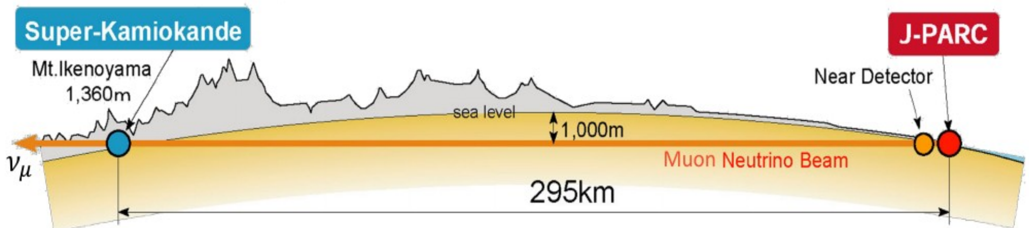
T2K-2

GDR Neutrino – May 2017, Paris

S.Bolognesi (CEA/IRFU)

T2K: Tokai (JPARC) to Kamioka (SuperKamiokande)

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



Far Detector:

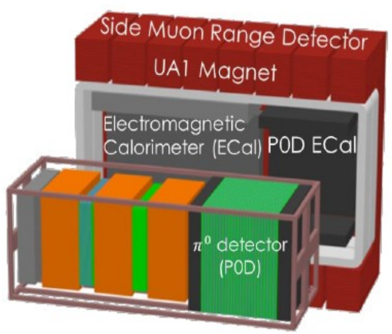
huge water cherenkov detector (50 kTon) with optimal μ/e identification to distinguish ν_e, ν_μ

Far Detector

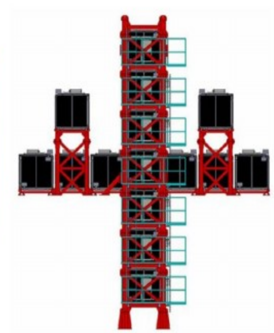
Super-Kamiokande

Near Detectors

Off-Axis: ND280



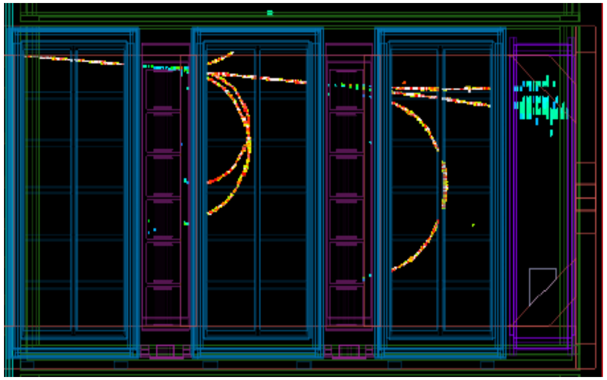
On-Axis: INGRID

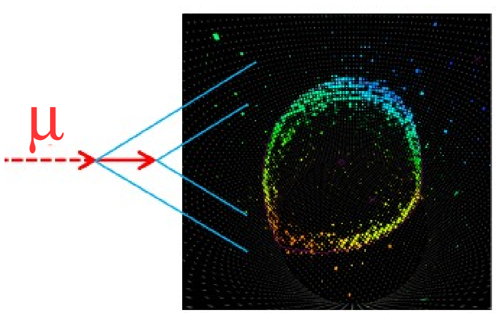


Near Detectors:

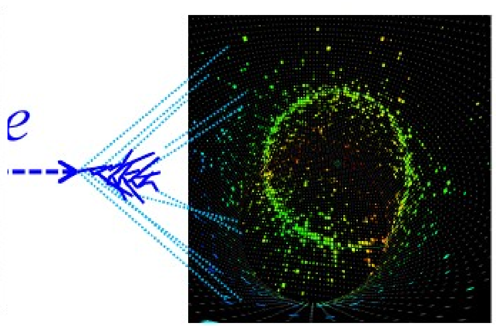
On-axis:
iron/CH scintillator
monitoring of beam angle and position

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

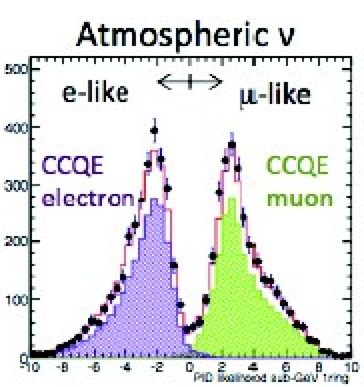




clear ring



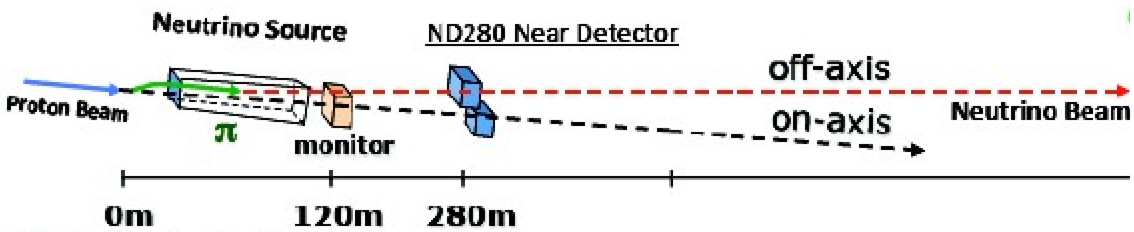
fuzzy ring



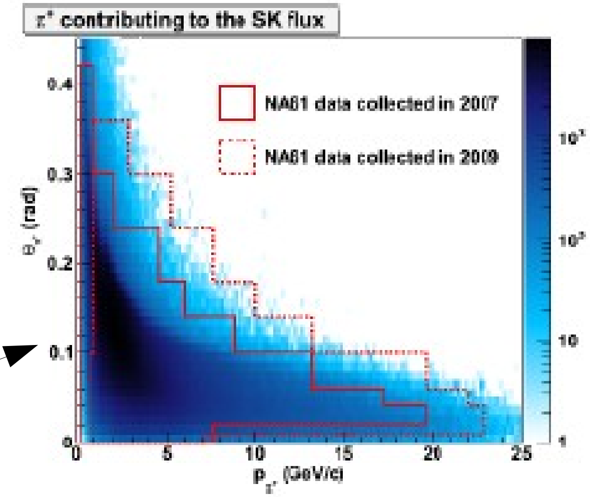
1% mis-id

T2K beam

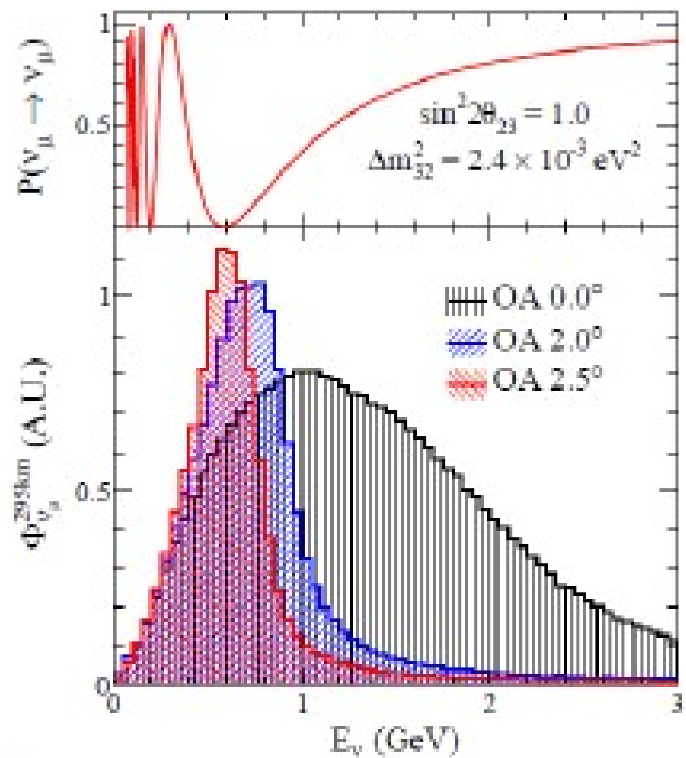
- Production of **muon neutrino beam:**



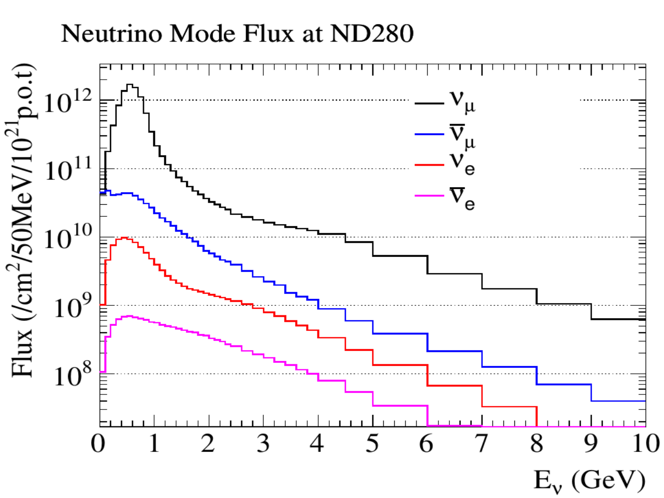
- Flux prediction tuned from pion and kaon production measurements at **NA61 experiment** at CERN

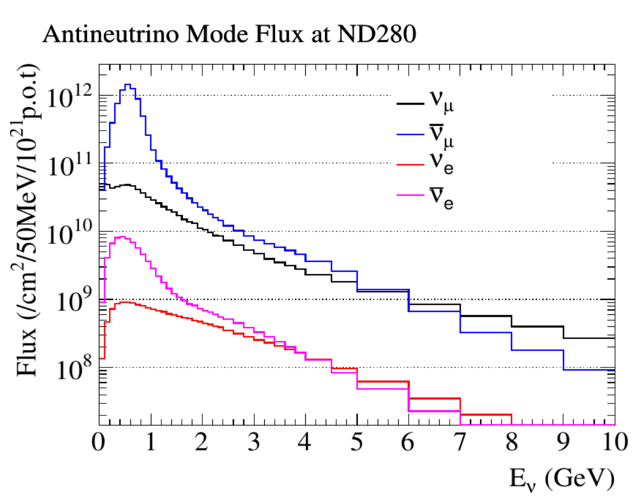


- **Off-axis** → narrow flux at the maximum of the neutrino oscillation



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

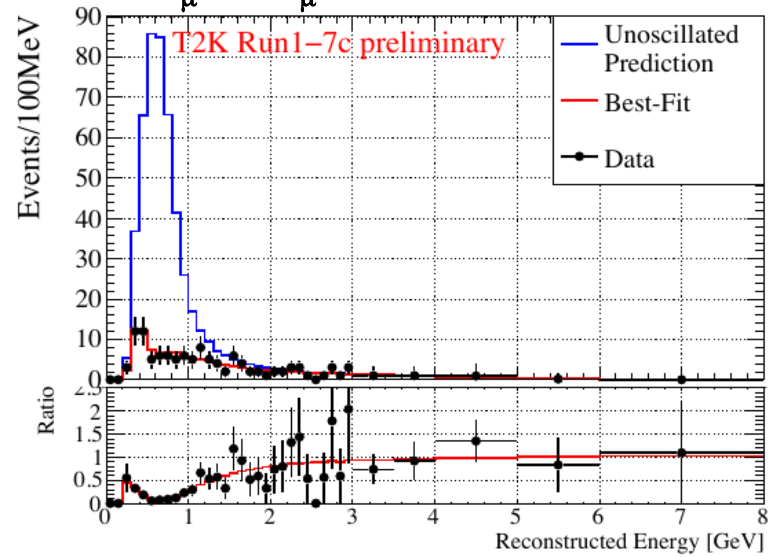




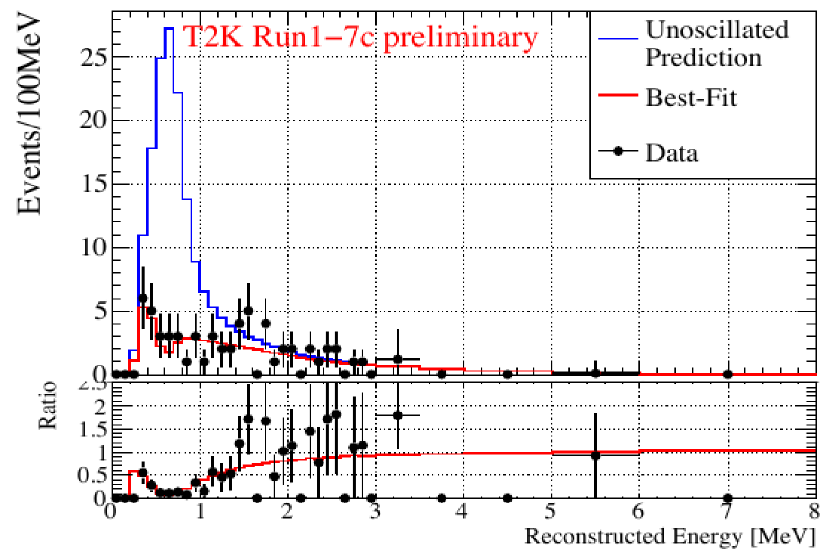
T2K oscillation analysis

- ν-mode: 7.48×10^{20} POT
- $\overline{\nu}$-mode: 7.47×10^{20} POT

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



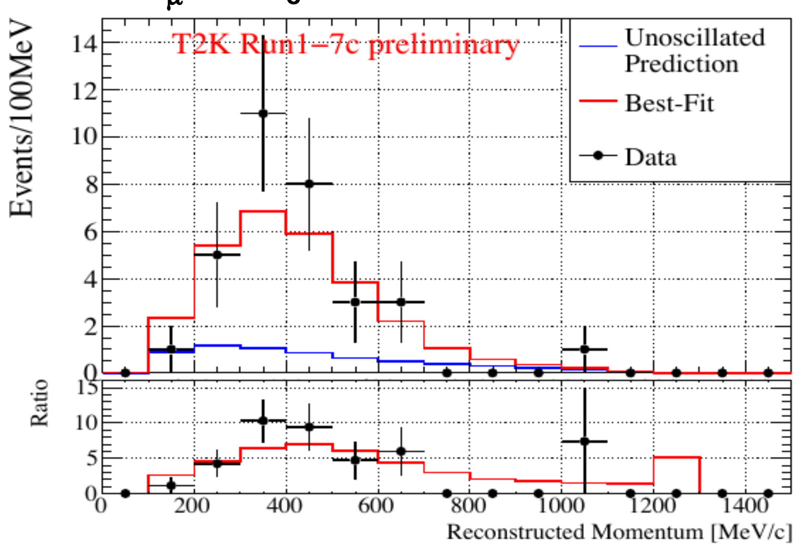
$\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu$ (disappearance)



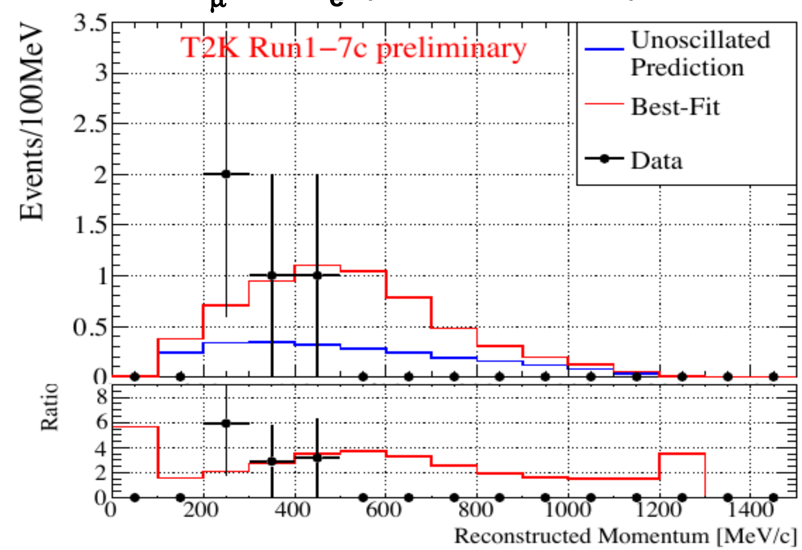
Large disappearance signal and clear oscillation shape (beyond counting experiment)

Clear signal in **antineutrino** as well!

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



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

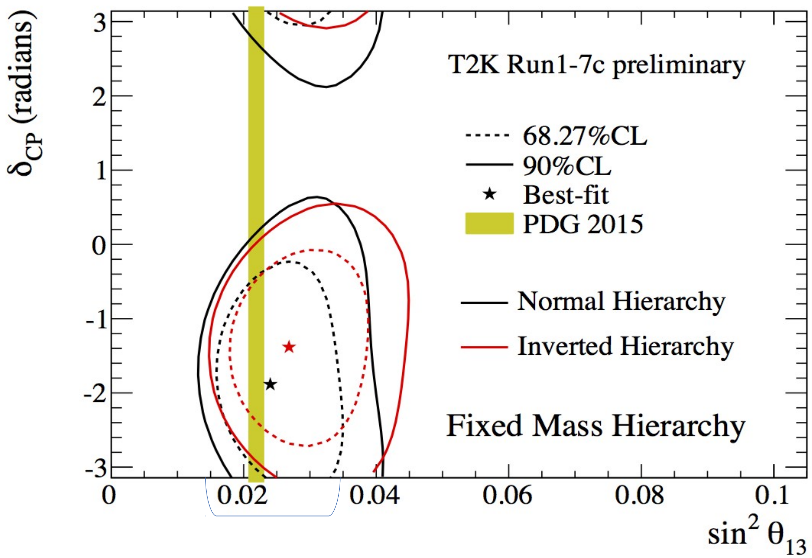


7.5 sigma observation of ν_e appearance

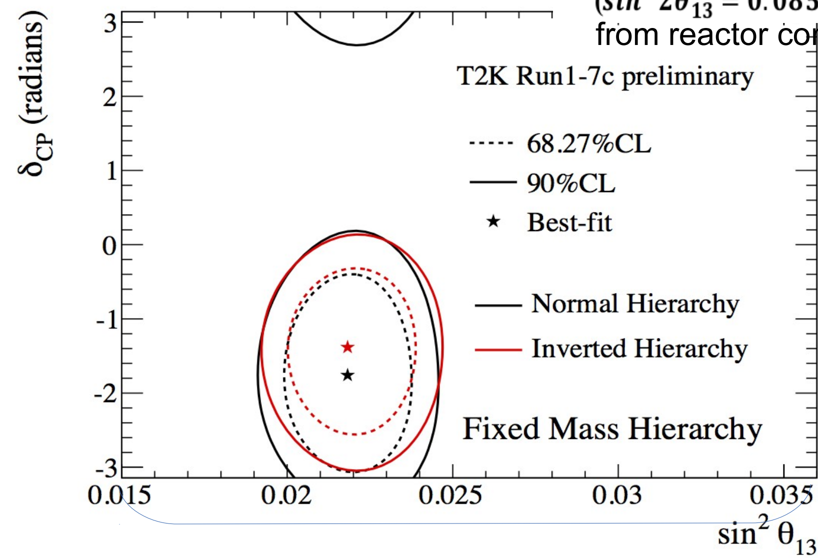
Growing statistics of $\overline{\nu}_e$ appearance: (~20% of final design statistics)

First 90% limits on δ_{CP}!!

