T2K-II
the upgrade of T2K

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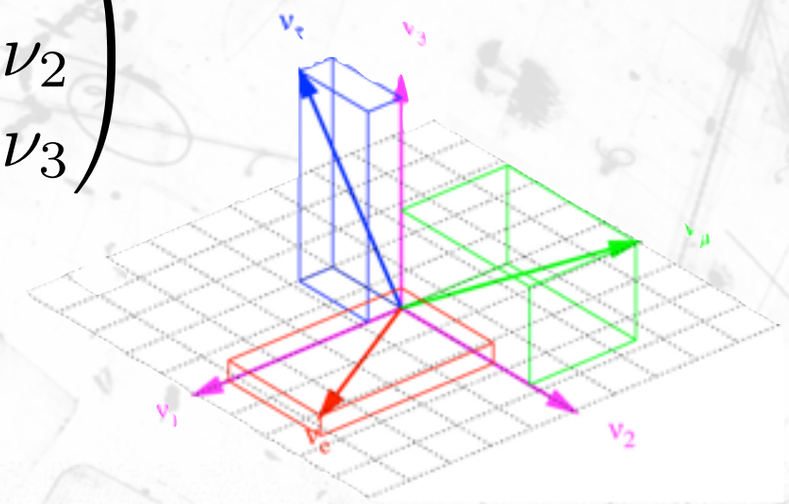
Outlook

- Why an upgrade of T2K?
- What is required/planned?
  - Statistics:
    - Beam
    - Far detector
  - Systematic errors:
    - Near Detector
    - Intermediate detector
- Physics potential.
- (Political) Status.

ν oscillations

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

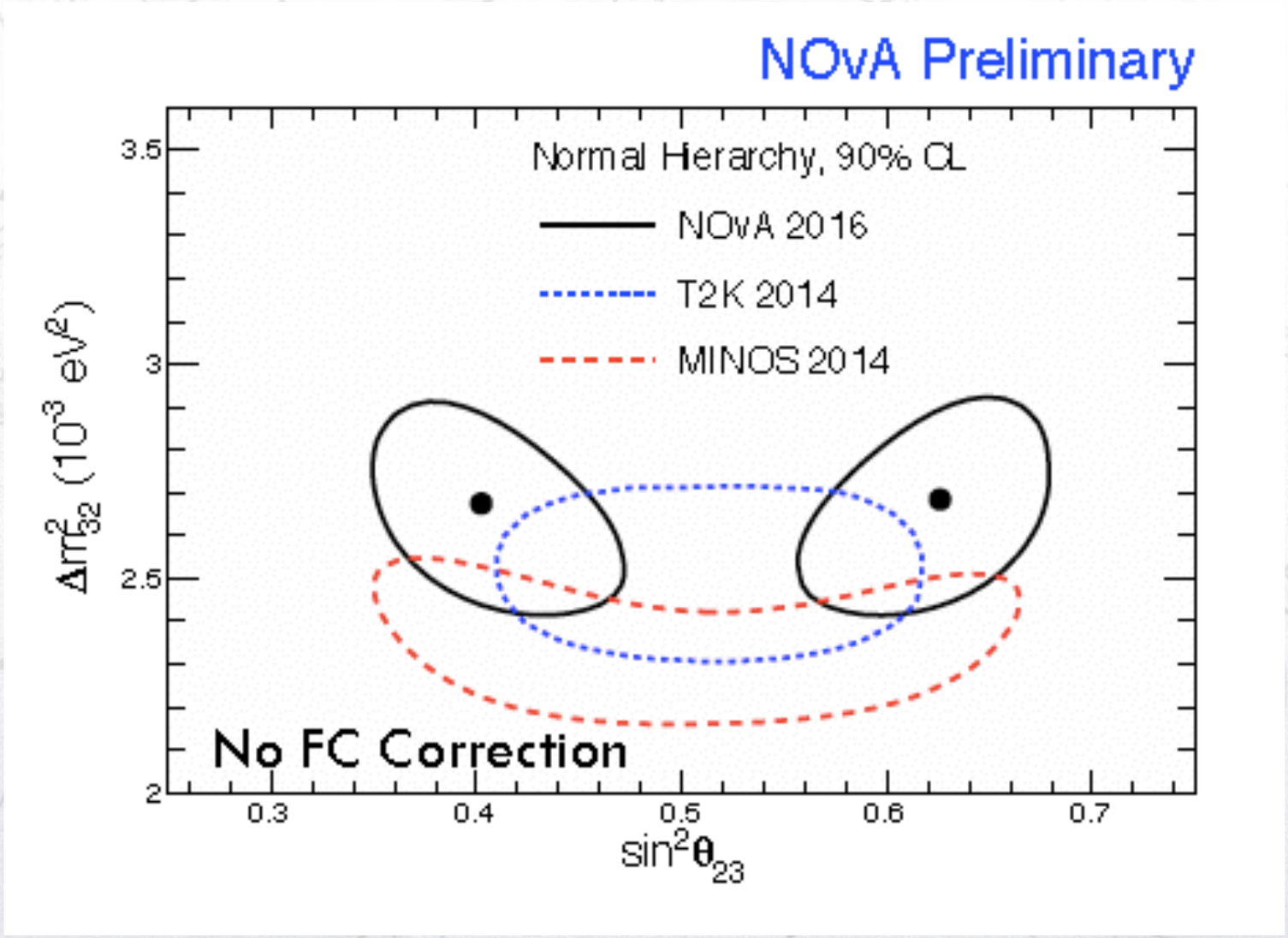


$$U_{PNMS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- With 3ν, there are 3 angles and 1 imaginary phase:
- CP violation phase similar to the quark sector.
- 2 values of Δm^2, traditionally Δm^2_{12} &Δm^2_{31}.
- Observed through the transition between neutrino flavour through quantum interference.
- PNMS is assumed to be unitary

Why an upgrade?

