T2K & beyond :

δ_{cp} measurements in T2K and prospects in neutrino physics in Japan.

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INFN Bari

LNF 21 Maggio 2020

Outlook

- Neutrino Oscillation in a "Nutshell"
- The T2K Experiment
- Data Analysis
- T2K result on "δ_{cp} "
- Medium term prospects (2022-2026)
  - T2K-II
- Long term (>2026)
  - HYPER-K (T2HK)

Neutrino Oscillation

If mass and weak eigenstates are different:

- Neutrino is produced in a weak eigenstate
- It travels a distance L as a mass eigenstate
- It will be detected in a (possibly different) weak eigenstate

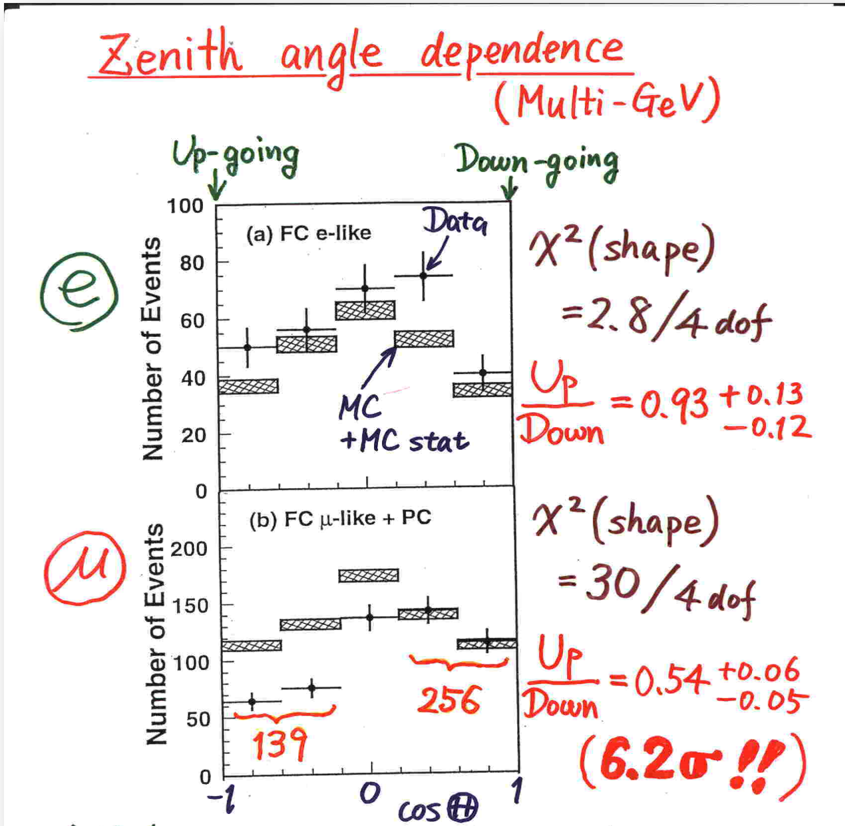
Bruno Pontecorvo
1969

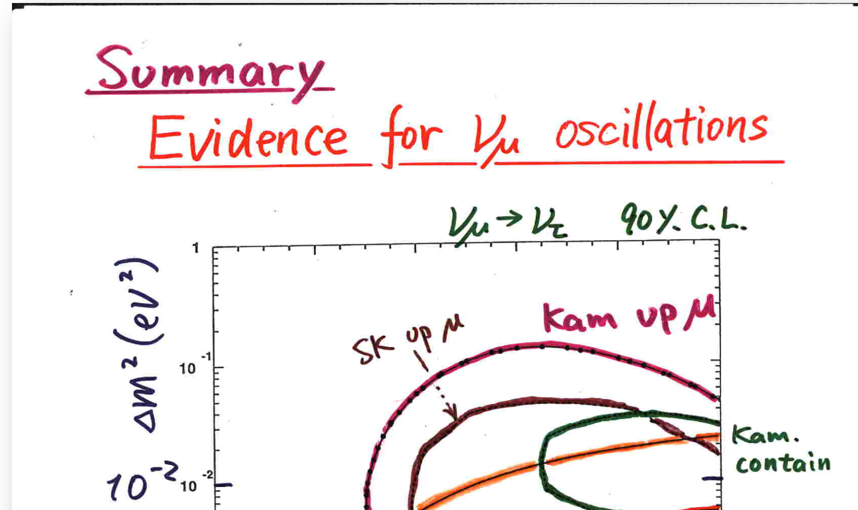
ν_μ → ν_1, ν_2, ν_3 → ν_μ, ν_e or ν_τ

$$\begin{pmatrix} \nu_\mu \\ \nu_x \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad P(\nu_\mu \rightarrow \nu_x) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

Evidence for neutrino oscillations (Super-Kamiokande @Neutrino '98)

Y. Fukuda et al., PRL 81 (1998) 1562





Super-Kamiokande concluded that the observed zenith angle dependent deficit (and the other supporting data) gave evidence for neutrino oscillations.

$\Delta m^2 \sim 3\times10^{-3}\ eV^2$

$L/E \approx 1000$ (KM/GeV)

Long-Baseline

T.Kajita (Nobel Prize 2015)

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix < 2011

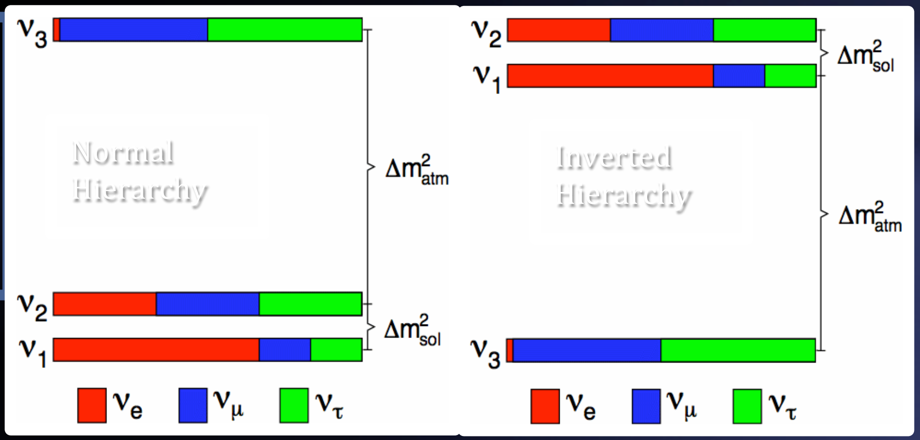
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{bmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{bmatrix} \times \begin{bmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{bmatrix} \times \begin{bmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{bmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$c_{ij} = \cos\theta_{ij}$$
$$s_{ij} = \sin\theta_{ij}$$

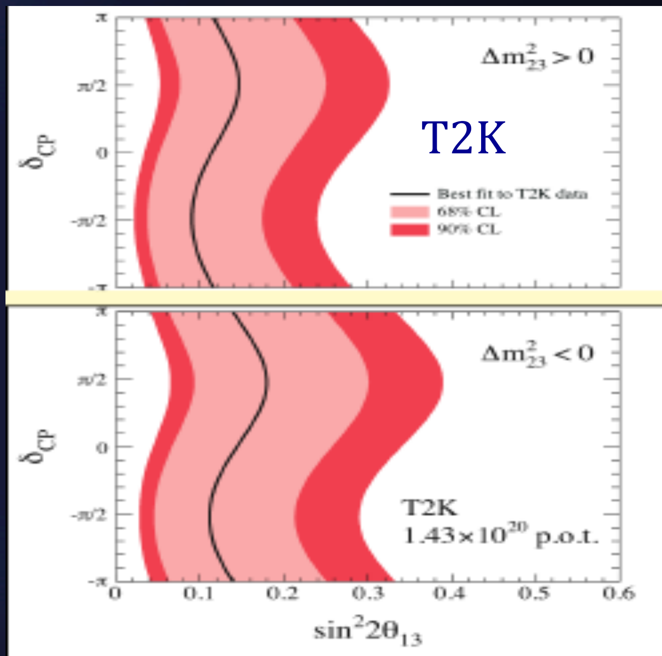
atmosferic ν accelerator ν	SBL reactor ν accelerator ν	solar ν LBL reactor ν
	interference	
$\sin^2\theta_{23} \sim 1/2$		$\sin^2\theta_{12} \sim 1/3$
$\Delta m^2 \sim 3\times10^{-3}\ eV^2$	$\sin^2\theta_{13} \sim 0$?	$\delta m^2 \sim 8\times10^{-5}\ eV^2$

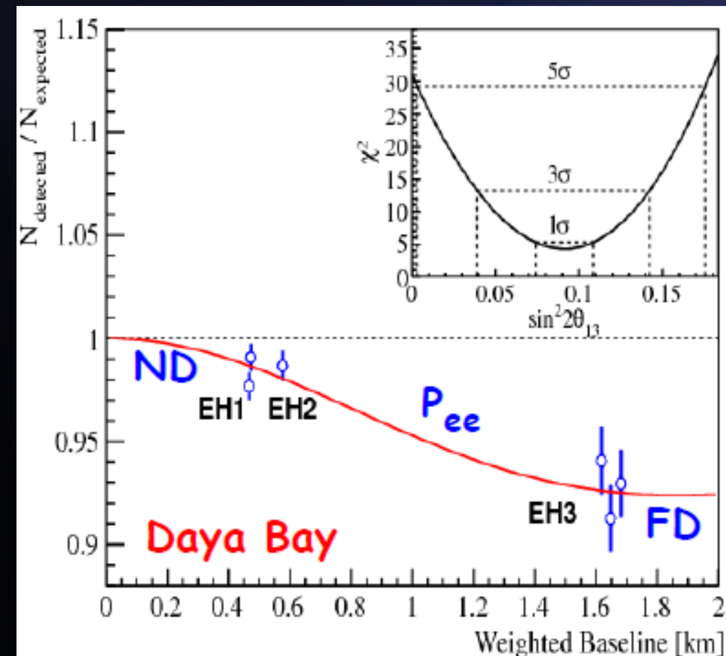
Source of neutrino:

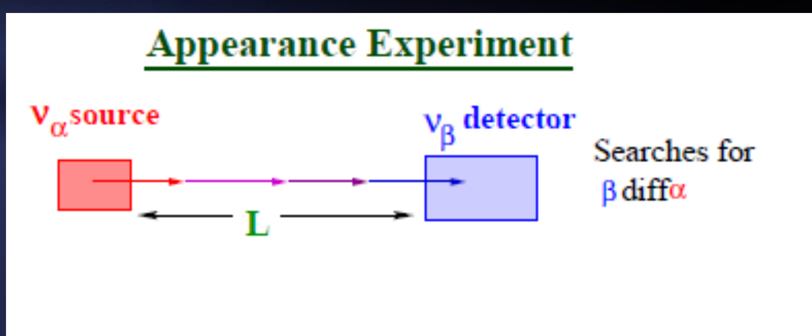
- Solar & Atmospheric
- Reactors
- Accelerators («Long Baseline»)

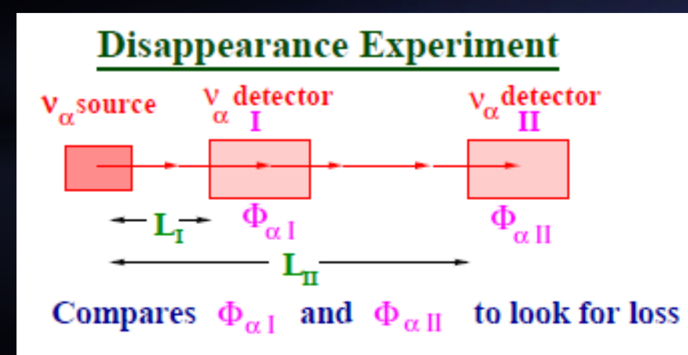


Everything changes: 2011/2012









ν Experiments: LBL vs Reactors

- In LBL APP $\nu_\mu \to \nu_e$

$$P_{\mu e} \simeq s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{31}}{B_\mp}\right)^2 \sin^2\left(\frac{B_\mp L}{2}\right)$$
$$+\tilde{J}\,\frac{\Delta_{12}}{V_E}\,\frac{\Delta_{31}}{B_\mp}\,\sin\left(\frac{V_E L}{2}\right)\sin\left(\frac{B_\mp L}{2}\right)\cos\left(\frac{\Delta_{31} L}{2} \pm \delta_{CP}\right)$$

$B_\pm = \Delta_{31} \pm V_E \quad \tilde{J} = c_{13}\sin^2 2\theta_{13}\sin^2 2\theta_{23}\sin^2 2\theta_{12}$

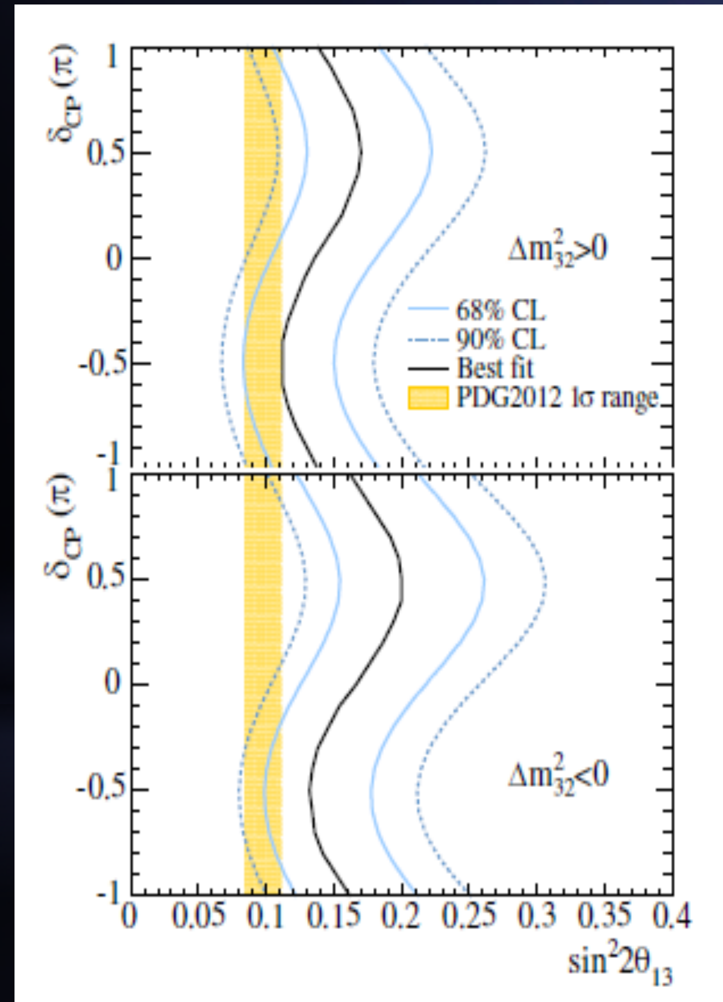
So $\sin^2 2\theta_{\rm APP} = 2\sin^2\theta_{23}\sin^2 2\theta_{13}$

- In Reactor $P_{ee} \simeq \sin^2 2\theta_{13}\sin^2\left(\frac{\Delta_{31} L}{2}\right)$

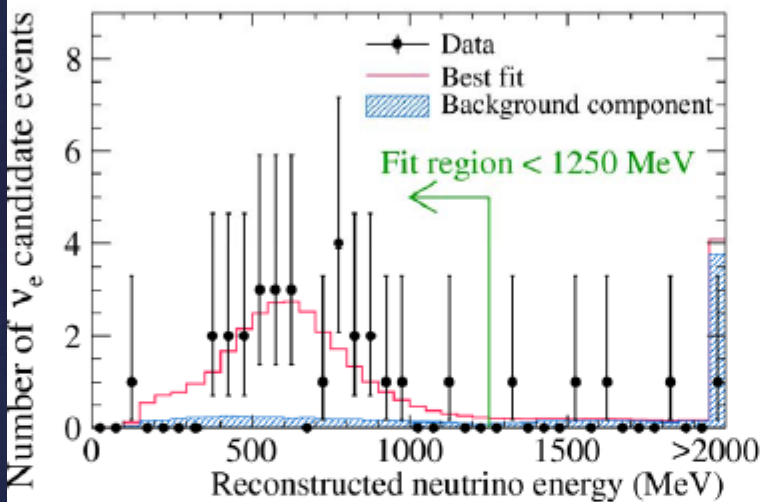
So $\sin^2 2\theta_{\rm REAC} = \sin^2 2\theta_{13}$

Concha Gonzalez-Garcia

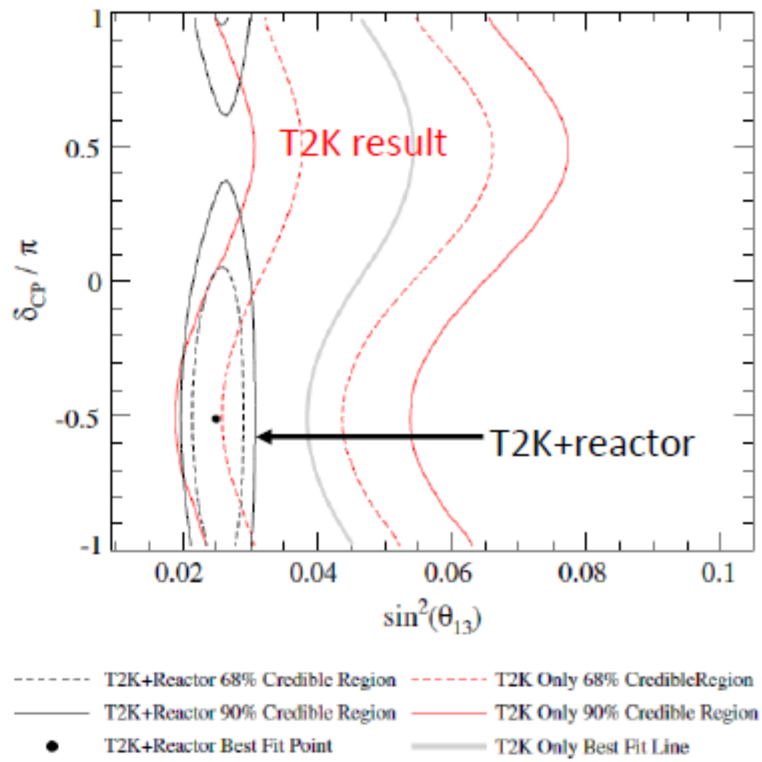
T2K 2013



ν_e appearance by T2K

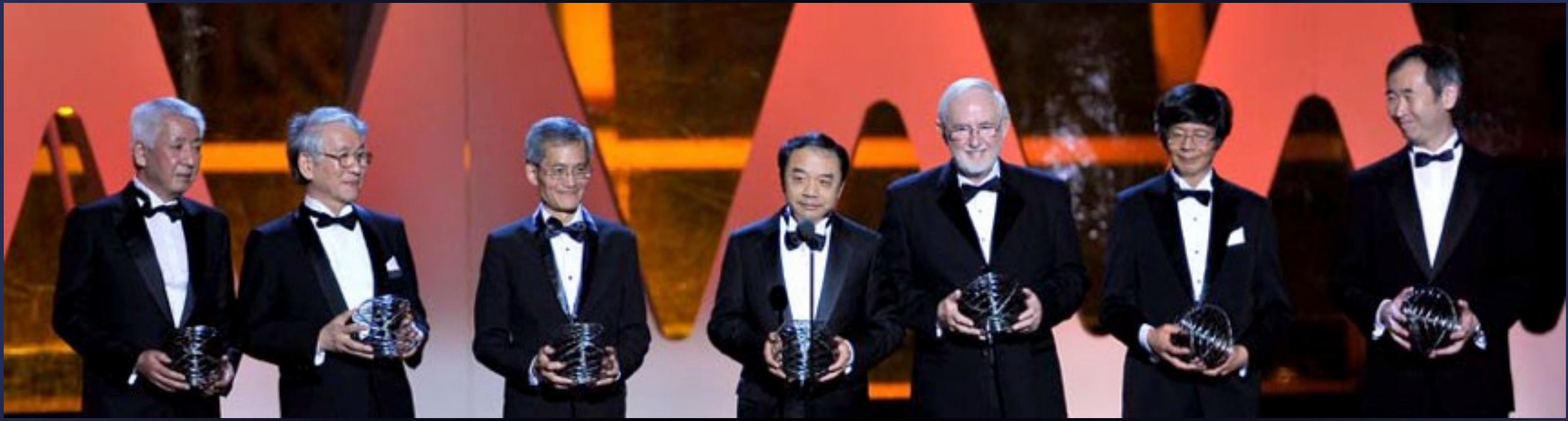


PhysRevLett.112.061802 (2014)



28 events observed over 4.92±0.55 bkgs → 7.3σ excess
First Confirmation of 'Appearance phenomenon' w/ > 5σ significance.

Breakthrough Prize 2016



T2K & K2K	KamLAND	Daya Bay	SNO	Super-Kamiokande
Δm^2_{32}	Δm^2_{21}	Δm^2_{31}	Δm^2_{21}	Δm^2_{32}
θ_{23} θ_{13}	θ_{12}	θ_{13}	θ_{12}	θ_{23}

…. "For the fundamental contributions to the discovery of neutrino Oscillation"

Everything solved ???

PDG2018

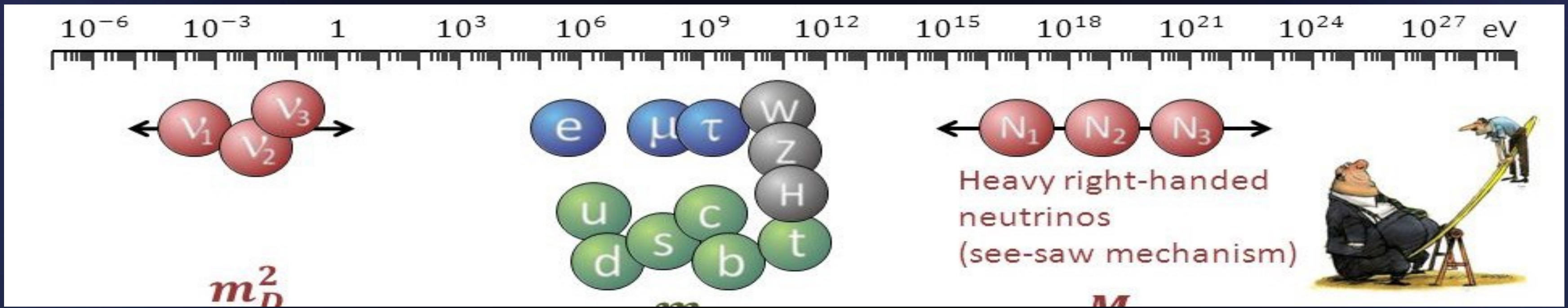
	Parameter	best-fit	3σ
~4%	Δm^2_{21} [10^{-5} eV ^{2}]	7.37	6.93 – 7.96
~3%	$\Delta m^2_{31(23)}$ [10^{-3} eV ^{2}]	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)
~11%	$\sin^2\theta_{12}$	0.297	0.250 – 0.354
~15%	$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425	0.381 – 0.615
	$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589	0.384 – 0.636
~7%	$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215	0.0190 – 0.0240
	$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216	0.0190 – 0.0242
~31%	δ/π	1.38 (1.31)	2σ: (1.0 - 1.9) (2σ: (0.92-1.88))

- What is the value of δ_{CP}??
- What is the mass hierarchy?

Most of the parameters measured with <10% precision

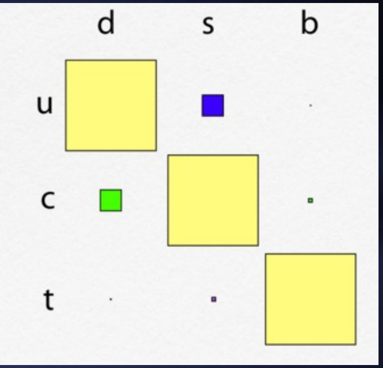
θ_{23} is known with 15% precision

PNMS vs CKM

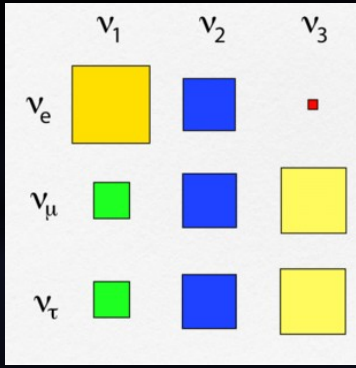


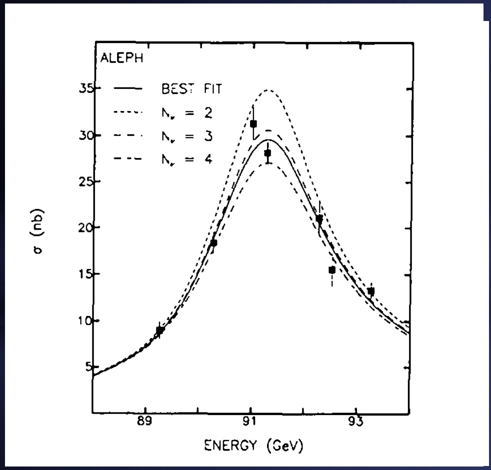
- What is the absolute mass scale?
- Why so small??

CKM



PNMS





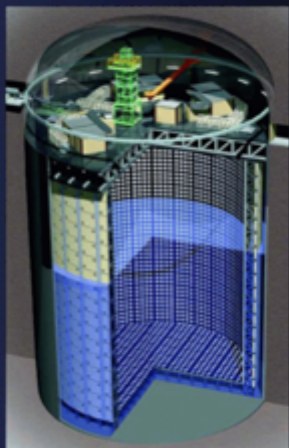
Mostly diagonal

Unitarity enforced by construction

Is the PMNS parameterization correct?

The Tokai to Kamioka (T2K) Experiment

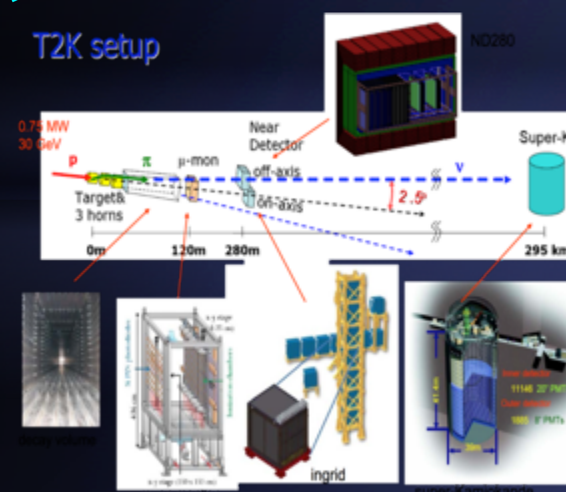
Super-K Detector



J-PARC Accelerator

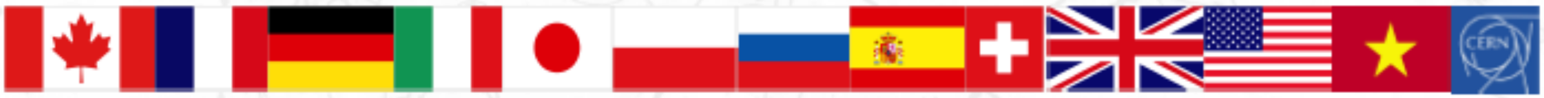
* The T2K experiment searches for neutrino oscillations in a **high purity ν_μ beam**
* A near detector located 280 m downstream of the target measures the un-oscillated neutrino spectrum
* The neutrinos travel 295 km to the Super-Kamiokande water Cherenkov detector

Near Detector



- ν_e ($\bar{\nu}_e$)appearance
- ν_μ ($\bar{\nu}_\mu$) disappearance
- δ_{cp}
- X-sections +exotics

T2K Collaboration

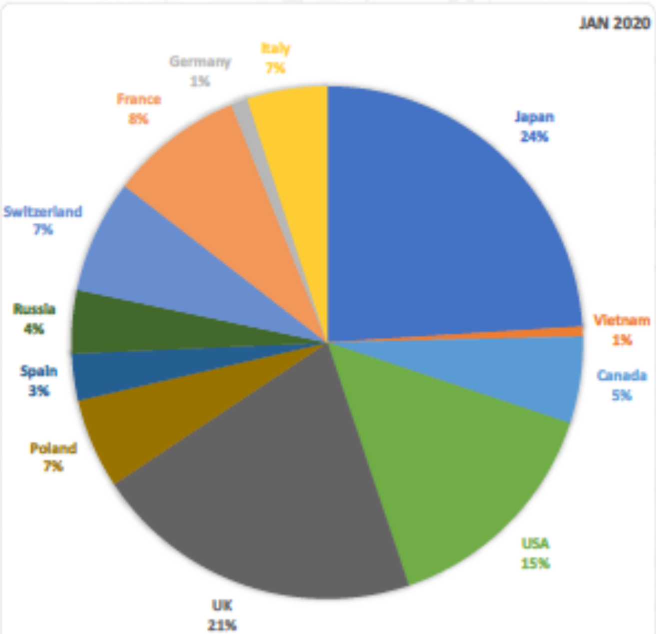


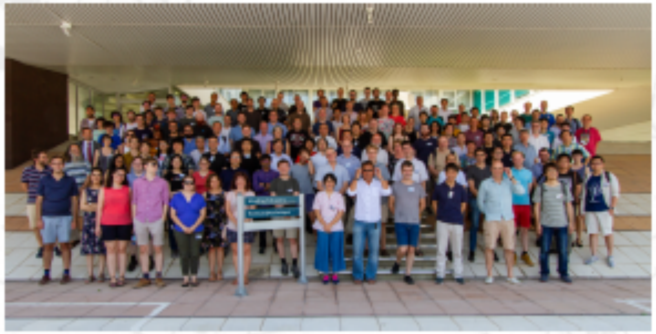
~500 members, 69 Institutes, 12 countries

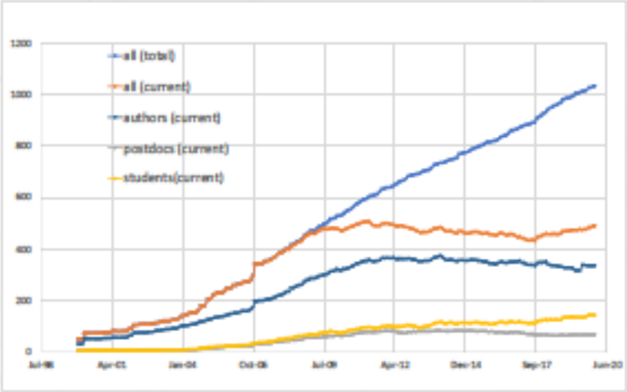
Asia	117
Japan	114
Vietnam	3

Americas	96
Canada	26
USA	70

Europe	261
France	38
Germany	5
Italy	28
Poland	28
Russia	19
Spain	14
Switzerland	30
UK	99

