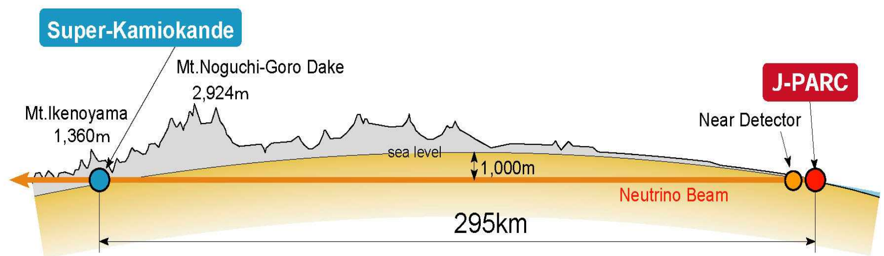
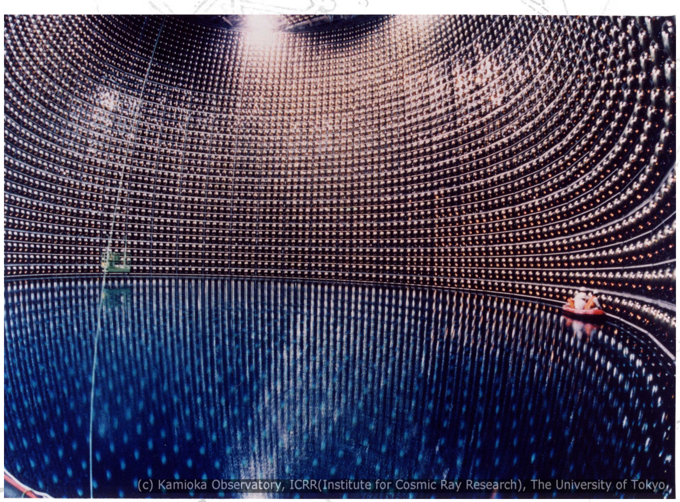


NuFact16 (August the 23rd, 2016)

Search for $\bar{\nu}_e$ appearance at T2K & latest oscillation results.

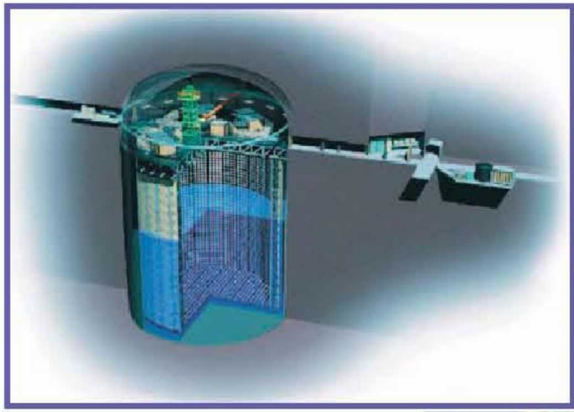
Benjamin Quilain (Kyoto University) on behalf of the T2K collaboration



Outline :

1. The T2K experiment
3. Results of the $\bar{\nu}_e$ appearance search.
4. Latest constraints on atmospheric parameters & CP violation.
5. Future improvements & TK Phase-II sensitivity

I-Overview of the T2K Experiment



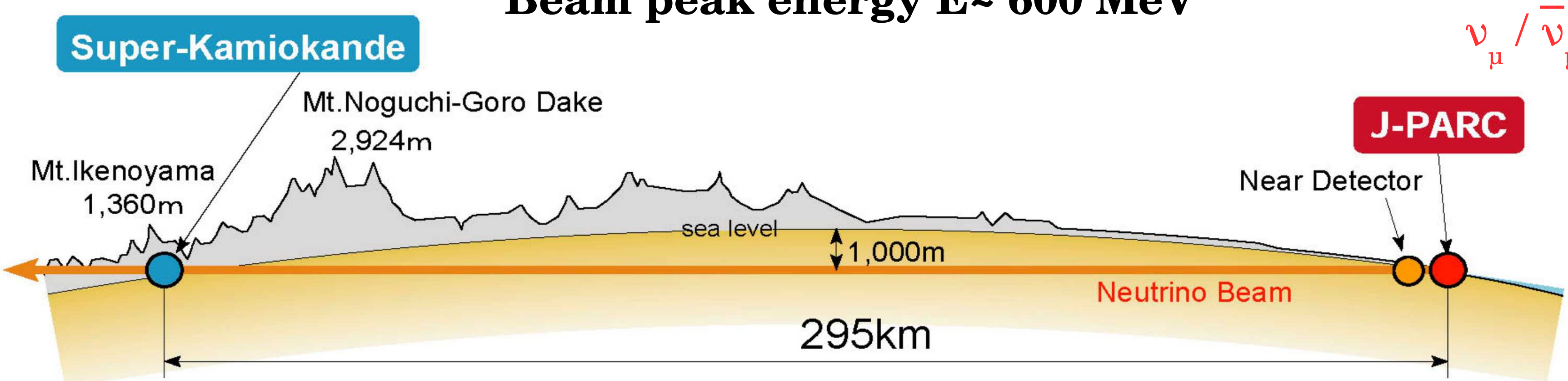
Super-Kamiokande
(ICRR, Univ. Tokyo)

J-PARC Main Ring
(KEK-JAEA, Tokai)

→ 295 km away from J-PARC
→ Detection of ν_μ, ν_e / $\bar{\nu}_\mu$, $\bar{\nu}_e$

Baseline L~295 km
Beam peak energy E~ 600 MeV

Production of a ν_μ / $\bar{\nu}_\mu$ beam

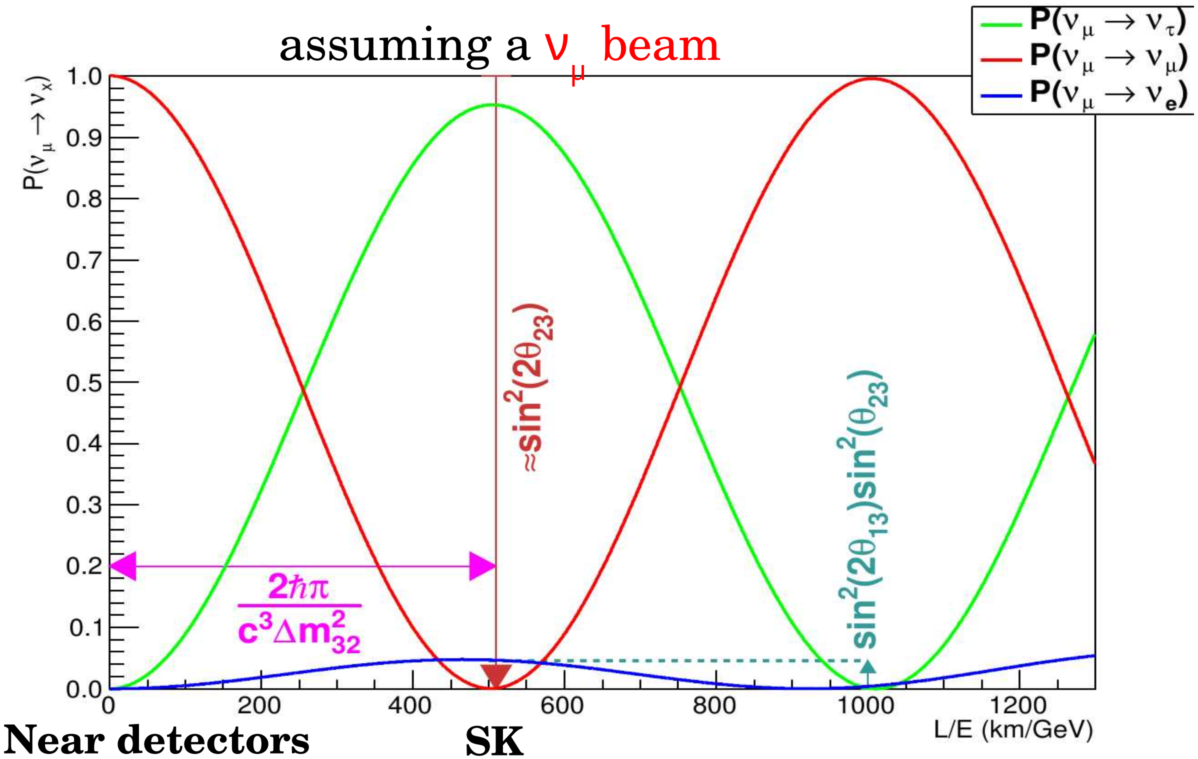


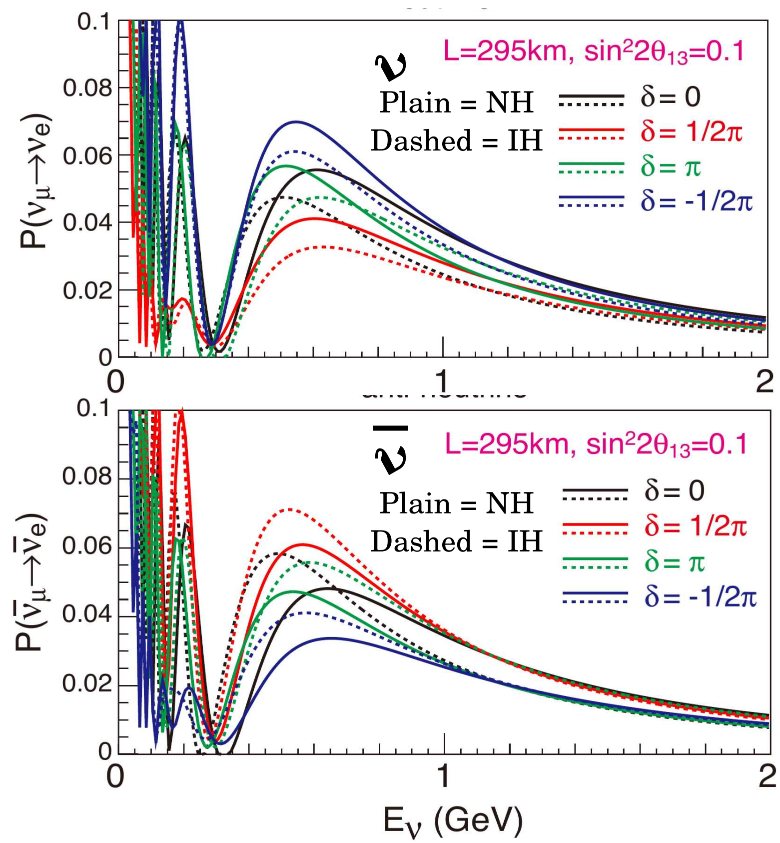
→ Observation of ν_e appearance in a ν_μ beam and ν_μ disappearance & $\bar{\nu}$ equivalents

Benjamin Quilain

Summary of the oscillations at T2K

- **<u>Oscillation probability @ 3 flavours in L/E :</u>**





Disappearance of ν_μ / $\bar{\nu}_\mu$: Leading term ~ $\sin^2(2\theta_{23})$ ~ 1 → High (maximal) $\nu_\mu \to \nu_\tau$ oscillation

Appearance of ν_e / $\bar{\nu}_e$: Leading term ~ $\sin^2(2\theta_{13})$ ~ 0.085 → Small $\nu_\mu \to \nu_e$ oscillation

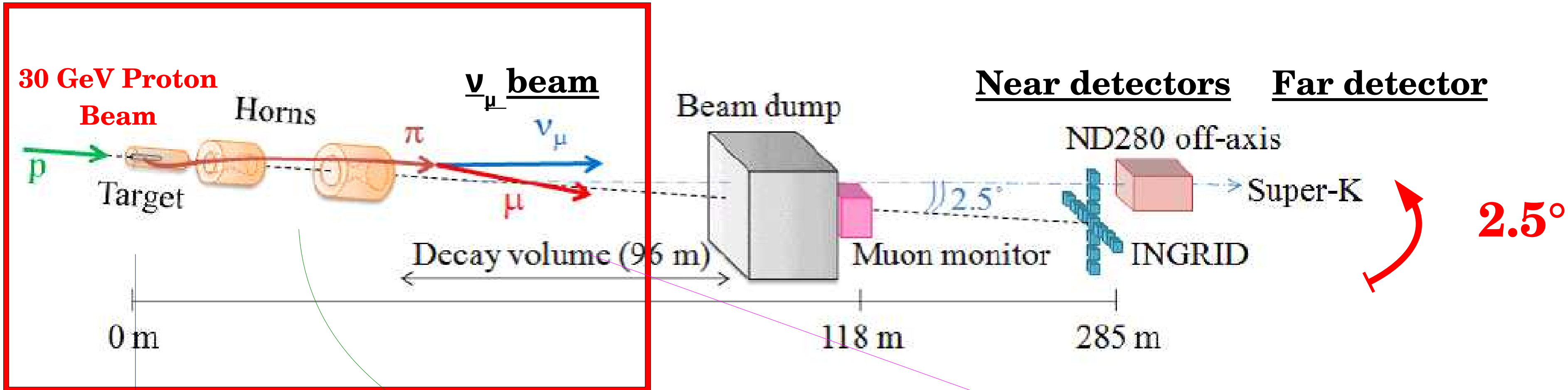
<u>+ CP-odd effect :</u> if δ_{CP}=-π/2 → enhance $\nu_\mu \to \nu_e$ (suppress $\bar{\nu}_\mu \to \bar{\nu}_e$) ~27% @T2K ($\sin^2(2\theta_{23})$=1)

<u>+ Mass hierarchy effect :</u> if NH → enhance $\nu_\mu \to \nu_e$ (suppress $\bar{\nu}_\mu \to \bar{\nu}_e$) ~10% @T2K ($\sin^2(2\theta_{23})$=1

Benjamin Quilain

Muon neutrino beam production

- Observation of ν_e appearance in a ν_μ beam and ν_μ disappearance & $\bar{\nu}$ equivalents

