Stato e prospettive delle oscillazioni di neutrino

Maria-Gabriella Catanesi INFN Bari

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Oscillazioni di Neutrino

Se gli autostati elettrodeboli e di massa sono differenti:

* Il neutrino e' prodotto in un determinato autostato "debole"
* Viaggia a una distanza L come autostato di massa
* Puo' essere rivelato con un differente autostato "debole"

Bruno Pontecorvo
1969

ν_μ → → → $\nu_\mu,\ \nu_e$ or ν_τ

ν_1, ν_2, ν_3

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

La matrice Pontecorvo-Maki-Nakagawa-Sakata (PMNS)

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

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

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

atmosferic ν
accelerator ν

SBL reactor ν
accelerator ν

solar ν
LBL reactor ν

$\sin^2\theta_{23} \sim 1/2$

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

interferenza

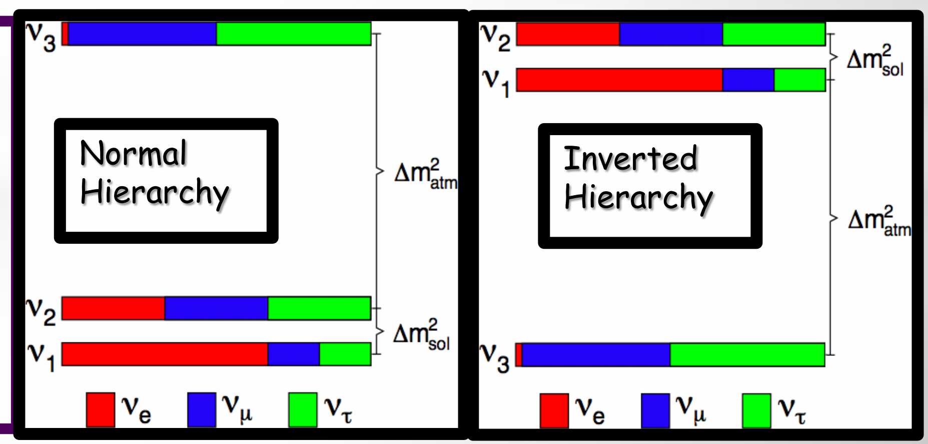
$\sin^2\theta_{13} \sim 0$?

$\sin^2\theta_{12} \sim 1/3$

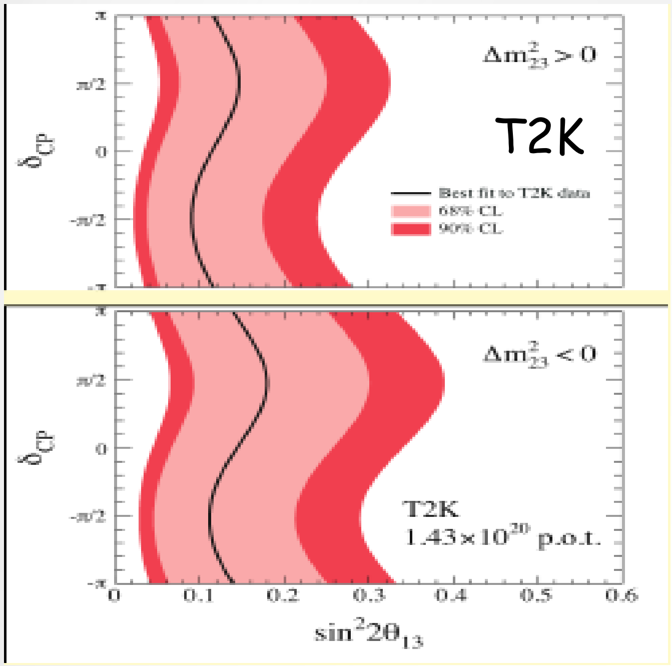
$\delta m^2 \sim 8\times10^{-5}\ eV^2$

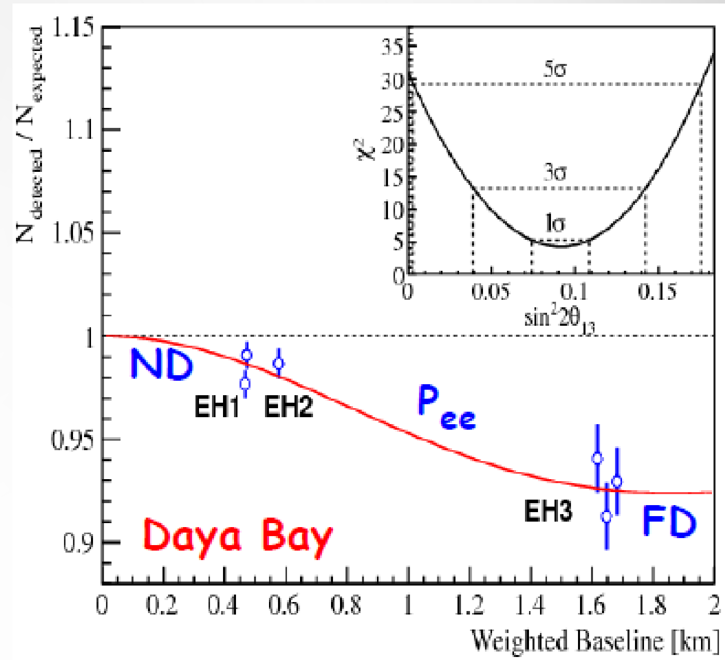
Sorgenti di neutrini

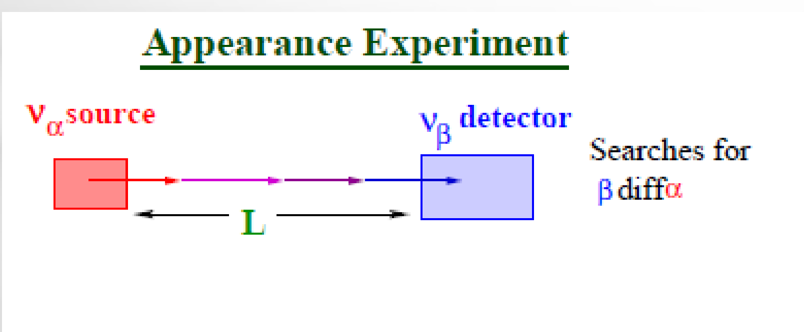
- Sorgenti naturali (neutrini solari e atmosferici)
- Neutrini da reattori
- Neutrini da acceleratori («Long Baseline»)

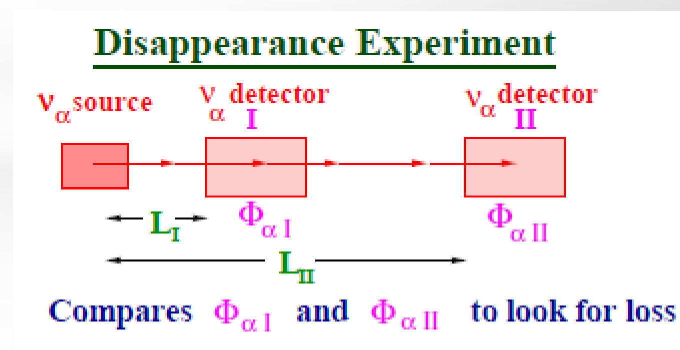


Tutto cambia nel 2011/2012









γ Experiments: LBL vs Reactors

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

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

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

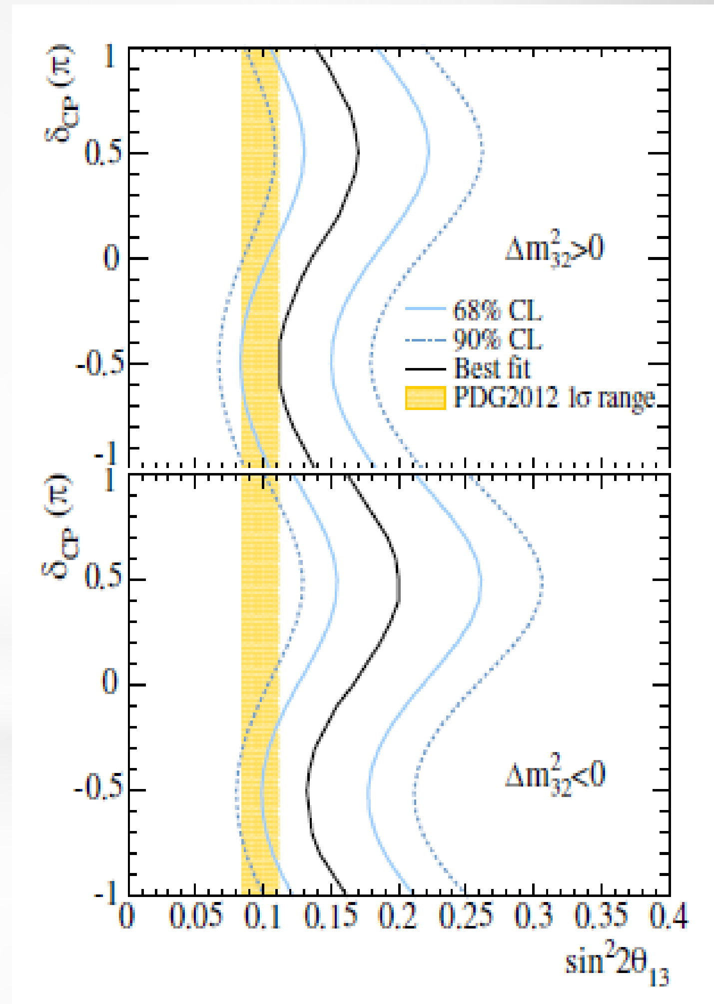
So $\sin^2 2\theta_{APP} = 2 \sin^2 \theta_{23} \sin^2 2\theta_{13}$

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

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

Concha Gonzalez-Garcia

T2K 2013



Quale esperimento / quali parametri/ quando

* T2K/T2K(2)/Nova/ => ϑ_{13}, $\delta_{cp,}$ Δm_{23}, MH(?) < 2020(25?)
* JUNO (RENO50) => Δm_{12}, MH > 2020

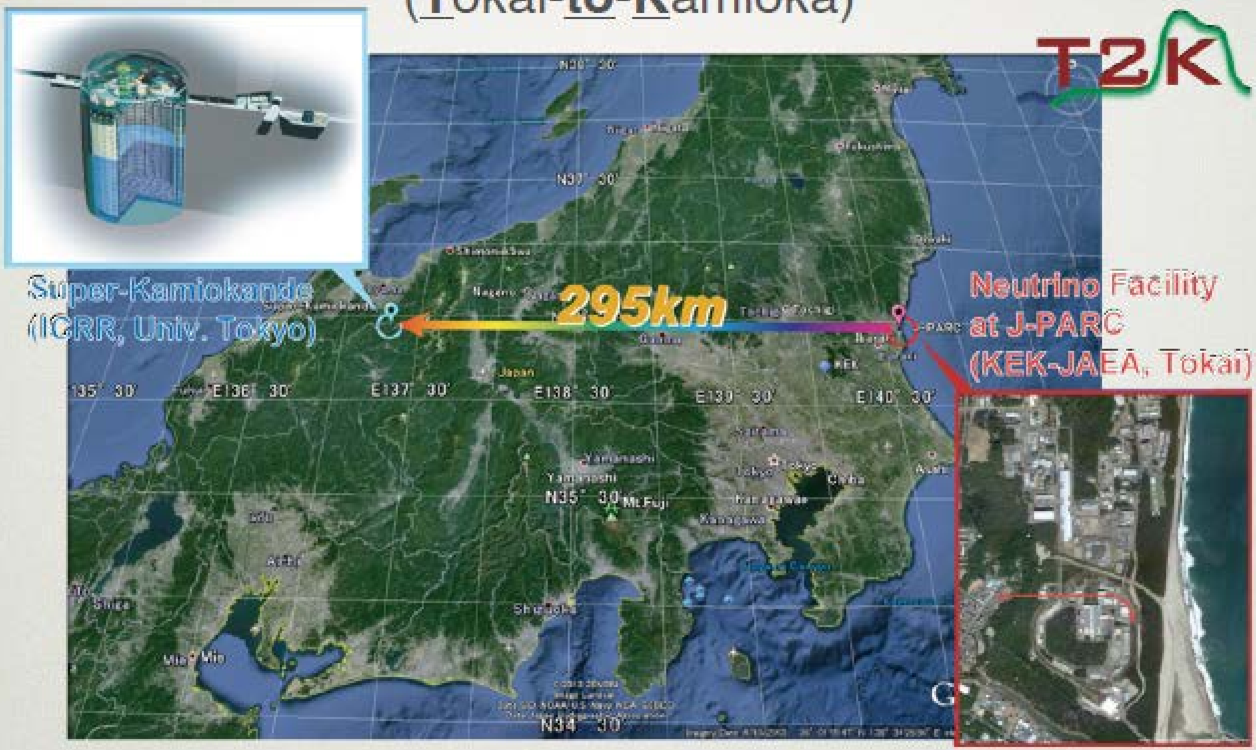
* PINGU/ORCA => Δm_{23}, MH >2020
* HyperK/DUNE > 2025

