Latest oscillation results from T2K

Simon Bienstock
(on behalf of the T2K Collaboration)
LPNHE Paris
simon.bienstock@lpnhe.in2p3.fr

Rencontres du Vietnam 2017
18/07/2017

Neutrino oscillations

Neutrino can change flavour while propagating

- ➤ This mechanism can be described by 6 parameters :
  - ➡ 3 mixing angles, θ_{12} θ_{13} and θ_{23} and 2 Δm^2_{ij}
  - ➡ A CP violating phase : δ_{CP}

Two neutrino mixing probability

$$P(\nu_x \to \nu_y) = sin^2(2\theta) sin^2(1.27\Delta m^2 \frac{L(km)}{E(GeV)})$$

Three neutrino mixing

(+ Majorana phases)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} cos\theta_{12} & sin\theta_{12} & 0 \\ -sin\theta_{12} & cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} cos\theta_{13} & 0 & sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -sin\theta_{13}e^{i\delta} & 0 & cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos\theta_{23} & sin\theta_{23} \\ 0 & -sin\theta_{23} & cos\theta_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavour — **Solar and reactor** — **Reactor and accelerator** — **Atmospheric and accelerator** — **Mass**

Neutrino oscillations

Neutrino can change flavour while propagating

➤ This mechanism can be described by 6 parameters :

➡ 3 mixing angles, θ_{12} θ_{13} and θ_{23} and 2 Δm^2_{ij}

➡ A CP violating phase : δ_{CP}

(+ Majorana phases)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} cos\theta_{12} & sin\theta_{12} & 0 \\ -sin\theta_{12} & cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} cos\theta_{13} & 0 & sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -sin\theta_{13}e^{i\delta} & 0 & cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos\theta_{23} & sin\theta_{23} \\ 0 & -sin\theta_{23} & cos\theta_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

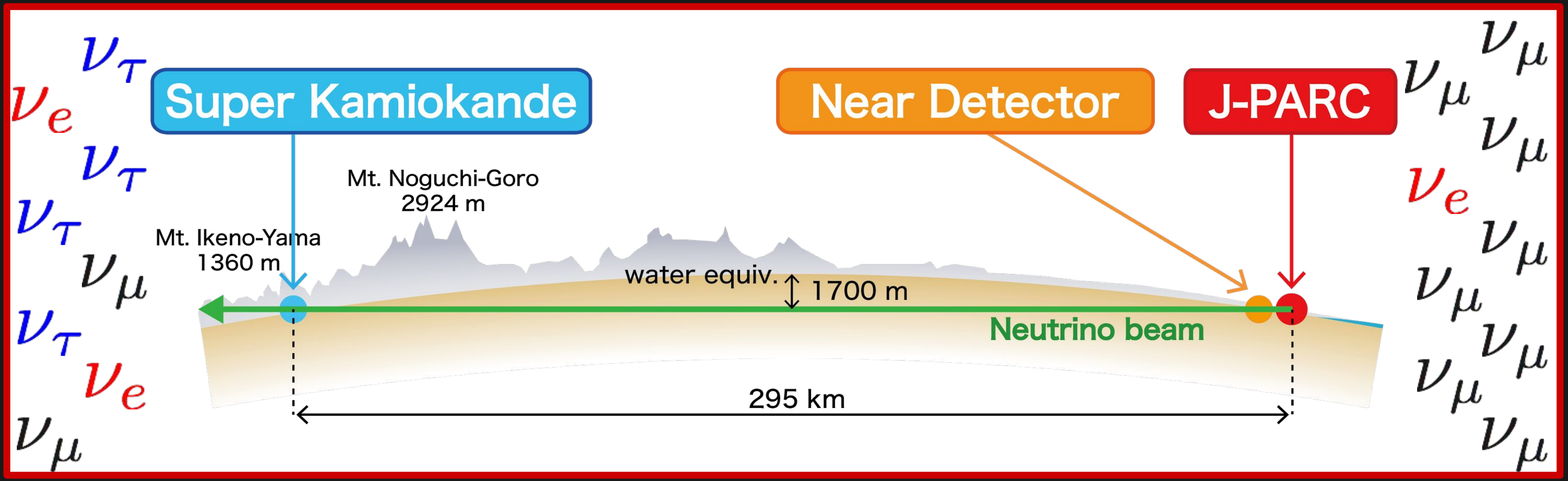
Flavour **Solar and reactor** **Reactor and accelerator** **Atmospheric and accelerator** **Mass**

$\theta_{12} = (33.6 \pm 0.8)°$
$|\Delta m^2_{12}| = (7.50 \pm 0.18) \cdot 10^{-5}\, eV^2$

$\theta_{23} = (45 \pm 3)°$
$|\Delta m^2_{32}| = (2.52 \pm 0.04) \cdot 10^{-3}\, eV^2$

$\theta_{13} = (8.5 \pm 0.15)°$
$\delta_{CP} \approx -90°$ slightly favored

Tokai to Kamioka



T2K is a long-baseline neutrino oscillation experiment

- A ν_μ beam, peaked at ~600 MeV is produced at J-PARC (Tokai, Japan)
- The neutrinos are then detected in the near detector ND280, and in the far detector, 295 km away, Super-Kamiokande (Kamioka).

T2K physics goals

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} cos\theta_{12} & sin\theta_{12} & 0 \\ -sin\theta_{12} & cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} cos\theta_{13} & 0 & sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -sin\theta_{13}e^{i\delta} & 0 & cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos\theta_{23} & sin\theta_{23} \\ 0 & -sin\theta_{23} & cos\theta_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Two main initial goals :
  - ➡ Precise measurement of ν_μ disappearance :
    → Atmospheric sector, measurement of θ_{23} and Δm^2_{32} ✓
  - ➡ Observation of ν_e appearance in the ν_μ beam :
    → Access to the interference parameter θ_{13} ✓
- Now taking data with anti-neutrino ⇒ combined ν_e and $\bar{\nu}_e$ appearance :
  → First constraints of δ_{CP}

Oscillation probability

- **ν_μ disappearance probability**
  - ➡ In T2K, given the energy of the neutrino, we can simplify the formula to :

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \left(\underbrace{\cos^4\theta_{13} \cdot \sin^2 2\theta_{23}}_{\text{Leading term}} + \underbrace{\sin^2 2\theta_{13} \cdot \sin^2\theta_{23}}_{\text{Next-to-leading}}\right) \times \sin^2 \frac{\Delta m^2_{31} \cdot L}{4E}$$

Can be used to resolve octant

- **ν_e appearance probability**
  - ➡ Around T2K's oscillation maximum :

a = 2 √2 G_F n_e E and becomes -a for anti-neutrino

$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\left(1+\frac{2a}{\Delta m^2_{31}}(1-2\sin^2\theta_{13})\right)$$

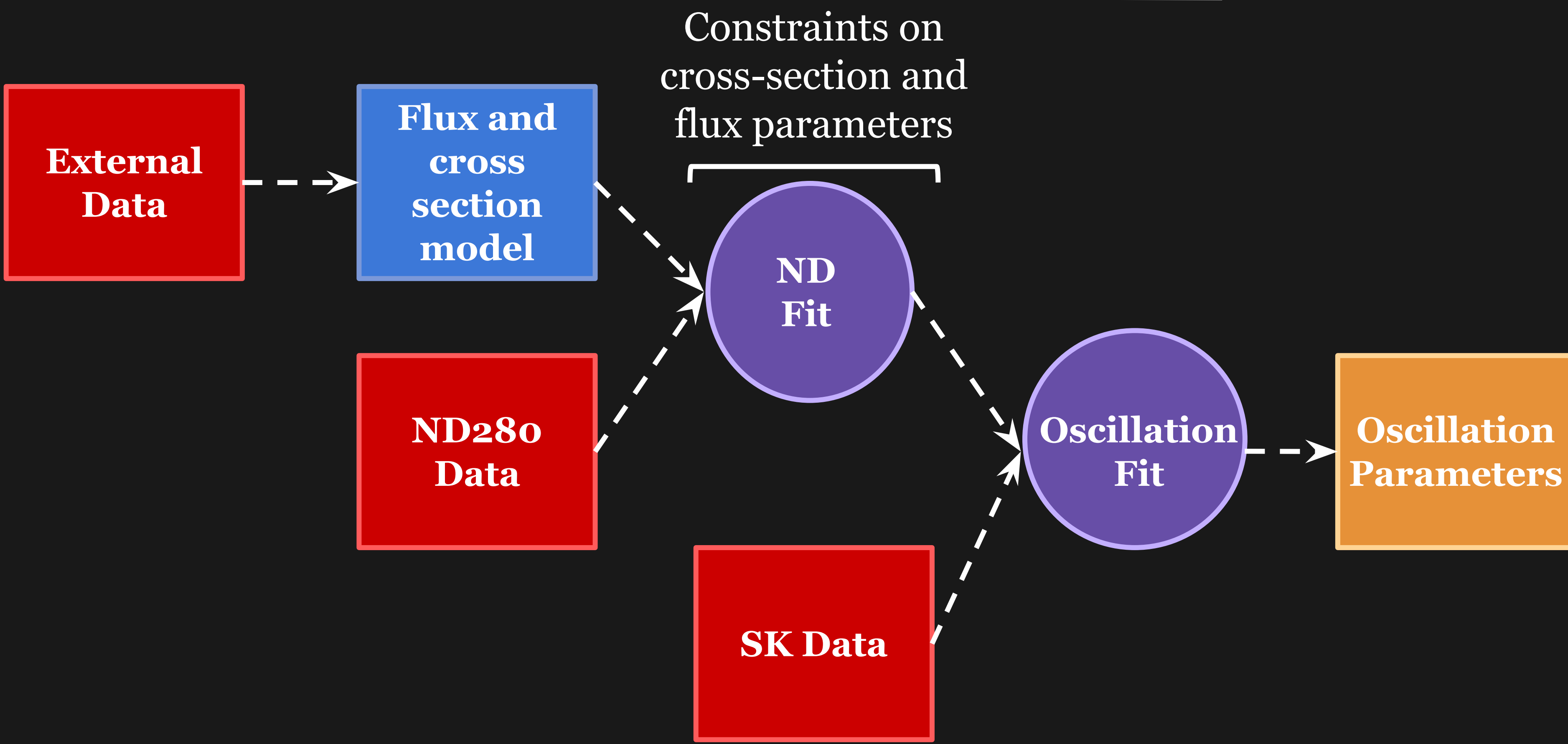
Leading including matter effect

$$-\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\sin\delta\sin^2\left(\frac{\Delta m^2_{32}L}{4E_\nu}\right)\sin\left(\frac{\Delta m^2_{21}L}{4E_\nu}\right)$$