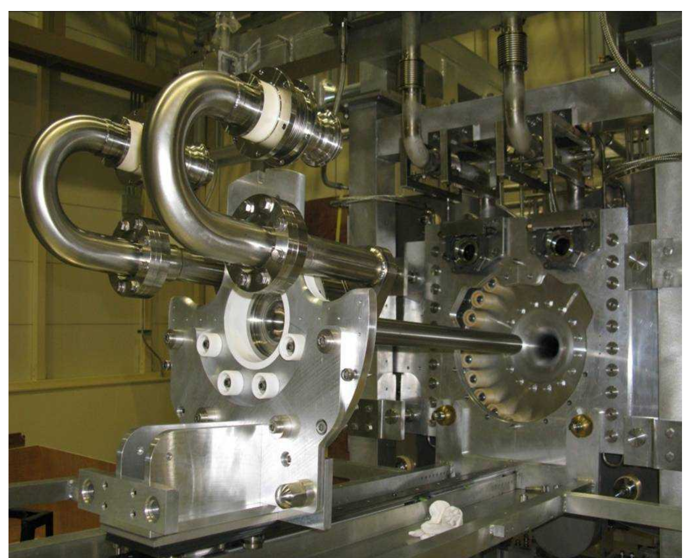


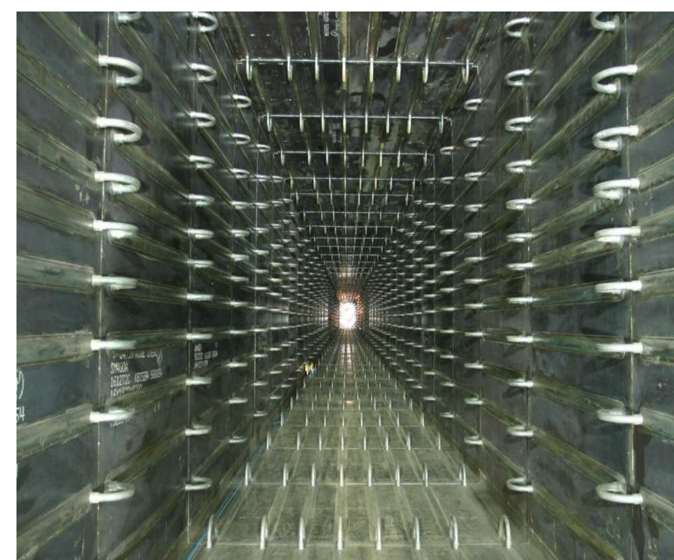
Primary beamline

Target & Horns

Horn current change → ν / $\bar{\nu}$-mode

Decay Volume





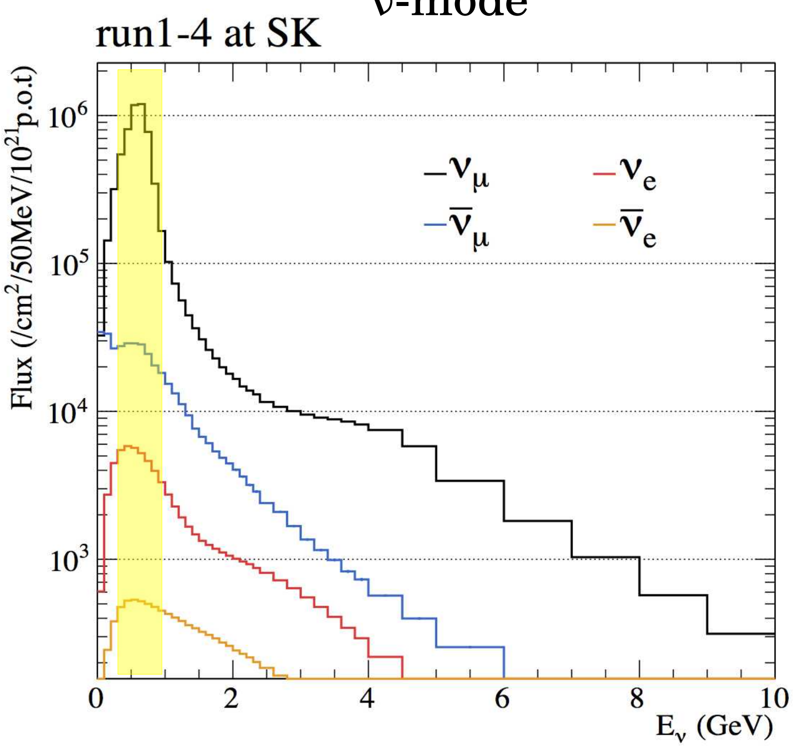
Benjamin Quilain

Beam direction

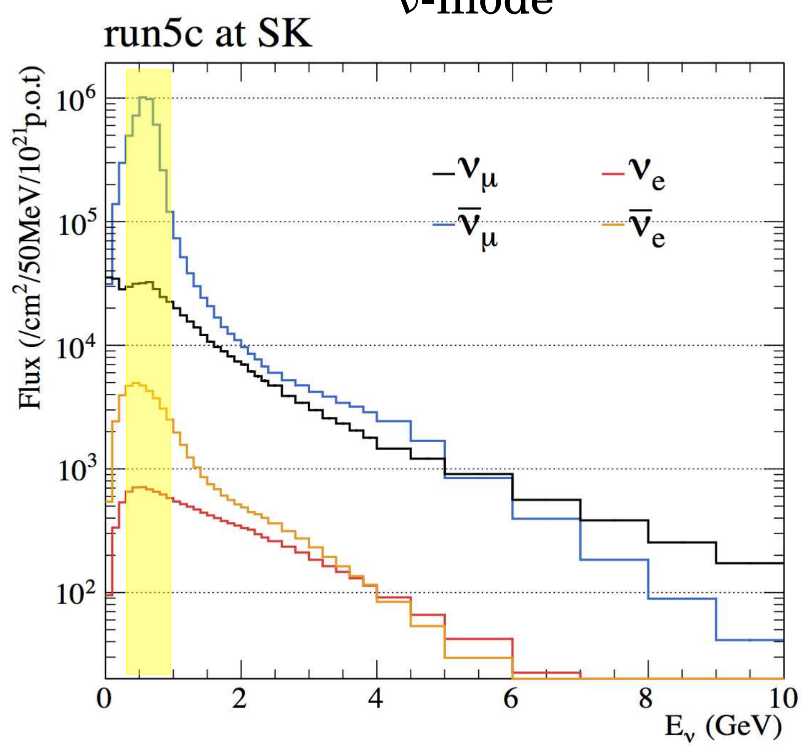
- **T2K is an off-axis experiment :** neutrino beam aimed at 2.5° from Super-K to maximize the oscillation at 295 km → Tune energy spectrum (600 MeV)

- **But :**
    - ν beam does not have one flavour & energy.
    - ν beam intensity & shape are not perfectly known.

ν-mode



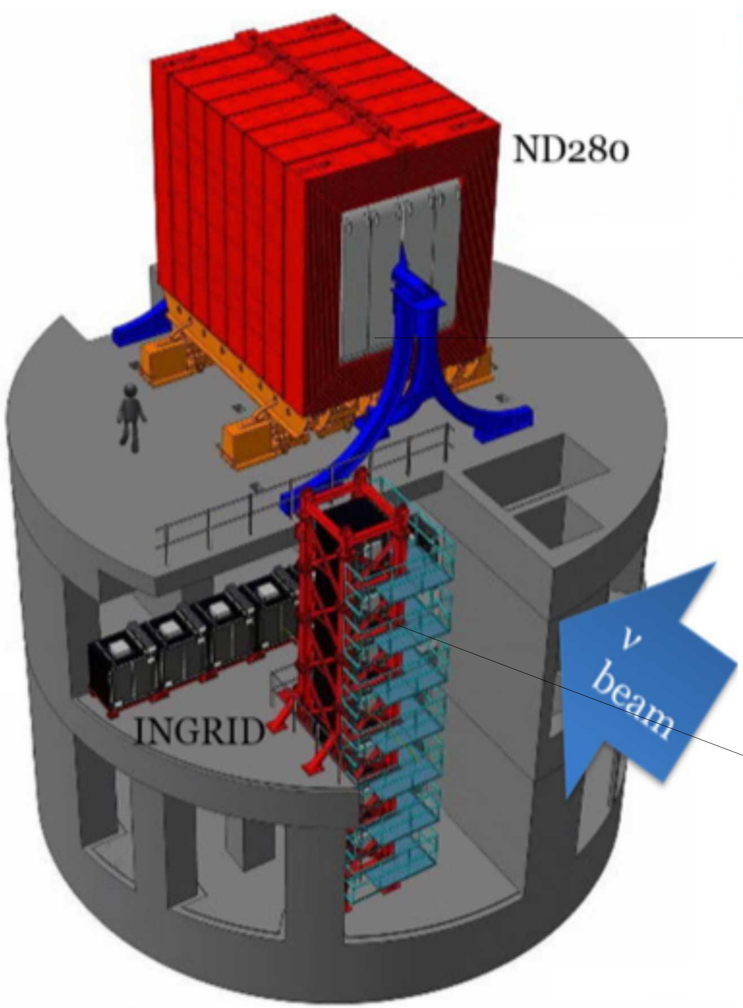
$\bar{\nu}$-mode



- → Requires beam rate & shape measurements before oscillation !

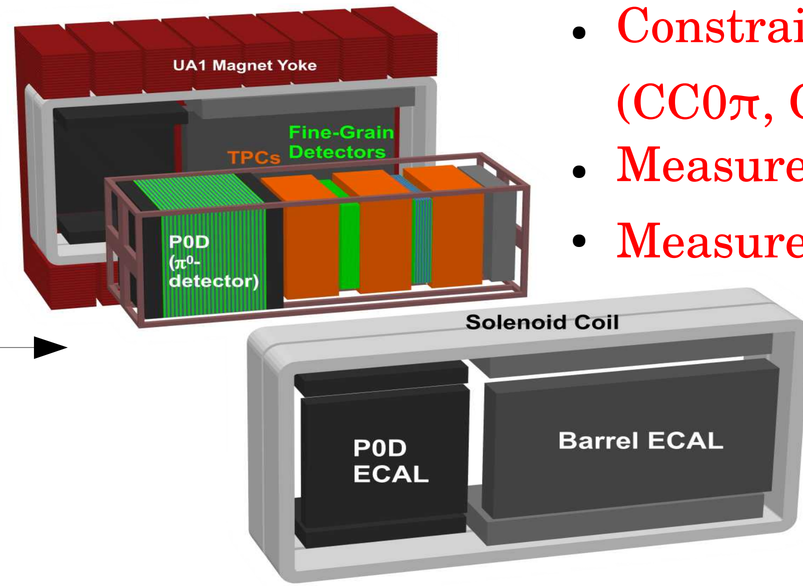
ND280 detectors constraints on flux

Complementary near detectors



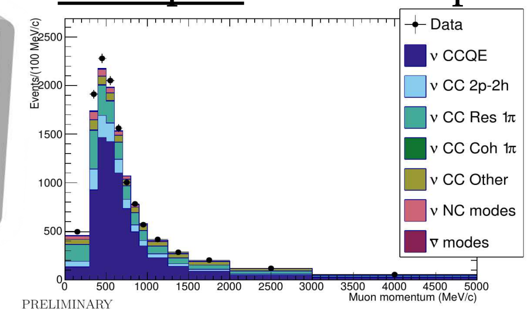
- Beam stability
- Off-axis angle : constrains neutrino spectra

Off-axis near detector: ND280

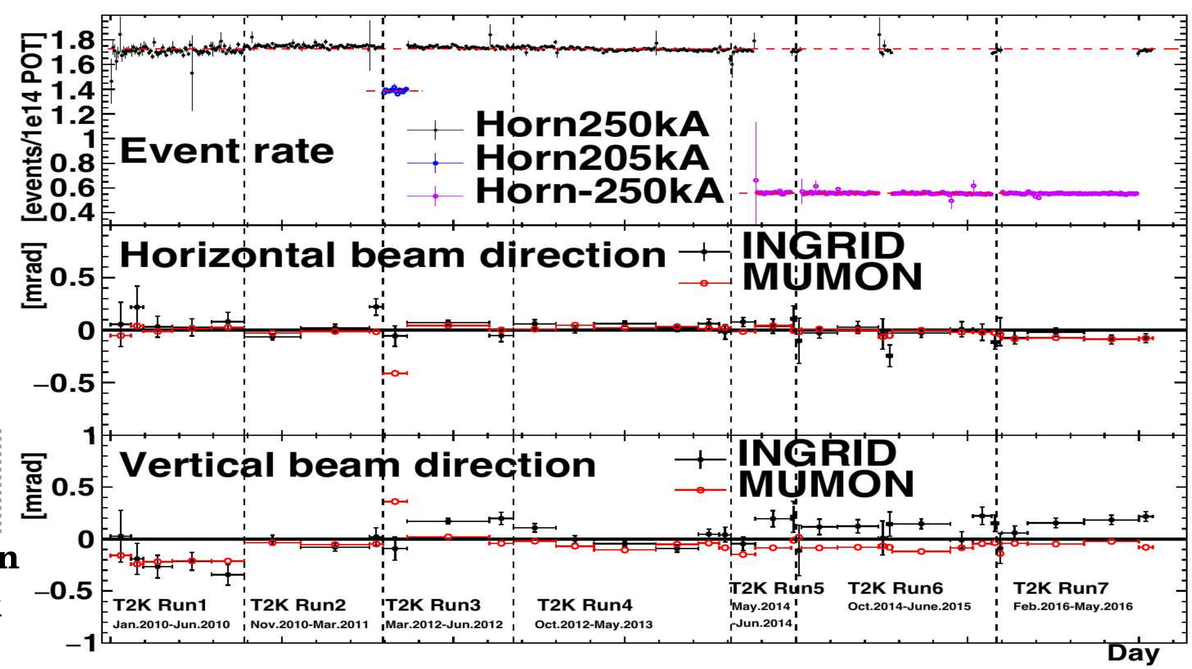


- Constraints on ν_μ spectrum (CC0π, CC1π, CCOthers)
- Measure ν_e beam contamination
- Measure cross sections

Example : CC0π sample



On-axis near detector: INGRID



2 % on peak

Flux & cross-section extrapolation at SK

Flux simulation :
- Measurement on the proton beamline.
- Hadron cross-sections measured by NA61.
- INGRID measurements (off-axis angle + intensity)

Flux of ν

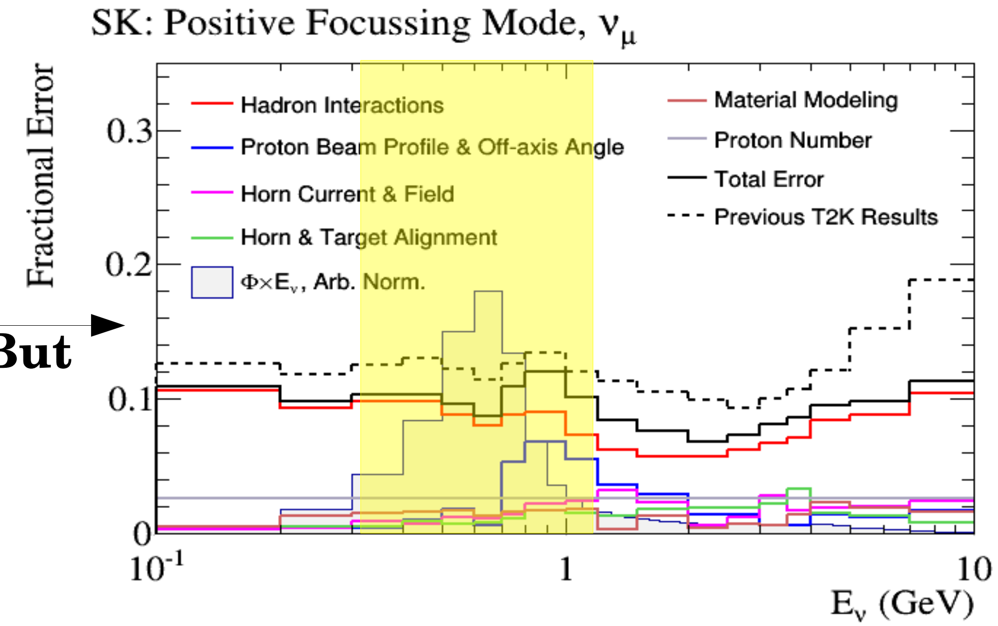
Cross-section model :
- External experiment measurements.