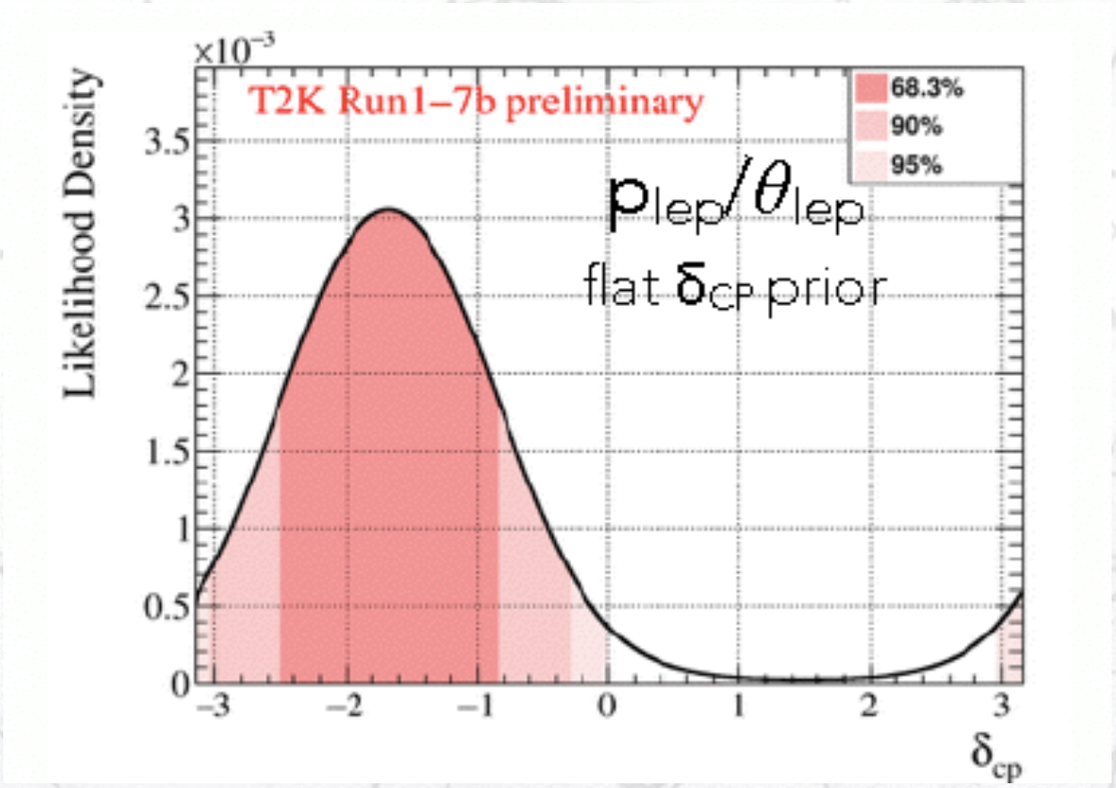
Physics I

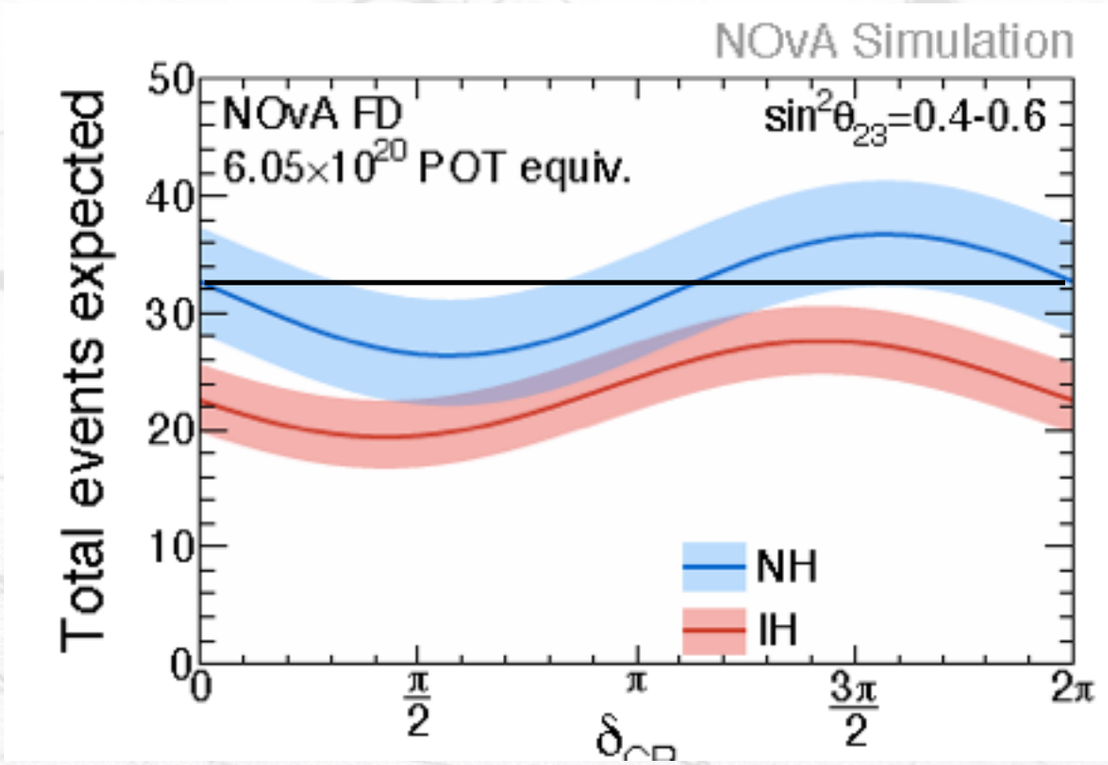


Why an upgrade?

Physics II

- Are we seeing CP violation ?





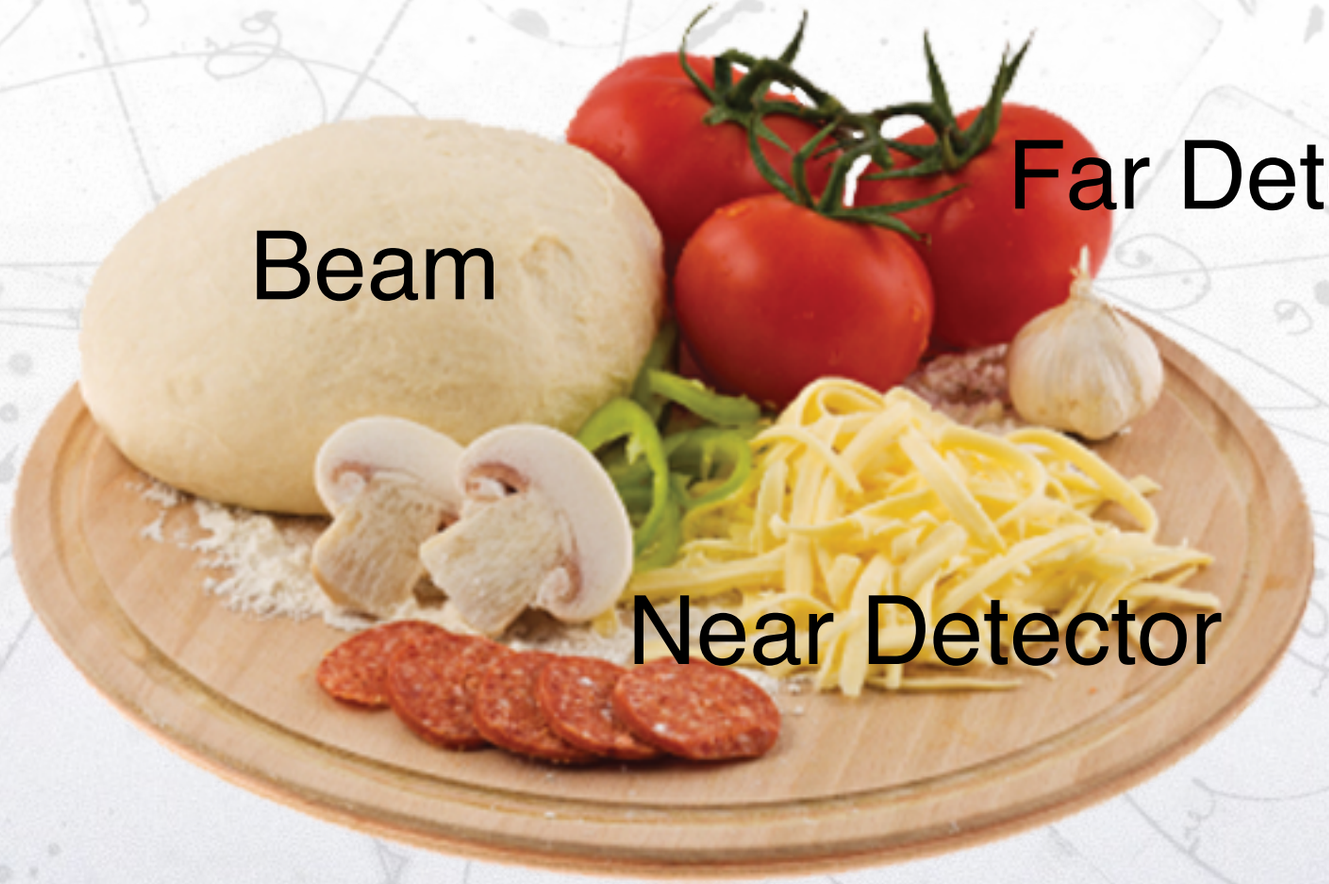
- CP violation indication is weak: < 2 σ
- It arises from tensions between Nova&T2K with Daya-Bay.
- There is a faint support from antineutrino results from T2K.

