T2K-2 and HyperKamiokande

Atelier Long Baselines – January 2018, LAL Orsay

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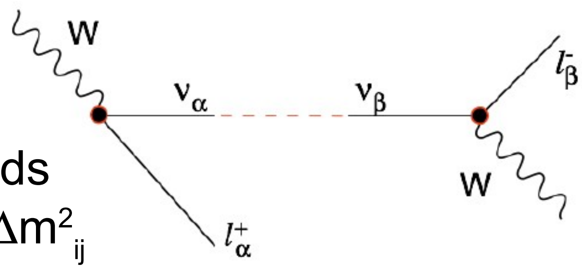
Neutrino oscillations

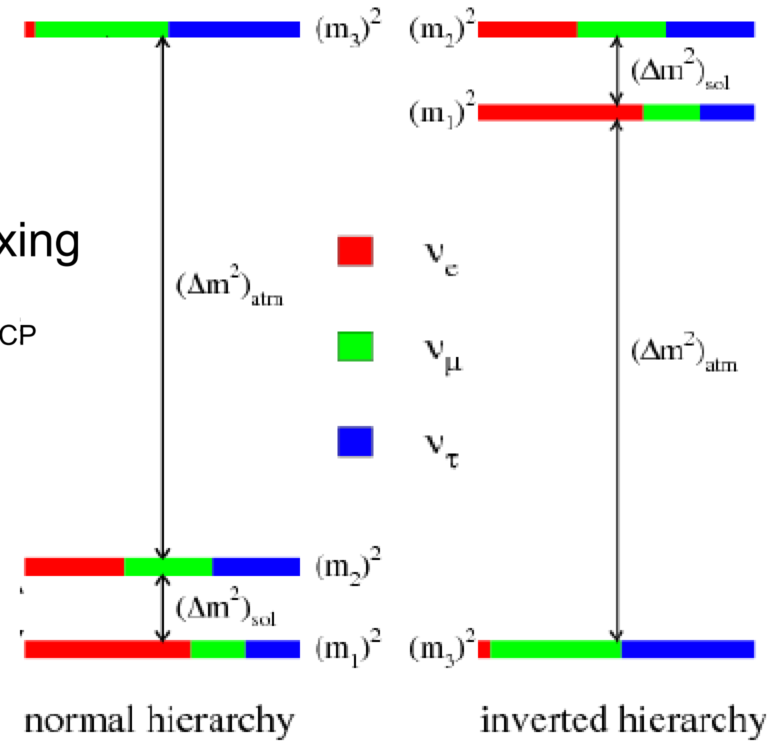
- $$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} \\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} \\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$ $U_{\alpha i}$ are expressed in terms of 3 mixing angles (θ_{13}, θ_{23}, θ_{12}) and a phase δ_{CP}

$P(\nu_\alpha \rightarrow \nu_\beta)$

neutrino oscillation probability also depends on mass differences: Δm^2_{ij}





- **Long baseline neutrino accelerator** experiments observe $\nu_\mu \rightarrow \nu_{\mu/e}$:
  - **$|\Delta m^2_{32}|$** known at ~4%, **θ_{23}** ~ $\pi/4$ → maximal mixing? **Mass ordering** unknown.
    (θ_{13} and θ_{12}, Δm^2_{21} measured with solar and reactor experiments)

    → flavour pattern may indicate the symmetry beyond ν oscillation (door to New Physics!)

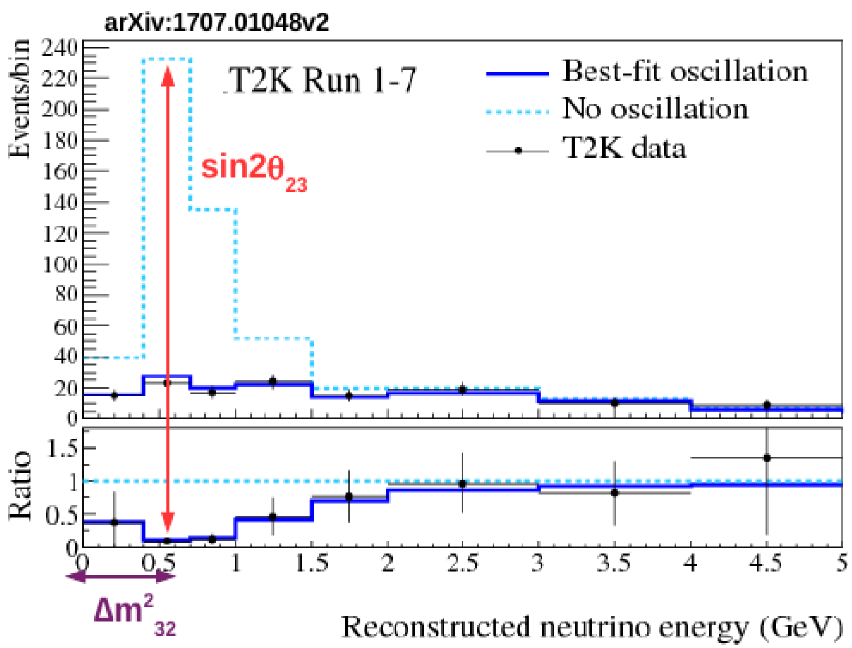
    → precise measurement needed to test unitarity of PMNS matrix

  - **δ_{CP} phase (unknown)** parametrize the difference between ν and $\bar{\nu}$ oscillation
    → involved with **matter-antimatter asymmetry** in leptogenesis scenarios

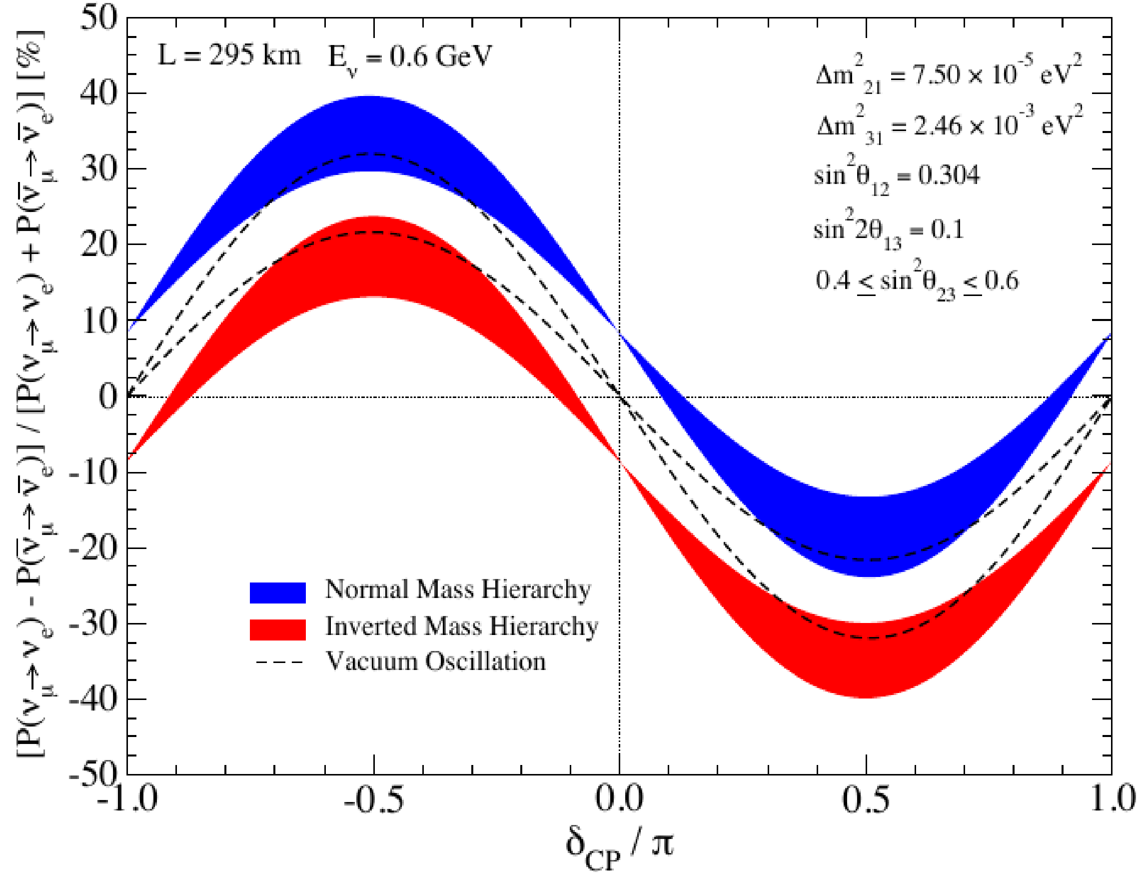
How do we measure the oscillation parameters in long baselines?

ν_μ (and $\bar{\nu}_\mu$) disappearance

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$



ν_e and $\bar{\nu}_e$ appearance



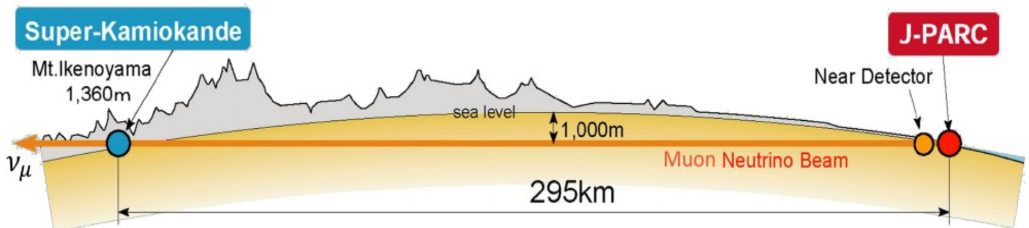
Outline

The granting of the future success of HyperKamiokande (and T2HK) relies on the excellent performances of SuperKamiokande (and T2K)

- Update on latest T2K results
- Plans for T2K-2: upgrade of the near detector complex
- Road to HyperKamiokande and expected sensitivity

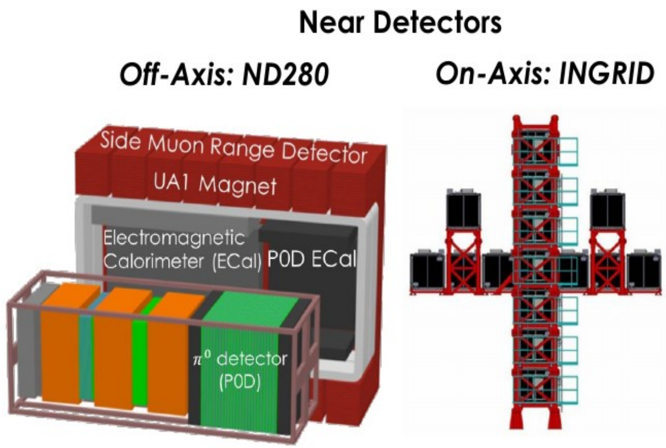
T2K: Tokai (JPARC) to Kamioka (SuperKamiokande)

Long baseline (295 km) neutrino oscillation experiment with off-axis technique:



Far Detector:

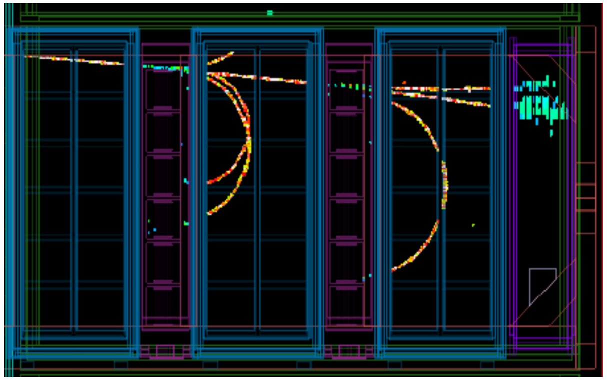
huge water cherenkov detector (50 kTon) with optimal μ/e identification to distinguish ν_e, ν_μ

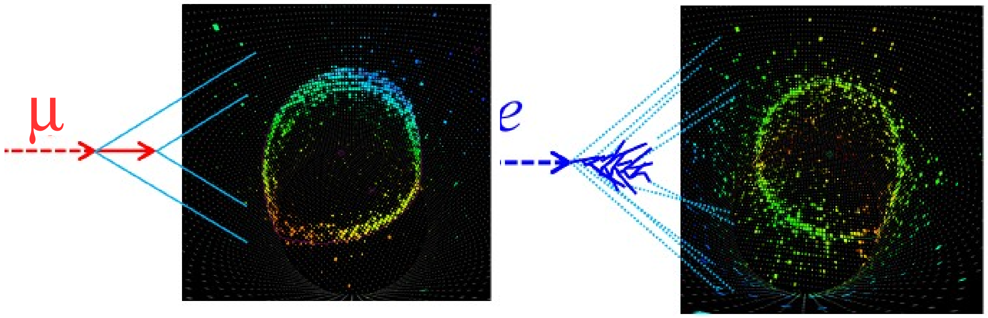


Near Detectors:

On-axis:
iron/CH scintillator
monitoring of beam angle and position

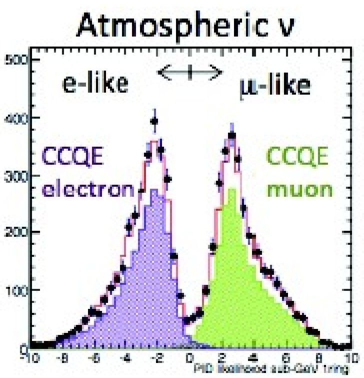
Off-axis:
full tracking and particle reconstruction in near detectors
(magnetized TPC!)





clear ring

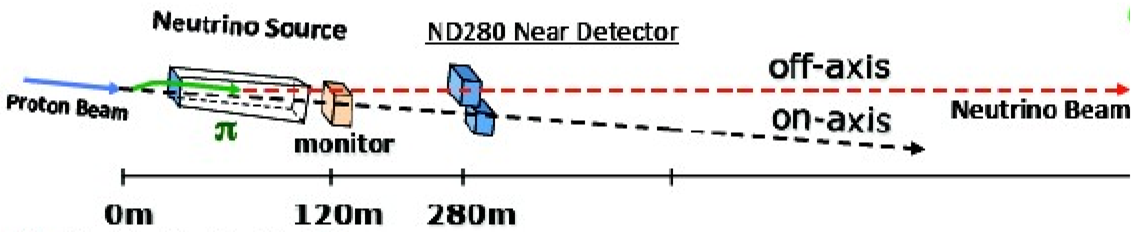
fuzzy ring



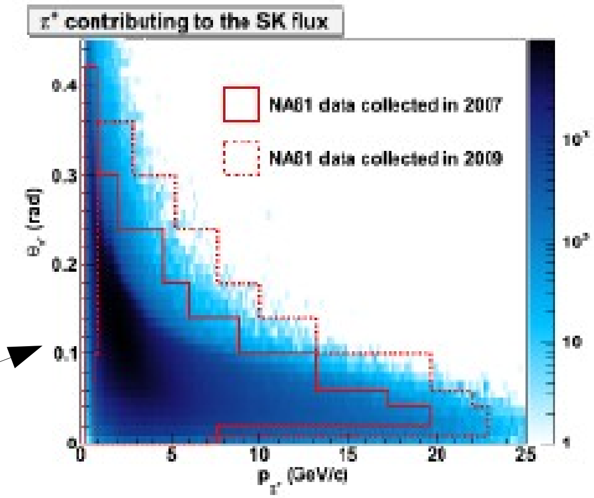
1% mis-id

T2K beam

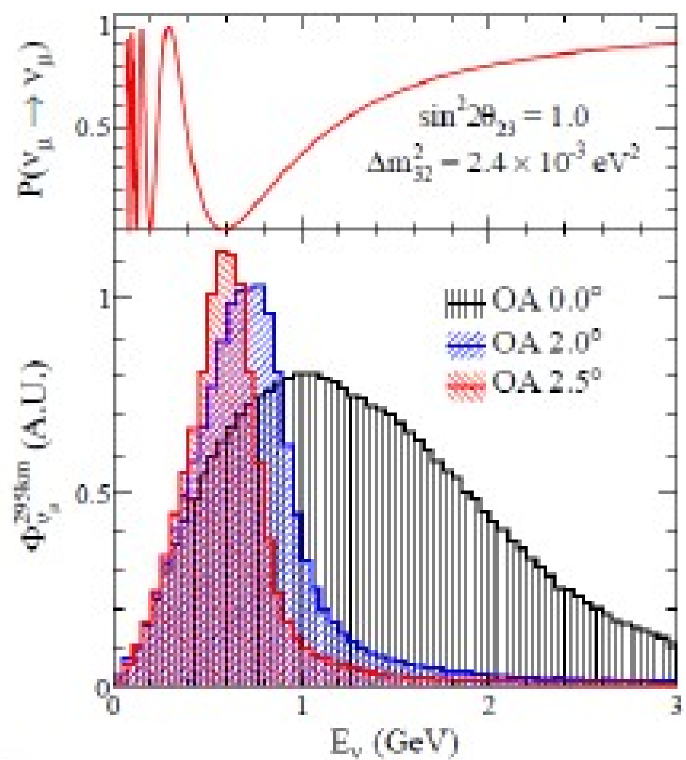
- Production of **muon neutrino beam:**



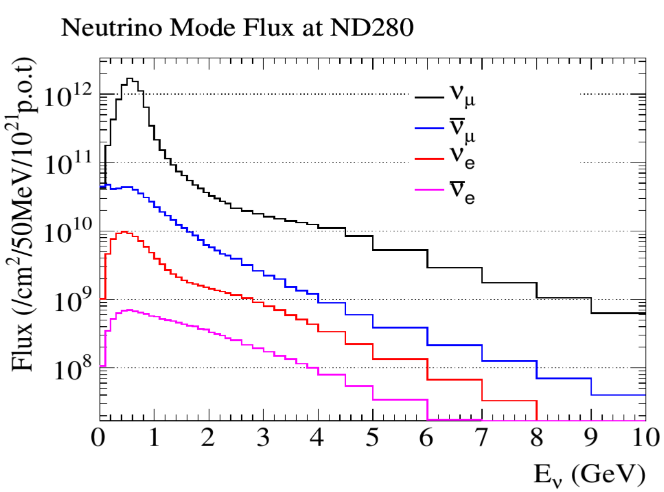
- Flux prediction tuned from pion and kaon production measurements at **NA61 experiment** at CERN

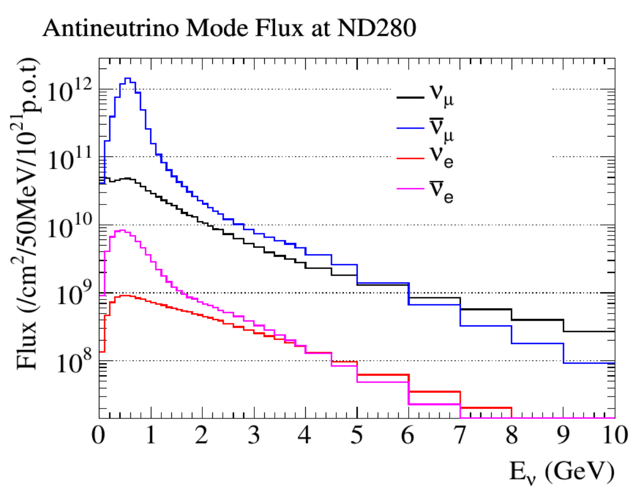


- **Off-axis** → narrow flux at the maximum of the neutrino oscillation



- **Neutrino and antineutrino mode** changing the horn current (→ focusing hadrons of opposite charge)

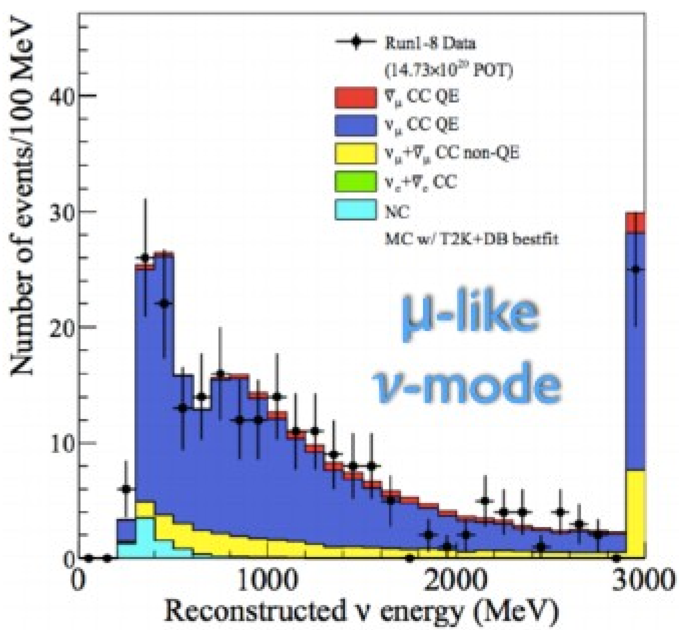




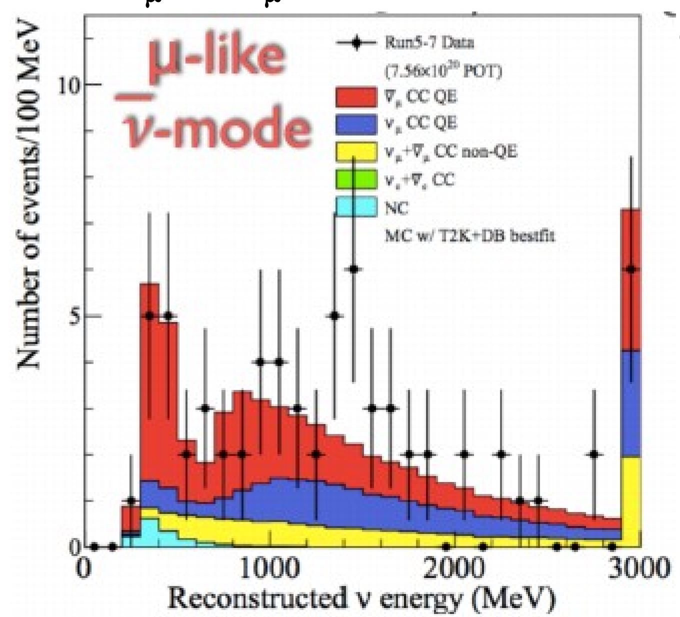
T2K oscillation analysis

ν mode POT: 14.93 x 10^{20} (66.2%)
$\bar{\nu}$ mode POT: 7.62 x 10^{20} (33.8%)

$\nu_\mu \rightarrow \nu_\mu$ (disappearance)

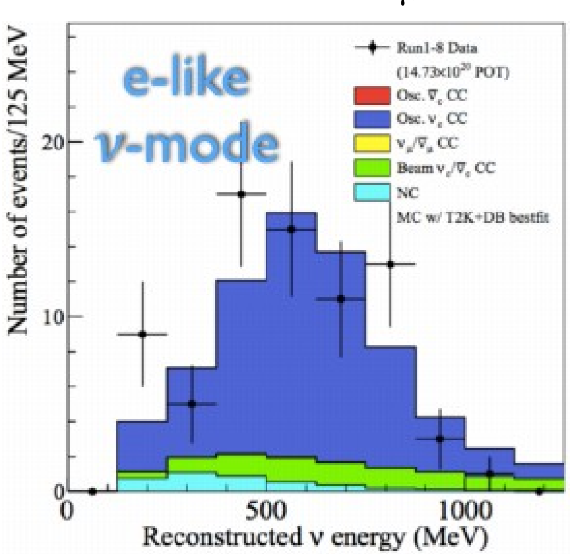


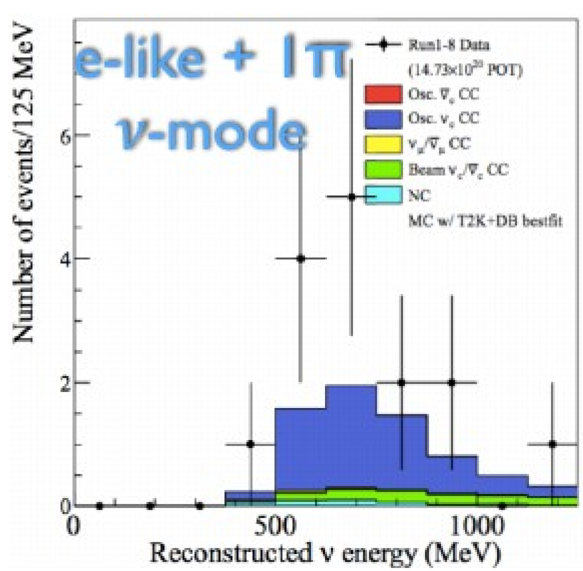
$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ (disappearance)



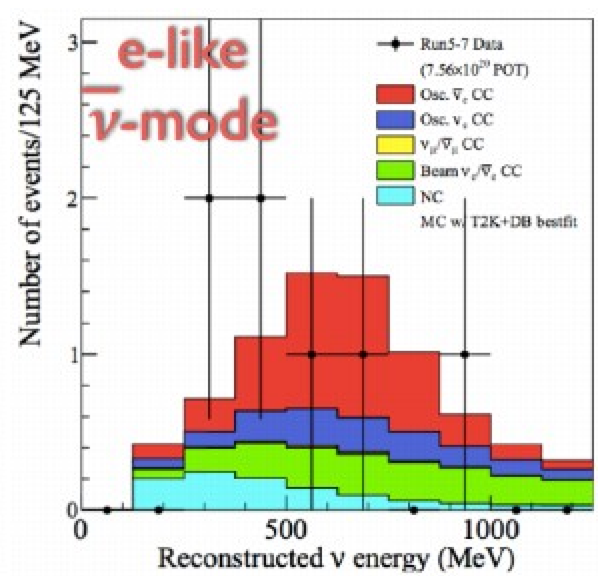
- Large disappearance signal and clear oscillation shape (well beyond a counting experiment)
- Clear signal in **antineutrino** as well!

$\nu_\mu \rightarrow \nu_e$ (appearance)





$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (appearance)



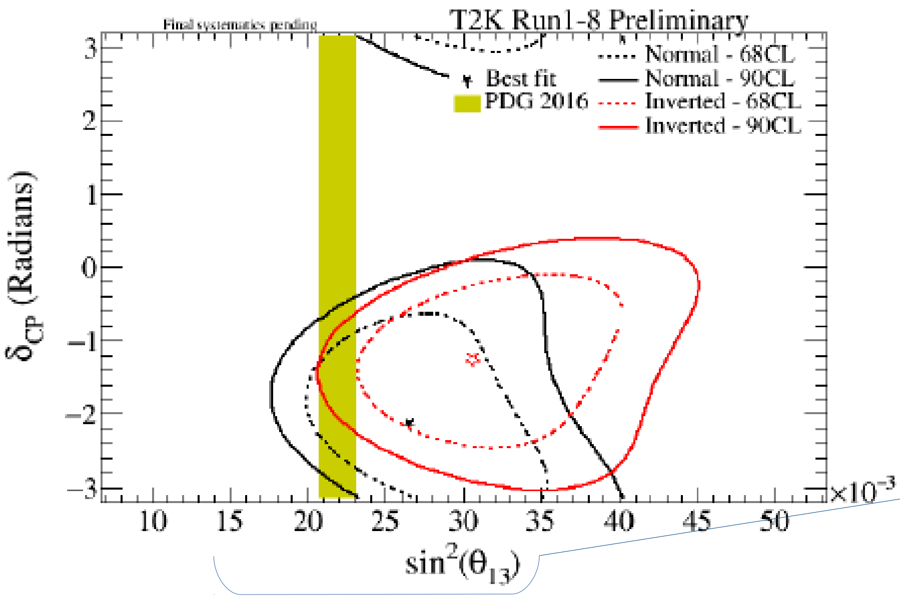
- Growing statistics of $\bar{\nu}_e$ appearance

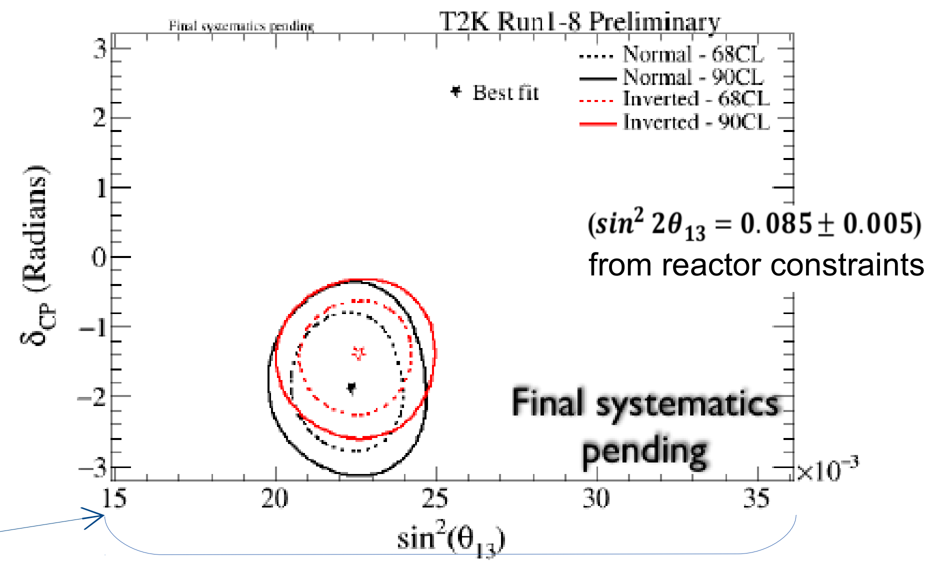
(~30% of final T2K statistics)

- >7σ observation of ν_e appearance

First 95% limits on δ_{CP}!!