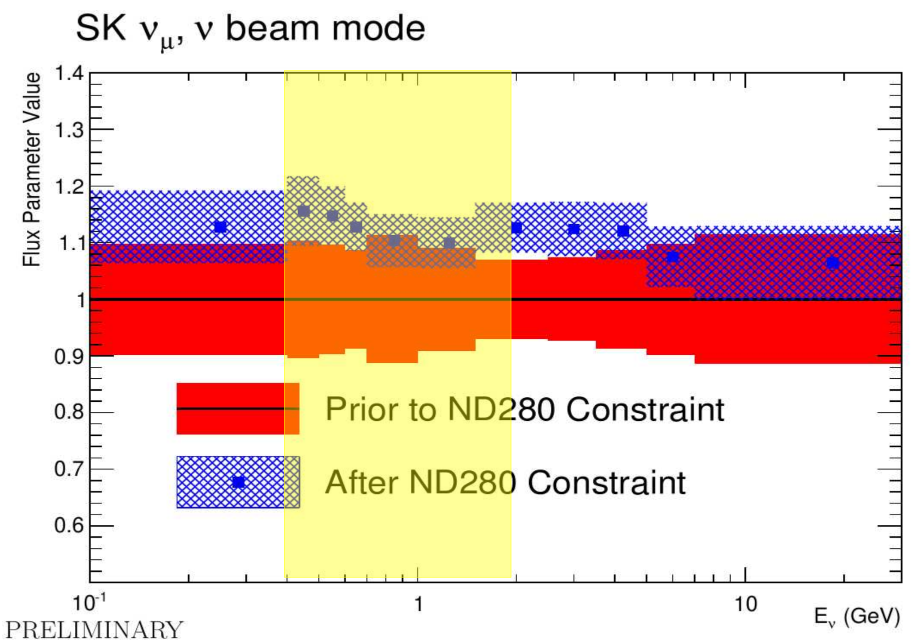
Interacting ν

Apply ND280 Reconstruction & Compare with data
- Measure ν_μ, ν_e spectra & cross-sections

Extrapolate flux & cross-section @SK :
- Uses the high correlation between the ND280 & SK flux & cross-sections.
- Error Flux×Cross-sections reduced ~10 % to <5 % (see slide 12)

But

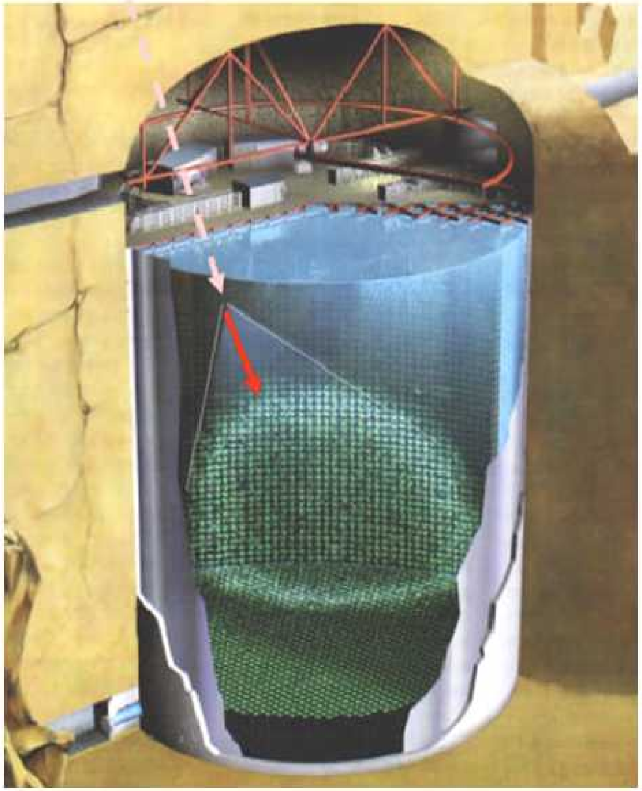


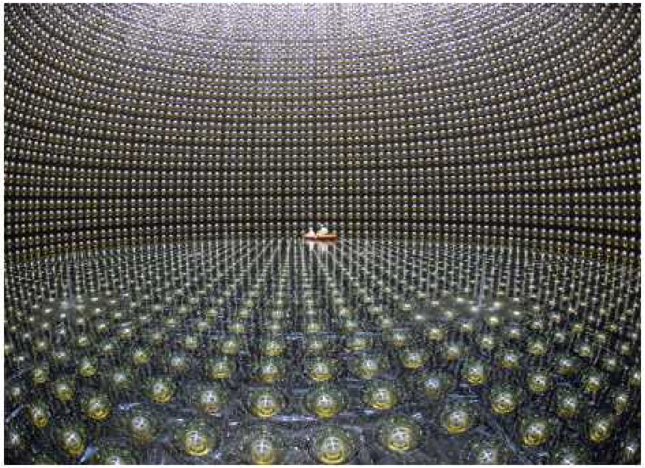


→ Compare the number of reconstructed events between data and simulation

→ Require the SK measurement & reconstruction efficiency

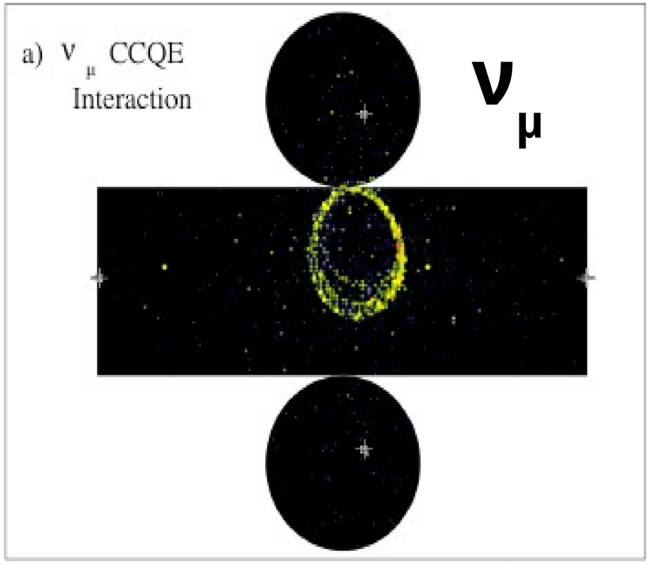
The Far Detector : Super-Kamiokande



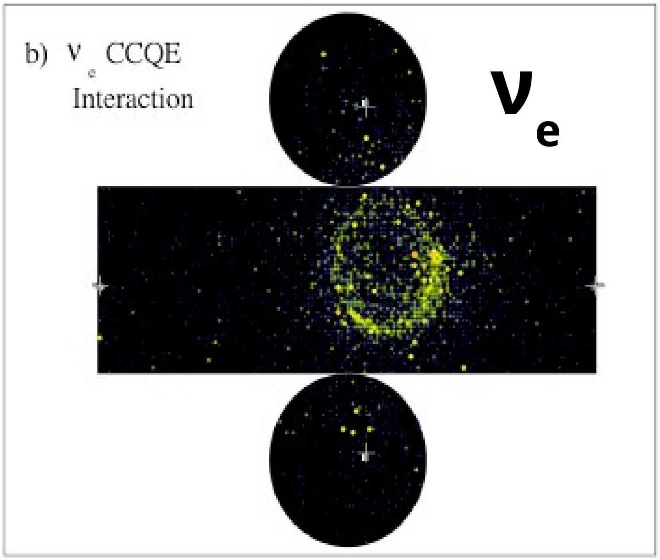


- 50 kT water Cherenkov detector (Fiducial Volume = 22.5 kT)
- T2K event selection : [-2, 10] μs around beam trigger.
- High μ/e separation (ring sharpness): misidentification probability of a signle electron is 0.7 % (0.8 % for μ)

Single ring μ-like (SK-1Rμ) ~ CCQE (ν_μ)



Single ring e-like (SK-1Re) ~ CCQE (ν_e)

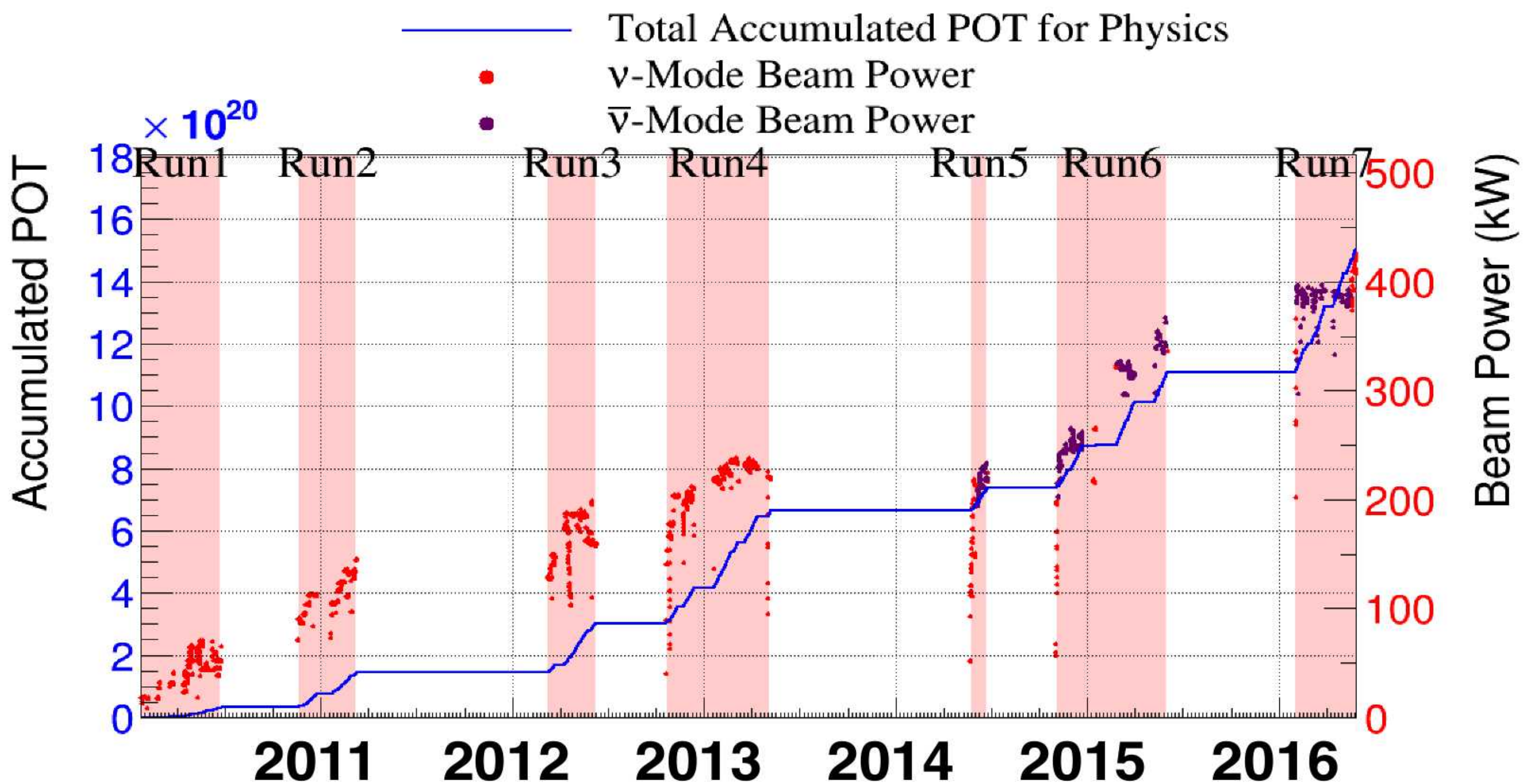


- ν-mode & $\bar{\nu}$-mode treated as separated samples.

→ 4 samples : ν-mode & $\bar{\nu}$-mode SK-1Rμ & SK-1Re

II-Oscillation results from the T2K experiment

Accumulated neutrino beam



27 May 2016
POT total: 1.510×10^{21}

ν-mode POT: 7.57×10^{20} (50.14%)
$\bar{\nu}$-mode POT: 7.53×10^{20} (49.86%)

- Beam power reached 425 kW.
- Accumulated ~same number of POT (protons-on-target) in ν-mode & $\bar{\nu}$-mode.
- Recently, almost taken only data in $\bar{\nu}$-mode → today's results update mainly in $\bar{\nu}$-mode.

Selected events at Super-Kamiokande

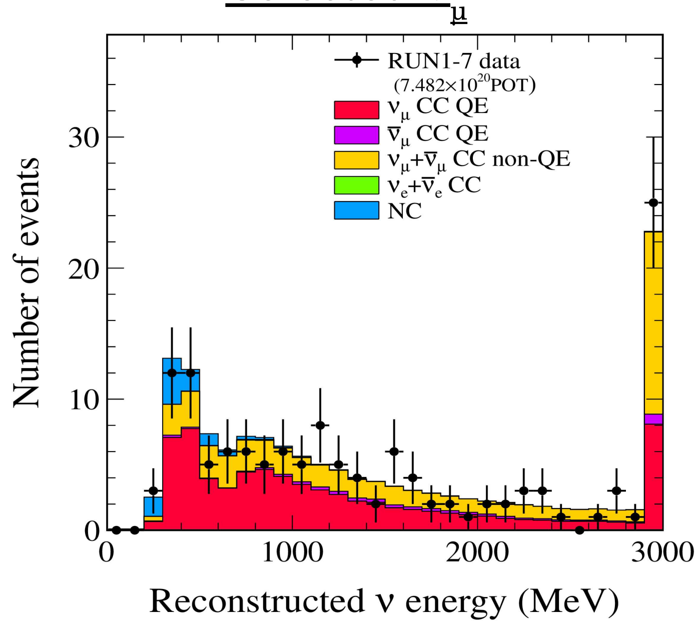
- <u>4 samples :</u> ν-mode & $\bar{\nu}$-mode SK-1Rμ & SK-1Re
- MC predictions shown here for Asimov with NH & δ_{CP}=-π/2
- <u>Number of events :</u>

Parameter	Value
$\sin^2\theta_{12}$	0.304
$\sin^2 2\theta_{13}$	0.085
$\sin^2\theta_{23}$	0.528
Δm^2_{21}	7.53×10^{-5} eV^2/c^4
Δm^2_{32}	$+2.509\times10^{-3}$ eV^2/c^4
δ_{CP}	-1.601

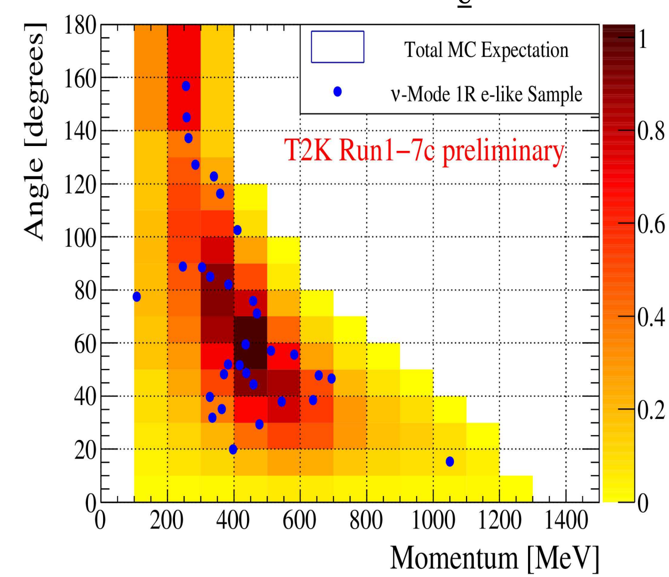
		Normal hierarchy				
Beam mode	Sample	$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$	$\delta_{CP}=\pi$	Observed
neutrino	μ-like	135.8	135.5	135.7	136.0	135
neutrino	e-like	28.7	24.2	19.6	24.1	32
antineutrino	μ-like	64.2	64.1	64.2	64.4	66
antineutrino	e-like	6.0	6.9	7.7	6.8	4