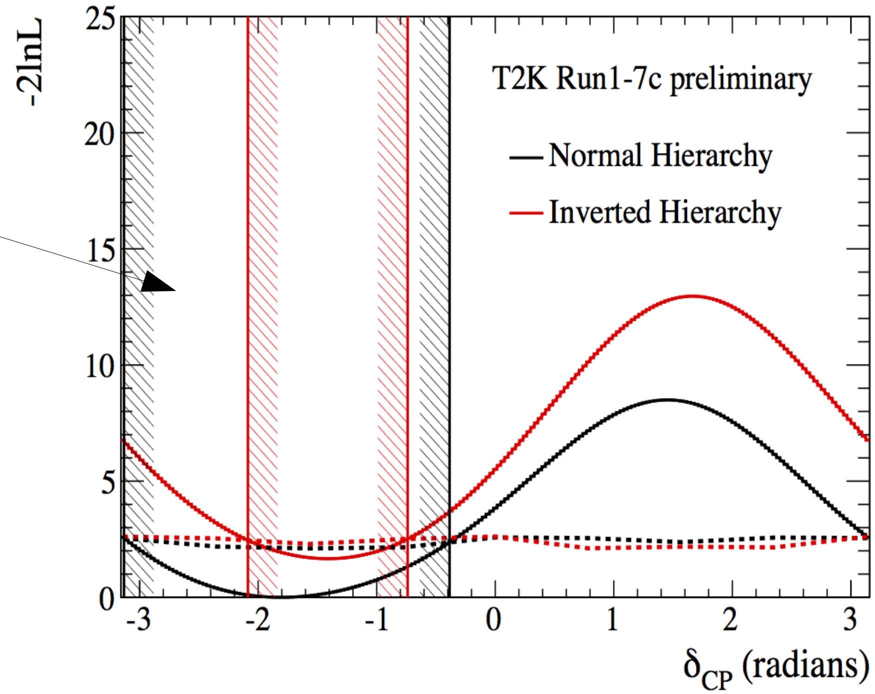
Full joint fit of all data ($\nu_\mu \rightarrow \nu_{\mu/e}$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_{\mu/e}$) with all proper statistical and systematic uncertainty included and exploiting also shape information :



($sin^2 2\theta_{13} = 0.085 \pm 0.005$) from reactor constraints



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



Feldman-Cousins confidence interval:

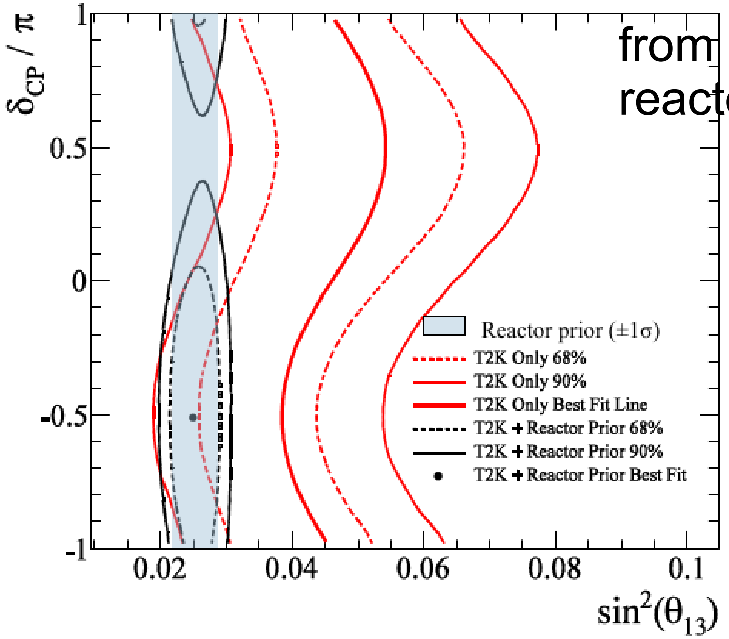
δ_{CP} = [-3.13, -0.39] NH
[-2.09, -0.74] IH
at 90% CL

(NH slightly favoured)

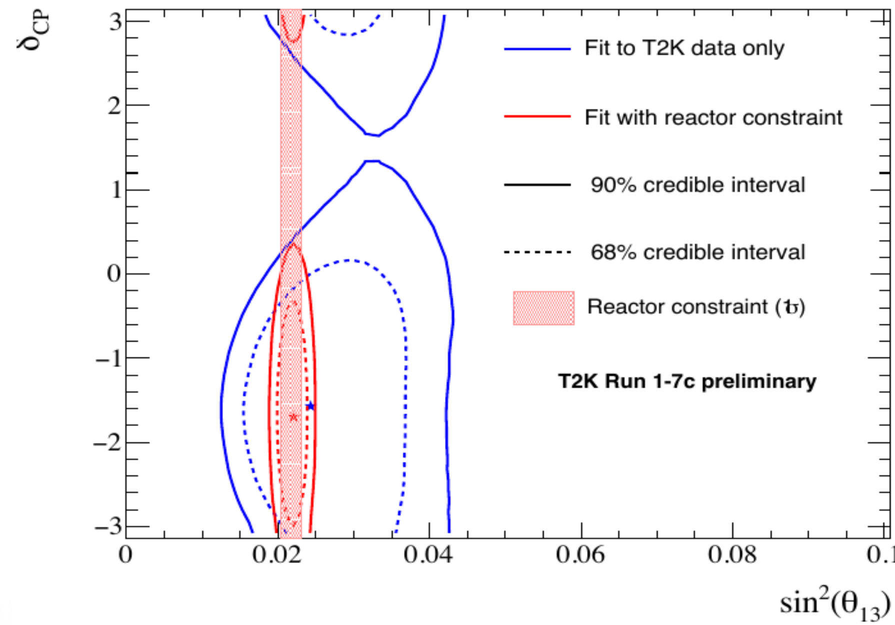
Growing statistics

- **Big improvement in δ_{CP} limits from data in antineutrino mode**

2015 ν only: T2K — T2K+ θ_{13} from reactors

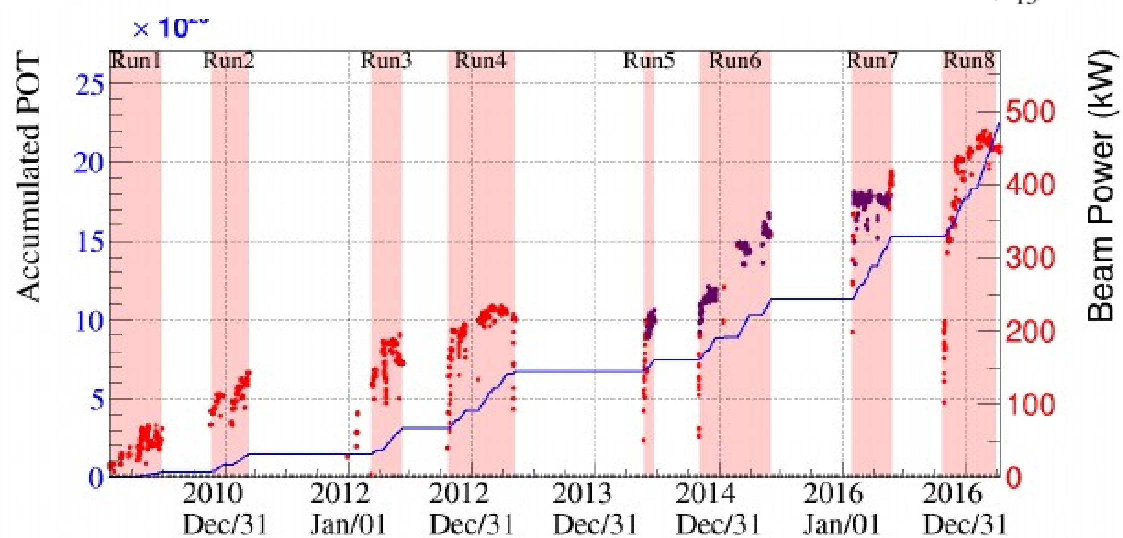


2016 ν+$\bar{\nu}$: T2K — T2K+θ_{13} from reactors



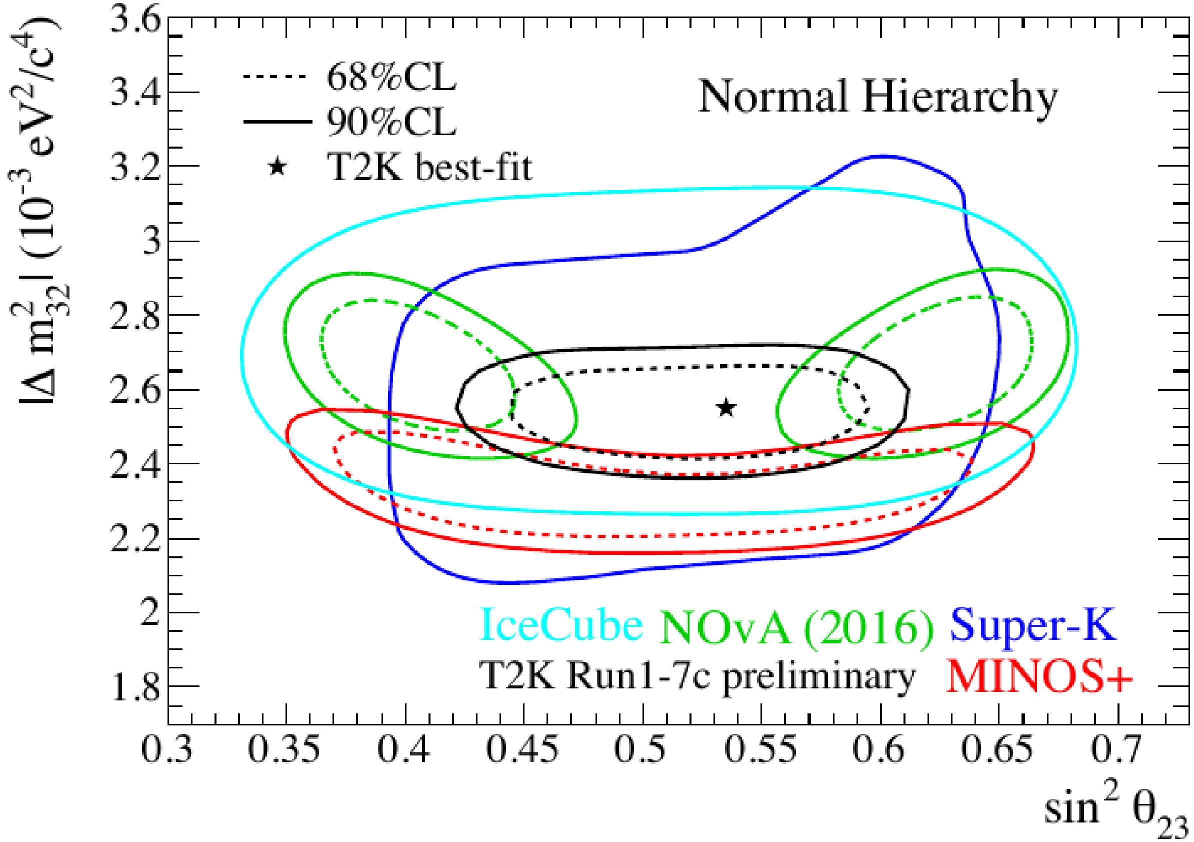
- **Statistics growing faster and faster: improvements in beam power**

new results in summer 2017: ν POT doubled since last summer



The other oscillation parameters (θ_{23}, $|\Delta m^2_{32}|$): mostly from ν_μ and $\bar{\nu}_\mu$ disappearance

- $\sin^2\theta_{23}$ enhance/suppress both ν_μ and $\bar{\nu}_\mu$ disappearance
- $|\Delta m^2_{32}|$ regulate the position of the oscillation maximum as a function of the energy



T2K data show maximal disappearance → **prefer maximal mixing: $\theta_{23} = \pi/4$** ($\sin^2\theta_{23}$=0.5)

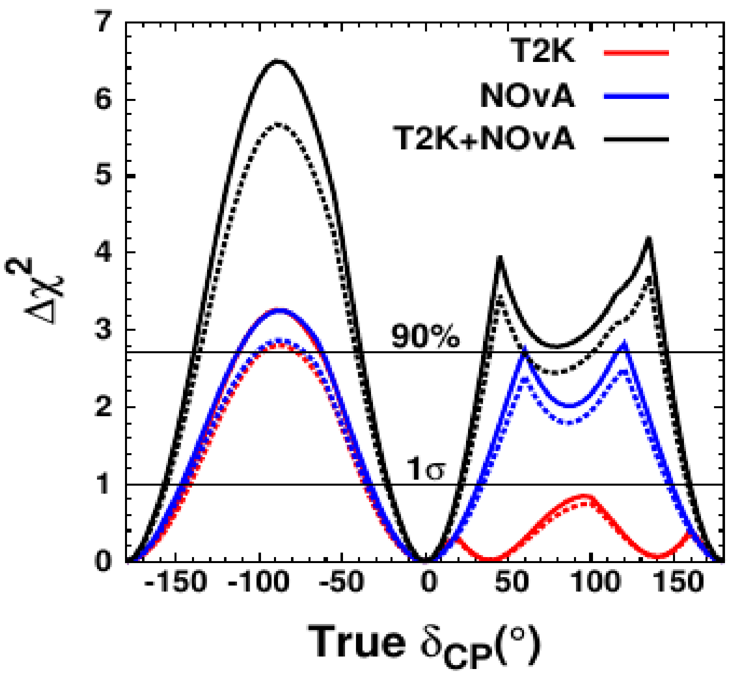
NOVA data excludes maximal mixing at 2.5σ

	T2K (NH)	NOVA (NH)
$\sin^2\theta_{23}$	$0.532^{+0.046}_{-0.068}$	$0.40^{+0.03}_{-0.02}$ $0.63^{+0.02}_{-0.03}$
$\lvert\Delta m_2^{32}\rvert$ [10^{-3} eV^2]	$2.545^{+0.081}_{-0.084}$	2.67 ± 0.12

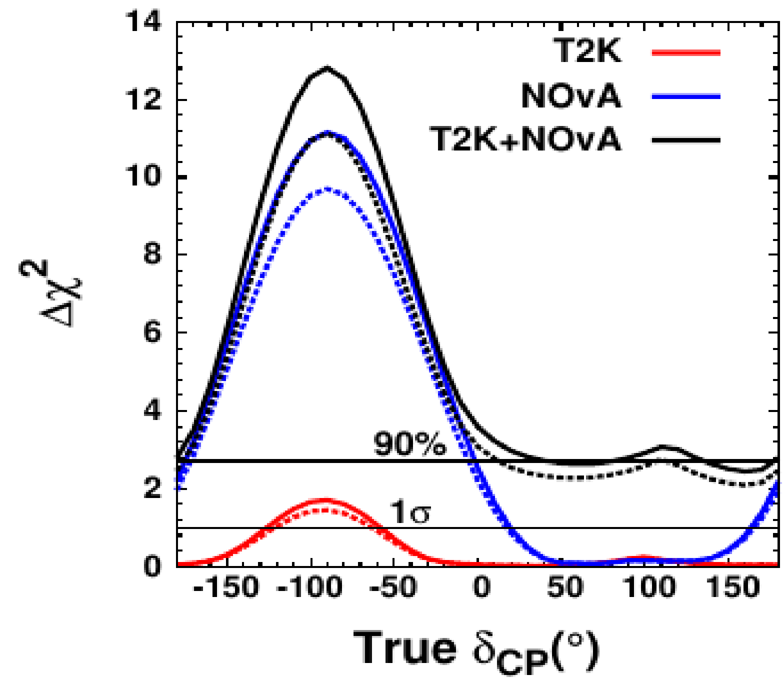
Prospects for future

NOVA – T2K combination with final dataset (~2021):

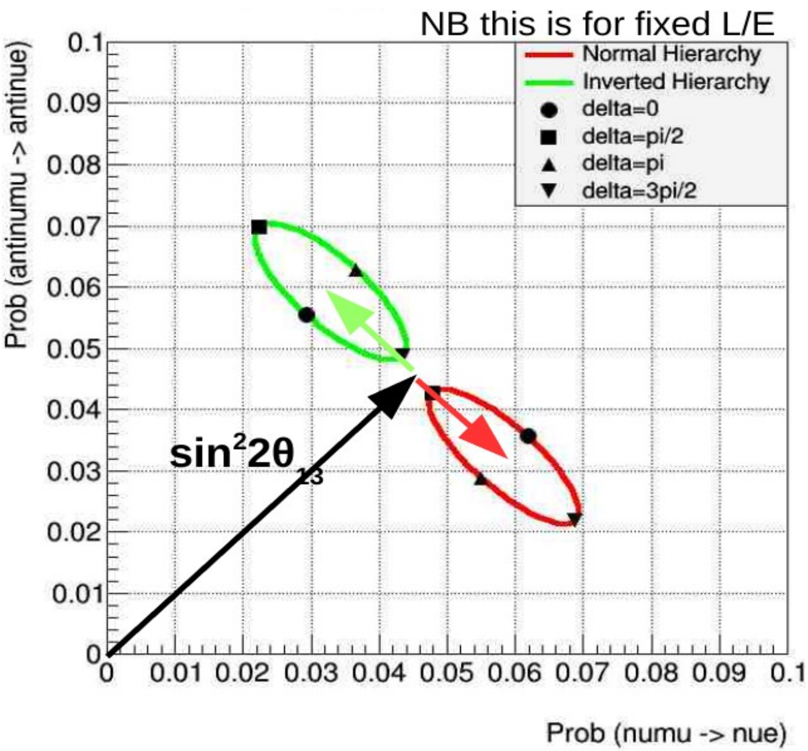
sensitivity CPV (True NH)



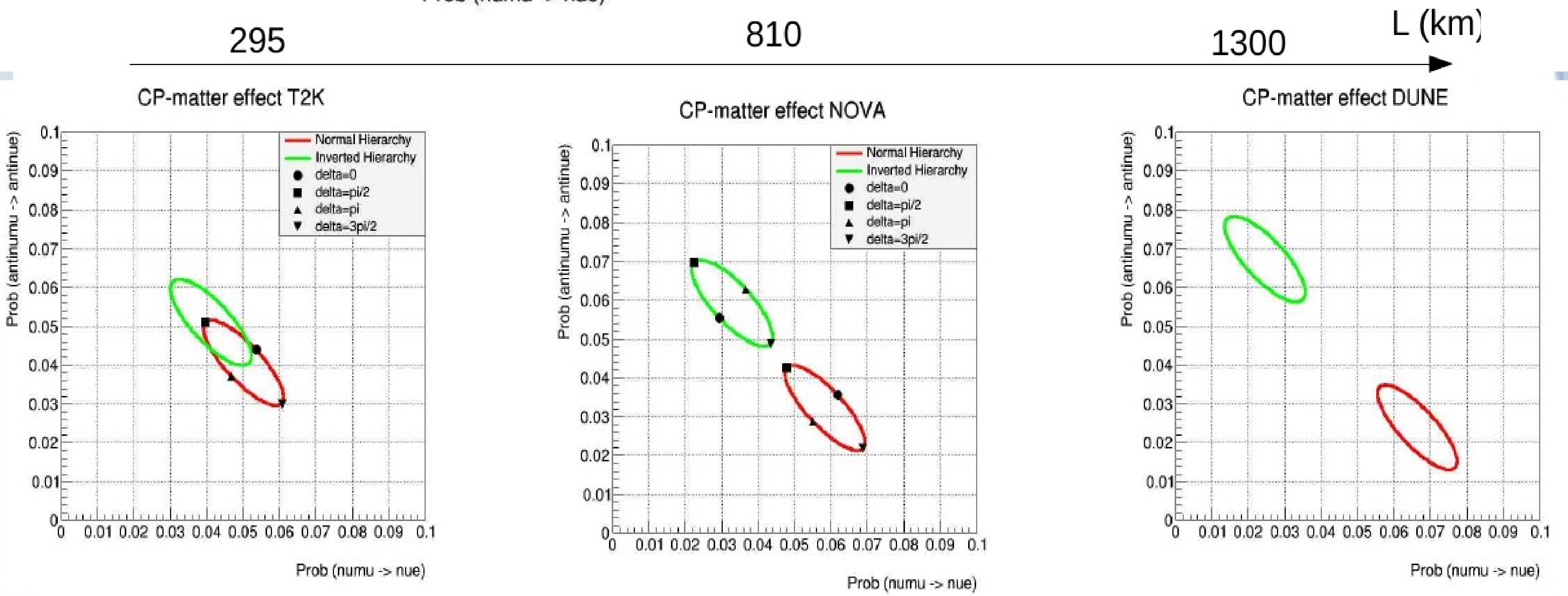
sensitivity MH (True NH)



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%) → small sensitivity to MH



CP sensitivity at T2K

- **At T2K very clean δ_{CP} measurement:**
  - small δ_{CP}-MH degeneracy
  - very large far detector (SuperKamiokande → Hyperkamiokande) with narrow beam → **mostly a counting experiment ν_e vs ν_e**

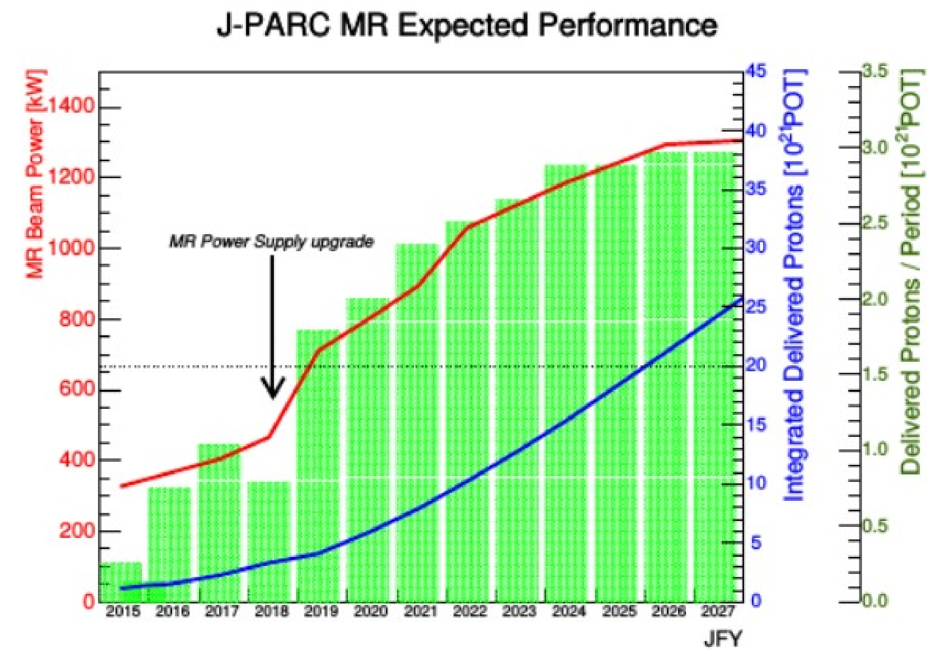
at the end of T2K (7.8x10^{21} POT in 2021) we will still be limited by statistics and not by systematics

