Oscillation Analysis in the T2K and Hyper-K Experiments

Denis Carabadjac

dcarabadjac@llr.in2p3.fr

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Motivation

Probing the models beyond the Standard Model

Probing cosmology theories

Neutrino - pivotal indicator

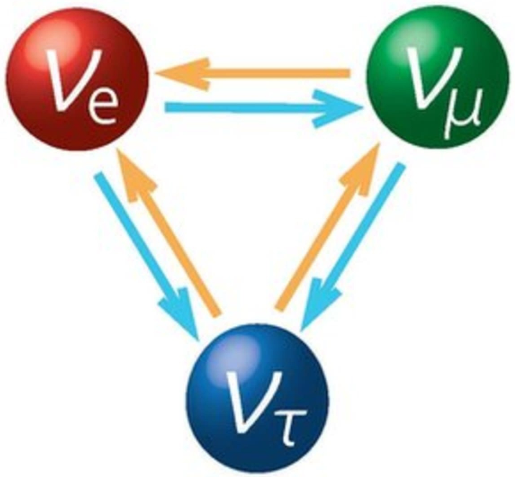
The study of neutrino oscillations is a pursuit of fundamental scientific knowledge

Neutrino oscillations

The study of neutrino oscillations is a pursuit of fundamental scientific knowledge

Neutrino oscillations describe a physics phenomenon where a neutrino created with a specific lepton flavor (electron, muon, or tau) can later be measured to have a different flavor.

Apearance dis. define



Flavour eignenstates

Mass eignestates

$$\begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix} \longleftrightarrow \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \longleftrightarrow \begin{pmatrix} m_1 \\ m_2 \\ m_3 \end{pmatrix}$$

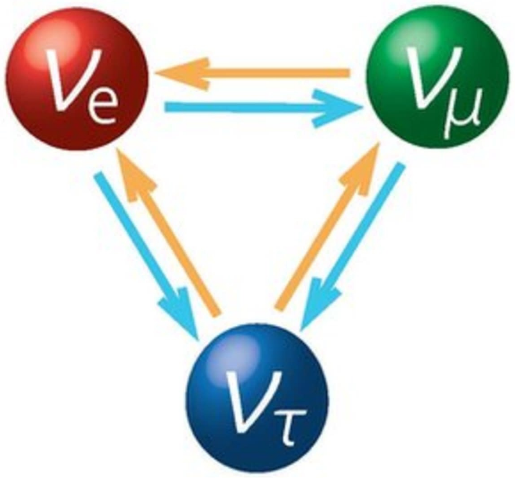
Participate in neutrino interactions and productions

Propagation in space-time

Neutrino oscillations

Petkov will speak about it

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



$$U_{PMNS} = U(\delta_{CP}, \theta_{12}, \theta_{13}, \theta_{23})$$

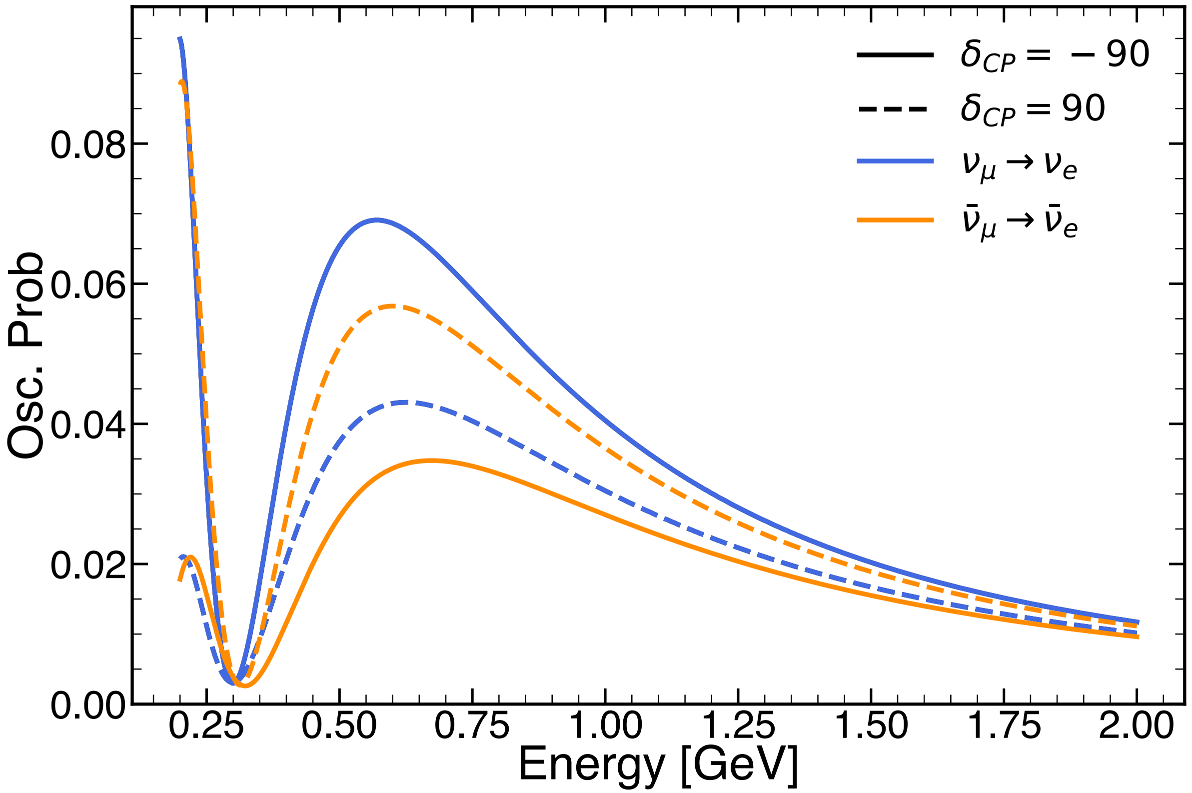
$$\Delta m^2_{ij} = m^2_i - m^2_j$$

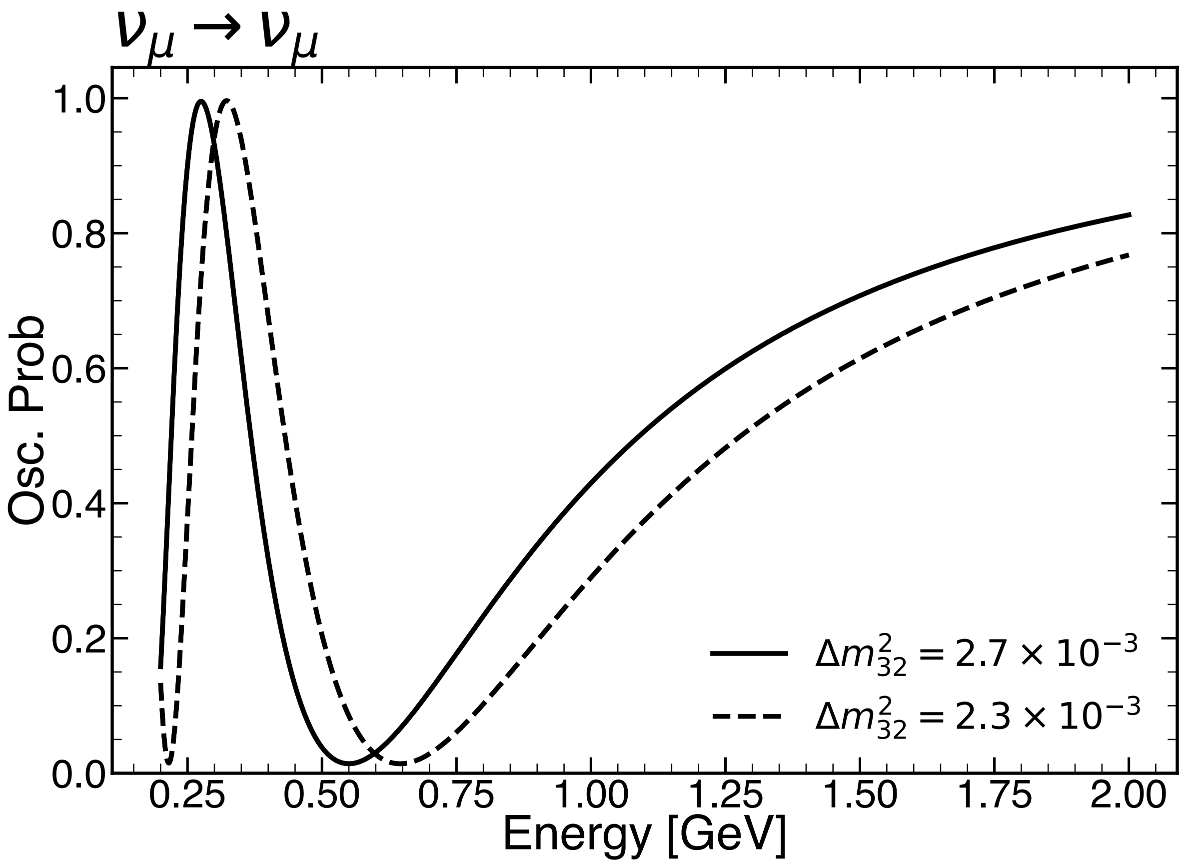
Oscillation parameters: $\delta_{CP}, \theta_{12}, \theta_{13}, \theta_{23}$ + Δm^2_{12}, $|\Delta m^2_{32}|$, $\mathrm{sign}(\Delta m^2_{32})$(Mass ordering)

With accelerator neutrino experiment we can measure δ_{CP}, θ_{23}, θ_{13}, $|\Delta m^2_{32}|$
Small sensitivity to mass ordering (MO)*

*thus usually results are presented under different hypothesis of MO

Neutrino oscillations





- **neutrino energy** measurement is **crucial** for oscillation inference
- **oscillation channel** (to electron or muon) and **mode** (neutrino or antineutrino) carries **comlementary information,** on oscillation

> - To infere the neutrino oscillation we need to **measure accurately** the **flavour** and **neutrino energy**
> - **We would like to measure different oscillation channels and different modes**

Requirements for an experiment

- We need neutrino which we can be produced with abundant flux
- We need to monitor this flux
- We need measure this flux before neutrino oscillations
- Finally, we need to measure this flux after neutrino oscillations

T2K experiment

T2K experiment

Experimental measurement

- We need neutrino which we can be produce with abundant flux
- We need to monitor this flux
- We need measure this flux before neutrino oscillations
- Finally, we need to measure this flux after neutrino oscillations

T2K experiment

Proton accelerator

- 30 GeV proton accelerator
- Carbon target for pions production
- 3 magnetic horns for pion focusing (positive or negative)

$\pi^+ \rightarrow \mu^+ + \bar{\nu}_\mu$ ⟶ Antineutrino mode

Horn polarity

Neutrino mode

T2K experiment

Accelerator

- **30 GeV proton accelerator**
- **Carbon target for pions production**
- **3 magnetic horns for pion focusing (positive or negative)**

$\pi^+ \rightarrow \mu^+ + \bar{\nu}_\mu$ ⟶ Antineutrino mode

Horn polarity

$\pi^- \rightarrow \mu^- + \nu_\mu$ ⟶ Neutrino mode

T2K experiment

Accelerator

- **30 GeV proton accelerator**
- **Carbon target for pions production**
- **3 magnetic horns for pion focusing (positive or negative)**

$\pi^+ \rightarrow \mu^+ + \bar{\nu}_\mu$ ⟶ Antineutrino mode

$\pi^- \rightarrow \mu^- + \nu_\mu$ ⟶ Neutrino mode

T2K experiment

ν_μ $\bar{\nu}_\mu$

T2K experiment

$$\nu_\mu \quad \& \quad \bar{\nu}_\mu$$

Accelerator neutrino experiment can measure properties on neutrino and antineutrino and to study the assymetry between them

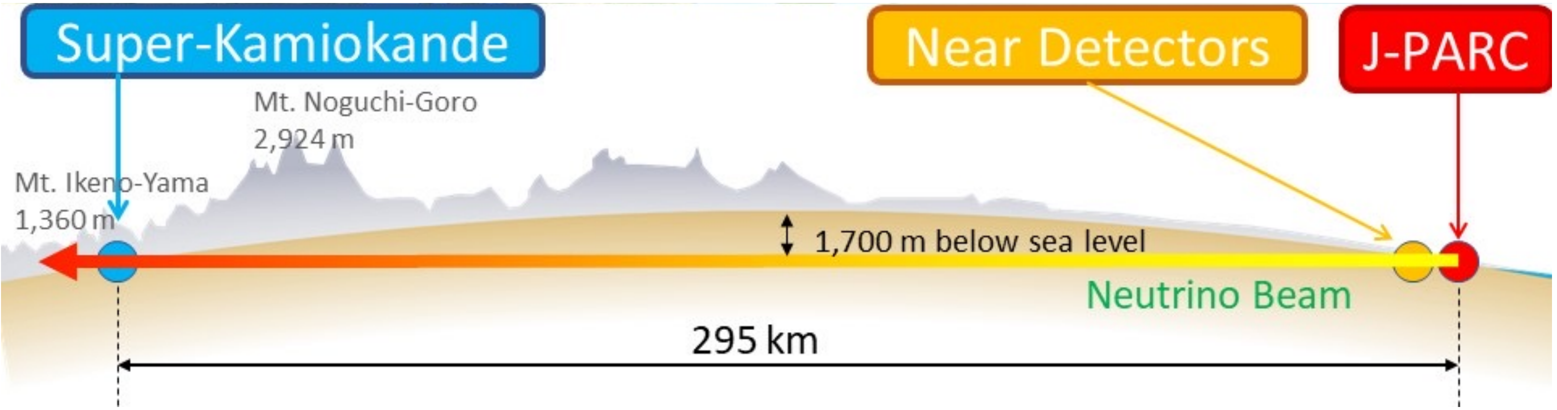
⬇

Can measure δ_{CP} responsible for CP violation in lepton sector

Experimental measurement

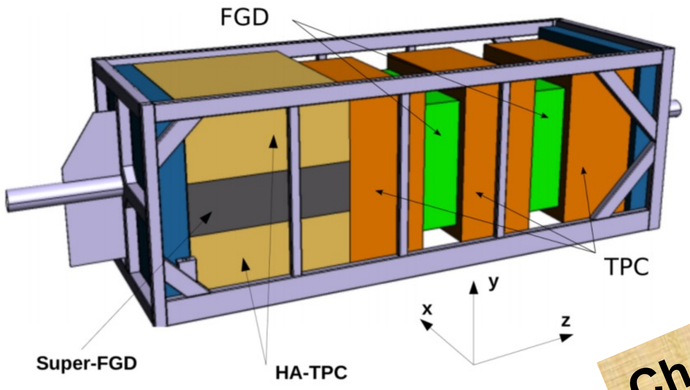
- We need neutrino which we can be produce with abundant flux ✓
- We need to monitor this flux
- We need measure this flux before neutrino oscillations
- Finally, we need to measure this flux after neutrino oscillations

