IN2P3 contributions to the Japanese neutrino program: T2K, T2K-II, Super-K and Hyper-K

Claudio Giganti
for the LLR and LPNHE neutrino groups

IN2P3 Scientific Council – 28/06/2018

>30 years program

IN2P3 groups join T2K

T2K starts data taking

Take data in $\overline{\nu}$-mode

LLR joins Super-K

T2K phase-II + ND280 upgrade

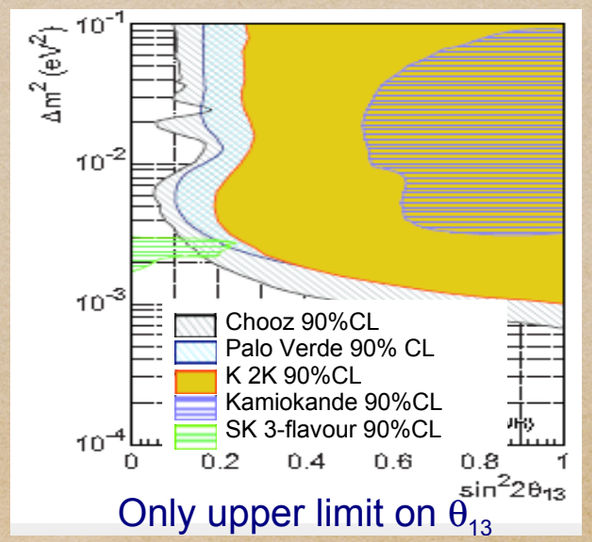
Start of Hyper-K

2004 2006 2008 2010 2012 2014 2016 2018 2020 2022 2024 2026 2036

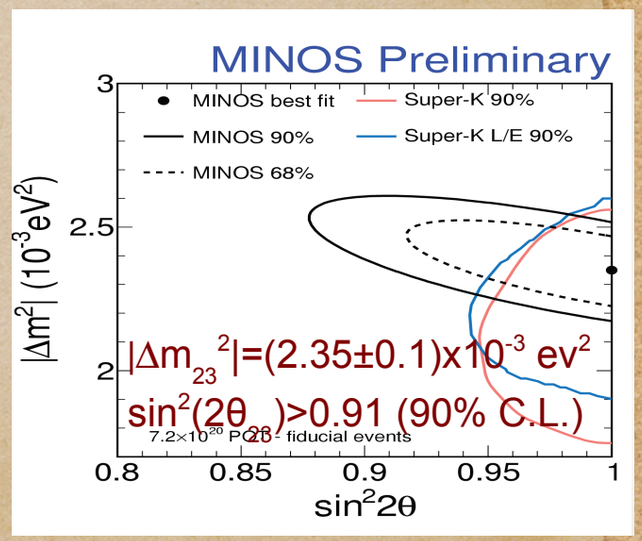
~2009

θ_{13} and δ_{CP} unknown

Atmospheric (SK, K2K, Minos)
→ θ_{23}, Δm_{32}



Only upper limit on θ_{13}



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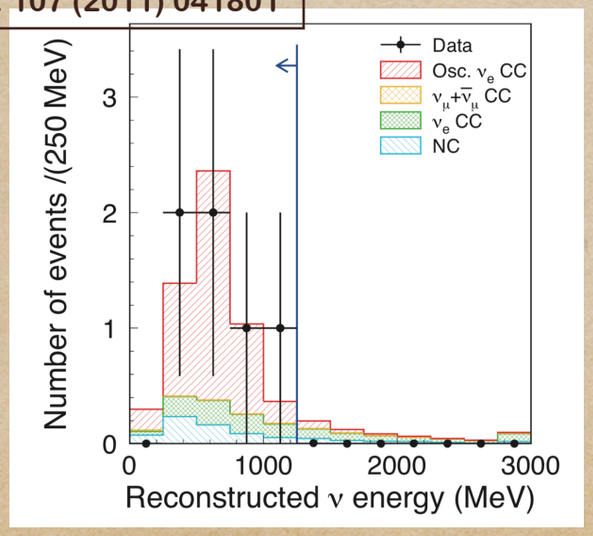
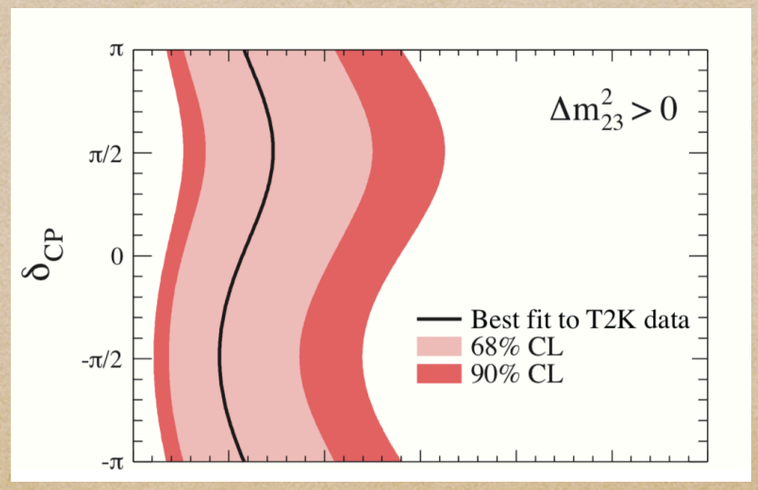
Phys.Rev.Lett. 107 (2011) 041801





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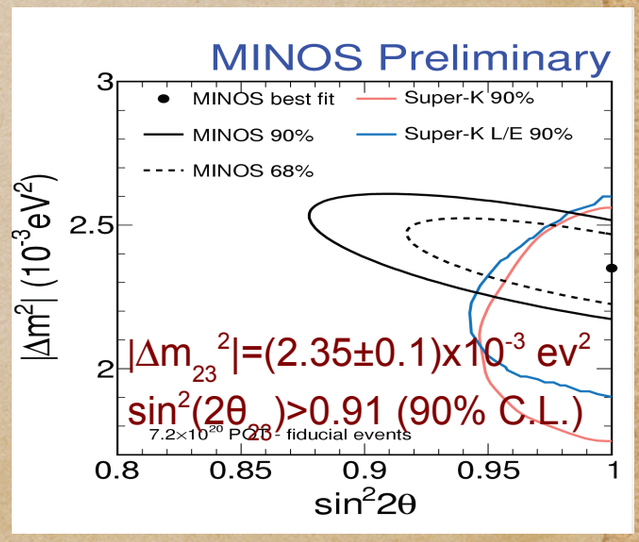

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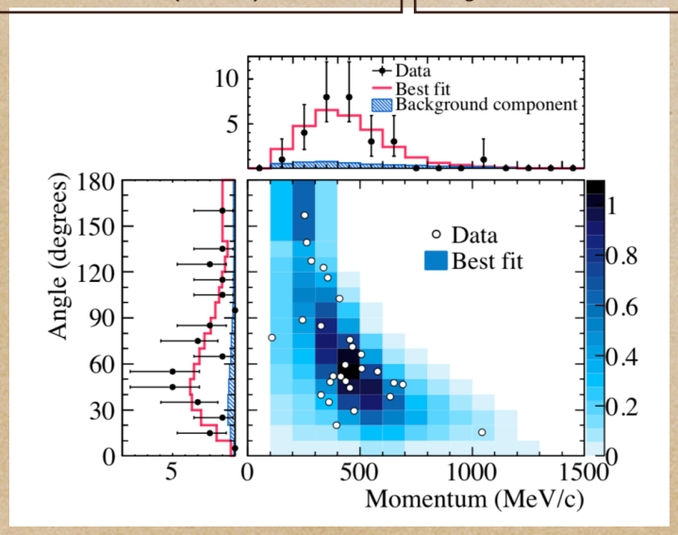

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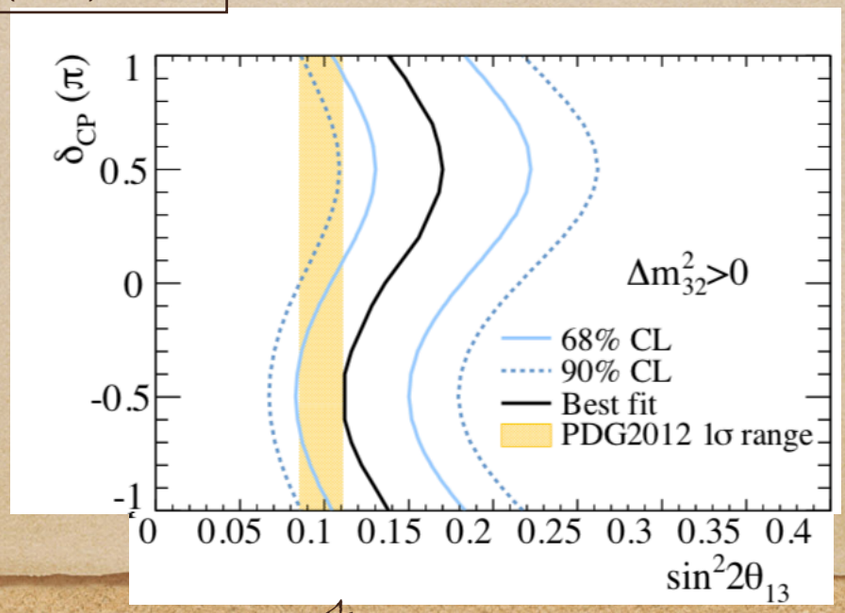

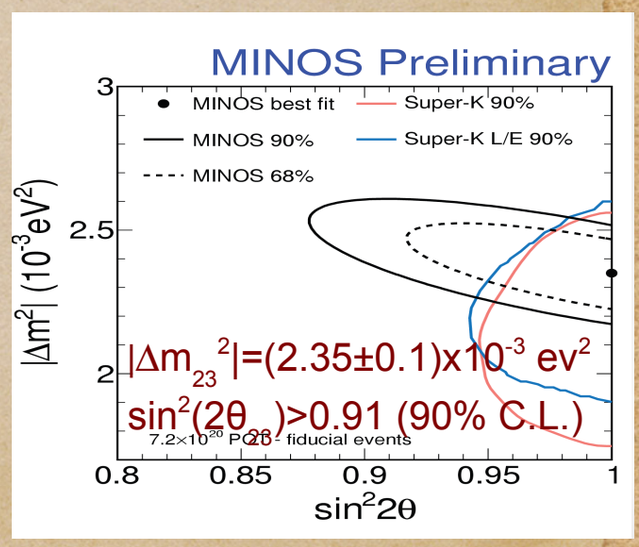

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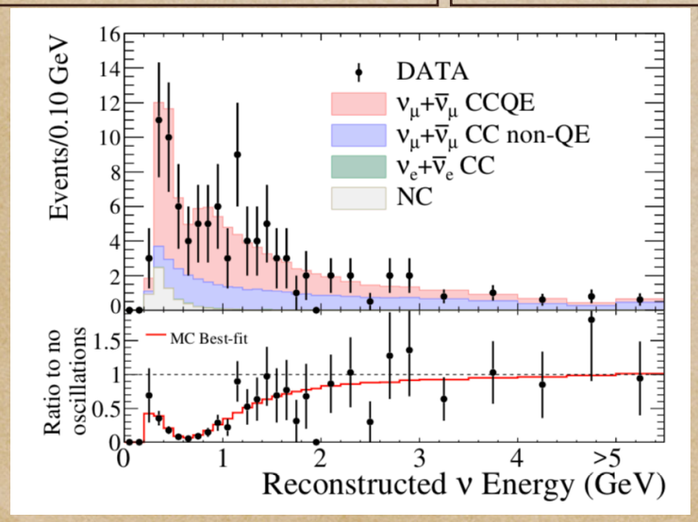

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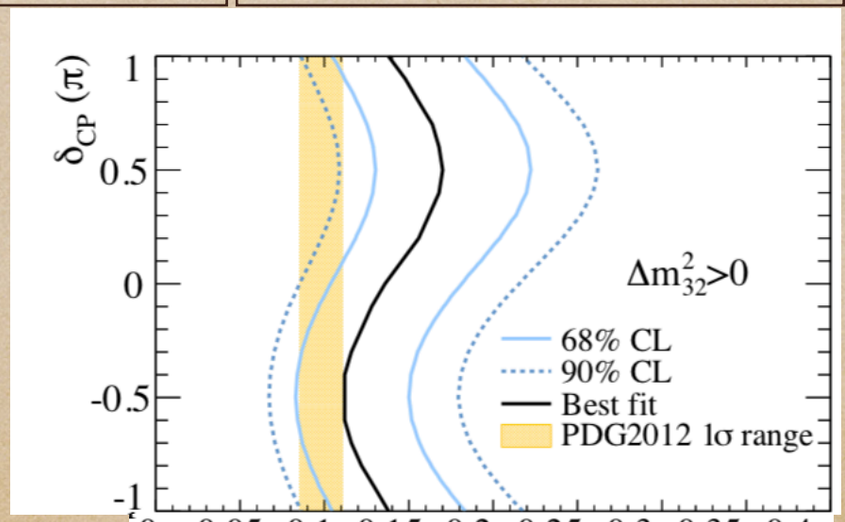

Precise measurement of θ_{23}, Δm^2_{32}

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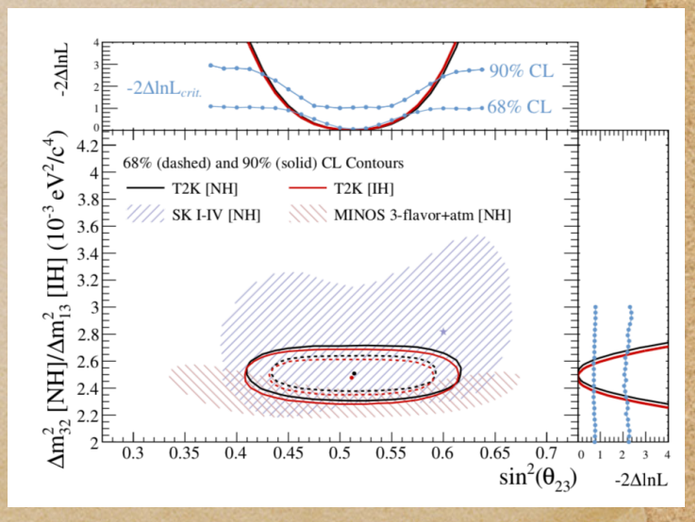