CP violating

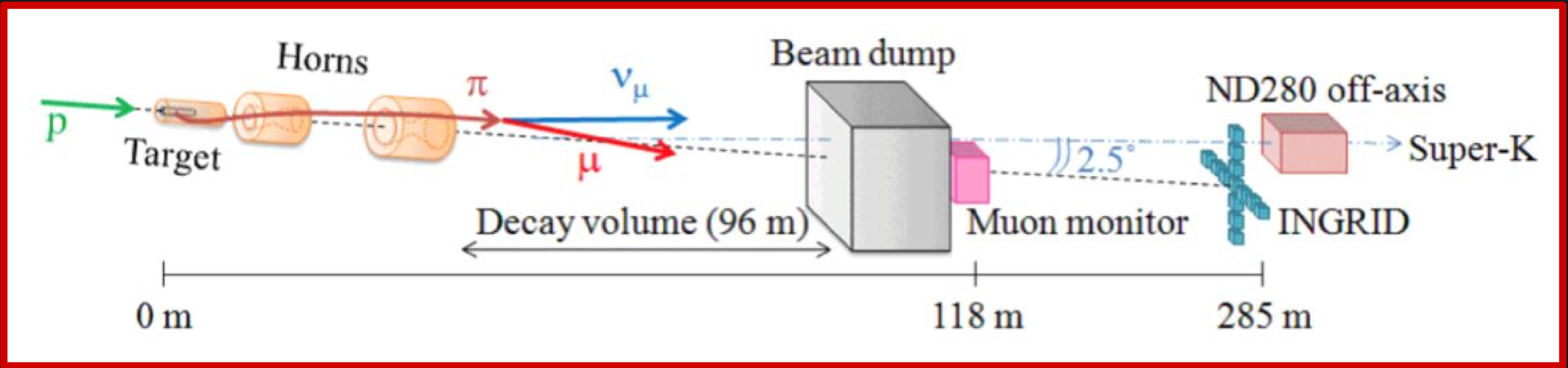
Replace by -δ for anti-neutrino

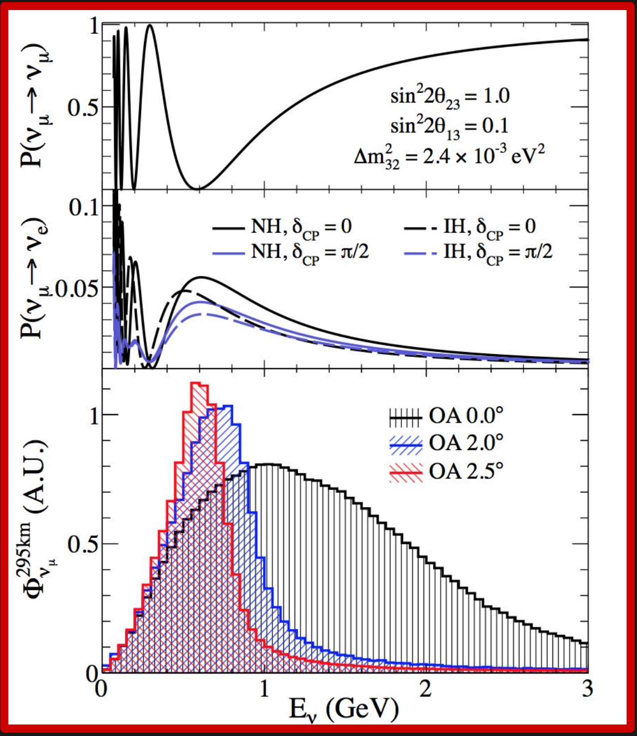
T2K oscillation analysis chain



We do a first fit with the near detector data in order to constrain our flux and cross-section models, to have a precise prediction of the number of events we expect at the far detector.

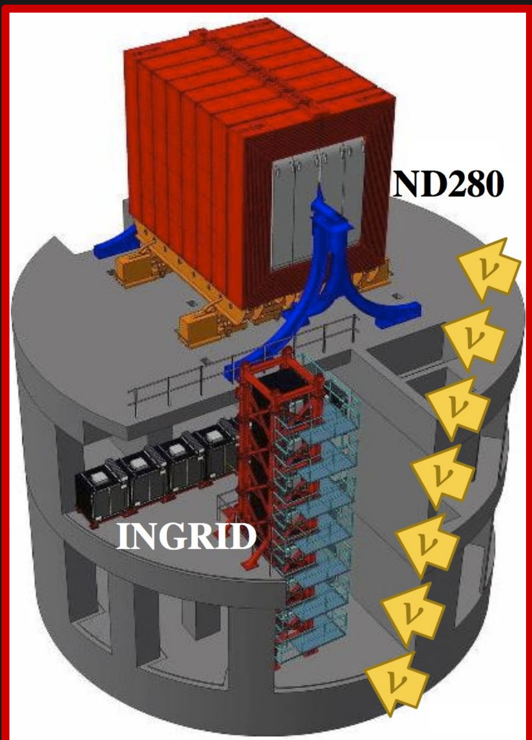
T2K beam

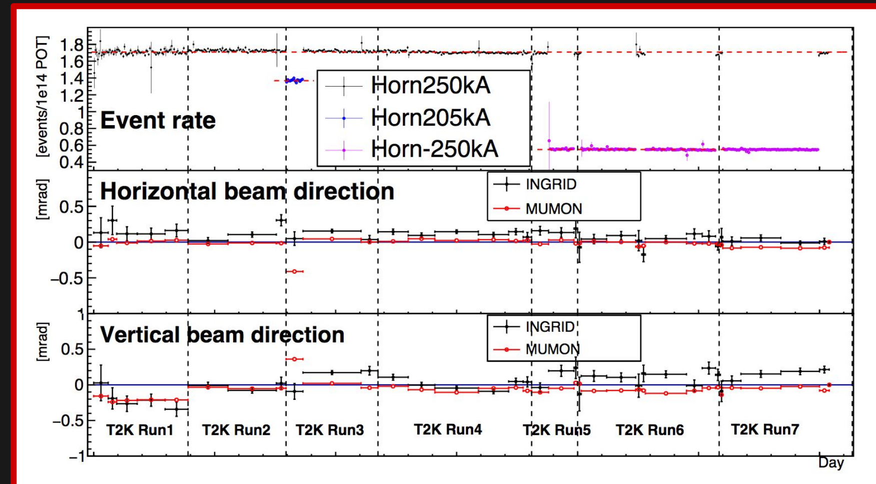


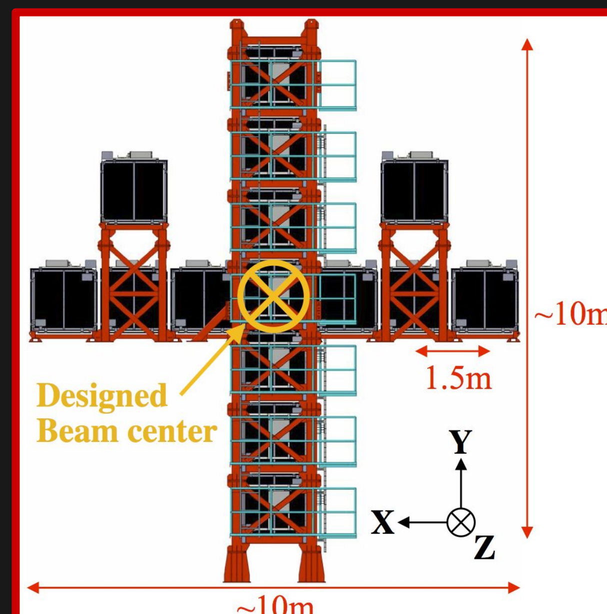


- First use of off-axis ν_μ beam to get a beam more peaked in energy.
  - ➡ The energy is peaked around oscillation maximum (0.6 GeV).
- The pion and kaon production at target is constrained by the NA61/SHINE experiment at CERN, allowing us to reduce systematic uncertainties on the flux of neutrino.
- An anti-neutrino beam can be obtained by reversing current in the magnetic horns.

