Recent Results from the Long Baseline Neutrino Oscillation Experiments

Pablo Fernández Menéndez

Instituto de Física Corpuscular

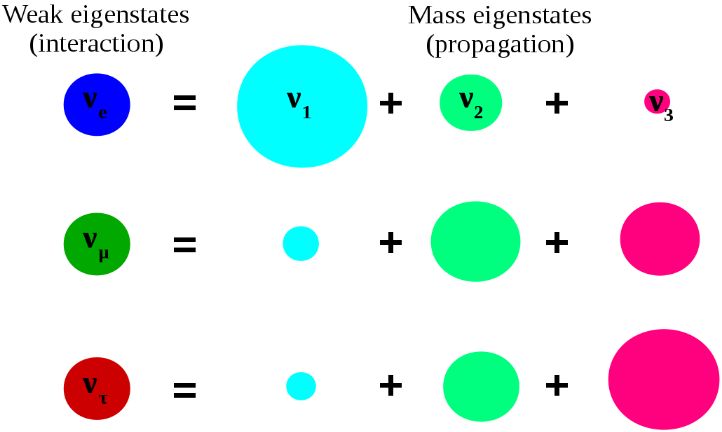
The 15th International Workshop on Tau Lepton Physics
Vondelkerk, Amsterdam

26 September 2018

Outline

Neutrino Oscillation Physics

Neutrinos have different weak and mass eigenstates, and they cannot be determined at the same time



Neutrino Oscillation Probabilities

The (SM) U_{PMNS} Matrix

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U_{PMNS}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} \tag{1}$$

$$U_{PMNS} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \tag{2}$$

where, $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$

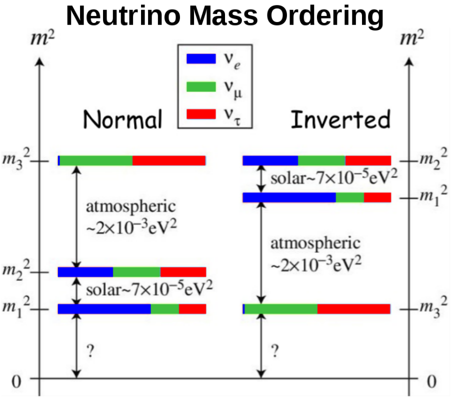
Neutrino Oscillations are possible due to the fact that neutrinos are massive
This is the first evidence of physics beyond the SM

This makes neutrino physics one of the most interesting research fileds

Neutrino Oscillation Parameters

Total of 6 independent neutrino oscillation parameters in SM:
θ_{12}, θ_{13}, θ_{23}, δ_{CP}, Δm^2_{21}, Δm^2_{31} ($\Delta m^2_{32} = \Delta m^2_{31} - \Delta m^2_{21}$)
The most important remaining unknowns are:

- The neutrino mass ordering, which is parametrized by the sign of Δm^2_{32}
- The lepton CP-violating phase, δ_{CP}
- The value for θ_{23} mixing angle



Disappearence Channel Probability

This channel is most sensitive to the θ_{23} mixing angle and the value and sign of Δm^2_{32}

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu) \cong 1 - 4\sin^2\theta_{23}\cos^2\theta^M_{13}(1-\sin^2\theta_{23}{}^2\cos^2\theta^M_{13})\sin^2\left(\tilde{\Delta}\frac{L}{E}\right) \tag{3}$$

Appearence Channel Probability

This is most sensitive to θ_{13}, δ_{CP} and the sign and value of Δm^2_{31}

$$\begin{aligned} P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \cong & \underbrace{\sin^2\theta_{23}\frac{\sin^2 2\theta_{13}}{(A-1)^2}\sin^2\left((A-1)\Delta\frac{L}{E}\right)}_{\text{leading term, }\theta_{13}} + \alpha^2\cos^2\theta_{23}\frac{\sin^2 2\theta_{12}}{A^2}\sin^2\left(A\Delta\frac{L}{E}\right) \\ & + \frac{\alpha J_{CP}}{A(1-A)}\sin\left(A\Delta\frac{L}{E}\right)\sin\left(\Delta(1-A)\frac{L}{E}\right)\left(\underbrace{\cot\delta_{CP}\cos\left(\Delta\frac{L}{E}\right)}_{\text{CP conserving term}} \underbrace{\pm\sin\left(\Delta\frac{L}{E}\right)}_{\text{CP violating term}}\right) \end{aligned} \tag{4}$$

$\Delta m^2_{ij} = m^2_i - m^2_j$, $\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$, $A = \sqrt{2}G_F N_e^{man}\frac{2E}{\Delta m^2_{31}}$, $J_{CP} = \cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\sin\delta_{CP}$

