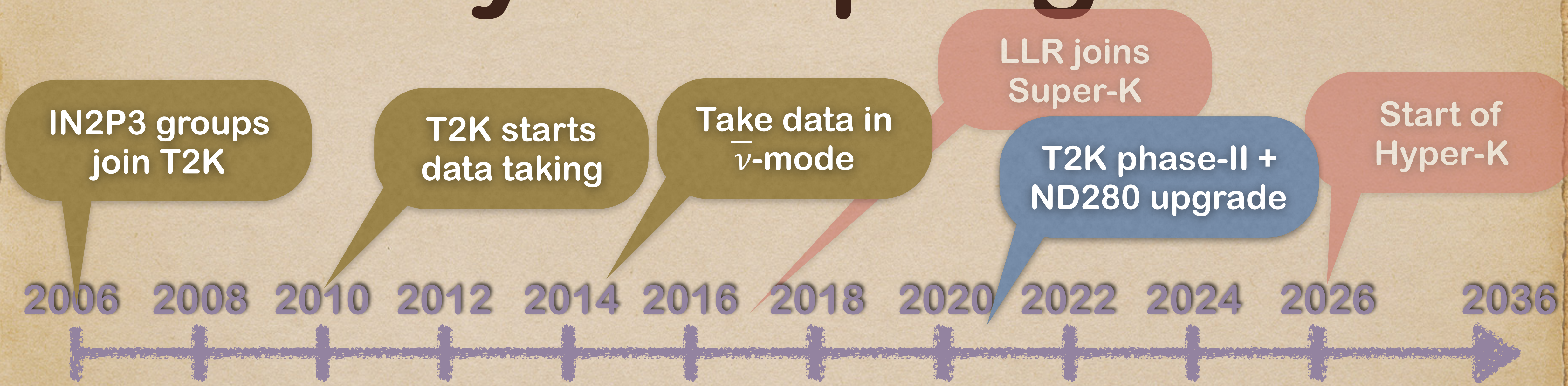
IN2P3 contributions to the Japanese neutrino program: T2K, T2K-II, Super-K and Hyper-K

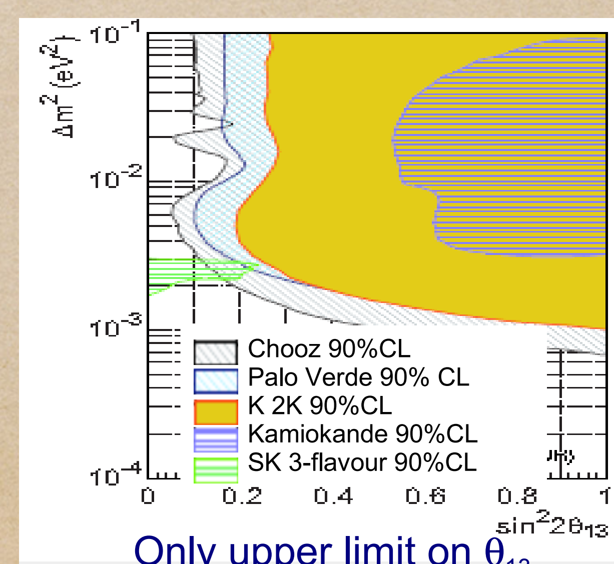
Claudio Giganti
for the LLR and LPNHE neutrino groups

IN2P3 Scientific Council – 28/06/2018

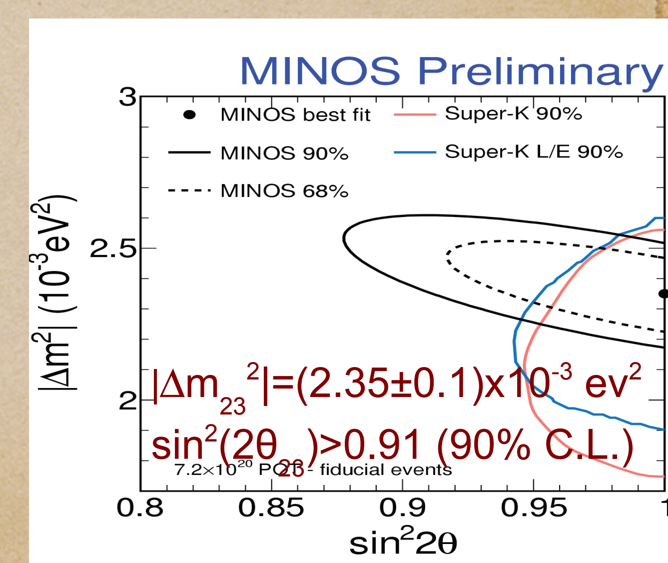
>30 years program



θ_{13} and δ_{CP} unknown



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



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IN2P3 groups join T2K

T2K starts data taking

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

LLR joins Super-K

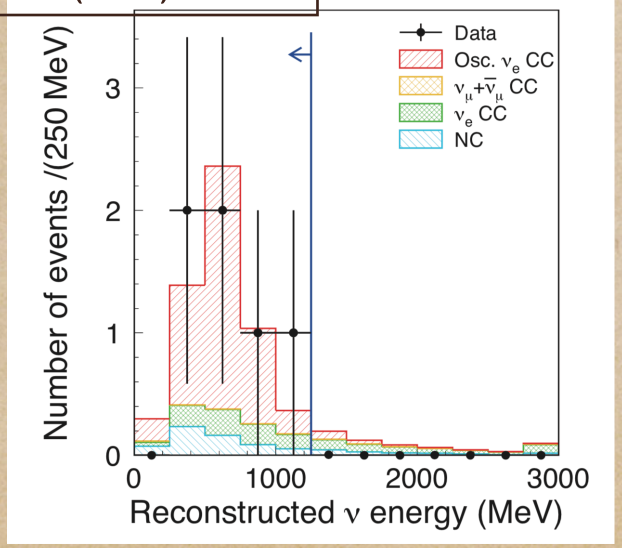
T2K phase-II + ND280 upgrade

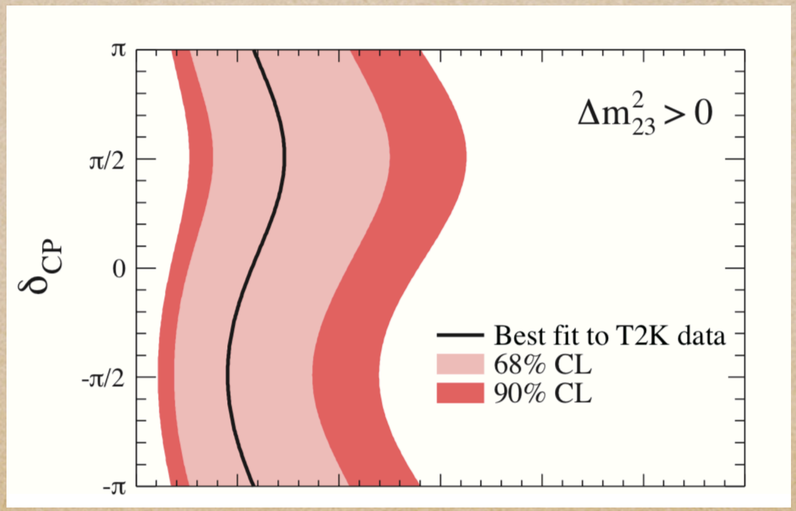
Start of Hyper-K

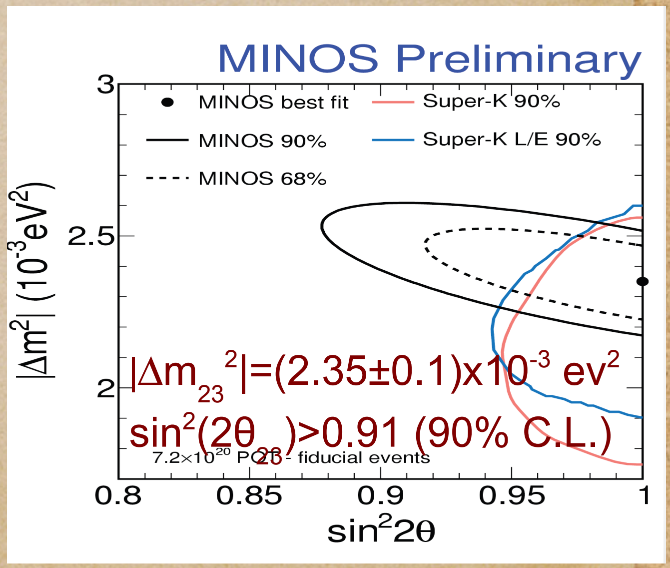
2006 2008 2010 2012 2014 2016 2018 2020 2022 2024 2026 2036

Hints of ν_e appearance ($\theta_{13}\neq0$@2.5σ)

Phys.Rev.Lett. 107 (2011) 041801







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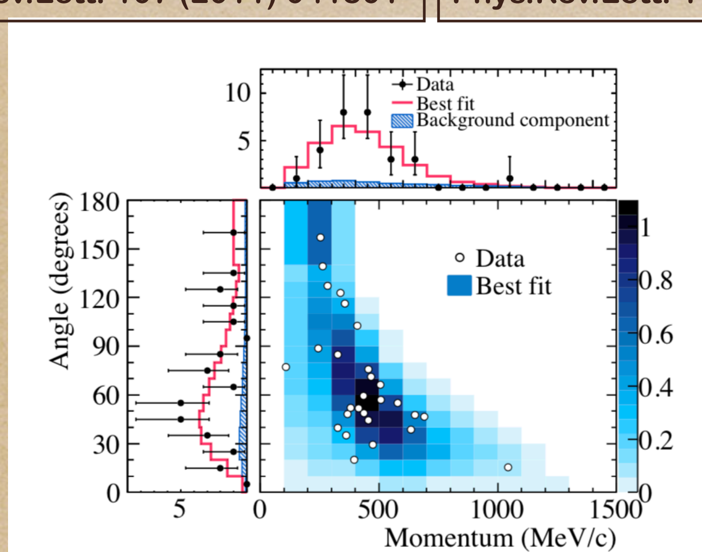

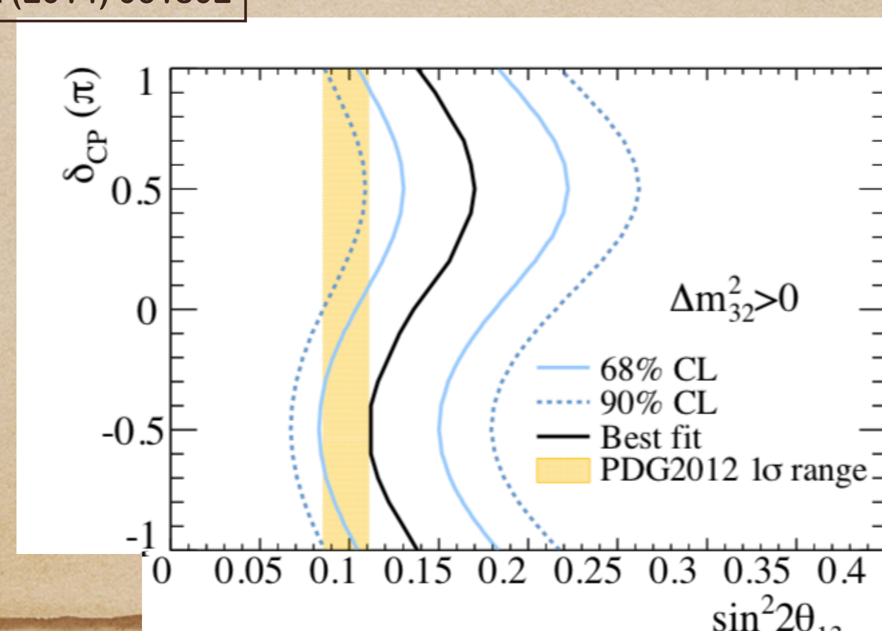

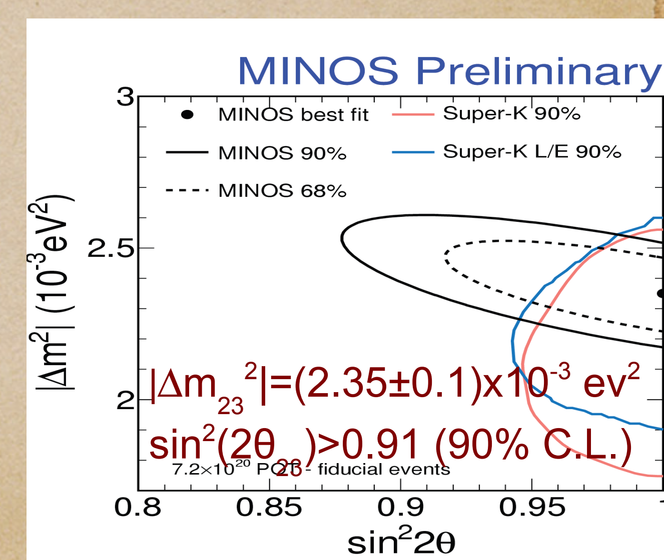

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Precise measurement of θ_{23}, Δm^2_{32}

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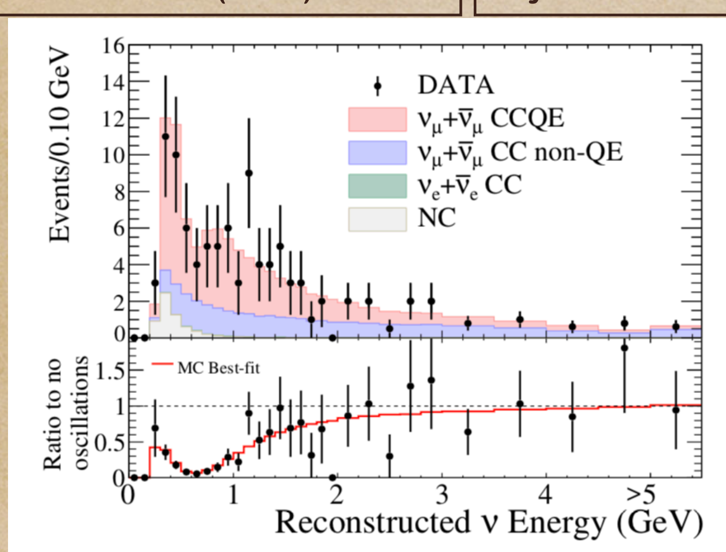

