T2K status and perspectives

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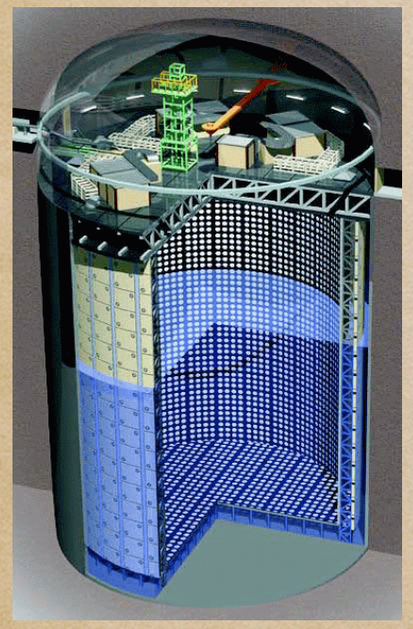
for the T2K Collaboration

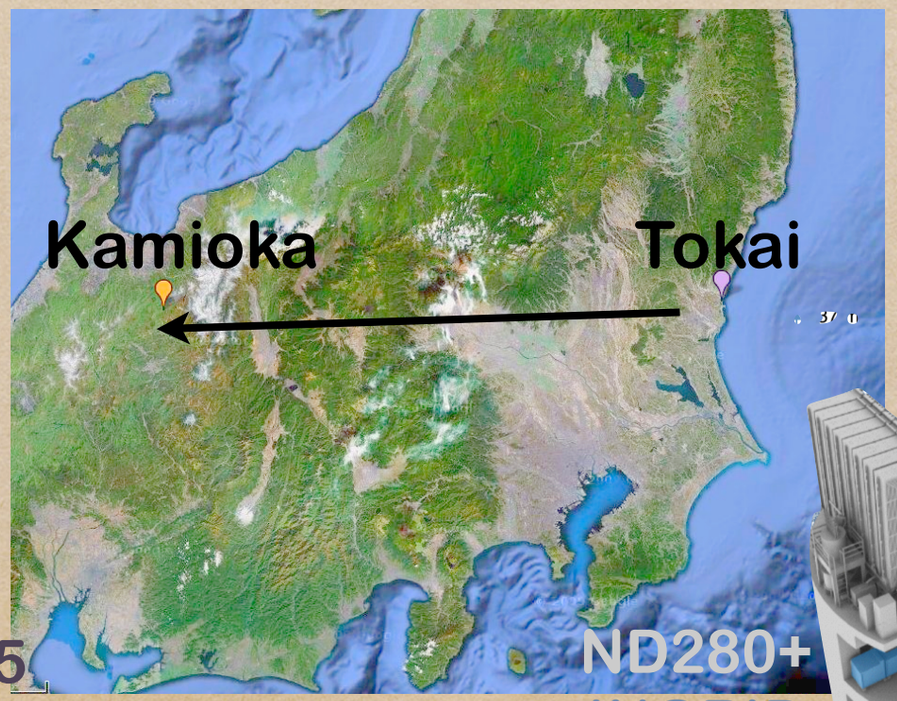
JENNIFER Consortium meeting – 30/10/2018

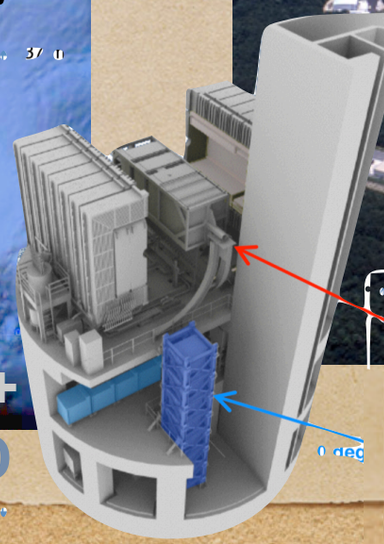
The T2K experiment

- High intensity ~600 MeV ν_μ beam produced at J-PARC (Tokai, Japan)
- Neutrinos detected at the Near Detectors (INGRID+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}

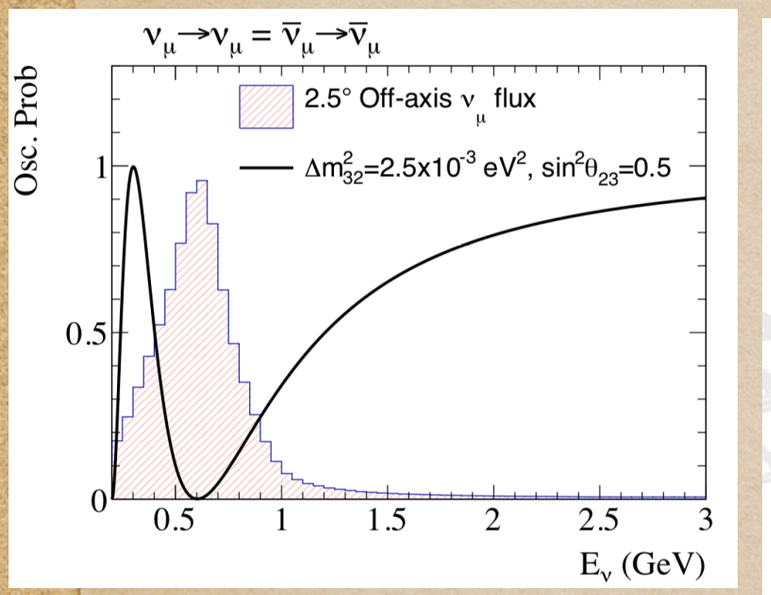


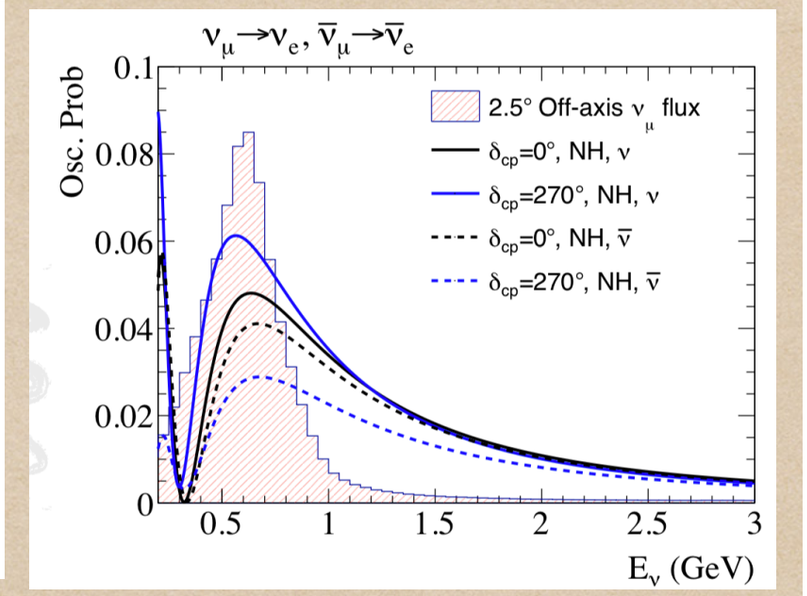
Super-Kamiokande: 22.5 kt fiducial volume water Cherenkov detector

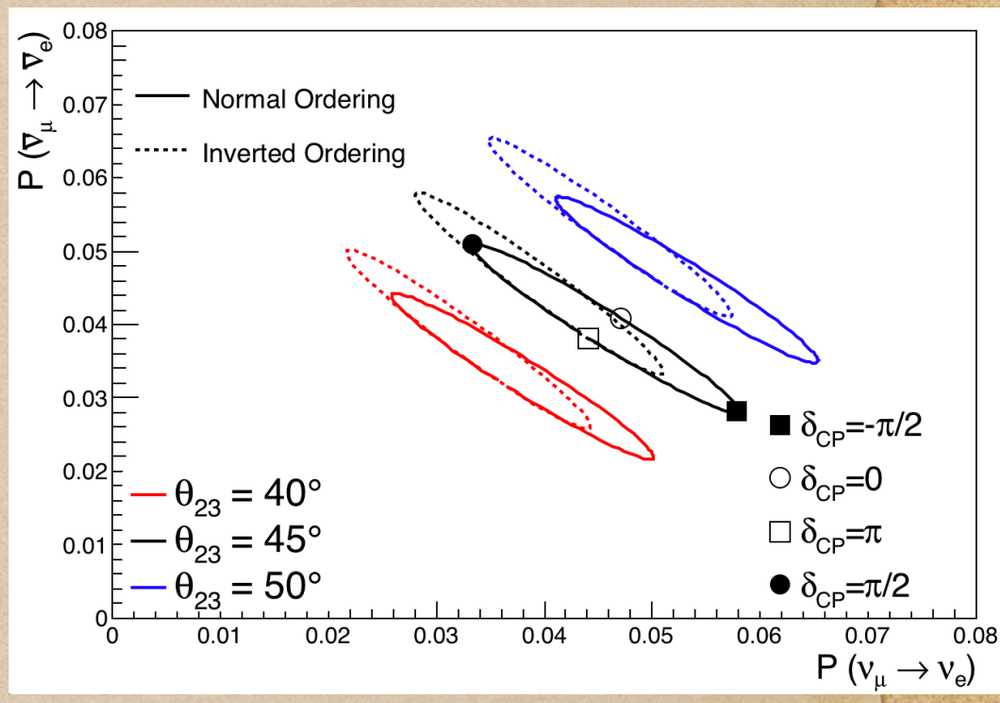




Sensitivity to oscillation parameters



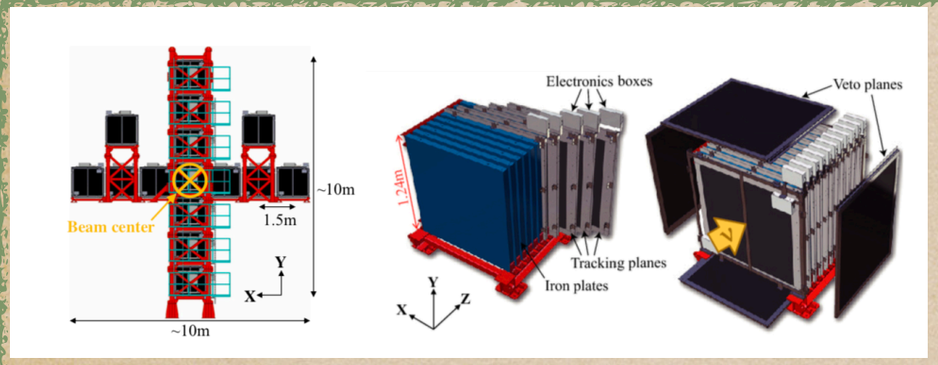




- $P(\nu_\mu \to \nu_\mu) = P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$
  - Test of CPT conservation
  - Measure $\sin^2(2\theta_{23})$ → weak sensitivity to the octant
  - Measure $|\Delta m^2_{23}|$ → cannot distinguish NO and IO
- $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$
  - Sensitive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

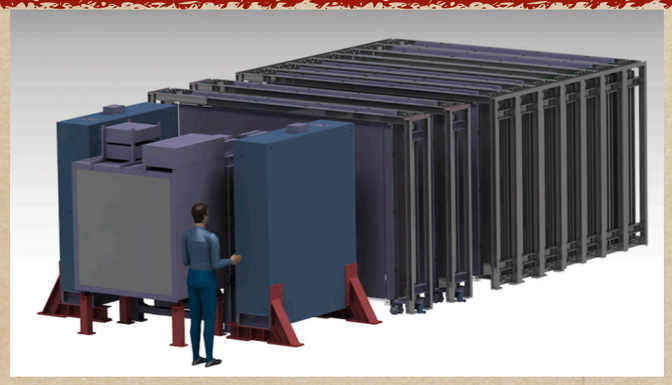
T2K goals:
measure ν_μ and $\bar{\nu}_\mu$
disappearance and ν_e and $\bar{\nu}_e$
appearance probabilities

Near Detectors



INGRID: monitor ν beam profile and direction during data taking

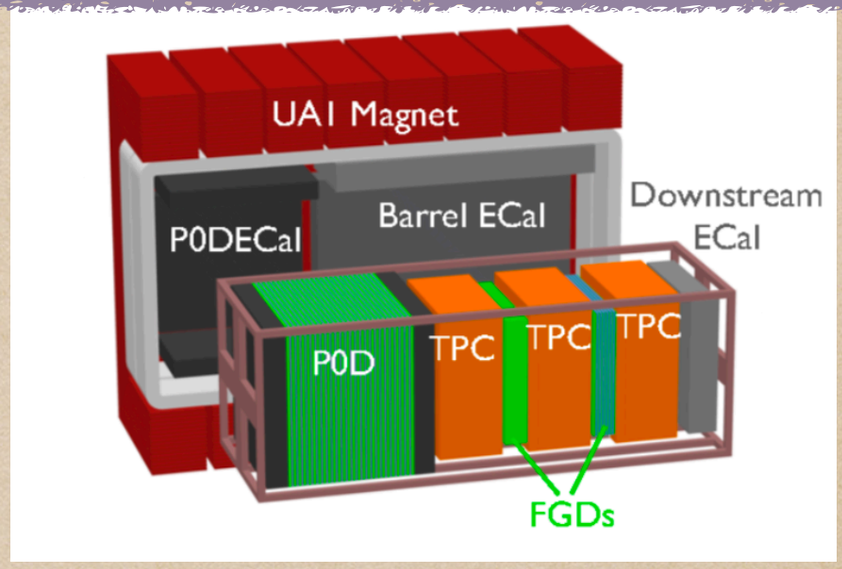
Measure ν and $\bar{\nu}$ cross-sections



WAGASCI + BabyMIND

First T2K upgrade (part of T2K since 2018)

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



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

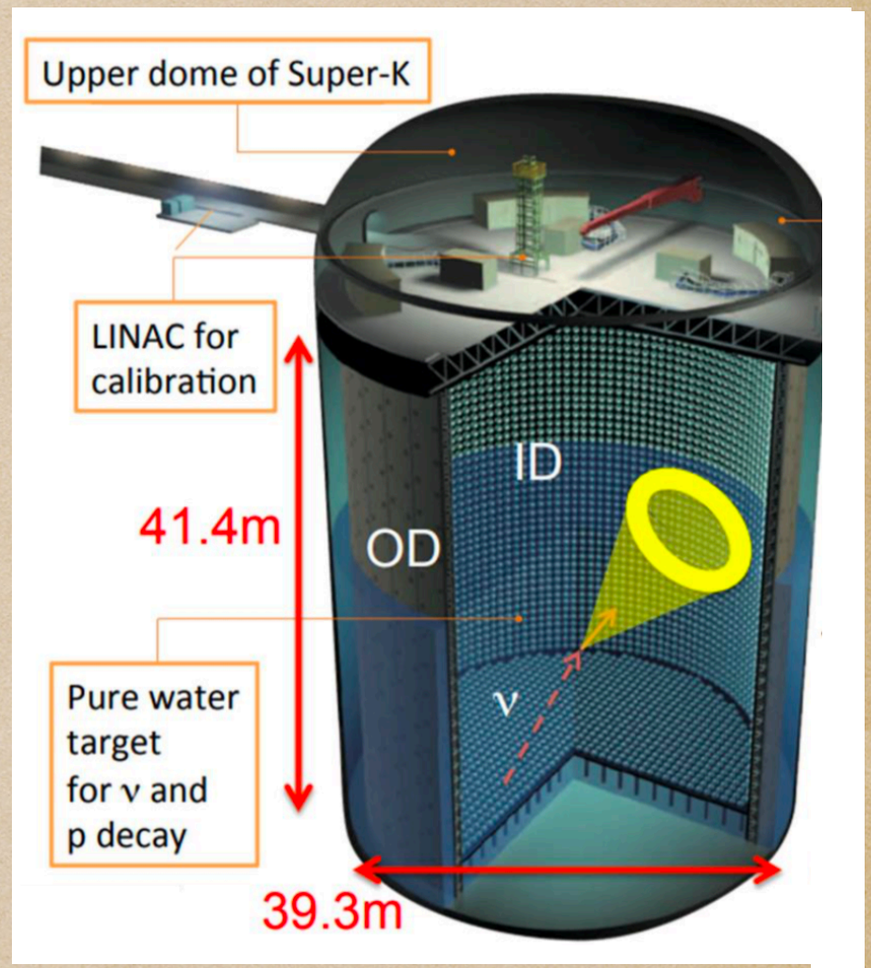
Fundamental input to T2K OA

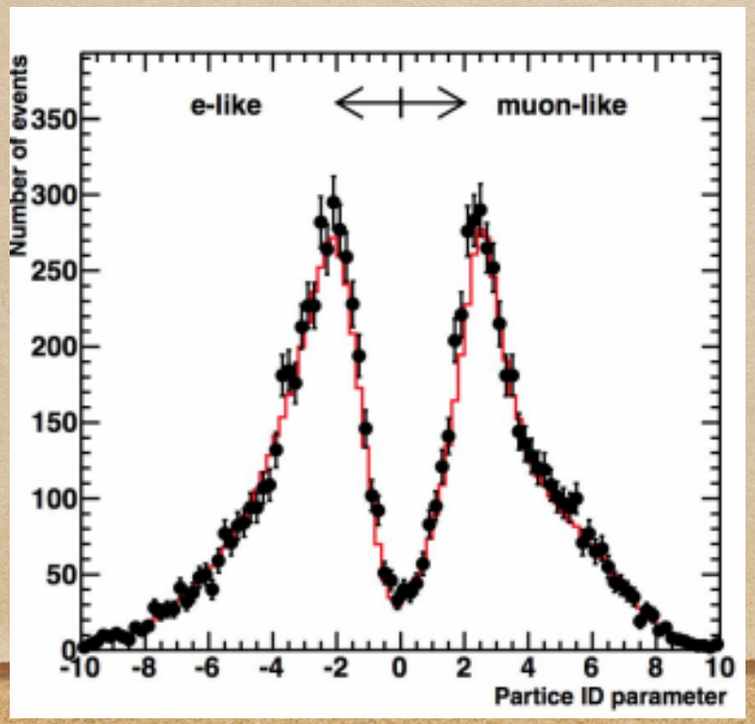
2 Fine Grained Detectors → active target for ν interactions