Experimental measurement



- We need measure this flux before neutrino oscillations
- We need to monitor this flux

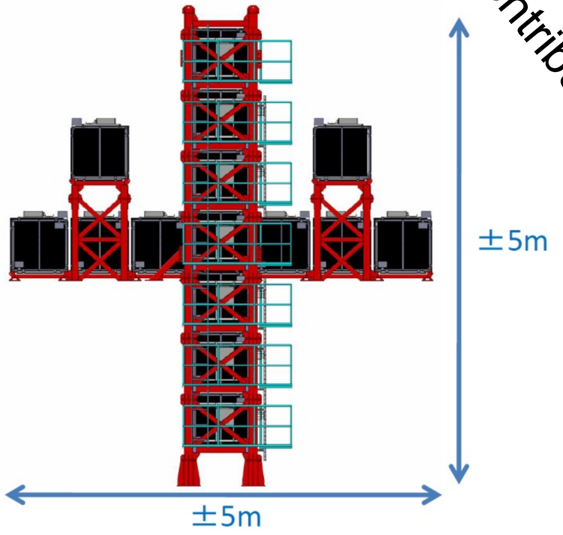
ND280Upgrade



Contribution from LLR to SFGD electronics

Check Viet's slides

INGRID

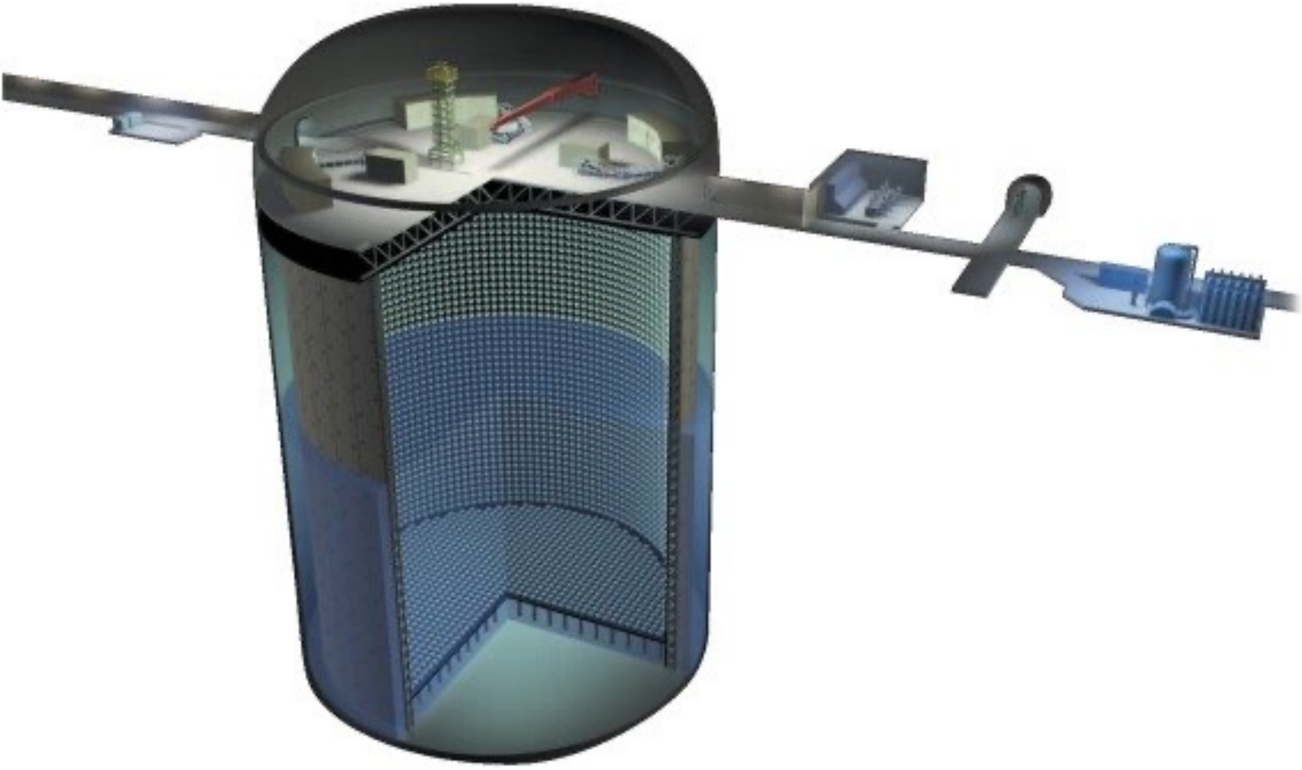


Contribution from LLR

Experimental measurement

- We need neutrino which we can be produce with abundant flux ✓
- We need to monitor this flux ✓
- We need measure this flux before neutrino oscillations ✓
- ➡ Finally, we need to measure this flux after neutrino oscillations

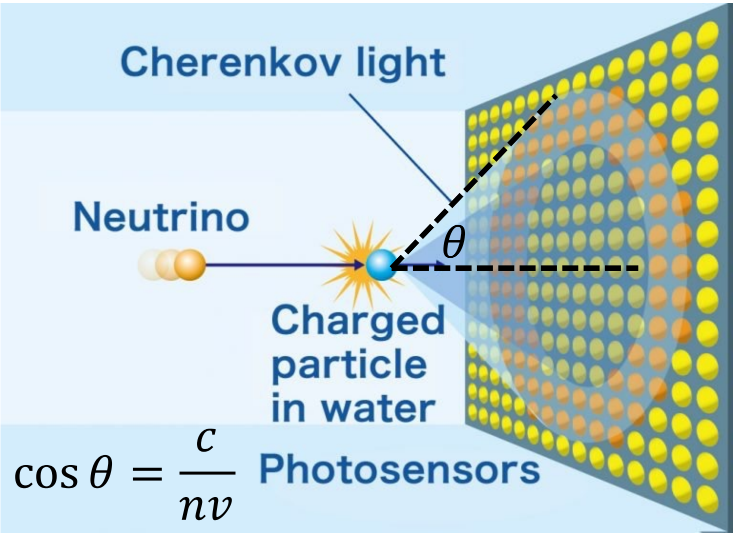
T2K experiment

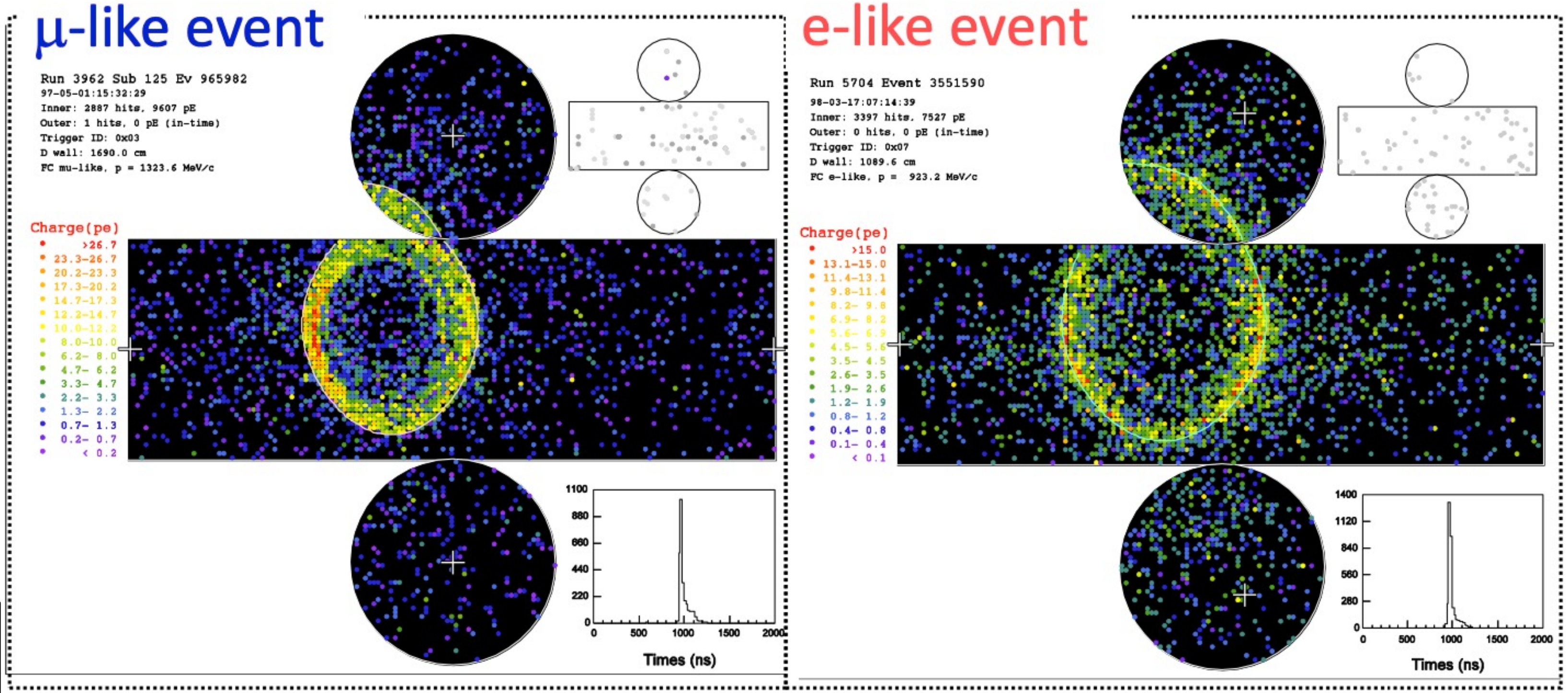


Detects water Cherenkov light from charged particle and reconstructs events with PMT charge & timing information.

	Super-Kamiokande
Site	Mozumi
Number of ID PMTs	11,129
Photo-coverage	40%
Mass/Fiducial Mass	50 kton/22.5 kton

Super-Kamiokande events





Ring imaging water Cherenkov detector provides informative event reconstruction:

1) Number of Cherenkov photons ∝ **momentum of the particle**

2) Arrival time ∝ **interection position**

3) Number of cherenkov rings ∝ **number of the produced charged particle**

4) The ring shape ∝ **type of the particle**:

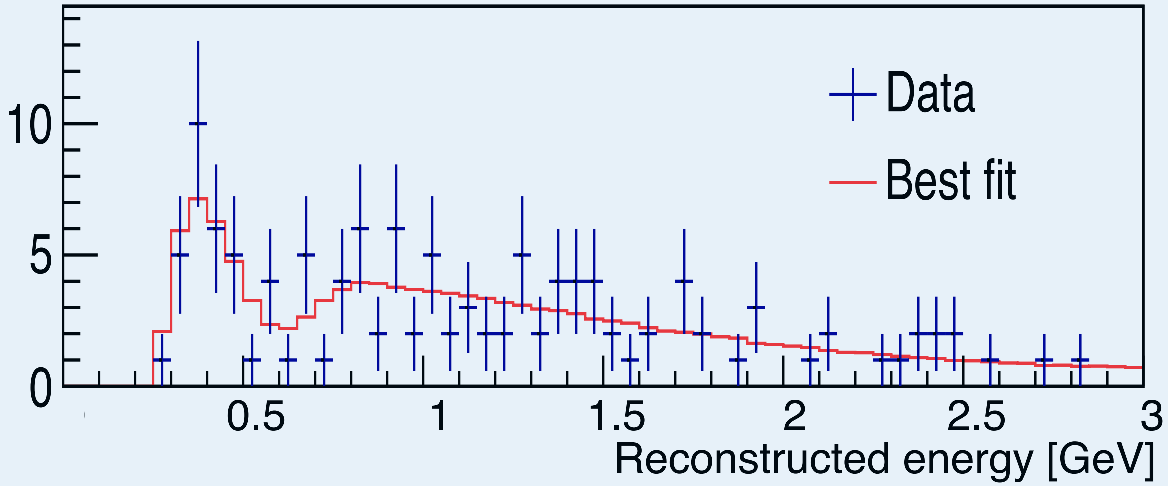
- electron generates electro-magnetic shower ring is diffused
- muon generates a sharp ring