* Ricerche in corso e delle prospettive nel settore delle ricerche esotiche e/o dei neutrini sterili (SBL a Fermilab) vedi comunicazione di Andrea Falcone (Icarus)

* T2K

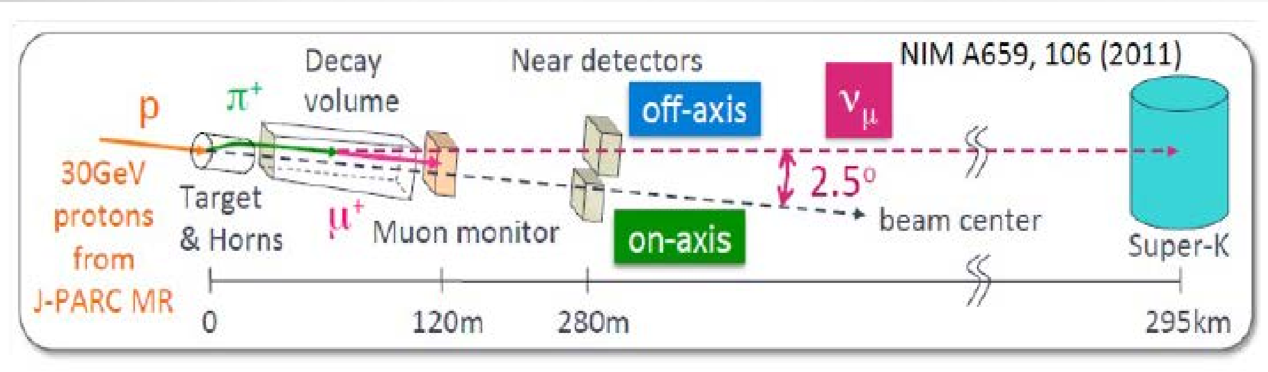
The T2K experiment

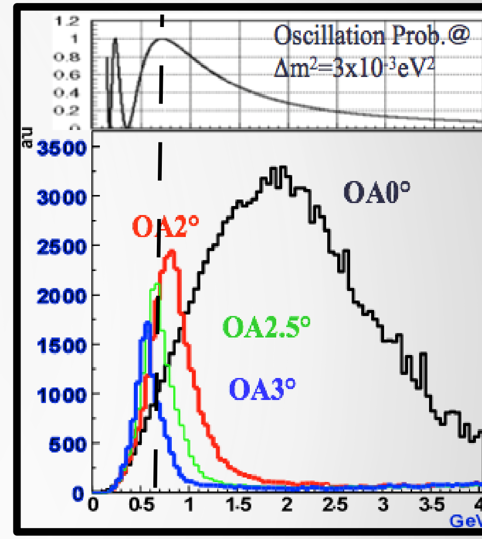
(Tokai-to-Kamioka)



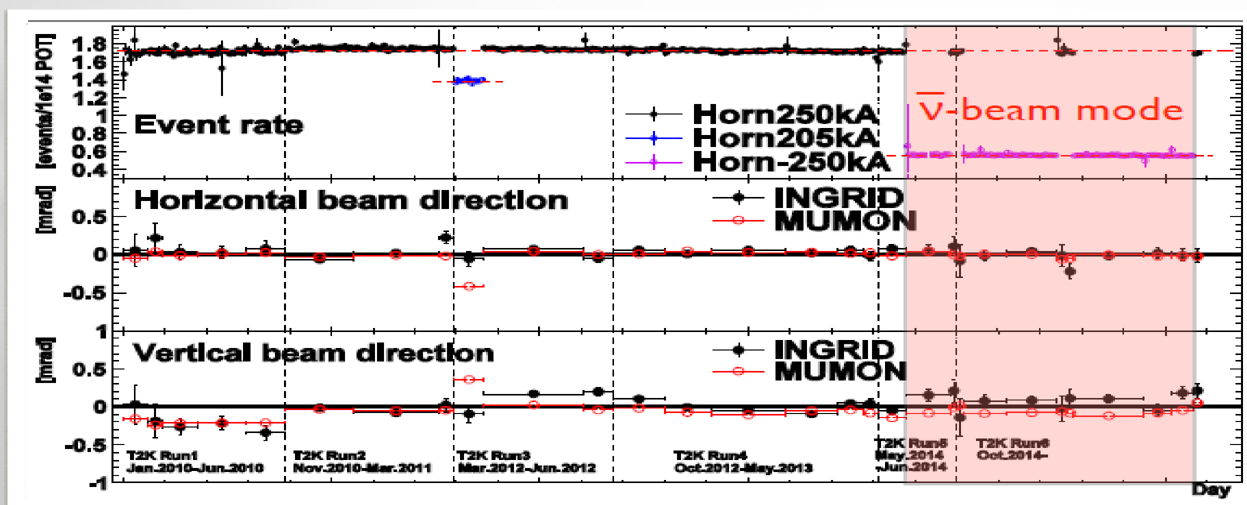
- Goals of T2K:
  - Full picture of the neutrino oscillations/mixings
  - Measurement of CP asymmetry in the neutrino sector

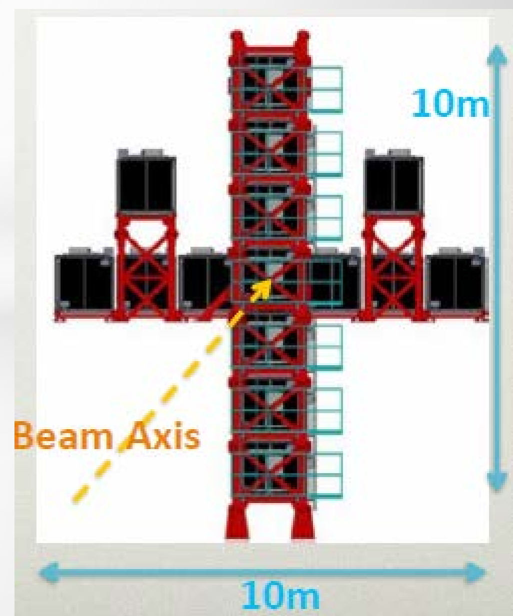
*Il fascio di neutrini di T2K



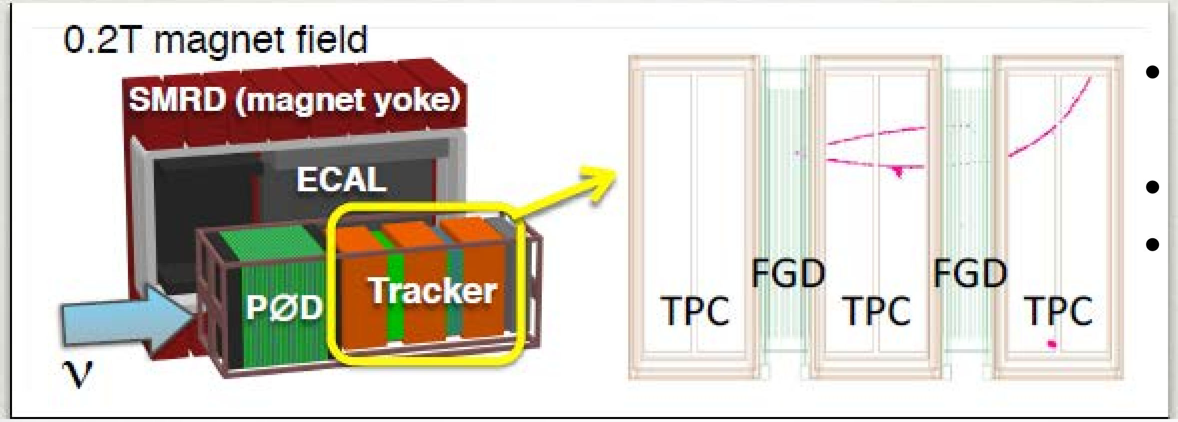


* T2K usa un fascio “off axis” di 2.5 gradi al fine di ottenere neutrini piccati a 600 MeV di energia (massimo di oscillazione)
* “On axis INGRID permette di monitorare il fascio di neutrini con alta precisione (1%)





Off-Axis neutrino detector measures ν flux/spectrum before oscillation



- FGDS (Fine-grained detector)
- TPCs (readout MM)
- PiD by dE/dx

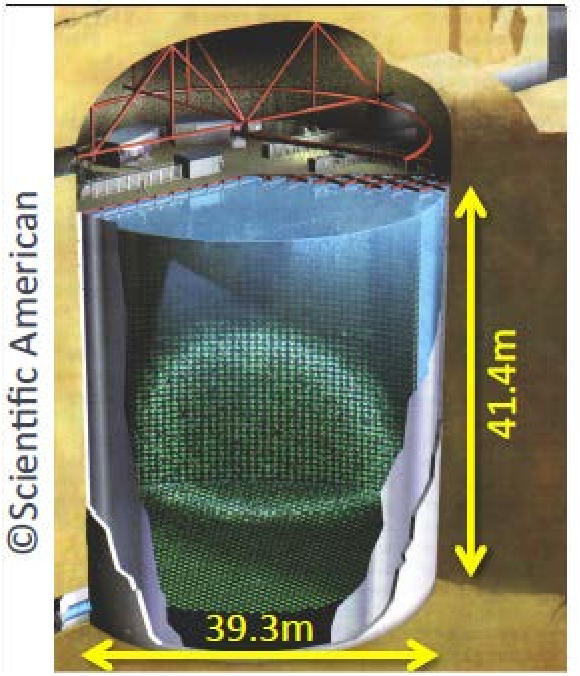
T2K systematic uncertainty

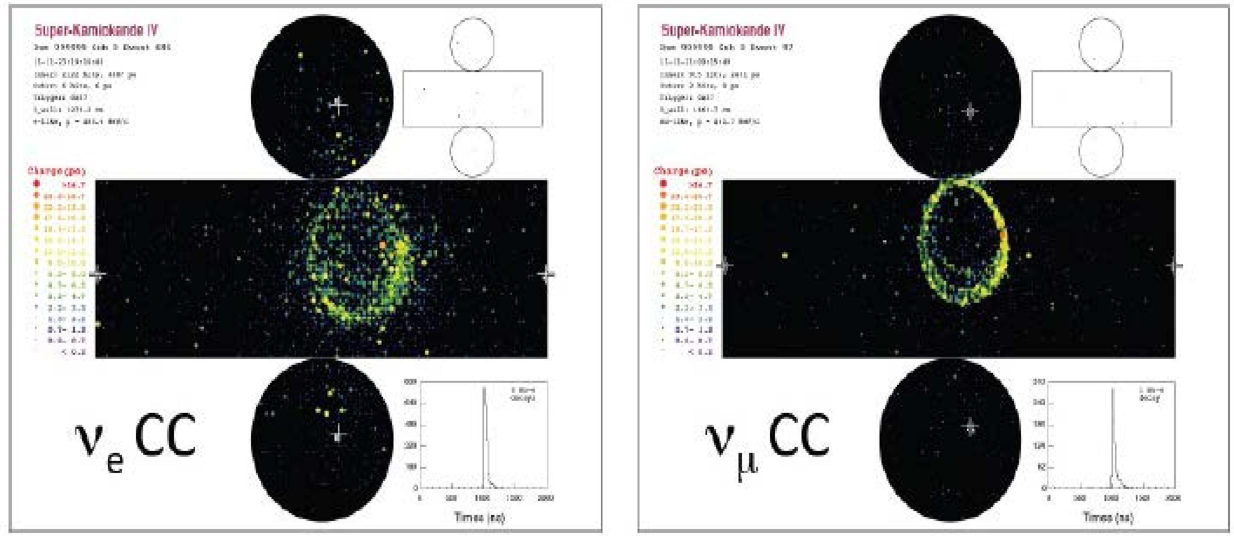
Fractional error on number-of-event prediction