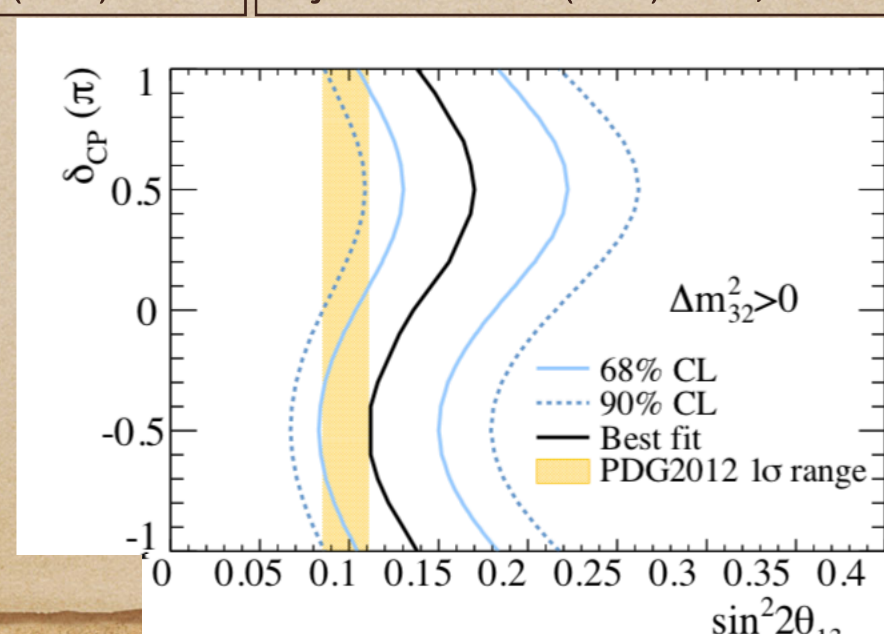

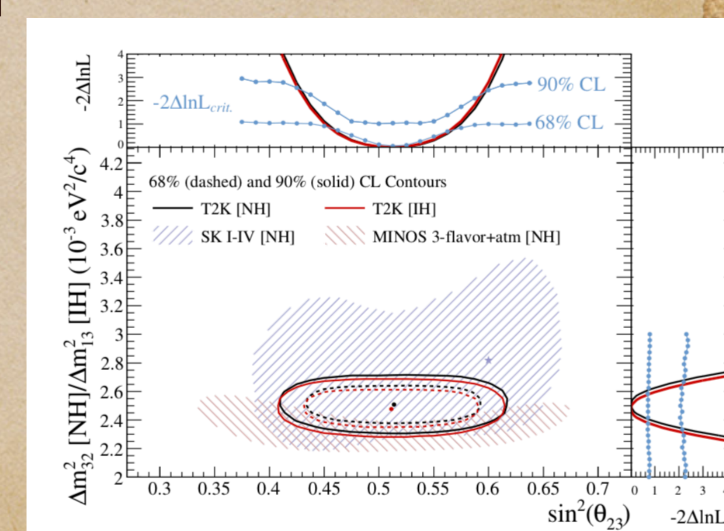

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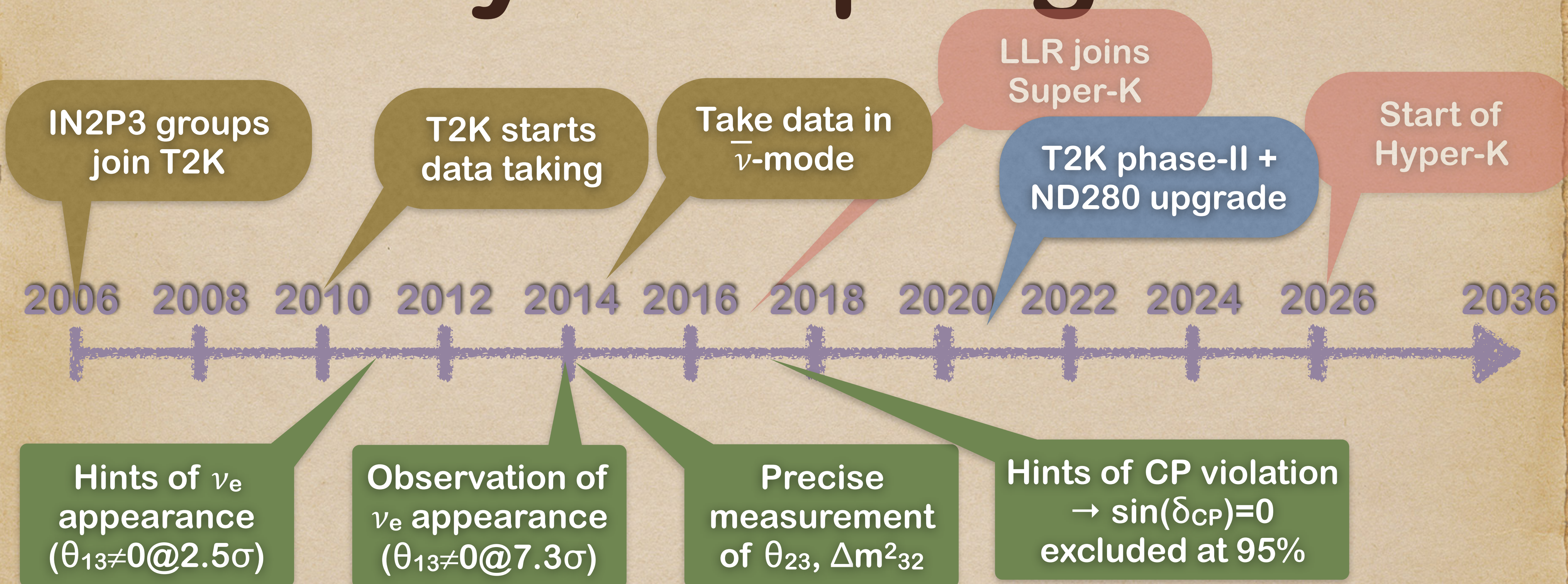

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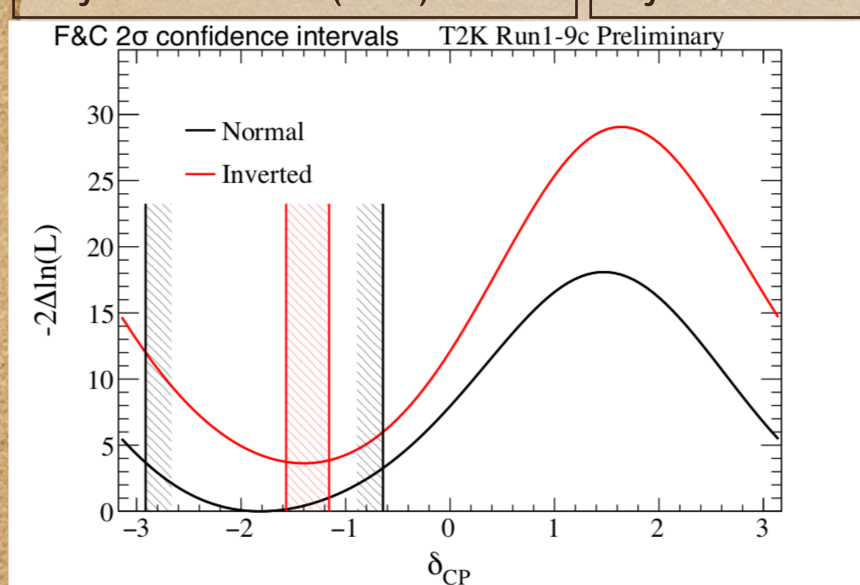
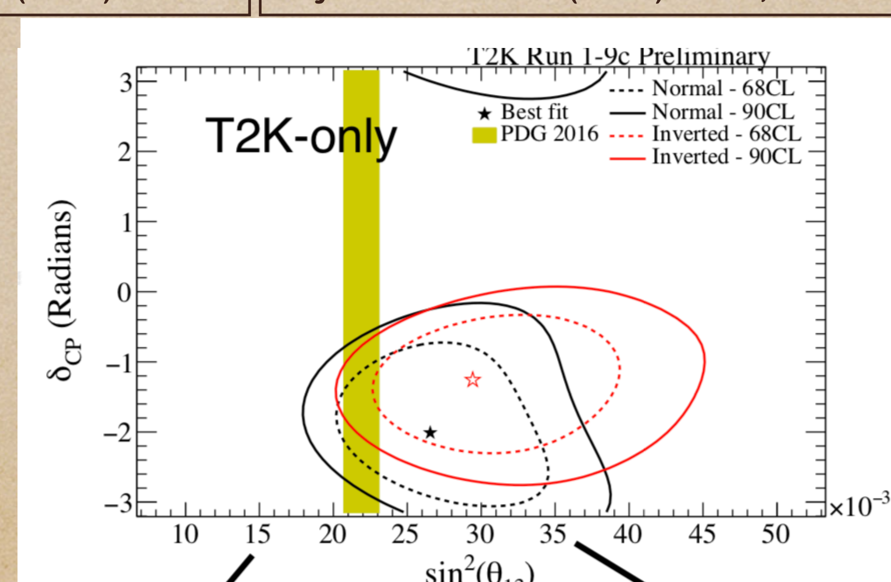
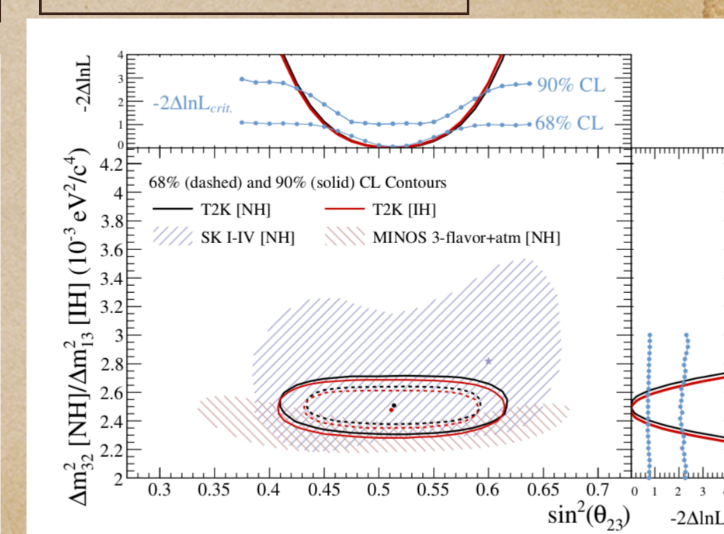
M. Wascko, Neutrino 2018







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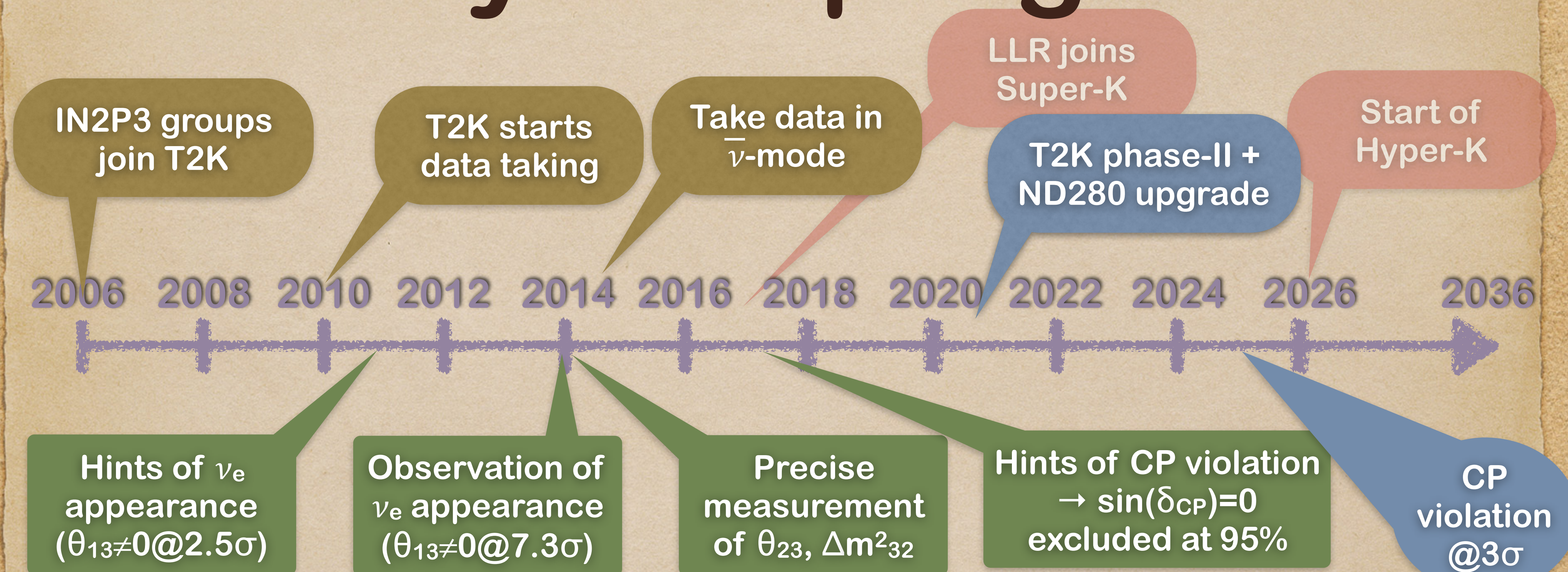

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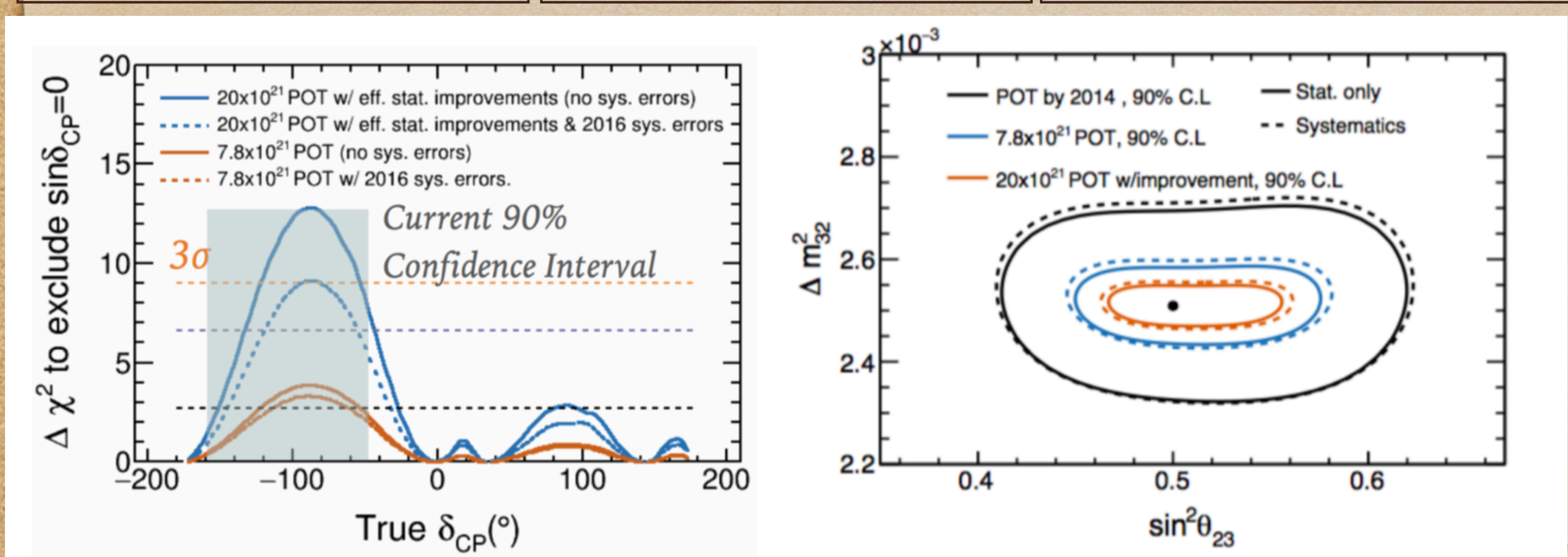


- CP violation at >3σ → >5σ with Hyper-K
- Mass ordering
- $\sin^2\theta_{23}$ octant
- And many ν and $\bar{\nu}$ cross-section measurements

IN2P3 groups in T2K

FTE* (including students and postdocs)

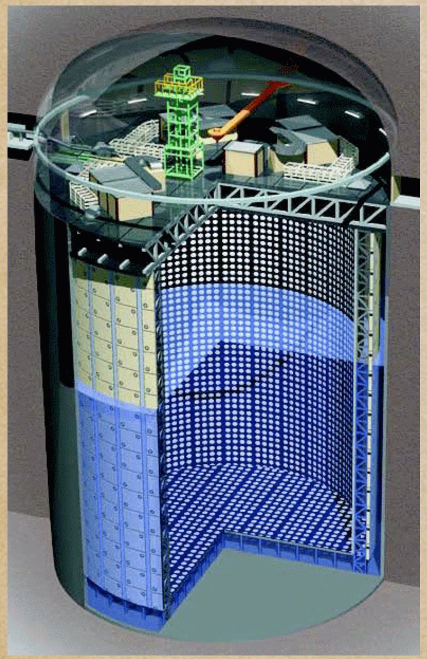
	T2K+T2K-II	NA61	Wagasci	SK	HK
LLR	3.0	0	2.0	3.5	0.5
LPNHE	4.0	1.0	0	0	1.0

*as of today

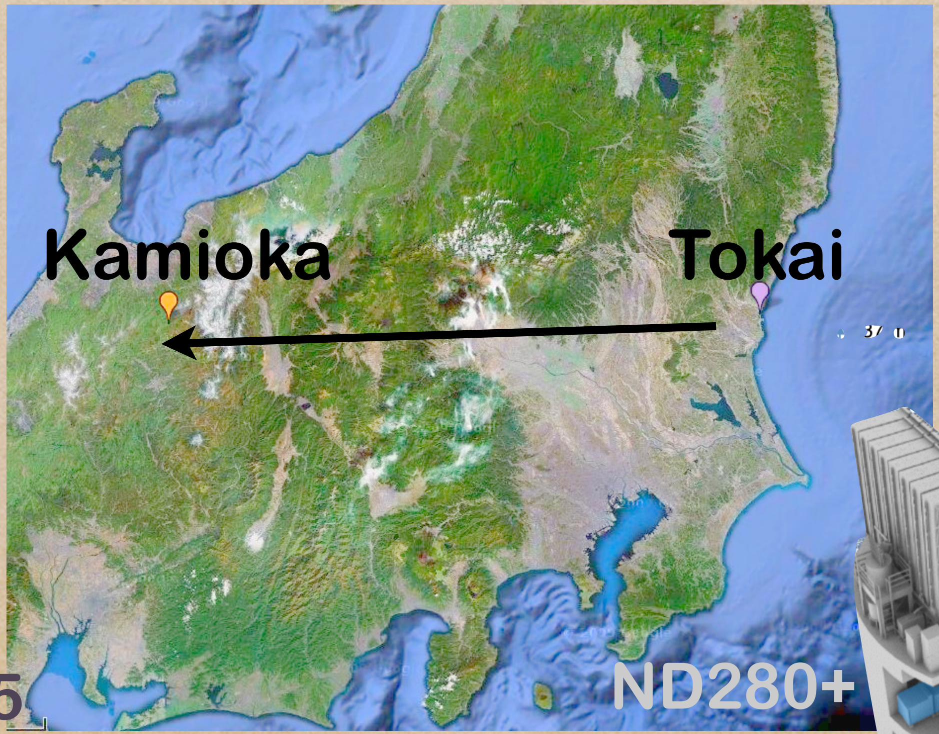
- Main responsibilities:
  - Convener of T2K beam group
  - NA61/SHINE analysis coordinator
  - Convener of T2K oscillation analysis
  - 2 conveners of CC-0π cross-section group
  - Convener of INGRID and Wagasci
  - 7 PhD theses defended since 2009, 4 PhD theses on-going