Full joint fit of all data ($\nu_\mu \rightarrow \nu_{\mu/e}$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_{\mu/e}$) with all proper statistical and systematic uncertainty included and exploiting also shape information :



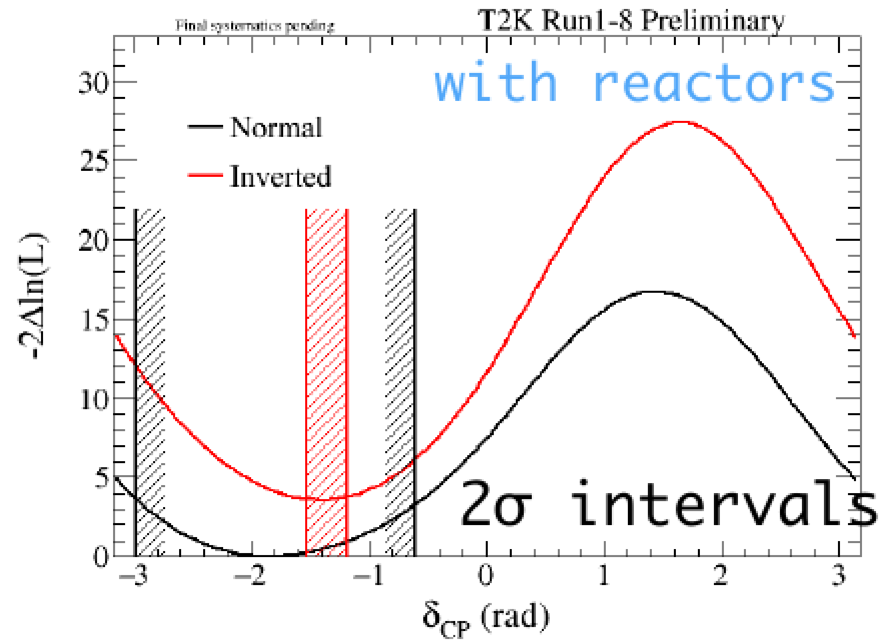


Not Gaussian behaviour → need to through toys to evaluate correct confidence interval

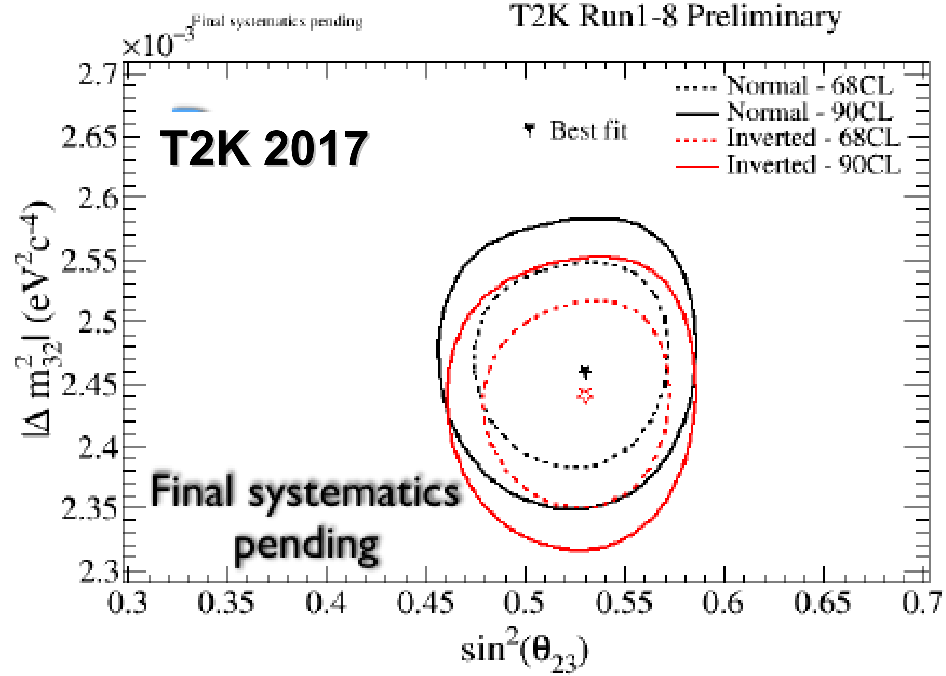
Feldman-Cousins confidence interval:

δ_{CP} = [-2.98, -0.60] NH
[-1.53, -1.19] IH
at **95%** CL

(NH slightly favoured)

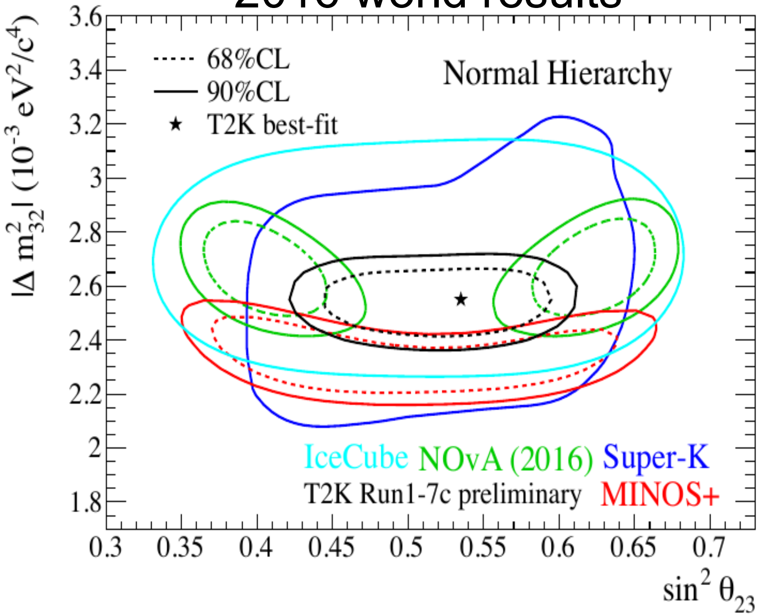


The other oscillation parameters (θ_{23}, $|\Delta m^2_{32}|$)

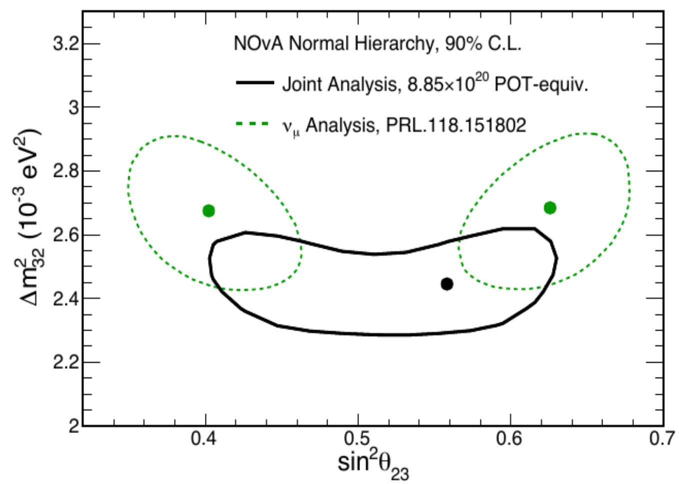


T2K data show maximal disappearance →
prefer maximal mixing: $\theta_{23} = \pi/4$
($\sin^2\theta_{23}$~0.52)

2016 world results



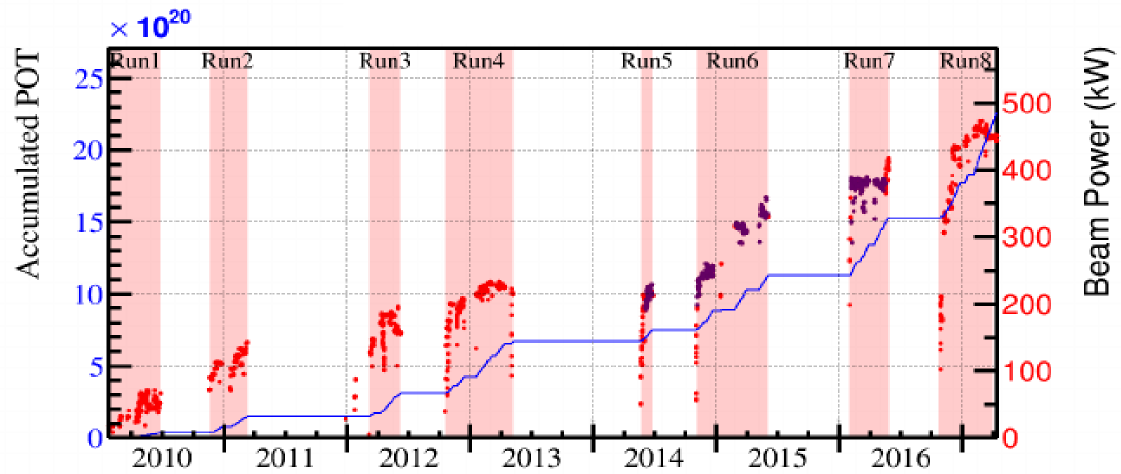
Brand new NOVA results



NOVA data in 2016 was excluding maximal mixing at 2.5σ → improved neutrino-nucleus interaction model and better detector modelling: **now well compatible with maximal mixing**

⇨ Precision era in neutrino physics: importance of knowledge/control of target nucleus and detector technology!

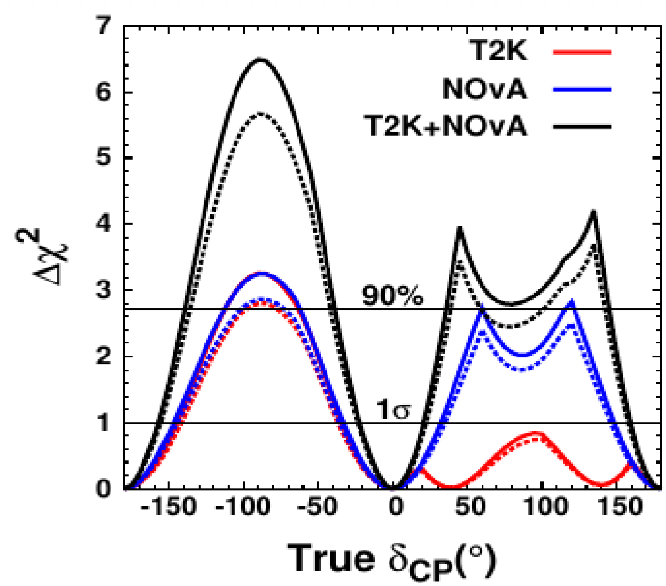
Prospects for future



- Today 22.5 x 10^{20} → expected at the end of **T2K (2021) 78x10^{20} POT**

- **NOVA – T2K combination with final dataset (~2021):** sensitivity CPV about 2σ

at the end of T2K we will still be limited by statistics and not by systematics !



- 5σ δ_{CP} measurement at DUNE/HK after 2030 → a lot of room for interesting results before that + need to keep physics output and analysis know-how **before DUNE/HK start taking data**

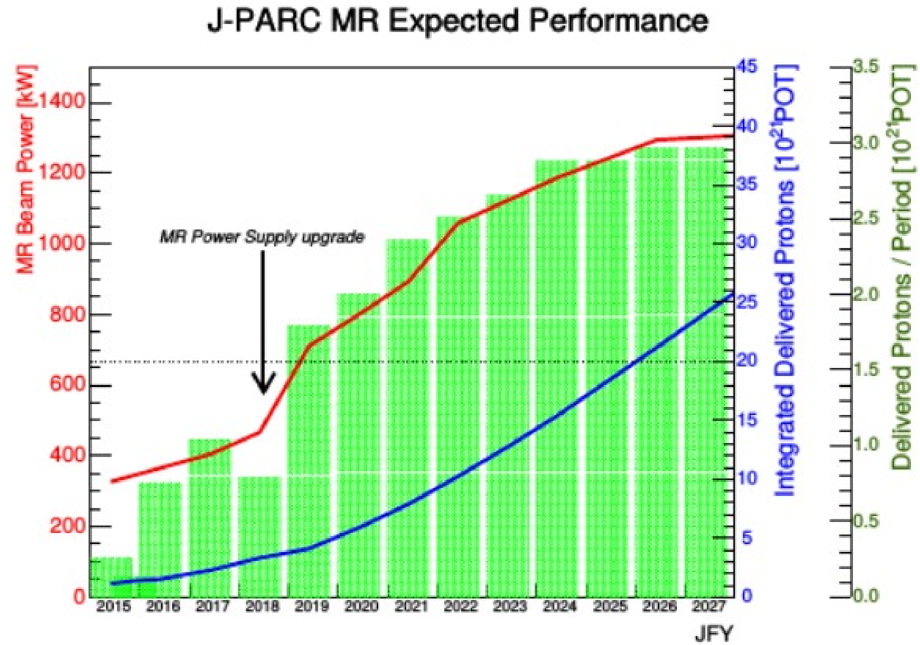
T2K-2

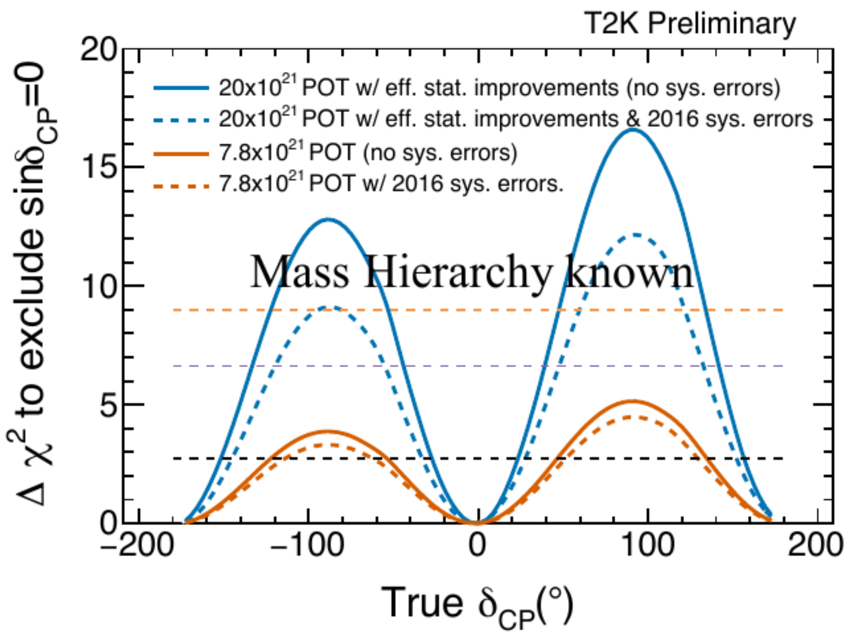
- **Request for new run of T2K** beyond design statistics (7.8×10^{21} POT by) → **20×10^{21} POT by 2026:**

JPARC Main Ring upgrade approved: beam power up to 1.3MW in view of HyperKamiokande

T2K-2: 440 ν_e events, 50 $\bar{\nu}_e$ events

→ good chances to observe **CP violation at > 3σ** by 2026 for a sizeable fraction of δ_{CP} values

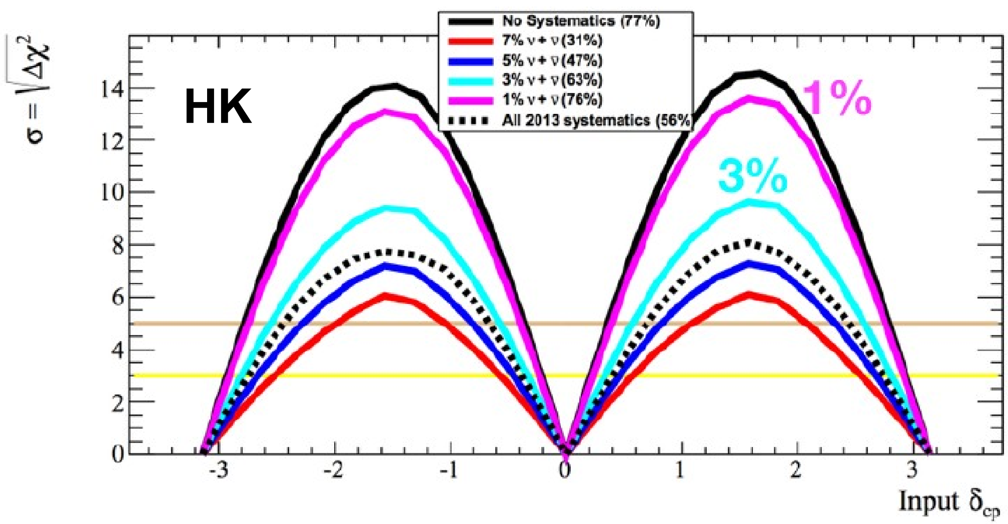


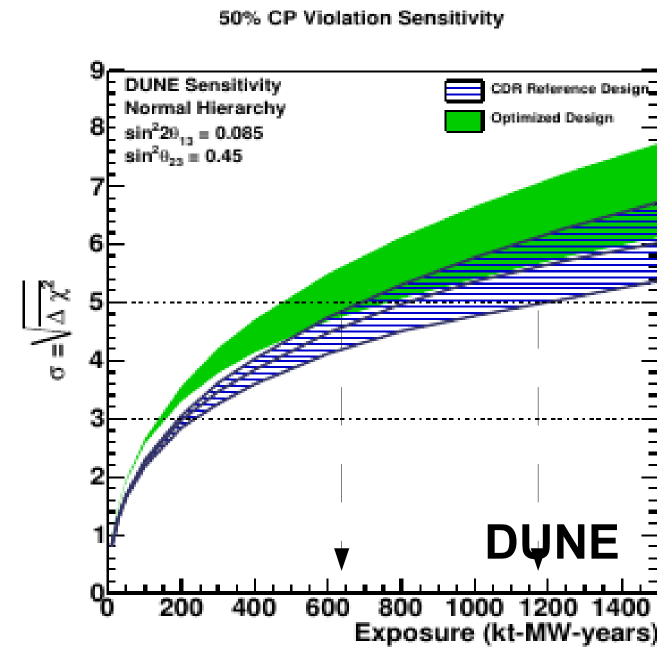


Systematics and near detector

- In T2K-2 the systematics starts to be a limiting factor for sensitivity

  Even more important for definitive δ_{CP} measurement at next generation of long baseline experiments: HyperKamiokande, DUNE





5% ± 1%

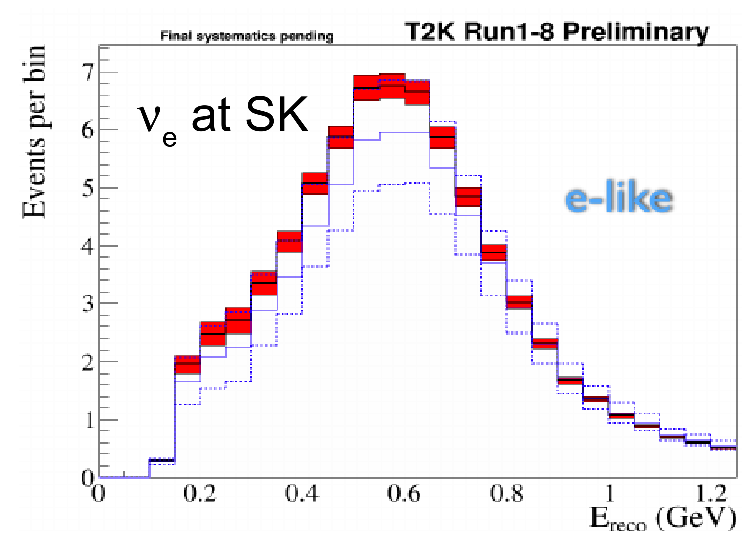
5% ± 2%

5% ± 3%

→ equivalent to factor 2 in exposure!

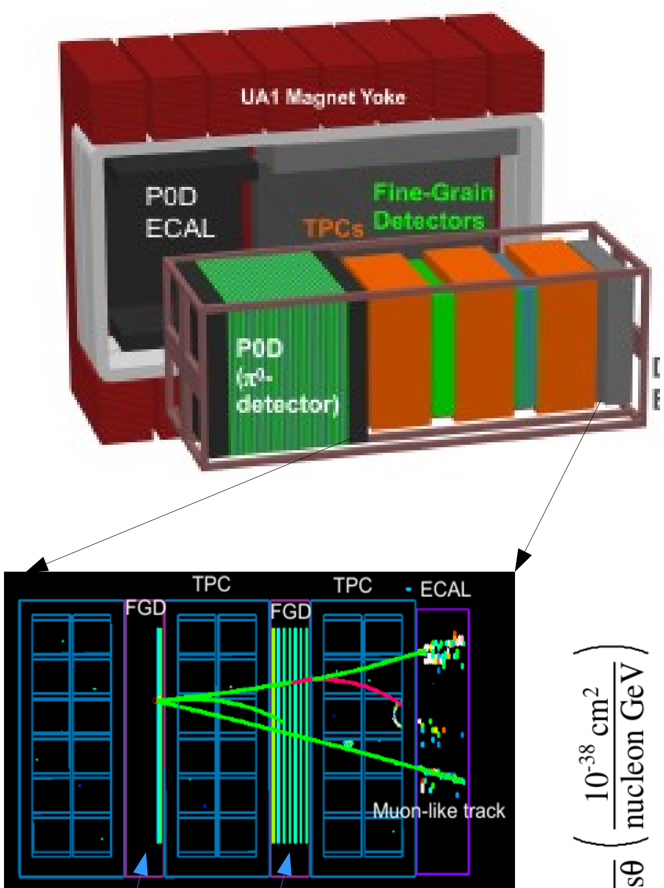
- Crucial role of near detector: example from ν_e appearance at T2K (2016 results)

Systematics $\delta N_e/N_e$	w/o ND280 constraint	w/ ND280 constraint
Flux	8.94%	3.64%
Cross Section	7.17%	4.13%
Flux + Cross Section	11.5%	2.88%
Final State/Secondary interaction Super-K	2.50%	2.50%
Super-K detector	2.39%	2.39%
Total	11.9%	5.41%

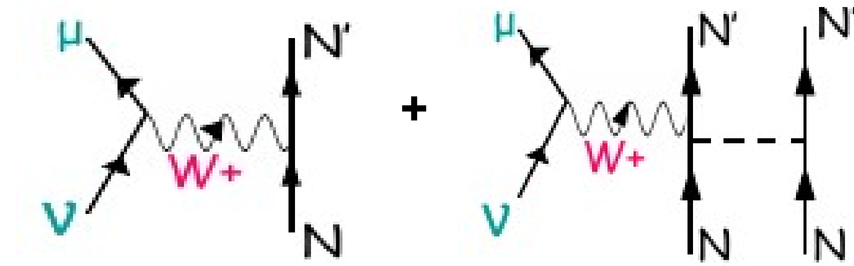


Neutrino-nucleus interaction

- Xsec measured with limited precision on free nucleons in old bubble chamber experiments. In modern experiment ν interacts with target detectors of carbon, water or argon → large nuclear effects not well known



Cross section of main T2K signal:



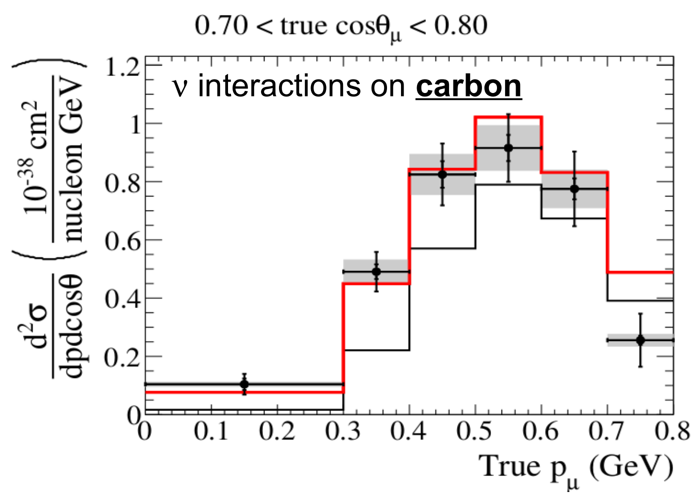
Charged Current Quasi-Elastic

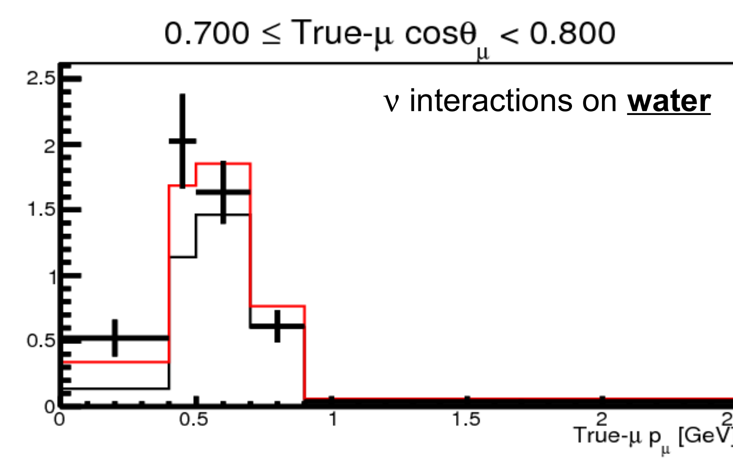
higher order corrections in nuclear target

Model delevoped by Martini et al. (CEA, SPhN)