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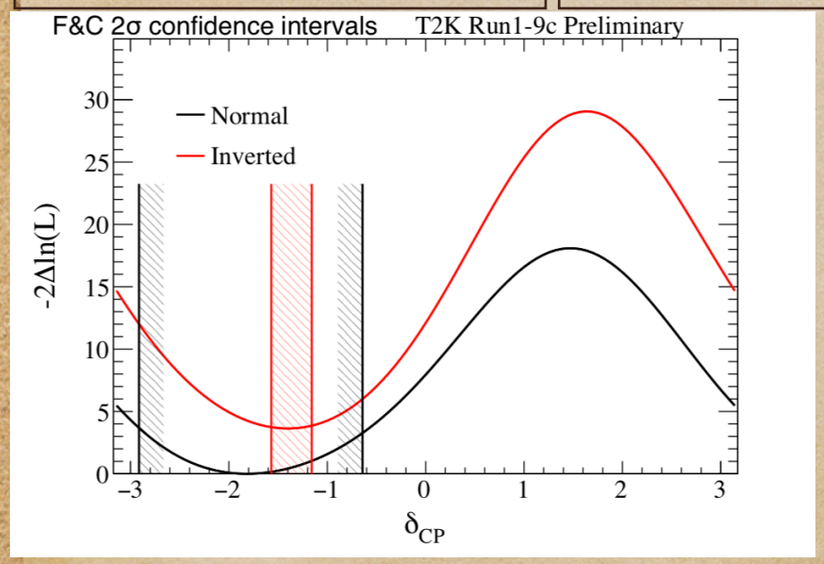
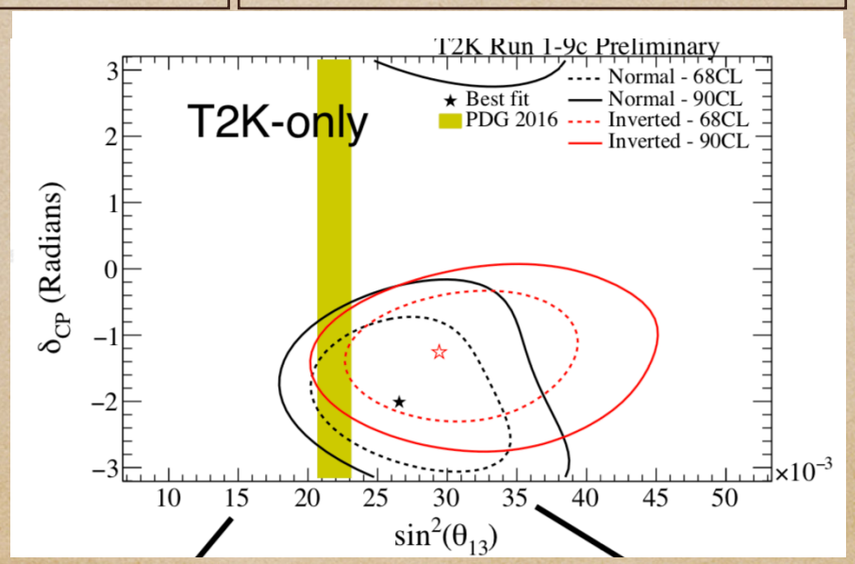
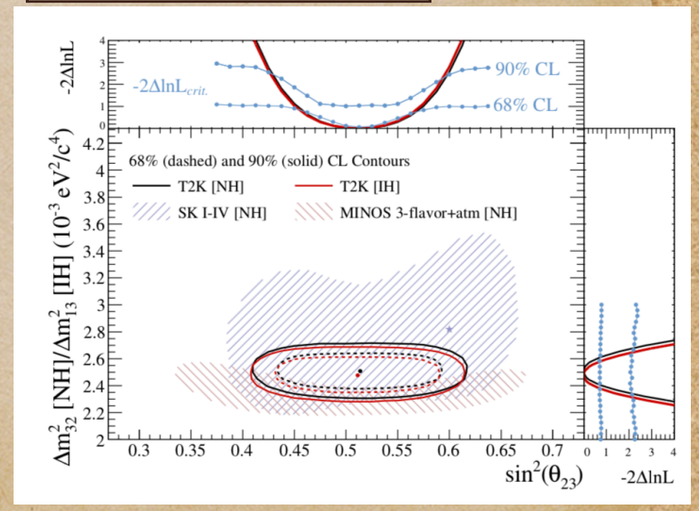
M. Wascko, Neutrino 2018







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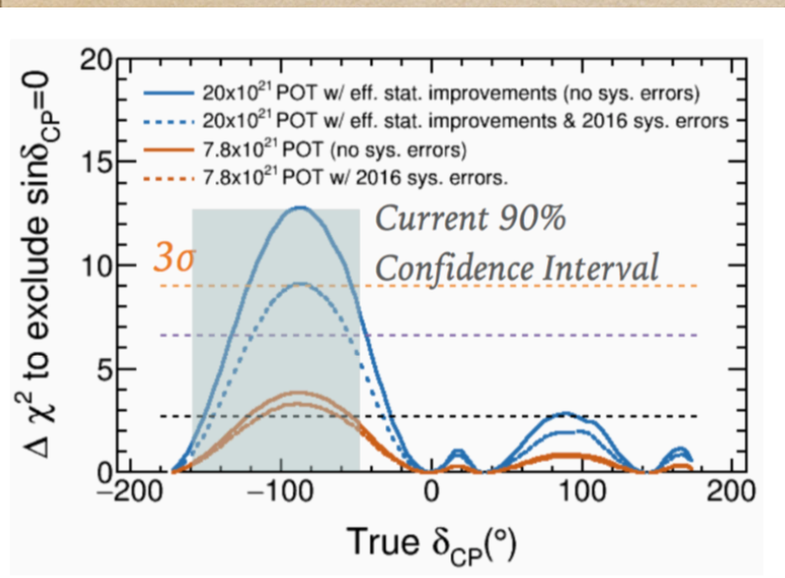
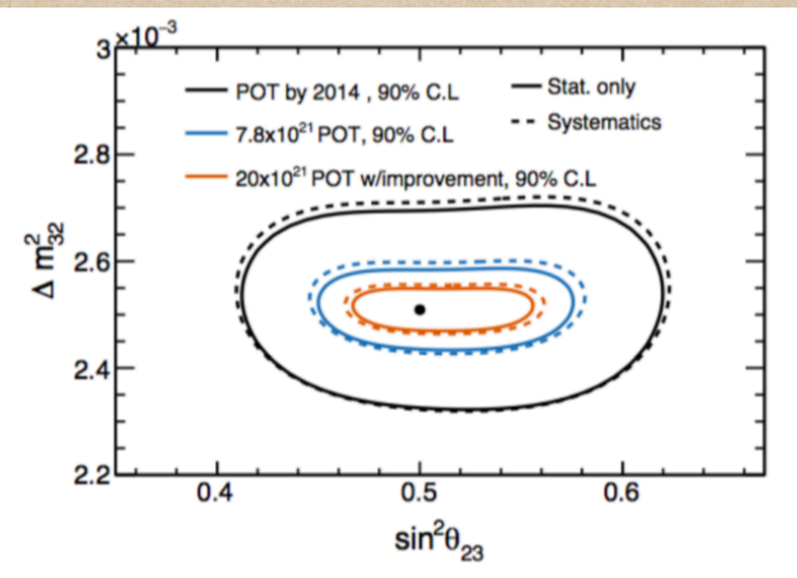
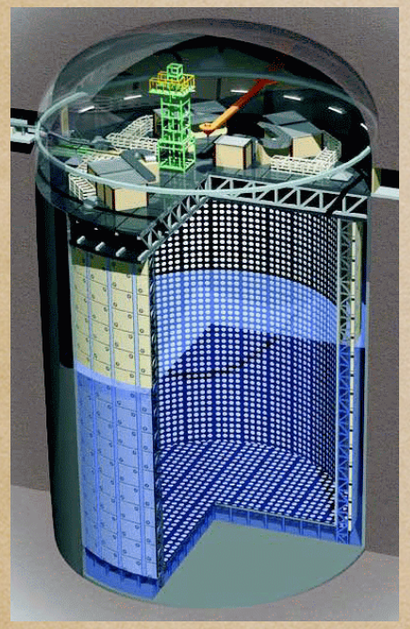




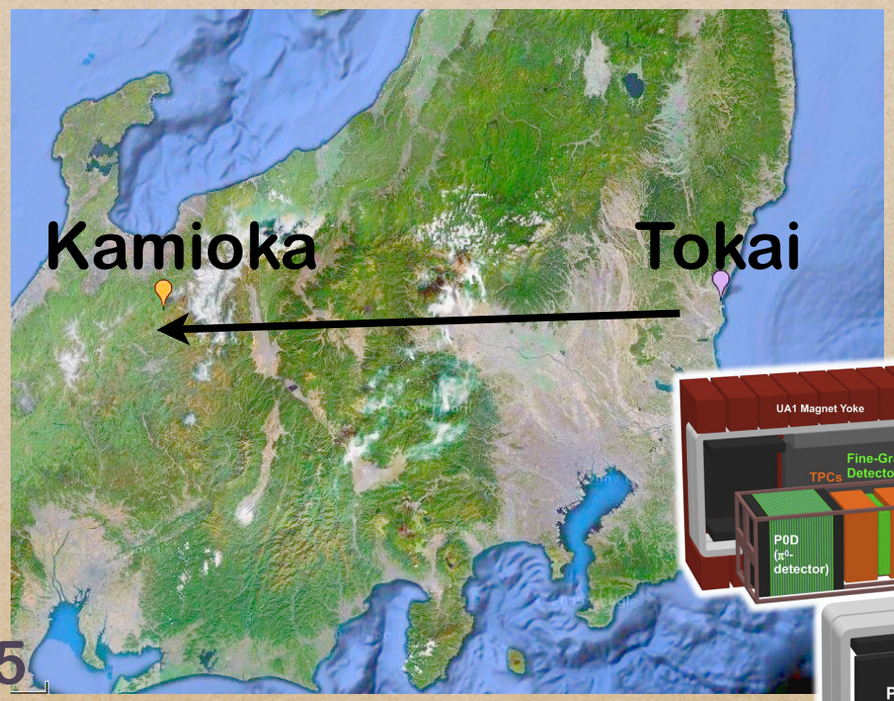
- CP violation at >3σ ? → >5σ with Hyper-K?
- Mass ordering?
- $\sin^2\theta_{23}$ octant?
- And many ν and $\bar{\nu}$ cross-section measurements

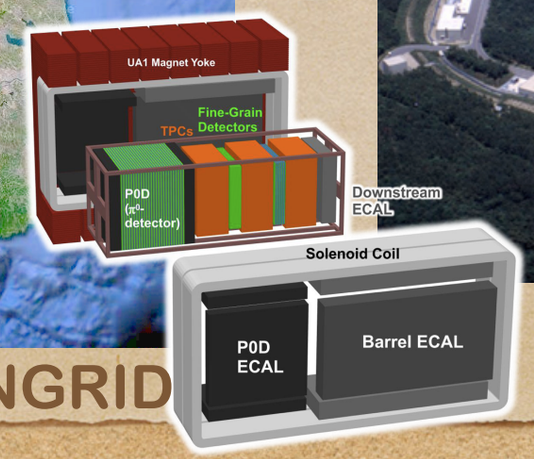
The T2K experiment

- High intensity ~600 MeV ν_μ beam produced at J-PARC (Tokai, Japan)
- Neutrinos detected at the Near Detectors (ND280) and at the Far Detector (Super-Kamiokande) 295 km from J-PARC
- Can run in ν or $\bar{\nu}$ mode by changing horn polarity
- Main physics goals:
  - Observation of ν_e and $\bar{\nu}_e$ appearance → determine θ_{13} and δ_{CP}
  - Precise measurement of ν_μ ($\bar{\nu}_\mu$) disappearance → θ_{23} and Δm^2_{32}



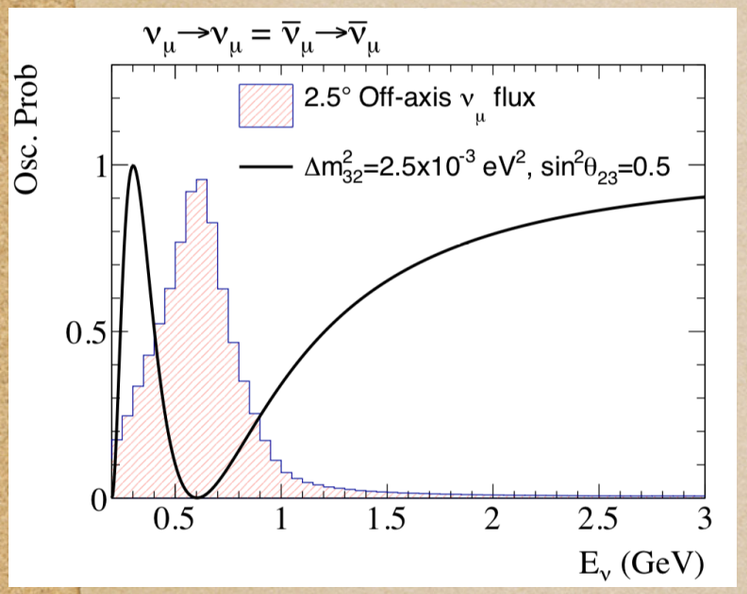
Super-Kamiokande: 22.5 kt fiducial volume water Cherenkov detector

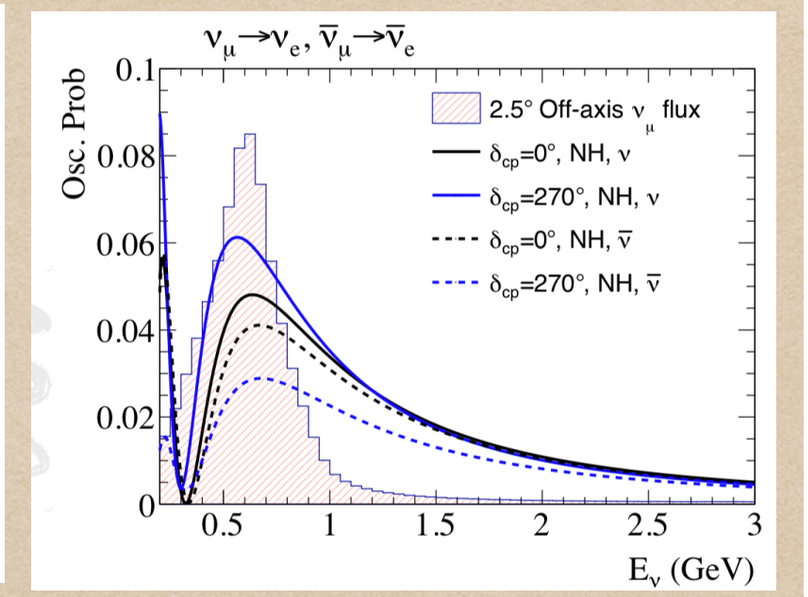


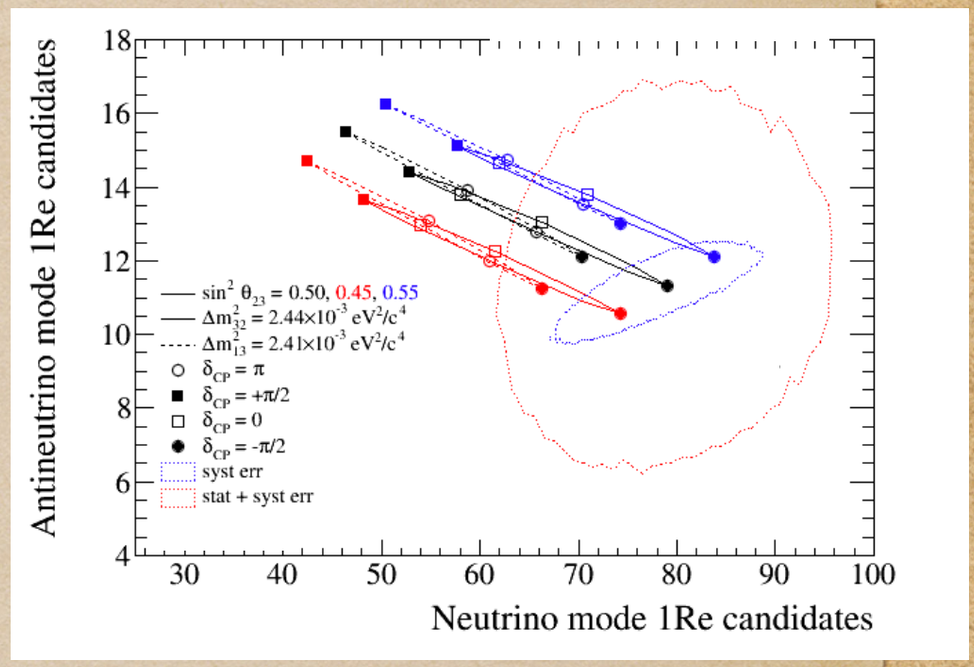


ND280+INGRID

Sensitivity to oscillation parameters







- $P(\nu_\mu \to \nu_\mu) = P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$
  - Test of CPT conservation
  - Sensitive to $\sin^2(2\theta_{23})$ → cannot distinguish the octant
  - Sensitive to $|\Delta m^2_{23}|$ → cannot distinguish NO and IO
- $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$
  - Sensitive to CP violation
  - Sensitive to octant of $\sin^2(\theta_{23})$
  - Sensitive to matter effects (hierarchy) → weak in T2K since L is (relatively) short