$\sin^2\theta^M_{13} = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13}+(A-\cos 2\theta_{13})^2}$, $\Delta = \frac{\Delta m^2_{31}}{4}$, $\tilde{\Delta} = \frac{\Delta m^2_{32}+\Delta m^2_{21}\sin^2\theta_{12}+\Delta m^2_{21}\cos\delta_{CP}\sin 2\theta_{12}\sin\theta_{13}\tan\theta_{23}}{4}$

Current Long Baseline (LBL) Neutrino Experiments

- Long Baseline neutrino experiments consist on near and far detectors, to which muon (anti-)neutrinos produced in accelerators are thrown
- These experiments are design so the distance between the neutrino target and the far detector and the energy of the produced neutrinos so L/E lies on and oscillation minimum (disappearence channel) or maximum (appearence channel)
- Long baseline experiments are looking into the main remaining unknown oscillation parameters, such as $\underline{\text{the } \theta_{23} \text{ octant}}$, $\underline{\text{the neutrino mass ordering}}$ and, specially, **the CP-violating phase**

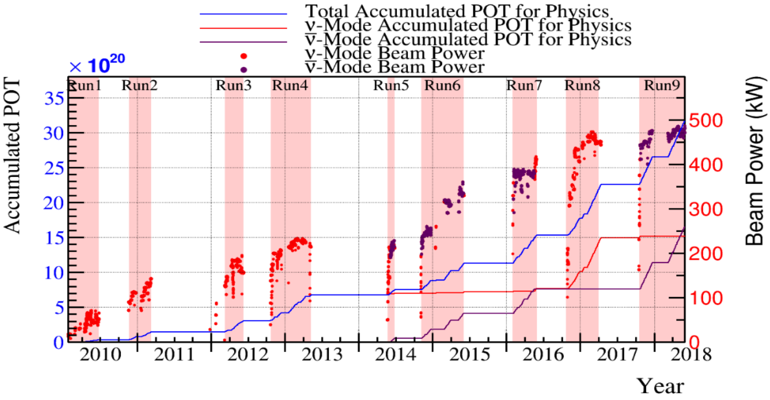
Next, the current LBL experiments and their latest results are summarized

The T2K Experiment

Dedicated to measure θ_{23}, θ_{13} and δ_{CP}

The T2K Beam

It uses the J-PARC beam to produce, mainly, ν_μ (ν-mode) or $\overline{\nu}_\mu$ ($\overline{\nu}$-mode)
The mean beam power this year was of $\sim$485 kW, achieving up to 500 kW



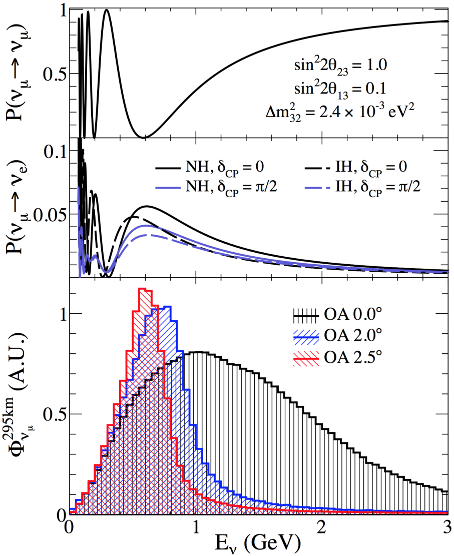
23 Jan. 2010 – 31 May 2018
POT total: 3.16 x 10^{21}

ν-mode 1.51 x 10^{21} (47.83%)
$\bar{\nu}$-mode 1.65 x 10^{21} (52.17%)

The T2K Beam

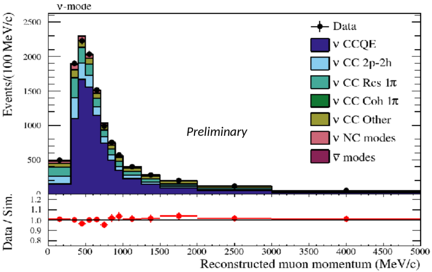
- The beam is 2.5^0 off-axis with respect to the far detector
- T2K was the first experiment to implement the off-axis technique around
- This technique provides a narrower neutrino energy spectrum with its maximum at $E_\nu \sim 0.7$ GeV, at the disappearance minimum and appearance maximum

It has been agreed to extend (T2K phase-II) the operation of T2K to a second phase that will run until 2026 with the goal of $20 \cdot 10^{21}$ POT



Near Detector (ND280 and INGRID)