— CCQE

— CCQE + multi-nucleon interactions

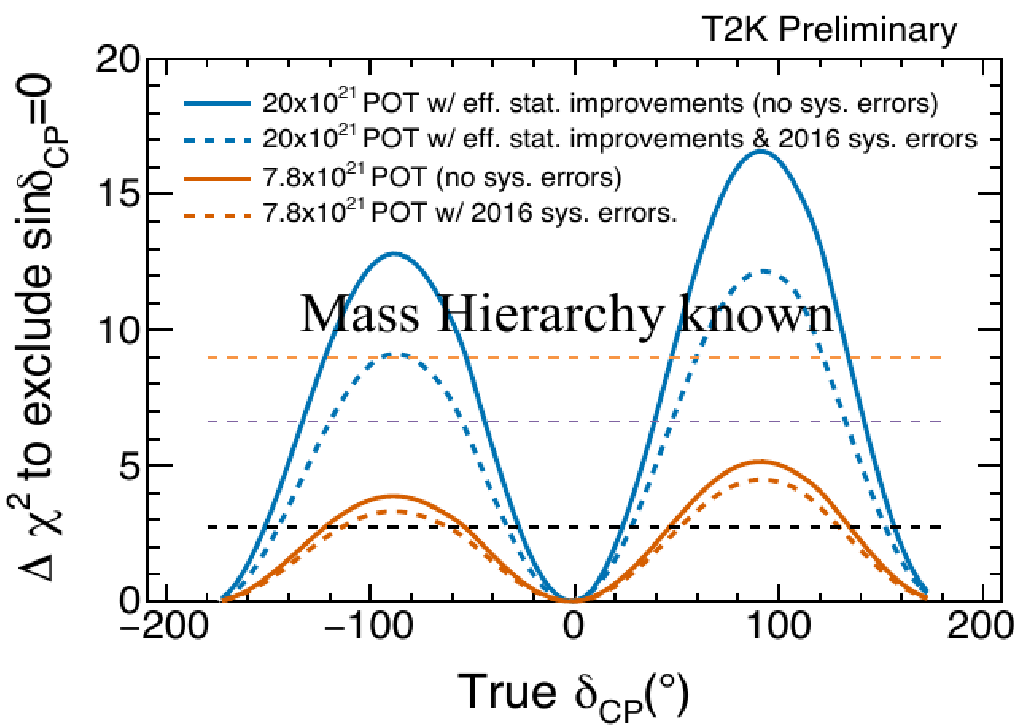


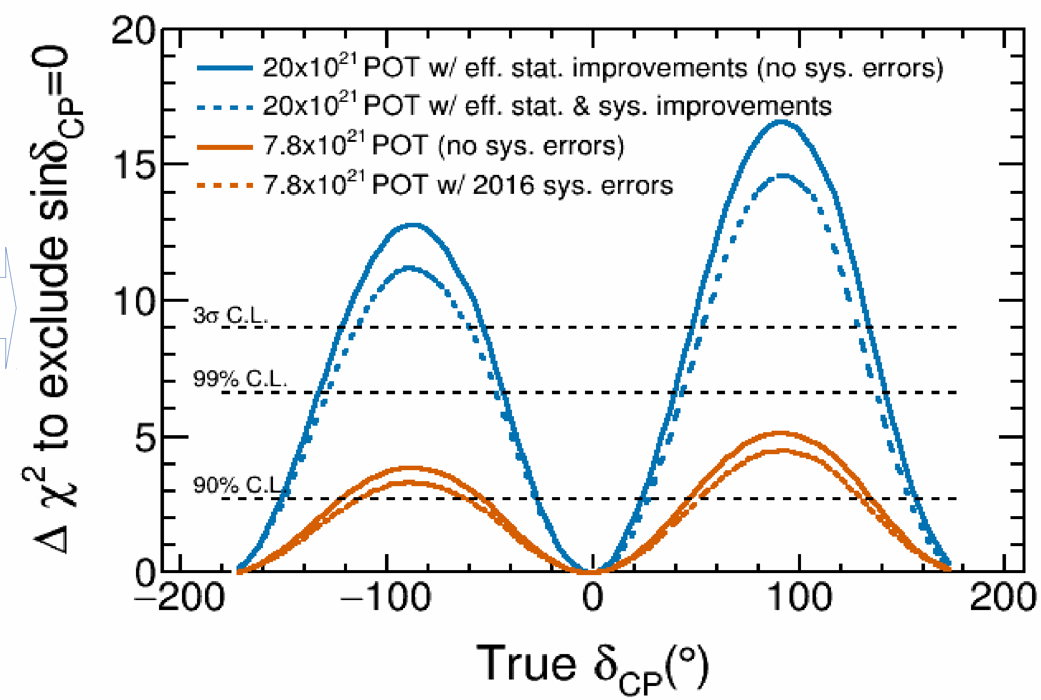


ND280 Upgrade for T2K Phase II

- T2K-II will require a 2% precision on the expected number of events at SK (~5% today) to match the 400 ν_e appearance events

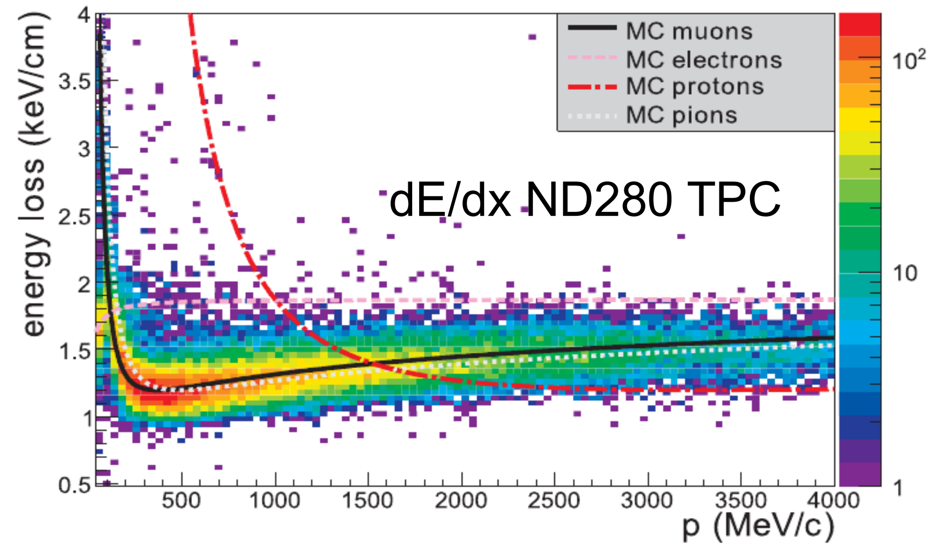
→ We are currently studying **an upgrade of the near detector ND280 to improve the constraints on the systematics**



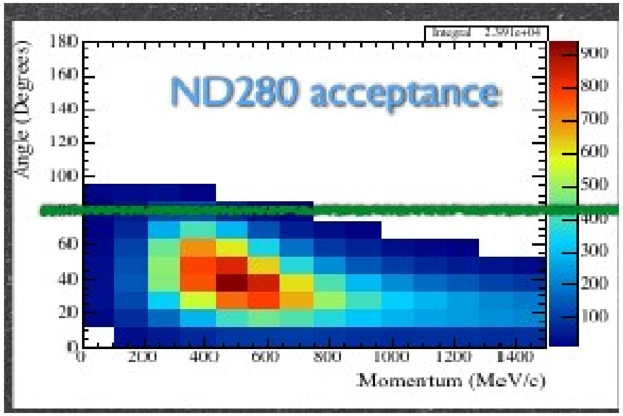


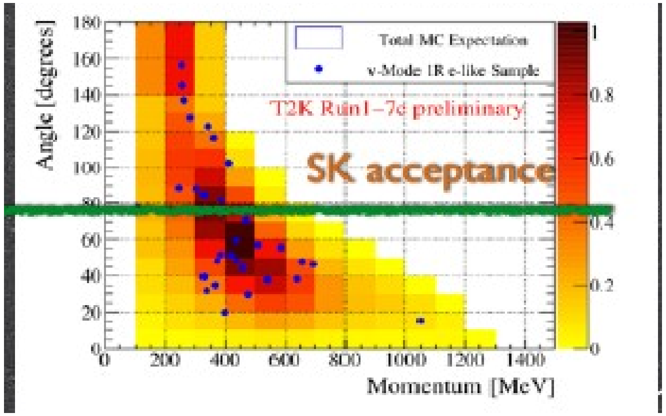
→ **better understanding of neutrino-nucleus interactions crucial also for next-generation of experiments (DUNE/HK)**

Physics drivers



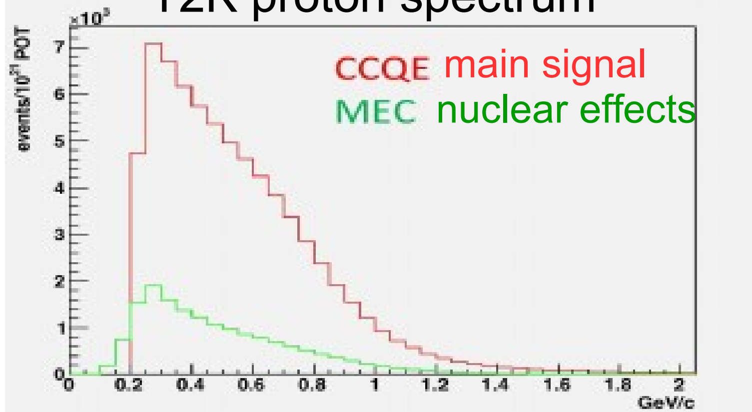
- Keep the very good e/μ separation → **TPCs !**



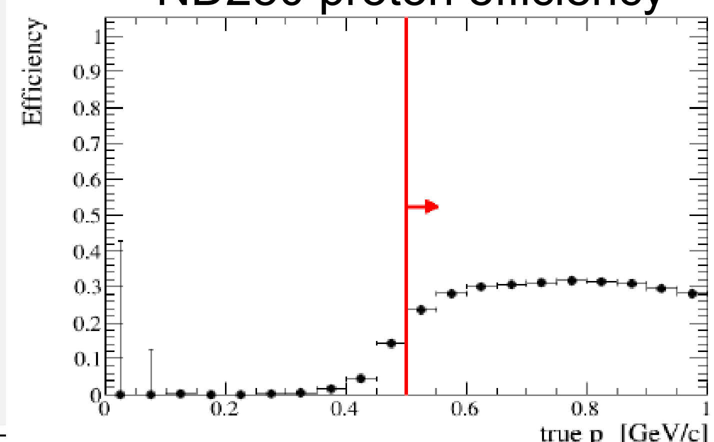


- Improving the angular acceptance over the full azimuthal angle → **new geometry**

T2K proton spectrum

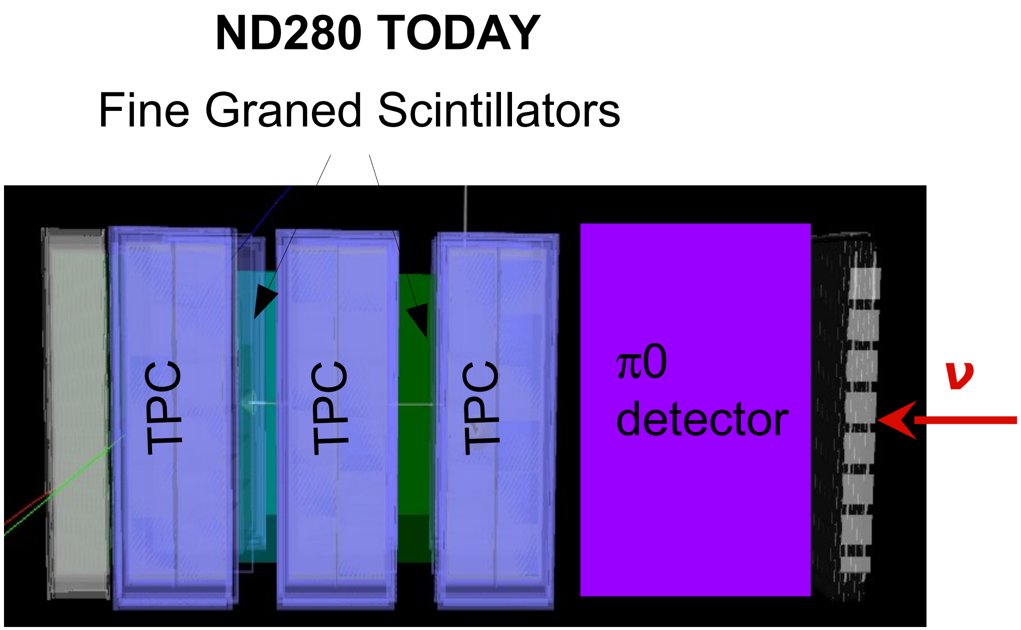


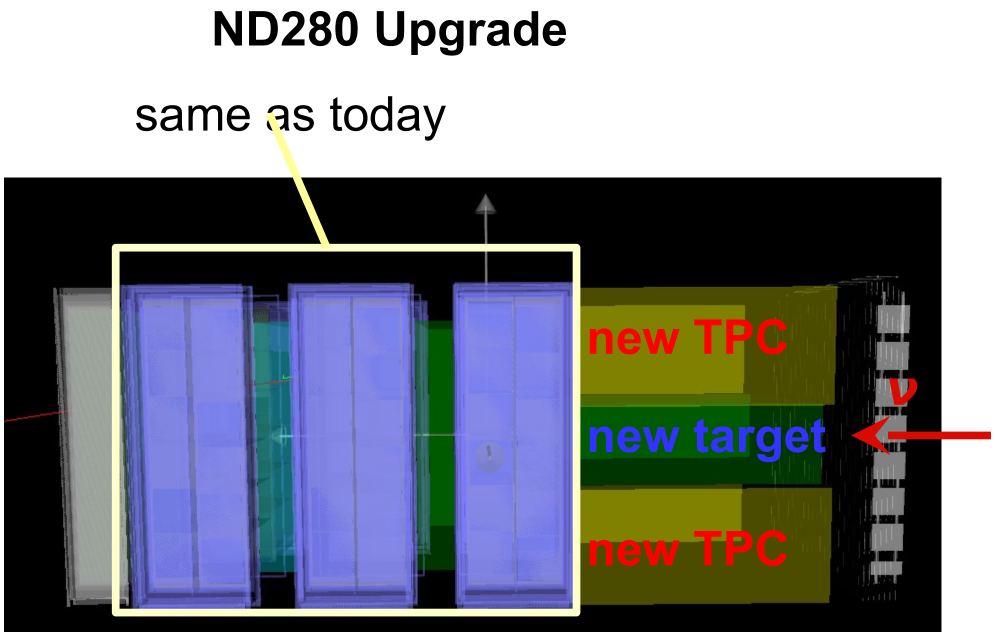
ND280 proton efficiency



- Lower threshold for low momentum particles (muons, protons, pions) → **new target detector**

ND280 upgrade configuration

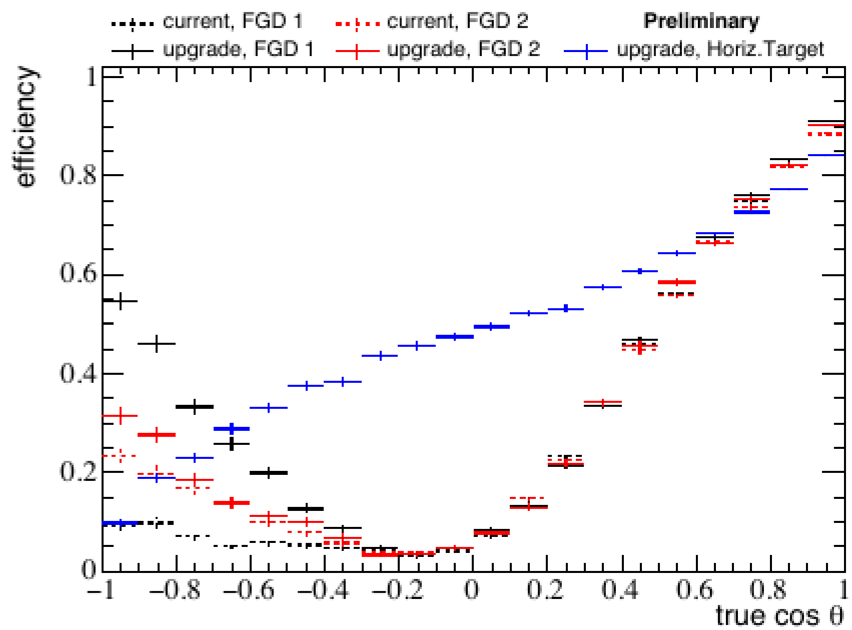




- Add new target+TPCs with **'horizontal' geometry**
- Add **Time Of Flight** detectors to identify track direction
- Surrounded by same ECAL and magnet as ND280

New TPCs

- **New horizontal target and new horizontal TPCs to enlarge high angle acceptance**



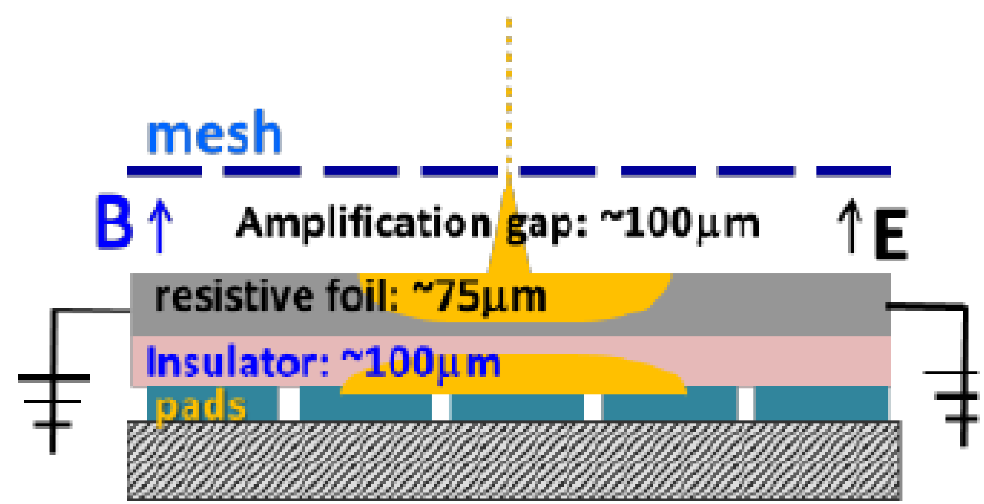
10^{21} POT

Selection	Current-like	Upgrade-like
ν_μ (ν beam)	93,401	194,654
$\bar{\nu}_\mu$ ($\bar{\nu}$ beam)	33,437	63,687

- Development of resistive bulk Micromegas for the TPC read-out (CEA)

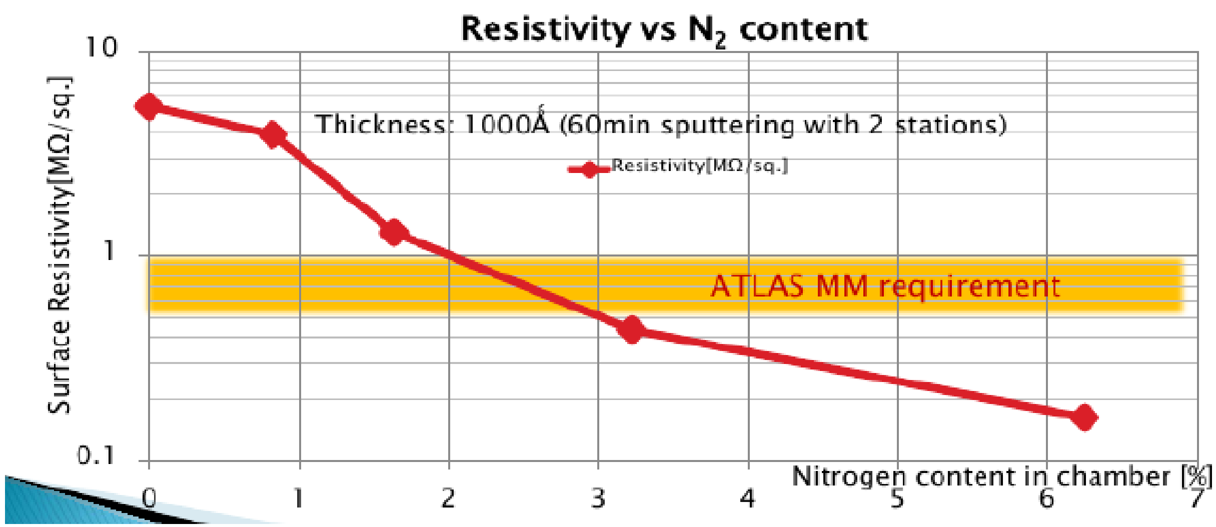
→ **improve spatial resolution and/or decrease the number of channels**

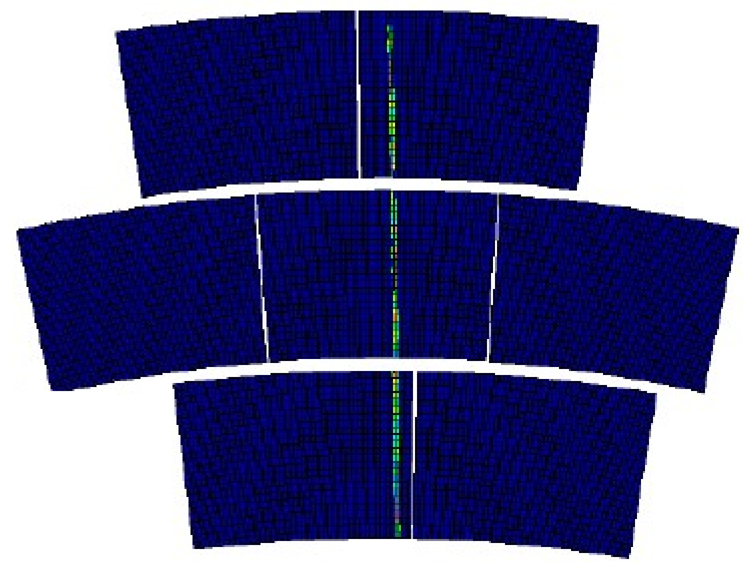
- Front and back-end TPC electronics (CEA and LPNHE)



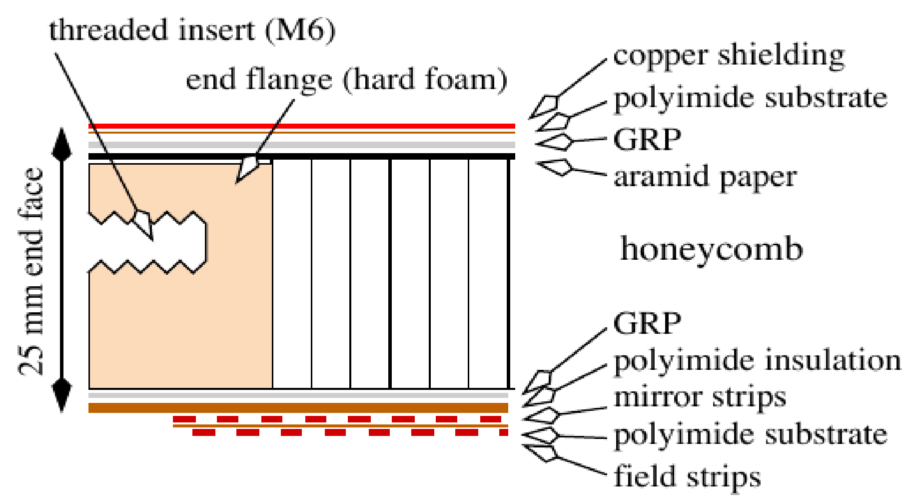
R&D for TPC

- **Resistive foil** with sputtered Diamond-like carbon as used for ILC TPC R&D and ATLAS New Small Wheels



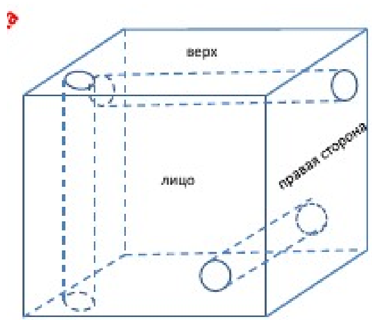


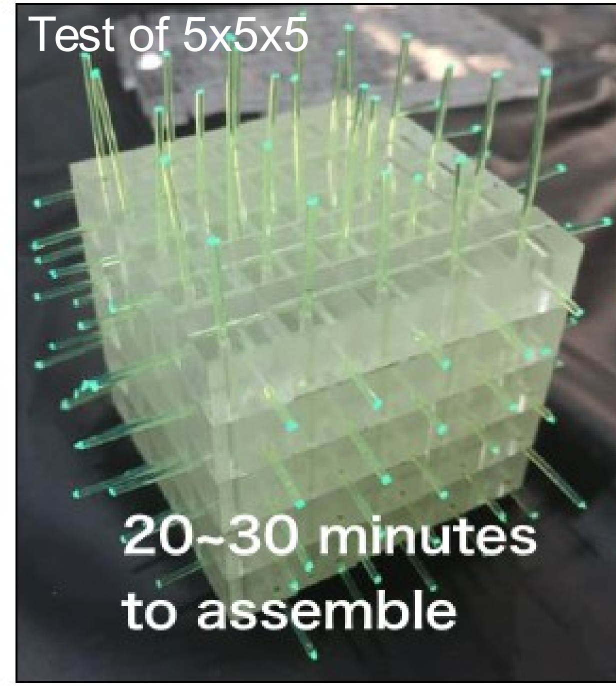
- Light **field cage** to minimize the background due to interactions on passive material (similar to Aleph/ILC field cage)



Tracker R&D

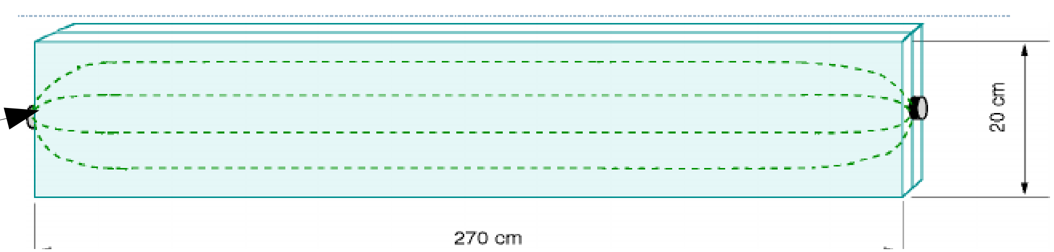
- **New detector idea:**
  3-D 'pixeled' scintillator
  (arXiv:1707.01785)

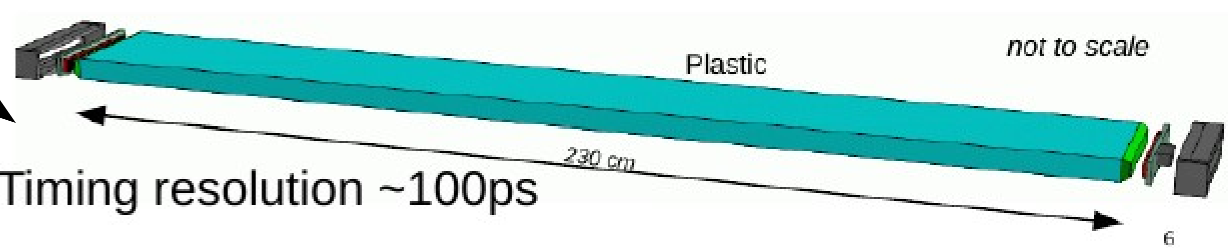




- Different **ToF technologies,** eg:

  - scintillator+fibers
  - light reader on the plastic
    (joint R&D with SHIP)