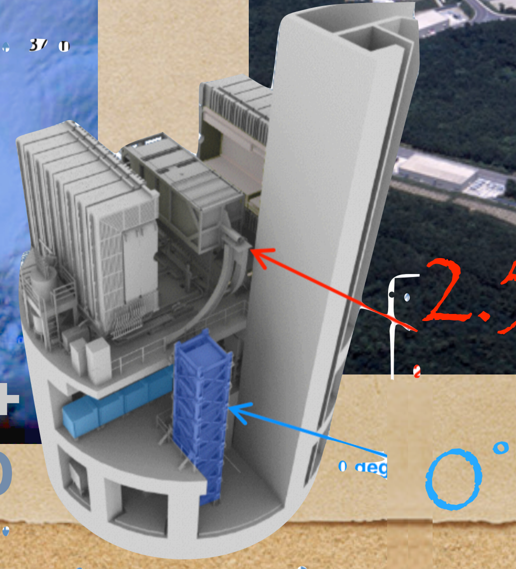
The T2K experiment

- 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}



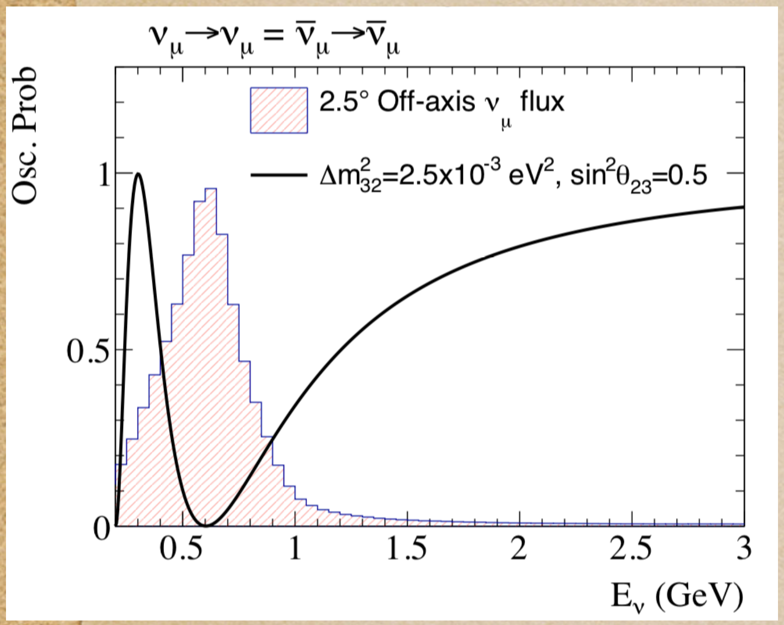
Super-Kamiokande: 22.5 kt fiducial volume water Cherenkov detector

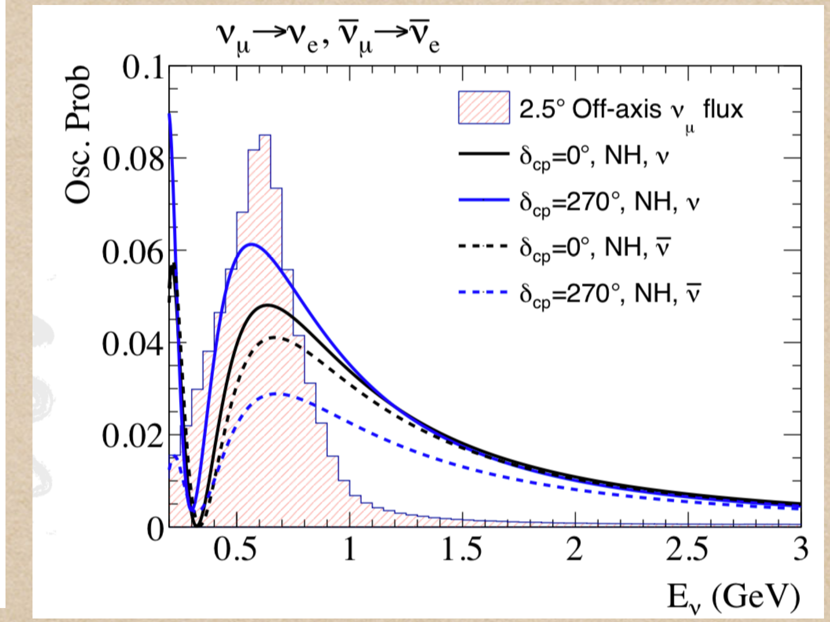


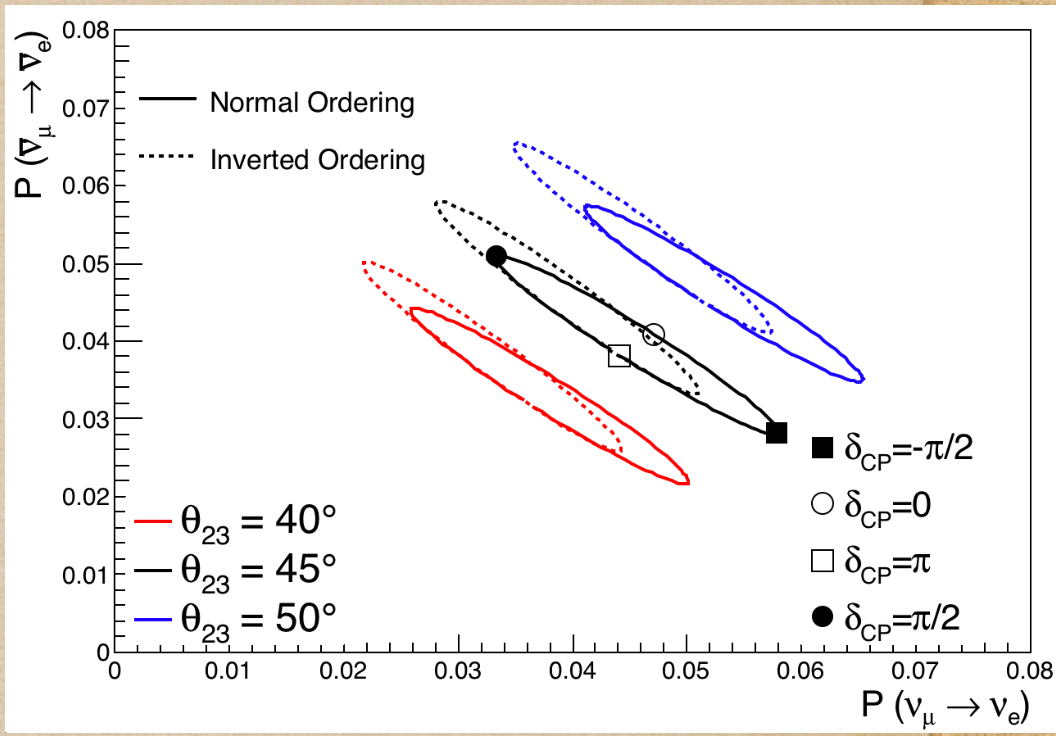


ND280+ INGRID

Sensitivity to oscillation parameters



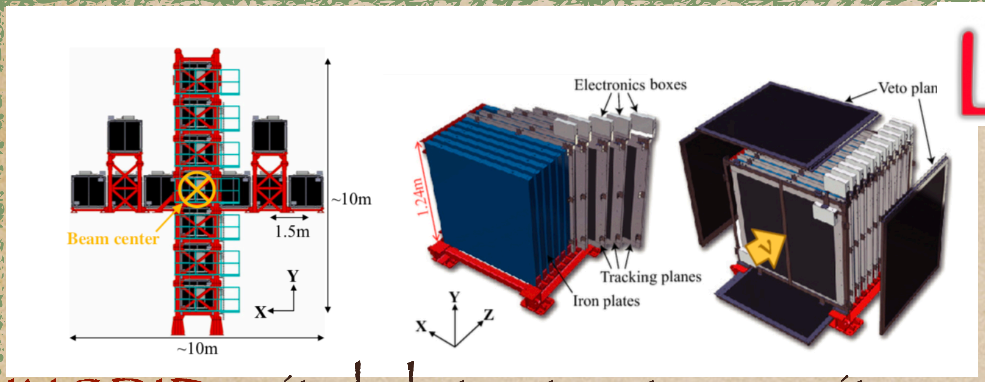




- **$P(\nu_\mu \to \nu_\mu) = P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$**
  - **Test of CPT conservation**
  - **Measure $\sin^2(2\theta_{23})$ → weak sensitivity to the octant**
  - **Measure $|\Delta m^2_{23}|$ → cannot distinguish NO and IO**
- **$P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$**
  - **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: vital detector to monitor ν beam profile and direction during data taking

Measure ν cross-sections

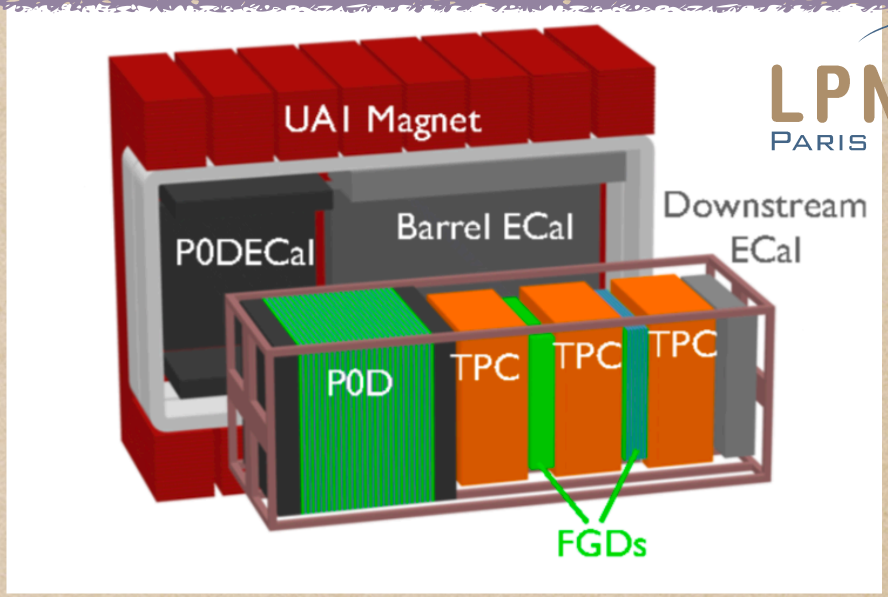
LLR: full design of the detector

WAGASCI + BabyMIND

First T2K upgrade (part of T2K since 2018)

Measure ν and ν̄ cross-sections on water

LLR: full design of mechanics and DAQ



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

Fundamental input to T2K OA

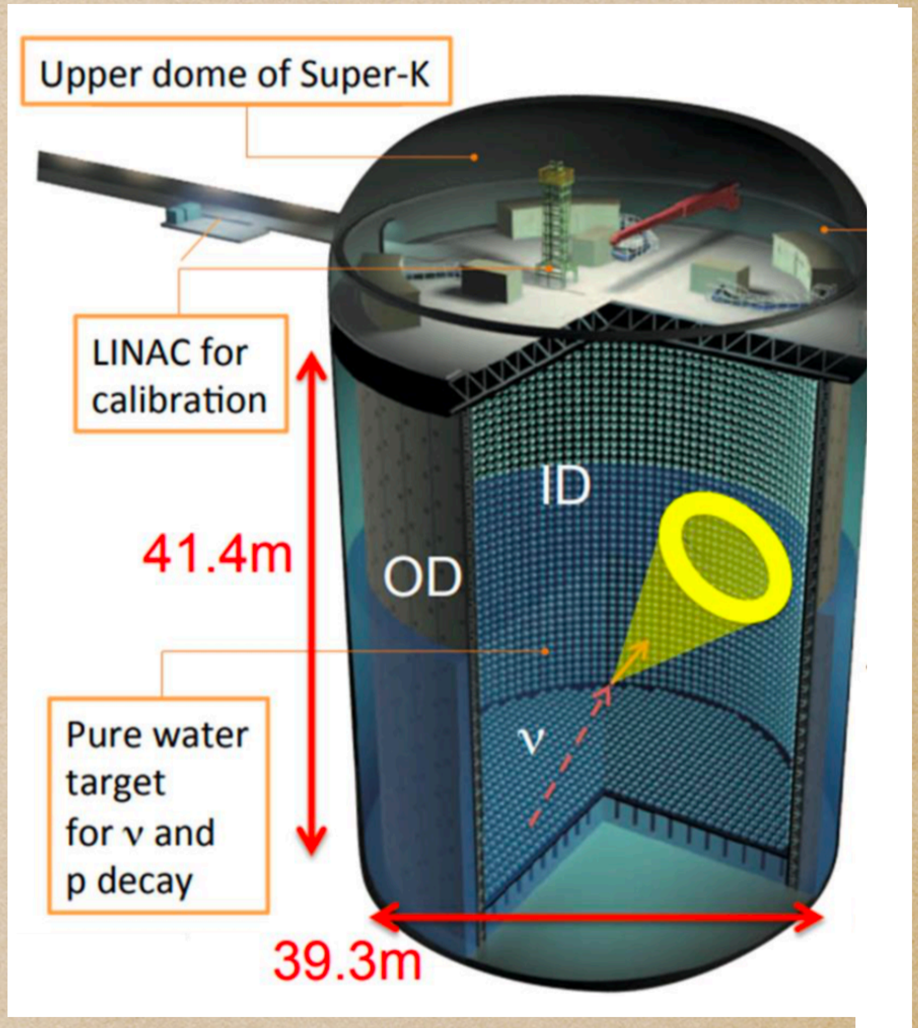
2 Fine Grained Detectors → active target for ν interactions

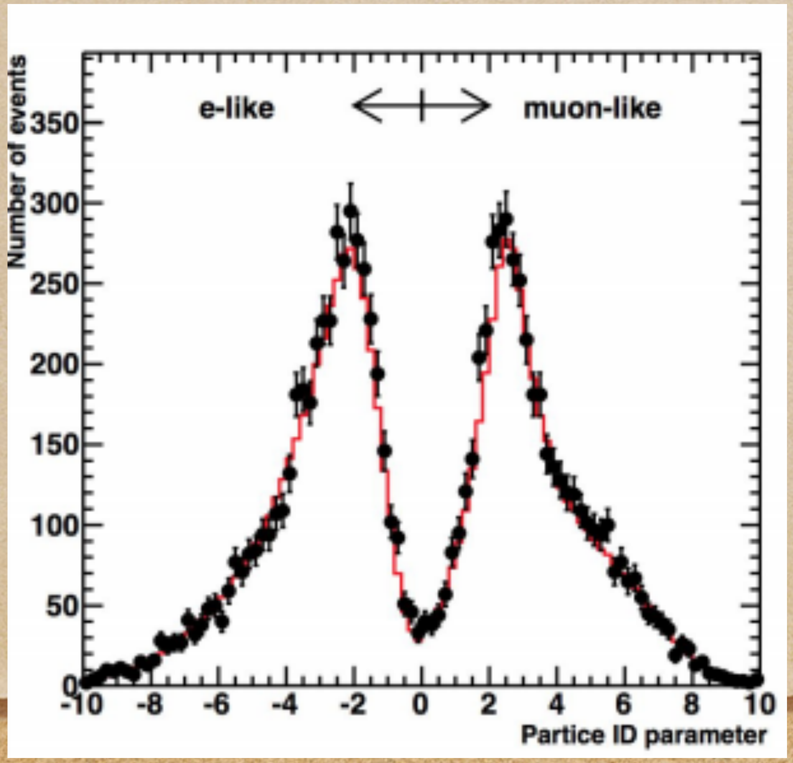
3 Time Projection Chambers to measure charge, momentum and PID of leptons emitted in ν interactions