Why an upgrade?

Facts of life

- You want to run T2K-II because:
  - there will be no other experiment beyond Nova running until 2030 (if lucky!).
  - T2K can't leave the glory to Nova alone.
  - Nova and T2K are complementary in energy reconstruction technique and due to different base line and matter effects.
  - T2K need to pave the road to the next generation of Japanese oscillation experiments. (HyperK).
  - The beam and the detectors are there and there are running (almost) smoothly.
  - We are still learning from the neutrino-nucleus cross-sections:
    - We need more data, better data and better models.
    - If we achieve these goals the systematics will be reduced and the sensitivity increased.

Ingredients



Beam

f_{rep}=0.4 Hz	PPP = 2.2×10^{14}	30 GeV	=	425kW

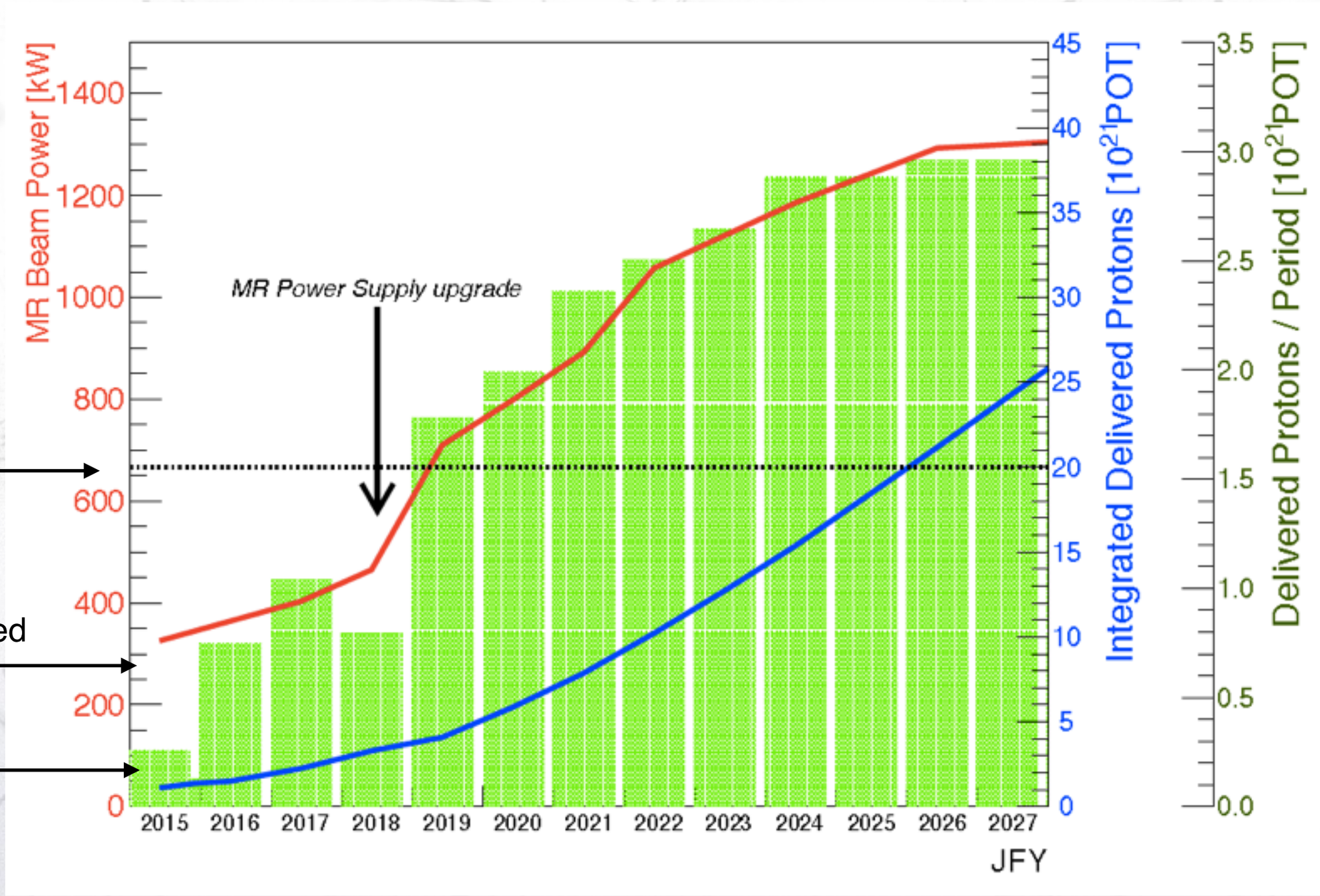
Approved/in construction — January 2019

f_{rep}=0.77 Hz	PPP = 2.2×10^{14}	30 GeV	=	810kW

Machine development

f_{rep}=0.77 Hz	PPP = 3.2×10^{14}	30 GeV	=	1.2MW

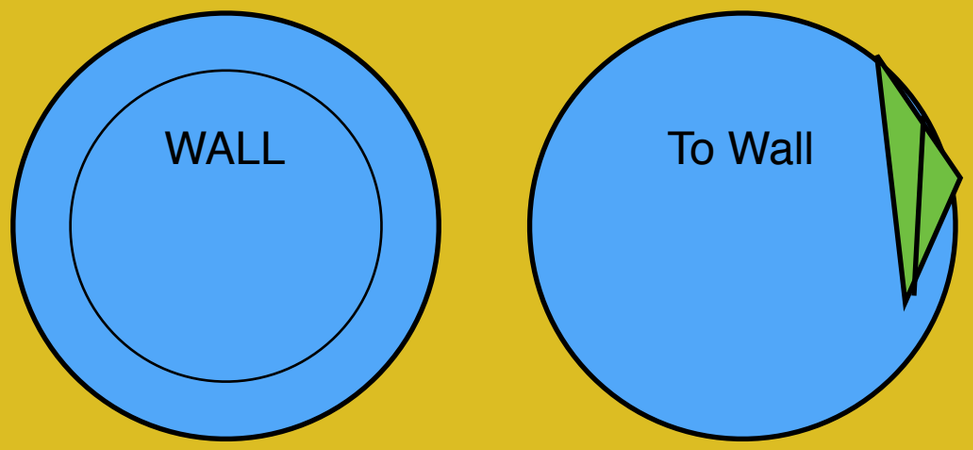
Beam

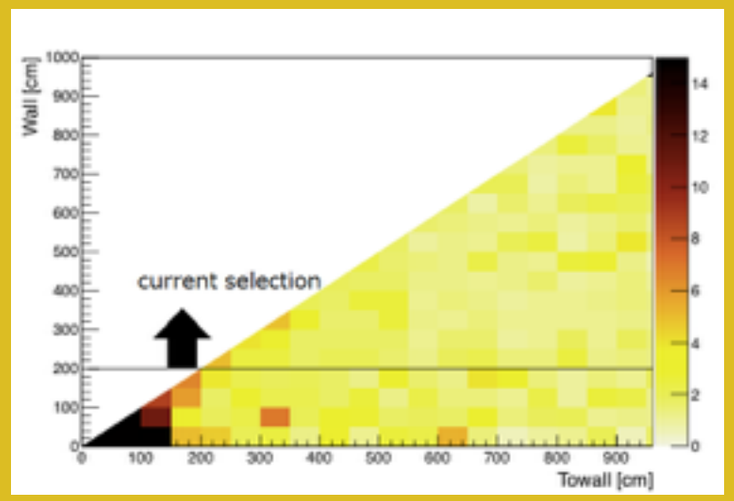

MR Beam Power [kW]
1400
1200
1000
800
600
400
200
0
MR Power Supply upgrade
T2K II
T2K Approved
T2K NOW
45
40
35
30
25
20
15
10
5
0
Integrated Delivered Protons [10^21POT]
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Delivered Protons / Period [10^21POT]
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
JFY