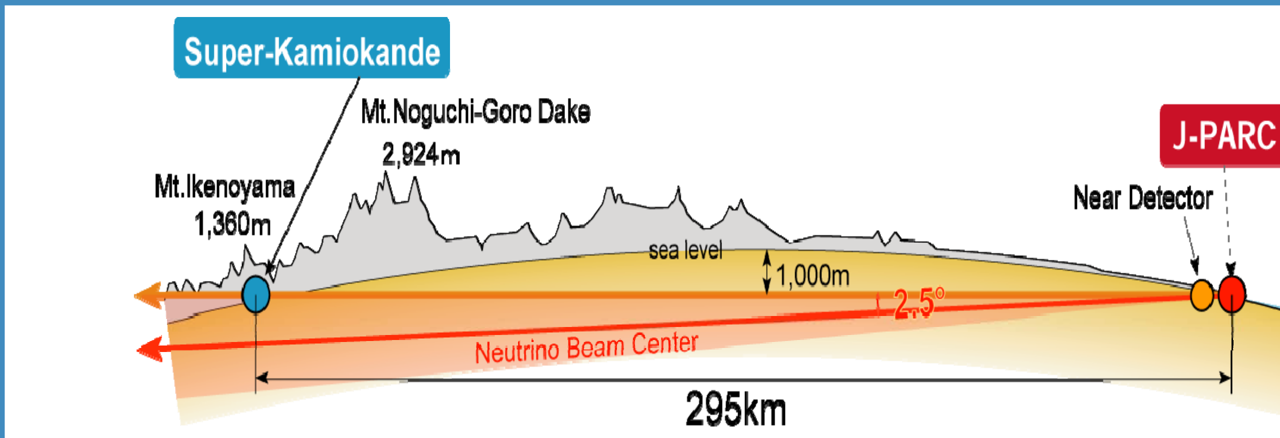


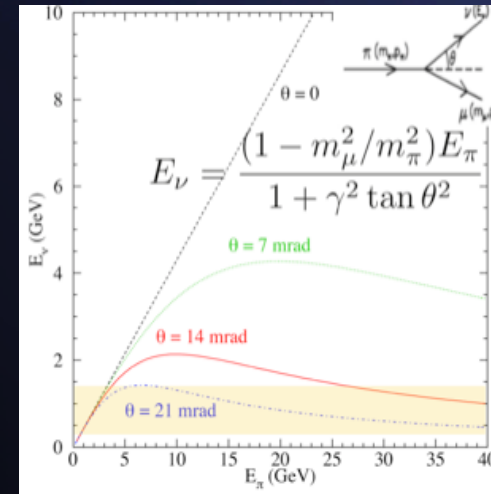




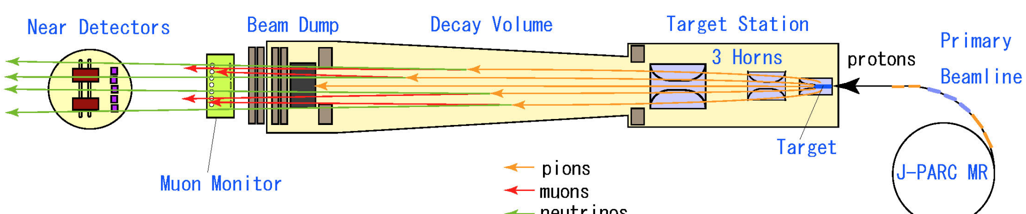
Very strong European contribution including CERN

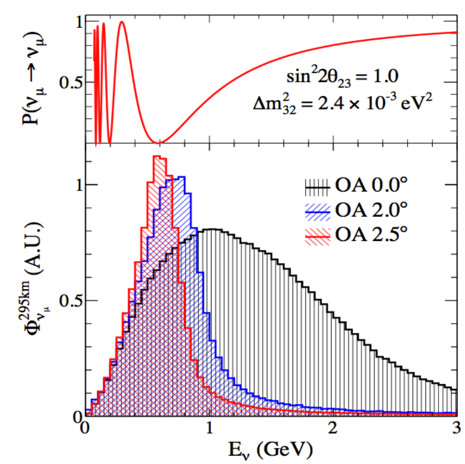
Off-Axis Beam



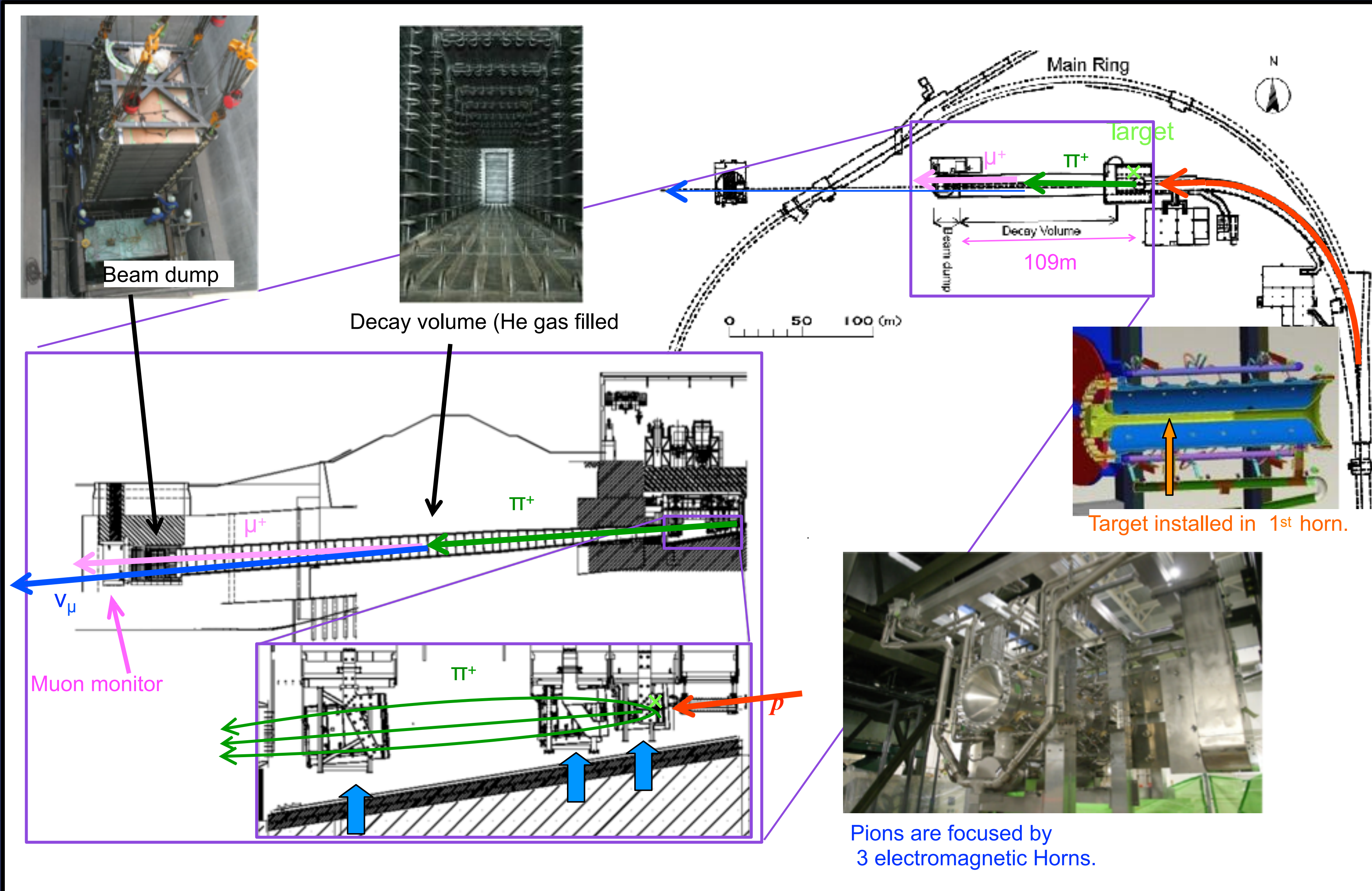


- 30 GeV proton beam generated by J-PARC Main Ring (MR) directed to the graphite target
- Secondary pions collected and focused by the magnetic horns
  - ν beam: $\pi^+ \rightarrow \mu^+ + \nu_\mu$ (Forward horn current)
  - $\overline{\nu}$ beam: $\pi^- \rightarrow \mu^- + \overline{\nu}_\mu$ (Reverse horn current)
- Uses off-axis method to make the spectrum peak at 600 MeV
  - Expected oscillation maximum at L=295 km

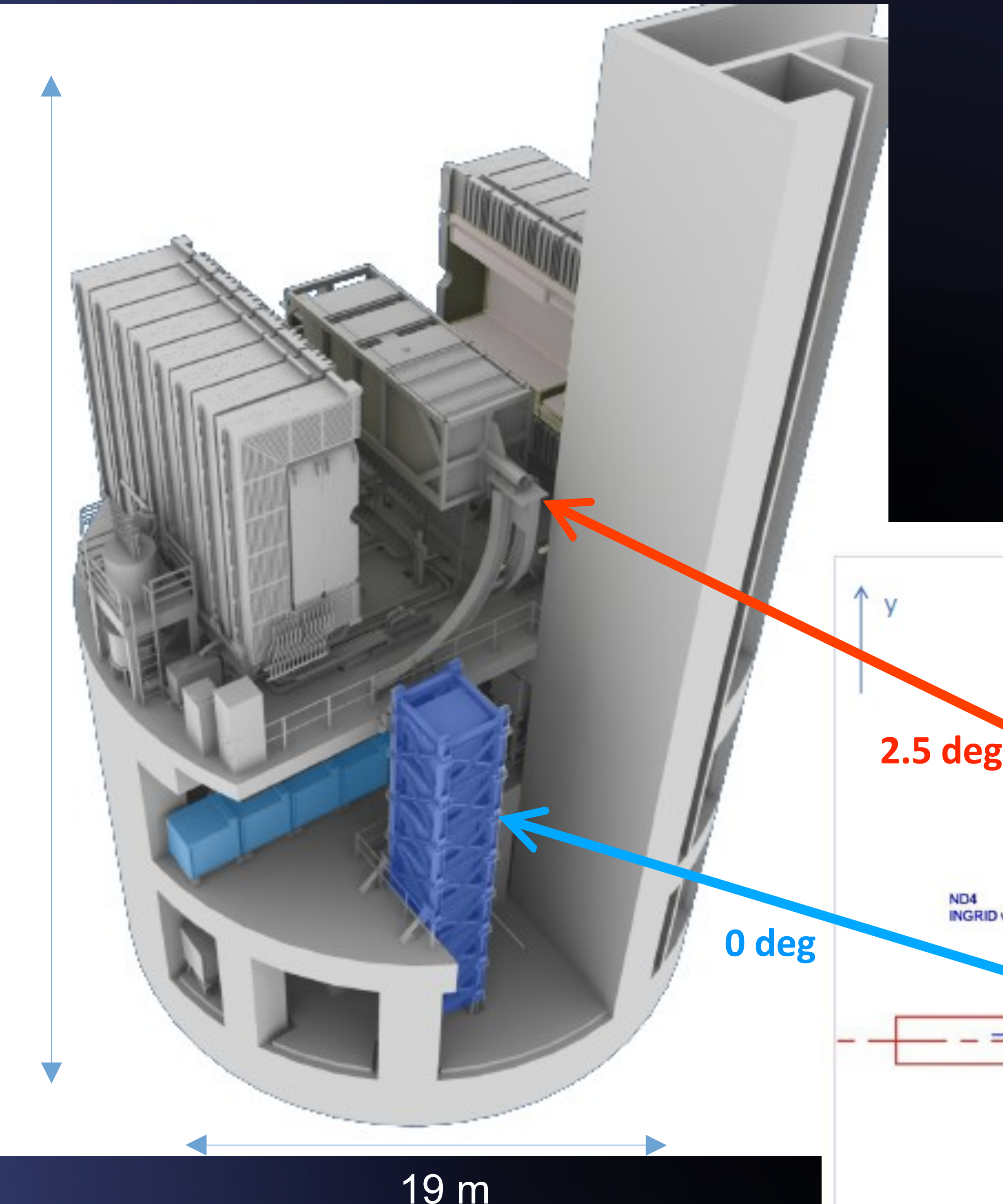


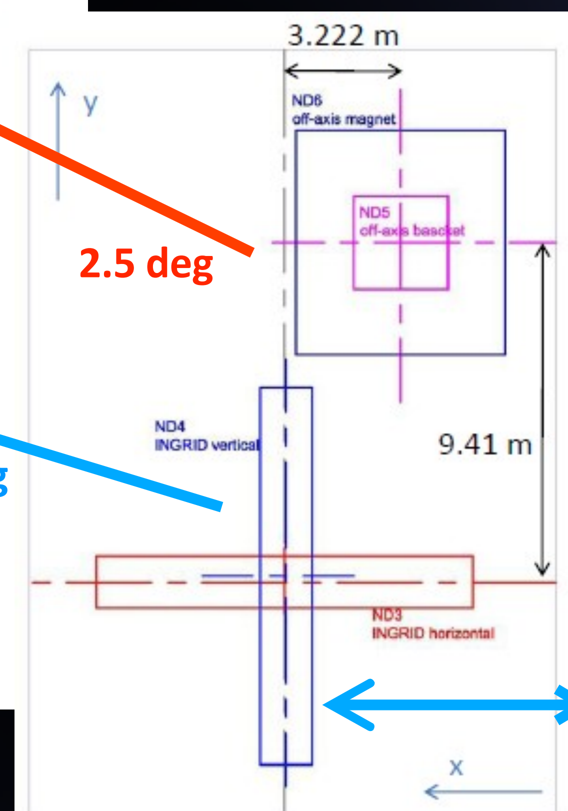


J-PARC neutrino beamline overview

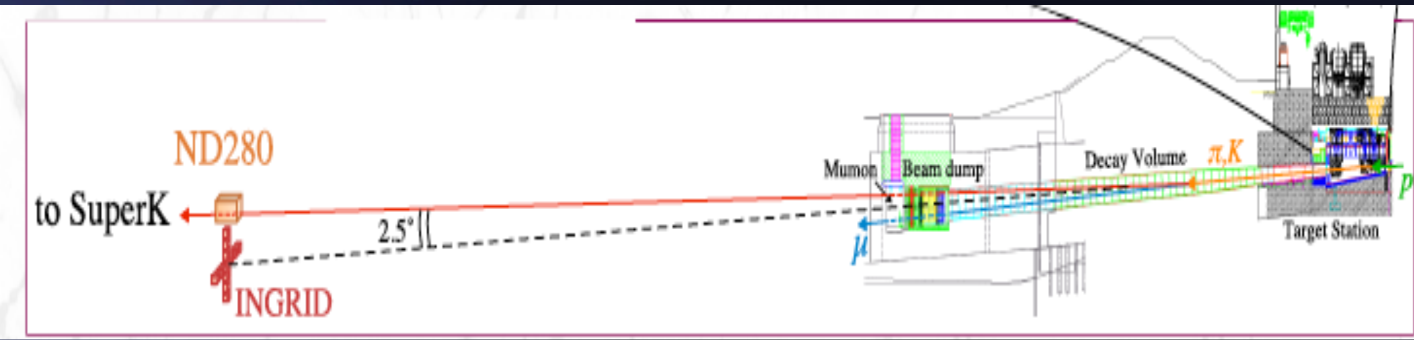


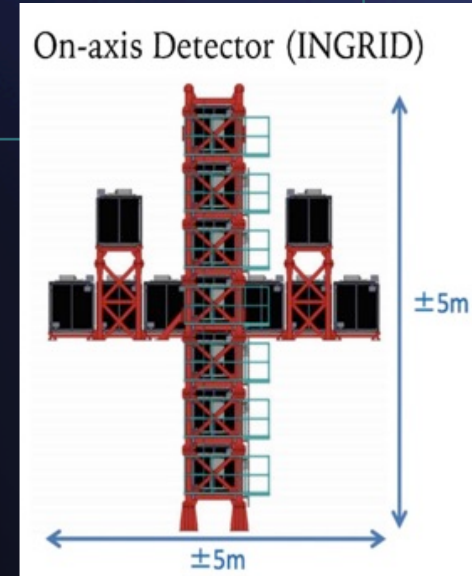
T2K Near Detector pit houses both the off-axis (ND280) and on-axis (INGRID) detectors

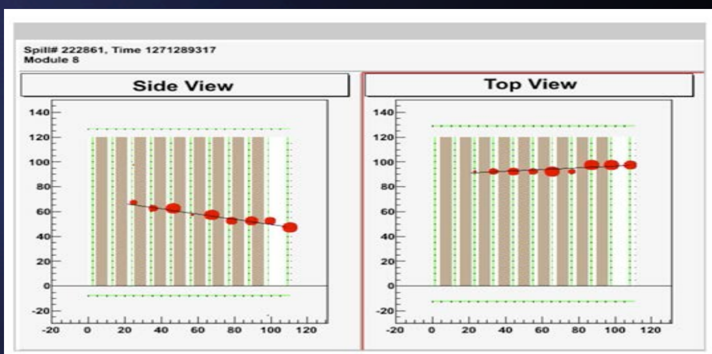


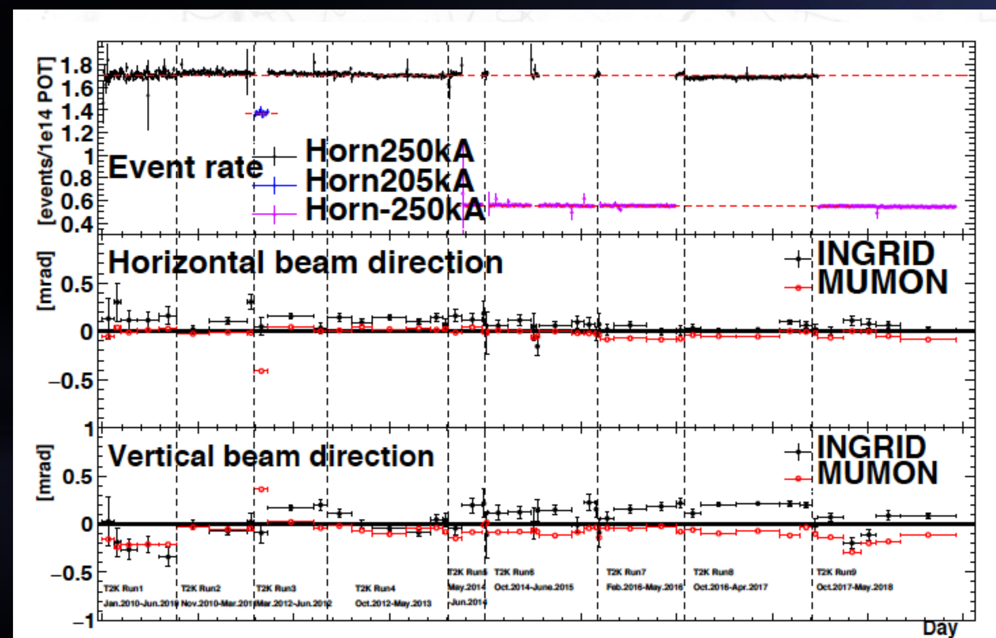


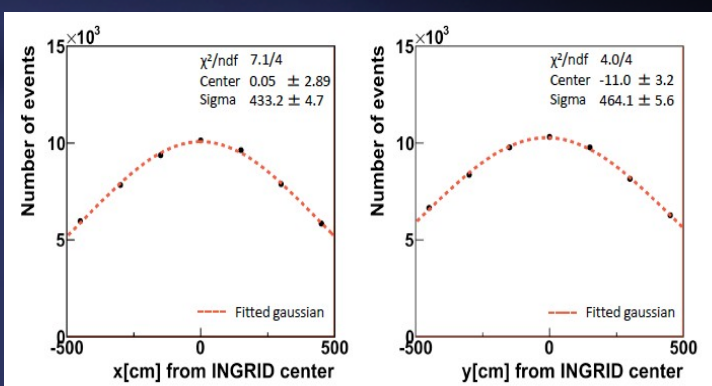
On-Axis near Detector



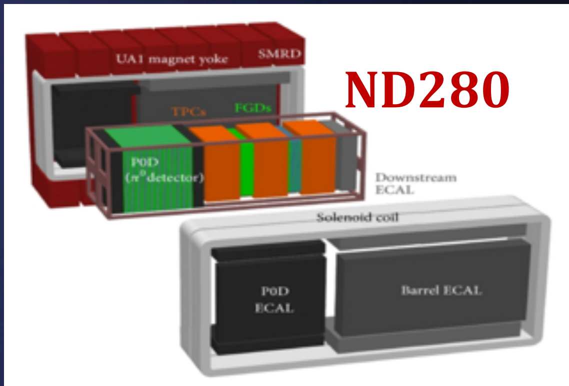


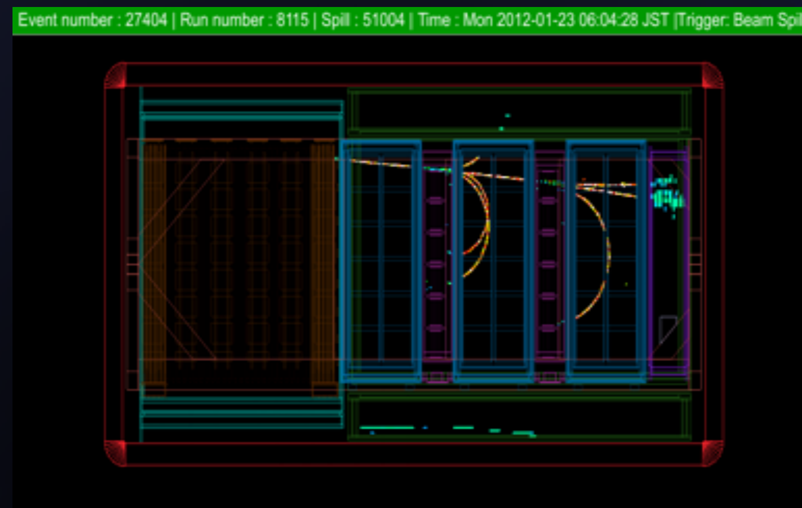


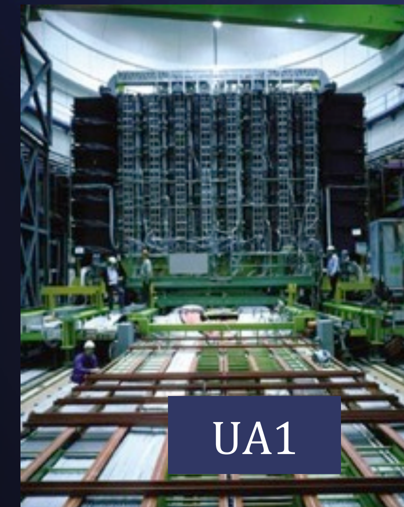




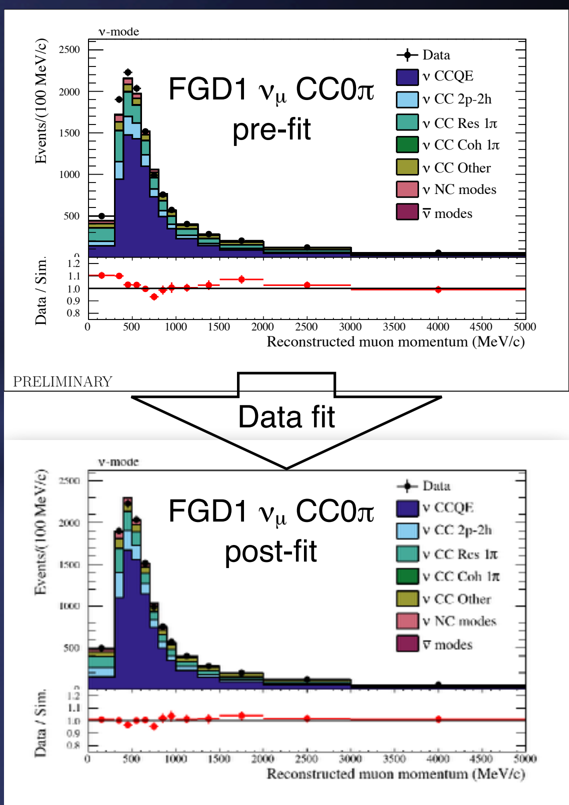
Off-axis near detector:ND280

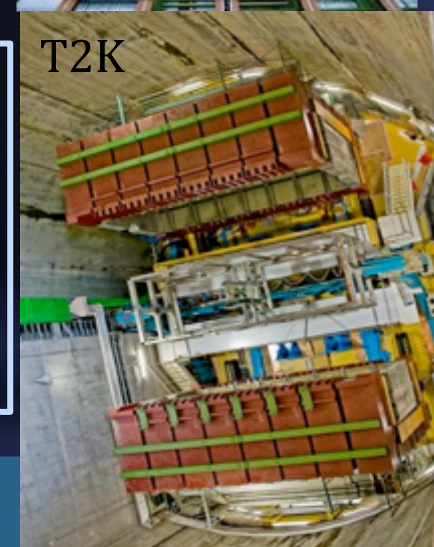






- **UA1 magnet (0.2 T)**
- Fine Grained Detector (FGD) (target)
- **Time Projection Chambers (TPC)**
  Momentum Res. < 10%
  PID (< 10% dE/dx Res.)

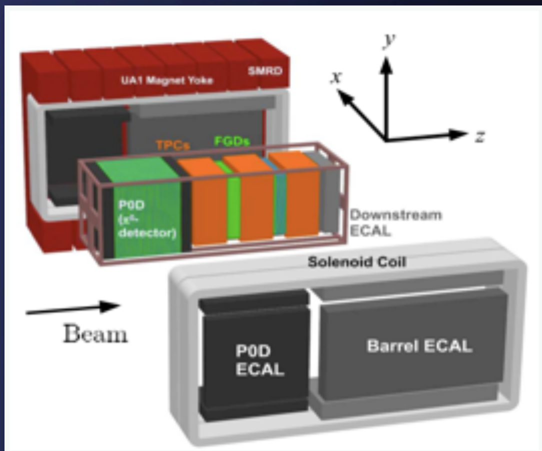


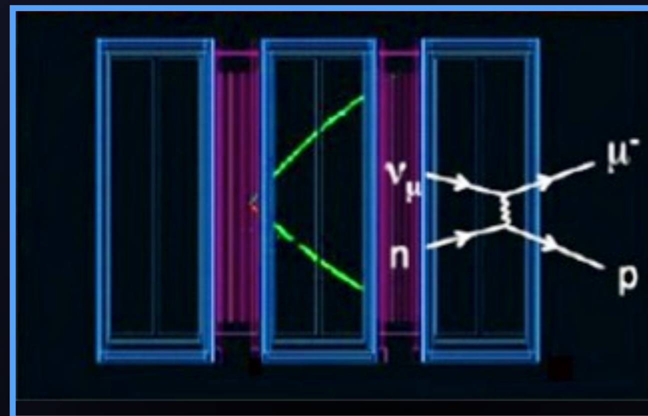


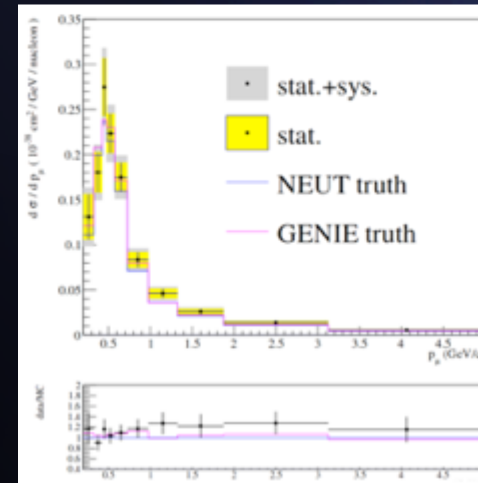
- **ND280** @ 2.5 degree off-axis
- Normalization of Neutrino Flux
- Measurement of neutrino cross sections.