- 5σ δ_{CP} measurement at DUNE/HK after 2030 → a lot of room for interesting results before that and 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:**

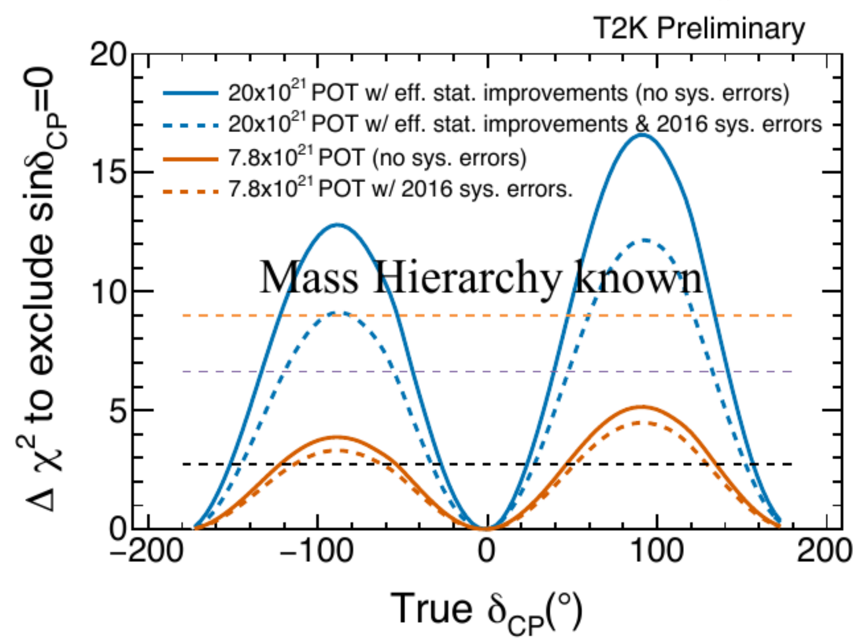
JPARC Main Ring upgrade approved: beam power up to 1.3MW in view of HyperKamiokande



today: 32 ν_e event, 4 $\bar{\nu}_e$ events

T2K-2: 400 ν_e events, 100 $\bar{\nu}_e$ events

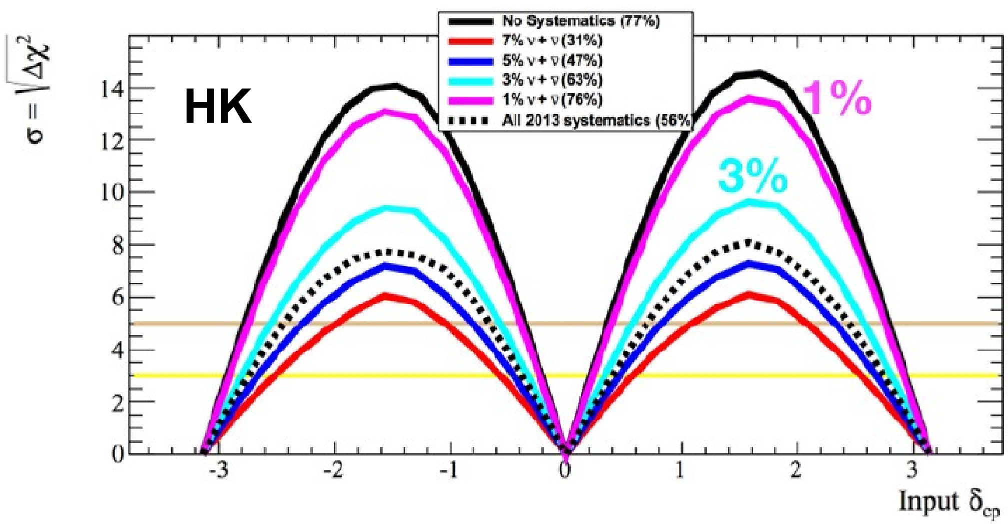
→ good chances to observe **CP violation at > 3σ** by 2026 for a sizeable fraction of δ_{CP} values

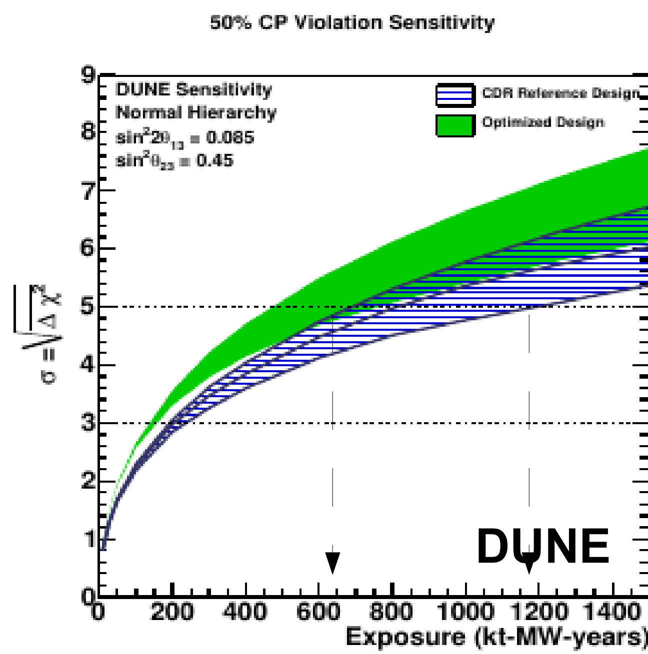


Systematics and near detector

- 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%

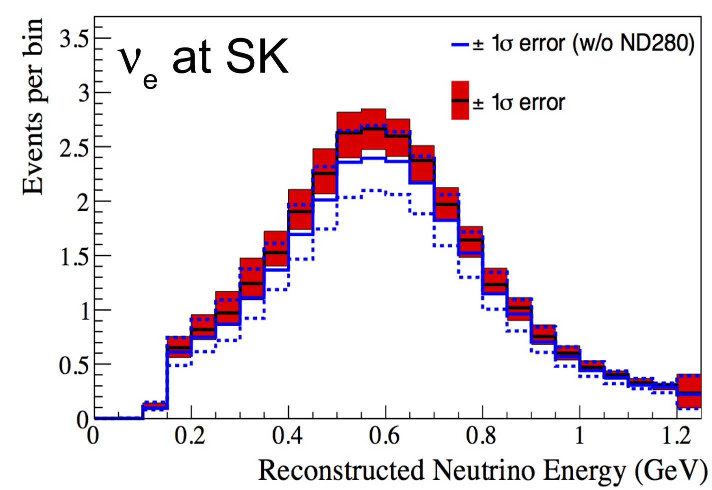
5% ± 2%

5% ± 3%

→ equivalent to factor 2 in exposure!

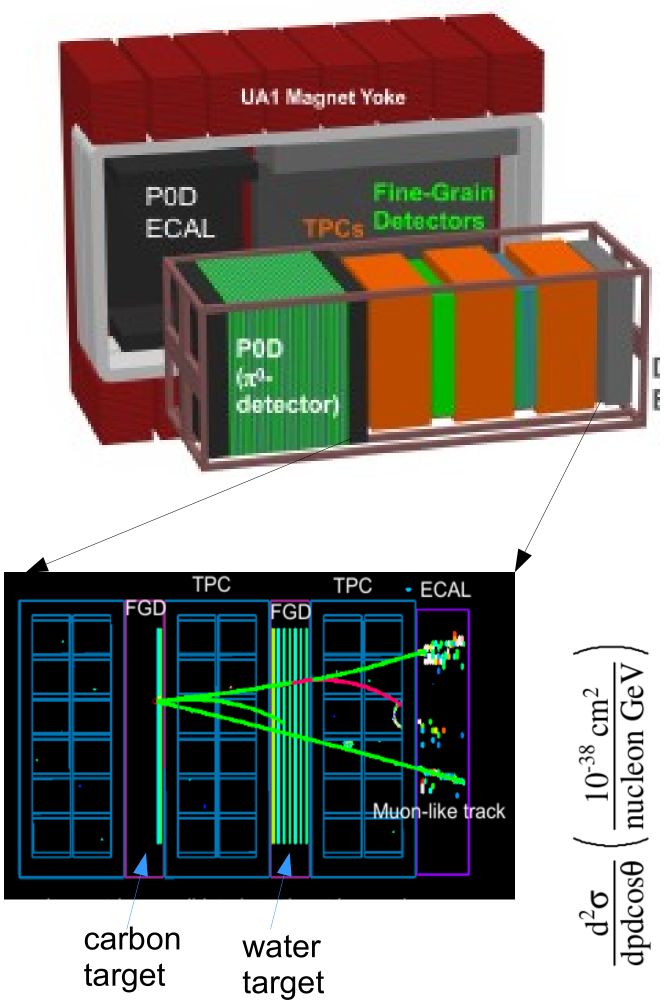
- Crucial role of near detector: example from ν_e appearance at T2K

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%

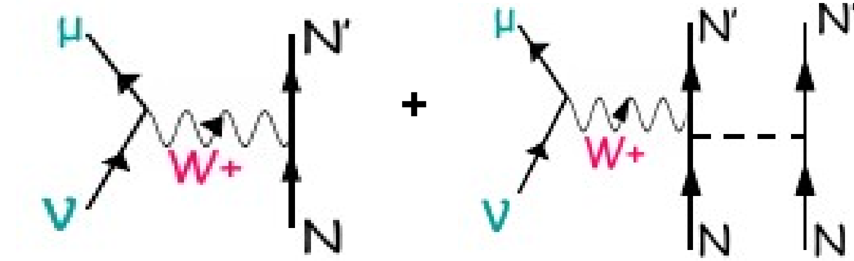


Neutrino-nucleus interaction

- 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:



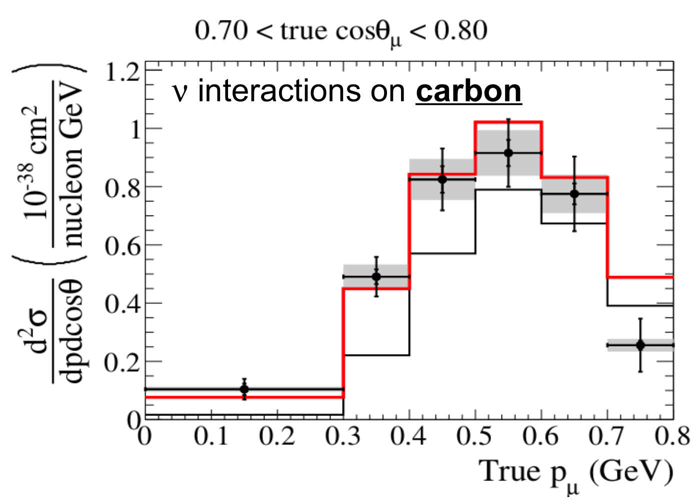
Charged Current Quasi-Elastic

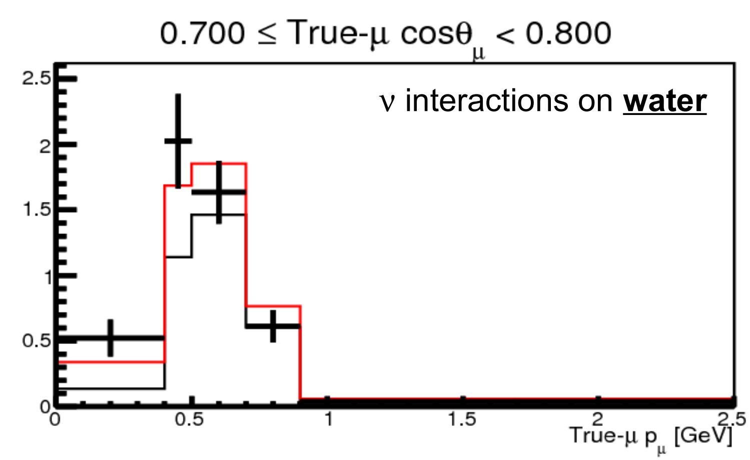
higher order corrections in nuclear target

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

— CCQE

— CCQE + multi-nucleon interactions

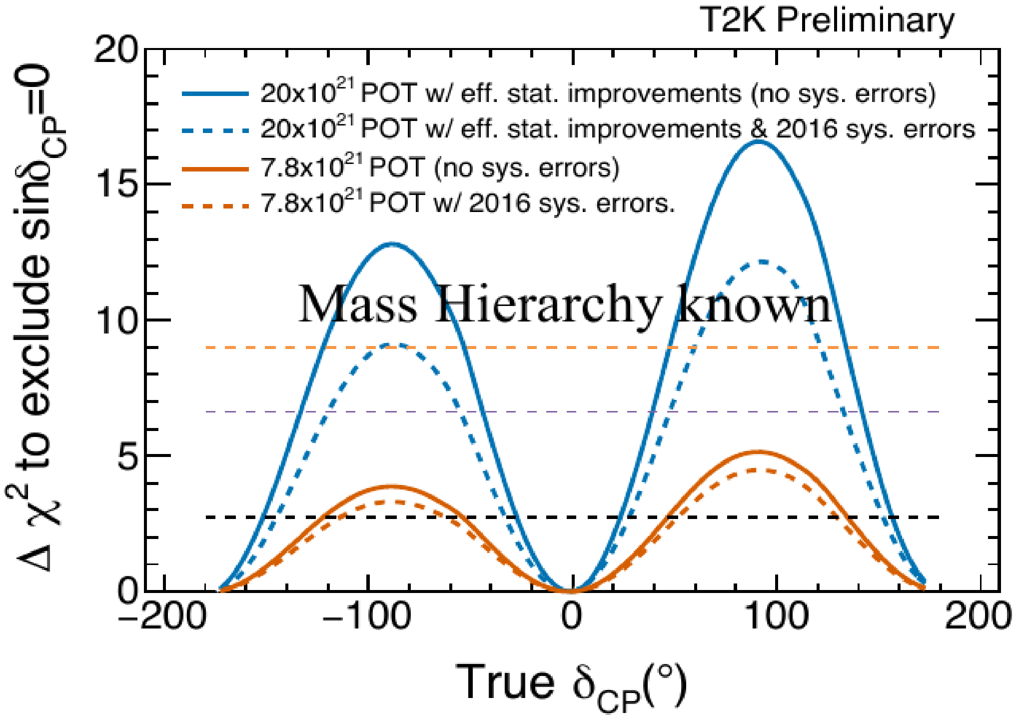


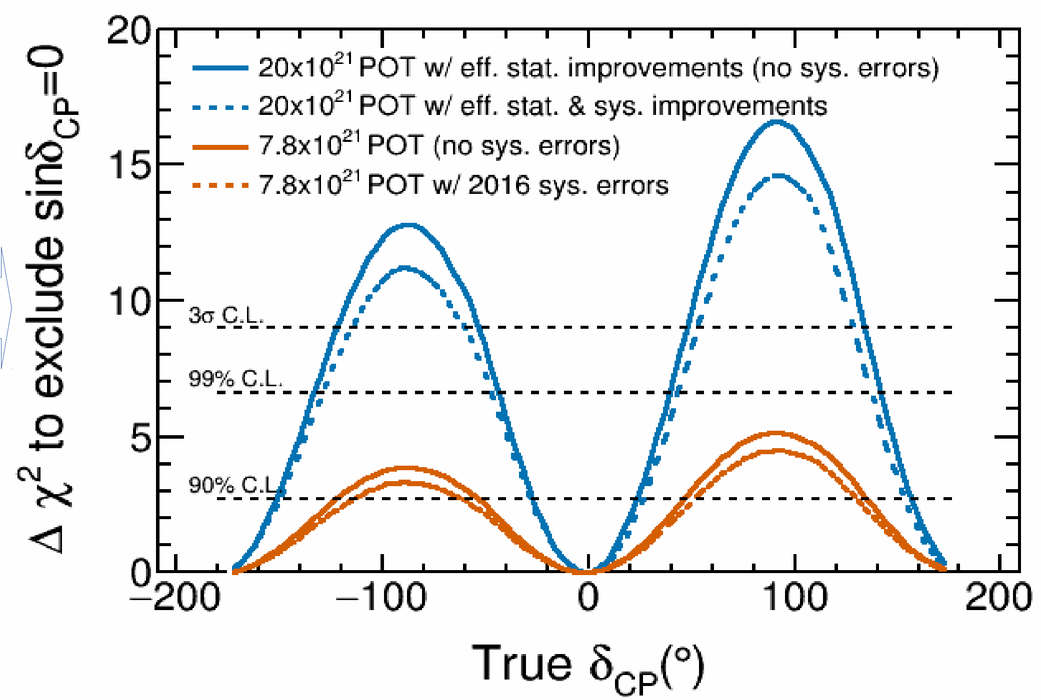


ND280 Upgrade for T2K Phase II

- 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

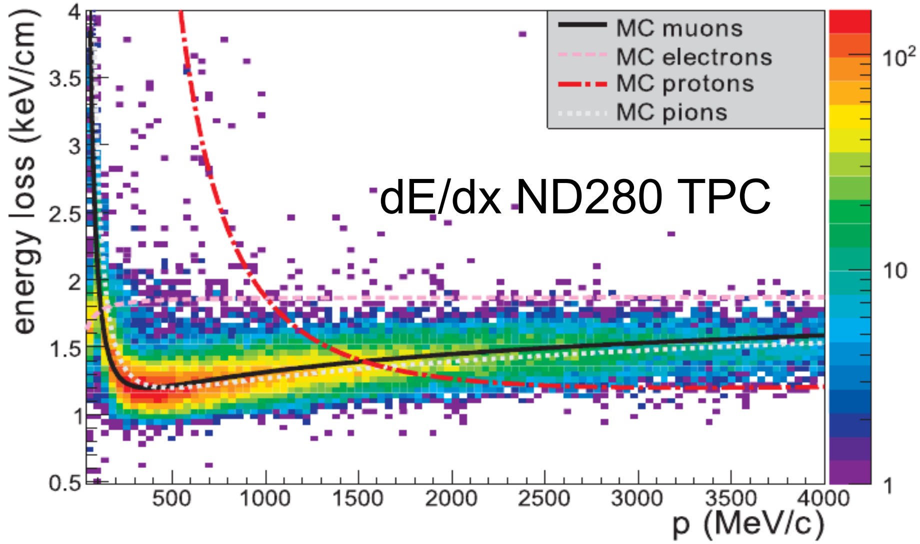
→ We are currently studying **an upgrade of the near detector ND280 to improve the constraints on the systematics**



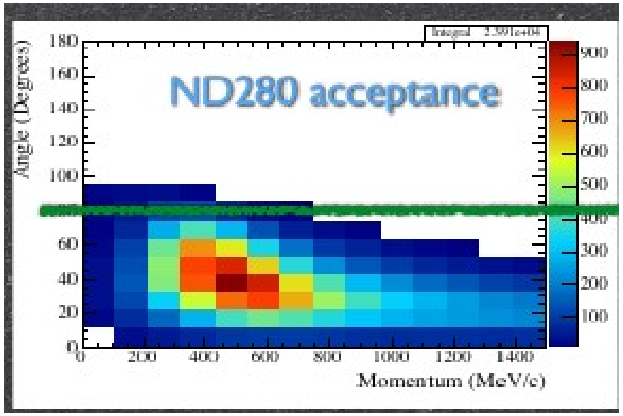


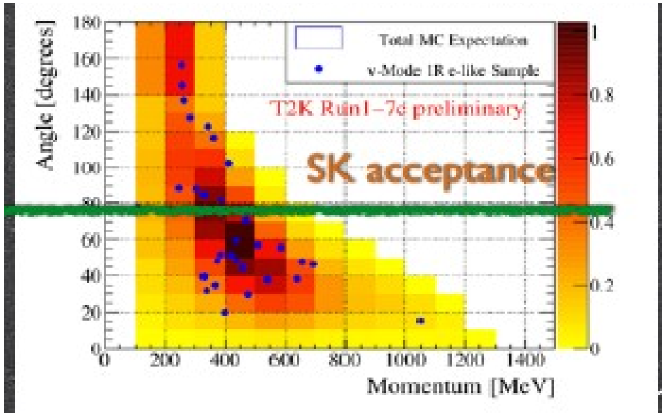
→ **better understanding of neutrino-nucleus interactions crucial also for next-generation of experiments (DUNE/HK)**