- At 280 m from the neutrino target

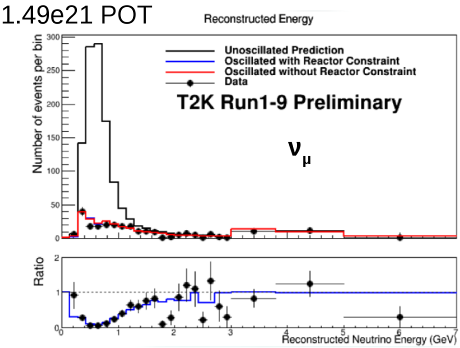


- ND280
  - 2.5^0 off-axis
  - The detector is composed of trackers, a combination of fine grained detectors (FGDs) and Ar TPCs
  - Will be upgraded for phase-II to reduce systematics up to 4%
- INGRID:
  - On-axis
  - Scintillation light detector made up by sixteen modules of iron plates and tracking scintillators

Used for cross-section studies and reduction of the systematic errors related to the neutrino flux and interactions at the far detector

Far Detector (Super-Kamiokande)

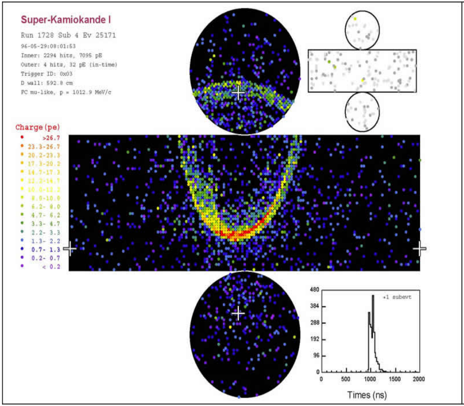
- 2.5^0 off-axis
- Water-Cherenkov detector with 50 kton of ultra-pure water
- 1000 m (2700 m.w.e.) of rock overburden (Kamioka mine)
- 11,143 20"-PMT facing inwards (inner detector) with 40% photocoverage
- 1,885 8"-PMT facing outwards (outer detector) and used for veto



- Being upgraded and refurbished for adding of Gd (SuperK-Gd), enhancing hugely its neutron-tagging capabilities (during phase-II)
- The NA61/SHINE hadron production experiment at CERN provides input for reducing the T2K flux uncertainties to $\sim 5\%$

Super-Kamiokande Neutrino Candidate Event Topologies

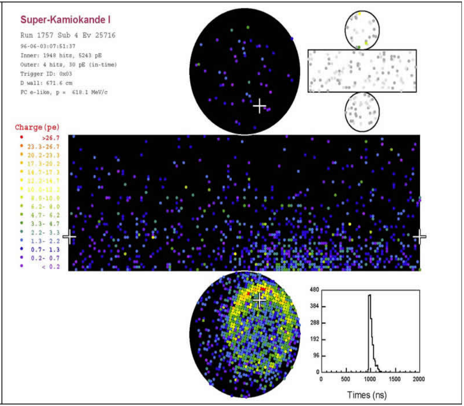
μ-like event



Super-Kamiokande I

Run 1728 Sub 4 Ev 25171
96-05-29:08:01:53
Inner: 2294 hits, 7095 pE
Outer: 4 hits, 32 pE (in-time)
Trigger ID: 0x03
D wall: 592.8 cm
PC mu-like, p = 1012.9 MeV/c

e-like event



Super-Kamiokande I

Run 1757 Sub 4 Ev 25716
96-06-03:07:51:37
Inner: 1948 hits, 5243 pE
Outer: 4 hits, 30 pE (in-time)
Trigger ID: 0x03
D wall: 671.6 cm
PC e-like, p = 618.1 MeV/c

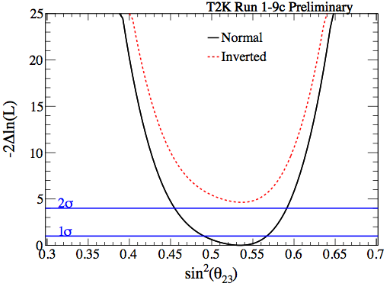
T2K Oscillation Analysis Results

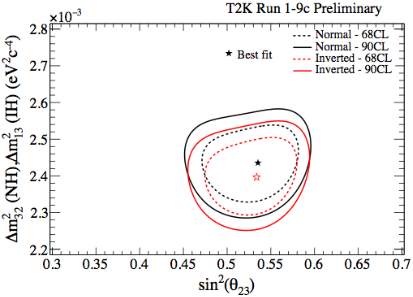
Compare observed event rates at SK to predictions under oscillation hypothesis, with inputs from ND rates
Results are for, ν-mode: $1.49\cdot 10^{21}$ POT + $\overline{\nu}$-mode: $1.12\cdot 10^{21}$ POT

Sample	**Prediction**				**Data**
	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=\pi/2$	$\delta_{CP}=\pi$	
FHC 1R(ing) μ	268.5	268.2	268.5	268.9	243
RHC 1R(ing) μ	95.5	95.3	95.5	95.8	102
FHC 1R e 0 decay-e	73.8	61.6	50.0	62.2	75
FHC 1R e 1 decay-e	6.9	6.0	4.9	5.8	15
RHC 1R e 0 decay-e	11.8	13.4	14.9	13.2	9