T2K-ND280: INFN Contributions (Ba,LNL,Na,Pd,Rm1)

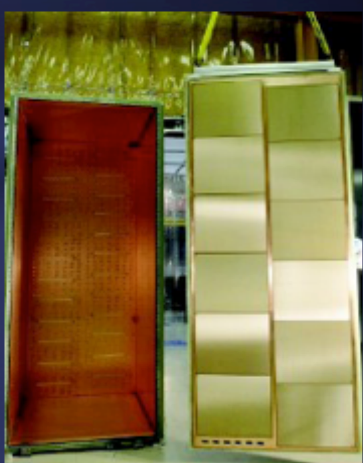
"Inclusive CC anti-ν Differential Cross-Section on Carbon "



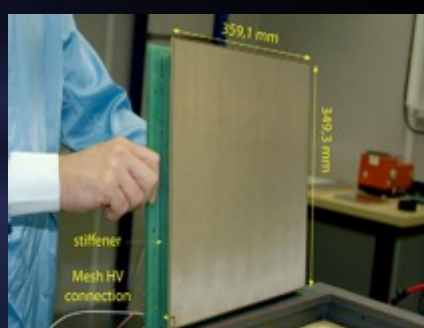




First large TPC with MPGD



TPC assembling

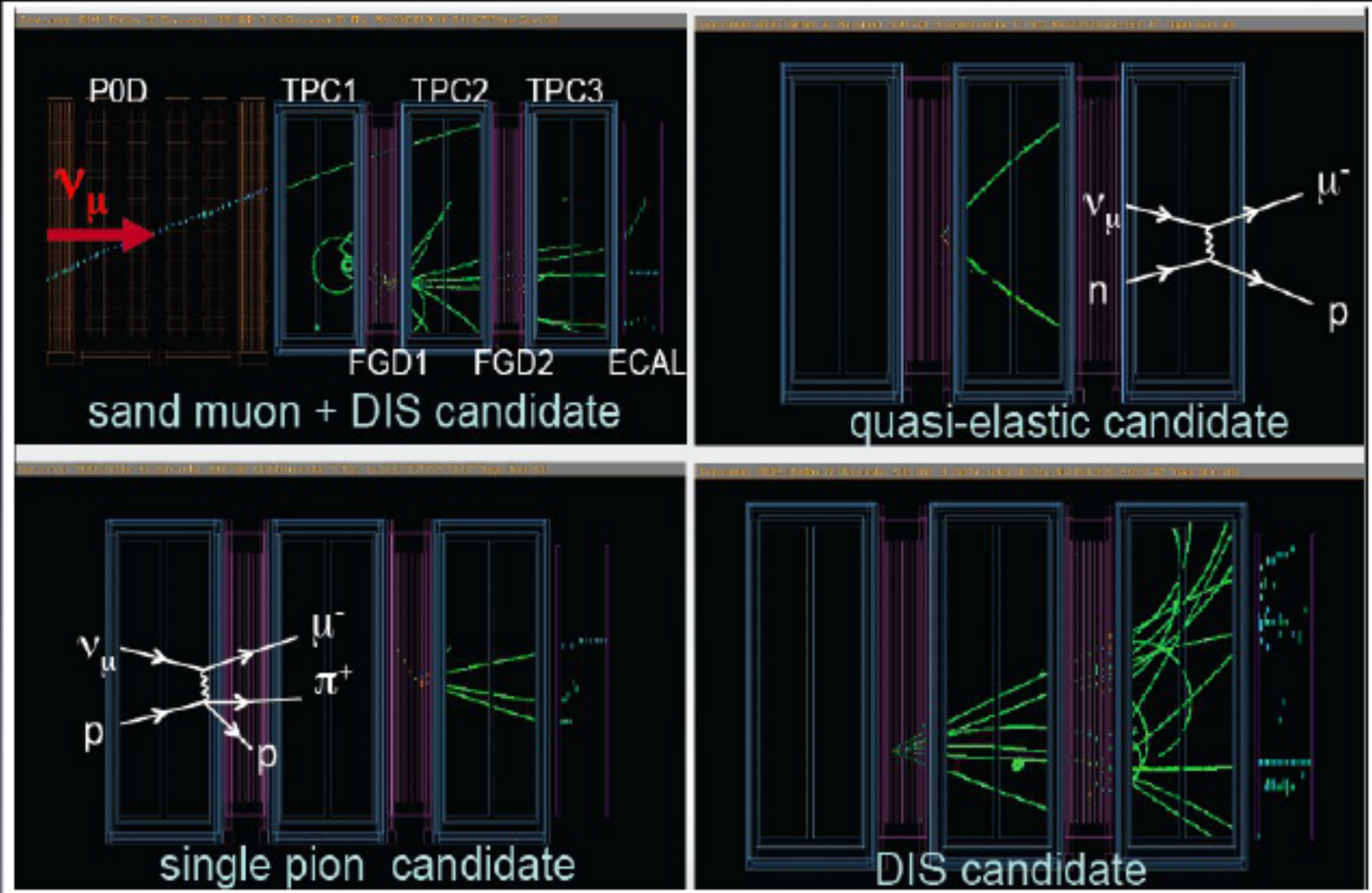


TPC design with advanced detectors (MPGD)

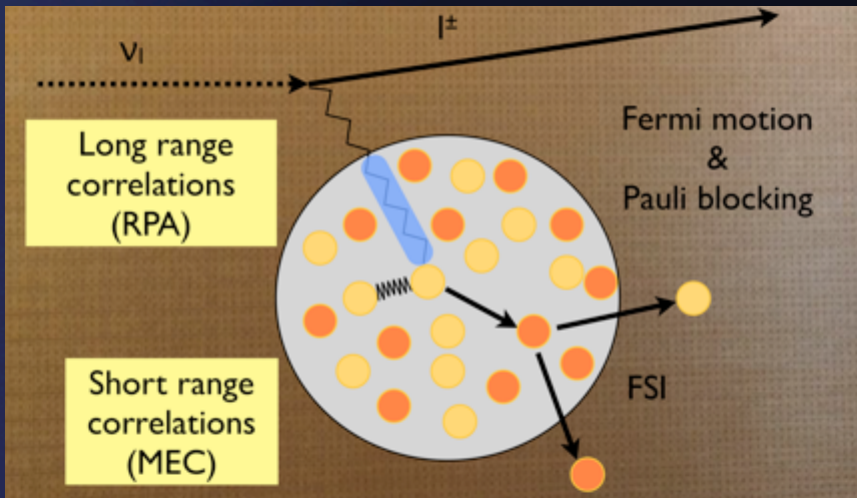
INFN in T2K

- ✓ TPC design, assembling, calibration, maintenance and operation
- ✓ Initial idea and calculations for a magnetized detector
- ✓ Leading role in anti-ν Analysis @ ND280
- ✓ Several Management & Coordination Roles

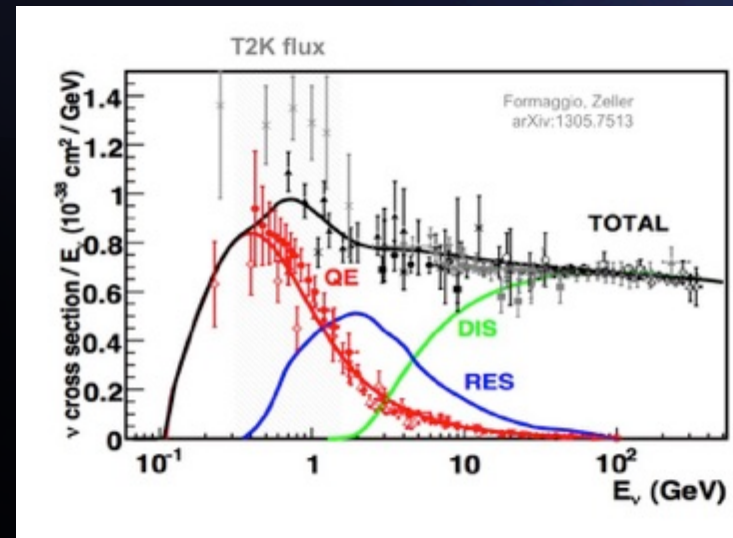
ND280 off-axis event gallery



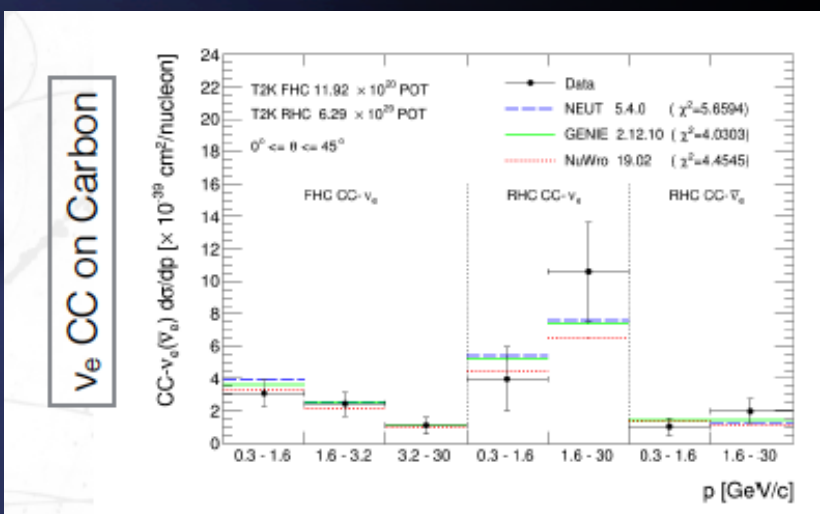
νA cross-sections

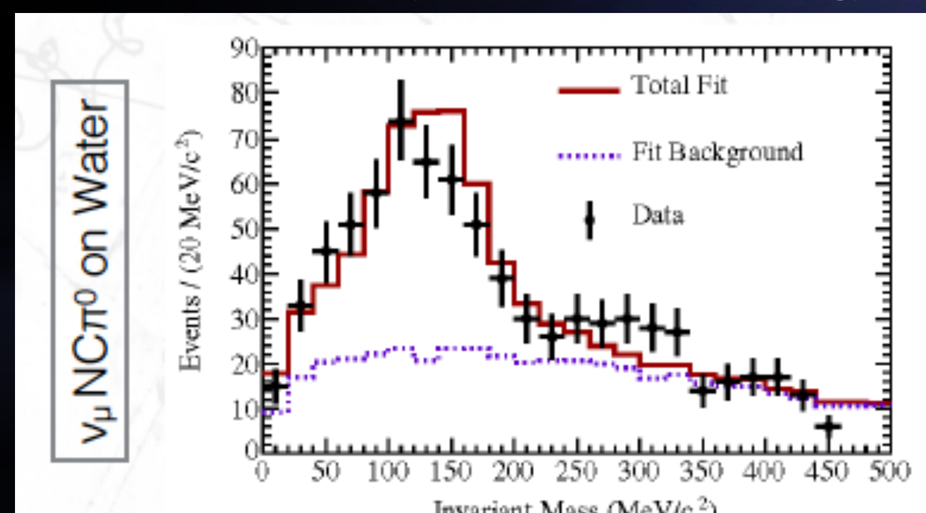


Large discrepancy in the models predictios



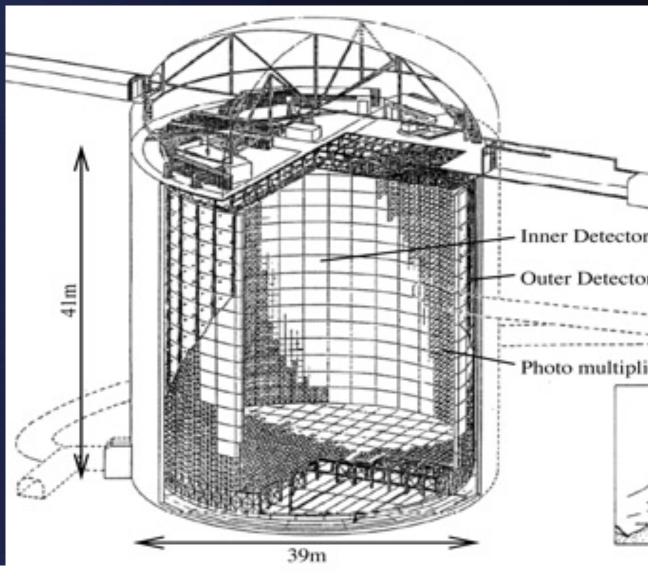
Cross sections poorly known at low energy



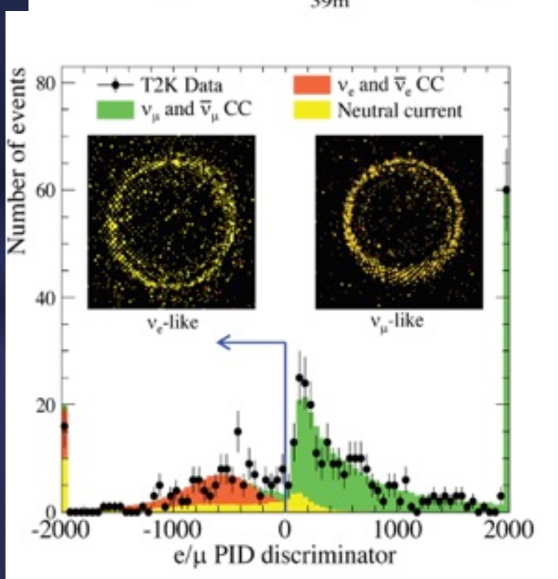


A couple of examples : many papers published in the last years

* The Far detector: Super-Kamiokande



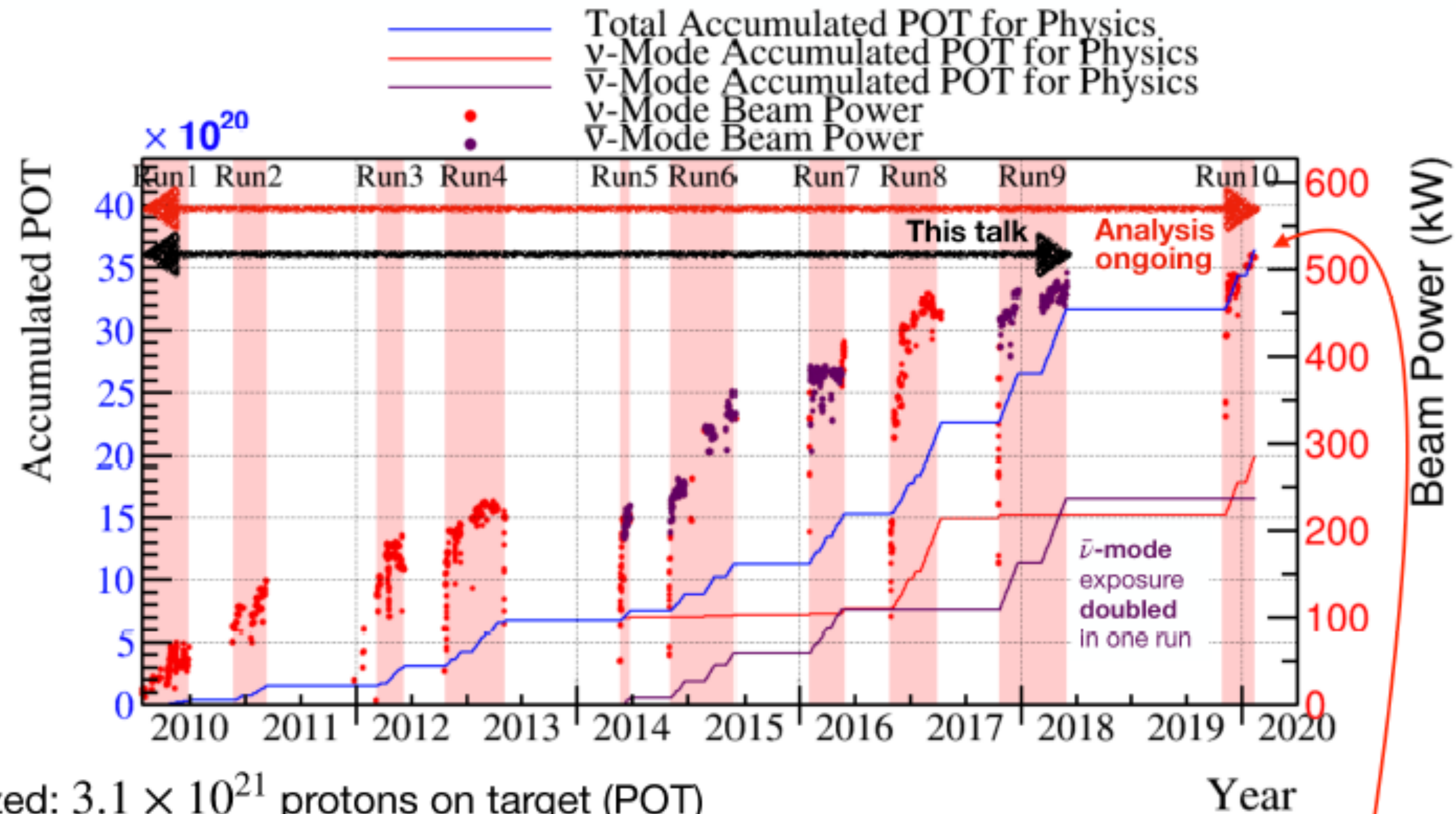
Probability to mis-id μ as electron is ~1%



- 50 kton Water Cherenkov detector 1 km underground
- Typically 61% ν_e signal eff.
- 95% π_0 rejection
- 32 kton inner volume (22.5 kton fiducial volume)
- 2 m outer volume to identify entering particles

All triggers in +/- 0.5 ms of neutrino arrival time are recorded

Data Set



Analyzed: 3.1×10^{21} protons on target (POT)

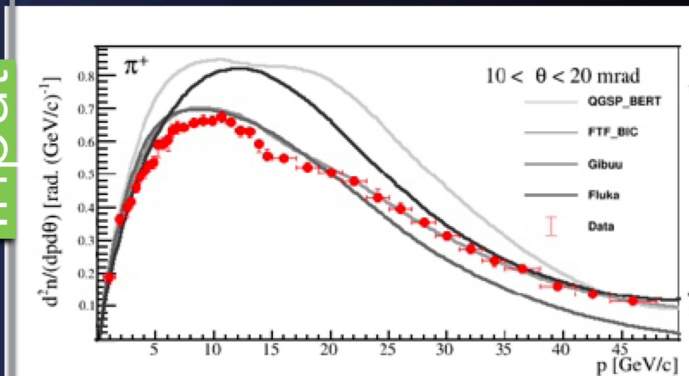
approx 50% ν - 50% ν̄

515 kW stable operation in 2019
+ 33% of ν-mode for next analysis

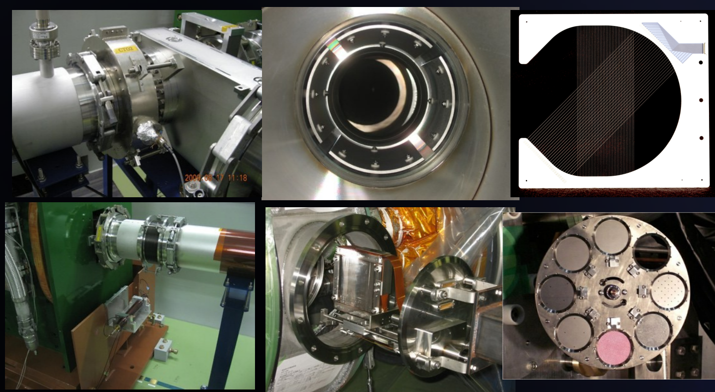
Beam model

Beam model is obtained from a full GEANT simulation of the particle transport reweighed by the NA61 (Shiνe) results

Input

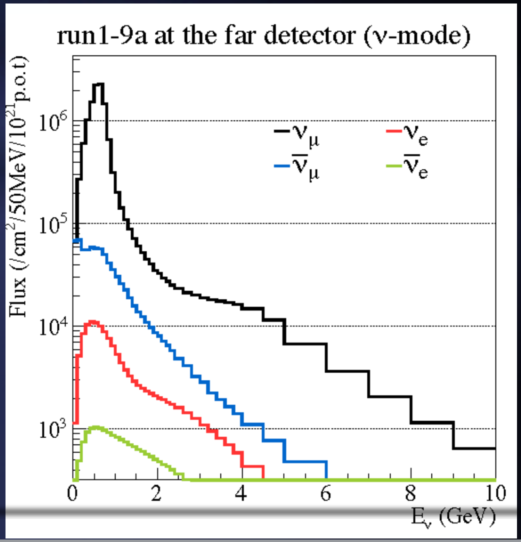


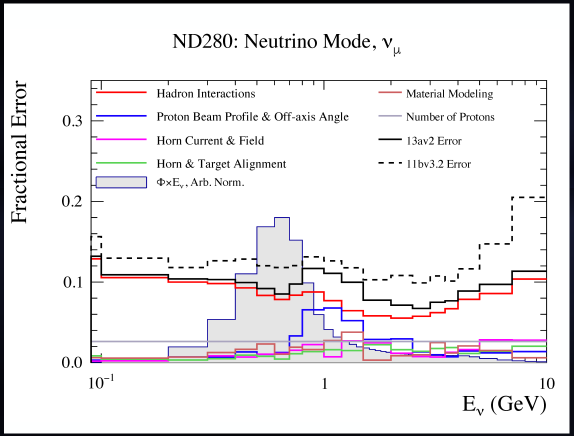
Beam monitors

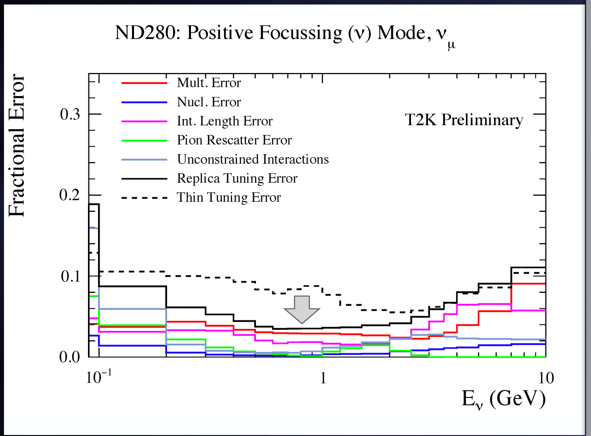


GEANT

Output



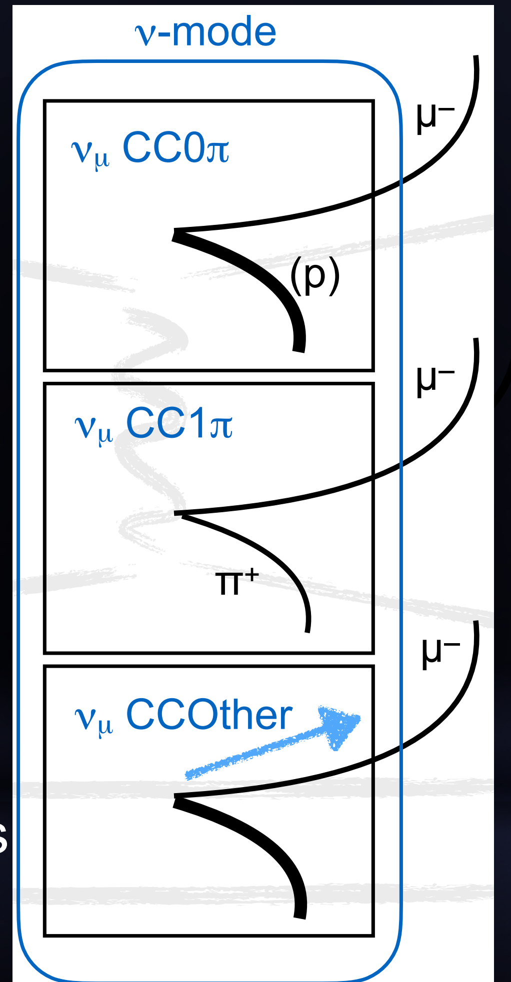


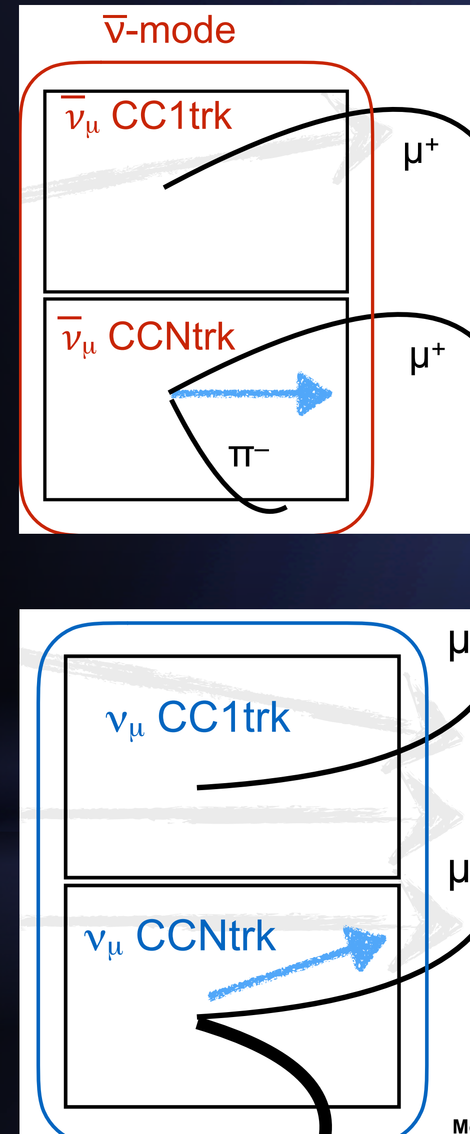


Including error covariance matrix

ND280 data for Oscillation Analysis

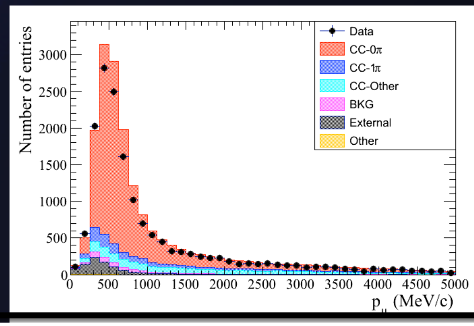
- 14 total ND280 data samples used by oscillation analysis fit
- ν-mode (FHC)
  - sort by $\pi^{\pm}$ multiplicity
  - 2 FGDs (C,O)
  - ➡6 samples
- $\bar{\nu}$-mode (RHC)
  - sort by muon charge
  - sort by number of tracks
  - 2 FGDs (C,O)
  - ➡8 samples

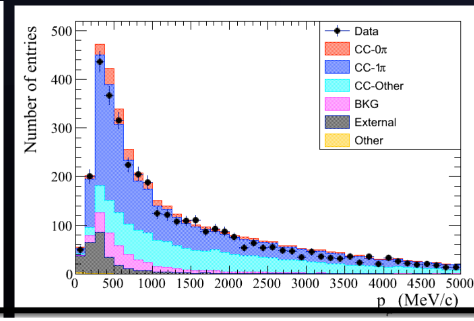


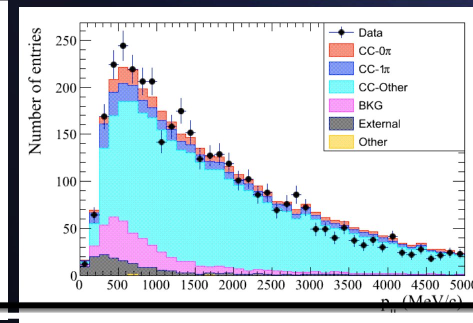


Analysis Model

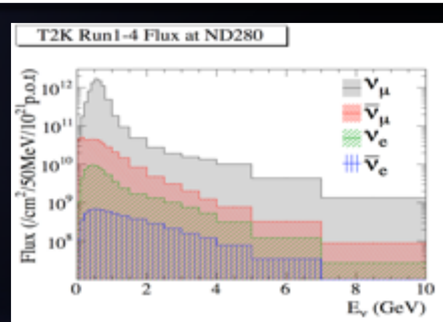
Near detector data







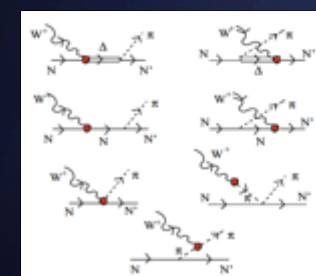
⊕ Hadron production flux prediction Shive + beam monitors



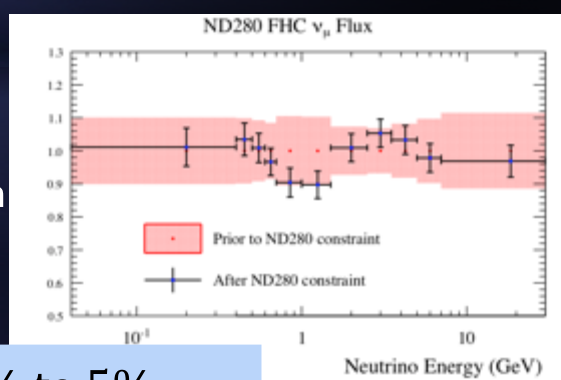
feed back

⊕

Cross-section model

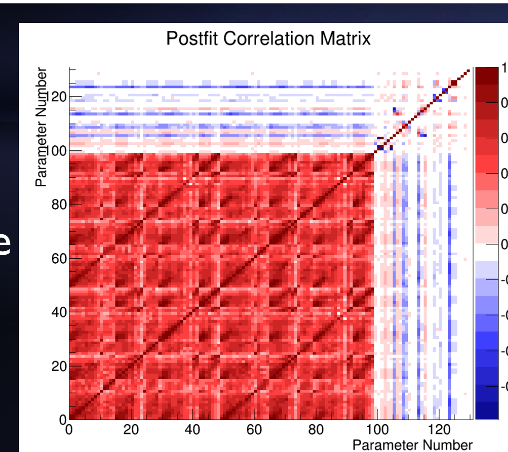


= Corrected flux and cross-section model



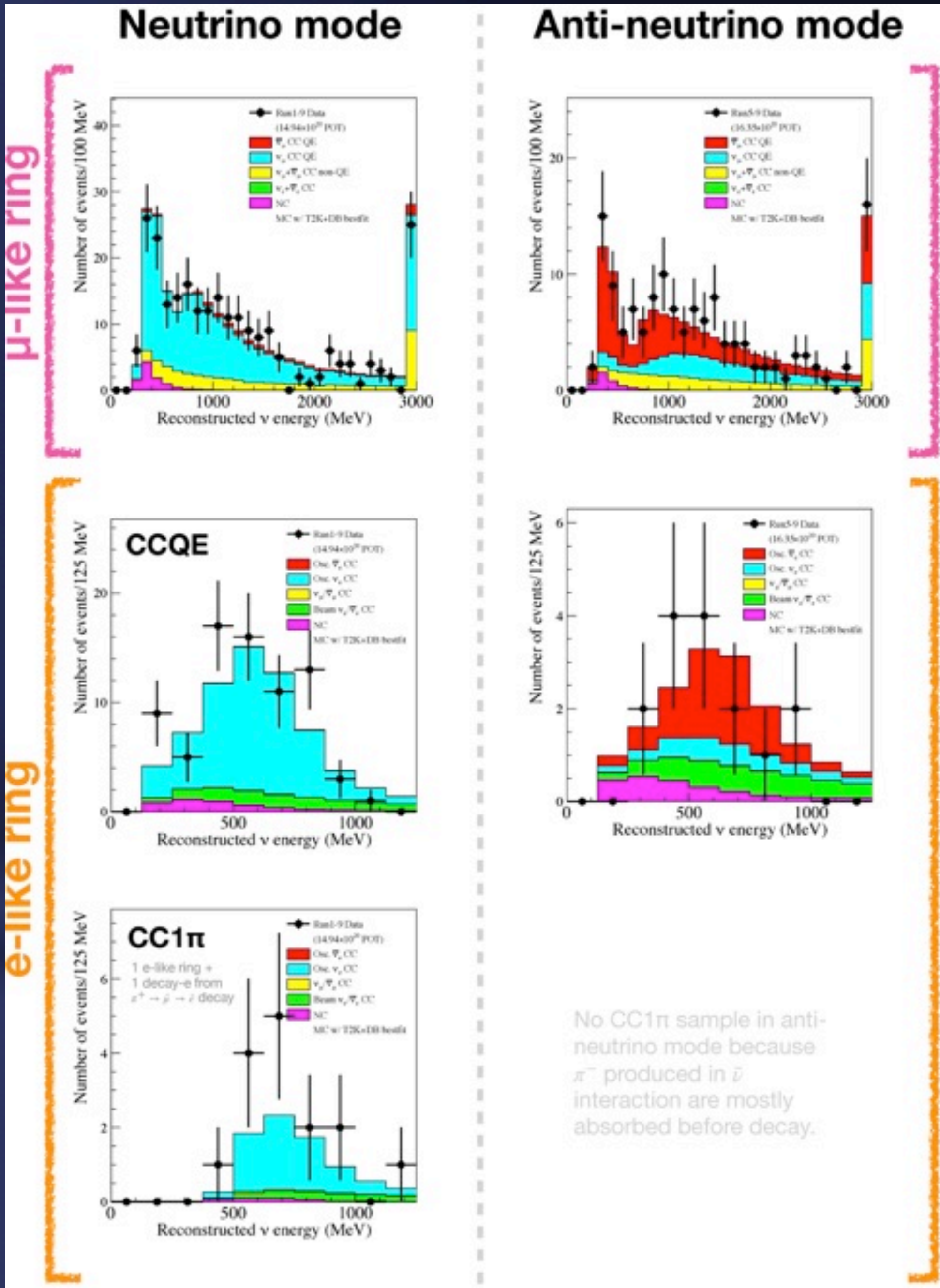
&

error covariance matrix



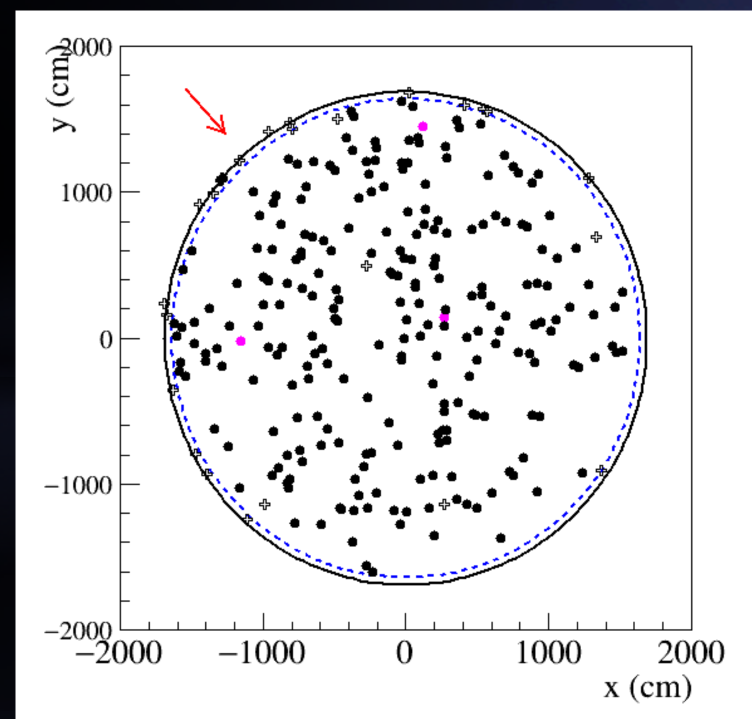
Sys. Error from 15% to 5%

SK data



5 SK samples

1. muon neutrinos
2. muon antineutrinos.
3. electron neutrinos.
4. electron neutrino + pion (Michel electron)
5. electron antineutrino.