Physics drivers

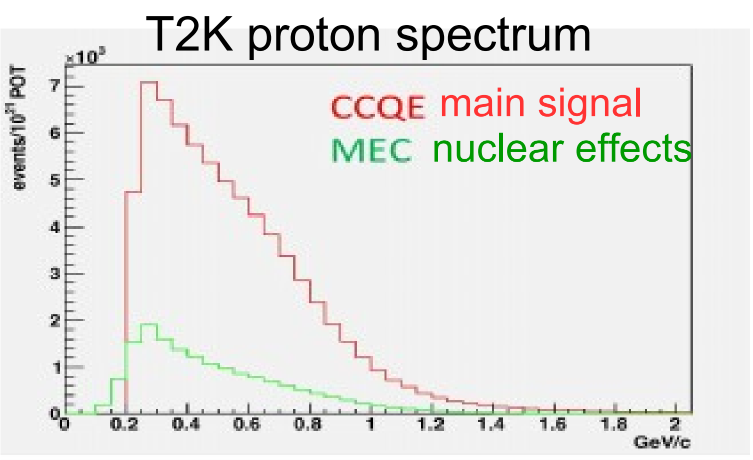


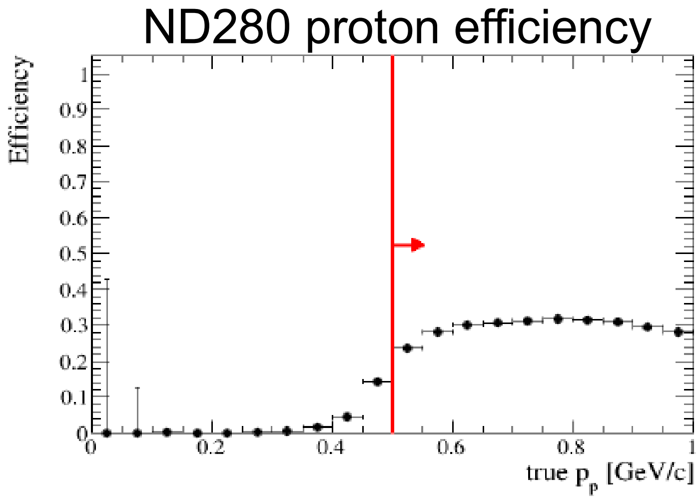
- Keep the very good e/μ separation





- Improving the angular acceptance over the full polar angle and



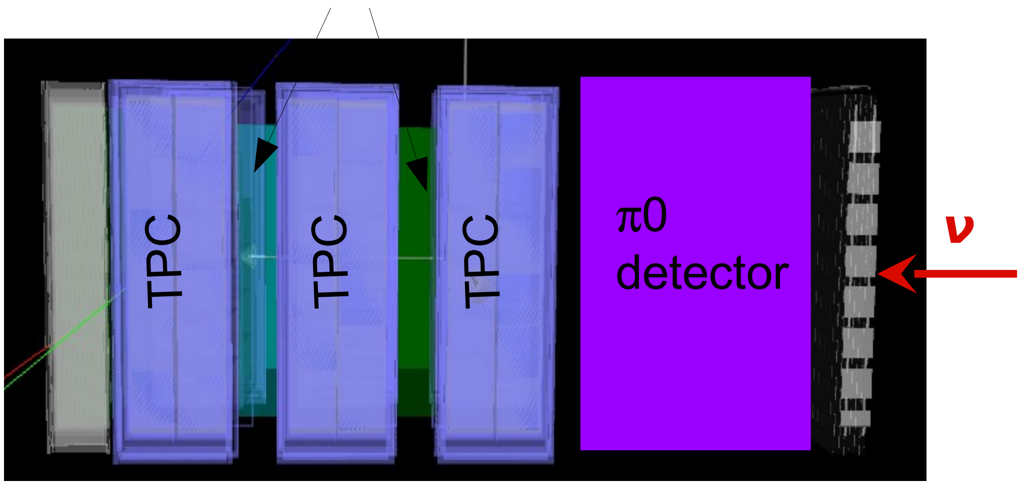


- Lower threshold for low momentum particles (muons, protons, pions)

Possible configuration

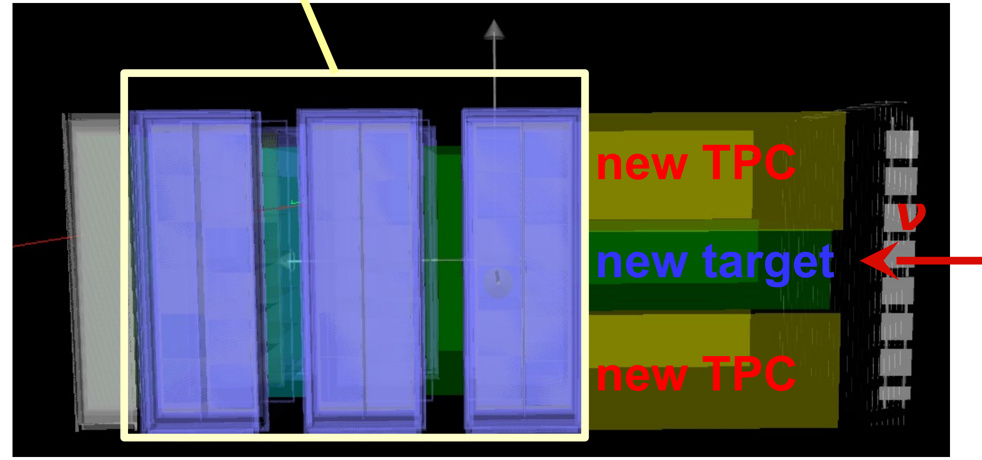
ND280 TODAY

Fine Graned Scintillators



ND280 Upgrade

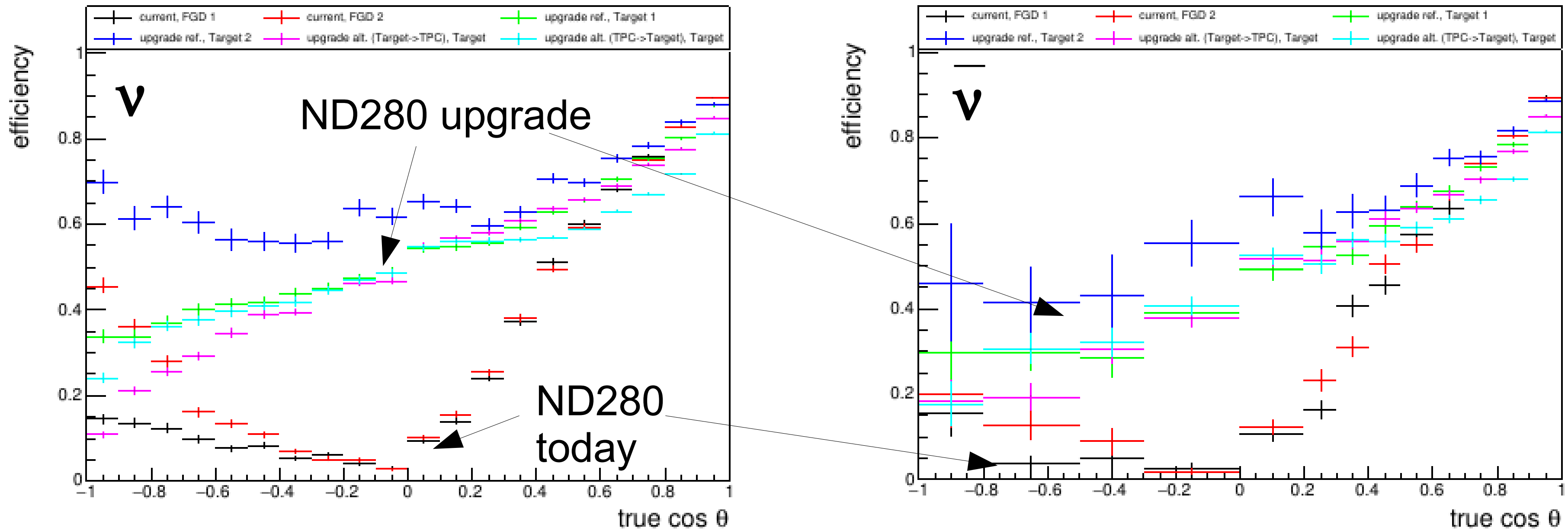
same as today



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

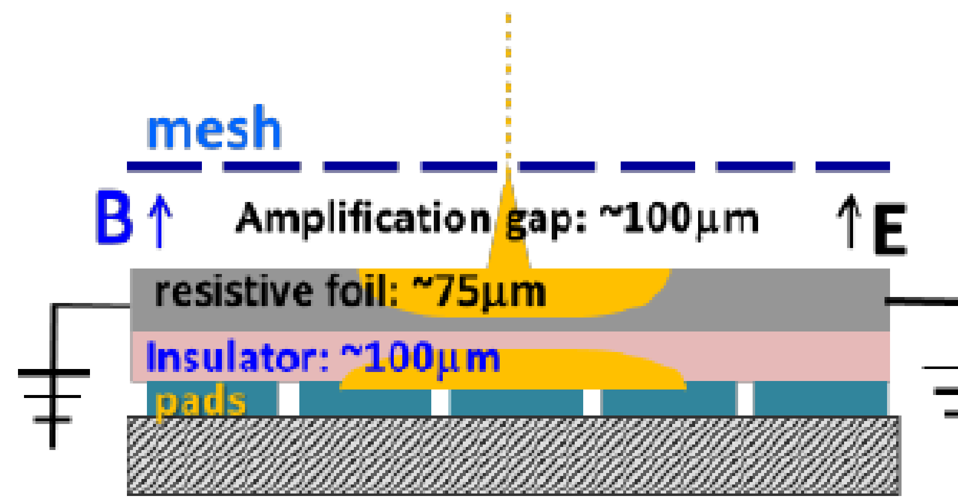
New TPCs

- **New horizontal TPCs to enlarge high angle acceptance**



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

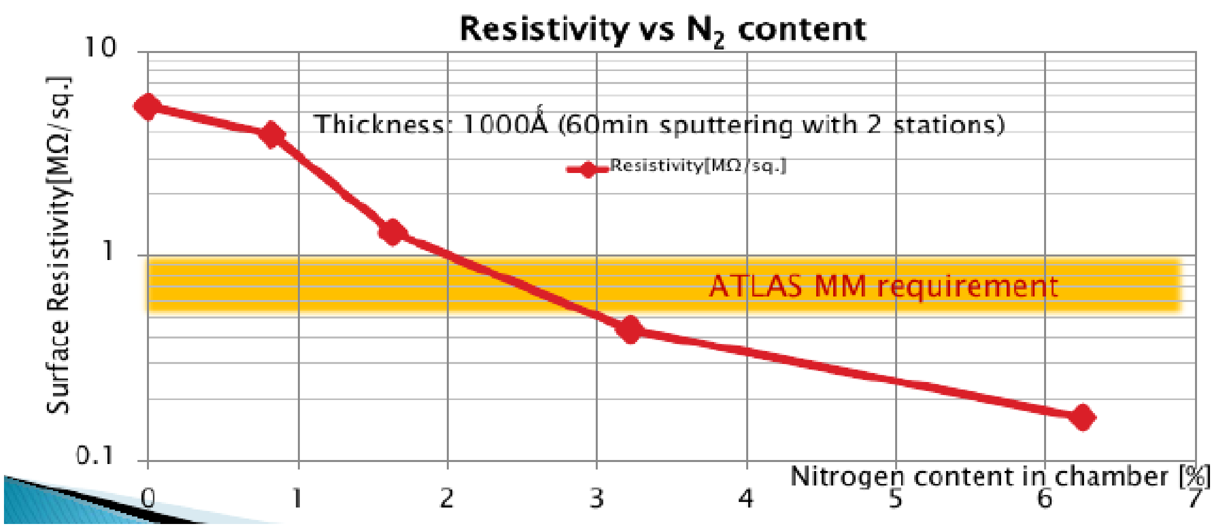
→ **improve spatial resolution and/or decrease the number of channels**

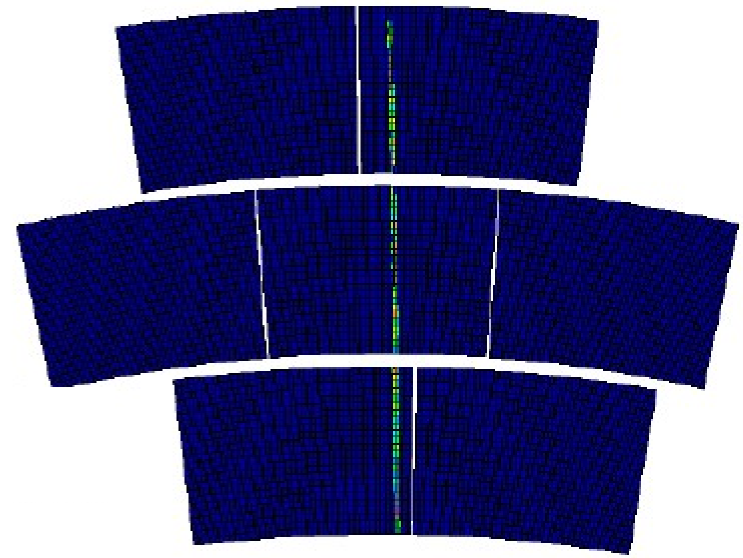


- Front and back-end TPC electronics (CEA and LPNHE)

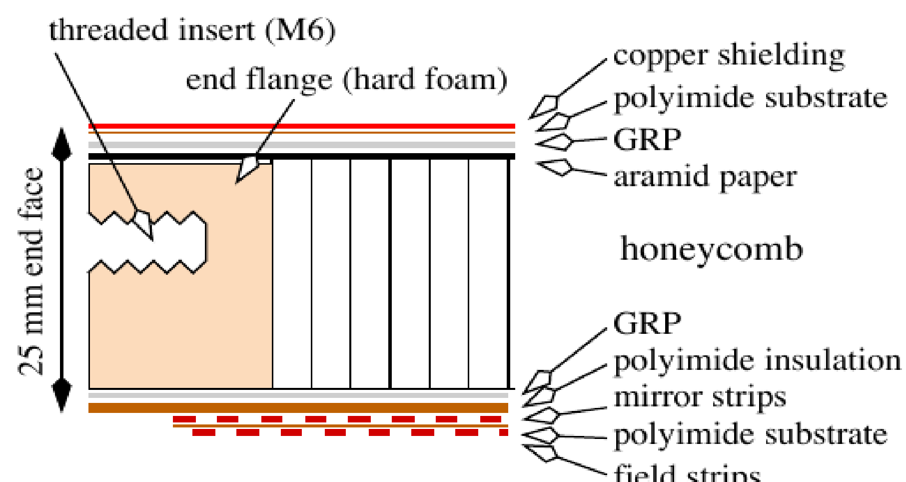
R&D for TPC

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



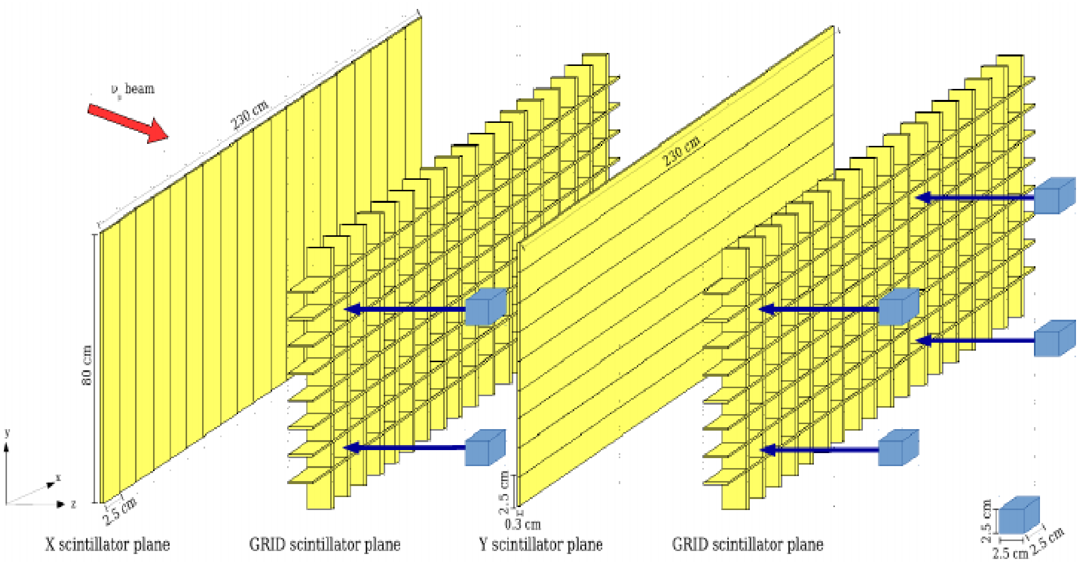


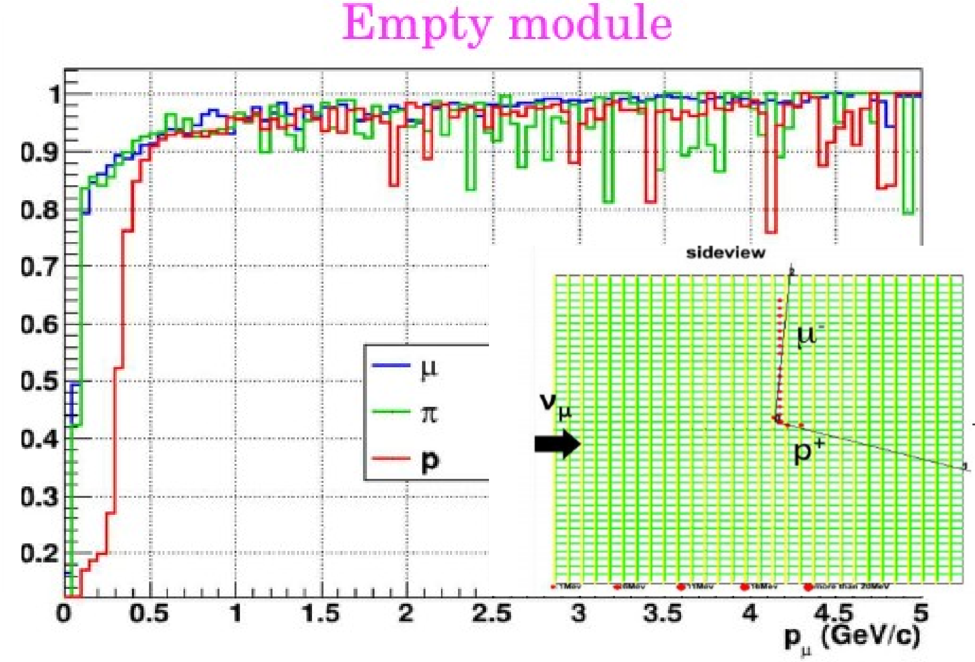
- Light **field cage** to minimize the background due to interactions on passive material (similar to Aleph/ILC field cage)



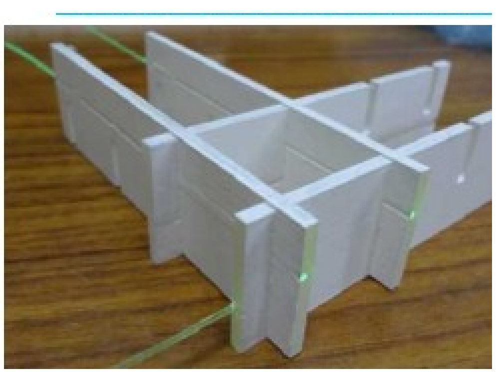
Possible design for new target

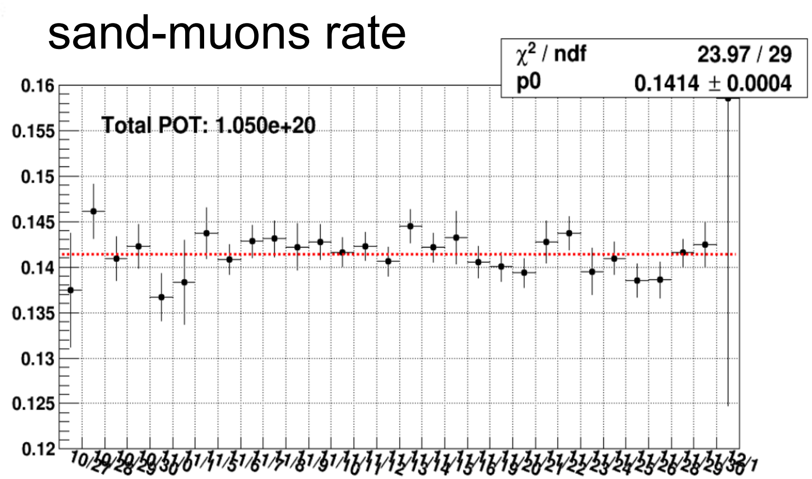
WAGASCI (LLR): new grid-like geometry allowing for low threshold or to be filled with water for same target as far detector