T2K goals:
measure ν_μ and $\bar{\nu}_\mu$ disappearance and ν_e and $\bar{\nu}_e$ appearance probabilities

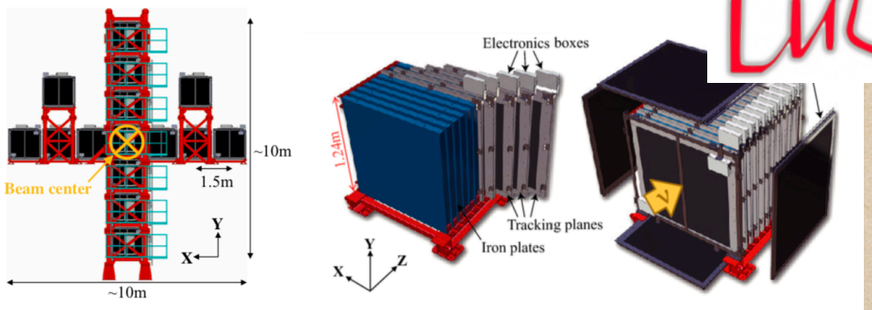
IN2P3 groups in T2K

	T2K	NA61	Wagasci	T2K-II	SK	HK
LLR	4	0	3	4	4	5
LPNHE	3	2	0	5	0	5

Permanent physicists only

- **Main responsibilities:**
  - Convener of T2K beam group
  - NA61/SHINE analysis coordinator
  - Convener of T2K oscillation analysis
  - 2 conveners of CC-0π cross-section group
  - Convener of INGRID and Wagasci electronics
  - 7 PhD theses defended since 2009, 4 PhD theses on-going

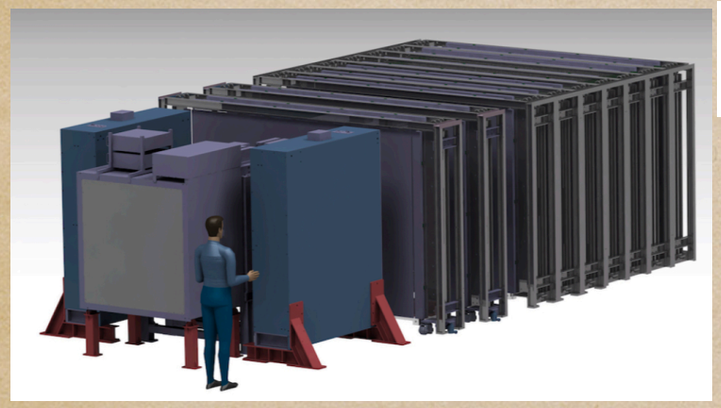
Near Detectors



INGRID: monitor neutrino beam profile and direction

Measure ν cross-sections

LLR contributed to mechanics and MPPC testing

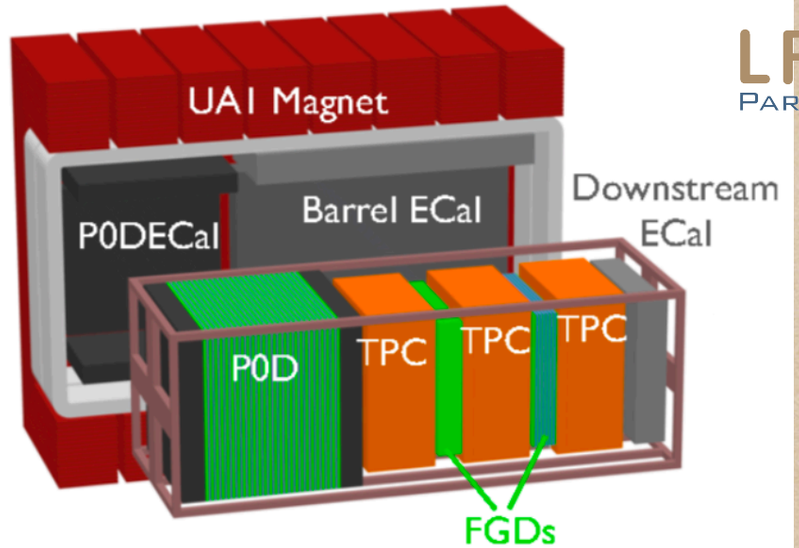


WAGASCI + BabyMIND

Newly installed ND (part of T2K since 2018)

Measure ν and $\bar{\nu}$ cross-sections on water

LLR: contributed to mechanics and DAQ



ND280 off-axis: detectors installed in the UA1/NOMAD magnet (0.2 T)

Fundamental input to T2K oscillation analysis

Tracker system composed by

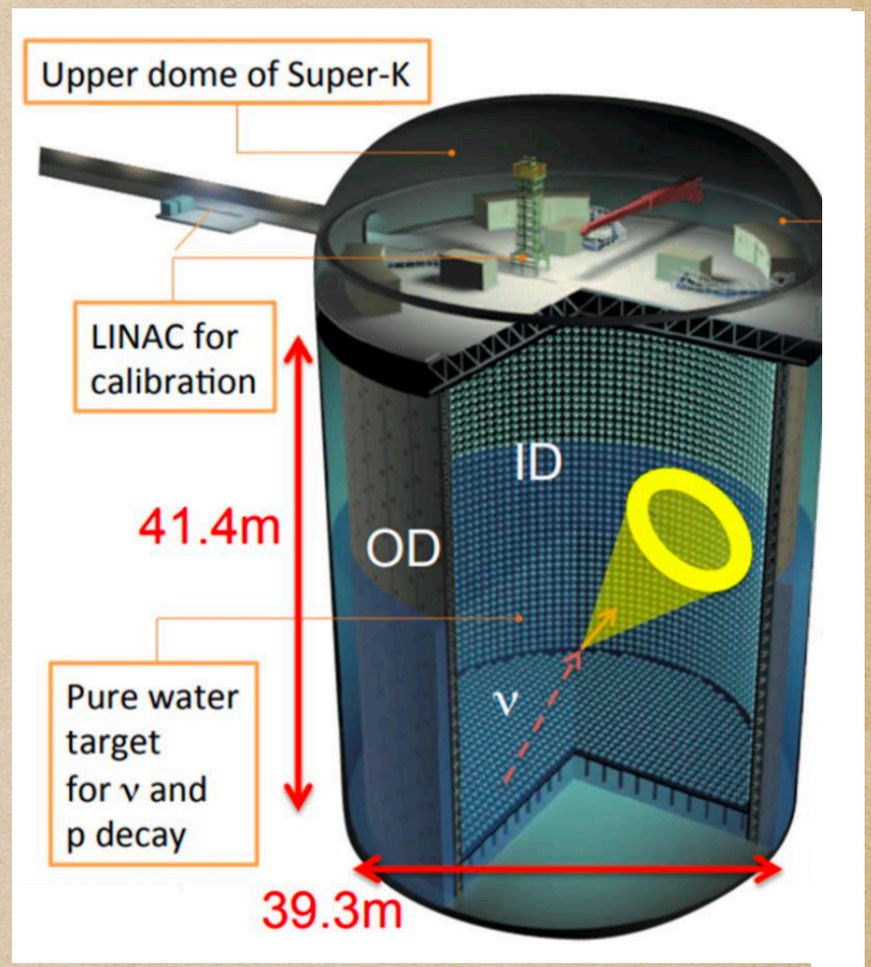
2 Fine Grained Detectors → active target for ν interactions

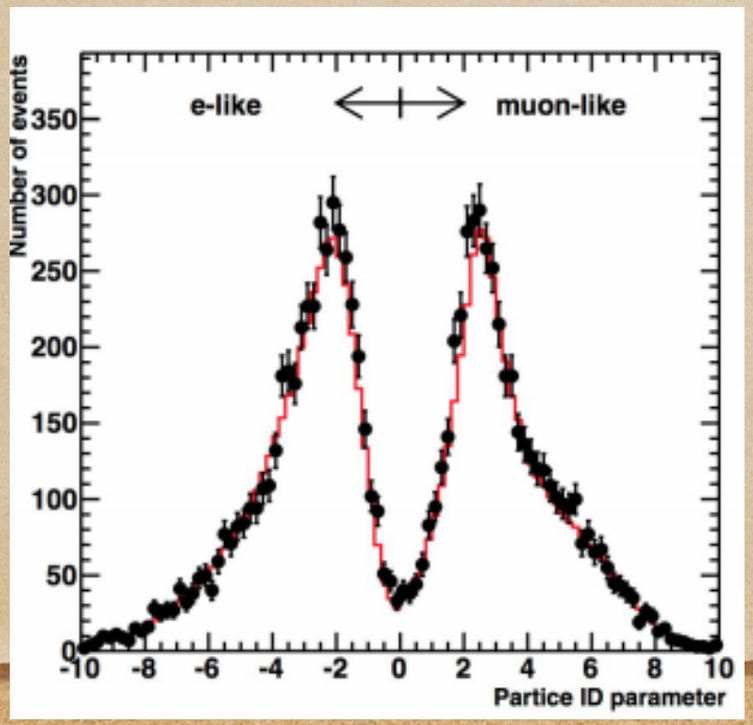
3 Time Projection Chambers to measure charge, momentum and PID of leptons emitted in ν interactions

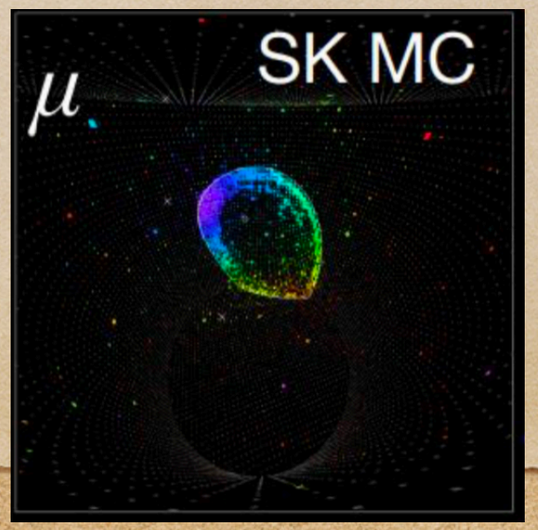
LPNHE contributed to magnet and TPC electronics

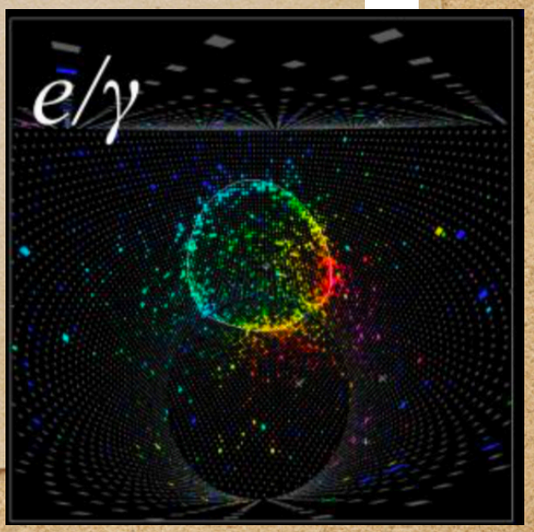
Super-Kamiokande

- 50 kton Water Cherenkov detector
  - ~11000 PMTs for ID, ~2000 for OD
- 1000 m underground at Kamioka mine operated since 1996
- Very good PID capabilities to distinguish between ν_e and ν_μ thanks to shape of Cherenkov ring → <1% misidentification probability

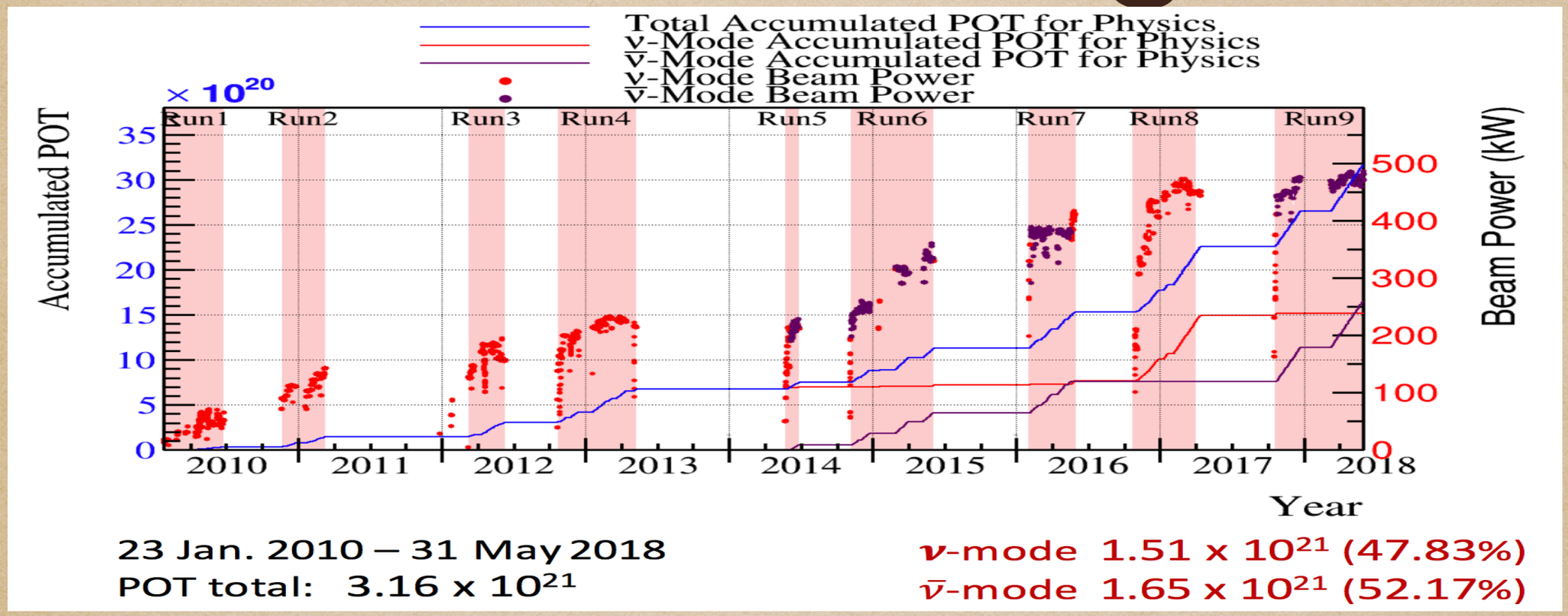




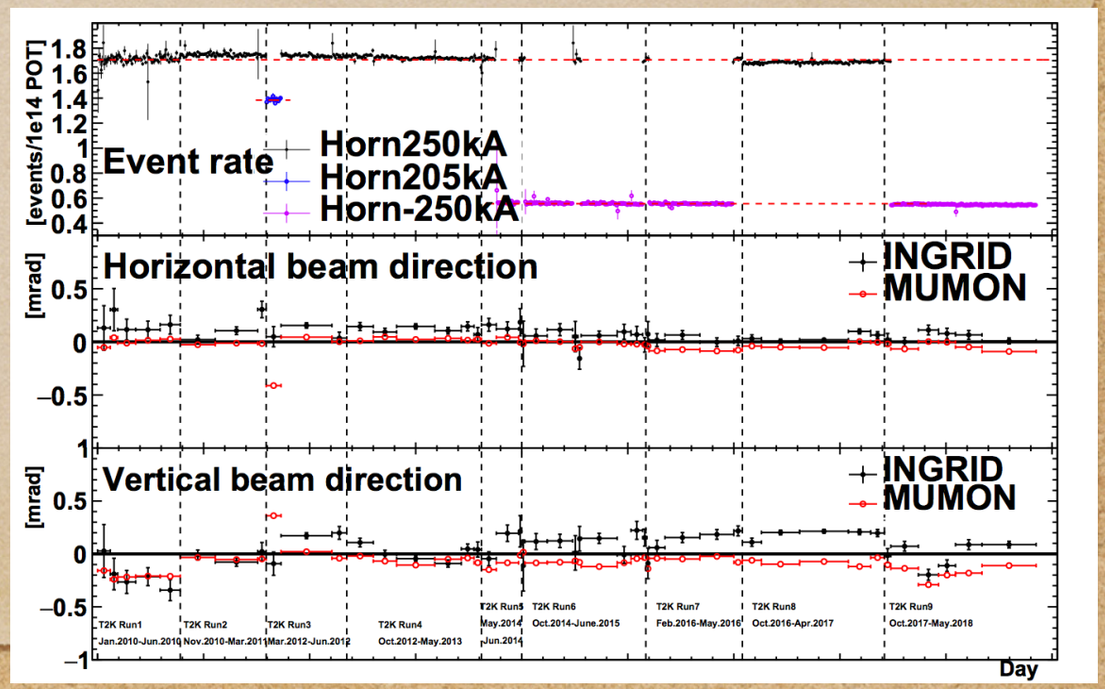




Data taking



- Collected >3.16x10^{21} protons on target (~half ν and half $\bar{\nu}$)
  - 40% of approved p.o.t.
- Reached 500 kW beam power
- Beam stability over the whole beam period measured by INGRID