Oscillation Analysis in T2K

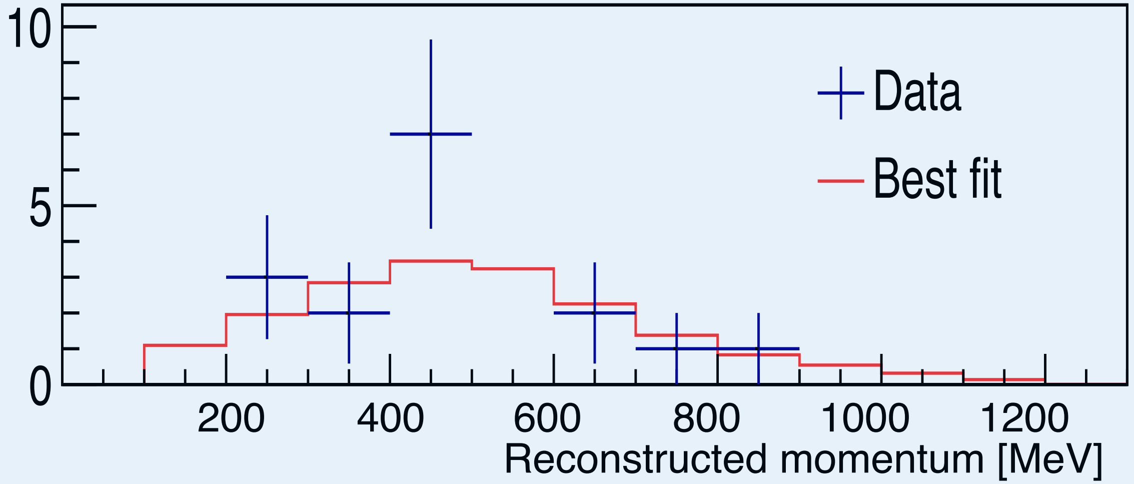
T2K Data

Antinumode

Muon-like 1R



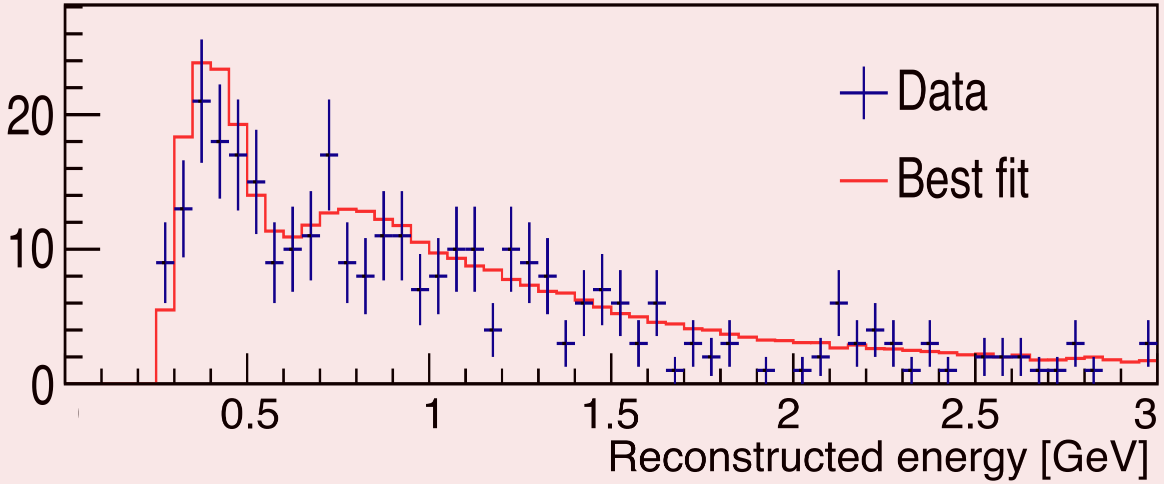
Electron-like 1R



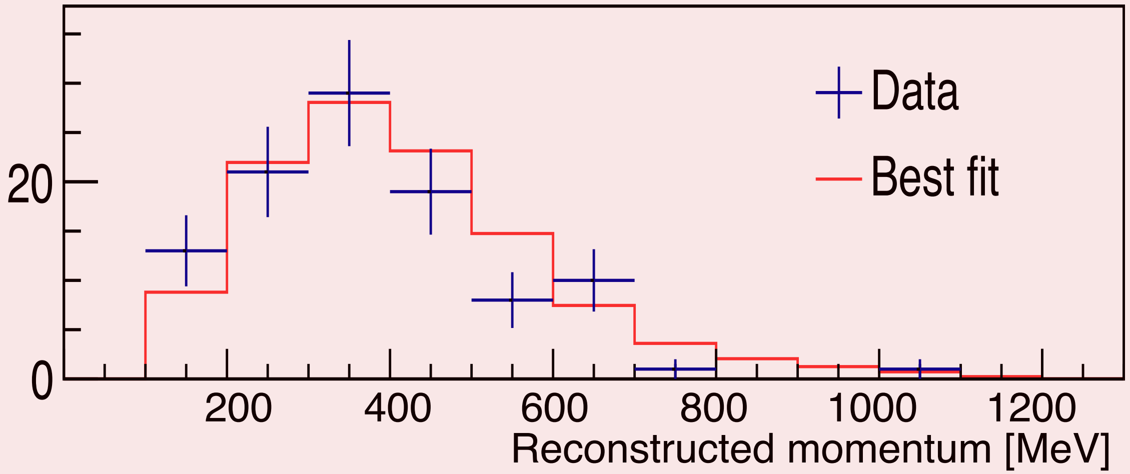
Numode

Change namings

Muon-like 1R Numu dis



Electron-like 1R



Multi-ring samples are also used

Spectra at ND

Comparison unosc/oscilated flux

Dis, app

T2K Oscillation Analysis

Data → **Neutrino oscillations**

↑

How?!

T2K Oscillation Analysis

$$N_{obs}^{\nu_\alpha}(E_\nu^{true}) =$$

$$\Phi(E_\nu^{true}) \otimes \sigma(E_\nu^{true}) \otimes \epsilon(E_\nu^{true}) \otimes S(E_\nu^{true}, E_\nu^{reco}) \otimes \boldsymbol{P}_{\nu_\mu \to \nu_\alpha}(\boldsymbol{E}_\nu^{true}, \vec{\boldsymbol{o}})$$

Neutrino flux

Interection cross-section

Detector efficiency

Energy smearing matrix

Oscillation probability

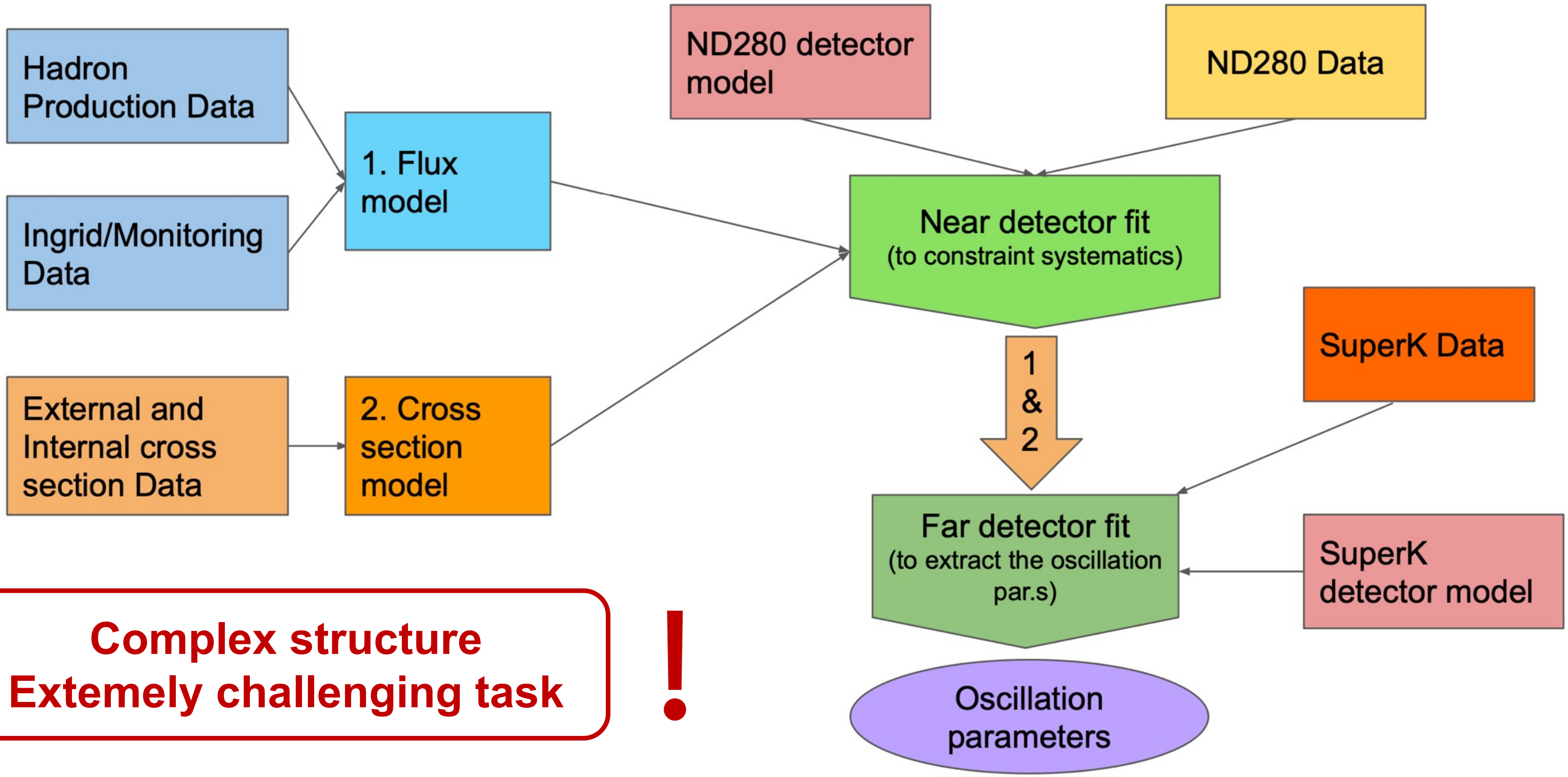
We want to extract this!

Systematics

$$(\vec{\boldsymbol{f}})$$

$$\alpha = e, \mu$$

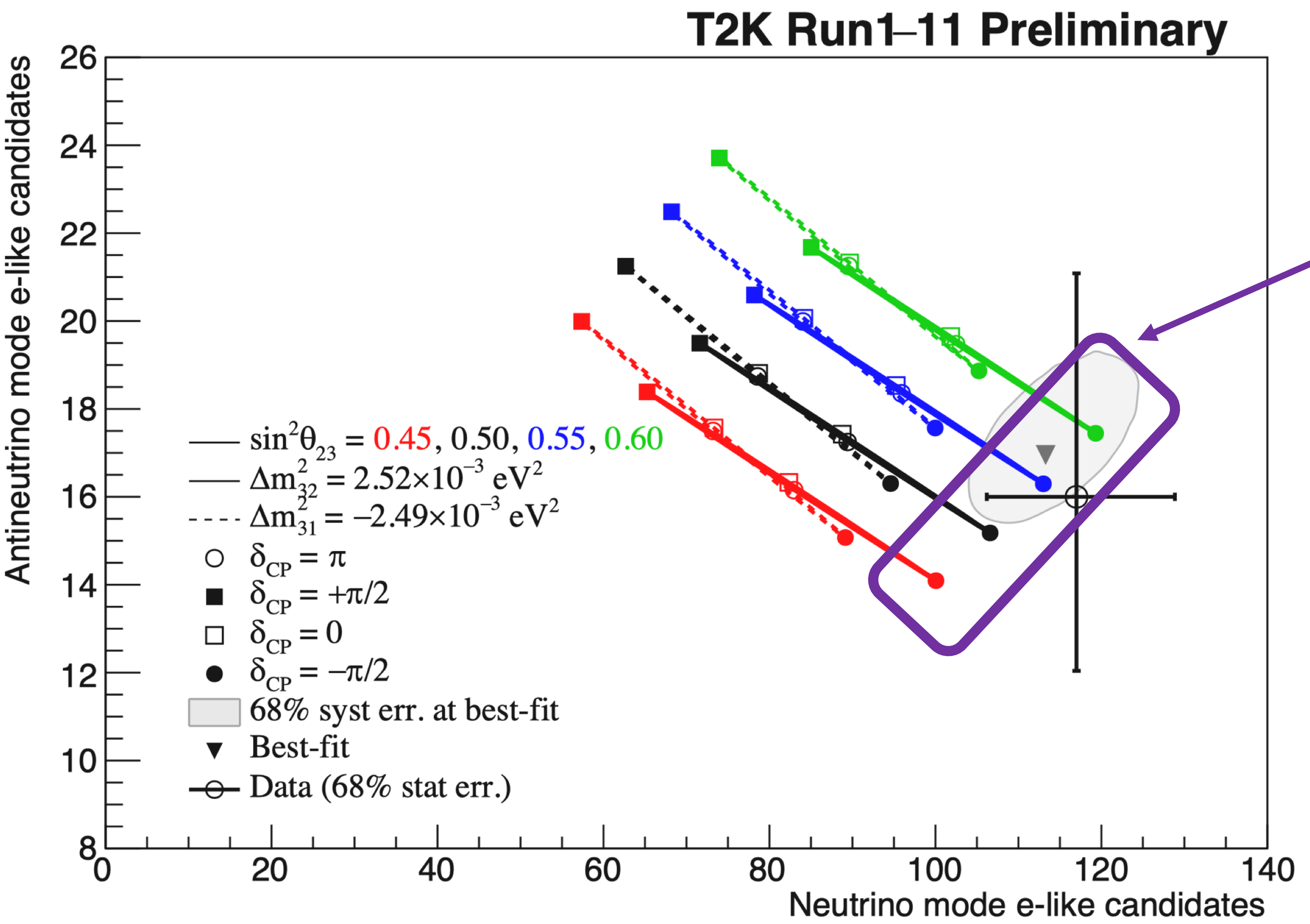
T2K Oscillation Analysis



Complex structure
Extemely challenging task

!

