JOINT ν_μ DISAPPEARANCE AND ν_e APPEARANCE ANALYSIS IN T2K WITH A FREQUENTIST APPROACH

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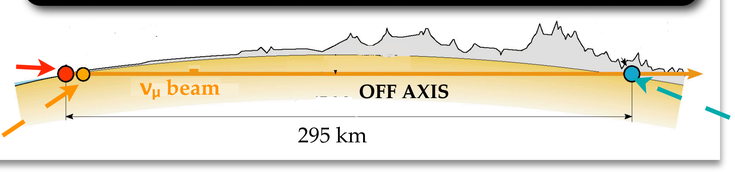
J-PARC accelerator complex (30GeV p^+ beam)

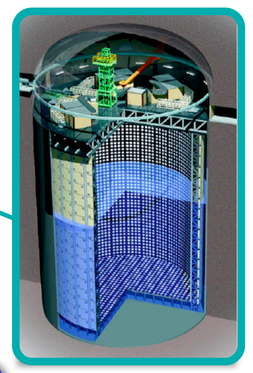
Pions produced in the interaction of protons with the graphite target mainly decay in

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

THE T2K EXPERIMENT

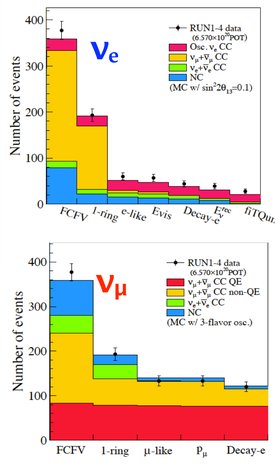


T2K[1] is the first long-baseline neutrino oscillation experiment with an off-axis configuration (2.5º). It uses a highly pure ν_μ beam. Neutrino spectra are measured before and after oscillations in the near and far detectors respectively.



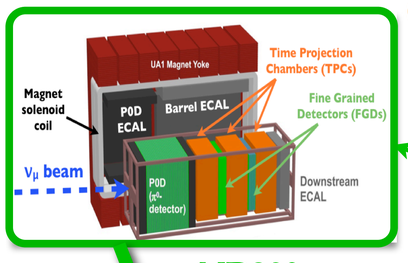
Far detector: Super-Kamiokande

Event candidates: **6.57×10^{20} POT**

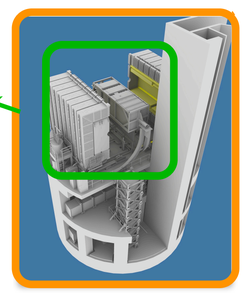


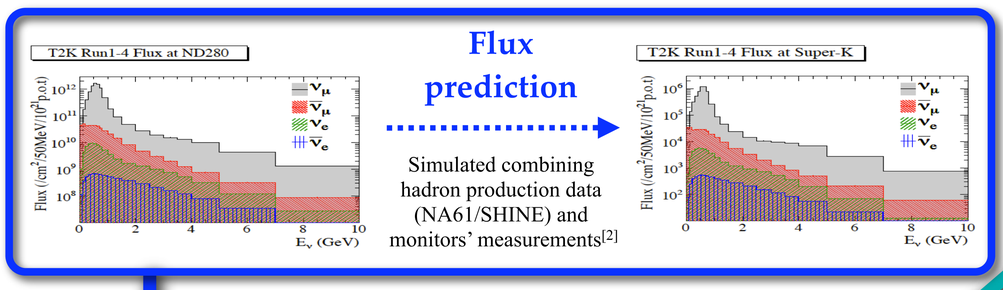
Observed in total 120 ν_μ and 28 ν_e events

Near detectors (280m from target)