*Oscillation fits

$\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ combined analysis within the 3ν oscillation paradigm (PMNS).

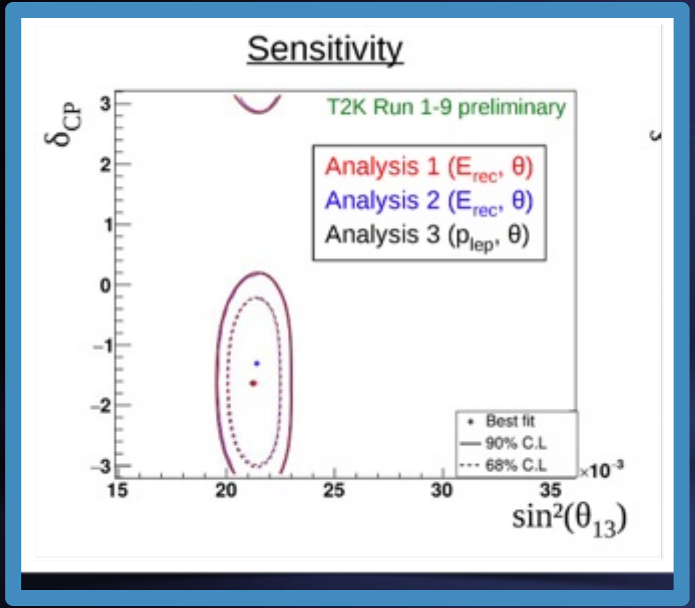
Other oscillation parameters from 2018 PDG values.

Binned likelihood comparing data to MC predictions.

$$-2\ln\lambda(\overline{\delta_{CP}};\boldsymbol{a}) = 2\sum_{i=1}^{N}\left[n_i^{obs}\ln\left(\frac{n_i^{obs}}{n_i^{exp}}\right) + n_i^{exp} - n_i^{obs}\right] + (\boldsymbol{a}-\boldsymbol{a}_0)^T \mathbf{C}^{-1}(\boldsymbol{a}-\boldsymbol{a}_0)$$

Bins of reconstructed energy from lepton kinematics assuming CCQE two body interactions.

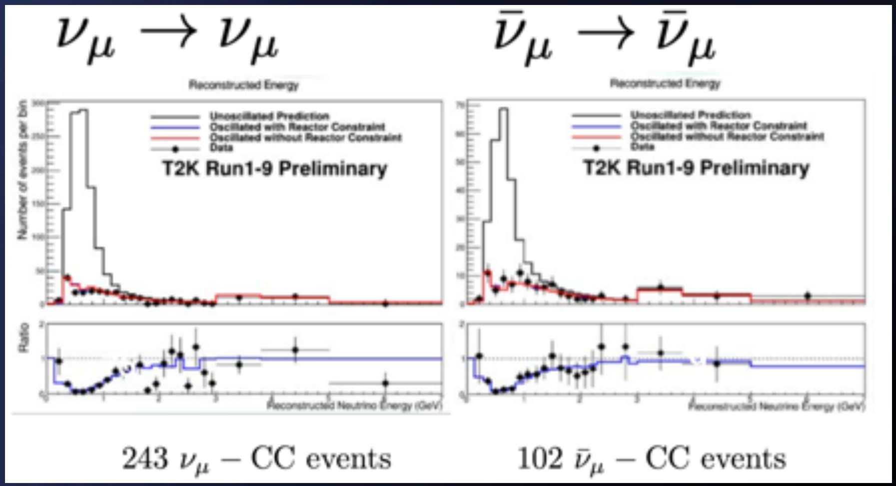
ν_e sample also bins in θ_e

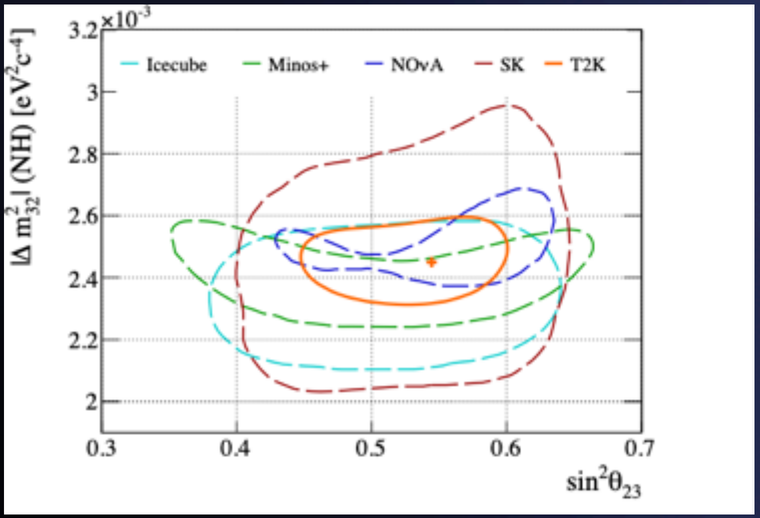


Bayesian Markov Chain MonteCarlo and 2 frequentist approach.

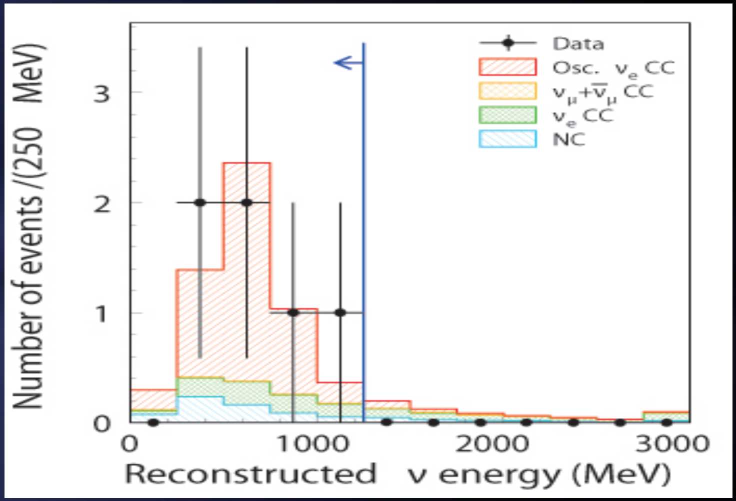
Frequentists confidence intervals (grid search) agree with the Bayesian factors and credible intervals.

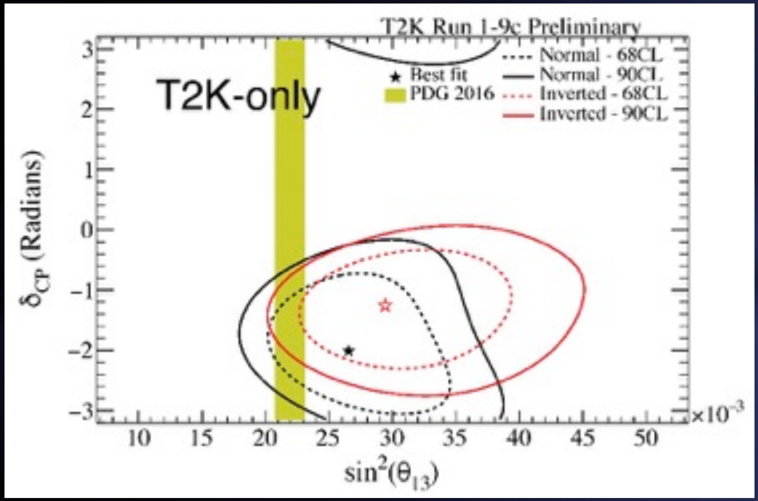
T2K highlights





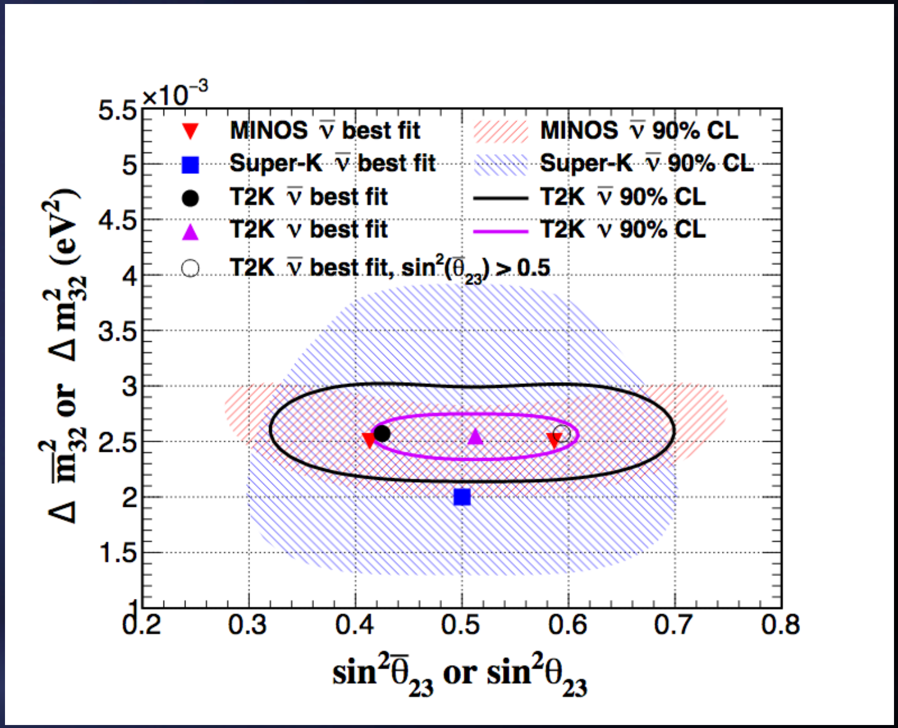
Word best measurements in disappearance mode



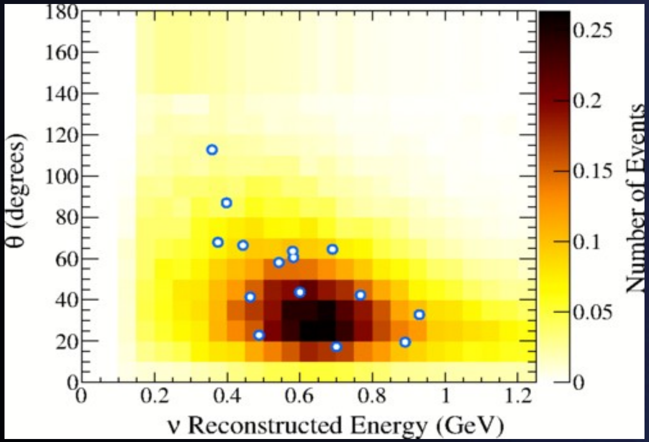


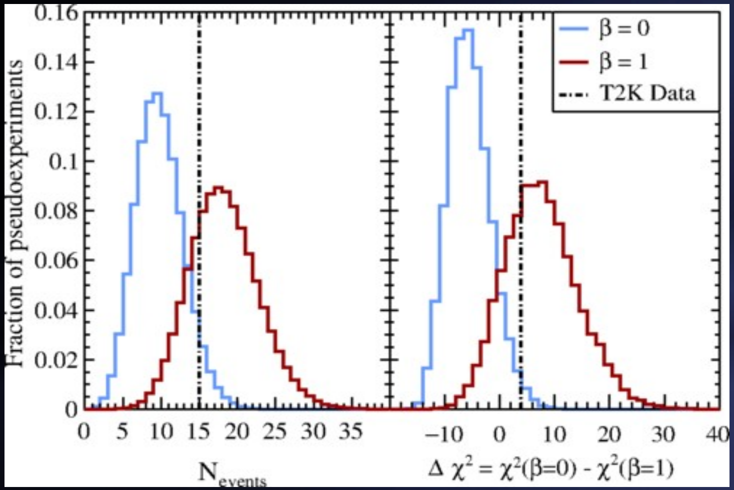
Θ_{13} measurements (appearance mode) by T2K

$\bar{\nu}_\mu$ & $\bar{\nu}_e$



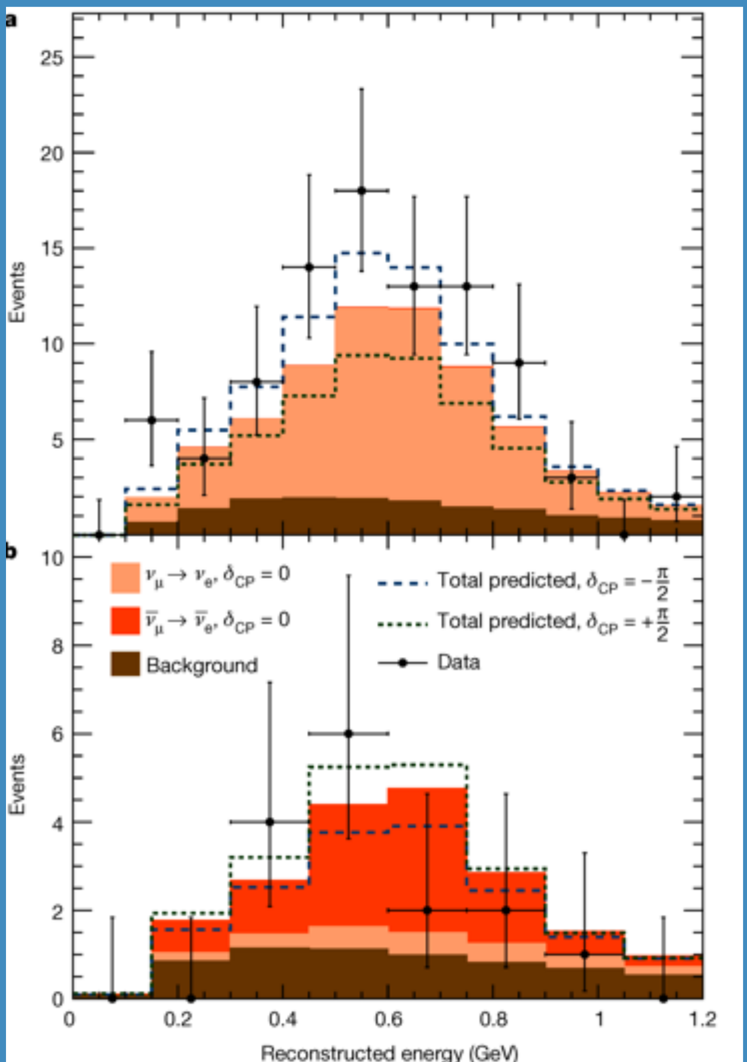
ν_μ disappearance
(best word result)





No $\bar{\nu}_e$ appearance disfavoured to 2.4σ

CP violation phase

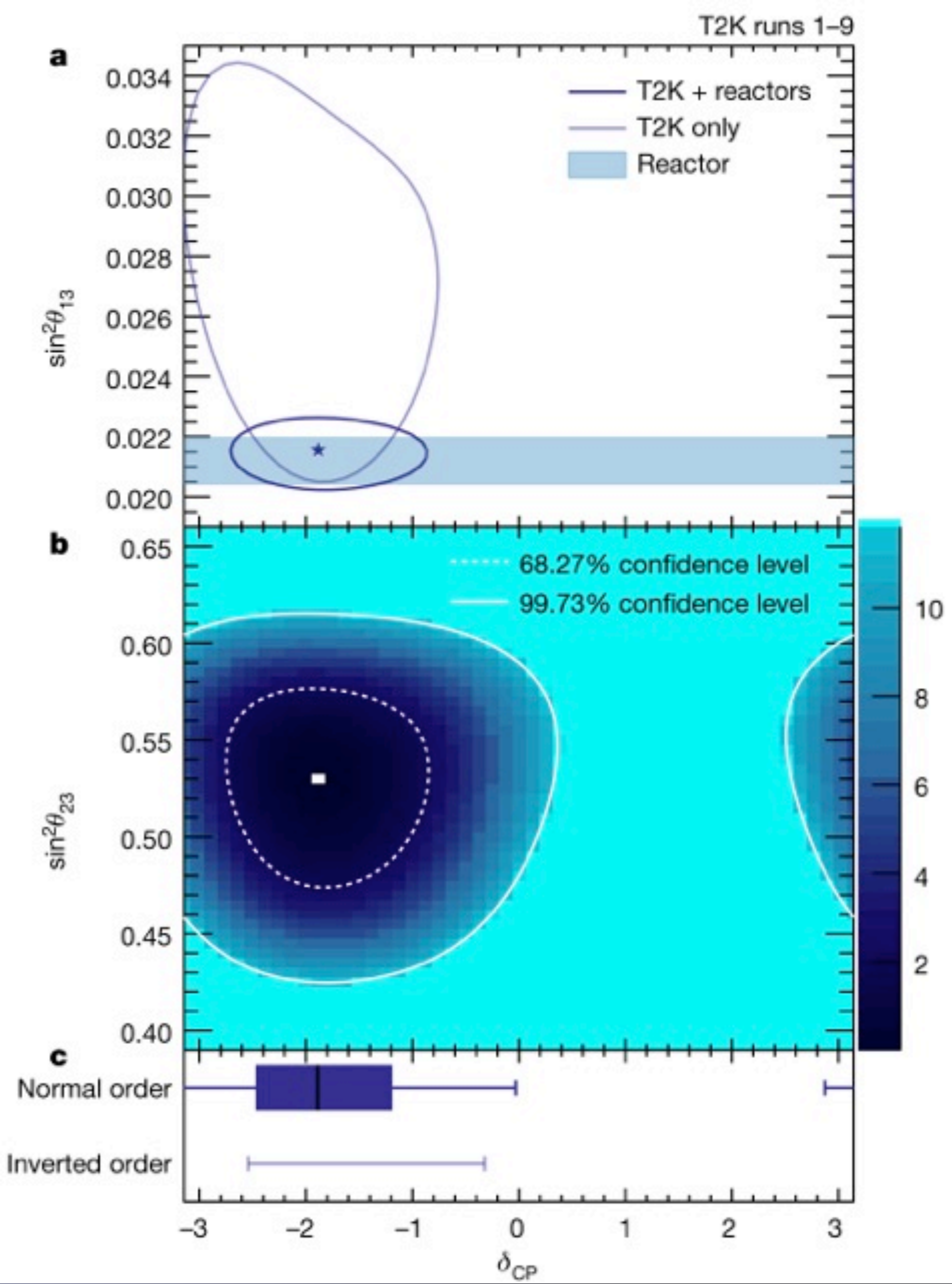


c

	1e0de ν-mode	1e0de $\bar{\nu}$-mode	1e1de ν-mode
$\nu_\mu \to \nu_e$	59.0	3.0	5.4
$\bar{\nu}_\mu \to \bar{\nu}_e$	0.4	7.5	0.0
Background	13.8	6.4	1.5
Total predicted	73.2	16.9	6.9
Systematic uncertainty	8.8%	7.1%	18.4%
Data	75	15	15

$\nu_e/\bar{\nu}_e$ Systematic Uncertainty

Type of Uncertainty	$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%
Super-K Detector Model	1.5
Pion Final State Interaction and Rescattering Model	1.6
Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
Electron Neutrino and Antineutrino Interaction Model	3.0
Nucleon Removal Energy in Interaction Model	3.7
Modeling of Neutral Current Interactions with Single γ Production	1.5
Modeling of Other Neutral Current Interactions	0.2
Total Systematic Uncertainty	6.0

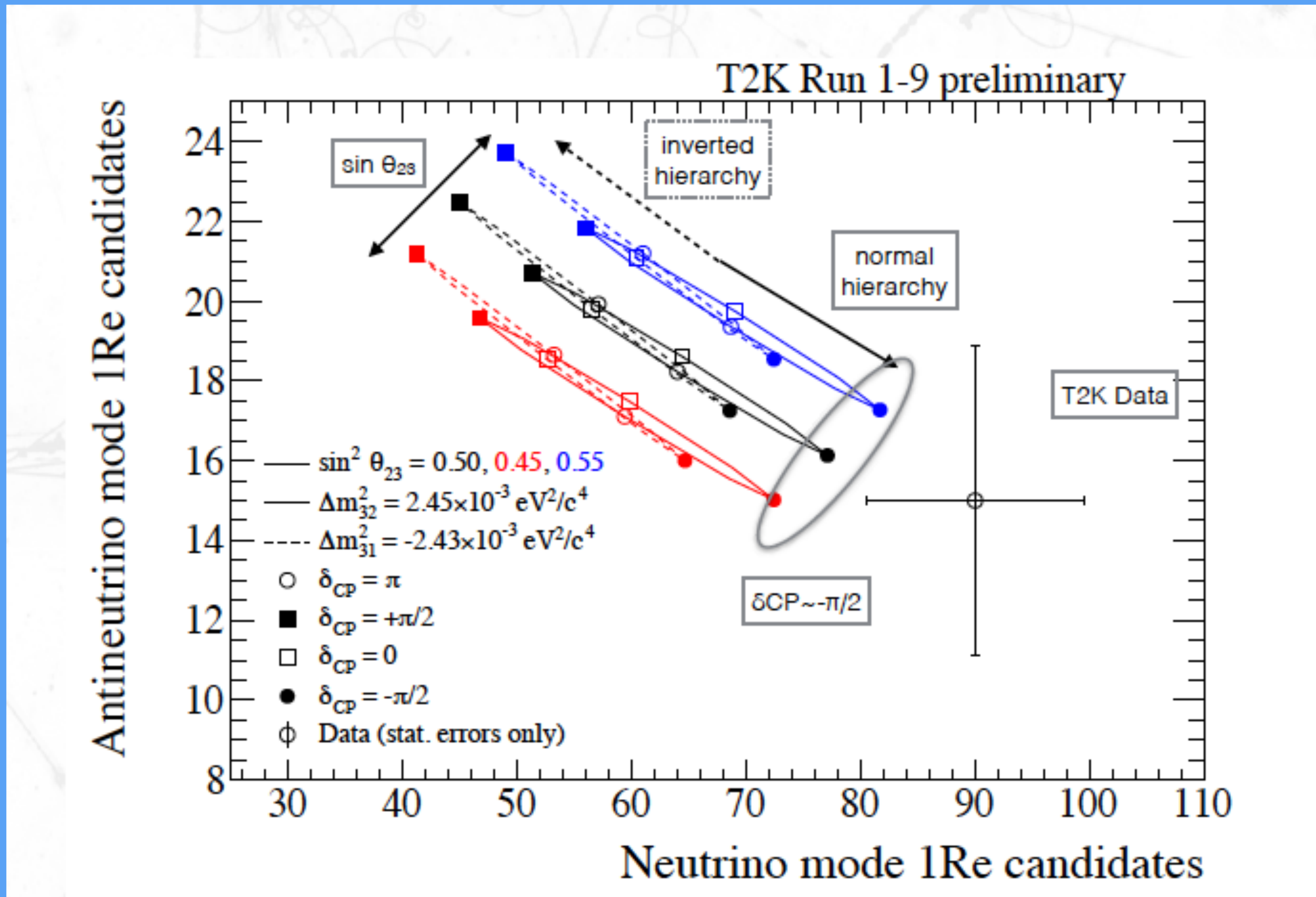


δ_{CP} measurement

Fit uses the value of θ_{13} from reactor experiments

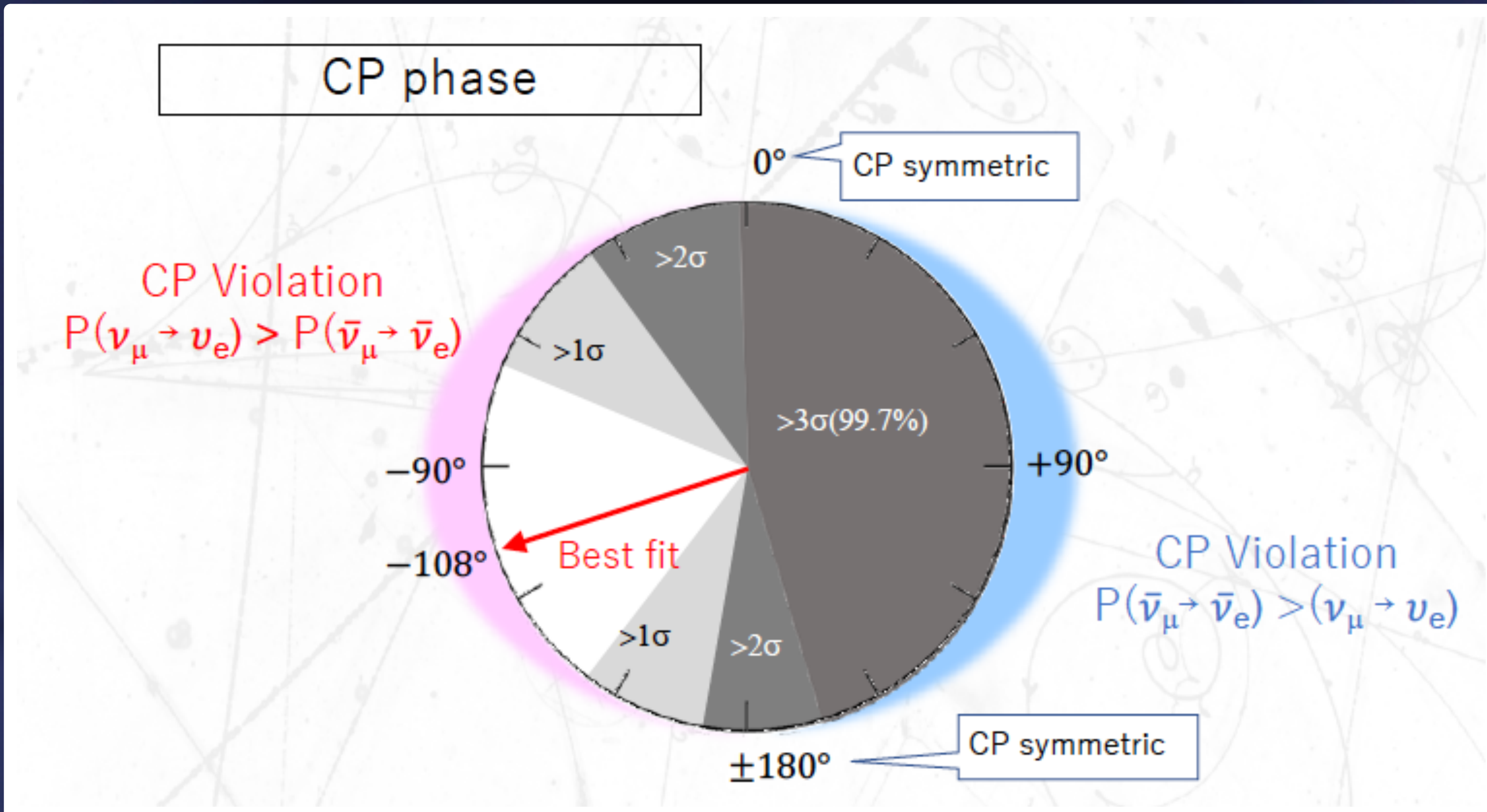
Data also prefers Normal Hierarchy with a posterior probability of 89%

CP violation phase



CP violation phase

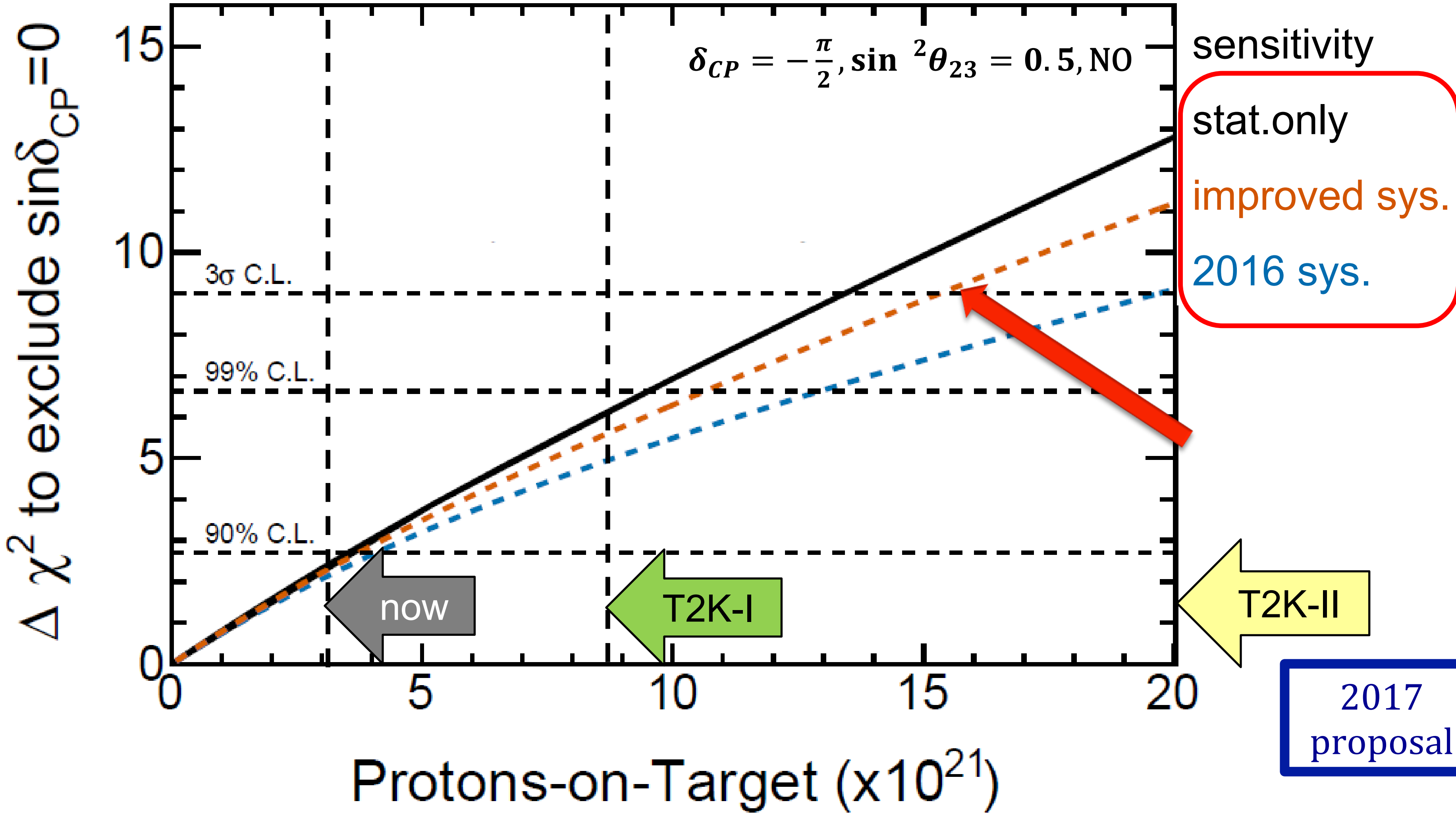
T2K result excludes most of the $\delta_{CP}>0$ values @ 99.7% CL



Technically not a *discovery* (it is not 5 sigma), but the first step in the long path towards the measurement of leptonic CP violation

* Prospects

CPV: what's next ?

