S.BORDONI

ACADEMIC TRAINING LECTURES: EXPERIMENTAL NEUTRINO PHYSICS

Part II

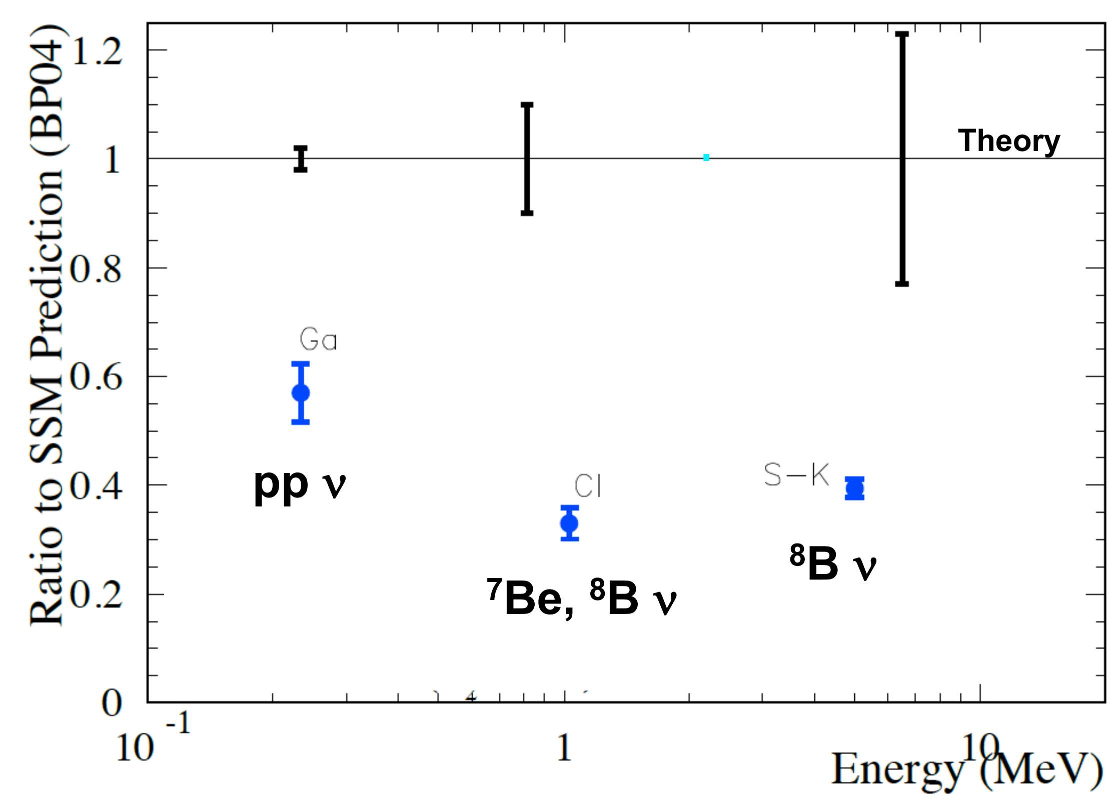
CERN, 16 March 2017

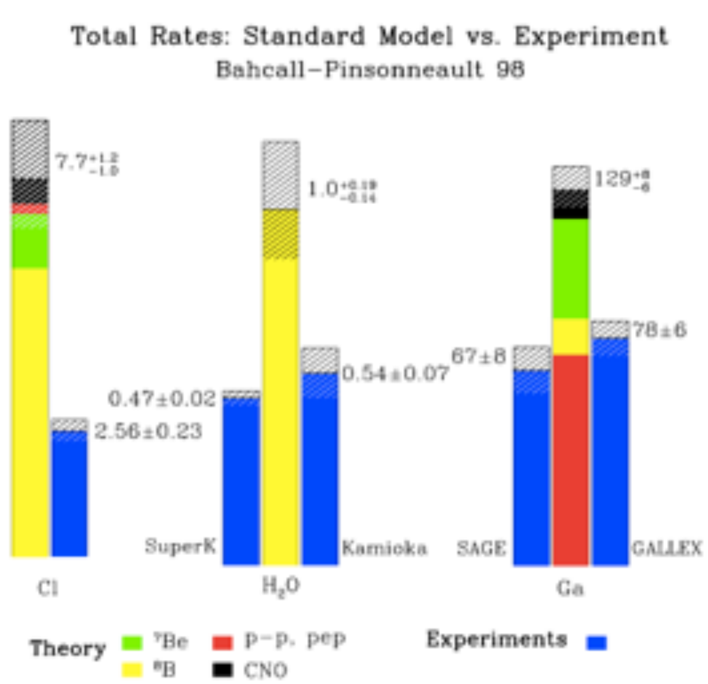
CONTENT OF THE LECTURE

- Neutrino oscillations discovery and parameter determination
- latest results for "standard" neutrino oscillations
- hints of sterile neutrinos

THE SOLAR PROBLEM

- The sun produce a very intense flux of ν_e
- Several **experiments** with different techniques **measured a clear deficit** wrt the theory prediction