Far detector

- Efforts to increase the far detector statistics: (+ 20/30 %)

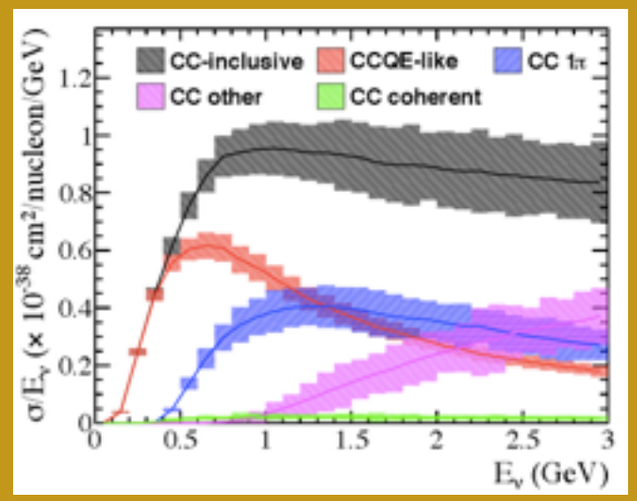
Smarter fiducial volume





New interaction channels

- T2K uses the CCQE channel because it is a 2-body to 2-body reaction and we can compute the neutrino energy.
- Most of the CC1π come for the resonance Δ^{++}. This is a 2-body reaction so we can also use it to detect neutrinos.
- It is also a different channel with slightly different systematics.

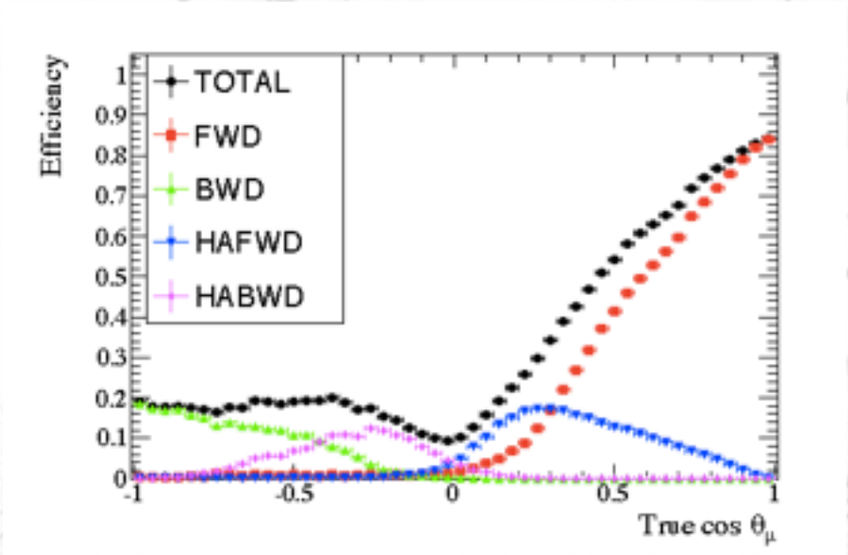


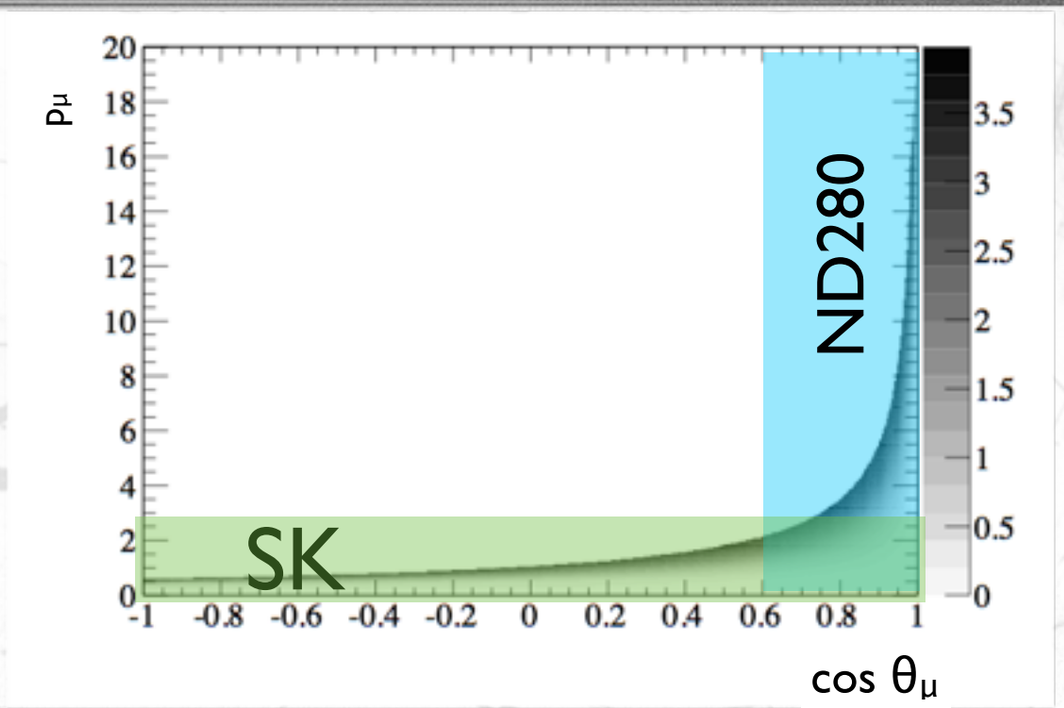
Systematic errors

- Systematic errors are dominated at the moment by νA Cross-Section systematics.
- Several sources:
  - Carbon/Oxygen cross-section ratio. NEAR DETECTOR
  - Cross-section models:
    - High angle acceptance. NEAR DETECTOR
    - Low energy hadron energy. NEAR DETECTOR
  - ν_e/ν_μ cross-section ratios. BEAM