T2K near detector : INGRID

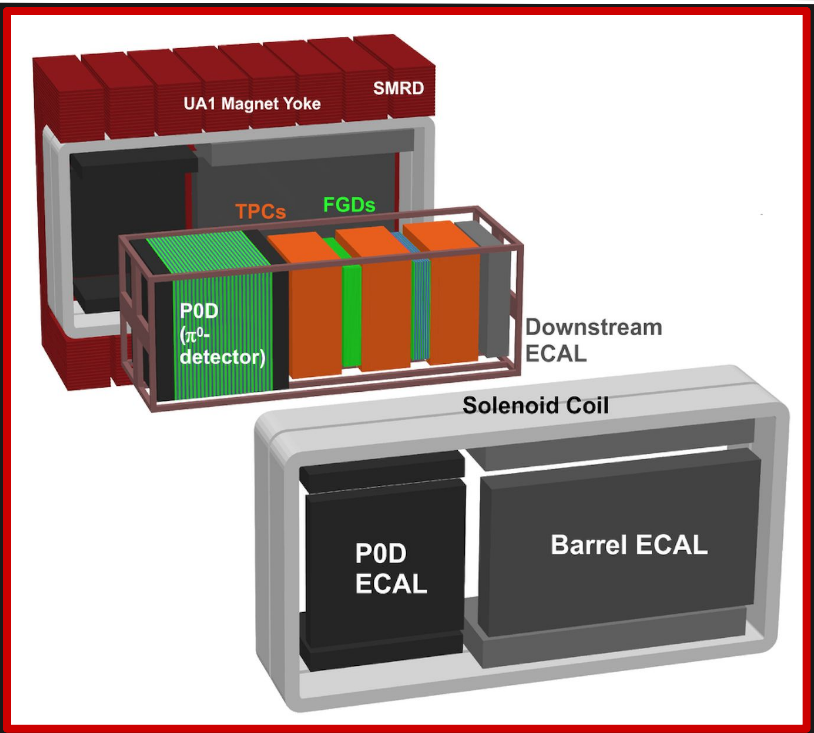






- Near detector pit at 280 m from the target
- INGRID is located on-axis.
  - iron/scintillator tracking calorimeters (16 modules)
  - Monitor beam, direction, stability.
  - Used to constrain flux systematic errors.

T2K near detector : ND280



- ND280 is located 2.5° off-axis (same as Super-K).
- Several sub-detectors inside the magnet :
  - Fine Grained Detector (FGD), plastic scintillator bars for FGD1 and scintillator/water for FGD2 as target.
  - Time Projection Chamber (TPC) to reconstruct momentum and charge.
  - Pi0 detector (P0D) and Electromagnetic calorimeter (ECal).
- **Measure neutrino spectrum and composition before oscillations.**

$$N_{ND} = \int dE \; \Phi(E) \times \sigma(E) \times \epsilon_{ND}(E)$$

# of events

Flux

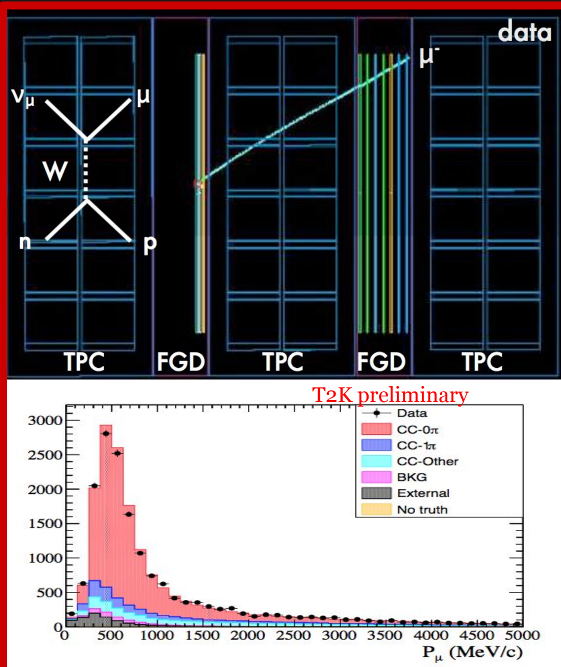
Cross-section

Detector efficiency

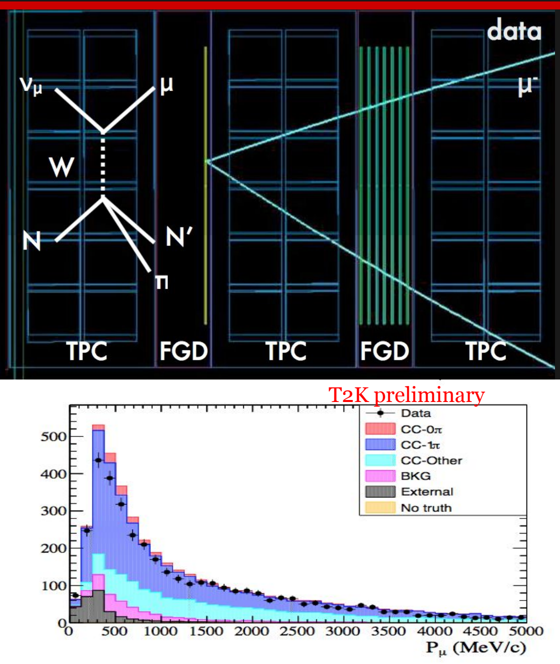
In common with the far detector

T2K near detector in the oscillation analysis

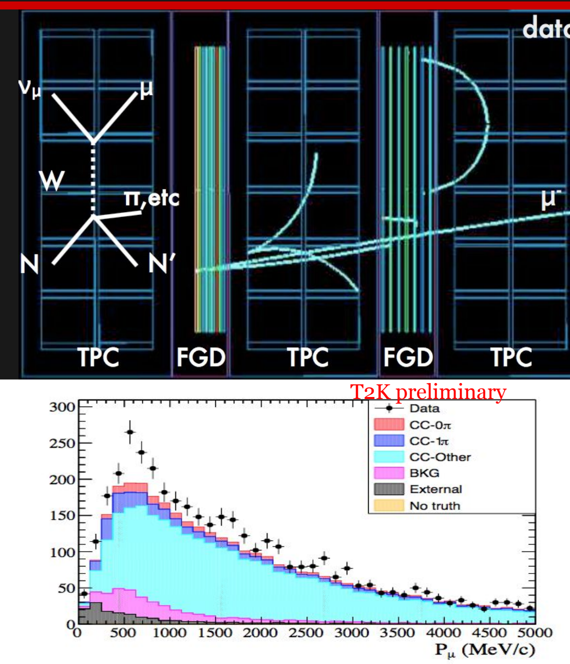
- Select charged-current (CC) muon neutrino interactions in the tracker.
  - The FGDs are used as targets.
  - With the TPCs, retrieve the momentum and charge of the tracks produced.
- Constrain flux and cross-section models with the momentum and angle of the muon produced by the CC interaction.