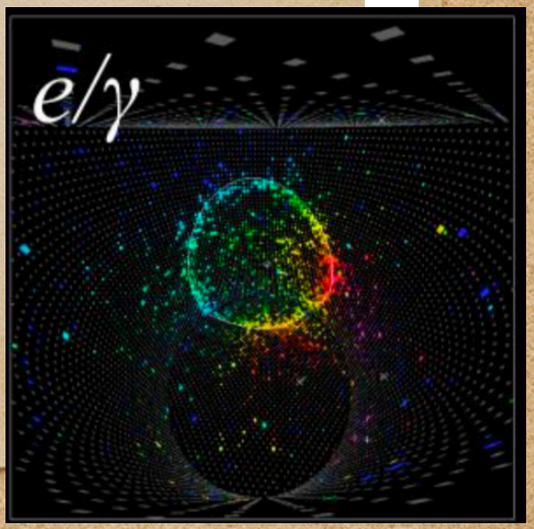
3 Time Projection Chambers to measure charge, momentum and PID of leptons emitted in ν interactions

Super-Kamiokande

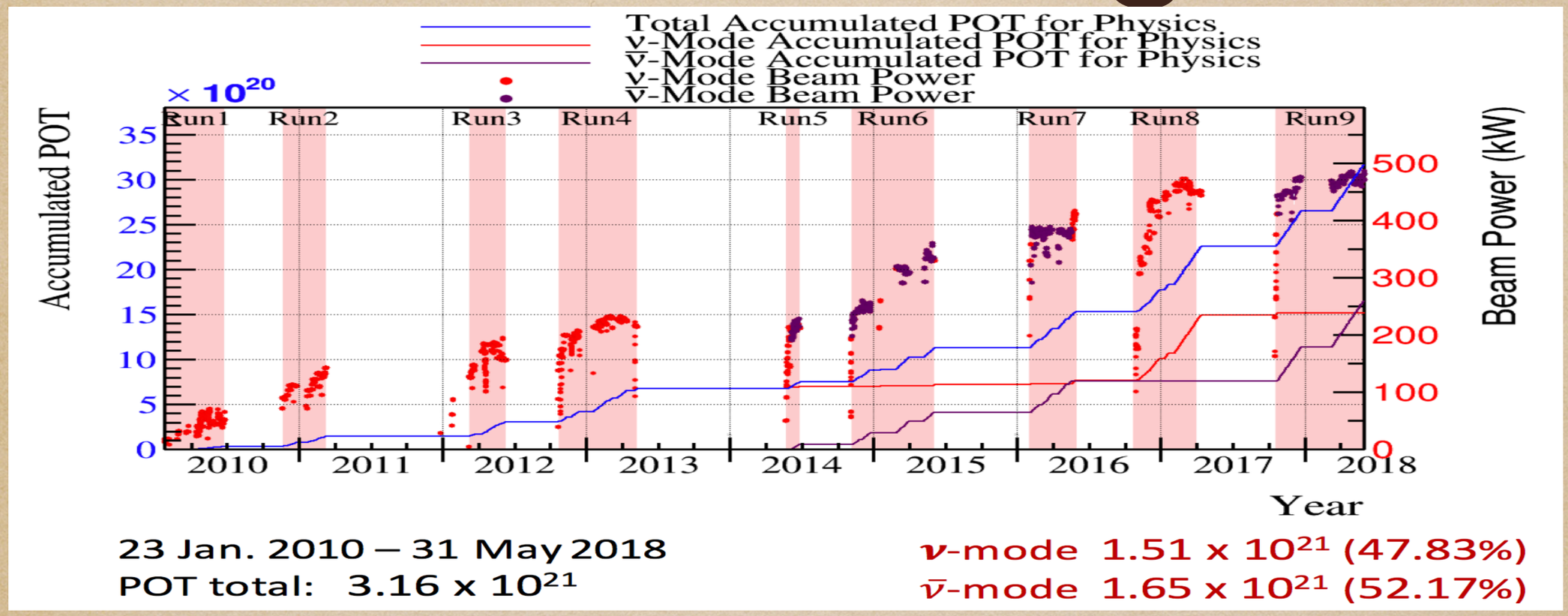
- 50 kton Water Cherenkov detector
  - ~11000 PMTs for ID, ~2000 for OD
- 1000 m underground at Kamioka mine operated since 1996
- Very good PID capabilities to distinguish between ν_e and ν_μ thanks to shape of Cherenkov ring → <1% misidentification probability



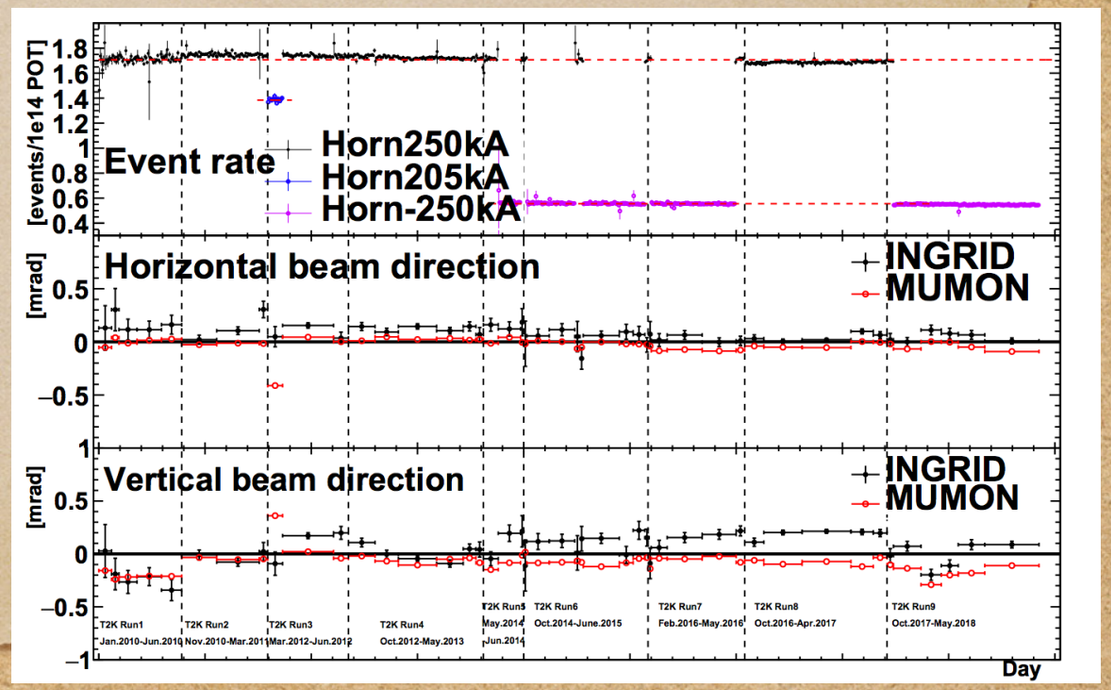




Data taking



- Collected 3.16x10^{21} protons on target (half ν and half $\bar{\nu}$)
  - ~40% of approved p.o.t.
- Reached ~500 kW beam power
- Stability of the beam rate and direction over the whole data taking period measured by INGRID
- Oscillation Analysis results presented at Neutrino2018 with data up to Dec. 2017



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

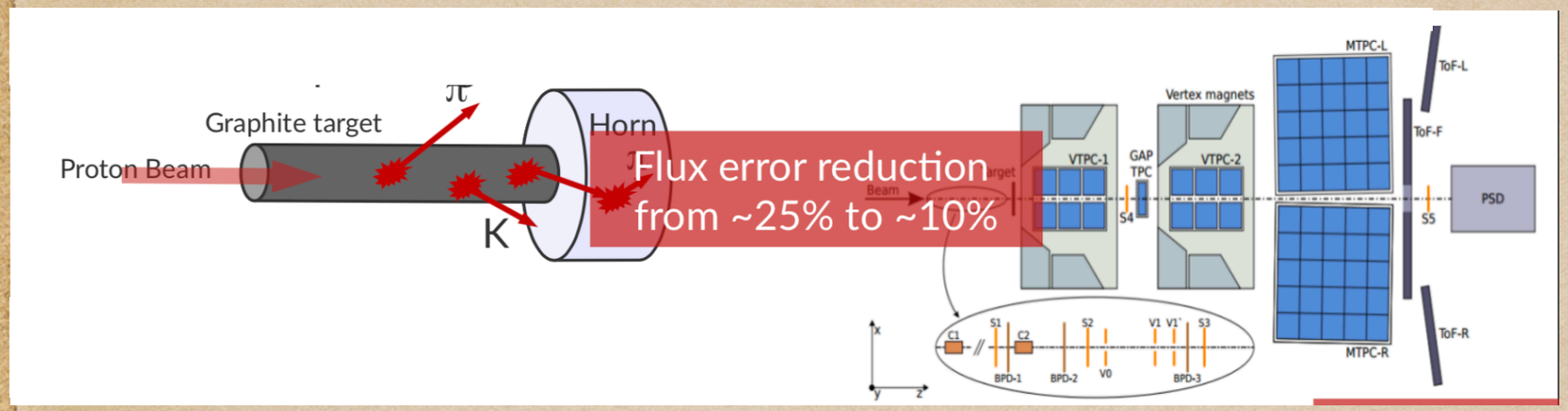
Prediction at the Far Detector:
Combine flux, cross section and ND280 to predict the expected events at SK

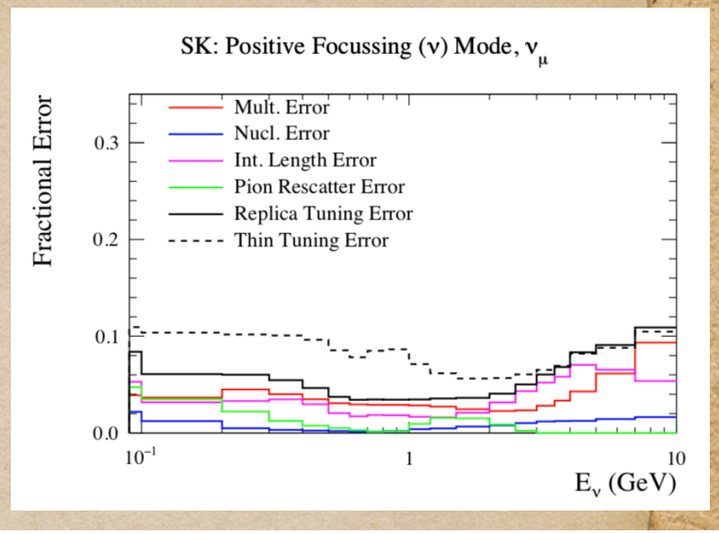
Extract oscillation parameters!

SK measurements:
Select CC ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$ candidates after the oscillations

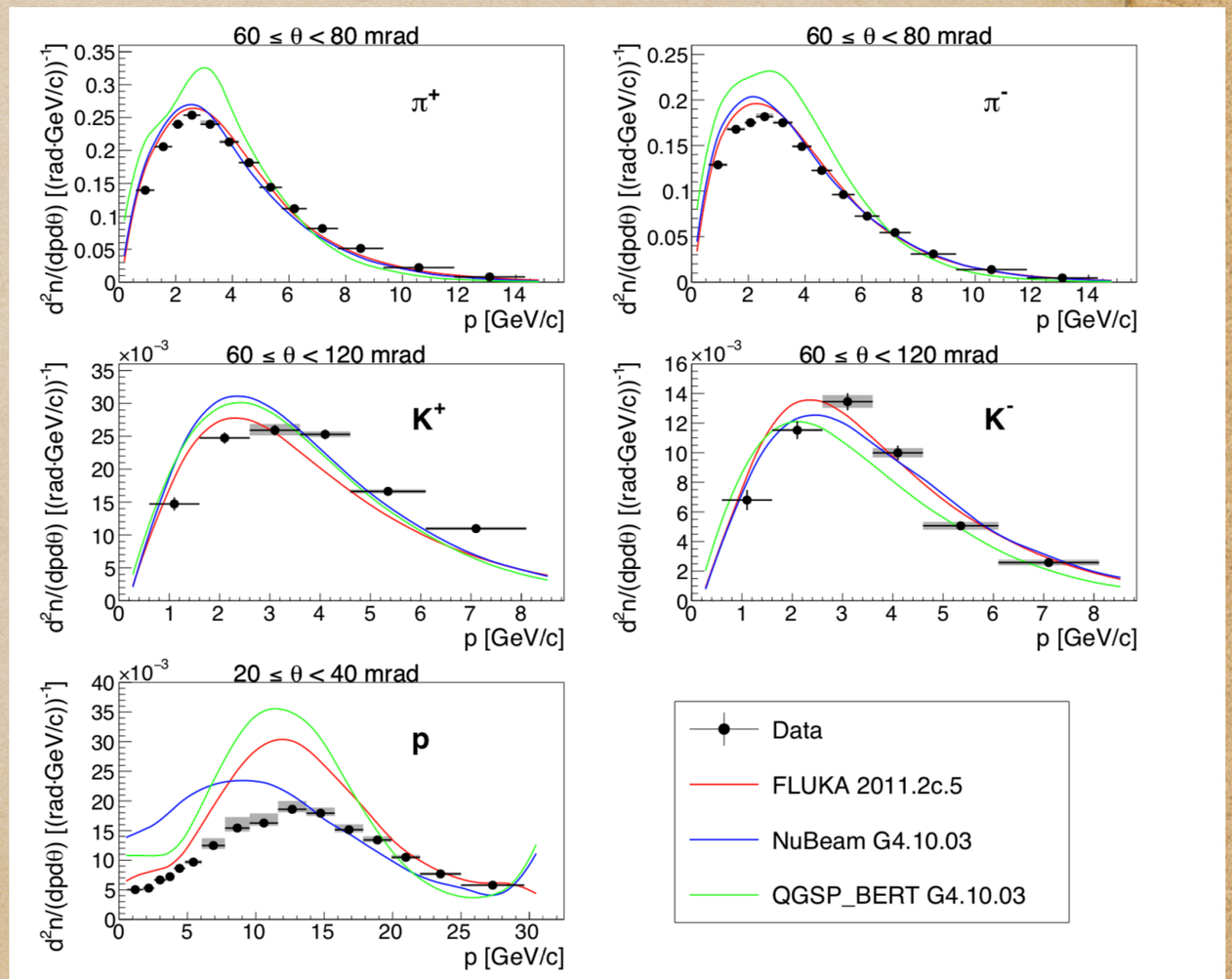
Neutrino interactions:
Cross-section models
External data (Minerva, MiniBooNE, …)