More ν_e & less $\bar{\nu}_e$ events observed than expected !
→ Even with NH & δ_{CP}=-π/2

<u>Selected ν_μ</u>

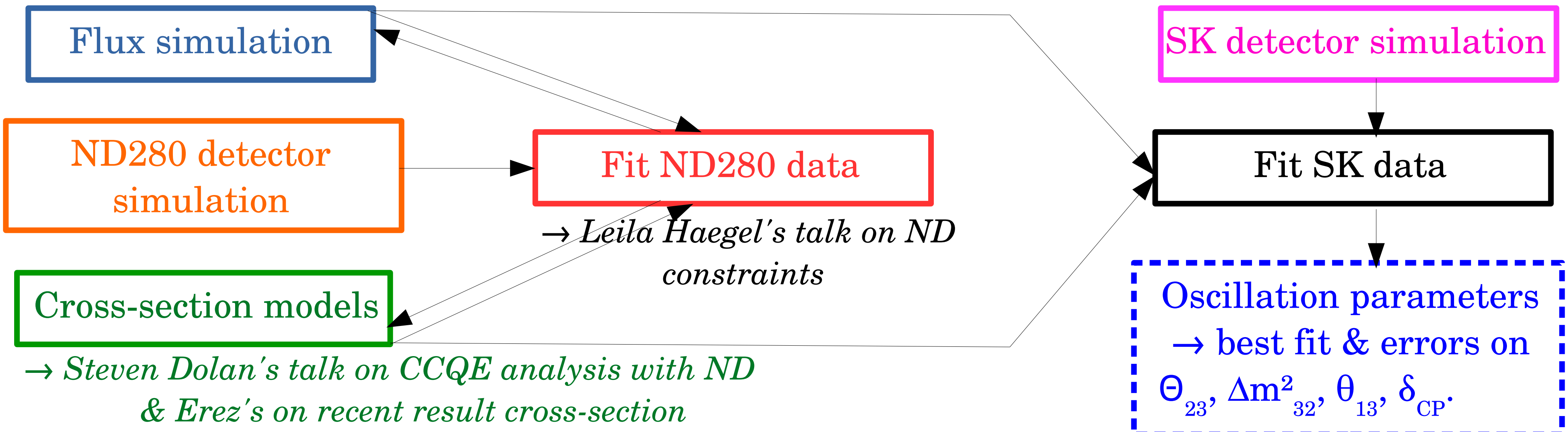


<u>Selected ν_e</u>



The joint fit method & errors

- Oscillation & systematic parameters shared between the 4 SK samples
  → Joint fit of the 4 samples → maximize sensitivity to the oscillation parameters !



- Near detector fit : fit for a number of neutrino events

  → Flux & cross-sections anti-correlated by measurement

  → Provides constraint on flux x cross-section smaller than for independent sources

  → Prediction best fit are tuned in all 4 samples & error reduced from ~14 % to 6 %.

Example : $\bar{\nu}$-mode SK-1Re

Source of uncertainty	$\delta N_{SK}/N_{SK}$
SKDet+FSI+SI	3.95%
SKDet only	3.09%
FSI+SI only	2.46%
Flux	3.77%
2p-2h (corr)	2.97%
2p-2h bar (corr)	2.36%
NC other (uncorr)	0.33%
NC 1gamma (uncorr)	2.95%
XSec nue/numu (uncorr)	1.50%
XSec Tot (corr)	4.32%
XSec Tot	5.45%
Flux+XSec (ND280 constrained)	3.22%
Flux+XSec	4.63%
Flux+XSec+SKDet+FSI+SI	6.19%
Flux+XSec+SKDet+FSI+SI (pre-fit)	13.7%

$\bar{\nu}_e$ appearance search

- Motivations : $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ has never been observed !

- To test the $\bar{\nu}_e$ appearance only : $P(\nu_\mu \rightarrow \nu_e)$ unchanged.

  $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ [PMNS] $\rightarrow$ $\beta \times P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

$\beta=0 \rightarrow$ No $\bar{\nu}_e$ appearance, $\beta=1 \rightarrow \bar{\nu}_e$ appearance predicted by PMNS

- Null hypothesis testing : no $\bar{\nu}_e$ appearance ($\beta=0$) + PMNS model testing ($\beta=1$).

- Prior used for the parameters :

Parameter	Prior	Variation range
$\sin^2\theta_{12}$	fixed	0.304
$\sin^2 2\theta_{13}$	gaussian	0.085 ± 0.005
$\sin^2\theta_{23}$	uniform	$[0.3; 0.7]$
Δm^2_{21}	fixed	7.53×10^{-5} eV^2/c^4
Δm^2_{32}	uniform	$[2; 3] \times 10^{-3}$ eV^2/c^4
δ_{CP}	uniform	$[-\pi; +\pi]$
Mass hierarchy	uniform	0.5 for NH and IH

- Joint fit is used $\rightarrow$ Apply the T2K constraints from the ν_μ, ν_e & $\bar{\nu}_\mu$ data samples on the $\bar{\nu}_e$ sample.

- Correlations between the 4 samples are maintained using a posterior predictive method.

- 2 analyses :
  Rate-only $\rightarrow$ Observable is the number of observed events.
  Rate+shape $\rightarrow$ Observable is the fitted χ^2 difference between $\beta=0$ & $\beta=1$ hypotheses.

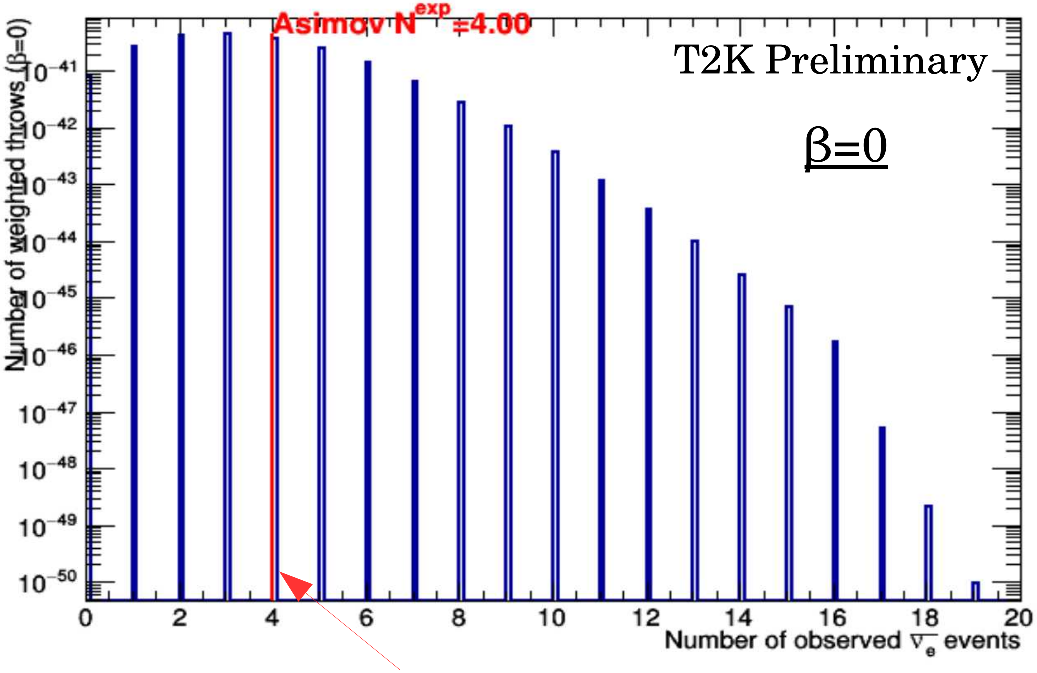
$$\Delta\chi^2 = \chi^2(\beta=0) - \chi^2(\beta=1)$$

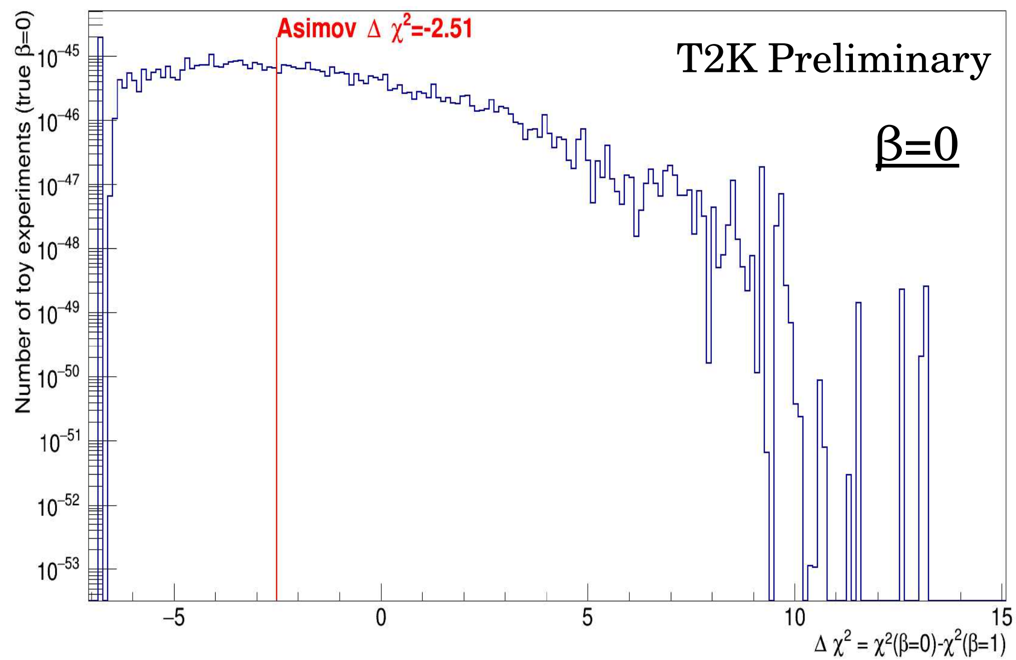
$\bar{\nu}_e$ appearance search

- Results are shown for β=0 hypothesis in the toy generation)

Rate-only : Number of observed $\bar{\nu}_e$ events @SK.

Rate+shape : $\Delta\chi^2 = \chi^2(\beta=0) - \chi^2(\beta=1)$





- p-value= $\frac{N^{obs}_{\bar{\nu}e} > \text{data}}{\text{Total } N^{obs}_{\bar{\nu}e}}$ for rate-only (Rate+shape : $N^{obs}_{\bar{\nu}e}$ is replaced by $\Delta\chi^2$).

- Results on the number of events :

	ν_e	$\bar{\nu}_e$
Expected (Asimov NH & δ_{CP}=-π/2	28.7	6.0
Observed (Data)	32	4

- Again → Higher discrepancy between ν_e & $\bar{\nu}_e$ events observed than expected!

Interpretation of the results

- Results summary :

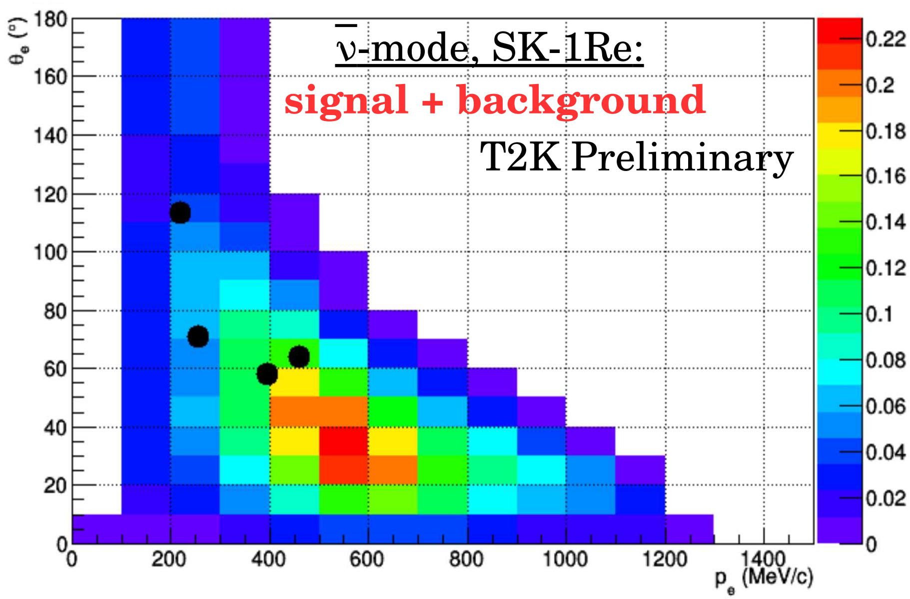
	P-value (β=0)	P-value (β=1)
Rate-only	0.41	0.21
Rate+shape	0.46	0.07

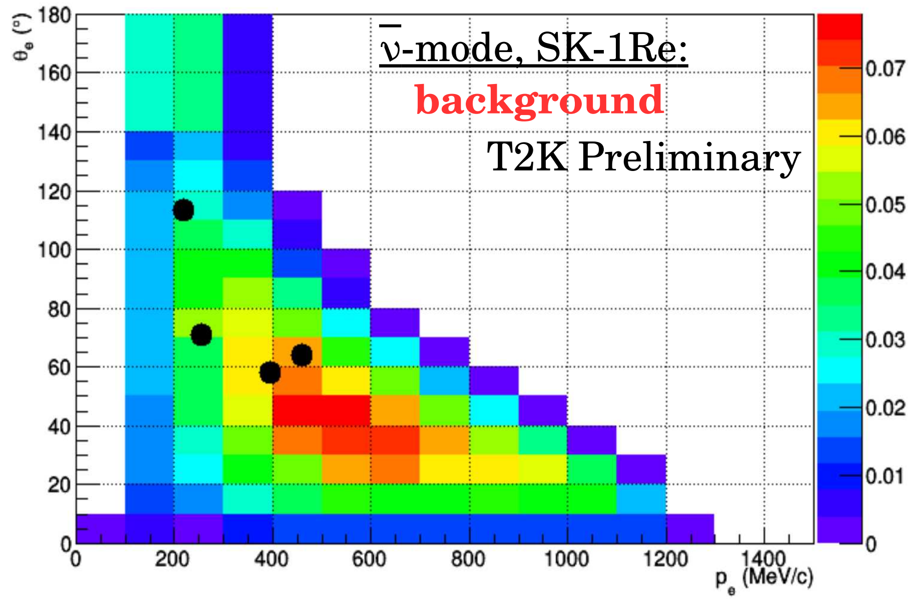
$N^{obs}_{\bar{\nu}e} = 4$ ($N^{exp}_{\bar{\nu}e}$ =6.0)→ lower rate → Data set compatible with no $\bar{\nu}_e$ appearance.