T2K oscillation analysis

Flux prediction:

- ✓ Proton beam measurement
- ✓ Hadron production (NA61 and others external data)

ND280 measurements:

- ✓ ν_μ and $\bar{\nu}_\mu$ selections to constrain flux and cross-sections

Neutrino interactions:

- ✓ Interaction models
- ✓ External cross-section data

Prediction at the Far Detector:

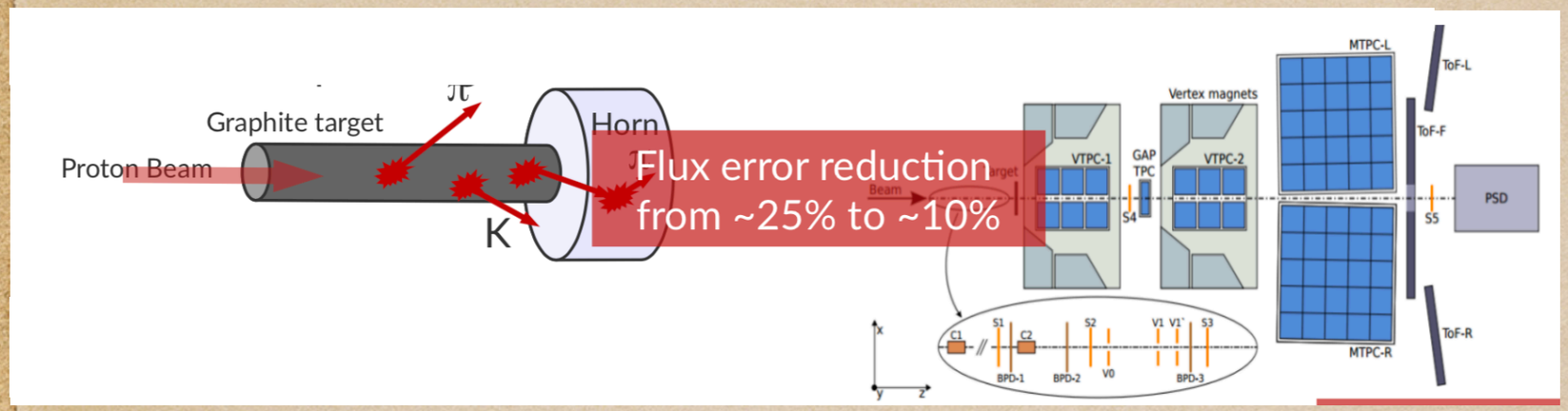
- ✓ Combine flux, cross section and ND280 to predict the expected events at SK

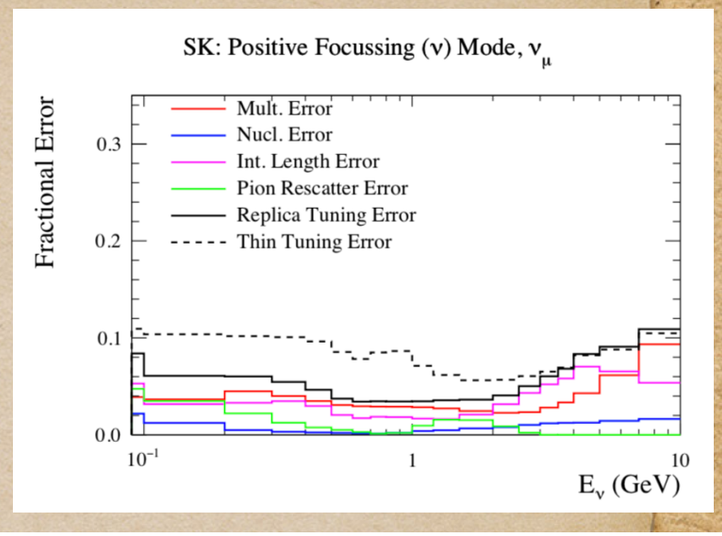
Extract oscillation parameters!

Super-Kamiokande measurements:

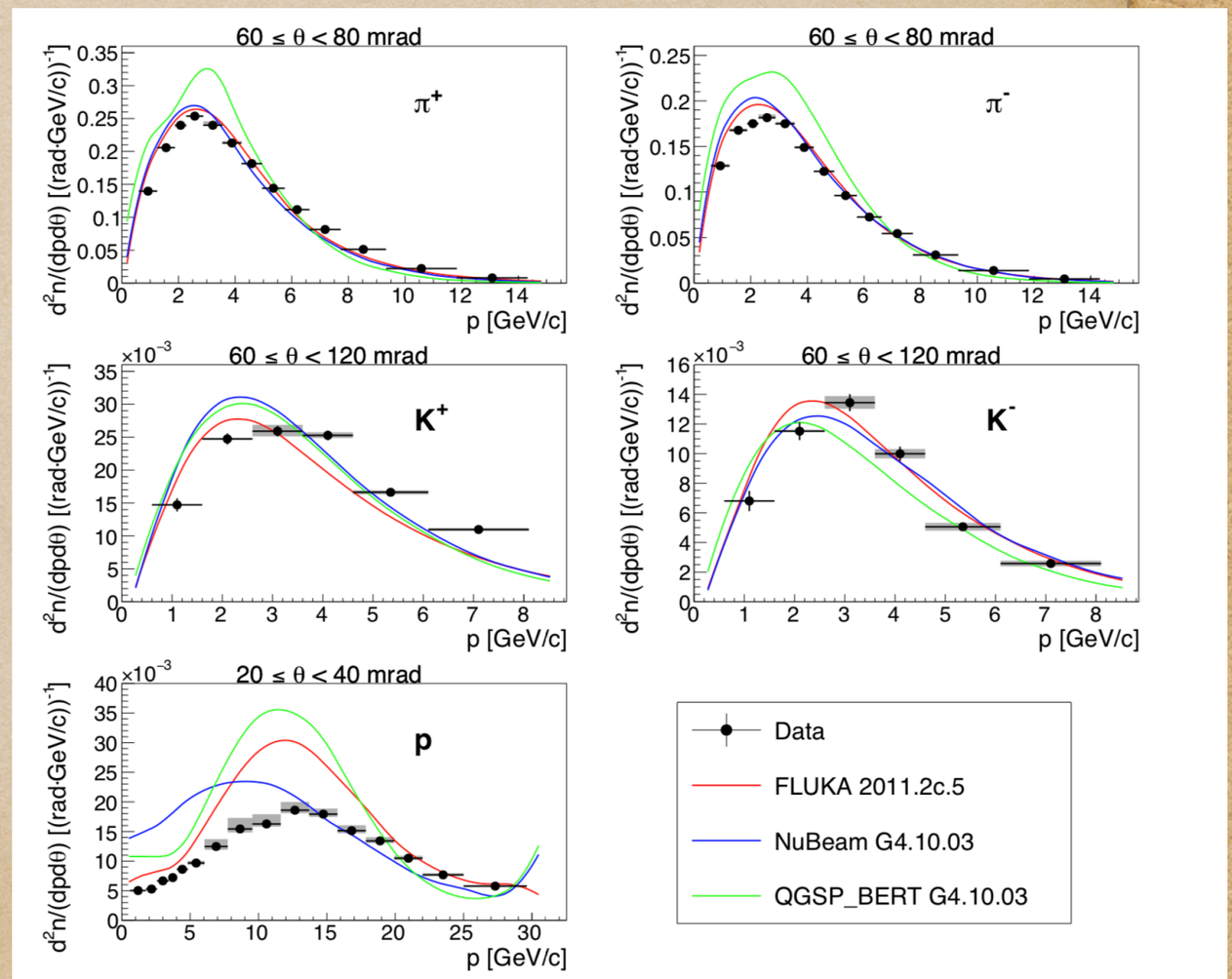
- ✓ Select CC ν_μ and ν_e candidates after the oscillations

Flux uncertainties: NA61/SHINE

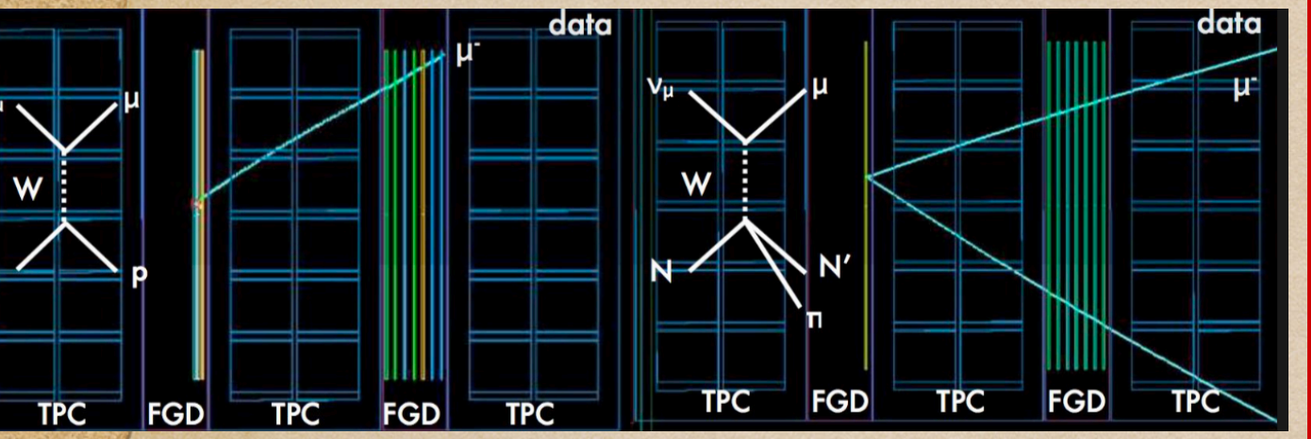


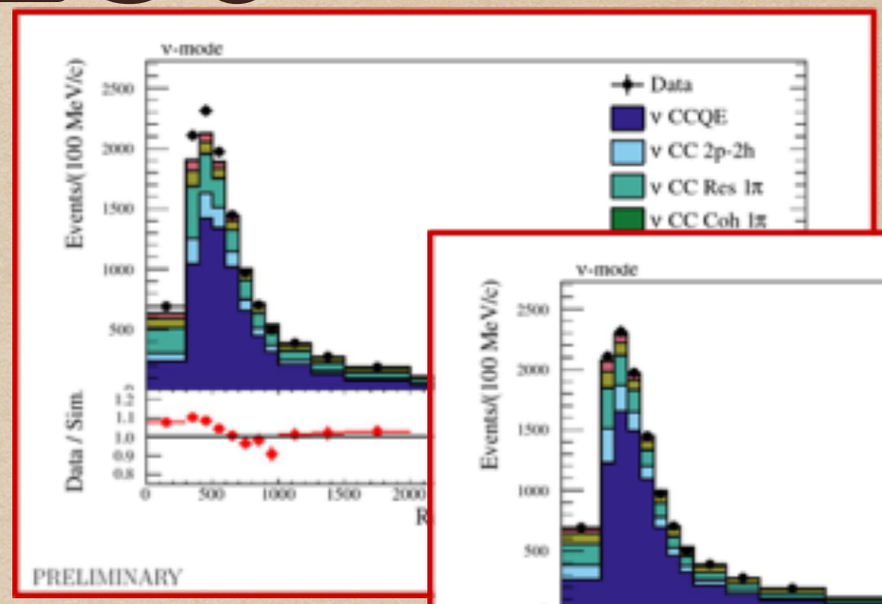


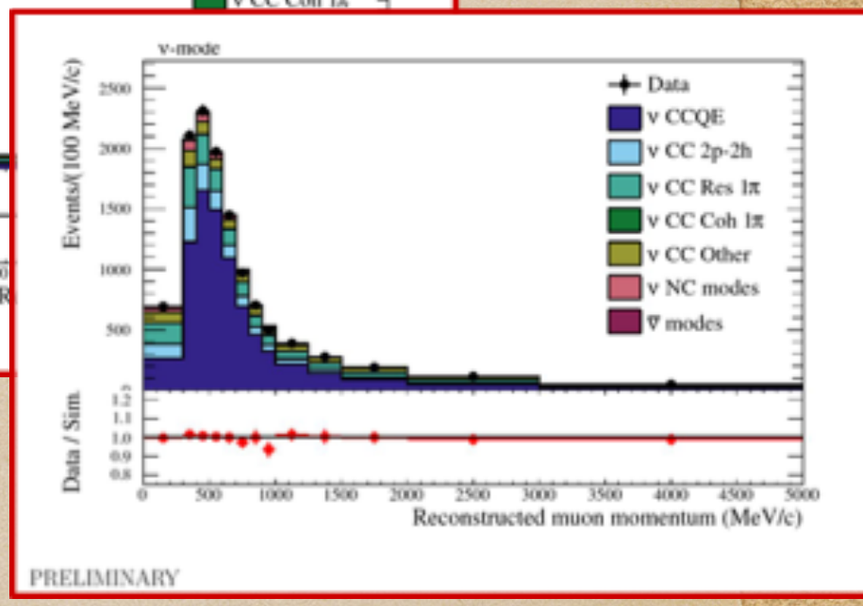
- **Multipurpose detector @ CERN → precision hadron production measurements for T2K (and FNAL) neutrino fluxes predictions**
- **Took data for T2K in 2007, 2009, 2010 with thin and replica target**
- **Thin target data already used → 10% uncertainties on neutrino fluxes**
- **Inclusion of 2010 data with replica target will allow to reduce flux uncertainties to ~5% level**