2014 → 2015

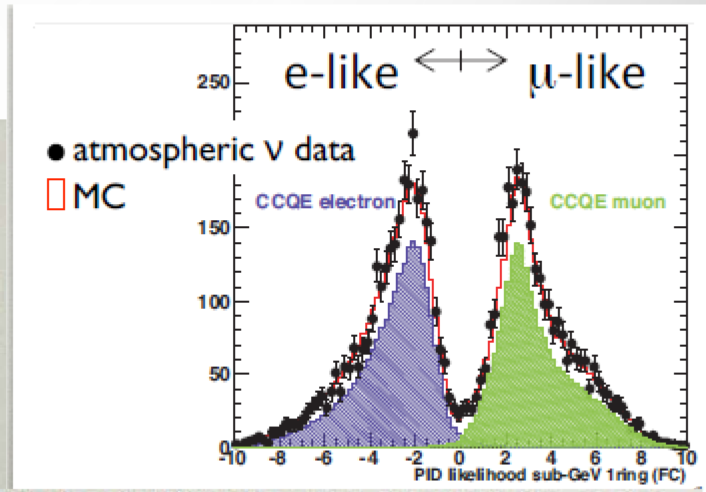
		ν_μ sample	ν_e sample	$\overline{\nu}_\mu$ sample	$\overline{\nu}_e$ sample
ν flux		16%	11%	7.1%	8%
ν flux and cross section	w/o ND measurement	21.8%	26.0%	9.2%	9.4%
	w/ ND measurement	2.7%	3.1%	3.4%	3.0%
ν cross section due to difference of nuclear target btw. near and far		5.0%	4.7%	10%	9.8%
Final or Secondary Hadronic Interaction		3.0%	2.4%	2.1%	2.2%
Super-K detector		4.0%	2.7%	3.8%	3.0%
total	w/o ND measurement	23.5%	26.8%	14.4%	13.5%
	w/ ND measurement	7.7%	6.8%	11.6%	11.0%

*T2K Far Detector : SK





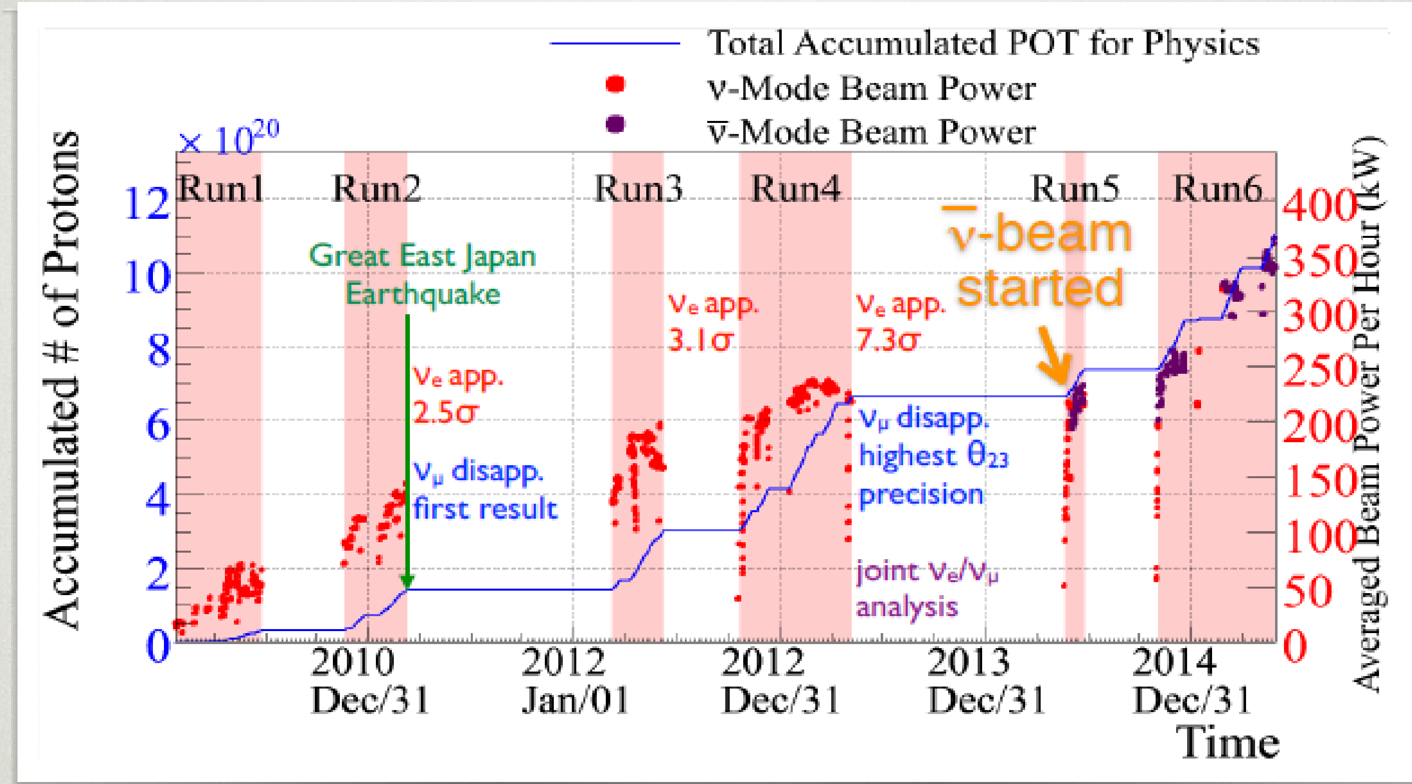
- 50 kton water Cherenkov detector
  - 22.5 kton fiducial volume
  - Charged particles produce "Cherenkov ring" on the detector wall
  - Inner detector: 11,129 50cm PMTs
  - Outer detector (veto): 1,885 20cm PMTs
  - Excellent particle identification (efficient separate of μ and e)
- 1,419 days of atmospheric neutrino data control samples



Probability that a muon is mis-identified as an electron is less than 1%

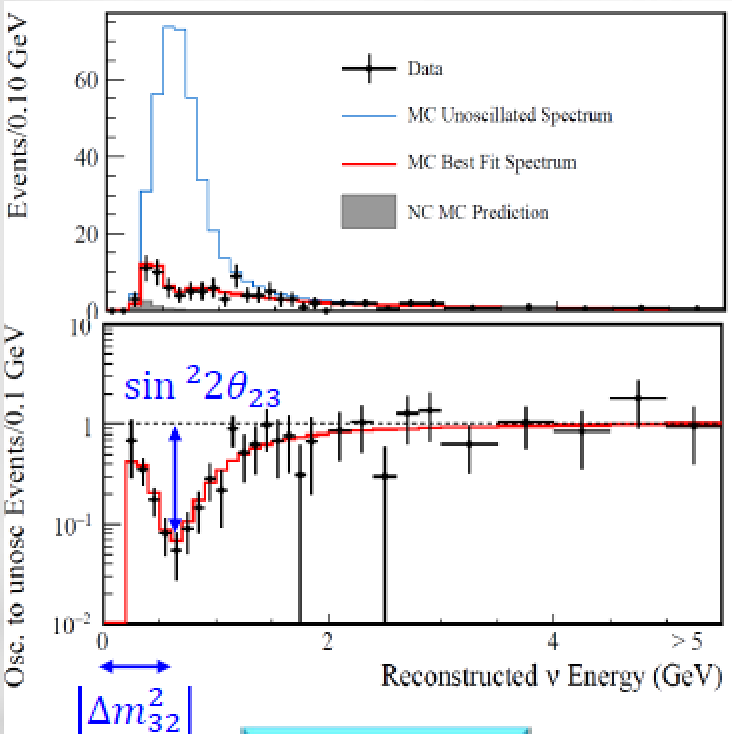
*T2K data taking

14% della
Statistica finale



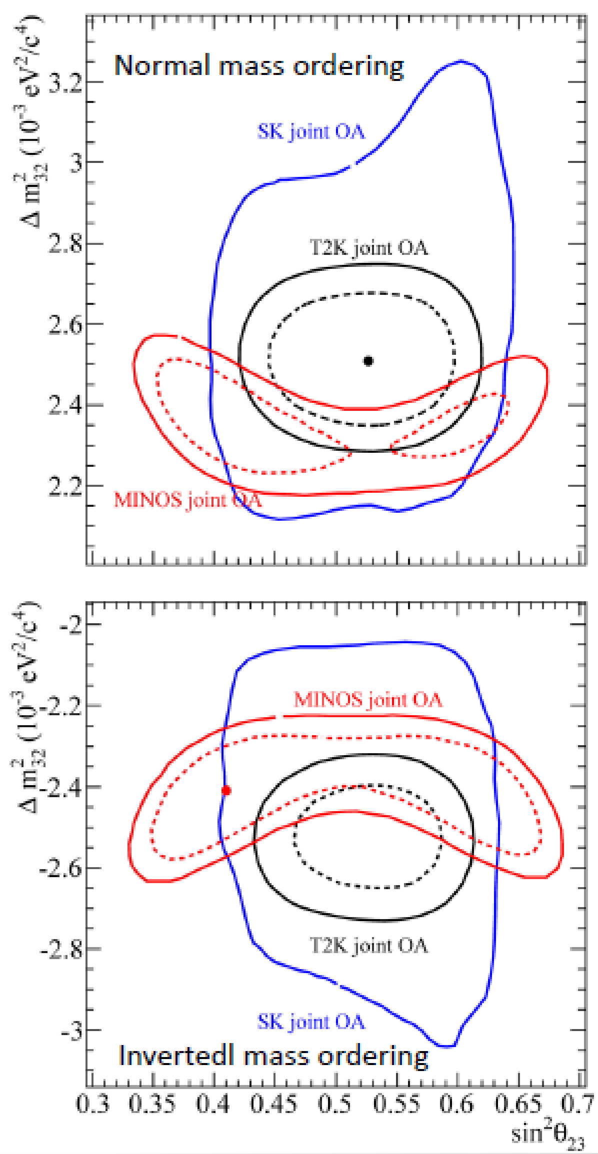
- Total protons on target (POT) so far: 11.04×10^{20}
- Beam power increasing (thanks to J-PARC acc. team!)
  ➜ Maximum beam power achieved 371kW
- **Antineutrino analysis results today: 4.01×10^{20} POT**
  - Full antineutrino-beam mode data (up to June, 2015)