- Data are in mild tension with the PMNS model

→ Due to Higher assymetry between ν_e & $\bar{\nu}_e$ than expected w/ maximal CPV & NH

→ Not only rate, but shape also increases the disagreement.





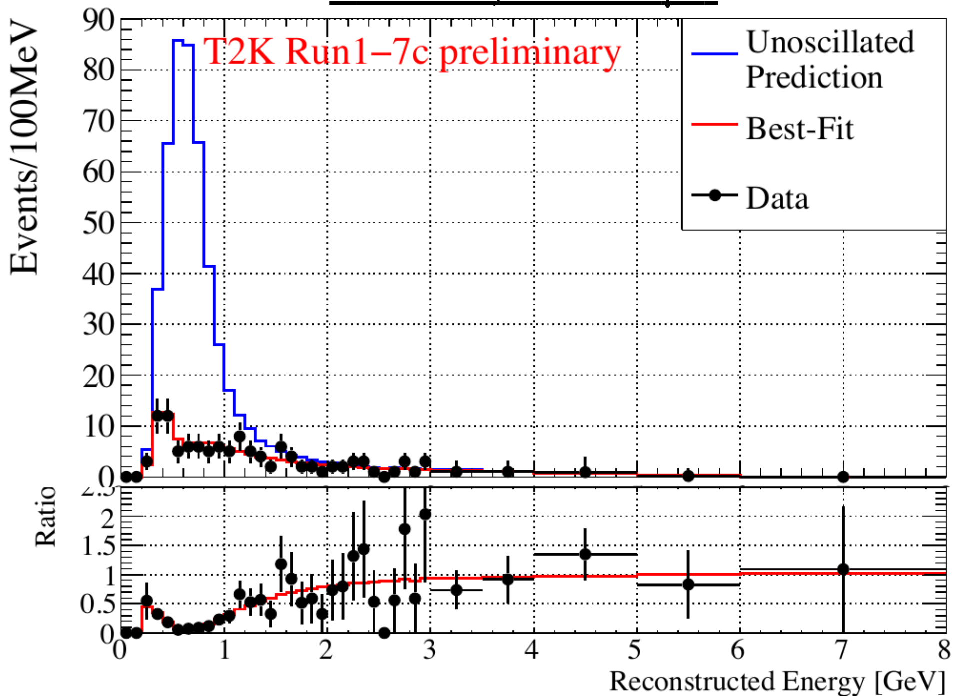
- 2 data point far from data peak → Not only the rate is low, but the shape of $\bar{\nu}_e$ events looks like background ! → Rate+Shape : ~2σ deviation from PMNS

ν_μ & $\bar{\nu}_\mu$ disappearance

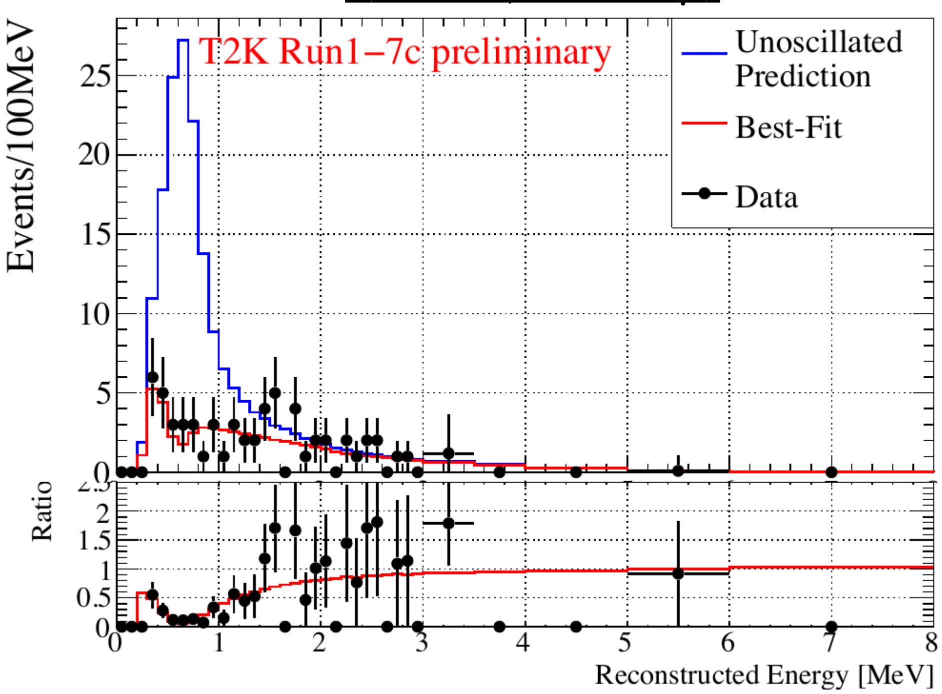
- Motivations :
  - Test CPT conservation by comparing $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$ and $P(\nu_\mu \to \nu_\mu)$.
  - Assuming PMNS model (CPT conservation), tighten constraint on θ_{23} & Δm^2_{32}.

- Results :

ν-mode, SK-1Rμ :



$\bar{\nu}$-mode, SK-1Rμ:

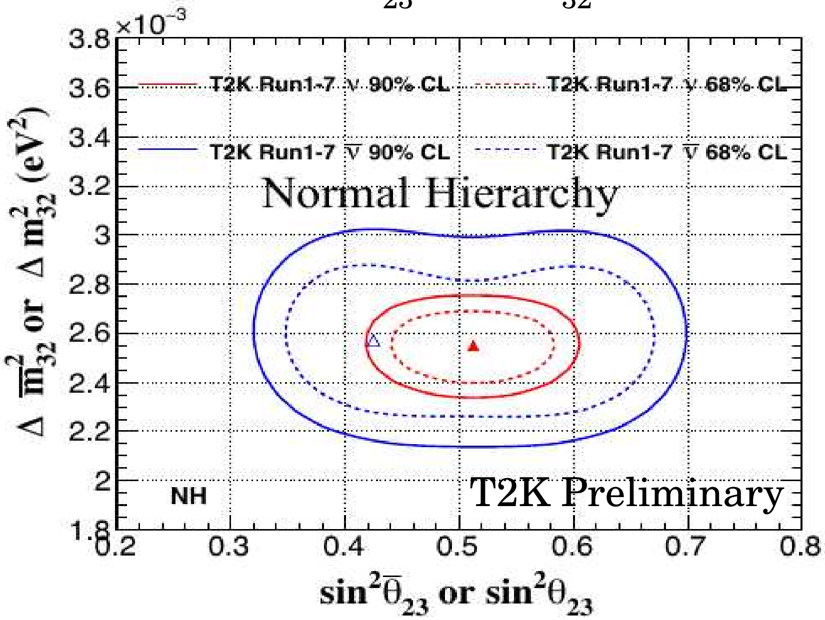


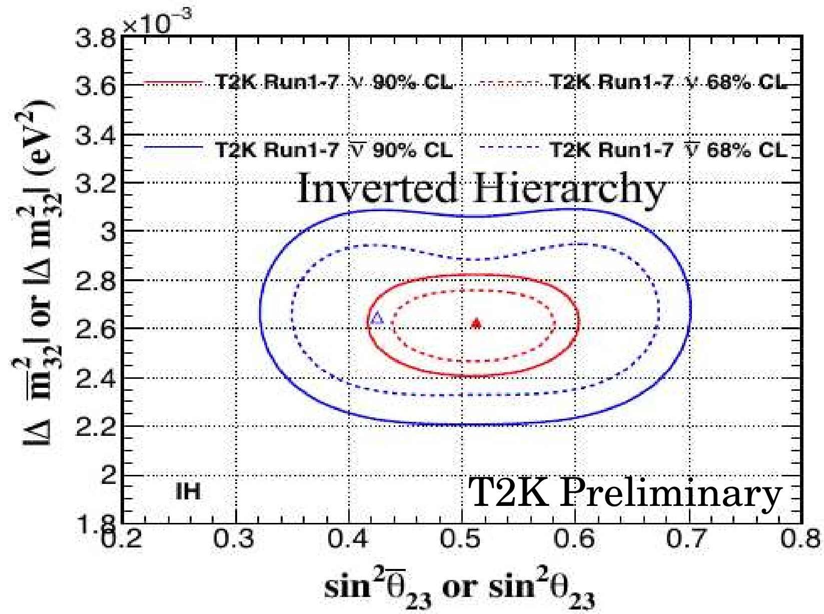
ν-mode events: 135.8 exp. / 135 obs / $\bar{\nu}$-mode events: 64.2 exp. / 66 obs.

$\bar{\nu}_\mu$ disappearance clearly observed in rate & shape @ 600 MeV.

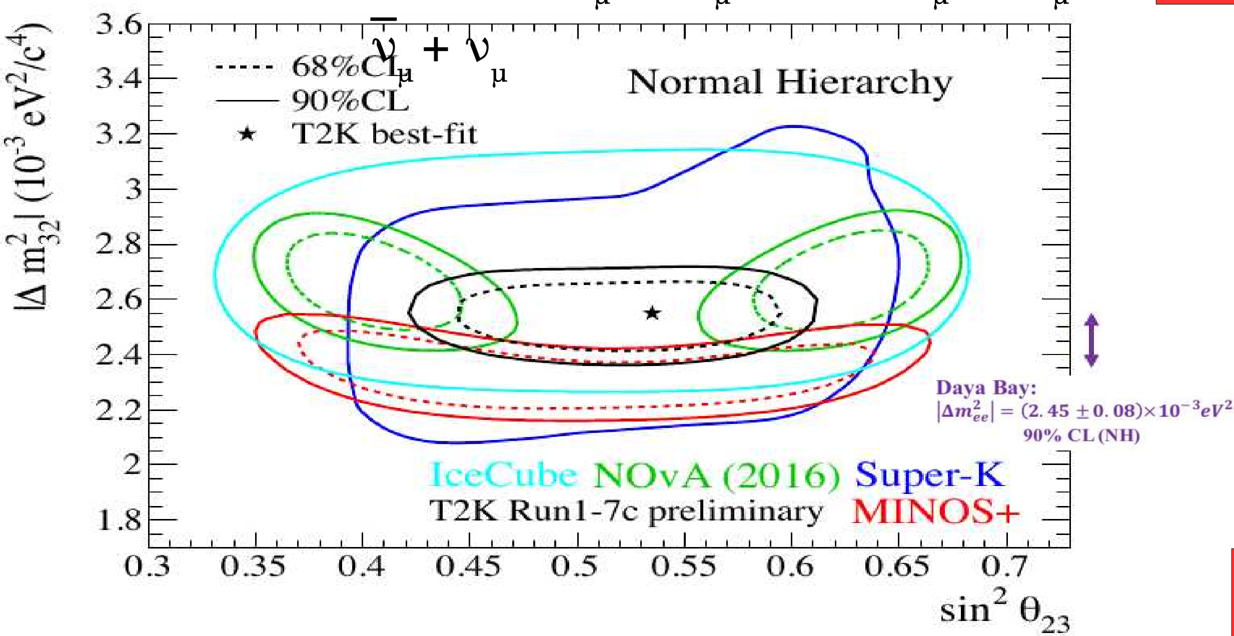
ν_μ & $\bar{\nu}_\mu$ disappearance

Constraints on the θ_{23} & Δm^2_{32} parameters:





- Agreement between $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$ and $P(\nu_\mu \rightarrow \nu_\mu) \rightarrow$ No sign of CPT violation.



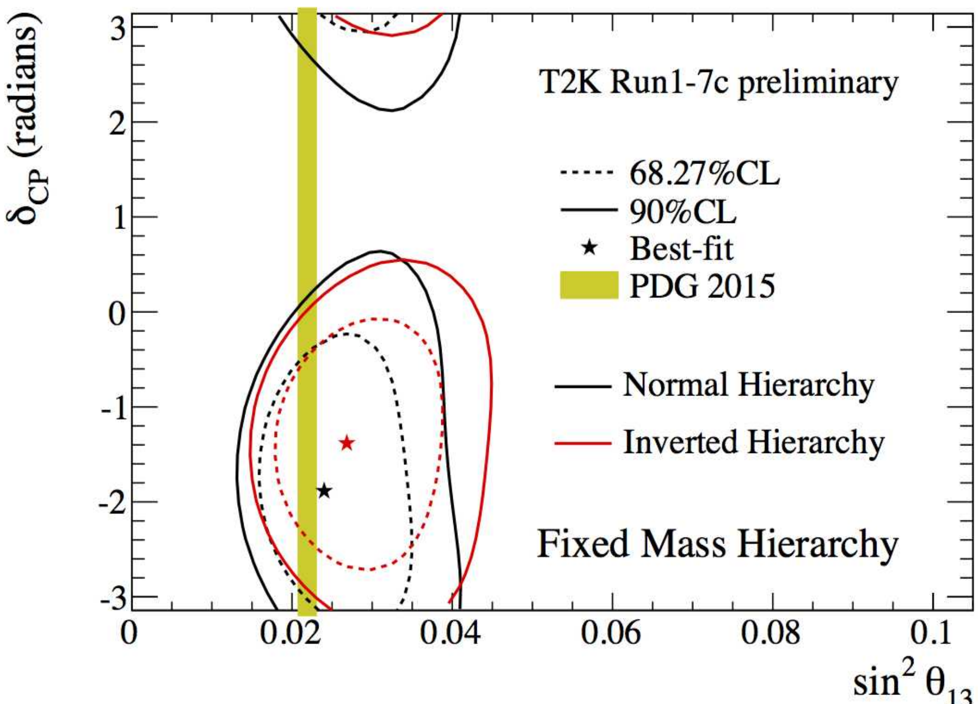
	NH
$\sin^2(\theta_{23})$	$0.532^{+0.046}_{-0.068}$
$\lvert\Delta m^2_{32}\rvert$ (x 10^{-5} eV^2/c^4)	$254.5^{+8.1}_{-8.4}$

- $\lvert\Delta m^2_{32}\rvert$ compatible with T2K former results & Nova
- T2K compatible w/ maximal mixing

Full joint fit : constraints on θ_{13} & δ_{CP} .