ND280

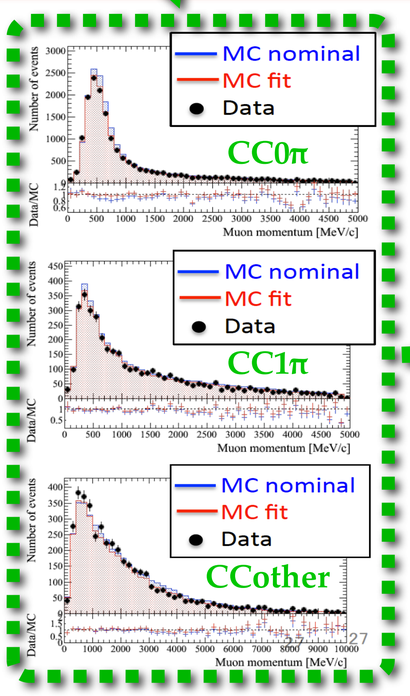




Flux prediction

Simulated combining hadron production data (NA61/SHINE) and monitors' measurements[2]

SYSTEMATIC UNCERTAINTIES



ND280 data fit

FLUX UNCERTAINTIES

Main uncertainty for flux prediction related to hadron production (NA61/SHINE data)[2]

SK EFFICIENCIES

The SK detector efficiencies are estimated with control samples of atmospheric ν, cosmic rays...

CORRELATED CROSS SECTIONS

Common to the far and near detectors

INDEPENDENT CROSS SECTIONS

Related to the nuclear model (^{12}C in ND280, ^{16}O in SK).

FSI+SI

Covariance for FSI+SI computed by changing π interaction probabilities in NEUT

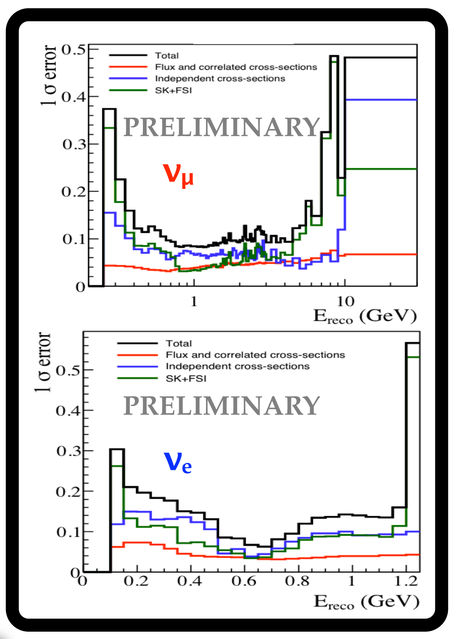
Total of 64 systematic parameters considered in the joint analysis.

The fit to the ND280 data[3] constrains the uncertainties on the flux and some cross sections

NEUT interaction models

Some cross section uncertainties are constrained with a fit to MiniBooNE data[4]

EFFECT OF SYSTEMATICS

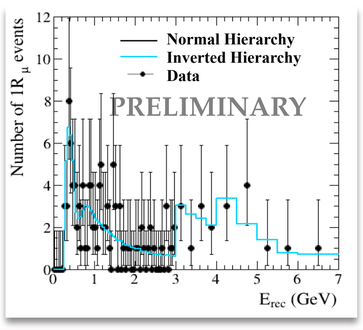


JOINT OSCILLATION ANALYSIS

It is a **simultaneous fit** of the 4 oscillation parameters **$\sin^2\theta_{23}$, $\sin^2\theta_{13}$, Δm^2 & δ_{CP}** in a 3 flavour framework including matter effects, taking their dependencies into account and fitting at the same time the **reconstructed spectra** of the SK **ν_μ & ν_e samples** by minimizing the **likelihood ratio**

ν_μ DISAPPEARANCE

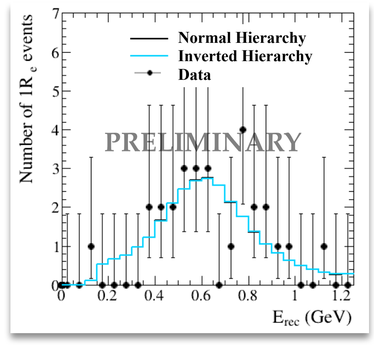
$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right)$$