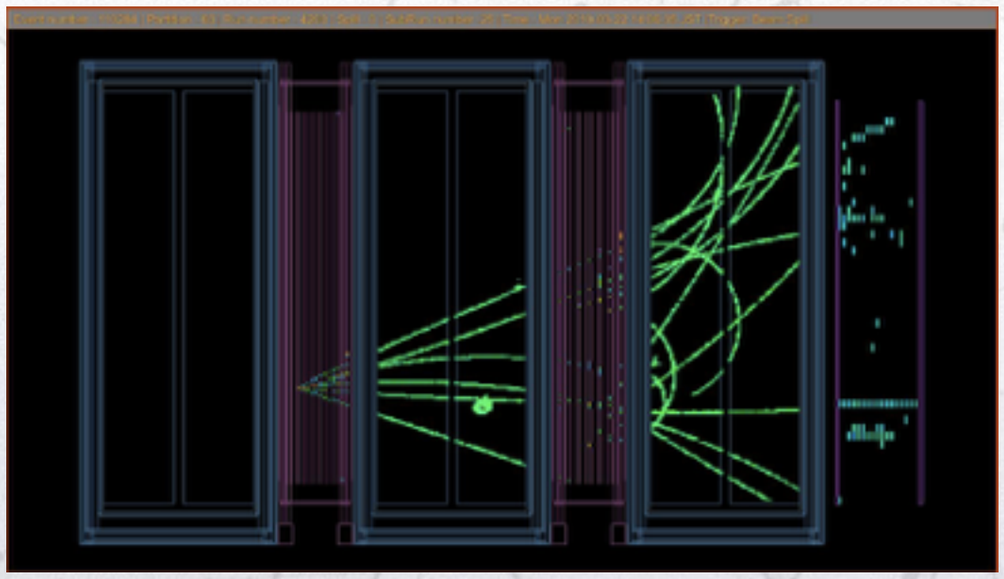
Near detector I

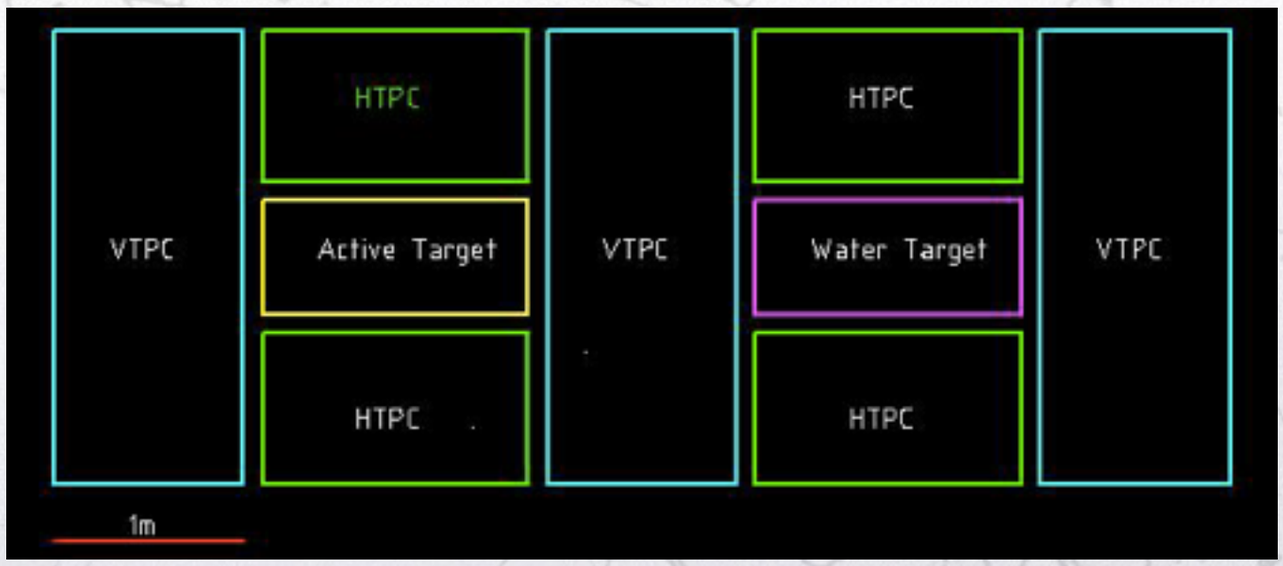
- Actual angular acceptance:





- Proposed modification of the Near Detector.



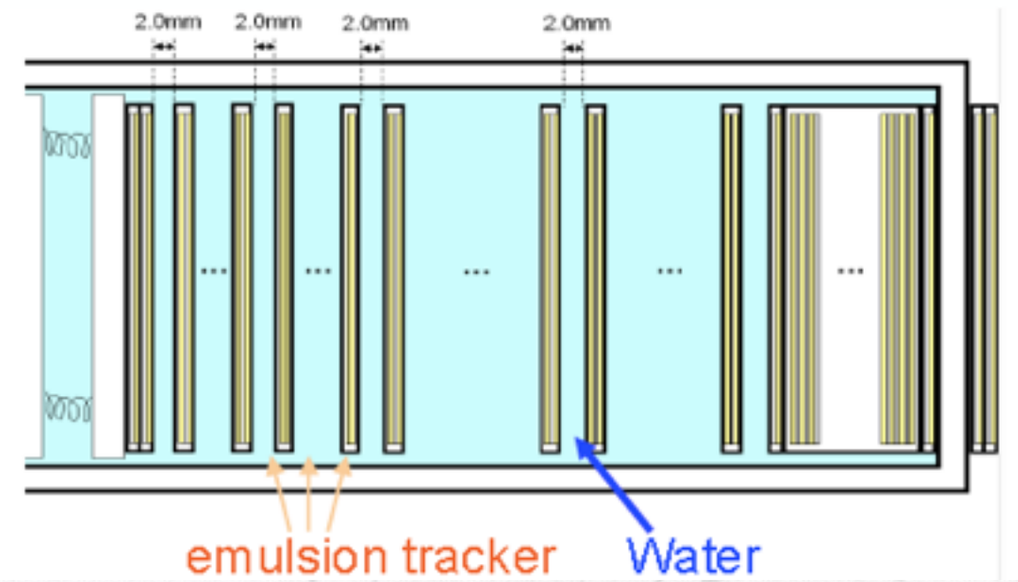


https://indico.cern.ch/event/568177/

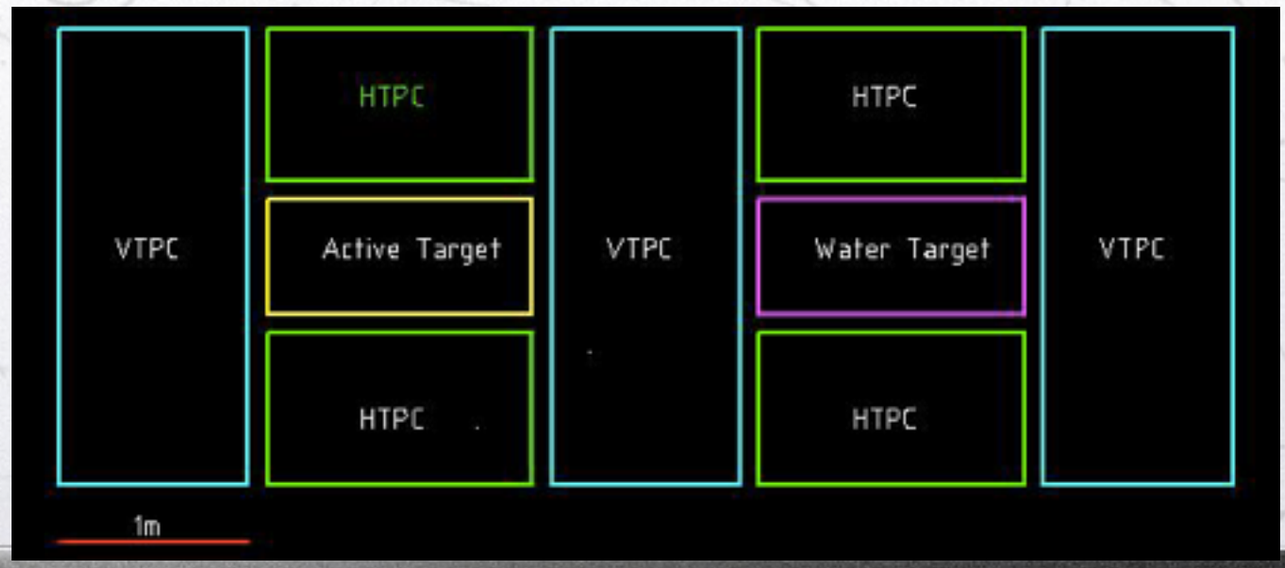
Near detector II

- Carbon vs Oxygen:

Emulsion tracker to identify water interactions



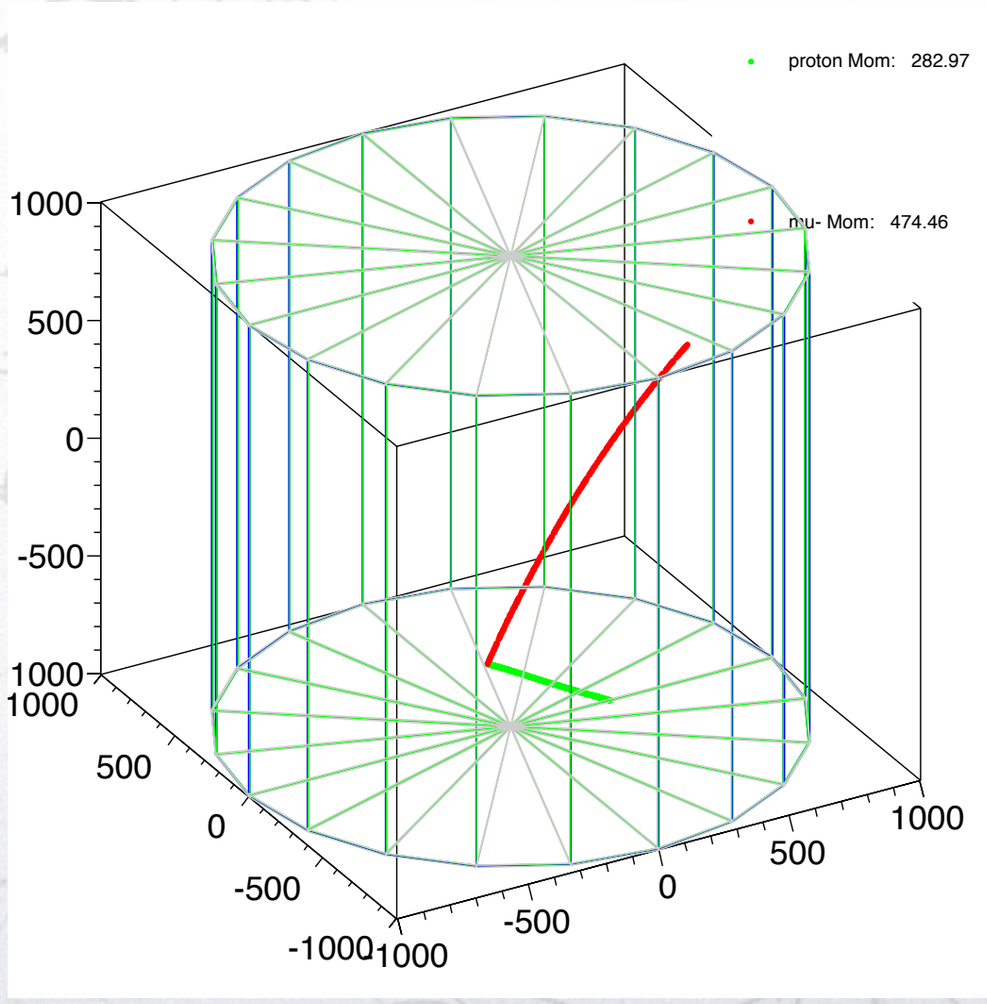
Compare interactions in two targets



Near detector III

- Low energy hadron detection
  - Full active
  - Low stopping power detector.
- High Pressure but also atmospheric pressure TPC can do the job.
- Target .ne. Water !!!!!

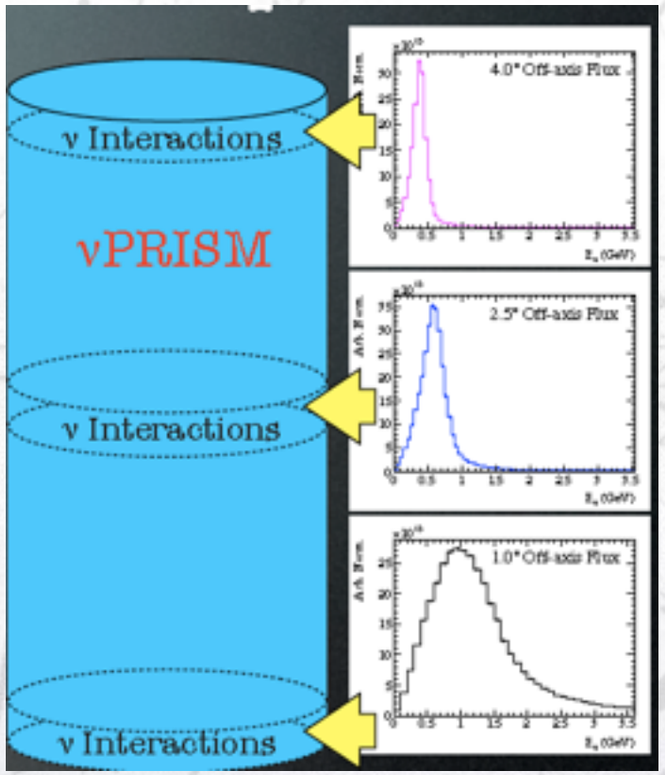
Low Energy hadrons contain information about the interaction channel.



Near detector III

- Discussing the possibility of an intermediate detector using NuPrism technology:
  - movable water Cerenkov detector!.

$\Sigma_i a_i$



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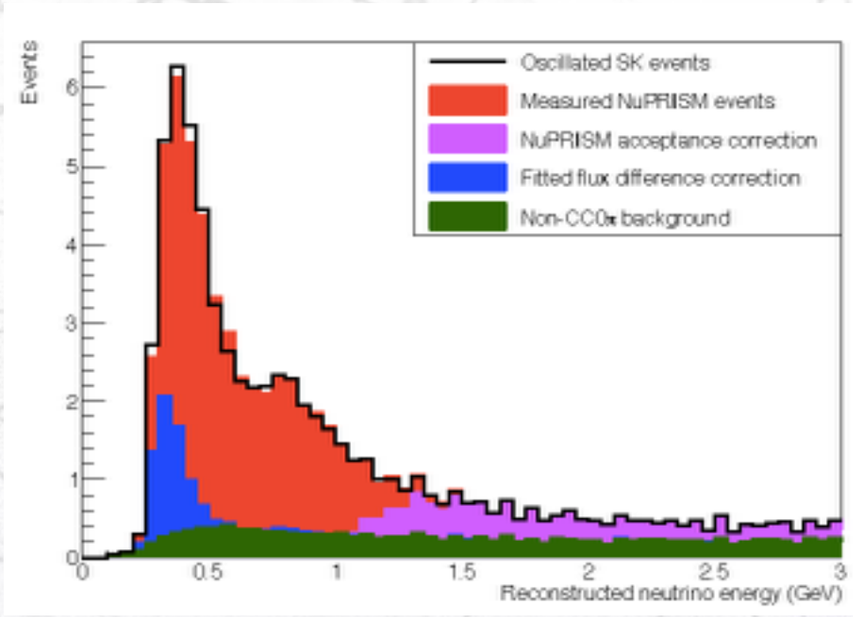
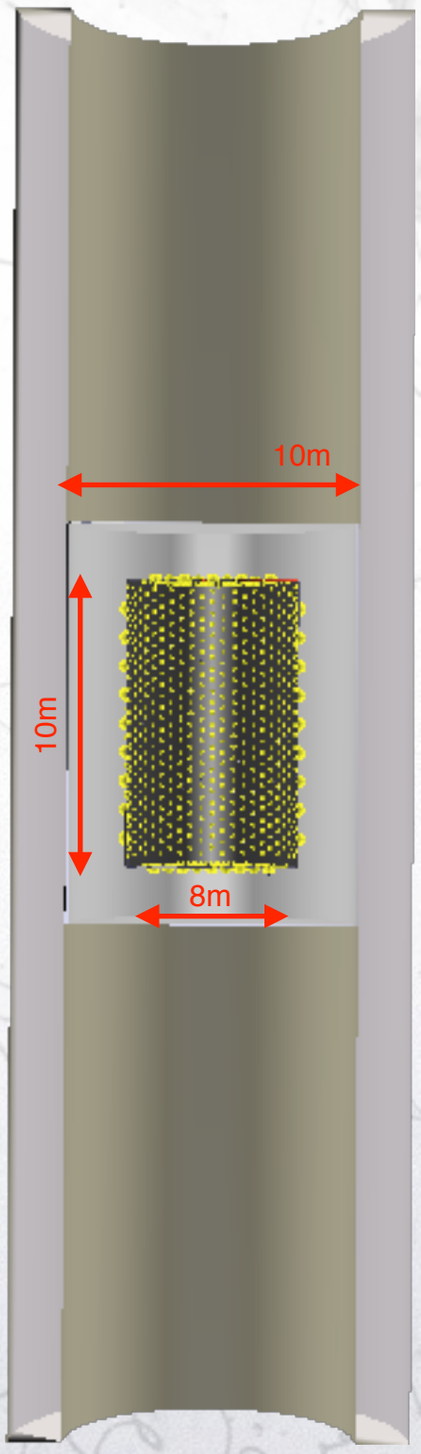