Quasi-elastic candidate



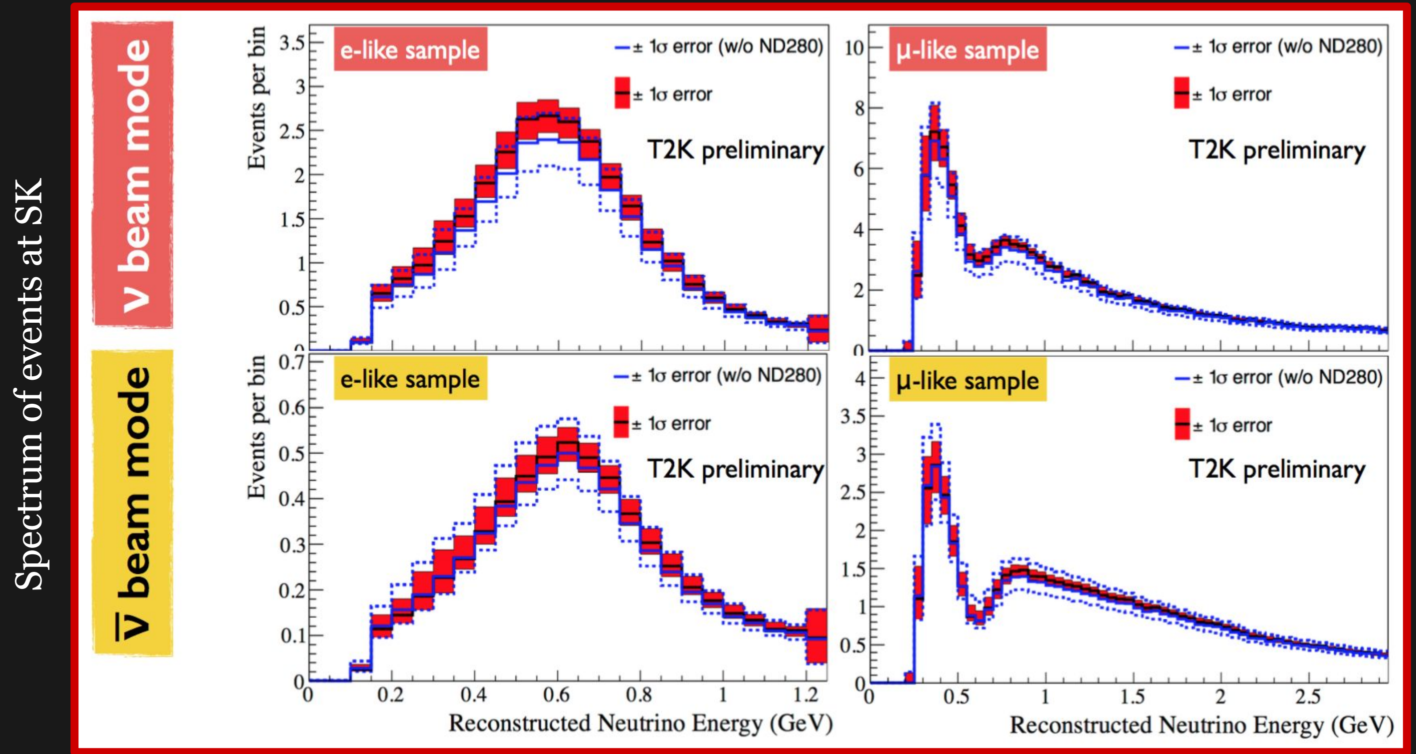
Single pion candidate



DIS candidate

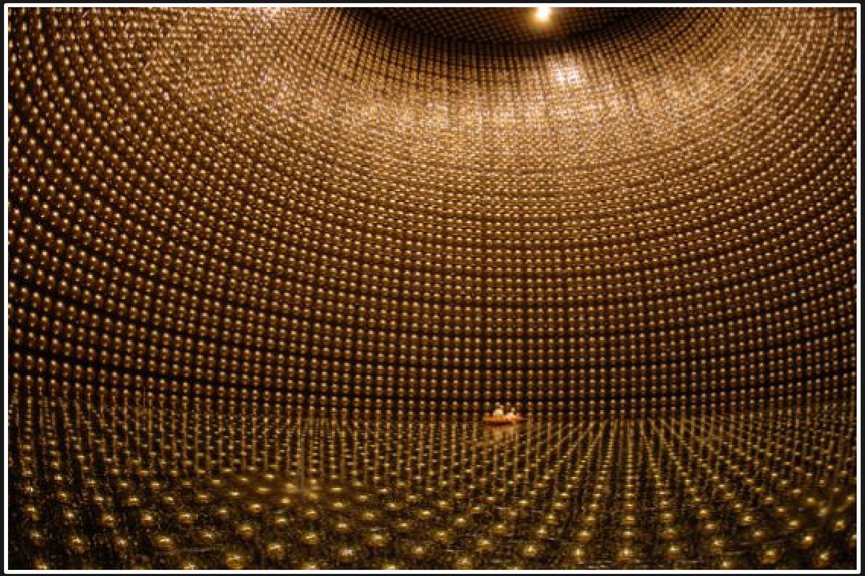
T2K near detector in the oscillation analysis

ND280 helps to reduce the systematic uncertainties in the oscillation analysis from ~14% to ~6%



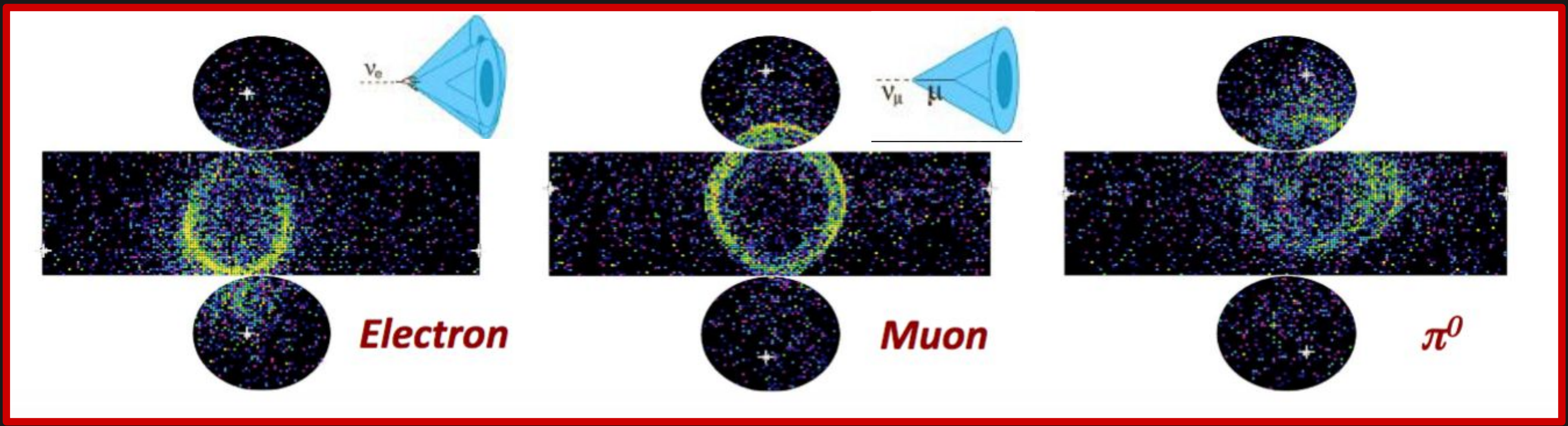
	ν_μ sample ν-mode	ν_e sample ν-mode	$\bar{\nu}_\mu$ sample ν̄-mode	$\bar{\nu}_e$ sample ν̄-mode
Total w/o ND280	12,0%	11,9%	12,5%	13,7%
Total with ND280	**5,0%**	**5,4%**	**5,2%**	**6,2%**

The far detector : Super-Kamiokande

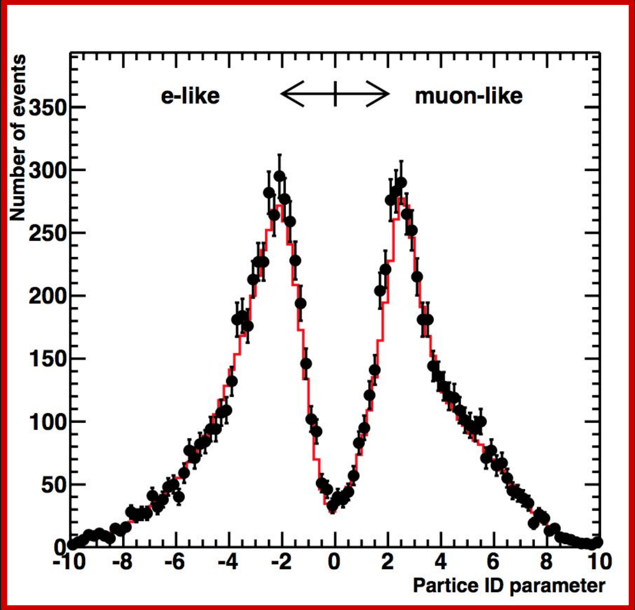


Cherenkov detector with 50 kT of water.

- ➤ Detect neutrino CC interactions
- ➤ Excellent muon/electron separation thanks to the shape of the Cherenkov ring.
- ➤ Only 1% of muons are misidentified as electrons.

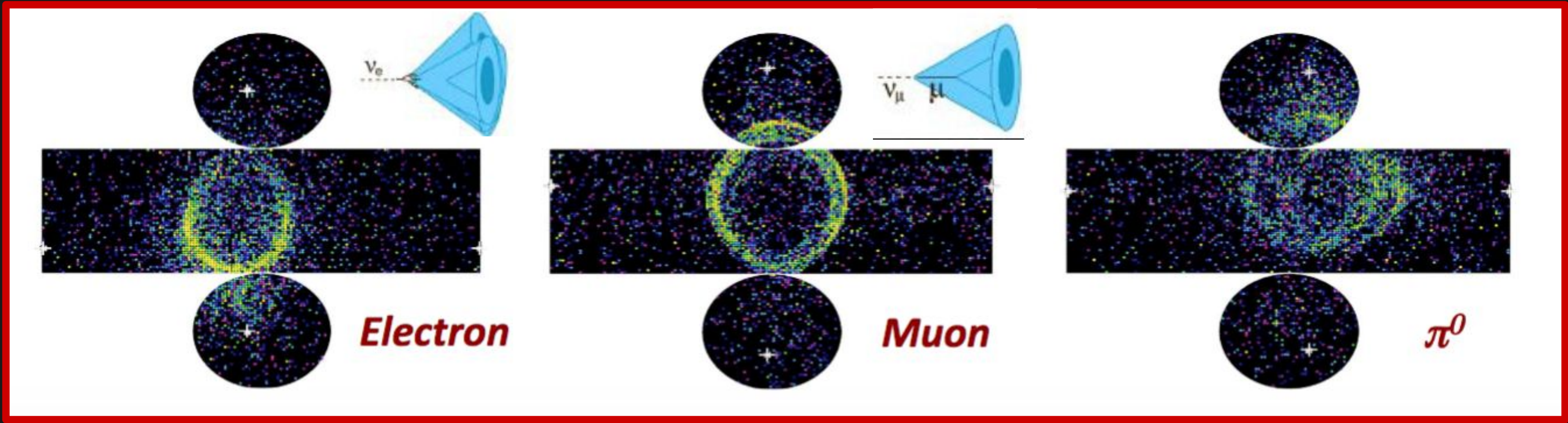


The far detector : Super-Kamiokande

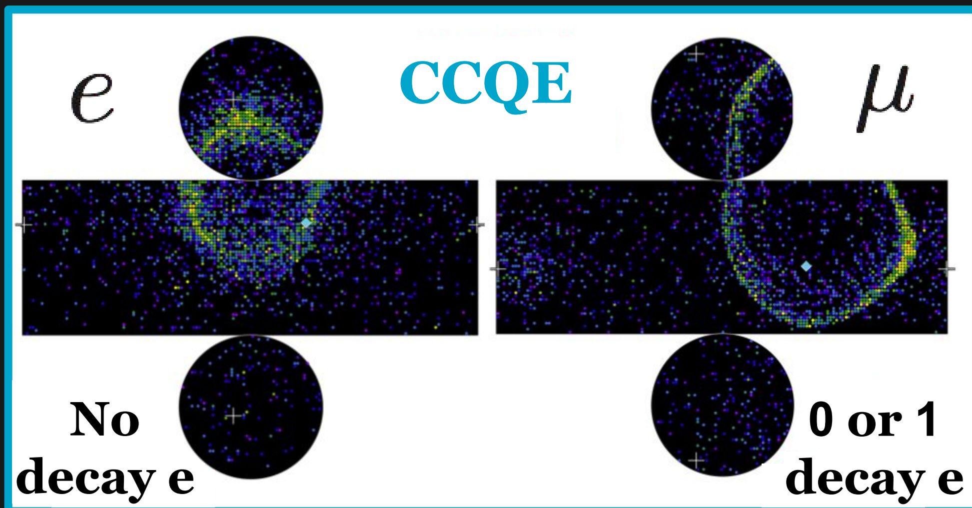


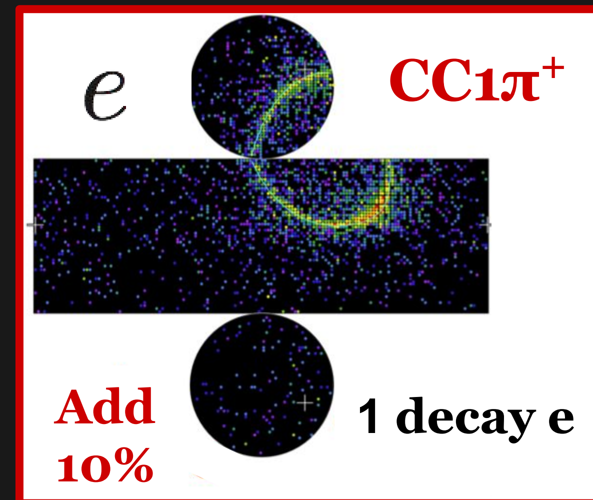
Cherenkov detector with 50 kT of water.

