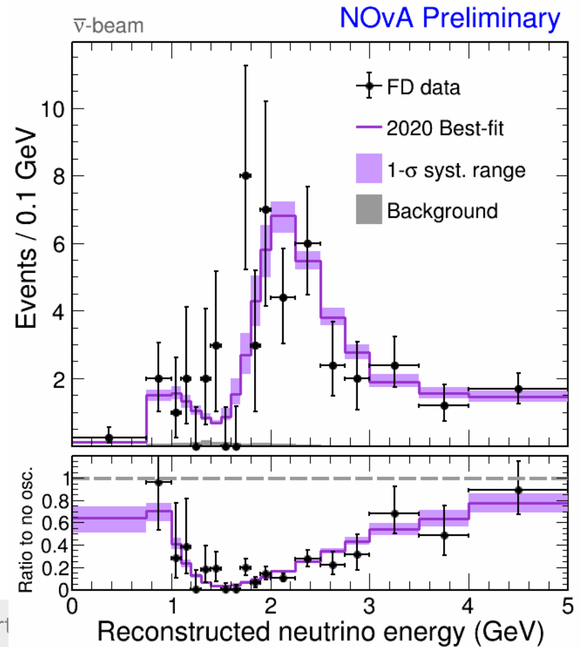
ν_μ



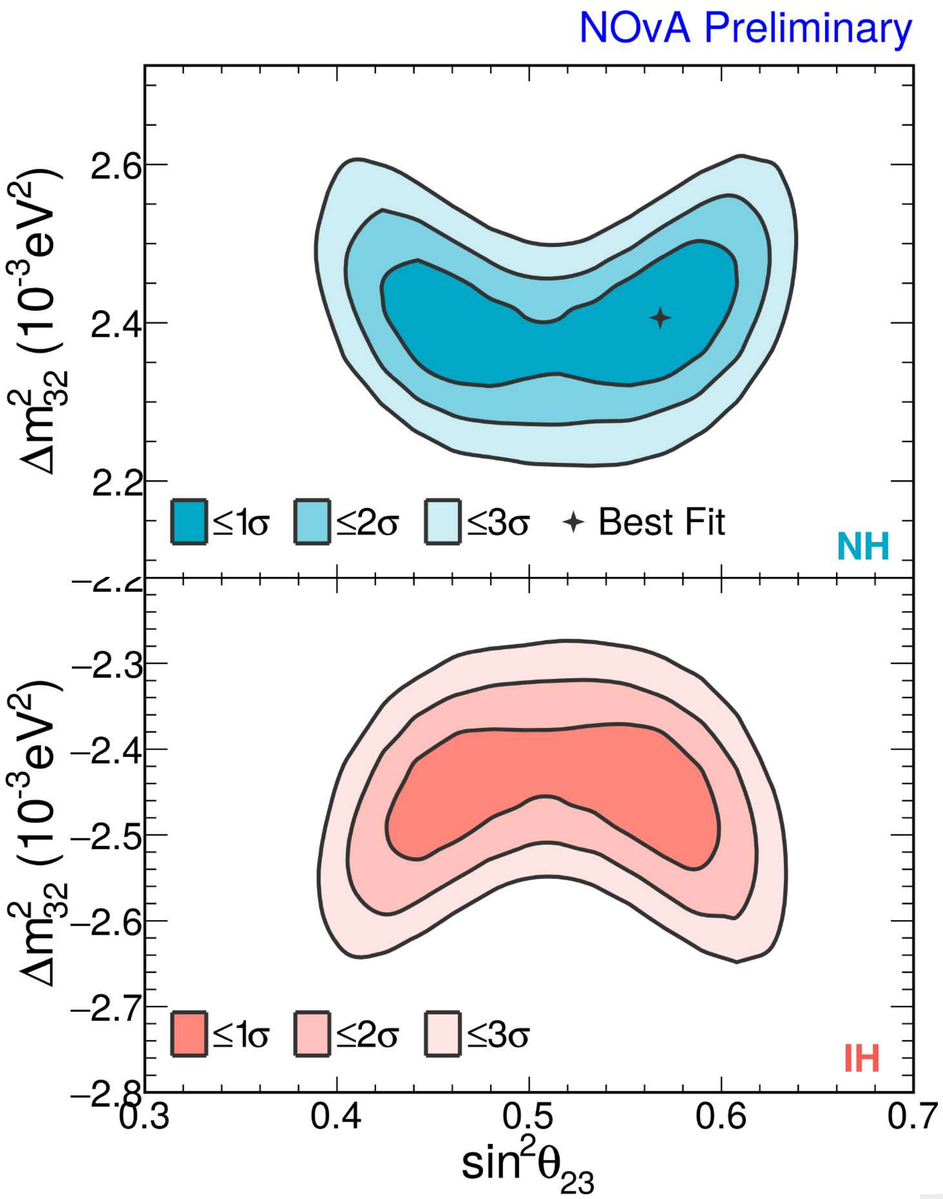


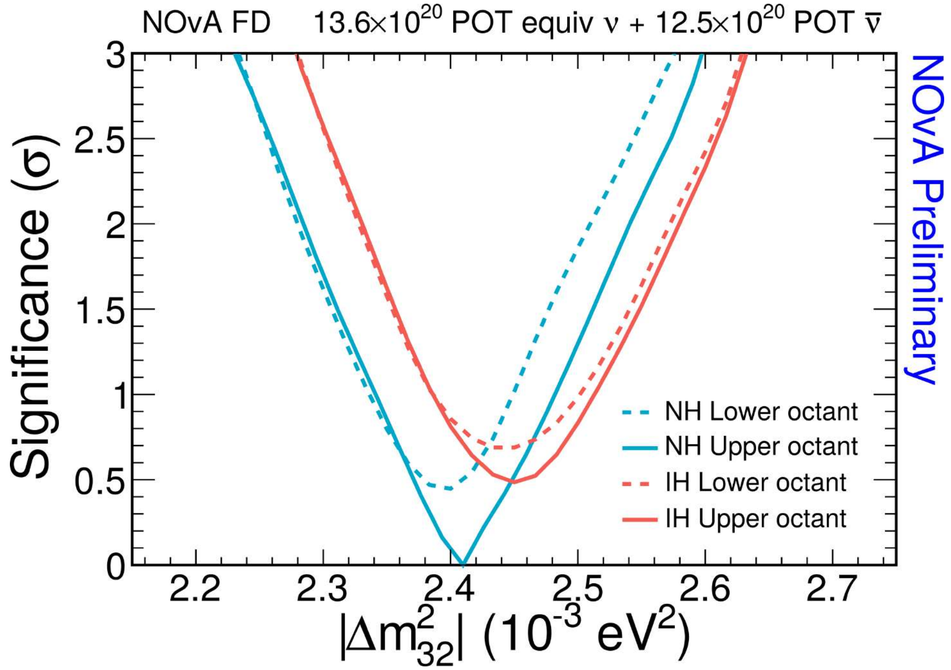
$\bar{\nu}_\mu$





Oscillations results





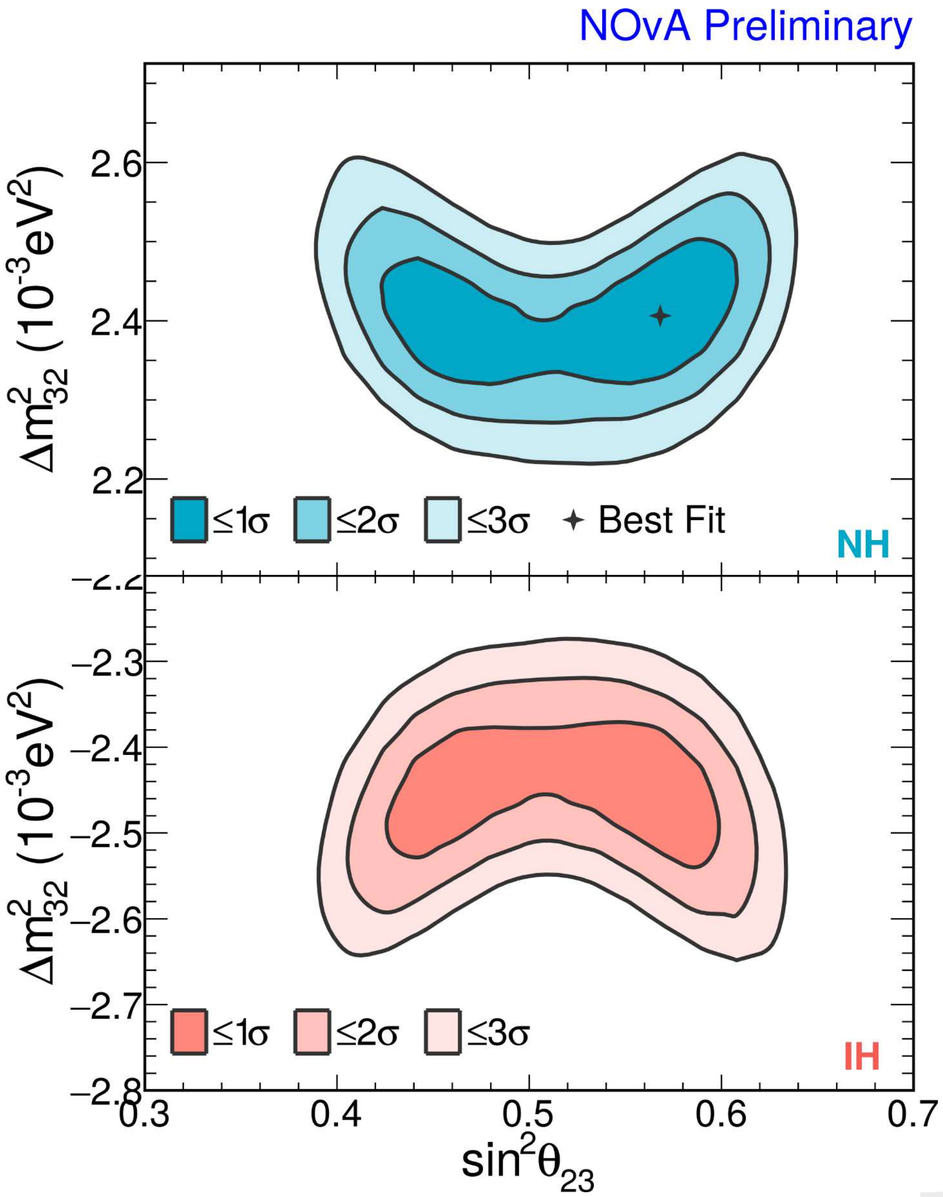
Best Fit

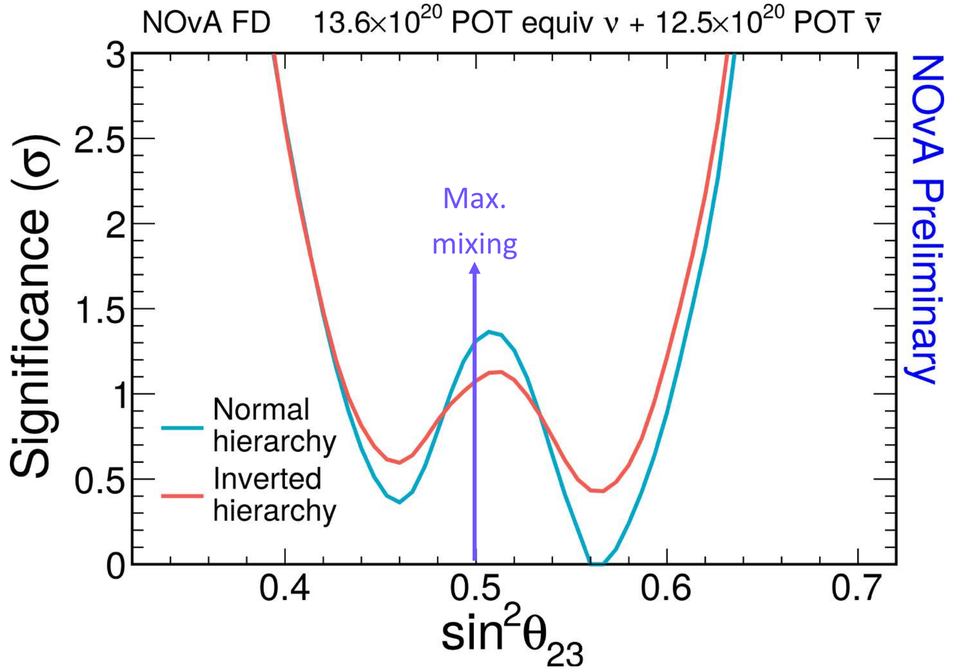
