THE NEUTRINO TURNS 60

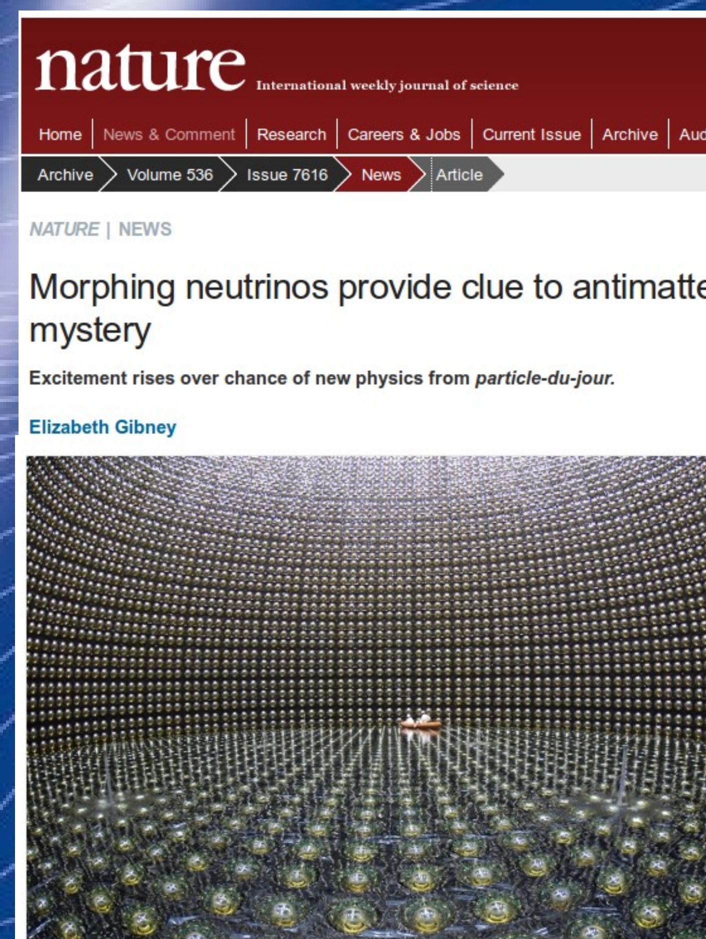
(Past), Present and Future of long baseline neutrino experiments

Journee SFP – 2 December 2016

S.Bolognesi (CEA Saclay)

Noble Prize 2015

BreakThrough Prize 2015



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NATURE | NEWS

Morphing neutrinos provide clue to antimatter mystery

Excitement rises over chance of new physics from *particle-du-jour*.

Elizabeth Gibney

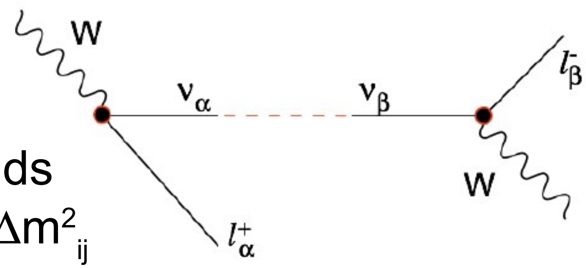
Neutrino oscillations

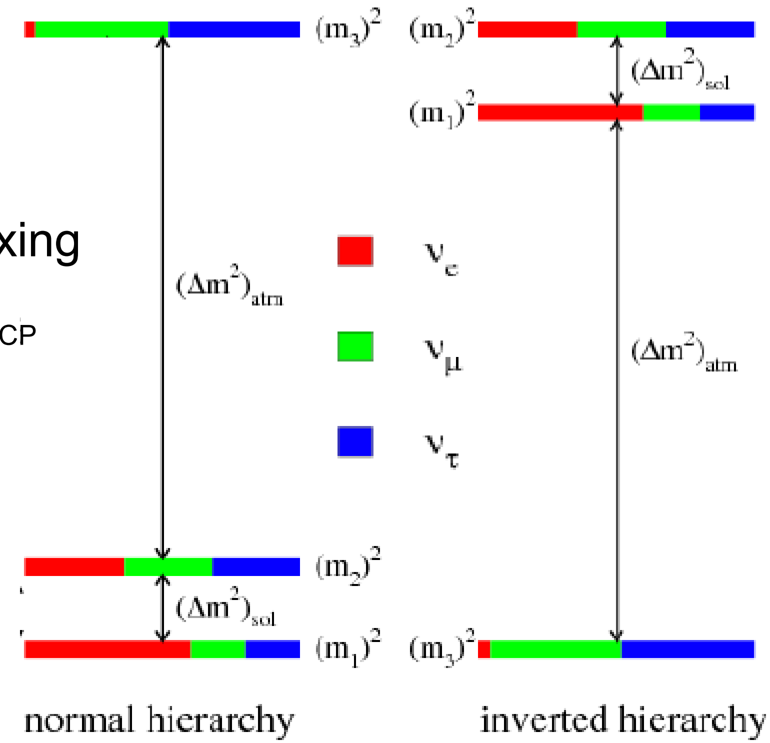
- $$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} \\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} \\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$ $U_{\alpha i}$ 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

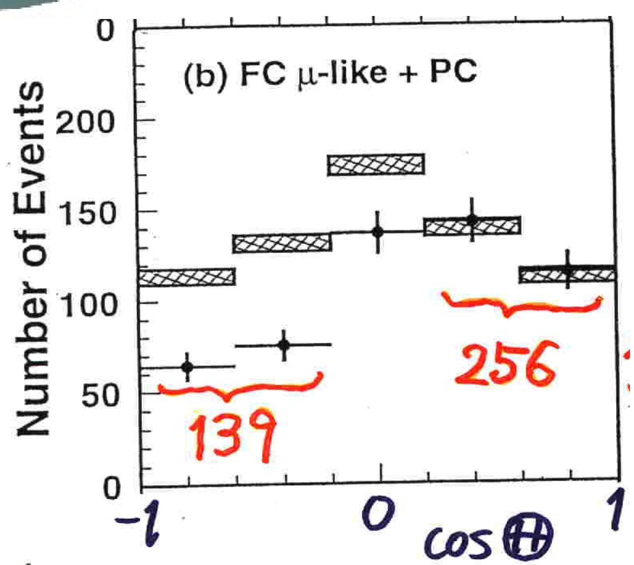
  - **δ_{CP} phase (unknown)** parametrize the difference between ν and $\bar{\nu}$ oscillation

    → involved with **matter-antimatter asymmetry** in leptogenesis scenarios

A bit of (recent) history...

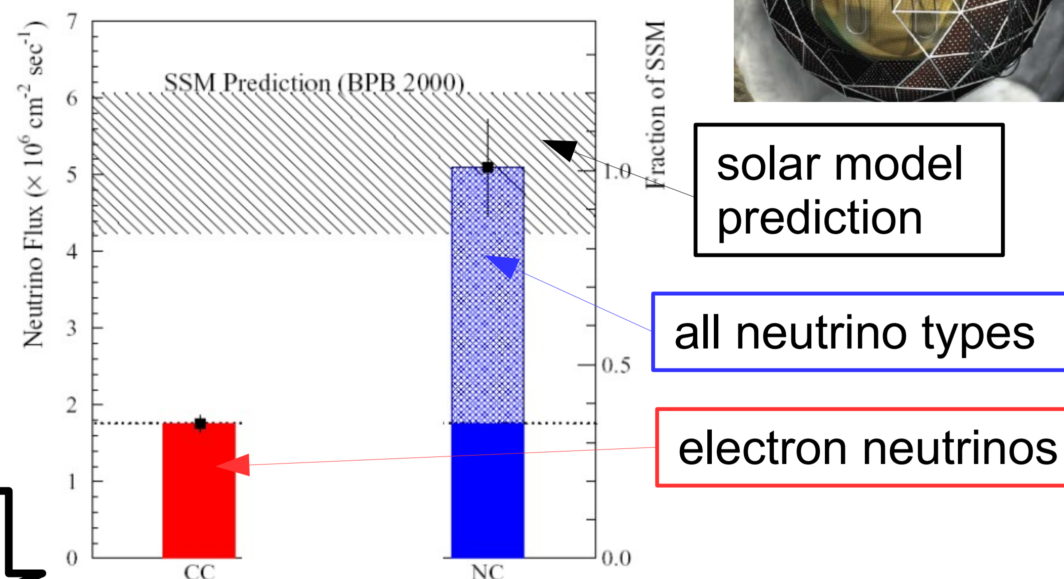
SuperKamiokande
1996 – today!

1998 Discovery of ν oscillation from zenith angle dependence of atmospheric ν_μ rate

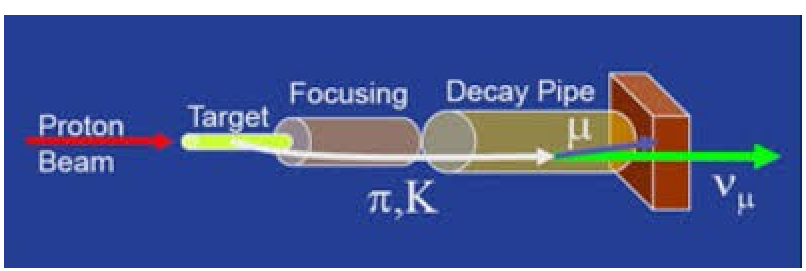


Sudbury Neutrino Observatory (SNO)
1999 – today!

2001 Solution of solar puzzle: $\nu_e / \Sigma\nu_\alpha \sim 1/3$



Confirmation from **accelerator experiment:** high purity and tunable neutrino flux → precise measurement of oscillation parameters



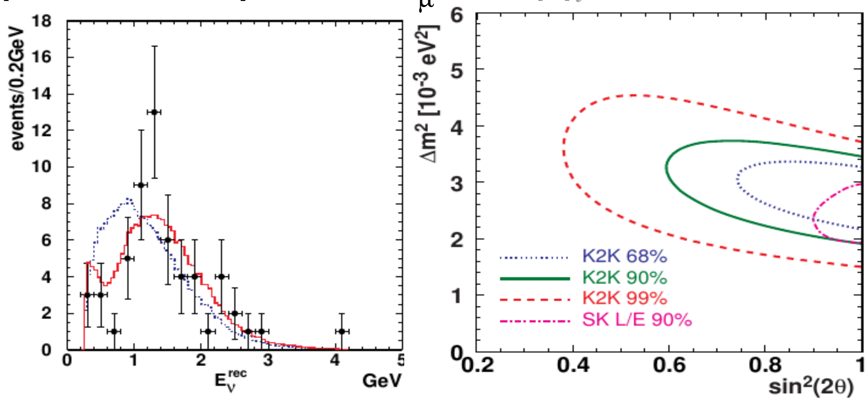
flux dominated by ν_μ (or $\bar{\nu}_\mu$) →

observation of ν_μ (or $\bar{\nu}_\mu$) disappearance

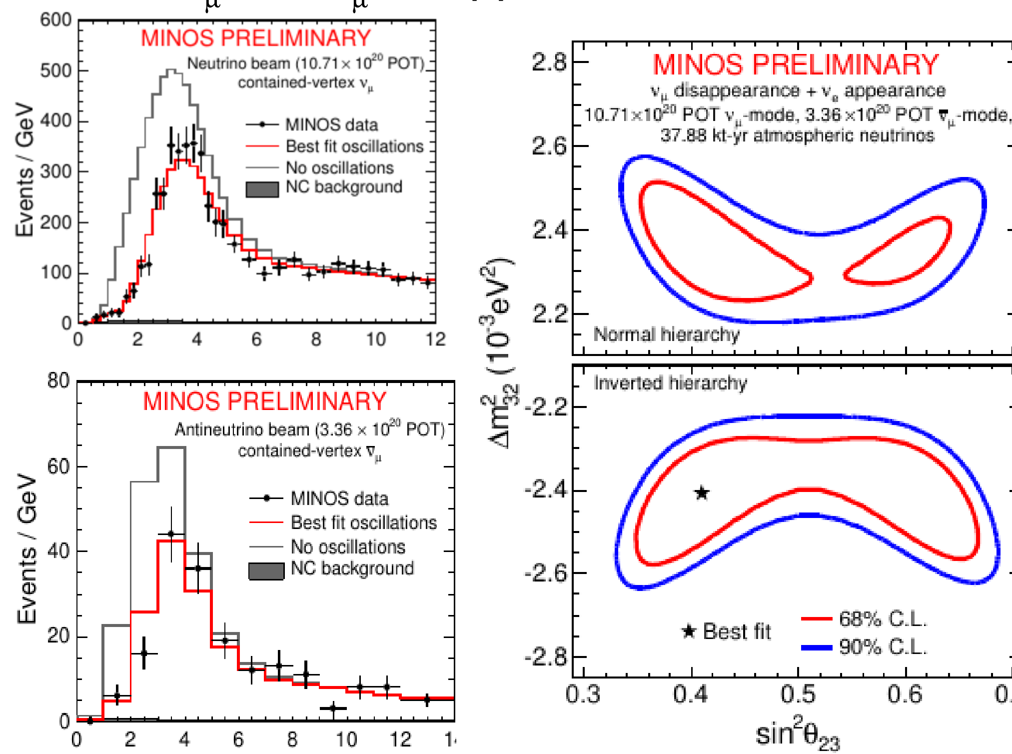
and apperance of ν_e (ν_τ)

Accelerator experiments

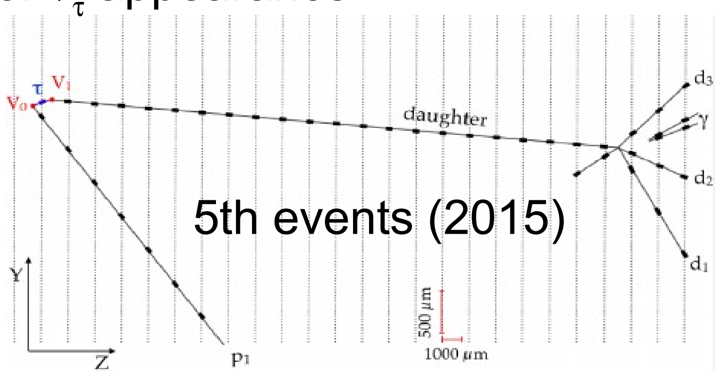
(1999-2006) K2K: ν_μ disappearance



2003 – 2015 MINOS (→ MINOS+):
ν_μ and $\bar{\nu}_\mu$ disappearance



(2008-2012) OPERA : observation of ν_τ appearance

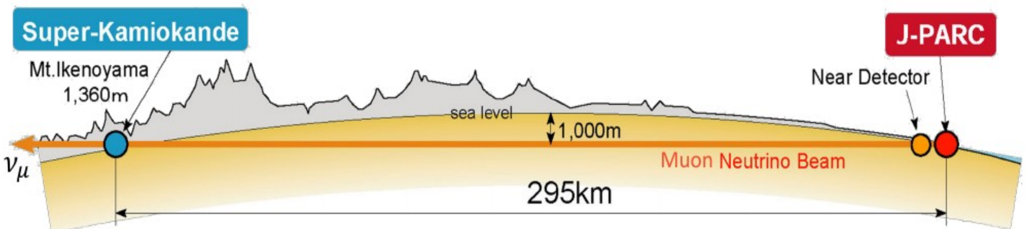


Beyond θ_{23} and Δm_{32}:

- **T2K (2010 – today)** observation of ν_e apperance
- to measure MH, longer baseline: **NOVA started last year**

→ first results on δ_{CP} !

T2K

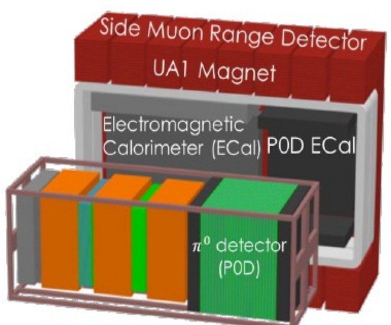


Far Detector

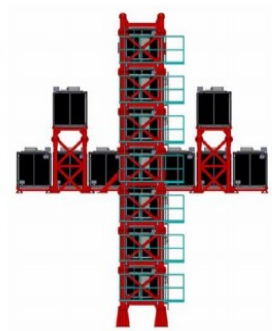
Super-Kamiokande

Near Detectors

Off-Axis: ND280

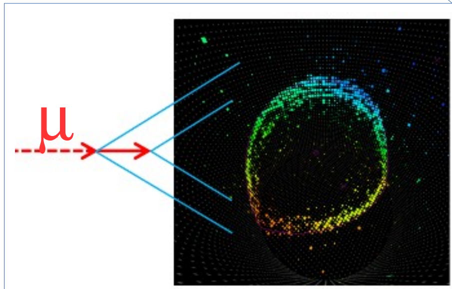


On-Axis: INGRID

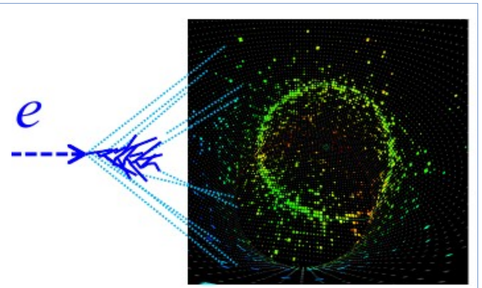


Huge water cherenkov detector (50 kTon) with optimal μ/e identification to distinguish ν_e, ν_μ

Full tracking and particle reconstruction in near detectors (magnetized TPC!): measure precisely neutrino flux before oscillation



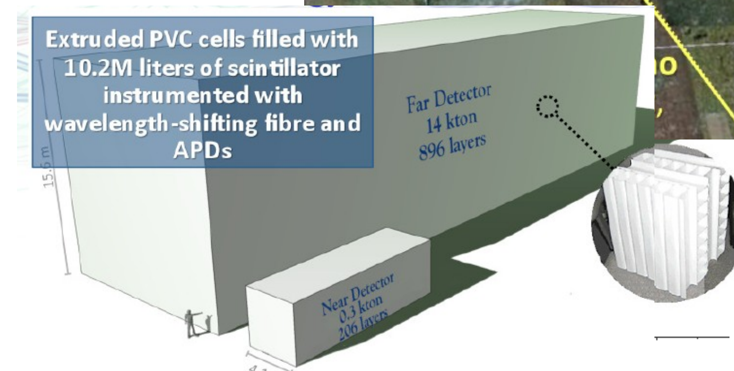
clear ring

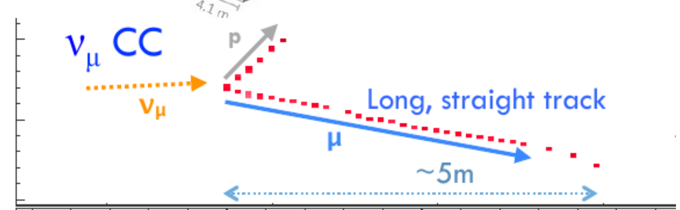


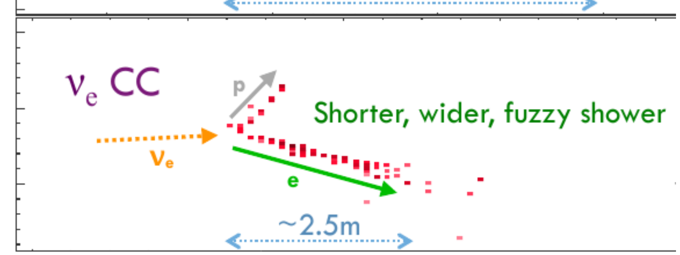
fuzzy ring

NOVA

Same technology for near and far detector (14kTon): cells filled of scintillator oil



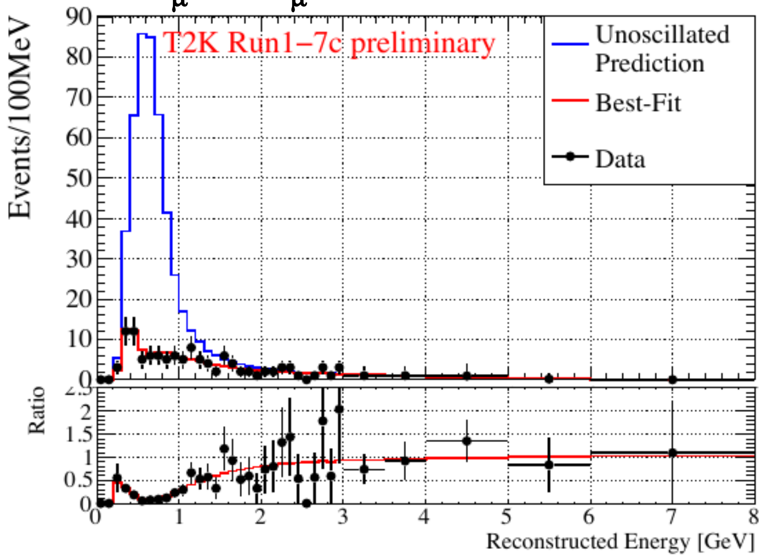




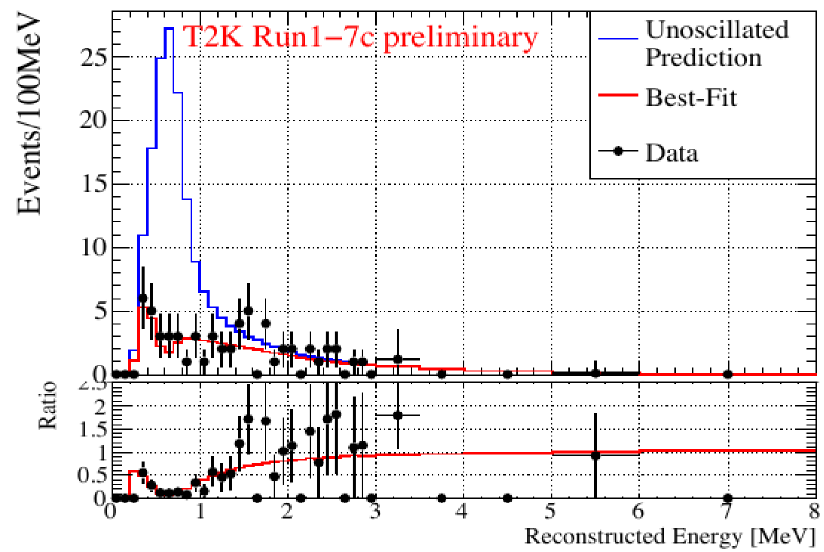
T2K data

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

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



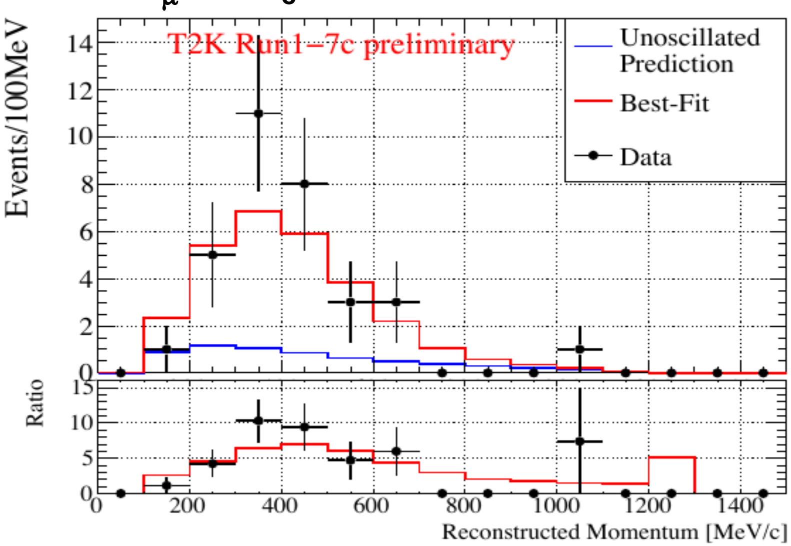
$\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu$ (disappearance)



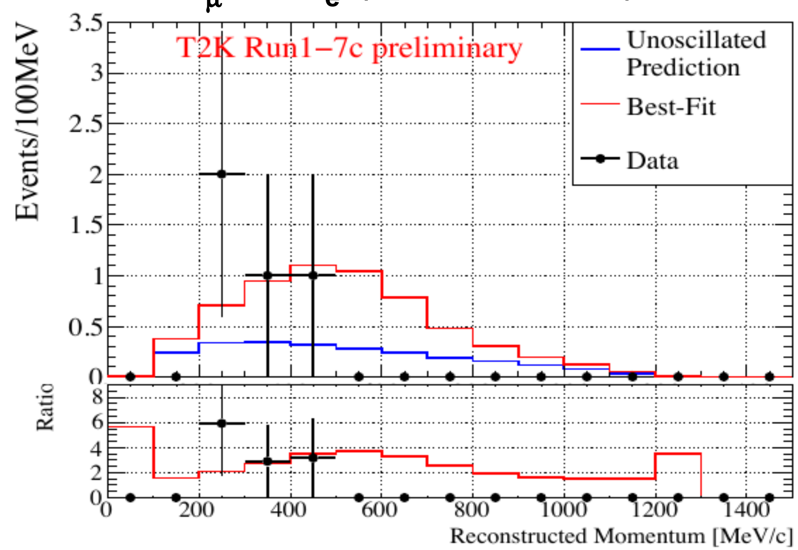
Large disappearance signal and clear oscillation shape (beyond counting experiment)

Clear signal in **antineutrino** as well!