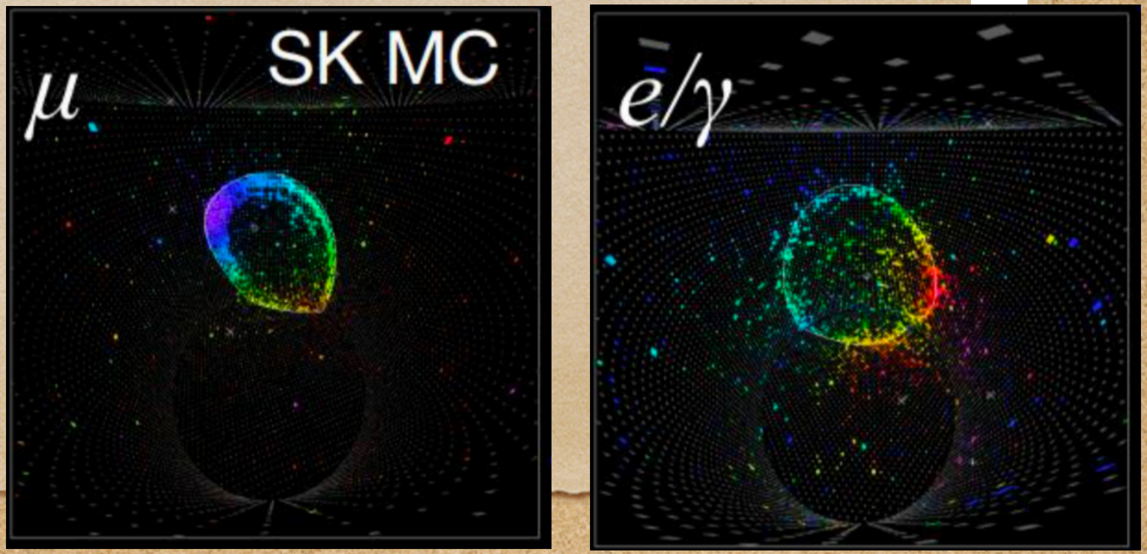
LPNHE contributed to magnet and TPC electronics

Super-Kamiokande

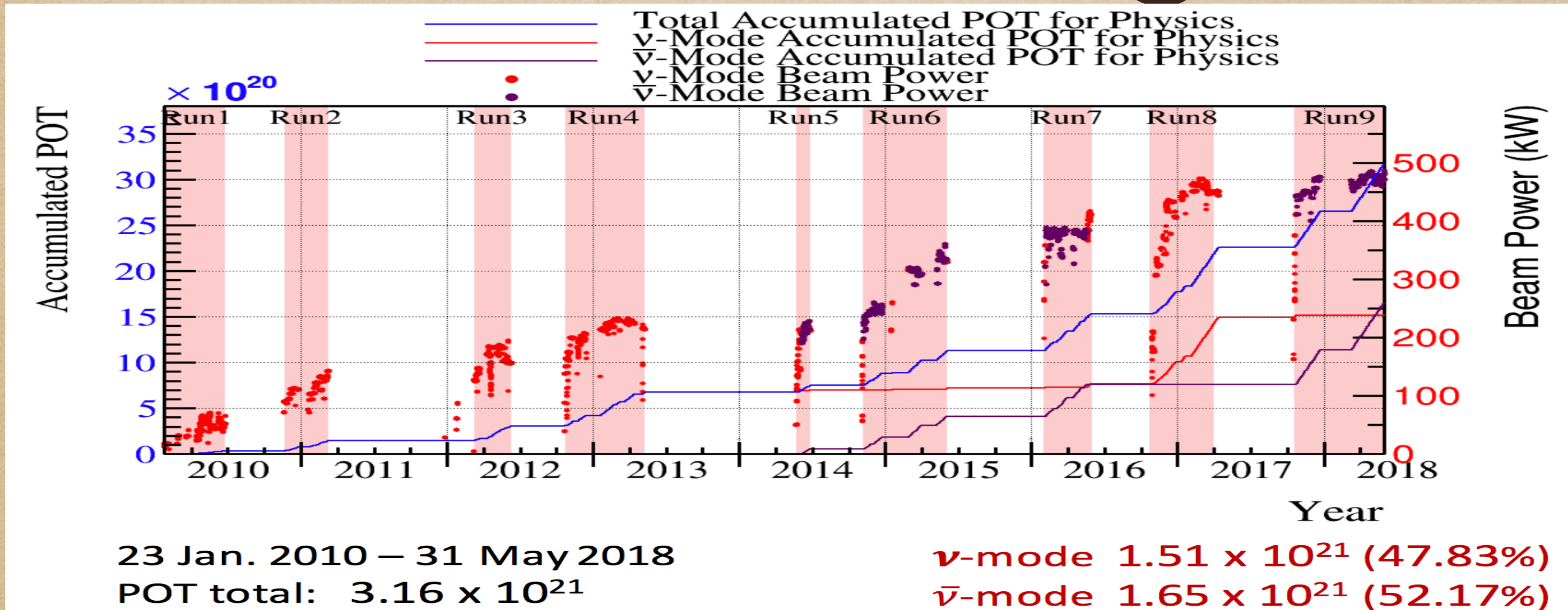
- 50 kton Water Cherenkov detector
  - ~11000 PMTs for ID, ~2000 for OD
- 1000 m underground at Kamioka mine operated since 1996
- Very good PID capabilities to distinguish between ν_e and ν_μ thanks to shape of Cherenkov ring → <1% misidentification probability



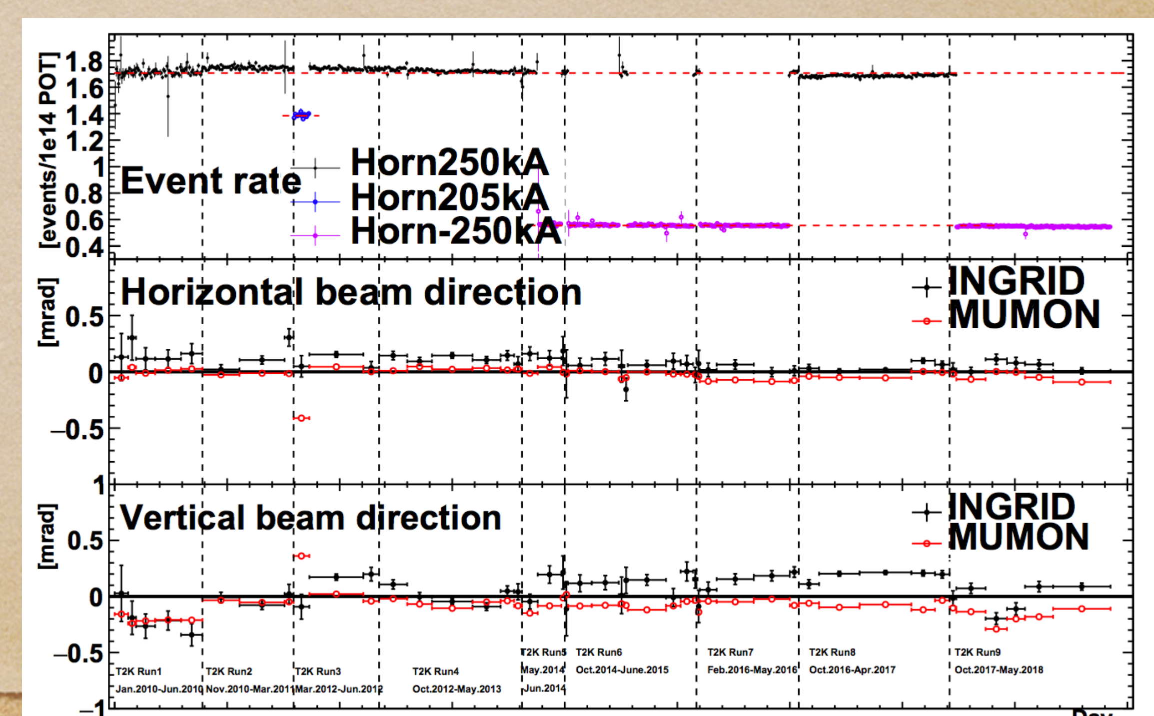




Data taking



- Collected 3.16×10^{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



T2K oscillation analysis

Flux prediction:
Proton beam measurement
Hadron production (NA61 and others external data)

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

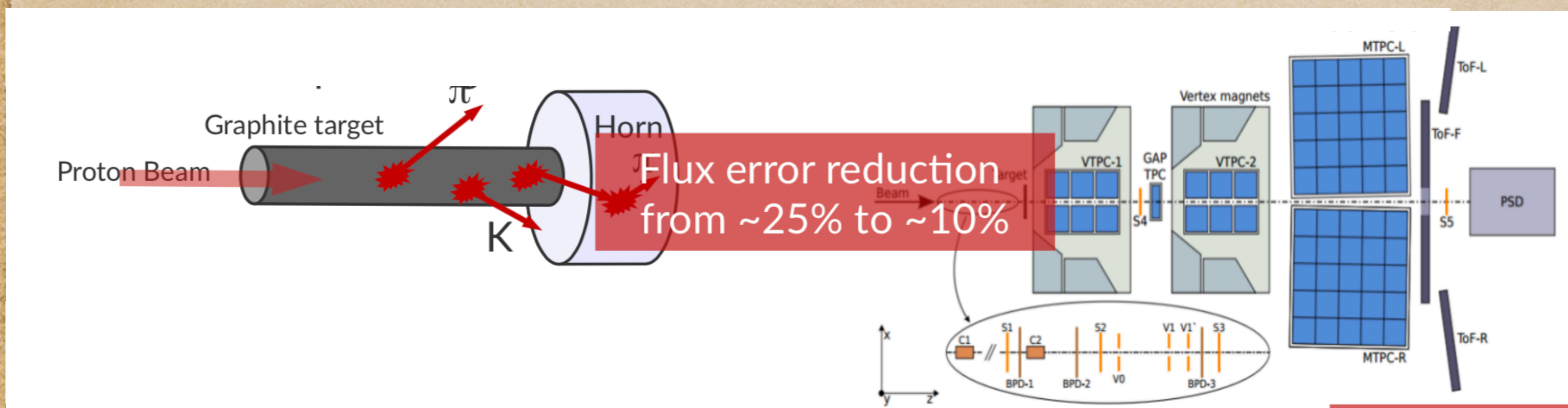
ND280 measurements:
ν_μ and $\overline{\nu}_\mu$ selections to constrain flux and cross-sections

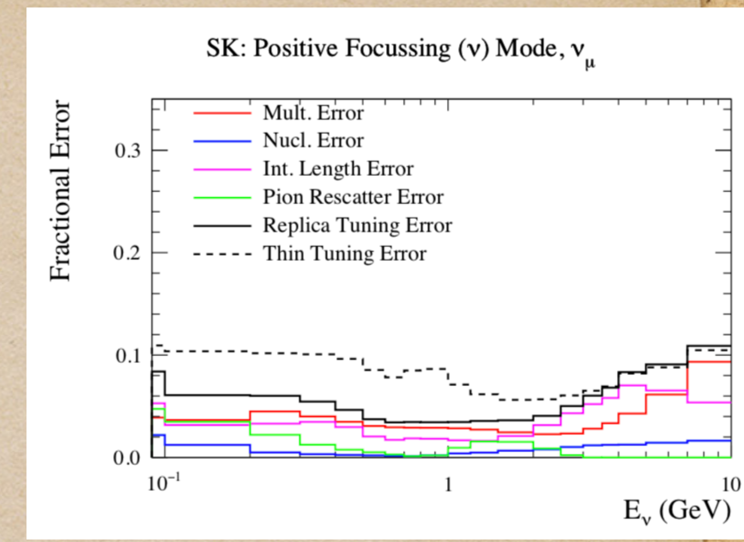
Prediction at the Far Detector:
Combine flux, cross section and ND280 to predict the expected events at SK

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

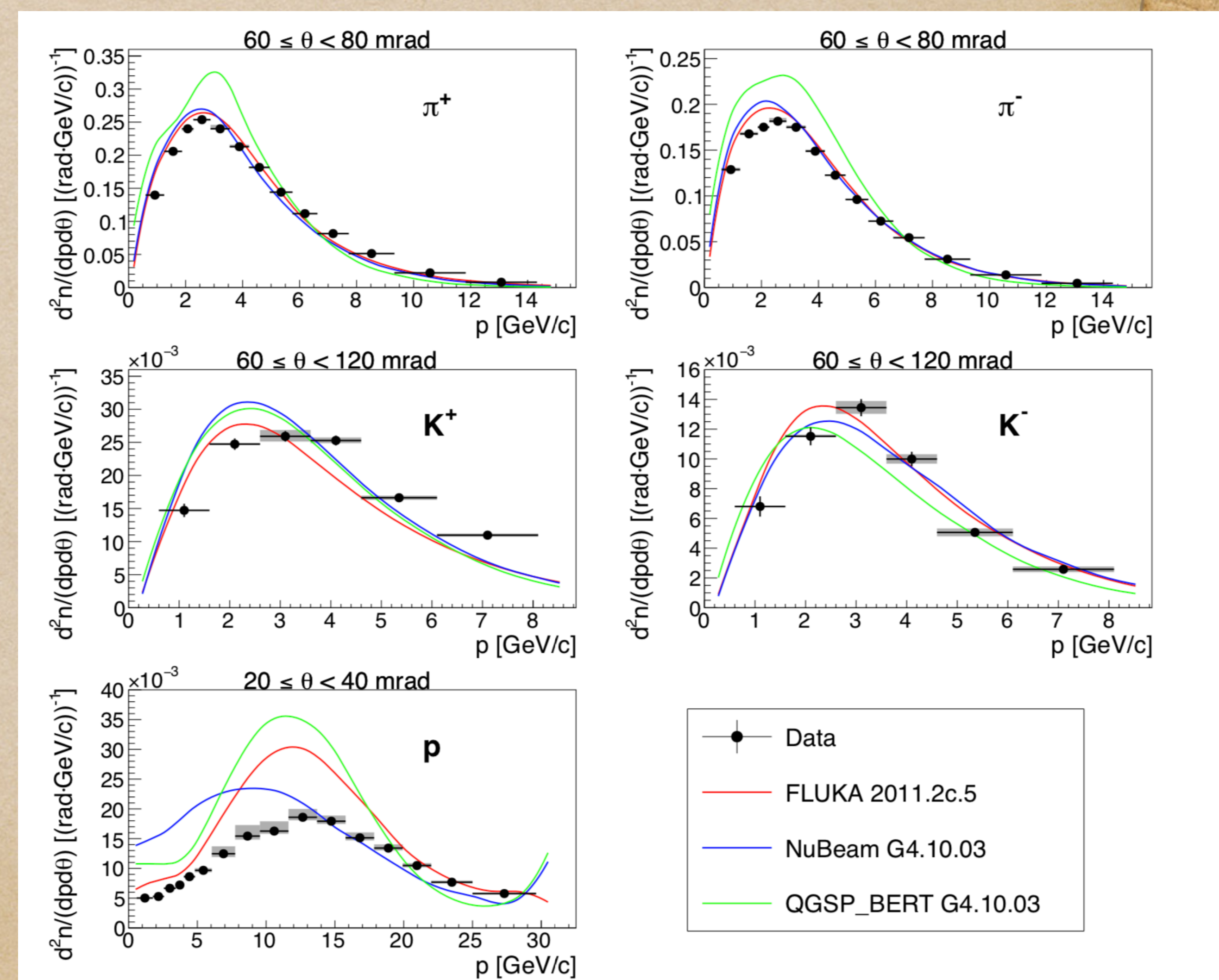
Extract oscillation parameters!