$$\Delta m^2_{32} = (+2.41 \pm 0.07) \times 10^{-3}\ \text{eV}^2\ (\text{NH})$$

$$\sin^2\theta_{23} = 0.57^{+0.03}_{-0.04}$$

$$\delta_{CP} = 0.82\pi$$

Oscillations results





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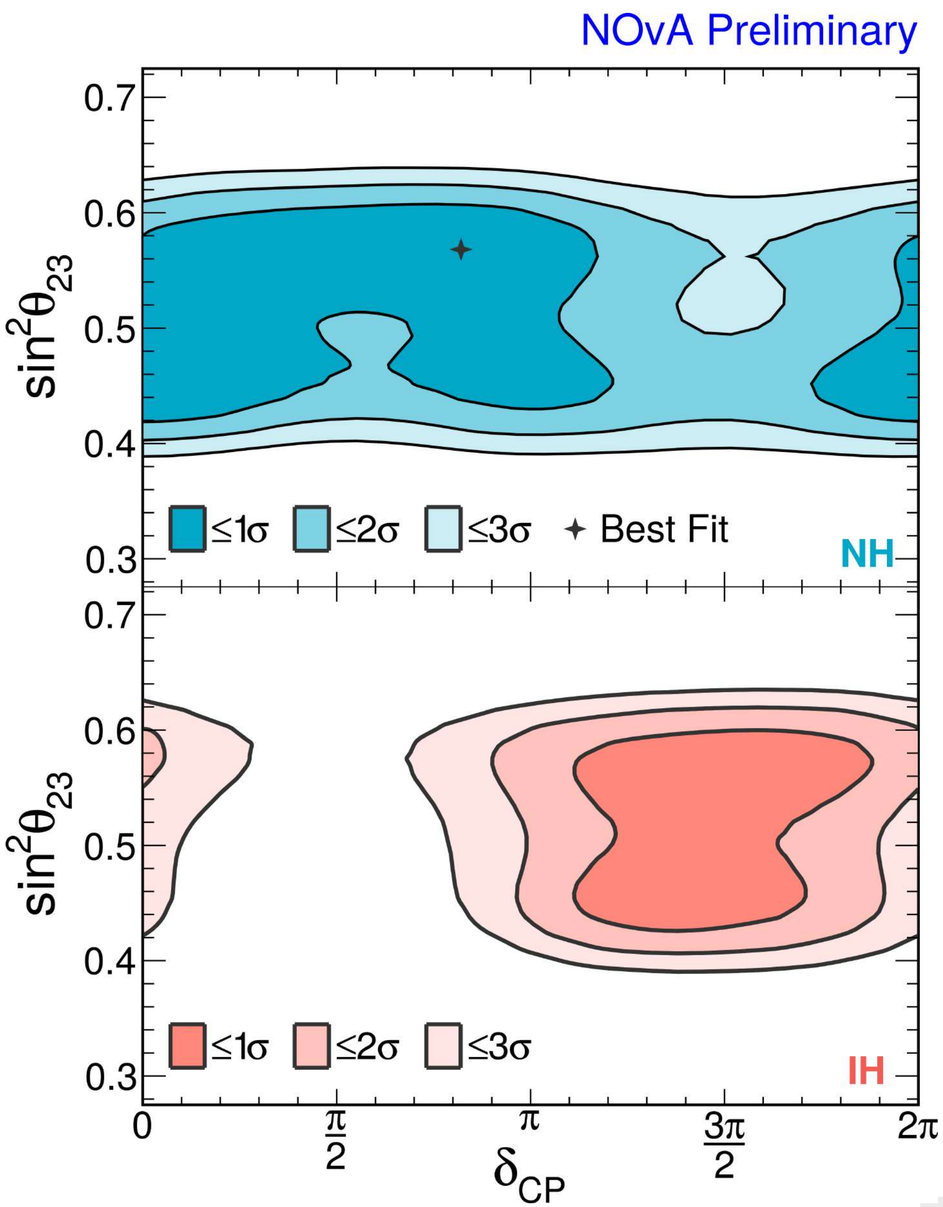
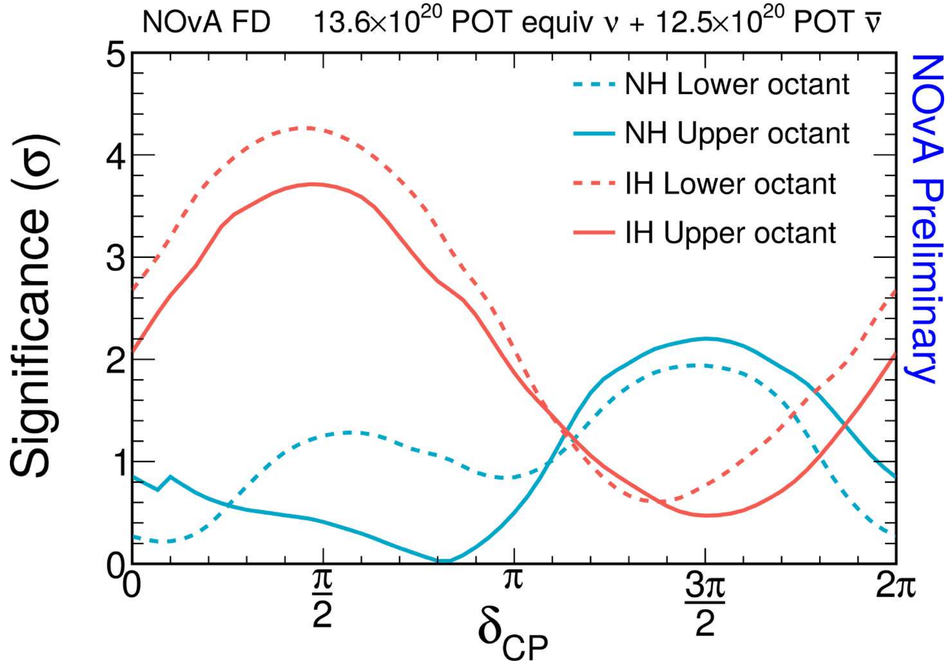
$$\delta_{CP} = 0.82\pi$$