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



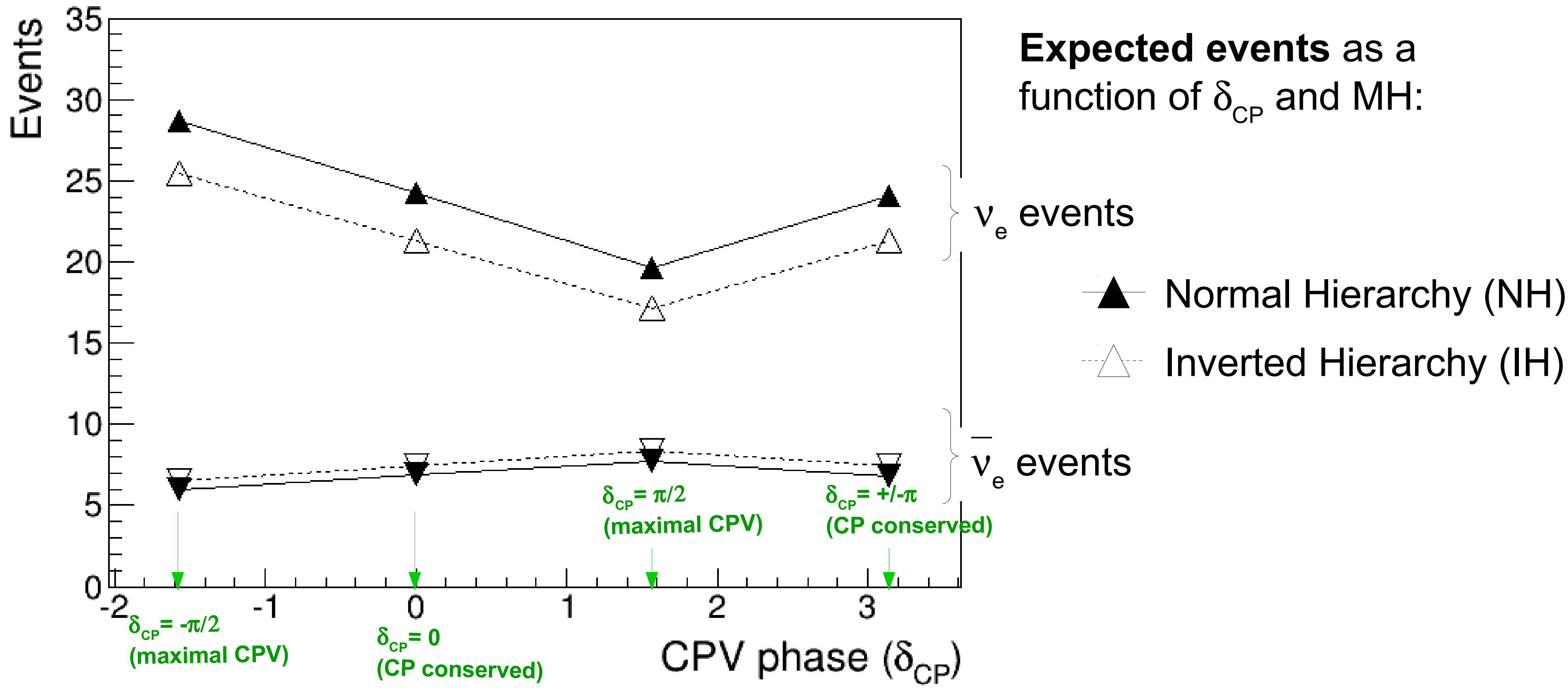
$\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ (appearance)



7.5 sigma observation of ν_e appearance

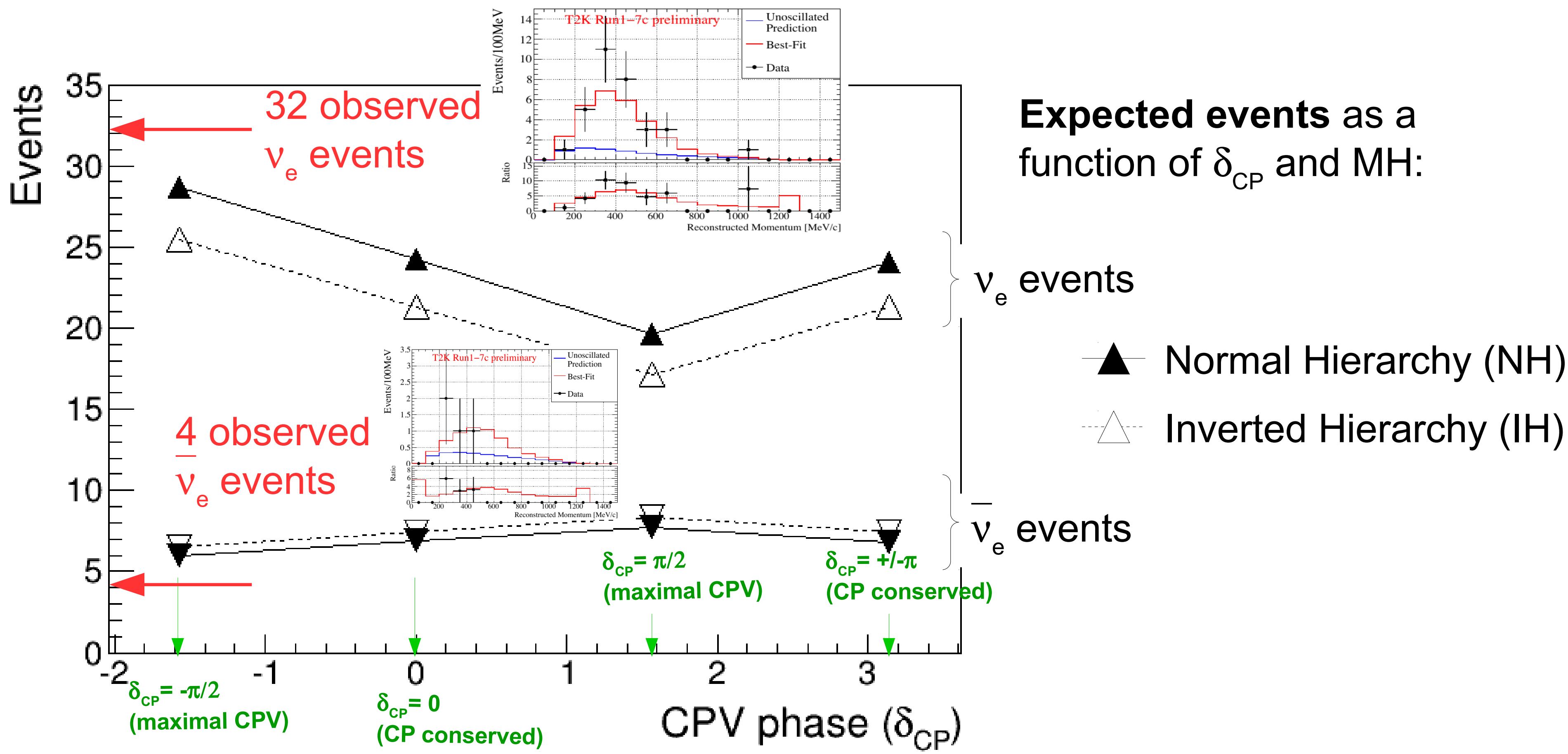
Growing statistics of $\overline{\nu}_e$ appearance: (~20% of final design statistics)

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 $\nu_\mu \rightarrow \nu_e$ / $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

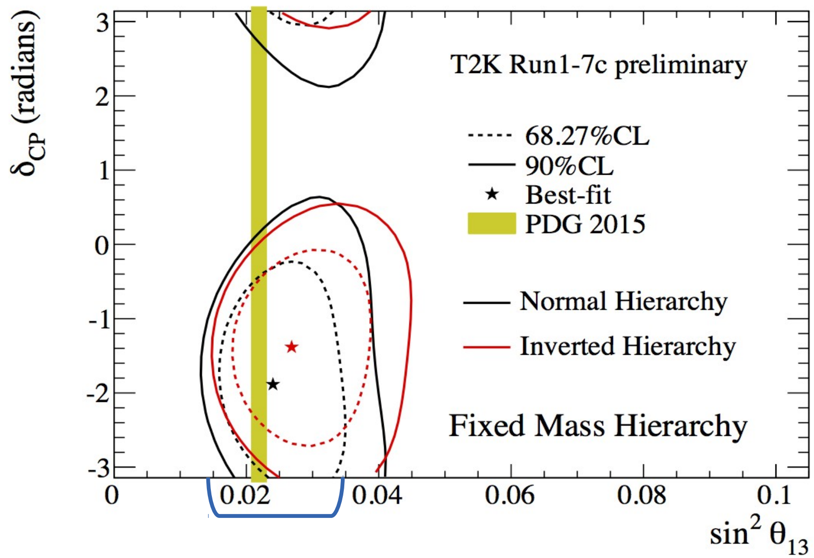


Expected events as a function of δ_{CP} and MH:

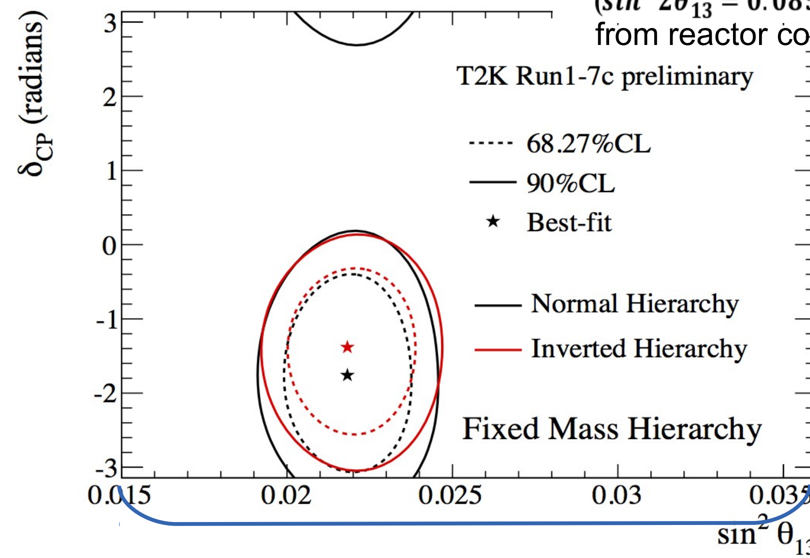
Results favour maximal CP violation (and slightly favour NH)

First 90% limits on δ_{CP}!!

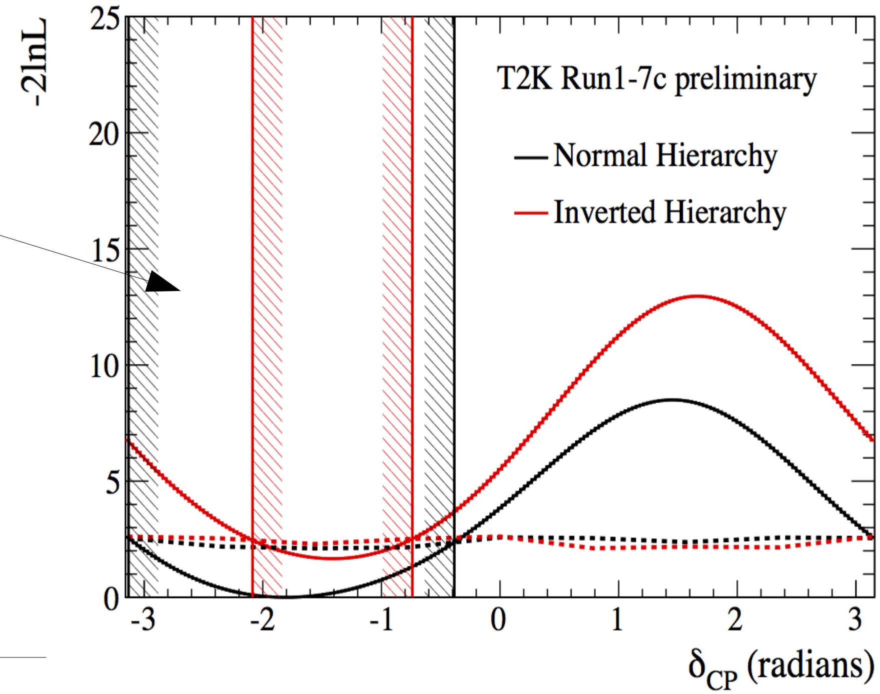
Full joint fit of all data ($\nu_\mu \rightarrow \nu_{\mu/e}$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_{\mu/e}$) with all proper statistical and systematic uncertainty included and exploiting also shape information :



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



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



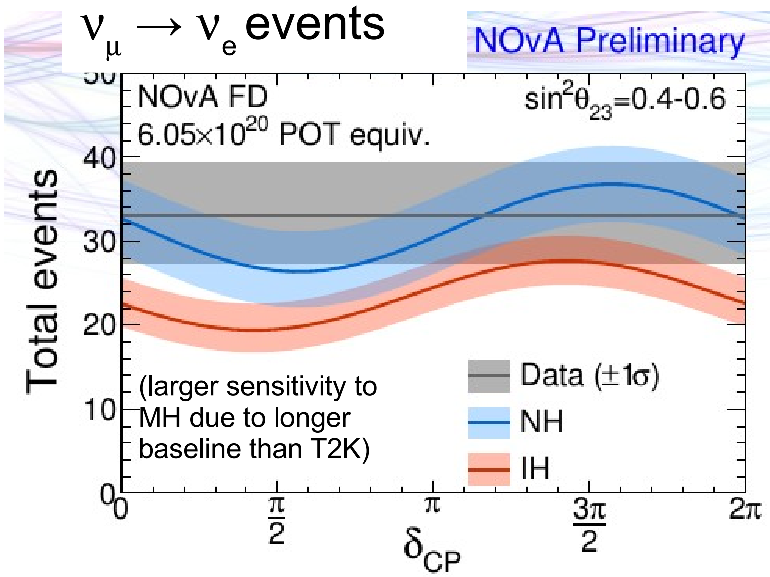
Feldman-Cousins confidence interval:

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

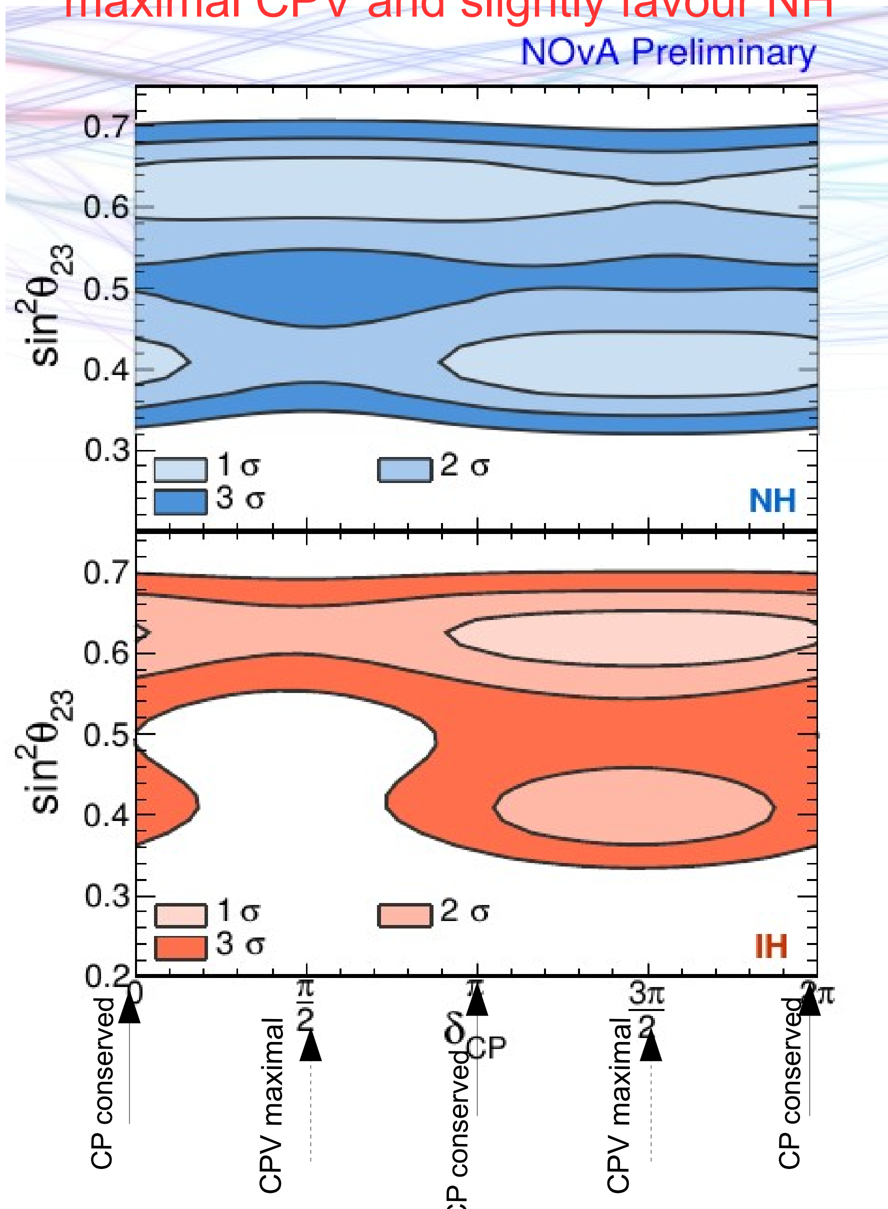
(NH slightly favoured)