*θ23



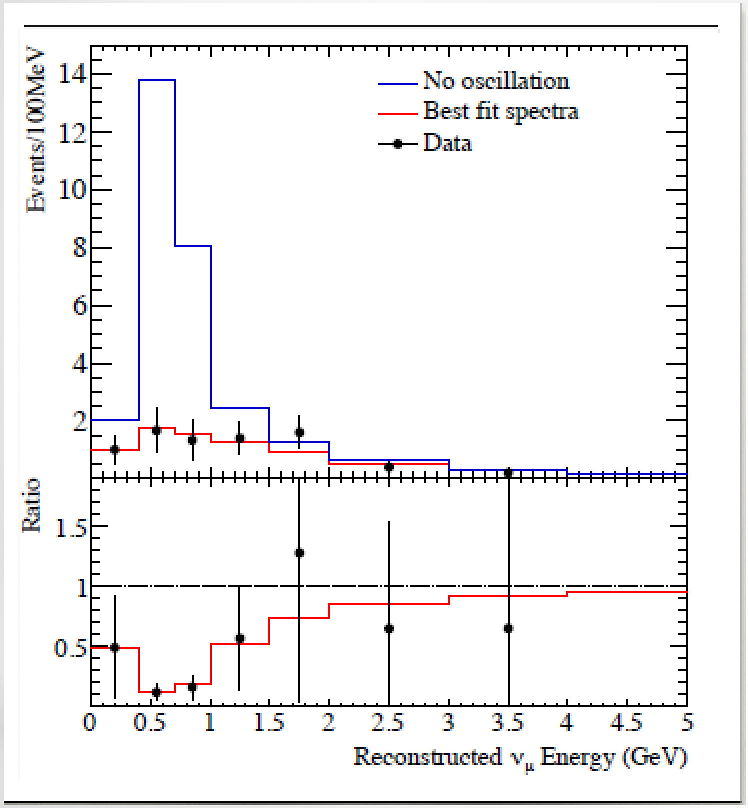
46° ± 3°

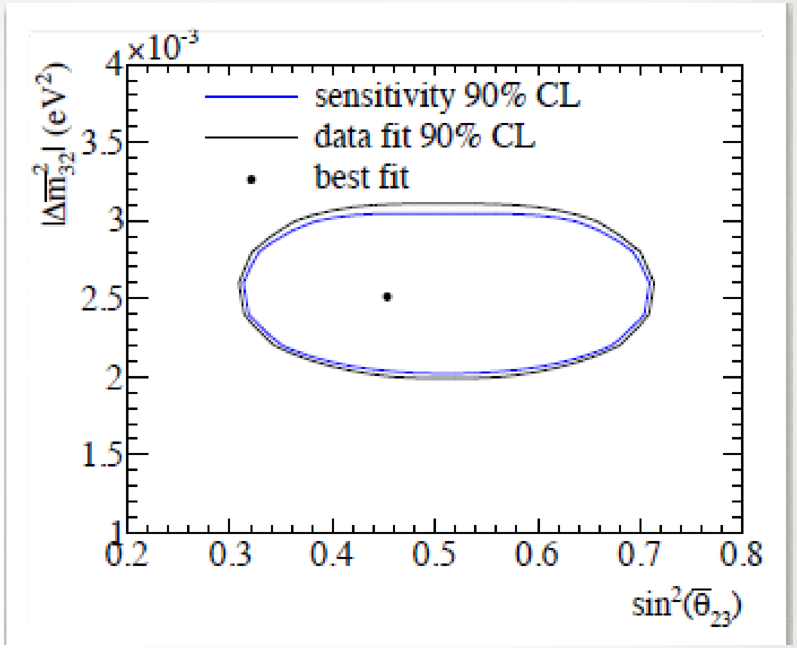
T2K



Phys. Rev. D 91, 072010 (2015)

* θ_{23} anti-ν_μ





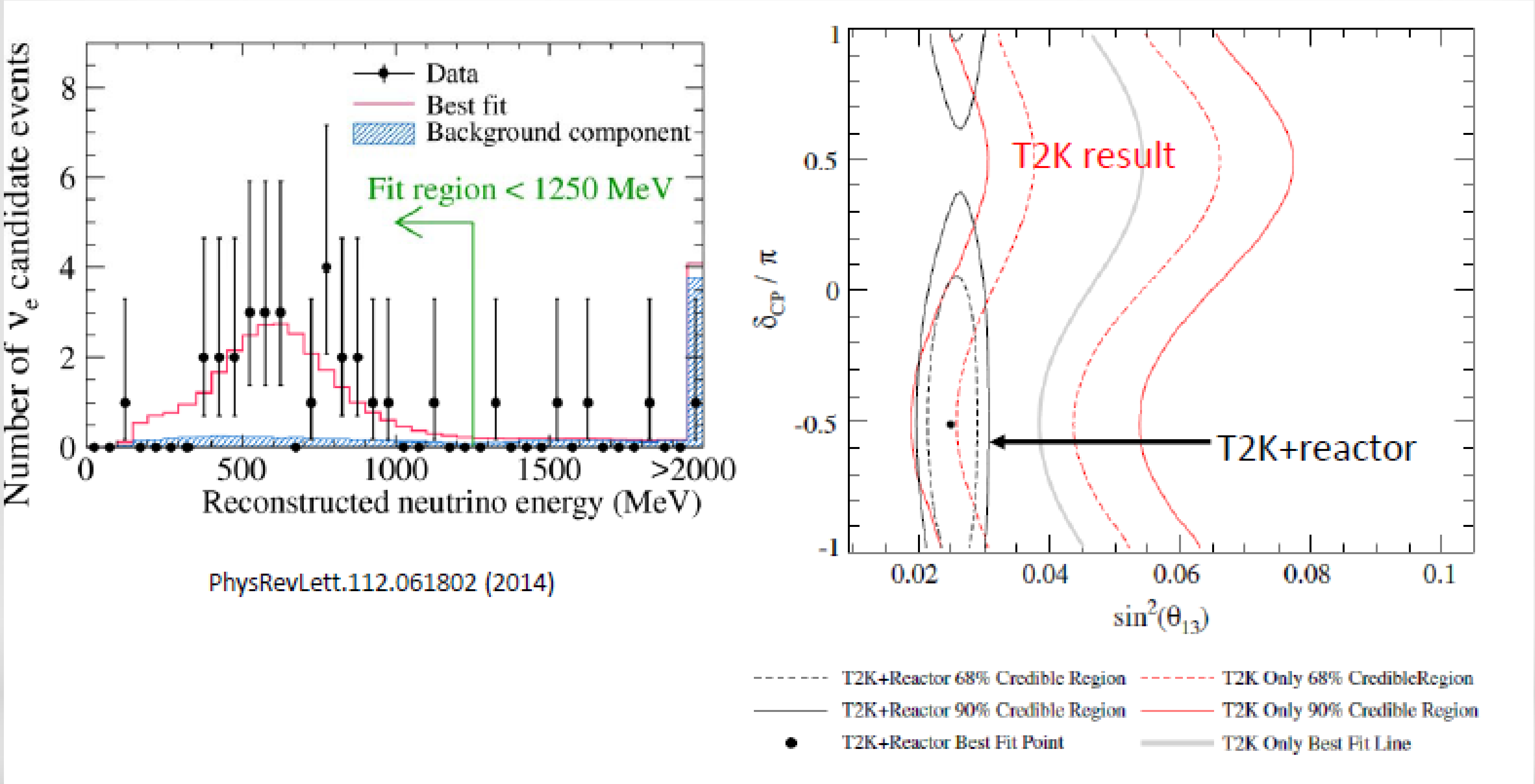
34 events observed

Expectation:

34.6 w/ oscillation

103.6 w/o oscillation

* ν_e appearance by T2K

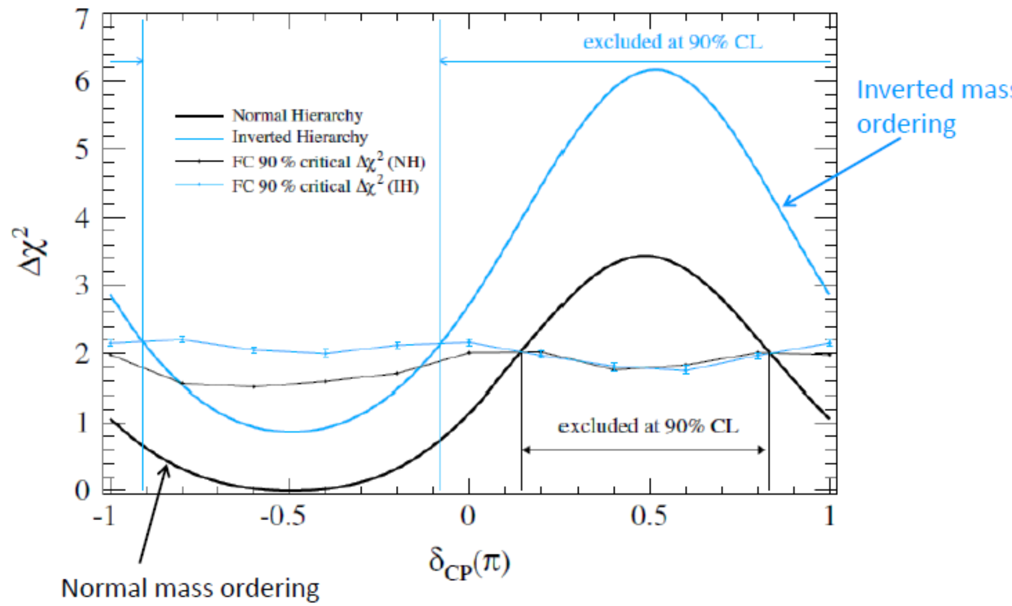


28 events observed over 4.92±0.55 bkgs → 7.3σ excess

First Confirmation of 'Appearance phenomenon' w/ > 5σ significance.

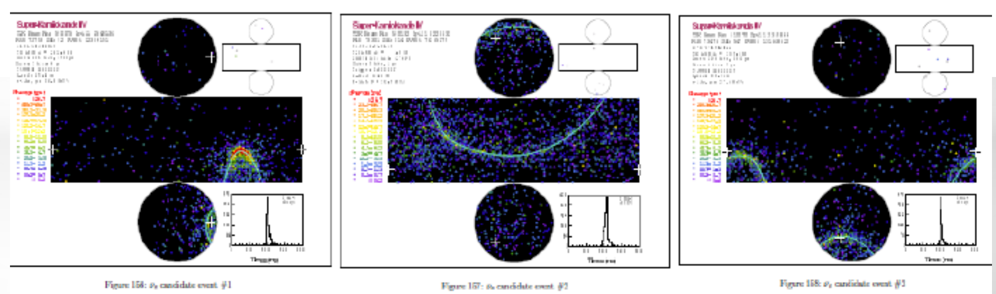
* ν_e (anti- ν_e) appearance by T2K

First constraint on δ_{CP} by T2K



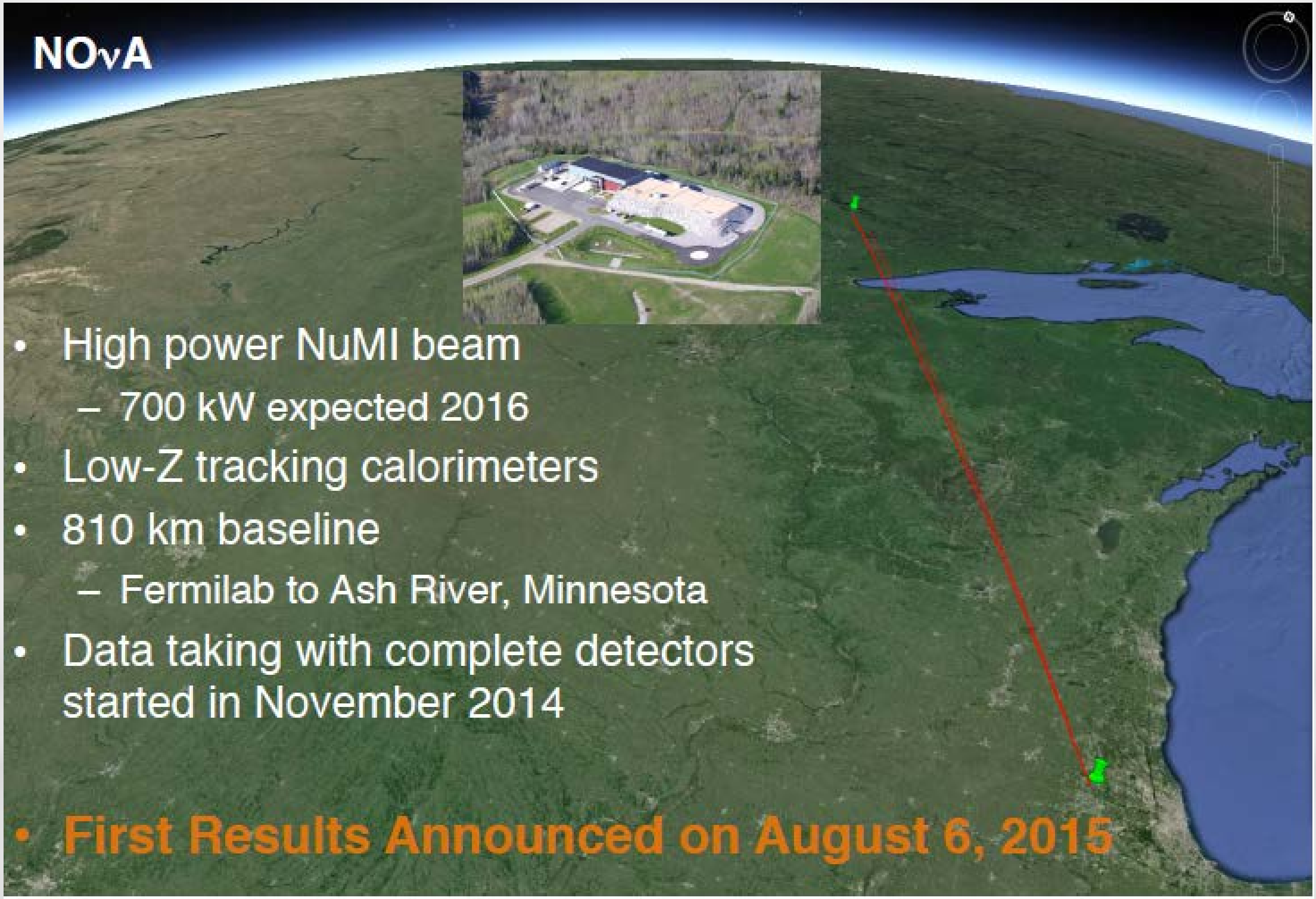
- Best value of δ_{cp}~$\pi/2$
- Values of ~ 0.2< δ_{cp}<0.8 excluded at more than 90%CL
- Week preference for NH and second octant