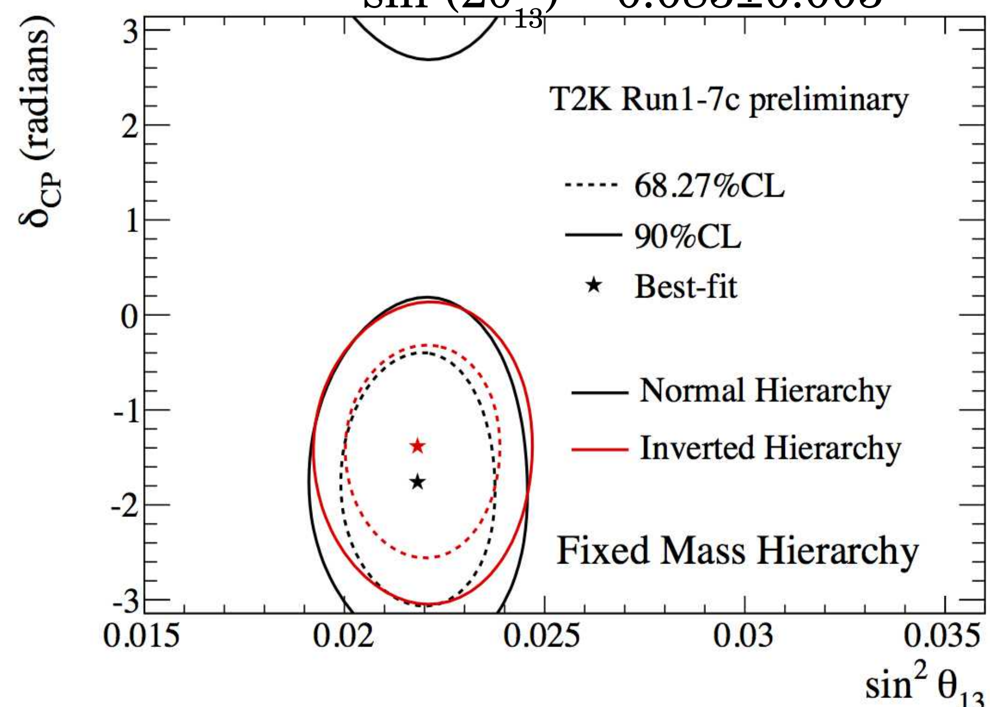
- Reminder : For NH & δ_{CP}=-π/2 : 27.0 ν_e & 6.0 $\bar{\nu}_e$ expected.
  → 32 ν_e & 4 $\bar{\nu}_e$ observed → T2K's observed difference between the observed events is larger than PMNS predictions for δ_{CP}=-π/2 !

- Results : T2K-only



T2K+reactor

$\sin^2(2\theta_{13})$ ~ 0.085±0.005



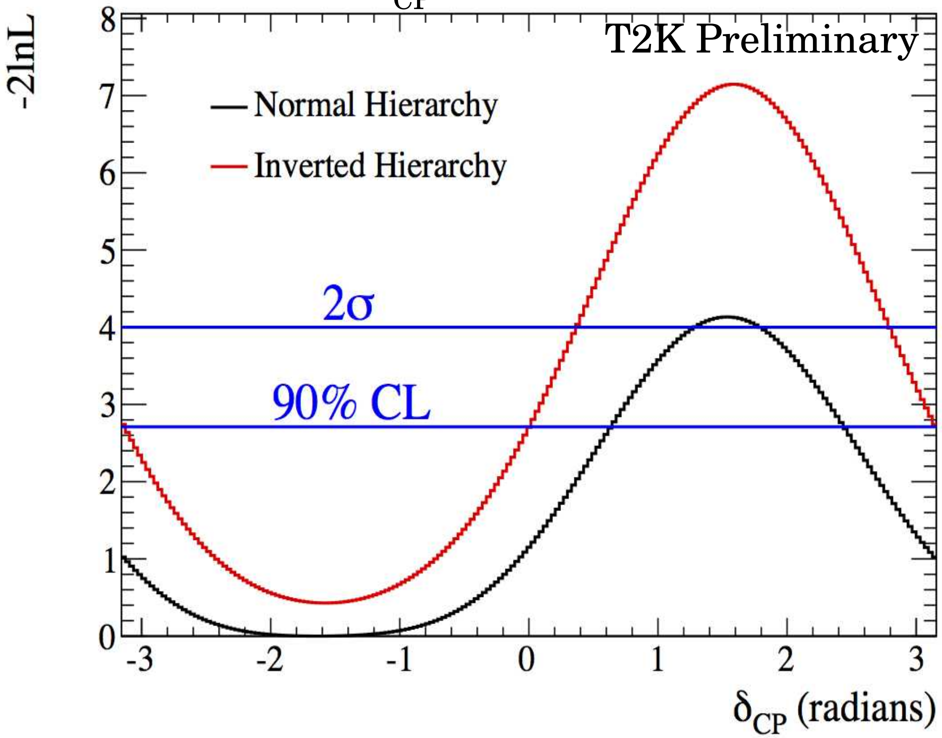
- T2K results are consistent with the reactor results.

- Maximal CPV favoured (δ_{CP}=-π/2) → The $\bar{\nu}_e$ data confirms the tendency seen in ν_e

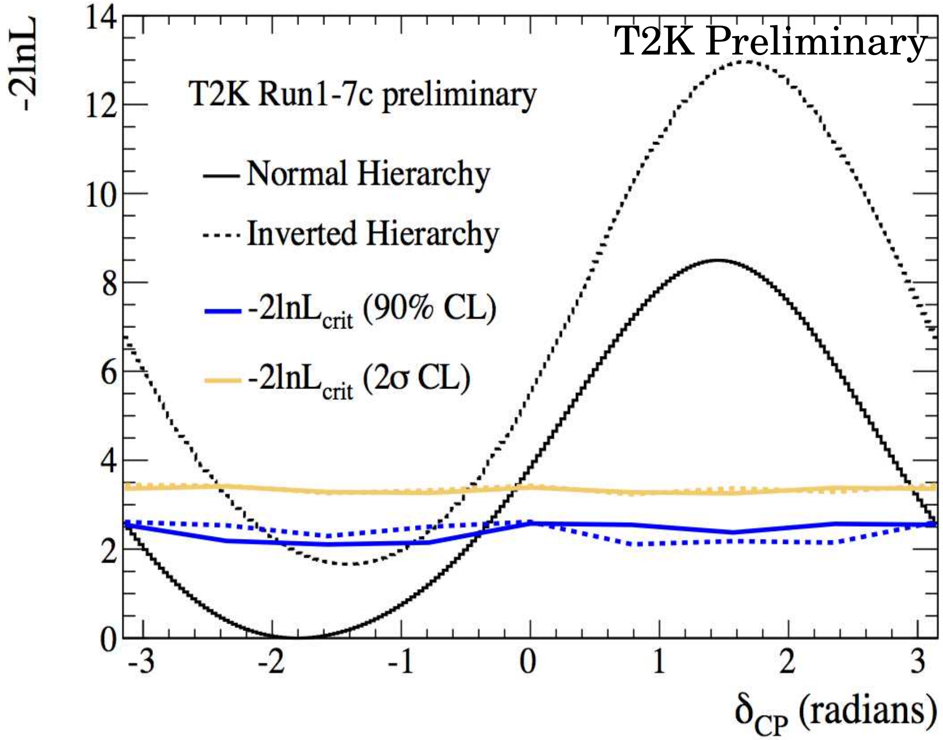
Full joint-fit : constraints on δ_{CP}

- Marginalize over $\sin^2(2\theta_{13})$ assuming the reactor constraints.

- Results : Asimov δ_{CP} =-π/2 (simulation)



Measurement (data)



- CP conservation excluded > 90 % CL.

- δ_{CP} 90 % CL : [-3.13, -0.39] (NH) and [-2.09, -0.74] (IH)

- δ_{CP} =0 excluded > 2σ.

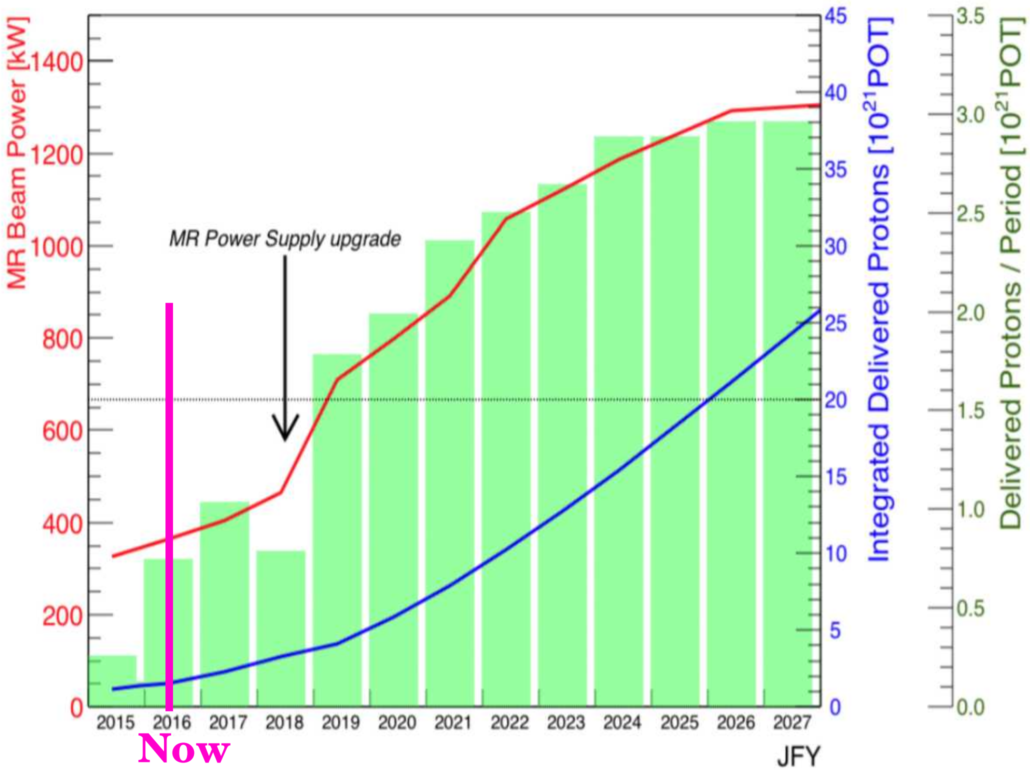
III-Improvements & prospects

- Continue to take data, with higher beam intensity
  → @500 kW this year → 750 kW in 2018 → > 1 MW in 2021 ?

- Flux, ND280 and SK analyses improvement → reduce systematics by 2/3 → reach 4 %.

- Include multi ring e-like at SK (+35 % statistics) & increase Fiducial Volume (+10~15%).

- <u>Future :</u> proposal for T2K-phase II experiment → #POT from 7.8 (T2K) to 20.0×10^{21} POT



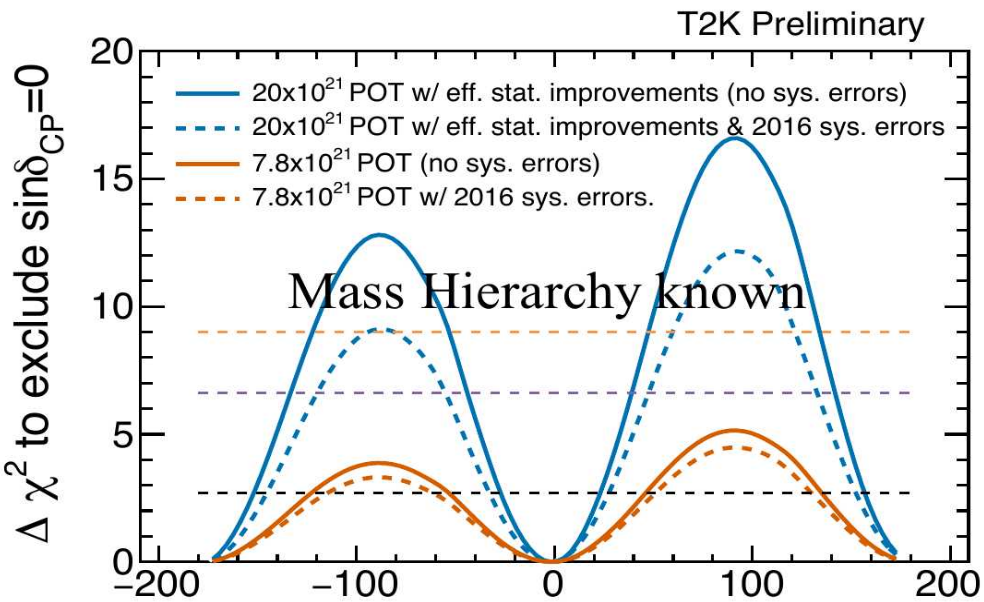
- T2K aim to reach the number of approved POT (7.8×10^{21}) in 2021 → starts T2K-II phase in 2021 → 2026.

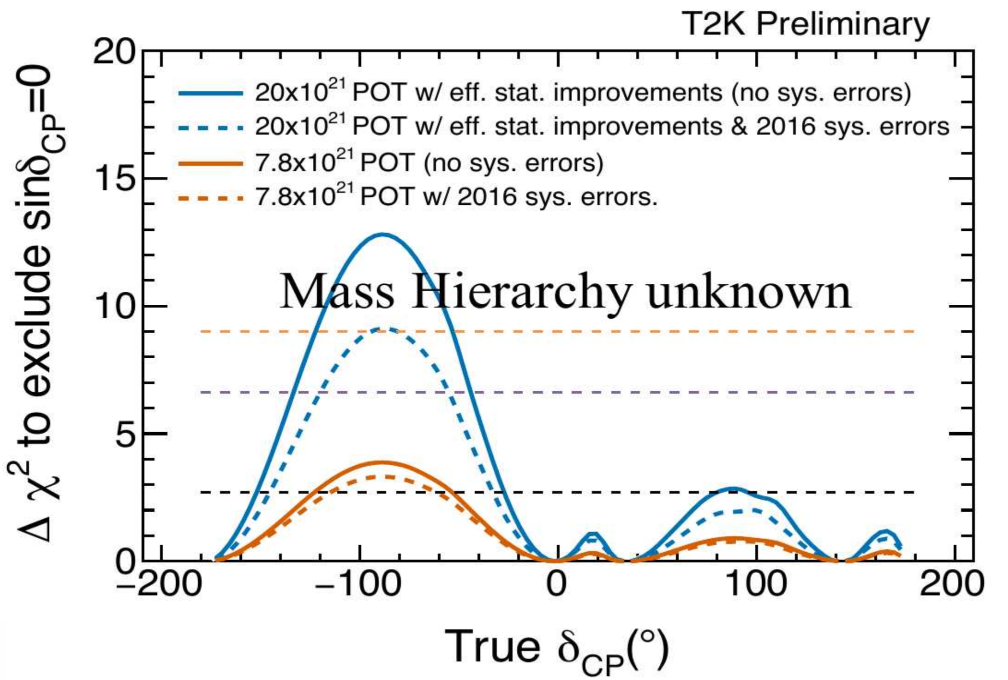
- 13 times more statistics than now (summer 2016)!