θ_{23} and Δm^2_{32}

T2K data with reactor experiments constraints





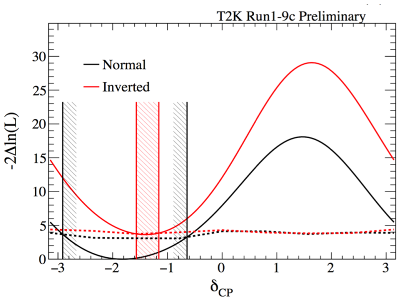
The normal mass ordering and the second octant of θ_{23} is preferred

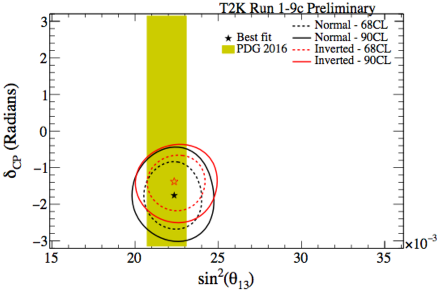
The best fit values are:

	Normal Ordering	Inverted Ordering
$\sin^2\theta_{23}$	$0.536^{+0.031}_{-0.046}$	$0.536^{+0.031}_{-0.041}$
$\Delta m^2_{32}\ (10^{-3} eV^2)$	2.434 ± 0.064	$2.410^{+0.062}_{-0.063}$

δ_{CP} and θ_{13}

T2K data with reactor constraints



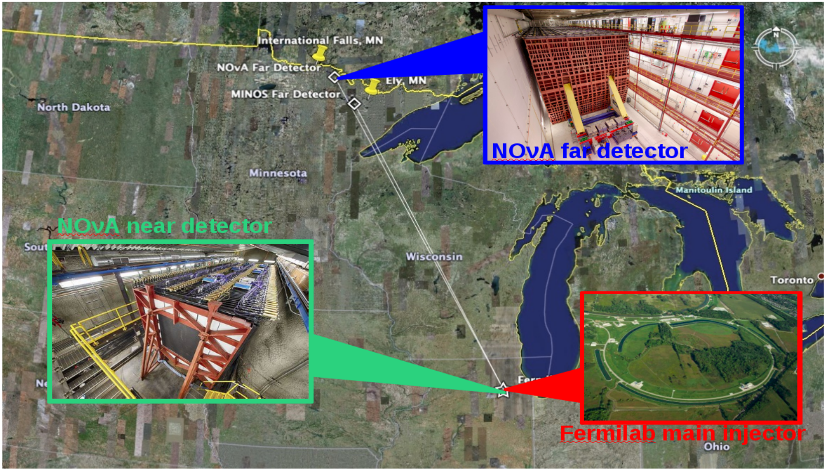


CP-conserving values are disfavoured by more that 2σ

	Mass Ordering	δ_{CP}
Best Fit	NH (2.0σ)	-0.57π

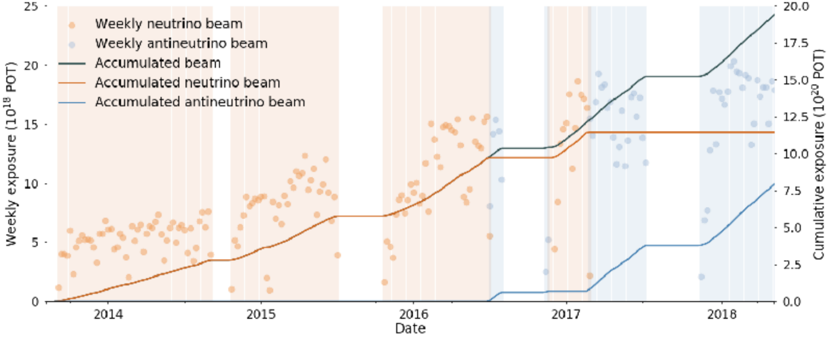
The NOνA Experiment

Dedicated to the measurement of θ_{23} and δ_{CP}



The NOνA Beam

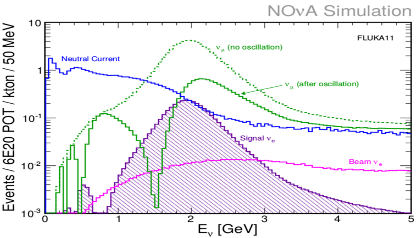
NOνA uses the NuMI beam to produce mainly ν_μ or $\overline{\nu}_\mu$
The beam is running at the design power, 700 kW, since January 2017
The highest power neutrino beam in the world