Flux uncertainties: NA61/SHINE

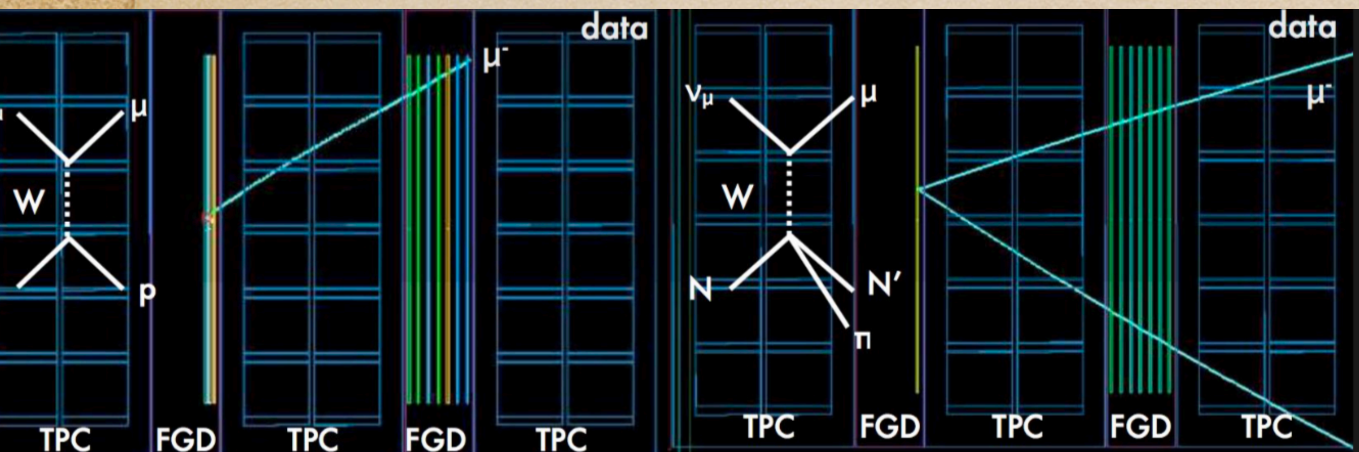


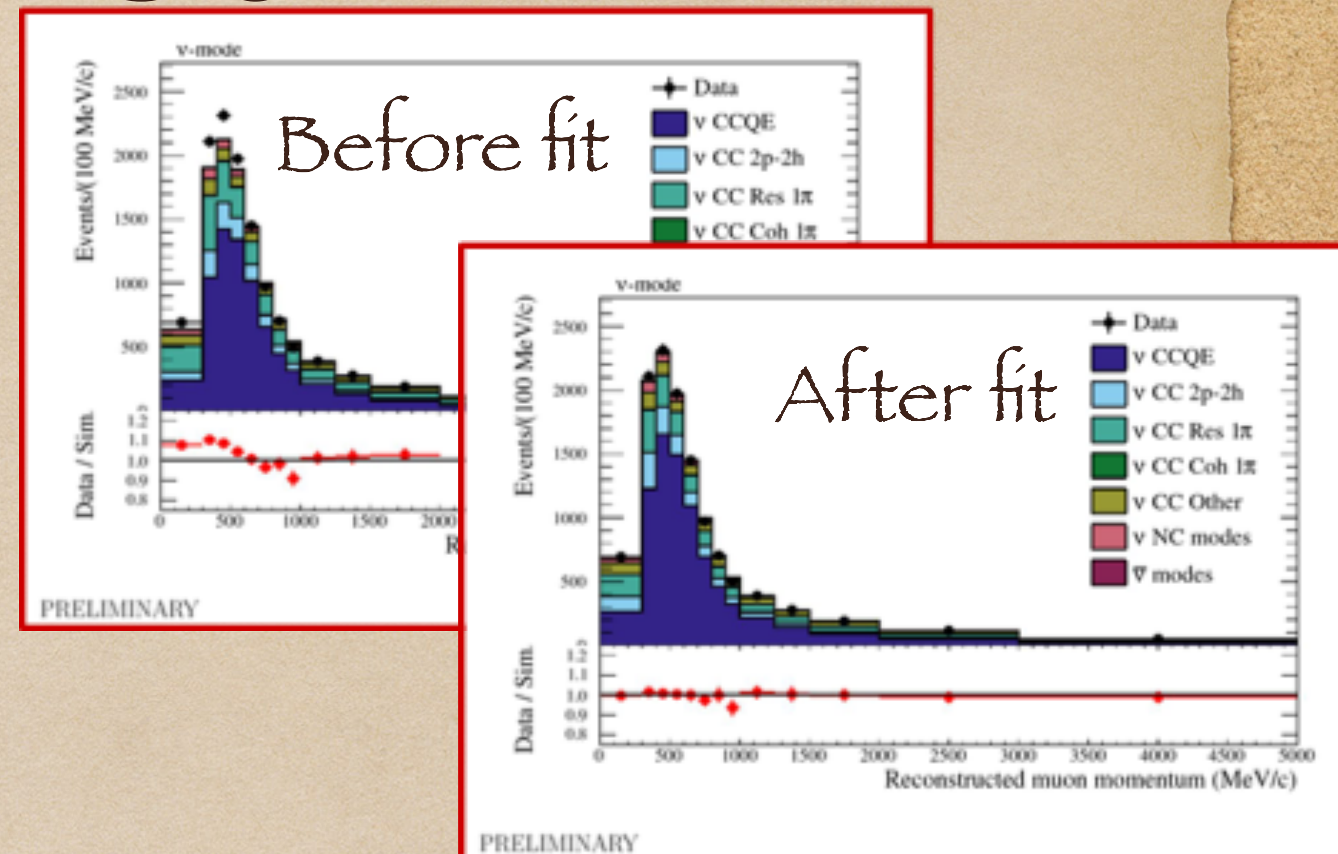


- Multipurpose detector @ CERN → precision hadron production measurements for T2K (and FNAL) neutrino fluxes predictions
- Took data for T2K in 2007, 2009, 2010 with thin and replica target
- Thin target data already used → 10% uncertainties on neutrino fluxes
- Inclusion of 2010 data with replica target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



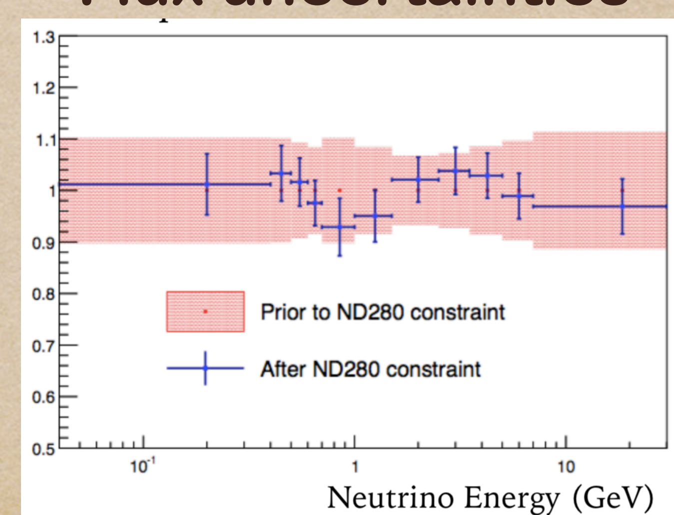
ND280



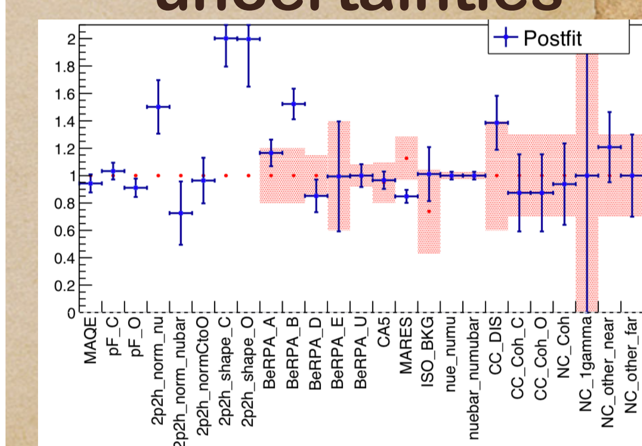


- **Select 14 samples of ν_μ and $\overline{\nu}_\mu$ interactions on Carbon and Water with 0,1,>1 π in the final state**
- **Likelihood fit to constraint flux and cross-section uncertainties for T2K Oscillation Analysis**
- **Reduce uncertainties from ~15% to ~5%**