Lower octant disfavored at 1.2σ

Maximal mixing disfavored at 1.1σ

Oscillations results





Best Fit

$$\Delta m^2_{32} = (+2.41 \pm 0.07) \times 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NH})$$

$$\sin^2\theta_{23} = 0.57^{+0.03}_{-0.04}$$

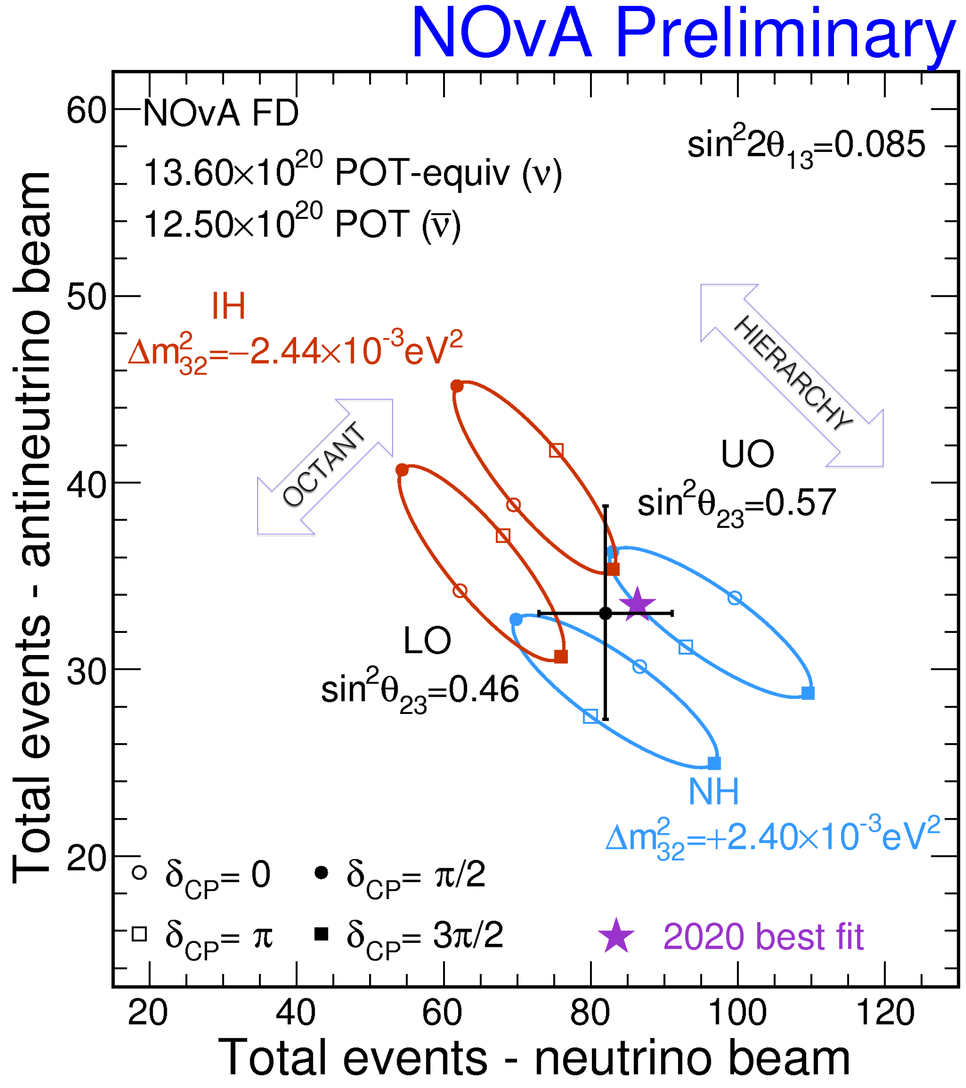
$$\delta_{CP} = 0.82\pi$$

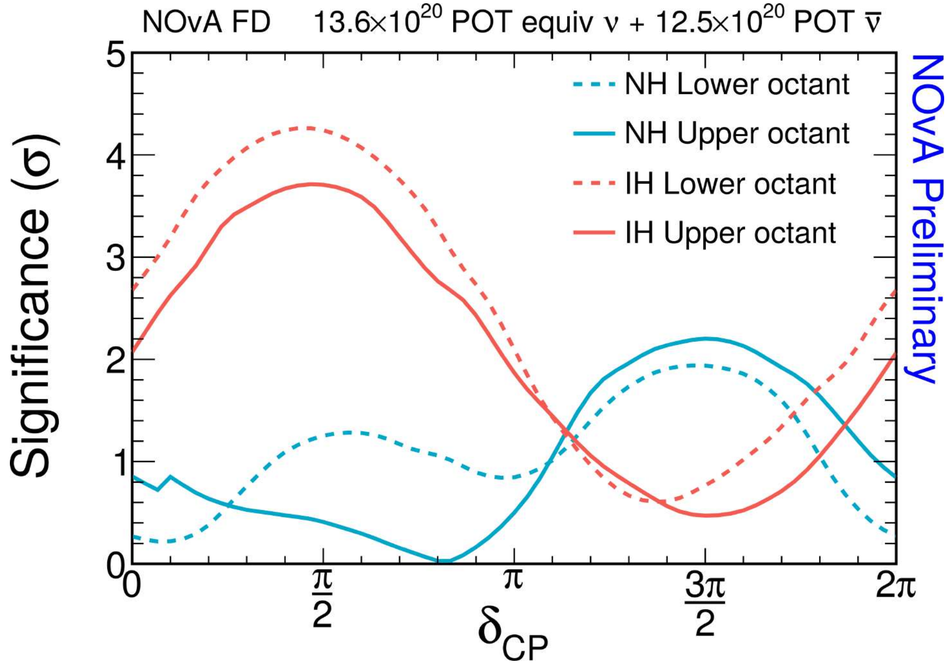
Lower octant disfavored at 1.2σ

Inverted Hierarchy disfavored at 1σ

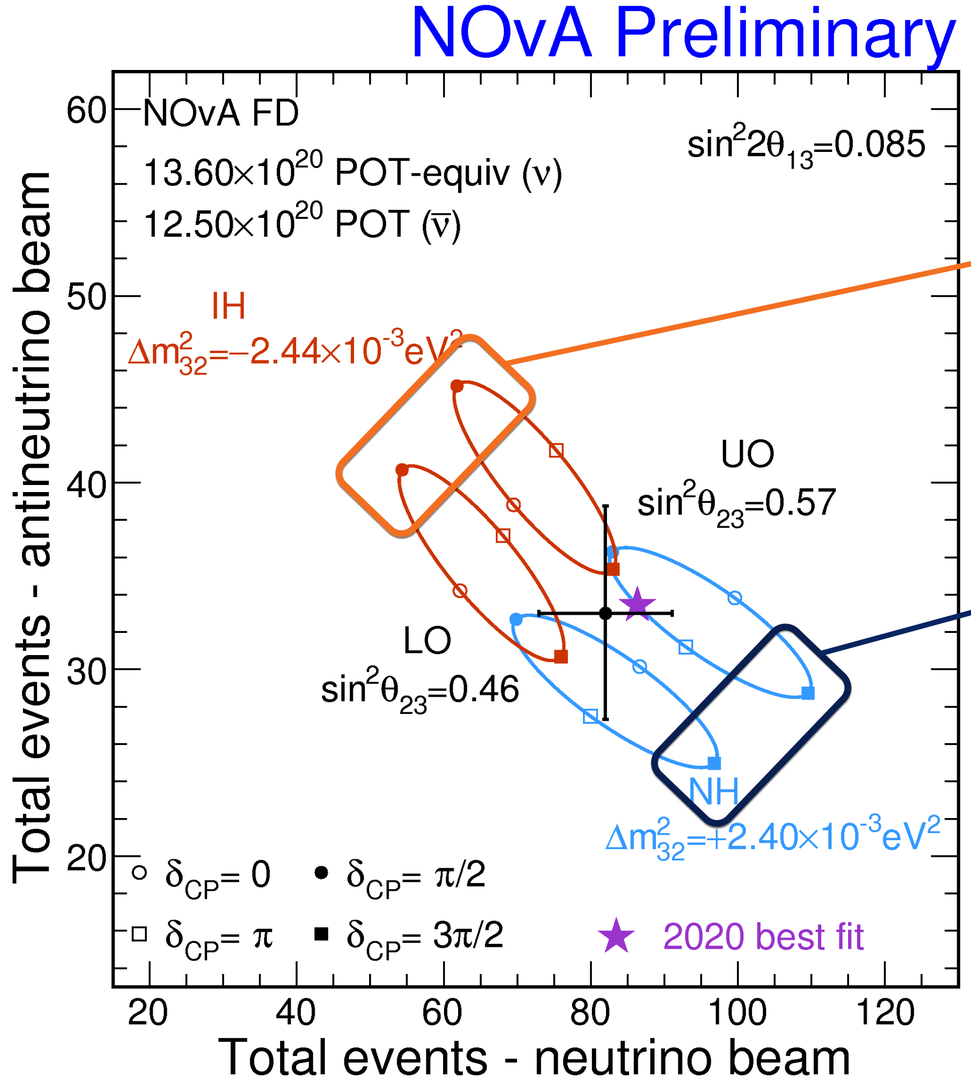
$\sin^2\theta_{13} = 0.085 \pm 0.005$ (PDG)