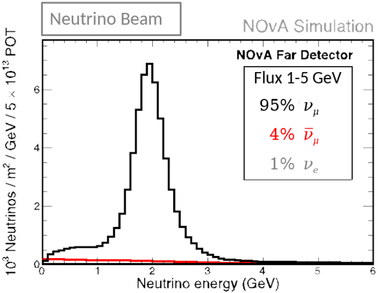


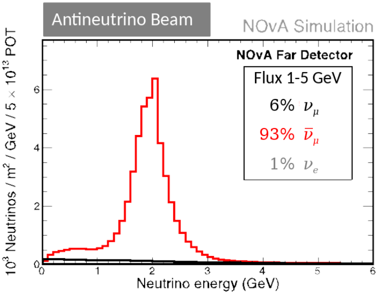
Accumulated $8.85 \cdot 10^{20}$ POT in ν-mode and $6.91 \cdot 10^{20}$ POT in $\overline{\nu}$-mode

The NOνA beam

The mean neutrino energy is $\langle E_\nu \rangle \sim 1.9$ GeV
The beam is 14.6 mrad ($\sim 0.84^0$) off-axis with respect to the far and near detectors







NOνA Detectors

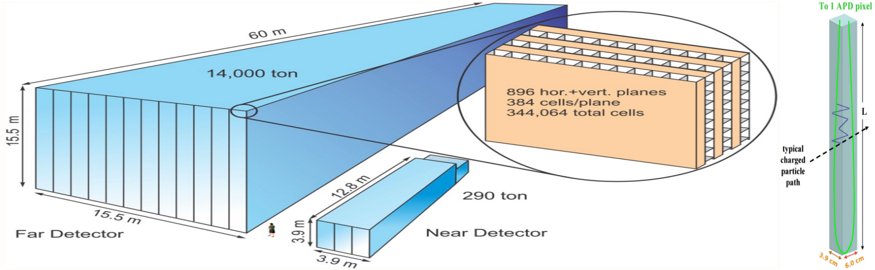
The NOνA experiment is composed by two identical (except for the size) detectors and 810 km apart

The detectors are made up of 344,000 cells of extruded and highly reflective plastic PVC filled with liquid scintillator

Each cell of the detectors measures 3.9 cm wide, 6.0 cm deep

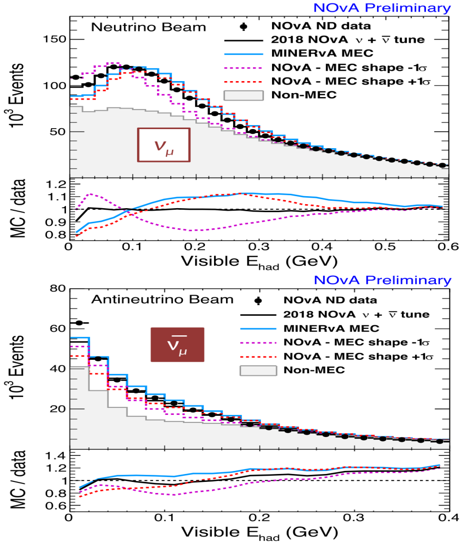
It also contains wavelength shifting fiber (WLS) agents

The fiber end readout is a single pixel of a 32 pixel avalanche photo diode (APD) array



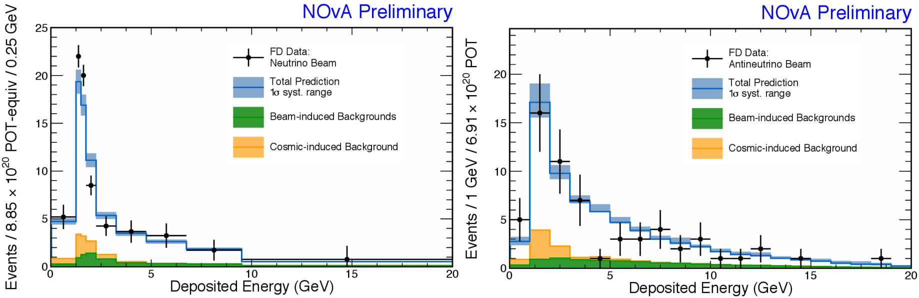
NOνA Detectors

- Near Detector
  - 290 ton detector
  - Cell length is 4 m
  - About 100 m underground
  - Placed at 1 km from the neutrino target
  - It reduces the systematic uncertainties related to the flux predictions and also conducts cross-section studies