  - radiochemical sources
  - Cherenkov
- About 2/3 of ν_e are missing!

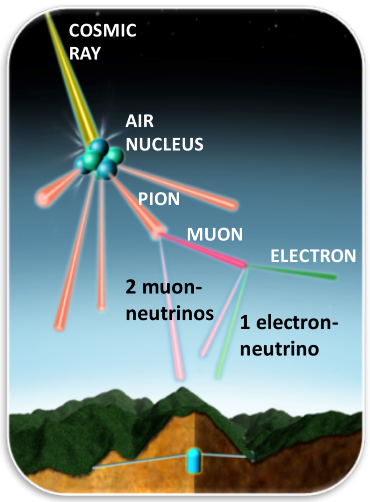




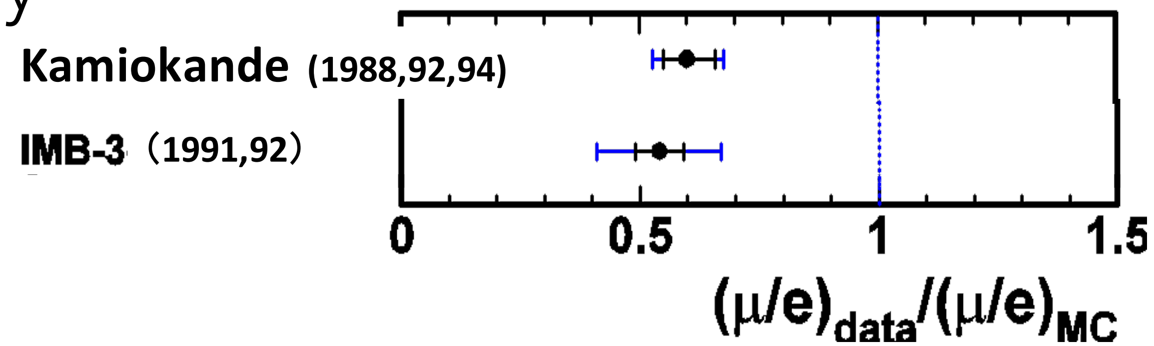
ATMOSPHERIC NEUTRINOS ANOMALY

- Atmospheric neutrinos come from the interaction of primary cosmic rays with the atmosphere
- Neutrino comes from pion and muon decay

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\downarrow$$
$$e^+ + \nu_e + \bar{\nu}_\mu$$



from T. Kajita (Neutrino 2016)



- ratio well known and expected to be 2:1 but observed ~1
- 1/2 of ν_μ are missing!