NOVA δ_{CP}

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

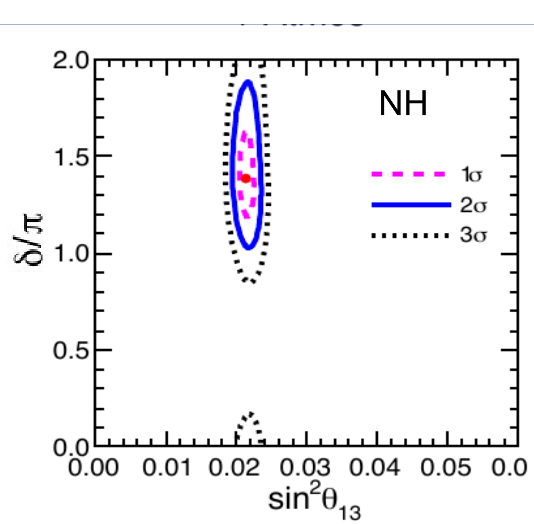


NOVA in agreement with T2K: favours maximal CPV and slightly favour NH



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

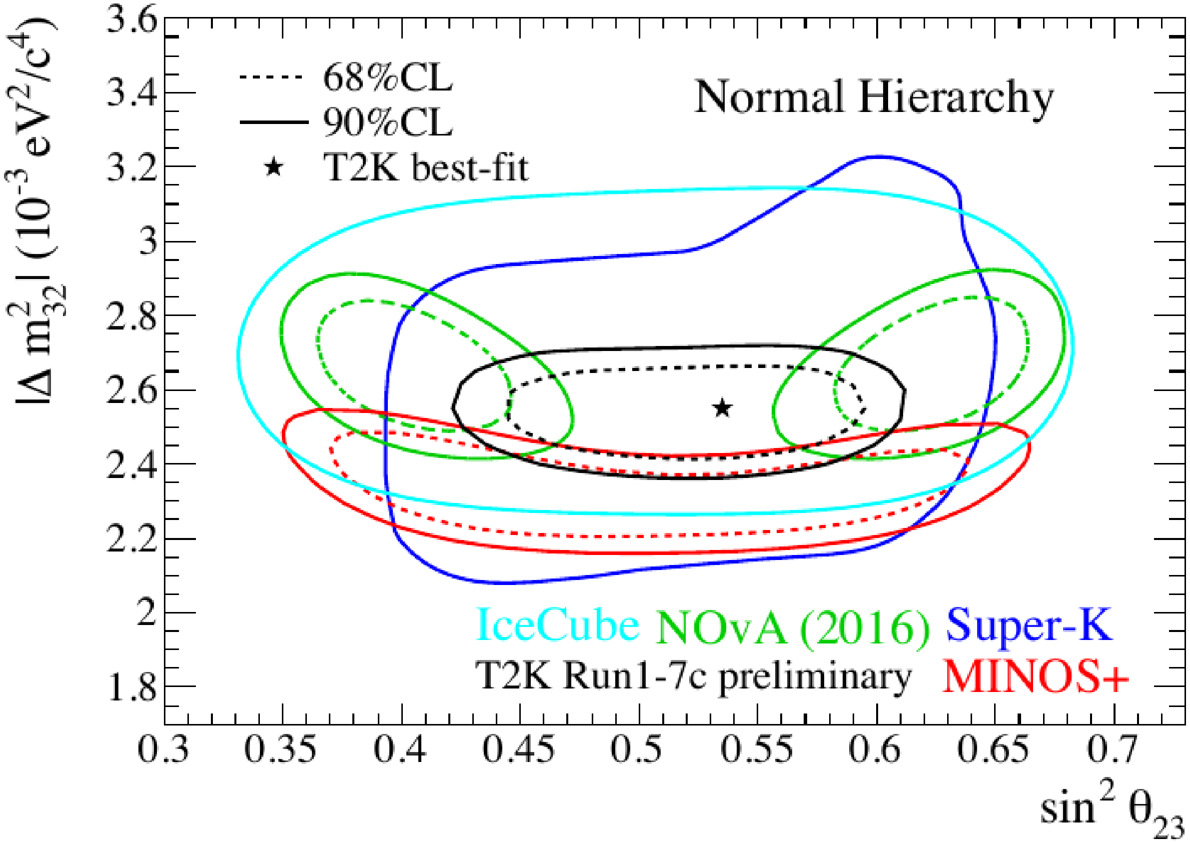
CP conservation excluded at 2σ



Lisi et al.
NEUTRINO 2016

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



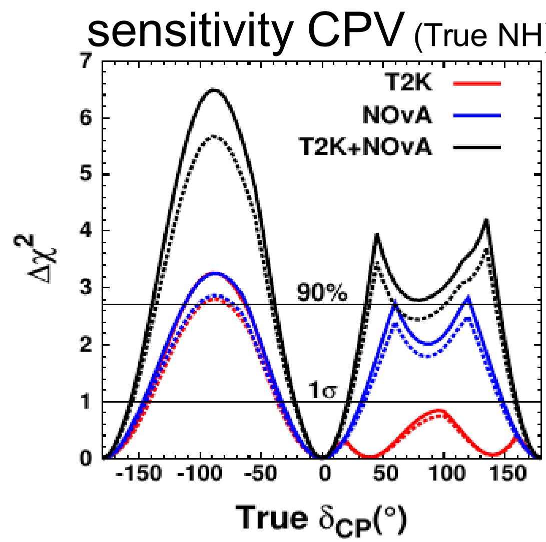
T2K data show maximal disappearance → **prefer maximal mixing: $\theta_{23} = \pi/4$** ($\sin^2\theta_{23}$=0.5)

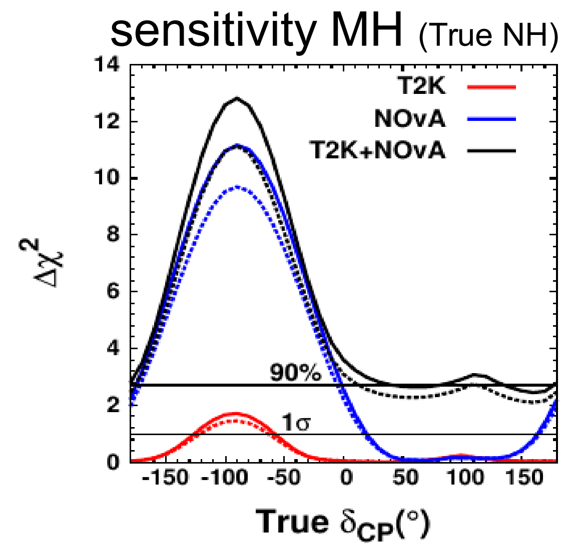
NOVA data excludes maximal mixing at 2.5σ

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

Prospects to 2026

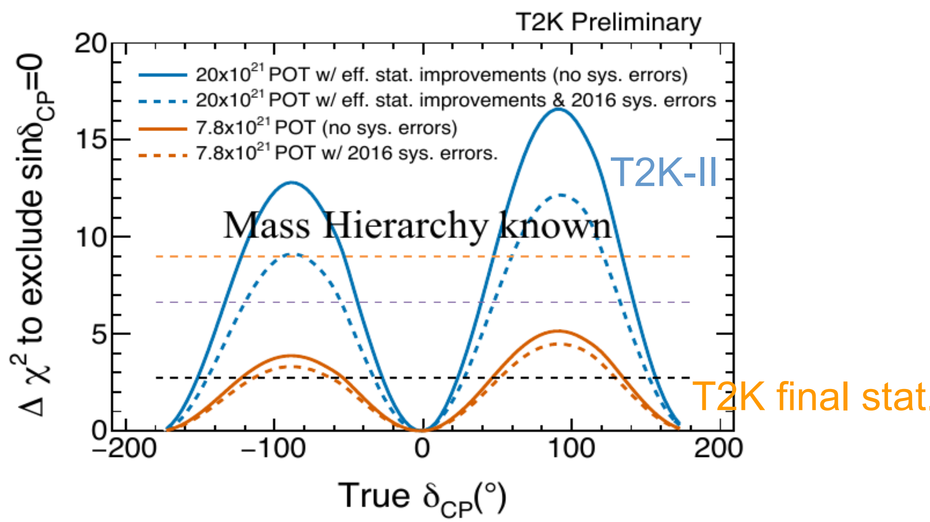
NOVA – T2K combination with final dataset (~2021)





Request for new run of T2K beyond design statistics (7.8x10[21] POT) → **20x10[21] POT by 2026**

- good chances to observe CP violation at > 3σ by 2026 for a sizeable fraction of values
- large impact of systematics → upgrade of ND280 near detector

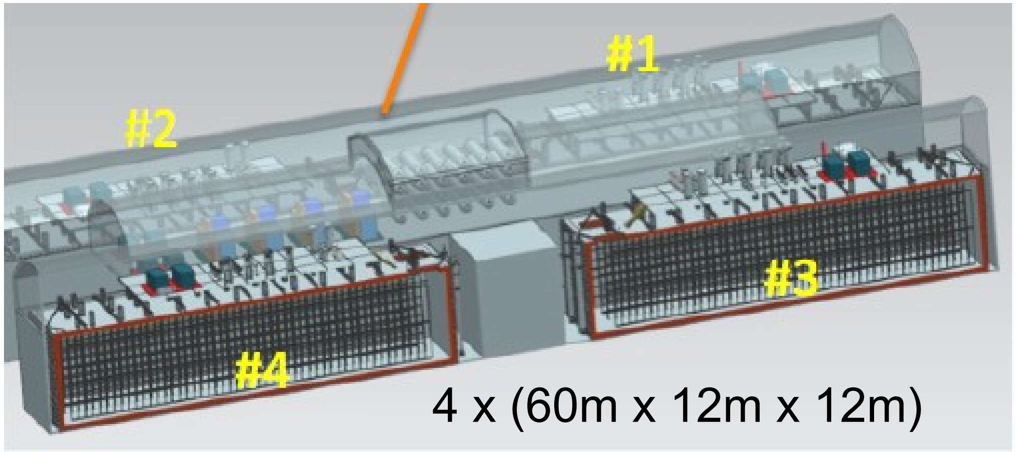


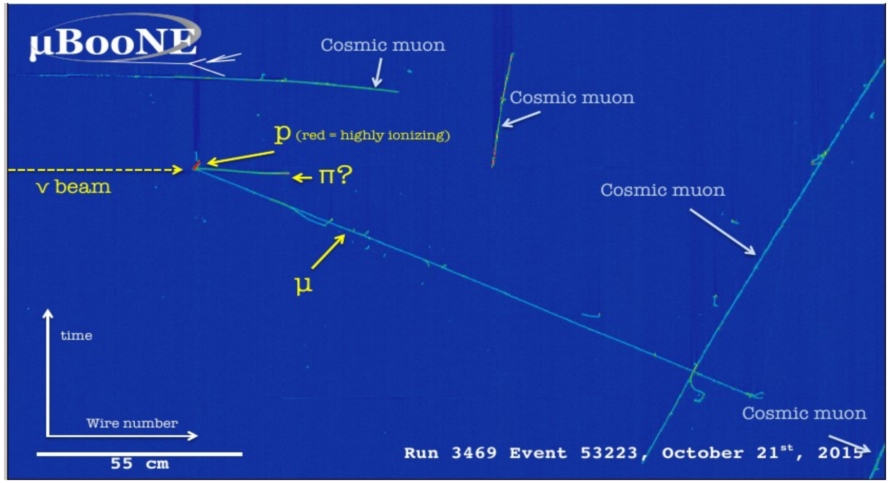
For definitive δ_{CP} measurement need new generation of long baseline experiments: HyperKamiokande, DUNE

Next generation Long-Baseline experiments

Liquid Argon in US
(1300 km Fermilab → Sanford)

DUNE: staged approach with 4 modules for a total mass of ~40kTon

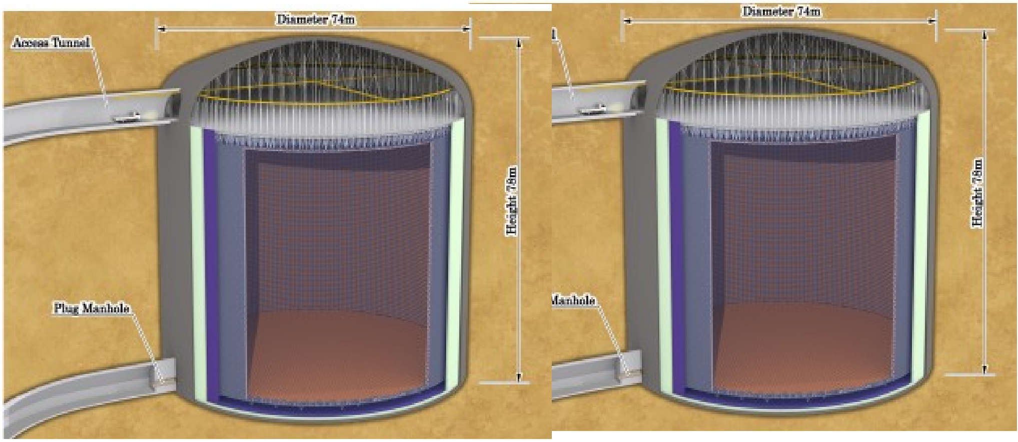


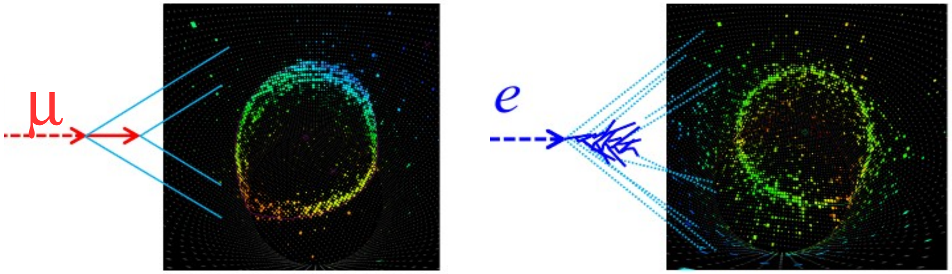


Powerful technology: to be proven on such large scale

Water Cherenkof in Japan
(same baseline as T2K: 300 km)

HyperKamiokande: 2 tanks for a total mass 380kTon





Well proven technology, easily scalable

Next generation LB: sensitivities

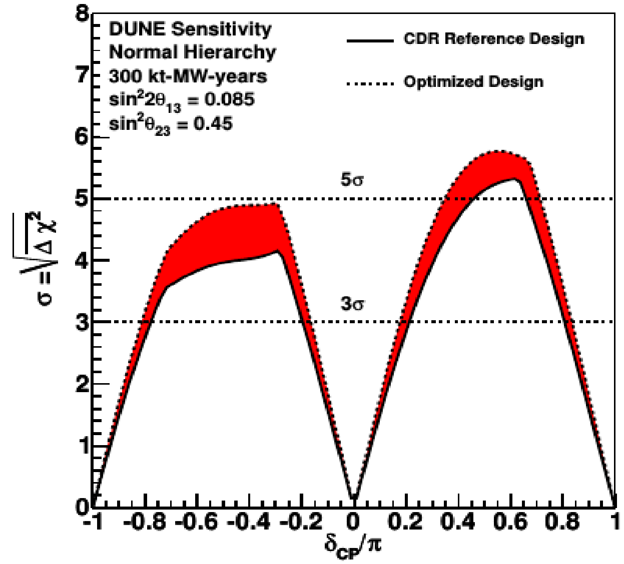
DUNE:

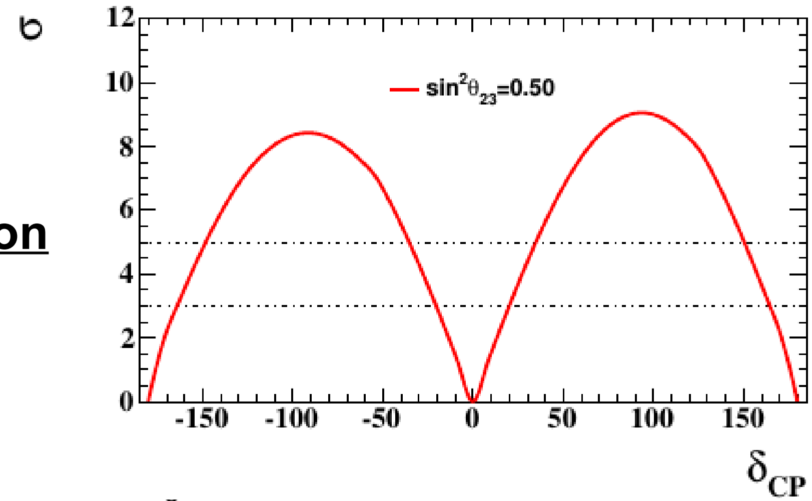
7.5y @ 1MW with 40kTon from day 1

HyperKamiokande:

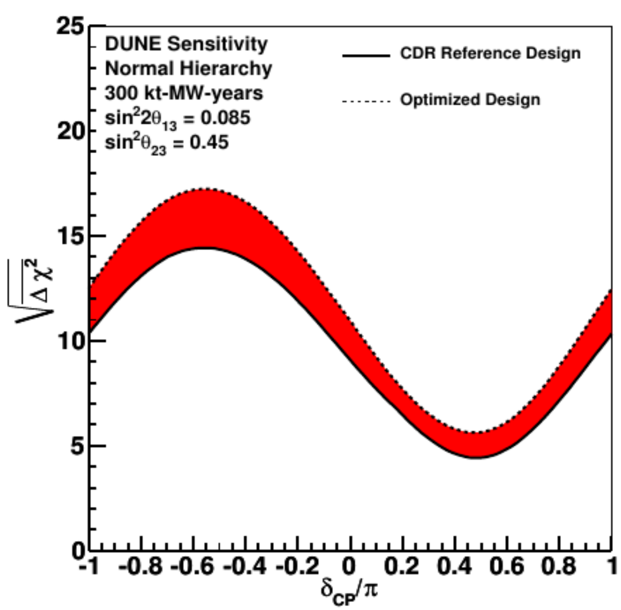
10y @ 1.3MW with new HK design and staged approach

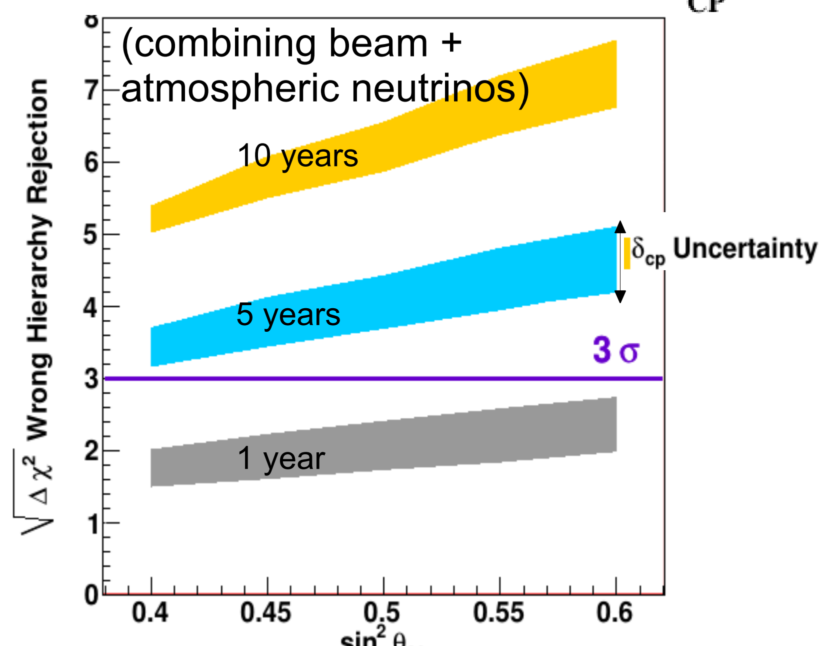
CP violation





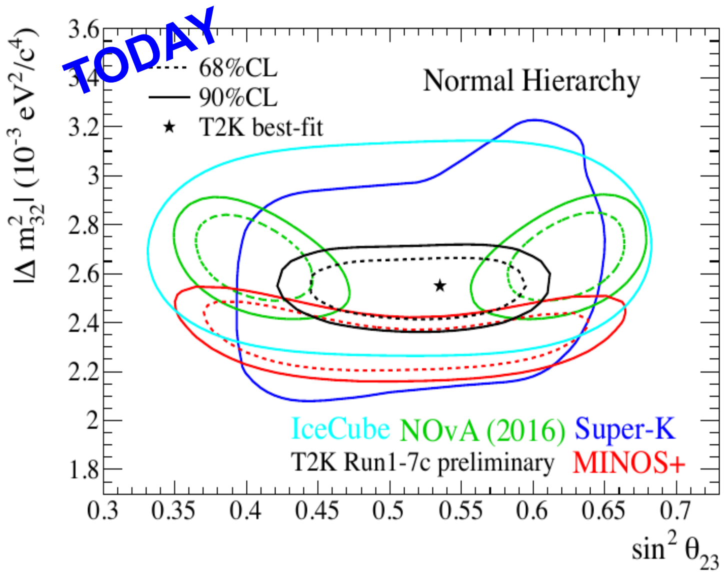
Mass Hierarchy

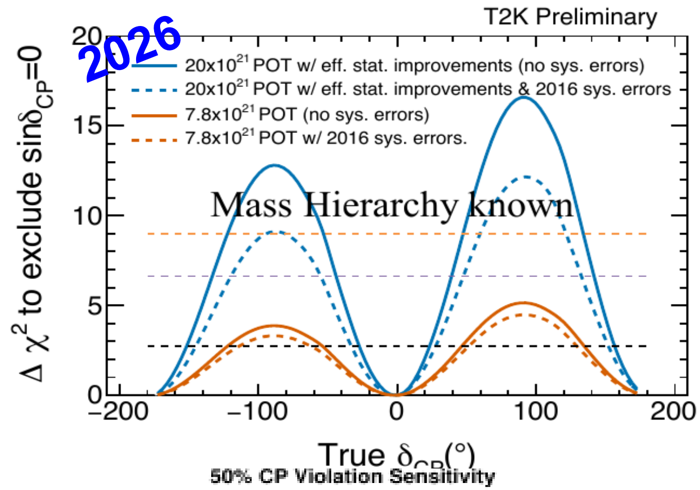




Systematics

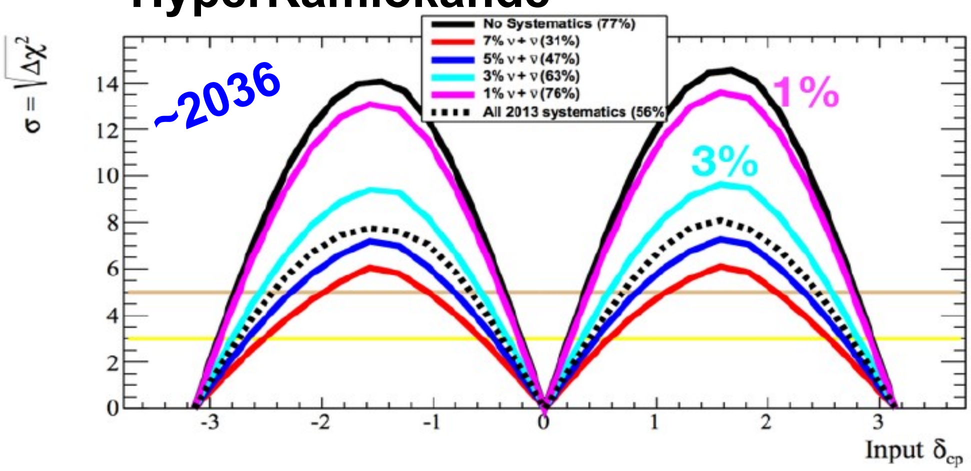
We are entering the precision era in neutrino physics! Unprecedented control on neutrino systematics is needed

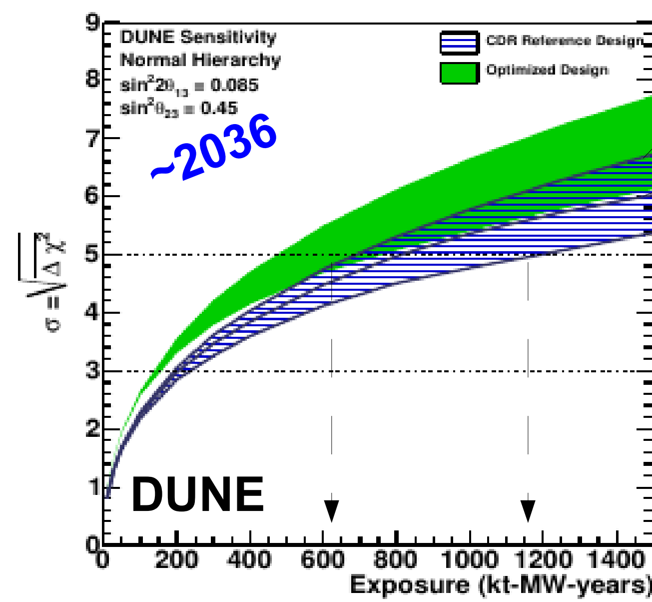




T2K-II

HyperKamiokande





5% ± 1%

5% ± 2%

5% ± 3%

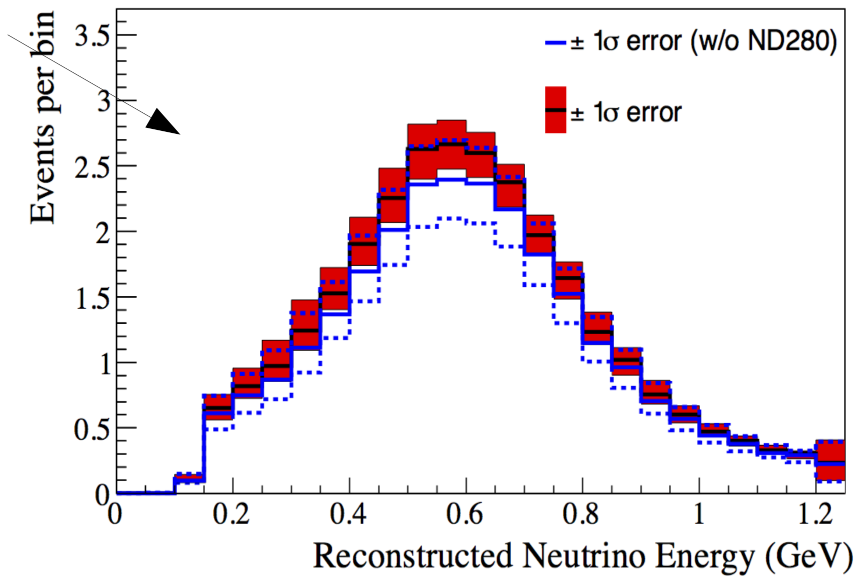
→ equivalent to factor 2 in exposure!