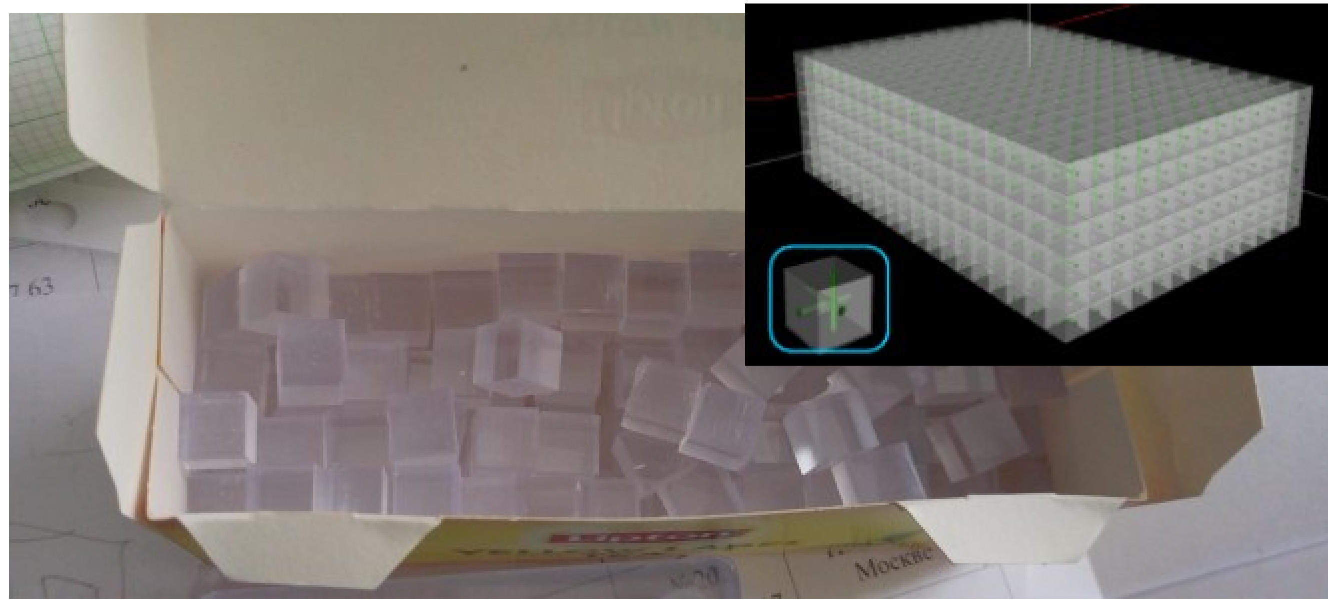
First prototype already installed at T2K on-axis and taking data





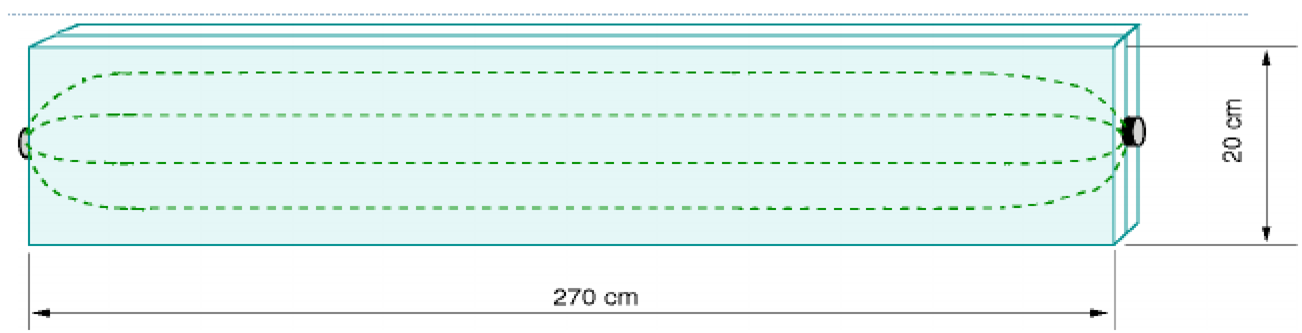
Further R&D

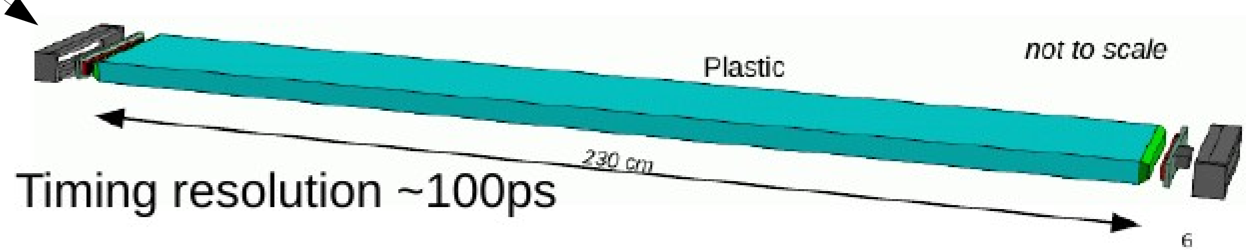
- More sophisticated target under study:
  fully 3D scintillator



- Different **ToF technologies,** eg:

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





Timing resolution ~100ps

ND280 upgrade: status

- **3 workshops with large participation** (2 at CERN and 1 in Japan)

  Linked with work on High Pressure TPC to measure neutrino cross-section and as possible DUNE near detector

- **Expression of Interest well received by CERN** (SPSC-EOI-015)

  signed by ~190 physicists from Bulgaria, Canada, France, Italy, Japan, Germany, Poland, Spain, Sweden, Switzerland, UK, USA, CERN

→ full proposal in Fall

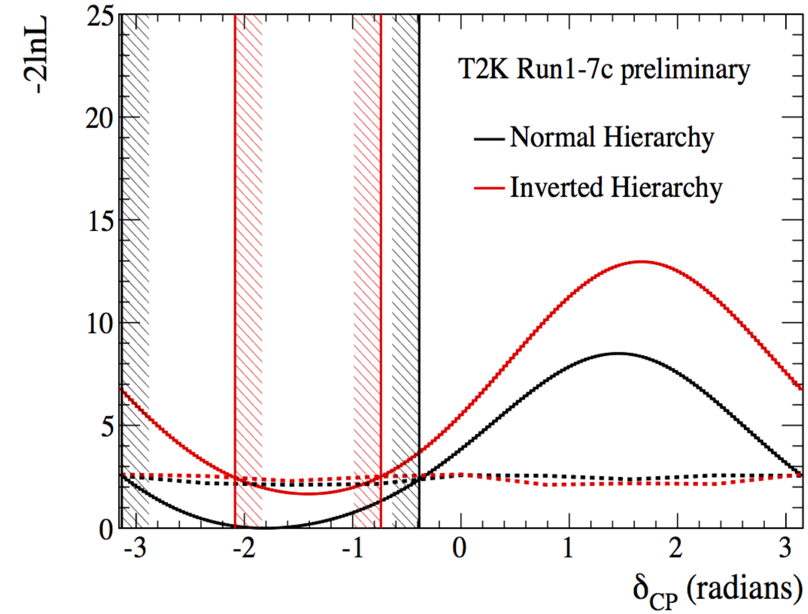
- **Important role of French T2K groups (CEA, LLR, LPNHE)**

  New collaborators welcome!!!

Summary

- **First 90% CL exclusion of CP conservation:** **hint for maximal ν-$\bar{\nu}$ asymmetry**

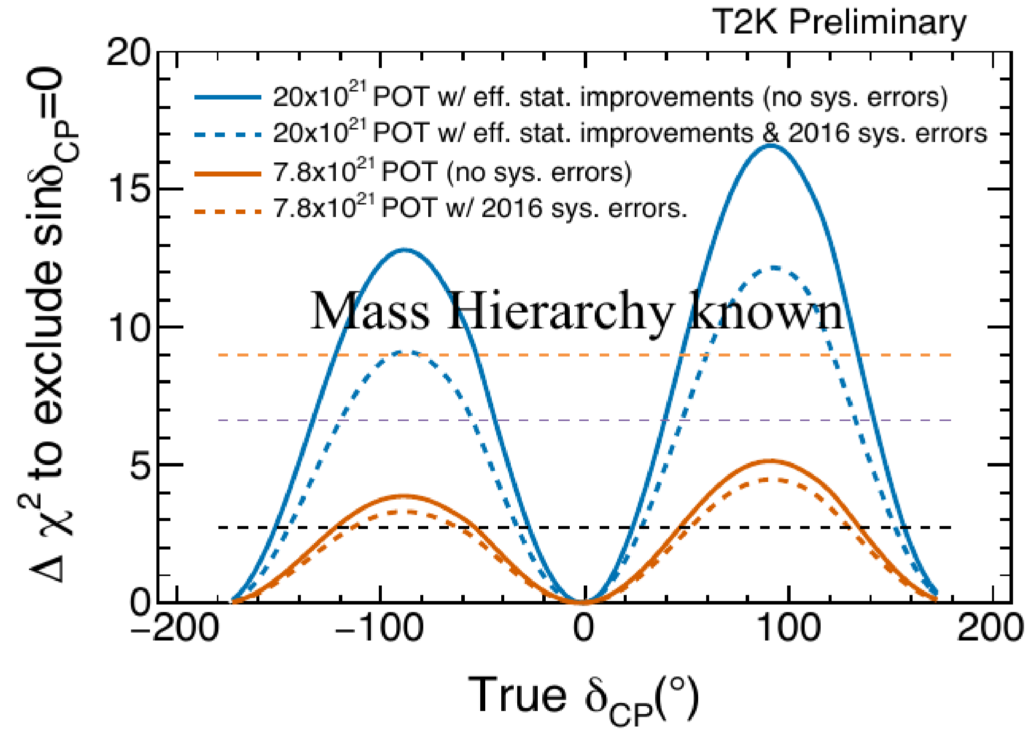
T2K δ_{CP} measurement will be until the end (2021) limited by statistics



- 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

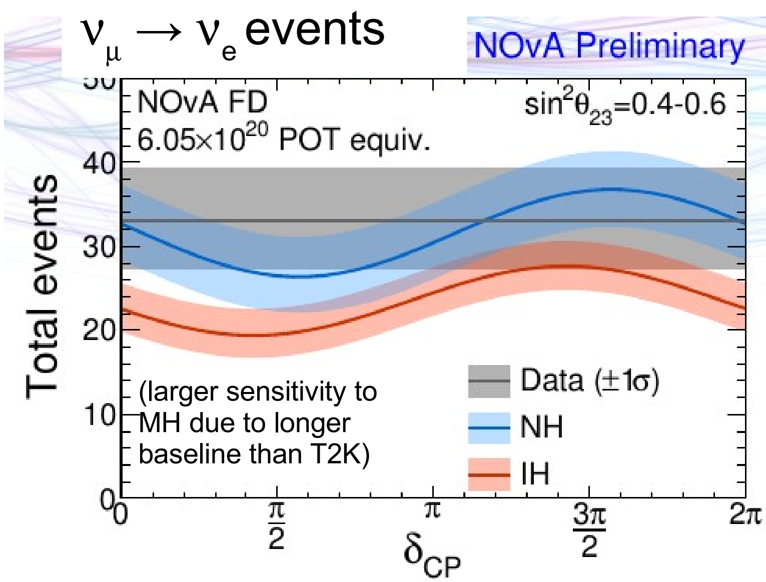


- **Precise measurements of ν-nucleus xsec (and better theoretical nuclear modeling)** thanks to T2K-2 will be also crucial for the success of DUNE and HyperKamiokande

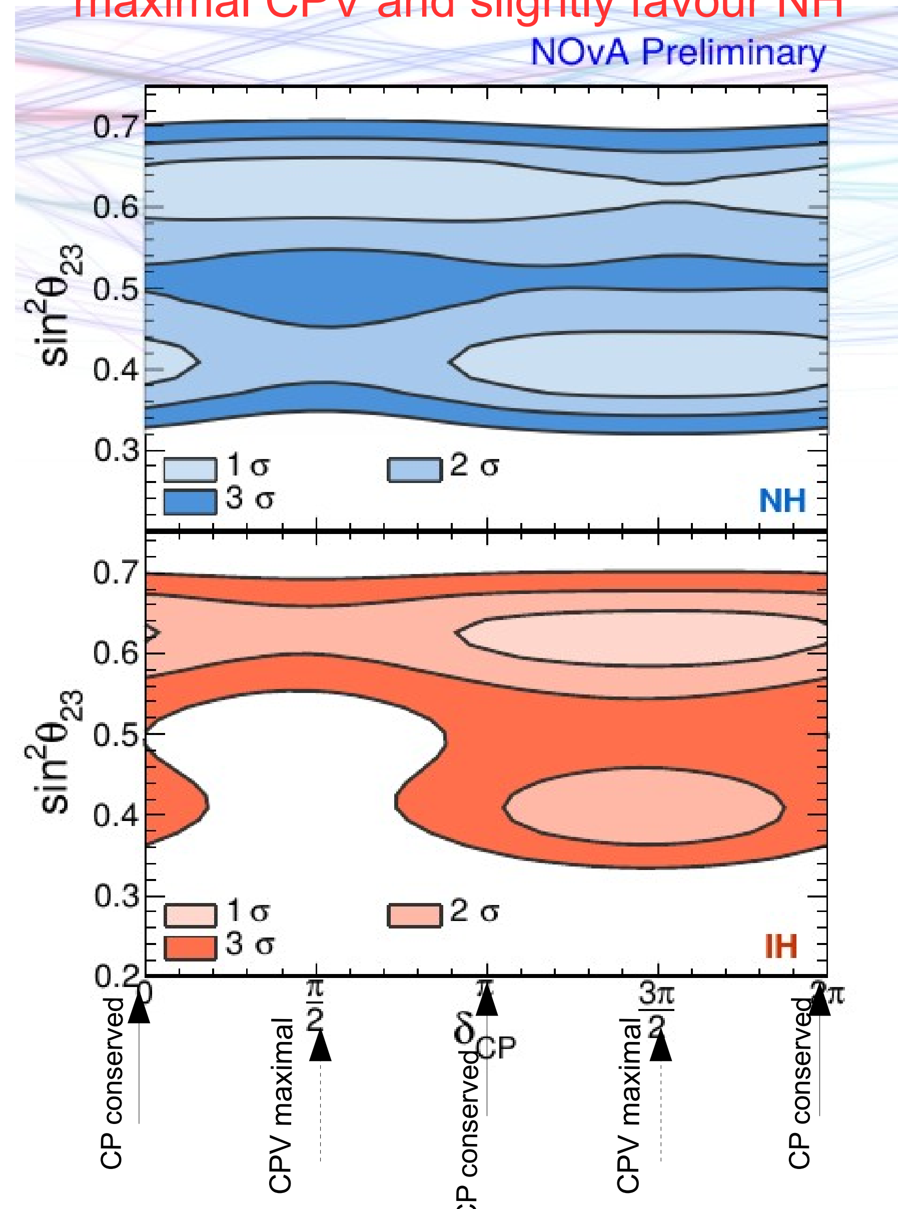
BACKUP slides

NOVA δ_{CP}

NOVA has taken 6.05×10^{20} POT in ν mode (no $\bar{\nu}$ data yet):

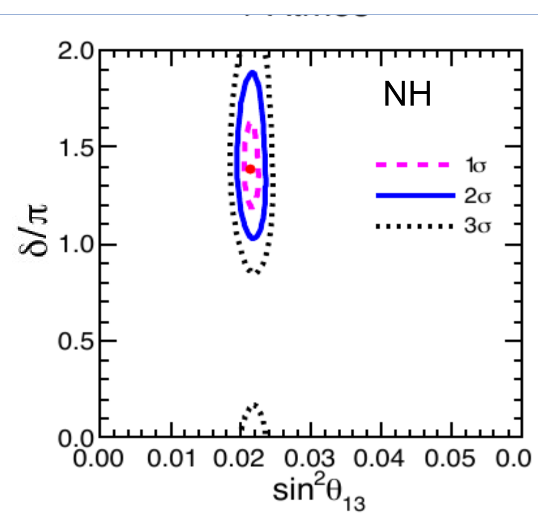


NOVA in agreement with T2K: favours maximal CPV and slightly favour NH



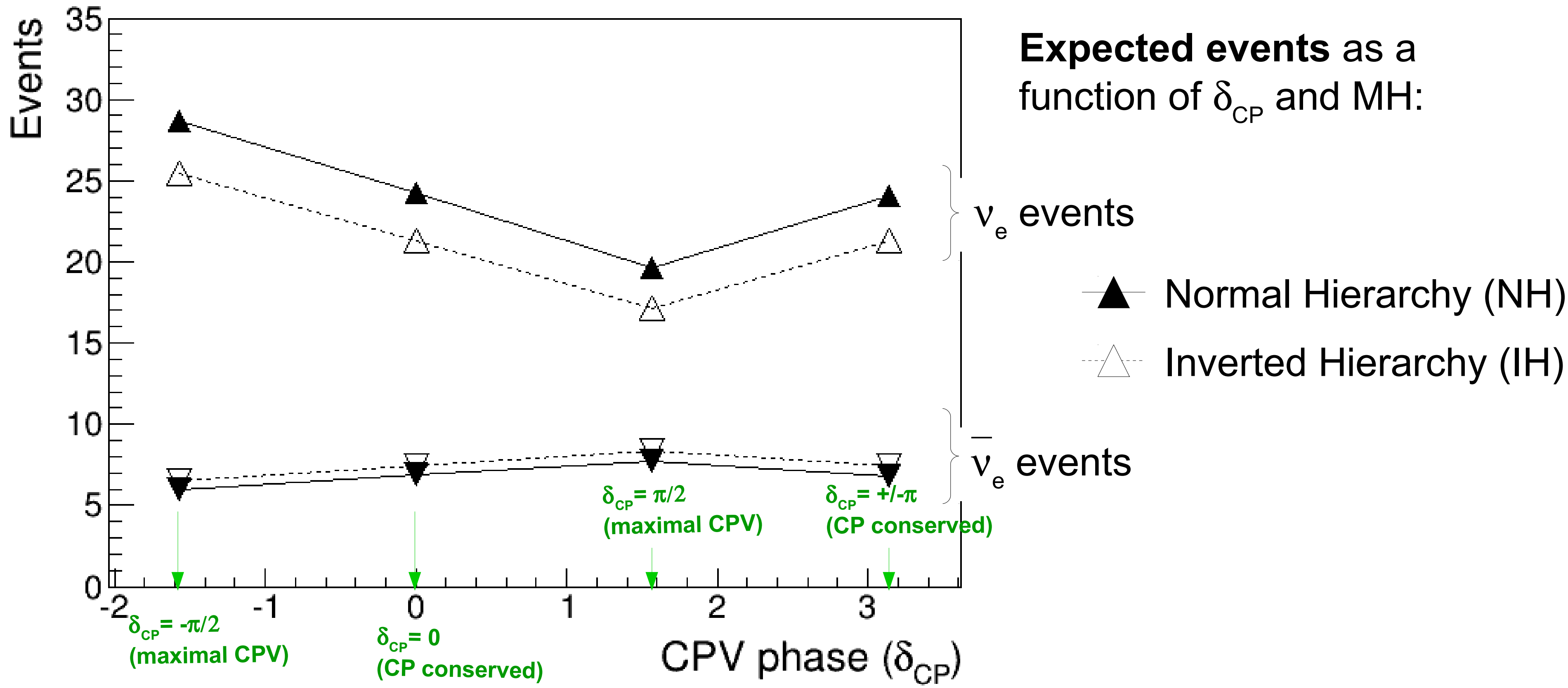
First combination of **all data (T2K, NOVA, SK, ...)**