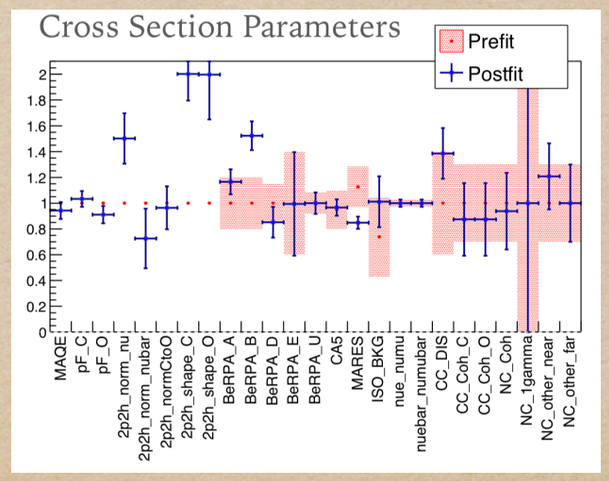
ND280

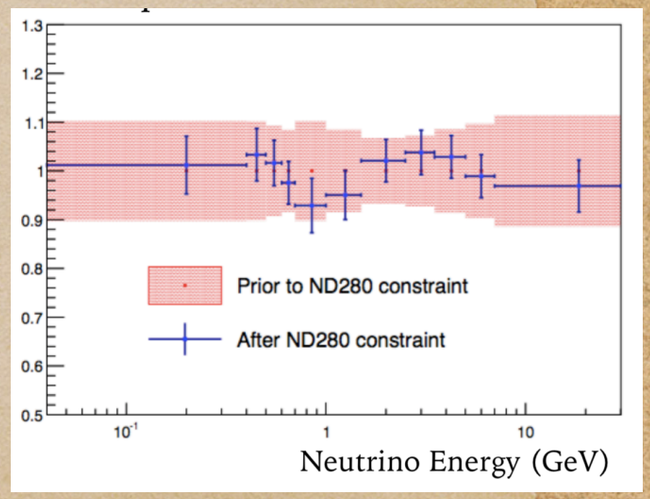






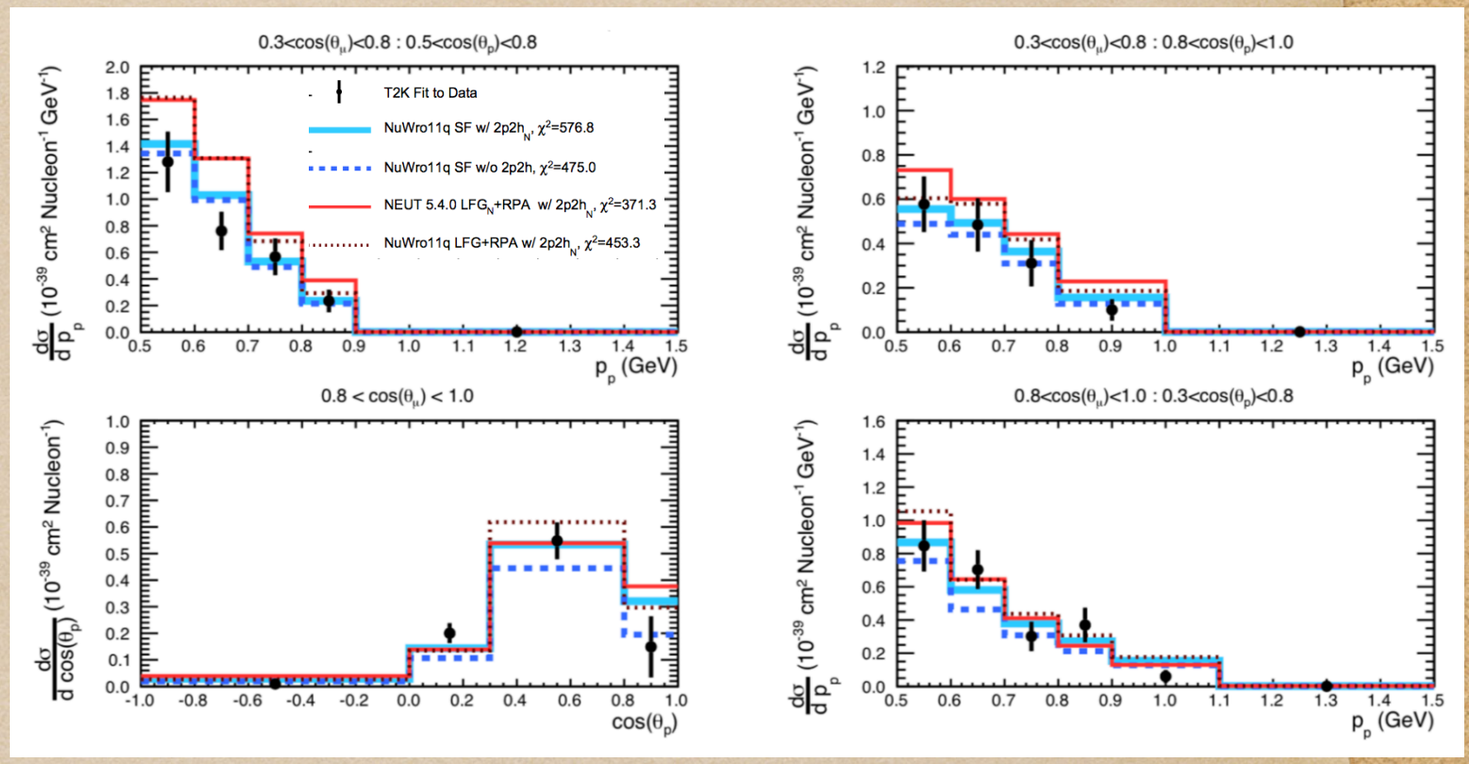
- Select 14 samples of ν_μ and $\overline{\nu}_\mu$ interactions on Carbon and Water with 0,1,>1 π in the final state
- Likelihood fit to constraint flux and cross-section uncertainties for T2K Oscillation Analysis
- Reduce uncertainties from ~15% to ~5%



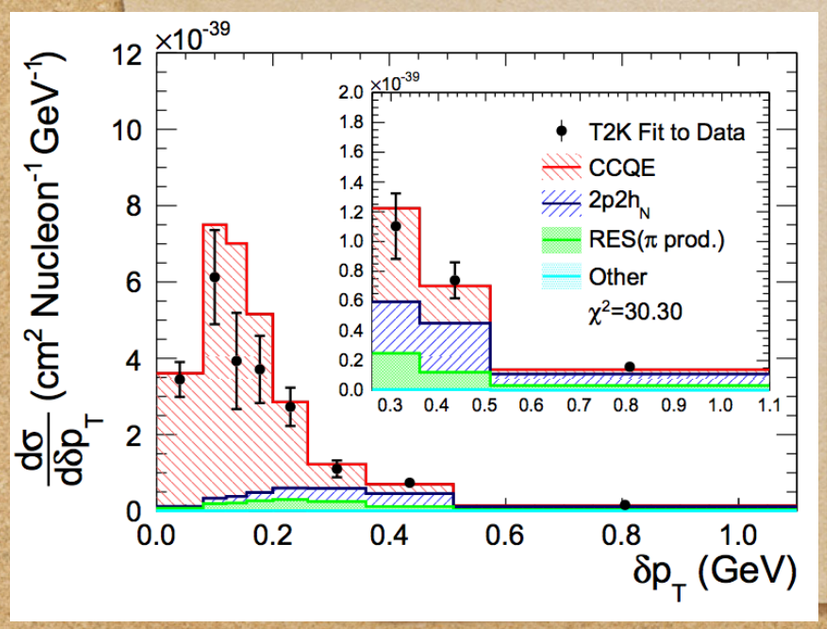


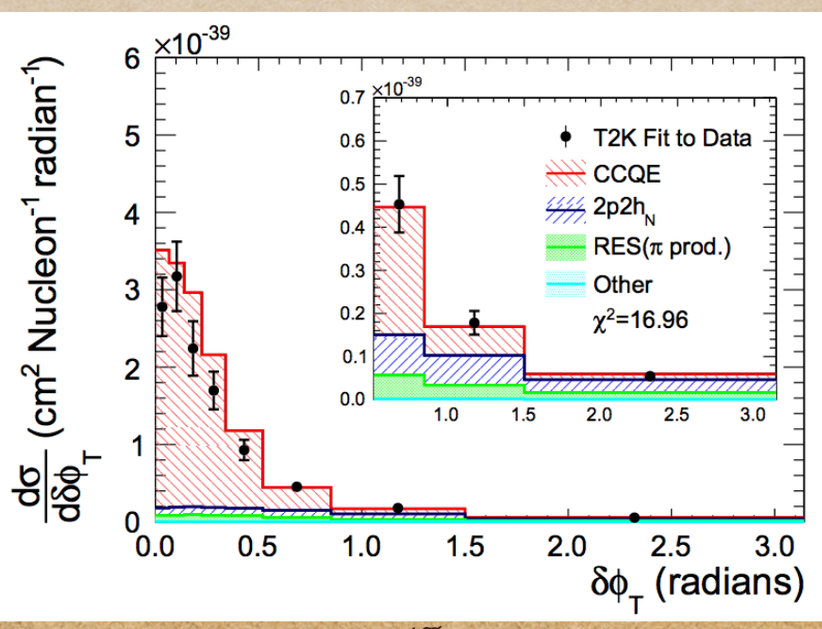
ND280 cross-sections

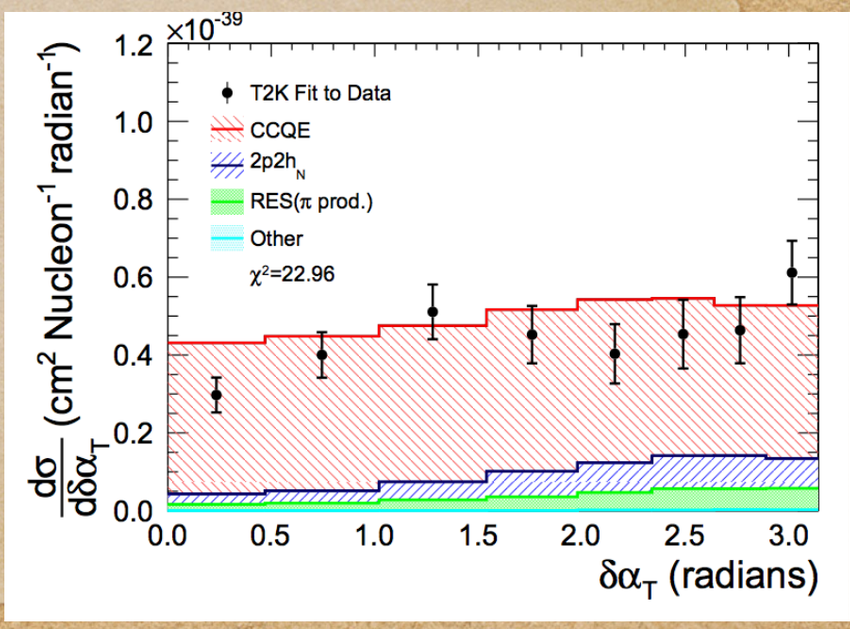
- **14** papers published for measurements of ν and $\bar{\nu}$ cross-sections @ND280
- Example of CC0π analysis with reconstructed protons in the final state (LPNHE,LLR)
- Extract cross-section in 4-dimensional (P_μ, θ_μ, P_p, θ_p)
- Look for single transverse variables sensitive to nuclear effects



arXiv:1802.05078

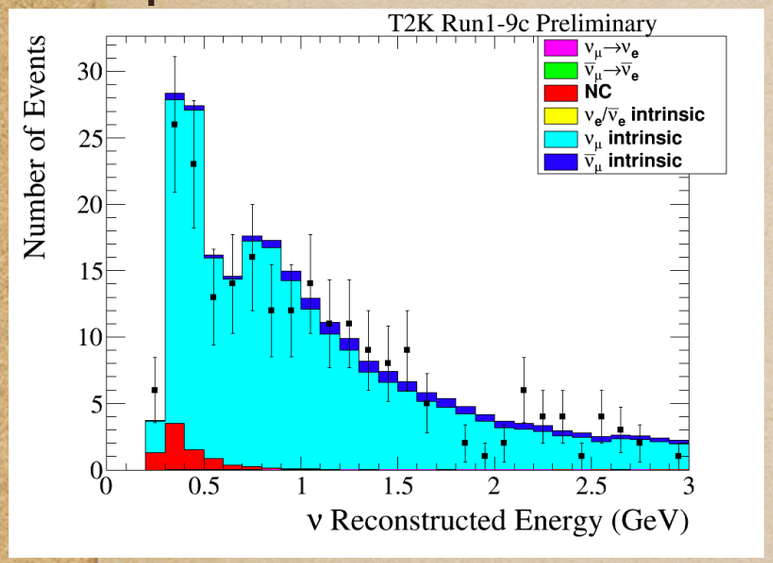




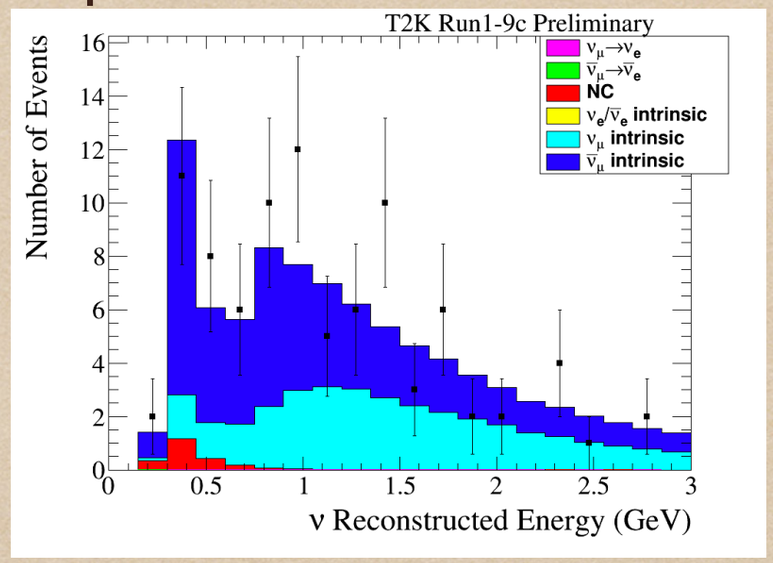


Super-K

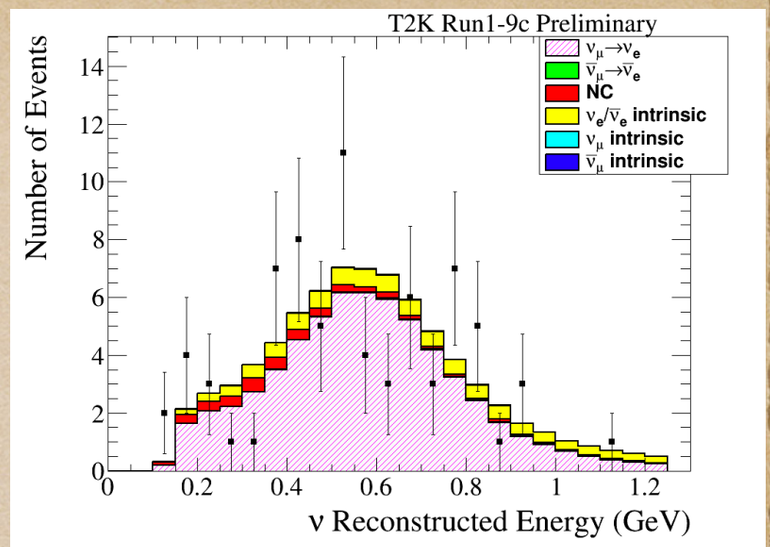
μ-like ν-mode

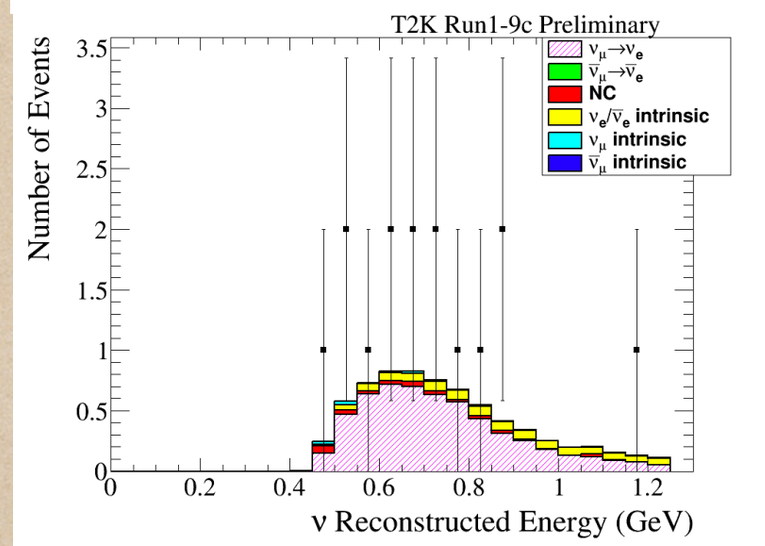


μ-like $\bar{\nu}$-mode

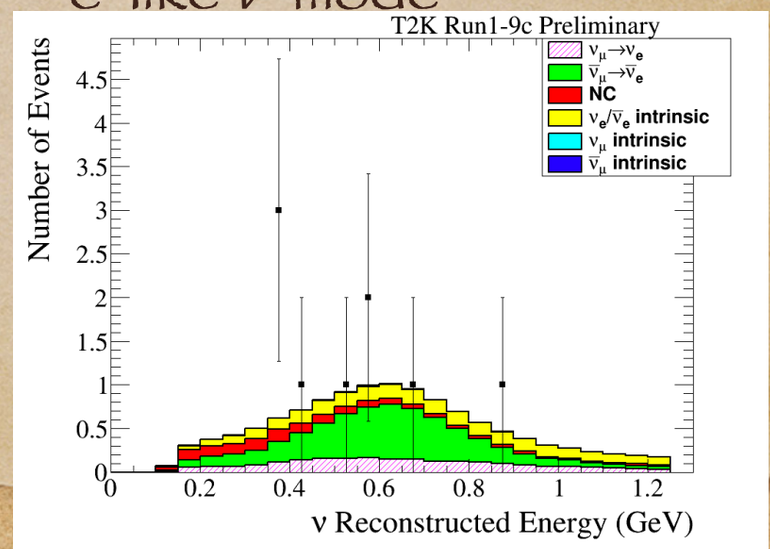


e-like ν-mode





e-like $\bar{\nu}$-mode



	Data	MC expected Number of events			
		$\delta_{CP}=-\pi/2$	$\delta_{CP}=0$	$\delta_{CP}=+\pi/2$	$\delta_{CP}=\pi$
ν-mode e-like	75	73.8	61.6	50.0	62.2
ν-mode e-like+1π	15	6.9	6.0	4.9	5.8
$\bar{\nu}$-mode e-like	9	11.8	13.4	14.9	13.2
ν-mode μ-like	243	268.5	268.2	268.5	268.9
$\bar{\nu}$-mode μ-like	102	95.5	95.3	95.5	95.8