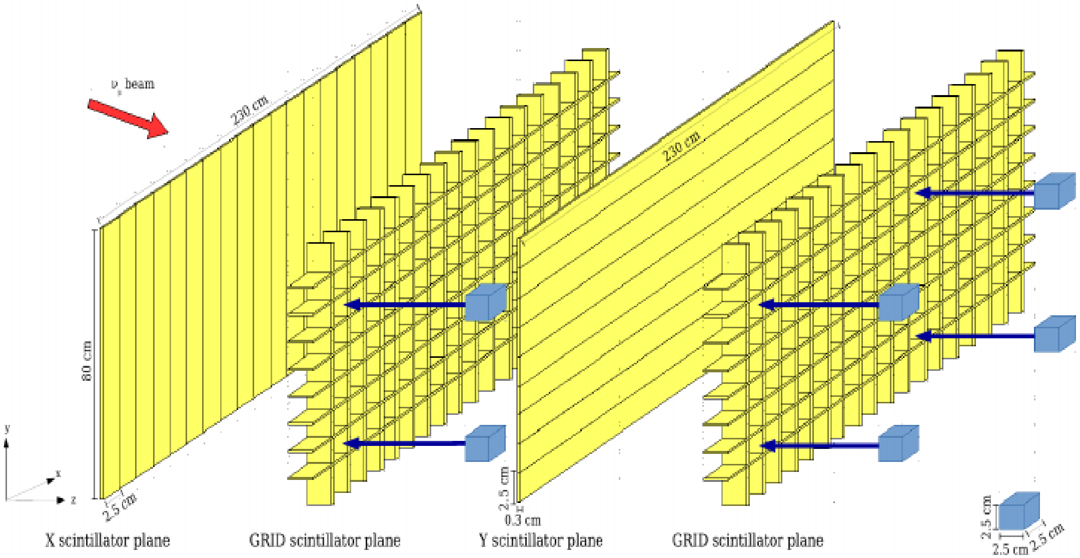


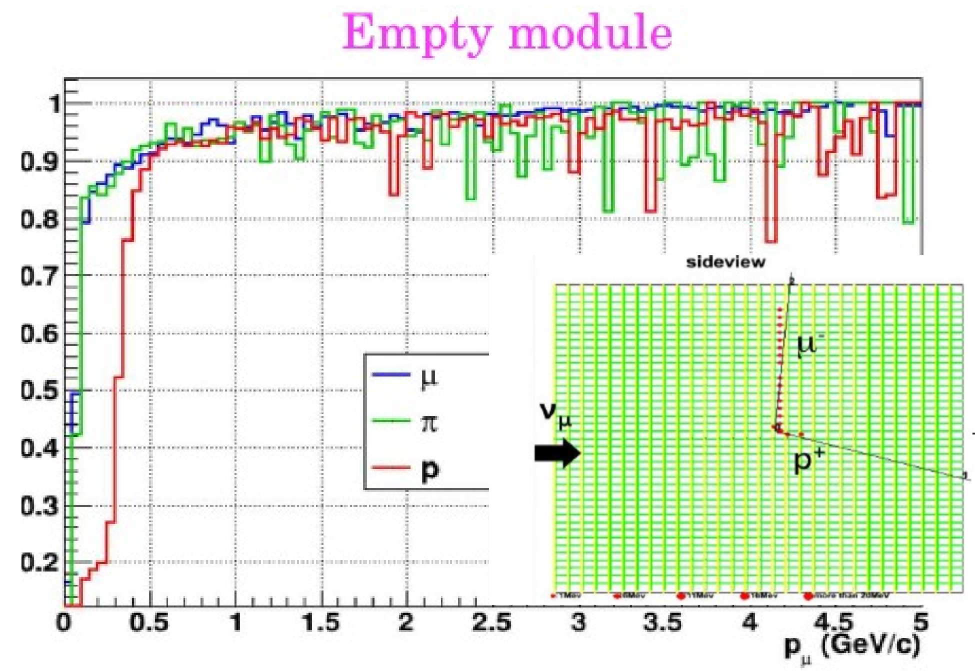


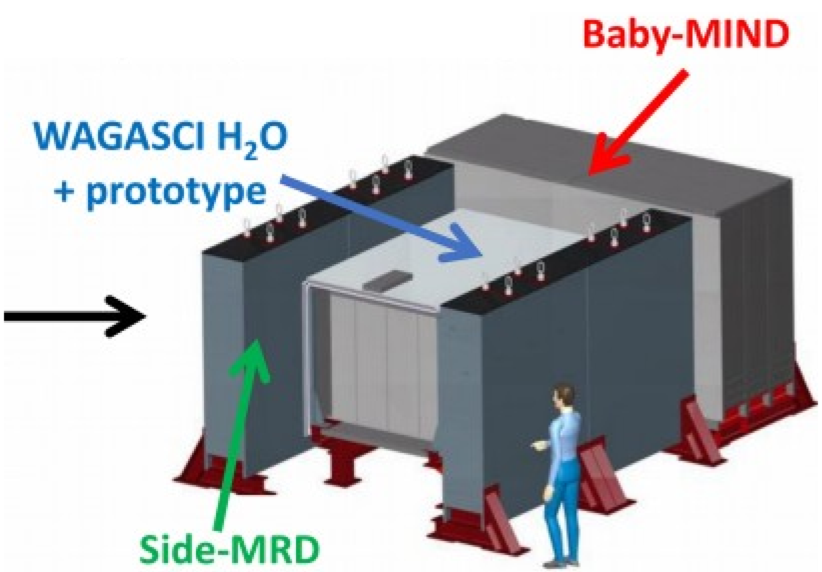
Timing resolution ~100ps

Other near detectors

- **WAGASCI** (LLR): new grid-like geometry allowing for low threshold or to be filled with water for same target as far detector







- **Baby-MIND** magnetized muon detector to measure momentum and charge of escaping muons

- Possibility also to upgrade **INGRID** (only used for checking beam position and direction)

ND280 upgrade: status

- **6 workshops with large participation** (3 at CERN and 3 in Japan)
  Linked with work on High Pressure TPC (to measure neutrino cross-section and/or as possible DUNE near detector)

- **Expression of Interest well received by CERN** (SPSC-EOI-015)
  signed by ~190 physicists from ~15 institutes

→ **full proposal submitted to CERN last week** (SPSC-P-357)!
  signed by ~220 physicists from ~40 institutes

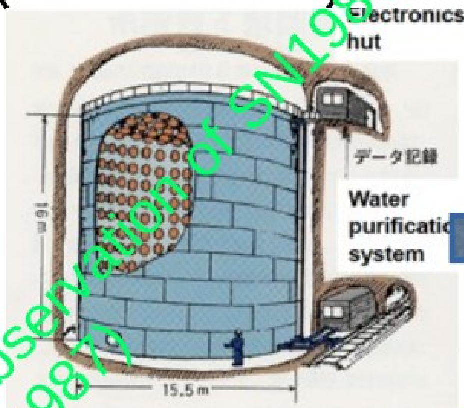
- **Important role of French T2K groups (CEA, LLR, LPNHE)**

  New collaborators welcome!!!

  e.g. work on TPC electronics in collaboration with LPNHE

The road to HyperKamiokande

Kamiokande
(1983-1996)

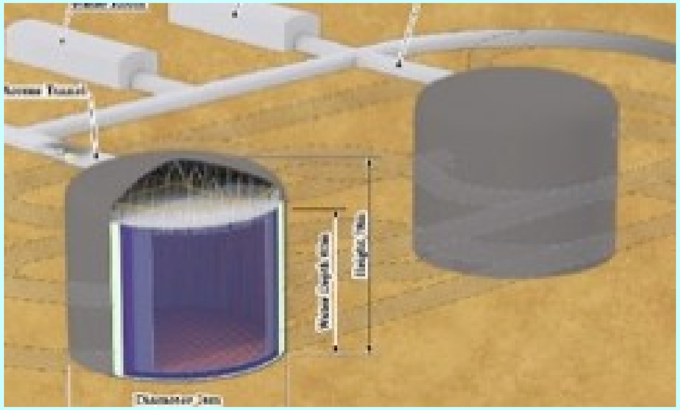


3kton
20% coverage

Super-Kamiokande
(1996-)

50kton
40% coverage

Hyper-Kamiokande
~2026



260 kton x 2 tanks
40% coverage with **high-QE**

Observation of SN1987A (1987)

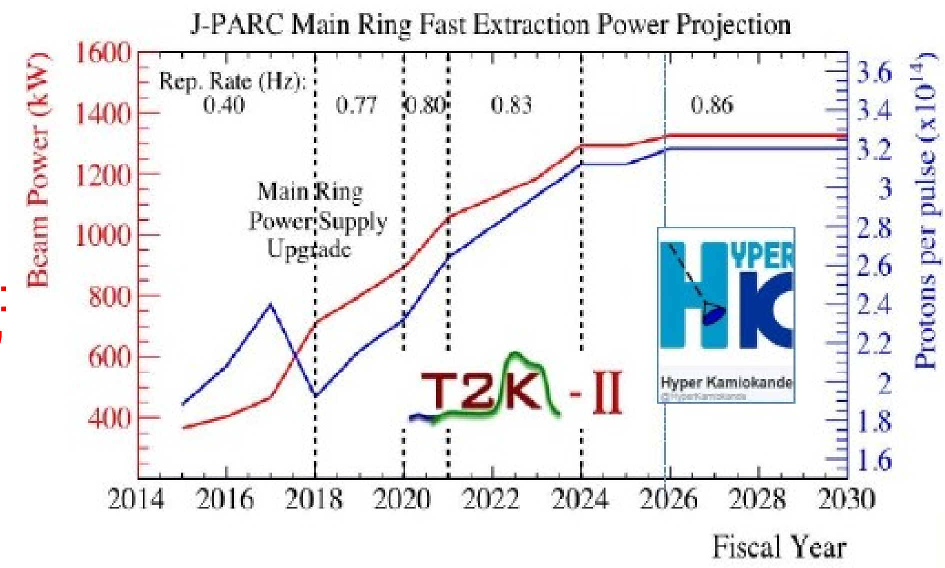
Discovery of neutrino oscillation (1998)

Observation of electron neutrino appearance (w/ beam, T2K, 2013)

x17

x10

Commitment for future ν program in Japan



- Review of KEK Project Implementation Plan (PIP): **'J-PARC upgrade for HK is the highest priority'**

Continuous beam upgrade up to 2030:

- Today beam power ~470 kW
- Upgrade of MR power supplies → 750kW by 2020
- Repetition rate increase to 0.86 Hz for 1.3MW by 2026

Nov. 8th, 2017 Inaugural ceremony

- UTokyo launched **'Next-generation Neutrino Science Organization (NNSO)'** btw ICRR, IMPU and School of Science (director T.Kajita)

- Major milestone in summer 2017: HK included in the MEXT (Japan Minister) large project roadmap → **first step to get government funding**
- “advancing neutrino physics fund" (10 million JPY for FY2018) for UTokyo which can be used for Hyper-K
- Shift of starting HK major construction in 2019

HyperKamiokande new design

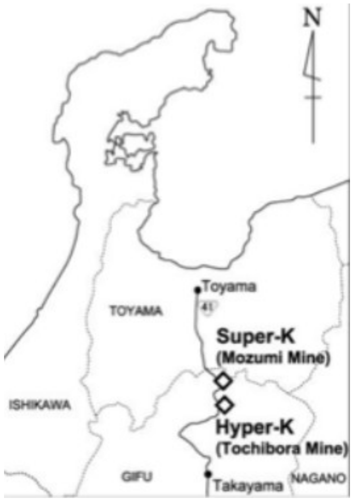
- **New staged approach with 2 cylindrical vertical tanks**

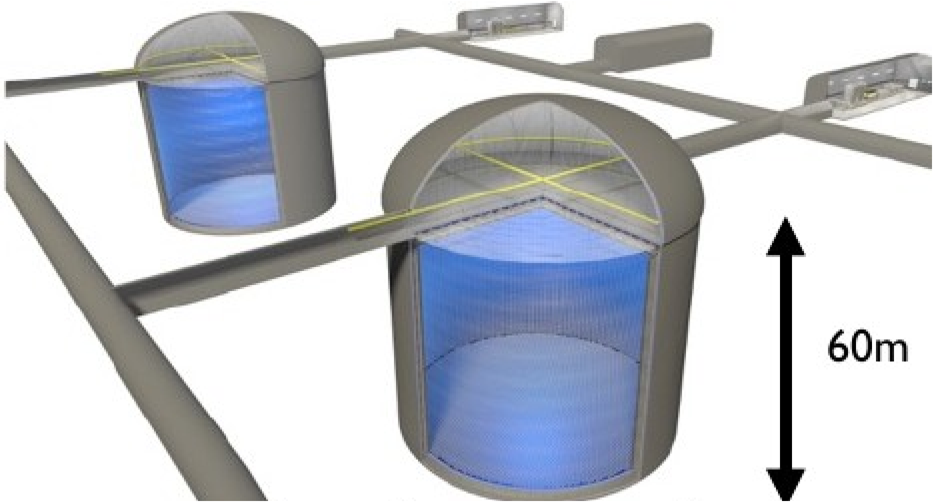
'symmetric' 2.5º off-axis position wrt SuperK

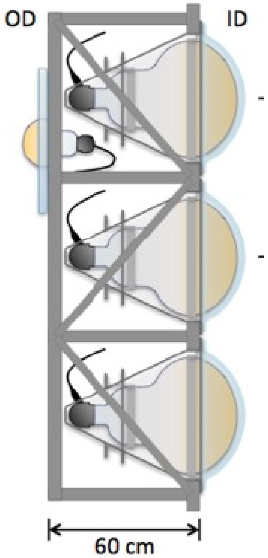
60 m height x 74 m diameter each

40000 50cm Inner Detector PMTs

6700 20cm Outer Detector PMTs



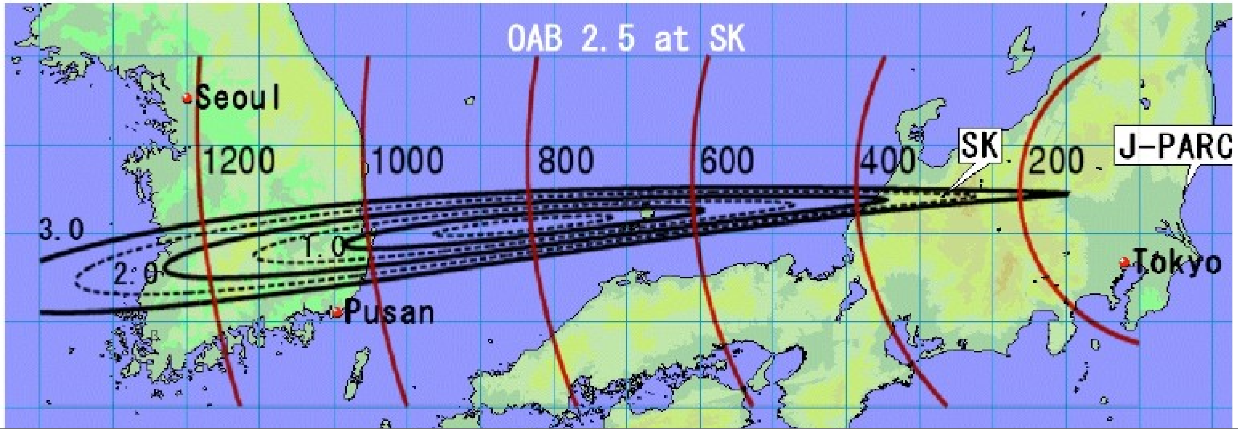




- Option: second tank in Korea to enhance MH and δ_{CP} sensitivity

1000-1200km baseline

1.3º – 3.0º off-axis

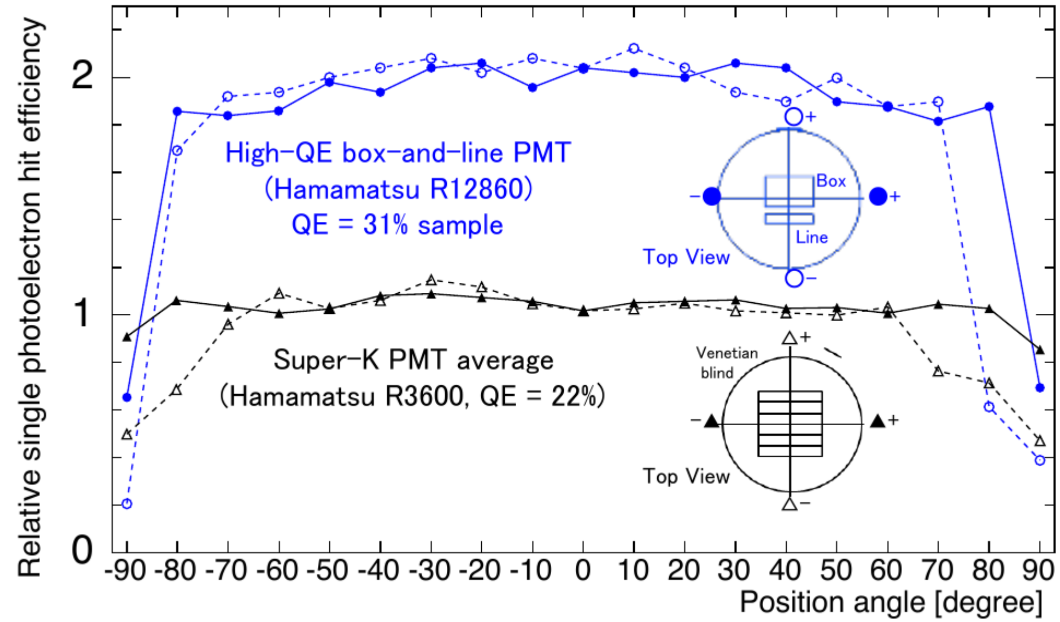


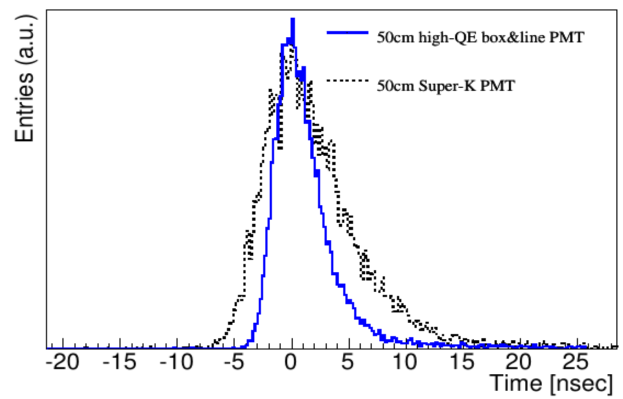
PMT development

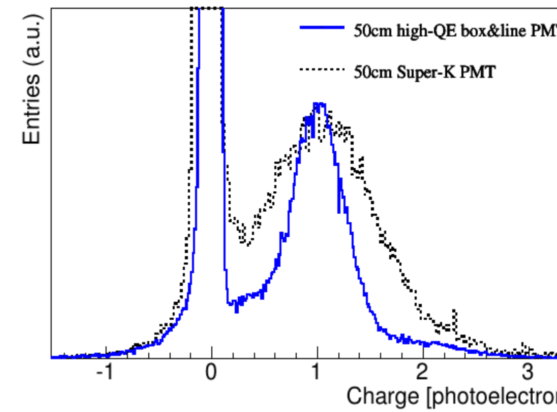
Super-K PMT

New PMT

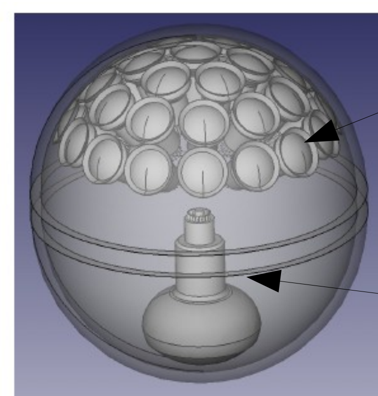
- Improved dynode:
  - 2x better photon efficiency
  - better time and energy resolution







- Further R&D on-going:
  - Multi-PMT module in collaboration with KM3NeT
  - PMT housing to prevent chain implosion



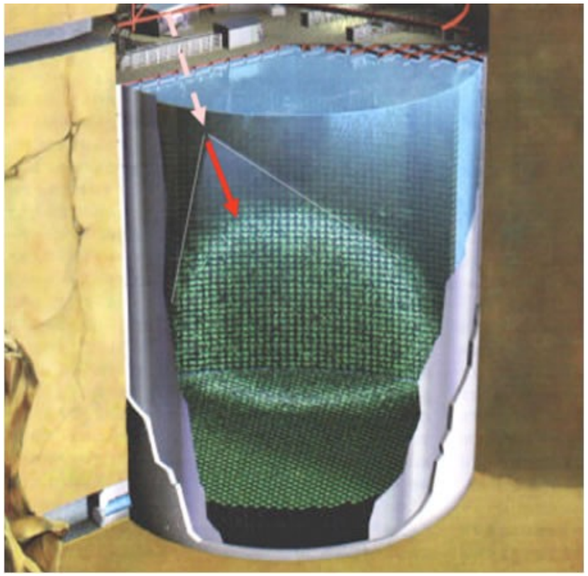
From SuperK to HyperK

		SuperKamiokande	HyperKamiokande
Total volume		50 kTon	258kTon x 2
Fiducial volume		22.5 kTon	**~370 kTon**
Tanks		1 cylindrical 41.4m (h) x 39.3m (d)	2 cylindrical 60m (h) x 74m (d)
PMTs	inner detector	11.129	40000
	outer detector	1885	6700
Photocoverage		40%	**40%**
Sensor efficiency (Quantum eff. x Collection)		18% (22%x80%)	**36%** (31%x85%)

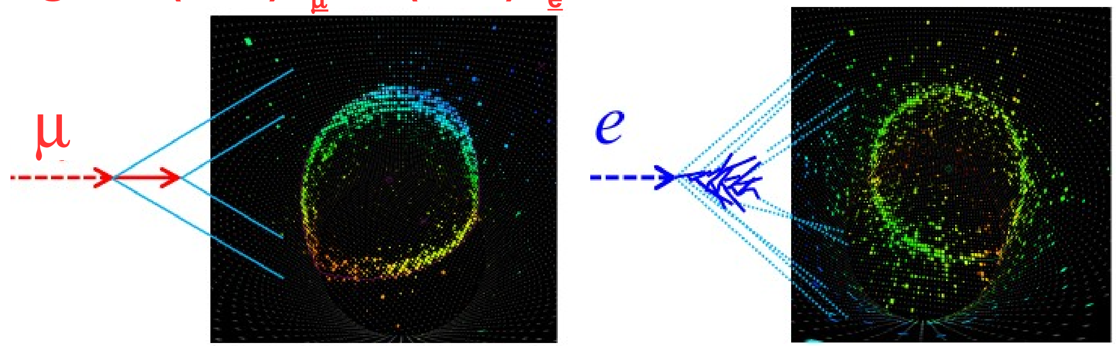
Major change in management: HyperKamiokande built as international collaboration since day1 → a lot of room for contributions:

e.g. PMT electronics: small prototype for PMT testing may be available from APC/LPNHE

How does it work?



- **Signal: (anti)ν_μ → (anti)ν_e oscillation**



clear ring **fuzzy ring**

- Lepton momentum and angle → neutrino energy
- Select events with no outgoing pions (1 ring) (Quasi-Elastic interactions) $\nu n \rightarrow l^- p$ (outgoing nucleon undetected)

- **Backgrounds:**

- Outer volume with outward facing PMT to veto external background
- **PMT timing** to select beam bunches and reconstruct vertex position in fiducial volume

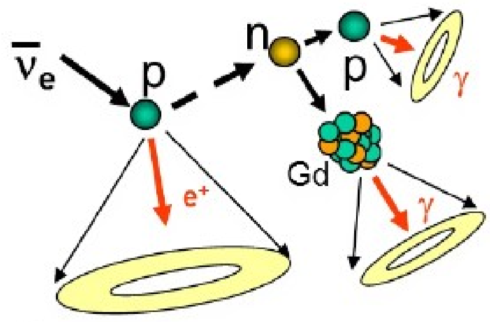
ν interactions from beam:
- intrinsic ν_e component in the beam
- pions: **$\pi^{+/-}$ undetected** and $\pi^0 \rightarrow \gamma\gamma \rightarrow$ e-like ring + **γ undetected**
- $\bar{\nu}$ oscillations: intrinsic ν component in the beam

No magnetic field → no charge measurement ($\nu/\bar{\nu}$)

Gd doping to tag neutrons to distinguish: $\nu n \rightarrow l^- p$ from $\bar{\nu} p \rightarrow l^+ n$

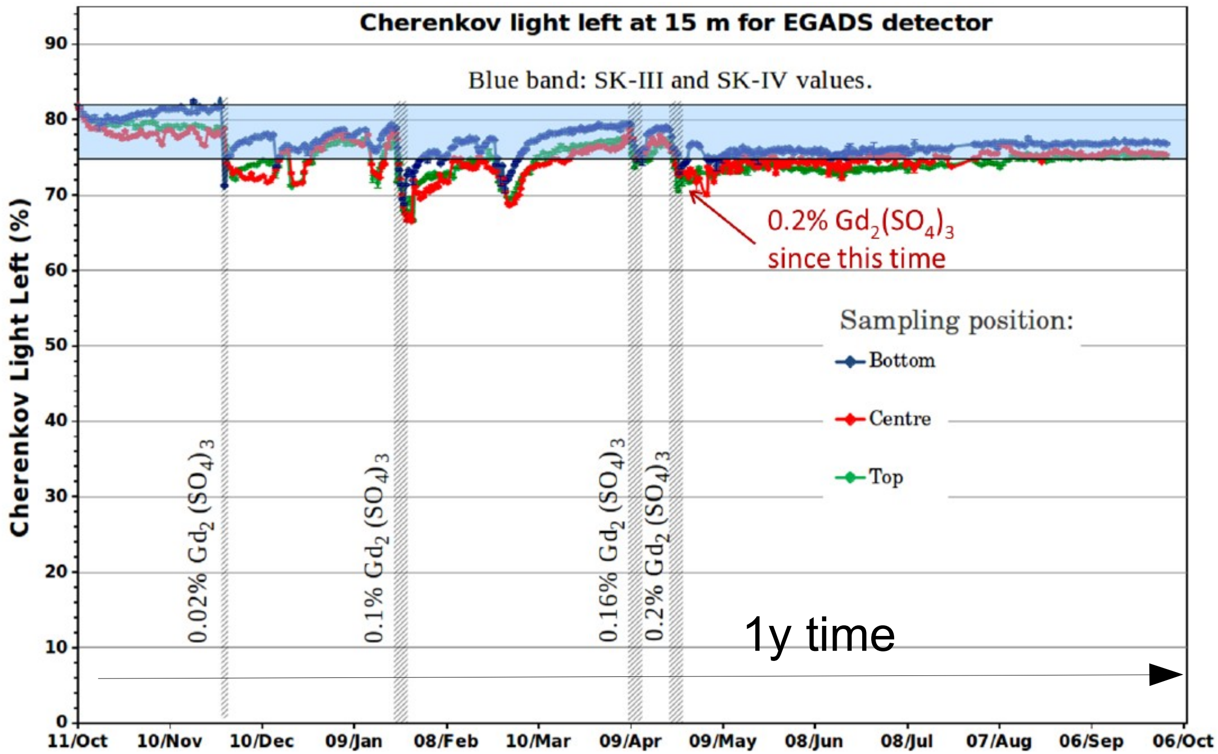
Gadolinium doping

- $\bar{\nu}p \rightarrow l^+n \rightarrow$ n get captured in Gd with emission of few γ ~8MeV
$\rightarrow$ useful to enhance sensitivity to SuperNova ν and proton decay
($\rightarrow$ for beam neutrino physics: ν vs $\bar{\nu}$ separation)



- **EGADS: 200 ton scale model of SuperKamiokande fully operative in Kamioka mine**

All the trick is about keeping water pure and transparent without loosing Gd (dedicated filtration system)

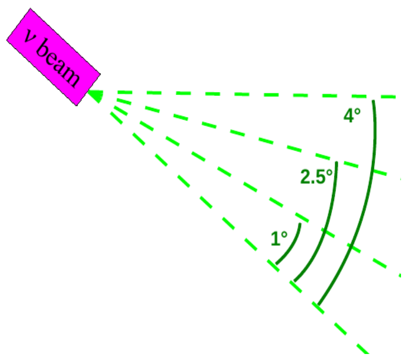


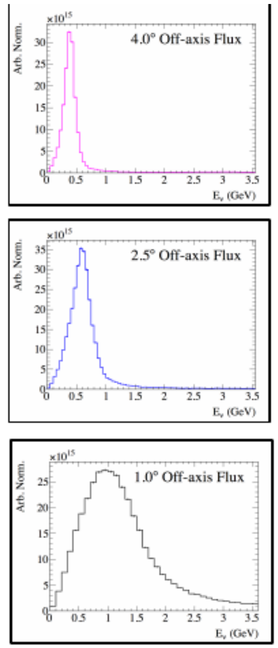
- SuperKamiokande will run with loaded Gd in next years!