CP conservation excluded at 2σ



Lisi et al.
NEUTRINO 2016

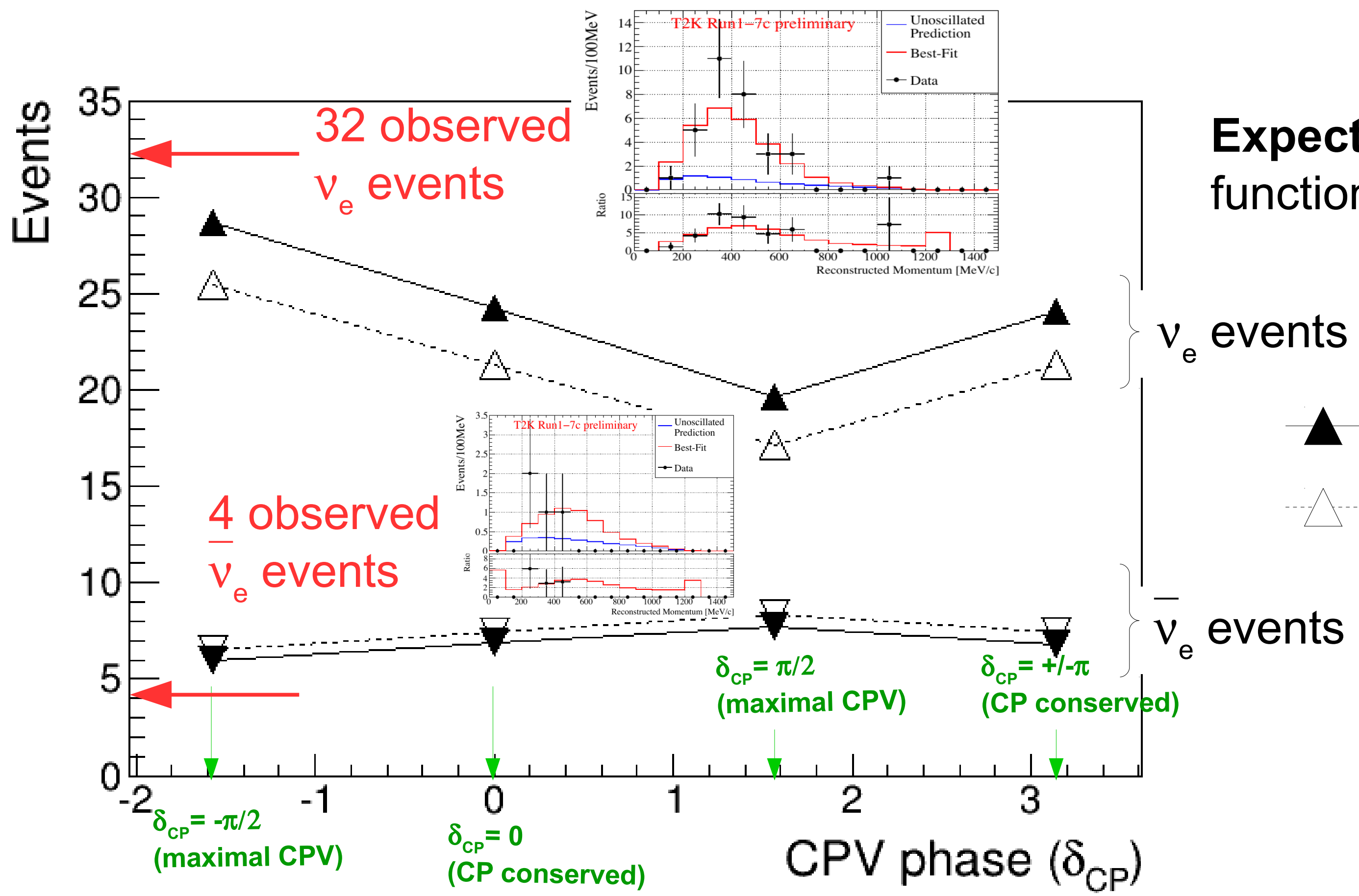
δ_{CP} and MH mainly from $\nu_\mu \rightarrow \nu_e$ / $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



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:



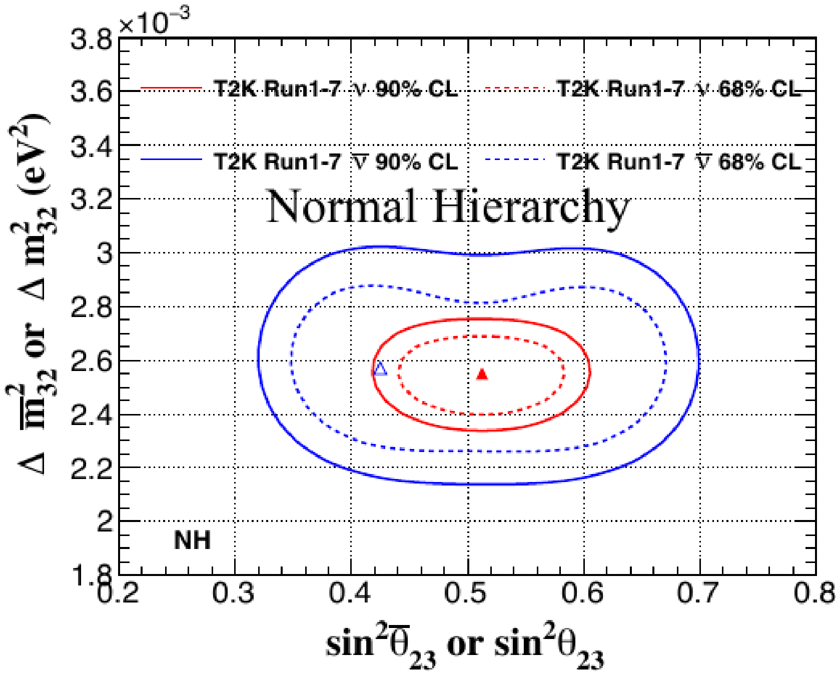
Normal Hierarchy (NH)

Inverted Hierarchy (IH)

Results favour maximal CP violation (and slightly favour NH)

Non standard scenarios

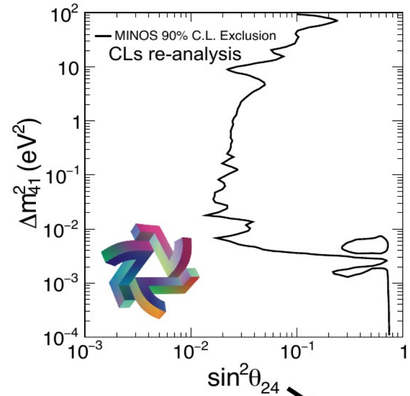
- **CPT violation** in T2K by comparing disappearance $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$

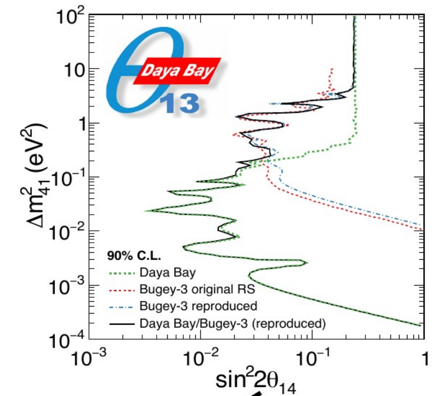


- Limits on **non-standard neutrino interactions** from MINOS+

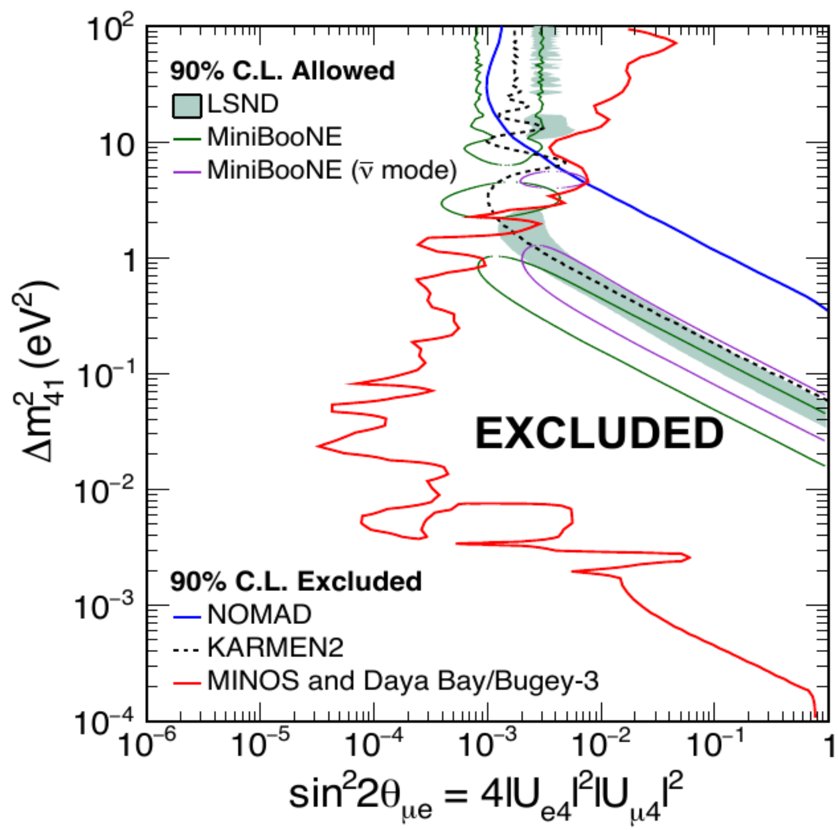
→ important to constrain to avoid degeneracies and biases with future precise δ_{CP} measurement!

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

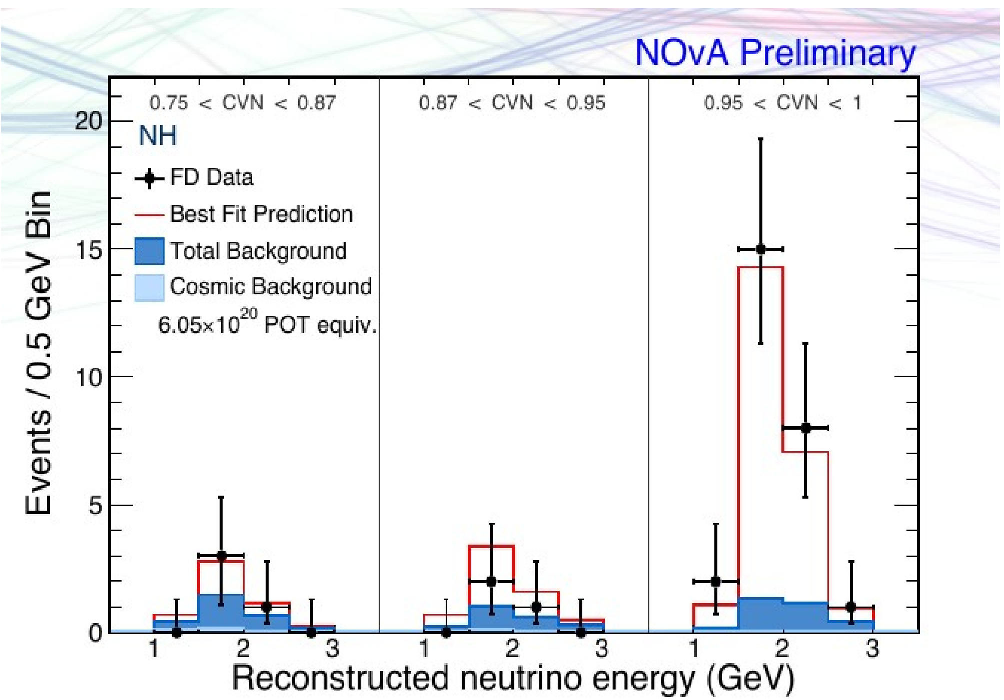




$$4|U_{\mu 4}|^2|U_{e4}|^2 = \sin^2\theta_{24}\sin^2(2\theta_{14}) \equiv \sin^2(2\theta_{\mu e})$$

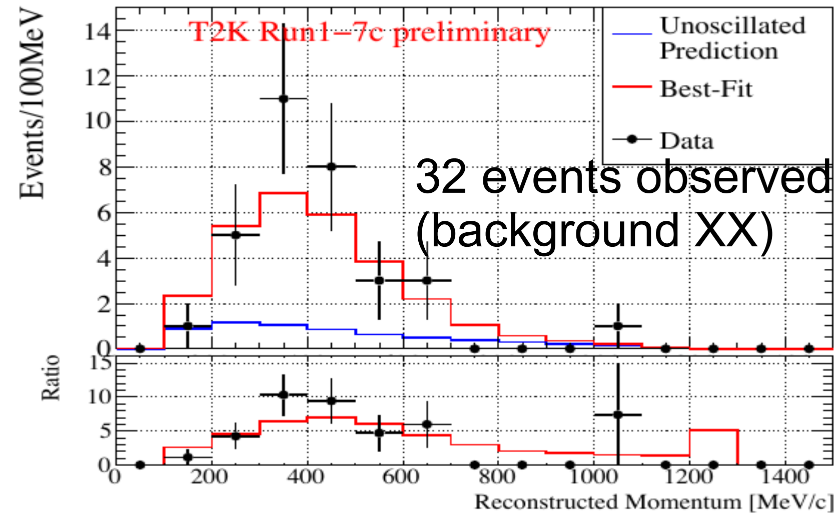


NOVA – T2K comparison: nue appearance

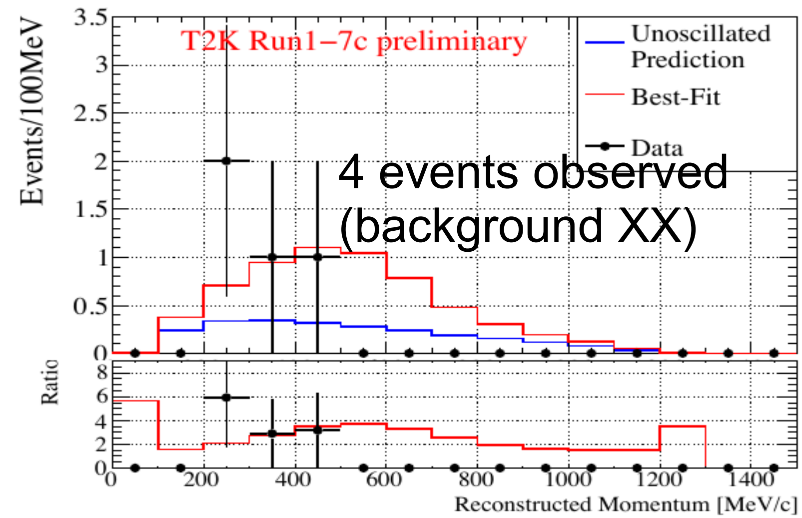


- Observe **33** events passing ν_e selection
- On 8.2 background

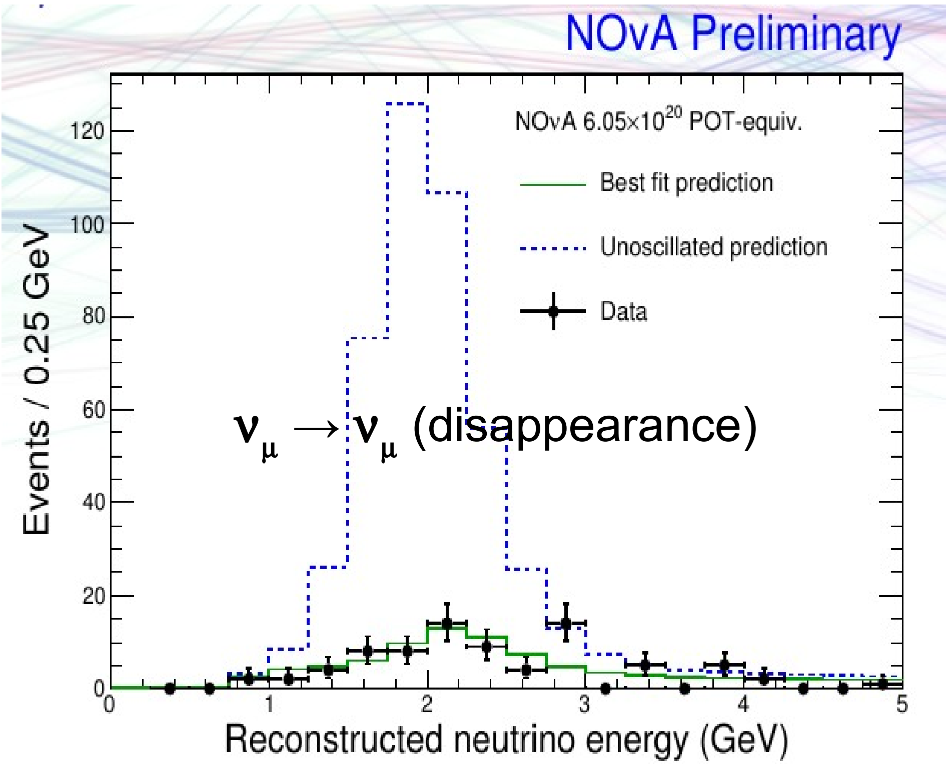
ν_e

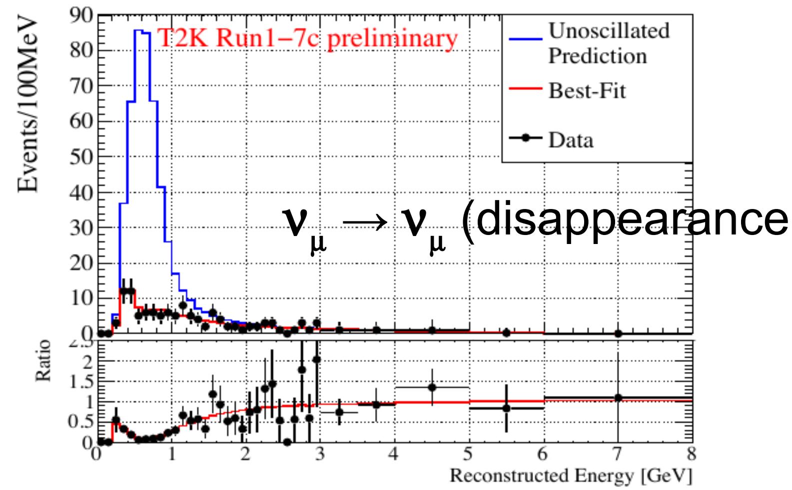


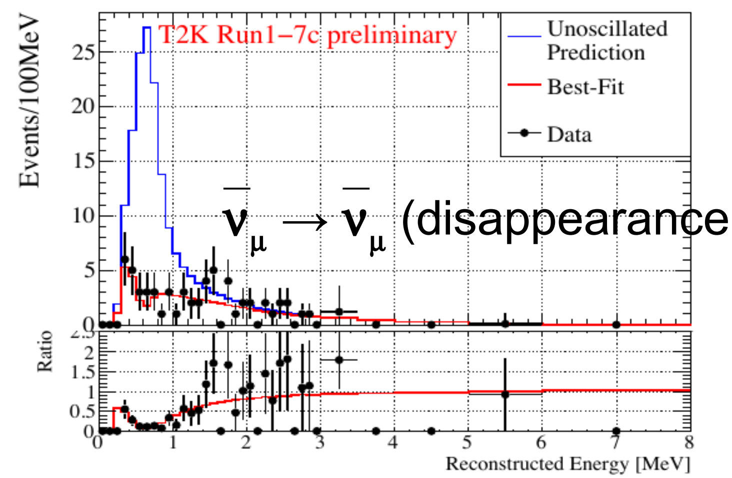
$\overline{\nu}_e$



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%**

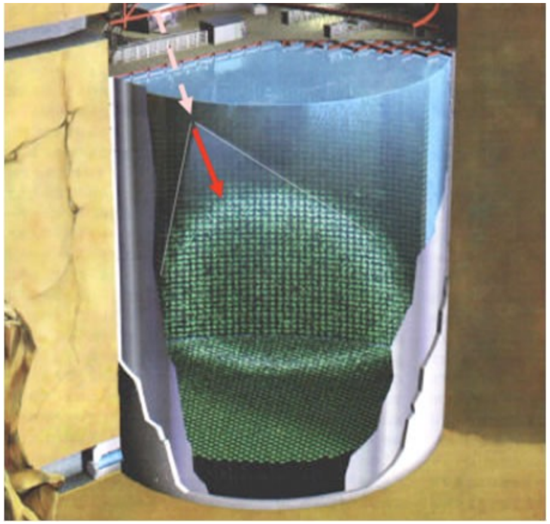
T2K systematics uncertainties (joint oscillation analysis)

Fractional error on the number of expected events at SK

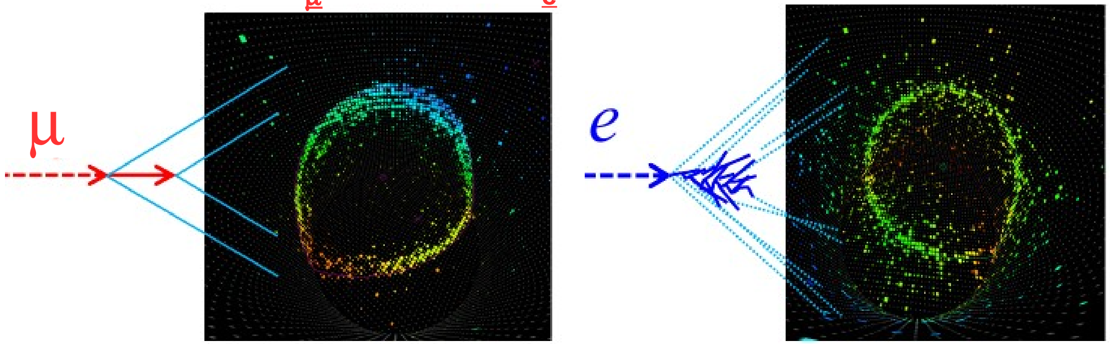
	ν_μ sample $1R_\mu$ FHC	ν_e sample $1R_e$ FHC	$\bar{\nu}_\mu$ sample $1R_\mu$ RHC	$\bar{\nu}_e$ sample $1R_e$ RHC	$1R_e$ FHC/RHC
ν flux+cross-section constrained by ND280	2,8%	2,9%	3,3%	3,2%	2,2%
ν_e/ν_μ and $\bar{\nu}_e/\bar{\nu}_\mu$ cross-sections	0,0%	2,7%	0,0%	1,5%	3,1%
NC γ	0,0%	1,4%	0,0%	3,0%	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%**

How does it work?