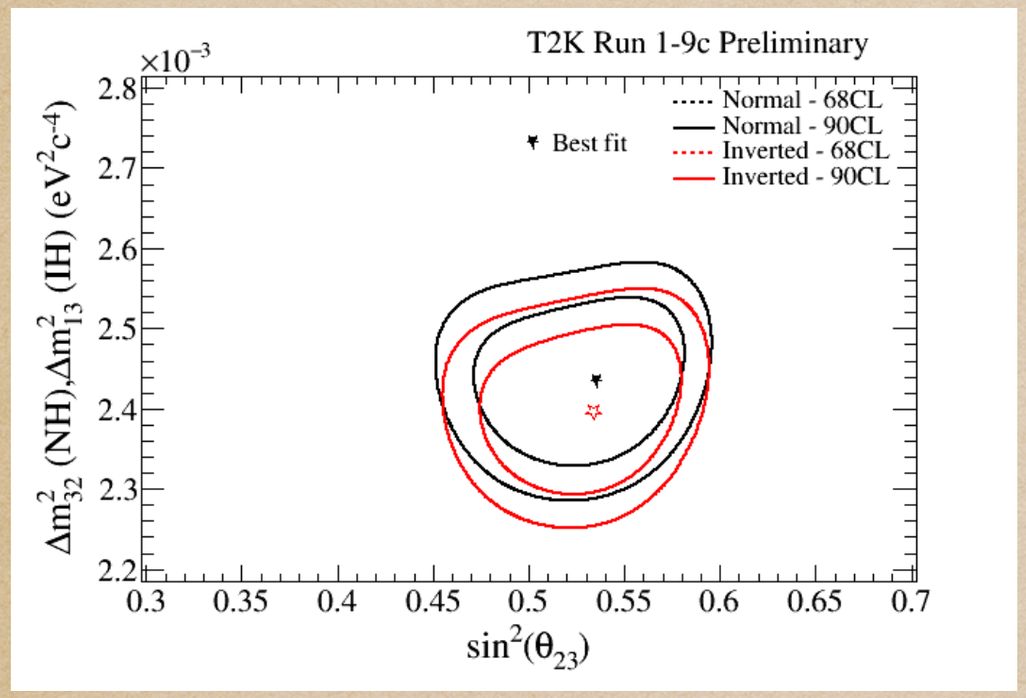
To be updated with full run9 stat during Summer (50% more data in $\bar{\nu}$ mode)

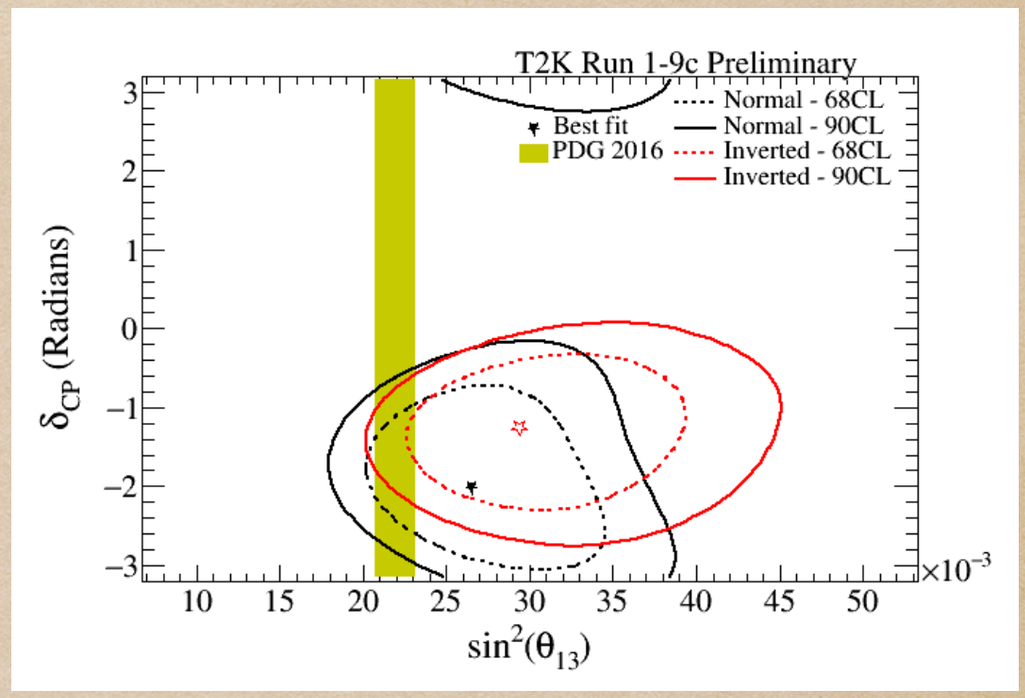
Systematics

	1R μ-like		1R e-like		
	ν-mode	$\bar{\nu}$-mode	ν-mode	ν-mode (+1π)	$\bar{\nu}$-mode
SK detector	2.4 %	2.0%	2.8%	13.1%	3.8%
SK FSI+SI+PN	2.2%	2.0%	3.0%	11.4%	2.3%
ND280 flux & cross-section	2.9%	2.7%	3.0%	3.8%	2.9%
Binding energy	2.4%	1.7%	7.2%	3.7%	3.0%
$\sigma(\nu_e)/\sigma(\nu_\mu)$	<0.05 %	<0.05 %	2.6%	2.6%	1.5%
Neutral currents	0.3%	0.3%	1.1%	1.0%	2.6%
Total	4.9%	4.3%	8.8%	18.3%	7.0%

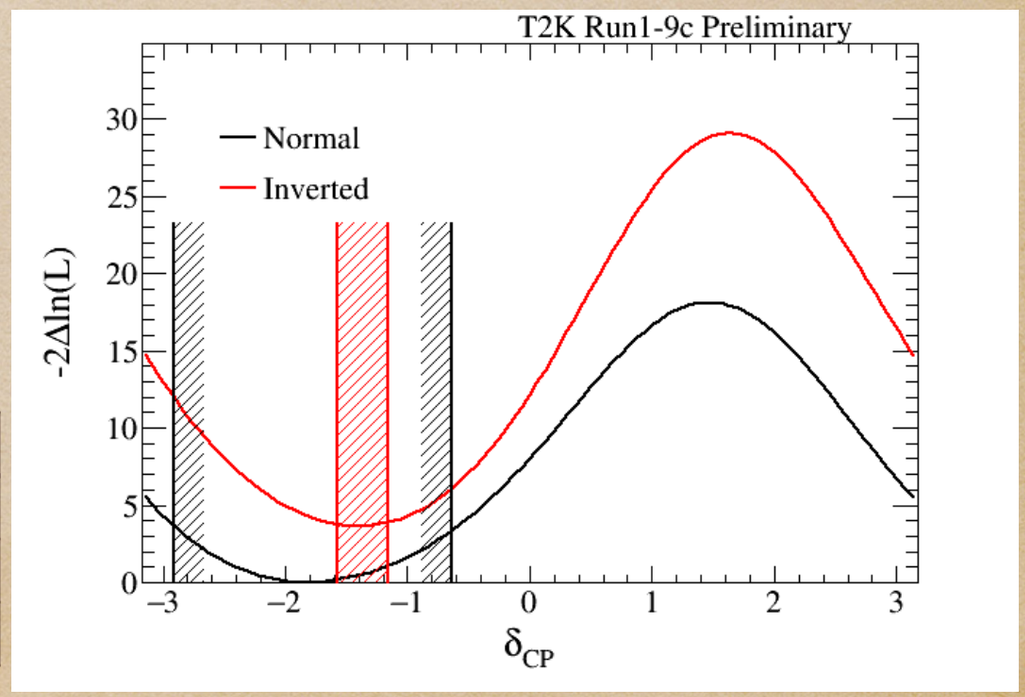
- Binding energy is treated as an effective parameter not fitted with ND280 → will be reduced in next round of analysis
- Contributions from flux and cross-section constrained by ND280
- SK detector and FSI+SI uncertainties (not constrained by ND280)
- Only use ν_μ selection at ND280 → uncertainties due to possible ν_e/ν_μ cross-section (theoretical uncertainties)

Oscillation results





- Precise measurement of sin2(θ_{23})→ compatible with maximal mixing
- T2K alone and T2K+reactor both prefer values of δ_{CP}~-π/2
- Normal ordering is also favoured



	$\sin^2\theta_{23}$<0.5	$\sin^2\theta_{23}$>0.5	SUM
NO (Δm^2_{32}>0)	20,4 %	68,4 %	88,8 %
IO (Δm^2_{31}<0)	2,3 %	8,9 %	11,2 %
SUM	22,7 %	77,3 %	100 %

The future

- Long Baseline Experiments are leading techniques to measure several oscillation parameters (δ_{CP}, θ_{23}, mass ordering)
- Next generation of LBL (DUNE, Hyper-K) will not come online before 2026
- T2K (and NOνA) will be the leading experiments for the next 8-10 years
- Let's get the best from them!

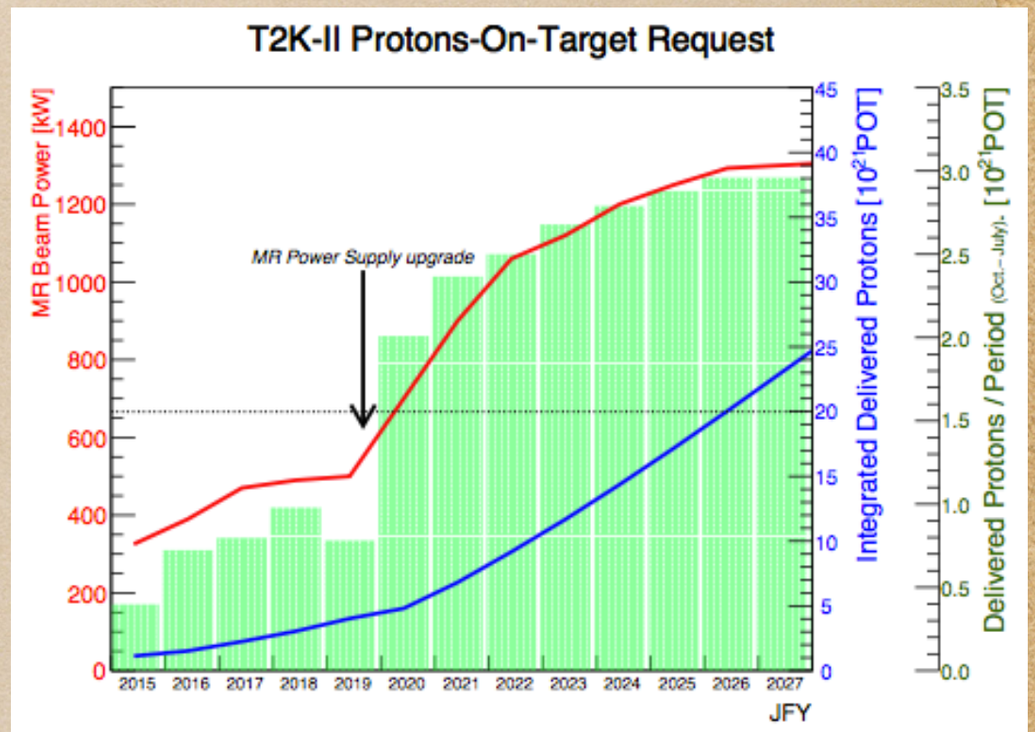
T2K phase II

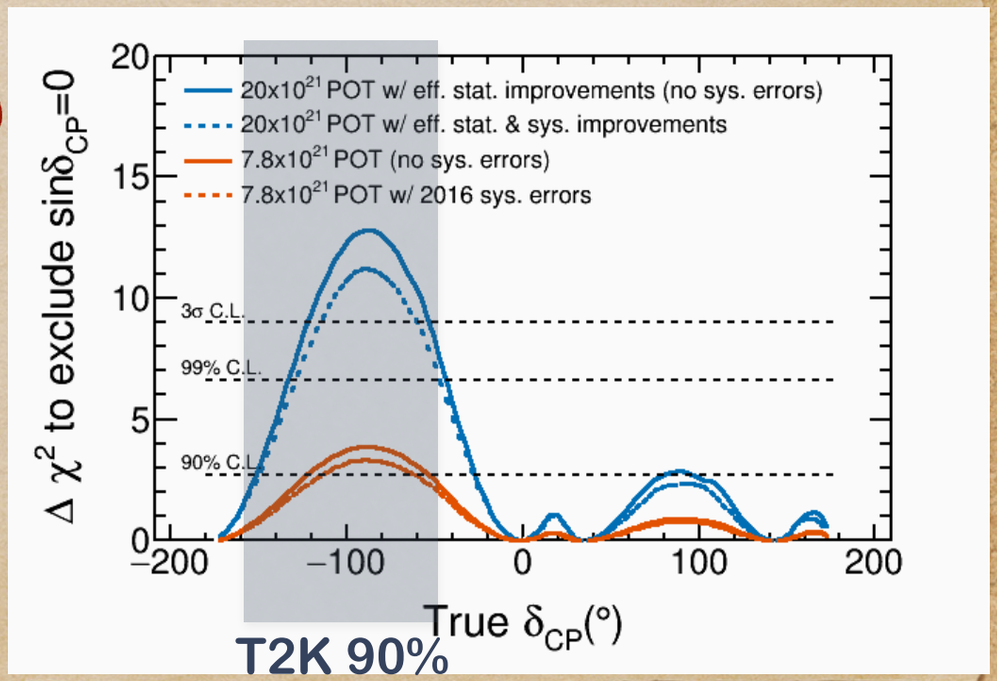
- T2K was originally approved to collect 7.8×10^{21} pot
  - Driven by sensitivity to θ_{13}
- Proposal for an extended run
  - T2K-II → 20×10^{21} pot
- Upgrade the Main Ring power supply to reach 1.3 MW operations

ν_e candidates: 460 ± 20% (δ_{CP} and ordering)

$\bar{\nu}_e$ candidates: 130 ± 13% (δ_{CP} and ordering)