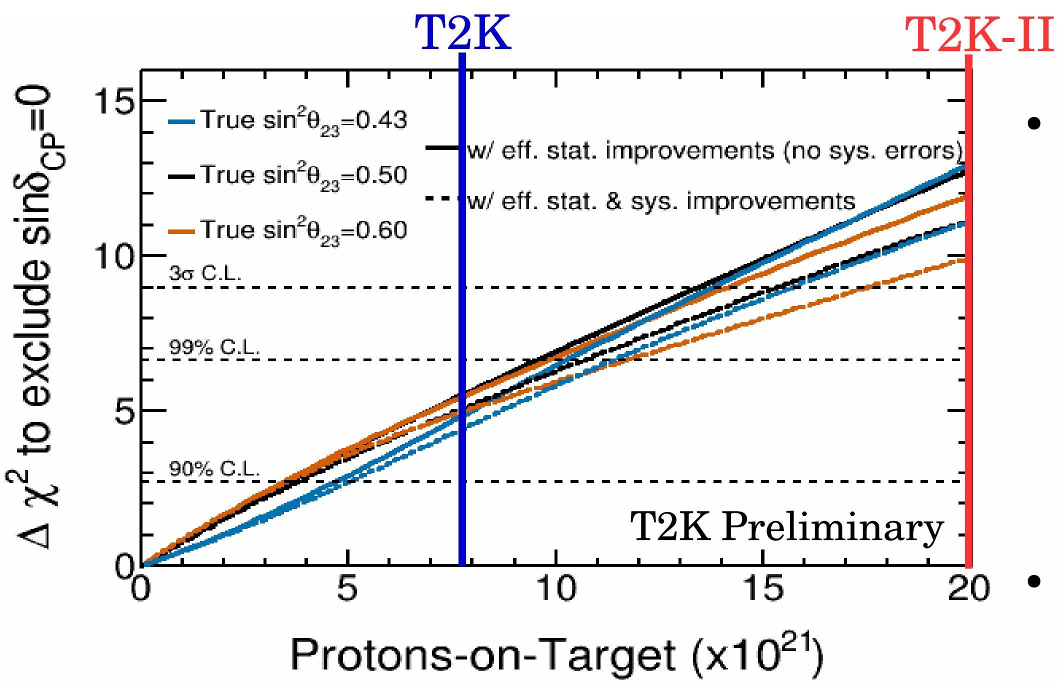
- <u>Rely on an beam performance upgrade :</u>
  → *see Nakadaira-san's talk*

III-T2K-II sensitivity

- Goal : First experiment to exclude CP conservation > 3σ !







- If maximal CPV (δ_{CP}=-π/2) :
  → T2K-II excludes CP conservation > 3σ even if Mass Hierarchy is unknown.

  → 3σ goal achieved whether θ_{23} is maximal or not.

- CP conservation might be excluded >3σ in this generation of experiments !

Conclusions

- T2K accumulated a total of 1.51×10^{21} POT (ν:$\bar{\nu}$= 1:1) ~ 19 % of T2K total stat.

  → T2K will continue to accumulate lots of data with an higher accumulation rate. (J-PARC beam operated @425 kW → 500 kW expected this autumn)

- <u>$\bar{\nu}_e$ appearance search :</u>

  → Data set is compatible with no $\bar{\nu}_e$ appearance → Only 4 events in the $\bar{\nu}_e$ ($\bar{\nu}$-mode SK-1Re) sample.

  → Higher assymetry between ν_e & $\bar{\nu}_e$ than expected + shape effect → the $\bar{\nu}_e$ appearance results deviate from ~2σ with respect to the PMNS model.

- $\bar{\nu}_\mu$ disappearance observed & compatible with ν_μ disappearance

  → No CPT violation observed

- T2K full data set favours maximal mixing for θ_{23}.

- <u>Joint fit constraints on θ_{13} & δ_{CP} :</u>

  → Agree with reactor's results.

  → Prefer large CP violation (δ_{CP}=-π/2) → Driven by the large assymetry between ν_e & $\bar{\nu}_e$.

- CP parity is excluded with more than 90 %CL → **Please, stay tuned.**

Additional slides

Selection at Super-Kamiokande

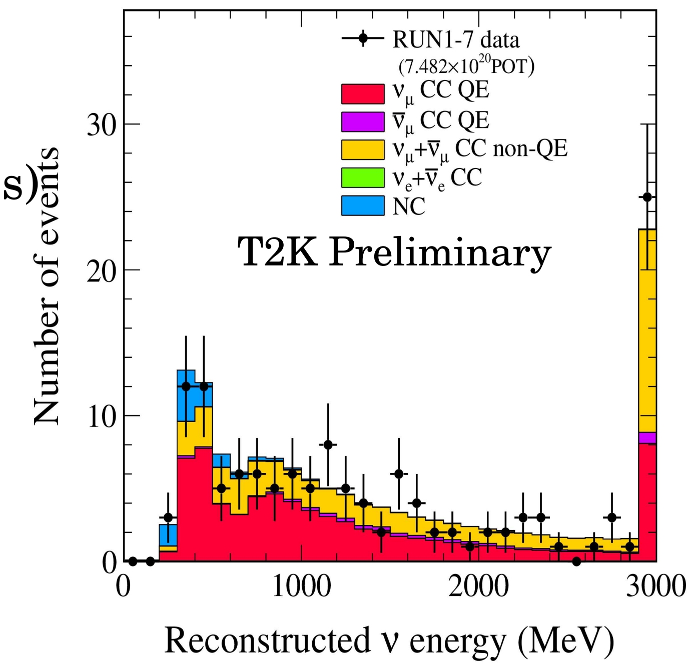
Single ring μ-like

1. Fully contained within the SK FV
2. Only one reconstructed ring
3. Be μ-like (PID using ring sharpness)
4. Reconstructed p_{μ} > 200 MeV/c
5. One or no decay-e

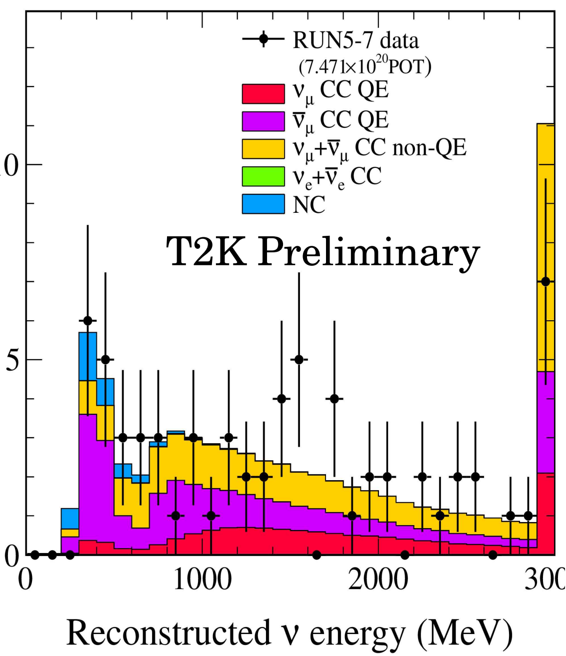
ν-mode events: 135.8 exp. / 135 obs.

$\bar{\nu}$-mode events: 64.2 exp. / 66 obs.

ν-mode



$\bar{\nu}$-mode



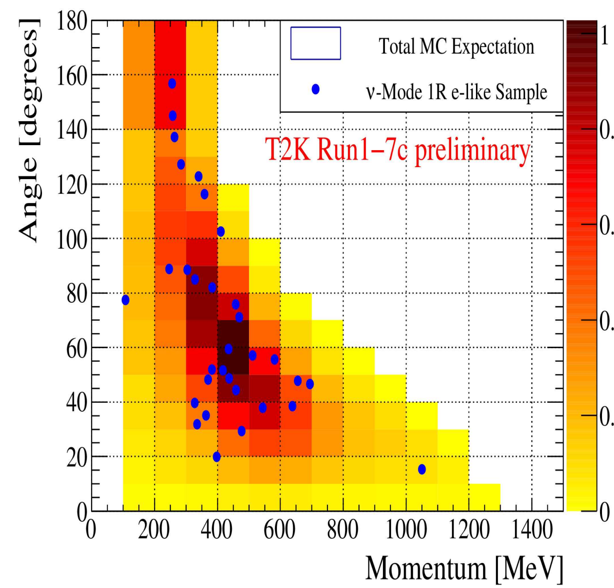
Single ring e-like

1. Fully contained within the SK FV
2. Only one reconstructed ring
3. Be e-like (PID using ring sharpness
4. Visible energy E > 100 MeV
5. One or no decay-e
6. Reconstructed E_{rec} < 1250 MeV
7. π^{0} mass and likelihood cut

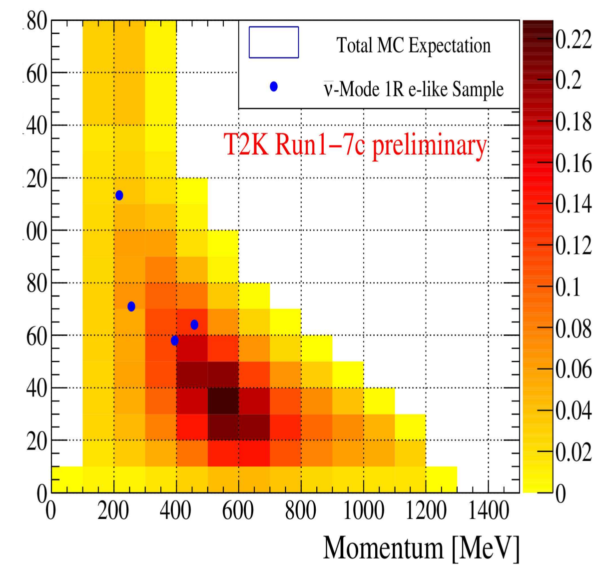
ν-mode events: 27.0 exp. / 32 obs.

$\bar{\nu}$-mode events: 7.0 exp. / 4 obs.

ν-mode

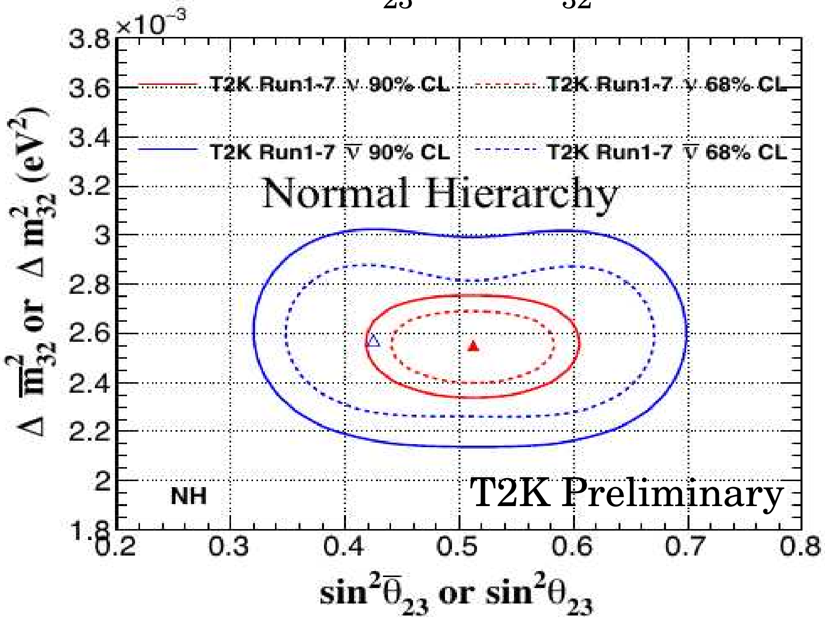


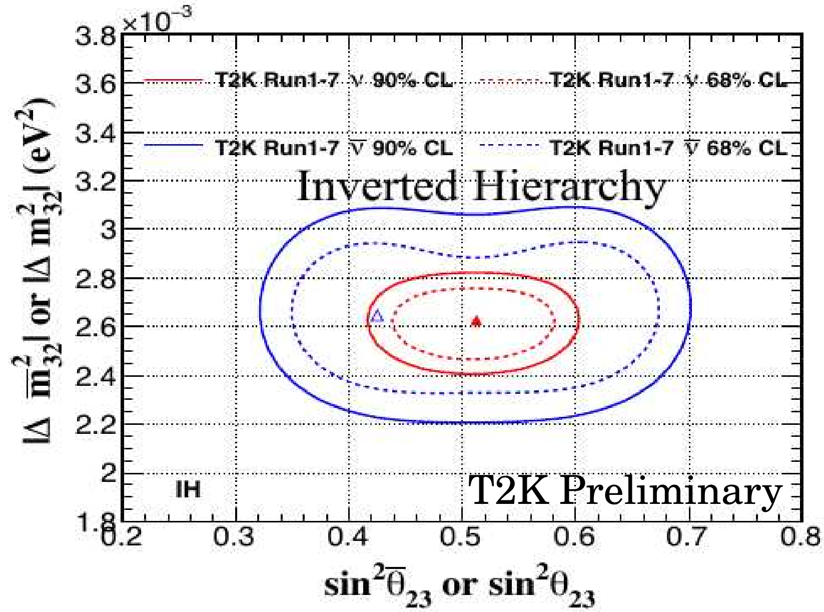
$\bar{\nu}$-mode



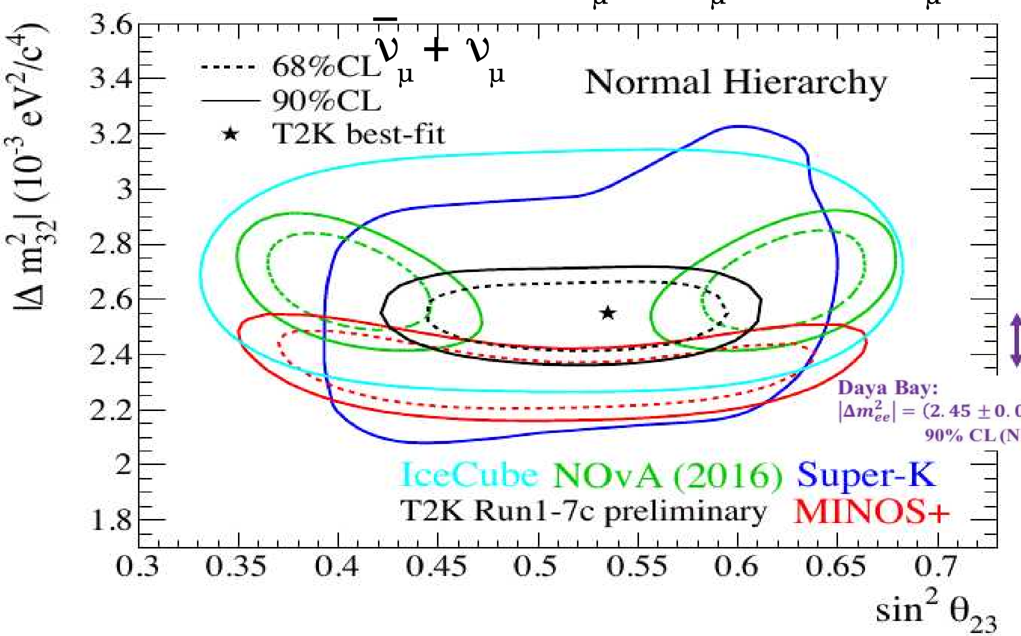
ν_μ & $\bar{\nu}_\mu$ disappearance

Constraints on the θ_{23} & Δm^2_{32} parameters:





- Agreement between $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$ and $P(\nu_\mu \rightarrow \nu_\mu)$ → No sign of CPT violation.