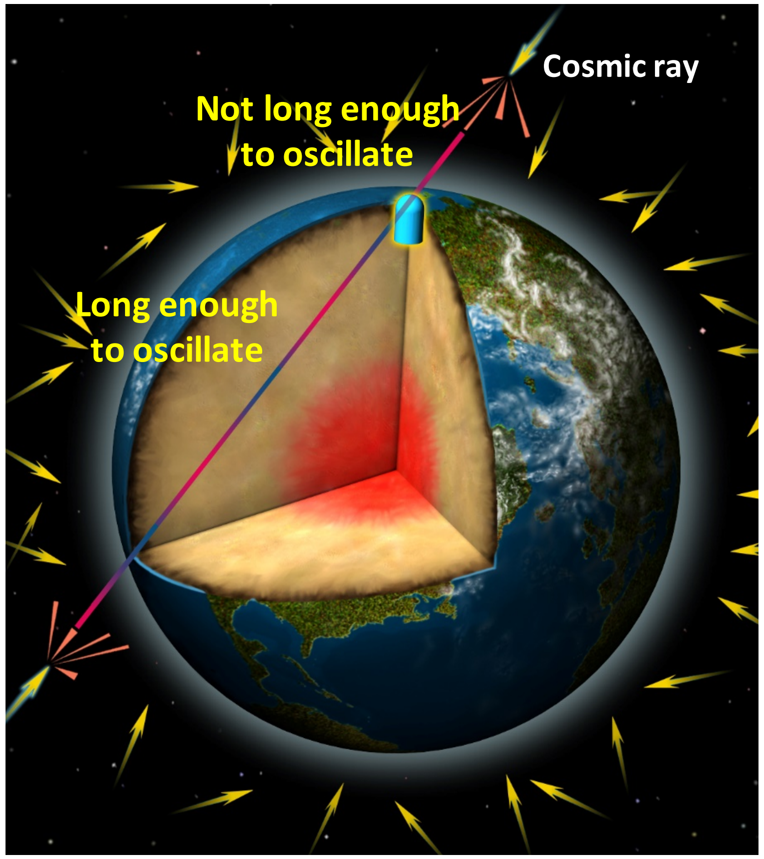
from Kamiokande Paper in 1988

K. Hirata et al, Phys.Lett.B 205 (1988) 416.

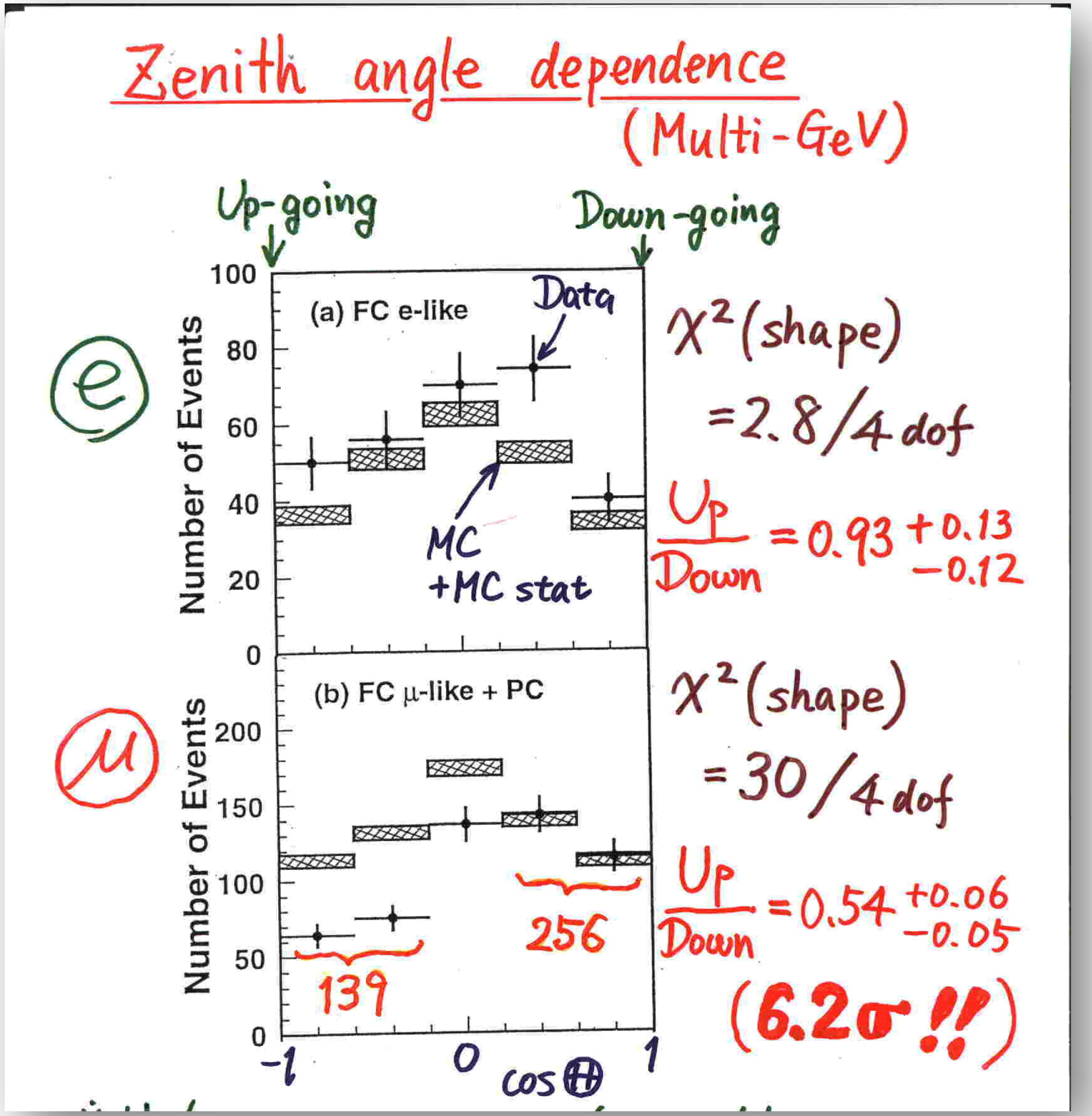
Paper conclusion: "We are unable to explain the data as the result of systematic detector effects or uncertainties in the atmospheric neutrino fluxes. Some as-yet-unaccounted-for physics such as neutrino oscillations might explain the data."