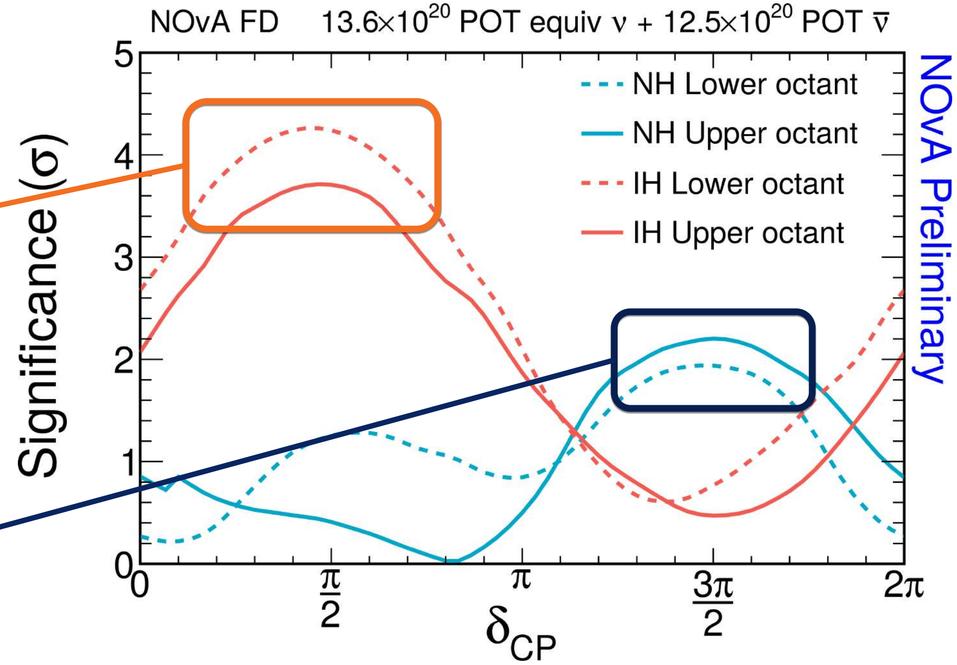
Oscillations results





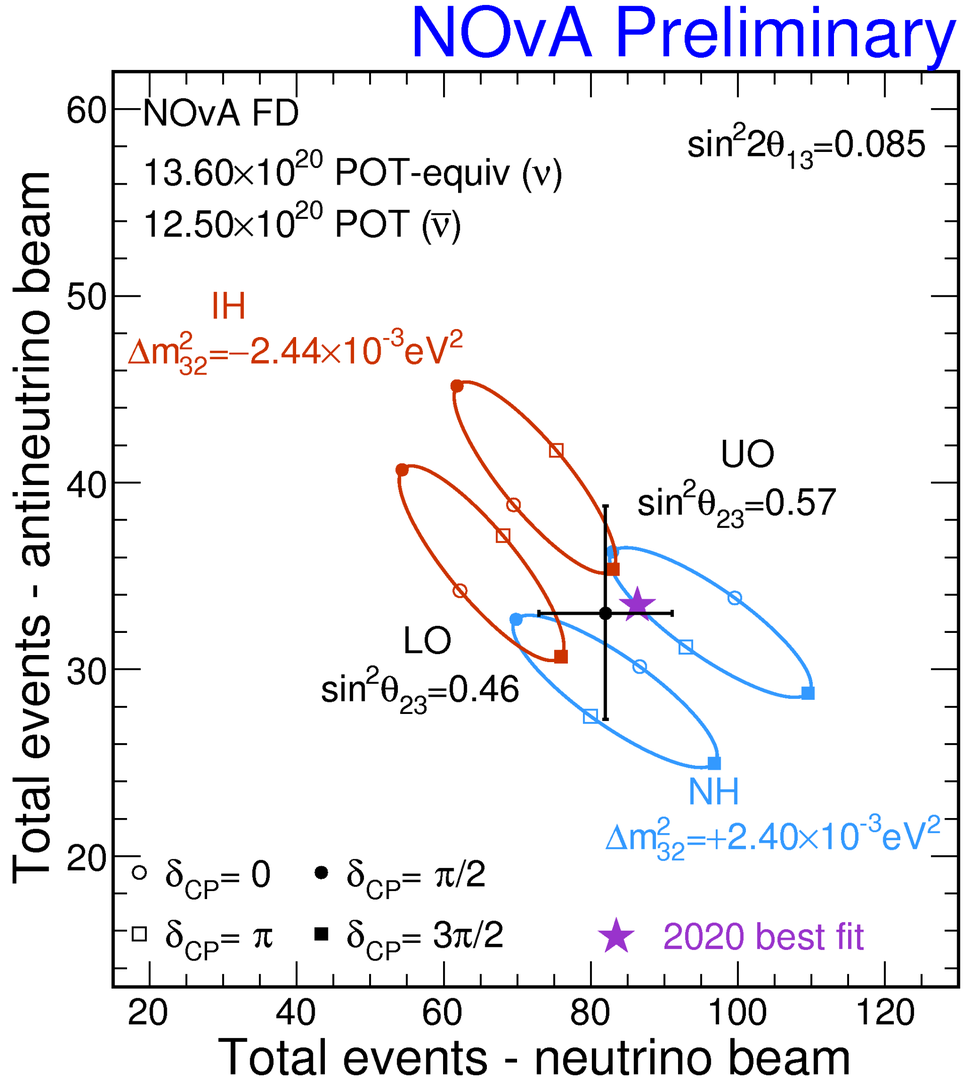
Oscillations results

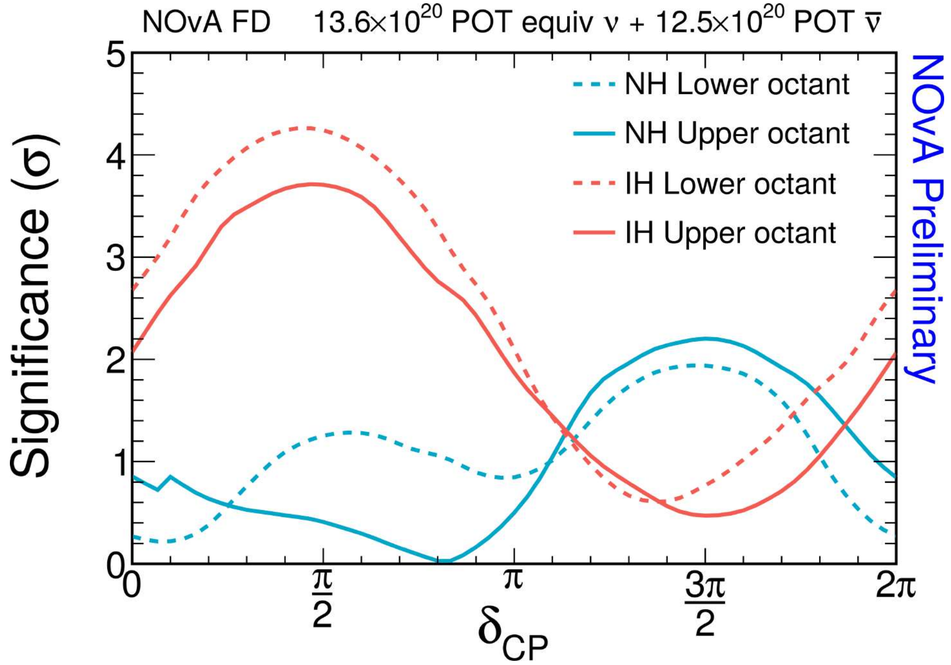




- Hie-oct-δ_{CP} combinations that produce *asymmetric* $\nu_e - \bar{\nu}_e$ appearance are disfavored
- Combinations that include some "*cancellation*" are preferred