T2K Oscillation Analysis

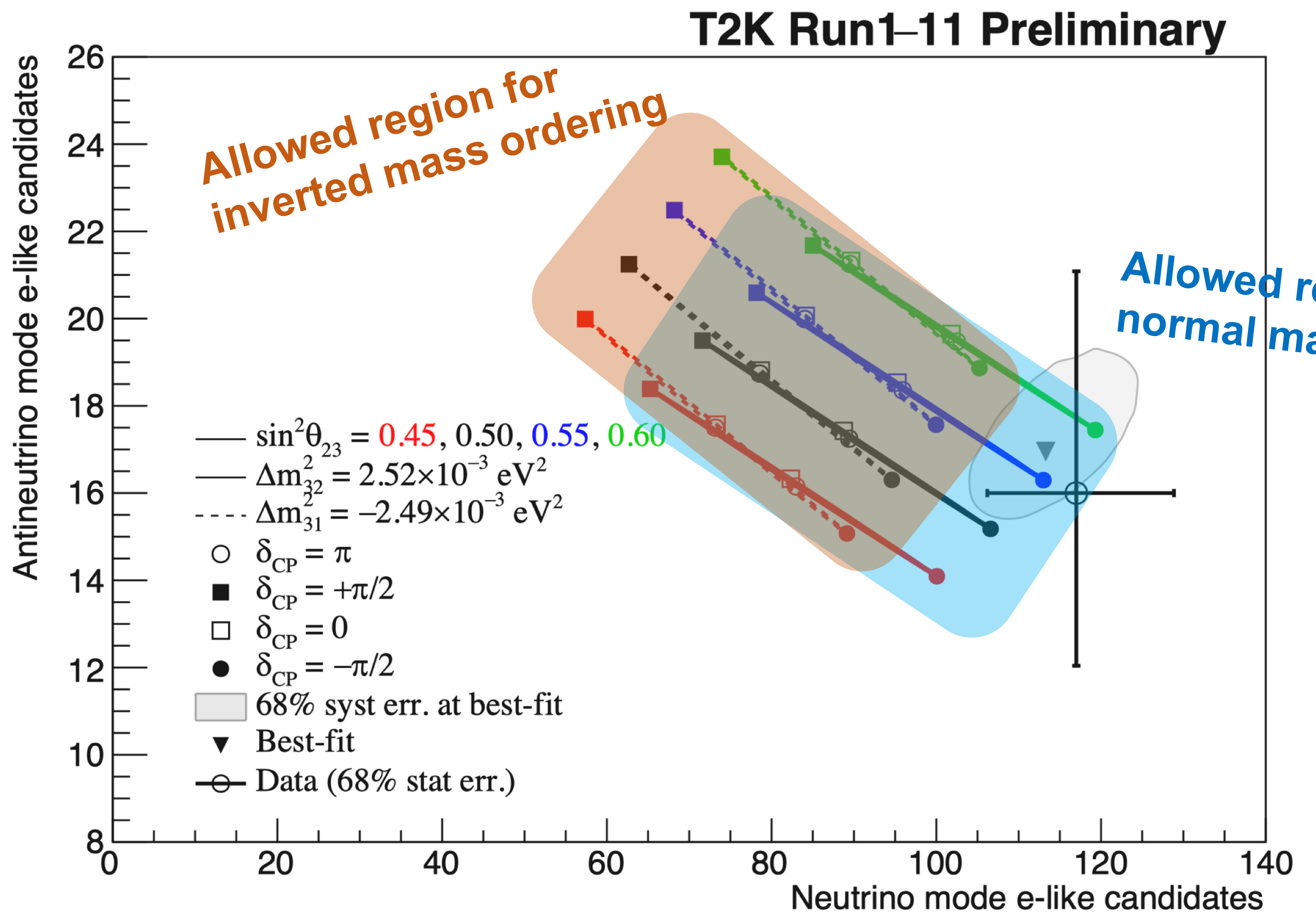


Max. CP-violation region

Best fit: $\delta_{CP} \approx -\frac{\pi}{2}$

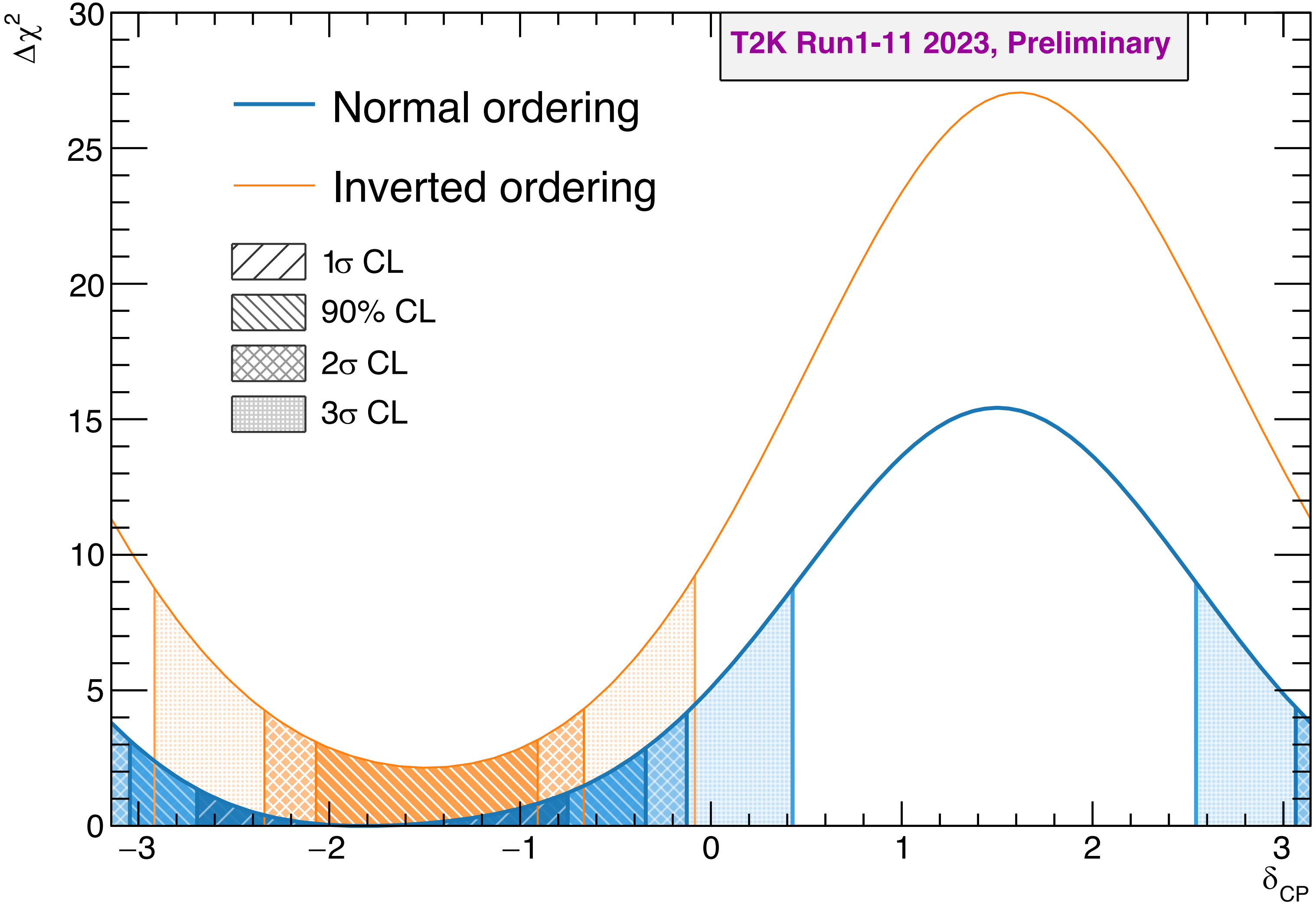
Weak preference of Normal Mass Ordering

T2K Oscillation Analysis



Weak preference of Normal Mass Ordering

T2K recent results



Results:

$\delta_{CP} = -2.08^{+1.33}_{-0.61}$

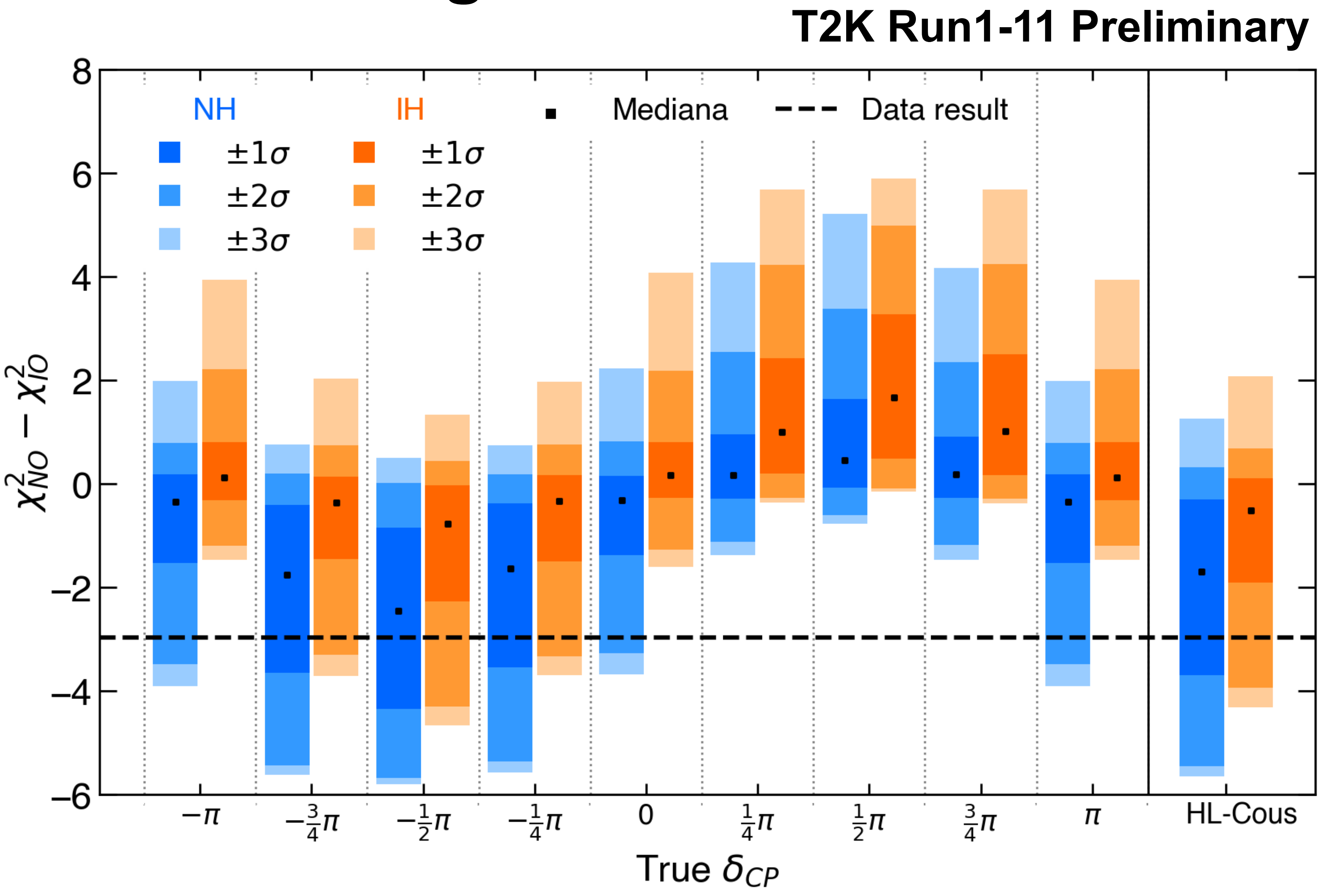
CP cons. excluded at 90% level

Exc. $\delta_{CP} = \pm\pi$ with 90% C.L.
Exc. $\delta_{CP} = 0$ with 2σ C.L.

Normal ordering preferred

At which level?
See next slide

Mass ordering results

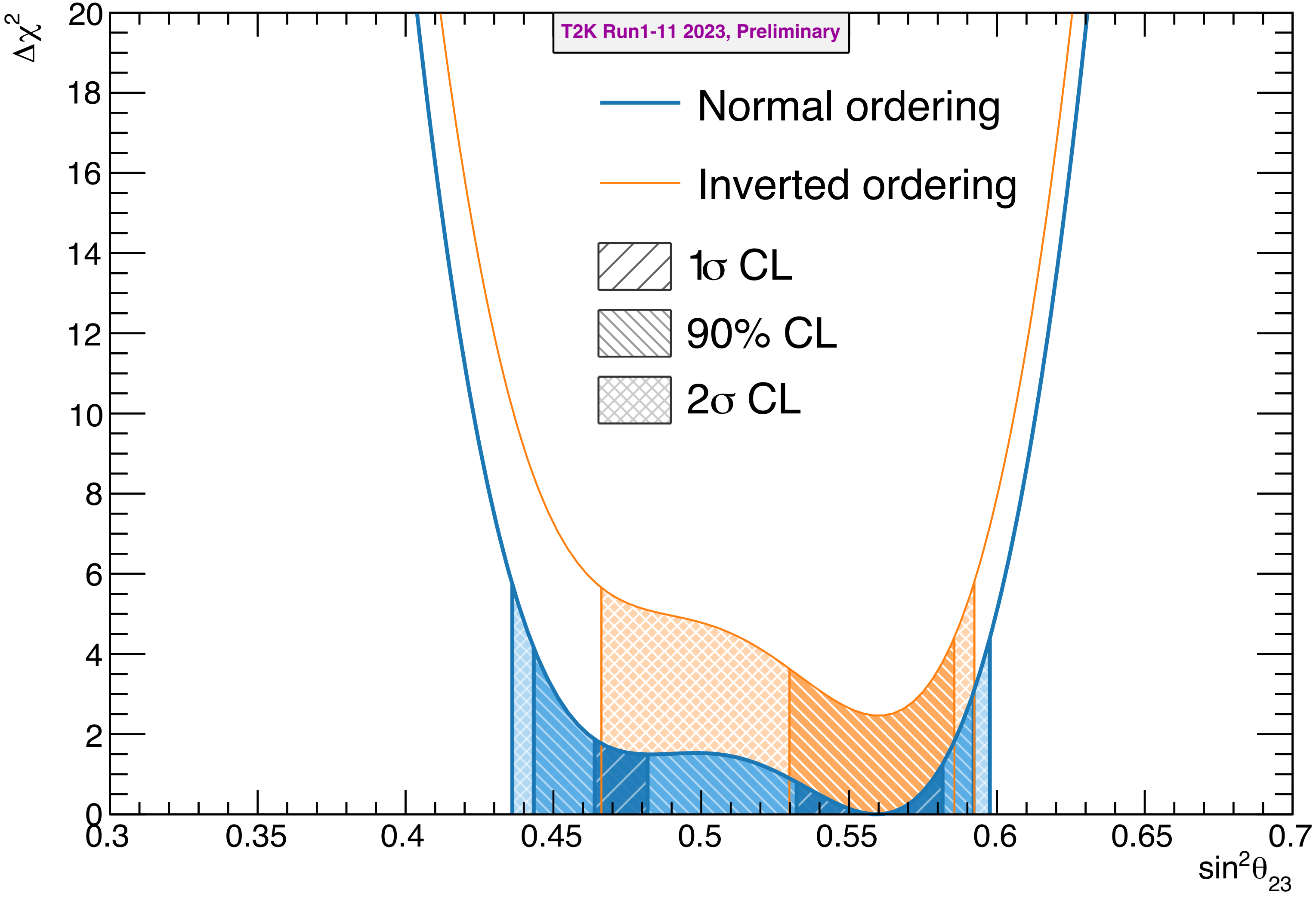


Inverted Ordering exclusion

p-value = 1.69σ
CLs = 1.27σ

$$\text{CLs} = \frac{p_{\text{value}}(\text{IH})}{1 - p_{\text{value}}(\text{NH})}$$