(%)	NH	IH	Sum
$\sin^2\theta_{23} \leq 0.5$	18	8	26%
$\sin^2\theta_{23} > 0.5$	50	24	74%
Sum	68%	32%	



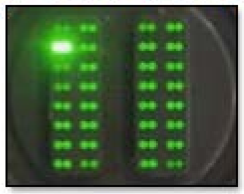
New! In $\bar{\nu}_\mu$ mode aspettati 3,7 eventi rivelati 3

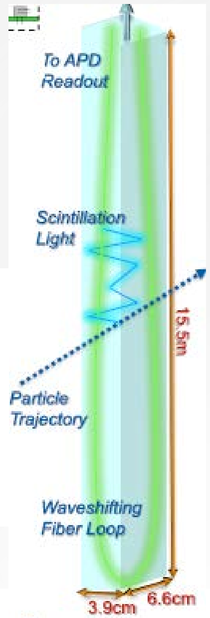
* Nova


NOvA
• High power NuMI beam
– 700 kW expected 2016
• Low-Z tracking calorimeters
• 810 km baseline
– Fermilab to Ash River, Minnesota
• Data taking with complete detectors started in November 2014
• First Results Announced on August 6, 2015

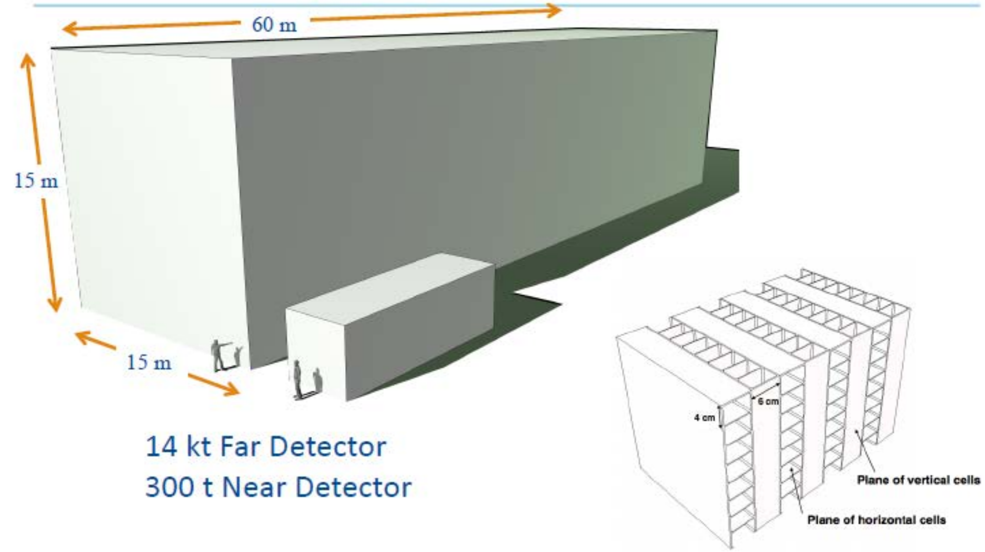
*Nova

32 cells per APD

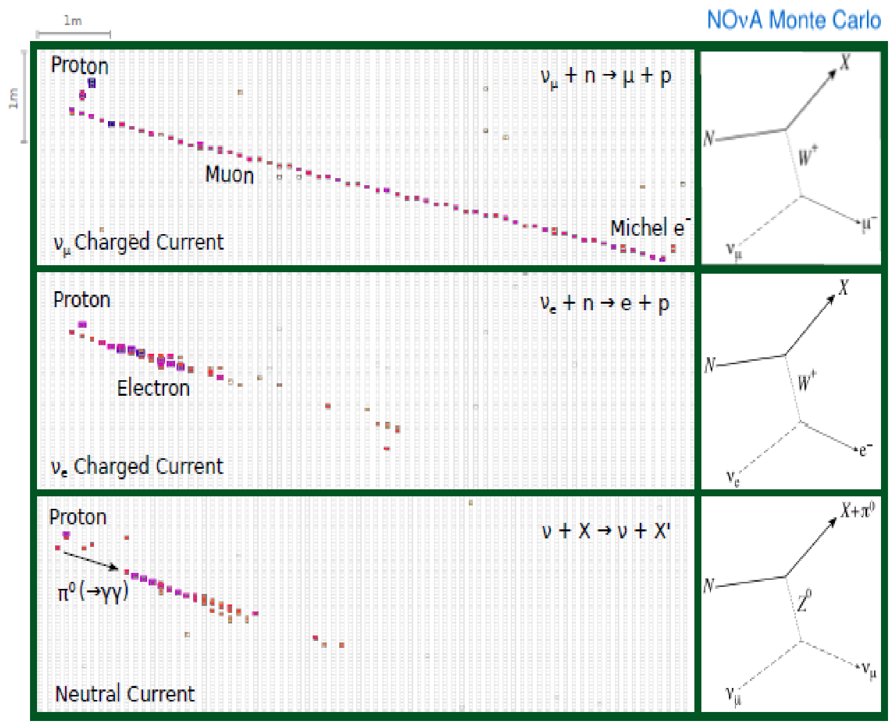




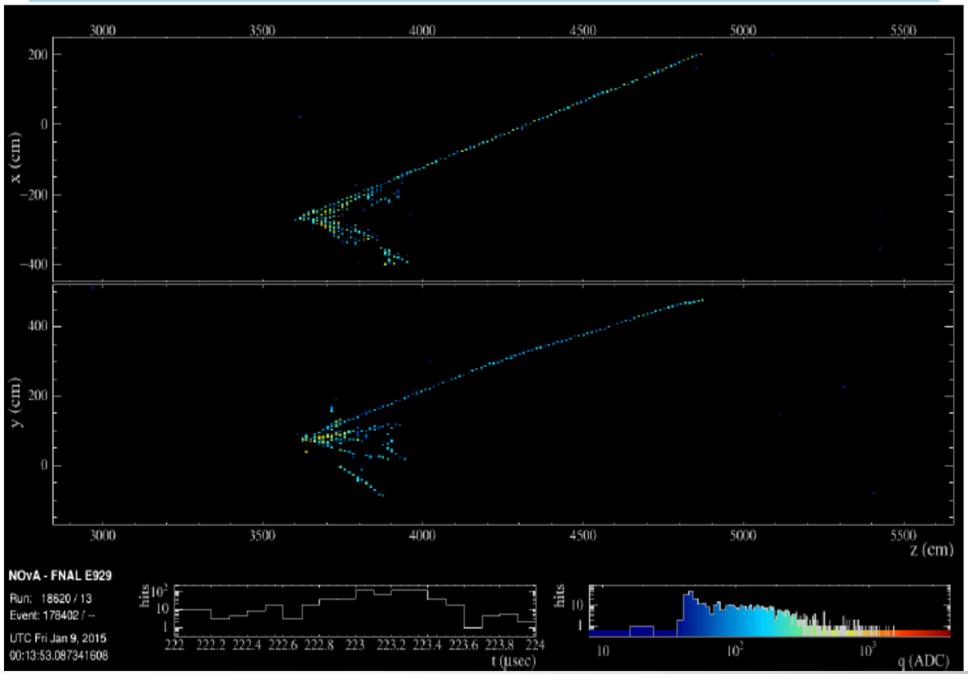
NOνA Detectors



Event Topologies



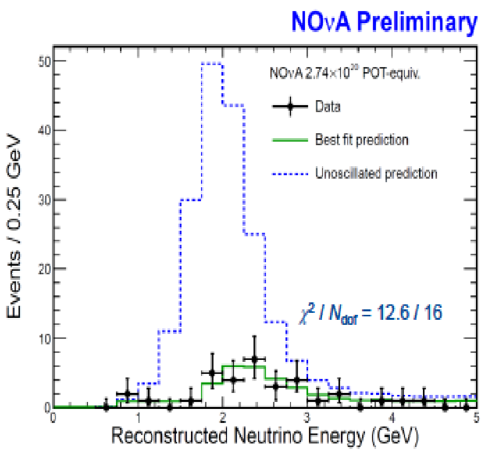
Neutrino Interaction the NOνA Far Detector

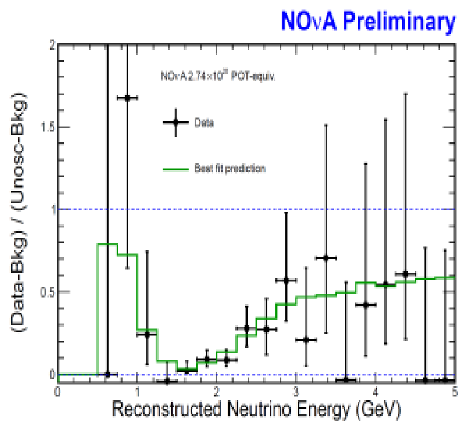


*Nova: Resultati Preliminari

NOνA Far Detector ν_μ Disappearance

- 33 Events selected in 0-5 GeV

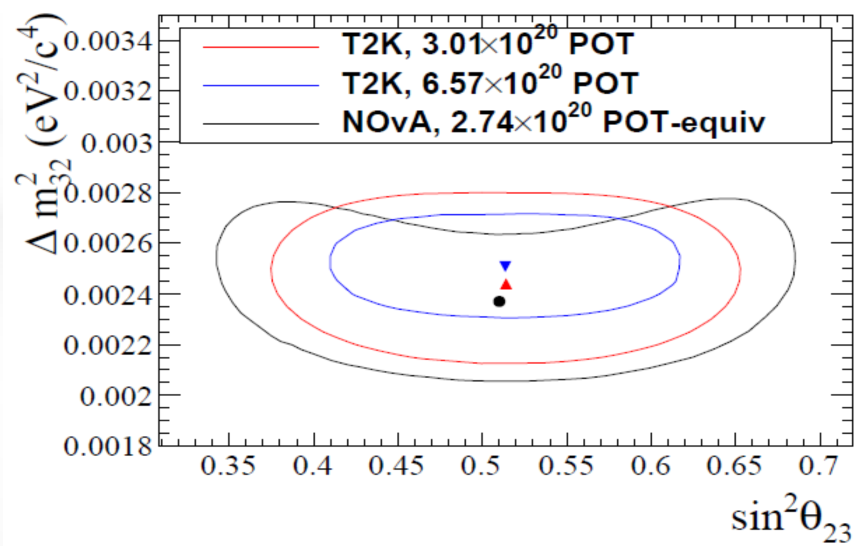




7.6% della statistica finale

$$\Delta m^2_{32} = \begin{cases} +2.37^{+0.18}_{-0.15} \text{ [NO]} \\ -2.40^{+0.14}_{-0.17} \text{ [IO]} \end{cases} \times 10^{-3}\ \text{eV}^2$$