Intermediate Cherencov detector

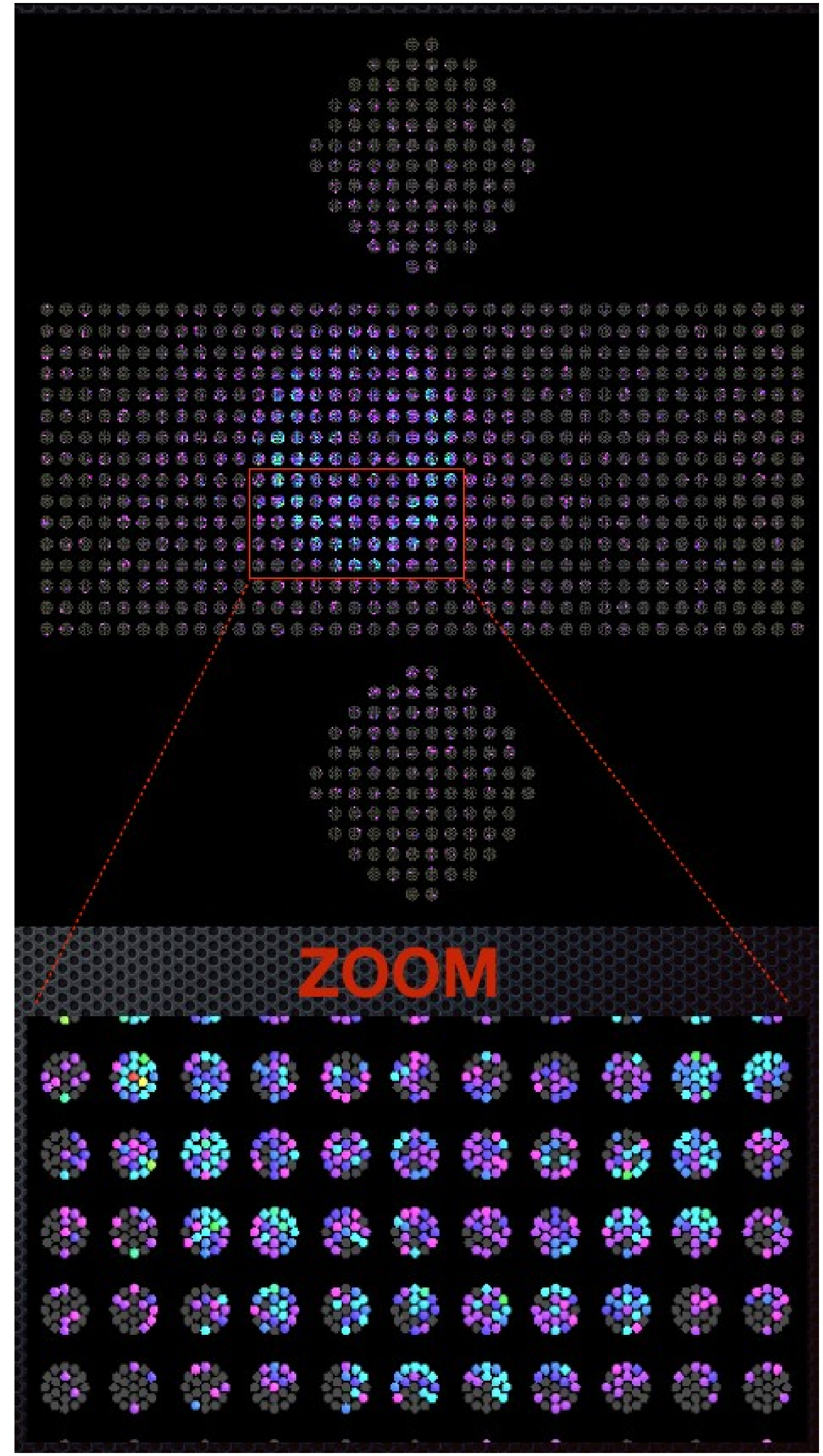
JPARC E61 **WC detector at ~1-2km** (TITUS + NuPrism)

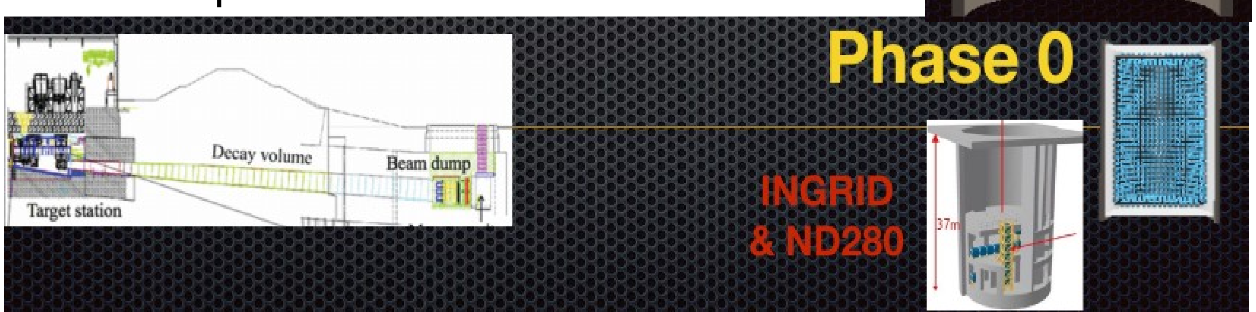
- spanning of off-axis angle ↔ different E_ν





- MultiPMT, Gd doping
- Phase 0 (6m height) : prove the technology and measure $\sigma(\nu_e)/\sigma(\nu_\mu)$ at ~3% precision

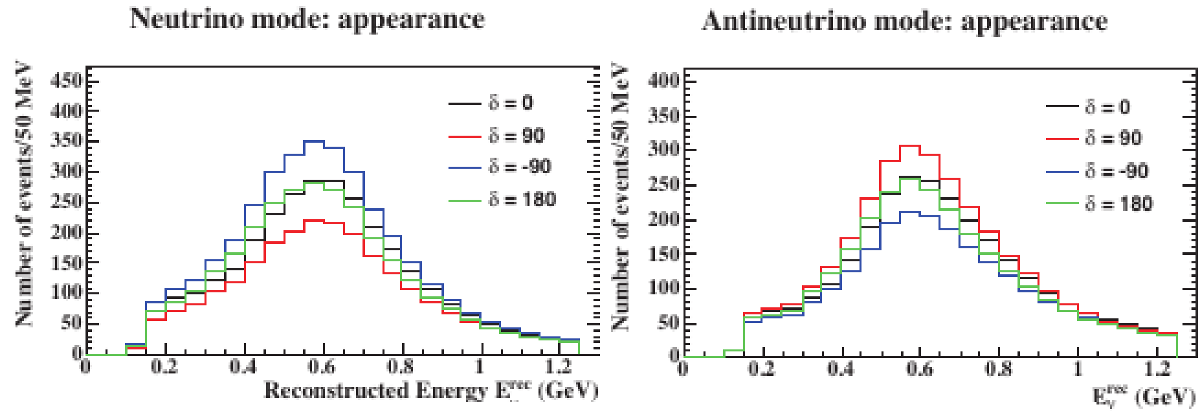




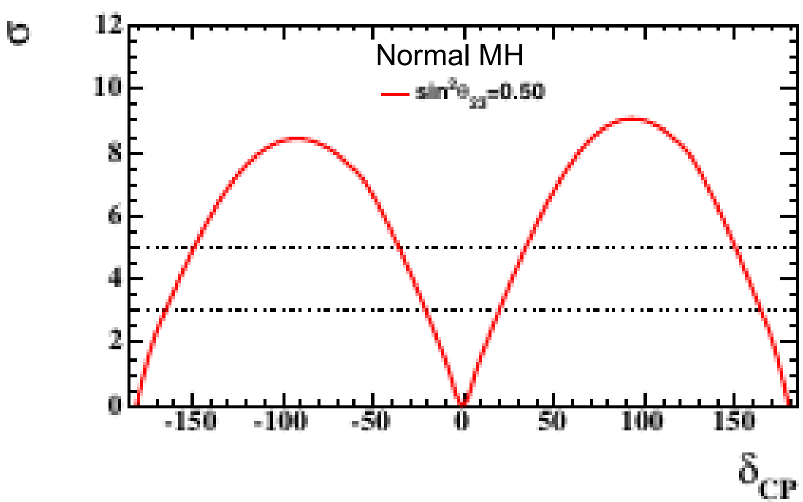
Sensitivity for neutrino oscillation

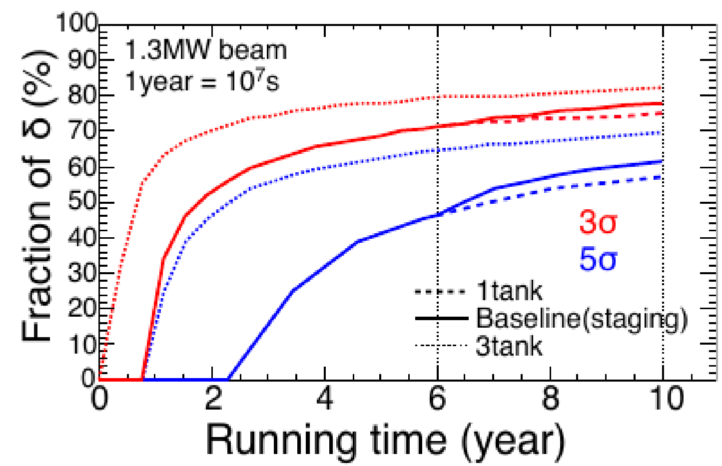
10 years 1.3 MW with old design
(new design ~2/3 fiducial volume)

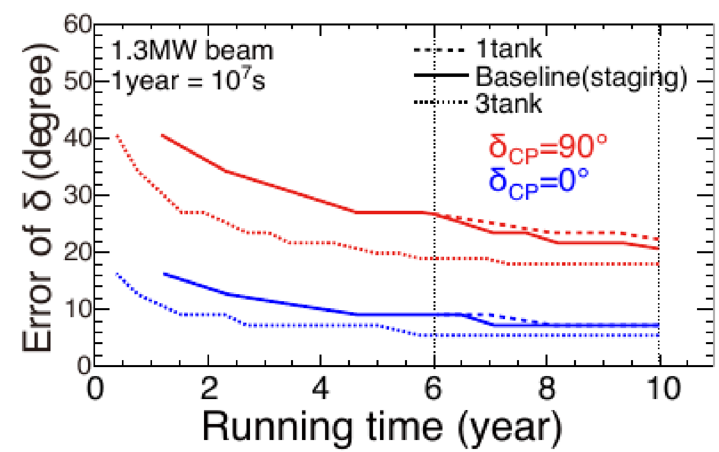
		signal			
		$\nu_\mu \to \nu_e$	$\overline{\nu}_\mu \to \overline{\nu}_e$	BG Total	Total
ν mode	Events	2300	21	560	2880
	Eff.(%)	63.6	47.3	1.6	—
$\bar{\nu}$ mode	Events	289	1656	724	2669
	Eff. (%)	45.0	70.8	1.6	—



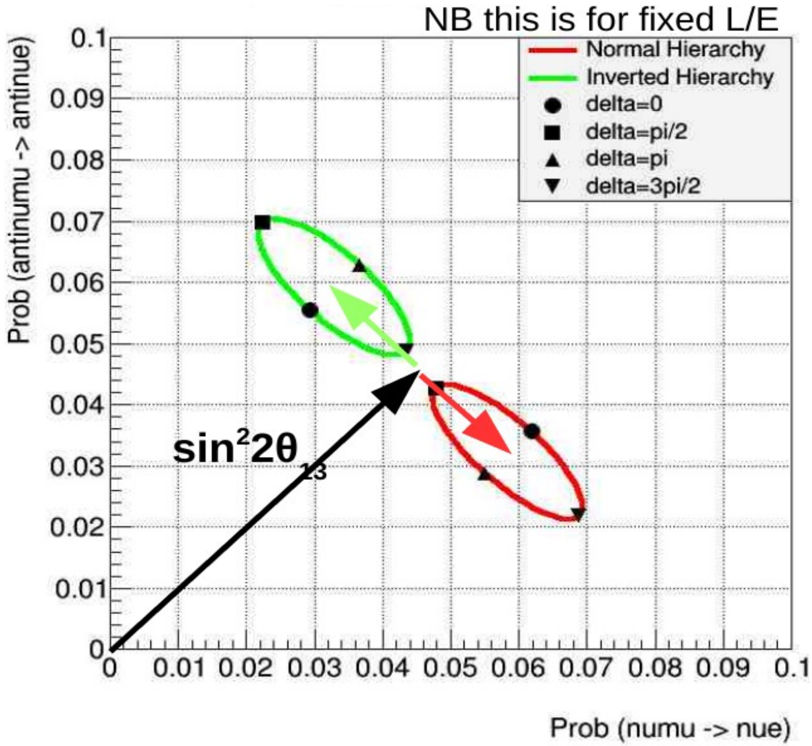
δ_{CP} sensitivity > 5σ





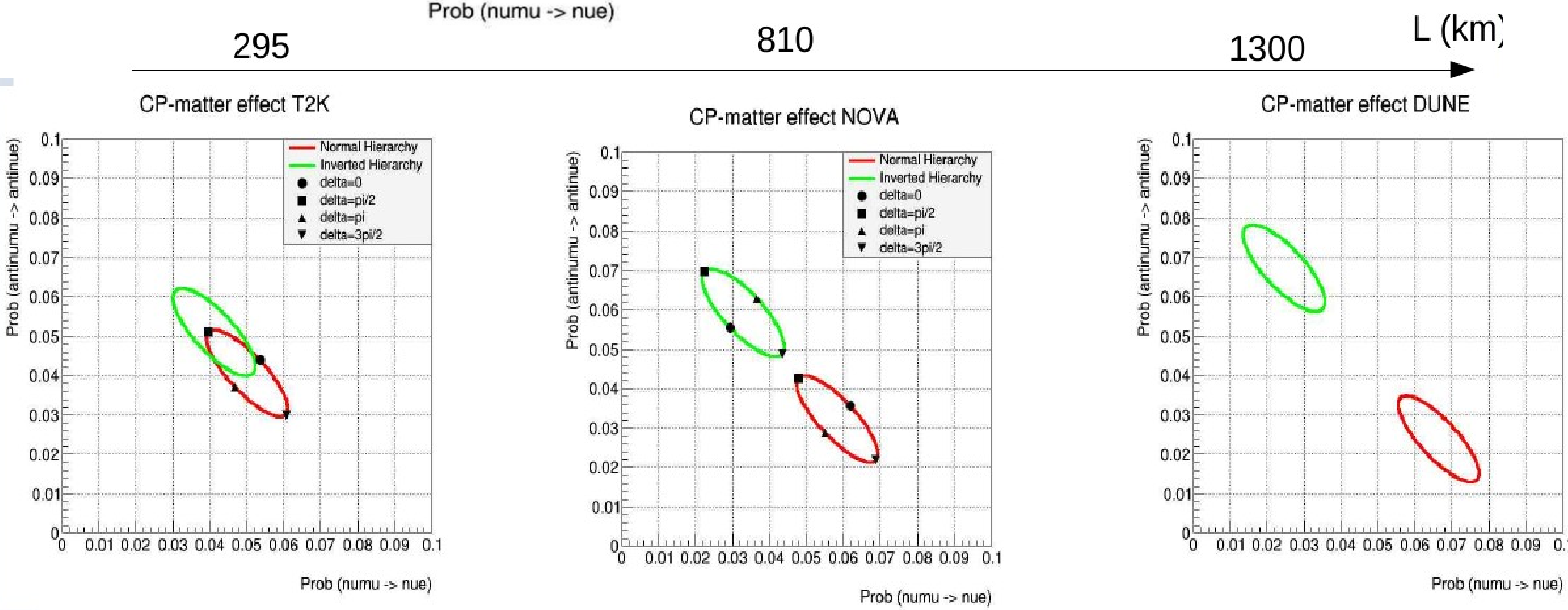


Added value : **robust model of systematic uncertainties from T2K experience**



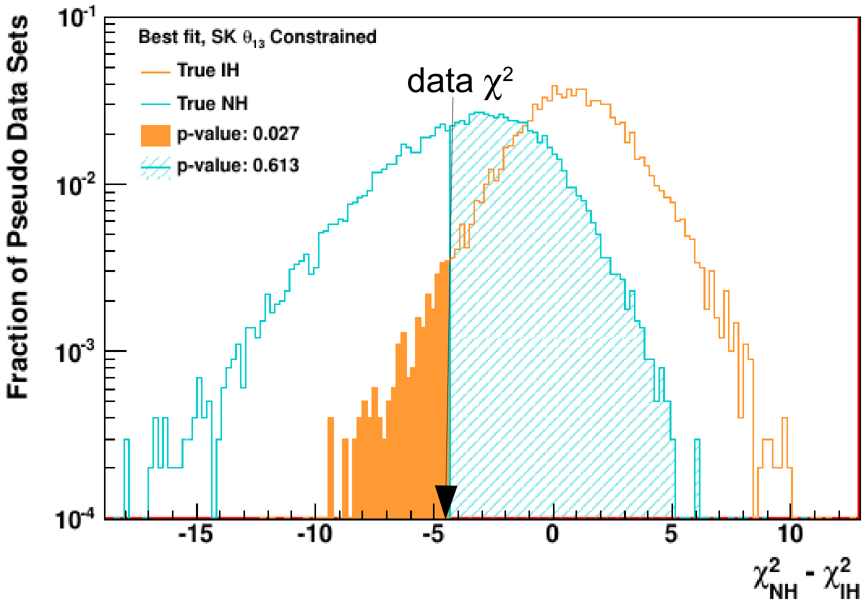
Mass Hierarchy

- NOVA can reach 3σ on MH for favorable δ_{CP} values
- Various other projects on-going aiming to 3σ on MH: JUNO, ORCA, PINGU
- Matter effects is a relatively small effect at T2K: ~10% versus the dominant effect of δ_{CP} (30%) → sensitivity at SK and HK from atmospheric ν!



MH sensitivity from SK (T2K) to HK (T2HK)

- **First SK + T2K combination →**
MH constraints (arXiv:1710.09126)



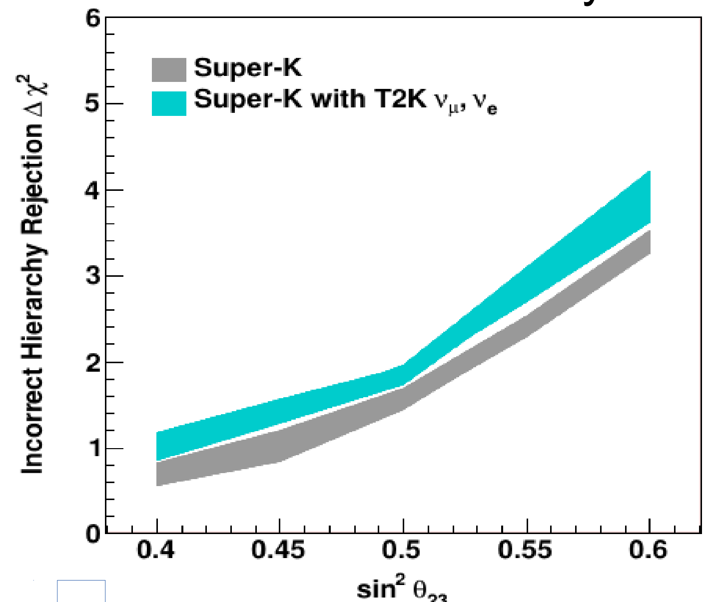
Uncertainty spanning 90% CL of other oscillation parameters:

IH disfavored at 81% - 97% (SK alone)

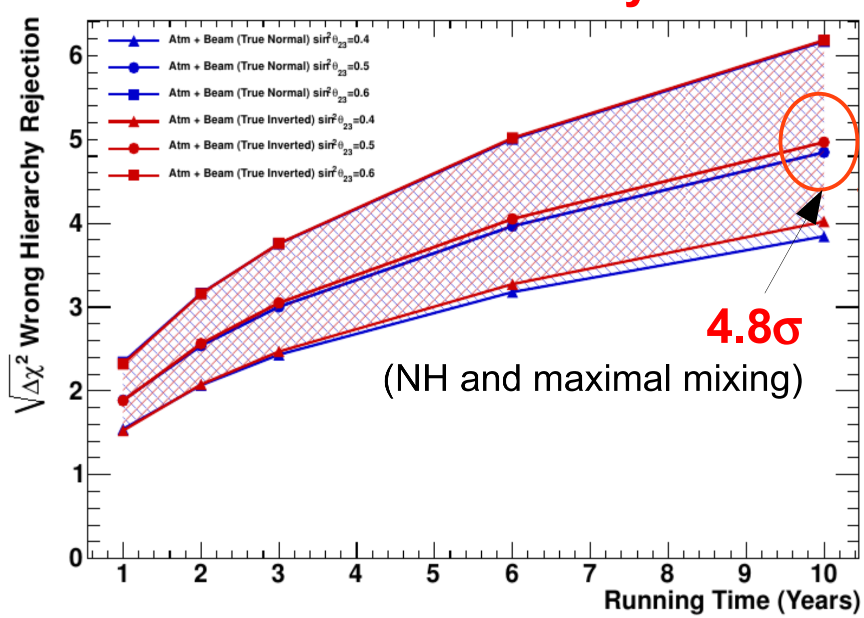
91.5% - 94.5% (SK + T2K)

- HK sensitivity ~4.8σ in 10y at most probable values from present data: maximal $\sin\theta_{23}$, δ_{CP} at $-\pi/2$ and NH

SK-T2K MH sensitivity



T2HK-HK MH sensitivity

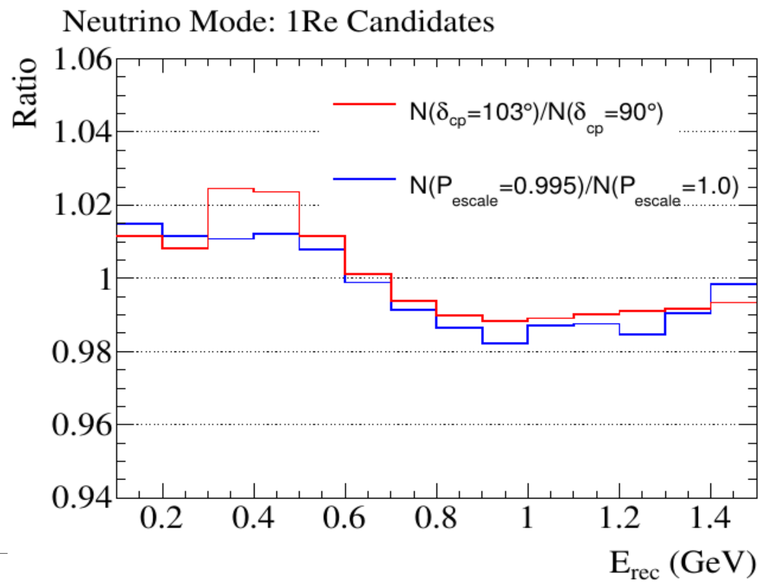


Systematic uncertainties

- Uncertainties in 2017 T2K results: dominated by knowledge of nuclear effects in ν-nucleus interactions (ν_e xsec) → importance of using **well known target nucleus**

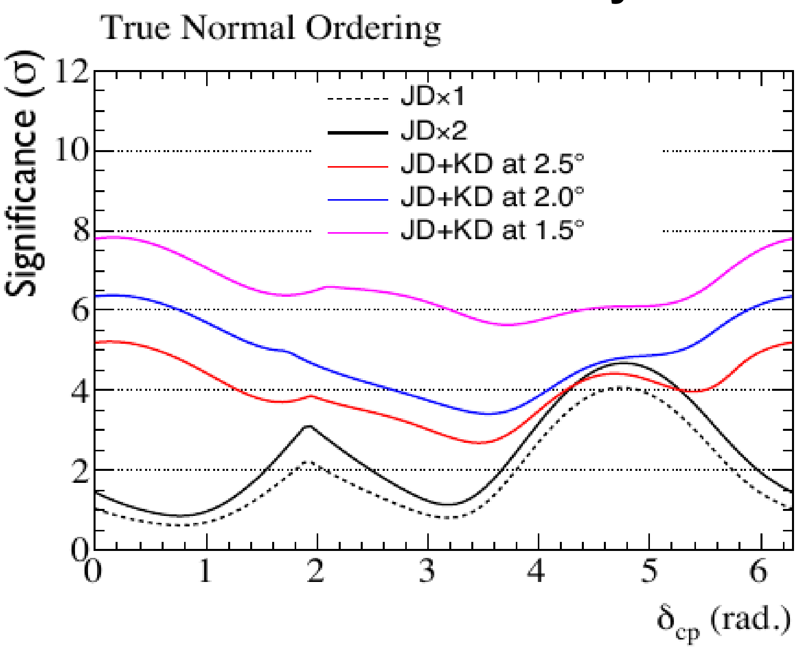
	% errors on predicted event rates				
	1R μ-like		1R e-like		
	ν-mode	ν̄-mode	ν-mode	ν-mode (+1π)	ν̄-mode
SK detector	1.9 %	1.5%	3.0%	16.7%	4.2%
SK FSI+SI+PN	2.2%	2.0%	3.0%	11.4%	2.3%
ND constraint (flux & cross-section)	3.2%	2.7%	3.2%	4.1%	2.9%
$\sigma(\nu_e)/\sigma(\nu_\mu)$	<0.05 %	<0.05 %	2.6%	2.6%	1.5%
Neutral currents	0.3%	0.3%	1.1%	1.0%	2.6%
Total	4.4%	3.8%	6.1%	20.9%	6.5%

- Importance of uncertainties in energy scale: 0.5% shift fully degenerate with 10° change in δCP !
  - need **stable and well known calibration and very good uniformity**
  - nuclear effects in E_ν reconstruction

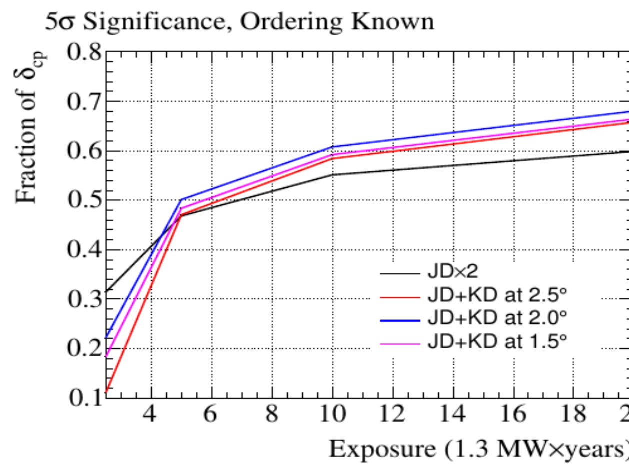


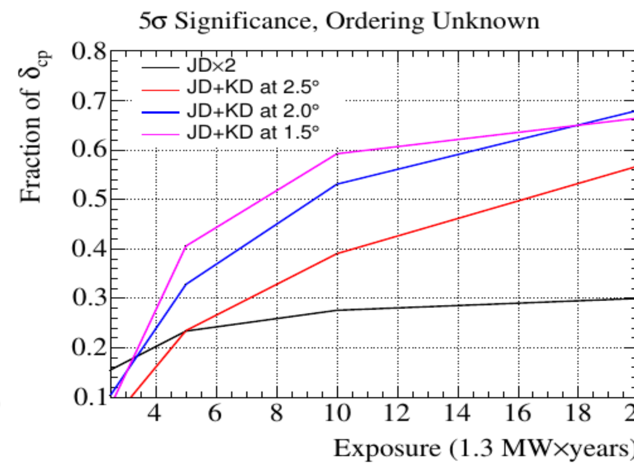
Boost to oscillation sensitivity with 2nd tank in Korea