NEUTRINO OSCILLATION: THE DISCOVERY

- **Super-Kamiokande** concluded that the observed angle dependent deficit on **atmospheric neutrinos** gave **evidence of neutrino oscillations**

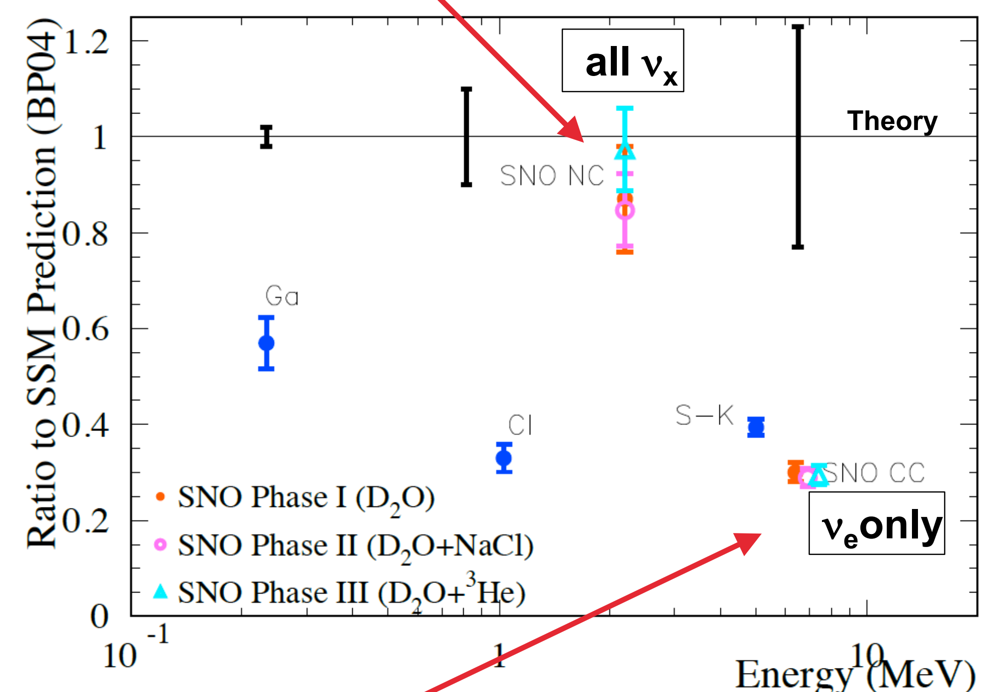