$$\sin^2(\theta_{23}) = 0.51 \pm 0.10$$



*Nova: Resultati Preliminari

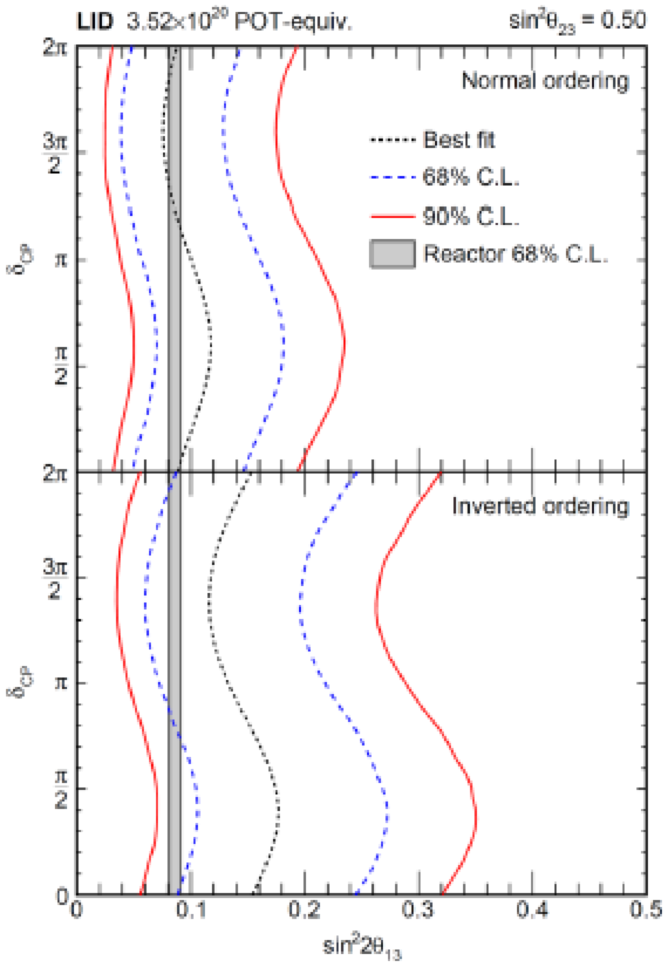
NOνA ν_e Appearance Result

- LID Selector: 6 ν_e Candidates

  3.3 σ significance for ν_e appearance

- δ_{CP}, $\sin^2\theta_{13}$ allowed regions
  - Feldman-Cousins contours
  - $\sin^2\theta_{23}$ fixed at 0.5
  - Marginalized over other parameters
- LEM Selector: 11 ν_e Candidates

  5.5 σ significance for ν_e appearance
  - Includes all 6 LID events
  - P value for this combination: 10%

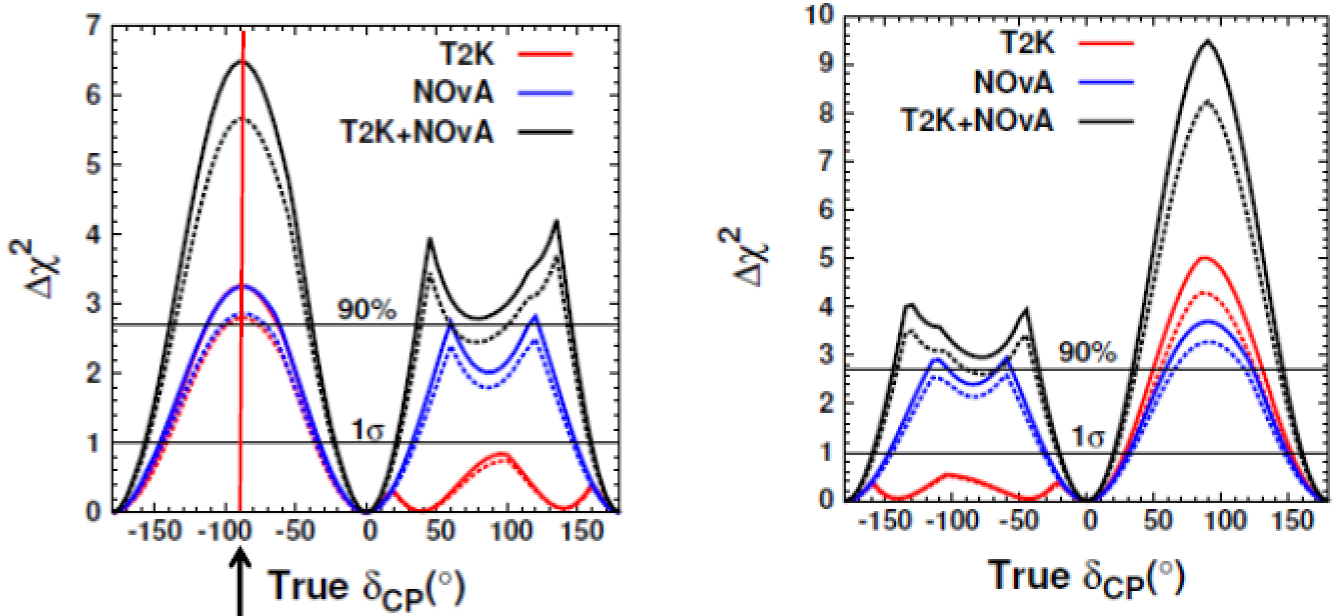


* Combinando T2K e Nova (full statistic) (~ 2018-2020)

- $\sin^2\theta_{23} = 0.5$
- solid : stat. only
- dash: 5% sys. error

NH case

IH case



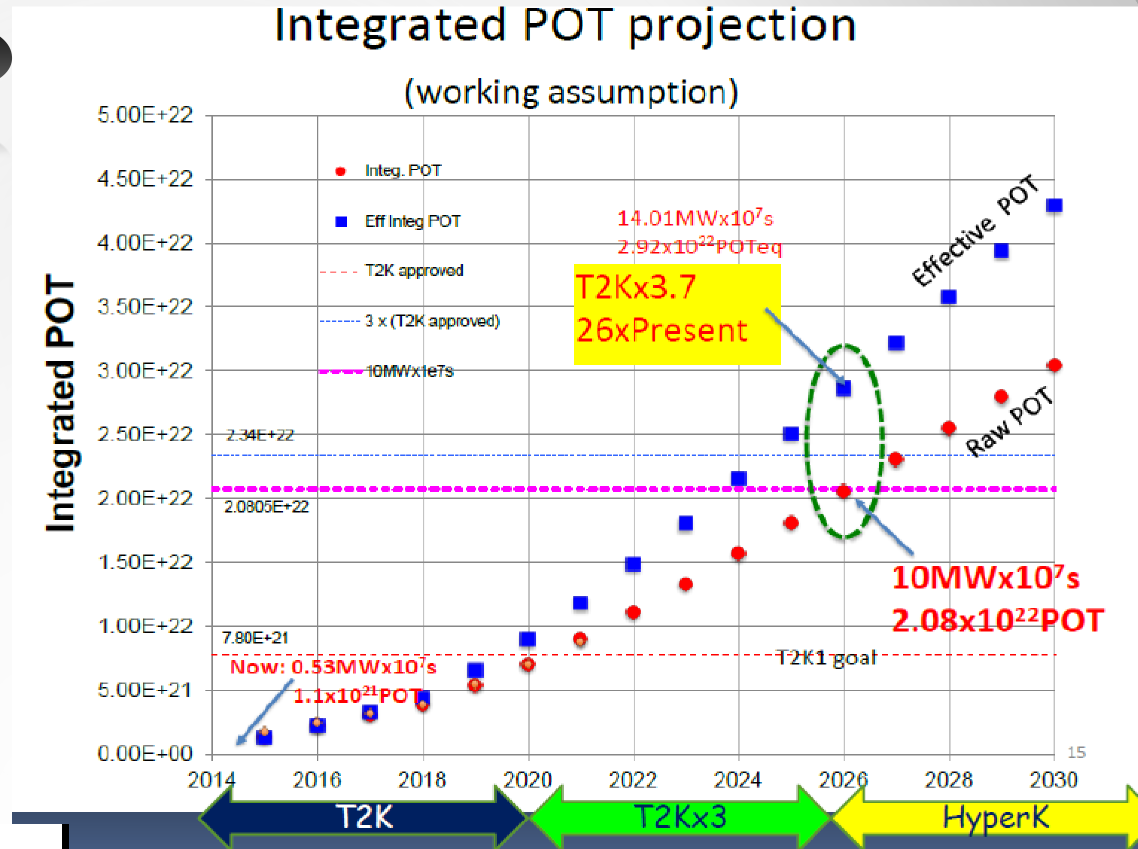
Current most probably situation. (NH, $\delta_{CP} = -90°$)

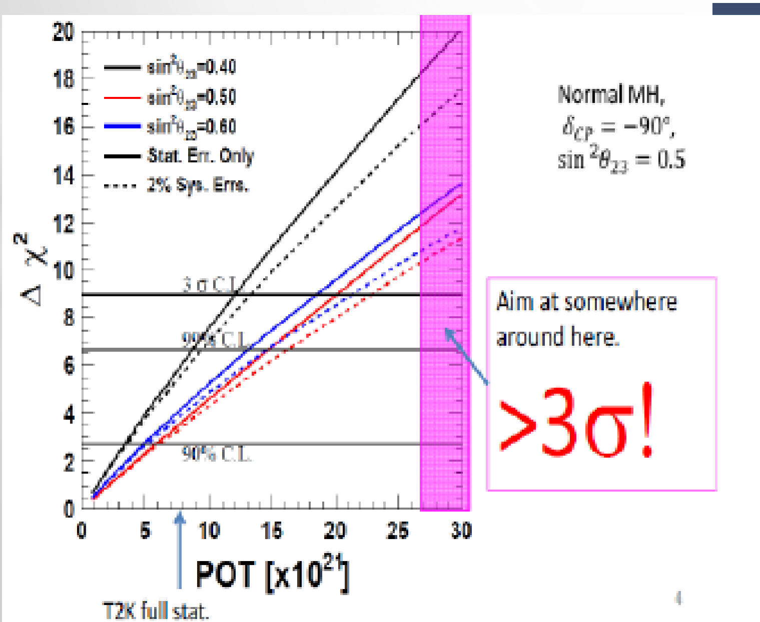
- Both competition and cooperation with NOvA are really important.
- combination w/ SuperK etc. would also enhance the sensitivity

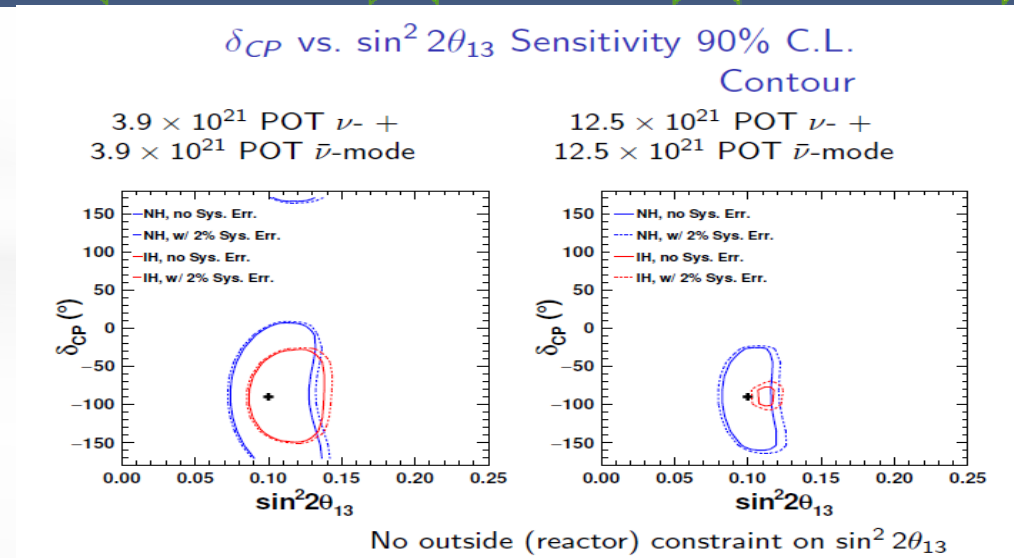
*What next ? (2020-2025)

T2K(x3)

CP violation in current favourable case from 90%CL to 3σ level (30% of δcp) (T2K (and NOvA?) extensions have a chance to determine CP and mass hierarchy.)