MH sensitivity

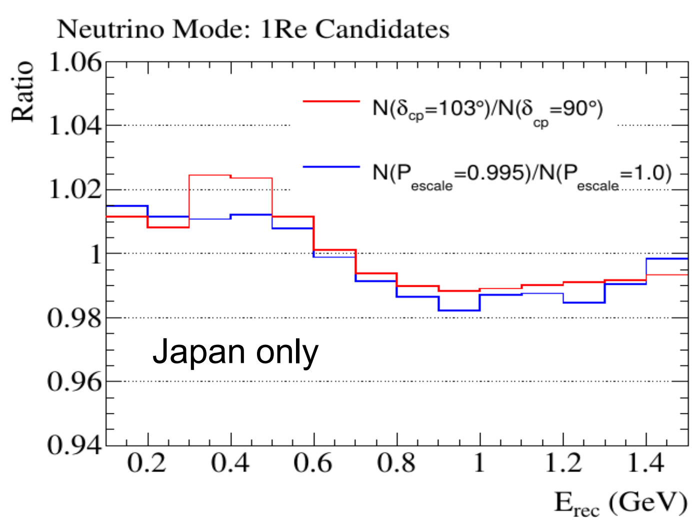


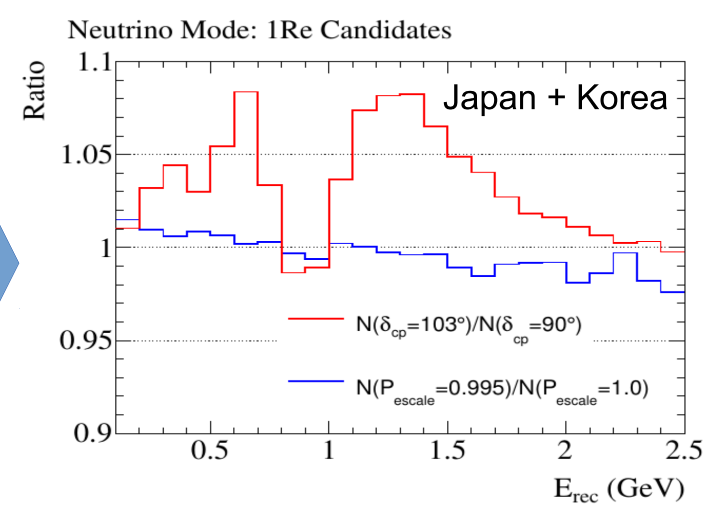
δ_{CP} sensitivity





δ_{CP} measurement less dependent on E_ν reconstruction

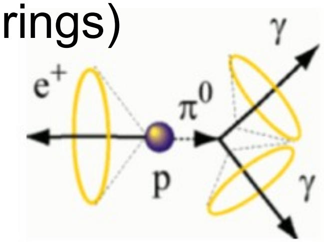




Proton decay

- **$p \to e^+ \pi^0 (\to \gamma\gamma)$**

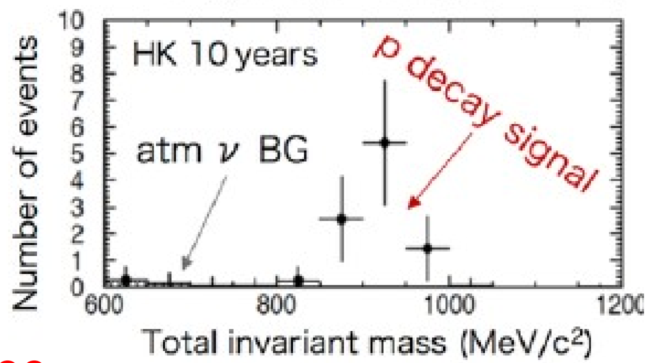
- Full recontruction of final state (2 or 3 rings)



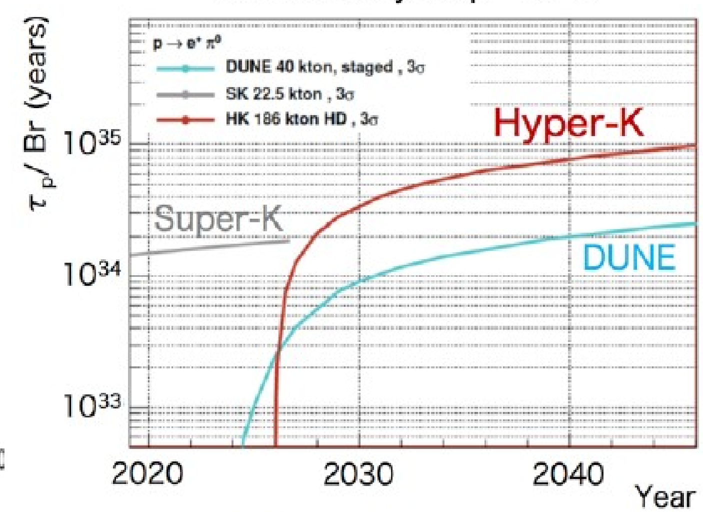
- CC Background removed with neutron tagging

~0.7 ev/MTon/y background free

Invariant mass assuming $\tau/Br = 1.7 \times 10^{34}$ years (SK 90% C.L. limit)

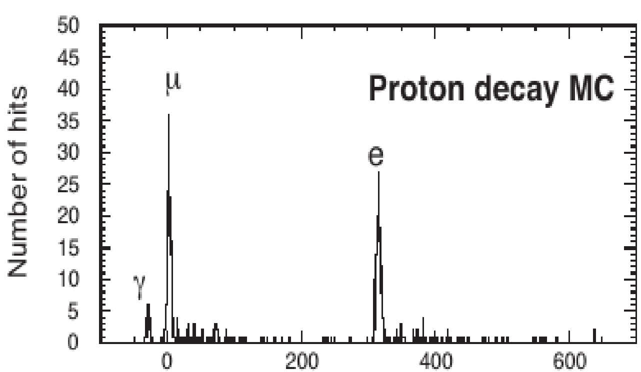


3σ sensitivity for $p \to e^+ \pi^0$

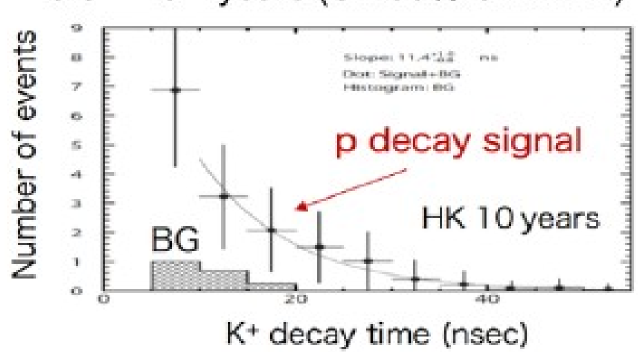


- **$p \to \bar{\nu} K^+$** (+ deexcitation γ 6.3MeV)

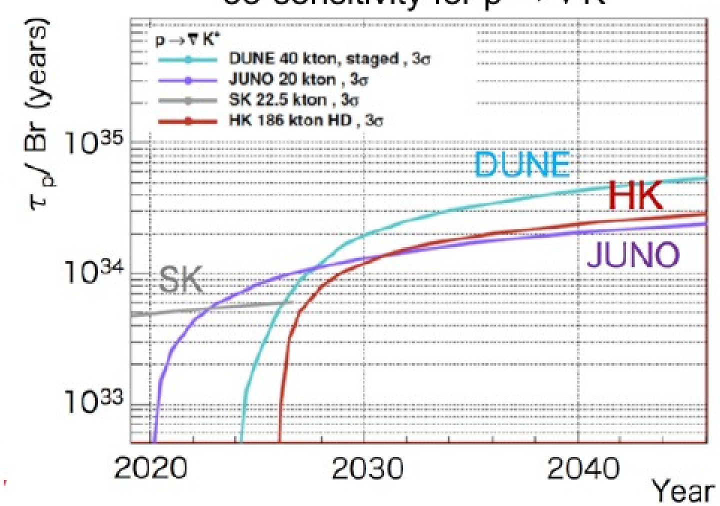
$K^+ \to \nu \mu^+$
$K^+ \to \pi^+ \pi^0$
delayed and monochromatic 236 MeV



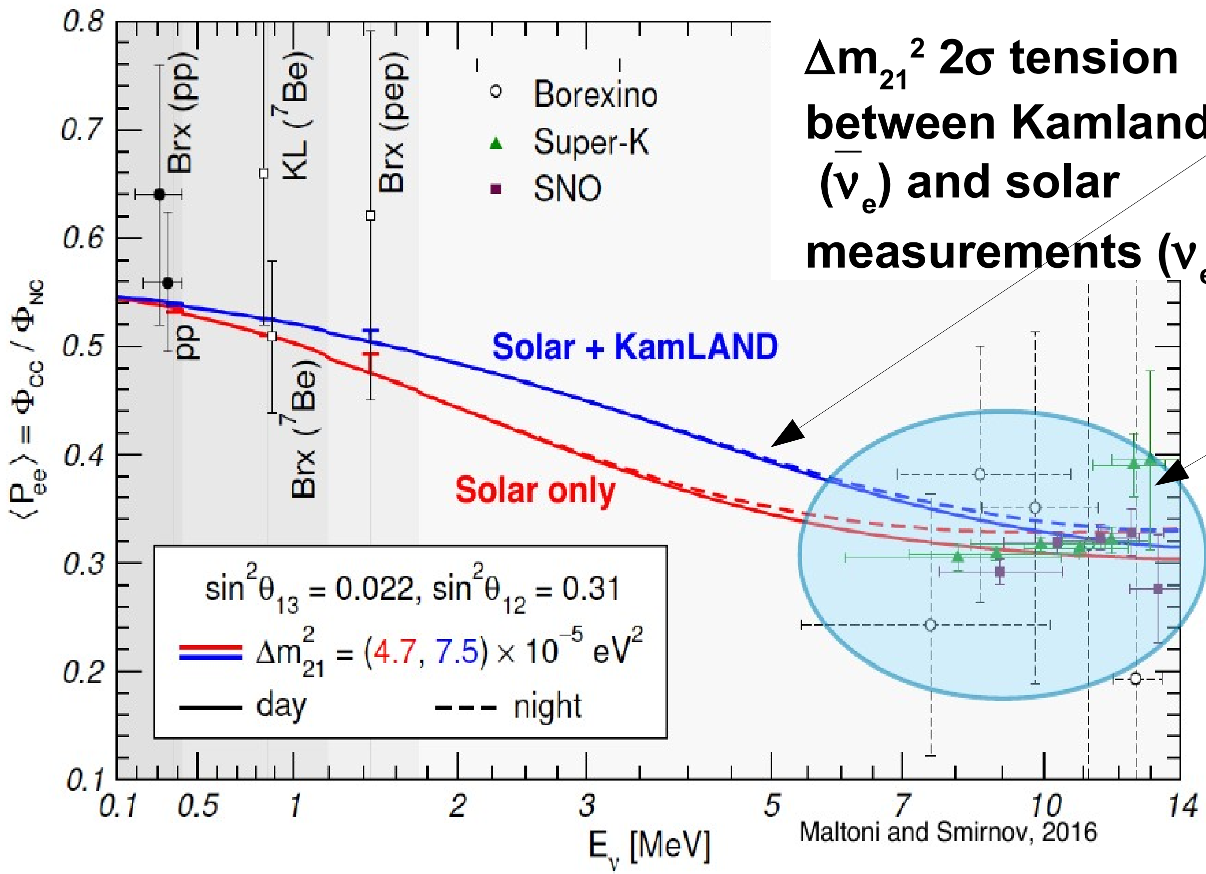
K^+ decay time assuming $\tau/Br = 6.6 \times 10^{33}$ years (SK 90% C.L. limit)



3σ sensitivity for $p \to \bar{\nu} K^+$



Solar neutrinos

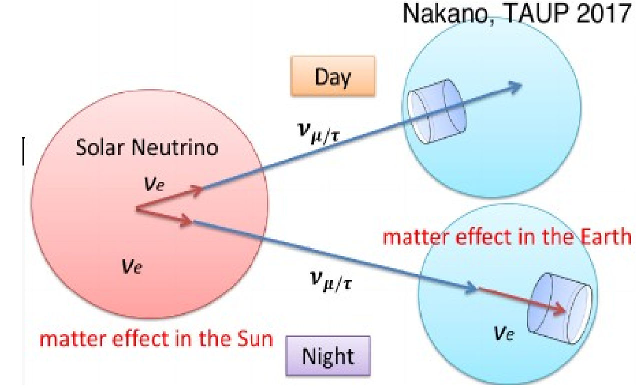


Δm_{21}^2 2σ tension between Kamland ($\bar{\nu}_e$) and solar measurements (ν_e)

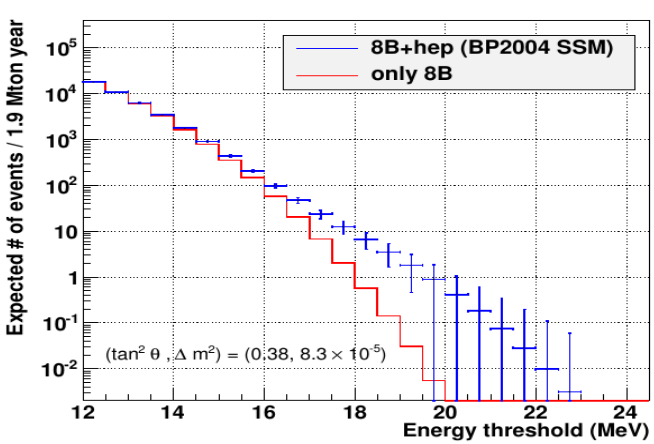
- it can be resolved with 'upturn' measurement (never measured!)

  HK threshold 4.5 (3.5) MeV → 3(5)σ in 10 years

- or with Day/Night asymmetry at 8B energy (3σ from SK in 2016!)

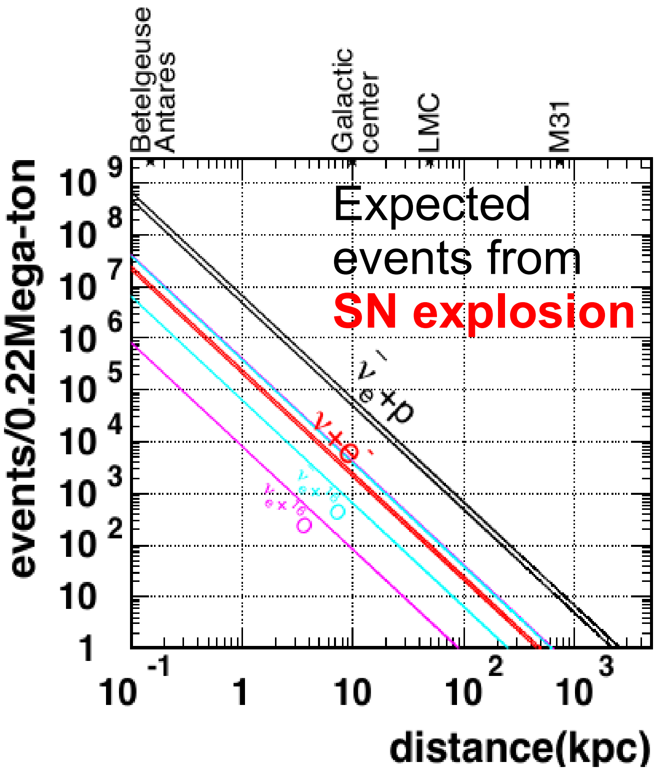


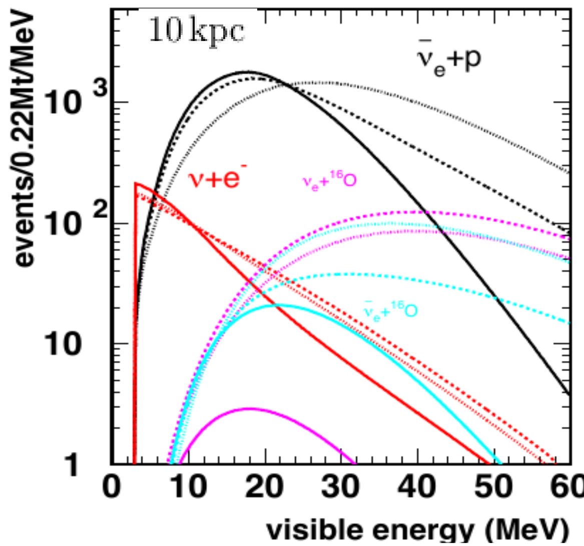
HK 5σ discovery → 4-6σ to distinguish the solar from reactor solution



- First measurement of hep neutrino (>15 MeV) possible at HK: **2-3 σ**

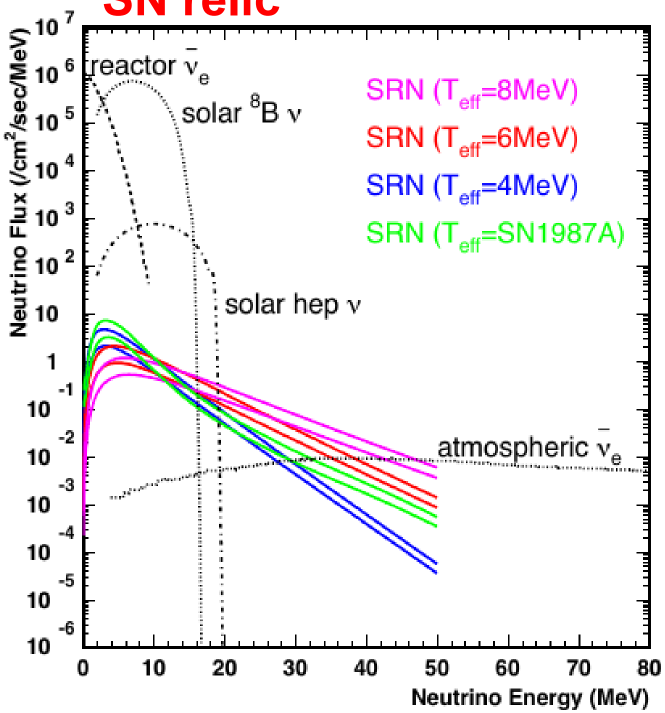
SuperNova ν

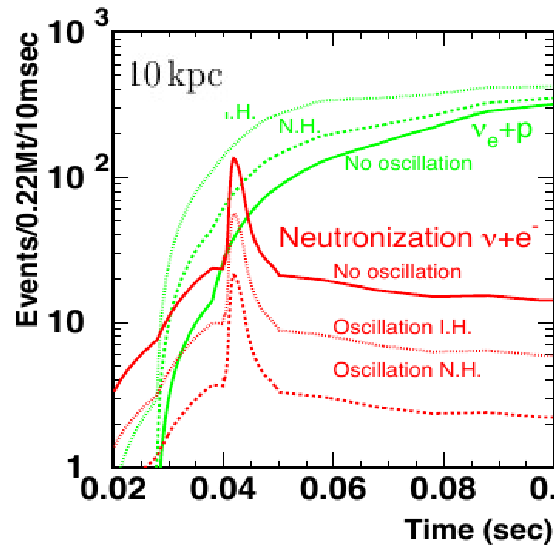


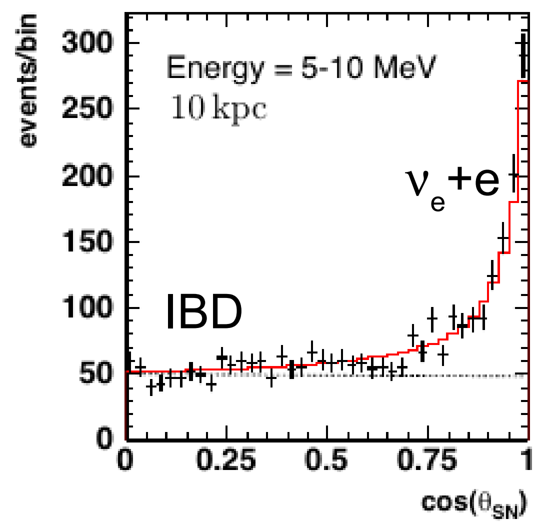


- Signal of $\bar{\nu}_e$+p (IBD)
- Signal of $\nu_e+e^- \rightarrow \nu_e+e^-$ can be identified with timing peak at neutronization and and directionality of interaction

SN relic





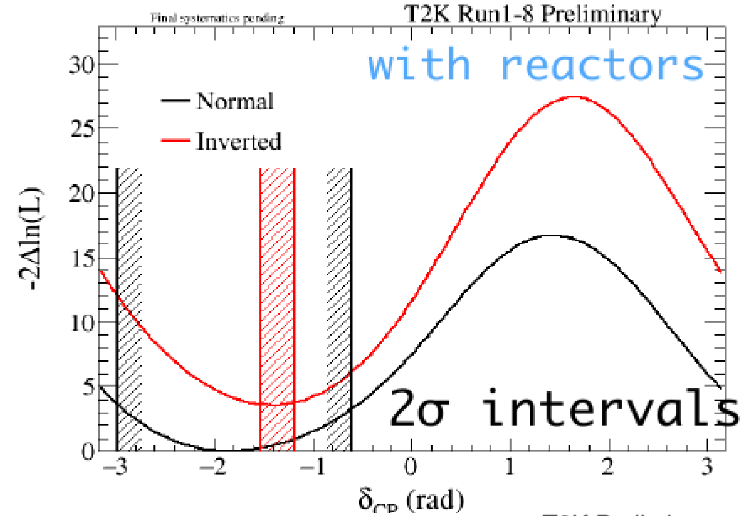


- SRN: background-free window 20-30 MeV
→ ~7 ev/year (~5σ in 12years)
- SK-Gd 10-20 MeV (Evis>5MeV) → ~30 ev/y

Summary

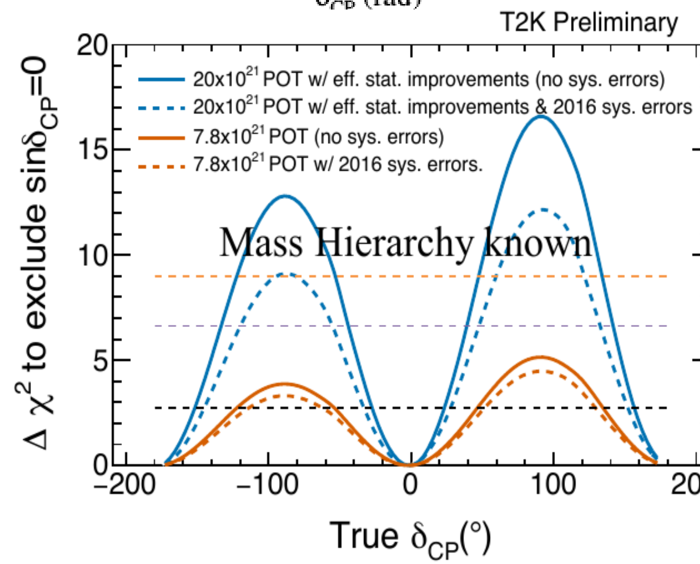
- **T2K running with excellent performances:**
  first 2σ CL for δ_{CP}
  (maximal CPV suggested in agreement with NOVA)

  T2K δ_{CP} measurement will be until the end (2021) limited by statistics



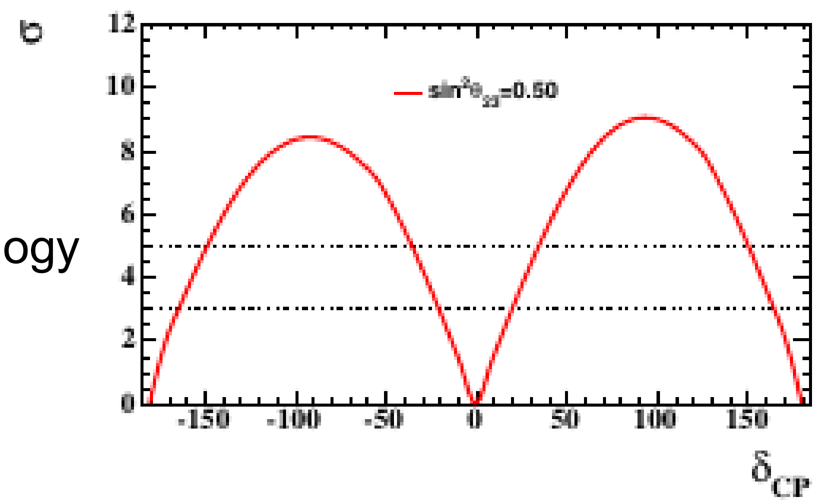
- Request for **T2K-2: 2.5 larger statistics by 2026**
  → **3σ evidence for CP violation possible**

  - JPARC Main Ring upgrade
  - Upgrade of the near detector to minimize the systematics



- **HyperKamiokande (T2HK) built on the SuperKamiokande (T2K) succes:**

  - commitment of Japan (KEK and MEXT)
  - fiducial volume x coverage x sensor efficiency ~15-30 times better than SK
  - **>5σ assured for δ_{CP} in 10y**: very well known technology and with robust model of detector and systematics
  - **Mass Hierarchy in 10y: 4.8σ** beam+ atmospheric and **6σ** with Korea tank



Conclusions

- **Very promising program of neutrino oscillation physics (and beyond: proton decay, …) assured in Japan for next ~20y**

- New spirit in HyperKamiokande collaboration: fully open and international collaboration

  → **a lot of room for contributions**

  \+ newcomers can get expertise on the physics through **T2K and T2K-2**, assuring major physics output until 2026!