Reconstructed energy spectra of the T2K Run1+2+3+4 ν_μ event candidates with the best fit from the joint oscillation analysis in both mass hierarchy assumptions

ν_e APPEARANCE

Reconstructed energy spectra of the T2K Run1+2+3+4 ν_e event candidates with the best fit from the joint oscillation analysis in both mass hierarchy assumptions



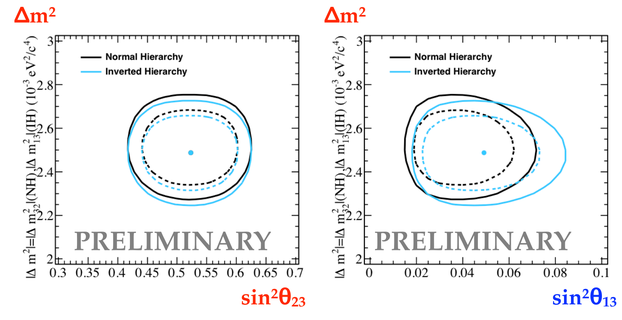
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right) - \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right) \sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right) \sin^2\left(\frac{\Delta m^2_{21} L}{4E_\nu}\right) \sin\delta_{CP} + \text{CPC} + \text{matter} + \text{solar terms} \quad (1)$$

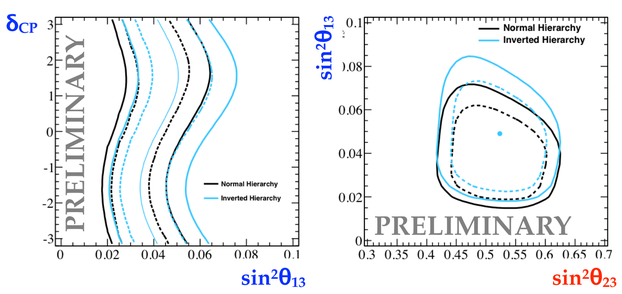
RESULTS

T2K DATA ONLY

Best-fit values of the oscillation parameters

MH	$\lvert\Delta m^2_{32}\rvert(NH)$ or $\lvert\Delta m^2_{13}\rvert(IH)$ $10^{-3}eV^2/c^4$	$\sin^2\theta_{23}$	$\sin^2 2\theta_{13}$	δ_{CP}	$N^{1R\mu}_{exp}$	N^{1Re}_{exp}	$\Delta\chi^2$
			PRELIMINARY				
NH	2.51	0.524	0.162	1.91	119.92	28.00	0.01
IH	2.49	0.523	0.187	1.01	119.95	28.00	-





Results with T2K Run1+2+3+4 dataset (6.57×10^{20} POT)

90% CL

68% CL

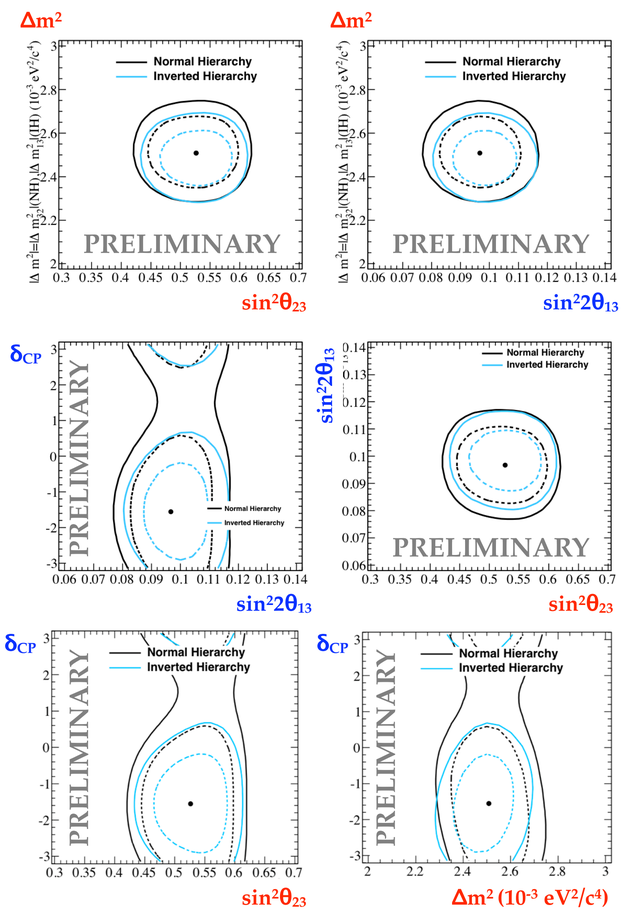
To build confidence regions:
- A common best-fit point, the one with smallest χ^2 (IH), was used for three of the 2D spaces for both mass hierarchies.
- The *raster scan* method was used in the ($\sin^2\theta_{13}$,δ_{CP}) space.
- Mass hierarchy treated as initial assumption
- The constant $\Delta\chi^2$ method was used to draw the contours.