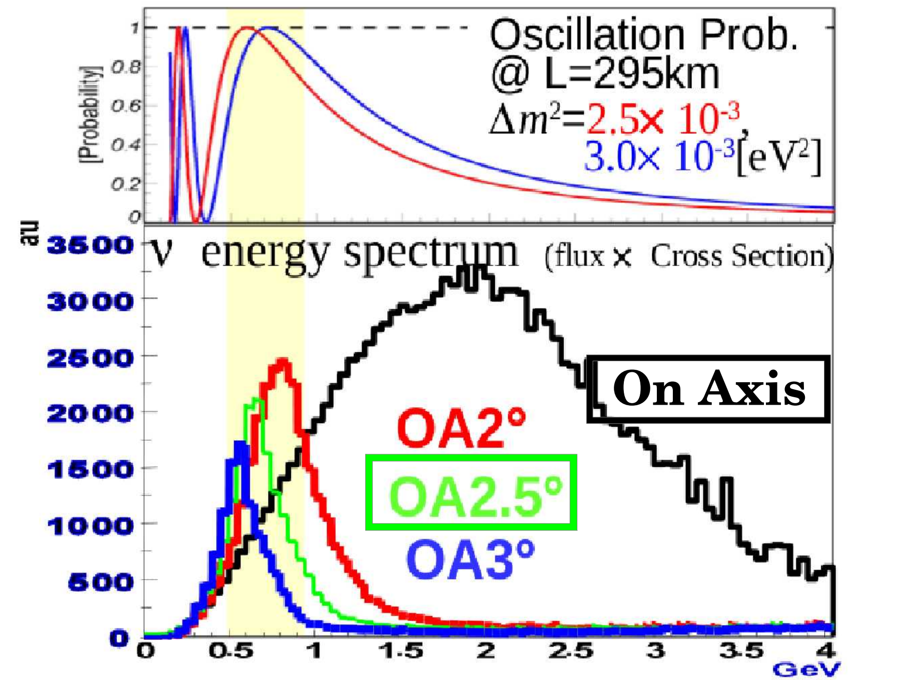
Daya Bay: $|\Delta m^2_{ee}| = (2.45 \pm 0.08)\times 10^{-3} eV^2$ 90% CL (NH)

	NH	IH
$\sin^2(\theta_{23})$	$0.532^{+0.046}_{-0.068}$	$0.534^{+0.043}_{-0.07}$
$\lvert\Delta m^2_{32}\rvert$ (x 10^{-5} eV²/c⁴)	$254.5^{+8.1}_{-8.4}$	$251.0^{+8.1}_{-8.3}$

- Favours maximal mixing
- $|\Delta m^2_{32}|$ compatible with T2K former results & Nova

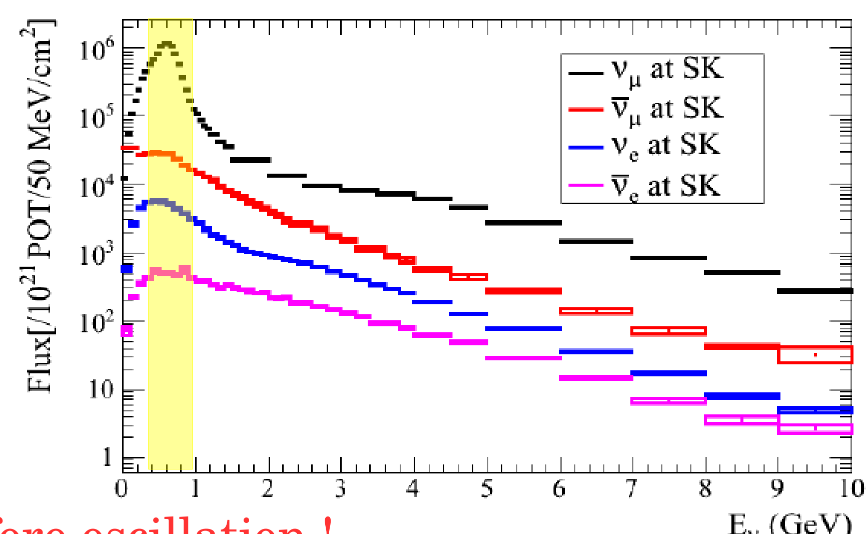
Off-axis technique

- **<u>T2K is an off-axis experiment :</u> neutrino beam aimed at 2.5° from Super-K.**



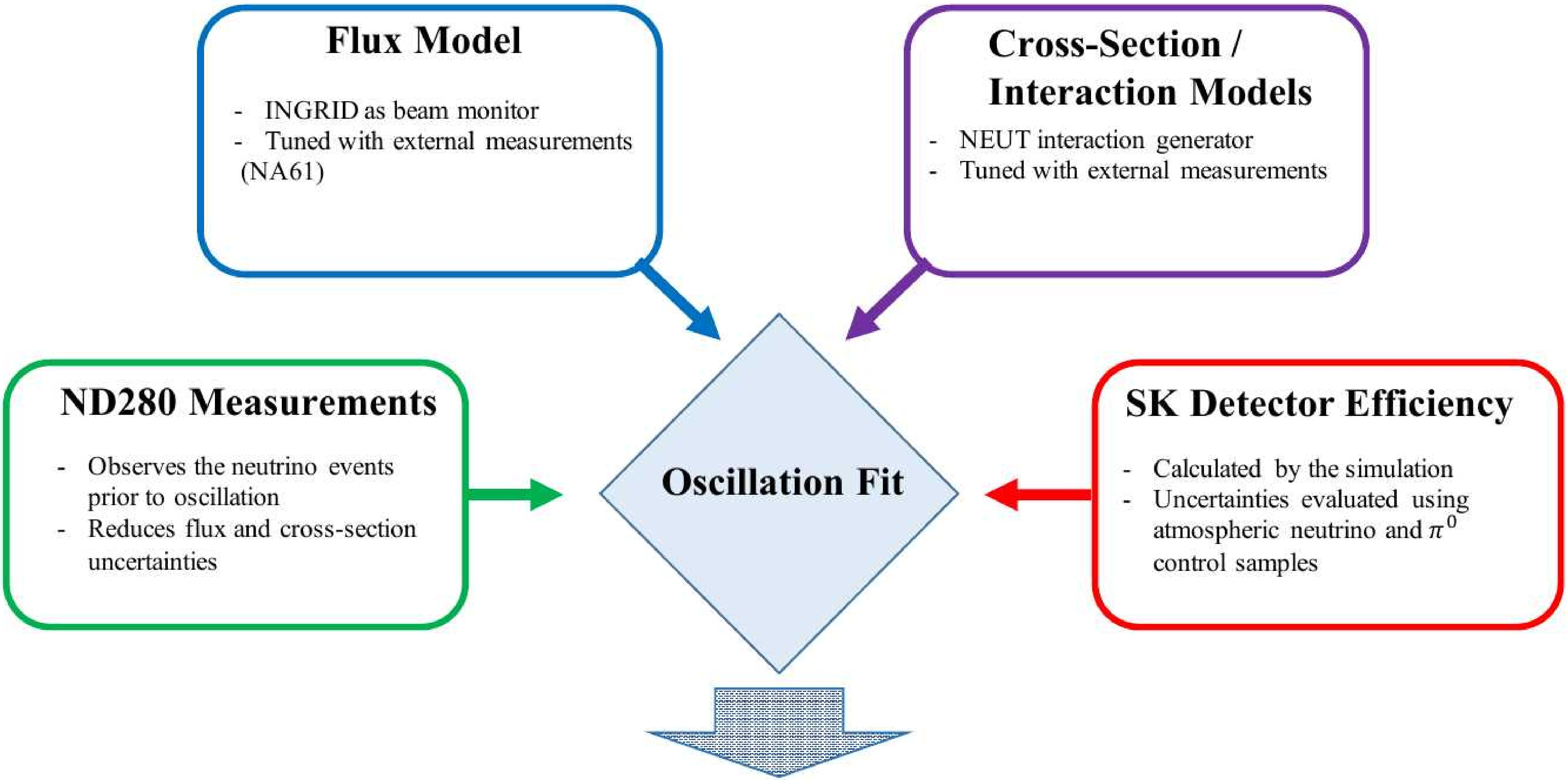
- **<u>Why ?</u>** maximize oscillation at 295 km
  → Tune energy spectrum (600 MeV)
  - **Higher statistics** of oscillated neutrinos
  - **Reduce contamination** from non-oscillated high-energy neutrinos
  - Reduce ν_e contamination

- **<u>But :</u>**
  - ν beam does not have one flavour & energy.
  - ν beam intensity & shape are not perfectly known.



- → Requires beam rate & shape measurements before oscillation !

The ND280 detector



Oscillation Parameters $(\theta_{13}, \delta_{cp}, \Delta m^2_{32}, \theta_{23})$

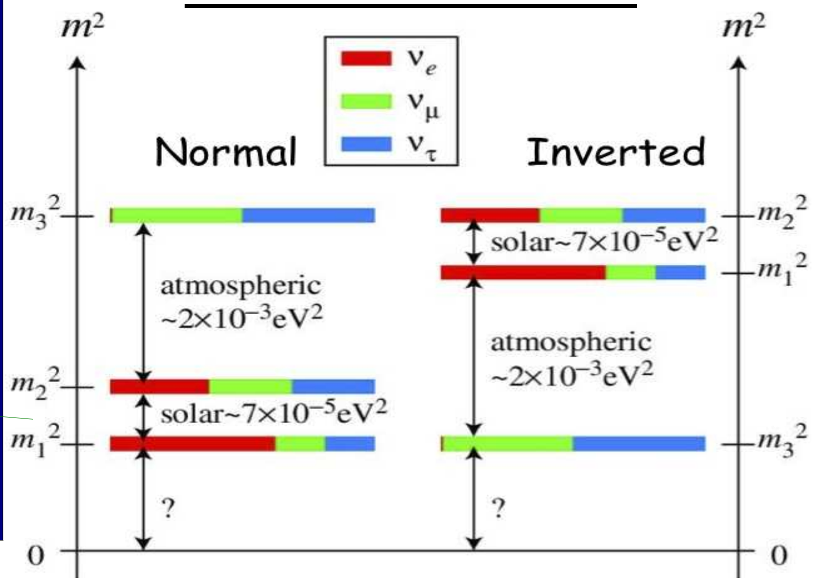
Remaining issues in neutrino oscillations

ν_μ / $\bar{\nu}_\mu$ disappearance @ T2K (~ «Atmospheric»)

1. **Is $\nu_2 \rightarrow \nu_3$ mixing maximal ? (Θ_{23}=45°)**
   (if not, what is the Θ_{23} octant ?)

2. **Δm^2_{32} sign unknown : mass hierarchy problem**
   - **Solar :** known (large matter effects in the Sun)
   - **Atmospheric :** Not known

Mass hierarchies :

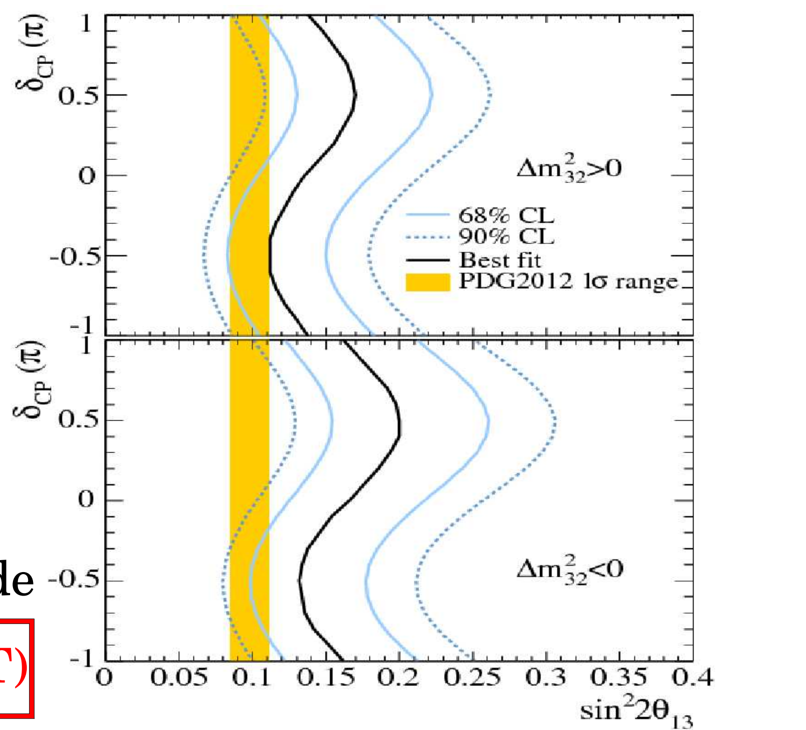


ν_e / $\bar{\nu}_e$ appearance @ T2K

Is CP violated in the leptonic sector ? ($\delta_{cp} \neq 0$)

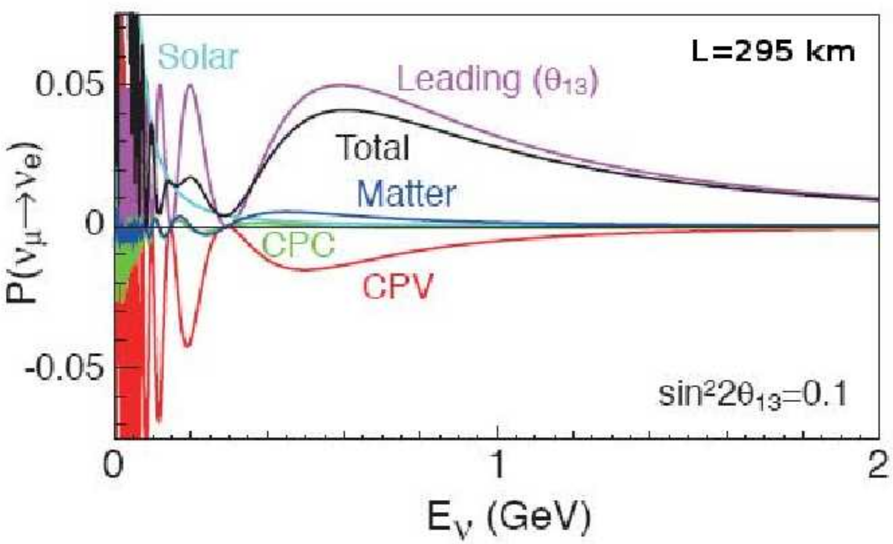
- T2K observed ν_e appearance
- T2K (ν_e) and reactor ($\bar{\nu}_e$) results in tension
  → Large CP violation ?
- To provide first answers : T2K currently runs in $\bar{\nu}$-mode

1st results on $\bar{\nu}_\mu$ disappearance @ T2K (2.3x10^{20} POT)



Appearance Formula

$$P(\nu_\mu \to \nu_e) = \boxed{4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31}}$$
$$+8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$
$$-8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$
$$+4s_{12}^2 c_{13}^2(c_{12}^2c_{23}^2 + s_{12}^2s_{23}^2s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\Delta_{21}$$
$$-8c_{13}^2 s_{12}^2 s_{23}^2 \frac{aL}{4E}(1-2s_{13}^2)\cos\Delta_{32}\sin\Delta_{31}$$
$$+8c_{13}^2 s_{13}^2 s_{23}^2 \frac{a}{\Delta m_{31}^2}(1-2s_{13}^2)\sin^2\Delta_{31}$$



Leading order :

- Sensitive theta13 & theta23

Higher orders :

- Dependence on solar parameters also
- Sensitivity to CP violation & matter effects