Oscillations results

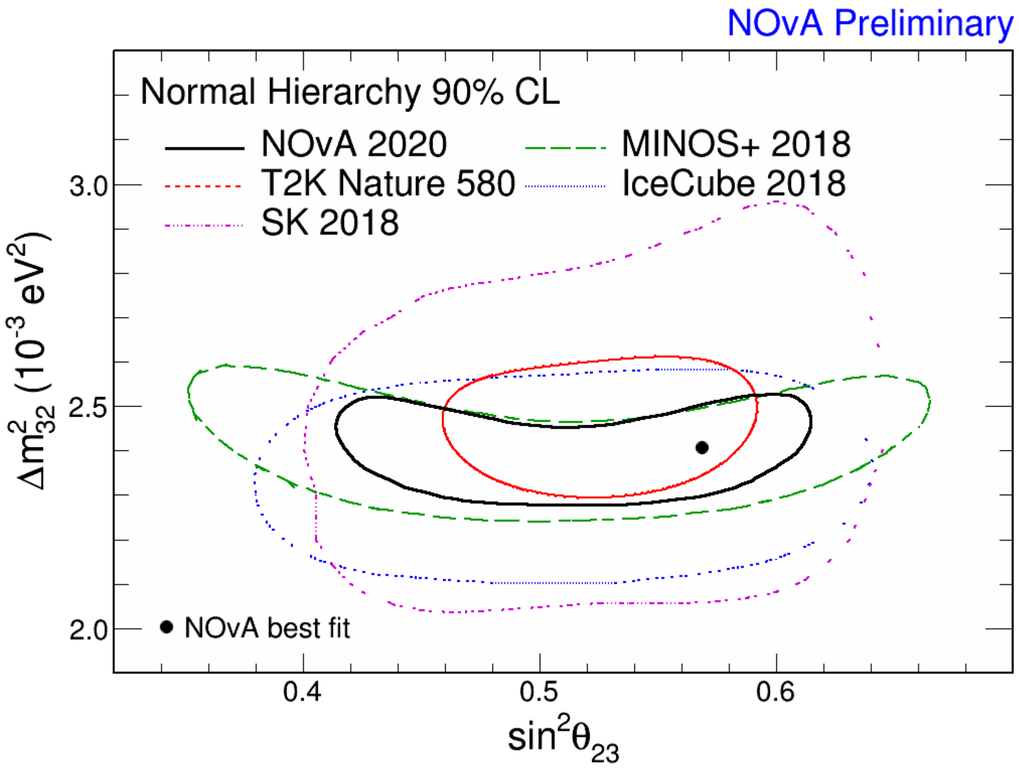


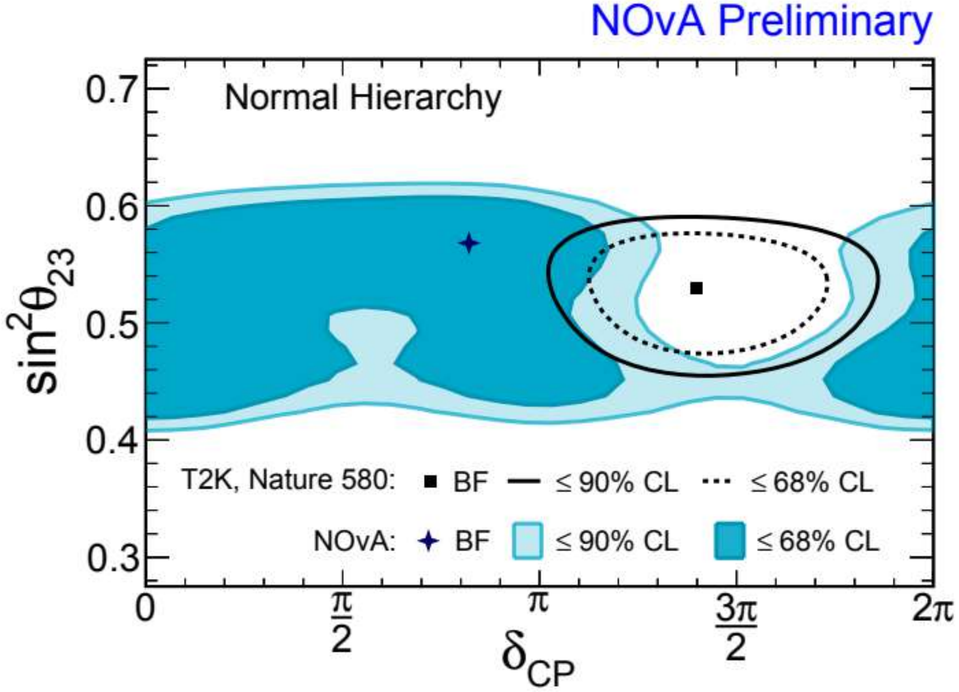


- No strong preference for hierarchy or octant
- Disfavor $(\mathrm{NH},\ \delta_{\mathrm{CP}} = 3\pi/2)$ at $\sim 2\sigma$
- Exclude $(\mathrm{IH},\ \delta_{\mathrm{CP}} = \pi/2)$ at $> 3\sigma$

Other oscillations results

NB: not yet updated after NEUTRINO 2020 results from all experiments





- Agreement with other *atmospheric* parameters measurements
- Apparent tension in allowed values of δ_{CP} between NOvA and T2K

Other oscillations results

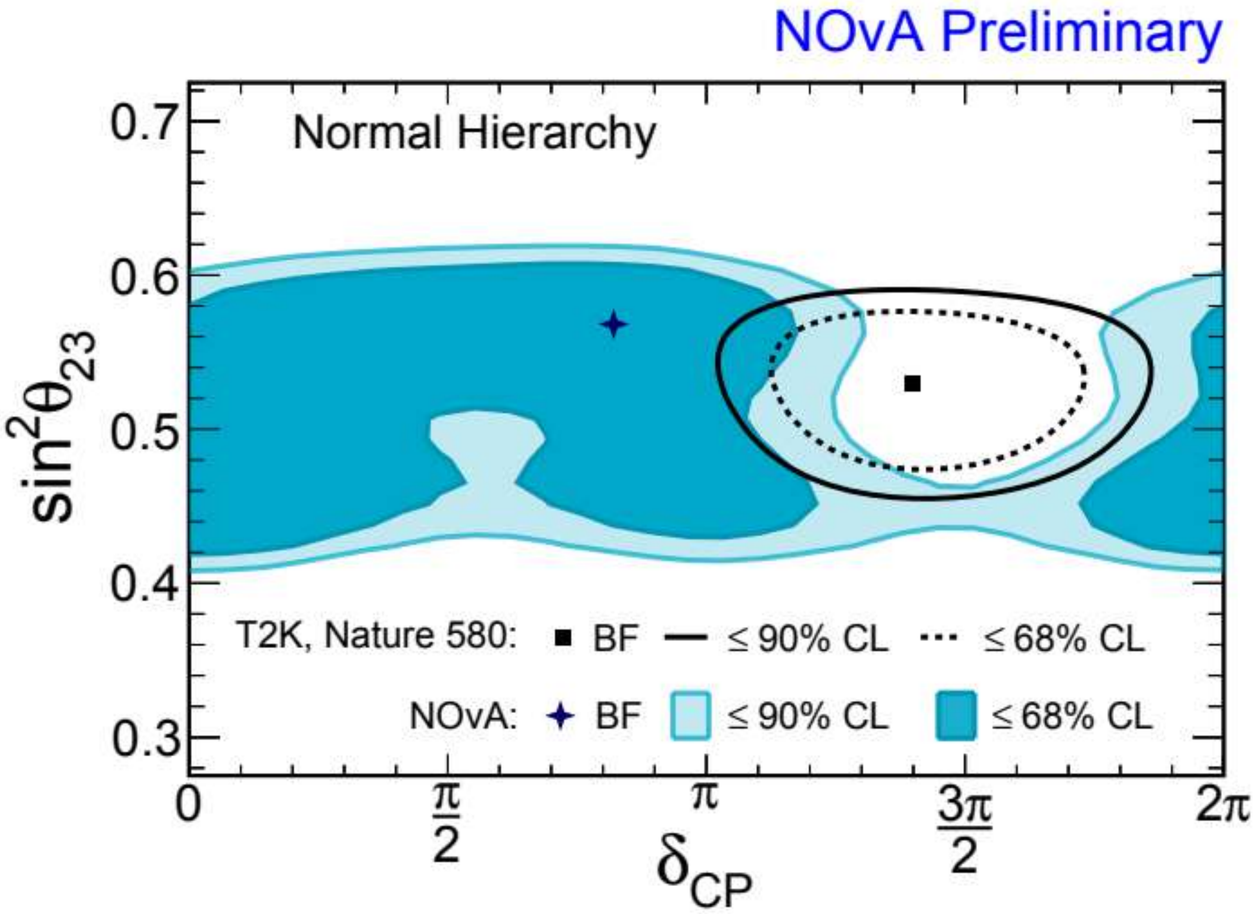
Attempts to “resolve” or explain this tension

- IH as the favored solution

  [K. Kelly et al., arXiv:2007.08526]

- New Physics: Non-Standard Interactions

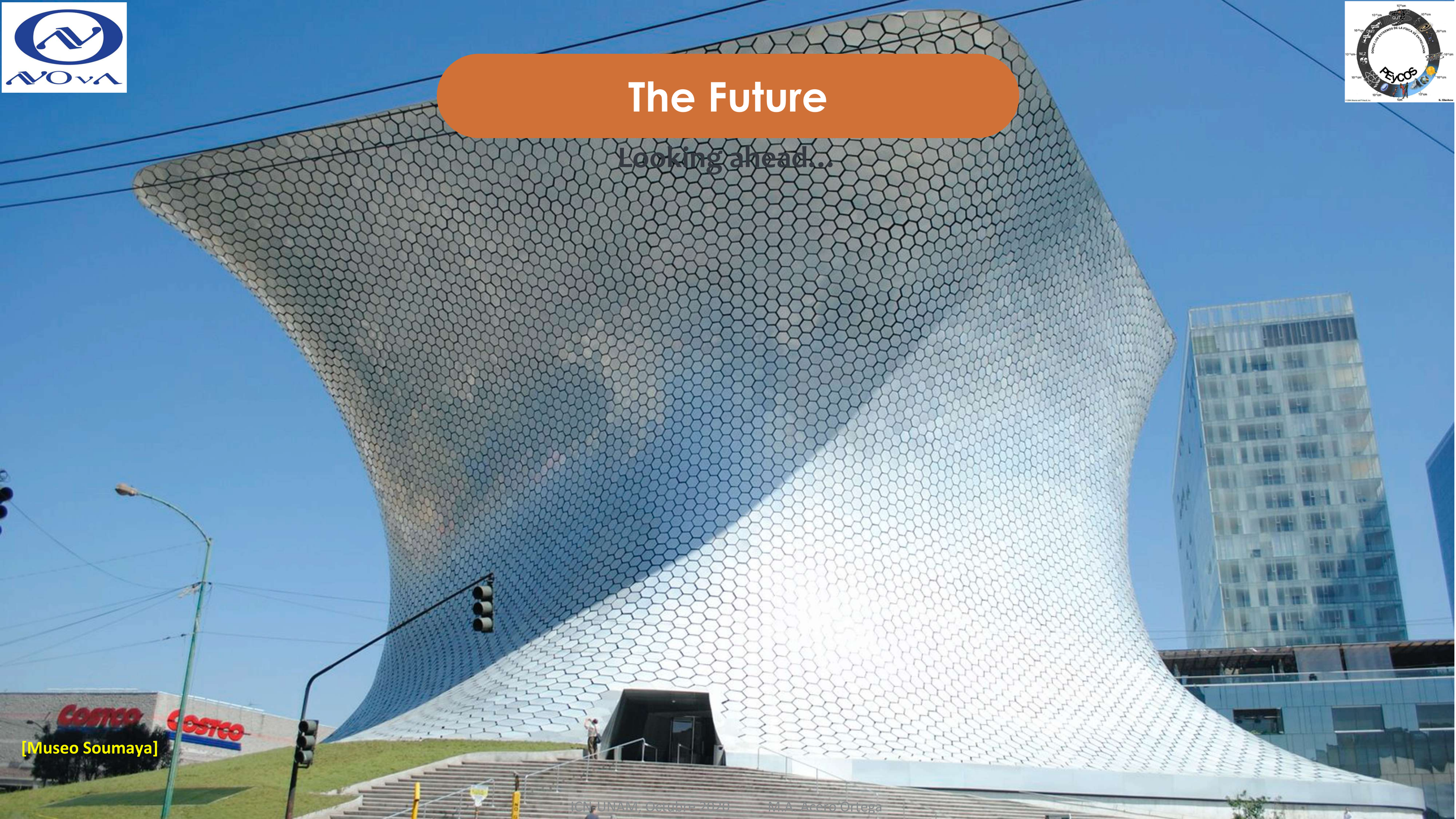
  [P. Denton et al., arXiv:2008.01110;
  S. Chatterjee & A. Palazzo, arXiv:2008.04161]



NOvA & T2K are working together on a fully self-consistent joint fit

The Future

Looking ahead...