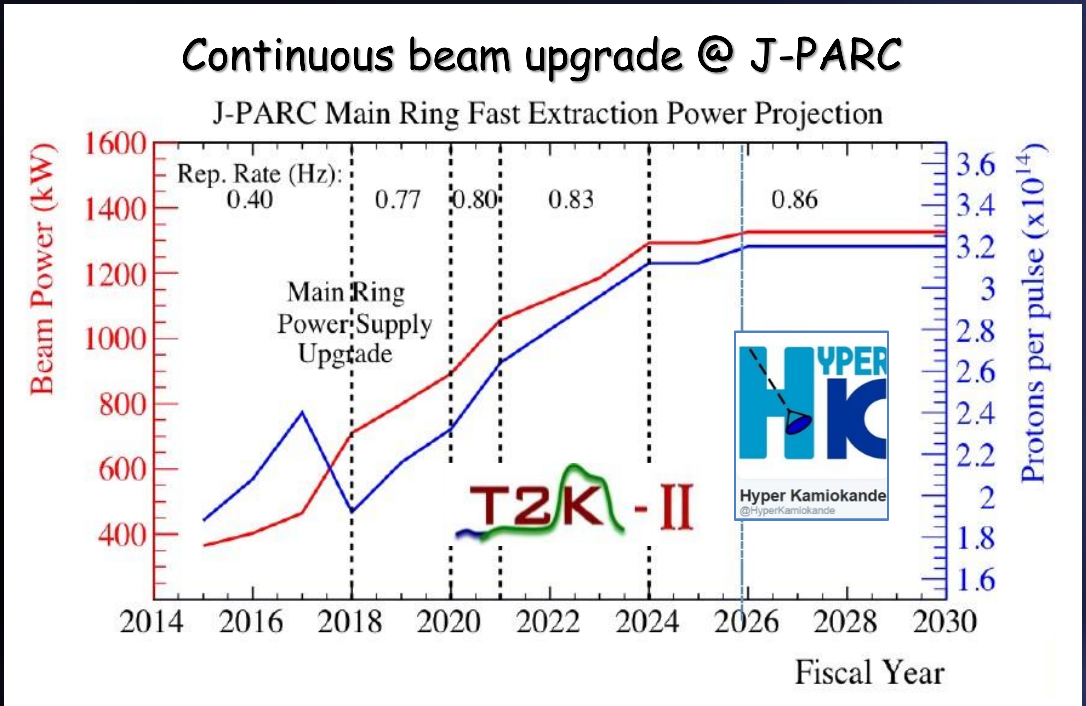


2017
proposal

Before HYPER-K/DUNE Era : 2022-2026

J-PARC neutrino beam upgrade

- Continuous upgrade of neutrino beam up to 2030
- Present beam power ~470 kW
- New MR power supply for 750kW by 2021
- Repetition rate increase to 0.86 Hz for 1.3MW by 2026

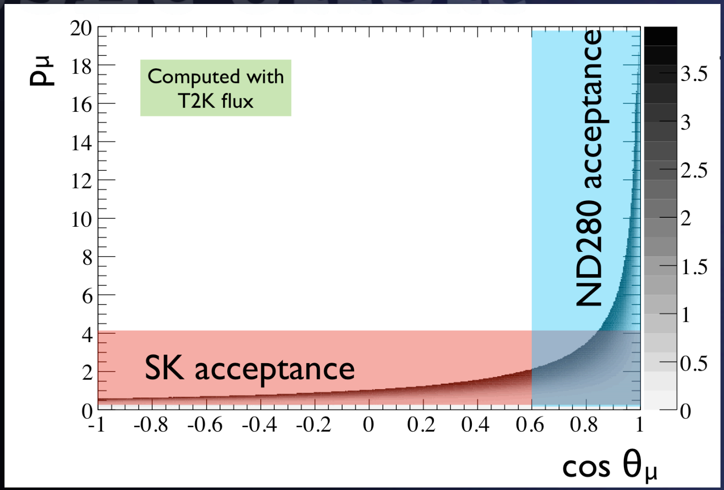


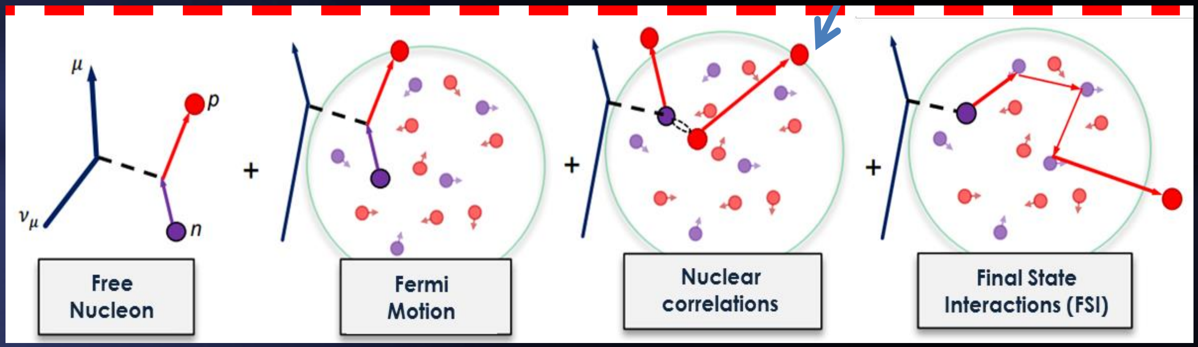
➢ J-PARC upgrade for Hyper-K is top priority in KEK Project Implementation Plan (KEK-PIP)

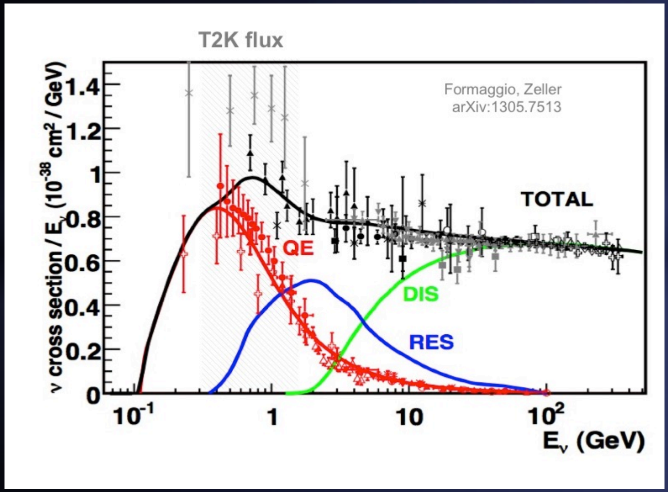
➢ Strong commitment for future neutrino program

Sources of systematic errors

- Different Acceptance Near/Far detector
- Cross sections poorly known at low energy (in particular ν_e, anti- ν_μ and ν_e/ν_μ ratio)
- Different target material Near/Far (CH/H_2O)
- Models

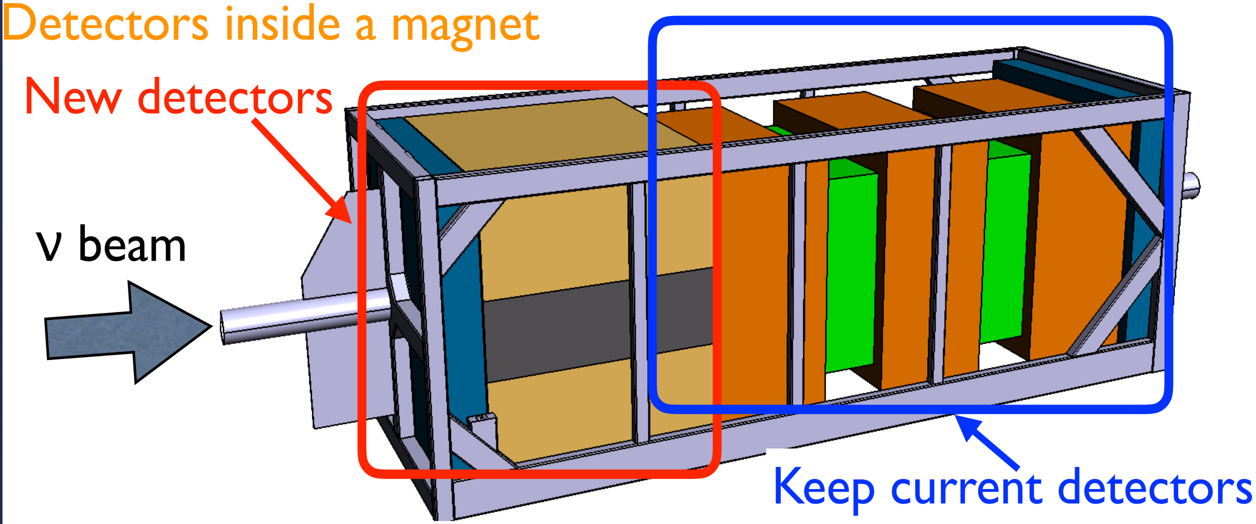




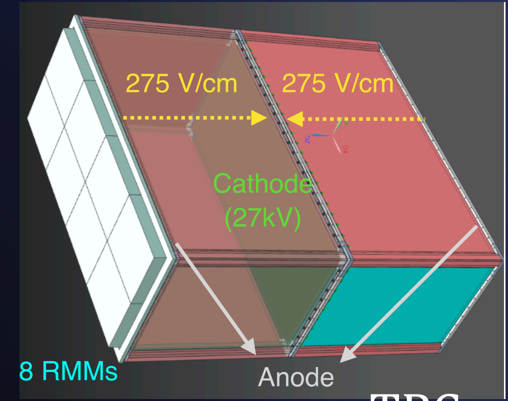


* ND280 Upgrade Project

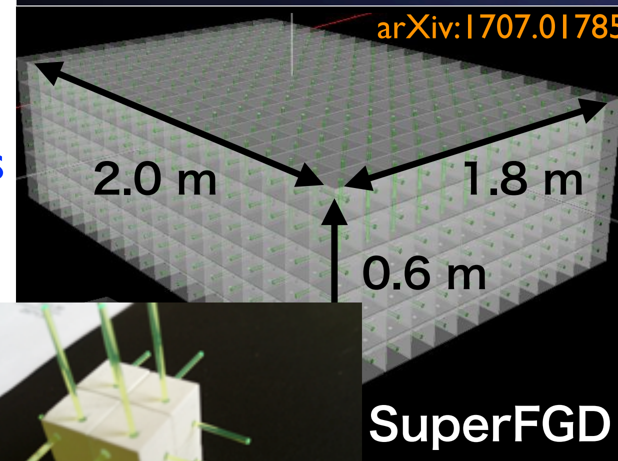
Detectors inside a magnet

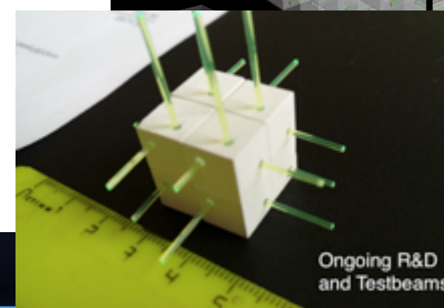


- Replace (most of) P0D with **Scintillator Detector** + 2 High-Angle TPCs + TOF
- Keep current "tracker" [2 FGDs + 3 TPCs] (& upstream part of P0D) as well as ECal, magnet & SMRD
  - For keeping continuity and forward acceptance



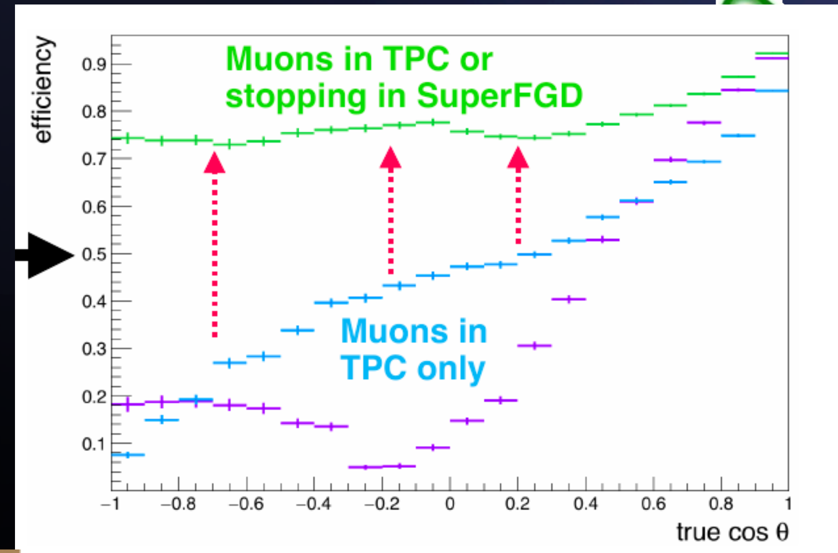
TPC

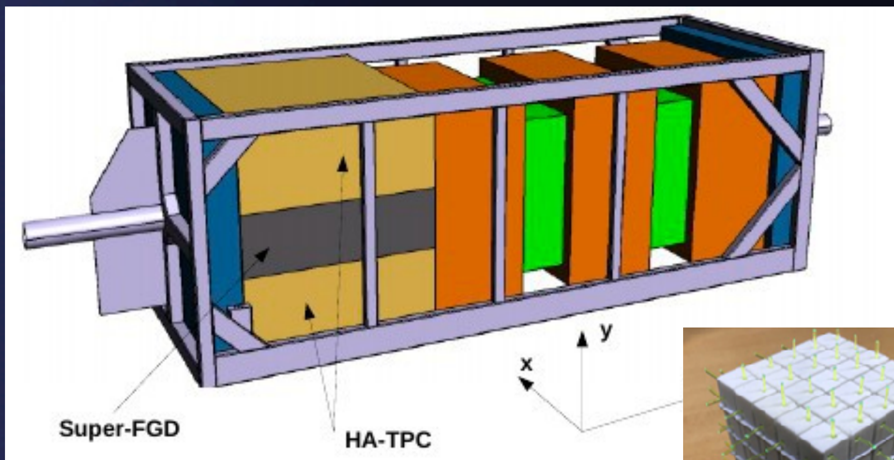


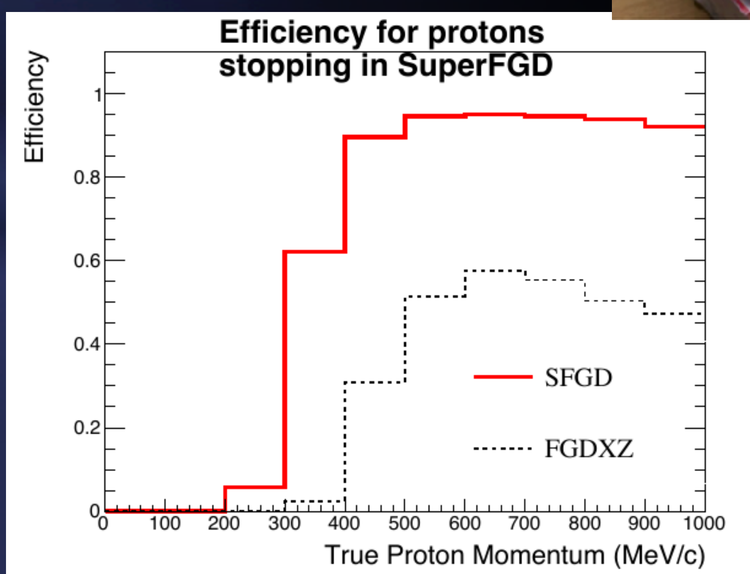


- ➢ Designed to improve systematics (from 6% => 3-4%)
- ➢ **2019-2021** Production, integration at CERN. System test (cosmics).
- ➢ **2021-22** Shipment to Japan, installation, commissioning.

*ND280 upgrade



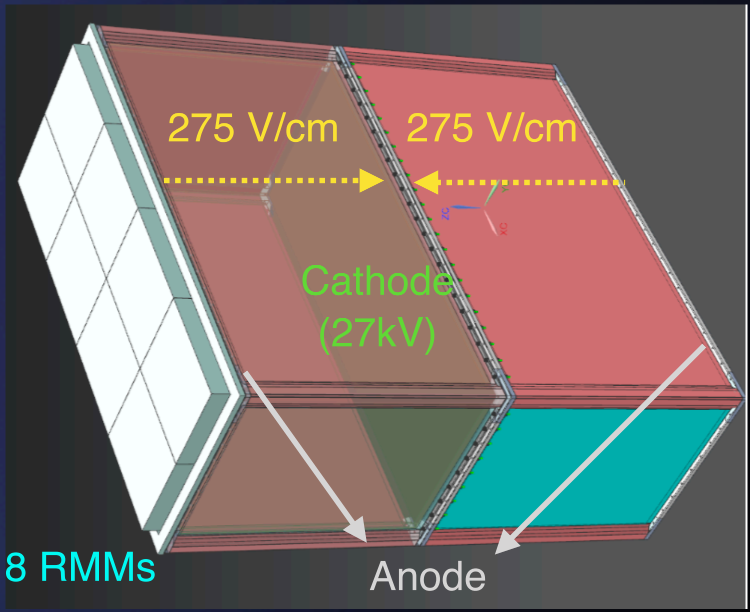




ND280 upgrade goals

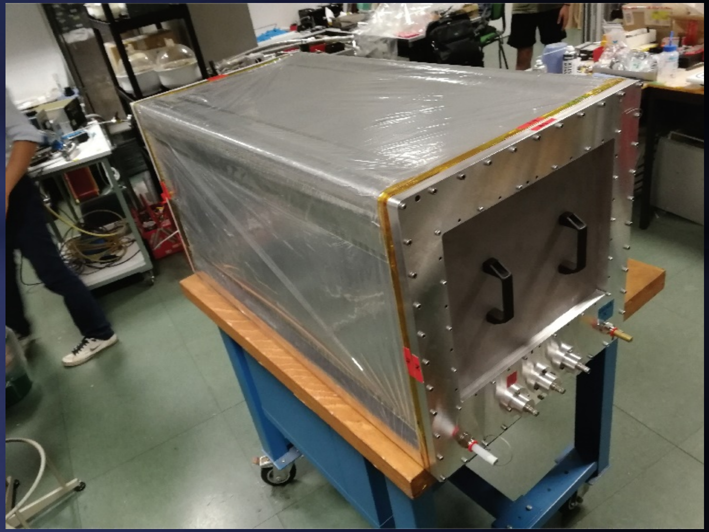
- quasi-3D imaging.
  - Improved target tracking.
  - Improved proton detection threshold.
  - neutron detection capabilities
- Improved high angle acceptance:
  - High Angle TPC's.
- x 2 in statistics for equal p.o.t.
- Time of Flight for background reduction.

INFN Contribution to T2K-II & beyond

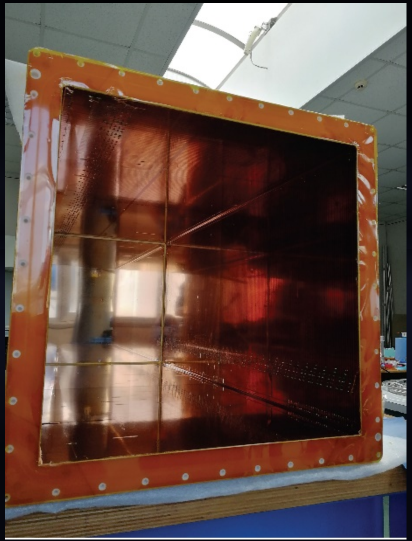


INFN Role in T2K-II

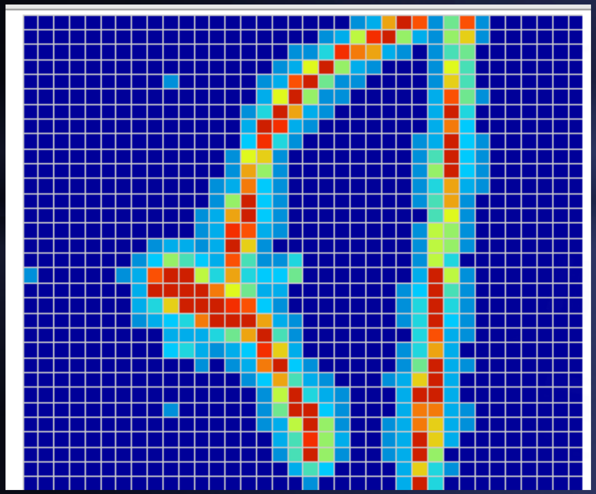
- ✓ Coordination of the TPC Project
- ✓ Field Cages construction (2018-2021)
  (0.5 MEur investment)
- ✓ ND280 Installation, maintenance & operation (2022 & beyond)
- ✓ <u>We are interested in future ND280 upgrades for HK</u>



TPC prototype

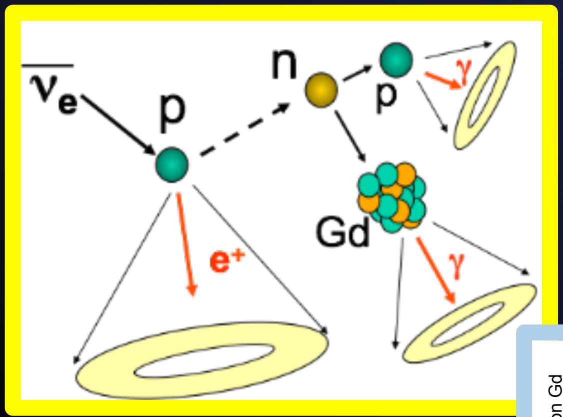


MM

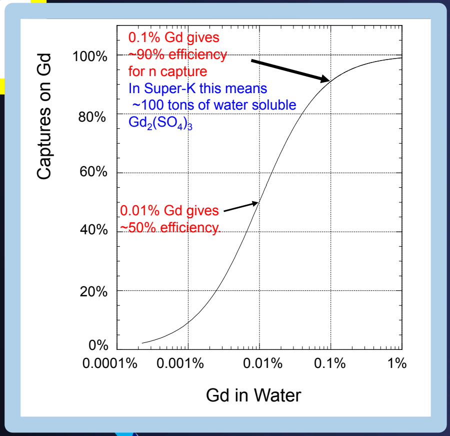


Test-Beam event

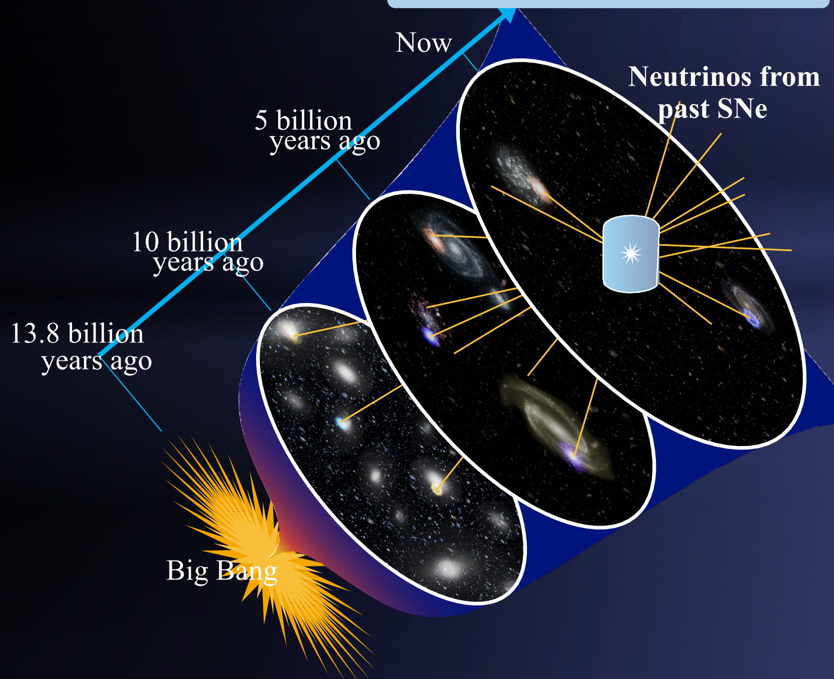
SK-V with Gd



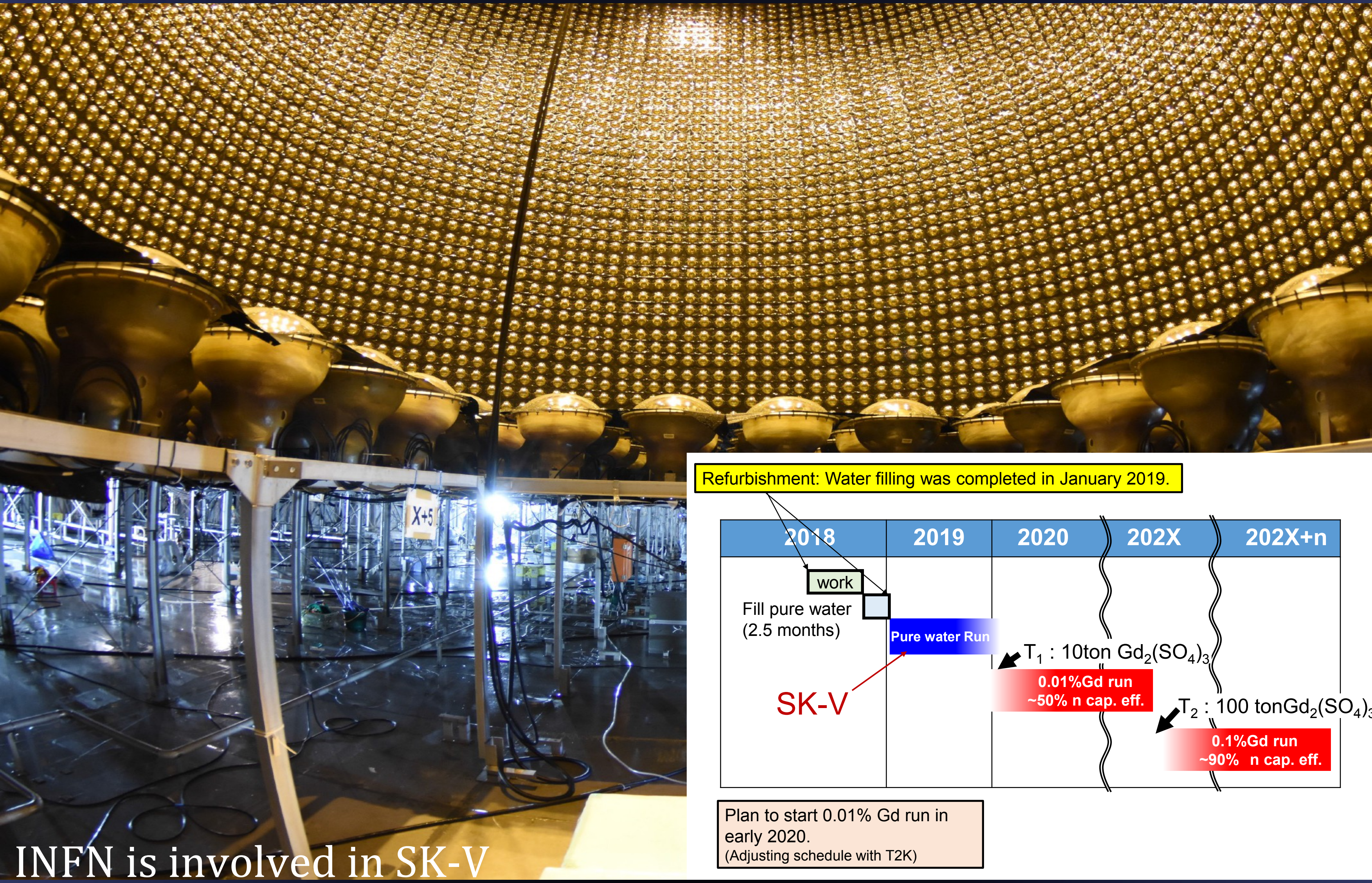
ΔT~30μs, Vertices within 50cm



- Loading Gd to Super-K (SK-Gd) to significantly enhance neutron detection capabilities.
- Aiming for the first detection of Supernova Relic Neutrinos (SRNs)
- Also aiming for many new measurements with T2K beam:
  - Neutron multiplicity and kinematics measurements from neutrino interactions
  - Improved oscillation measurements with neutrino-antineutrino separation and further background rejection
  - Non-standard oscillation searches with additional Neutral-Current samples with neutrons



SK-V with GD

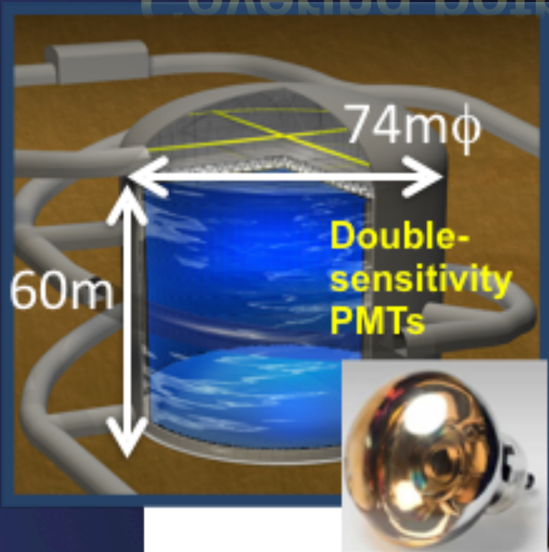


INFN is involved in SK-V

* Looking forward ….