- NuPrism can also address ν_e/ν_μ because at very large off-axis angle the background in ν_e selection is reduced.

Physics potential

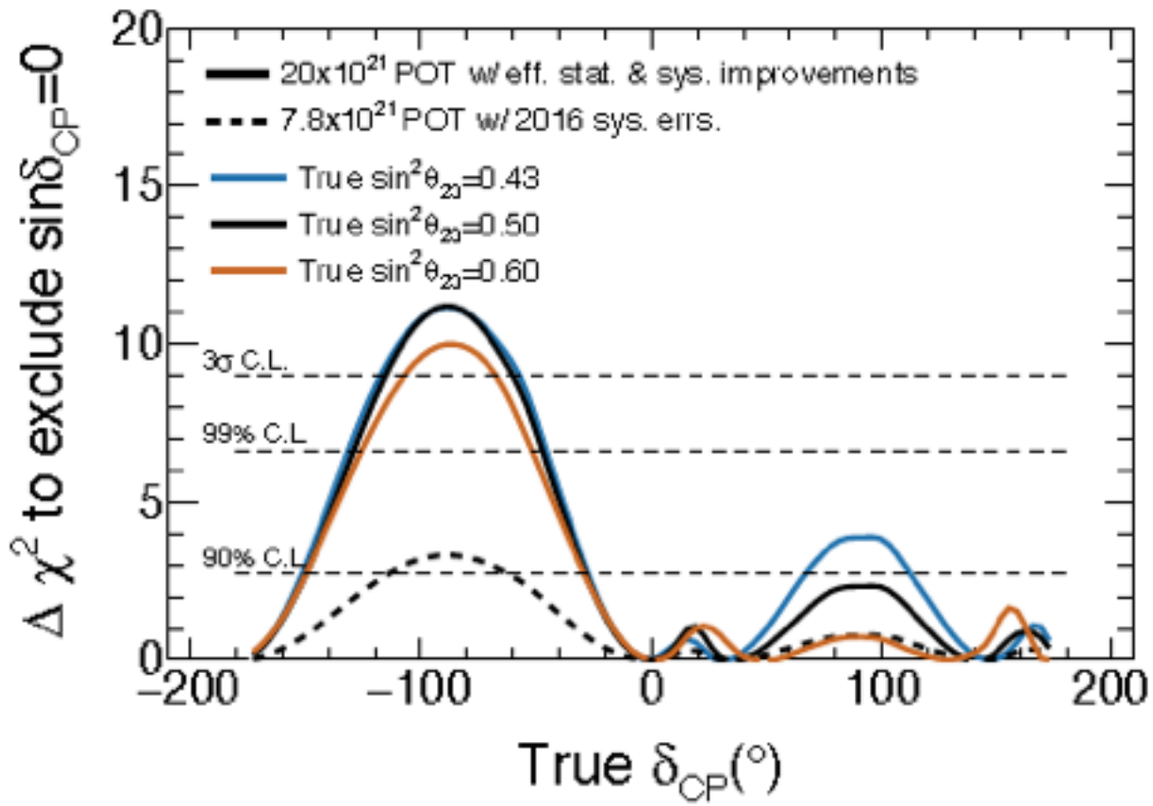
- Events to be observed if running 50% in neutrino and 50% in antineutrino configurations.

	True δ_{CP}	Total	Signal $\nu_\mu \to \nu_e$	Signal $\bar{\nu}_\mu \to \bar{\nu}_e$	Beam CC $\nu_e + \bar{\nu}_e$	Beam CC $\nu_\mu + \bar{\nu}_\mu$	NC
ν-mode	0	467.6	356.3	4.0	73.3	1.8	32.3
ν_e sample	$-\pi/2$	558.7	448.6	2.8	73.3	1.8	32.3
$\bar{\nu}$-mode	0	133.9	16.7	73.6	29.2	0.4	14.1
$\bar{\nu}_e$ sample	$-\pi/2$	115.8	19.8	52.3	29.2	0.4	14.1

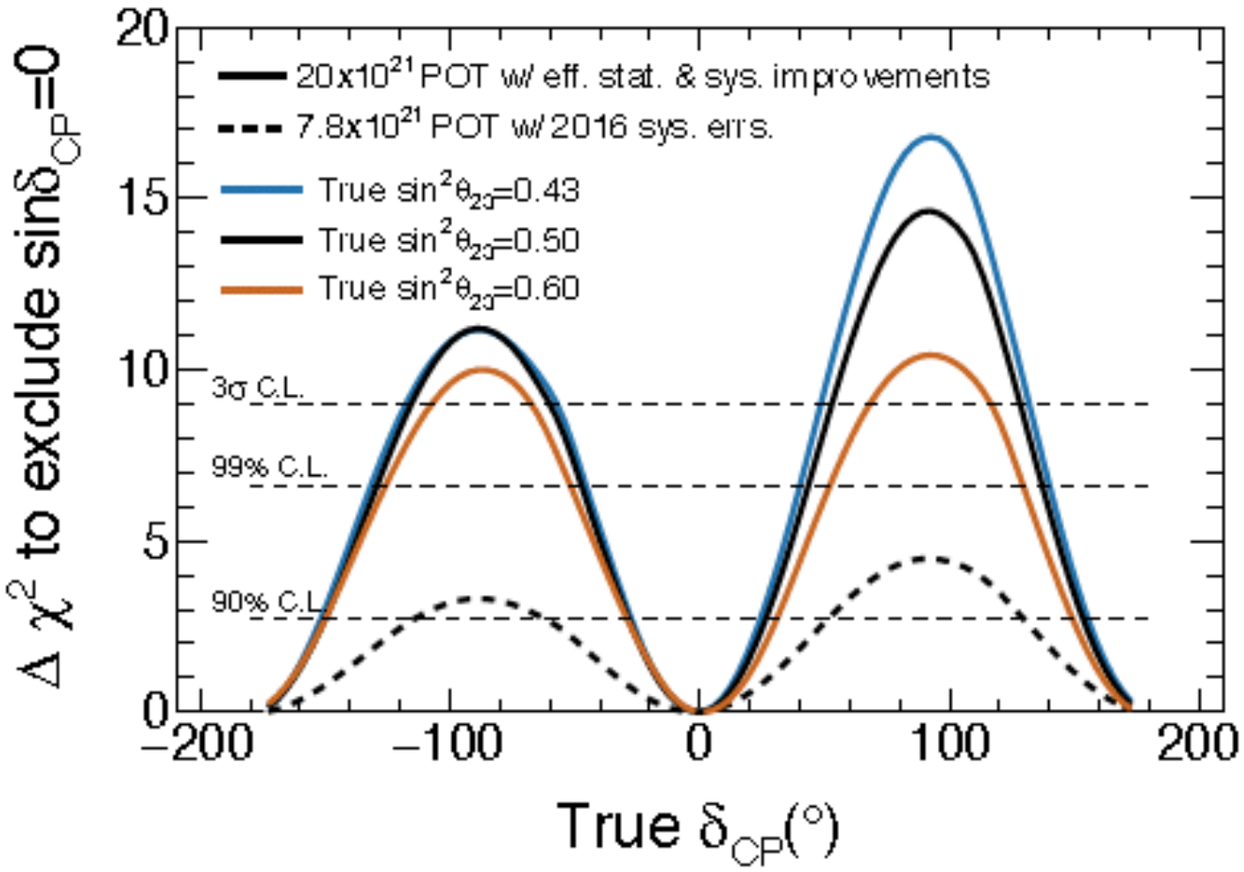
	Total	Beam CC ν_μ	Beam CC $\bar{\nu}_\mu$	Beam CC $\nu_e + \bar{\nu}_e$	$\nu_\mu \to \nu_e +$ $\bar{\nu}_\mu \to \bar{\nu}_e$	NC
ν-mode ν_μ sample	2735.0	2393.0	158.2	1.6	7.2	175.0
$\bar{\nu}$-mode $\bar{\nu}_\mu$ sample	1283.5	507.8	707.9	0.6	1.0	66.2