SUPERKAMIOKANDE



■ **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) $\nu n \to l^- p$ (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 $\pi^0 \to \gamma\gamma \to$ e-like ring + **γ undetected**
- $\bar{\nu}$ oscillations: intrinsic ν component in the beam

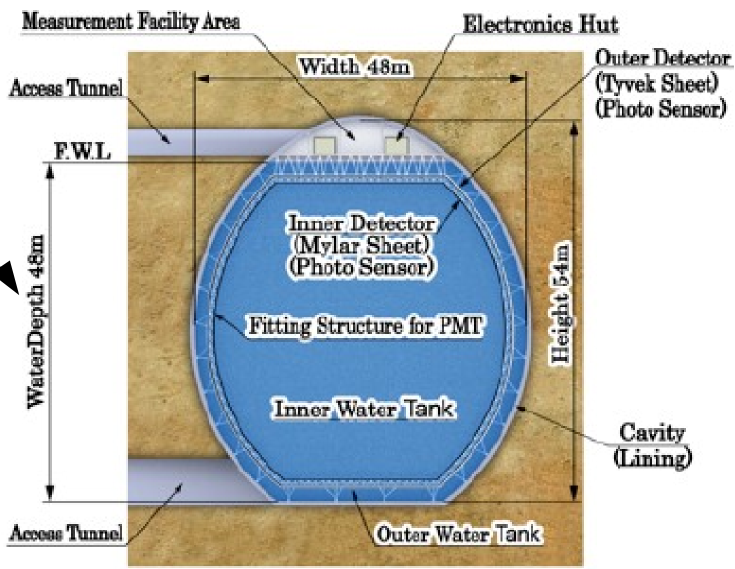
No magnetic field → no charge measurement ($\nu/\bar{\nu}$)

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

HYPERKAMIOKANDE: Working to improve PMTs and on Gd doping.
Electronics and calibration system very similar to SuperK

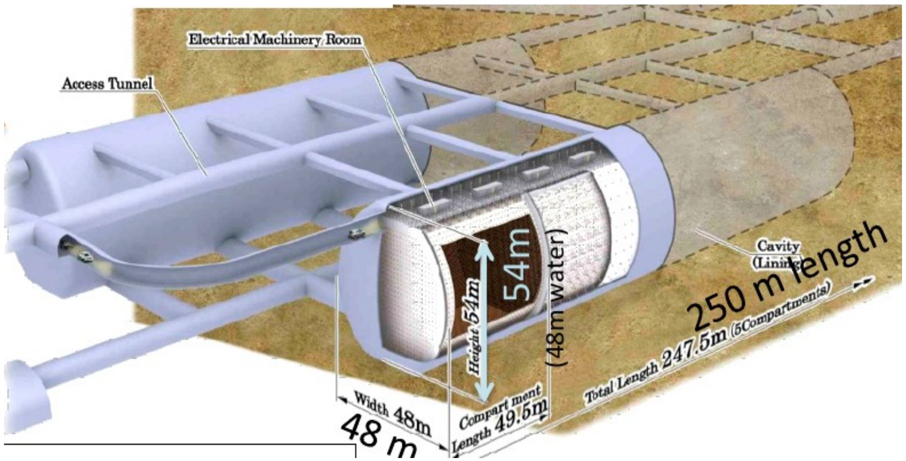
From SuperK to HyperK

Total volume		50 kTon	990 kTon
Fiducial volume		22.5 kTon	**560 kTon**
Tanks		1 cylindrical 41.4m (h) x 39.3m (d)	2 egg-shape tanks 48m (w) x 50m (h) x 250m (l)
PMTs	inner detector	11.129	50.000
	outer detector	1885	25.000
Photocoverage		40%	**20%**
Sensor efficiency (Collection x Quantum eff.)		18% (22x80%)	**29%** (30x95%)

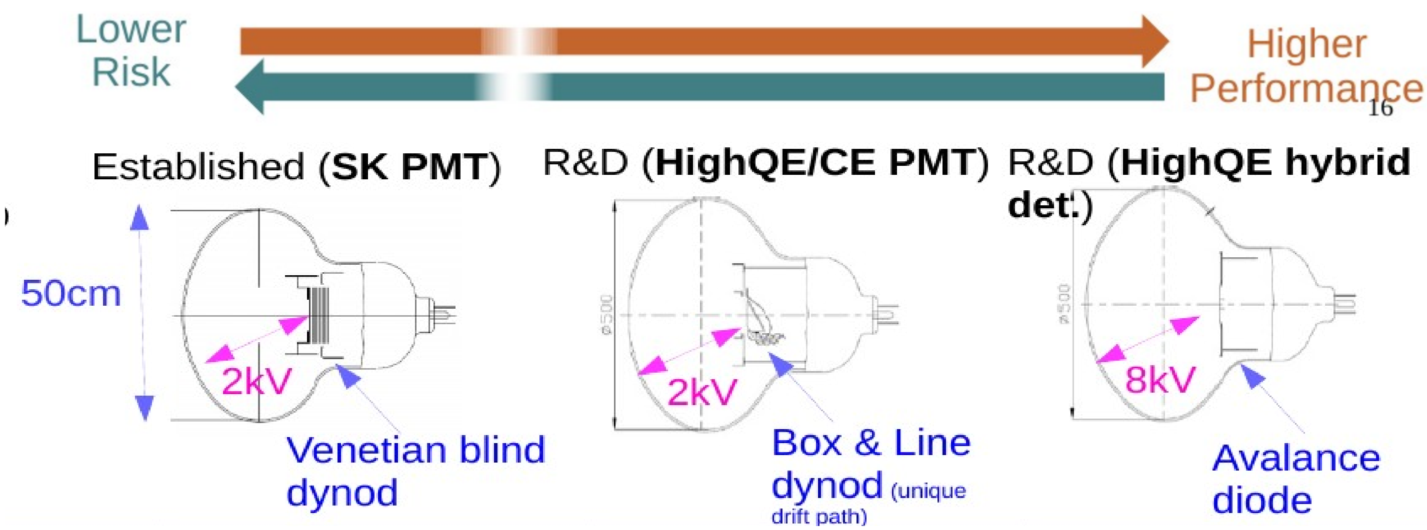


Tanks and PMT design under discussion:

- minimize risk due to pressure on PMTs (avoid cascade implosion as in SK 2001 incident)
- minimize cost (volume vs #PMTs)
- need PMT R&D (next slide)



R&D on PMTs

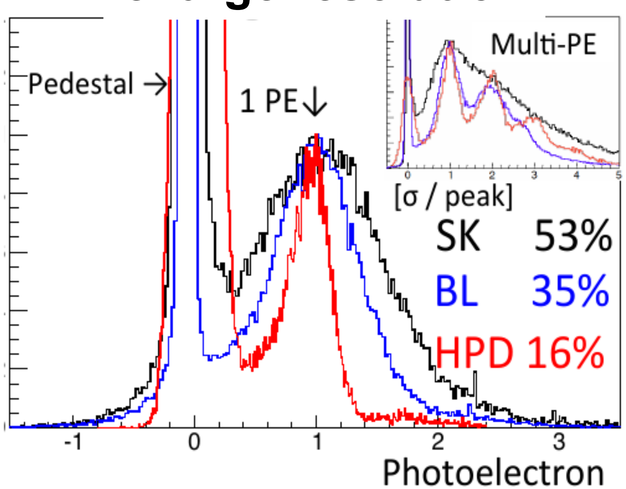


Quantum Eff. (QE)	22%	30%	30%
Collection Eff. (CE)	80%	93%	95%
Timing resol (FWHM)	5.5 nsec	2.7nsec	1nsec

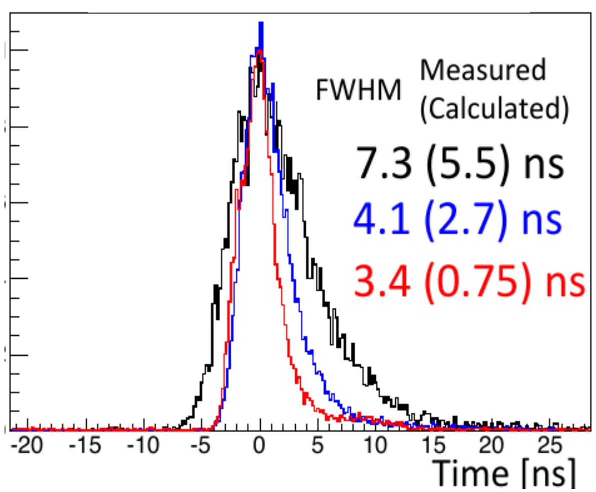
- Optimization should include **pressure resistance**
  possible to put protective cover → need precise control of glass quality

- Response to single photoelectron:

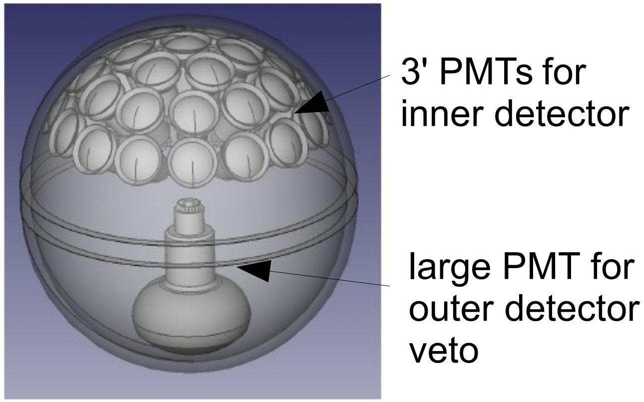
charge resolution



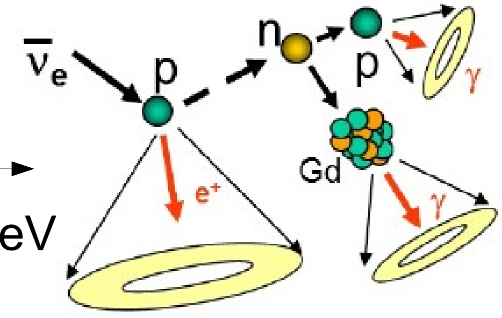
time resolution



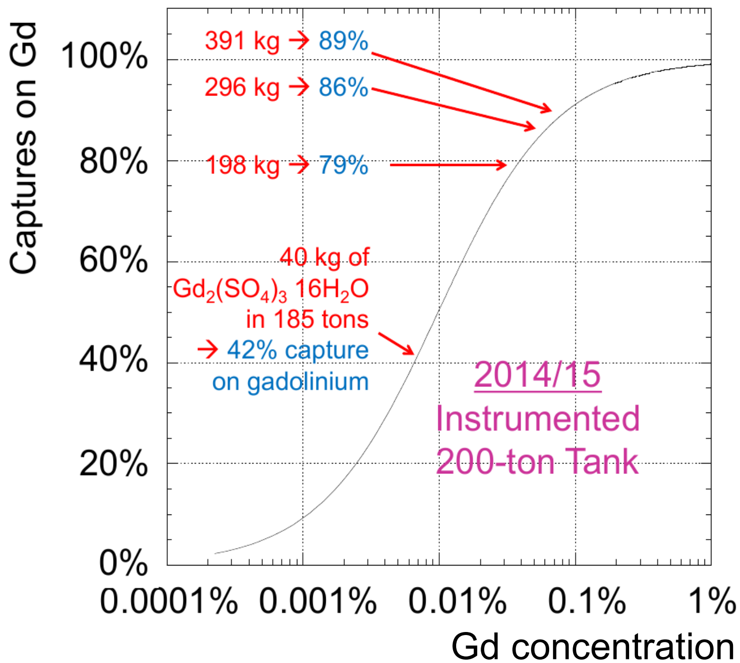
Integrated system of inner and outer PMTs under study (solve problems of pressure and in-water electronics)

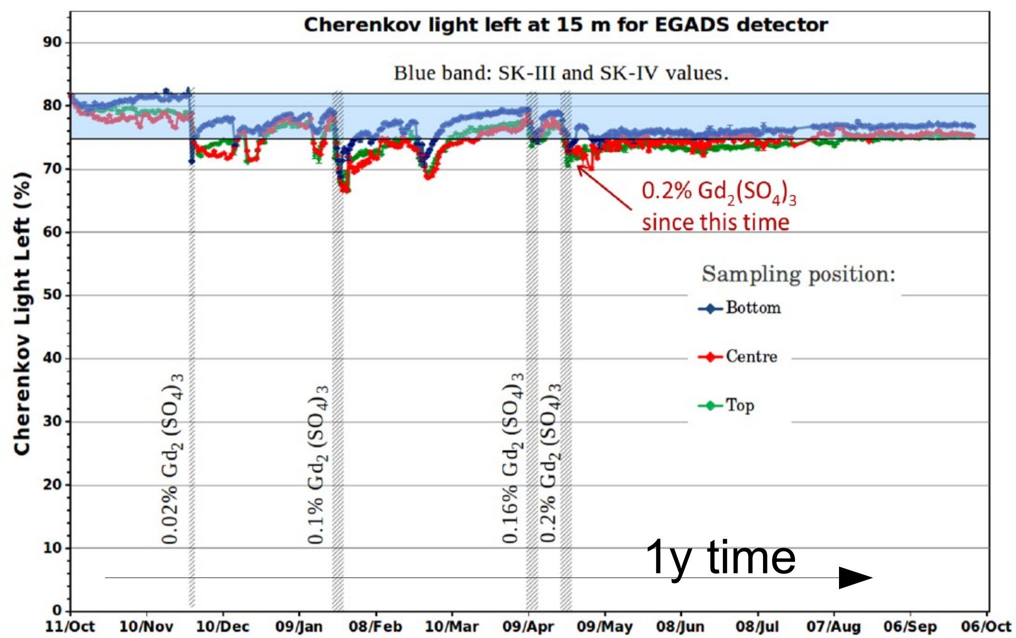


Gadolinium doping



- $\bar{\nu}p \to l^+n \to$ n get captured in Gd with emission of few γ ~8MeV
$\to$ for beam neutrino physics: ν vs $\bar{\nu}$ separation,
but also useful to enhance sensitivity to SuperNova ν and proton decay
- R&D studies (eg, WATCHMAN) as reactor monitoring
- **EGADS: 200 ton scale model of SuperK fully operative in Kamioka mine**





Neutron capture time tested with Am/Be source: data-MC perfect agreement

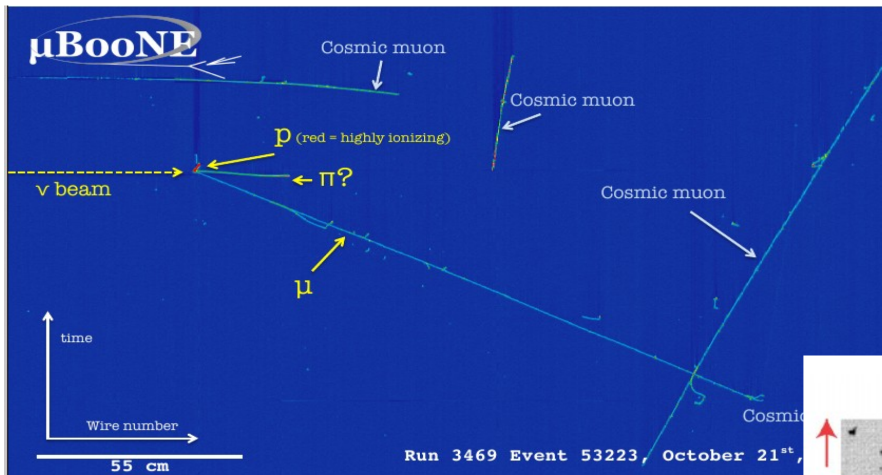
All the trick is about keeping water pure and transparent without loosing Gd (dedicated filtration system)

- SuperKamiokande will run with loaded Gd in next years!

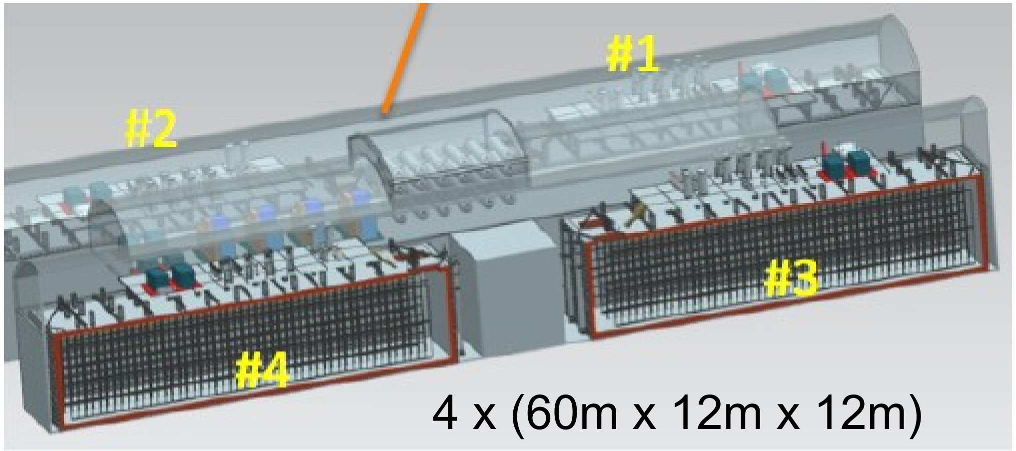
Liquid Argon technology

Ionizing particle in LAr → 2 measurements:

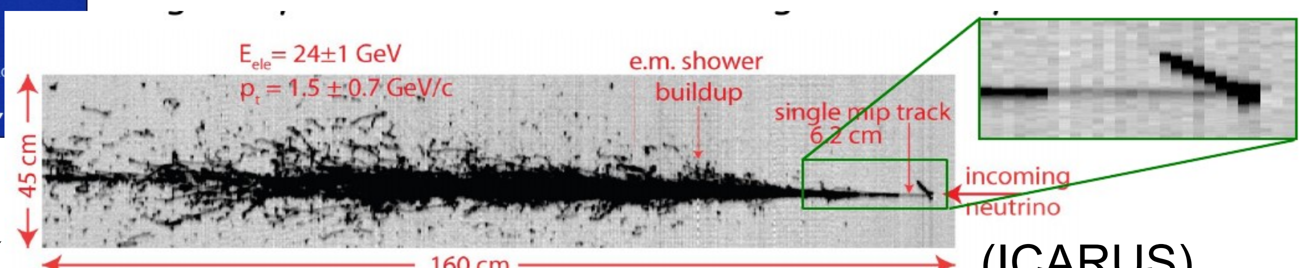
- **charge from ionization**
  → tracking and calorimetry
- **scintillation light** → trigger and t_0
  (drift time → third coordinate for non-beam events)



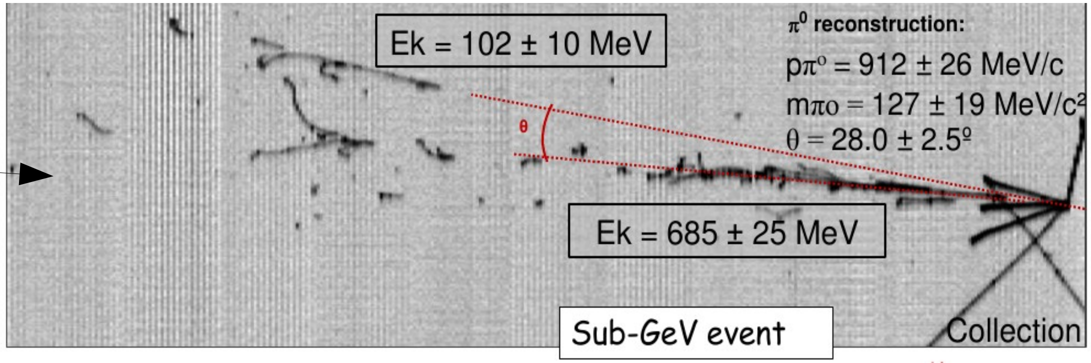
DUNE: staged approach with 4 modules of ~10kTon fiducial mass each



- μ track momentum from range
  (or from multiple scattering if not contained)
- PID from dE/dx
- Very good electron/γ ID and π^0 reconstruction
- Calorimetric energy from total collected charge (+ light)



(ICARUS)



Many other challenges

- **scintillation light:** single phase: first test of wavelenght shifting bars to SiPM integrated with a TPC

  double phase: standard PMTs (with coating),

- **high voltage on large surfaces:** cathode-anode ΔV ~few hundreds V (double phase)
  ~180 V (single phase)

- **large number of channels**

  → electronics in gas accessible only in double phase design

  → calibration and uniformity
  (eg: flattening of cathode and of charge readout plane,
  E field between different modules of charge readout ...)