Flux uncertainties

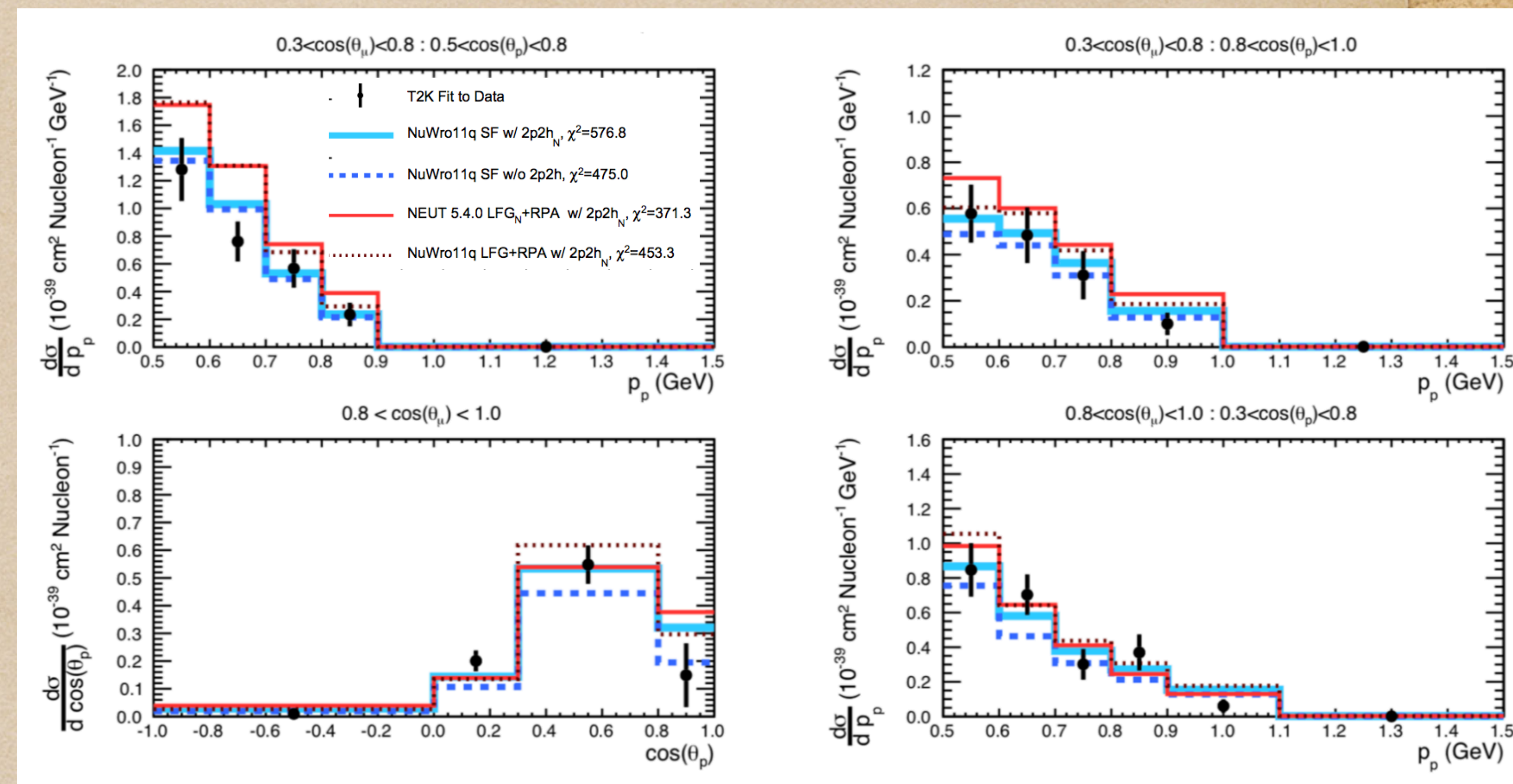


Cross-section uncertainties

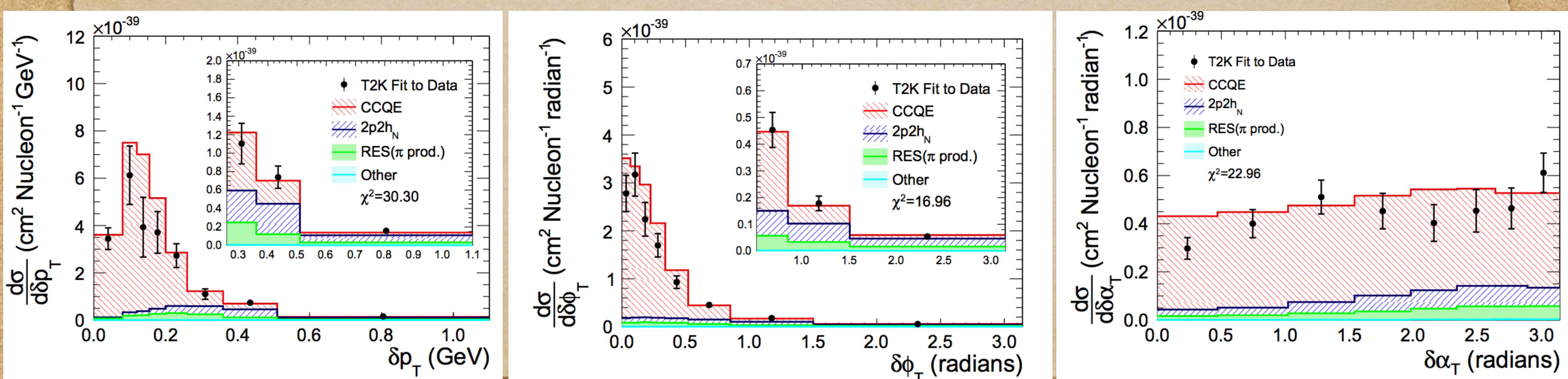


ND280 cross-sections

- **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

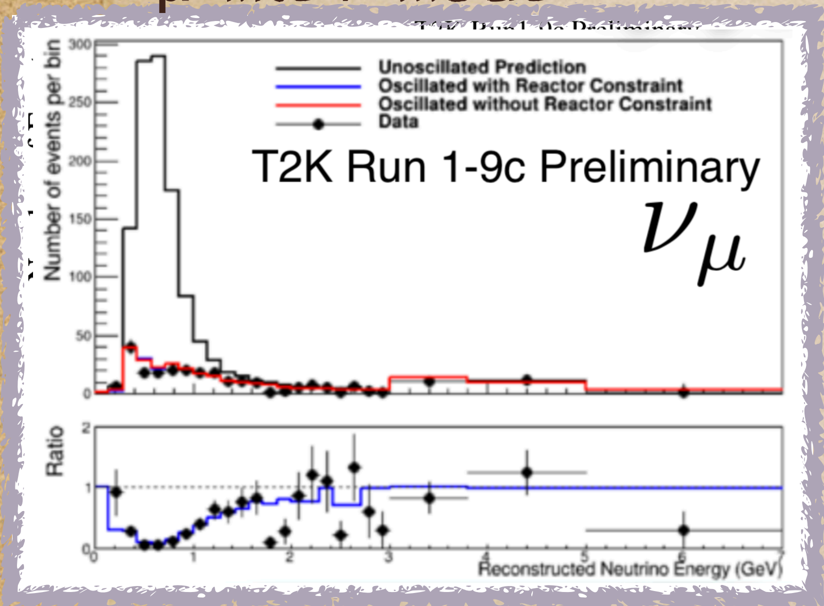


arXiv:1802.05078 submitted to PRD

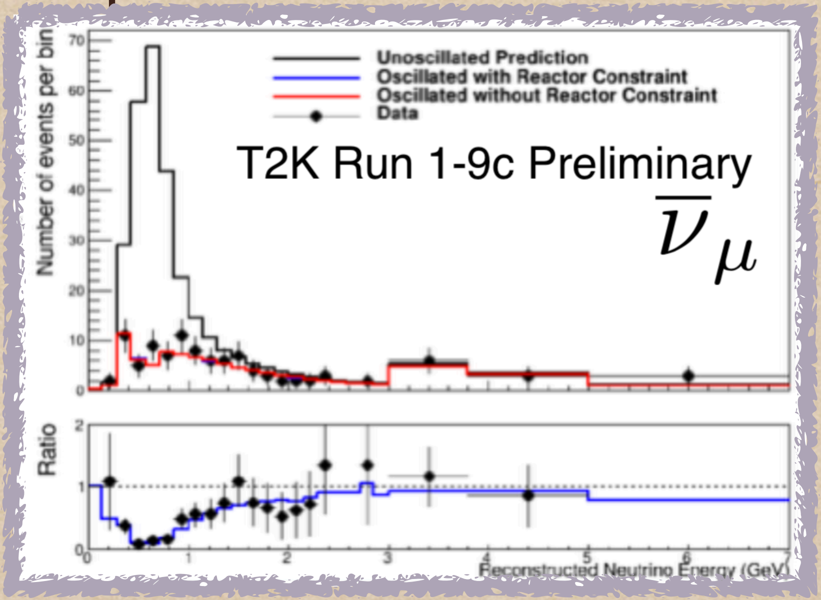


Super-K

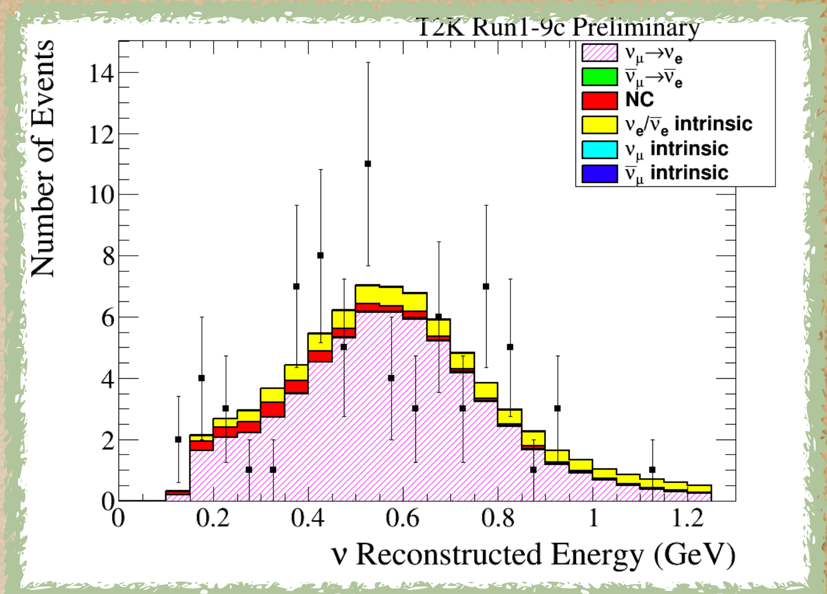
μ-like ν-mode

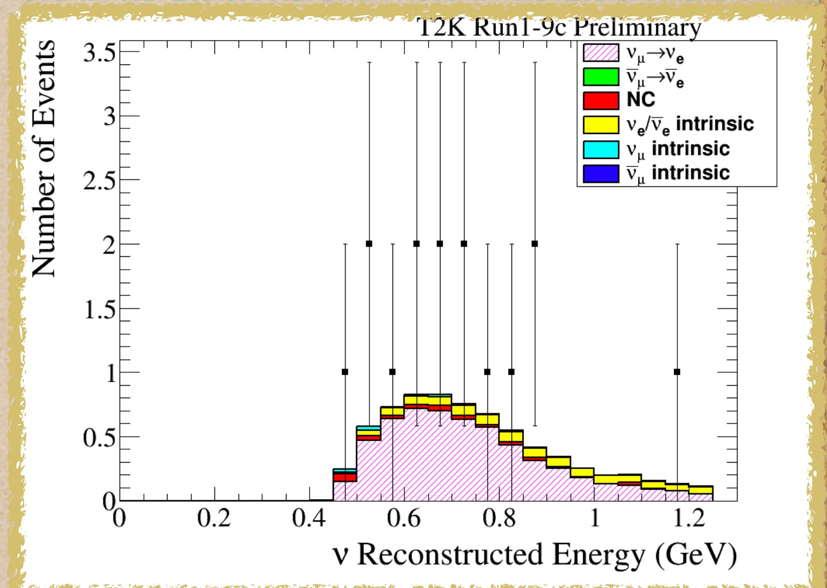


μ-like $\bar{\nu}$-mode



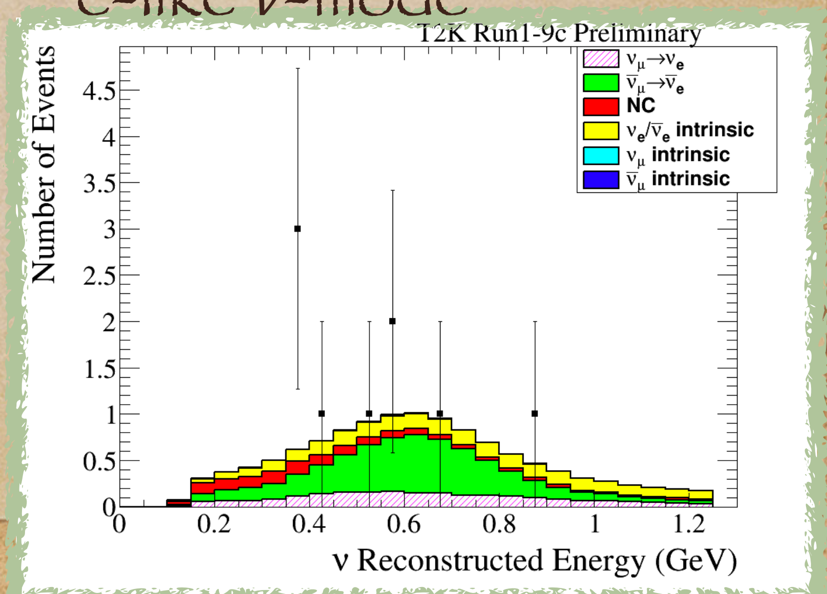
e-like ν-mode





	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

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



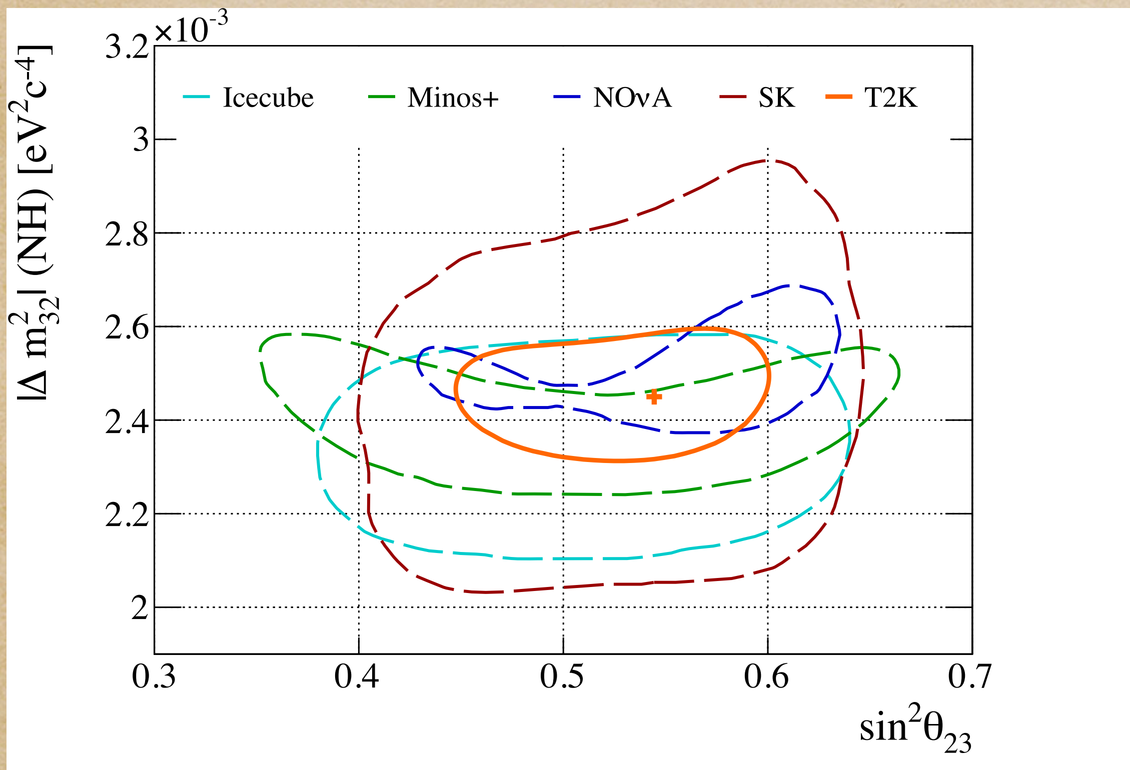
To be updated with full run9 stat during Summer (50% more data in $\bar{\nu}$ mode)

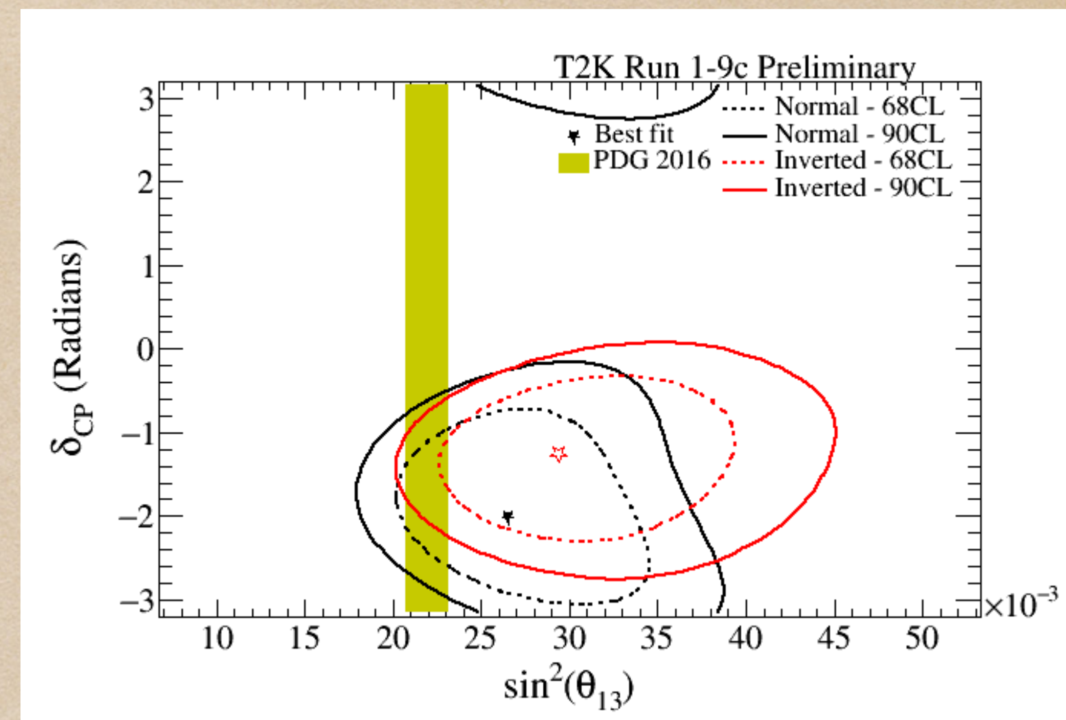
Systematics

	1R μ-like		1R e-like		
	ν-mode	$\bar{\nu}$-mode	ν-mode	$\bar{\nu}$-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%

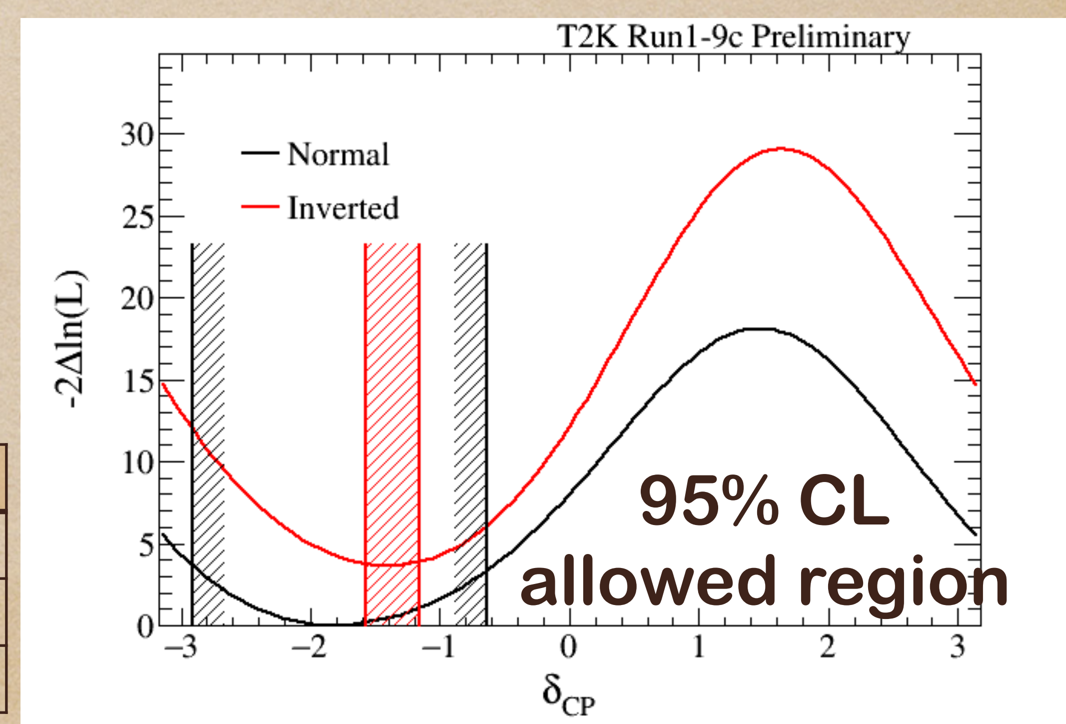
- Binding energy is treated as an effective parameter not fitted with ND280 → will be reduced in next round of analysis
- Contributions from flux and cross-section constrained by ND280
- SK detector and FSI+SI uncertainties (not constrained by ND280)
- Only use ν_μ selection at ND280 → uncertainties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

Oscillation results





- 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 %

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!

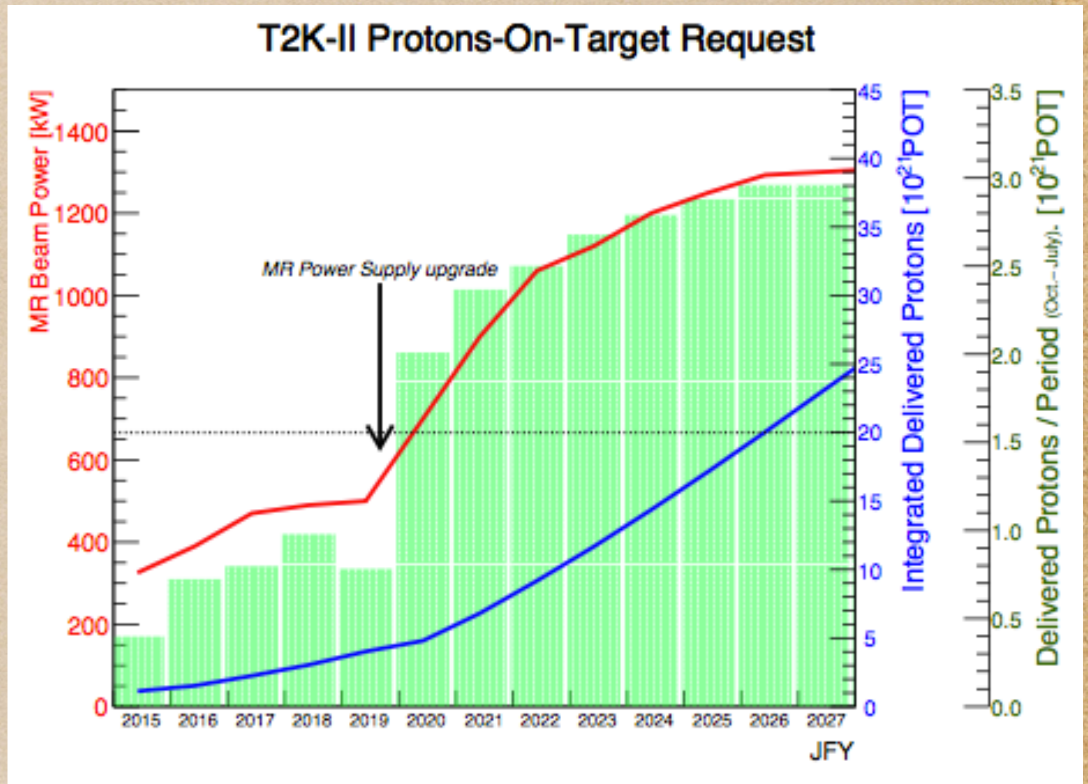
T2K phase II

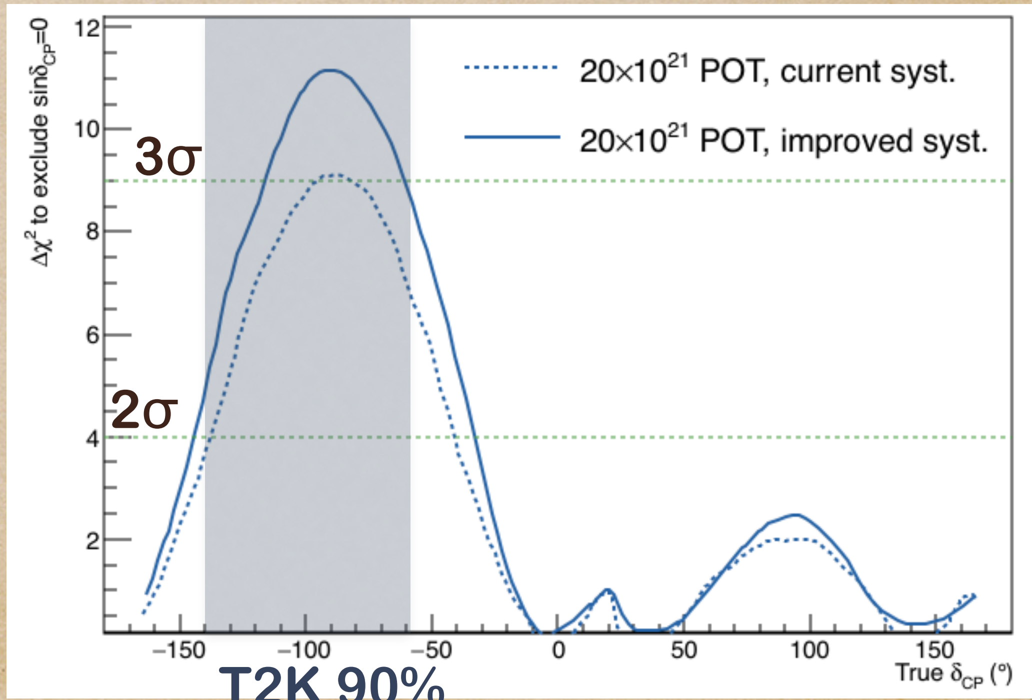
- T2K was originally approved to collect 7.8×10^{21} pot
  - Driven by sensitivity to θ_{13}
- Proposal for an extended run
  - T2K-II → 20×10^{21} pot
- Upgrade the Main Ring power supply to reach 1.3 MW operations