→ **IMPORTANCE OF NEAR DETECTORS!**

Near detectors and neutrino xsec

Let's take the ν_e sample at T2K

- total systematics before the ND constraints 11.9%
- total systematics after the ND constraints 5.41%
  - specific to SuperKamiokande : 3.46%
  - flux and ν cross-section : 4.17%
    - **flux 8.94% (before ND constr.) → 3.64% (after ND constr.)**
    - **xsec 7.17% (before ND constr.) → 5.12% (after ND constr.)**



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. Need for:**

- well designed **near detectors**
- very peculiar theoretical **expertise on nuclear physics**
- worldwide coordinated effort for **neutrino cross-section measurements** (and ancillary measurements: pion, proton, electron scattering...)

Summary

- Neutrino physics is a **promising door to look for New Physics** at energies well beyond direct collider searches

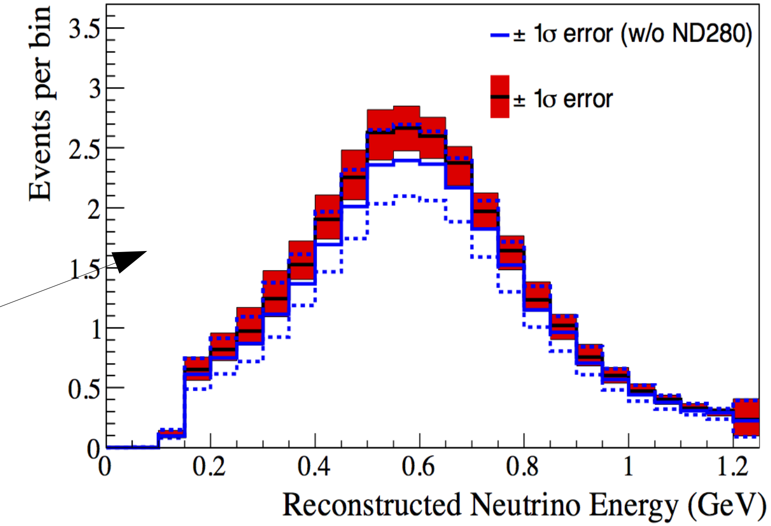
- Last summer: **first results on CP violation in the leptonic sector**
  - T2K+NOVA by 2021 may demonstrate CP violation at 90% CL
  - T2K-2 alone by 2026 can reach 3σ
  - Next generation (HyperKamiokande, DUNE) should reach 5σ both on CP-violation and MH

    ➔ to enter in the precision-era of neutrino oscillation a **vigorous program to reduce the systematics is necessary:**

    - neutrino-nucleus interaction measurements at Near Detectors
    - improvements of theoretical modelling of nuclear matter in neutrino interactions (→ see Marco Martini talk later)

BACKUP slides

Main systematics



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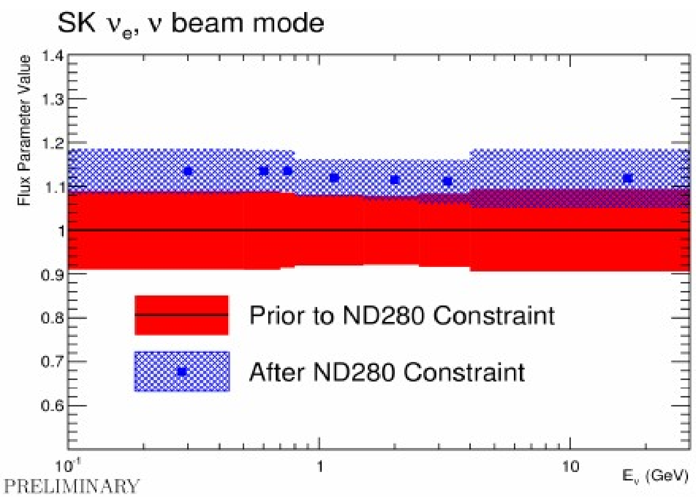
  - flux and ν cross-section : 4.17%
    - **flux 8.94% (before ND constr.) → 3.64% (after ND constr.)**

      Flux simulated (target and beamline with FLUKA/GEANT) and tuned to hadron scattering data in dedicated experiments (NA61)



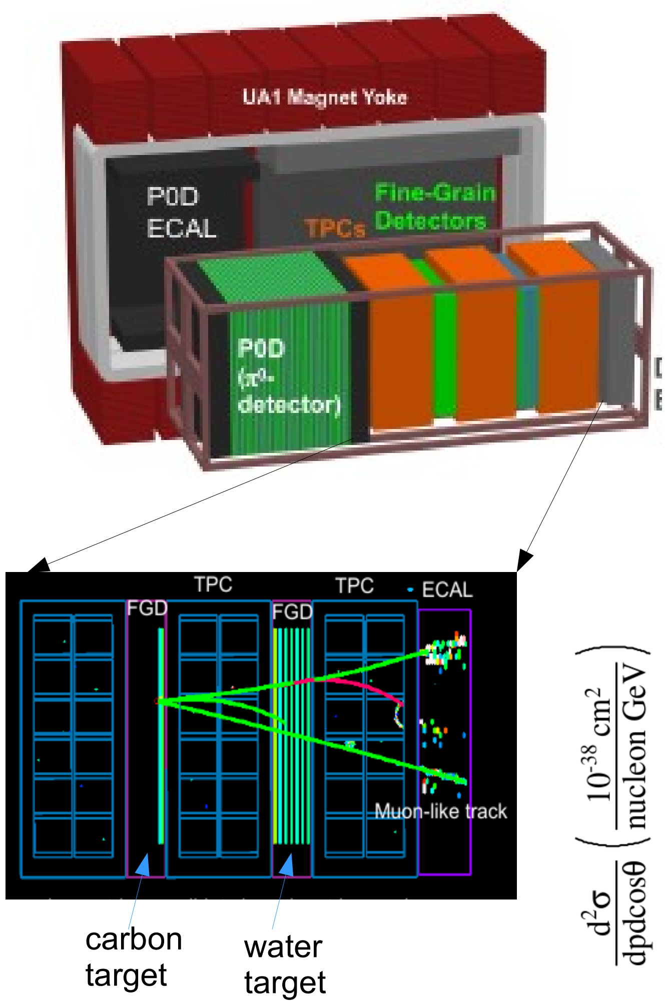
- **xsec 7.17% (before ND constr.) → 5.12% (after ND constr.)**

  dominated by nuclear effects which may give difference between ν_e/ν_μ and $\bar{\nu}_e/\bar{\nu}_\mu$ cross-section

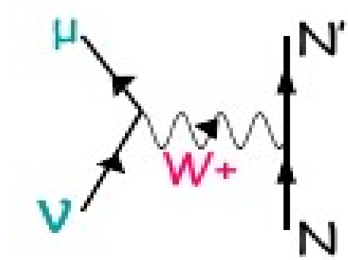
Xsec measured with limited precision on free nucleons in old bubble chamber experiments. In modern experiment ν interacts with target detectors of carbon, water or argon → large nuclear effects not well known (very peculiar theoretical expertise)

Neutrino-nucleus interaction

Crucial role of **T2K Near Detector (ND280)** : TPC (MicroMegas) developed at CEA for tracking, particle identification and momentum measurement



Cross section of main T2K signal:



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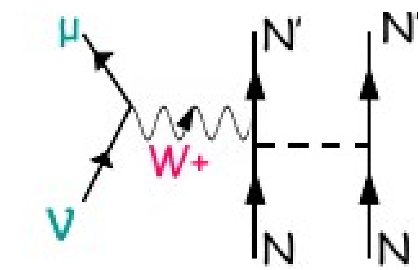


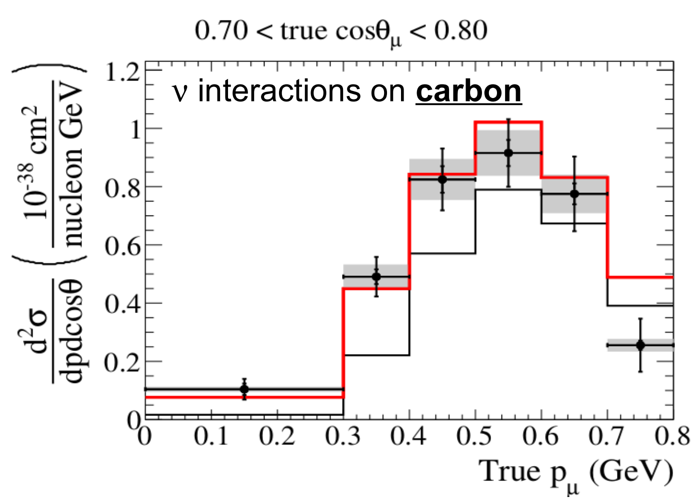
Charged Current Quasi-Elastic

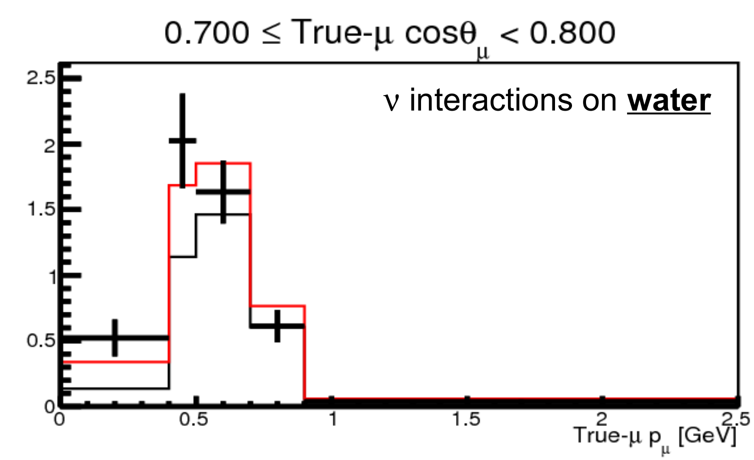
higher order corrections in nuclear target

Model delevoped by Martini et al. (SphN)

— CCQE

— CCQE + multi-nucleon interactions

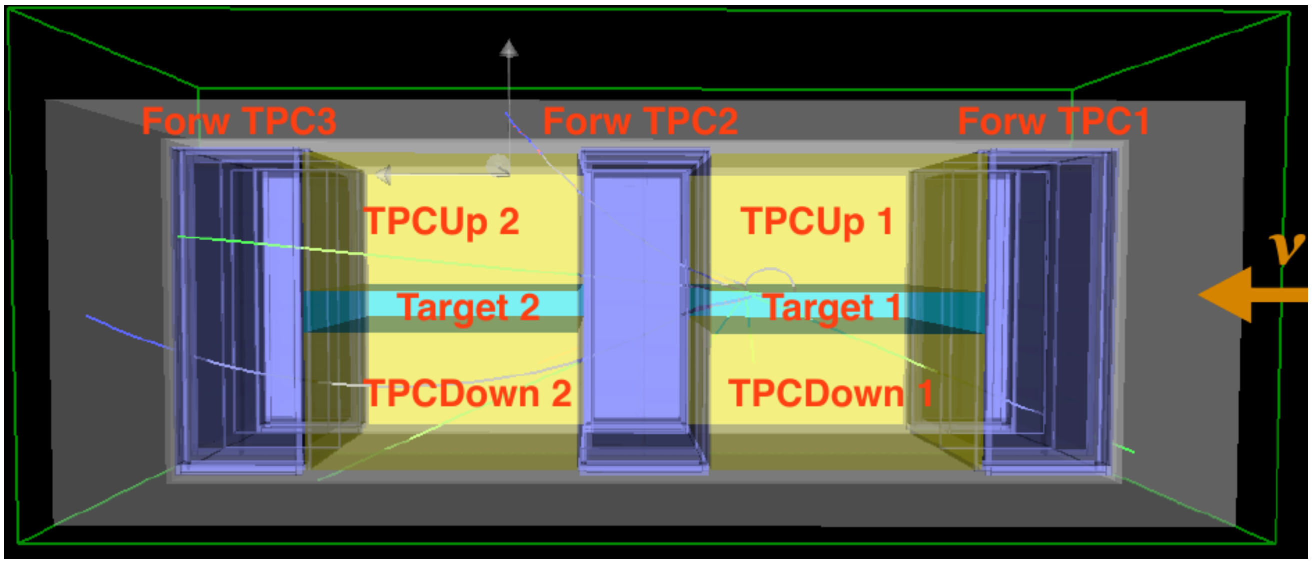


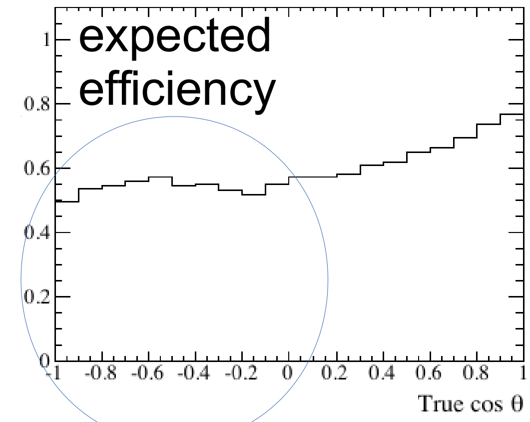


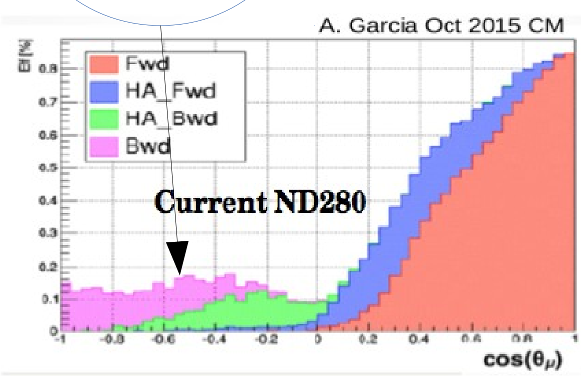
ND280 Upgrade for T2K Phase II

- 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 comprising 4 additional TPCs and two new active targets** (to be installed in 2020)







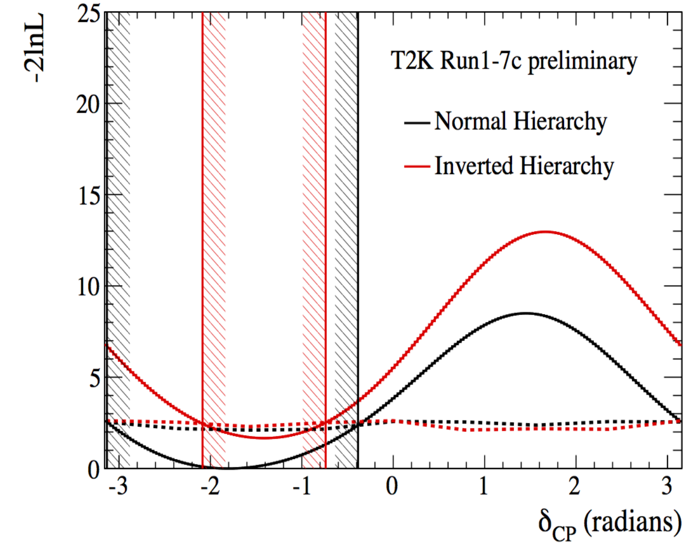
Aim: acceptance over the full polar angle, with better tracking inside the target and lower proton threshold

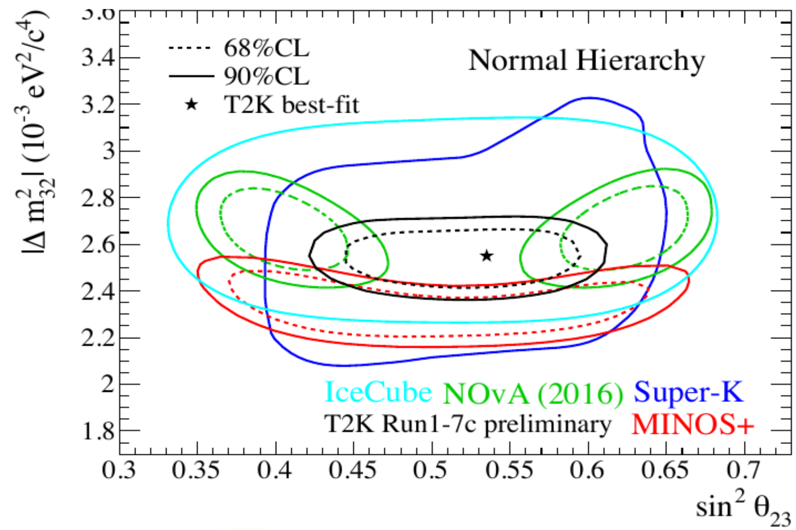
- **Workshop at CERN November 8-9th** (open to all interested people!)

Summary

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

- **T2K and NOVA: agreement on δ_{CP} while**
  2.5σ difference for θ_{23} measurement





Still mostly statistical limited
Heavy work ahead:

- **keep collecting data: NOVA, T2K-2 →**
  next generation of long baseline experiments
  (DUNE and HyperKamiokande)

- **need to minimize the systematics for high statistics measurement:**
  - precise measurements of ν-nucleus xsec and better theoretical nuclear modeling
  - upgrade of the T2K near detector under study

Neutrino oscillations

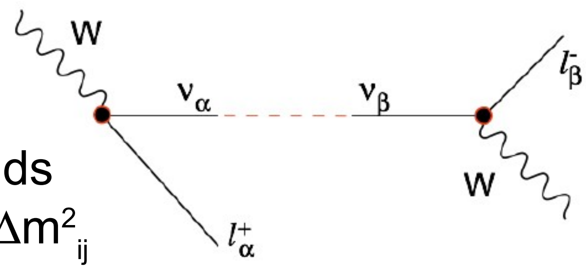
- $$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} \\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} \\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

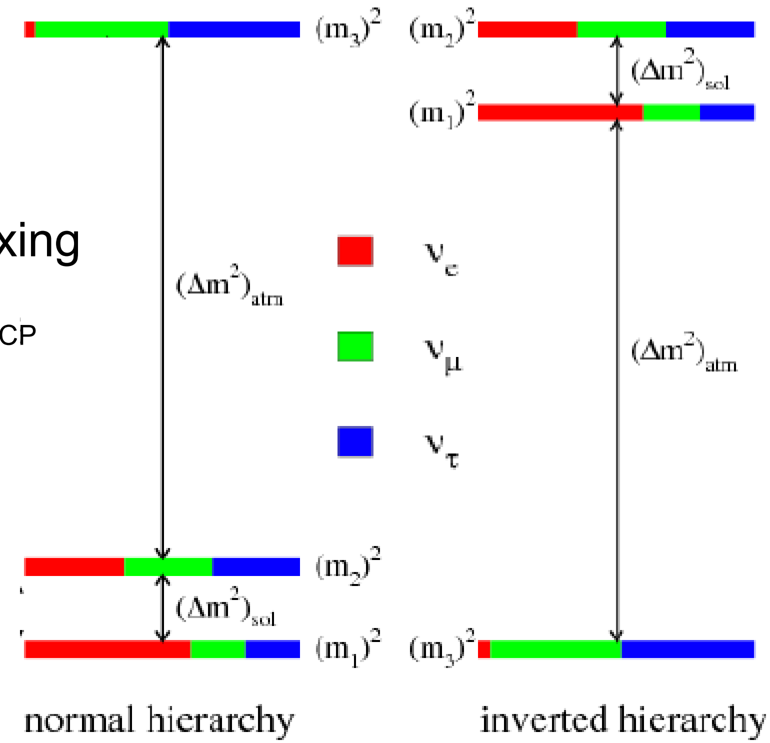
$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

$U_{\alpha i}$ are expressed in terms of 3 mixing angles (θ_{13}, θ_{23}, θ_{12}) and a phase δ_{CP}

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

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





- **Long baseline neutrino accelerator** experiments observe $\nu_\mu \to \nu_{\mu/e}$:
  - **$|\Delta m^2_{32}|$** 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)

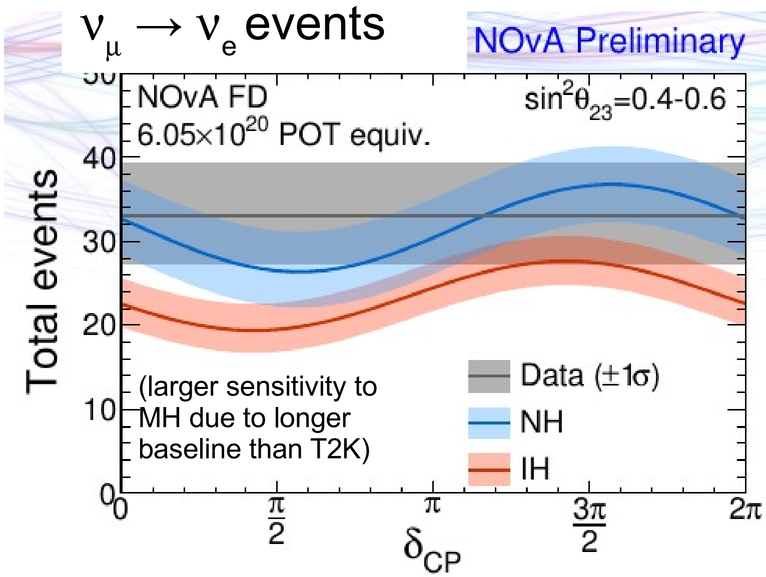
    → flavour pattern may indicate the symmetry beyond ν oscillation (door to New Physics!)