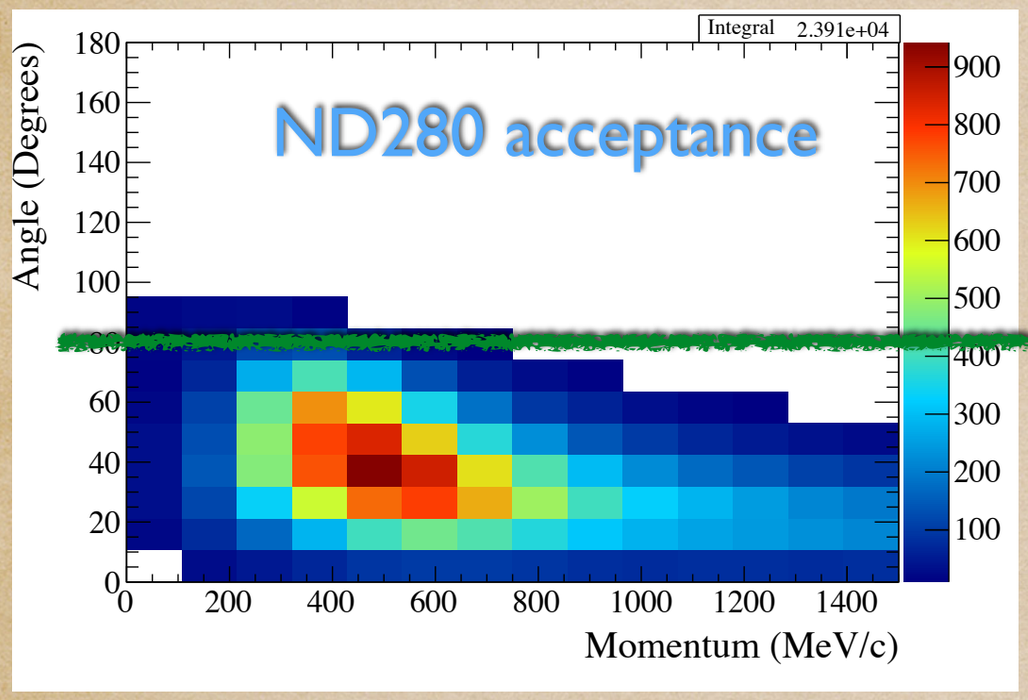
- >3σ measurement of CP violation (if lucky…)
- Need to reduce systematics to ~4% (<3% from ND280)

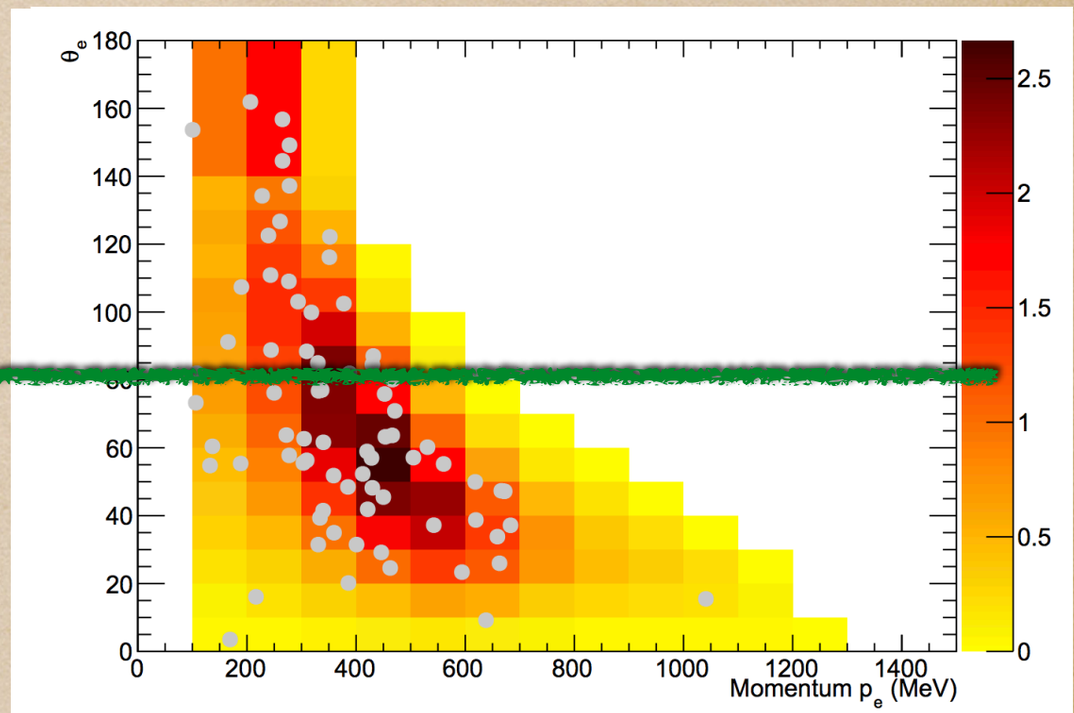




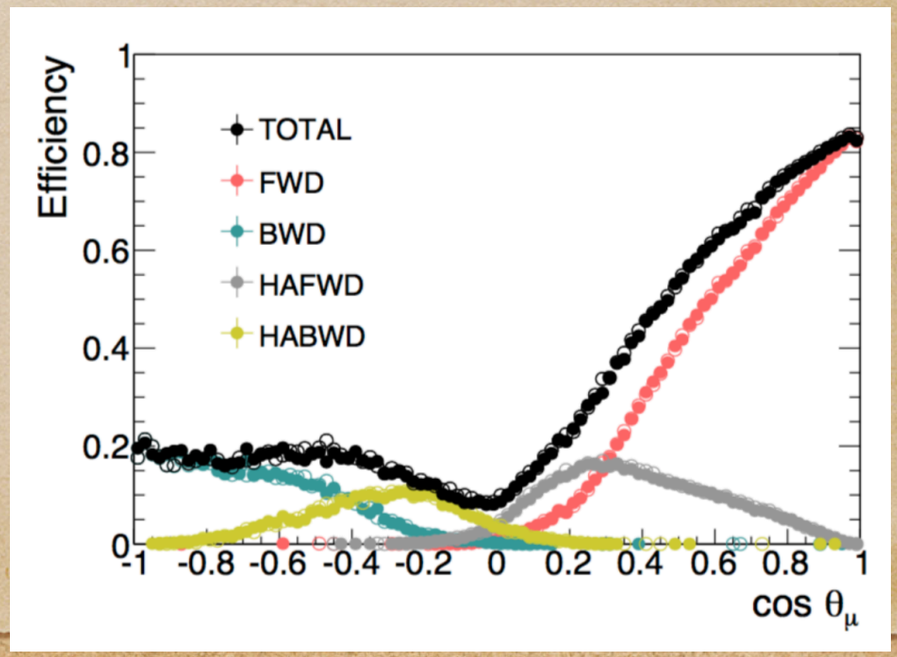
T2K 90% allowed region

ND280 upgrade





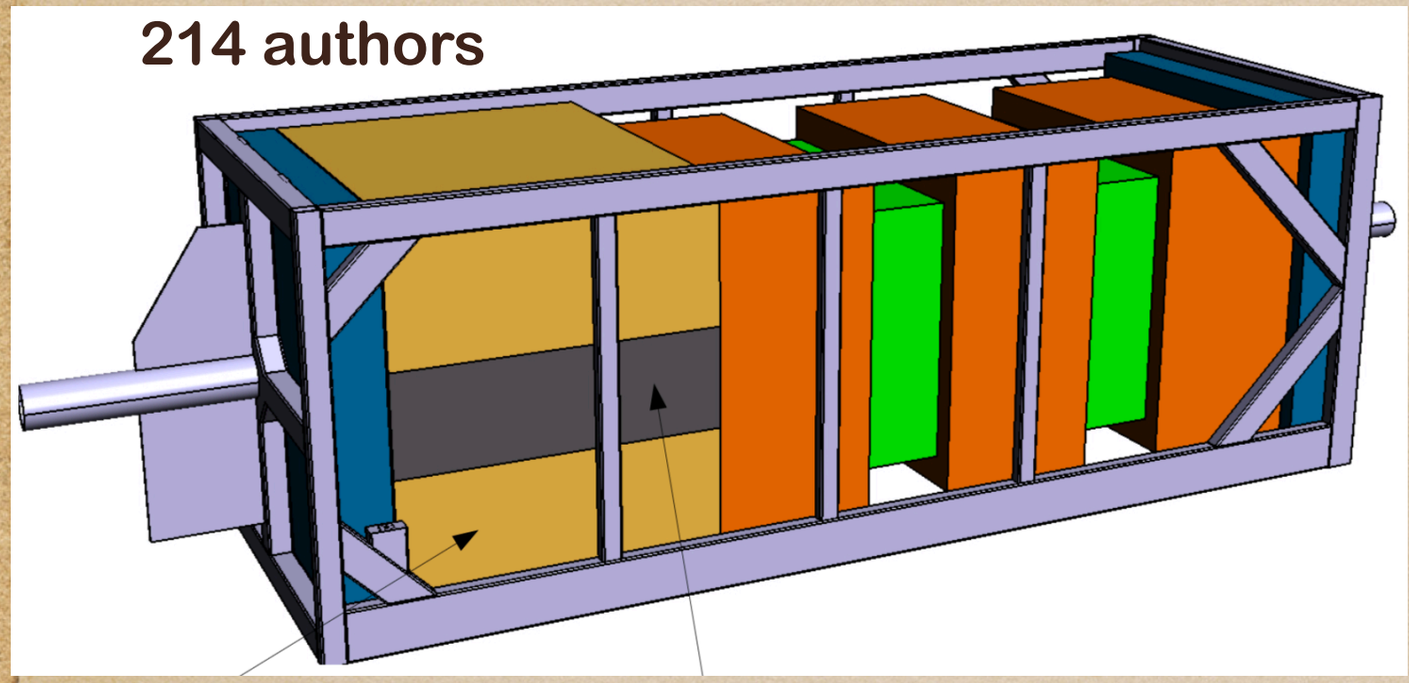
- Main limitation of ND280 : reduced angular acceptance → only forward going muons are selected with high efficiency
- An analysis dedicated to select tracks with high polar angles allow to select 20% of the events in that region
- We can do better with an upgrade!

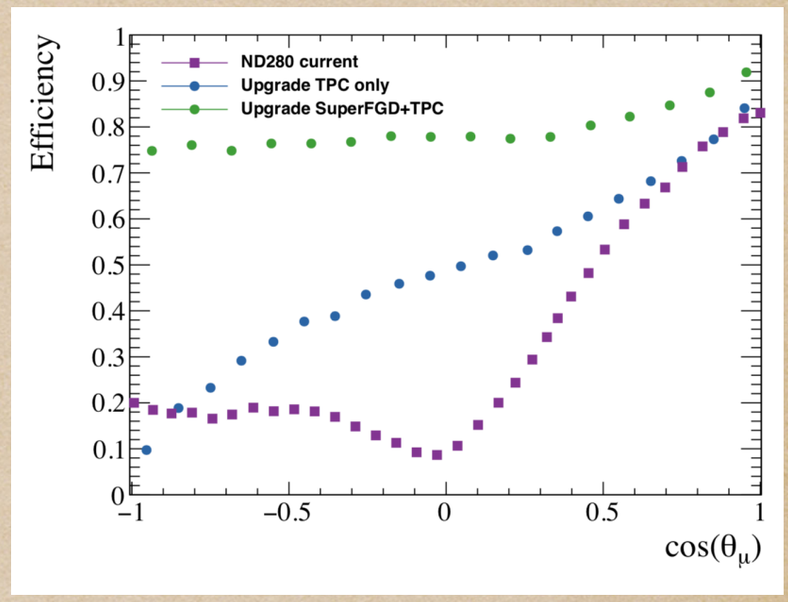


ND280 upgrade

CERN-SPSC-P357

214 authors



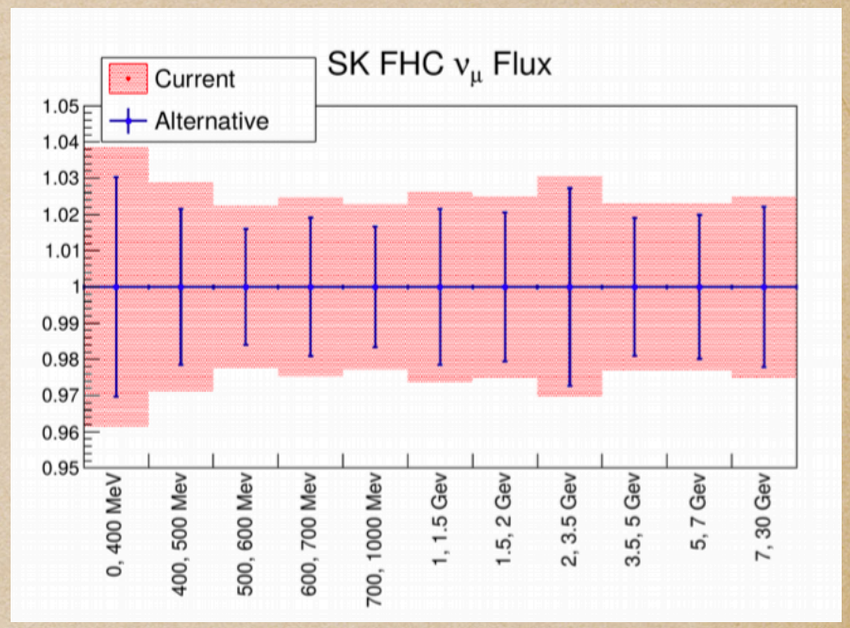


- Replace upstream part of ND280 with an horizontal fully active target (SuperFGD) and 2 horizontal TPCs
- This will allow to select μ and e at any angle with respect to the beam
- Proposal submitted to SPSC in 2017
- Test beam foreseen for Summer 2018

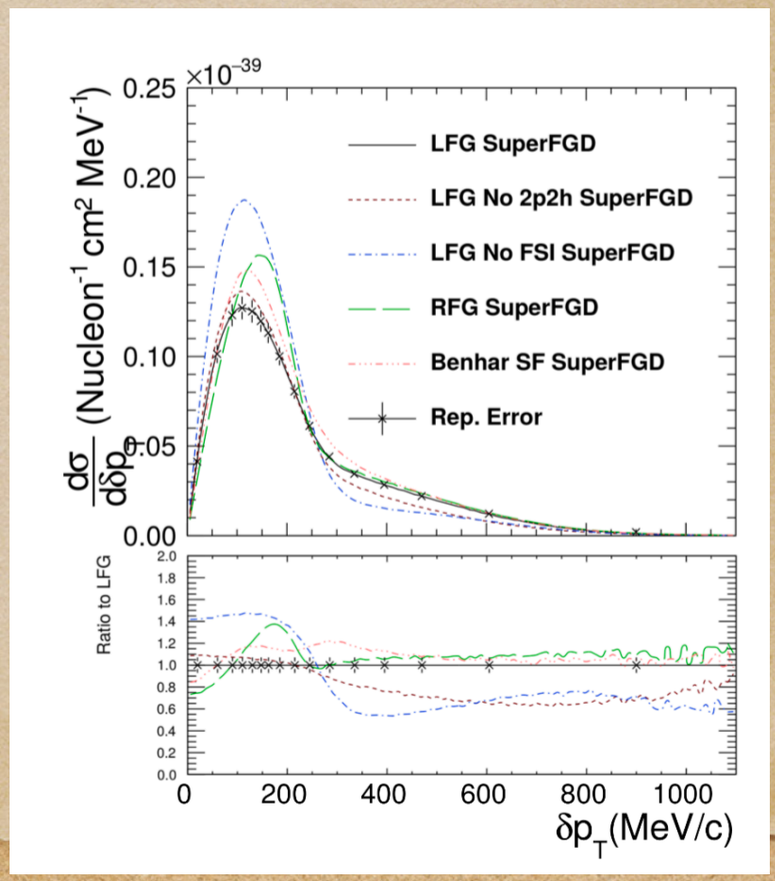
2017	2018	2019	2020	2021
Proposal	Prototypes, TDR	Construction	Construction	Installation