Hyper-Kamiokande project

Covering both accelerator and non-accelerator physics



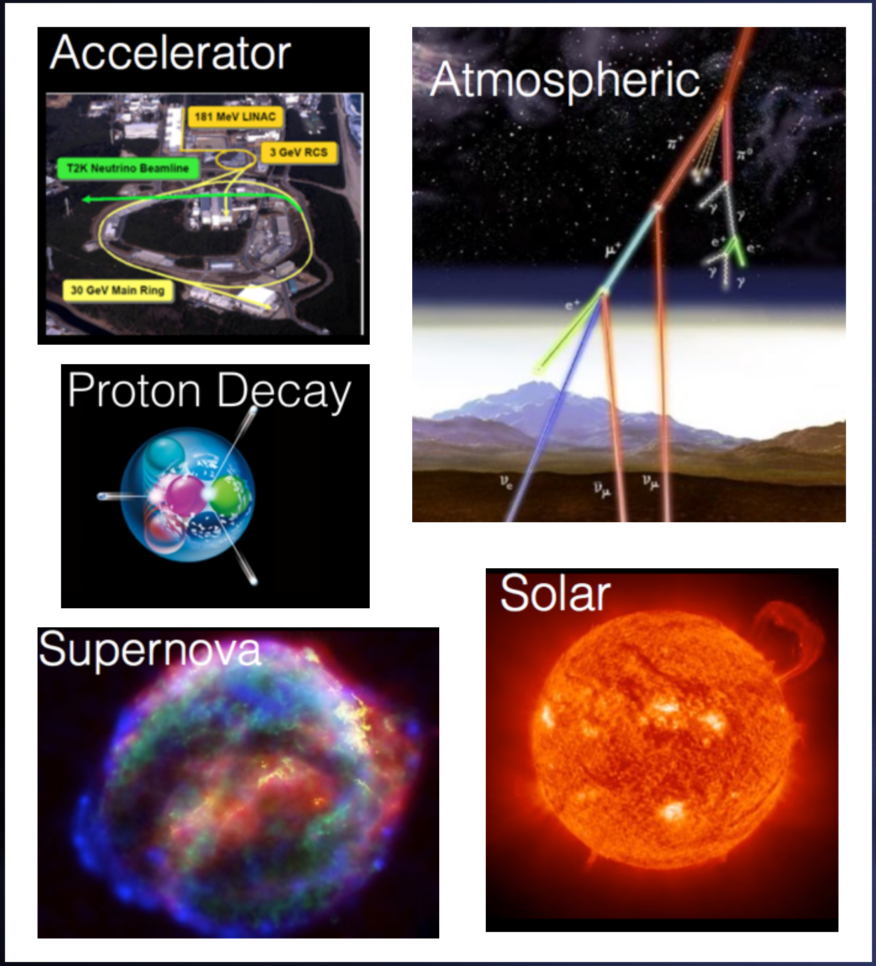
	Super-K	Hyper-K (1st tank)
Site (depth)	Mozumi (1000 m)	Tochibora (650 m)
Number of ID PMTs	**11,129**	**40,000**
Photo-coverage	40%	40% (**×2 sensitivity**)
Mass / Fiducial Mass	50 kton / **22.5 kton**	260 kton / **188 kton**

Design Report arXiv: 1805.04163

1. Hyper-K detector with **8.4 times larger fiducial mass** (190 kiloton) than Super-K and using **double-sensitivity PMTs**
2. J-PARC neutrino beam to be upgraded from 0.5 to **1.3 Mega Watt**
3. New and upgraded **Near Detectors** to control systematic errors

Hyper-K: a multi pourpose Experiment

- **Neutrino oscillation physics**
  - CP violation
  - Θ_{23} octant determination
  - Mass hierarchy with beam and atmospheric ν's
- **Nucleon decay discovery potential**
  - Possible discovery with ~×10 better sensitivity than Super-K
- **Neutrino astrophysics**
  - Precision measurements of solar ν
  - High statistics measurements of SN burst ν
  - Detection and study of relic SN neutrinos
- **Unexpected….**

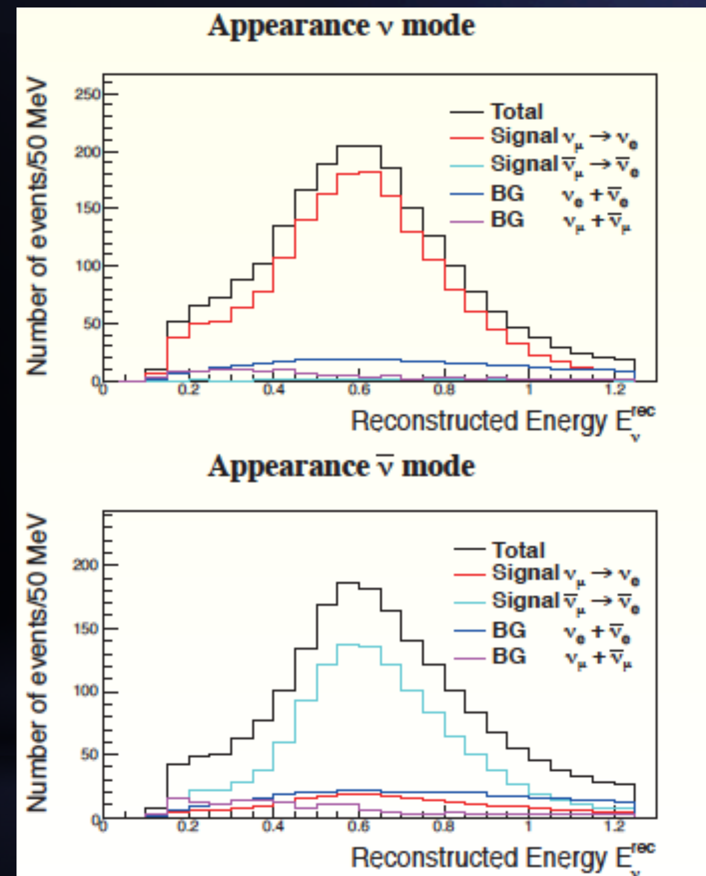


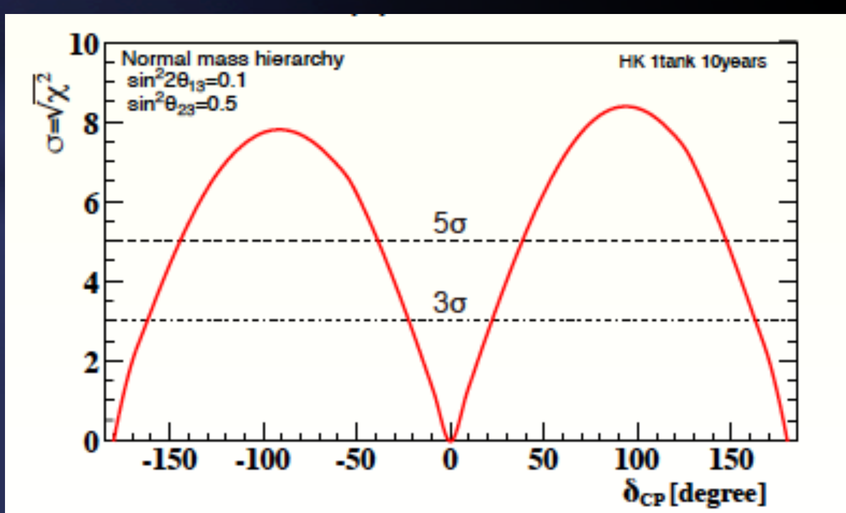
Extend highly successful program of Super-K

Physics with J-PARC neutrino beam

1.3MW×10years(10^8s)

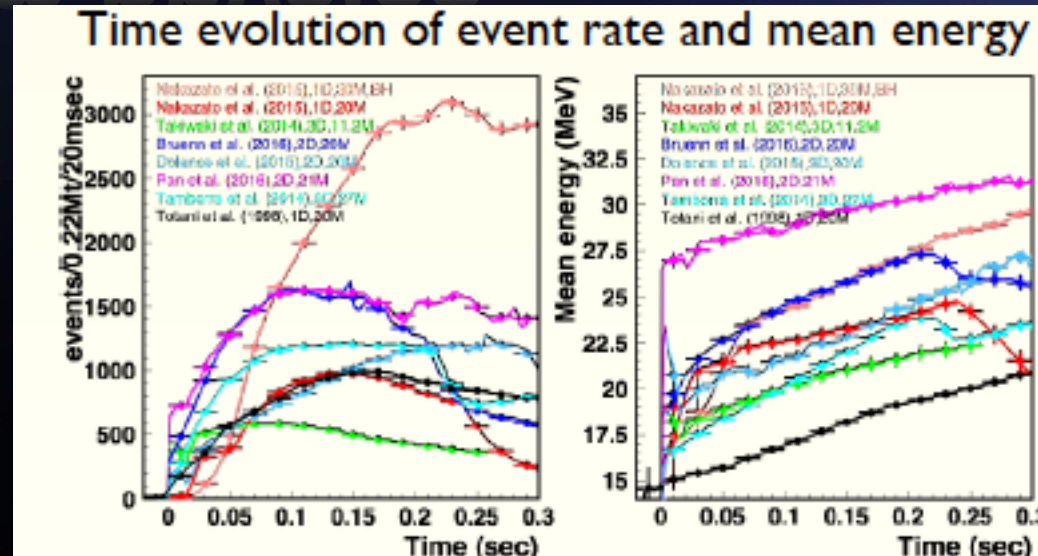
- Reliable sensitivity estimate based on T2K Experience directly applicable
- 1,000-2,000 events for both of ν_e and $\bar{\nu}_e$
- appearance
- cf. current T2K: 90 and 15 events Firm discovery and measurement of CP violation in neutrino oscillation
- Precision disappearance measurements

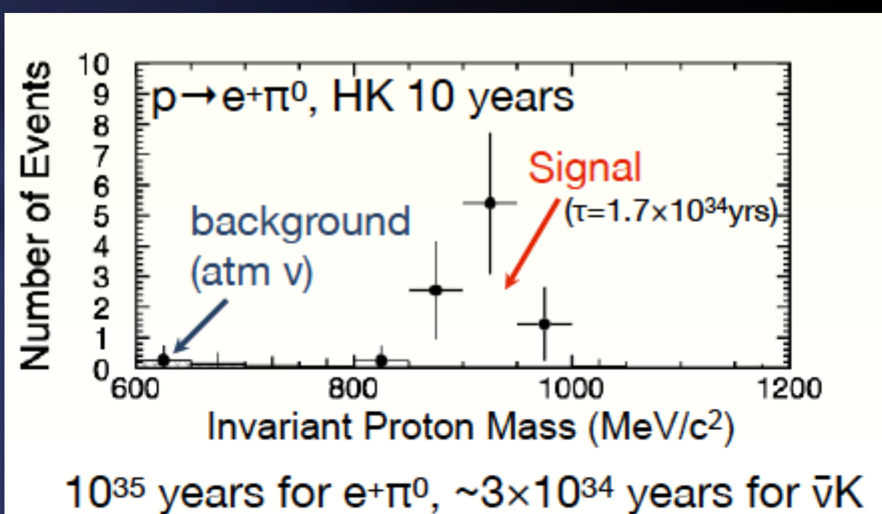


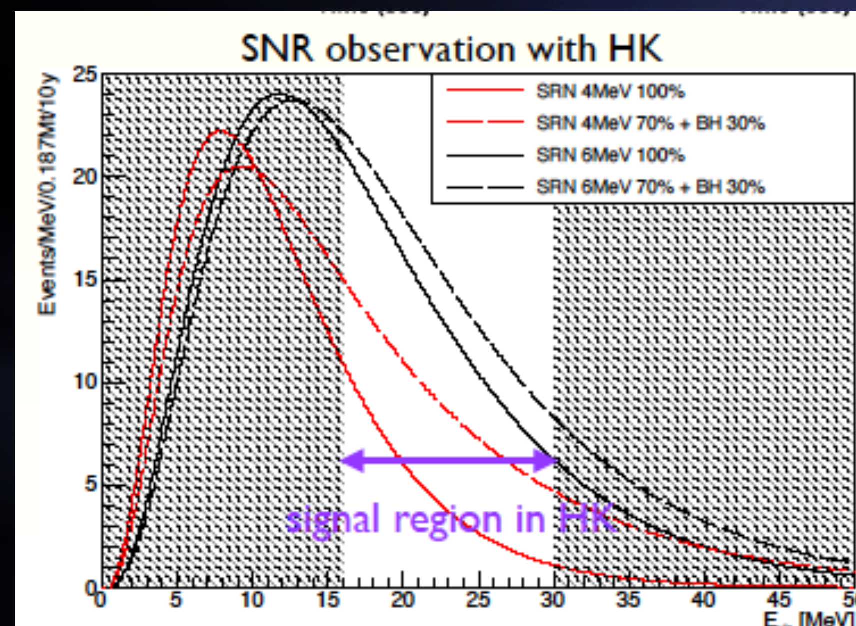


* Non-beam physics

* Very broad science targets!
* Nucleon decay searches
* Atmospheric neutrinos
* Solar neutrinos
* Supernova neutrinos
* Indirect dark matter search
* …



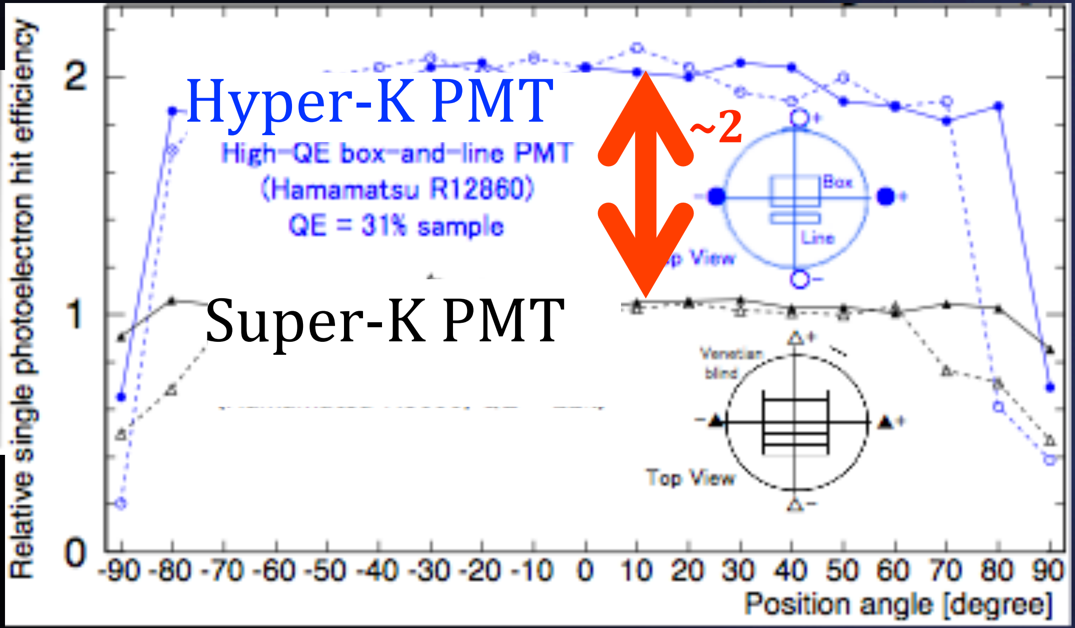




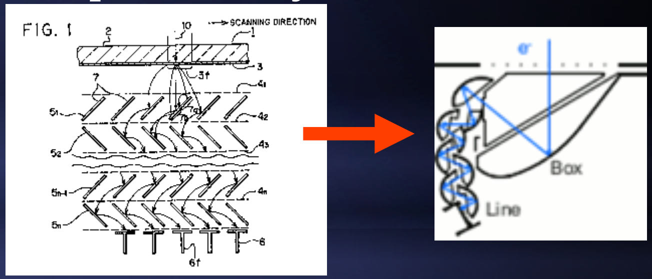
Newly developed 50cm PMT

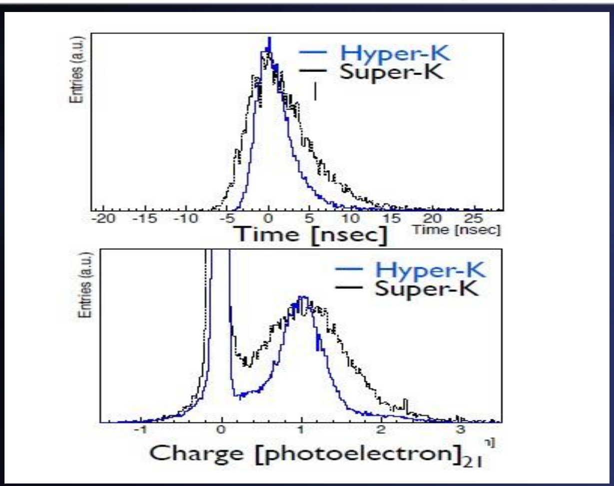
Super-K PMT

New PMT



Improved dynode

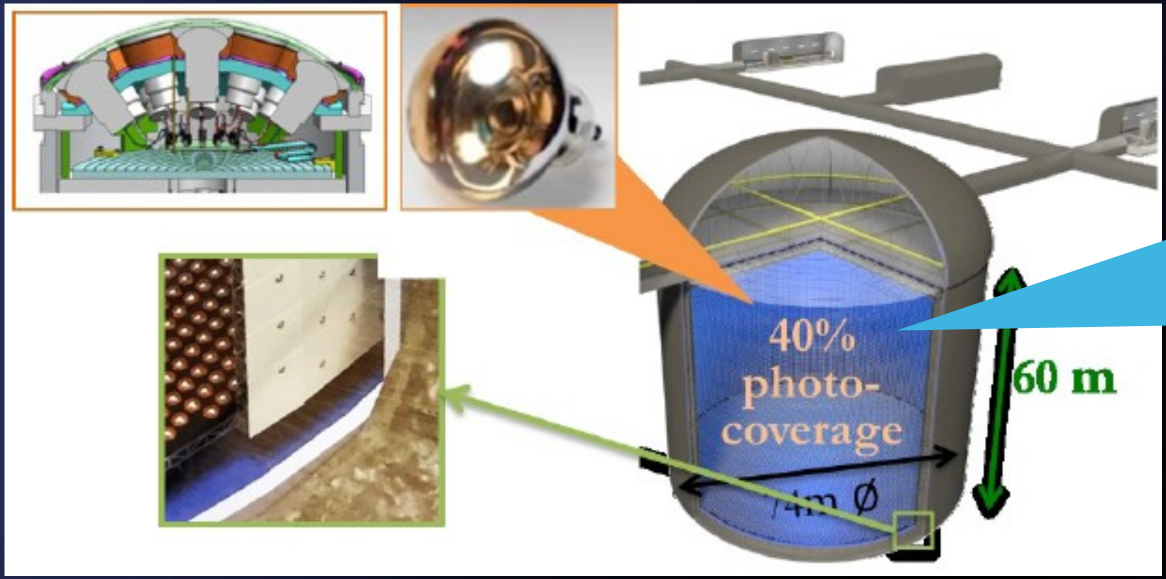


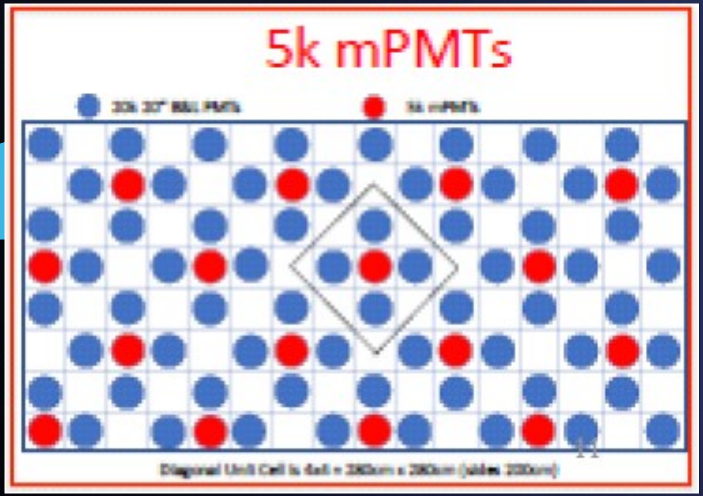


- ×2 better photon efficiency and timing resolution
  - Enhance physics potential (neutron tagging, low energy events)
- Higher pressure tolerance (> 80m)

* HYPER-K DETECTOR: HYBRID PMT CONFIGURATION

- Possible hybrid configuration with 20k 20"PMTs and 5k mPMTs

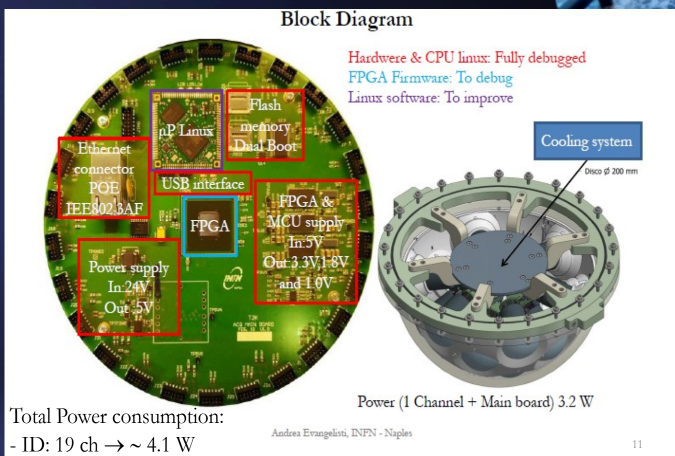


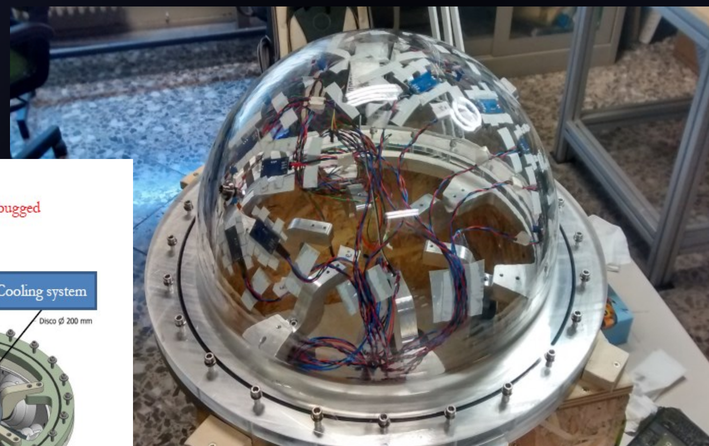


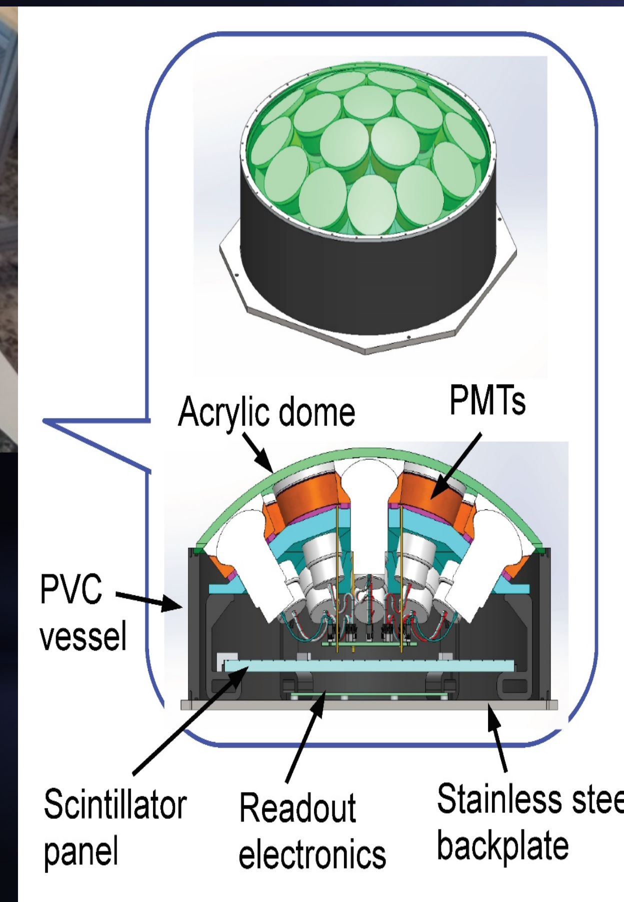
- **Complement 20" PMTs:**
- Max number of mPMTs limited by the production sites.
- Better directionality, granularity and timing resolution , less magnetic field sensitivity, pressure tolerance

Multi PMT Modules

- Derived from KM3NET mPMTs. ~5,000 mPMTs are now included in the HK baseline design.
- Proposed and designed by the Italian groups



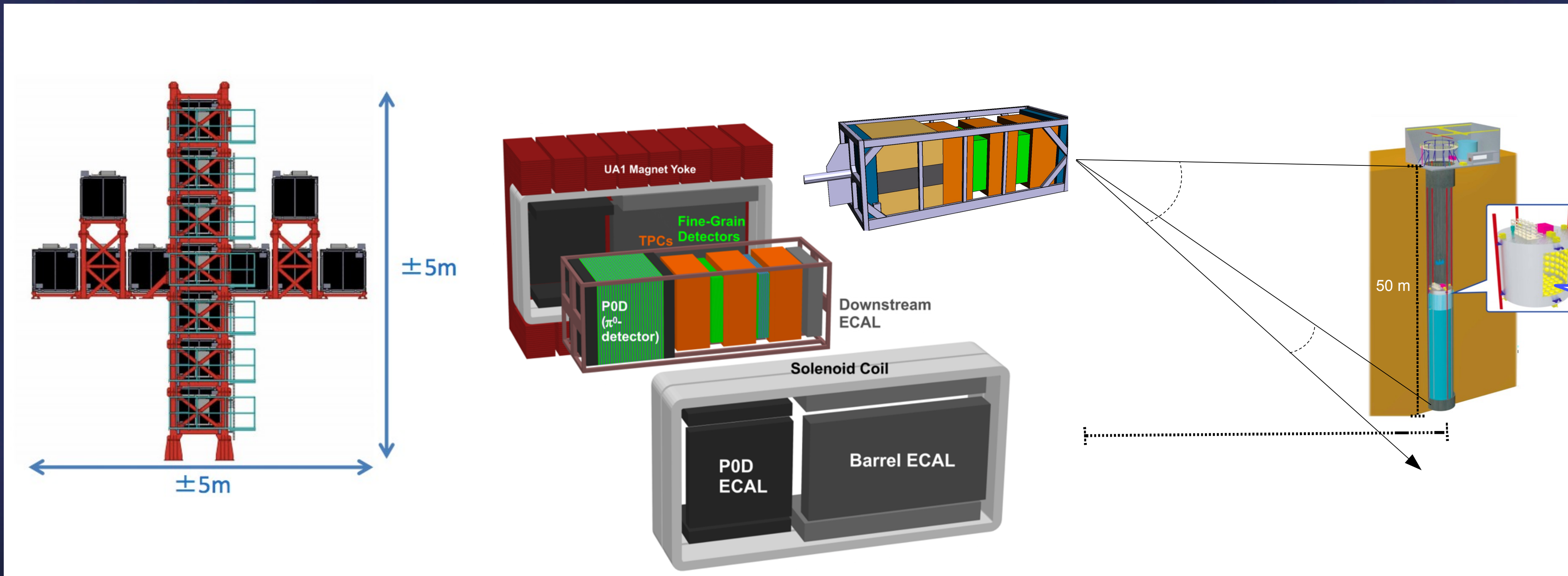




19 x 3" PMTs + reflectors

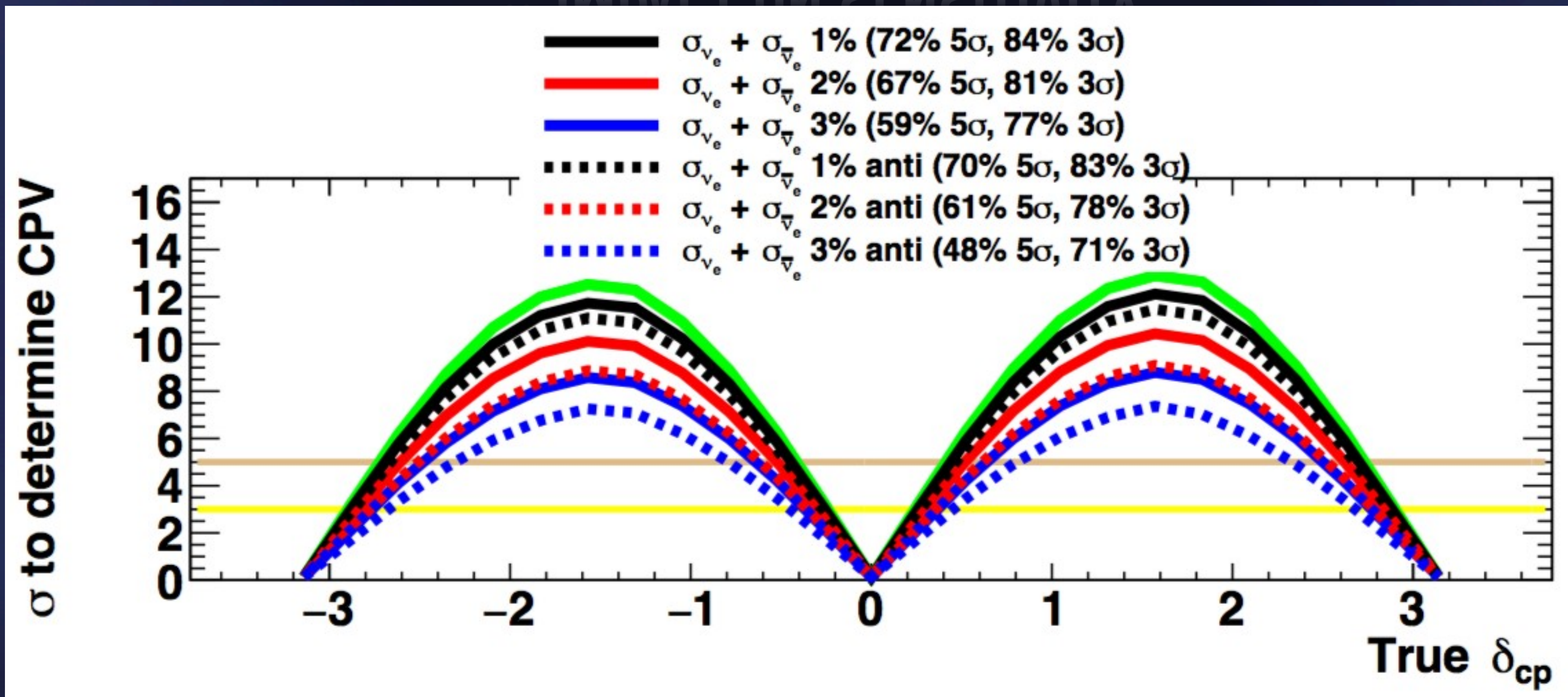
- ✓ 3" PMTs are Hamamatsu R14374 (or ETEL D794KFL or HZC XP82B20)
- ✓ Improved timing, spatial accuracy, dynamic range, lower dark rate with +HV