- ➤ Detect neutrino CC interactions
- ➤ Excellent muon/electron separation thanks to the shape of the Cherenkov ring.
- ➤ Only 1% of muons are misidentified as electrons.

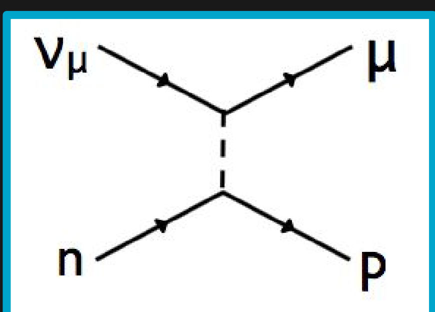


Five far detector samples

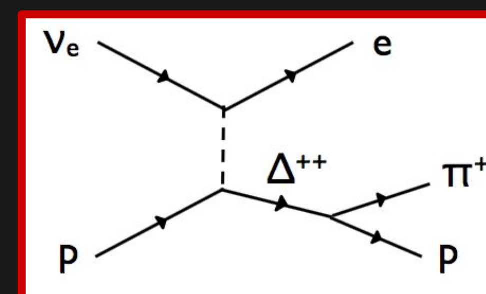




New sample



- One reconstructed ring electron and muon samples for both neutrino and anti-neutrino.
  - ➡ Mainly CC quasi-elastic events.
- Added during winter 2016 a new sample with 1 electron ring and 1 decay electron which add ~10% of events.
  - ➡ Mainly single pion production from electron neutrino.



T2K oscillation analysis

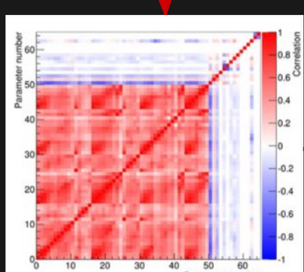
Flux model constrained by NA61/SHINE

Cross-section model constrained by other experiments (Minerva, Miniboone…)

Systematic error source	$\Delta N_{SK}/N_{SK}$ before ND fit	$\Delta N_{SK}/N_{SK}$ after ND fit
Flux	8.8%	3.2%
Cross section	7.1%	4.7%
Flux and cross section	11.4%	2.7%
Final state/secondary interactions at SK	2.5%	
SK detector	2.5%	
Total	11.9%	5.2%

ND Fit

lepton p-θ



Constrained covariance matrix

SK Fit

Oscillation Parameters

The far detector fit

$$N_{SK} = \int dE\ \Phi(E) \times \sigma(E) \times \epsilon_{SK}(E) \times P(\nu_\alpha \to \nu_\beta, E, \theta_{ij}, \Delta m^2_{ij}, \delta_{CP})$$

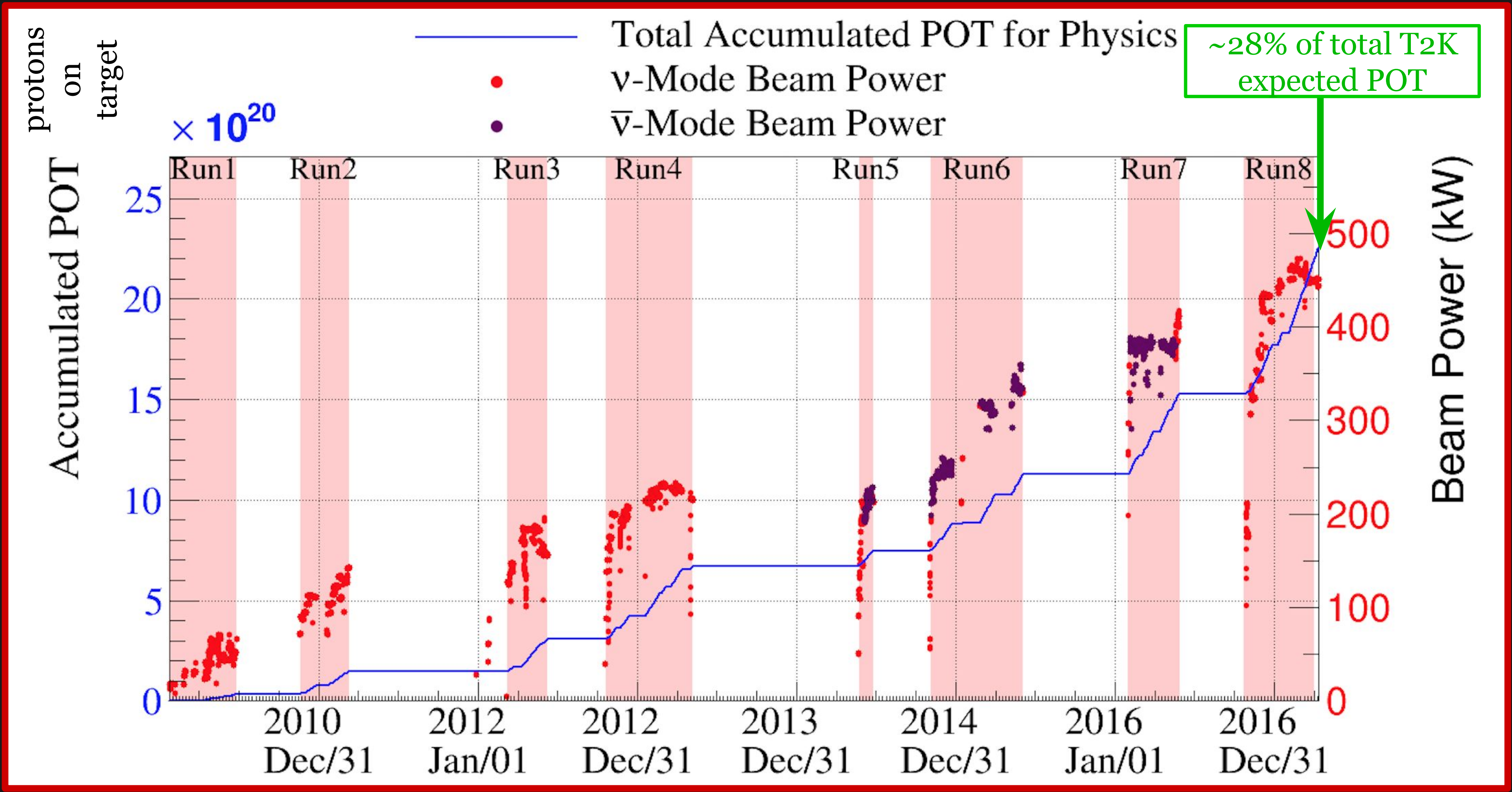
# of events — Flux — Cross section — Detector efficiency — Oscillation probability

Flux and Cross section: Constrained with the near detector

Three different analyses performed to extract the oscillation parameters :

- A frequentist analysis with a $\Delta\chi^2$ fit to
  - ➡ E_{rec} / θ_{lep} for electron neutrino and anti-neutrino.
  - ➡ E_{rec} for muon neutrino and anti-neutrino.
- A Bayesian analysis with a likelihood fit to
  - ➡ p_{lep} / θ_{lep} for electron neutrino and anti-neutrino.
  - ➡ E_{rec} for muon neutrino and anti-neutrino.
- A Bayesian with a Markov-Chain MC
  - ➡ E_{rec} for all samples.
  - ➡ Simultaneously fitting the near detector data.