    → precise measurement needed to test unitarity of PMNS matrix

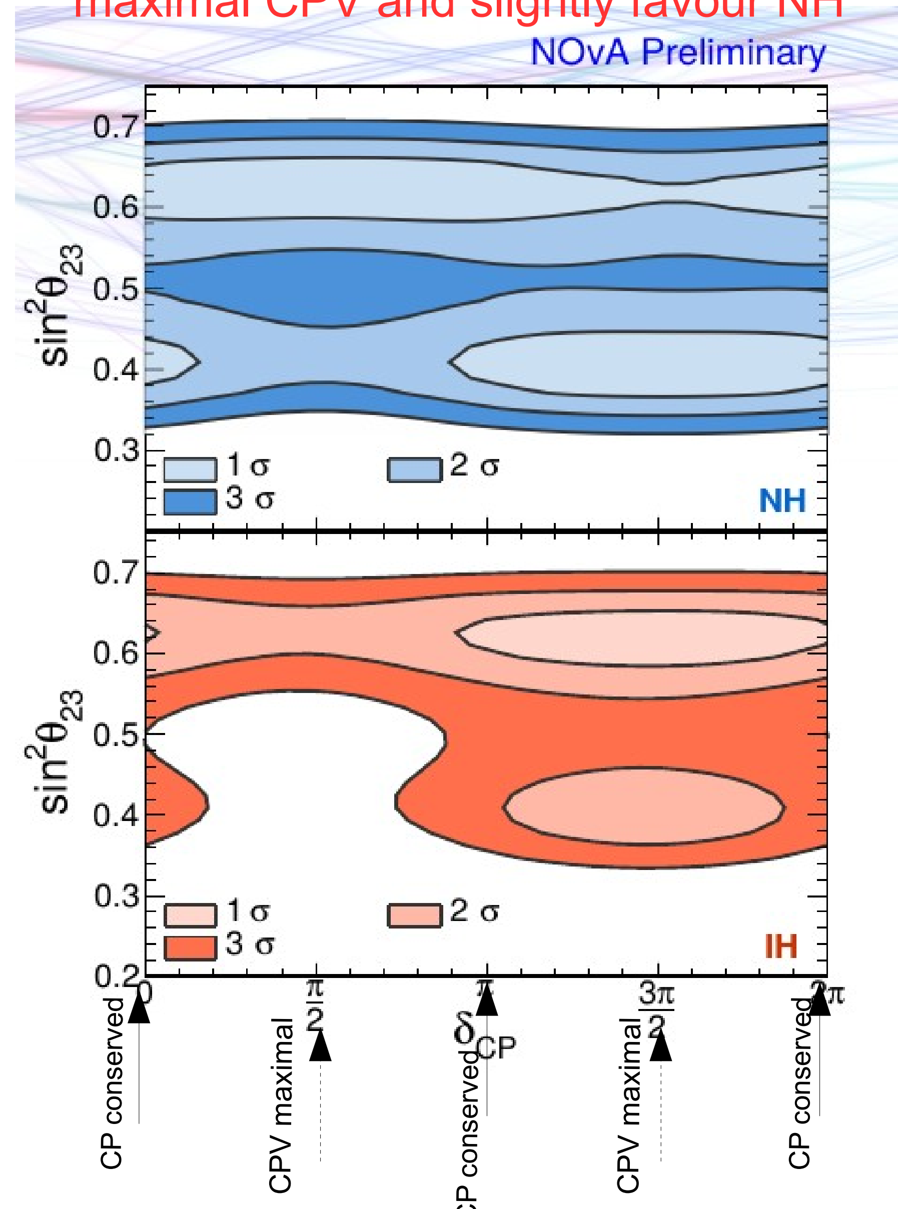
  - **δ_{CP} phase (unknown)** parametrize the difference between ν and $\bar{\nu}$ oscillation
    → involved with **matter-antimatter asymmetry** in leptogenesis scenarios

NOVA δ_{CP}

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

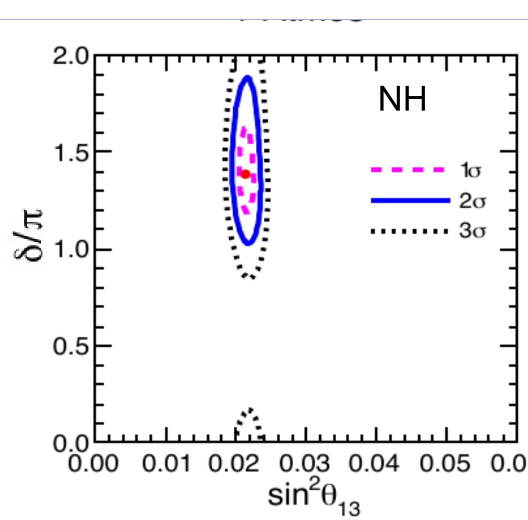


NOVA in agreement with T2K: favours maximal CPV and slightly favour NH



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

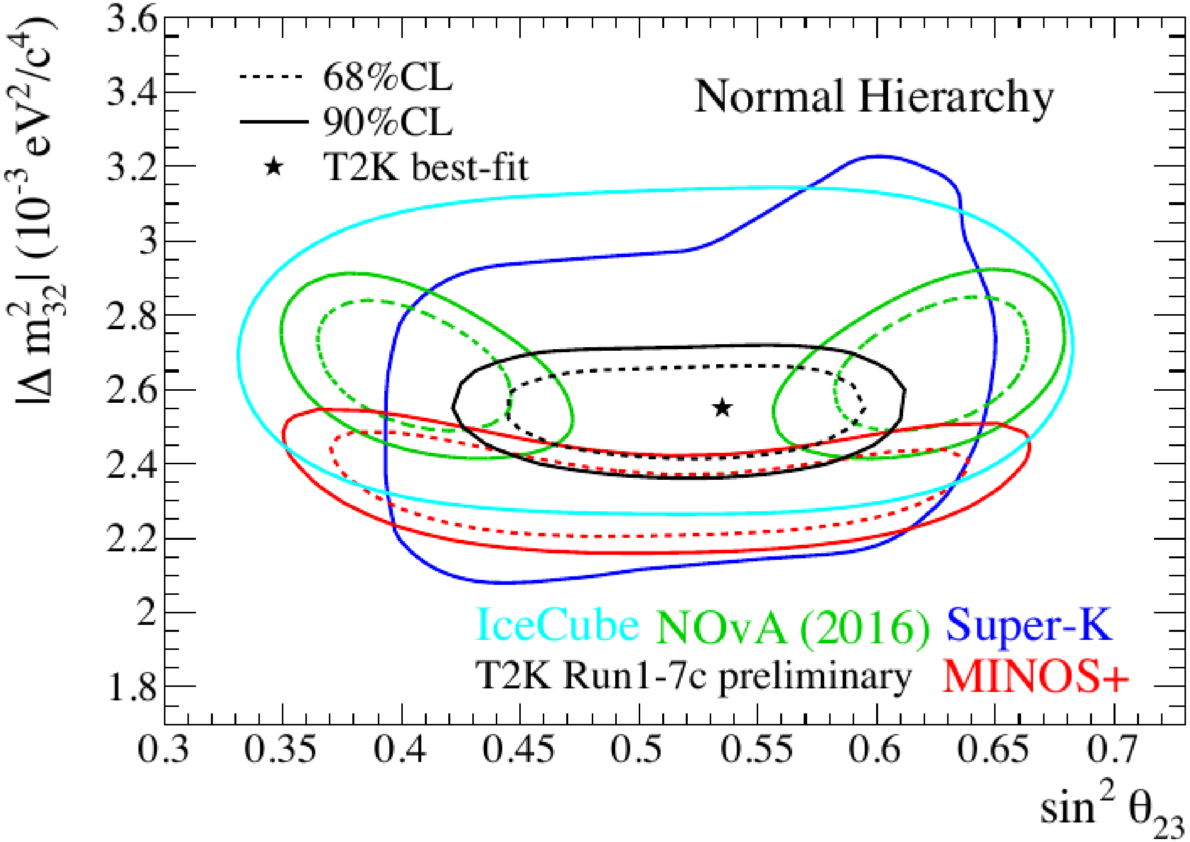
CP conservation excluded at 2σ



Lisi et al.
NEUTRINO 2016

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



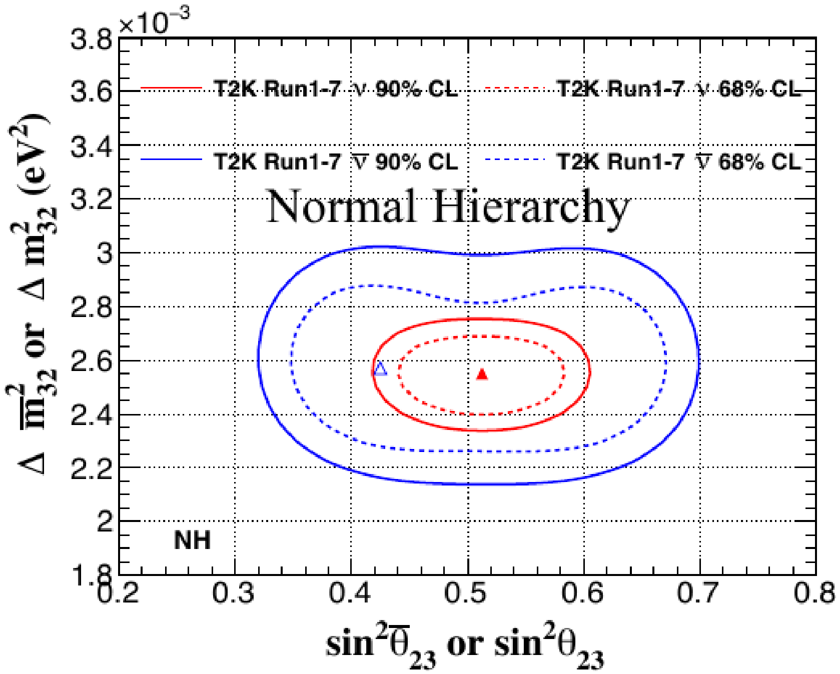
T2K data show maximal disappearance → **prefer maximal mixing: $\theta_{23} = \pi/4$** ($\sin^2\theta_{23}$=0.5)

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

Non standard scenarios

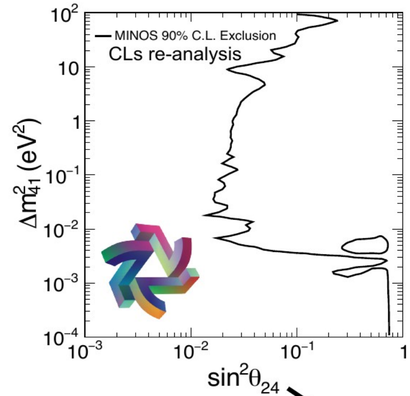
- **CPT violation** in T2K by comparing disappearance $\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$

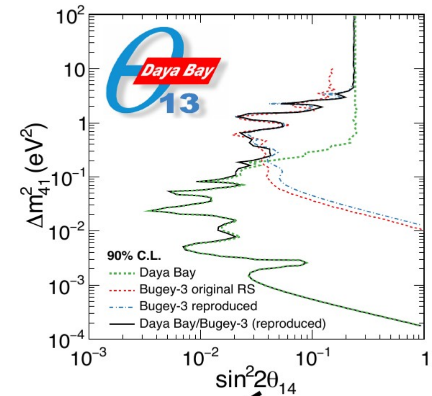


- Limits on **non-standard neutrino interactions** from MINOS+

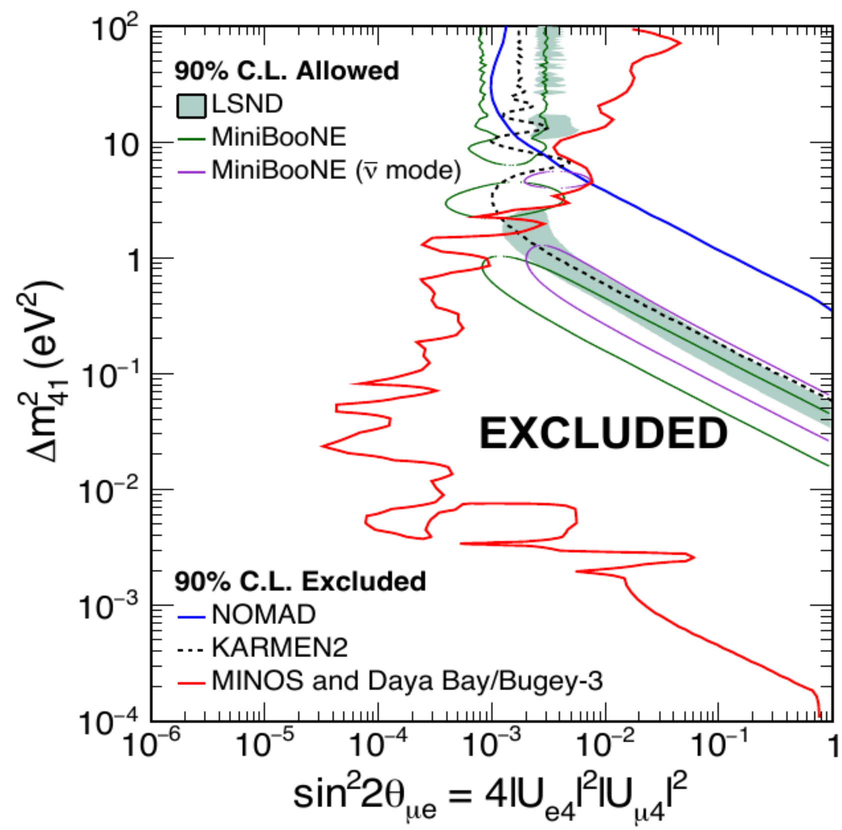
→ important to constrain to avoid degeneracies and biases with future precise δ_{CP} measurement!

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



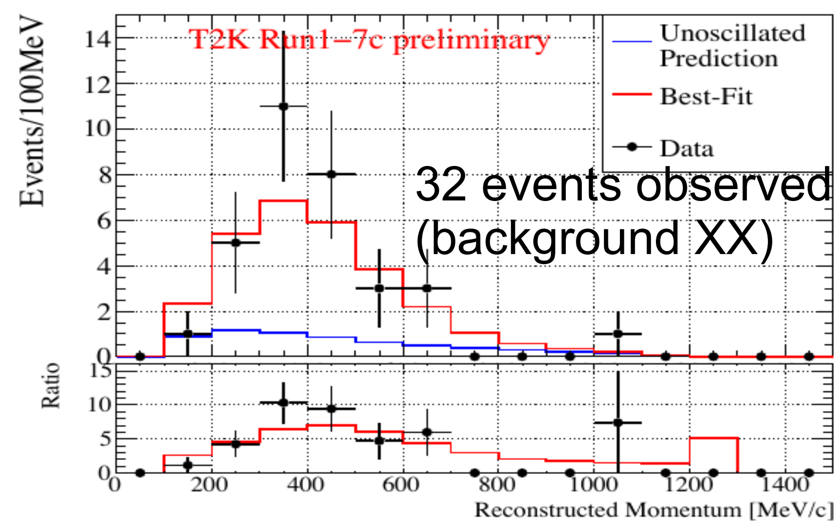


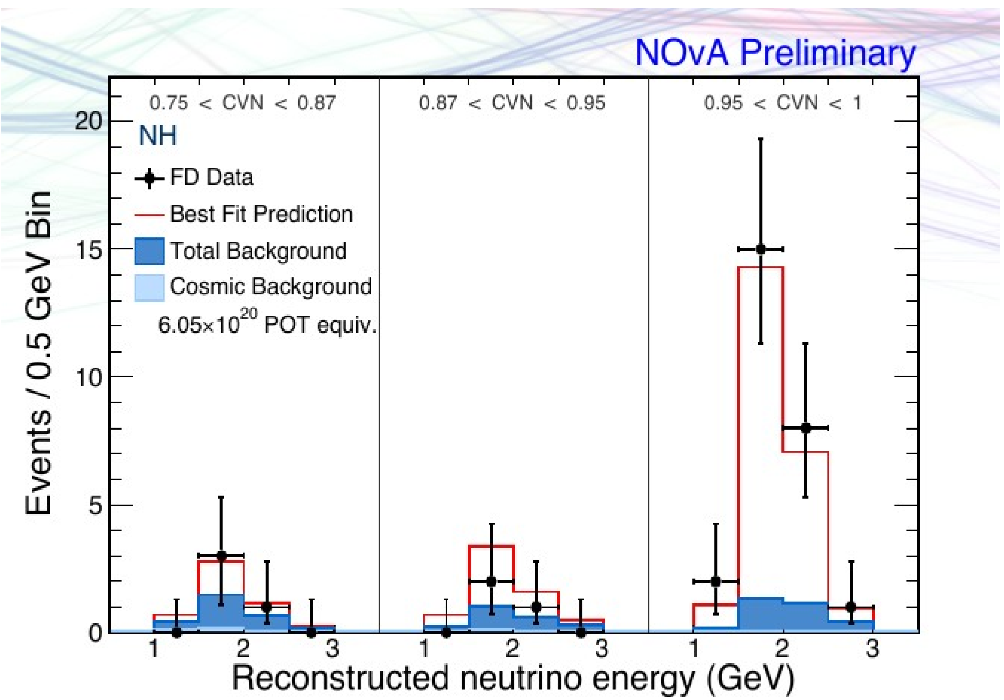
$$4|U_{\mu 4}|^2|U_{e4}|^2 = \sin^2\theta_{24}\sin^2(2\theta_{14}) \equiv \sin^2(2\theta_{\mu e})$$