  - work on T2K-2 TPC in collaboration with CEA and LPNHE

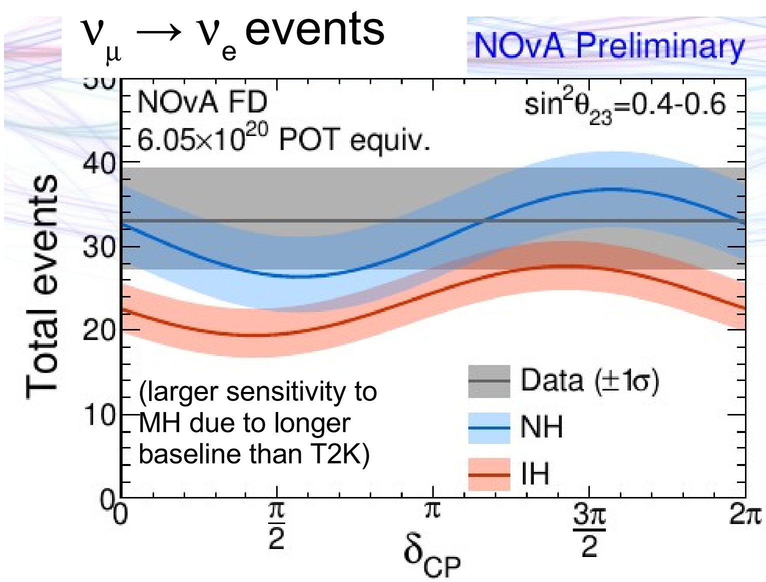
  - development and qualification of HK PMT electronics

  - manpower needed in the physics analyses

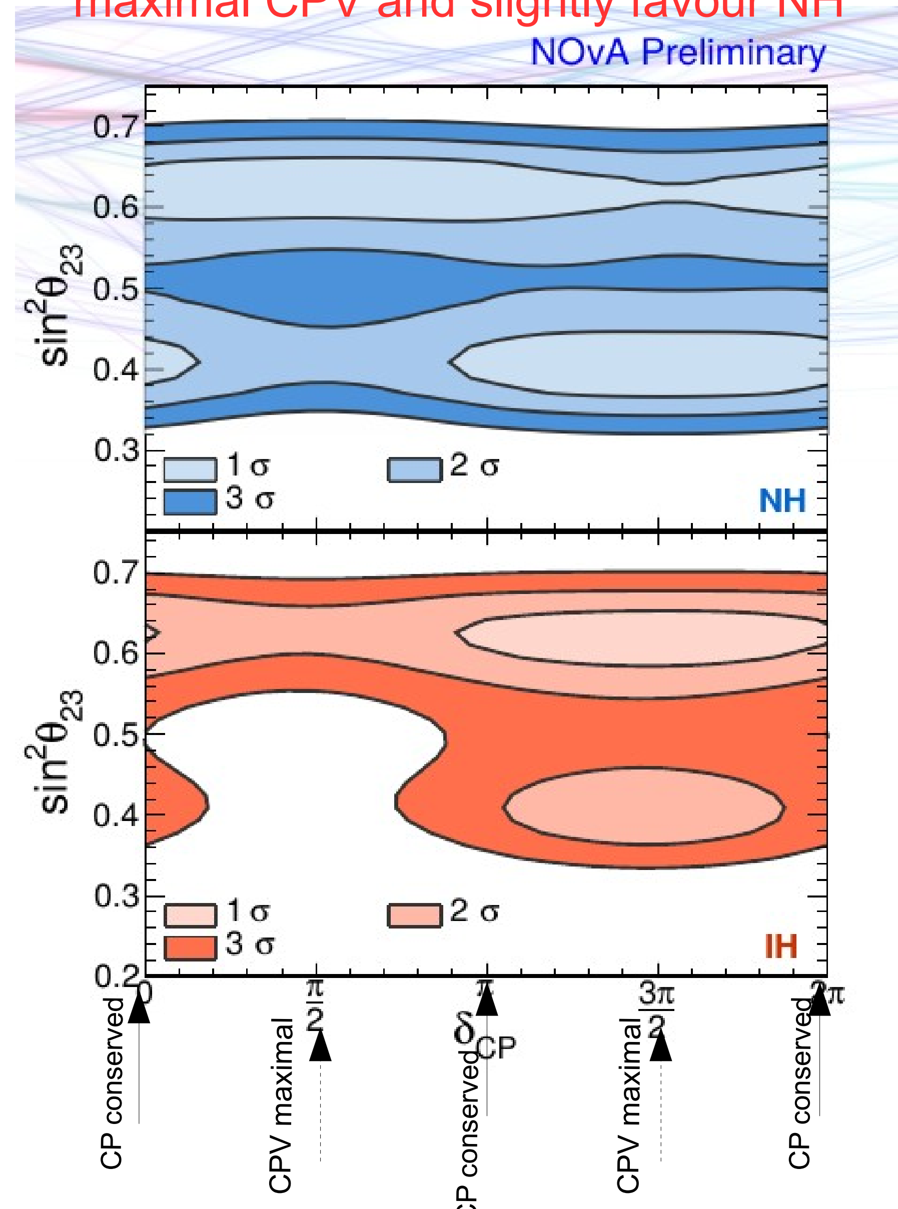
BACKUP slides

NOVA δ_{CP}

NOVA has taken 6.05x10[20] POT in ν mode (no $\bar{\nu}$ data yet):

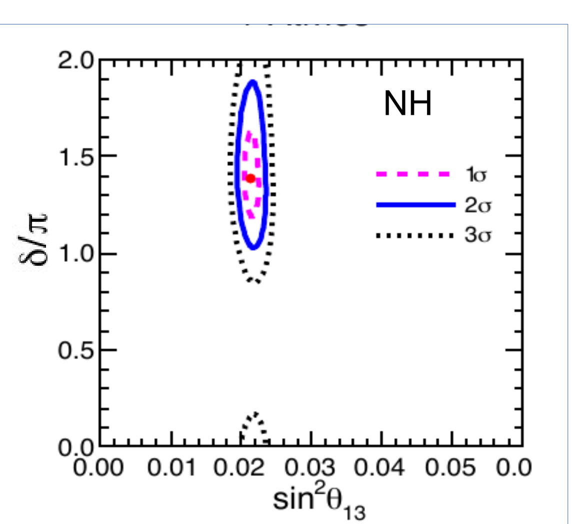


NOVA in agreement with T2K: favours maximal CPV and slightly favour NH



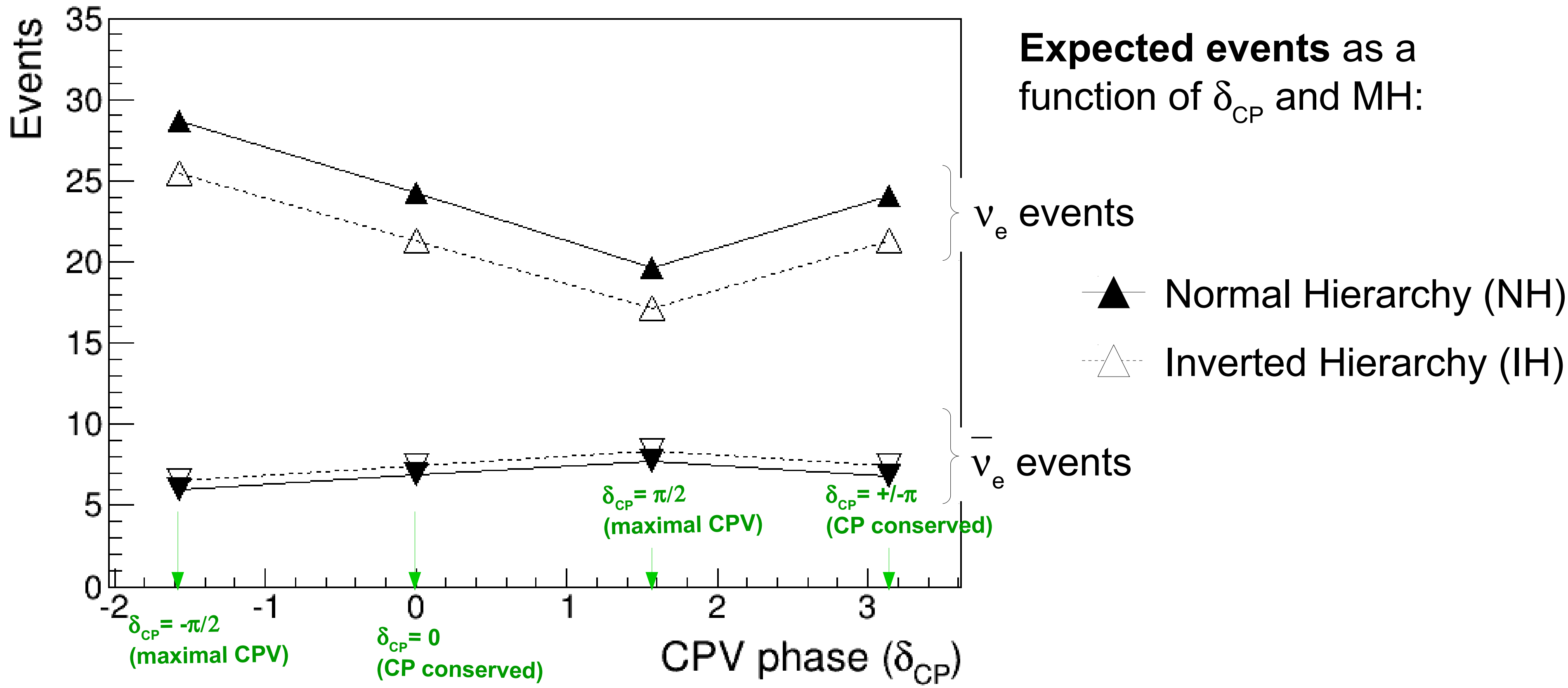
First combination of **all data (T2K, NOVA, SK, ...)**

CP conservation excluded at 2σ



Lisi et al.
NEUTRINO 2016

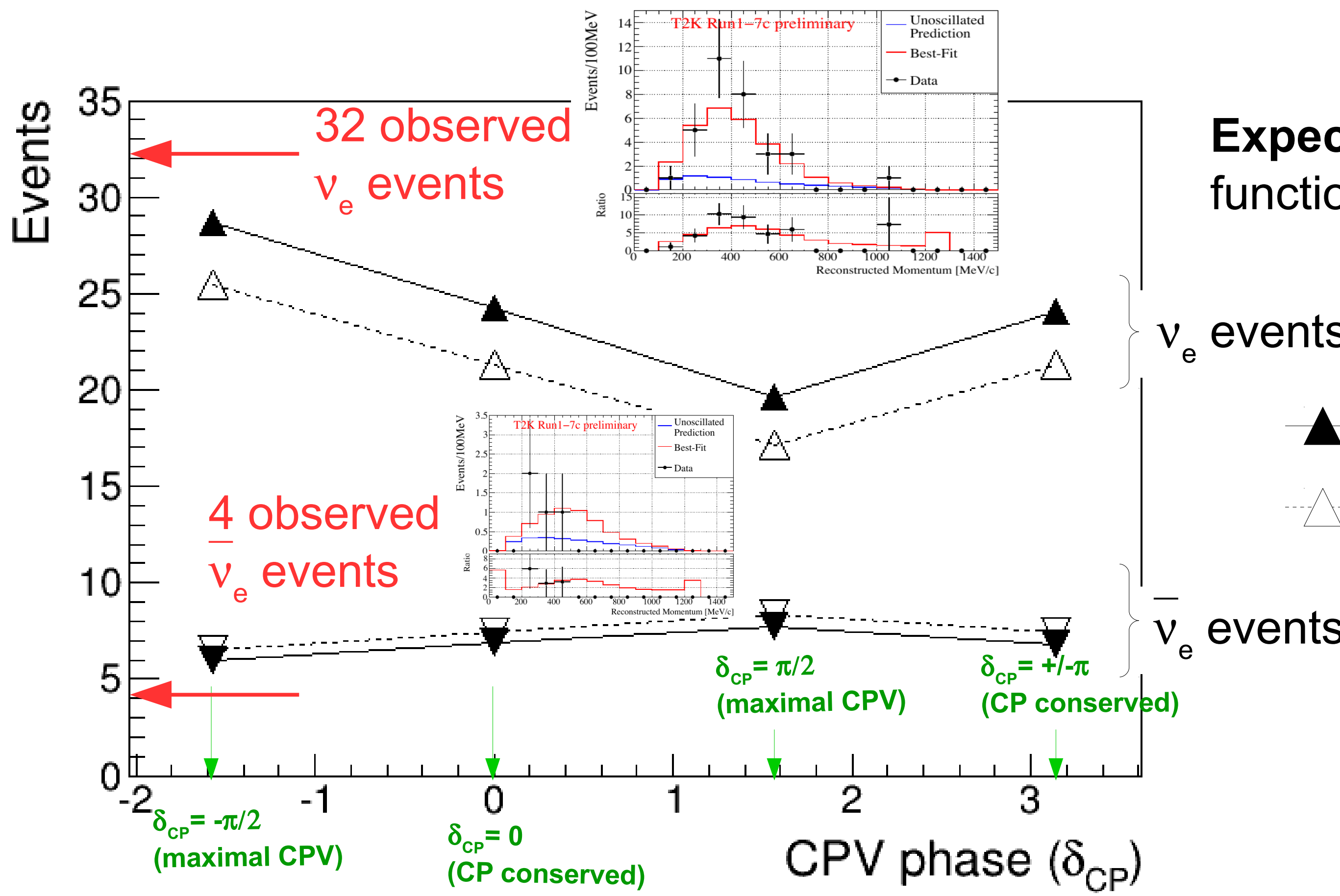
δ_{CP} and MH mainly from $\nu_\mu \rightarrow \nu_e$ / $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

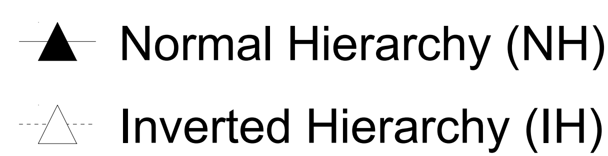


Expected events as a function of δ_{CP} and MH:

δ_{CP} and MH mainly from $\nu_\mu \rightarrow \nu_e$ / $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Expected events as a function of δ_{CP} and MH:

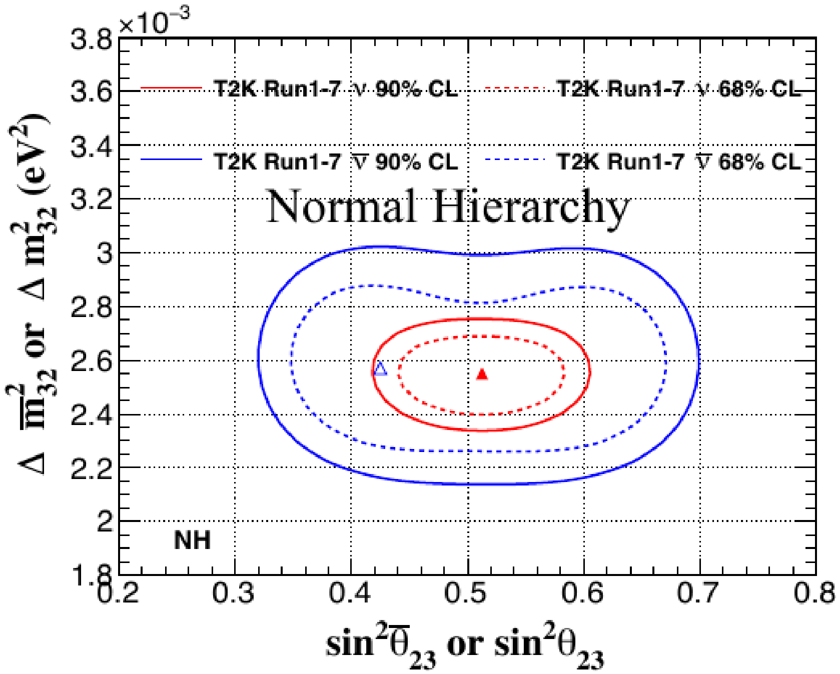




Results favour maximal CP violation (and slightly favour NH)

Non standard scenarios

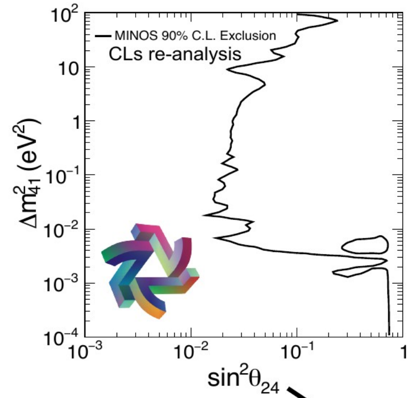
- **CPT violation** in T2K by comparing disappearance $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$

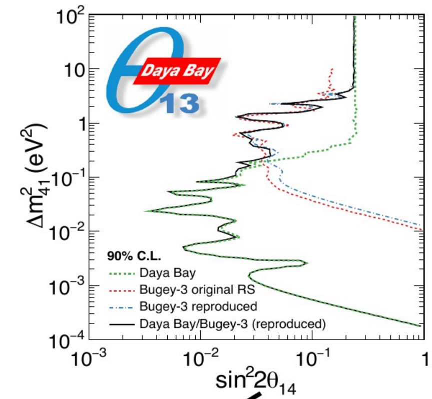


- Limits on **non-standard neutrino interactions** from MINOS+

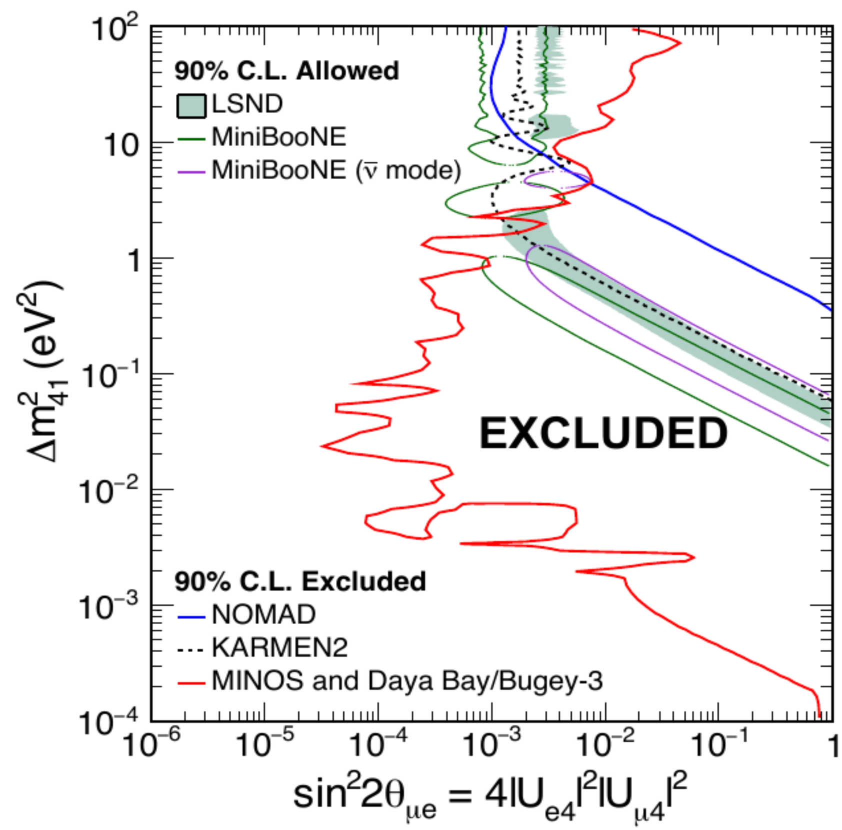
→ important to constrain to avoid degeneracies and biases with future precise δ_{CP} measurement!

- **Sterile neutrinos**: combination of MINOS, DayaBay and Bugey

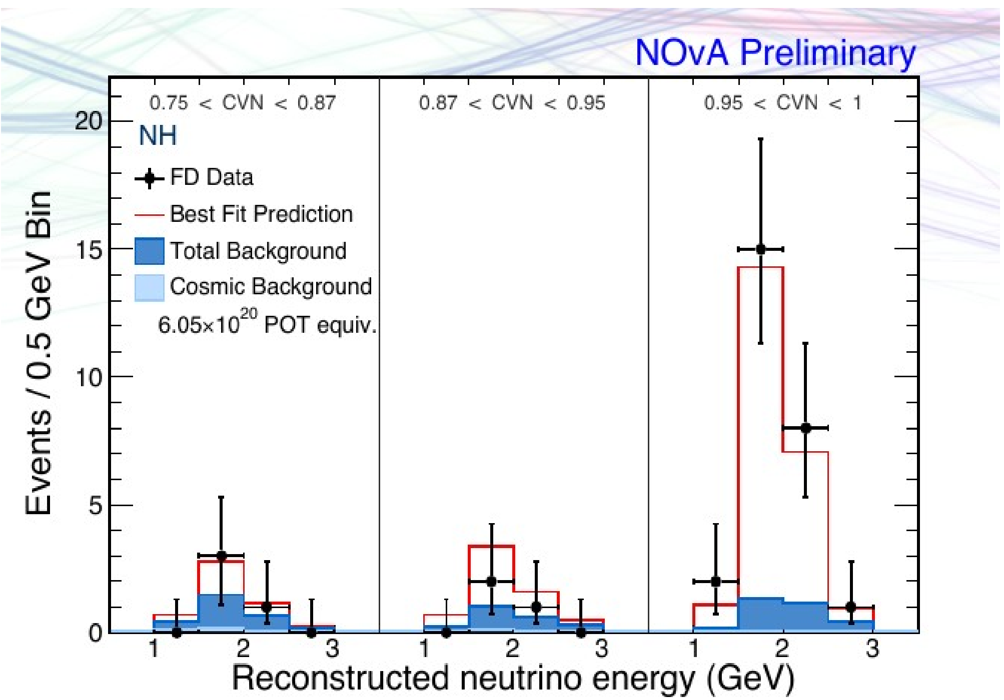




$$4|U_{\mu 4}|^2|U_{e4}|^2 = \sin^2\theta_{24}\sin^2(2\theta_{14}) \equiv \sin^2(2\theta_{\mu e})$$

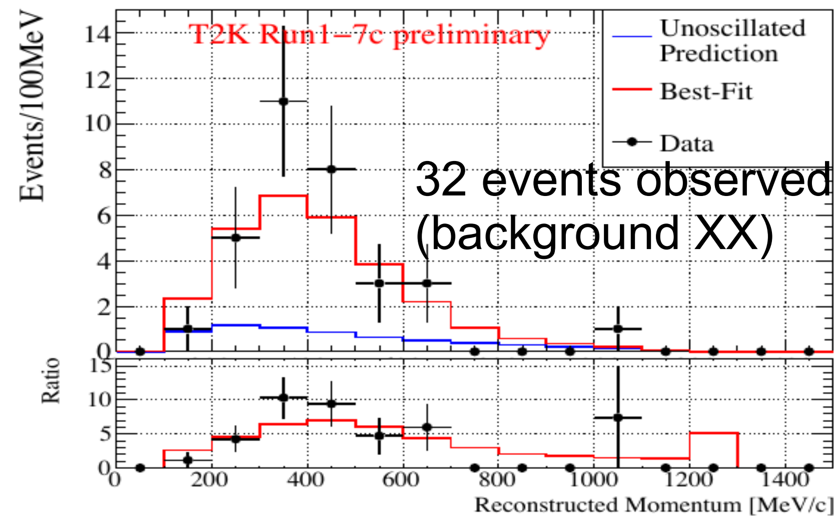


NOVA – T2K comparison: nue appearance

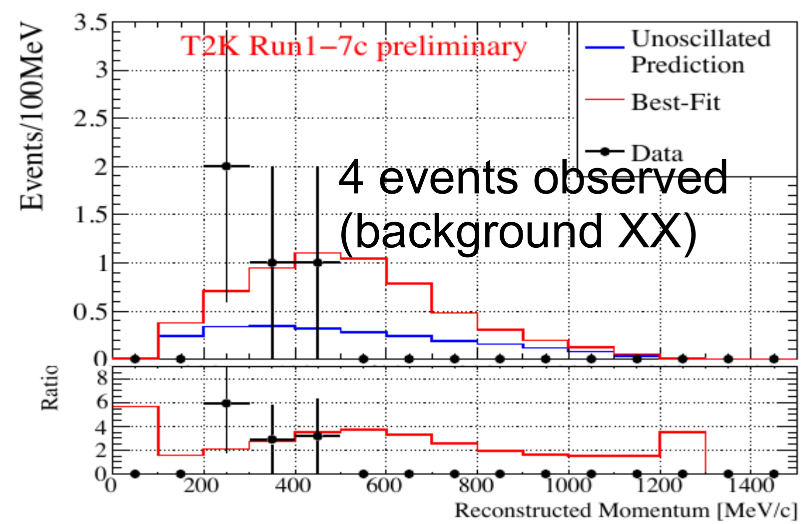


- Observe **33** events passing ν_e selection
- On 8.2 background

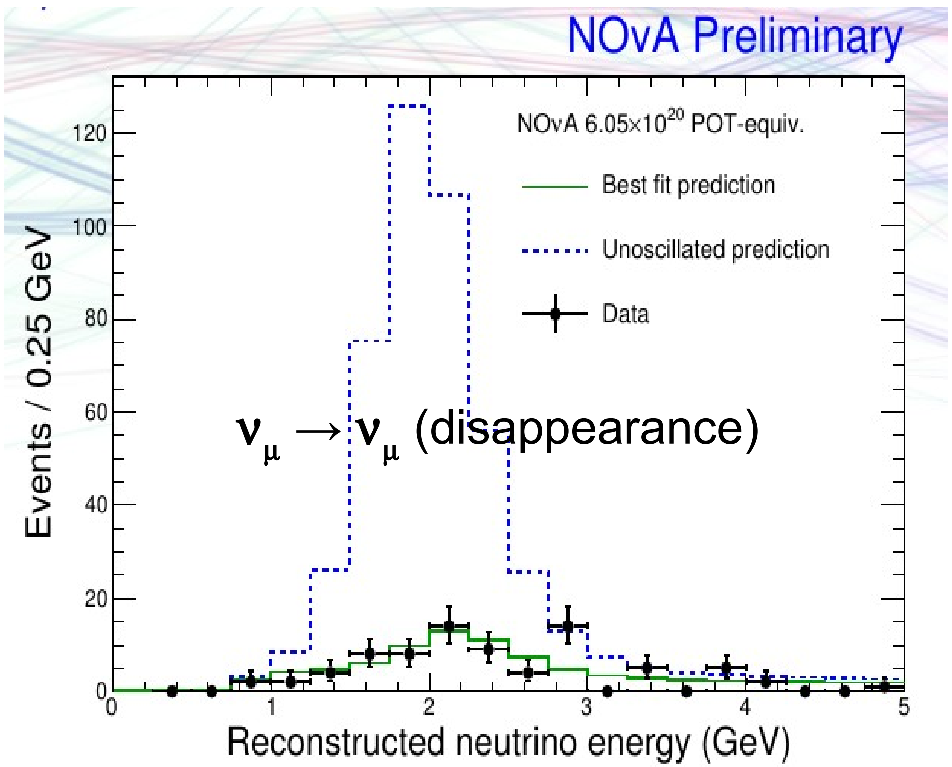
ν_e

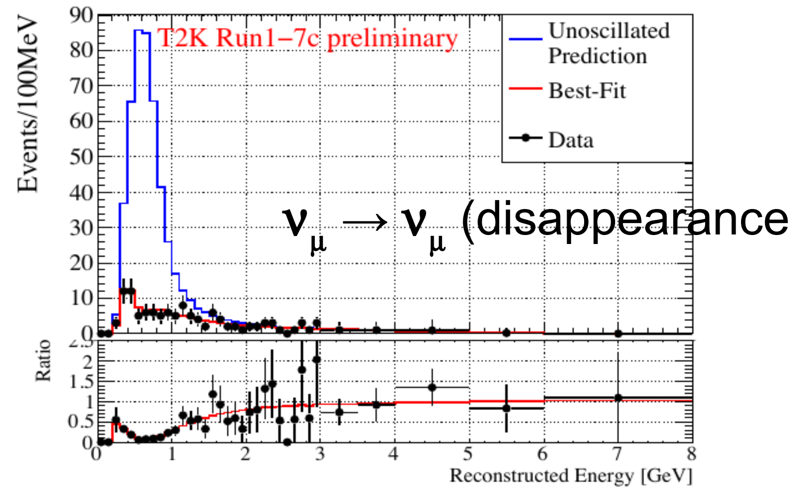


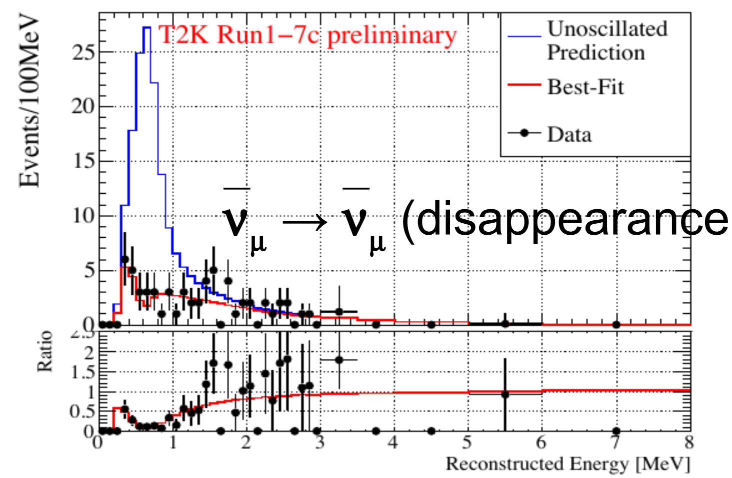
$\bar{\nu}_e$



NOVA – T2K comparison: ν_μ disappearance







	NOVA ν	T2K ν	T2K $\bar{\nu}$
Expected w/o oscillations	473 ± 30	522 ± 26	185 ± 10
Best fit	82	136	64
Observed	78	135	66

T2K: agreement between ν and $\bar{\nu}$ data

No clear suspect → T2K-NOVA difference is maybe just a statistical fluctuation ?