Physics Potential

- We do not know mass hierarchy

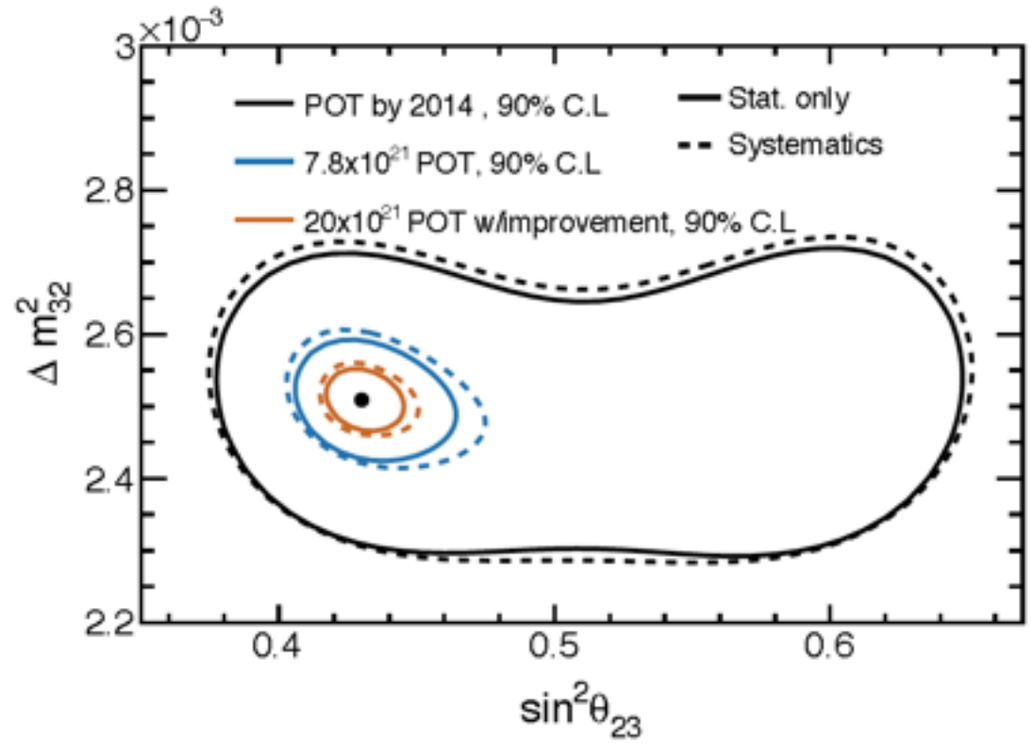


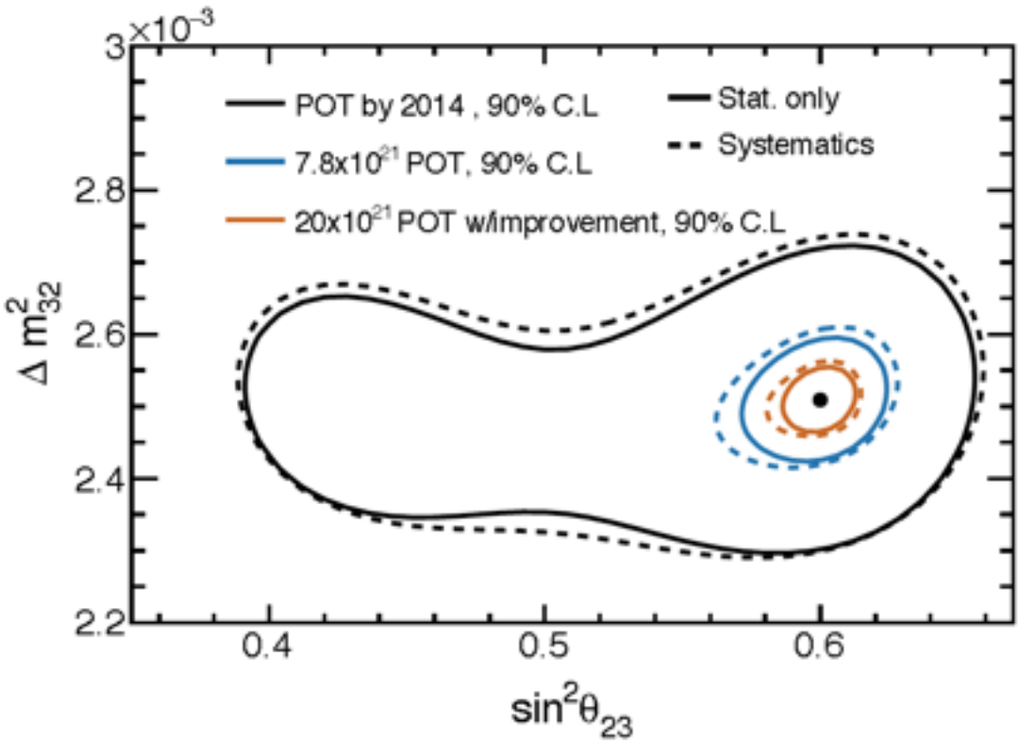
- We do know mass hierarchy



Physics Potential

- The knowledge of θ_{23} is critical





- But the sensitivity is much larger!

(Political) Status

- T2K-II expression of interest was submitted to the JPARC PAC in January with a very positive feed back.
- T2K-II proposal (basically the same as the eoi with a different name) was submitted in summer PAC and it has been approved at level I (this does not include NuPrism).
  - Level I means access to limited funding and infrastructure.
  - Second (and last) approval level will take place in 1/2 years.
- In the meanwhile, ND has started to look for possible scenarios for the upgrade:
  - CERN neutrino platform.
  - New collaborators.
  - Canada has requested 20 M$ for the NuPrism project: resolution in fe months!.

From T2K to T2KII

T2K

T2K-II