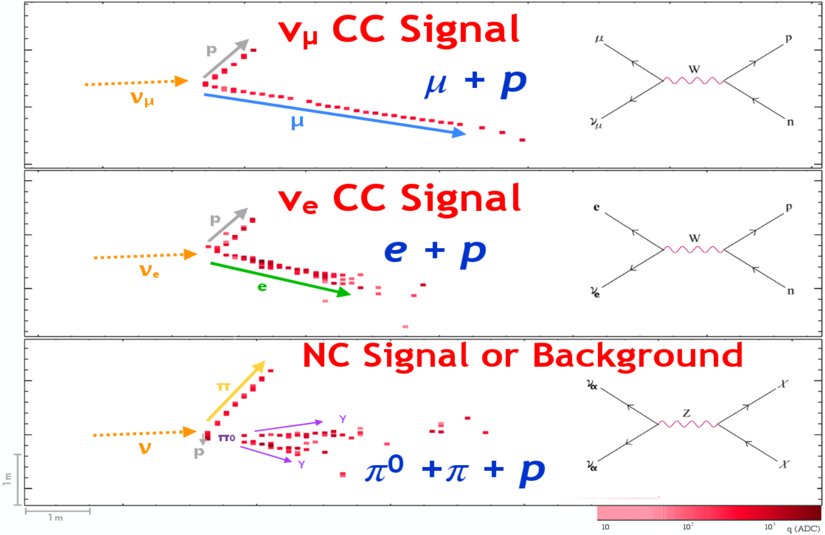


NOνA Detectors

- Far Detector
  - 14 kton detector
  - Cell is 15 m long
  - The detector is placed on the surface with a concrete and barite overburden, stopping a significant part of the cosmic rays



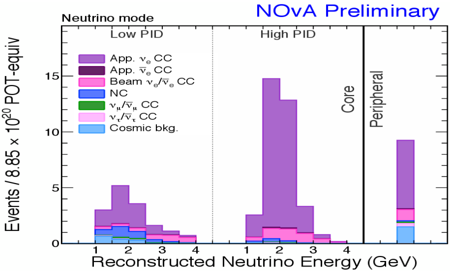
NOνA Neutrino Candidate Event Topologies

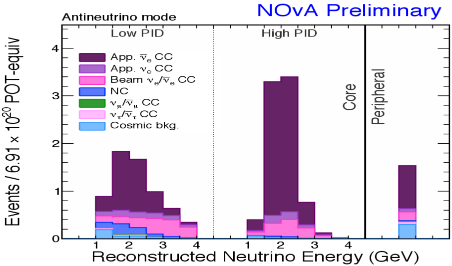


NOνA Oscillation Analysis Results

Despite being very different experiments, the NOνA and T2K analysis startegies are the same. The far detector event rates are compared with the oscillation predictions, and near detector data is used to reduce uncertainties related to the beam flux and the cross-section interactions

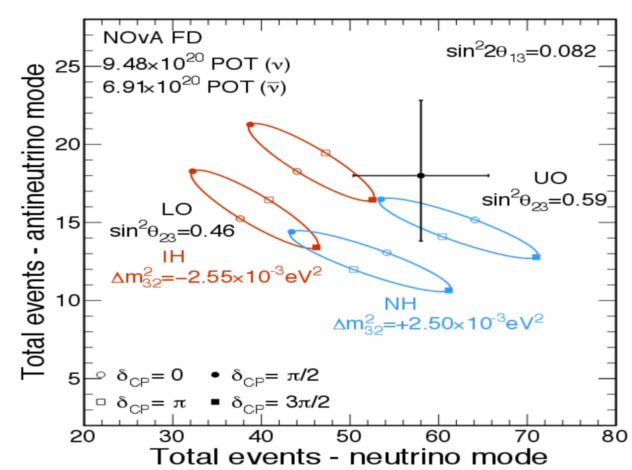
Beam Mode	Predictions	Data
ν-mode	30-75	58
$\overline{\nu}$-mode	10-22	18



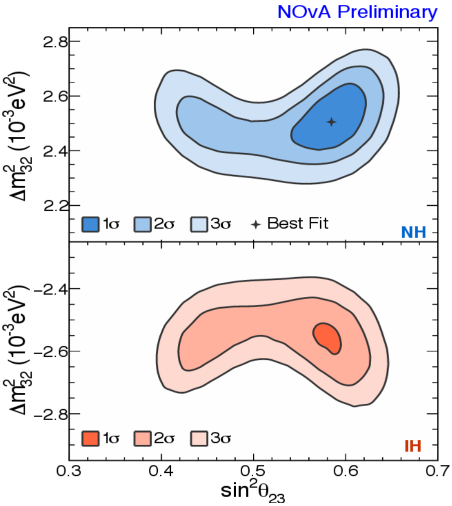


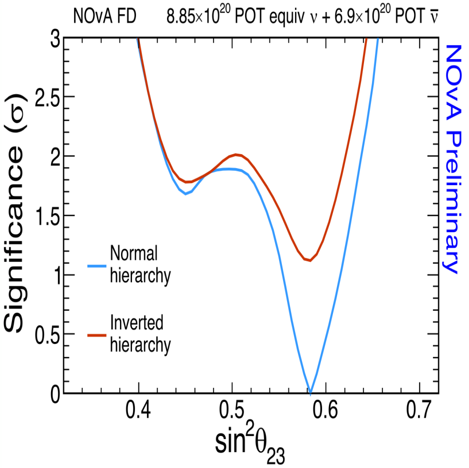
The data events agree with the current neutrino oscillation parameter measurements