Flux uncertainties: NA61/SHINE





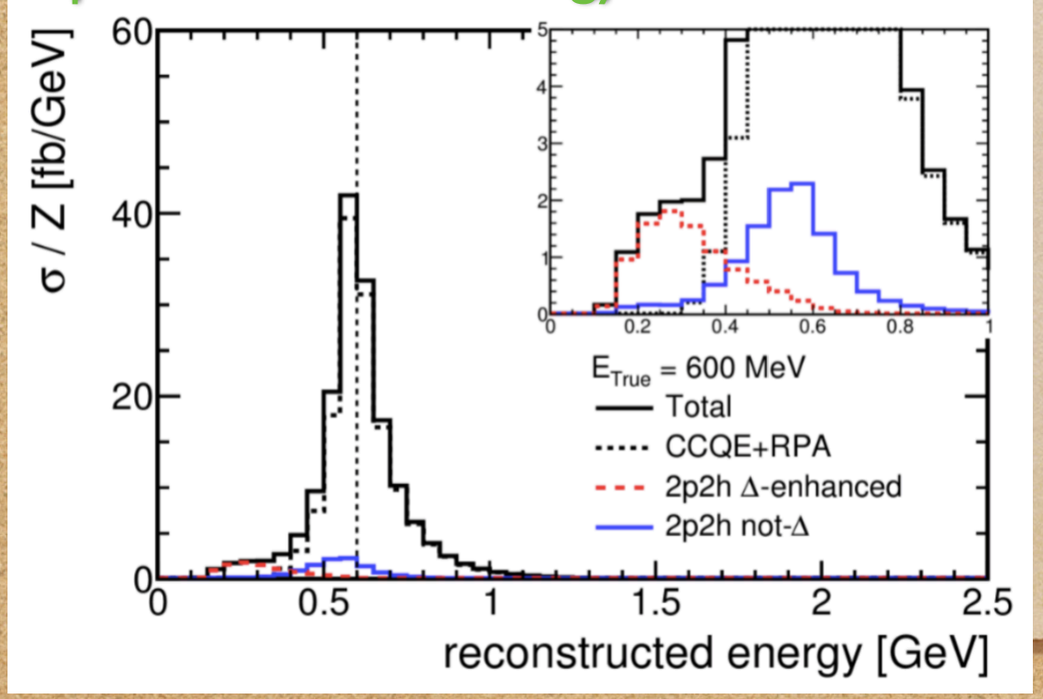
- **Multipurpose detector @ CERN → precision hadron production measurements for T2K (and FNAL) neutrino fluxes predictions**
- **Took data for T2K in 2007, 2009, 2010 with thin and replica target**
- **Thin target data already used → 10% uncertainties on neutrino fluxes**
- **Inclusion of 2010 data with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

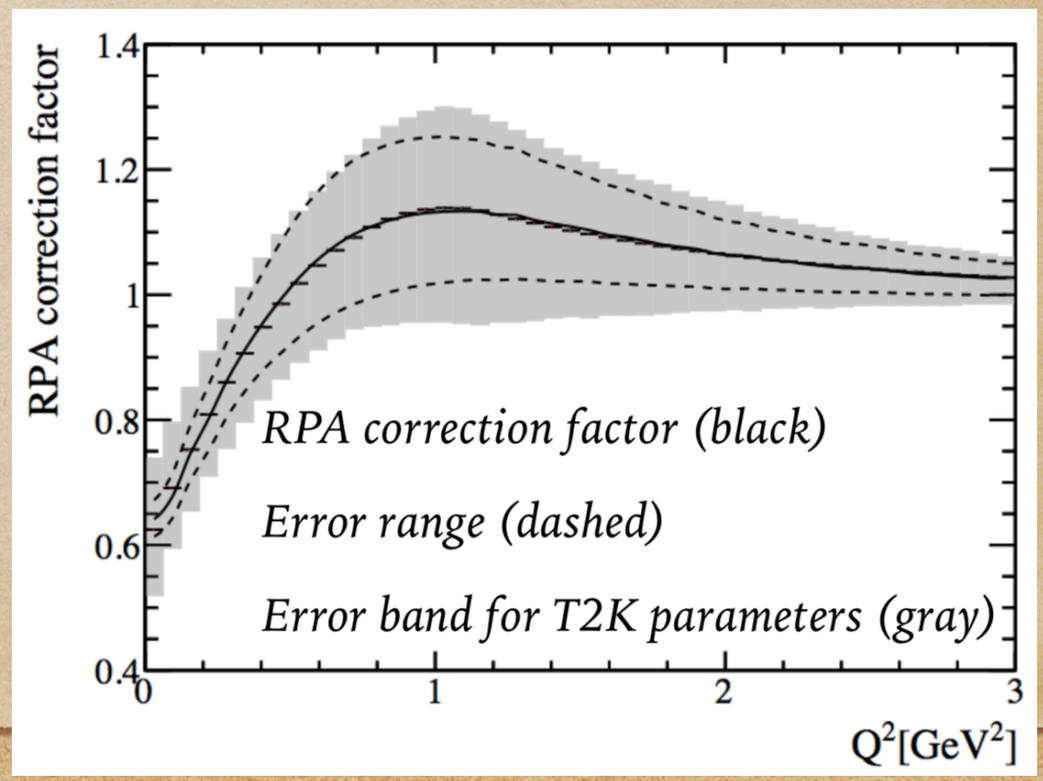


Cross-section uncertainties

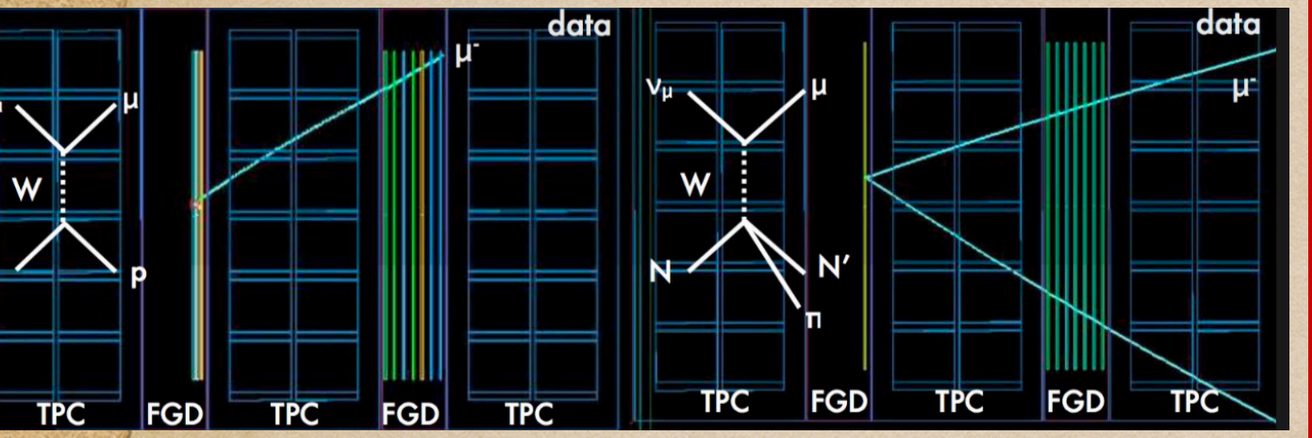
- At T2K energies the dominant contributions to cross-section are quasi-elastic
- Other contributions with pions in the final state also important
- Need to take into account nuclear effects (2p=2h, FSI, ….)
- We developed a new parametrization of the cross-section

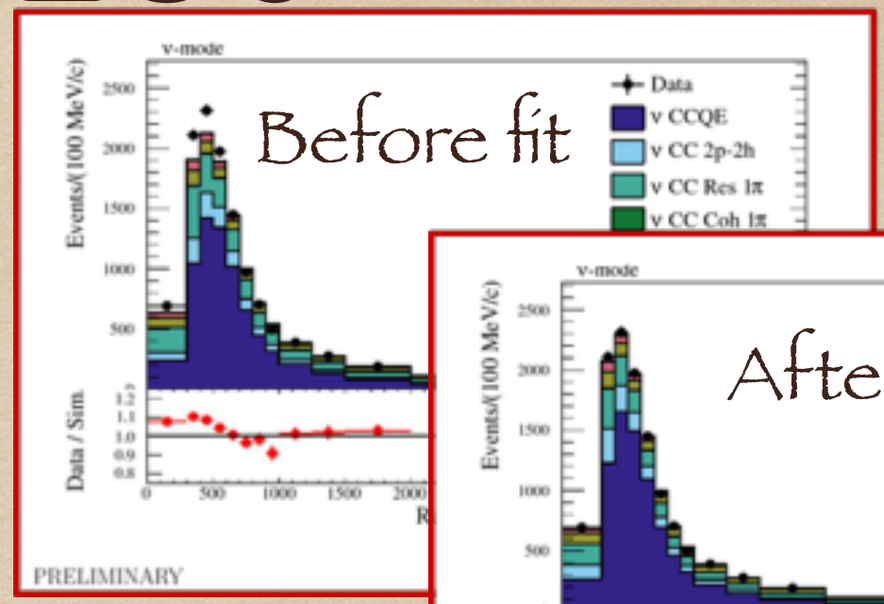
2p2h → bias the energy reconstruction

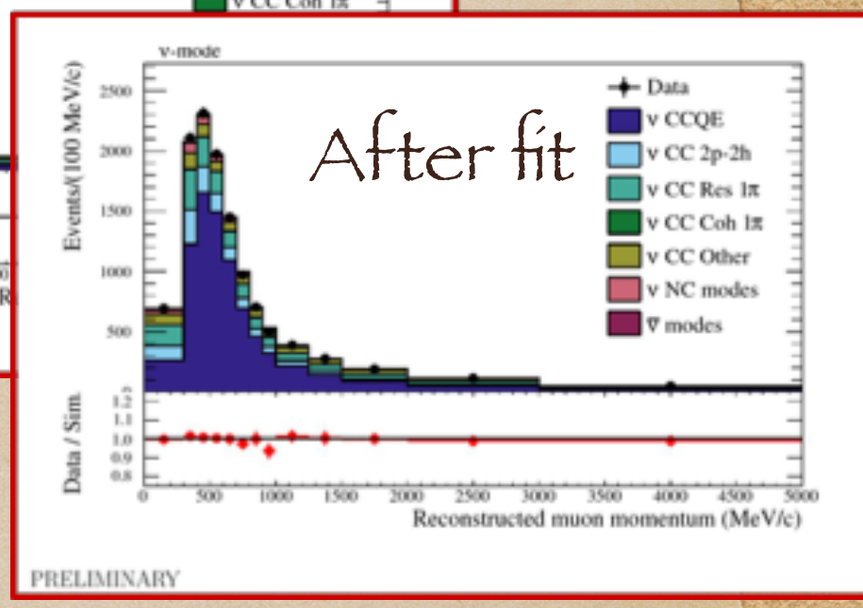




ND280

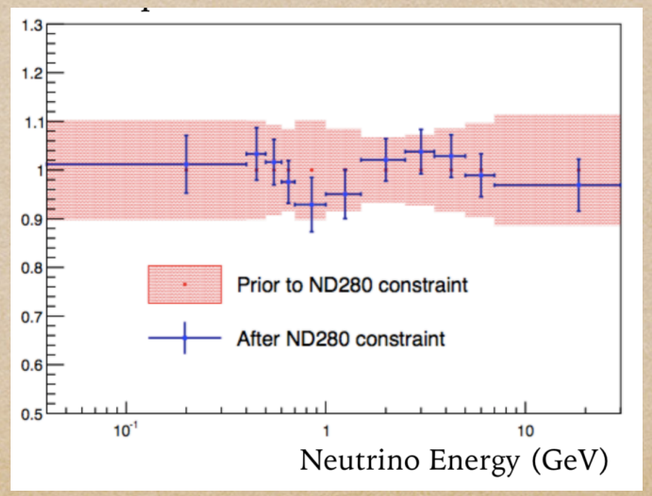




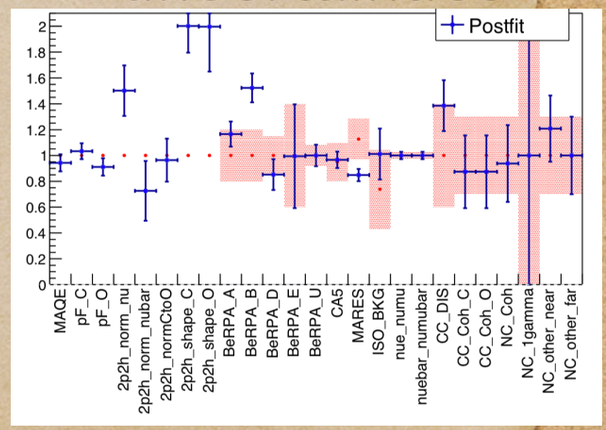


- Select 14 samples of ν_μ and $\overline{\nu}_\mu$ interactions on Carbon and Water with 0,1,>1 π in the final state
- Likelihood fit to constraint flux and cross-section uncertainties for T2K Oscillation Analysis