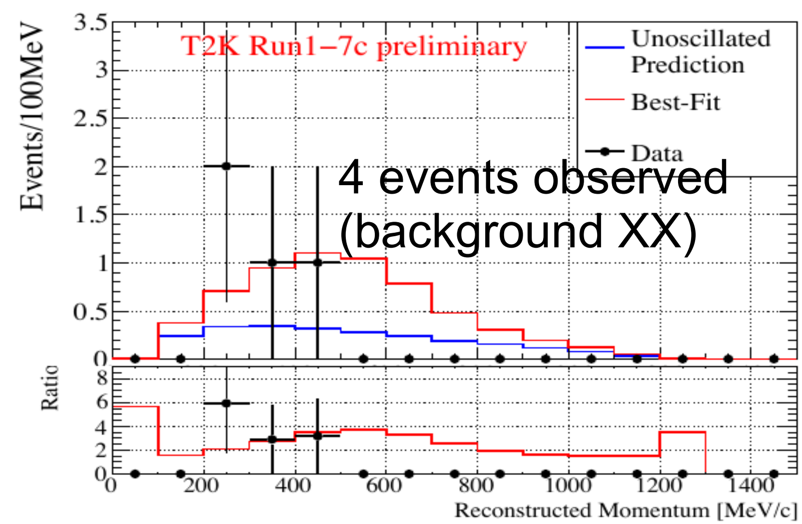
NOVA – T2K comparison: nue appearance

ν_e



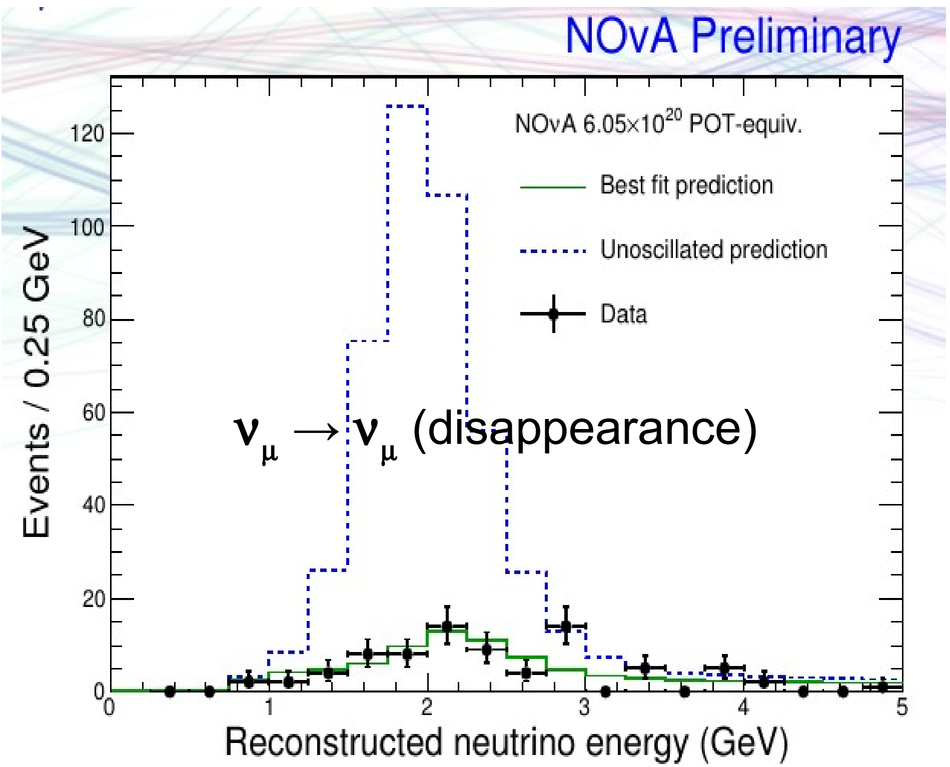


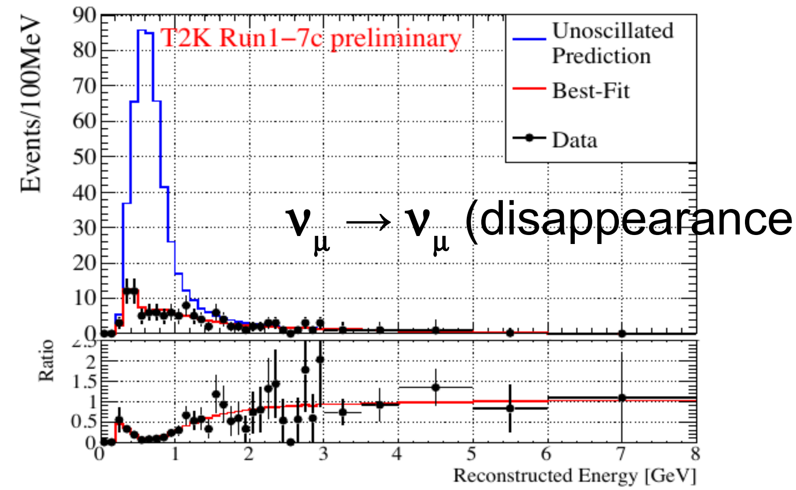
$\bar{\nu}_e$

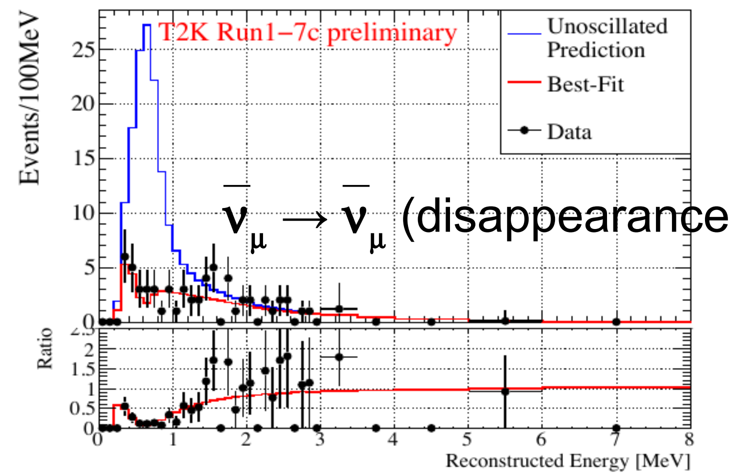


- Observe **33** events passing ν_e selection
- On 8.2 background

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%**

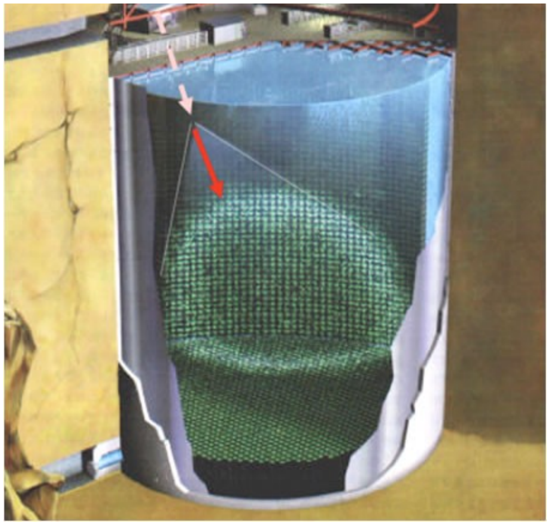
T2K systematics uncertainties (joint oscillation analysis)

Fractional error on the number of expected events at SK

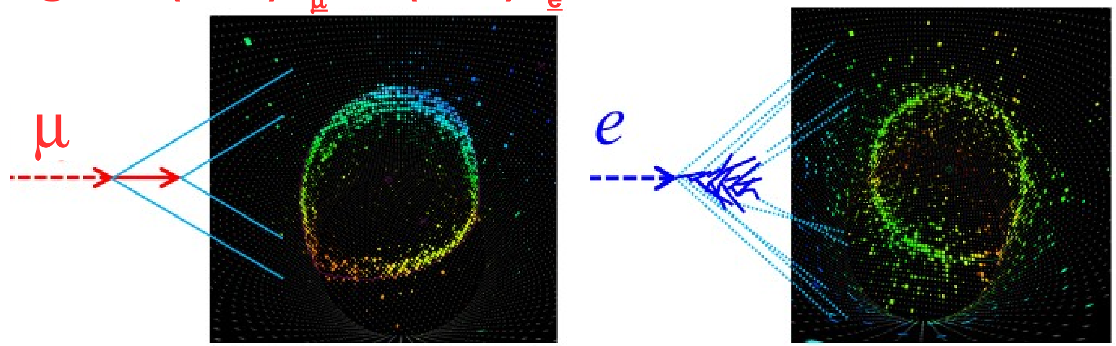
	ν_μ sample $1R_\mu$ FHC	ν_e sample $1R_e$ FHC	$\bar{\nu}_\mu$ sample $1R_\mu$ RHC	$\bar{\nu}_e$ sample $1R_e$ RHC	$1R_e$ FHC/RHC
ν flux+cross-section constrained by ND280	2,8%	2,9%	3,3%	3,2%	2,2%
ν_e/ν_μ and $\bar{\nu}_e/\bar{\nu}_\mu$ cross-sections	0,0%	2,7%	0,0%	1,5%	3,1%
NC γ	0,0%	1,4%	0,0%	3,0%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

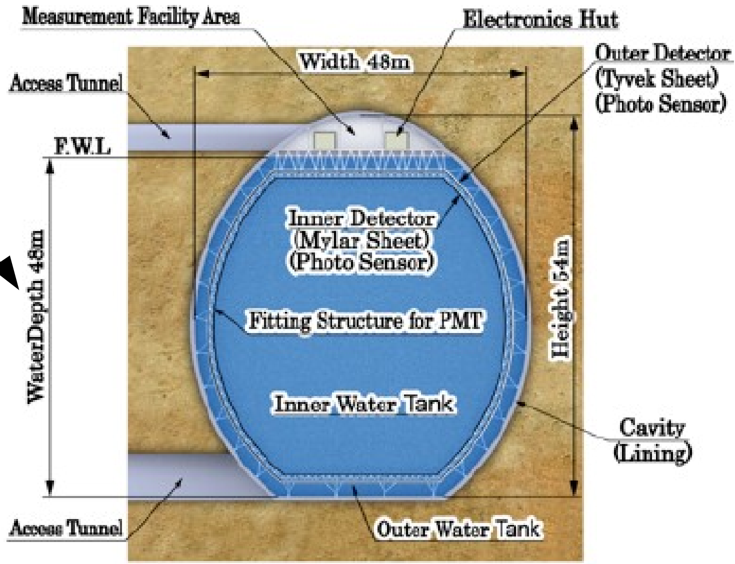
No magnetic field → no charge measurement ($\nu/\bar{\nu}$)

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

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

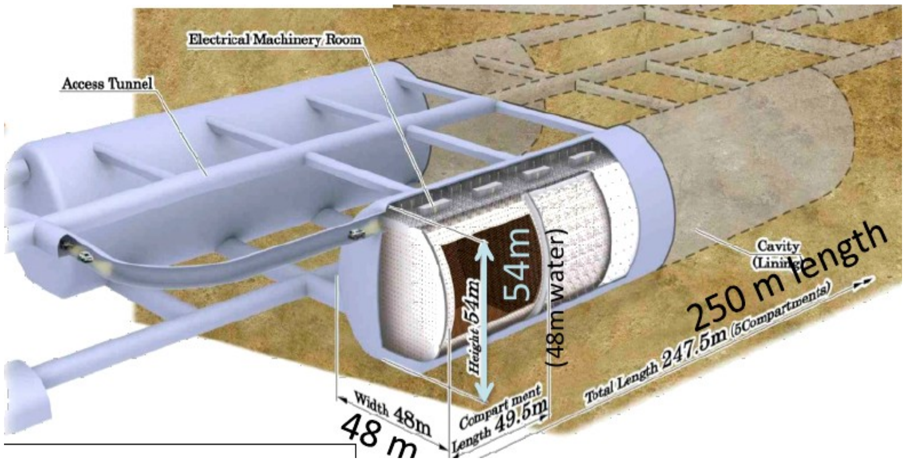
From SuperK to HyperK

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%)

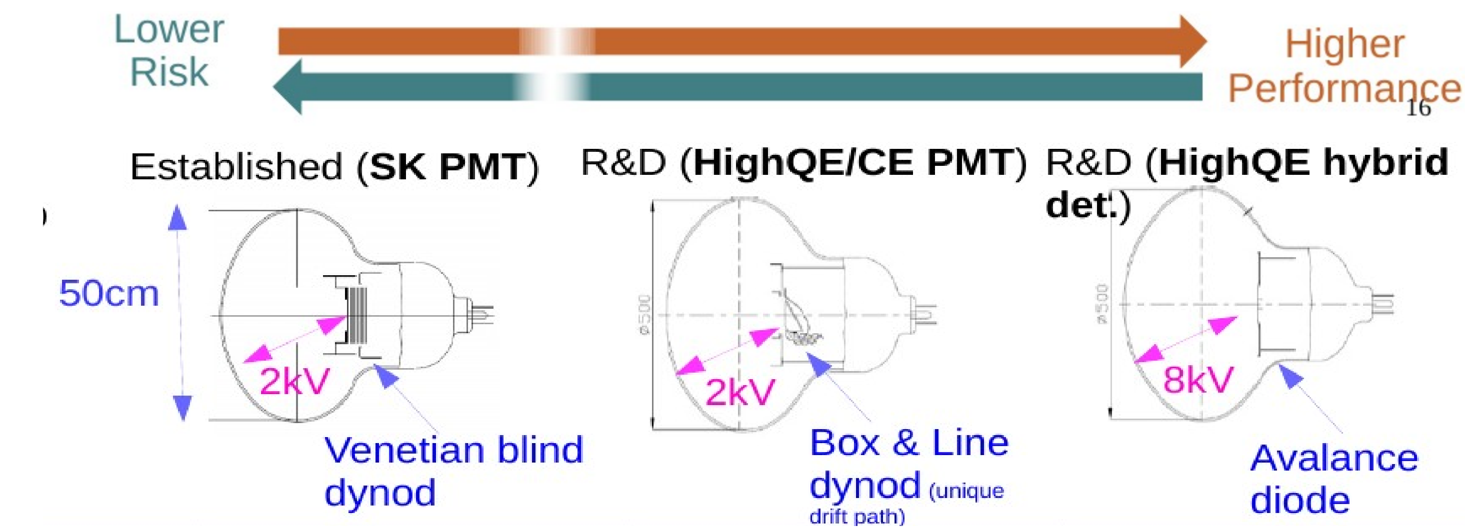


Tanks and PMT design under discussion:

- 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

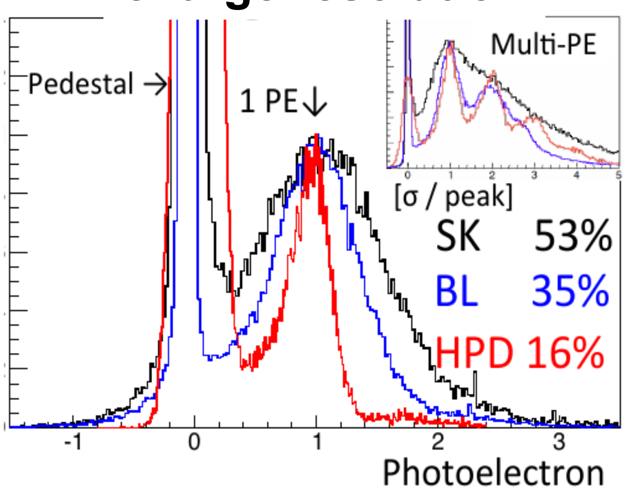


Quantum Eff. (QE)	22%	30%	30%
Collection Eff. (CE)	80%	93%	95%
Timing resol (FWHM)	5.5 nsec	2.7nsec	1nsec

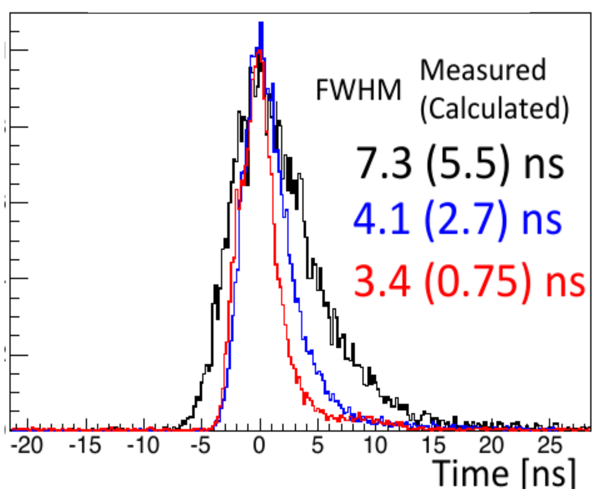
- Optimization should include **pressure resistance**
  possible to put protective cover → need precise control of glass quality

■ Response to single photoelectron:

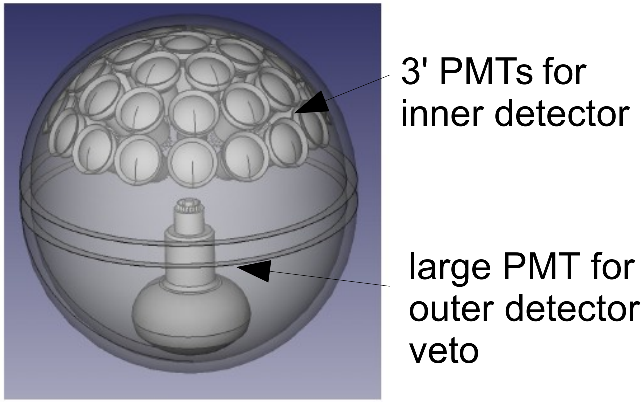
charge resolution



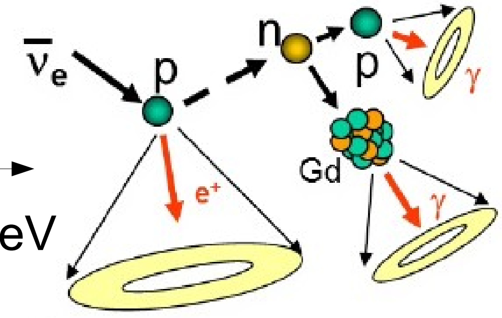
time resolution



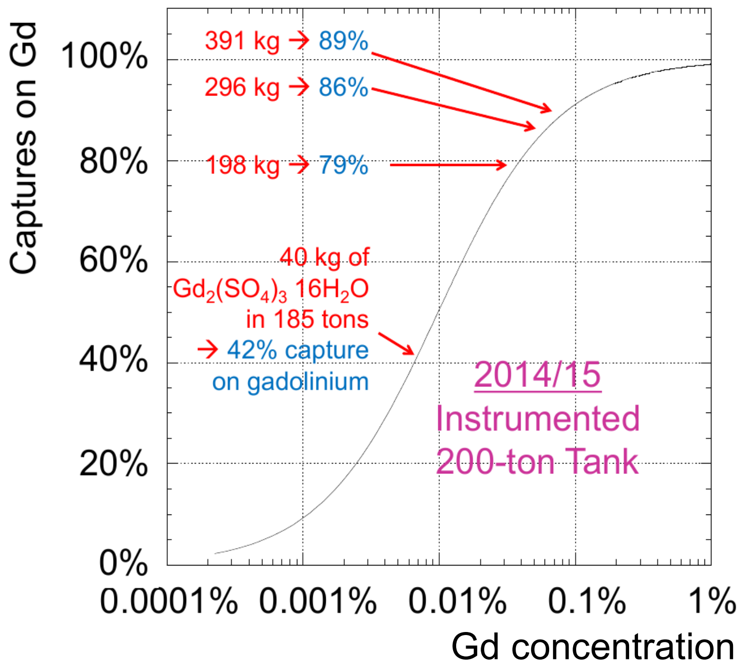
Integrated system of inner and outer PMTs under study (solve problems of pressure and in-water electronics)



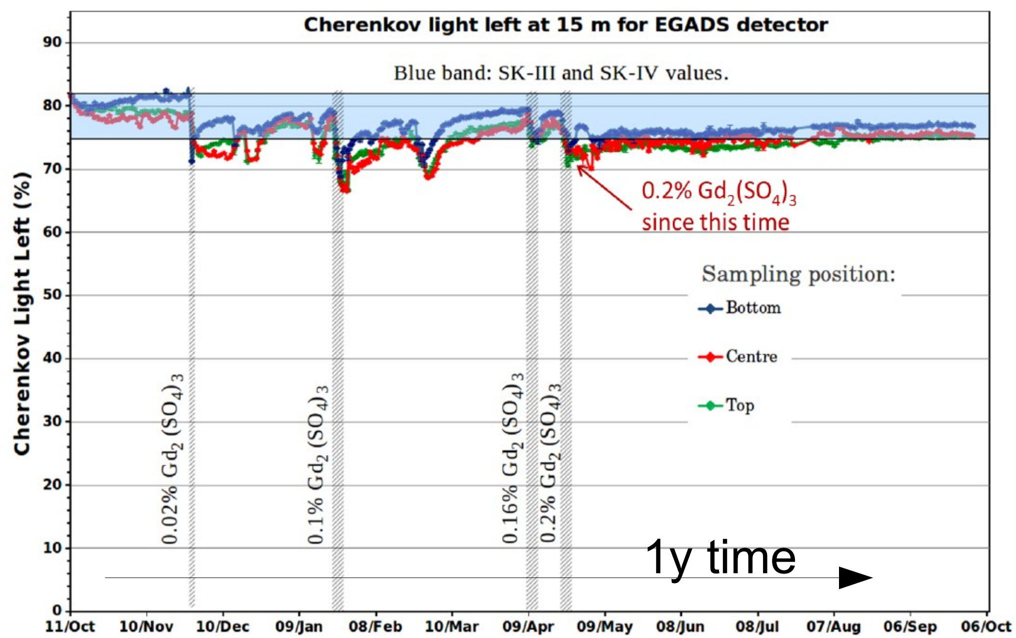
Gadolinium doping



- $\bar{\nu}p \rightarrow l^+n \rightarrow$ n get captured in Gd with emission of few γ ~8MeV
$\rightarrow$ 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)

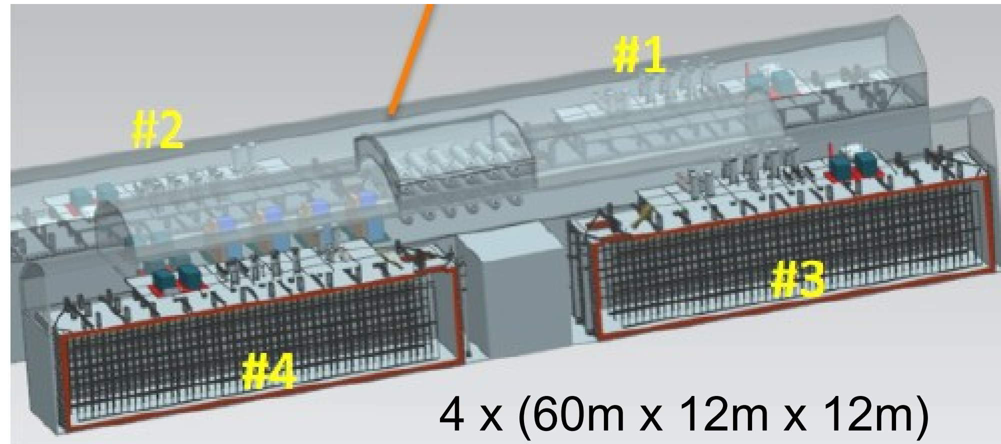
- SuperKamiokande will run with loaded Gd in next years!