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

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

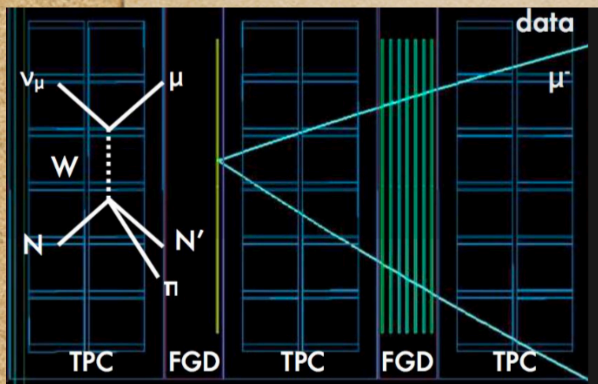
- >3σ measurement of CP violation (if δ_{CP} close to $-\pi/2$)
- Need to reduce systematics to ~4% (<3% from ND280)

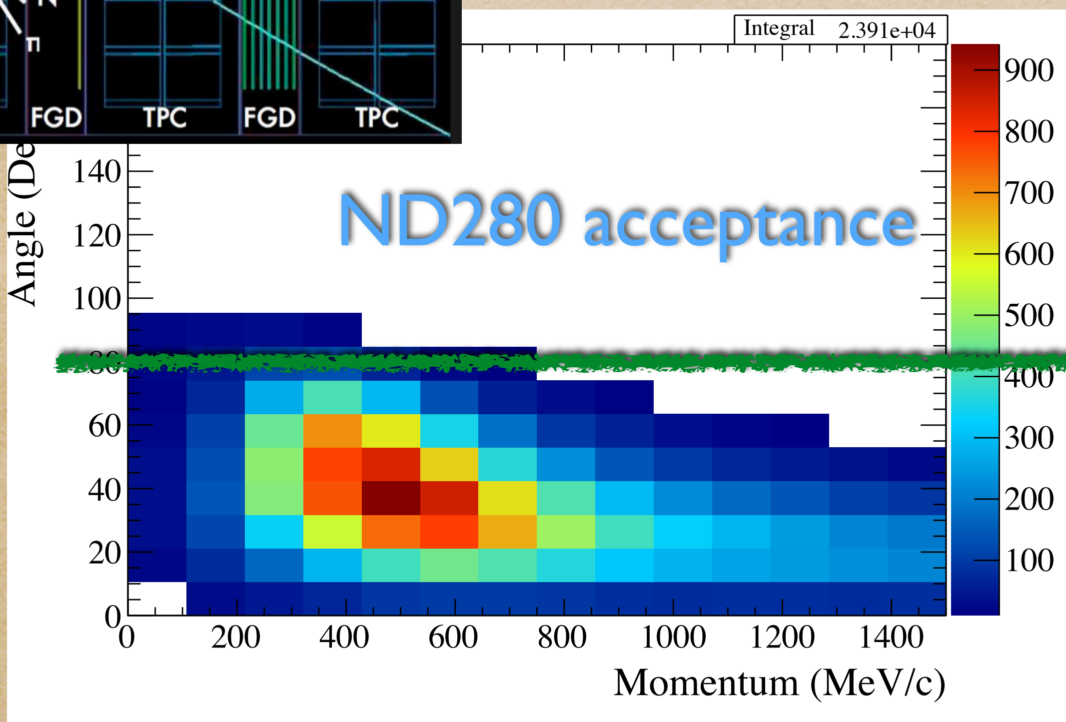


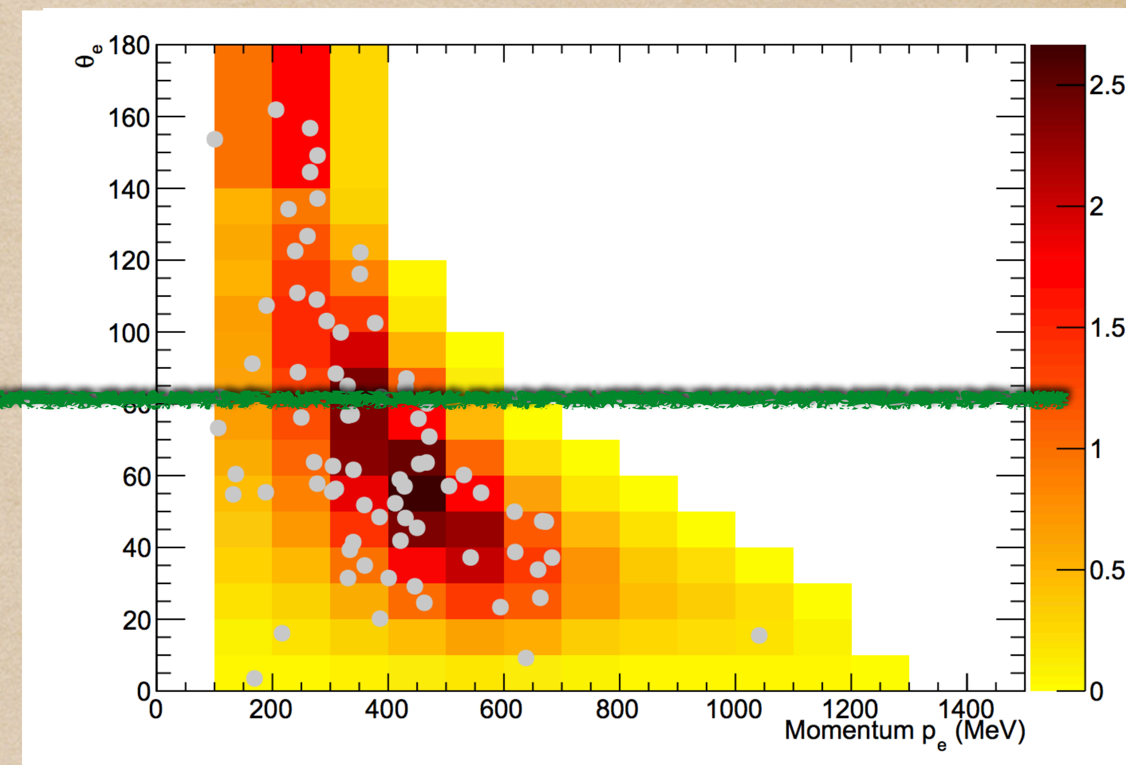


T2K 90% allowed region

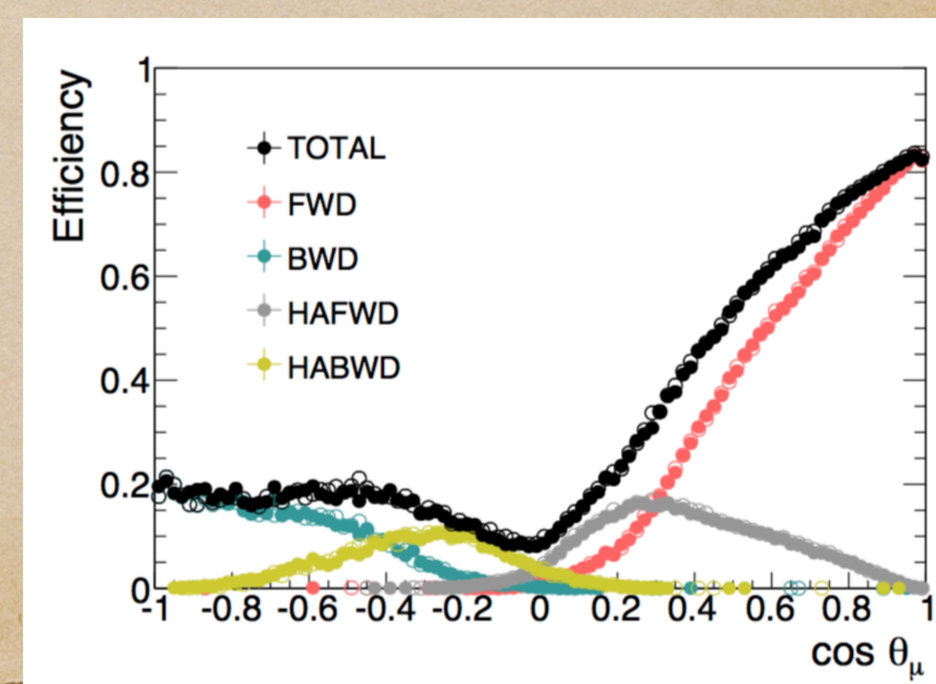
ND280 upgrade







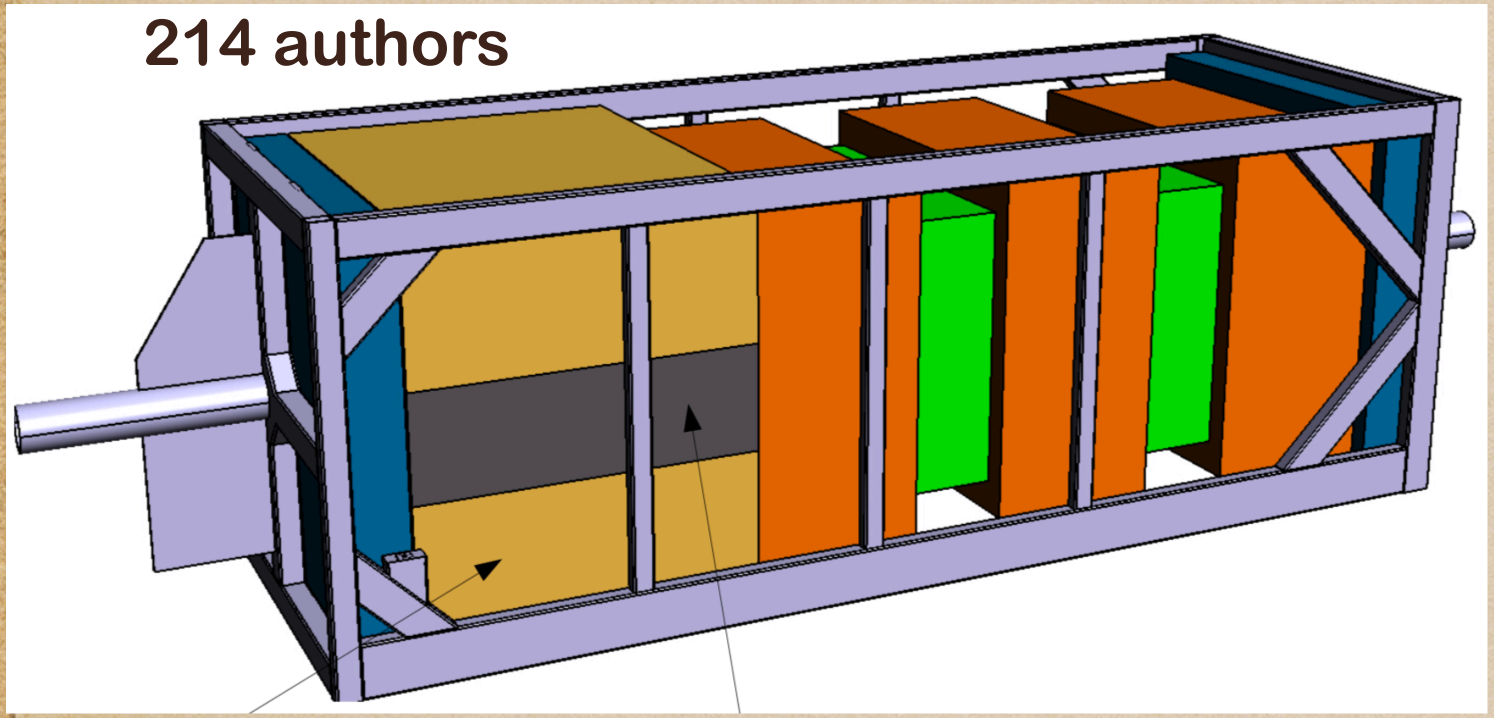
- Main limitation of ND280 : reduced angular acceptance → only forward going muons are selected with high efficiency
- An analysis dedicated to select tracks with high polar angles allow to select 20% of the events in that region
- We can do better with an upgrade!

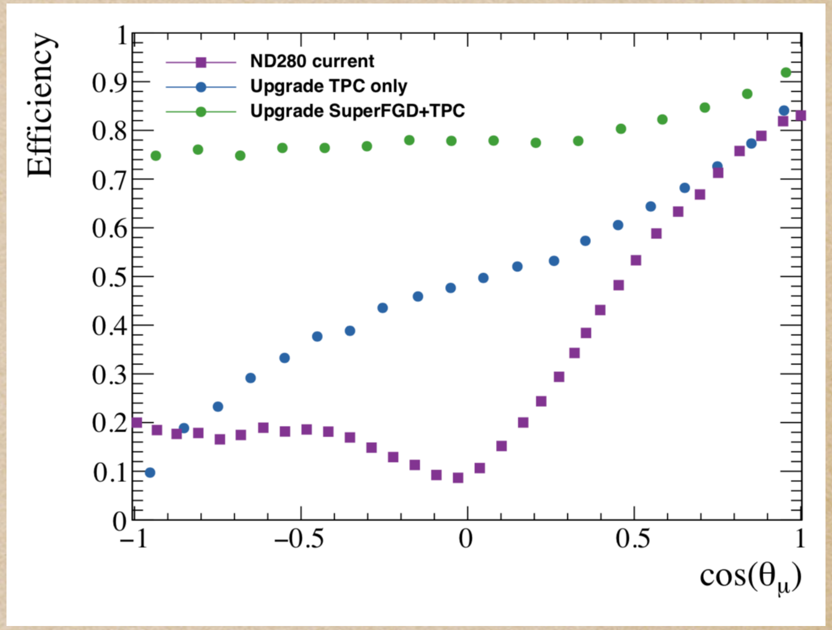


ND280 upgrade

CERN-SPSC-P357

214 authors



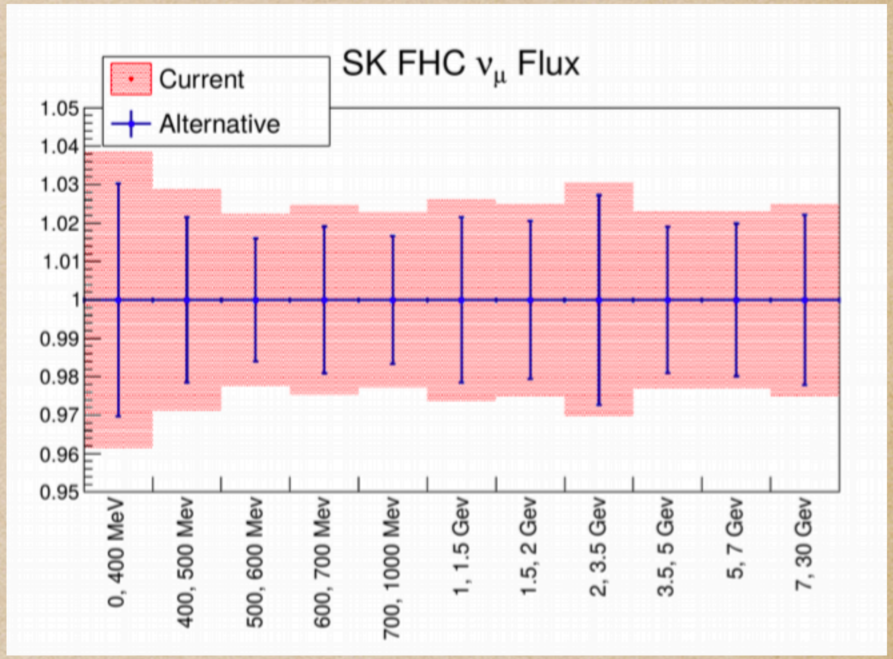


- **Replace upstream part of ND280 with an horizontal fully active target (SuperFGD) and 2 horizontal TPCs**
- **This will allow to select μ and e at any angle with respect to the beam**
- **Proposal submitted to CERN SPSC in 2017**
- **Test beam in Summer 2018 @ CERN**