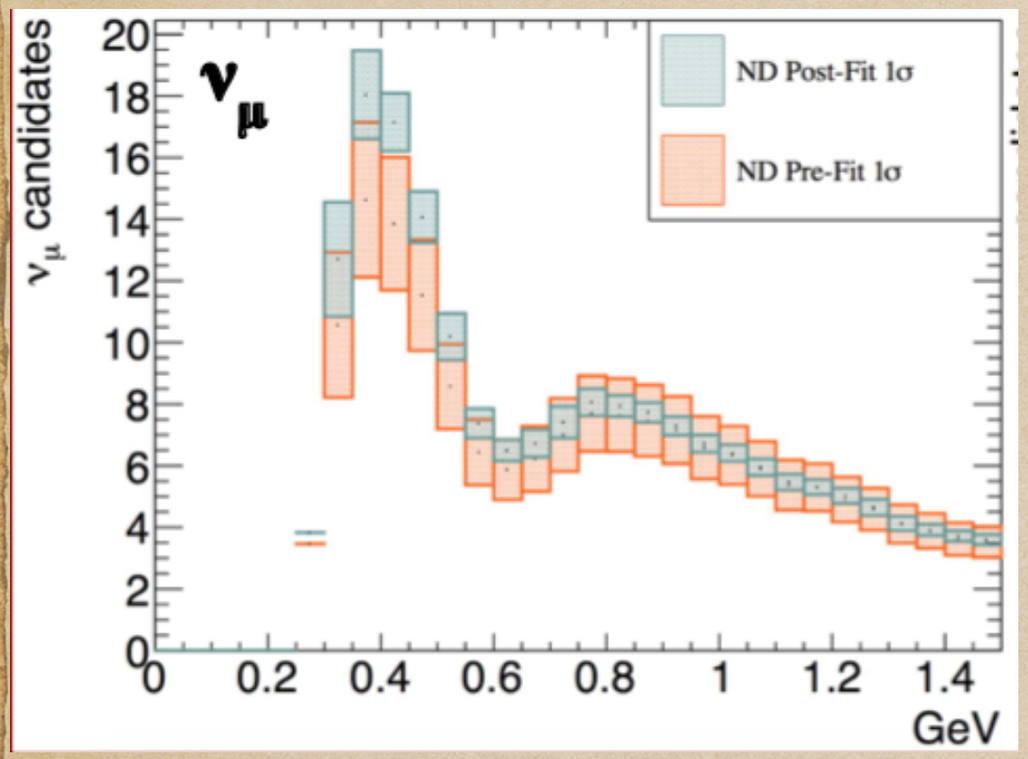
Flux uncertainties

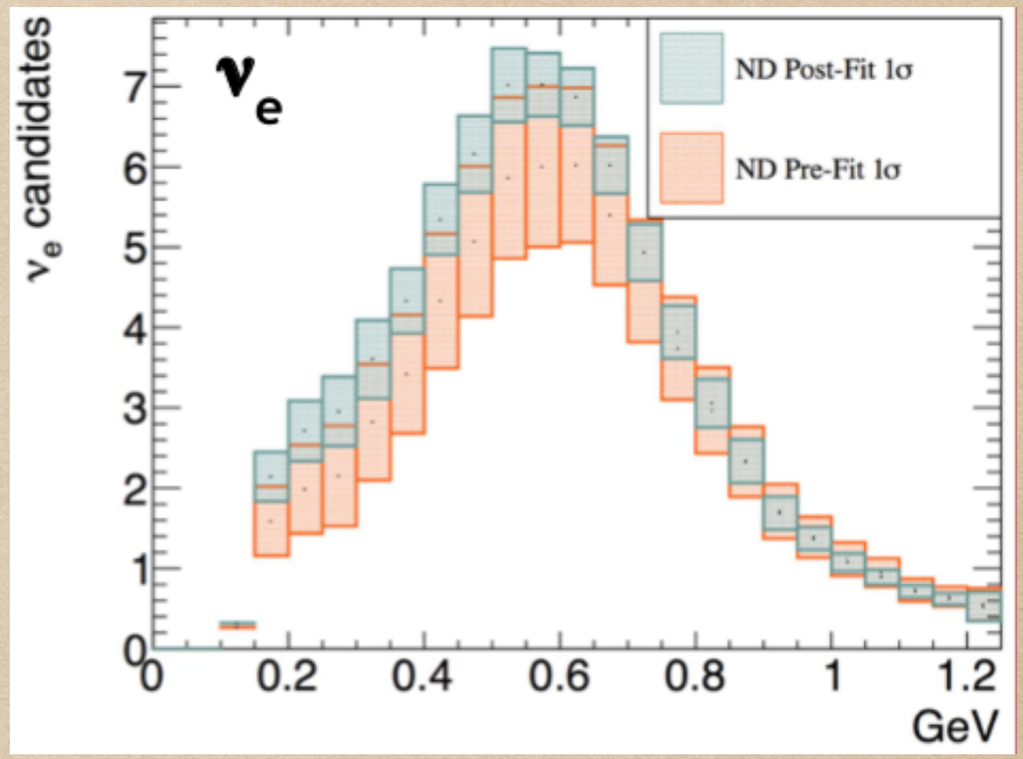


Cross-section uncertainties



Impact of ND280

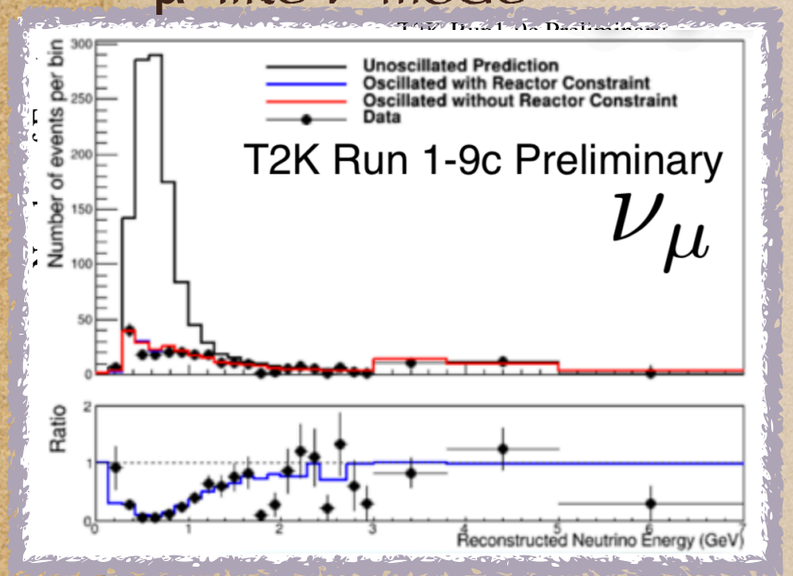




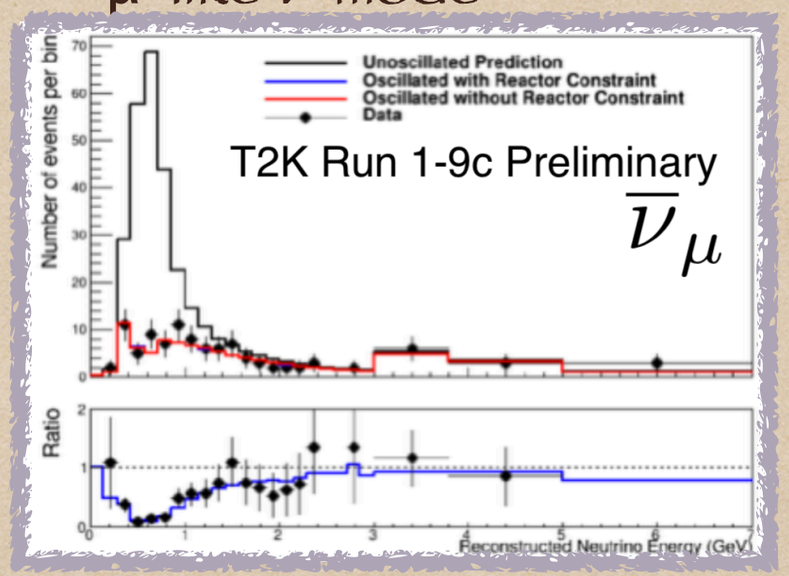
- Reduce uncertainties from ~15% to ~5% for both, ν_μ and ν_e
- Not covered in this talk → many ν and $\bar{\nu}$ cross-section measurements

Super-K

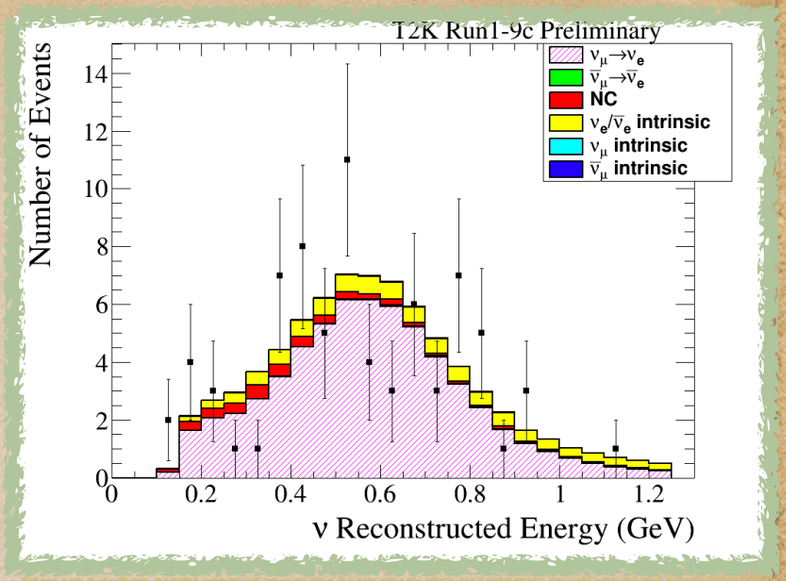
μ-like ν-mode

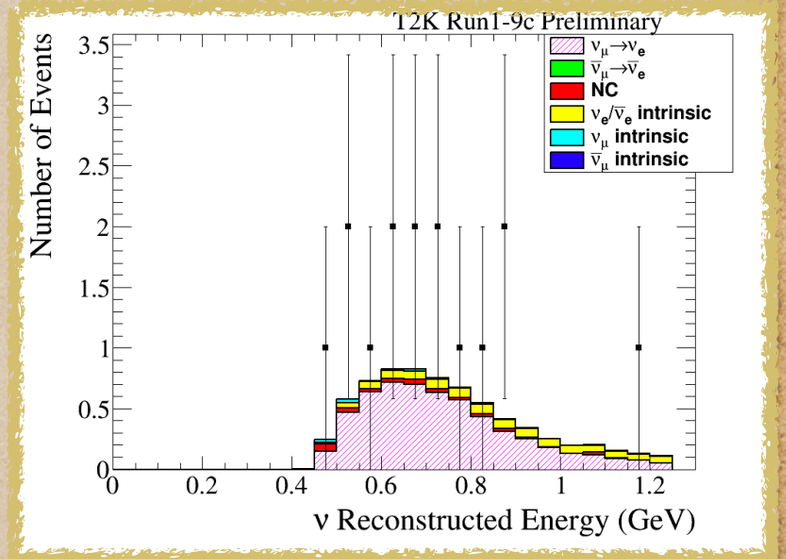


μ-like $\bar{\nu}$-mode

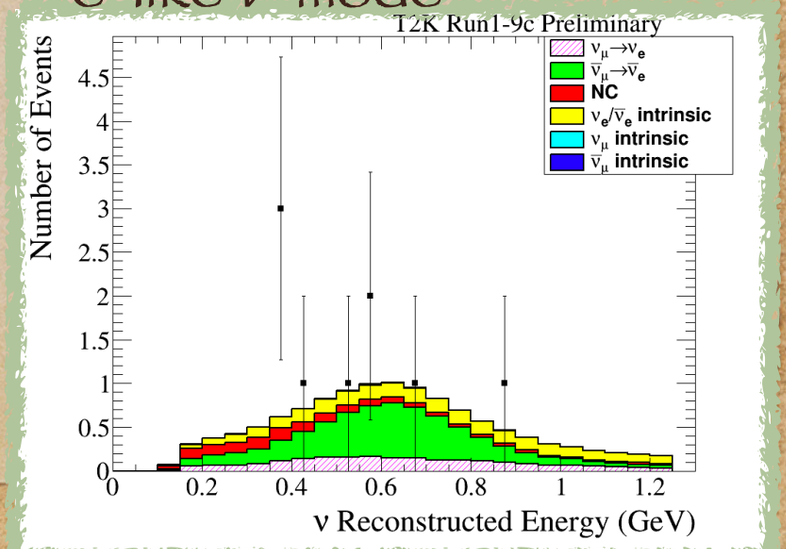


e-like ν-mode





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 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
ν-mode e-like	75	73.8	61.6	50.0	62.2
$\bar{\nu}$-mode e-like	9	11.8	13.4	14.9	13.2
ν-mode e-like+1π	15	6.9	6.0	4.9	5.8

To be updated with full run9 stat

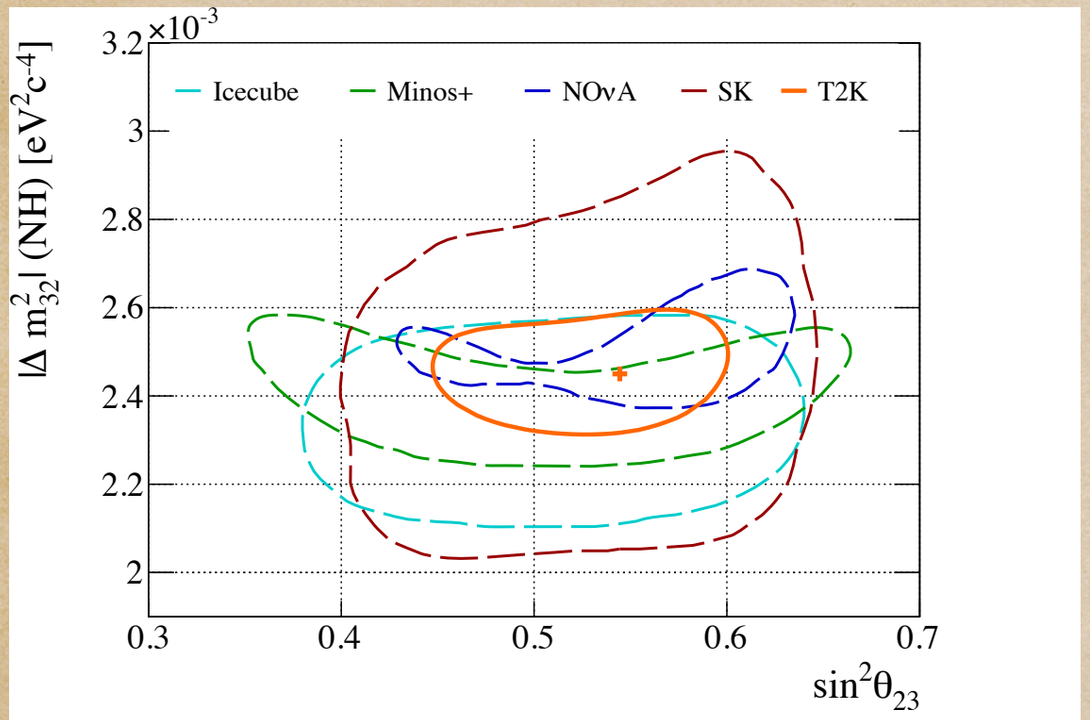
(50% more data in $\bar{\nu}$ mode)

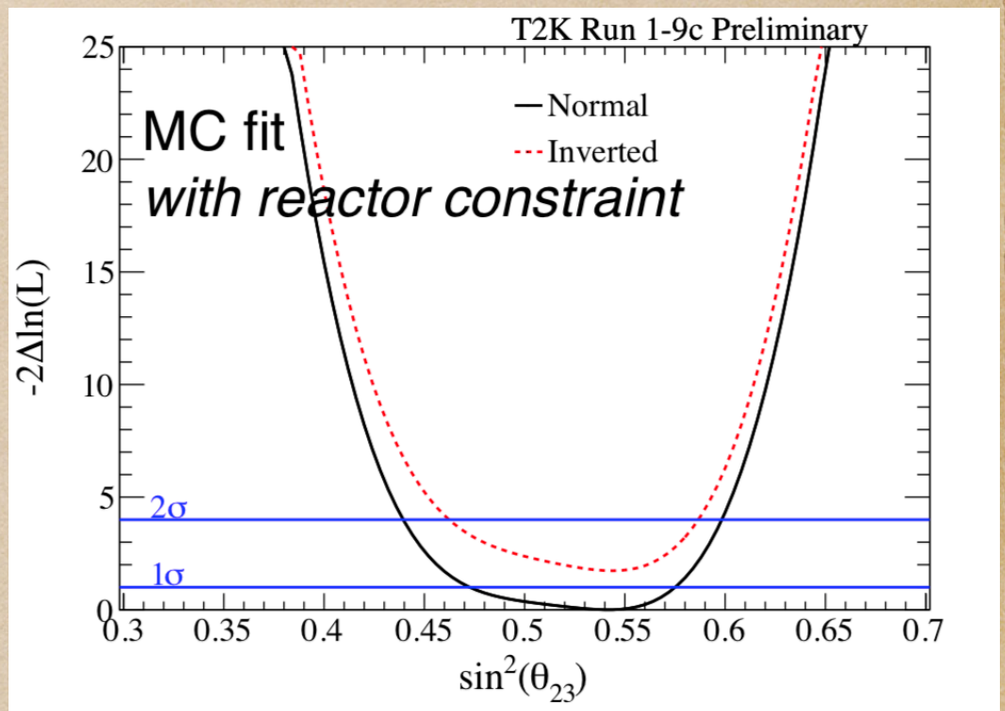
Systematics

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

- 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)