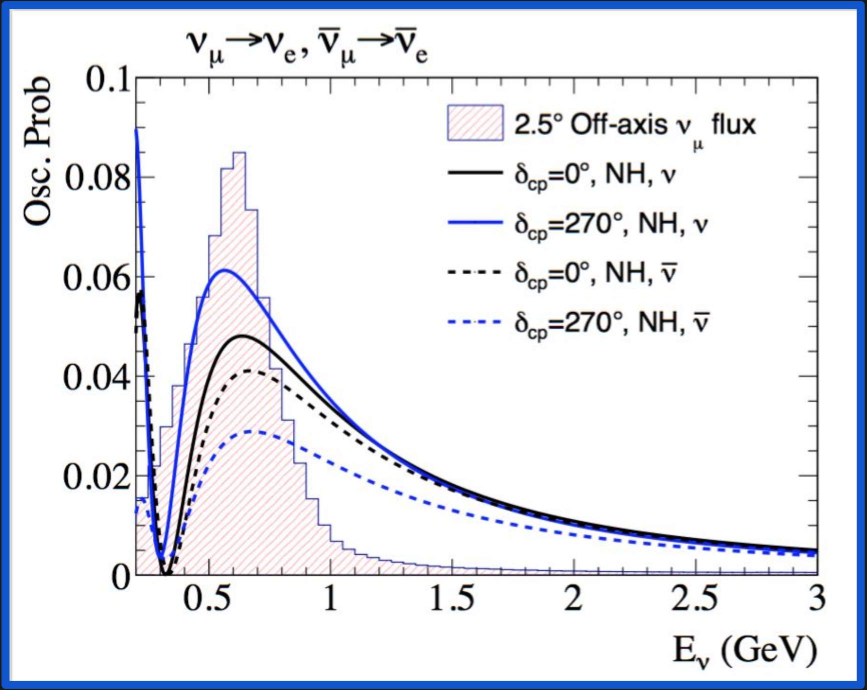
Data taking



Now running at an impressive 470 kW !

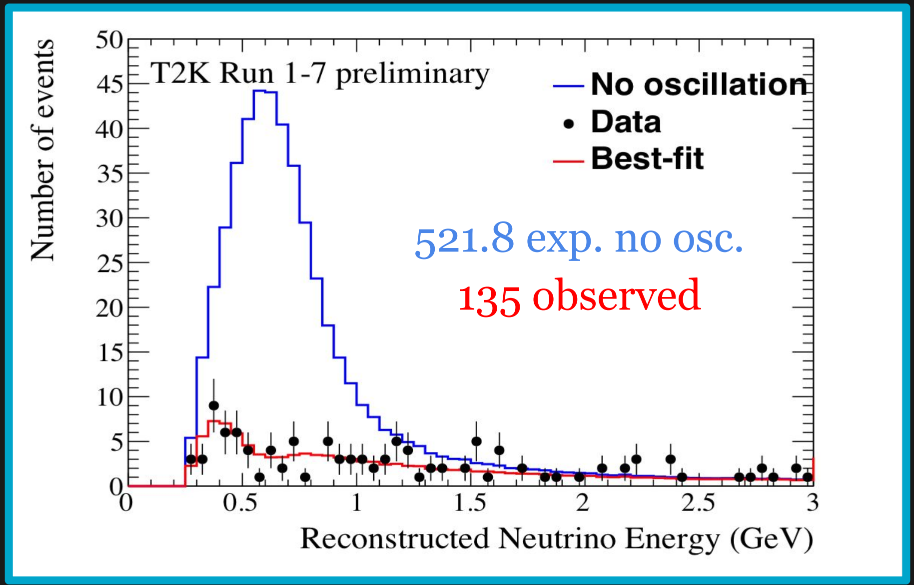
Joint neutrino and anti-neutrino mode analysis

- The five SK samples presented earlier are used in the analysis, allowing simultaneous study of the ν_e / $\bar{\nu}_e$ appearance channels, and ν_μ / $\bar{\nu}_\mu$ disappearance channels.
- Why is anti-neutrino mode data important ?
  - ➡ The difference between ν_e and $\bar{\nu}_e$ appearance is directly related to δ_{CP}

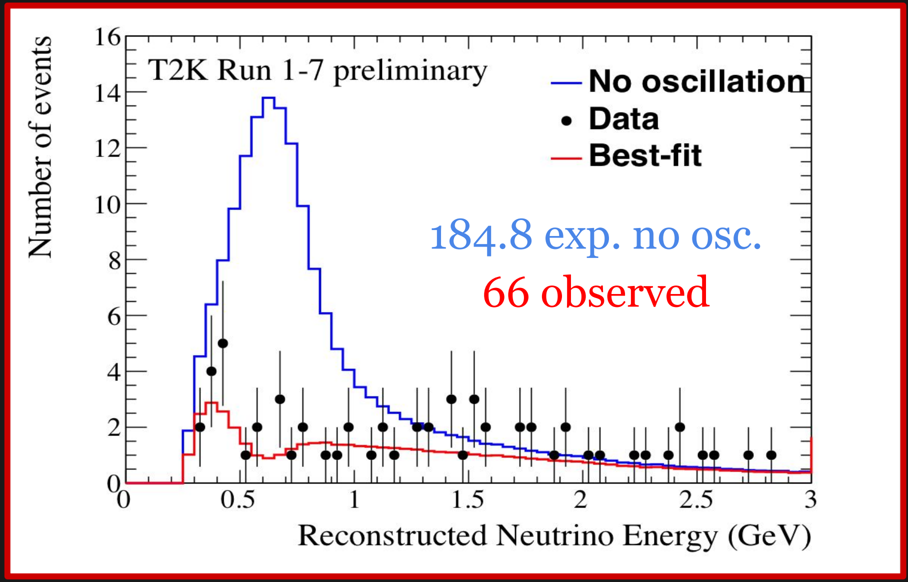


ν_μ and $\bar{\nu}_\mu$ disappearance

ν_μ



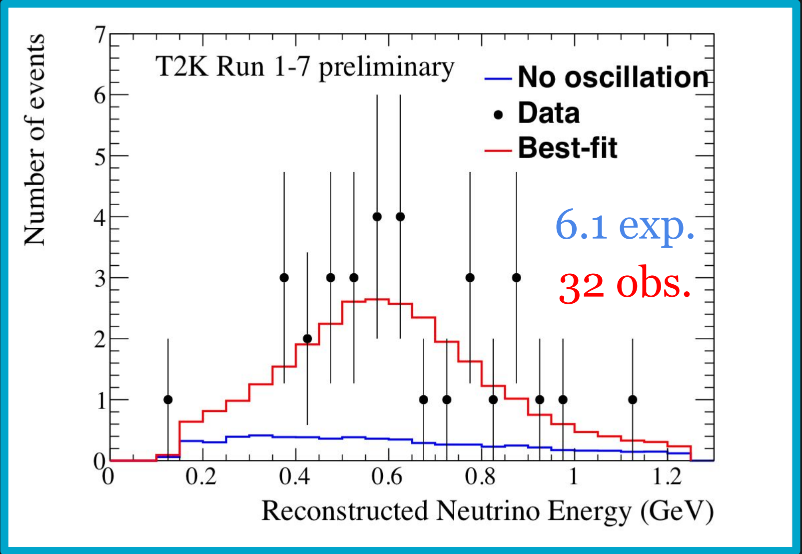
$\bar{\nu}_\mu$



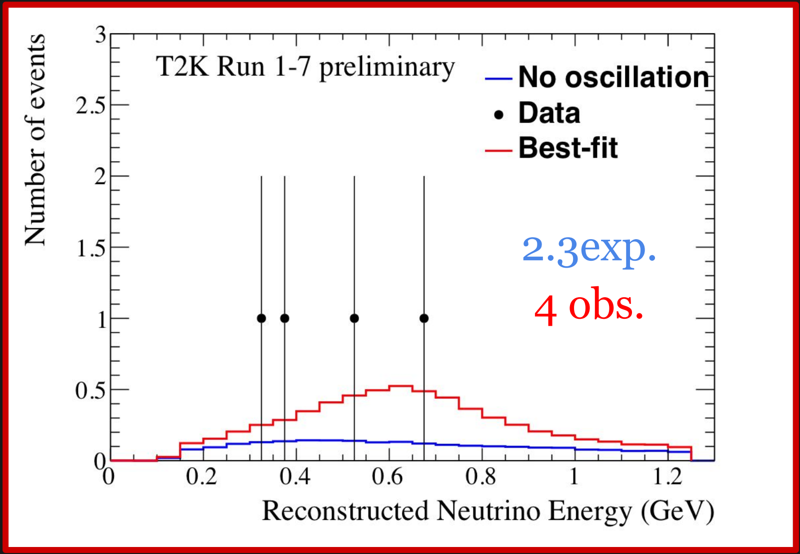
Reconstructed neutrino energy at the far detector for ν_μ and $\bar{\nu}_\mu$ candidate samples with the expected distribution in the no-oscillations hypothesis (blue) and the best-fit (red).