T2K recent results



Confidence level	Interval (NH)
1σ	[0.464,0.482] ∪ [0.532,0.582]
90%	[0.443,0.592]
2σ	[0.436,0.598]

Confidence level	Interval (IH)
1σ	
90%	[0.530,0.586]
2σ	[0.466,0.592]

$\varepsilon(\sin^2\theta_{23}) = 9\%$ (assuming upper octant)

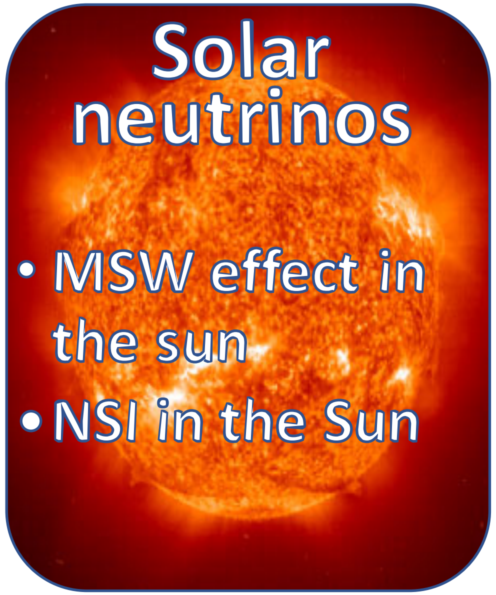
Week preference of upper octant

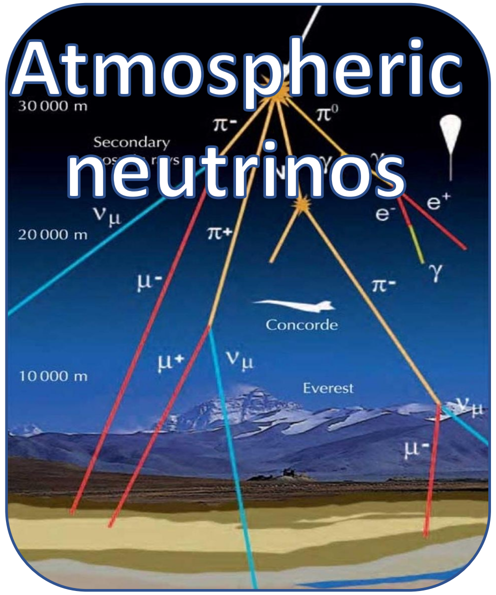
T2K experiment

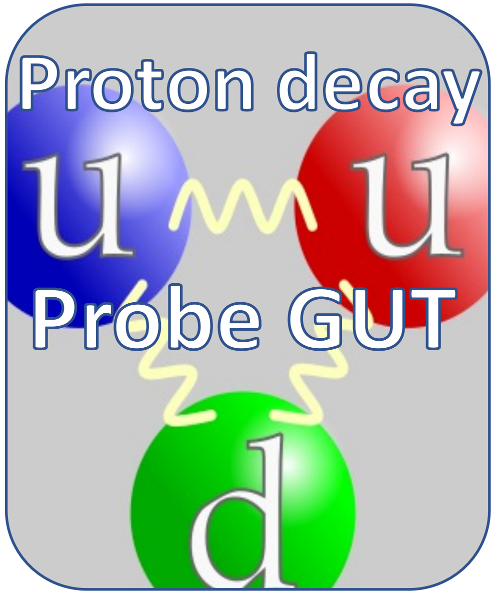
↓ after 2027

HK experiment

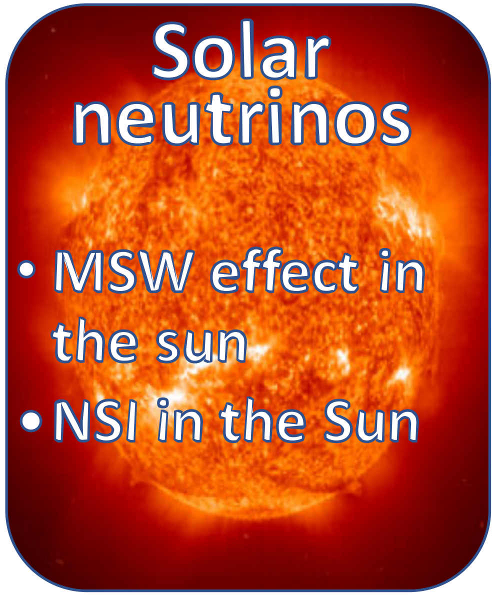
HyperK has an extensive physics program







HyperK has an extensive physics program

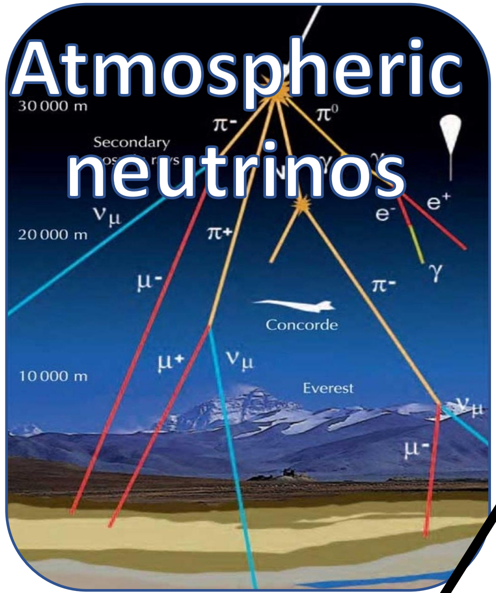


Solar neutrinos

- MSW effect in the sun
- NSI in the Sun

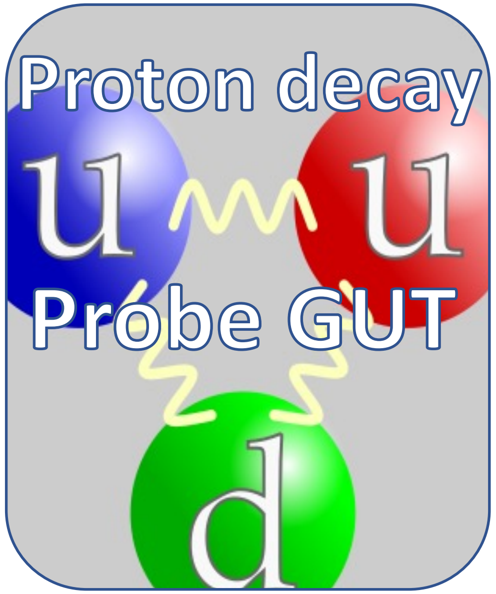
Supernova neutrinos

- Direct SNν :
- Relic SNν :



Atmospheric neutrinos

Accelerator neutrinos



Proton decay

Probe GUT

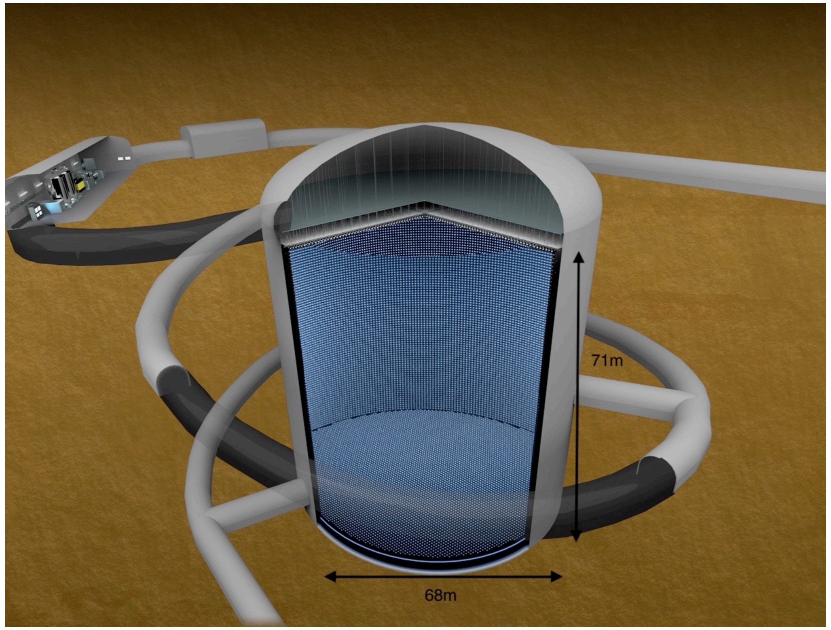
Focusing on that

Hyper-K experiment

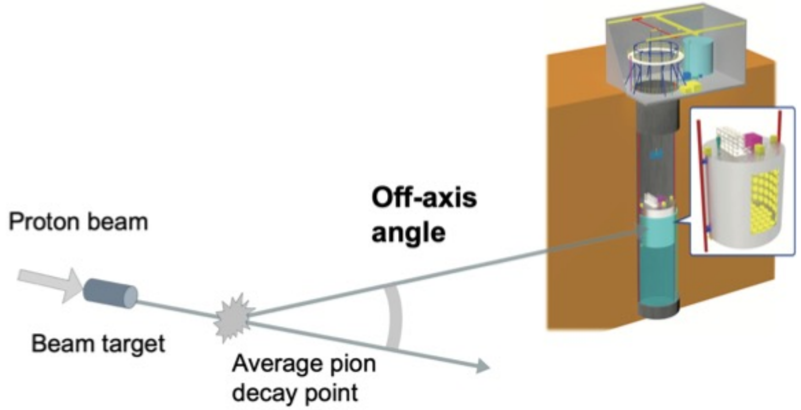
Next generation of long-baseline experiments

- New far detector (x8 of fiducial mass)
- Increase of beam power (500kW -> 1300kW)

x21 in stat!



- Additional near detector - Intermediate Water Cherenkov Detector (IWCD)
- ND280 Upgrade - Done