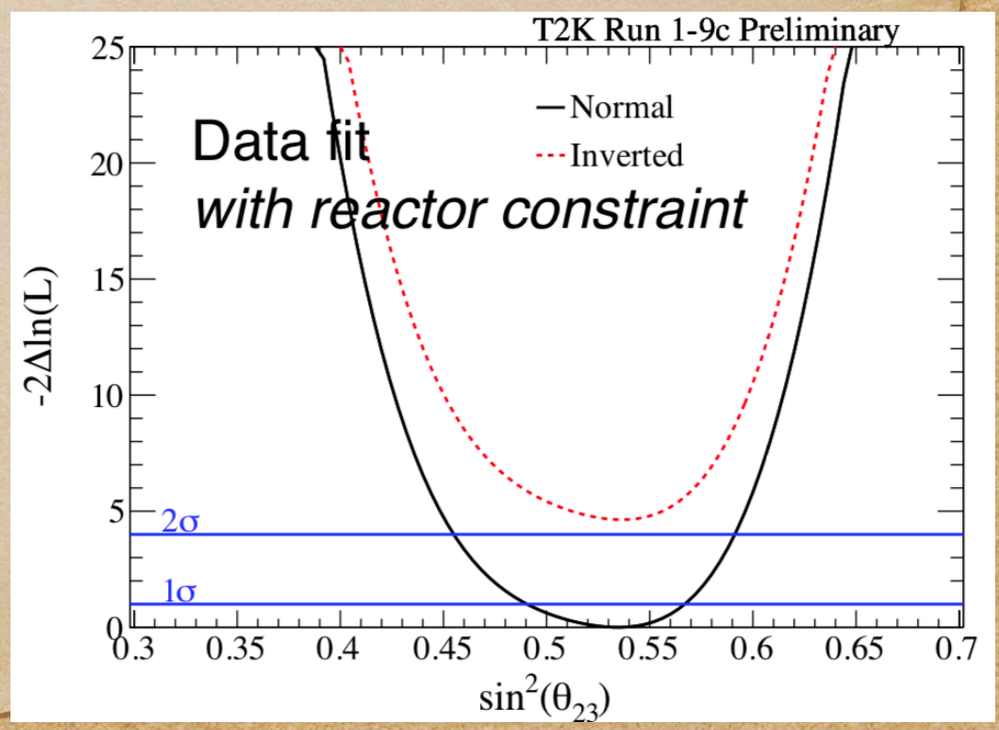
Oscillation results



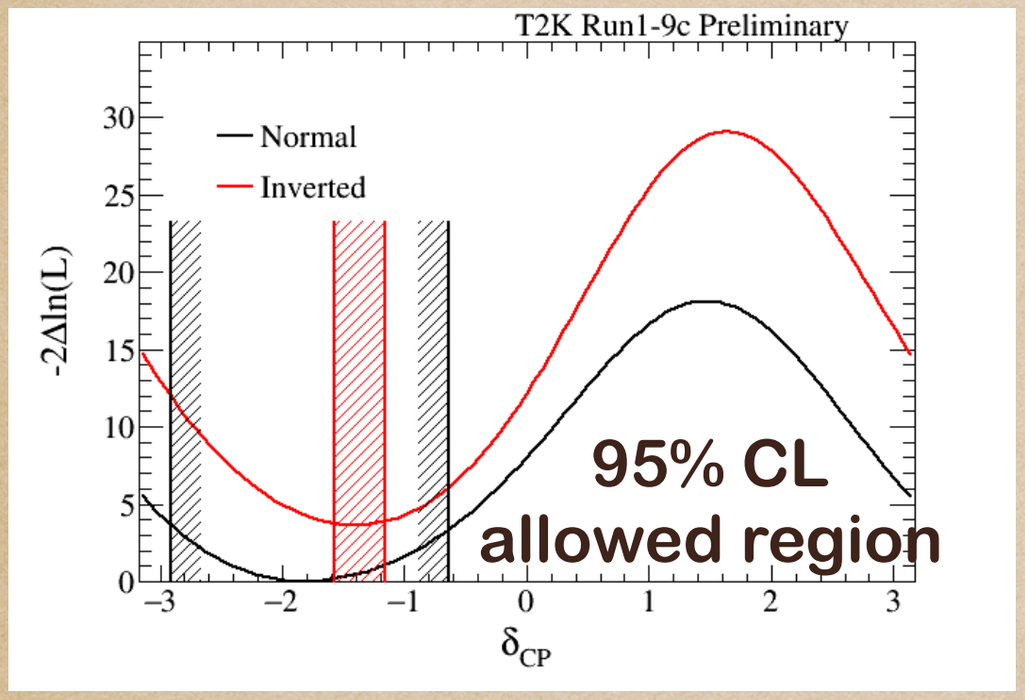


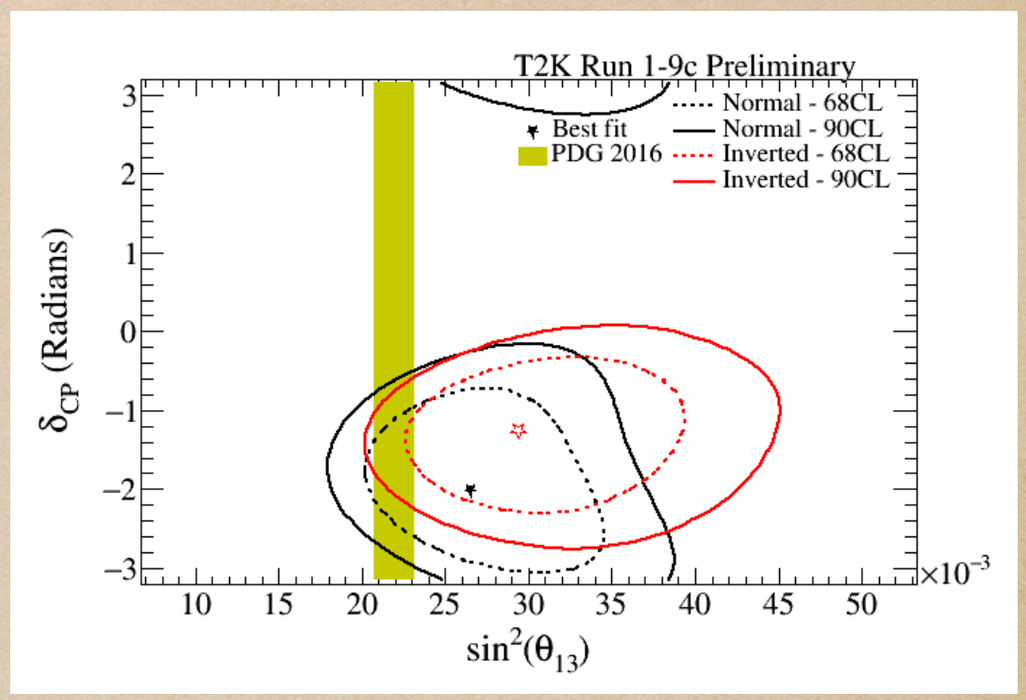
- **World best measurement of $\sin^2(\theta_{23})$→ compatible with maximal mixing**

	NH	IH
$\sin^2\theta_{23}$	$0.536^{+0.031}_{-0.046}$	$0.536^{+0.031}_{-0.041}$
$\lvert\Delta m^2\rvert$	2.434 ± 0.064	$2.410^{+0.062}_{-0.063}$



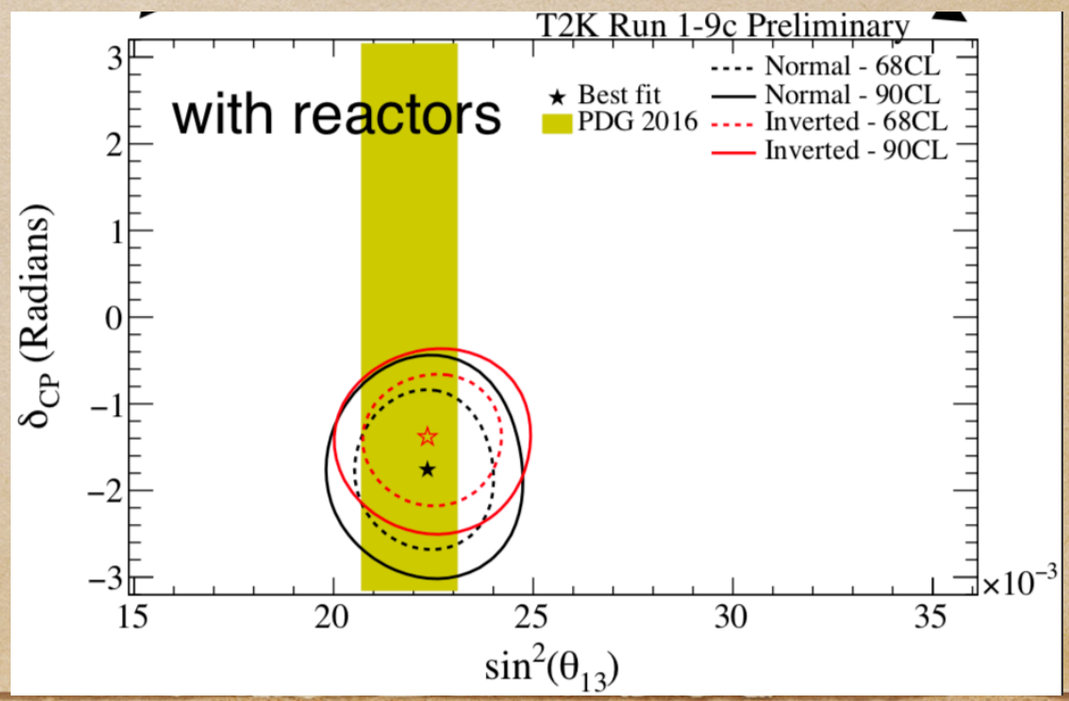
Oscillation results



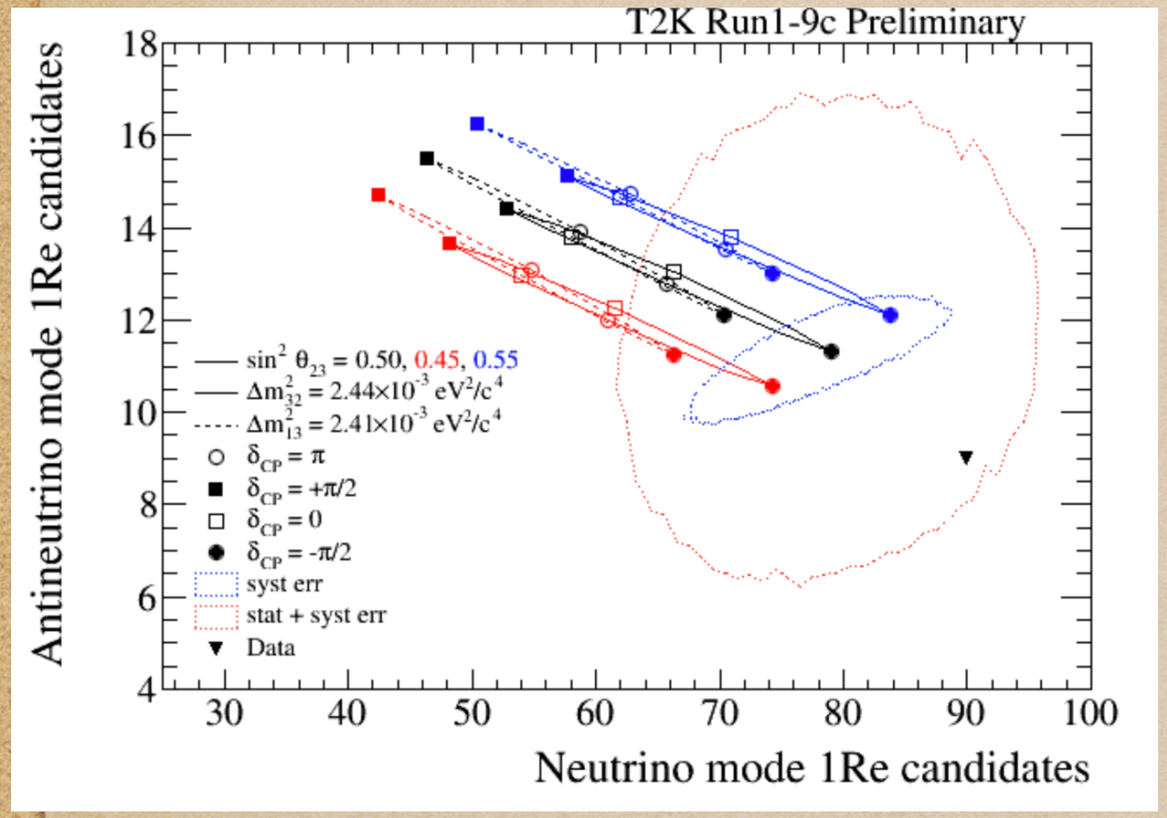


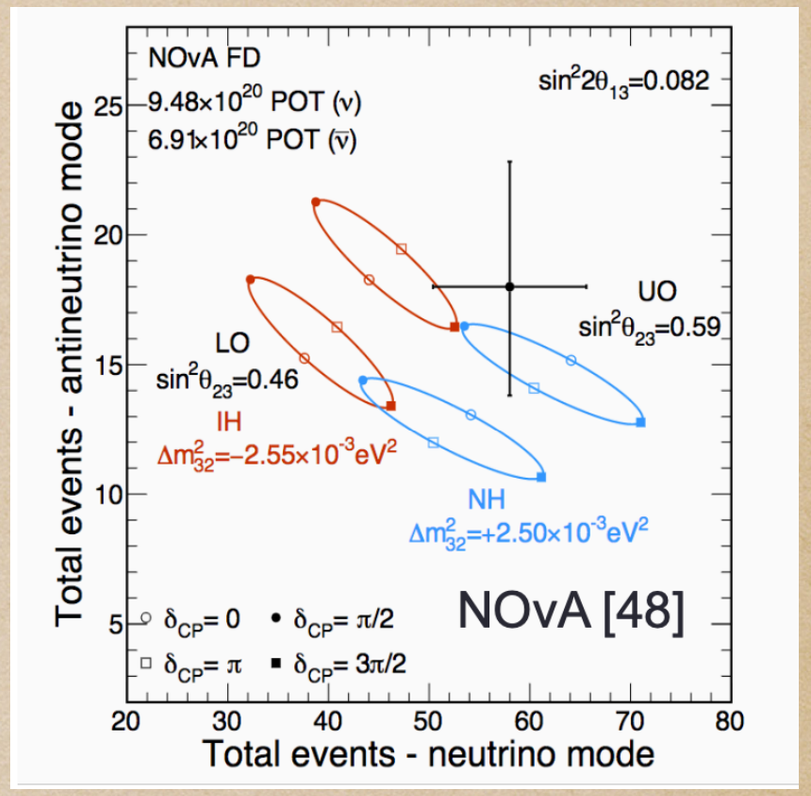
- Precise measurement of $\sin^2(\theta_{23})\rightarrow$ compatible with maximal mixing
- T2K alone and T2K+reactor both prefer values of $\delta_{CP}\sim-\pi/2$
- Normal ordering is also favoured

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



Comparison with NOνA





- NOνA is the other LBL experiment currently running
  - Plan to have combined T2K/NOνA Oscillation Analysis in 2022
- Currently we both prefer normal ordering
- Preference for maximal CP violation in T2K not confirmed by NOνA
- More statistics is needed!

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!

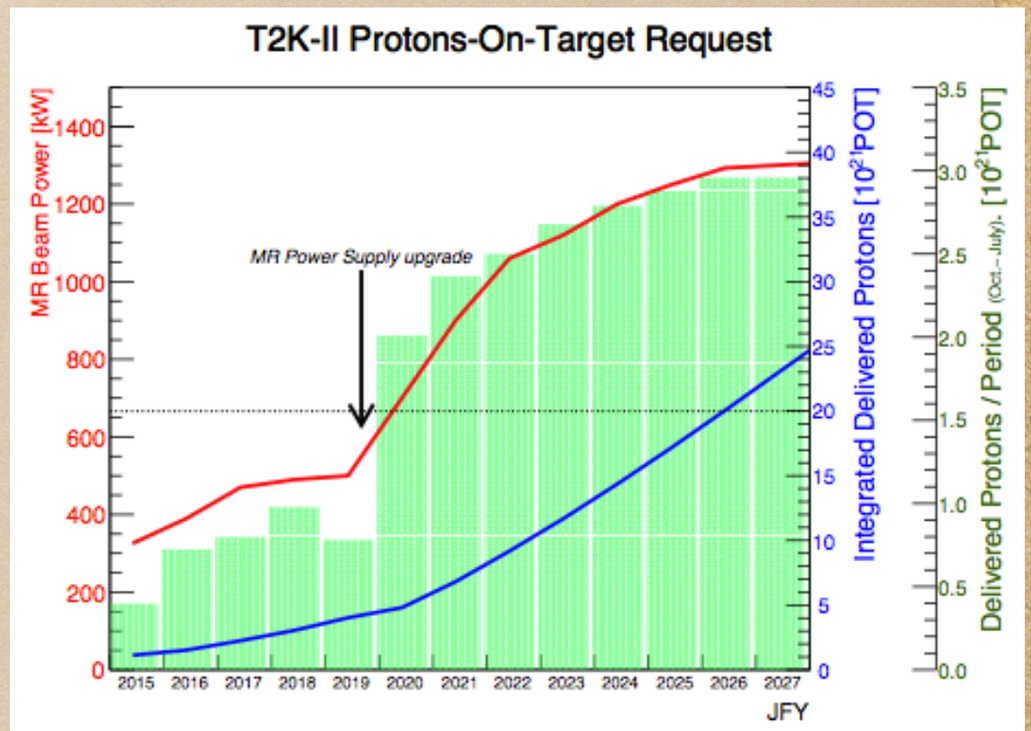
T2K phase II

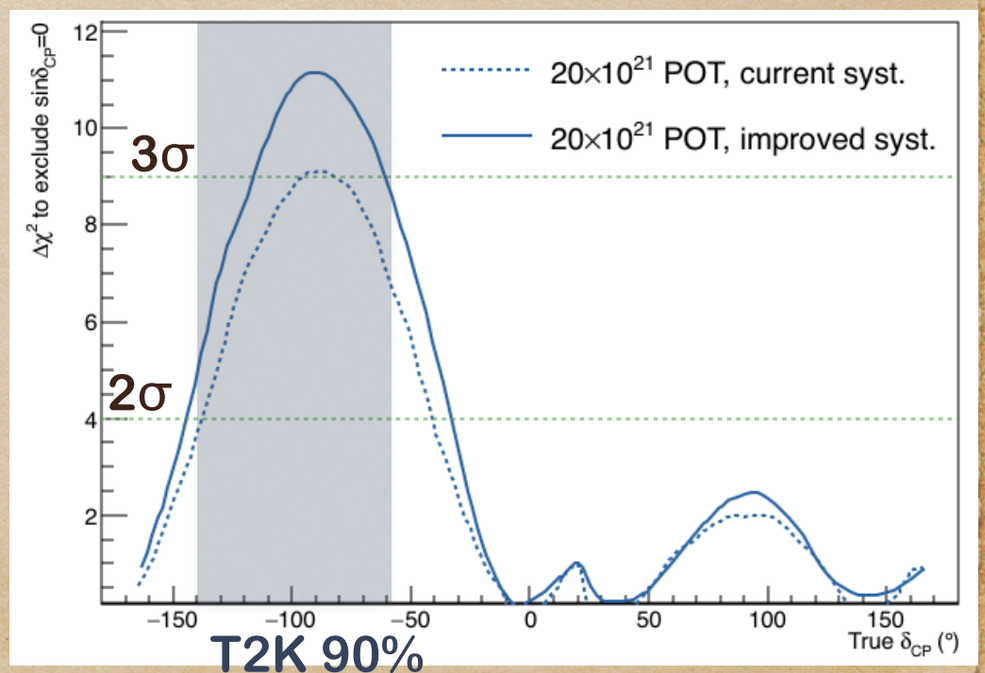
- T2K was originally approved to collect 7.8×10^{21} pot
  - Driven by sensitivity to θ_{13}
- Proposal for an extended run
  - T2K-II → 20×10^{21} pot
- Upgrade the Main Ring power supply to reach 1.3 MW operations