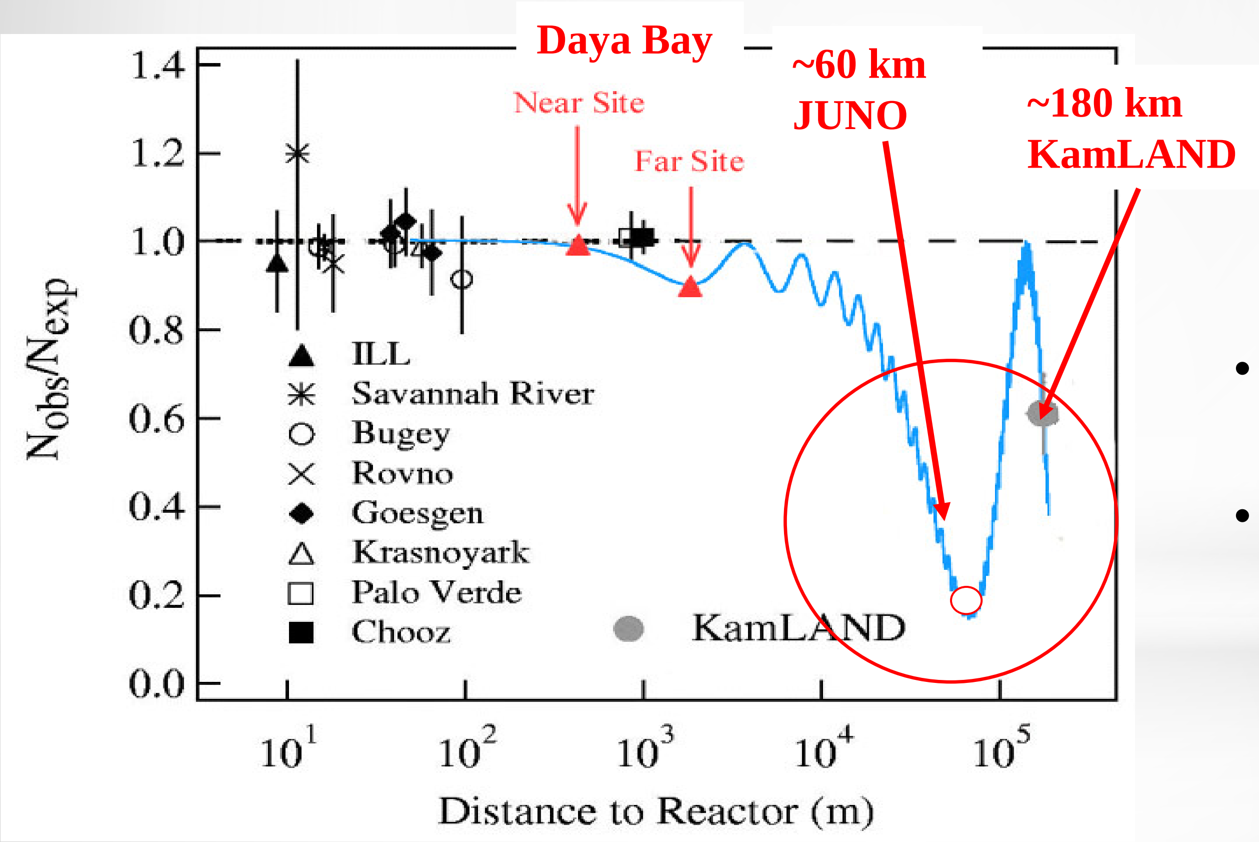




Reactor neutrinos: the JUNO proposal

anti–ν_e disappearance

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}\left(\cos^2 2\theta_{12}\sin^2\frac{\Delta m^2_{13}L}{4E} + \sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{23}L}{4E}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{12}L}{4E}$$



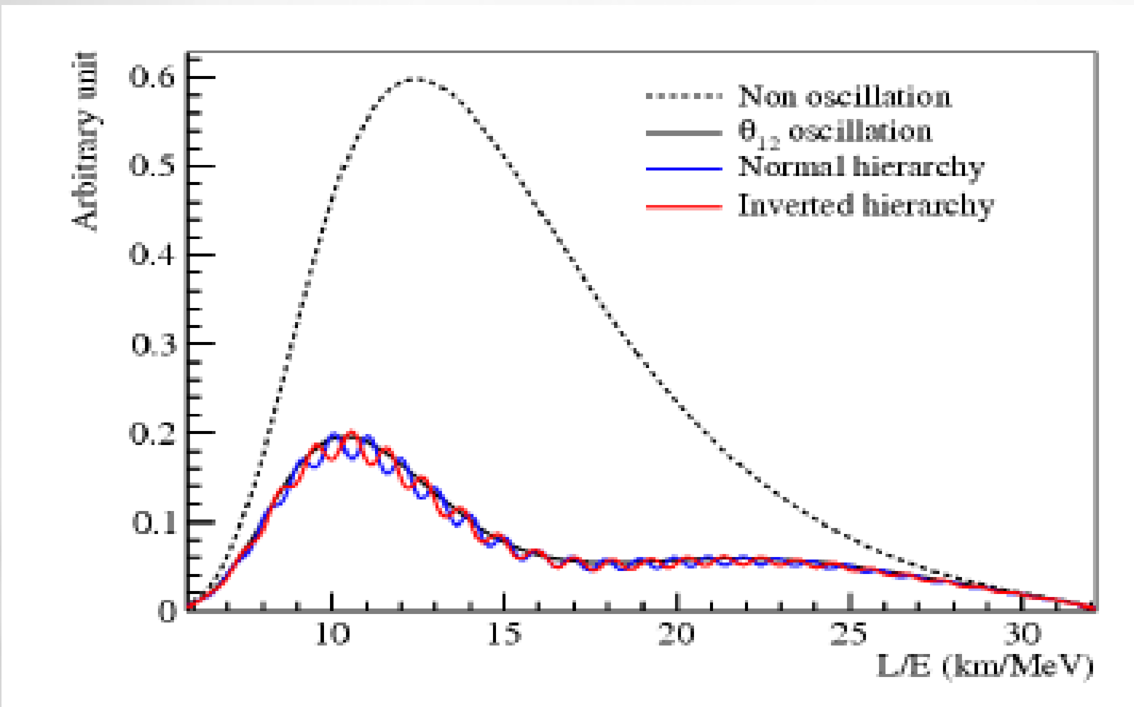
Exploit interference in ν oscillations between atmospheric and solar term;

- It is feasible because θ_{13} is relatively large!
- Unlike accelerator or atmosferic experiments this technique doesn't depend on δ_{CP} and θ_{23} !

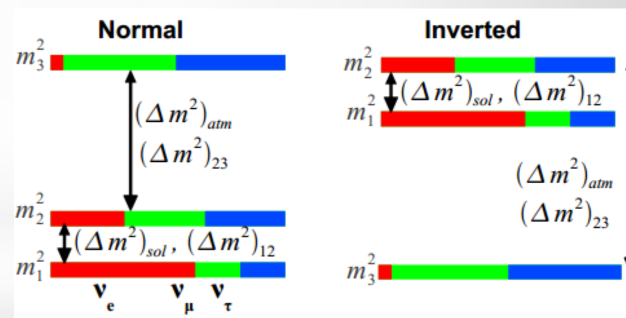
Reactor neutrinos: the JUNO proposal

anti–ν_e disappearance

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13}\left(\cos^2 2\theta_{12}\sin^2\frac{\Delta m_{13}^2 L}{4E} + \sin^2 2\theta_{12}\sin^2\frac{\Delta m_{23}^2 L}{4E}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{\Delta m_{12}^2 L}{4E}$$



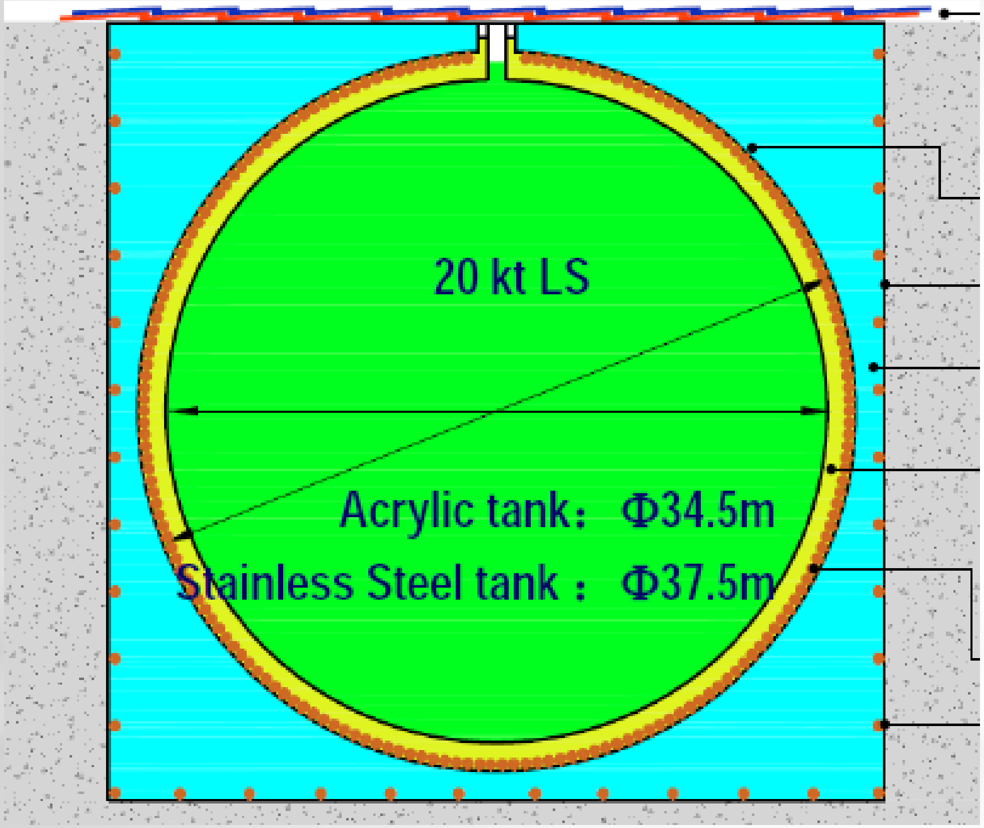
Exploit interference in ν oscillations between atmospheric and solar term;



$$\Delta m_{31}^2 = \Delta m_{32}^2 + \Delta m_{21}^2$$
$$\text{NH}: \; |\Delta m_{31}^2| = |\Delta m_{32}^2| + |\Delta m_{21}^2|$$
$$\text{IH}: \; |\Delta m_{31}^2| = |\Delta m_{32}^2| - |\Delta m_{21}^2|$$

Requires exceptional energy resolution

* Reactor neutrinos: the JUNO proposal



Civil construction: 2015-2018;

Detector Installation:2017-2020;

Filling and data-taking:> 2020;

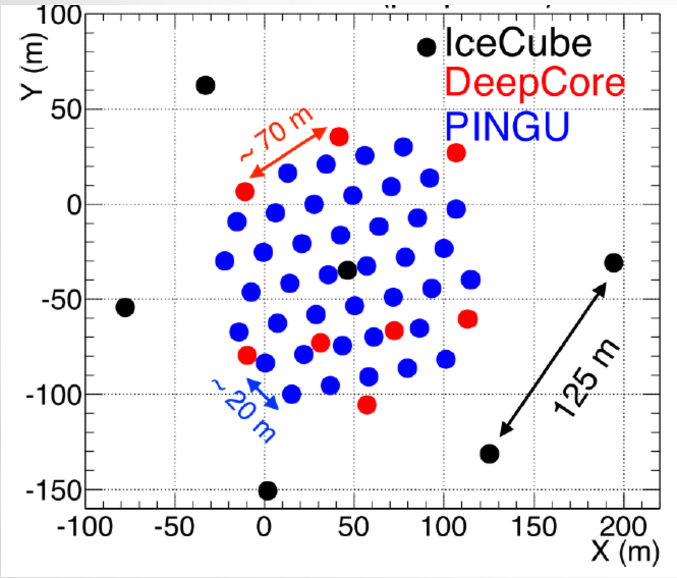
	KamLAND	Borexino	JUNO
LS Mass	1 ktons	0.5 kton	20 kton
Energy resolution	$6\%/\sqrt{E}$	$5\%/\sqrt{E}$	$3\%/\sqrt{E}$
Light Yield	250 p.e./MeV	511 p.e./MeV	1200 p.e./MeV