ν_e and $\bar{\nu}_e$ appearance

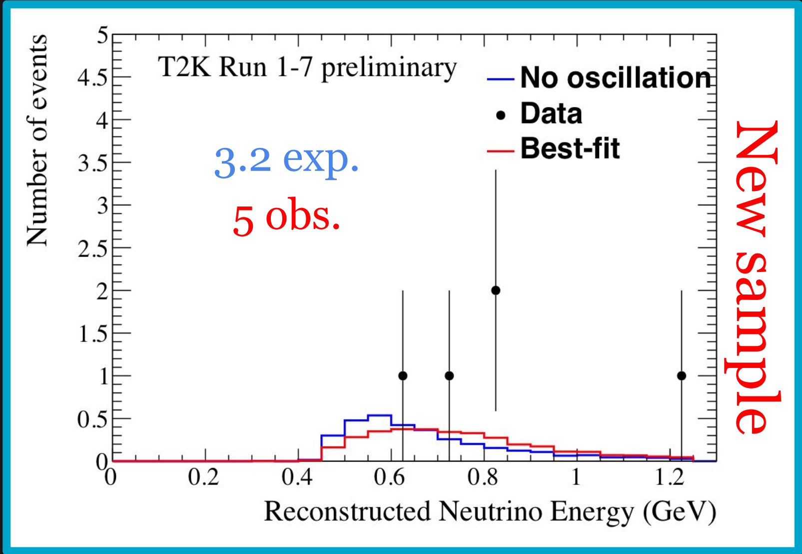
ν_e



$\bar{\nu}_e$



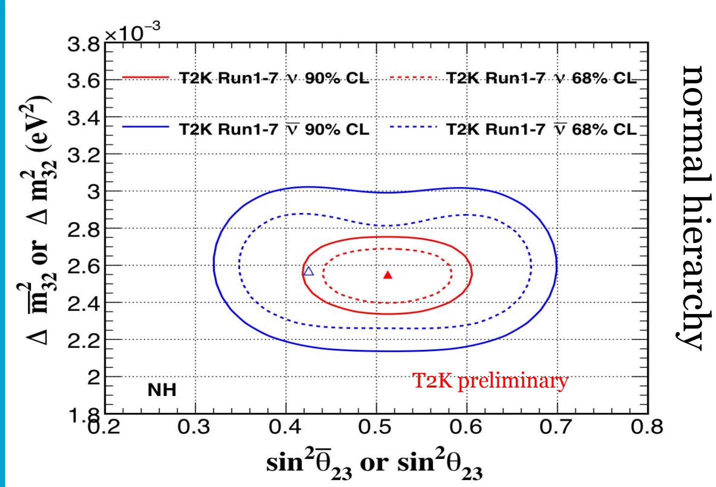
ν_e CC1π^+

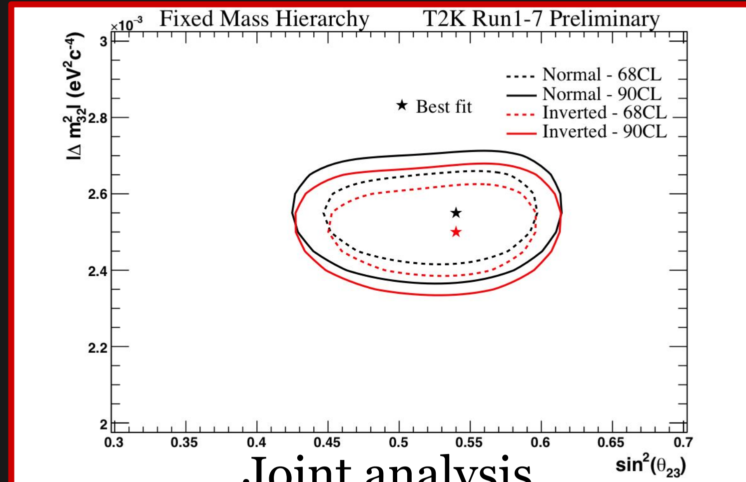


New sample

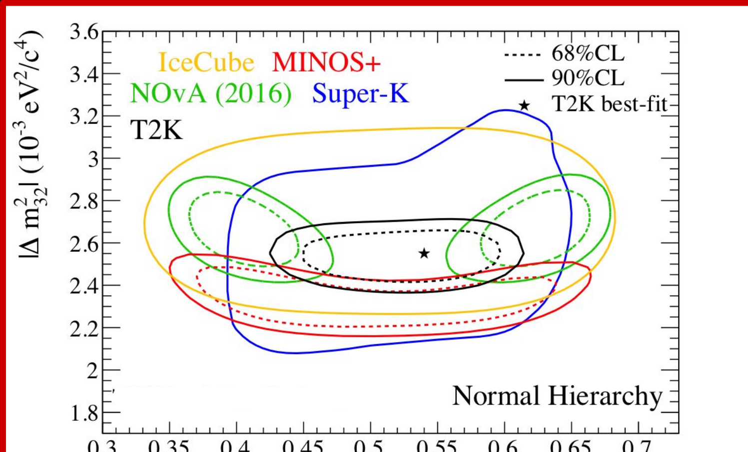
Confidence region in the $\sin^2\theta_{23}$ $|\Delta m^2_{32}|$ plane

ν and $\bar{\nu}$ analysis comparison





Joint analysis

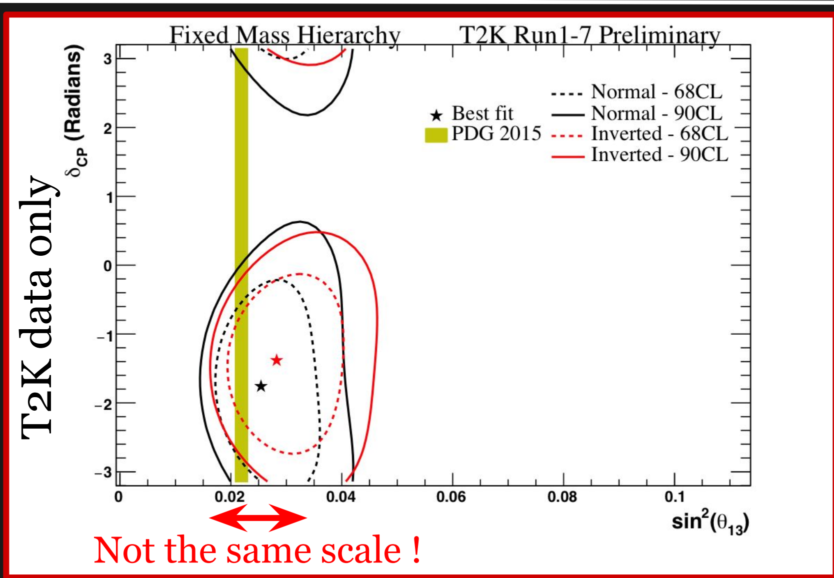


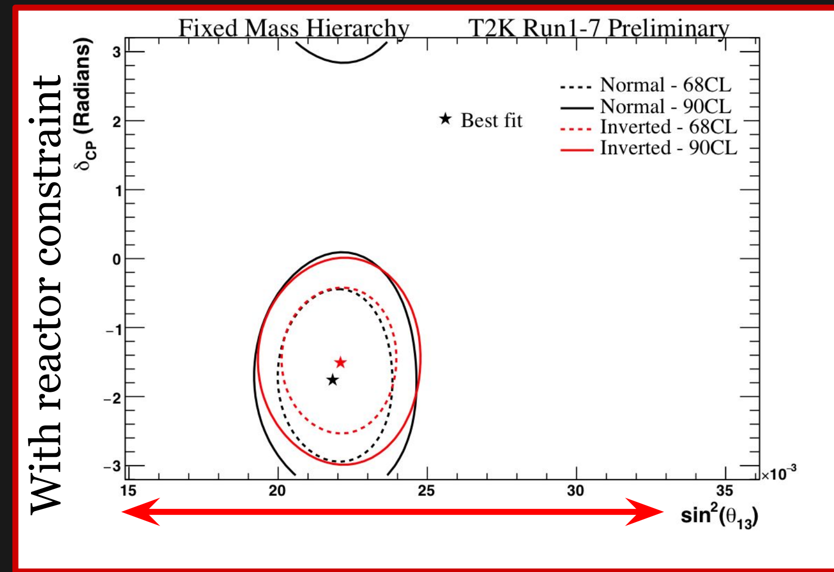
With other exp.

PhysRevLett.118.151801

- T2K results are consistent with past analysis results, maximal mixing (45°).
- It's also in agreement with other experiments.
- Weakly prefers second octant with posterior probability of 61%.
- From separated ν and $\bar{\nu}$ analysis comparison, no hint of CPT violation.

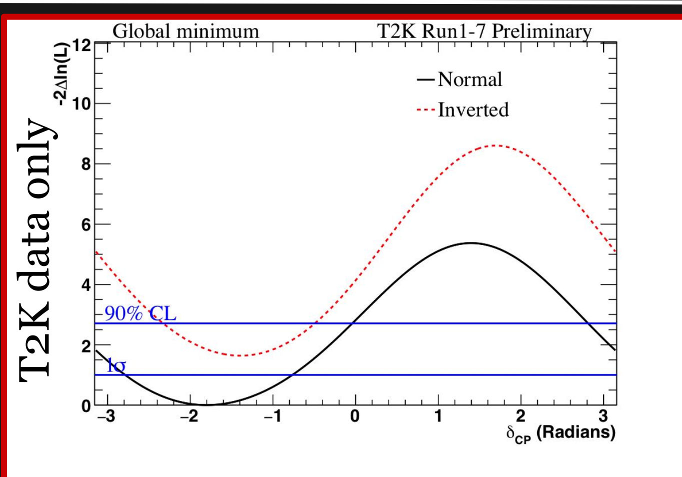
Confidence region in the $\sin^2\theta_{13}$ / δ_{CP} plane

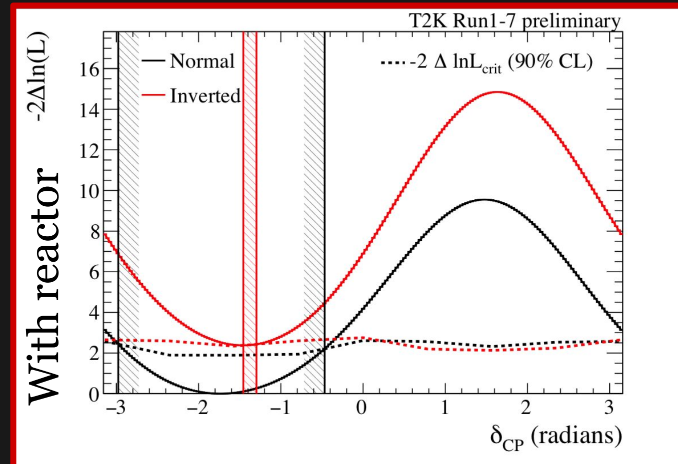




- With the anti-neutrino samples, T2K data by itself has already some sensitivity to δ_{CP} !
  - ➡ Disfavor region around $\delta_{CP} = +\pi/2$.
  - ➡ Preference for the $\delta_{CP} = -\pi/2$ region for both normal and inverted hierarchy.
- Good agreement between the reactor measurement of θ_{13} and T2K results.
- When adding the reactor constraint (PDG2015 : $\theta_{13} = 0.085 \pm 0.005$) the contour is further reduced.