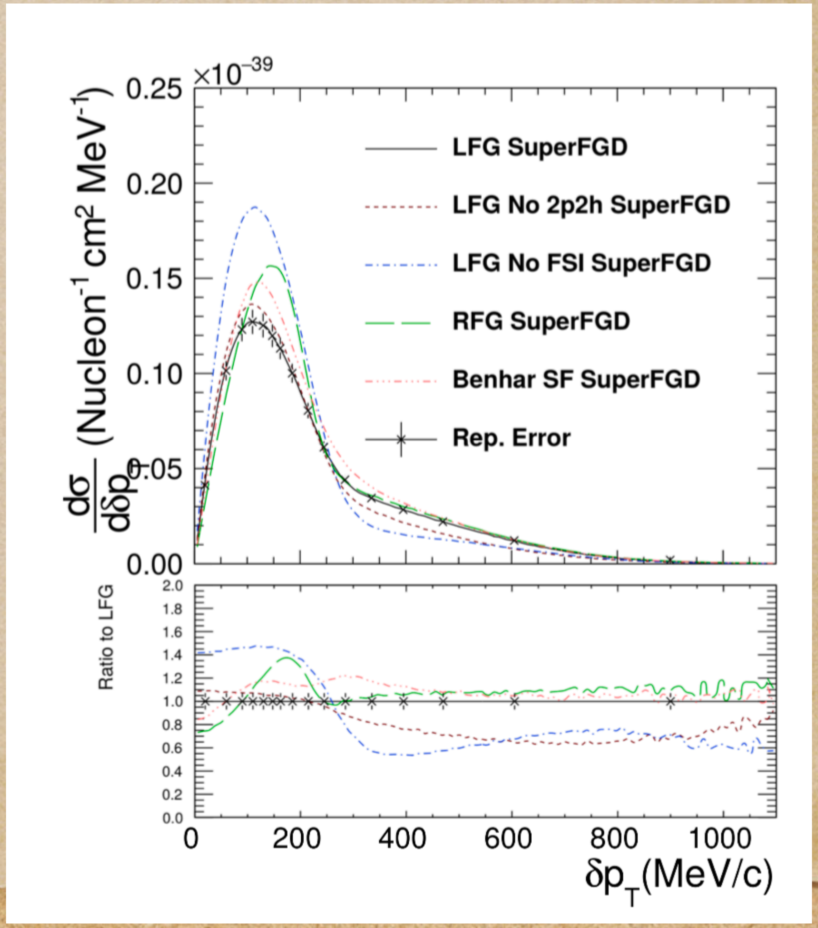
2017	2018	2019	2020	2021
Proposal	Prototypes, TDR	Construction	Construction	Installation

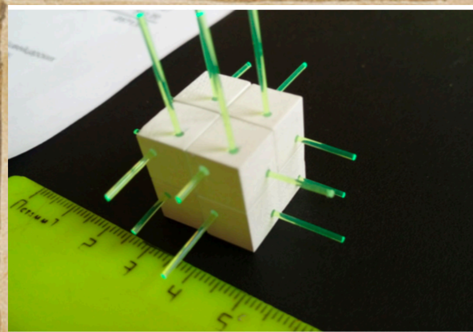
Upgrade performances

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

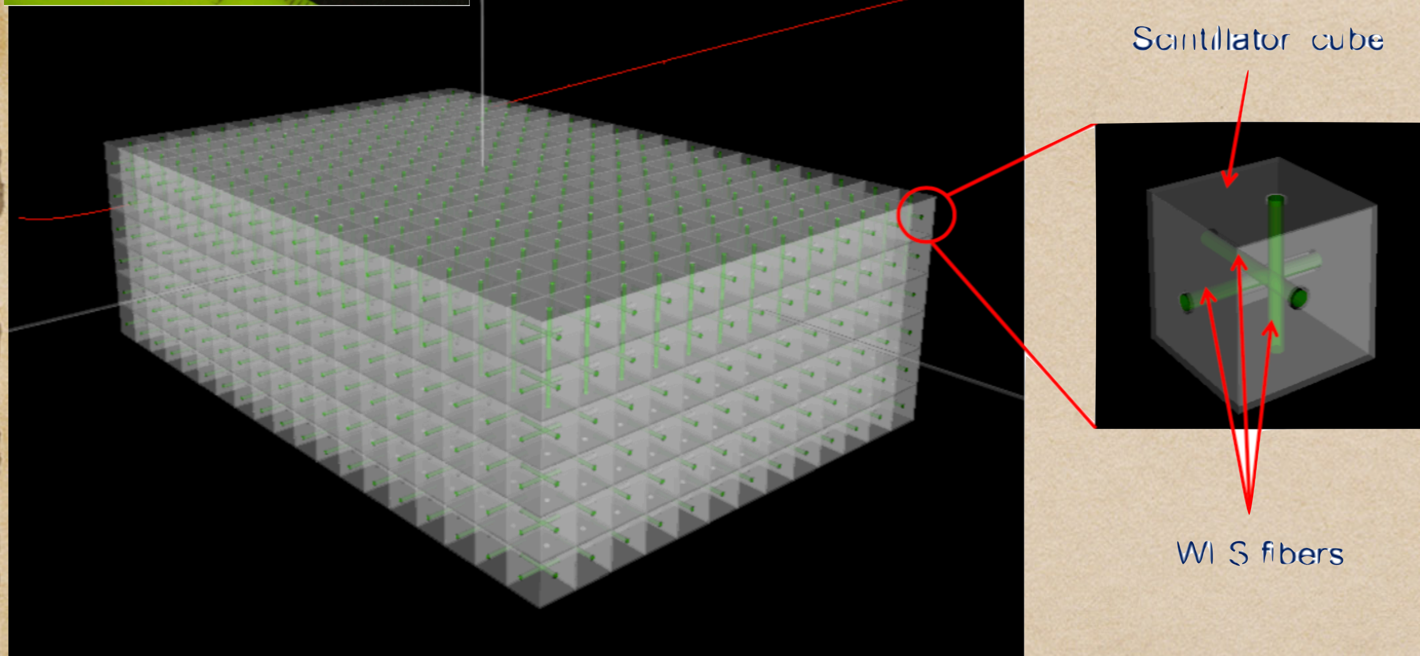


- For same POT → Reduce uncertainties on inputs to oscillation analysis by ~30%
- Low momentum threshold and full angular coverage → much better sample to study nuclear effects

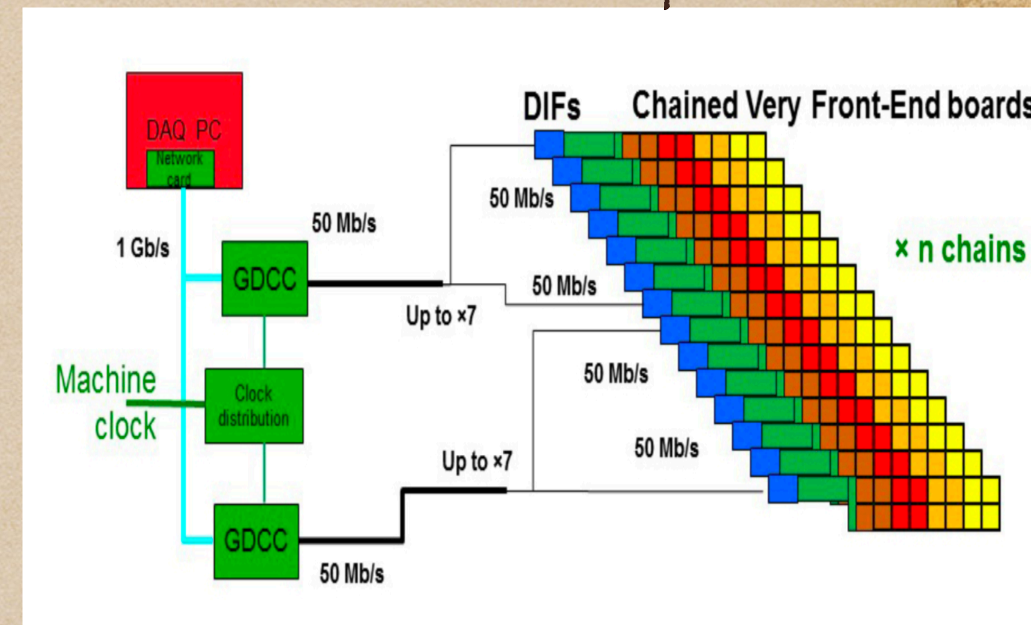




Super-FGD

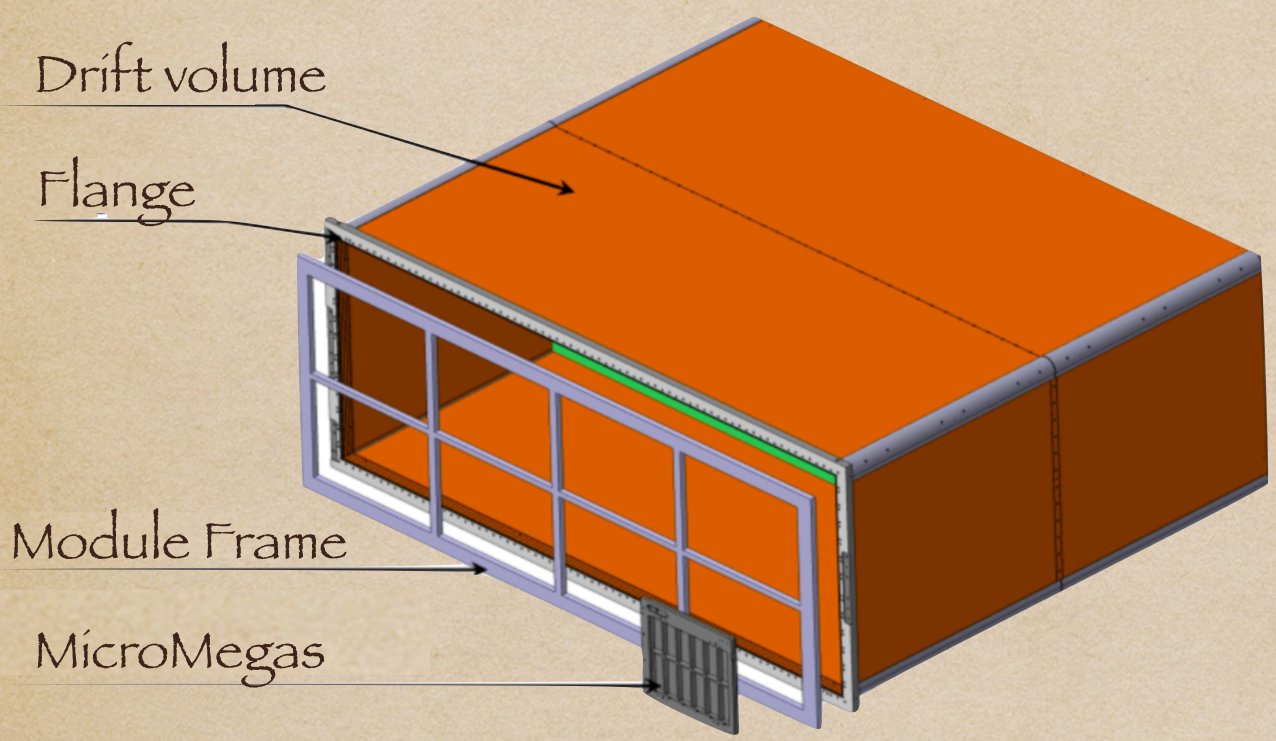


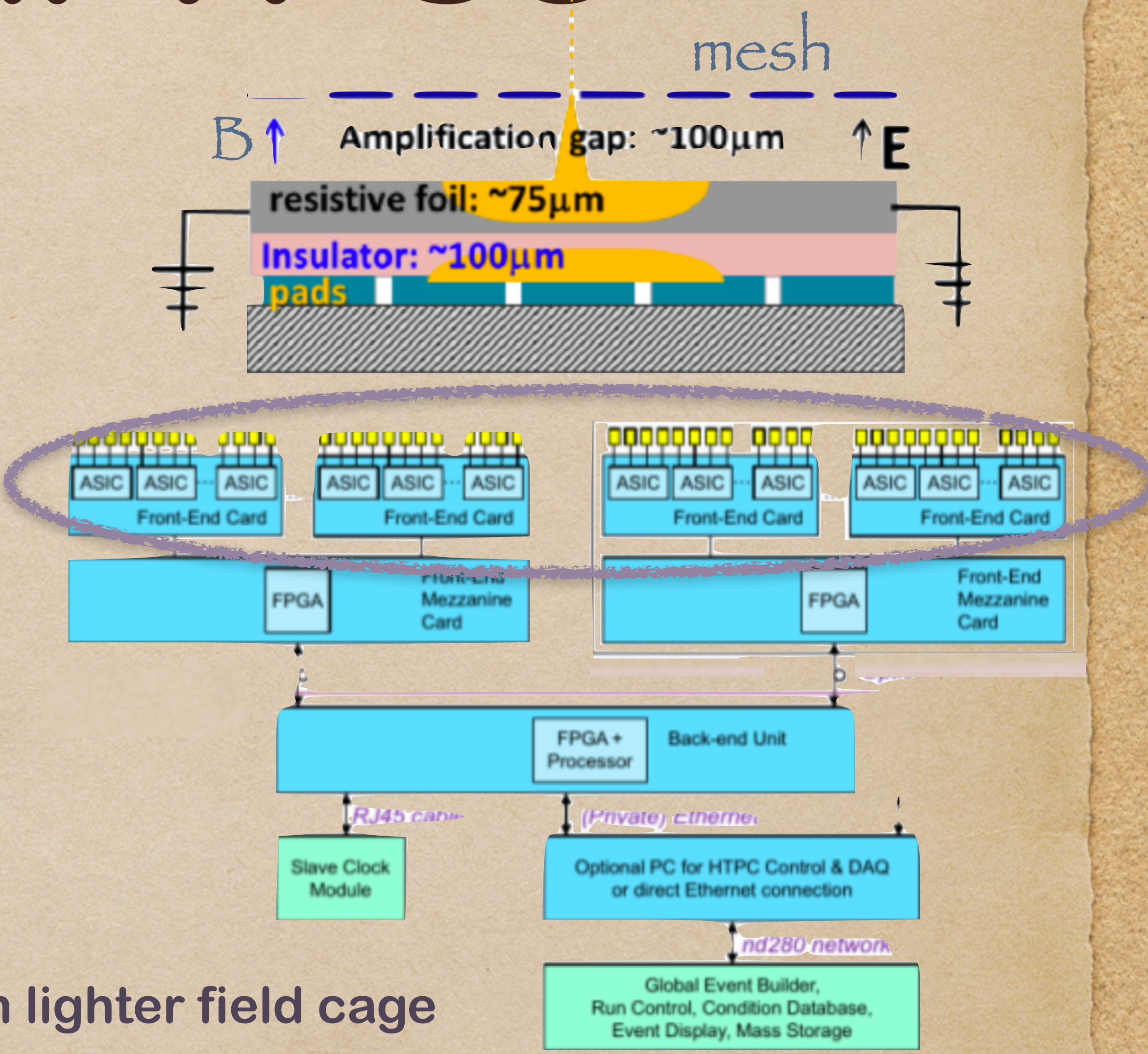
LLR electronics developed for Calice



- 2 ton target with 1x1x1 cm cubes read by 3 fibers
- Total of 60-80k channels read with MPPC
- Proposal from LLR to read the MPPCs with ~2000 SPIROC2E chips (ADC and TDC)
- Front End Boards on the detector
- CALICE DAQ already used for WAGASCI
- Proposal from LLR being discussed within the T2K 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 new resistive MicroMegas (8x2x2 modules)**
- **LPNHE will provide front end electronics boards to read existing AFTER chips (total of ~80 boards will be built) and cooling→ the lab already provided necessary ITA**
- **A mechanical engineer to study detectors integration in the basket has also been allocated to the project**
- **Total cost ~200 k€ (including cooling and mechanical support)**

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
- We propose to participate to an upgrade of the Near Detector in order to reduce systematics and fully profit of the additional statistics
- NA61/SHINE data taking after LS2 has been recommended by the SPSC for accelerator neutrino experiments → we expect to participate at similar level
- Coherent scientific program over the next 20 years with no interruption in data taking and exceptional discovery potential