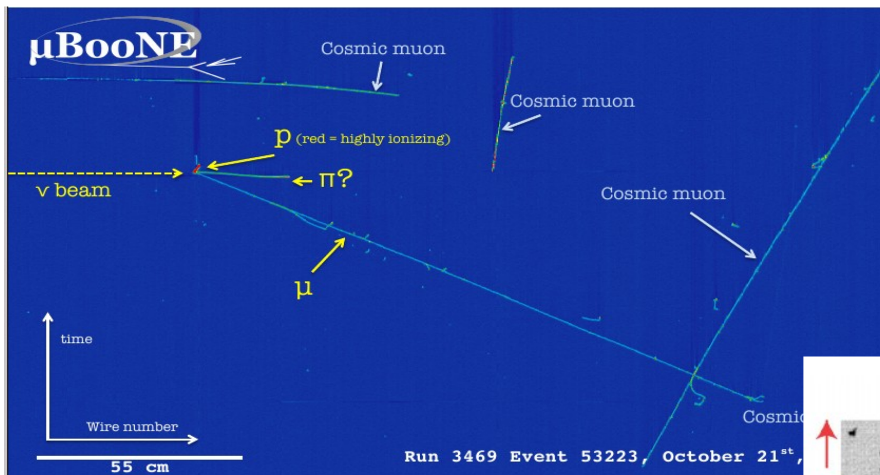
Liquid Argon technology

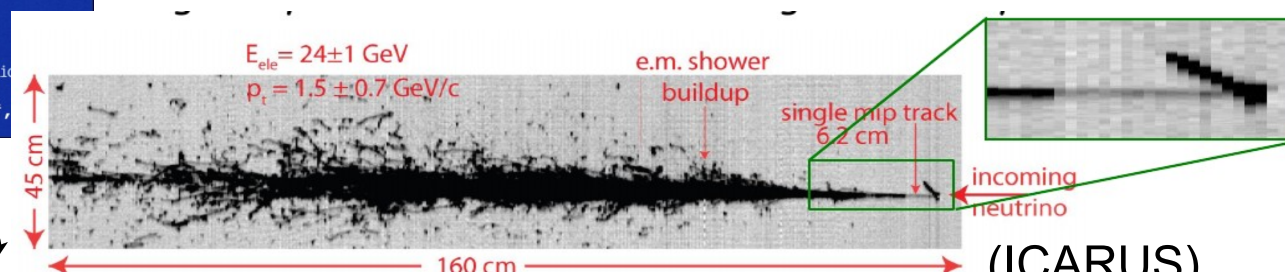
Ionizing particle in LAr → 2 measurements:

- **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

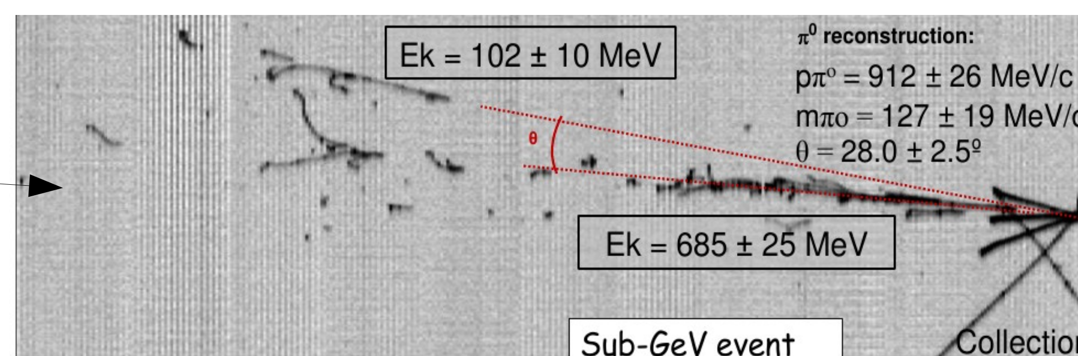




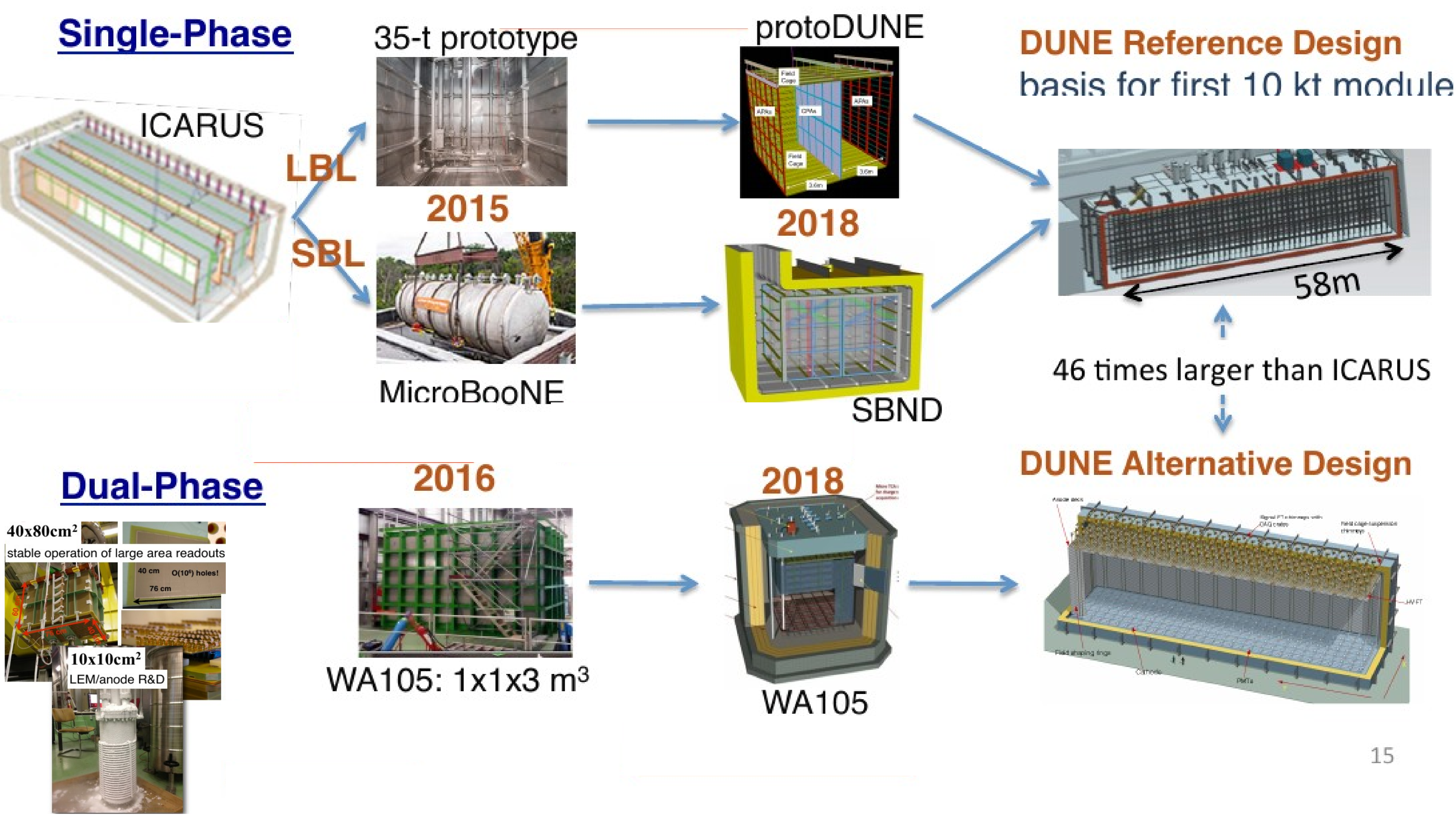


(ICARUS)

- 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)

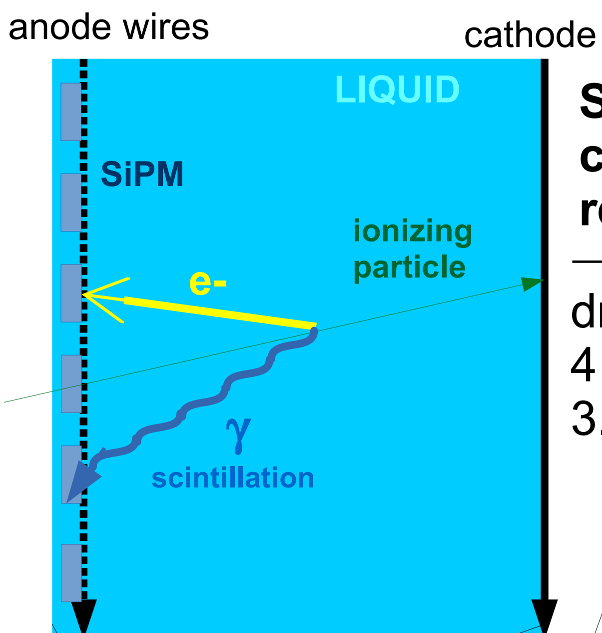


Result of years of R&D



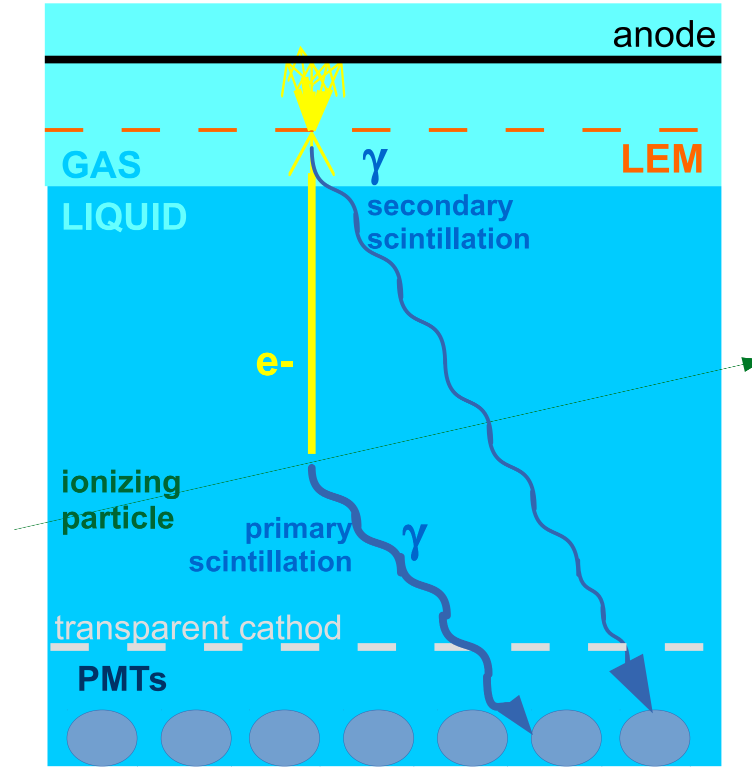
Single-phase VS Double-phase

- **Very long charge drift path → diffusion and attenuation**

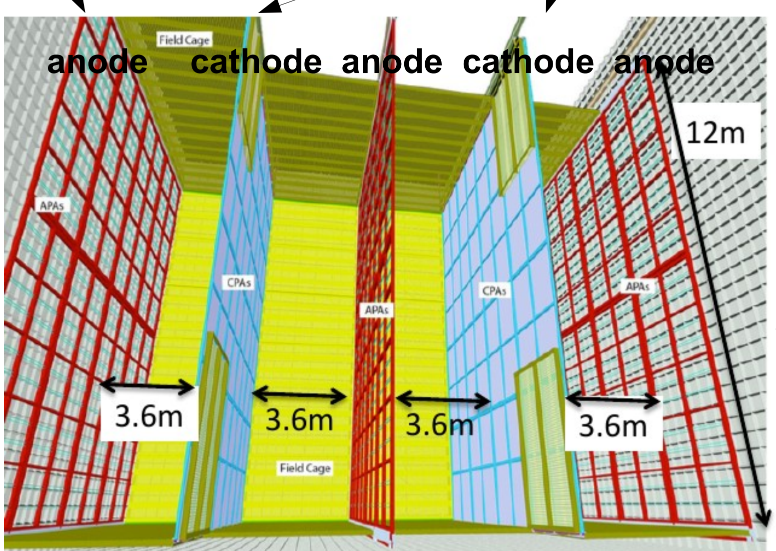


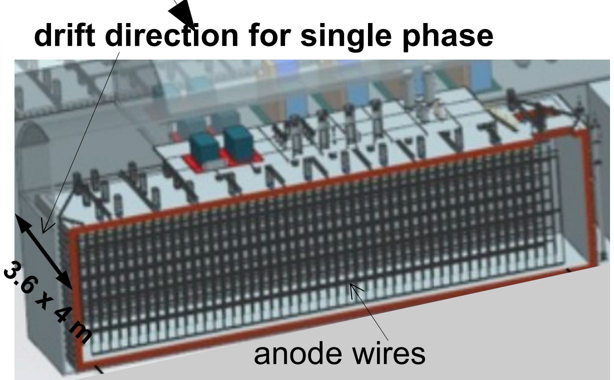
Single Phase charge readout
→ limited to short drift distances:
4 drift regions of 3.6m each

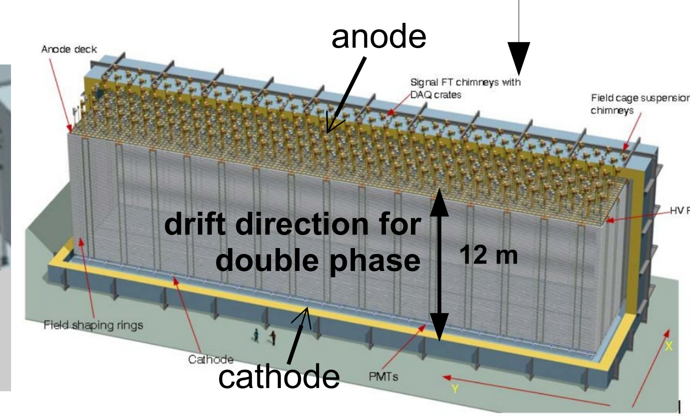
Double Phase charge readout



→ high signal/noise thanks to avalanche multiplication in gas





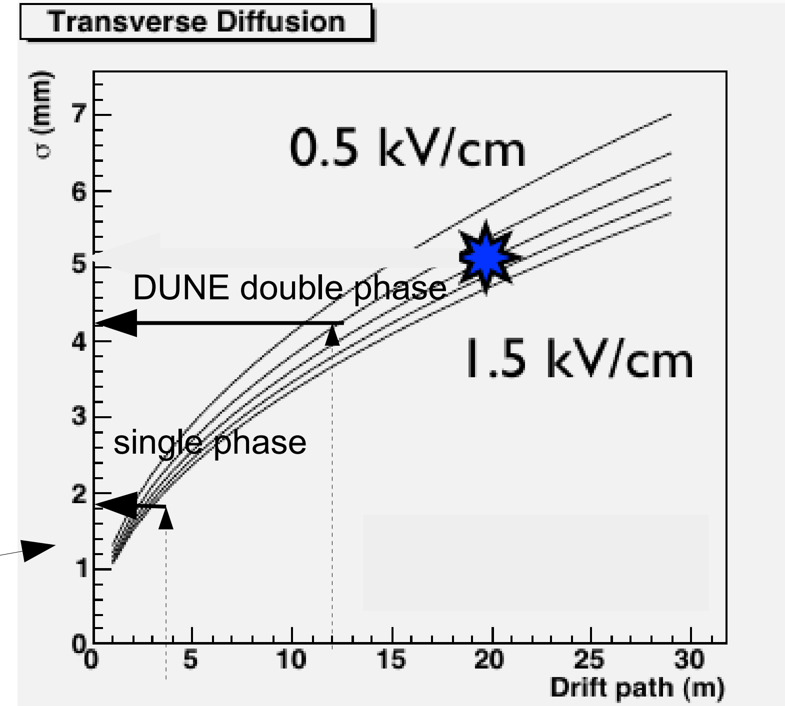


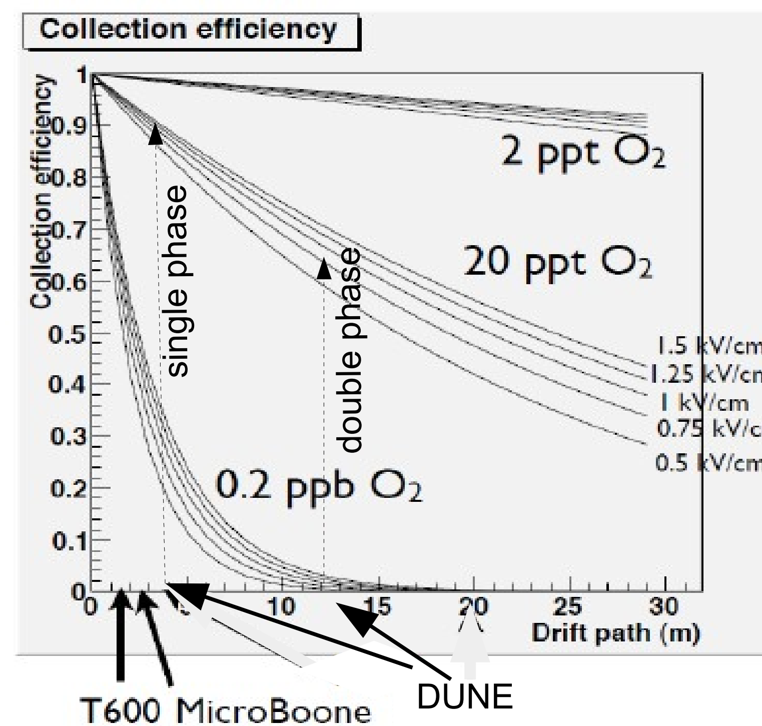
Charge signal

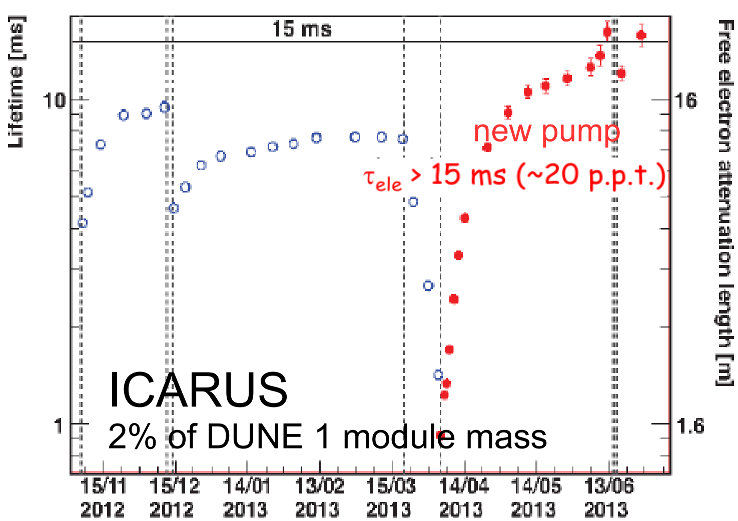
- W_e = 23.6 eV → mip produces ~ 100k e- per cm → 60k e- after recombination
- dirft velocity ~mm/µs (→ total drift time ~10 ms)

■ **Very long drift path → diffusion and attachment**

- diffusion ~few mm with 1-0.5 kV/cm (→ pitch readout few mm)
- O_2 pollution captures ionization electrons → charge attenuation (→ impurity ~20 ppt O_2 needed)

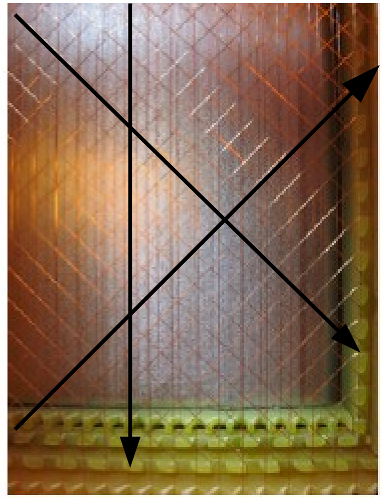


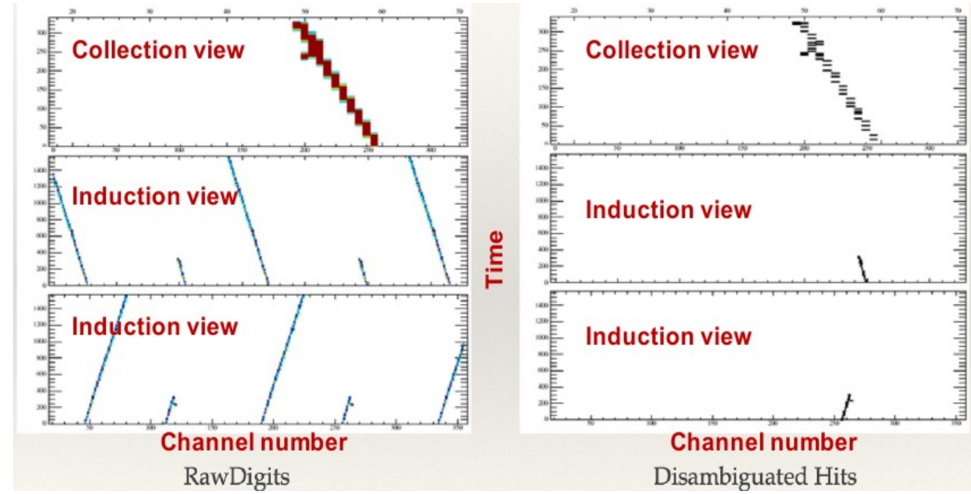




Charge readout plane (CRP)

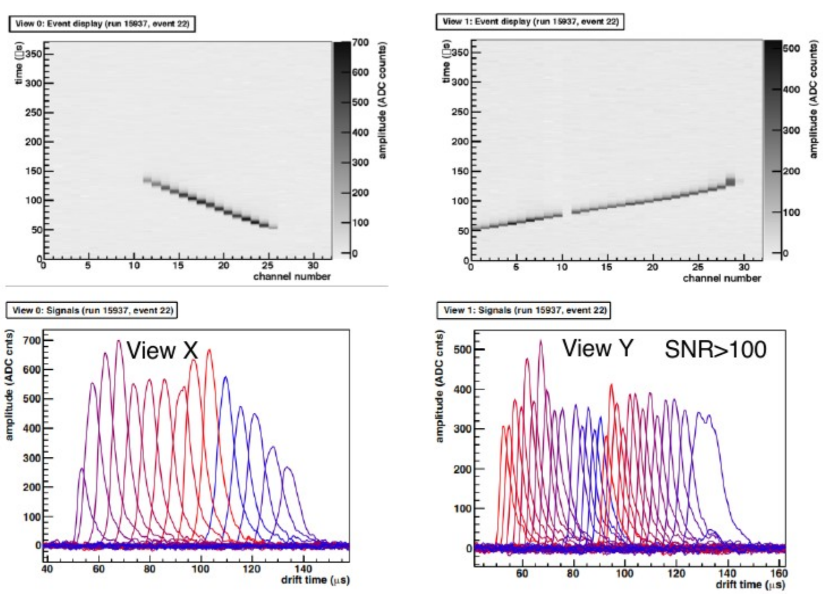
- **Single Phase**
  - no gain
  - 3 views
  - uniform CRP design