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

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

- >3σ measurement of CP violation (if δ_{CP} close to $-\pi/2$)
- Need to reduce systematics to ~4% (<3% from ND280)



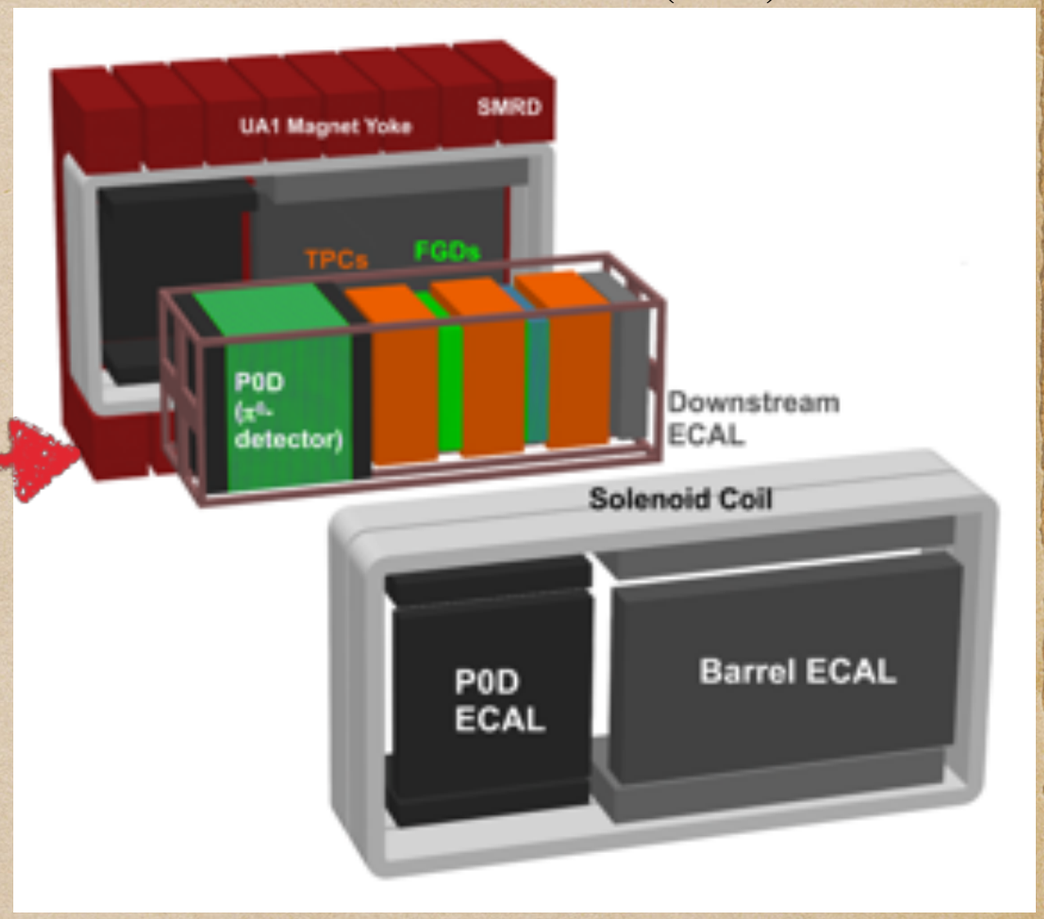


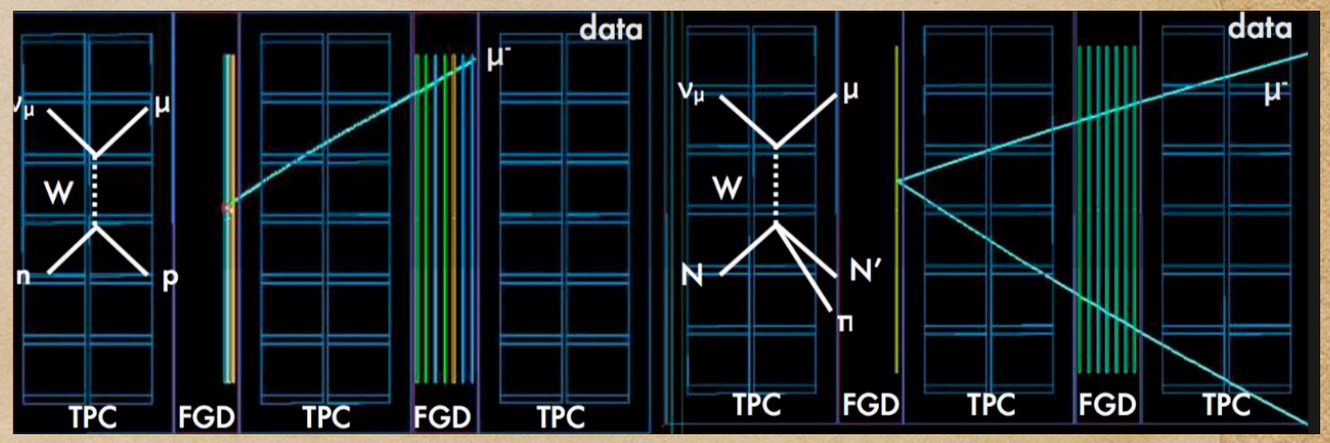
T2K 90% allowed region

Current ND280 detector

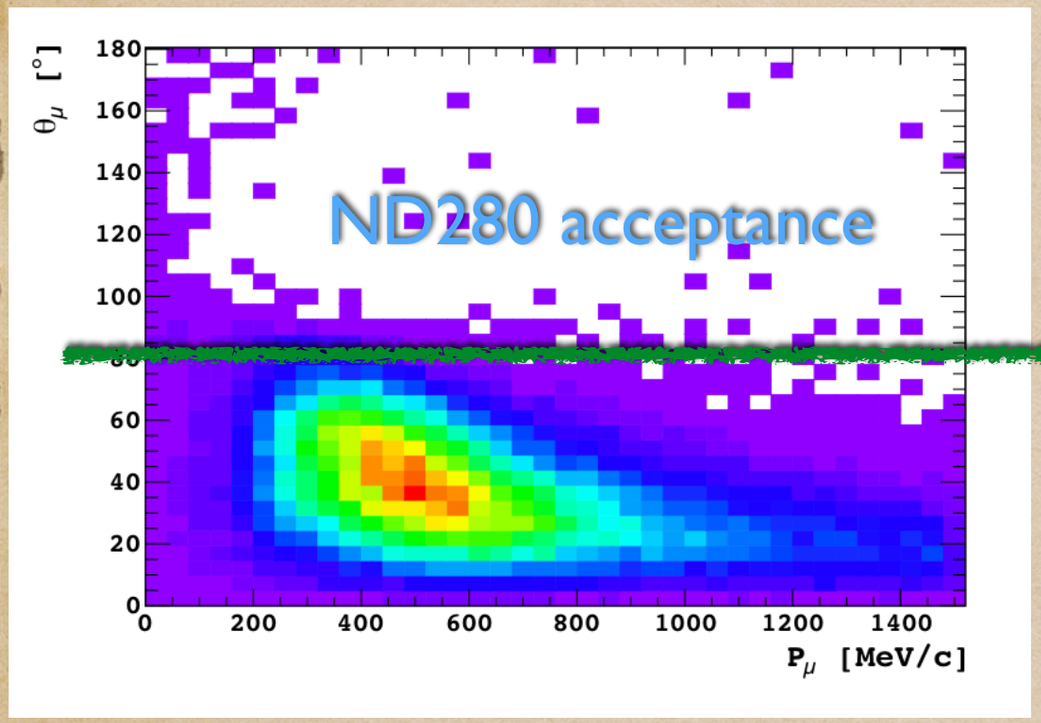
- Most of European groups in T2K were involved in ND280
- Magnetized detector with tracker system
- Precise measurement of particle charge, momenta and PID
  - $\nu\mu$ from $\bar{\nu}\mu$
  - νe from $\nu\mu$
- Excellent performances so far but optimized to detect forward going tracks

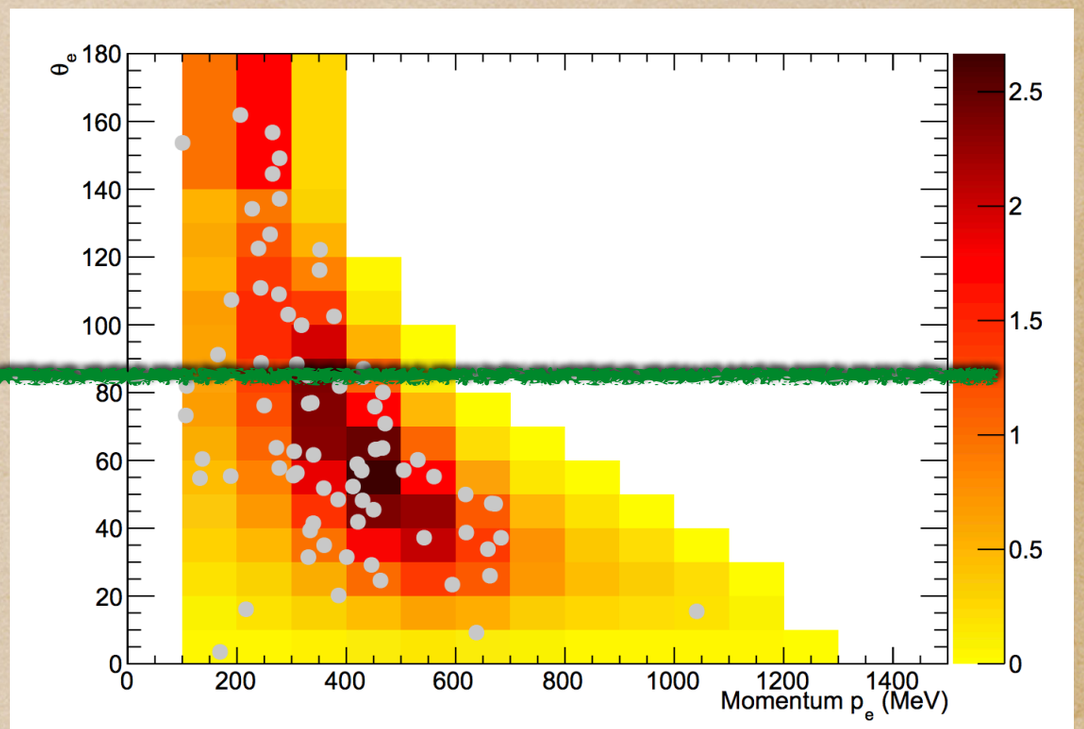
NIM A 659 (2011) 106–135



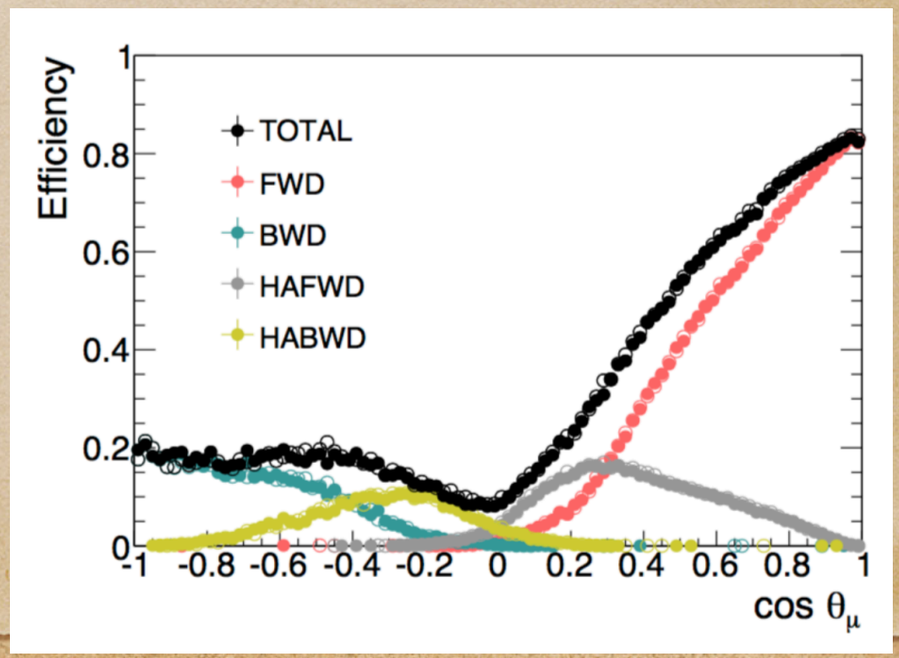


ND280 upgrade





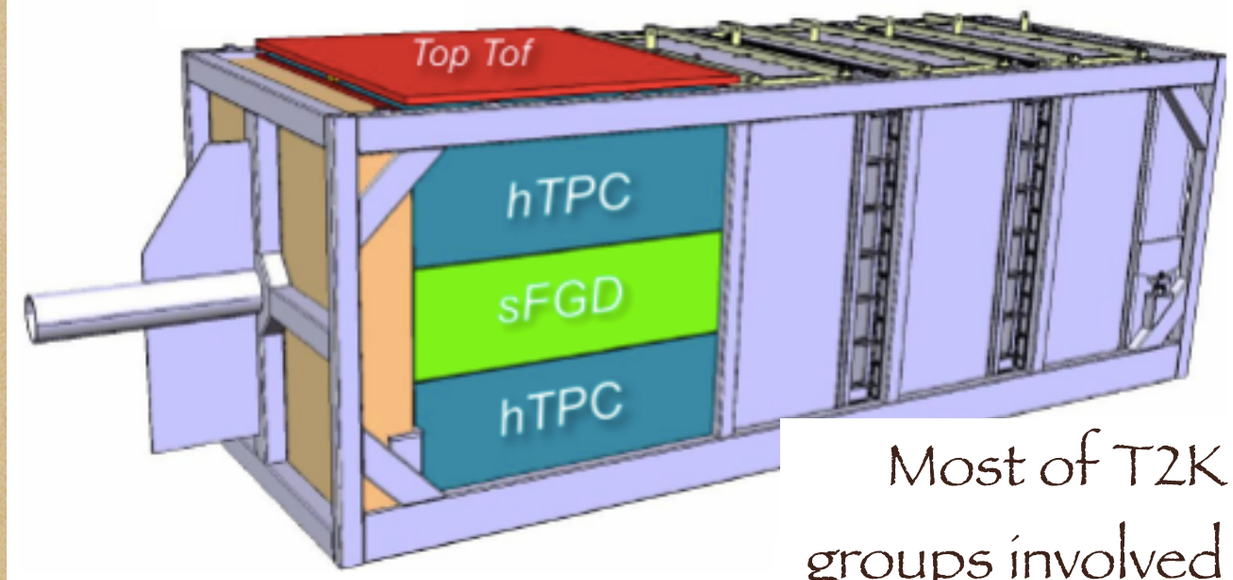
- Main limitation of ND280 : reduced angular acceptance → only forward going muons are selected with high efficiency
- An analysis dedicated to select tracks with high polar angles allow to select 20% of the events in that region
- We can do better with an upgrade!