T2K systematics uncertainties (joint oscillation analysis)

Fractional error on the number of expected events at SK with and without ND280

	ν_μ sample $1R_\mu$ FHC	ν_e sample $1R_e$ FHC	$\bar{\nu}_\mu$ sample $1R_\mu$ RHC	$\bar{\nu}_e$ sample $1R_e$ RHC
ν flux w/o ND280	7,6%	8,9%	7,1%	8,0%
ν flux with ND280	3,6%	3,6%	3,8%	3,8%
ν cross-section w/o ND280	7,7%	7,2%	9,3%	10,1%
ν cross-section with ND280	4,1%	5,1%	4,2%	5,5%
ν flux+cross-section	2,9%	4,2%	3,4%	4,6%
Final or secondary hadron int.	1,5%	2,5%	2,1%	2,5%
Super-K detector	3,9%	2,4%	3,3%	3,1%
Total w/o ND280	12,0%	11,9%	12,5%	13,7%
Total with ND280	**5,0%**	**5,4%**	**5,2%**	**6,2%**

T2K systematics uncertainties (joint oscillation analysis)

Fractional error on the number of expected events at SK

	ν_μ sample $1R_\mu$ FHC	ν_e sample $1R_e$ FHC	$\bar{\nu}_\mu$ sample $1R_\mu$ RHC	$\bar{\nu}_e$ sample $1R_e$ RHC	$1R_e$ FHC/RHC
ν flux+cross-section constrained by ND280	2,8%	2,9%	3,3%	3,2%	2,2%
ν_e/ν_μ and $\bar{\nu}_e/\bar{\nu}_\mu$ cross-sections	0,0%	2,7%	0,0%	1,5%	3,1%
NC γ	0,0%	1,4%	0,0%	3,0%	1,5%
NC other	0,8%	0,2%	0,8%	0,3%	0,2%
Final or secondary hadron int.	1,5%	2,5%	2,1%	2,5%	3,6%
Super-K detector	3,9%	2,4%	3,3%	3,1%	1,6%
Total	**5,0%**	**5,4%**	**5,2%**	**6,2%**	**5,8%**

Water Cherenkov vs Liquid Argon

- Hyperkamiokande much more sensitive to CP violation while DUNE much more sensitive to Mass Herarchy (see backup).

But sensitivities depend on assumed beam power, detector mass and on baseline.

- Comparison of technologies:

WATER CHERENKOV

- well known and solid technology
- very large mass (~MTon)
- info only about particles above Cherenkov threshold

→ model dependent assumptions to reconstruct E_ν

→ no need of precise E_ν shape: **mainly a counting experiment**

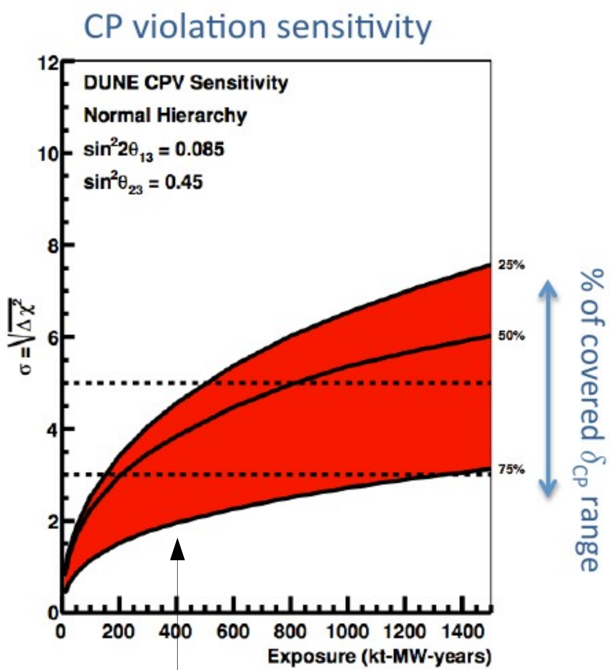
LIQUID ARGON

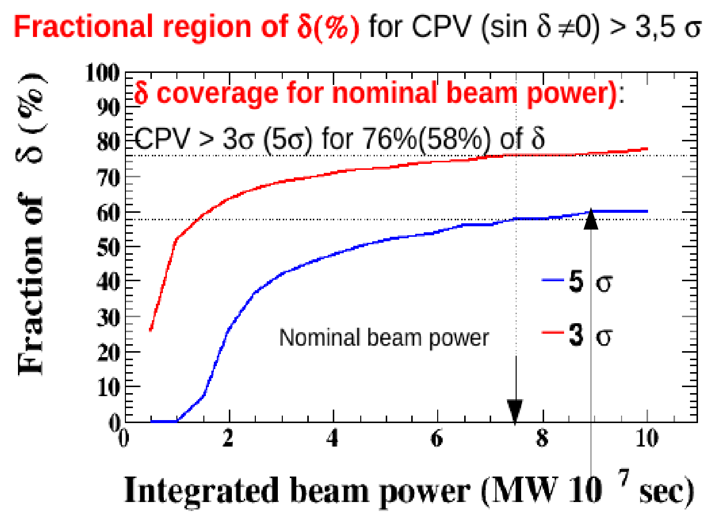
- successfull R&D → first very large scale realization
- size limited by drift length (~40KTon)
- full reconstruction of tracks and showers down to very low threshold, very good particle ID

→ precise E_ν shape accessible and needed for good sensitivity

→ **need to reach very good control on detector calibration/uniformity and on neutrino interaction modelling**

Sensitivities

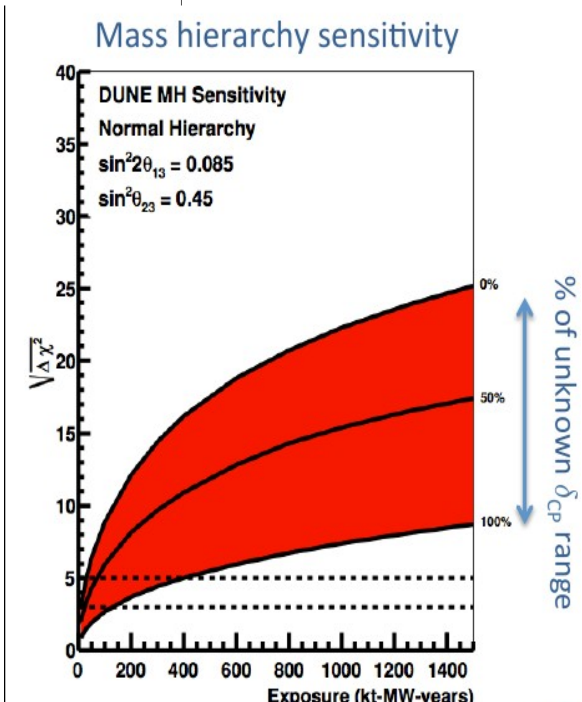




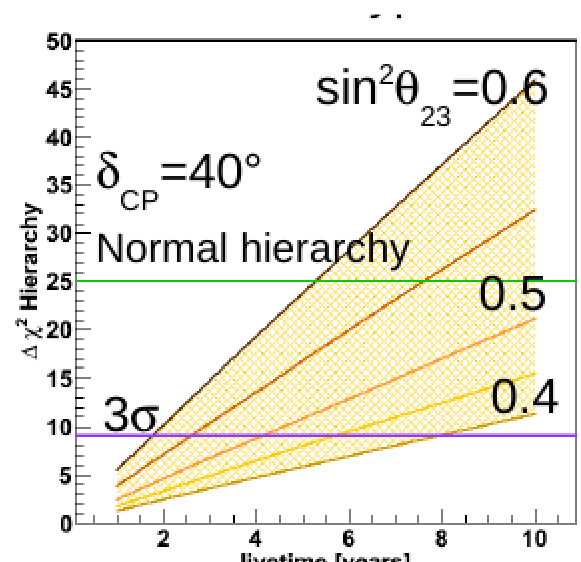
Assuming 1MW beam

HK 3 years (1MTon): CPV measured at 3s(5s) for 75% (60%) of dCP values

DUNE 10 years (40 kTon): CPV measured at 3s (5s) for >50% (~25%) of dCP values

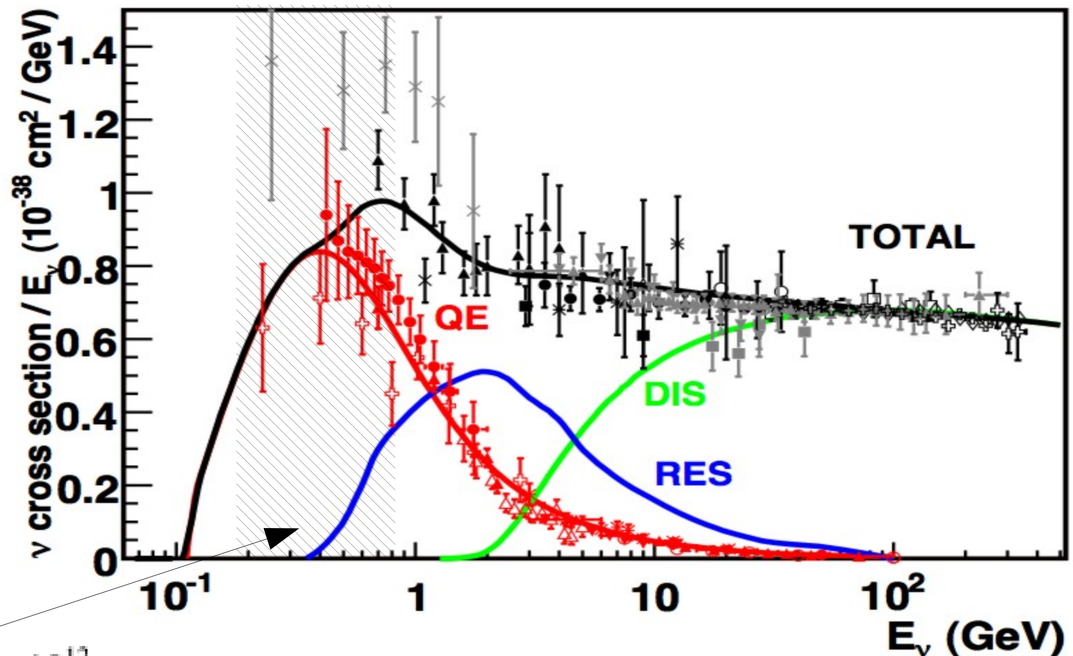


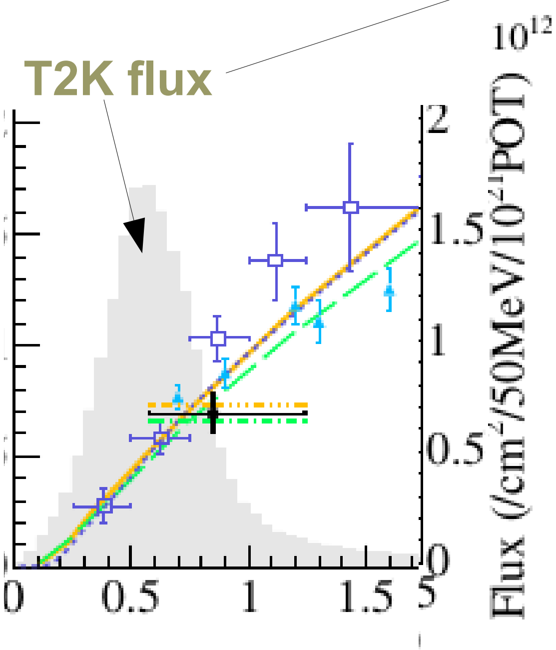
DUNE 10 years: definitive determination of MH

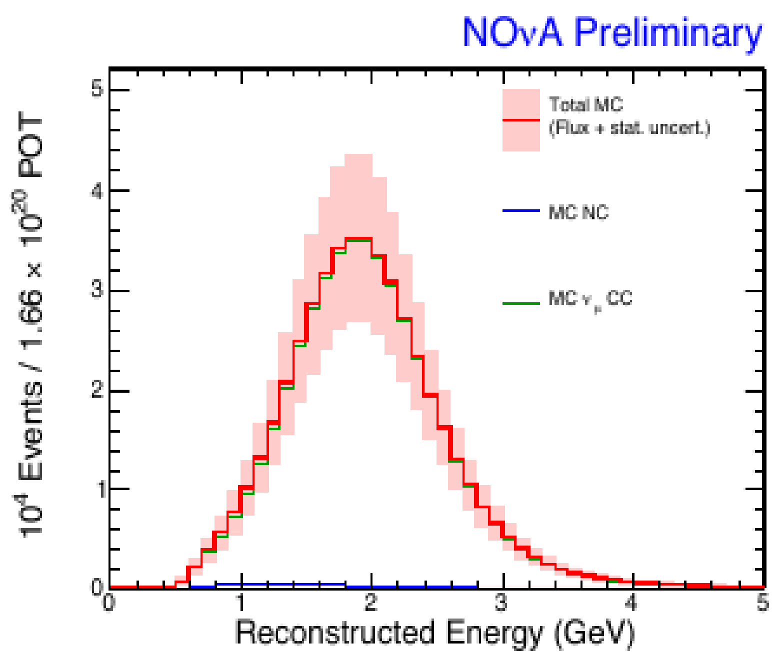


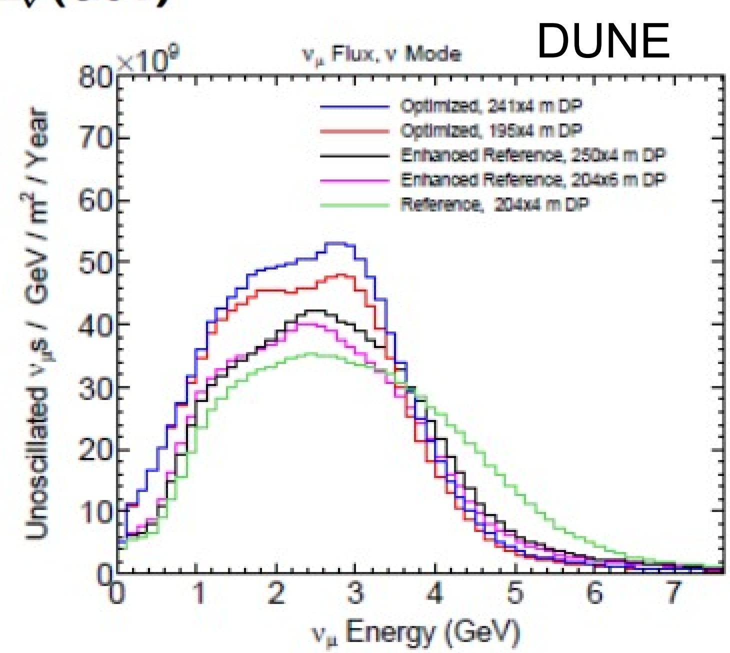
HK 10 years: wrong MH excluded at 3s

Moving to larger energies ...

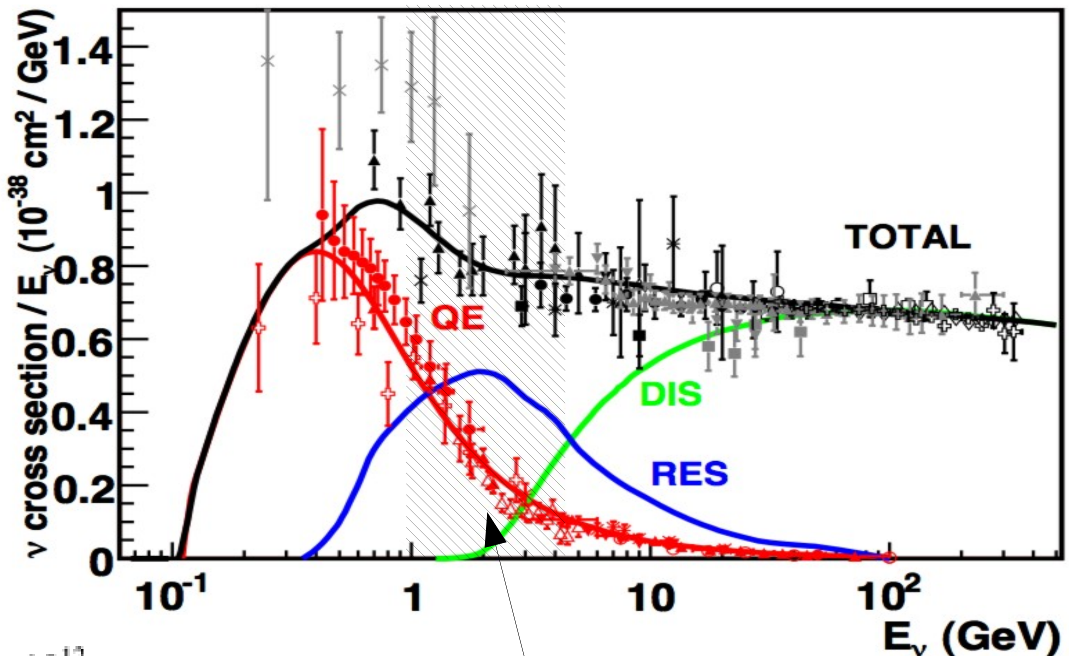


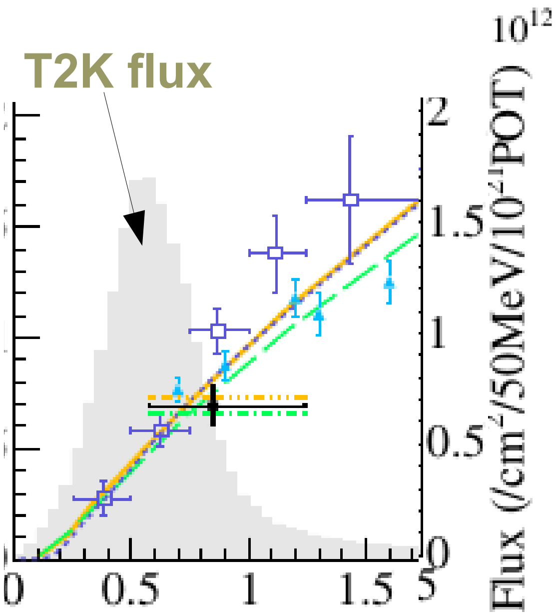




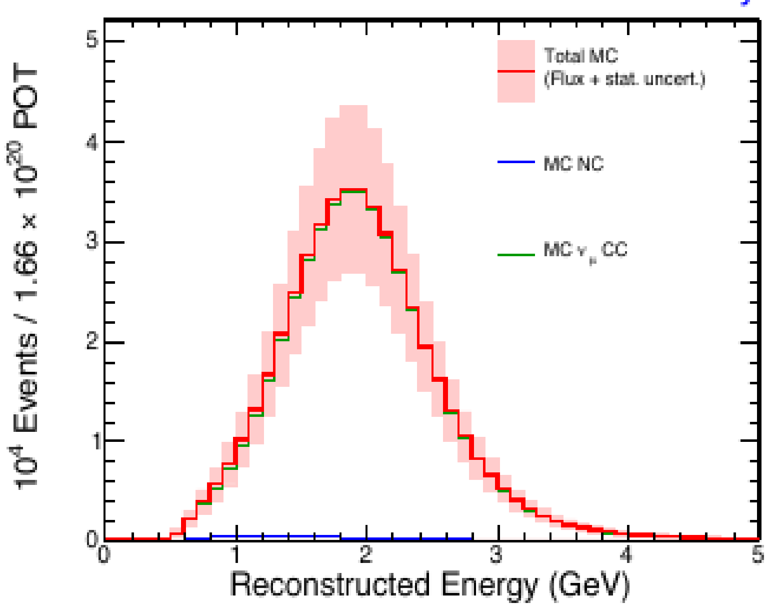


Moving to larger energies ...

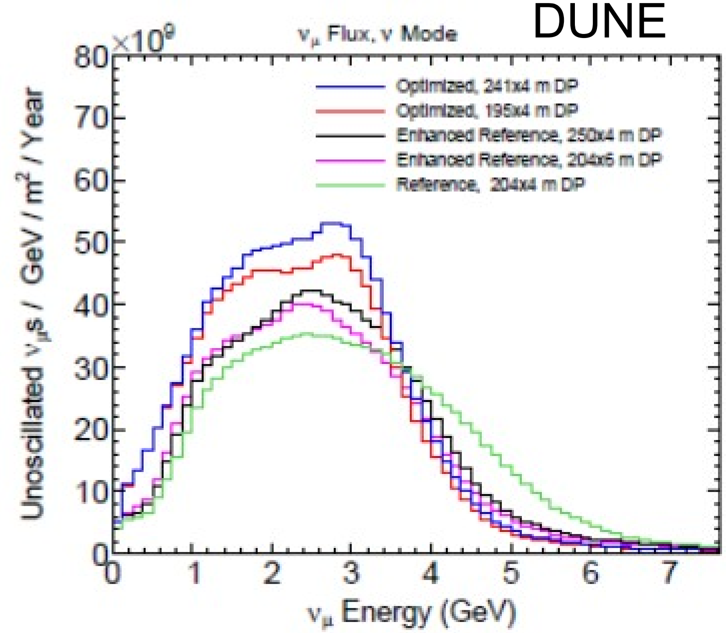




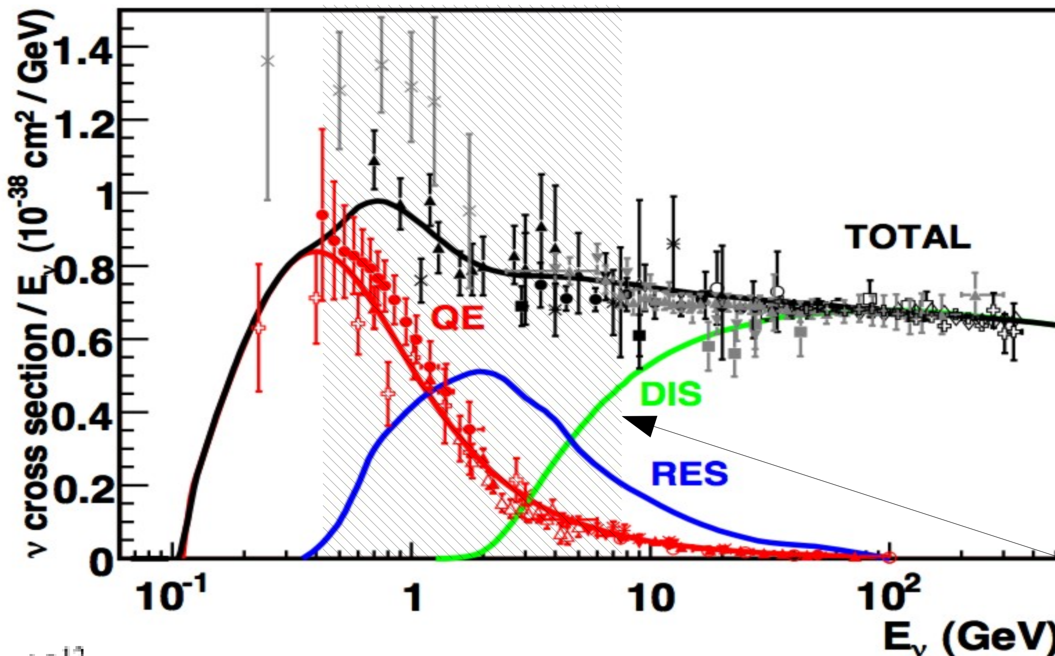
NOvA Preliminary



DUNE

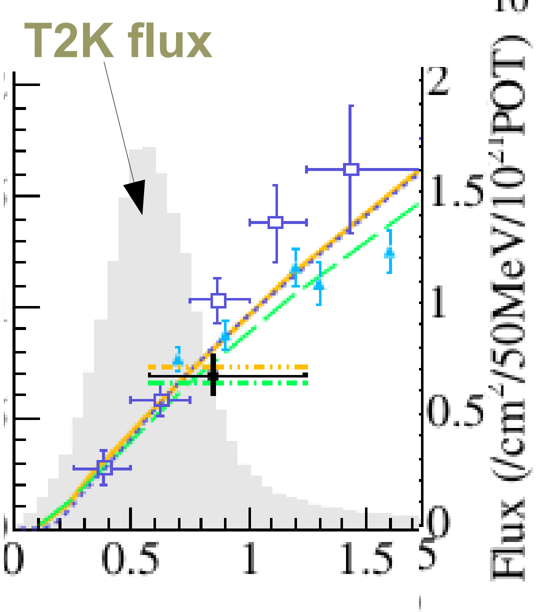


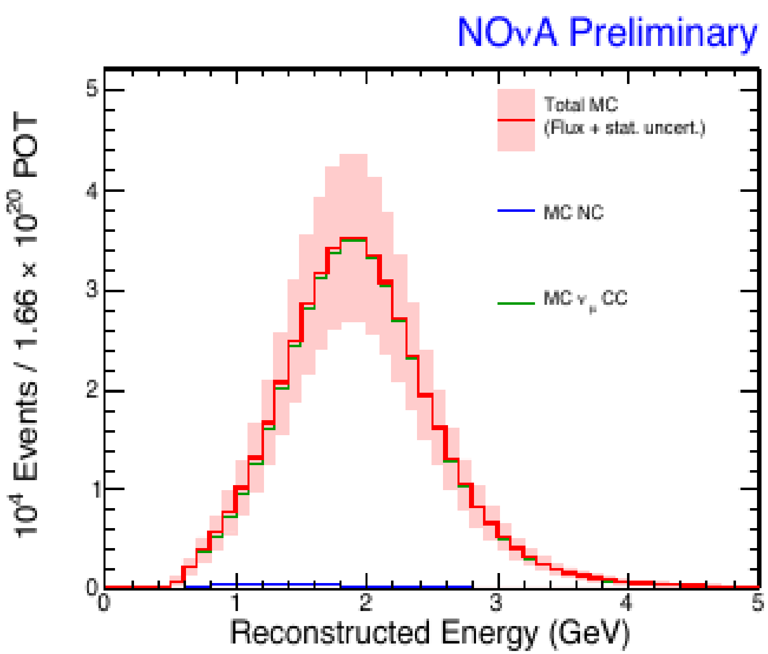
Moving to larger energies ...

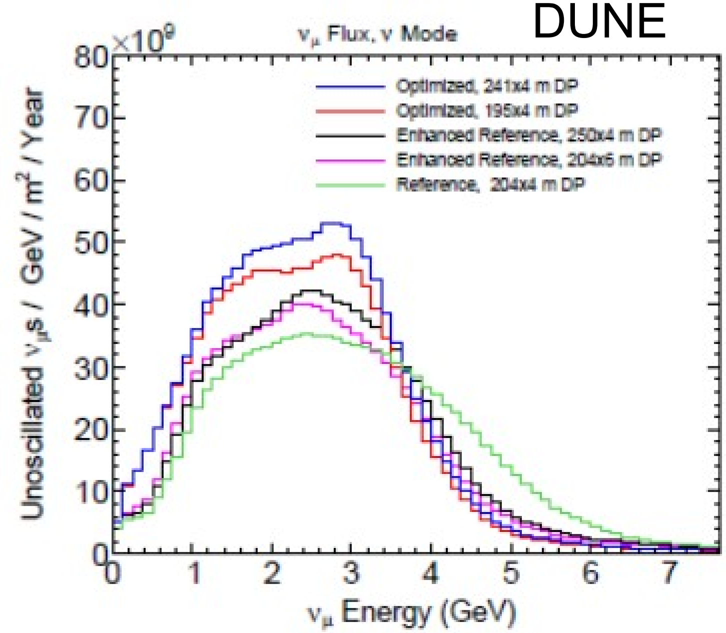


Need to control well all different xsec, each process has very different detector acceptance

DUNE







ν_μ Result- Comparison To Previous Result

Our previous result*:
2.6σ

↓

New simulation & Calibration:
~1.8σ

↓

New selection and analysis:
~0.5σ

↓

Full dataset:
~0.4σ

→

Full dataset*:
0.8σ

Our rejection of maximal mixing has moved from 2.6σ to 0.8σ. This change in the character of our result comes from a few key changes which I'll break down below.

Driven by updates to energy response model. Drop to 2.3σ expected due to new energy resolution. Additionally we have a <70 MeV> shift in our hadronic energy response. This energy shift would be expected to move 0.5 events out of the "dip" region. However it instead pushes 3 "dip" events past a bin boundary.

For combined analysis changes 5% of pseudo-experiments in a MC study had this size shift or larger. This probability is driven by a low expected overlap in background events, and to second order the addition of resolution bins.

New, 2.8×10^{20} POT, data prefers maximal mixing.

*Feldman-cousins corrected significance.

Joint Best Fits

IH at $\delta_{cp} = \pi/2$ disfavored at greater than 3σ.

Approaching IH rejection at 2σ.