[Museo Soumaya]

The Future

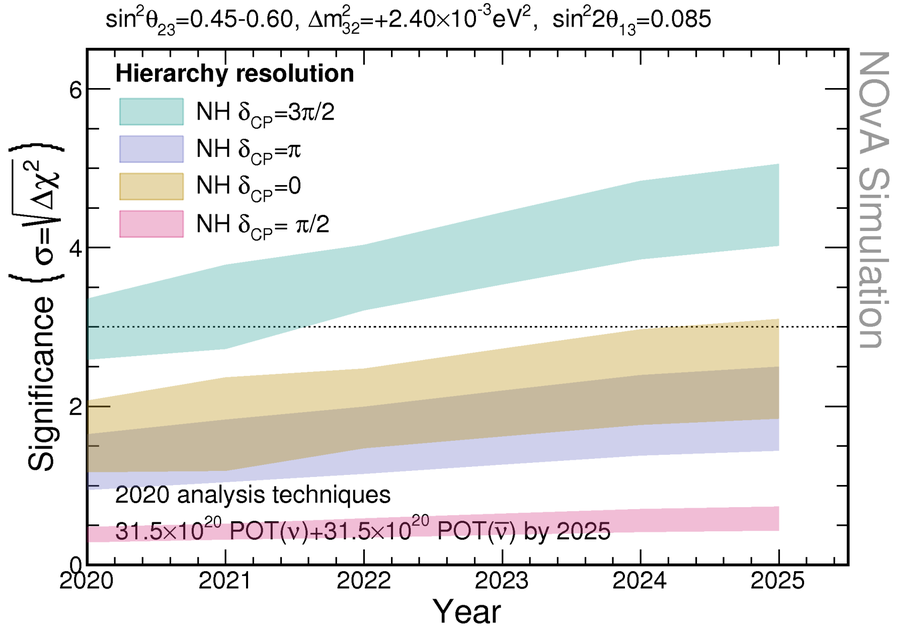
Currently beam is off…

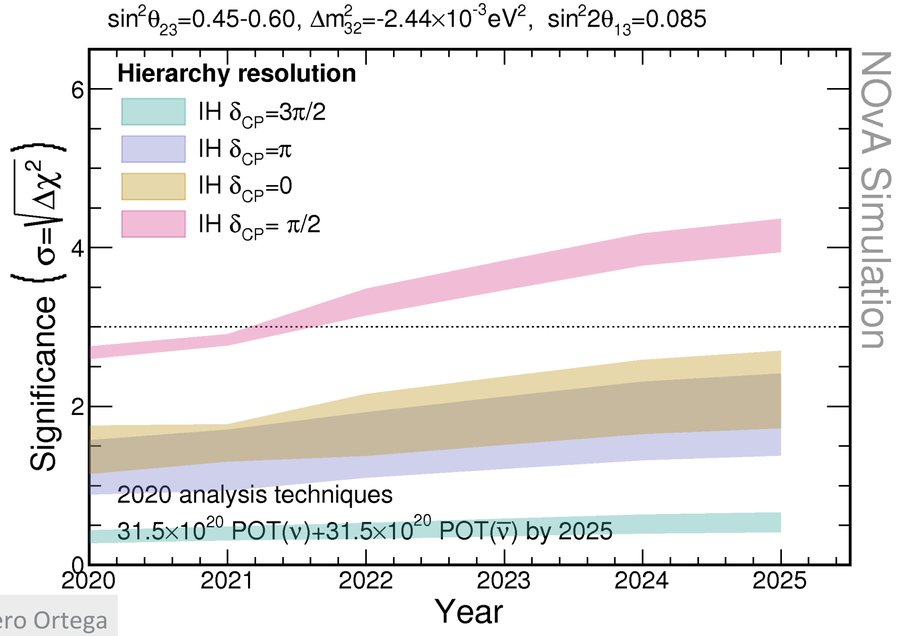
- Will resume in neutrino mode shortly
- Plan to get 50:50 ν: $\bar{\nu}$
- NOvA is expected to run until 2025

Sensitivity expectations…

- Potential 3-5σ sensitivity to Hierarchy

  for favorable parameters





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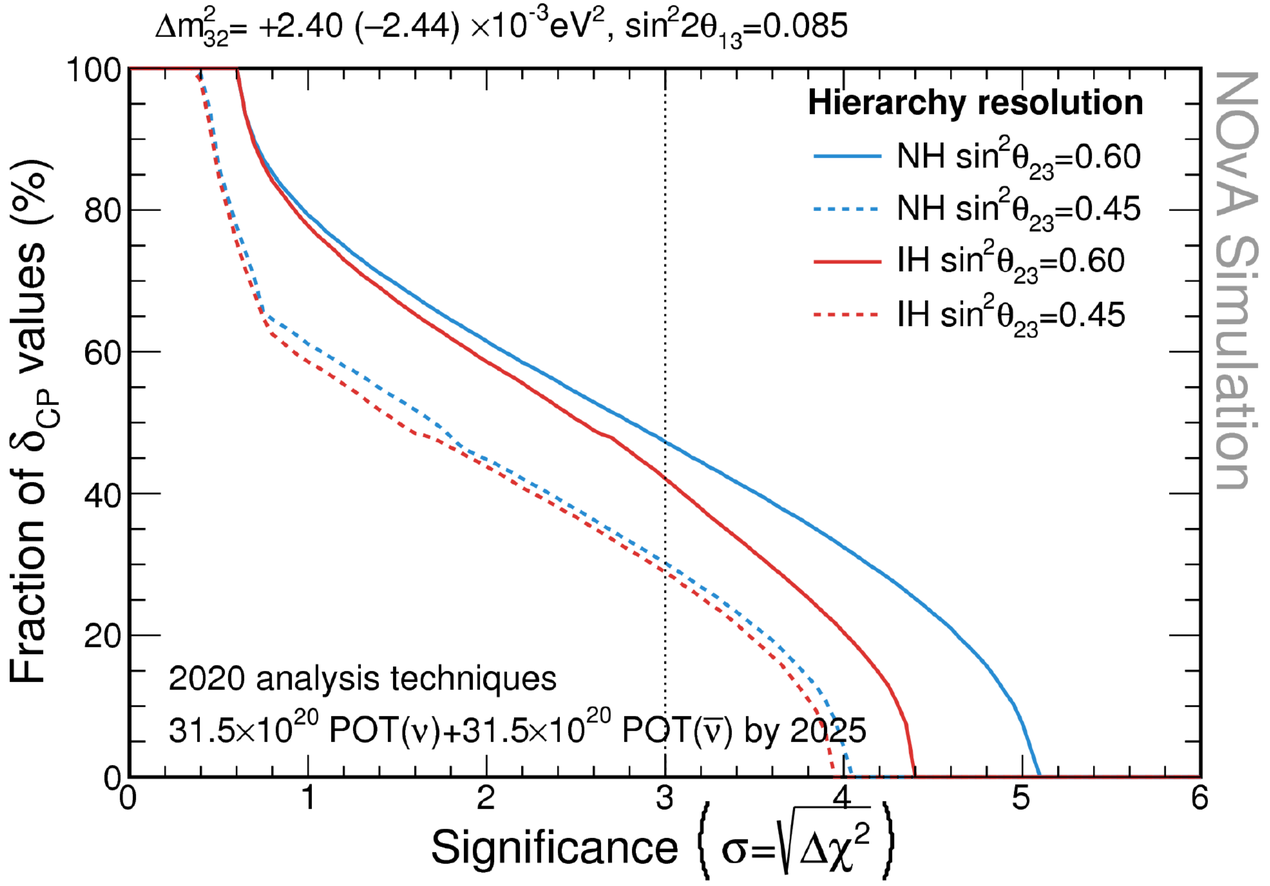
- Even 4-5σ for $\delta_{CP} = 3\pi/2$
- ≥3σ for 30-50% of δ_{CP} values

depending on the mixing and hierarchy



The Future

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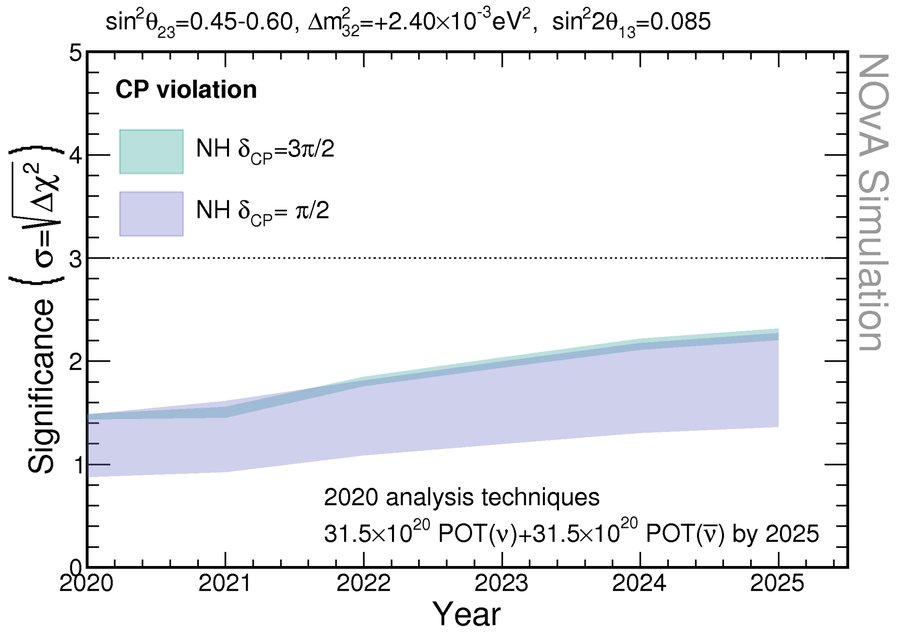
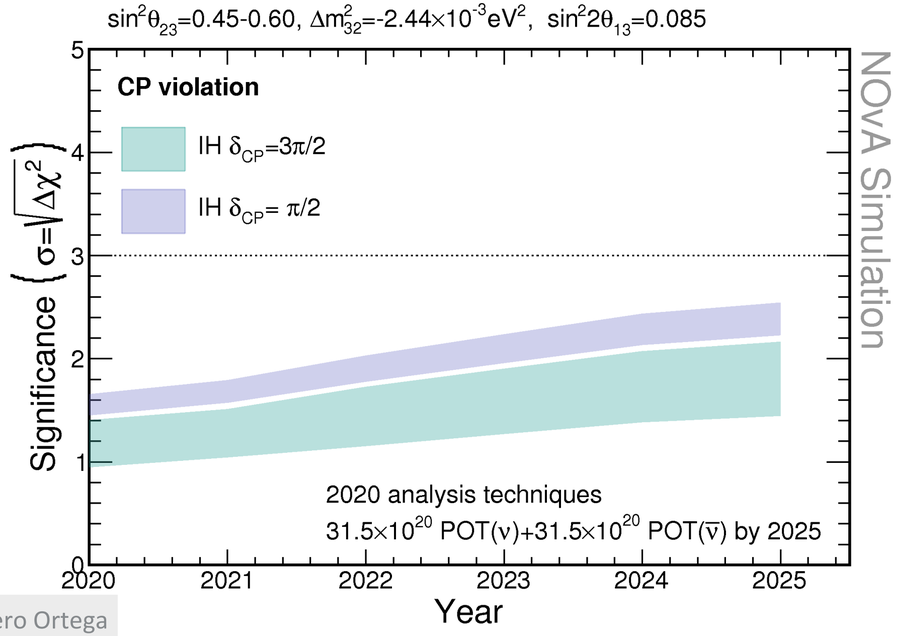
- Even 4-5σ for $\delta_{CP} = 3\pi/2$
- ≥3σ for 30-50% of δ_{CP} values
- Possible >2σ to CP violation