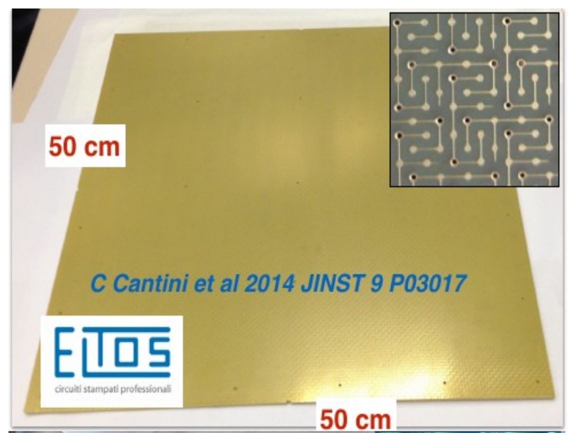


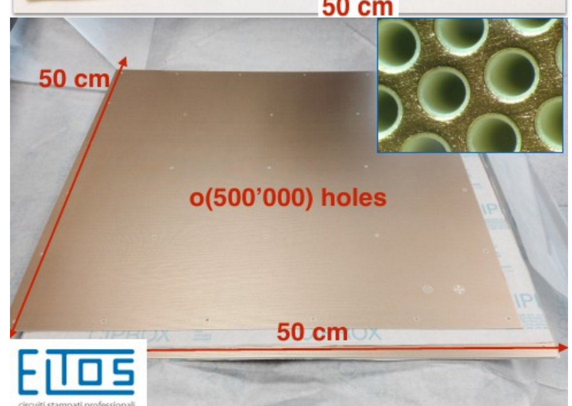


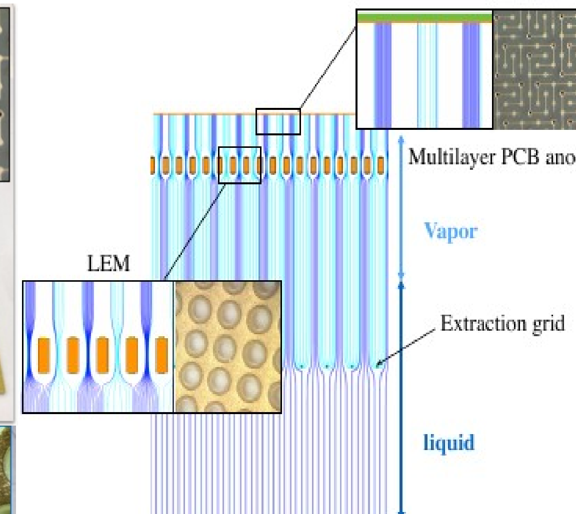
- **Double Phase**
  - stable gain of 20 on 10x10cm LEM
  - 2 views (x,y) of equal quality
  - to scale up: CRP segmented in 50x50cm modules

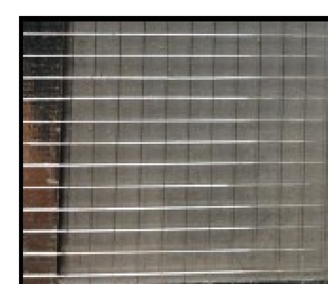
Cosmic event in double phase TPC at effective gain~20











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**

Future experiments: ν_e and $\bar{\nu}$ xsec

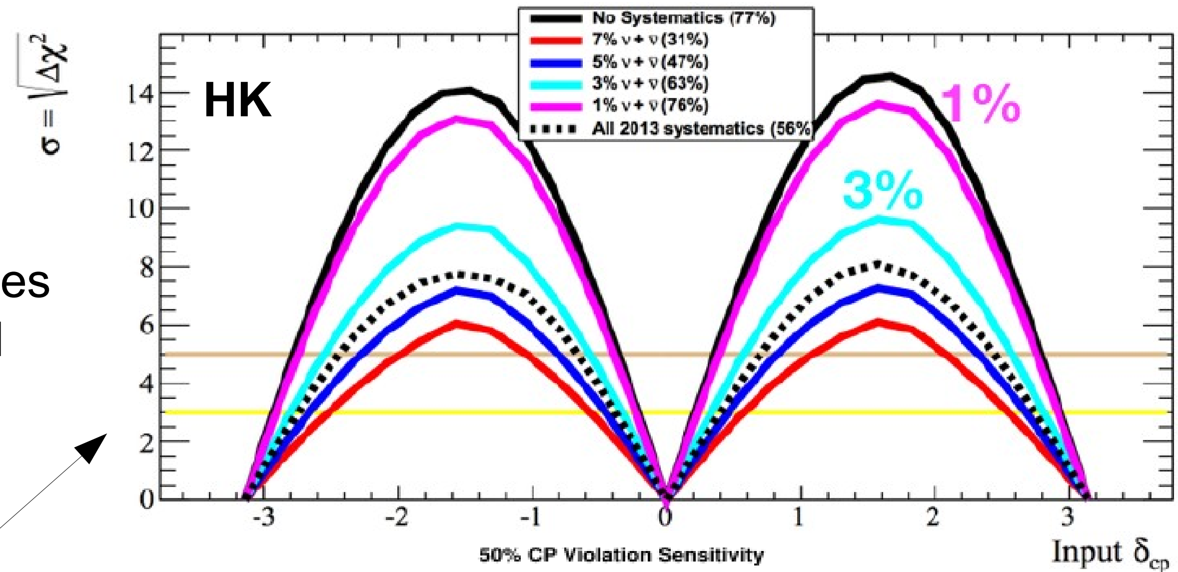
- We are interested to ν_e **appeareance and δ_{CP} from $\nu - \bar{\nu}$ comparison** but in ND we mostly measure ν_μ cross-sections.

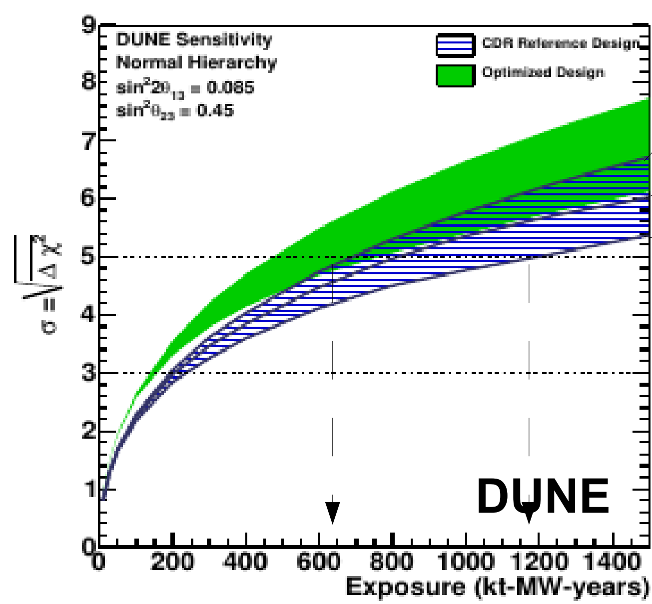
T2K:

ν_μ sample	ν_e sample	$\bar{\nu}_\mu$ sample	$\bar{\nu}_e$ sample
7.7%	6.8%	11.6%	11.0%

- In future (HK, DUNE) large samples of 4 ν species → the uncorrelated uncertainties are relevant
  - **HK** needed uncertainty to have negligible impact on dCP: **ν_e-$\bar{\nu}_e$ uncorrelated 1-2%**
  - For **DUNE** assumed: **uncorrelated ν_μ - $\bar{\nu}_\mu$ 5%** and **ν_e - $\bar{\nu}_e$ 2%**

(shape of ν_μ itself may be more important for DUNE: shape analysis and spanning over different xsec)





5% ± 1%

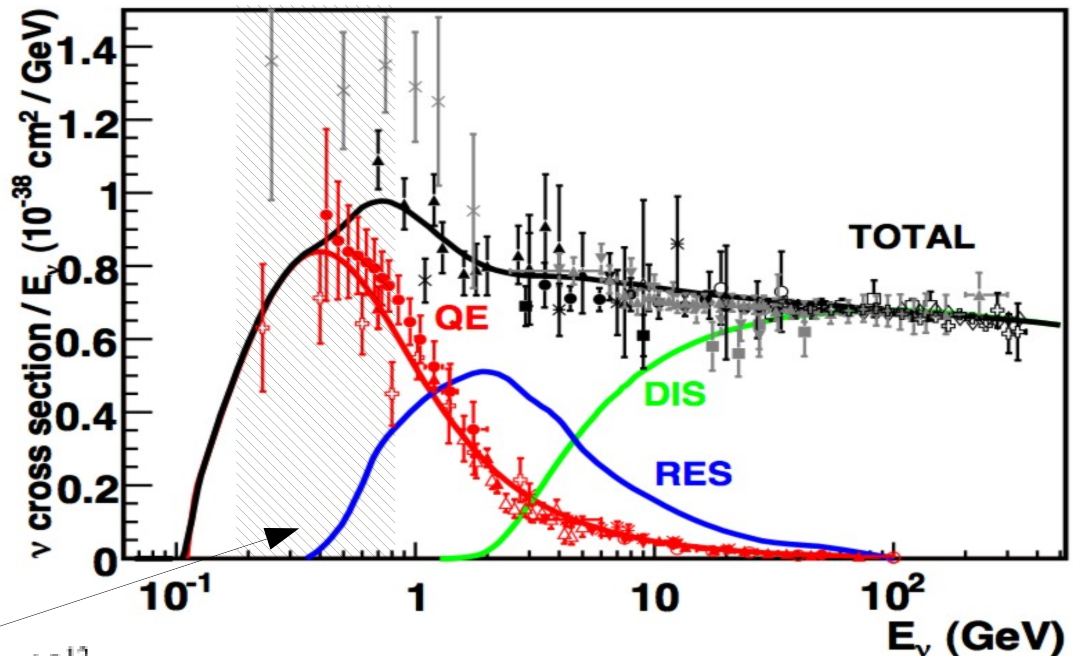
5% ± 2%

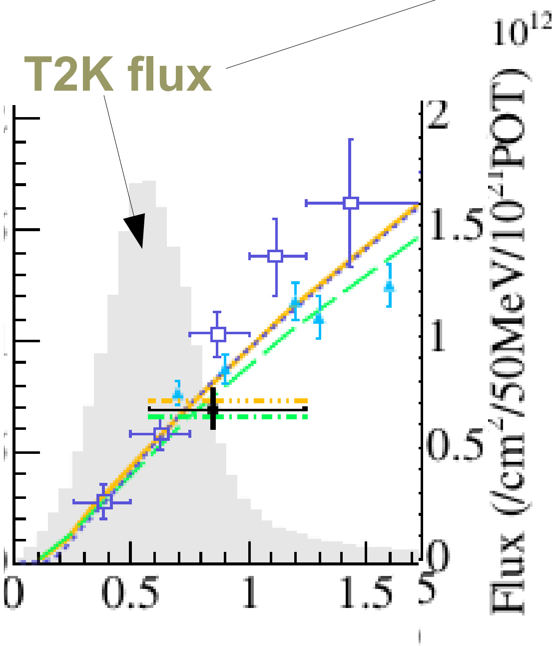
5% ± 3%

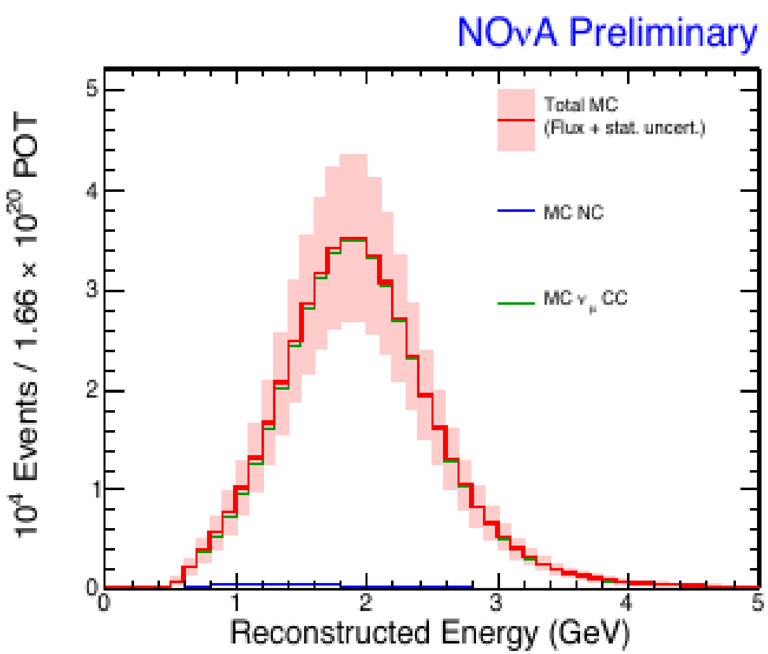
→ equivalent to factor 2 in exposure!

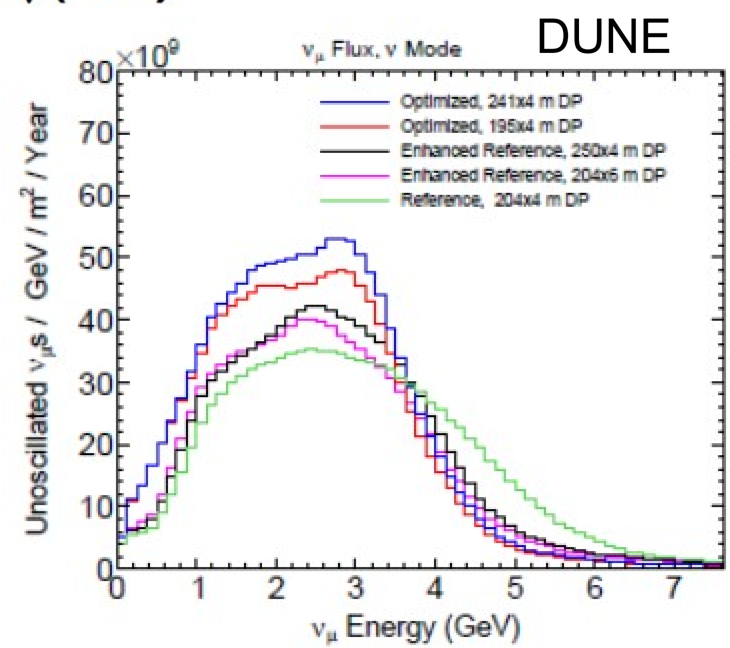
DUNE and HK talks @ NuFact 2015

Moving to larger energies ...

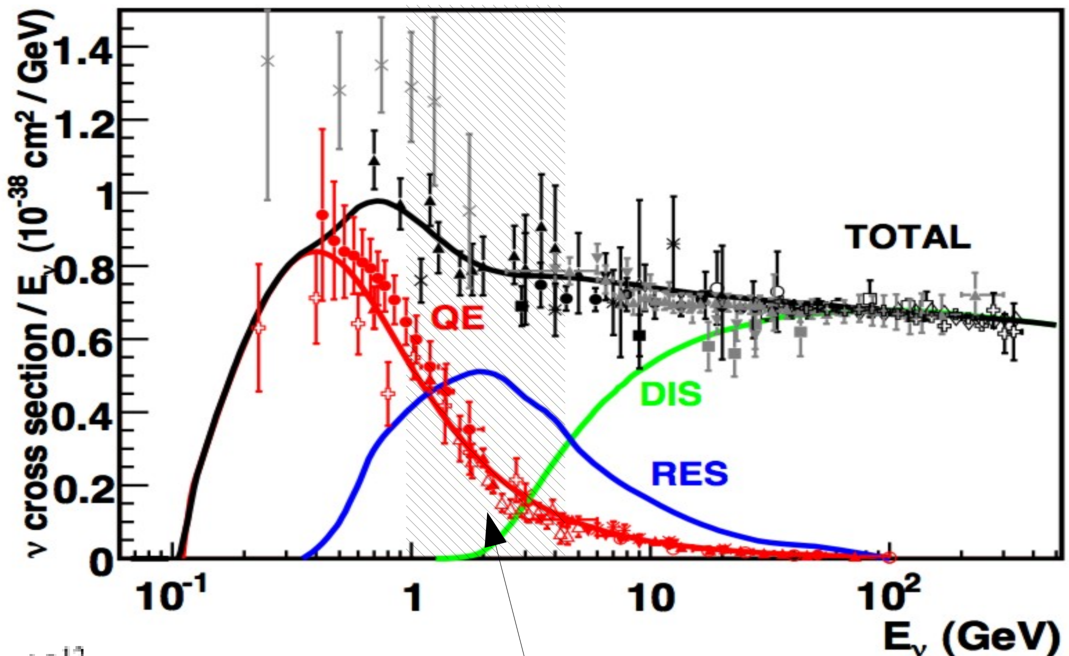




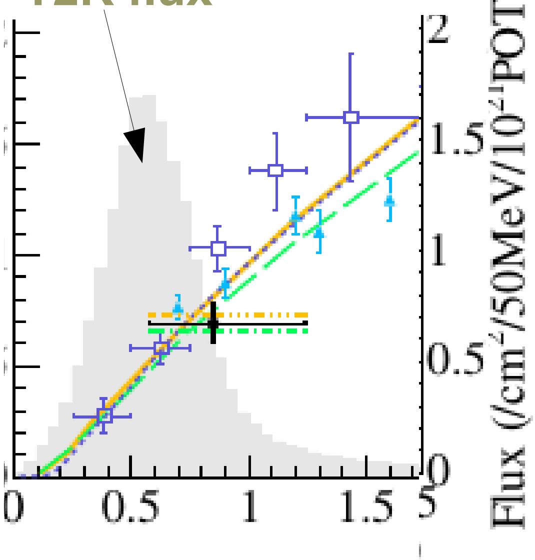




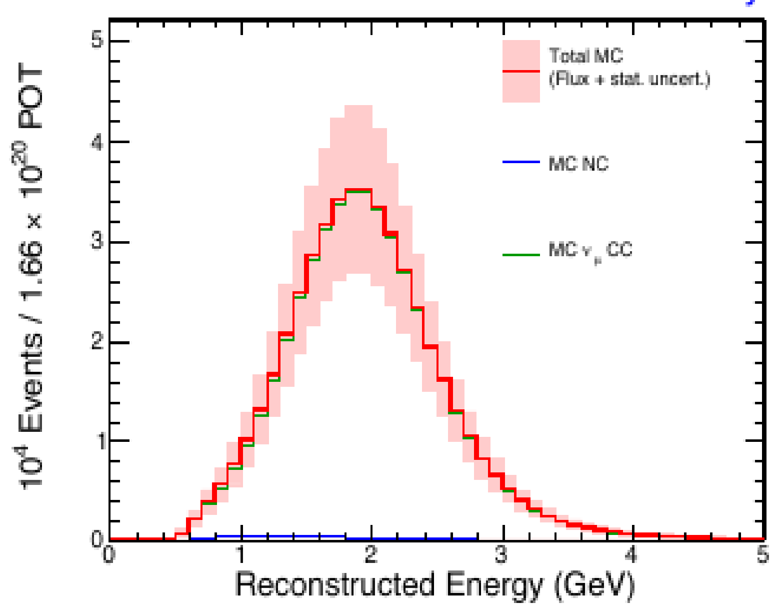
Moving to larger energies ...



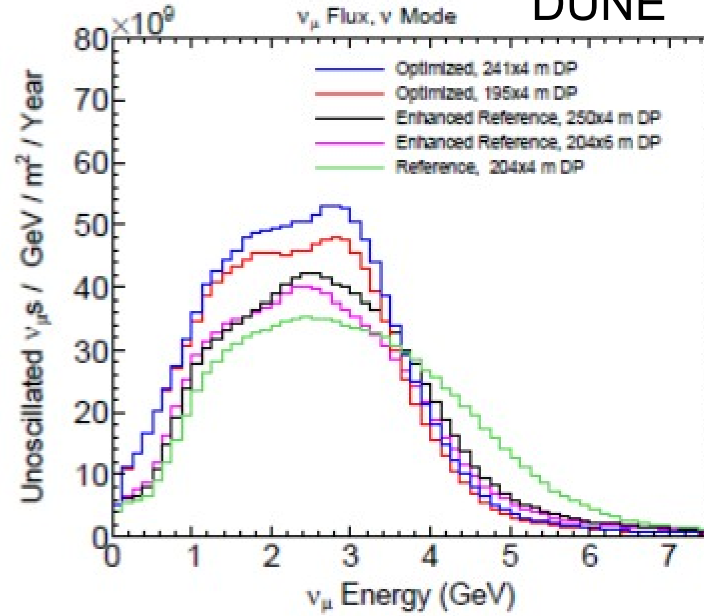
T2K flux



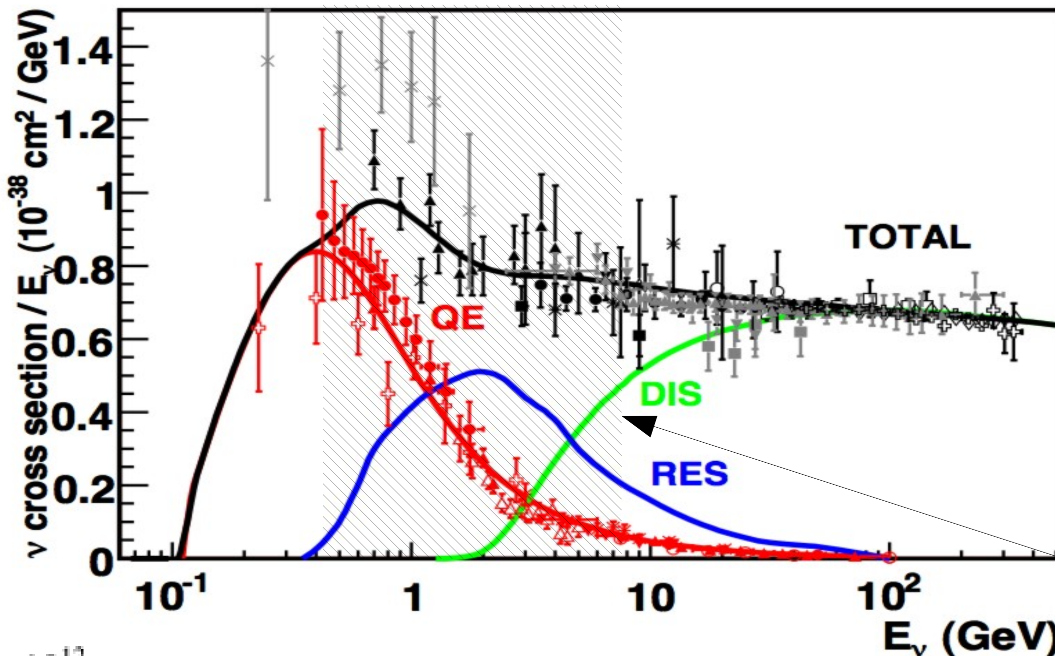
NOνA Preliminary



DUNE



Moving to larger energies ...



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