Presented at Neutrino Conference in 1998



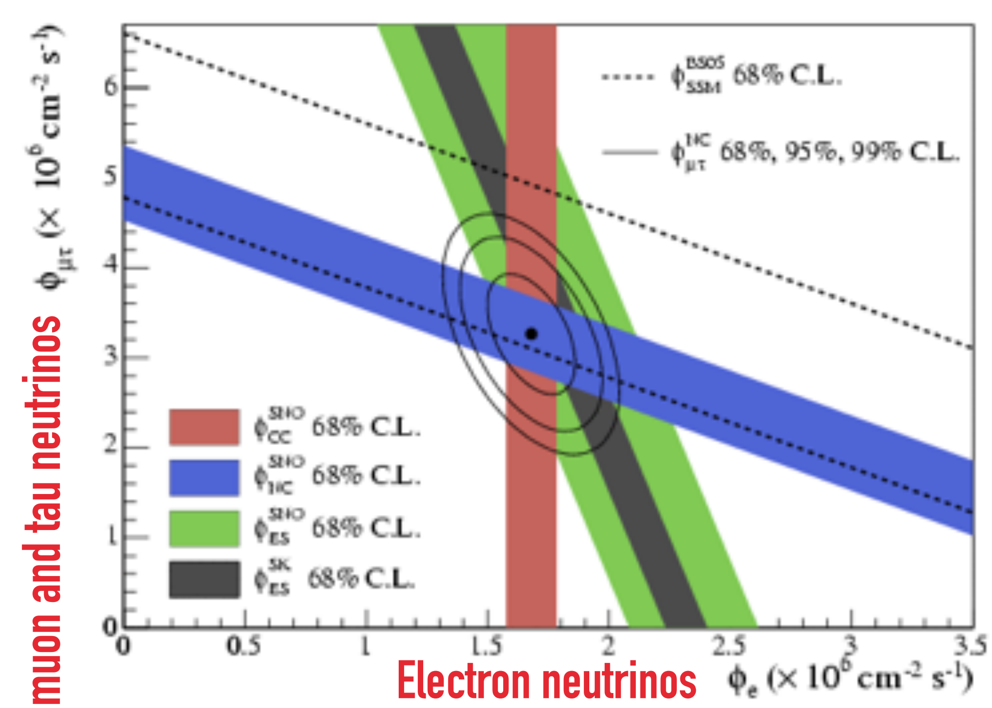
NEUTRINO OSCILLATION: THE DISCOVERY

Neutral currents in agreement with the prediction!



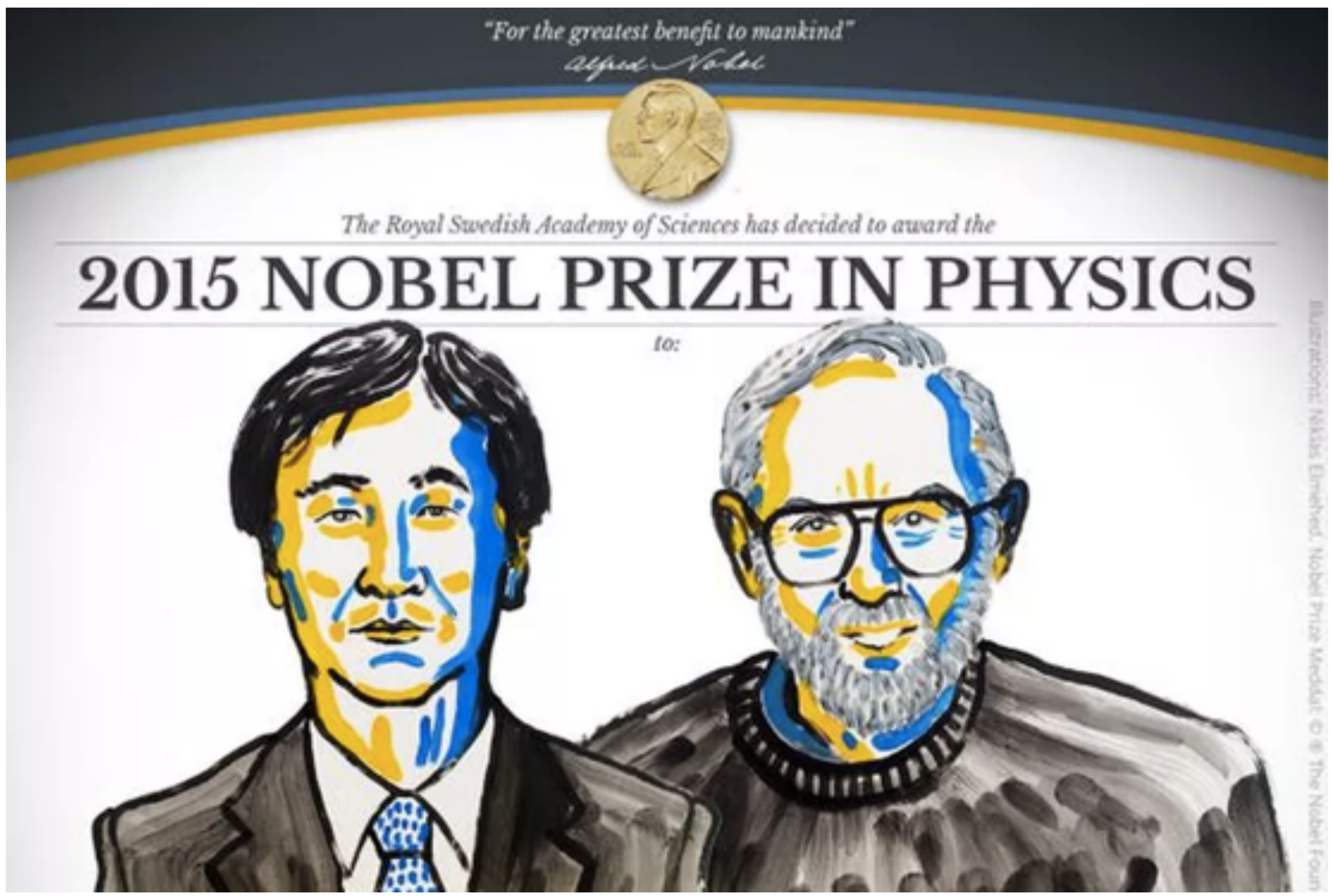
electron neutrinos are only ~1/3 of the total flux!