The plot shows the event rates predictions depending on the θ_{23} octant, the mass ordering and the δ_{CP}



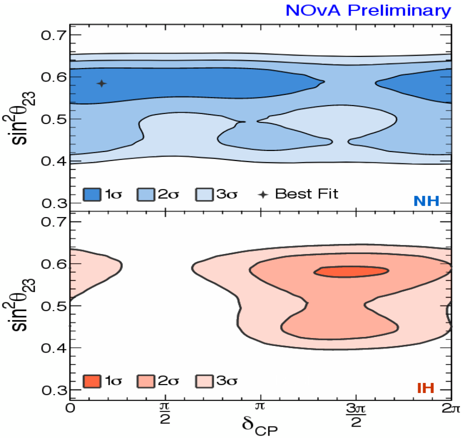
θ_{23} and Δm^2_{32}

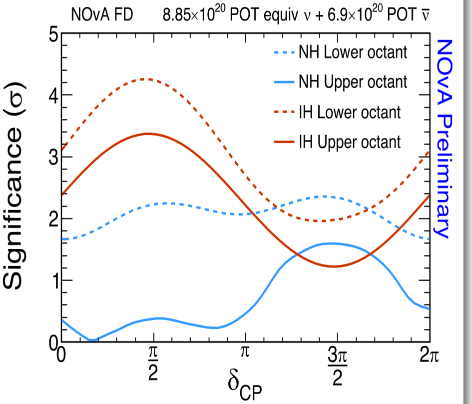




The normal mass ordering and the second octant of θ_{23} are preferred

δ_{CP}





	Mass Ordering	$\sin^2\theta_{23}$	Δm^2_{32} $(10^{-3}$ eV$^2)$	δ_{CP}
Best Fit	NH (1.8σ)	0.58 ± 0.03	$2.51^{+0.12}_{-0.08}$	-0.83π

T2K and NOνA Joint Neutrino Oscillation Analysis

The two collaborations agreed to the formation of a working group to perform a combined analysis of the data in order to improve the sensitivity to the neutrino oscillation parameters
The full joint analysis is forseen for 2021

T2K and NOvA collaborations to produce joint neutrino oscillation analysis

January 30, 2018

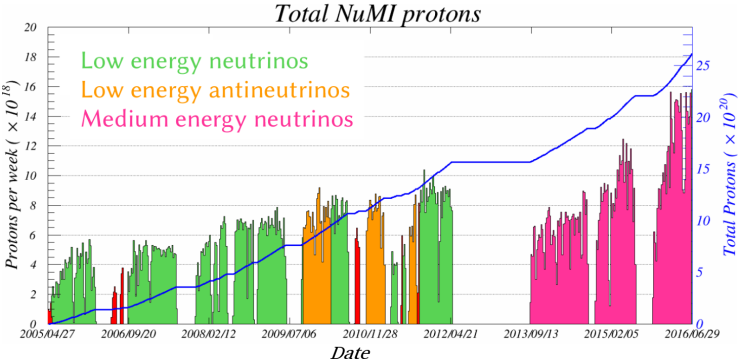
The MINOS and MINOS+ Experiments

MINOS was dedicated to measure the atmospheric oscillation parameters and MINOS+ is more focused on the additional (sterile) neutrinos search

The MINOS and MINOS+ Beam

They use the NuMI beam as the NOνA experiment

- MINOS period: $\langle E_\nu \rangle \sim 3$ GeV, $10.56 \cdot 10^{20}$ POT in ν-mode and $3.36 \cdot 10^{20}$ POT in $\overline{\nu}$-mode
- MINOS+ period: $\langle E_\nu \rangle \sim 7$ GeV, $9.69 \cdot 10^{20}$ POT in ν-mode



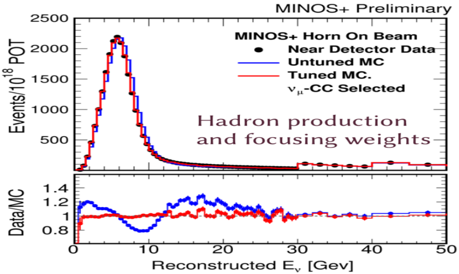
The MINOS/MINOS+ Detectors

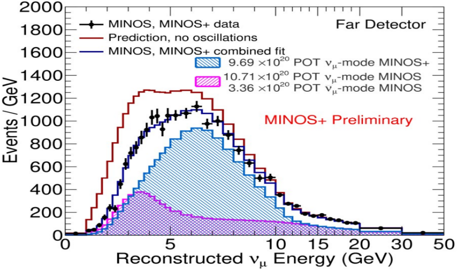
Both, near and far, detectors share the same technology and are aligned with the beam axis