Near Detectors for Hyper-K



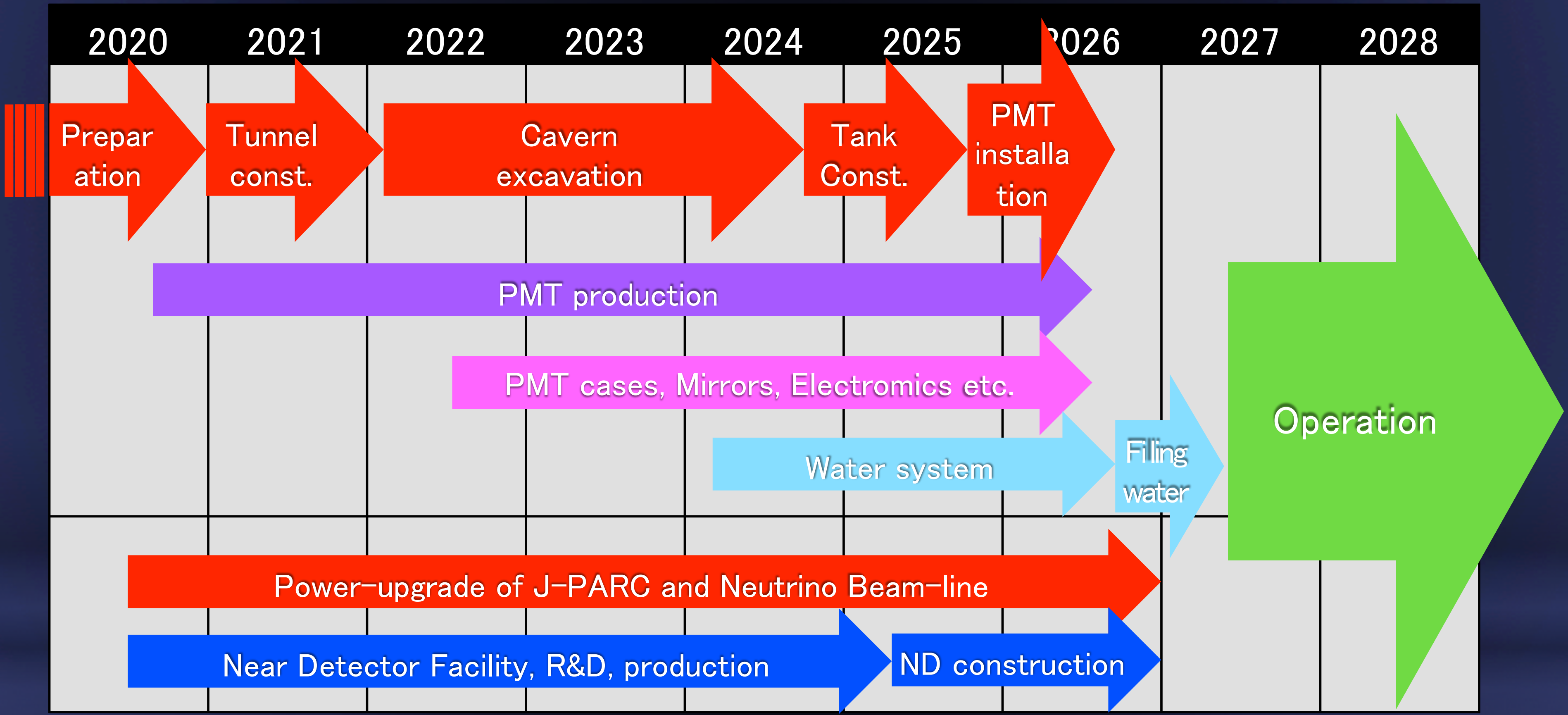
- Upgrade of existing (T2K) detectors + new IWCD
- Started discussion of possible INGRID/ND280 upgrade for HK
- Keeping ND280 infrastructure for HK era is already a big challenge…

* IMPACT ON SENSITIVITY



- To achieve 5σ for ~60% of δ_{cp} need **4% error on relative cross section**
- Other sources may introduce error on th[redacted]nmetry
  - Expect signal cross section error to d[redacted]ate budget
  - Keep other sources to the 1% level is possible

Project timeline



Hyper-K was approved in 2019

Construction from 2020 → Operation from 2027

Hyper-K vs Dune

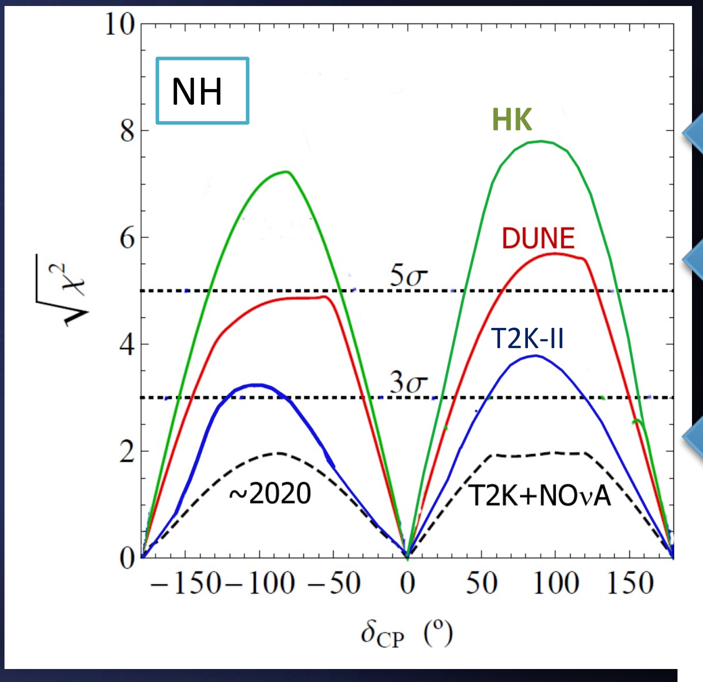
Experiment	Status	E_ν (GeV)	L (Km)	E/L (eV^2)	ν beam	ν type
DUNE 40KT Liquid Argon	Future (2026)	5	1300	$3.8x10^{-3}$	Fermilab newbeam	ν_μ /anti-ν_μ
HYPERK 190KT WC	Future (2026-27)	0.6	295	$2x10^{-3}$	KEK J-PARC (improved)	ν_μ /anti-ν_μ

Matter effects are large (big sensitivity on MO), all the neutrino interaction modes contribute (quasi-elastic, resonances, deep-inelastic).
The Liquid Argon far detectors can precisely reconstruct the event energy for all the topologies

Matter effects are small (optimized for CP), neutrino interaction are mostly quasi-elastic.
The water Cherenkov far detector can precisely reconstruct quasi-elastics and is very massive.

Great complementarity also in many astrophysics measurements

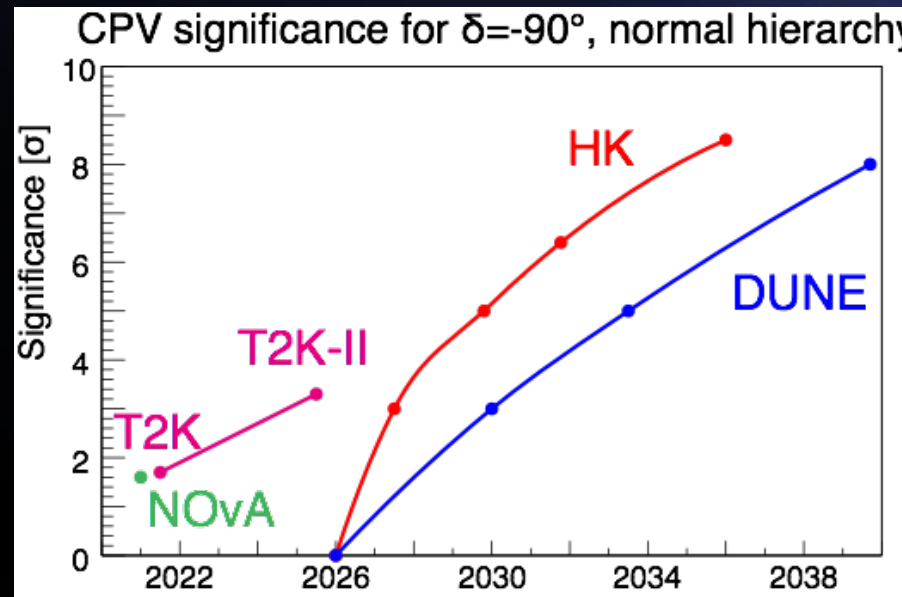
* In short ....



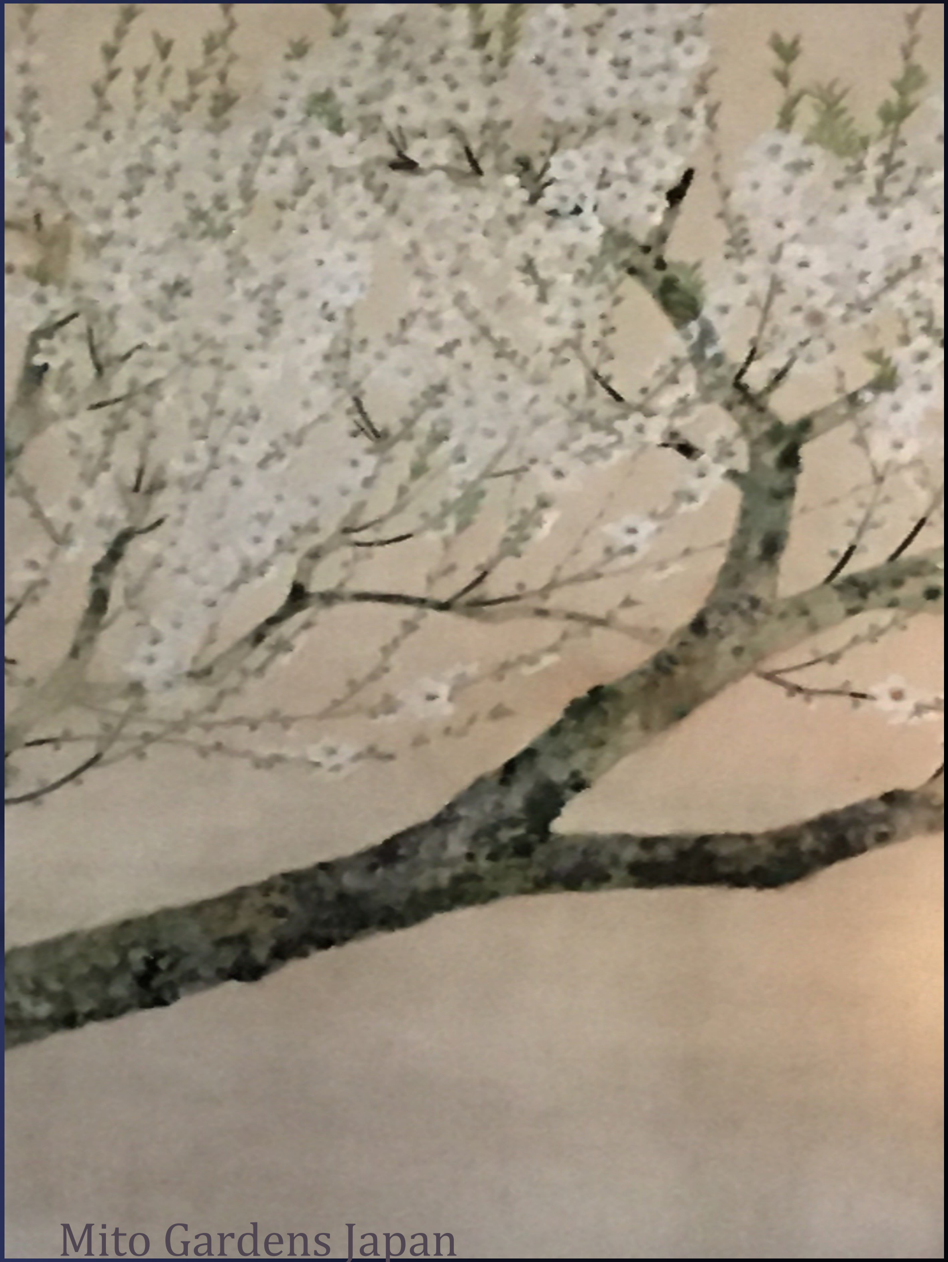
203X

2026-7

2022



**HyperK 10 y, Dune 7y full conf.



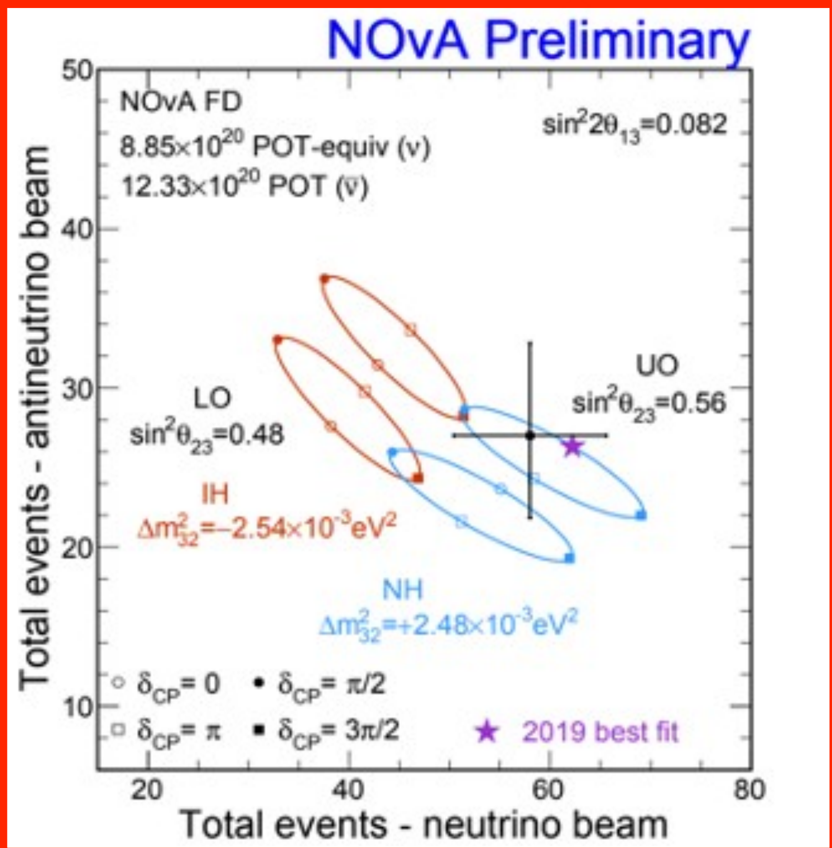
Thanks !

Backup

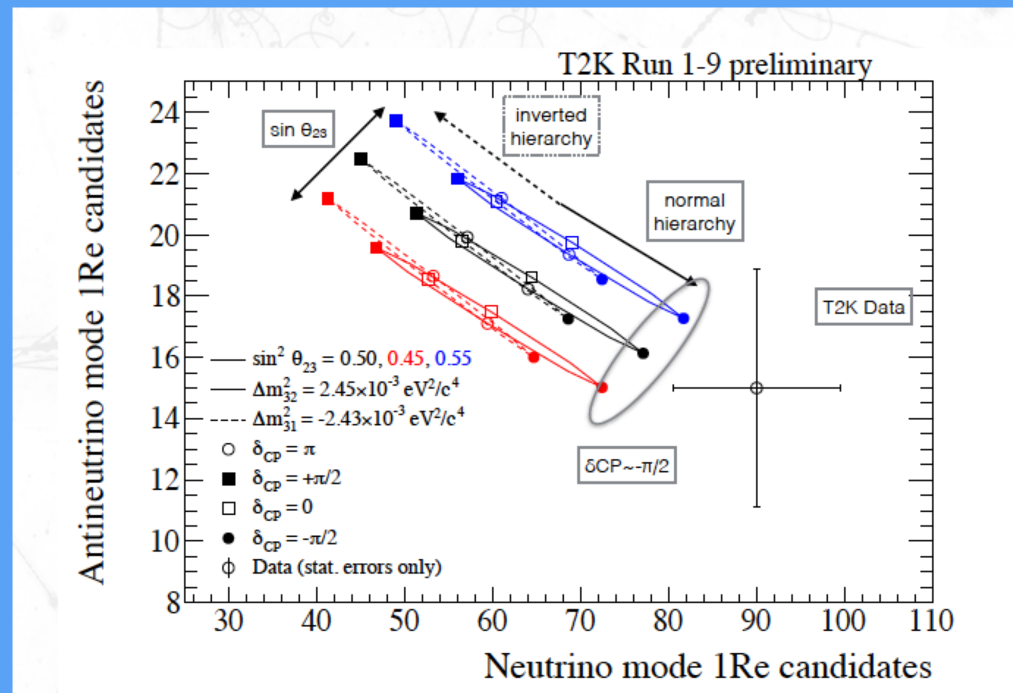
SK Data

	Predicted rates				Observed
Sample	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	**Events**
CCQE 1-Ring e-like ν	74.46	62.26	50.59	62.78	75
CCQE 1-Ring mu-like ν	272.34	271.97	272.30	272.74	243
CC1pi 1-Ring e-like ν	7.02	6.10	4.94	5.87	15
CCQE 1-Ring e-like anti-ν	17.15	19.57	21.75	19.33	15
CCQE 1-Ring mu-like anti-ν	139.47	139.12	139.47	139.82	140

*Noγa vs T2K

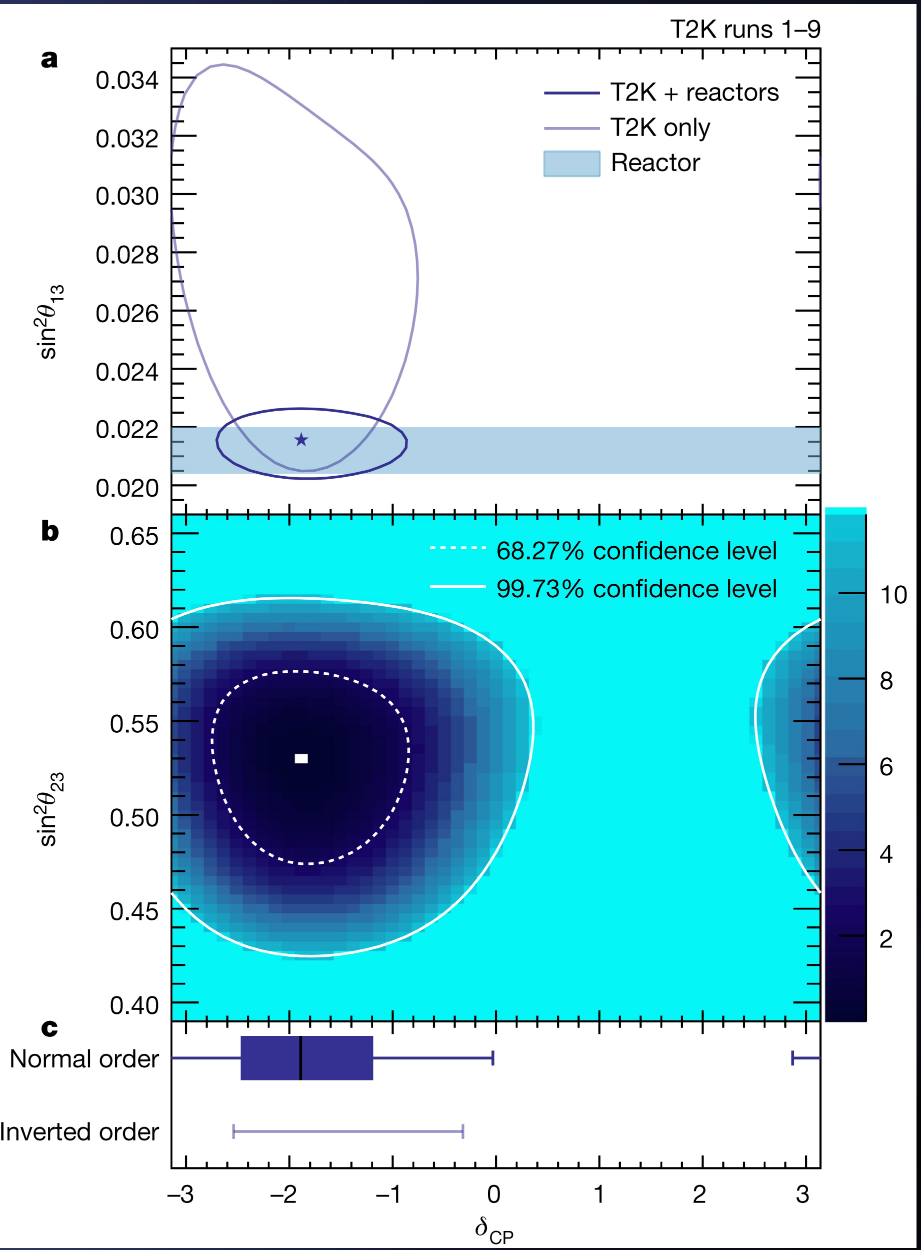


NOvA Preliminary
NOvA FD
8.85×10^20 POT-equiv (ν)
12.33×10^20 POT (ν̄)
sin²2θ13=0.082
UO
sin²θ23=0.56
LO
sin²θ23=0.48
IH
Δm²32=−2.54×10⁻³eV²
NH
Δm²32=+2.48×10⁻³eV²
δCP= 0
δCP= π/2
δCP= π
δCP= 3π/2
2019 best fit
Total events - antineutrino beam
Total events - neutrino beam

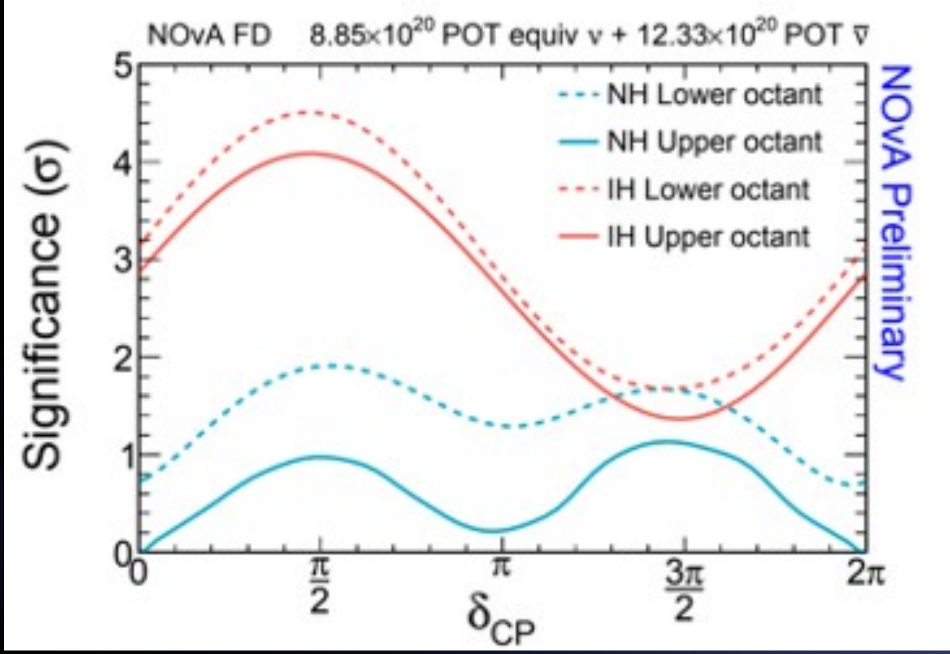


T2K Run 1-9 preliminary
sin θ23
inverted hierarchy
normal hierarchy
T2K Data
δCP~-π/2
sin² θ23 = 0.50, 0.45, 0.55
Δm²32 = 2.45×10⁻³ eV²/c⁴
Δm²31 = -2.43×10⁻³ eV²/c⁴
δCP = π
δCP = +π/2
δCP = 0
δCP = -π/2
Data (stat. errors only)
Antineutrino mode 1Re candidates
Neutrino mode 1Re candidates

*Noνa vs T2K



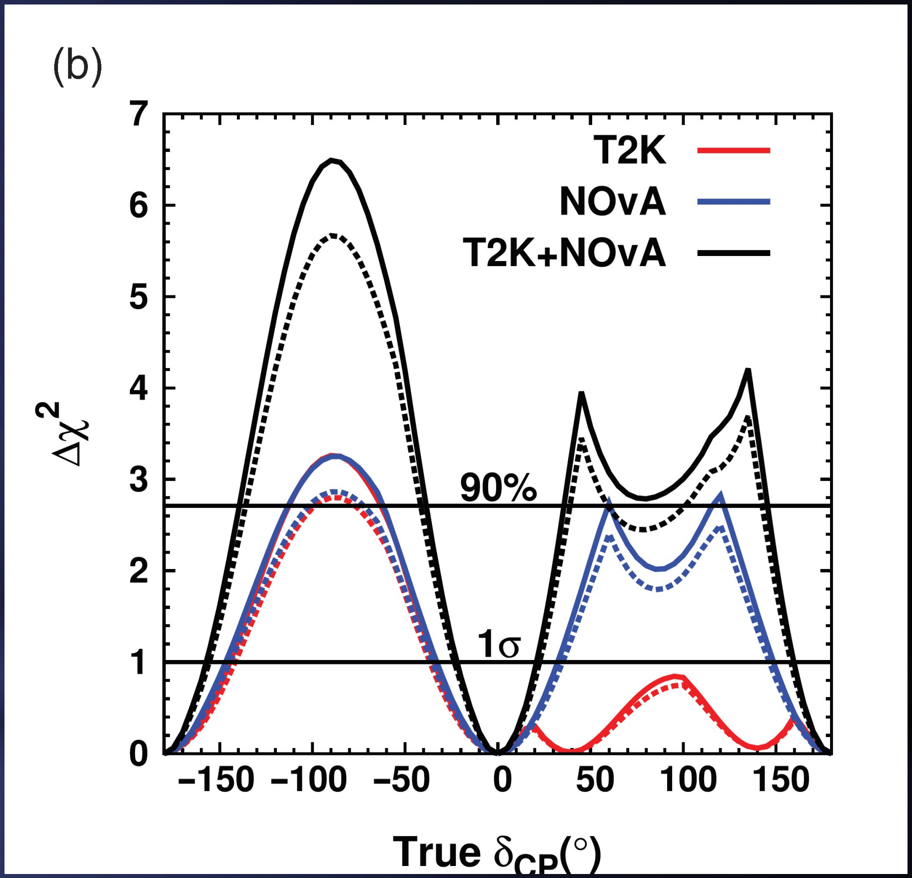
T2K runs 1–9
a
T2K + reactors
T2K only
Reactor
$\sin^2\theta_{13}$
b
68.27% confidence level
99.73% confidence level
$\sin^2\theta_{23}$
c
Normal order
Inverted order
δ_{CP}



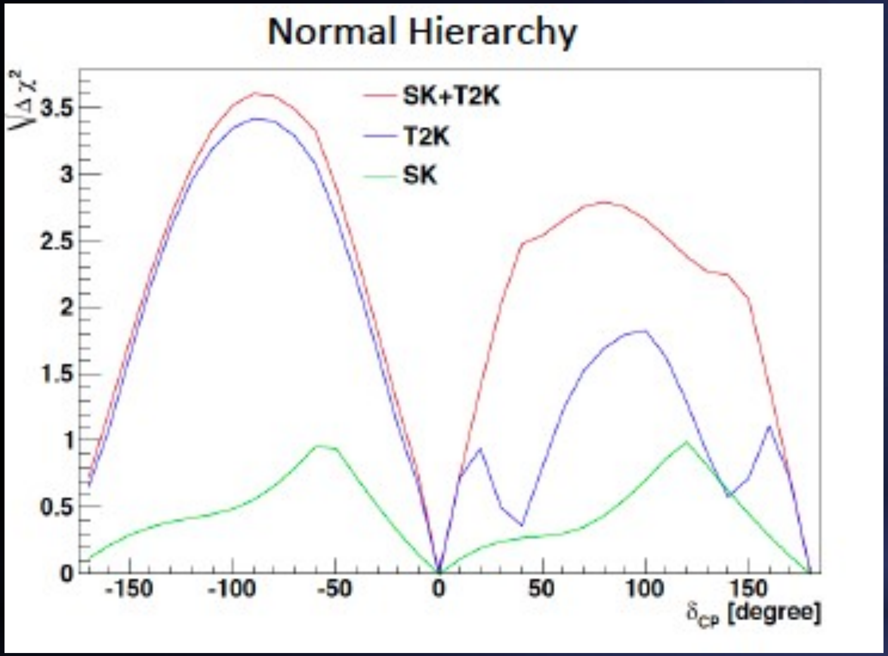
NOvA FD 8.85×10^20 POT equiv ν + 12.33×10^20 POT ν̄
NH Lower octant
NH Upper octant
IH Lower octant
IH Upper octant
NOvA Preliminary
Significance (σ)
δ_{CP}

*Combined analysis

Sensitivity T2K+Nova



Sensitivity T2K+SK



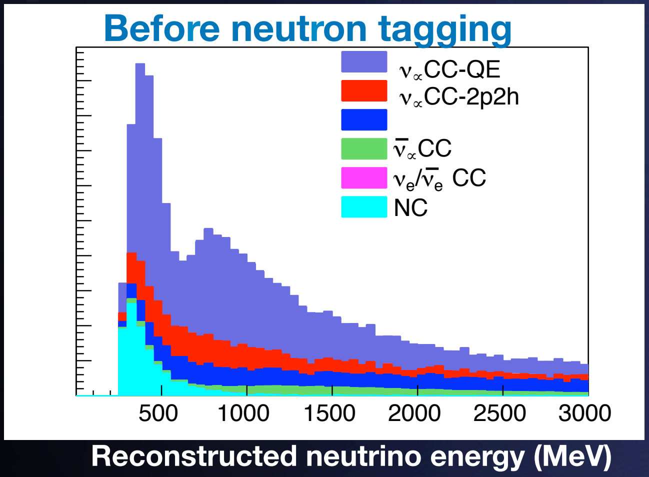
T2K formed working groups with Nova and SK to provide combined oscillation analyses

SK-GD: Impact for oscillation analysis

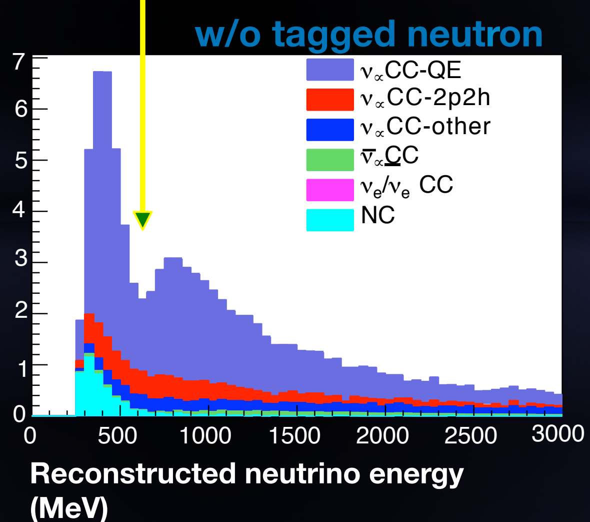
- Improvements for neutrino oscillation study:
  - CP violation search with neutrino-antineutrino separation with neutrons.
  - ν_μ disappearance measurement with reduced NC or CC-nonQE events
- Would provide important cross- check for neutrino interaction systematics and background assumptions.