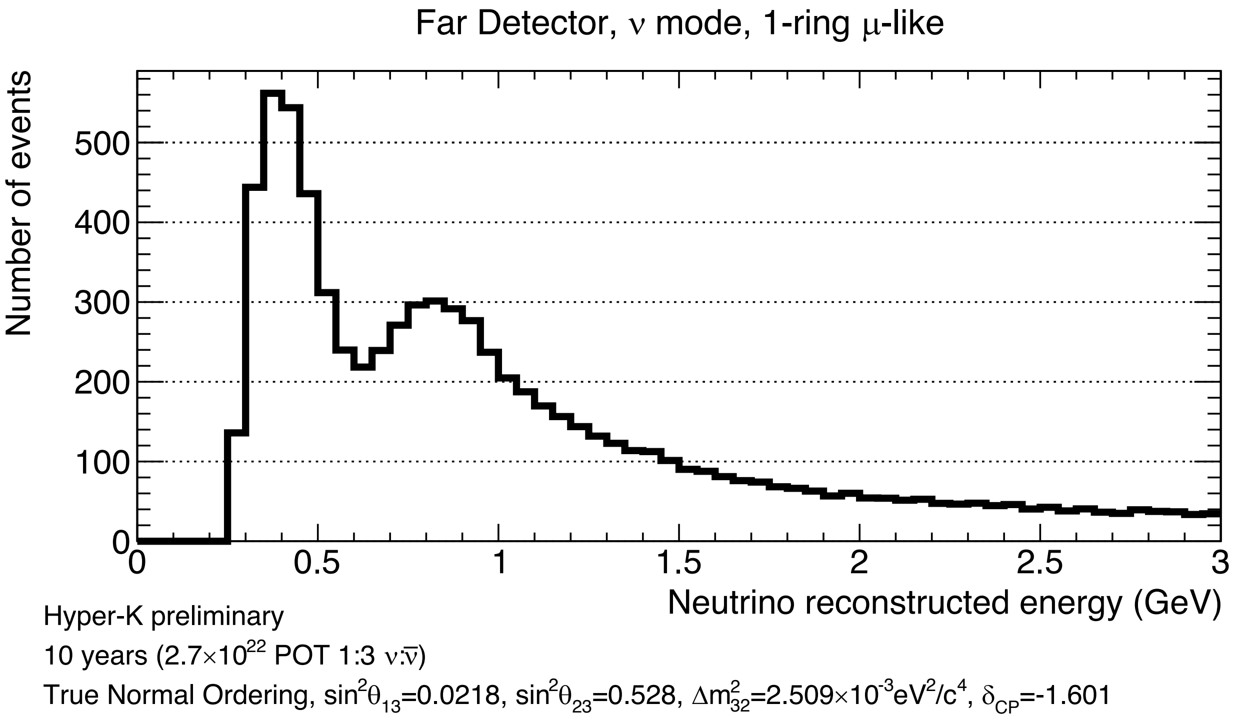


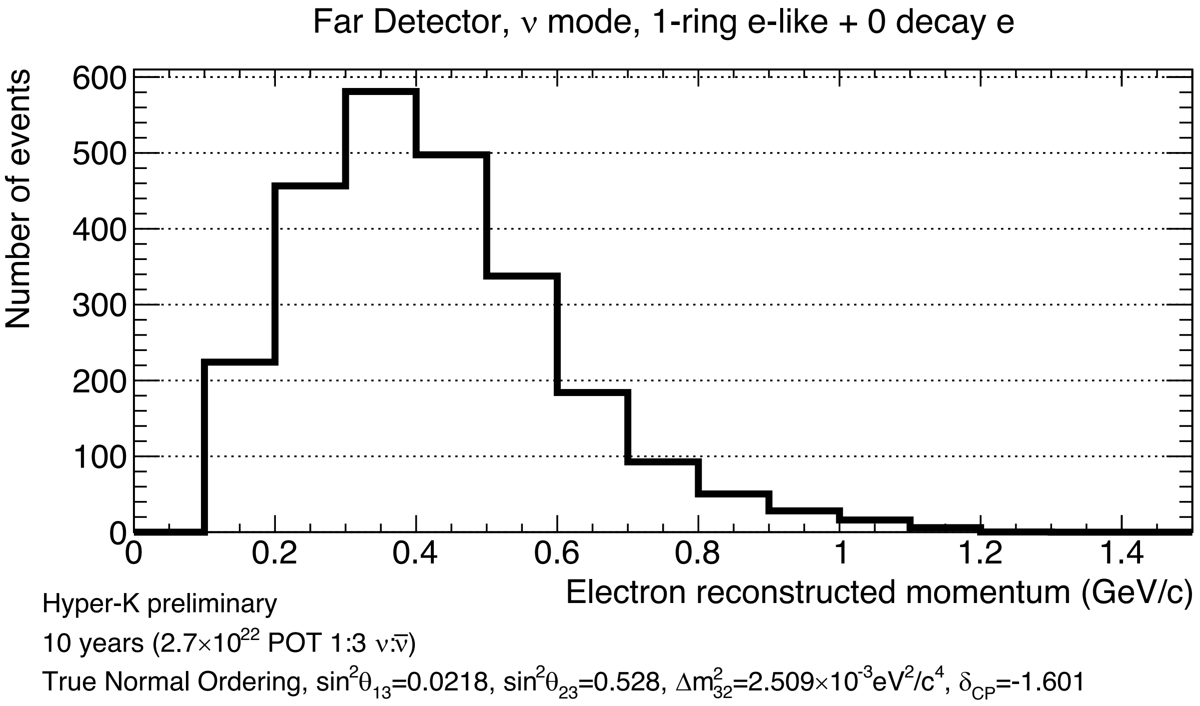
	Super-Kamiokande	**Hyper-Kamiokande**
Site	Mozumi	Tochibora
Number of ID PMTs	**11,129**	**20,000**
Photo-coverage	40%	20% (x2 sensitivity)
Mass/Fiducial Mass	50 kton / **22.5 kton**	260 kton / **187 kton**

Hyper-Kamiokande sensitivity studies

HK sensitivity studies

After 10 HK years





~8800 events

~2400 events

Total number of events in all **samples** more than 25000!

For comparison: T2K has recorded 600 events by 2024

HK sensitivity studies

Sensitivity studies are performed for three syst. models:

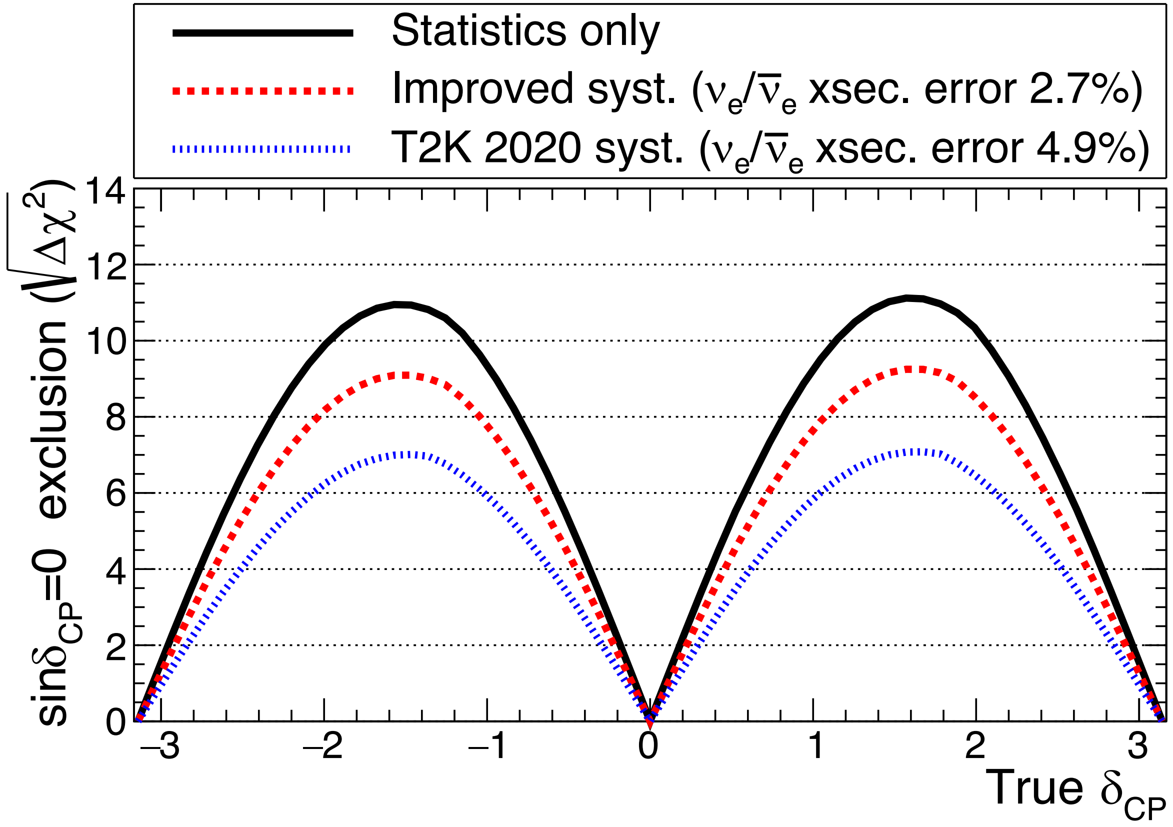
- Statistics only (zero systematic uncertainties)
- T2K 2020 systematics model (where we are now)
- Improved systematics

The Improved systematics model was produced by scaling the T2K-2020 error model by

- scaling the uncertainties by $\frac{1}{\sqrt{N}}$, where $N = 7.5$ is the relative increase in neutrino beam exposure from T2K to Hyper-K

- putting additional constraints to the cross-section model uncertainties (coming from higher expected performance of upgraded ND280 and IWCD)

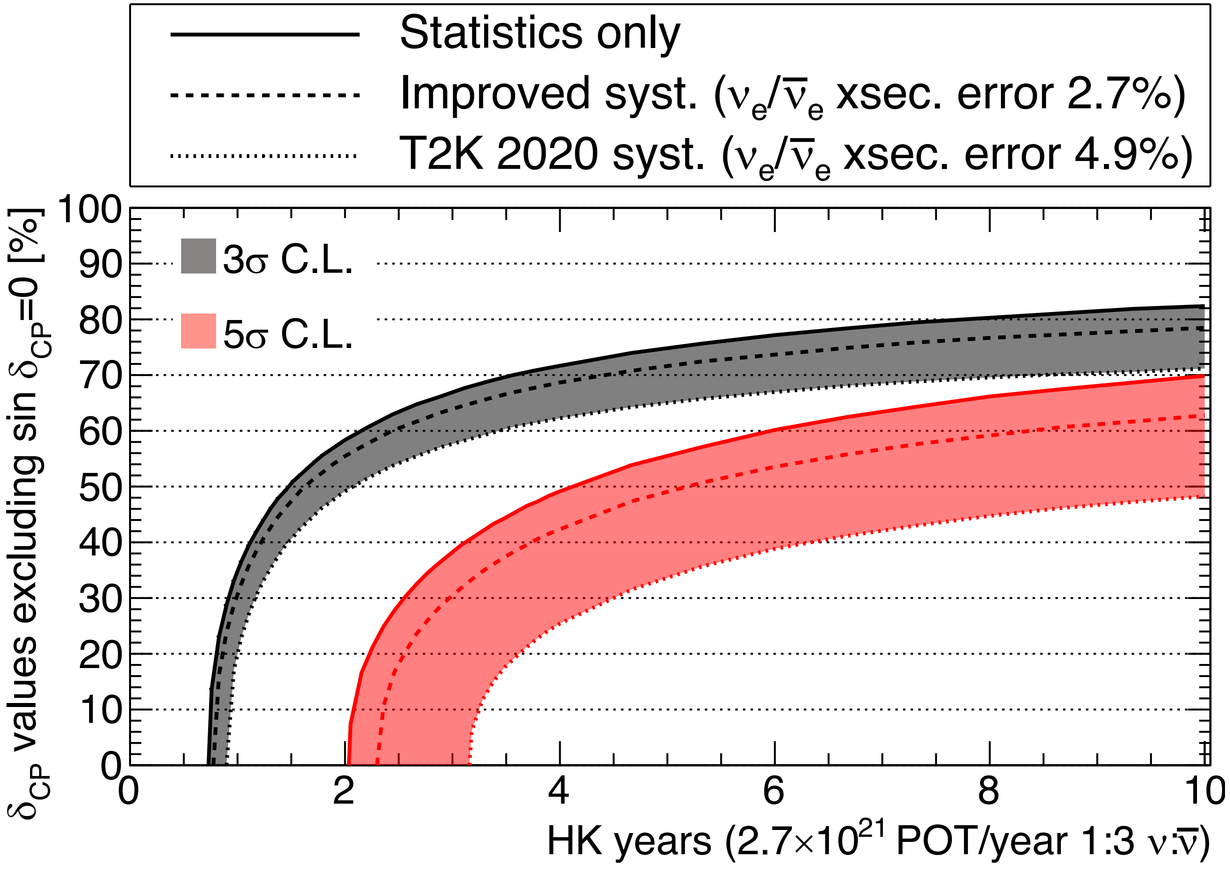
HK sensitivity to δ_{CP}



Hyper-K preliminary

True normal ordering (known), 10 years (2.7×10^{22} POT 1:3 $\nu:\bar{\nu}$)

$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}\mathrm{eV}^2/c^4$



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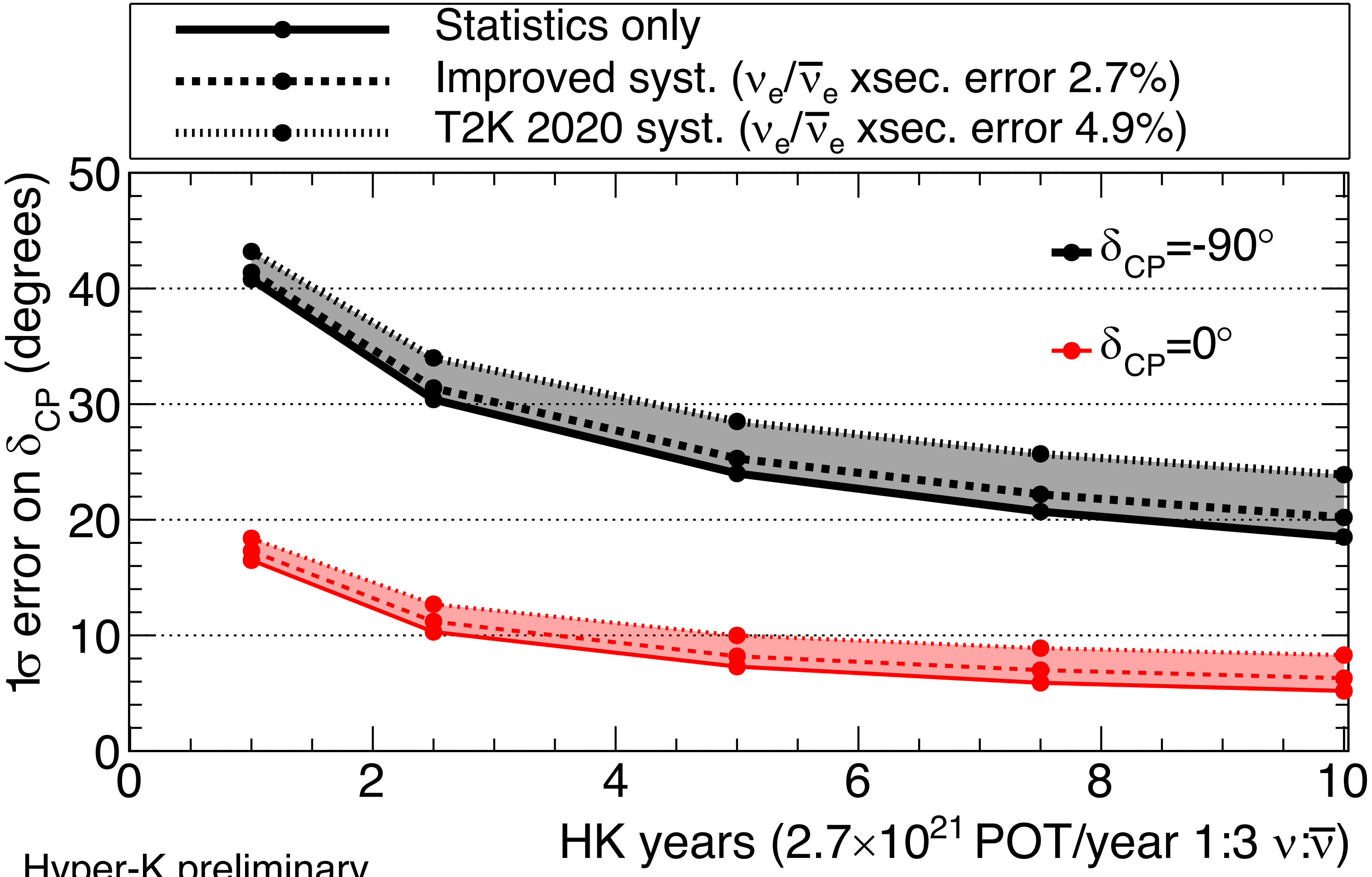
Significant impact from systematics