Upgrade performances

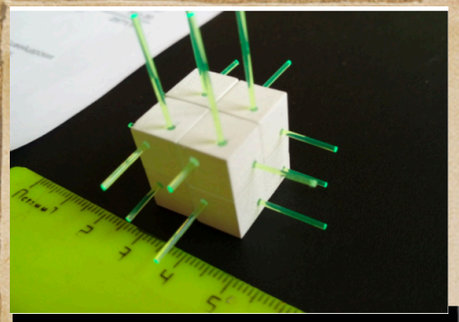
Parameters	Expected improvement on uncertainties
SK flux	$\sim 20\%$
FSI	$\sim 45\%$
CCQE/2p2h	$\sim 25 - 40\%$
Other (Q^2-dependent)	$\sim 25\%$

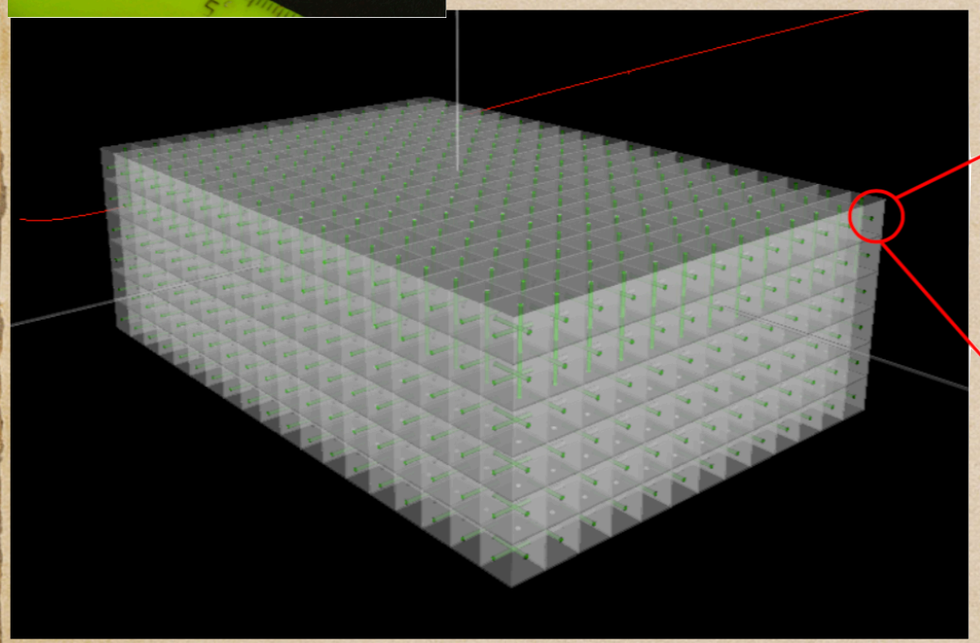


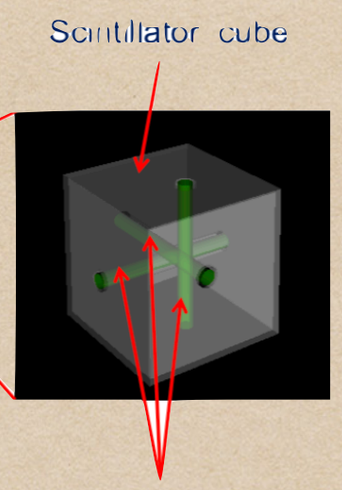
- For same POT → Reduce uncertainties on inputs to oscillation analysis by ~30%
- Low momentum threshold and full angular coverage → much better sample to study nuclear effects



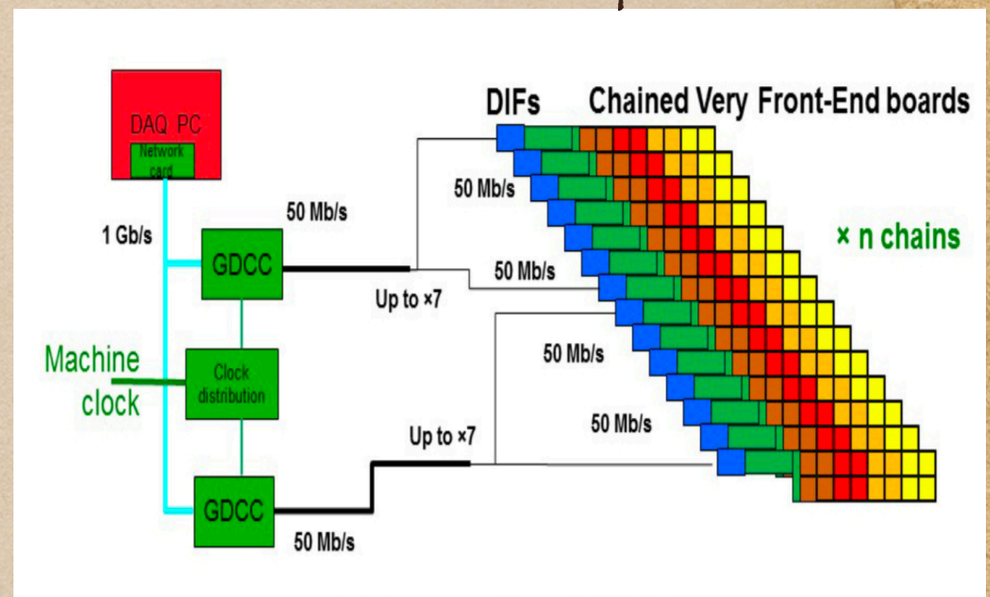
Super-FGD





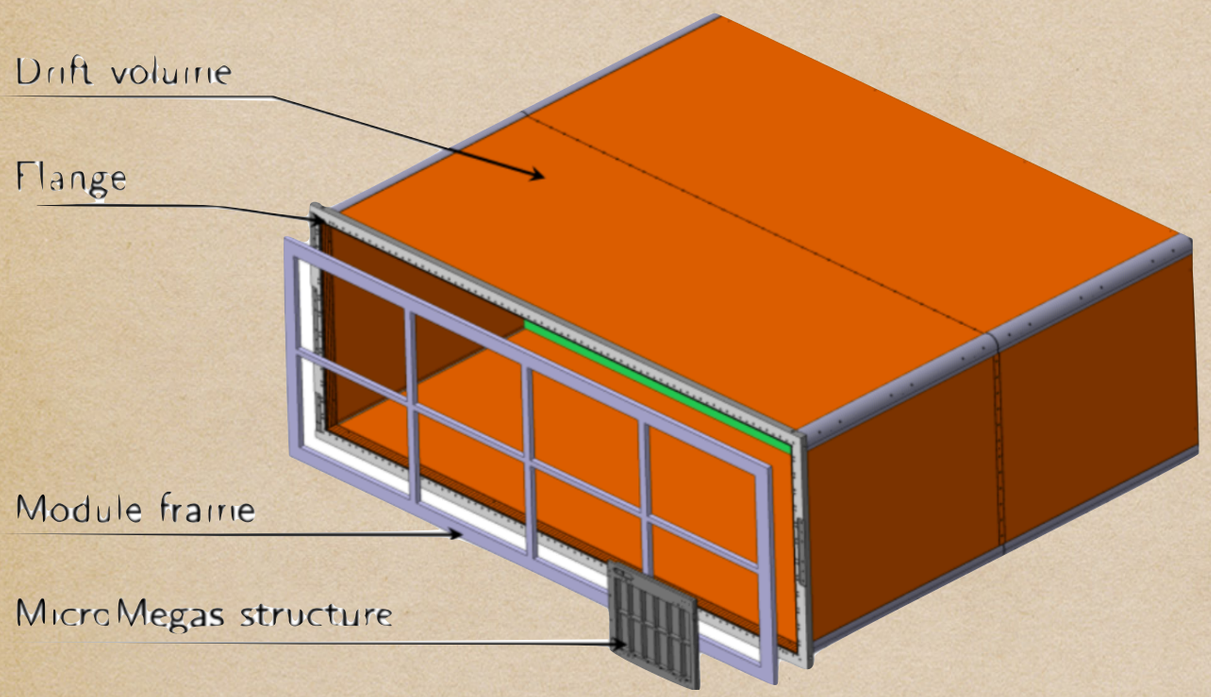


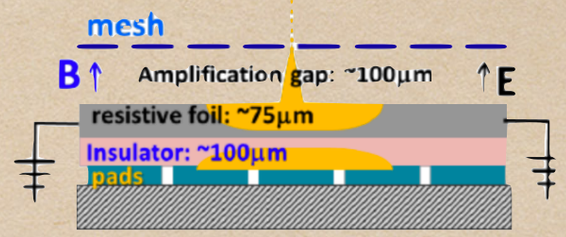
LLR electronics developed for Calice

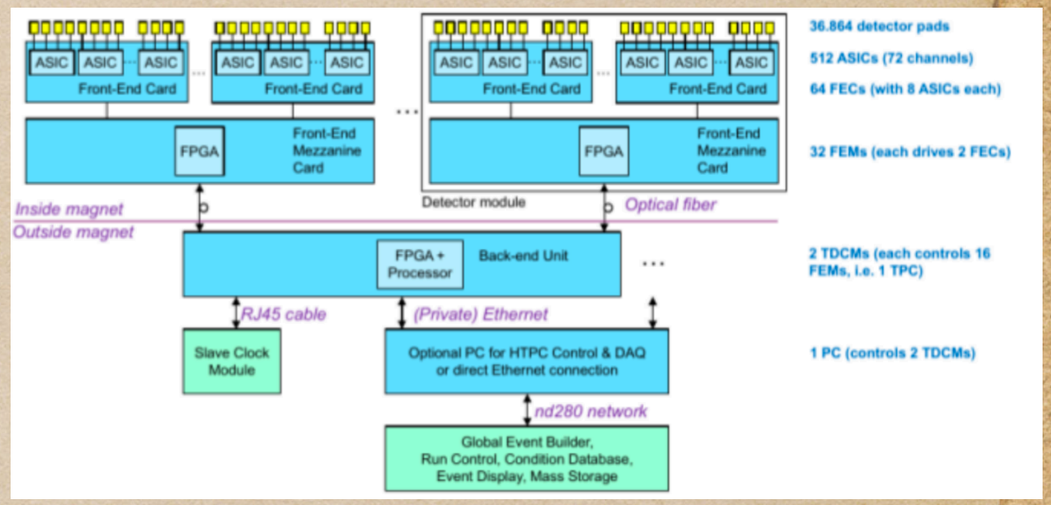


- 2 ton target with 1x1x1 cm cubes read by 3 fibers
- Total of 60-80k channels read with MPPC (80k if S-FGD will be split in 4 modules)
- Proposal from LLR to read the MPPCs with SPIROC2 chips → Front End Boards close to the detector equipped with 4 chips
- DIF will read up to 32 Front End Boards
- Signal from DIF is sent outside the magnet to a GDCC board → each GDCC can read 7 DIF → 1 GDCC and 7 DIF enough to read 20k channels)
- Proposal from LLR being discussed within the ND upgrade collaboration → total cost ~600 k€ + request for an electronic engineer

Horizontal TPCs





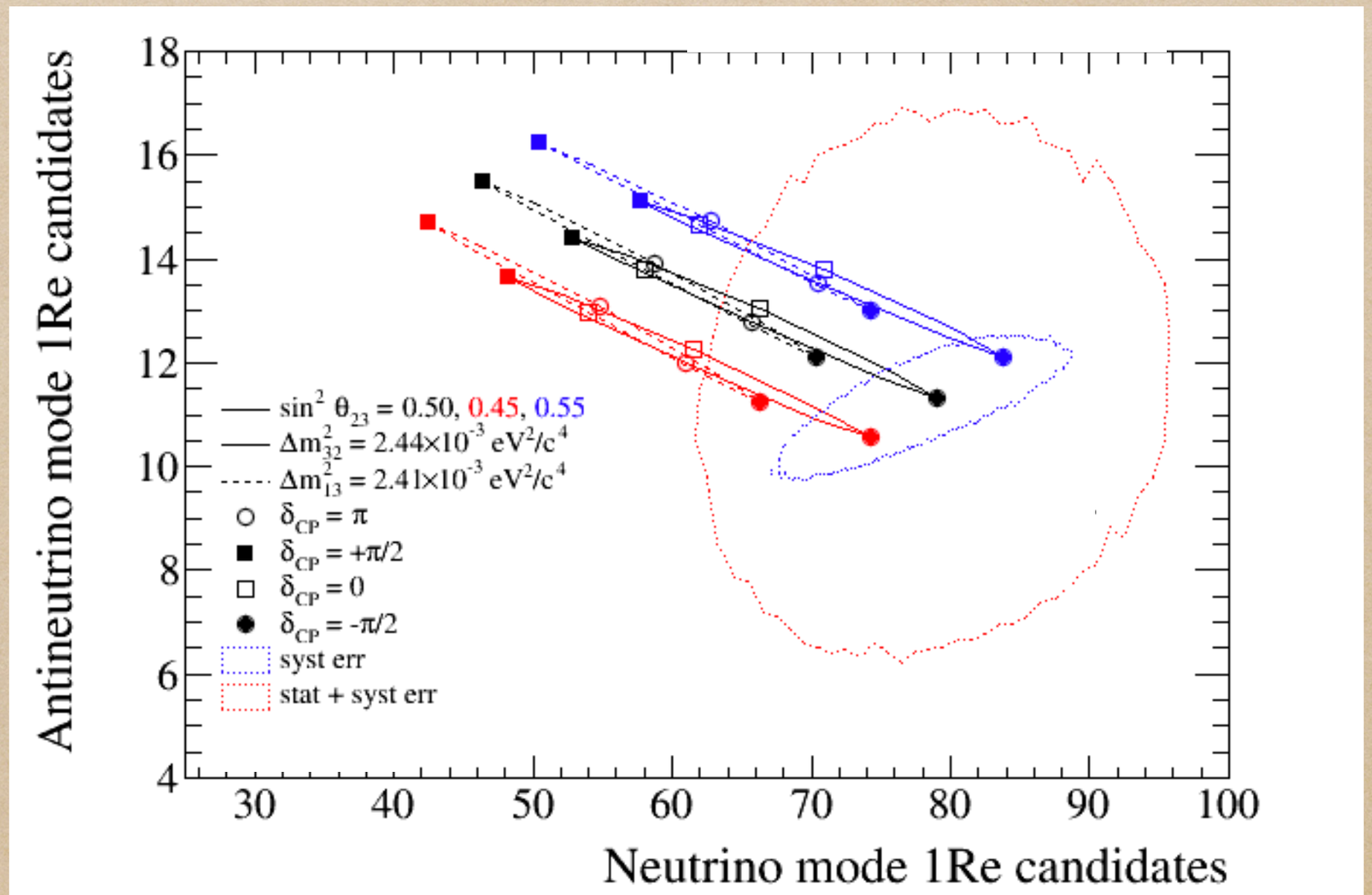


- Similar to existing TPCs but horizontal and with lighter field cage
- Equipped with resistive MicroMegas (8x2x2 modules)
- LPNHE will provide front end electronics boards to read AFTER chips (total of ~80 boards will be built) and cooling→ the lab already provided necessary ITA
- Total cost ~200 k€ (including cooling for electronics)
- A mechanical engineer to study detectors integration in the basket has also been allocated to the project

Conclusions

- T2K has been a very successful experiment
  - Observation of electron neutrino appearance
  - World best measurement of $\sin^2\theta_{23}$
  - First hints of CP violation

- **T2K-II** will allow us to be one of the two leading LBL experiments until ~2026
- We propose an **upgrade of the Near Detector** in order to reduce systematics and fully profit of the additional statistics
- Crucial know how (detectors, analyses, PhD theses) for future LBL experiments → see Michel's talk


Antineutrino mode 1Re candidates
Neutrino mode 1Re candidates
18
16
14
12
10
8
6
4
30
40
50
60
70
80
90
100
sin² θ23 = 0.50, 0.45, 0.55
Δm²32 = 2.44×10⁻³ eV²/c⁴
Δm²13 = 2.41×10⁻³ eV²/c⁴
δCP = π
δCP = +π/2
δCP = 0
δCP = -π/2
syst err
stat + syst err