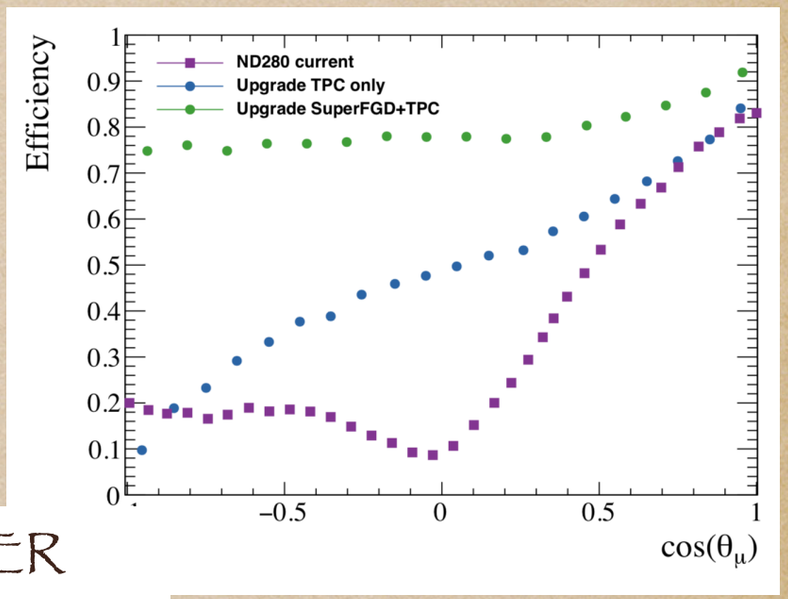


ND280 upgrade

CERN-SPSC-P357

214 authors





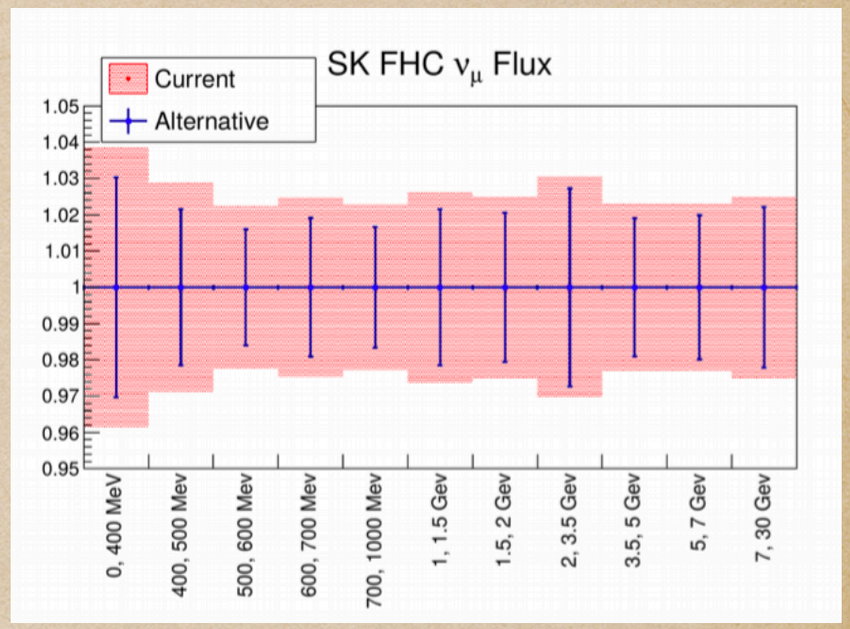
Most of T2K JENNIFER groups involved in ND upgrade

- **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 CERN SPSC in 2017**
- **Test beam in Summer 2018 @ CERN, writing TDR now**

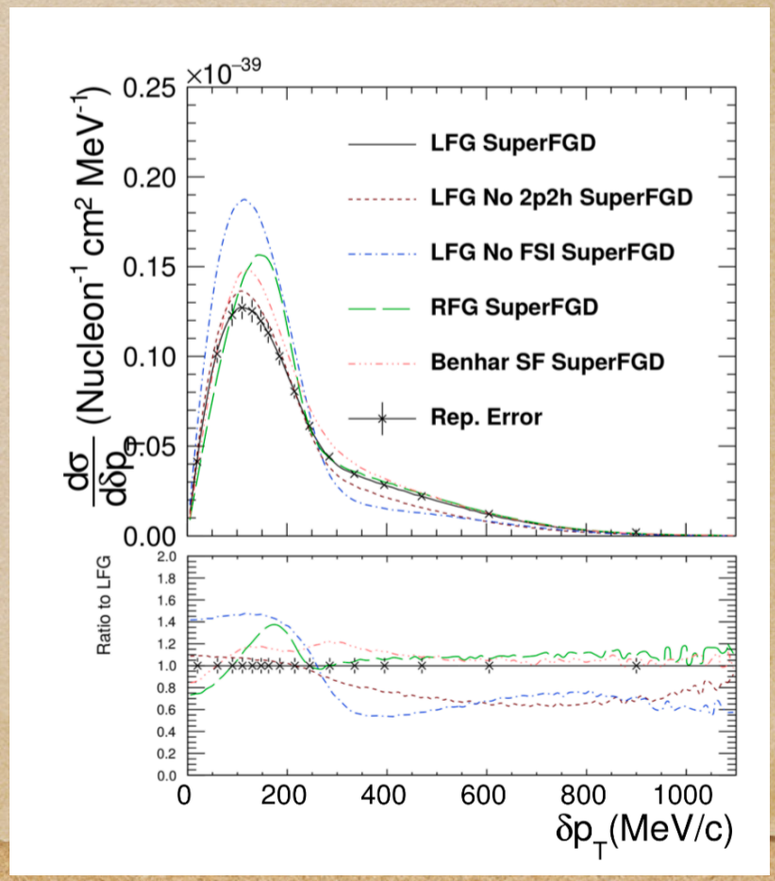
2017	2018	2019	2020	2021
Proposal	Prototypes, TDR	Construction	Construction	Installation

Upgrade performances

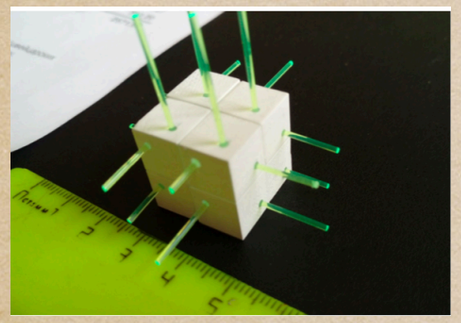
Parameters	Reduction of uncertainties by
Neutrino fluxes	20 %
σ_ν(CCQE / 2p2h)	25—40%
FSI	45 %
σ_ν(Q^2 dependent)	25 %

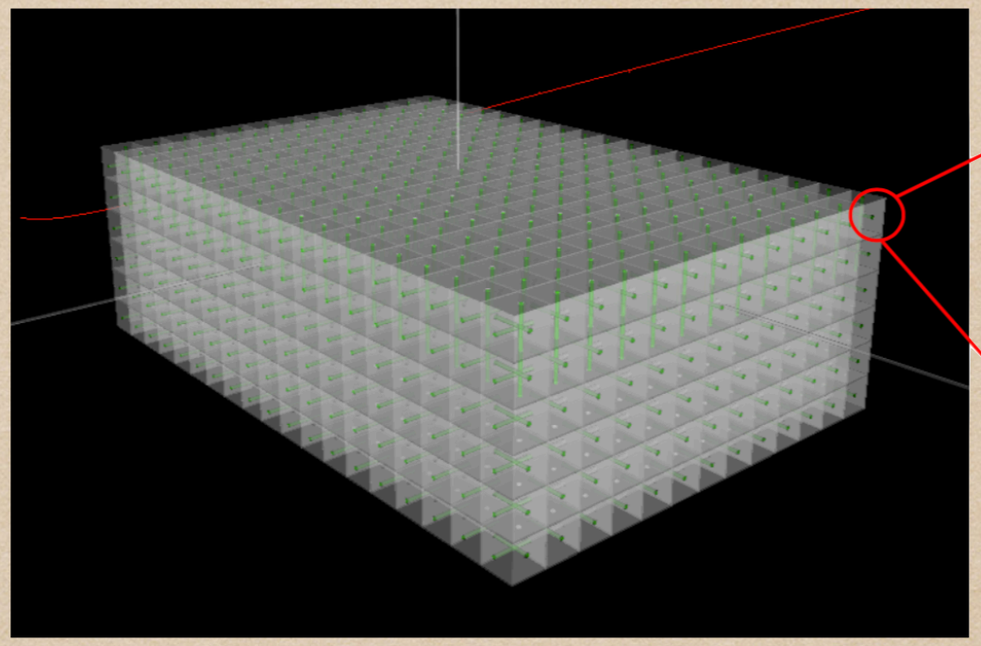


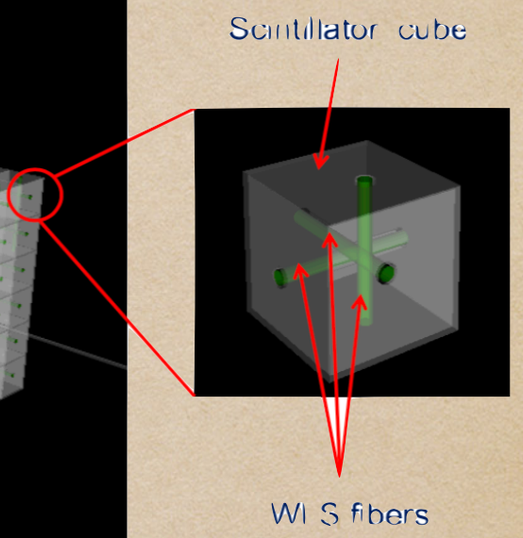
- For same POT → Reduce uncertainties on inputs to oscillation analysis by ~30%
- Low momentum threshold and full angular coverage → much better sample to study nuclear effects



Super-FGD



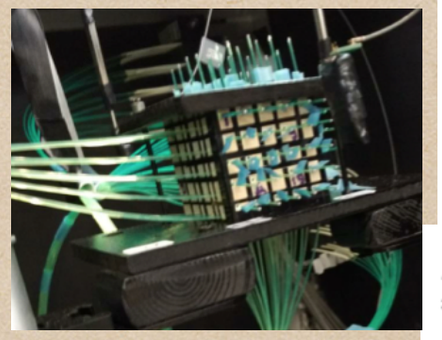




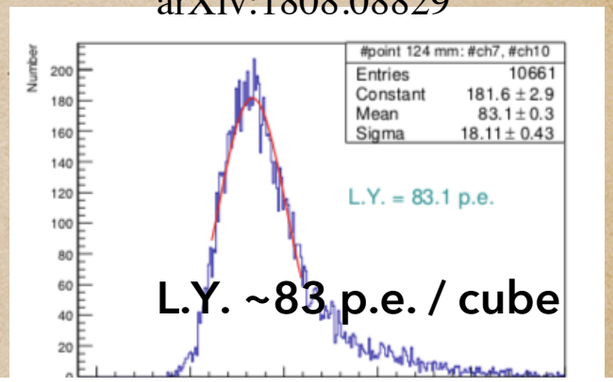
- 2 ton target with 1x1x1 cm cubes read by 3 fibers
- Total of 60k channels read with MPPC
- Full active plastic scintillator target
  - 3D view and reconstruction
  - 4π acceptance
  - Low momentum threshold to reconstruct charged particles
  - Potential to reconstruct neutrons through ToF

Super-FGD test beam @ CERN

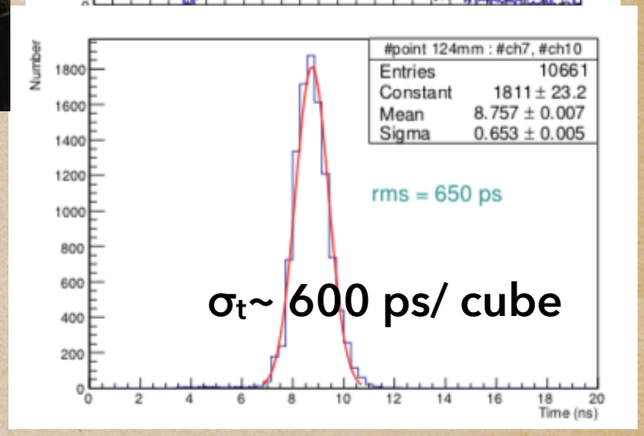
- Oct. 2017: 5x5x5 cm^3 prototype
- Summer 2018: 24x8x48 cm^3 prototype in B-field
  - Test the electronic response, tracking capability, pixel granularities



arXiv:1808.08829

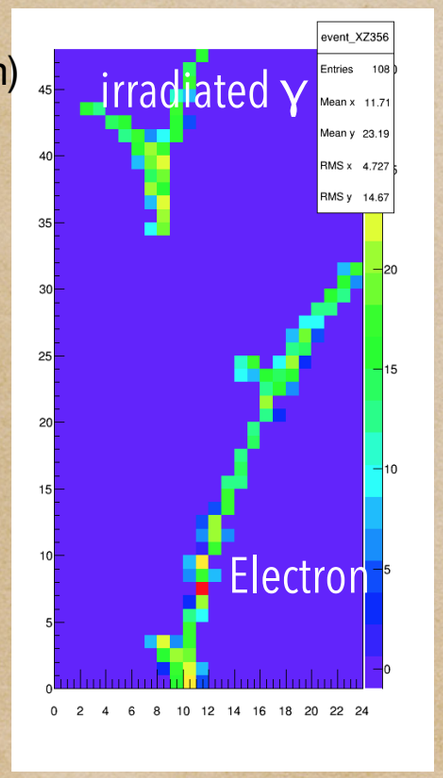


L.Y. ~83 p.e. / cube

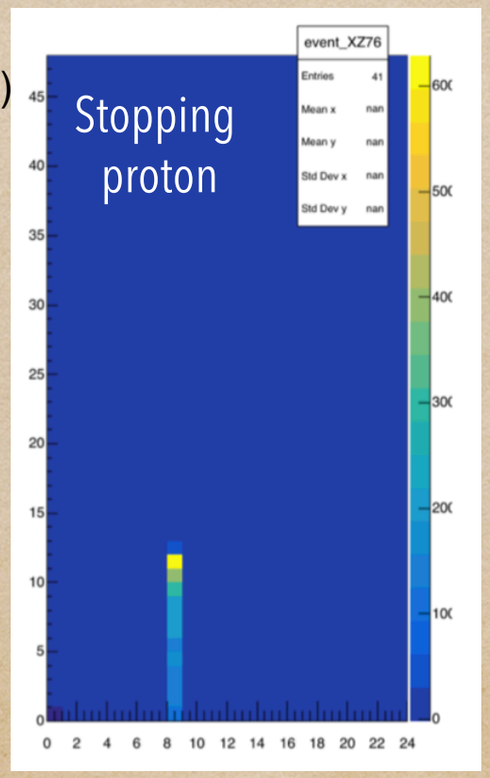


σ_t~ 600 ps/ cube

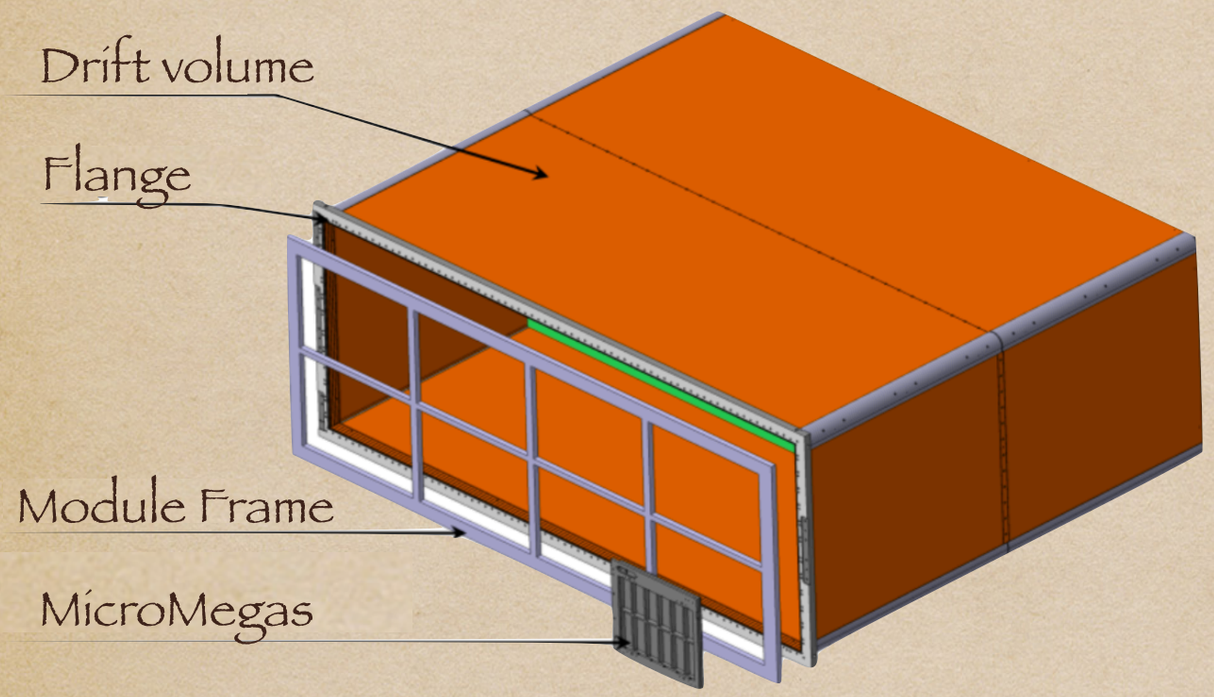
Z (cm)