The detectors are composed by iron-scintillator tracking calorimeters

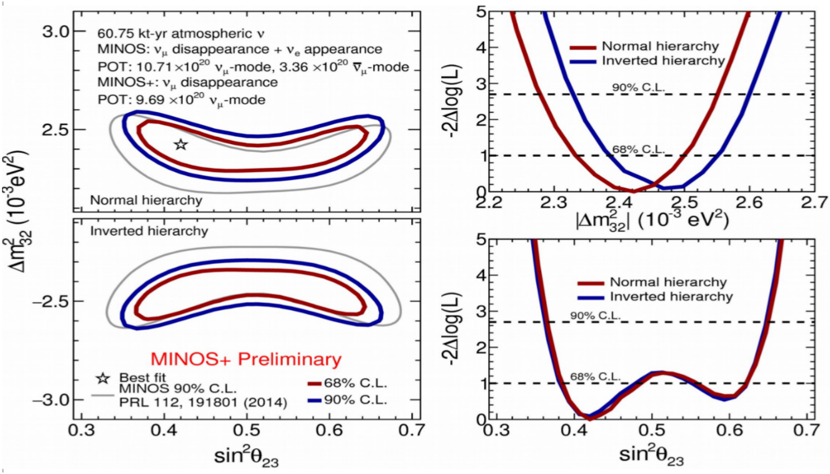
Both of them are magnetized, allowing for ν-$\overline{\nu}$ distinction and better energy reconstruction

- Near Detector: 1 km from target, 1 kton mass, 100 m underground
- Far Detector: 735 km from target, 5.4 kton mass, 716 m underground (Soudan mine)



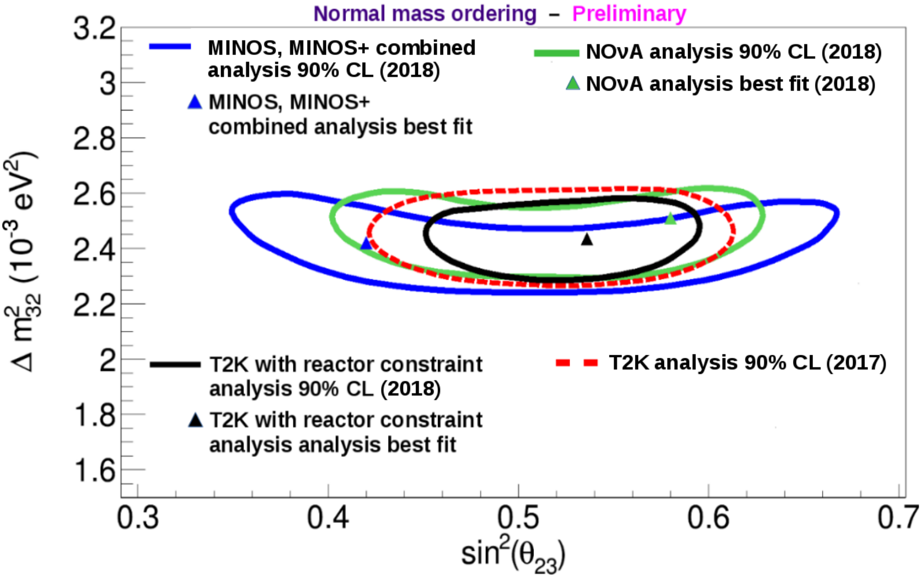


MINOS/MINOS+ Combined Oscillation Analysis Results



	Mass Ordering	$\sin^2\theta_{23}$	Δm^2_{32} (10^{-3} eV^2)
Best Fit	NH (slight pref.)	0.42	2.42

Summary of LBL Results



Summary

- The three main LBL neutrino experiments (except OPERA) have been reviewed and their most important results shown
- In terms of neutrino oscillation results,
    - All three experiments show a preference for normal neutrino mass ordering
    - NOνA and T2K data prefer the second octant of θ_{23} and large values of δ_{CP}, disfavouring CP-conservation in the lepton sector
    - MINOS and MINOS$+$ best fit is at the first octant of θ_{23}, although compatible with second octant at $< 1\sigma$
- T2K will keep taking data until 2026 with improved near and far detectors and the goal of $20 \cdot 10^{21}$ POT accumulated
- The proposed joint fit of NOνA and T2K will improve the sensitivity for the neutrino oscillation parameters, specially for the CP phase

Thank you very much !

Veel Dank !