HK sensitivity to δ_{CP}



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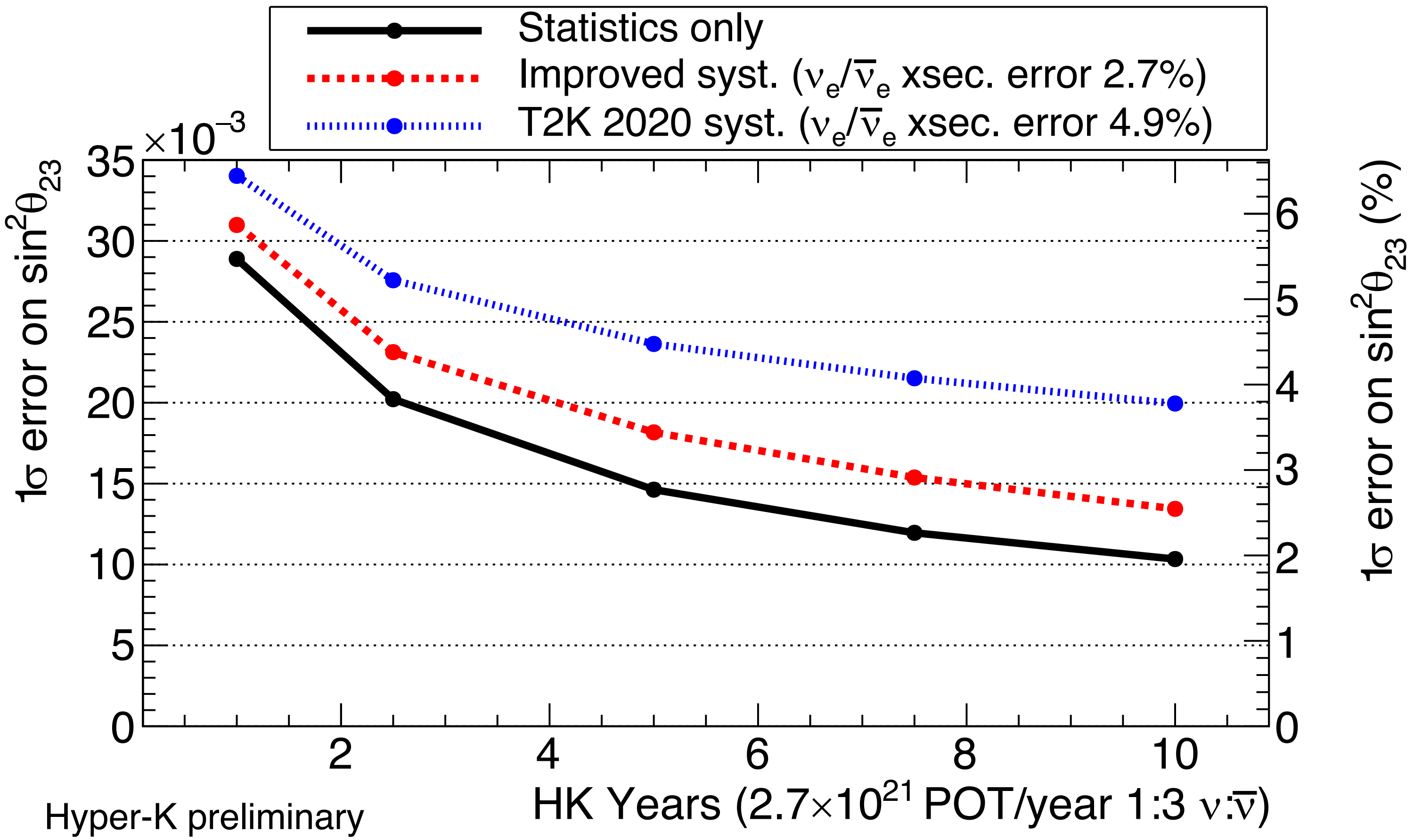
$\sin^2\theta_{13}$=0.0218±0.0007, $\sin^2\theta_{23}$=0.528, $\Delta m^2_{32}=2.509\times10^{-3}\,\mathrm{eV}^2/c^4$

1σ error on δ_{CP}

For Improved syst. model: **20.2°**
For T2K 2020 syst. model: **23.9°**

For comparison: T2K δ_{CP} resolution is around 70°

HK sensitivity to $\sin^2\theta_{23}$



Hyper-K preliminary

True normal ordering (known)

$\sin^2\theta_{13}$=0.0218±0.0007, $\sin^2\theta_{23}$=0.528, Δm^2_{32}=2.509×10^{-3}eV^2/c^4, δ_{CP}=-1.601

Relative 1σ resolution:

For Improved syst. model: $\boldsymbol{\varepsilon = 2.5\%}$
For T2K 2020 syst. model: $\boldsymbol{\varepsilon = 3.8\ \%}$

For comparison: T2K δ_{CP} resolution is around **9%**

Conclusions

- Neutrino is a way to find out the hints of fundamental physics and oscillations help to study the neutrino

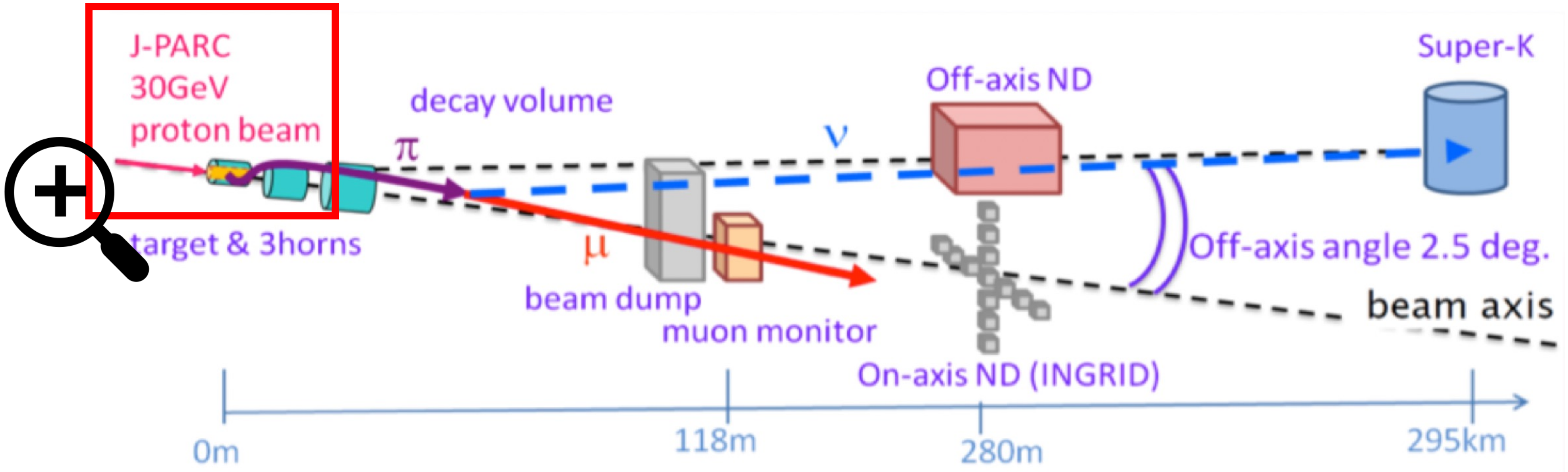
- Oscillation measurement faces many challenges from experimental and theoretical point nevertheless T2K could achieve fascinaing results

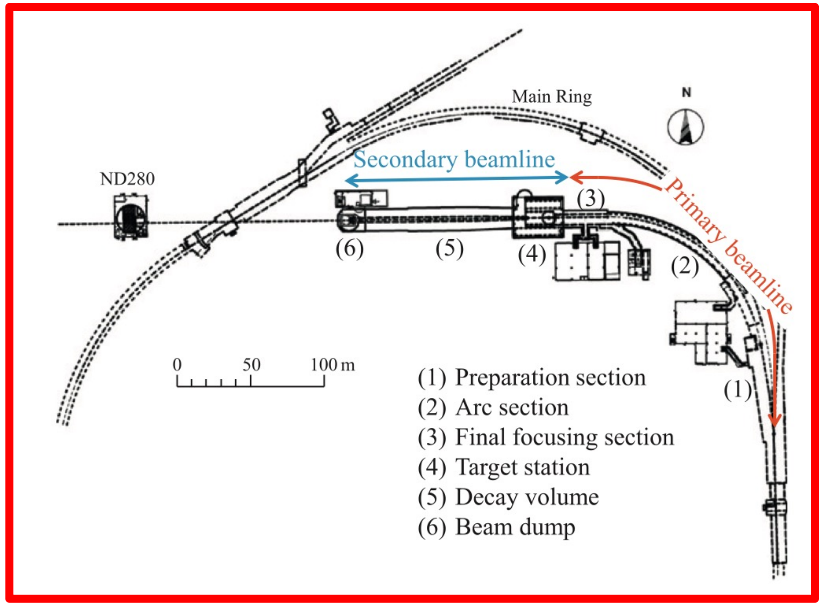
- Hyper-K being very ambitious project it comes with its own set of challenges (neutrino interaction and flux modelling, significant hardware challenges with various complex detectors, etc).

But it is very exciting as HK era promises to be a ground breaking period in neutrino research.

BACKUP

T2K experiment



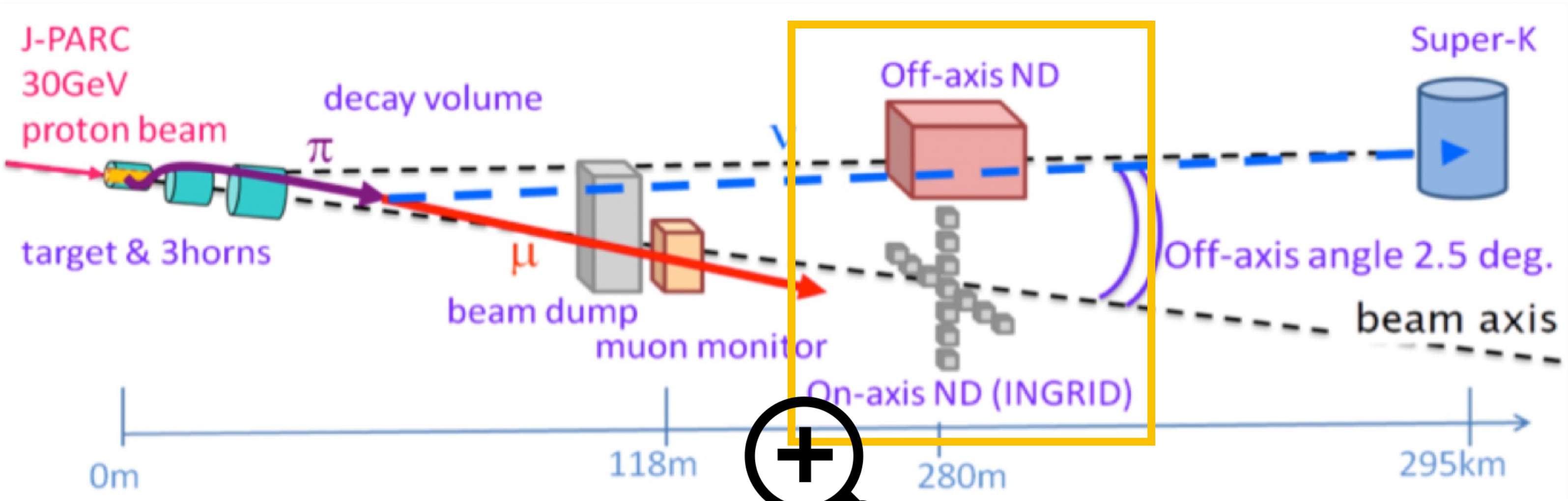


- 30 GeV proton accelerator
- Carbon target for pions production
- 3 magnetic horns for pion focusing (positive or negative)

$\pi^+ \rightarrow \mu^+ + \bar{\nu}_\mu$ ➡ Neutrino mode

$\pi^- \rightarrow \mu^- + \nu_\mu$ ➡ Antineutrino mode

T2K experiment

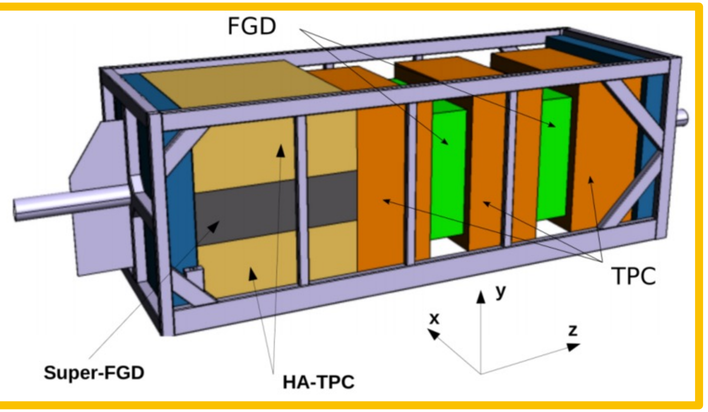


ND280Upgrade

- Off-axis detector
- Consists of multiple subdetectors
- Constrains neutrino flux and cross-section interaction

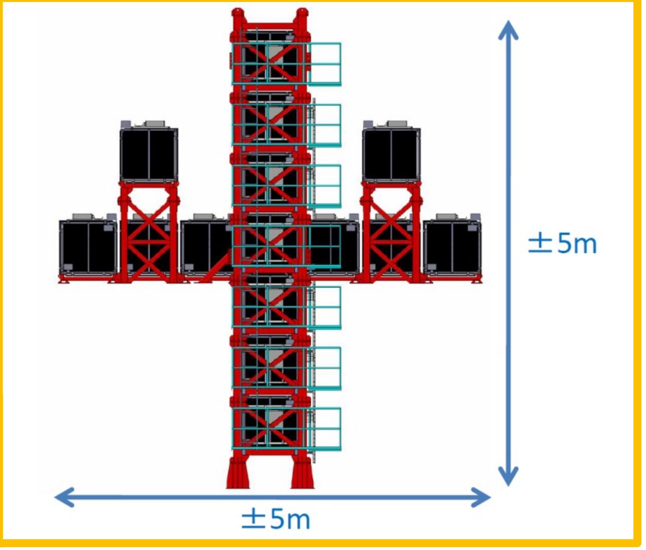
Have been recently upgraded providing:

- Lower down proton reconstruction threshold
- Neutron tagging.
- 4pi coverage of particles tracking

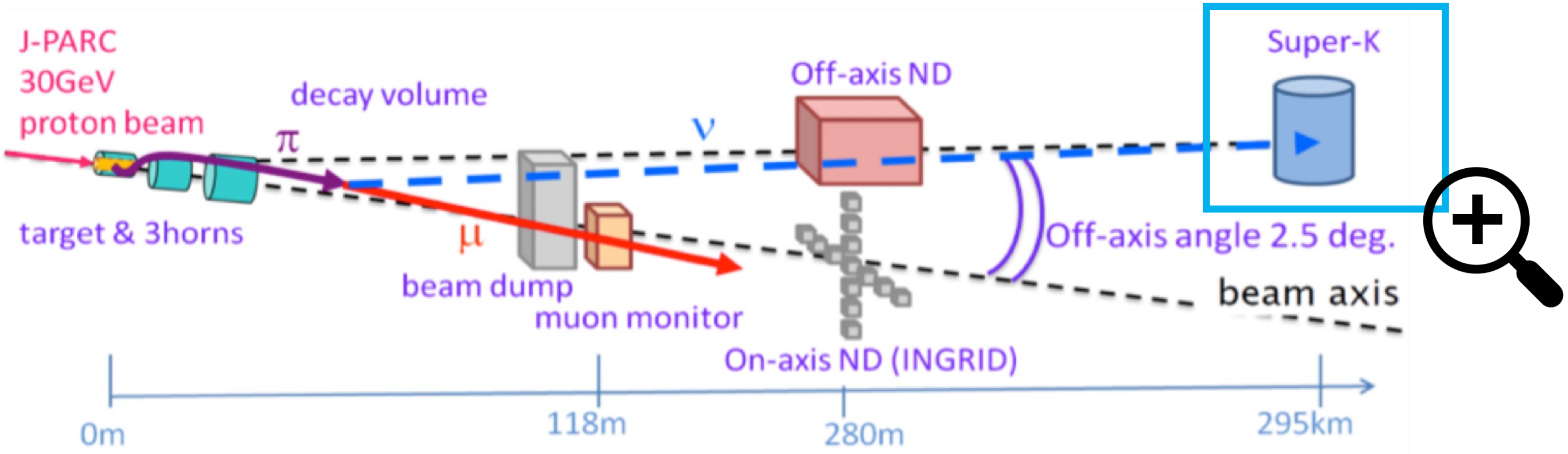


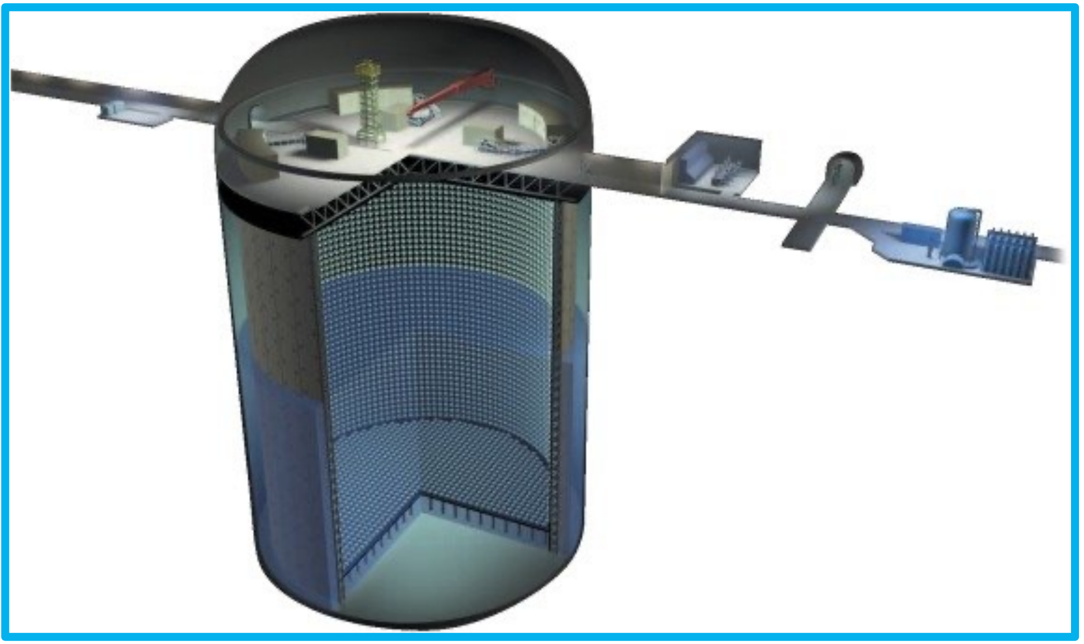
INGRID

- Monitors the neutrino beam direction and intensity



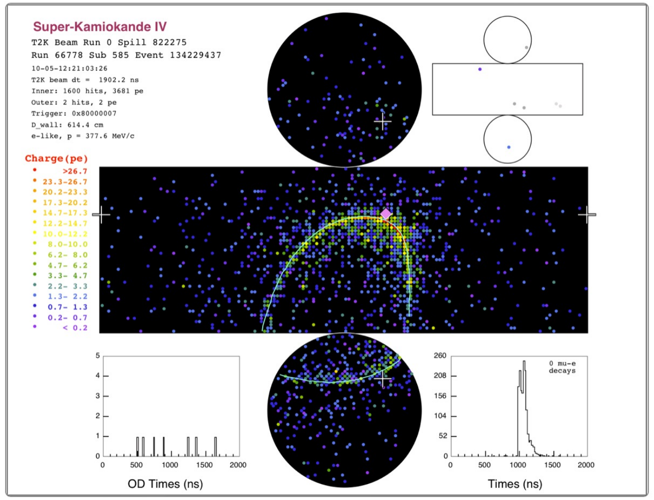
T2K experiment





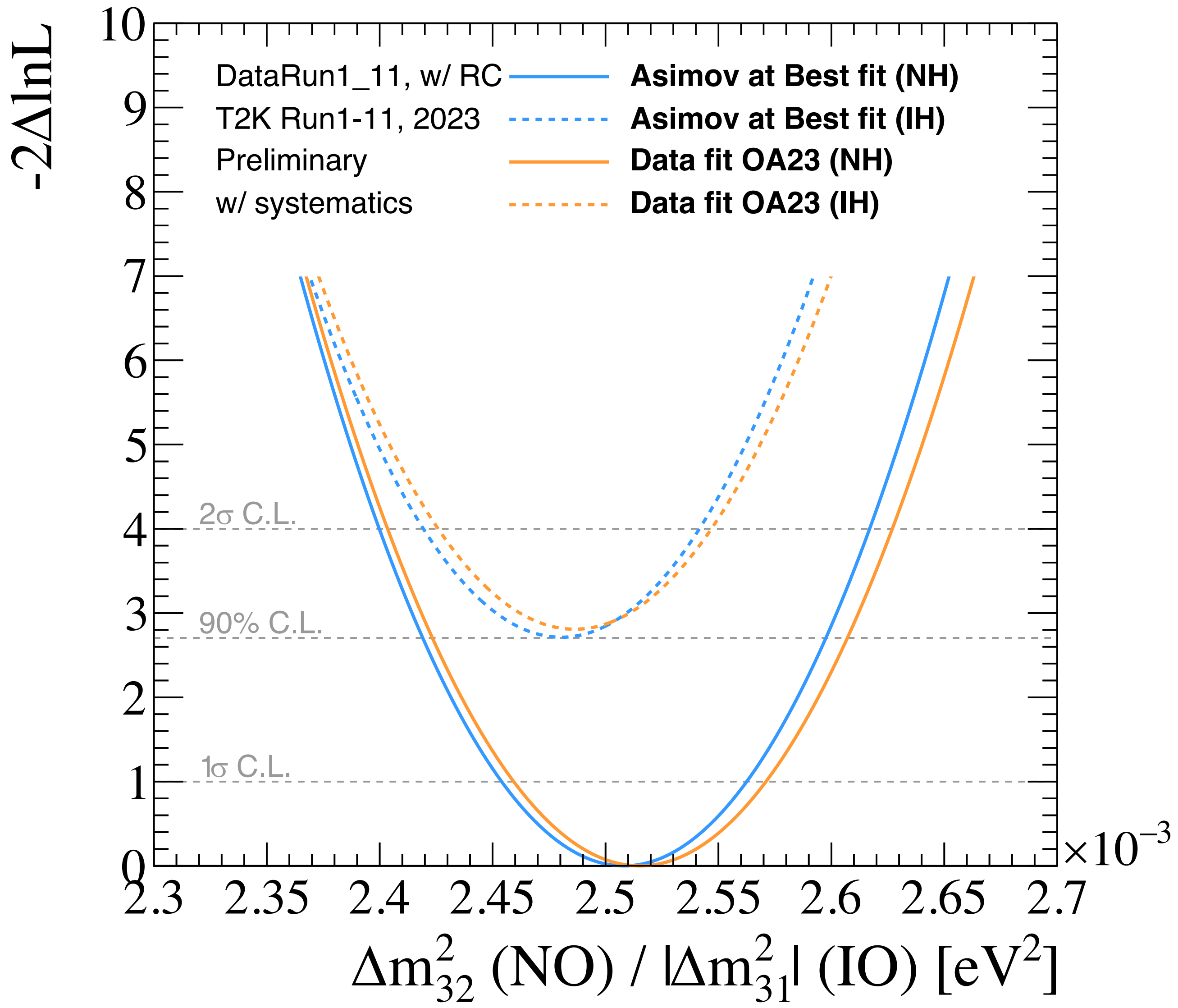
- Fiducial mass = 27.2 kton
- Detects water Cherenkov light from charged particle and reconstructs events with PMT charge & timing information.

Example of data event

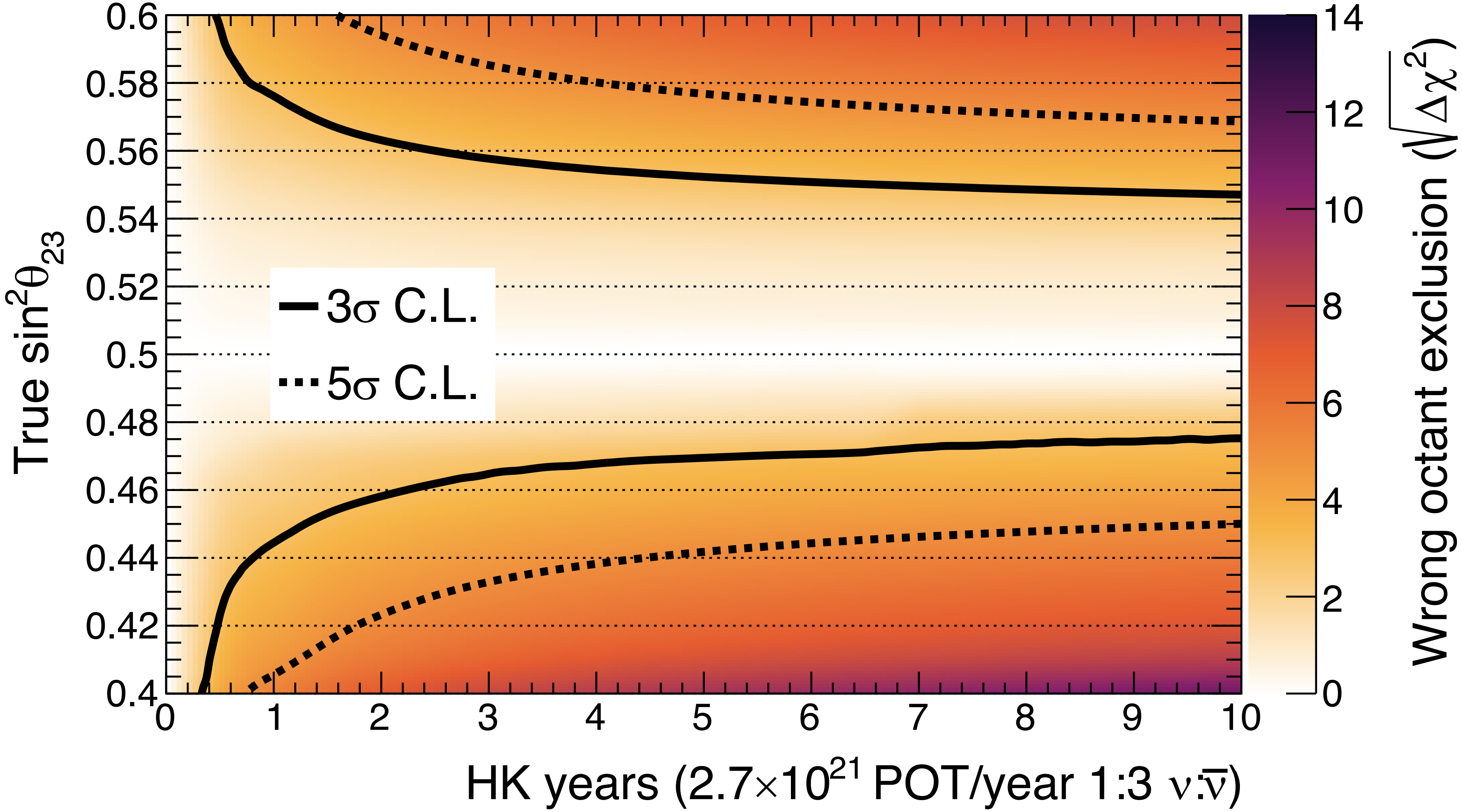


T2K recent results

Δm^2_{32}



HK sensitivity to $\sin^2\theta_{23}$ octant



Hyper-K preliminary

True normal ordering (known), Improved systematics

$\sin^2\theta_{13}=0.0218\pm0.0007$, $\delta_{CP}=-1.601$, $\Delta m^2_{32}=2.509\times10^{-3}\text{eV}^2/\text{c}^4$