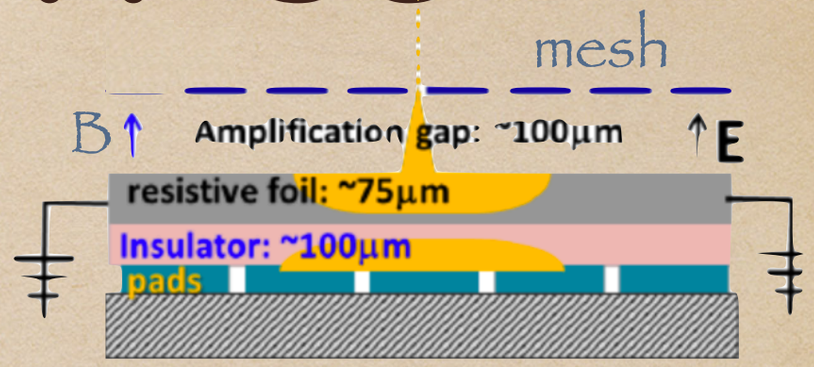


Z (cm)



Horizontal TPCs

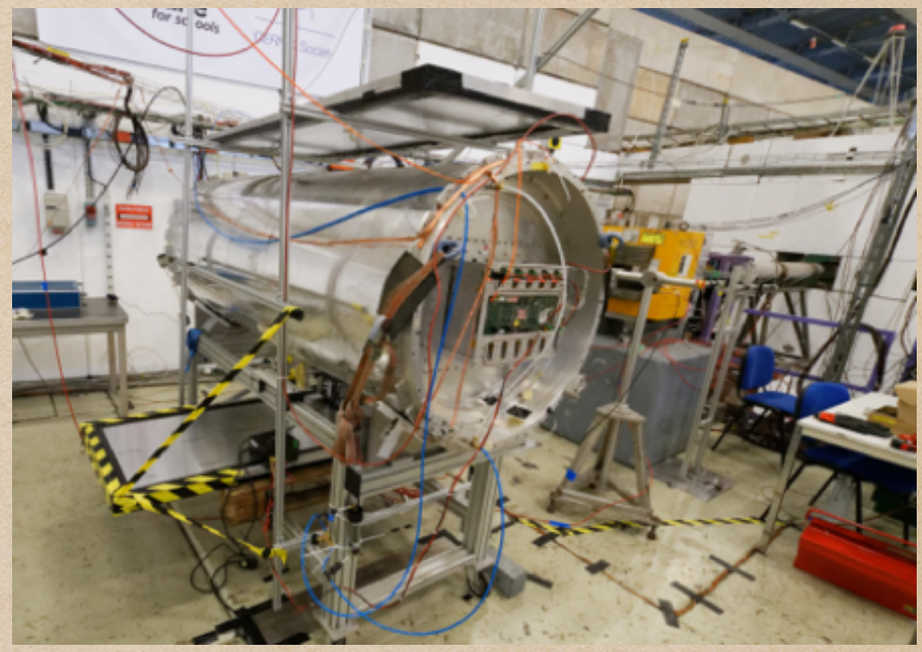




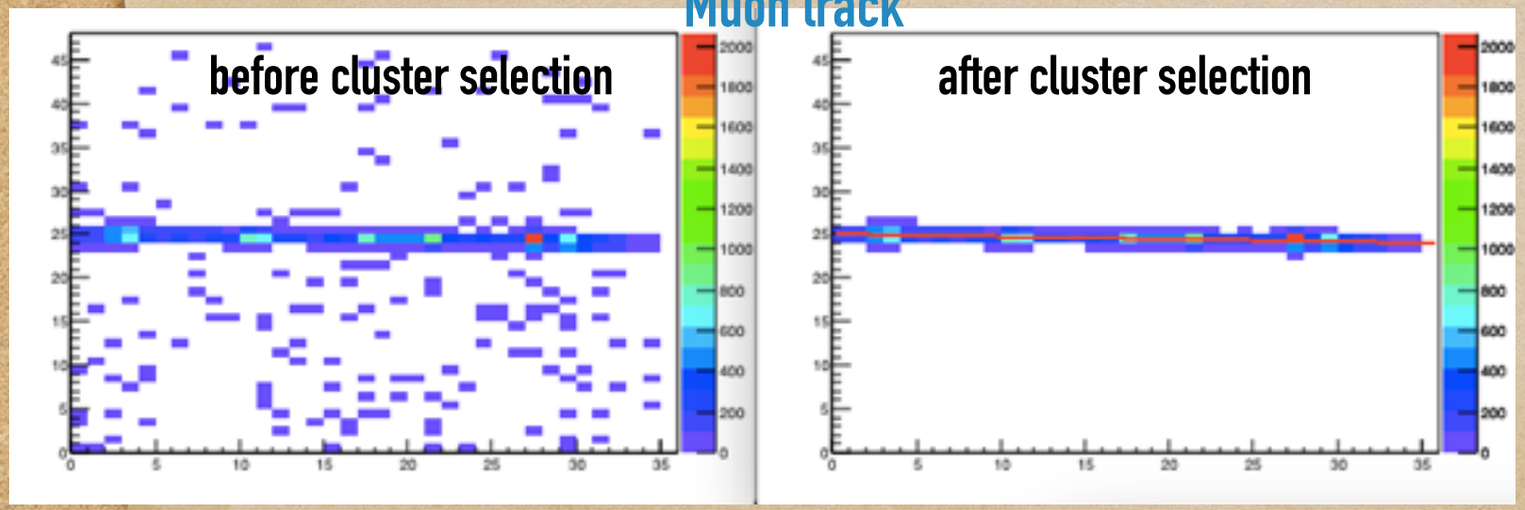
- Design based on existing TPCs
- 2 volumes per TPC, 8 MicroMEGAS per volume
- Single box field cage in order to reduce dead materials
- Use resistive MicroMEGAS → developed for ILC TPC prototypes
  - Charged spread on the pads → no sparks
  - Better spatial resolution

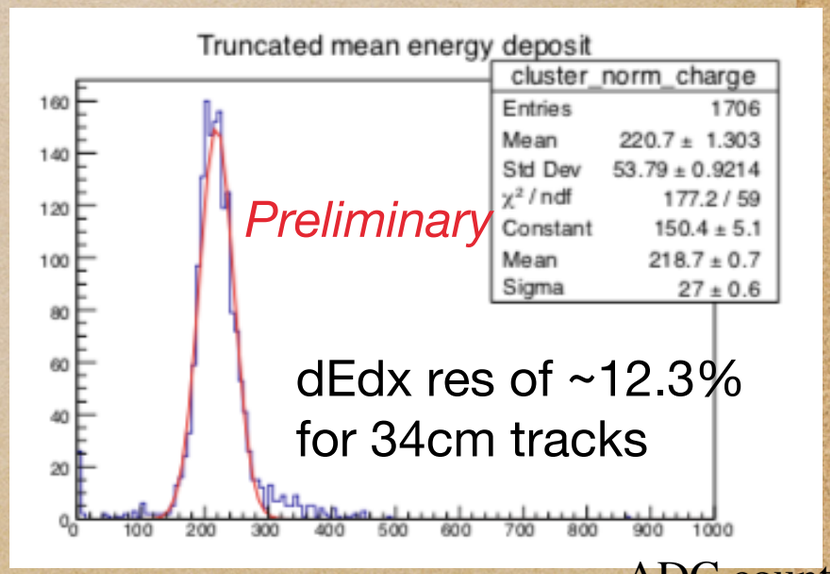
HA-TPC test beams @ CERN

- Use HARP field cage with one resistive MM
- Test beam with different particles (e, μ, π, p) and different momenta
- Data analysis on-going



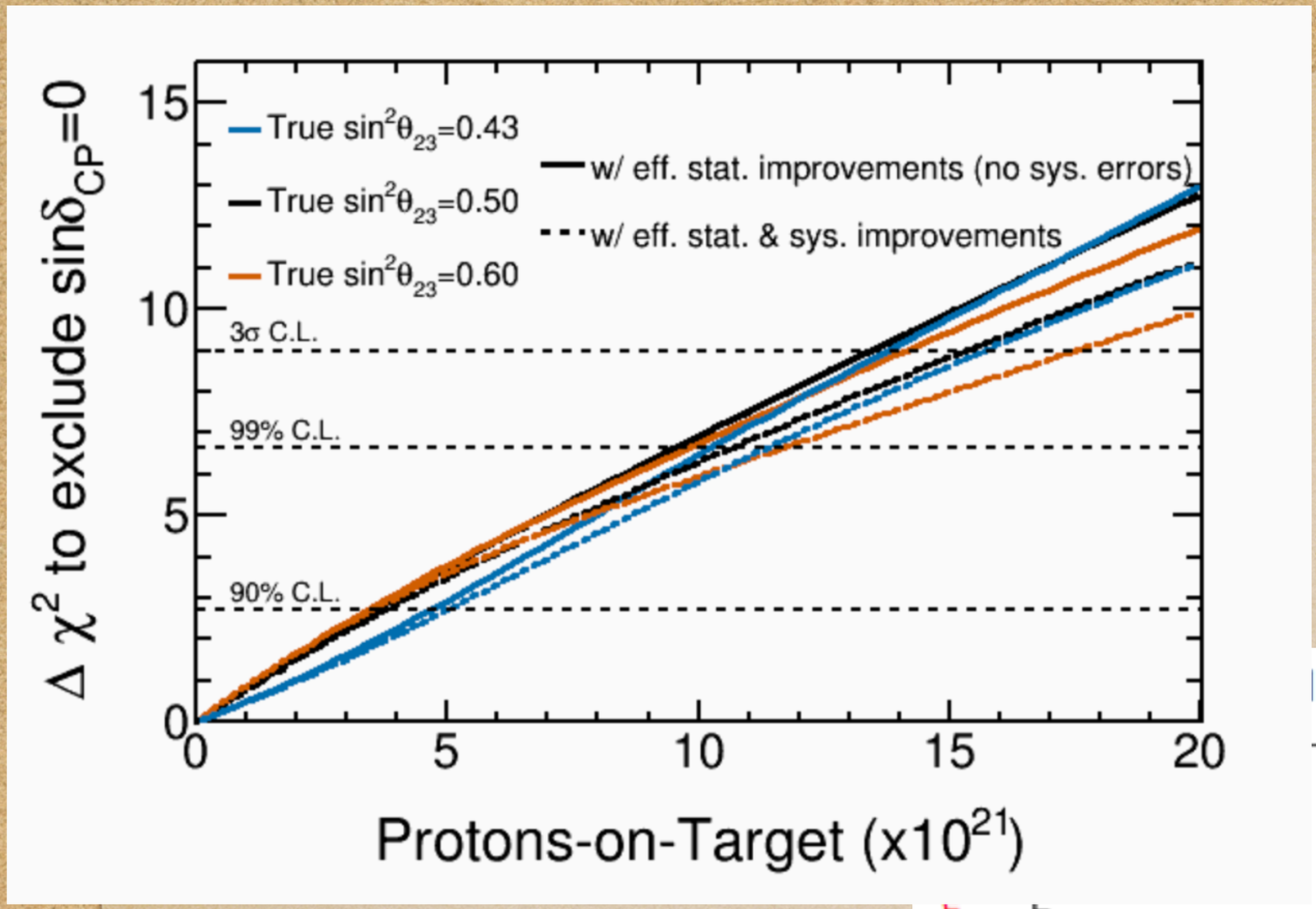
Muon track

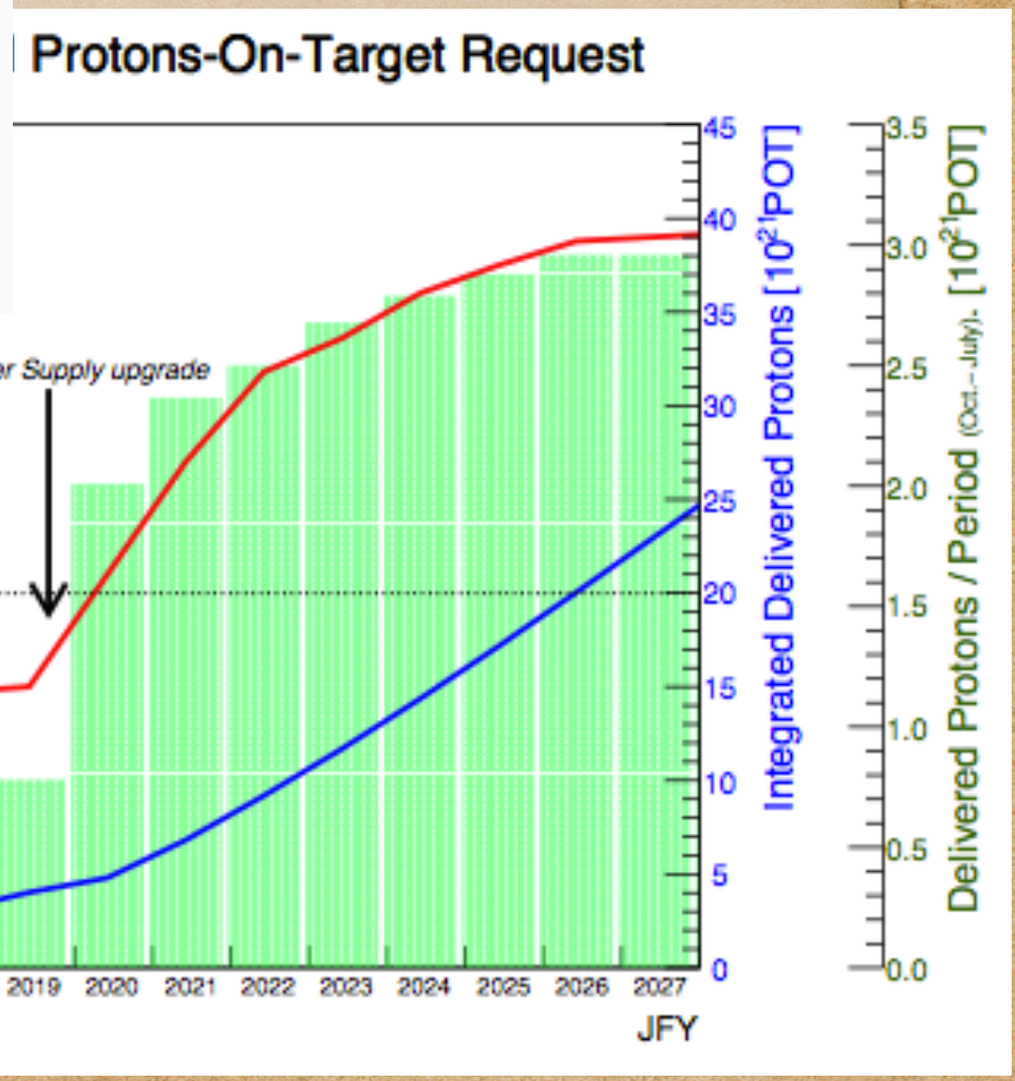




Conclusions

- T2K has been a very successful experiment
  - Discovery of electron neutrino appearance
  - World best measurement of $\sin^2\theta_{23}$
  - First hints of CP violation
- **T2K-II** will be one of the two leading LBL experiments until ~2026
- European groups heavily involved in the Upgrade of the Near Detector in order to reduce systematics and fully profit of the additional statistics
  - Test beams done in 2018
  - TDR being written → submit to J-PARC-PAC by the end of the year
  - Installation at J-PARC in 2021, start data taking 2022


True $\sin^2\theta_{23}$=0.43
True $\sin^2\theta_{23}$=0.50
True $\sin^2\theta_{23}$=0.60
w/ eff. stat. improvements (no sys. errors)
w/ eff. stat. & sys. improvements
3σ C.L.
99% C.L.
90% C.L.
$\Delta\chi^2$ to exclude $\sin\delta_{CP}$=0
Protons-on-Target ($x10^{21}$)


Protons-On-Target Request
MR Beam
MR Power Supply upgrade
Integrated Delivered Protons [10^{21}POT]
Delivered Protons / Period (Oct.–July). [10^{21}POT]
JFY