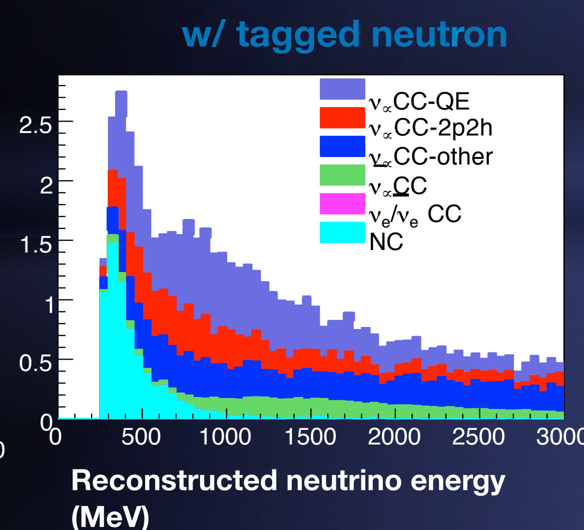
ν_μ CC-0π candidates

FHC, 9.2×10^{20} POT
0.02% $Gd_2(SO_4)_3$

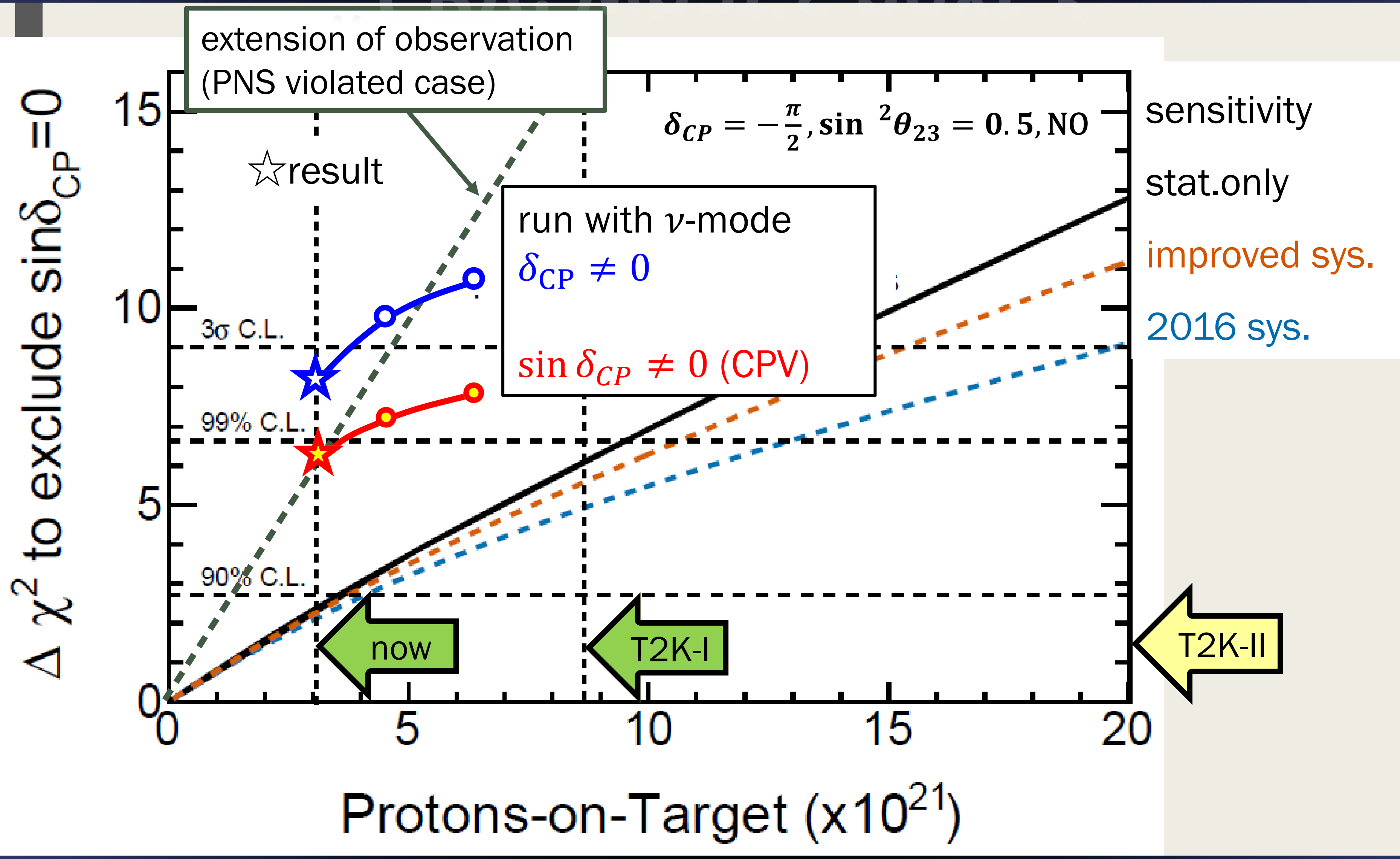


Less backgrounds at the oscillation maximum





CPV: what's next ?



High Power J-PARC Secondary Beamline

J-PARC secondary beamline infrastructure (shielding, decay volume, hadron absorber) were all designed for 3–4 MW

Component	Limiting Factor	Current Acceptable Value	Upgraded Acceptable Value
Target	Thermal Shock	3.3×10^{14} ppp	3.3×10^{14} ppp
	Cooling Capacity	0.75 MW	>1.5 MW
Horn	Conductor Cooling	2 MW	2 MW
	Stripline Cooling	0.54 MW	>1.25 MW
	Hydrogen Production	1 MW	>1 MW
	Operation	2.48 s & 250 kA	1 s & 320 kA
He Vessel	Thermal Stress	4 MW	4 MW
	Cooling Capacity	0.75 MW	>1.5 MW
Decay Volume	Thermal Stress	4 MW	4 MW
	Cooling Capacity	0.75 MW	>1.5 MW
Beam Dump	Thermal Stress	3 MW	3 MW
	Cooling Capacity	0.75 MW	>1.5 MW
Radiation	Radioactive Air Disposal	1 MW	>1 MW
	Radioactive Water	0.5 MW	0.75→1.3 or 2 MW

J-PARC Secondary Beamline Upgrades

However, need upgrades to improve cooling capacity, radiation containment, and irradiated cooling water disposal for 1+ MW

Component	Limiting Factor	Current Acceptable Value	Upgraded Acceptable Value
Target	Thermal Shock	3.3×10^{14} ppp	3.3×10^{14} ppp
	Cooling Capacity	0.75 MW	>1.5 MW
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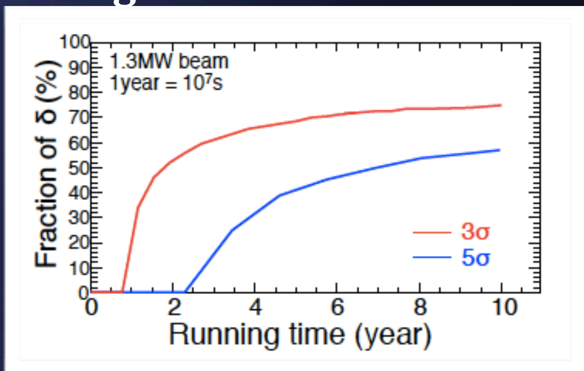
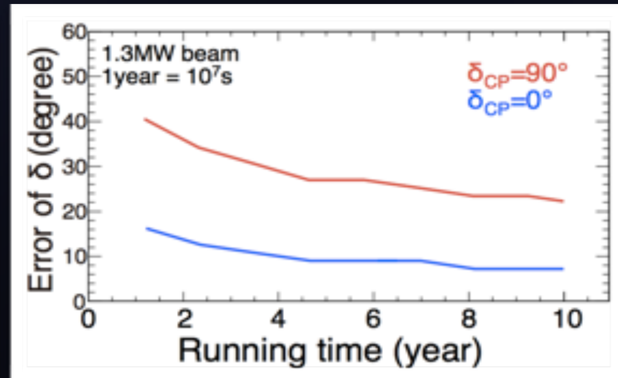
Beam Dump	Thermal Stress	3 MW	3 MW
	Cooling Capacity	0.75 MW	>1.5 MW
Radiation	Radioactive Air Disposal	1 MW	>1 MW
	Radioactive Water	0.5 MW	0.75→1.3 or 2 MW

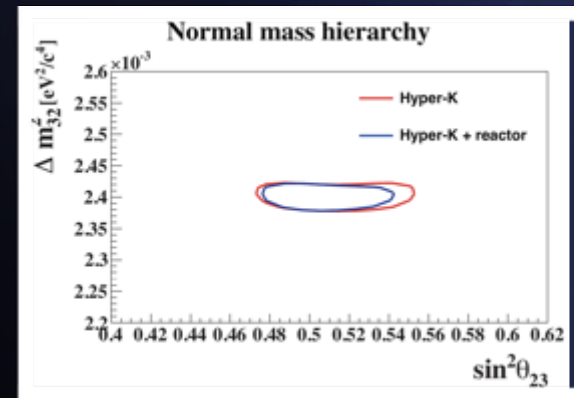
* hyper-kamiokande sensitivity

arXiv:1805.04163 [physics.ins-det].

Using neutrino beam





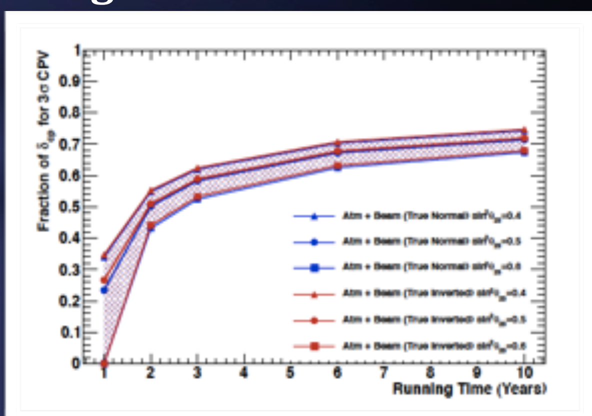


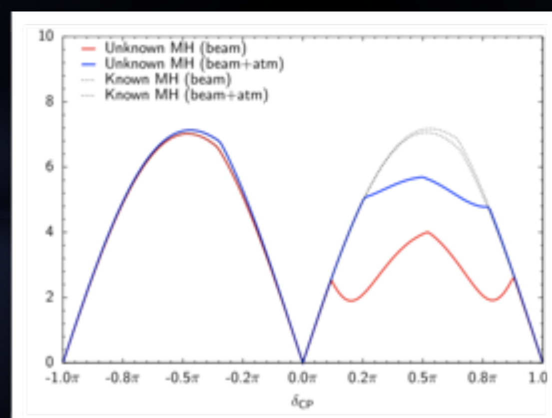
Fraction of for which sin= 0 can be excluded with more than 3(red) and 5(blue) assuming NH

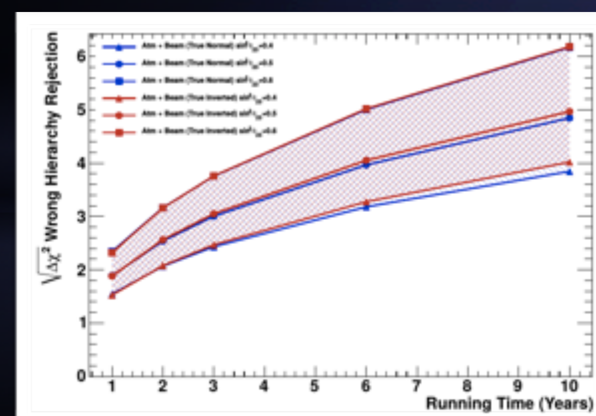
Expected 68% CL uncertainty of as a function of running time assuming NH

The 90% CL allowed regions in the plane.

Using neutrino beam + atmosferic





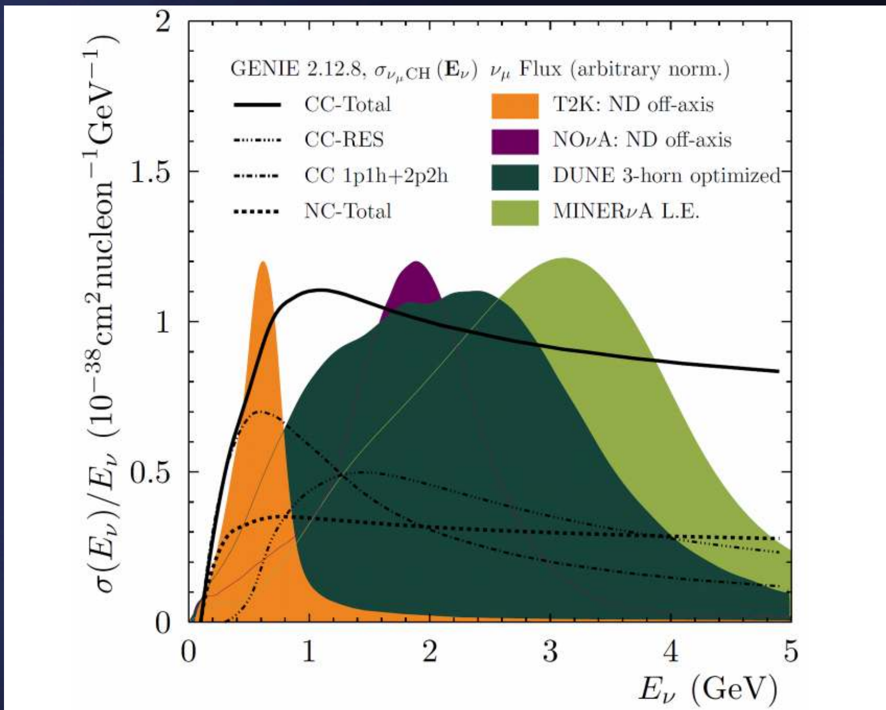


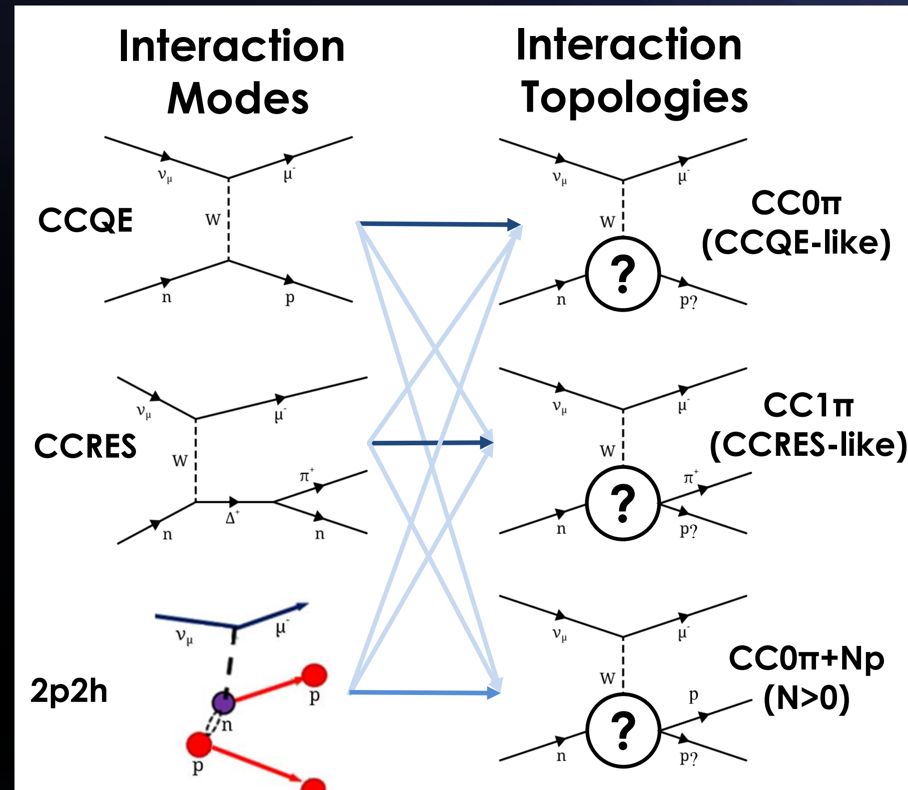
Fraction of phase space at which observation of CP violation can be made as function of time.

Constraints on after a 10 year exposure of Hyper-K with known and unknown MH.

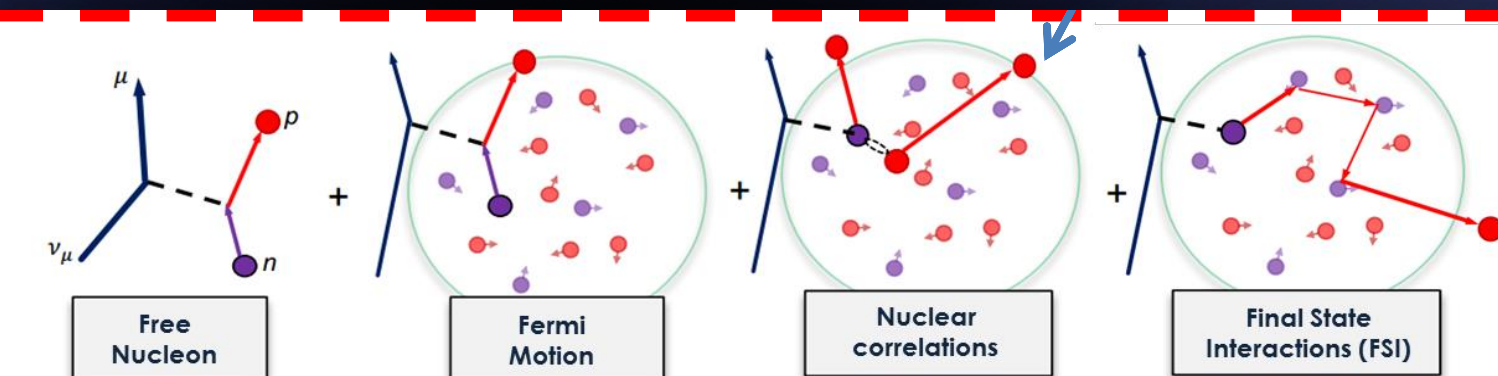
Expected sensitivity to the MH from a combined analysis of accelerator and atmospheric neutrinos

X-section measurements in T2K





Nuclear Effects



Diagrams by Patrick Stowell

Neutrino beams for precision physics: the ENUBET Project

- The next generation of short baseline experiments for cross-section measurement and for precision ν physics at short baseline (e.g. sterile neutrinos and NSI) should rely on:
- a high precision, **direct measurement of the fluxes**
- a beam covering the region of interest **from**
- **sub- to multi-GeV** a narrow band beam where **the energy is known a priori** from the beam width

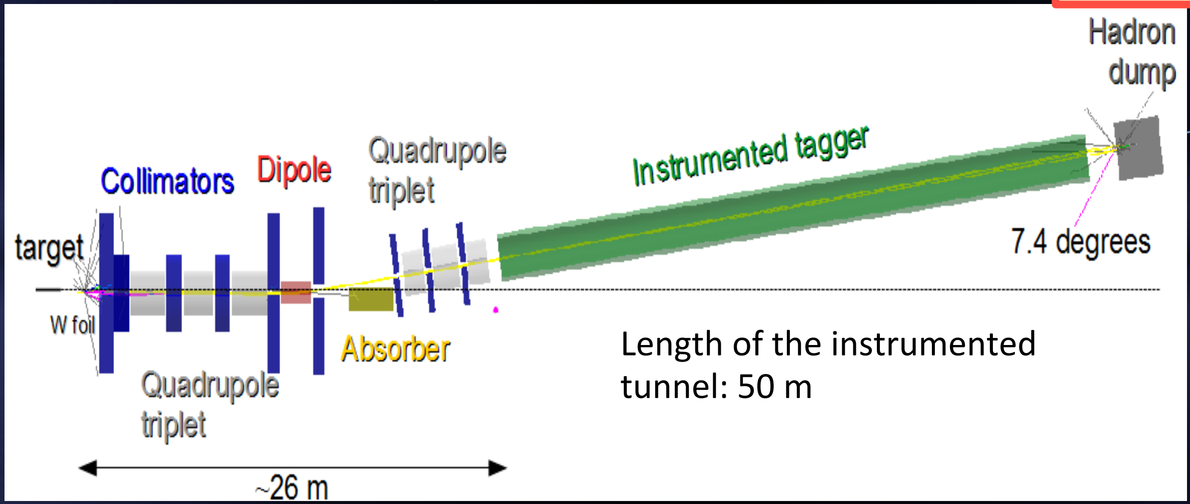
the ENUBET facility fulfills simultaneously all these requirements

Enhanced NeUtrino BEams from kaon Tagging

ERC-CoG-2015,
G.A. 681647 (2016-21)

A. Longhin, INFN

CERN-EoI: 41 physicists, 10 institutions:
CERN, IN2P3 (Bordeaux), INR, INFN (Bari, Bologna, Insubria, Milano-Bicocca, Napoli, Padova, Roma-I
+ NUTECH funding from the Italian Min. of Research (MIUR)



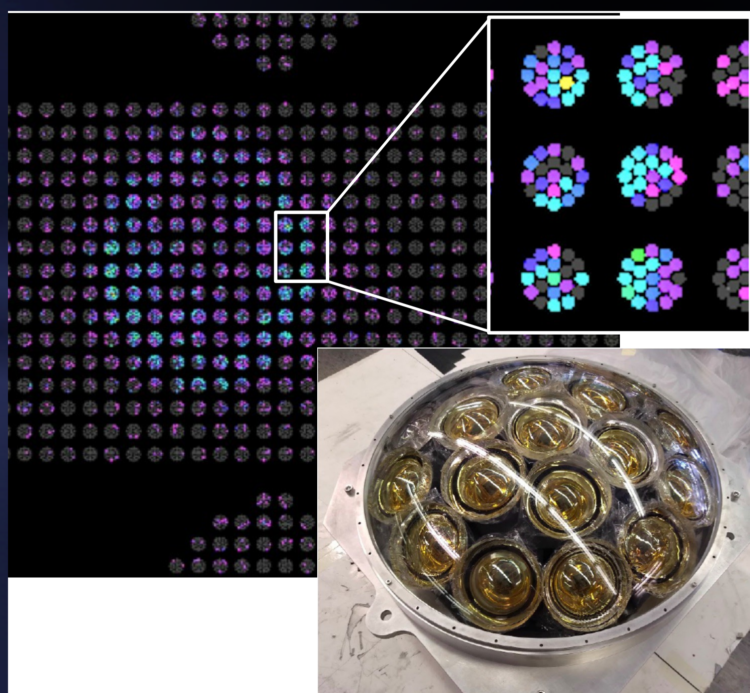
ν detector

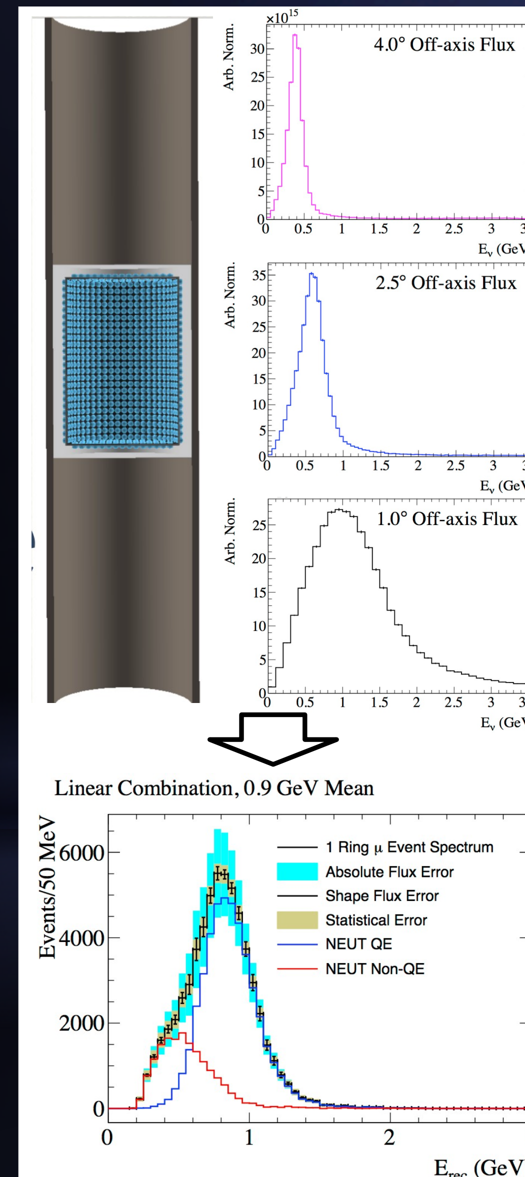
Length of the instrumented tunnel: 50 m

Reference parameters: **100 m baseline, 500 t detector**
(e.g. ICARUS@FNAL or Protodune-SP/DP@CERN)

Intermediate Water Cherenkov Detector (IWCD)

- Movable water Cherenkov detector to sample different off-axis angle beams
  - Measure E_ν-(p,θ) relation independent of neutrino interaction models
  - Measure ν_e and neutrons
- Smaller detector → utilize finer granularity with mPMT modules

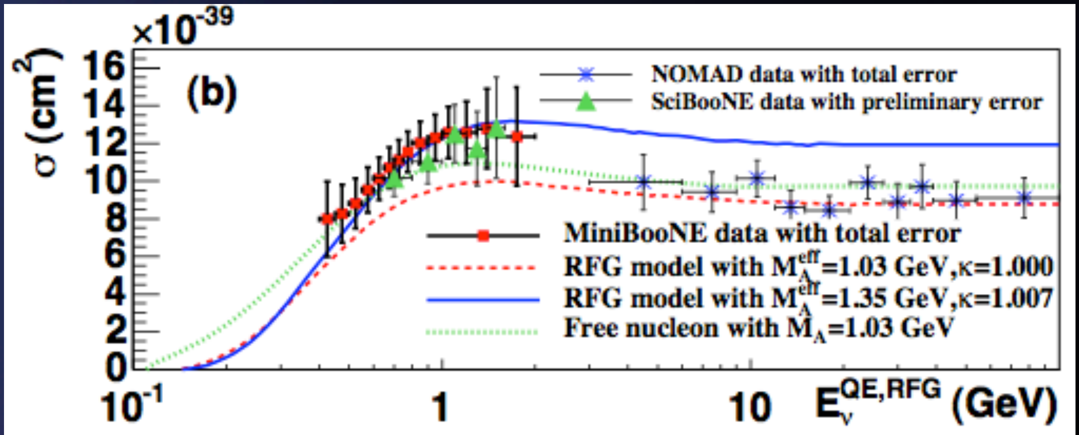


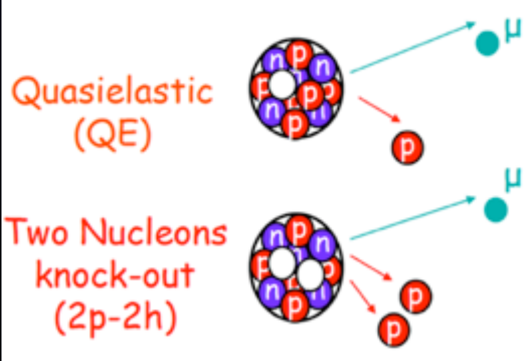


Near Detectors (High Pressure TPC)

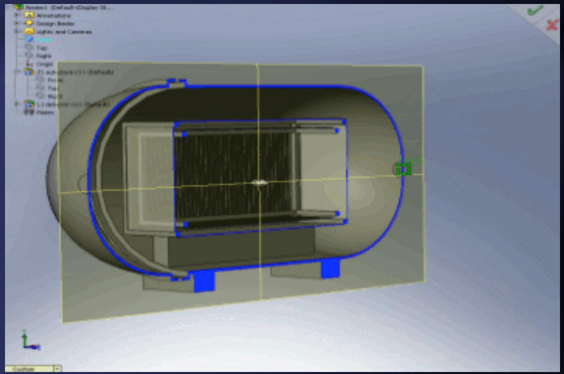
2) Add new detectors in the 280m pit: High pressure TPC to study low momentum final state particles and in particular resolve vertex
HPTPC detector design to reduce cross-sections systematics

arXiv:1002.2680 [hep-ex]





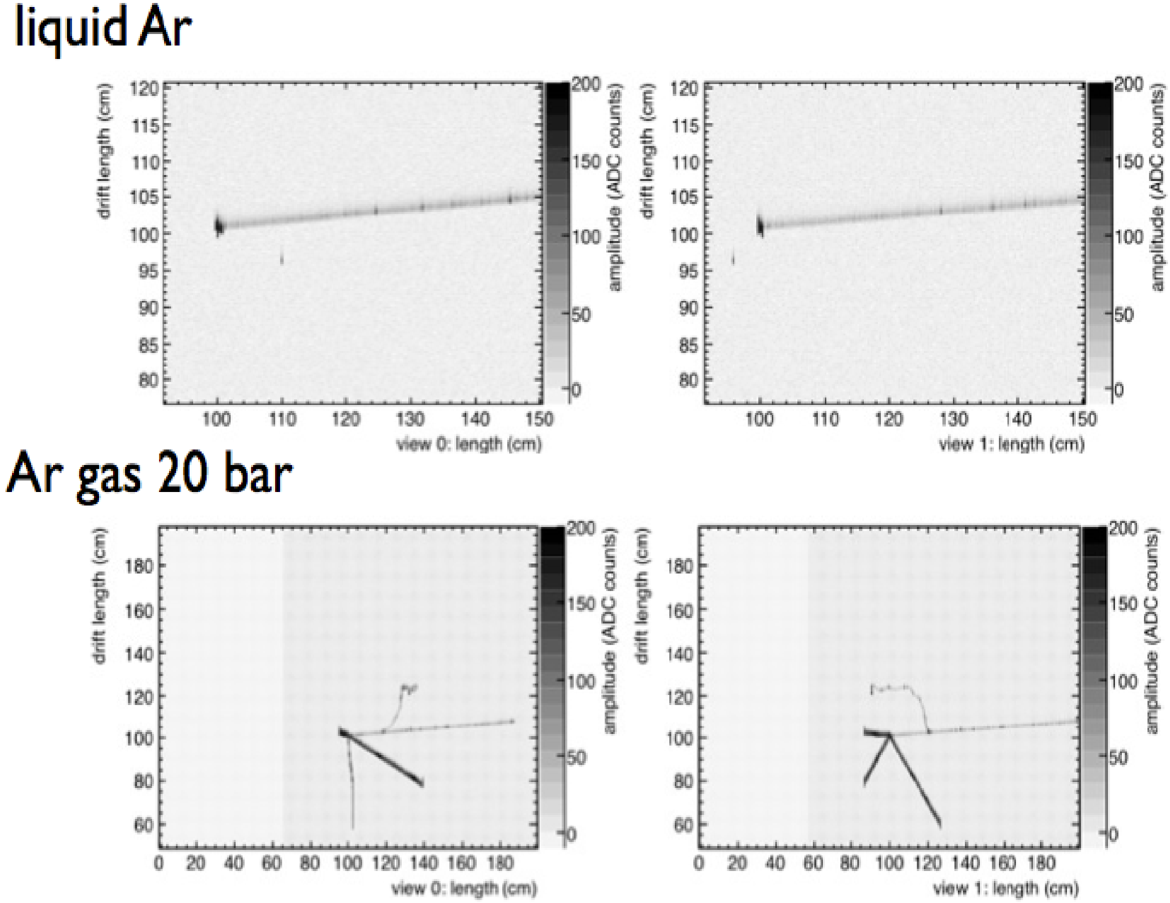
- Significant discrepancies on proton multiplicity and momentum distributions
- Need low momentum thresholds to reduce cross-sections systematics
- Important difference lie below threshold for liquid detectors



- T2K has pioneered (atm. pressure) gas TPCs for accelerator neutrinos
- Need a path to high pressures for sufficient statistics
- Generally applicable to next generation LBL experiments

Gas versus liquid argon

liquid Ar



A. Curioni

CC events assuming a $8m^3$ detector & full FV.

$2x2x2\ m^3$ 20°C	5 bars	10 bars
He	6.65 kg	13.3 kg
	520 evt/10^{21}pot	1040 evt/10^{21}pot
Ne	32.5 kg	67.1 kg
	2543 evt/10^{21}pot	5086 evt/10^{21}pot
Ar	66.5 kg	133 kg
	5203 evt/10^{21}pot	10406 evt/10^{21}pot
CF_4	146.3 kg	293 kg
	11450 evt/10^{21}pot	22893 evt/10^{21}pot