First hints about δ_{CP}





Beam mode	Sample	$\delta_{CP} = -1.601$	$\delta_{CP} = 0$	Exp. Not Osc	Observed
neutrino	e-like	28.687	24.170	6.147	32
antineutrino	e-like	6.004	6.902	2.335	4

- ➤ Confidence intervals are obtained through the Feldman-Cousins method. All the parameters are marginalized and θ_{13} is marginalized using reactor value.

Parameter	Reactors	Normal Hierarchy	Inverted Hierarchy
δ_{CP} (radians)	YES	[-2.978; -0.467]	[-1.466; -1.272]

- ➤ We observe :
  - ➡ Less $\bar{\nu}_e$ candidates than expected
  - ➡ More ν_e candidates
- ➤ $\delta_{CP} = -\pi/2$ is the most asymmetric value, and is therefore favored.
- ➤ CP conservation excluded at 90% confidence level ($\delta_{CP} \neq 0, \pi$).

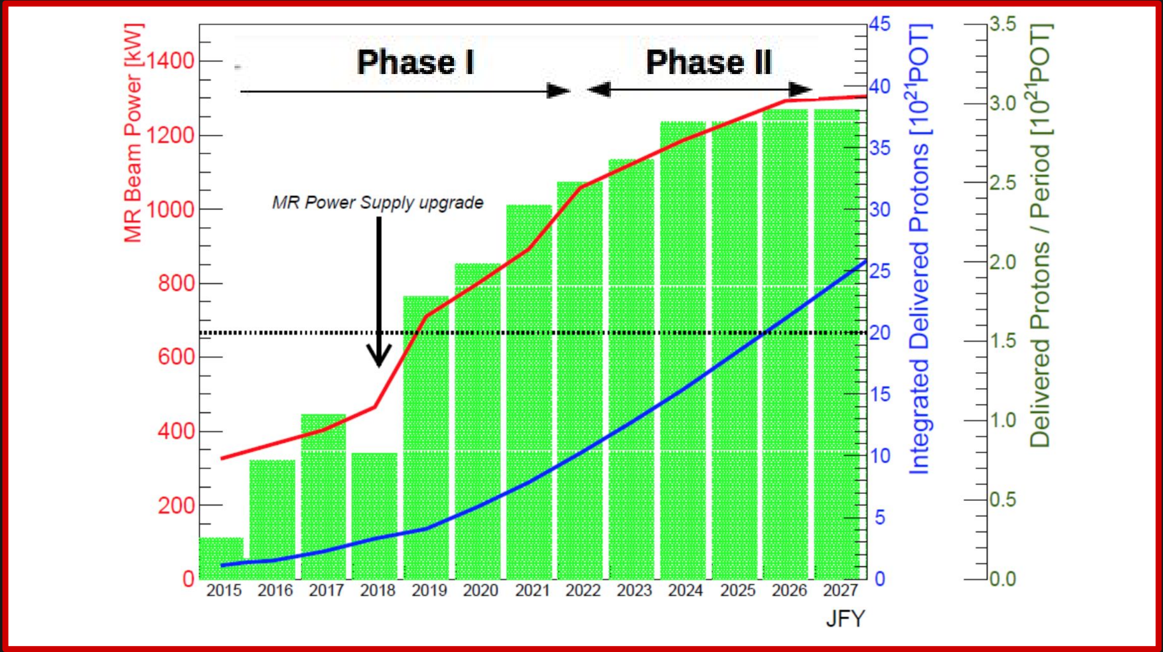
Future improvements

- Coming soon : a new analysis with different improvements !
  - Doubled neutrino-mode statistics.
  - More accurate neutrino interaction model, and new near detector fit for more precise measurement.
  - New SK reconstruction with larger fiducial volume. Expect 20% more events in ν_e appearance samples.

- Also working on different longer term improvements :
  - Reduced flux uncertainties thanks to new NA61/SHINE analysis.
  - Improved selections in the Near Detector (anti-neutrino and improved angular acceptance).
  - SK 2-rings samples.

T2K II

- ➤ T2K approved statistics (7.8 x 10^{21} POT) is expected to be reached in ~2021.
- ➤ 1st phase of J-PARC Main Ring improvement should begin in 2018.
  - ➡ T2K II would extend T2K run to 20 x 10^{21} POT in ~ 2026 (expected start of Hyper-K).
  - ➡ This requires both an accelerator and beamline upgrade to reach 1.3 MW and analysis improvements.

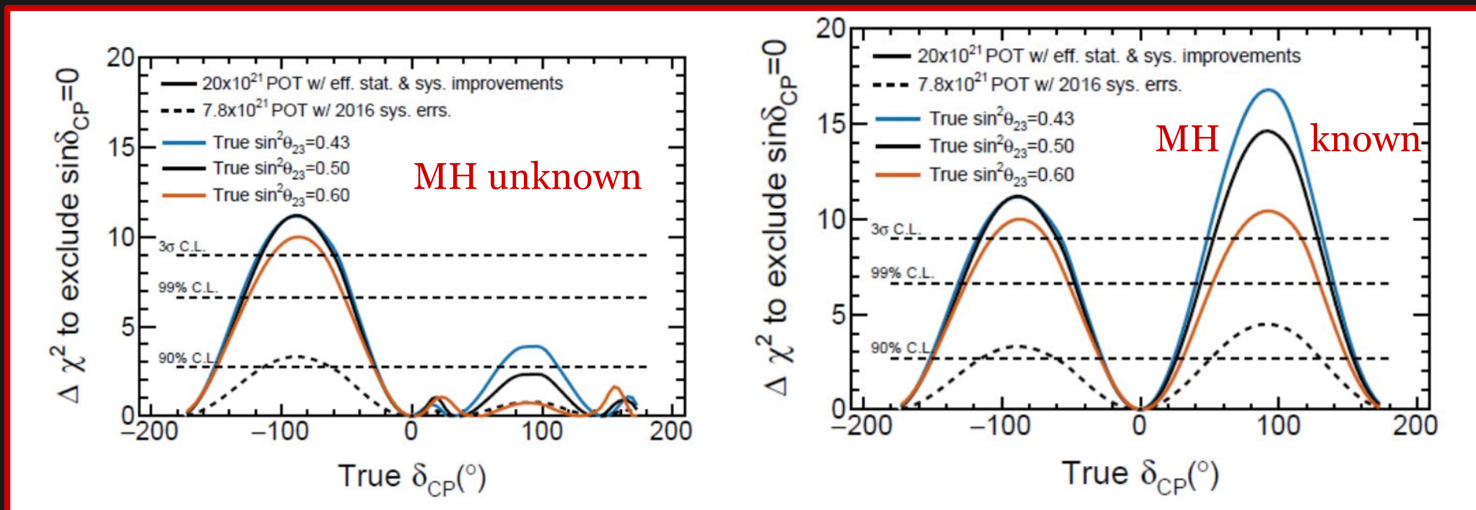


arxiv : 1609.04111

T2K II sensitivity and near detector upgrade

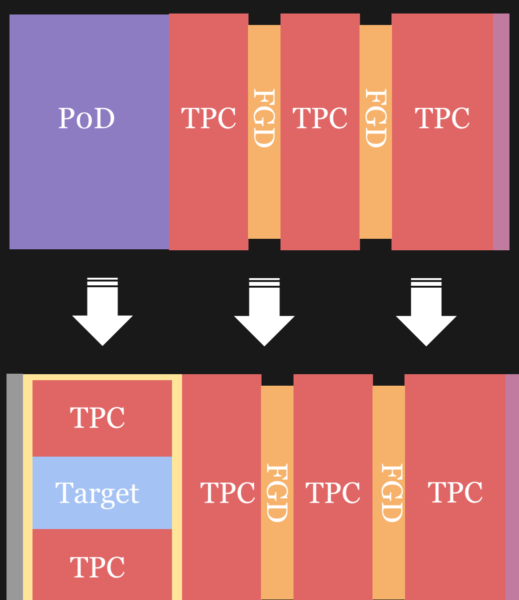
arXiv:1607.08004

based on the EOI submitted at J-PARC PAC



Current ND

Possible upgrade



- T2K II could reach ~3σ sensitivity to δ_{CP} for the parameter values currently favoured.
- This requires significantly lower systematics uncertainties
- An upgrade of the near detector is under study to see if we can achieve ~3% systematic uncertainties.

Summary

- Presented an overview of the latest T2K oscillation results :
  - Precise contour in the $\sin^2\theta_{23}$ / Δm^2_{23} plane, in very good agreement with the other experiments.
  - First search of CP violation with neutrino and anti-neutrino data !
    - Good agreement between T2K and the reactor measurements for $\sin^2\theta_{13}$.
    - CP conservation hypothesis excluded at 90% CL.
    - The new SK sample gives stronger δ_{CP} constraint
      - δ_{CP} (rad) = [-2.978, -0.467] for NH , [-1.466, -1.272] for IH at 90% CL.
- Soon to come (this summer) some new results with several improvements in the analysis and twice the neutrino data. Stay tuned !
- T2K also makes impressive cross-section measurements (talk from Lukas) !
- 7.8 x 10^{21} POT expected to be reached in ~2021.
  - Proposal for extending T2K data-taking period to 2026 and accumulate up to 20 x 10^{21} POT to continue doing nice physics !
  - Planning an upgrade of the near detector around 2020 to further reduce the systematic uncertainties.
  - If interested, come and join the T2K II effort !