All depends on true values in Nature

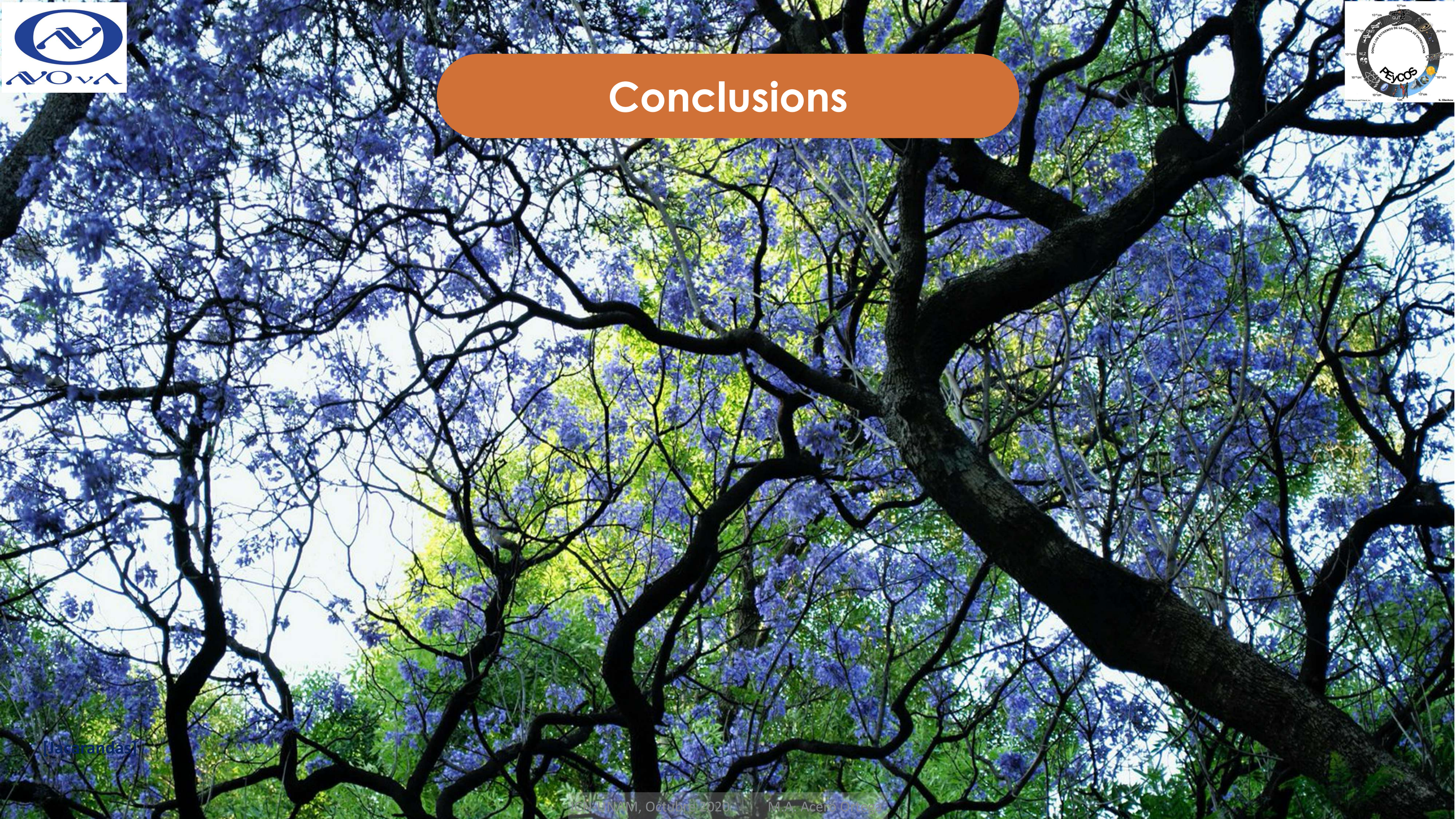
Improvements to come…

- Beam intensity
- Test Beam program (detector response)





Conclusions



[Jacarandas]

[Ángel de la Independencia]

Conclusions

With an exposure of $13.6 \times 10^{20}(\nu) + 12.5 \times 10^{20}(\bar{\nu})$ POT, we got:

- Atmospheric parameters

$$\Delta m^2_{32} = (2.41 \pm 0.07) \times 10^{-3}\,\mathrm{eV}^2$$
$$\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$$

- Constraints on strongly asymmetric $\nu_e - \bar{\nu}_e$ appearance PNMS solutions

$$(\mathrm{IH}, \delta_{\mathrm{CP}} = \pi/2) \rightarrow \text{excluded at } > 3\sigma$$
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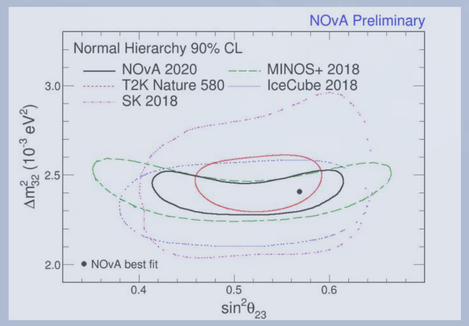
$$(\mathrm{NH}, \delta_{\mathrm{CP}} = 3\pi/2) \rightarrow \text{disfavored at } \sim 2\sigma$$

- More to come!
  - $\sim 3 - 5\sigma$ sensitivity to mass hierarchy determination for some values of δ_{CP}
  - Potential sensitivity to δ_{CP} up to 2σ
  - Input from NOvA Test Beam program and neutrino interactions community to further improve robustness to systematics



[Ángel de la Independencia]

¡Gracias!

Supplement

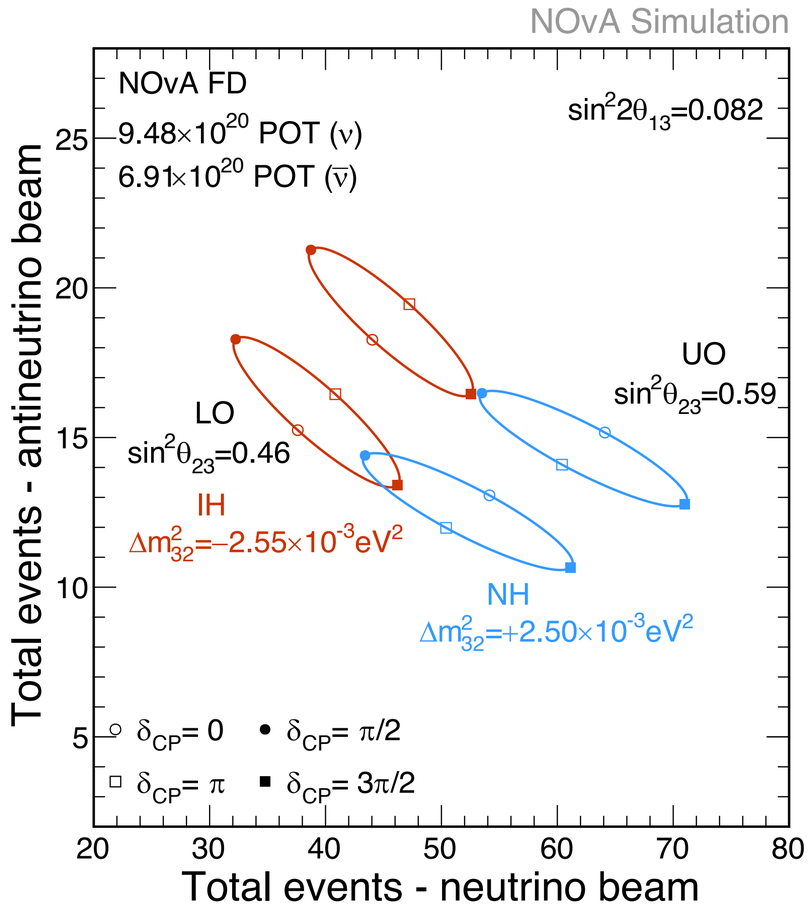
Additional information

Supplement

	1-σ range
$\sin^2\theta_{23}$ NH	[0.431 ; 0.487] ∪ [0.530 ; 0.602]
$\sin^2\theta_{23}$ IH	[0.433 ; 0.492] ∪ [0.526 ; 0.595]
Δm^2_{32} NHUO	[2.341 ; 2.482]
Δm^2_{32} NHLO	[2.336 ; 2.449]
Δm^2_{32} IHUO	[2.386 ; 2.513]
Δm^2_{32} IHLO	[2.386 ; 2.502]
δ_{CP} NHUO	[0 ; 1.09] ∪ [1.95 ; 2]
δ_{CP} NHLO	[0 ; 0.37] ∪ [0.84 ; 1.10] ∪ [1.81;2]
δ_{CP} IHUO	[1.22 ; 1.79]
δ_{CP} IHLO	[1.19 ; 1.59]
δ_{CP} NH	[0 ; 1.06] ∪ [1.82 ; 2]
δ_{CP} IH	[1.26 ; 1.73]