T2K + REACTOR CONSTRAINT

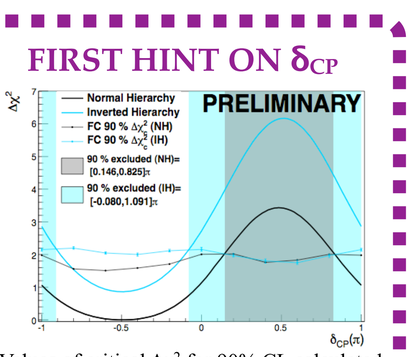
$\sin^2 2\theta_{13} = 0.095 \pm 0.010$

Adding a constraint in $\sin^2 2\theta_{13}$ with the averaged values measured by reactor experiments[5]

MH	$\lvert\Delta m^2_{32}\rvert(NH)$ or $\lvert\Delta m^2_{13}\rvert(IH)$ $10^{-3}eV^2/c^4$	$\sin^2\theta_{23}$	$\sin^2 2\theta_{13}$	δ_{CP}	$N^{1R\mu}_{exp}$	N^{1Re}_{exp}	$\Delta\chi^2$
			PRELIMINARY				
NH	2.51	0.527	0.097	-1.55	120.38	25.87	-
IH	2.48	0.533	0.098	-1.56	121.20	23.57	0.86

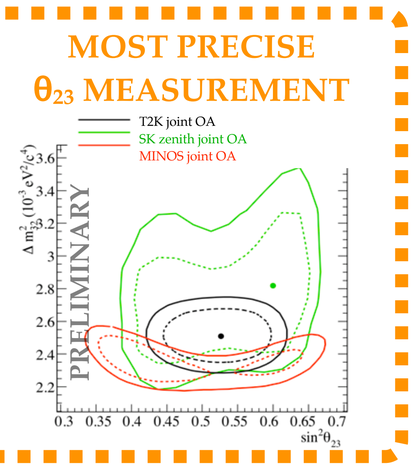


FIRST HINT ON δ_{CP}



Values of critical $\Delta\chi^2$ for 90% CL calculated with Feldman-Cousins

MOST PRECISE θ_{23} MEASUREMENT



CONCLUSIONS

With only ~8% of its goal POT, T2K has achieved world leading results: the best precision in θ_{23}[4], the strongest evidence of ν_e appearance in a ν_μ beam[3] and the first hint on δ_{CP}. It has also performed its first ν_μ+ν_e joint analysis, in which the high ν_e appearance rate observed, combined with the ν_μ disappearance measurement and the results from reactor experiments, indicates that δ_{CP} is consistent with $-\pi/2$.

REFERENCES: [1] NIMA DOI:10.1016/j.nima.2011.06.067; [2] Phys. Rev. D 87, 012001 (2013)
[3] Phys. Rev. Lett. 112, 061802 (2014); [4] Phys. Rev. Lett. 112, 181801 (2014); [5] PDG2013