- **software for automatic reconstruction**

  huge amount of info (efficient zero suppression)

- **LAr TPC as calorimeter**

  fully omogeneus with very low threshold

  very good resolution and detailed tracking inside shower → potential to improve shower models!

ICARUS:
- Low energy electrons: $\sigma(E)/E = 11\%/\sqrt{E(MeV)}+2\%$
- Electromagnetic showers: $\sigma(E)/E = 3\%/\sqrt{E(GeV)}$
- Hadron shower (pure LAr): $\sigma(E)/E \approx 30\%/\sqrt{E(GeV)}$

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

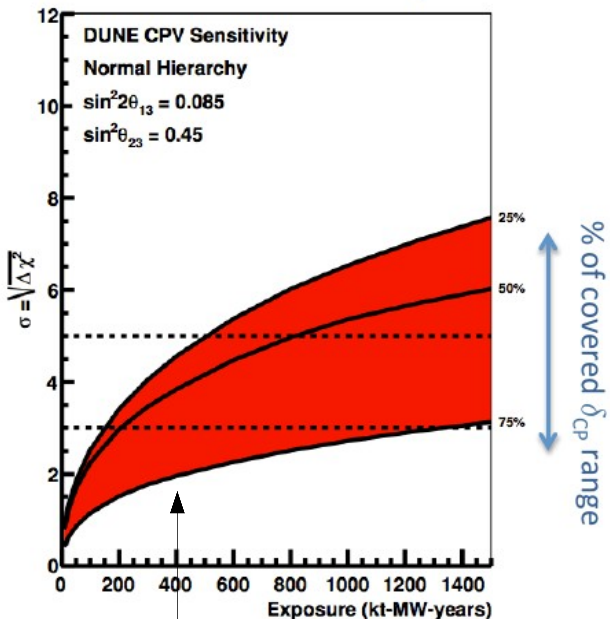
- successfull R&D → first very large scale realization
- size limited by drift length (~40KTon)
- full reconstruction of tracks and showers down to very low threshold, very good particle ID

→ precise E_ν shape accessible and needed for good sensitivity

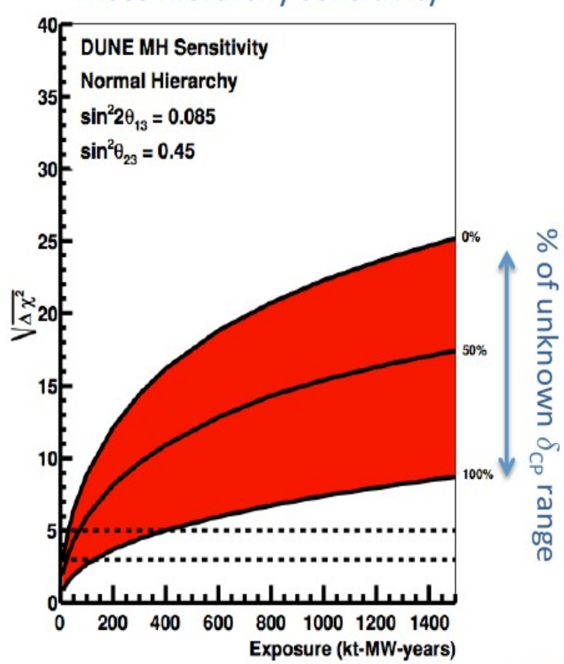
→ **need to reach very good control on detector calibration/uniformity and on neutrino interaction modelling**

Sensitivities

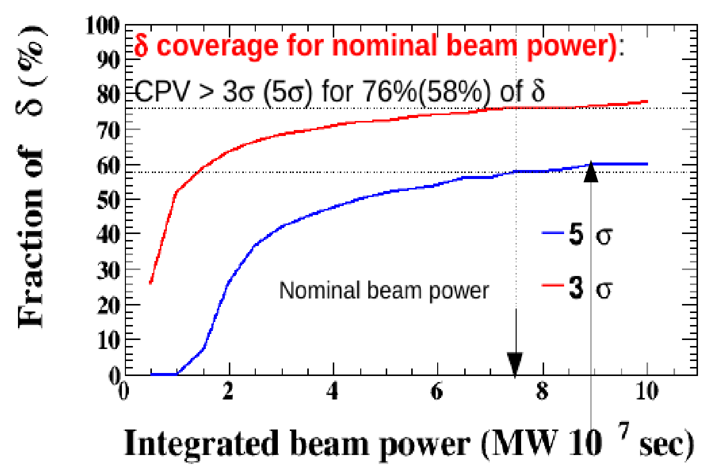
CP violation sensitivity



Mass hierarchy sensitivity



Fractional region of δ(%) for CPV (sin δ ≠0) > 3,5 σ

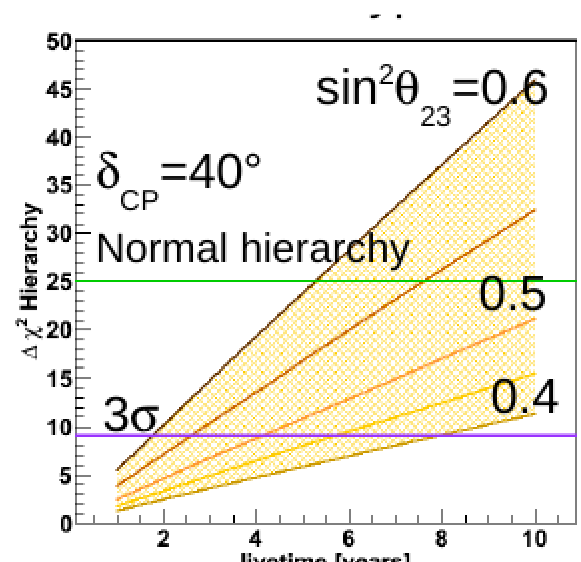


Assuming 1MW beam

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

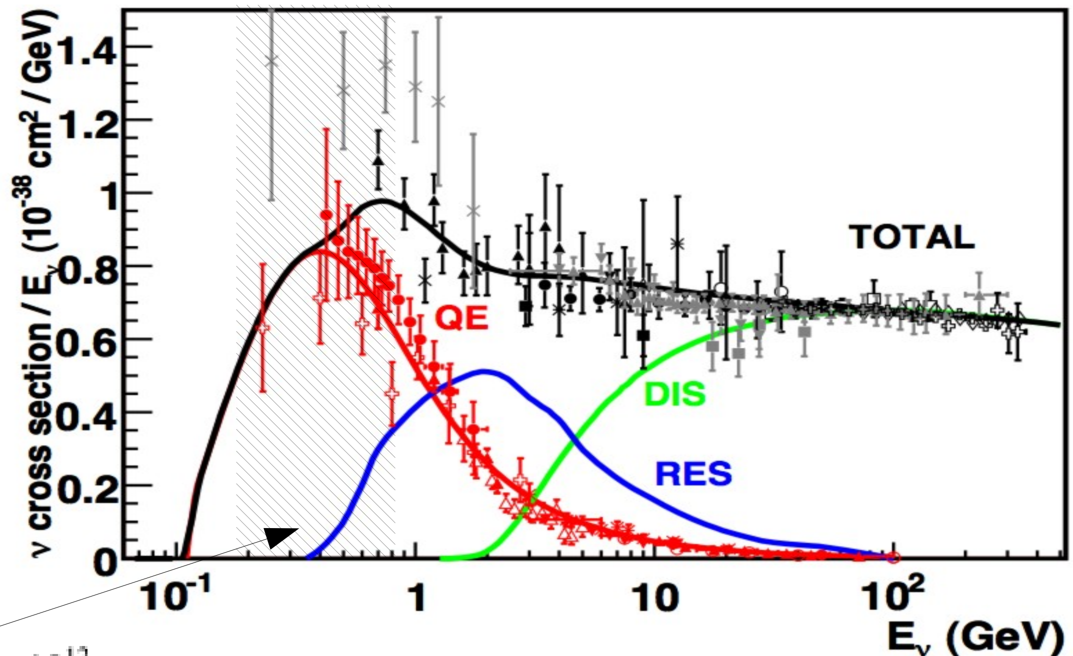
DUNE 10 years (40 kTon): CPV measured at 3s (5s) for >50% (~25%) of dCP values

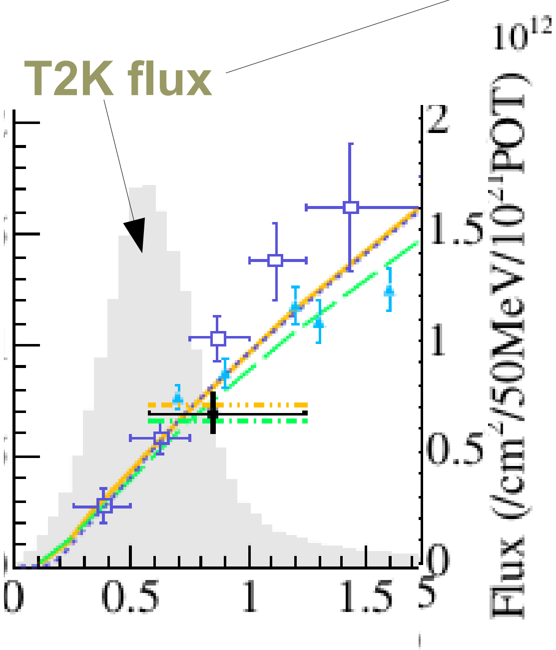
DUNE 10 years: definitive determination of MH

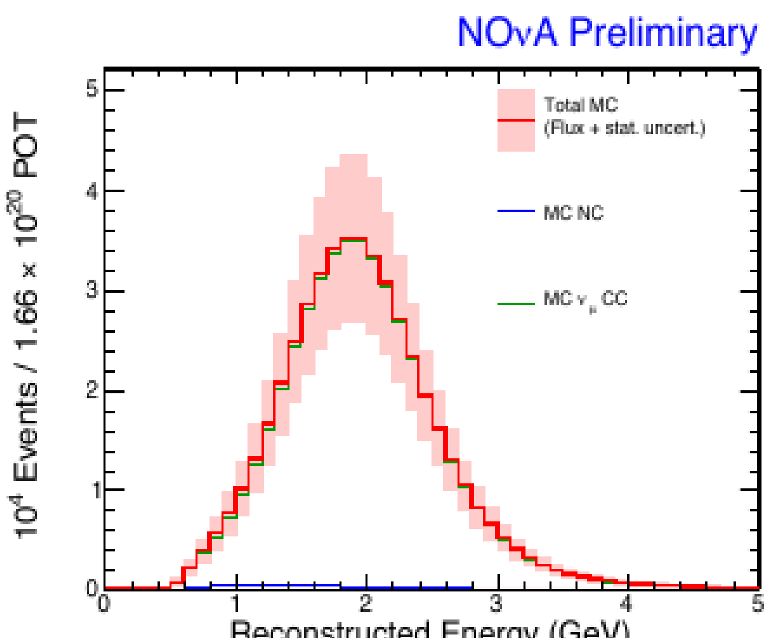


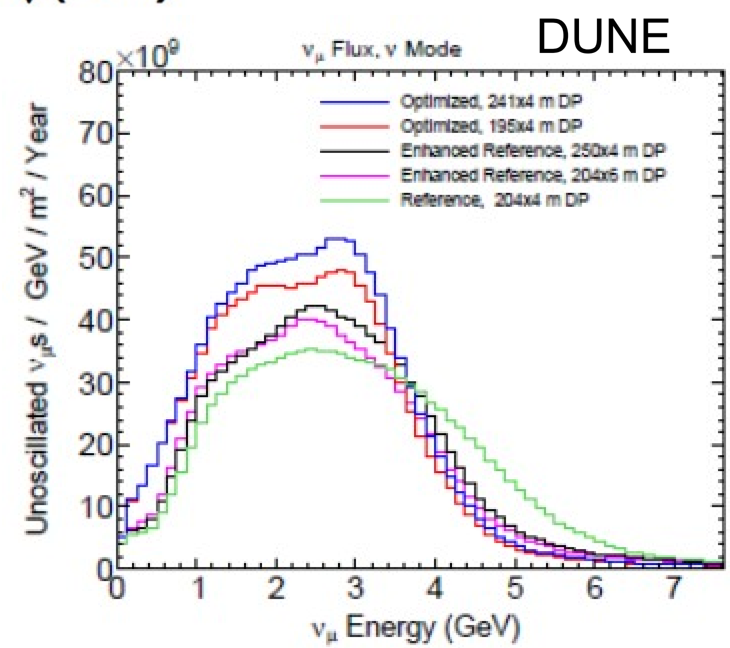
HK 10 years: wrong MH excluded at 3s

Moving to larger energies ...

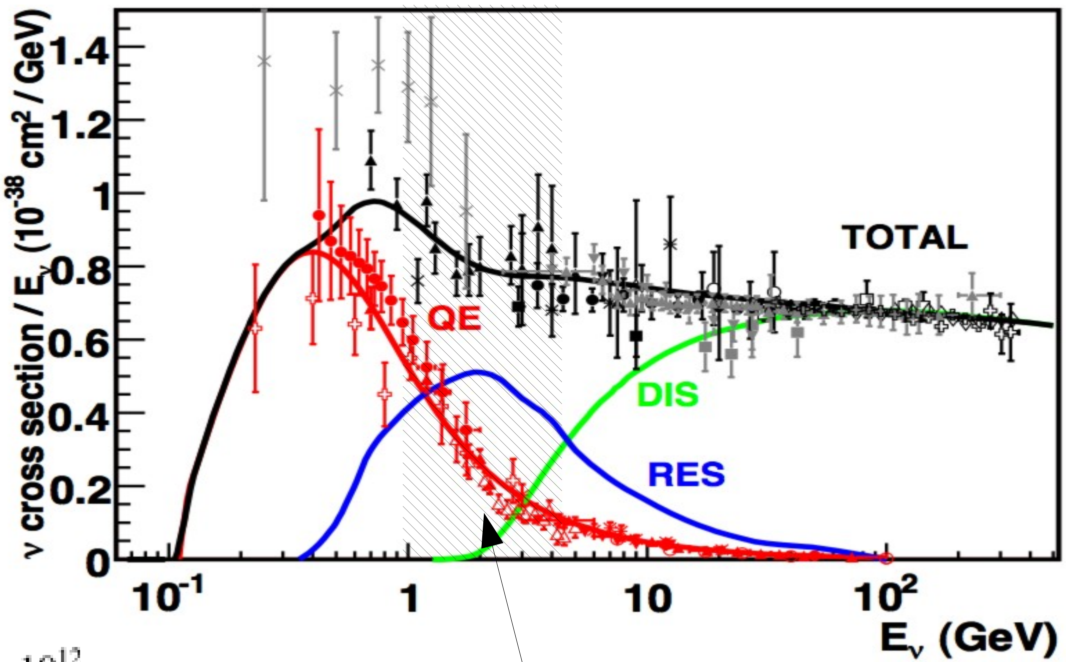




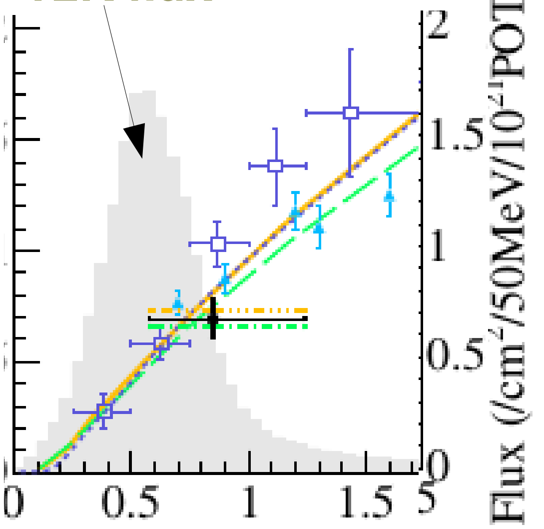


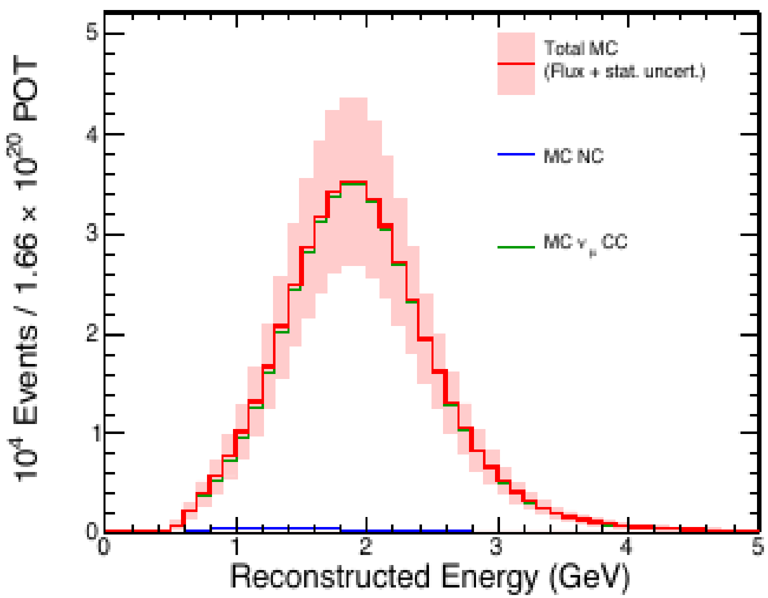


Moving to larger energies ...

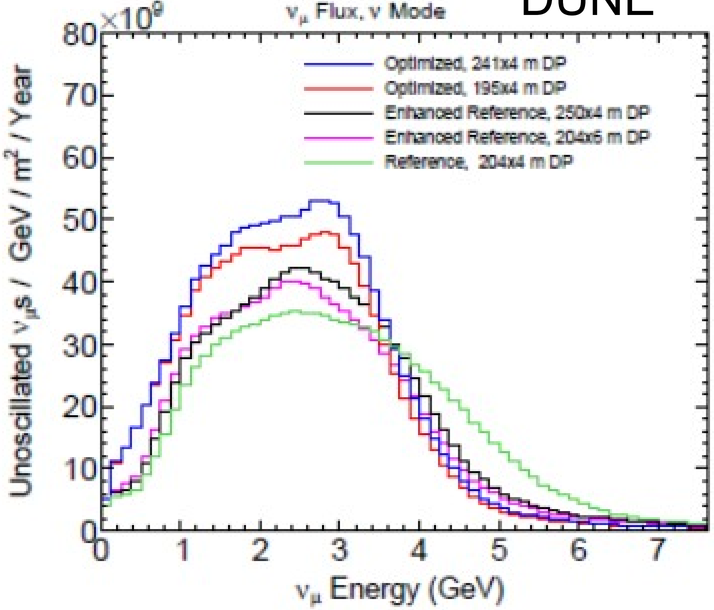


NOvA Preliminary

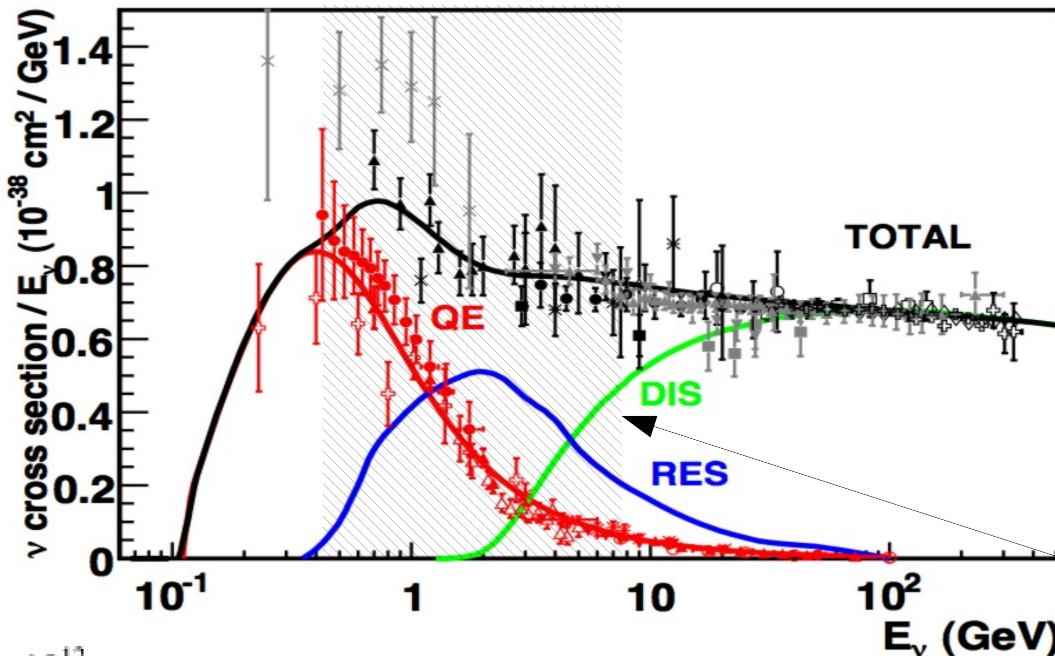




DUNE



Moving to larger energies ...



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

DUNE