Ranges for the oscillation parameters under different Mass Hierarchy and Octant constraints

Supplement

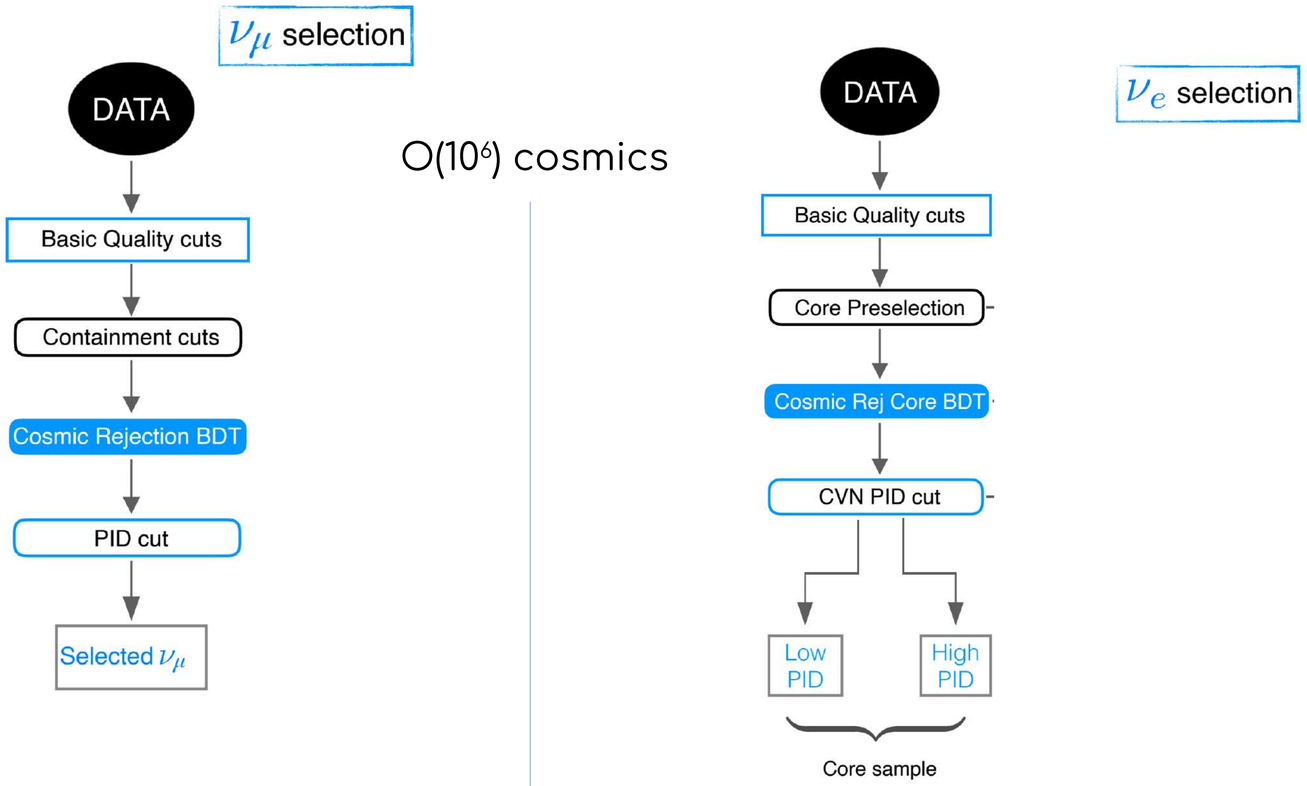


Key Comparison: Neutrino and Antinutrino events

- ✓ Mass Ordering/Hierarchy?
- ✓ Maximal mixing?
  - Upper Octant (larger oscillation probability)
  - Lowe Octant (smaller oscillation probability)
  - ν_μ - ν_τ Symmetry
- ✓ CP violation?
  - Different effects for neutrinos and antineutrinos

Supplement

Goal #1: finding ν_μs and ν_es

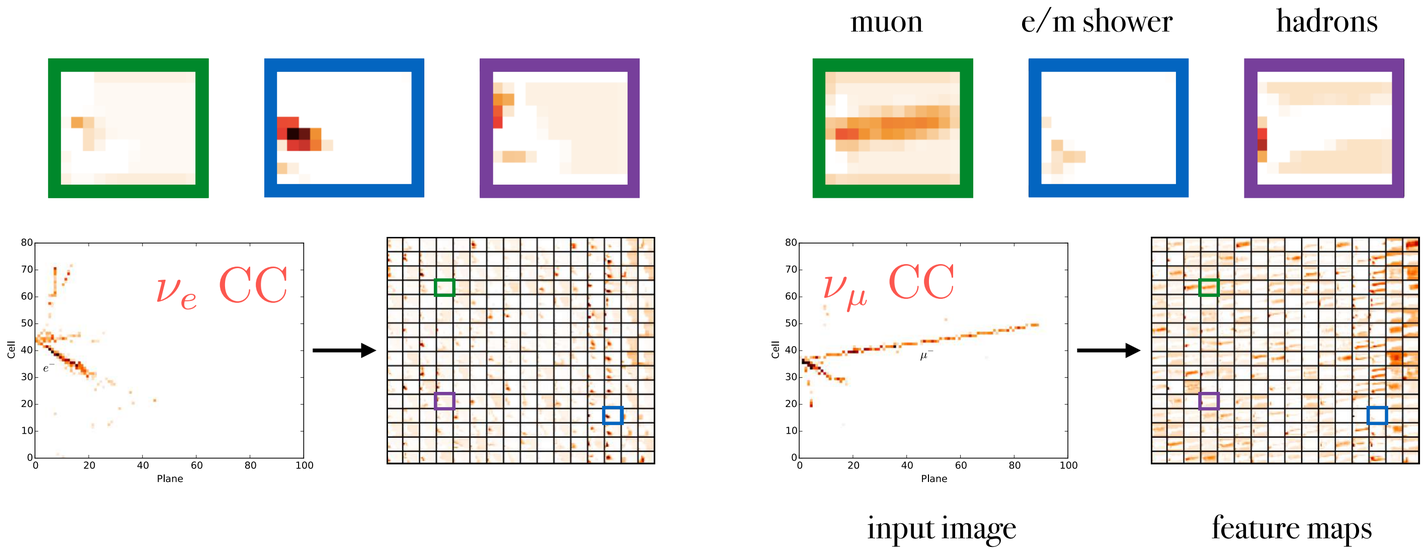


[J. Wolcott (2020), Fermilab W&C]

Key Procedure: event selection

Supplement

ν_e/ν_μ event selection with CVN



Key Procedure: event selection

CVN

- We use convolution neural network called CVN (Convolutional Visual Network).
- Particle identification technique based on ideas from GoogLeNet (computer vision and deep learning).
- Multi-label classifier – the same network used in multiple analyses: can classify ν_e, ν_μ, ν_τ, NC and cosmic.

A. Aurisano et. al, JINST 11, P09001 (2016)

[L. Kolupaeva (2020), ICPPA]

Supplement

- More physics results from NOvA

Search for active-sterile neutrino mixing using neutral-current interactions in NOvA

P. Adamson *et al.* (The NOvA Collaboration)
Phys. Rev. D **96**, 072006 – Published 30 October 2017

Measurement of neutrino-induced neutral-current coherent π^0 production in the NOvA near detector

M. A. Acero *et al.* (NOvA Collaboration)
Phys. Rev. D **102**, 012004 – Published 9 July 2020

Observation of seasonal variation of atmospheric multiple-muon events in the NOvA Near Detector

M. A. Acero *et al.* (NOvA Collaboration)
Phys. Rev. D **99**, 122004 – Published 28 June 2019

Search for multimessenger signals in NOvA coincident with LIGO/Virgo detections

M. A. Acero *et al.* (NOvA Collaboration)
Phys. Rev. D **101**, 112006 – Published 22 June 2020

Supernova neutrino detection in NOvA

M.A. Acero[b], P. Adamson[l], G. Agam[s], L. Aliaga[l], T. Alion[O], V. Allakhverdian[A], N. Anfimov[A], A. Antoshkin[A], E. Arrieta-Diaz[C], L. Asquith[O] + Show full author list

Published 5 October 2020 • © 2020 IOP Publishing Ltd and Sissa Medialab

Journal of Cosmology and Astroparticle Physics, Volume 2020, October 2020

Adjusting Neutrino Interaction Models and Evaluating Uncertainties using NOvA Near Detector Data

NOvA Collaboration and R. Group • M.A. Acero (U. Atlantico, Barranquilla) et al. (Jun 15, 2020)

e-Print: 2006.08727 [hep-ex]

Search for Slow Magnetic Monopoles with the NOvA Detector on the Surface

NOvA Collaboration • M.A. Acero (U. Atlantico, Barranquilla) et al. (Sep 10, 2020)

e-Print: 2009.04867 [hep-ex]

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