Similar concept and design for the RENO-50 proposal in Korea

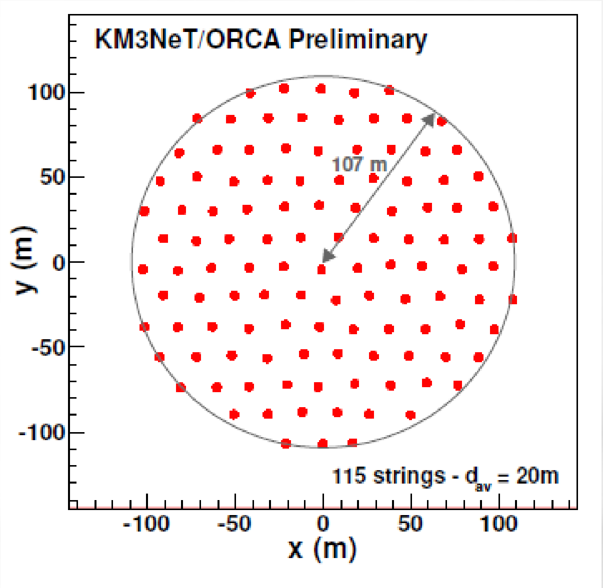
Atmosferic neutrinos and neutrino mass hierarchy

- In the framework of IceCube and Km3NET;
- Instrument ~ Mtons of ice (PINGU) or sea-water (ORCA)
- Fine granularity to have low threshold;

PINGU



ORCA

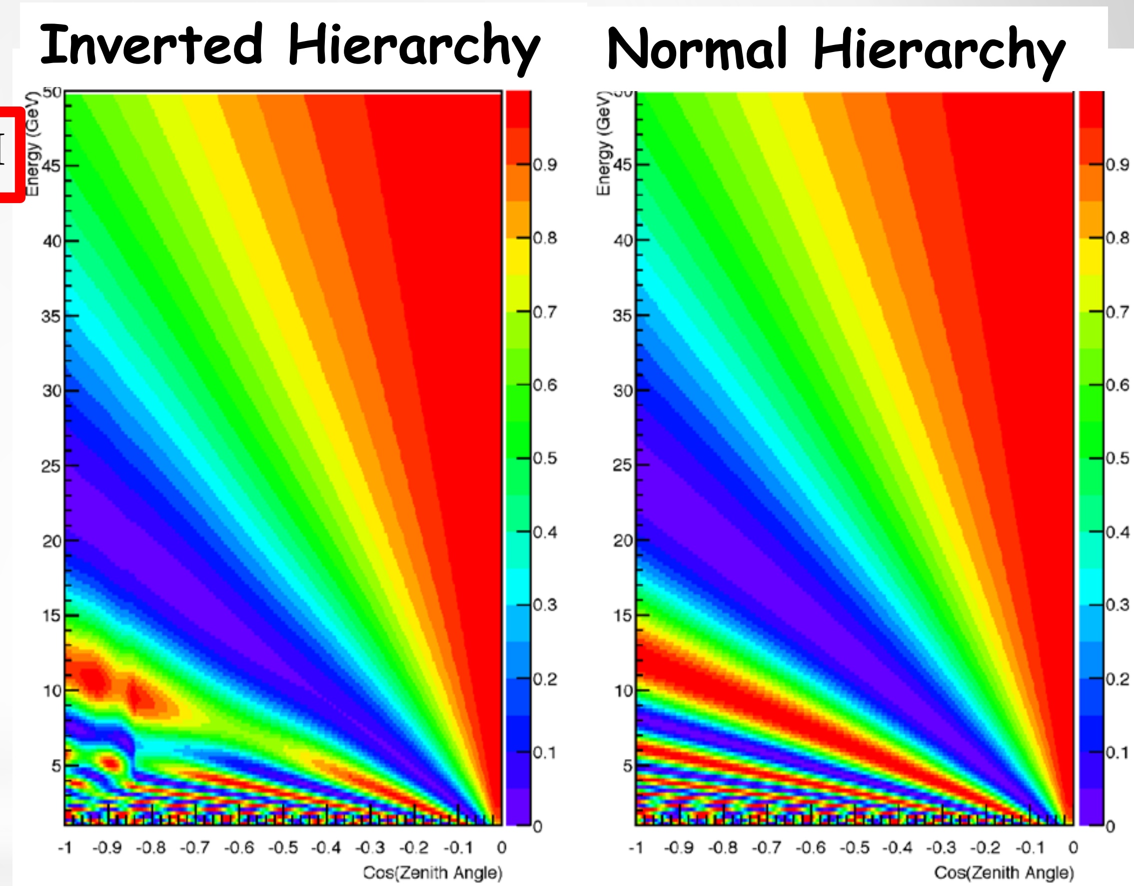


Pingu/Orca

$$P(\nu_\mu \rightarrow \nu_\mu) \text{ in NH} \cong P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) \text{ in IH}$$

- Se non e' possible distinguere fra ν and anti-ν → l'effetto dovuto alla gerarchia delle masse svanisce;
- Ma fortunatamente

$$\sigma(\nu_\mu) \neq \sigma(\bar{\nu}_\mu) \text{ and } \phi(\nu_\mu) \neq \phi(\bar{\nu}_\mu)$$

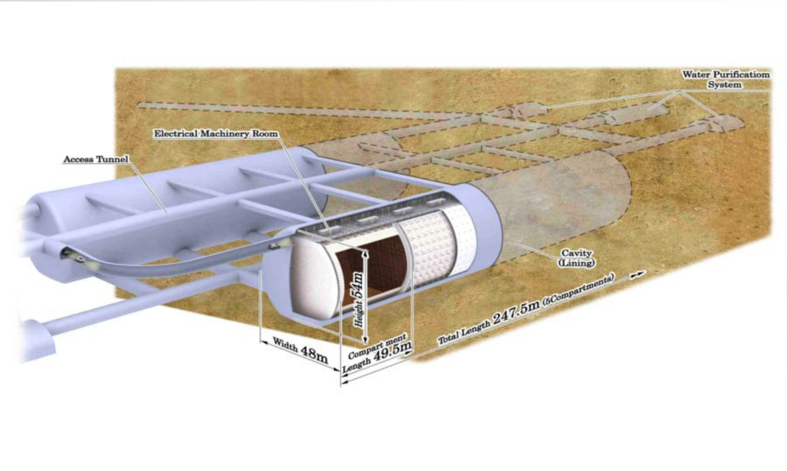


Letter of Intent PINGU- arXiV:1401.2046

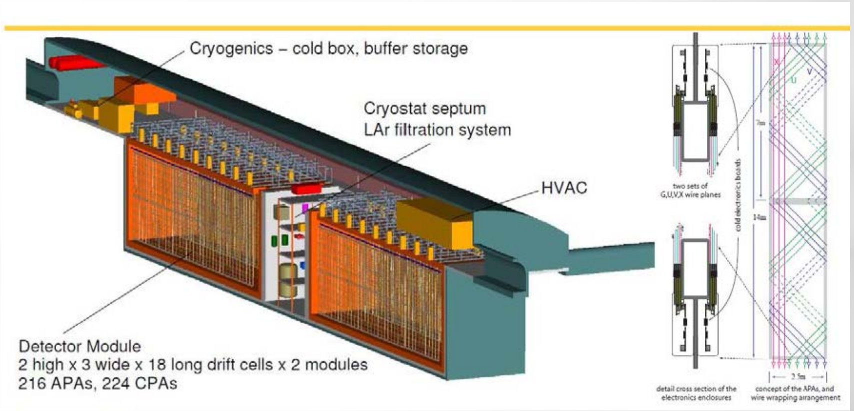
→ E' possible vedere un effetto di qualche %

* next-next: HyperK/Dune

Experiment	Status	E_ν (GeV)	L (Km)	E/L (eV^2)	ν beam	ν type
DUNE	Future (end of 2020s)	5	1300	3.8×10^{-3}	Fermilab newbeam	ν_μ /anti-ν_μ
HYPERK	Future (2025-26)	0.6	295	2×10^{-3}	KEK J-PARC (improved)	ν_μ /anti-ν_μ



HyperK: 560KT WC



Dune: 40KT Liquid Argon

HyperK ha un vantaggio nella ricerca di CP che gli viene dalla grande massa

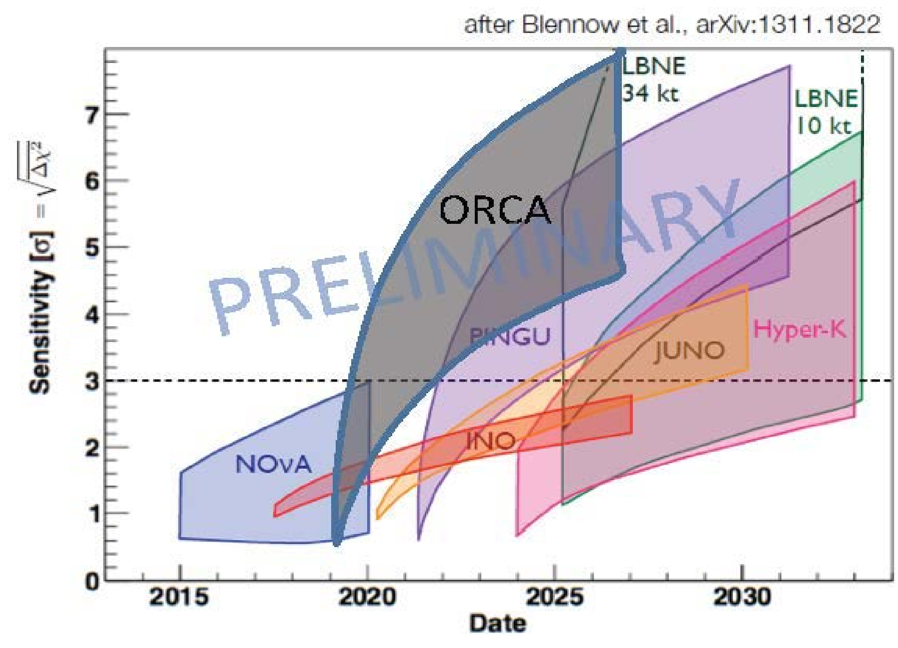
HYPERK , δ_{CP}=0, and NH

	Signal ($\nu_\mu \to \nu_e$ CC)	Wrong sign appearance	$\nu_\mu/\bar{\nu}_\mu$ CC	beam $\nu_e/\bar{\nu}_e$ contamination	NC
ν	3,016	28	11	523	172
$\bar{\nu}$	2,110	396	9	618	265

ELBNF 40KT

Run Mode	Signal Events δ_{CP}			Background Events			
	$-\pi/2$	0	$\pi/2$	ν_μ NC	ν_μ CC	ν_e Beam	ν_τ CC
Neutrino	1068	864	649	72	83	182	55
Antineutrino	166	213	231	41	42	107	33

Dune ha una notevole sensibilita' alla gerarchia delle masse che gli viene dalla "baseline" maggiore



Ambedue dovranno contenere gli errori sistematici < 3%

Conclusioni

- Negli ultimi 15 anni il campo della ricerca delle oscillazioni di neutrino si e' rivelato di grande soddisfazione in considerazione del gran numero di risultati di prima grandezza ottenuti
- La matrice PMNS che fino al 1998 era considerata poco piu' di una speculazione teorica e' ora una solida realta' corroborata da numerosi dati sperimentali
- Una nuova generazione di esperimenti e' pronta a svelare gli ultimi parametri ignoti ($\delta_{cp,}$ MH)
- In particolare δ_{cp} diverso da zero potrebbe spiegare la differenza fra materia e antimateria nell'universo
- Nonostante tutti questi risultati fantastici, molte sono le questioni aperte e altre ne verranno: esistono neutrini sterili? Perche' PMSN e CKM sono cosi diverse ? Etc. etc.
- Ci aspettano sicuramente anni eccitanti !