- Final measurement of Solar neutrinos by the SNO experiment (2000): 1 kton of heavy water seen by ~10k PMTs
- Sensitive to CC, ES and NC
  - CC: only 1/3 of expected flux
  - NC : no deficit observed!
- Solar neutrinos emitted by the sun as ν_e reach the Earth as mixture of ν_e, ν_μ and ν_τ : Oscillations!
- Deficit explanation: solar ν_e energies < 10 MeV: CC for ν_μ and ν_τ are forbidden (E < $M_{\mu/\tau}$)



NOBEL PRIZE

2015 Nobel Prize in Physics to Takaaki Kajita and Arthur B. McDonald for the discovery of neutrino oscillations



3 NEUTRINO OSCILLATIONS

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

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

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

atmospheric, accelerator — accelerator, reactor — solar, reactor

3 Flavour states

3 mixing angles, 2 squared mass difference, 1 complex phase (δ_{CP})

3 Mass states
$m_1 \neq m_2 \neq m_3$

more than15 years of experimental efforts

Parameters		Experiment	signal
$\lvert\Delta m_{21}\rvert^2 = \lvert m^2_2 - m^2_1\rvert$	ϑ_{12}	solar and reactor	$P(\nu_e \to \nu_{\mu,\tau})$
$\lvert\Delta m_{32}\rvert^2 = \lvert m^2_3 - m^2_2\rvert$	ϑ_{23}	atmospheric and accelerator	$P(\nu_\mu \to \nu_\mu)$ & $P(\nu_\mu \to \nu_\tau)$
	ϑ_{13}	reactor and accelerator	$P(\nu_\mu \to \nu_e)$ & $P(\bar{\nu}_e \to \bar{\nu}_e)$
	δ_{CP}	accelerator	$P(\nu_\mu \to \nu_e)$

from NuFit 2016

THE KNOWNS AND THE UNKNOWNS

Solar parameters

$$\theta_{12} = 33.6 \pm 0.8^{o}$$

$$\Delta m^2_{21} = +(7.5 \pm 0.2) \times 10^{-5} \mathrm{eV}^2$$

$P(\nu_e \rightarrow \nu_{\mu,\tau})$ SNO , SK, BOREXINO, GALLEX, SAGE..

$P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ KamLAND

Atmospheric parameters

$$\theta_{23} = (38 - 50)^{o}(3\sigma)$$

$$|\Delta m^2_{32}| \approx (2.5 \pm 0.4) \times 10^{-3} \mathrm{eV}^2$$

$P(\nu_\mu \rightarrow \nu_\mu)$ Kamiokande, SK, IMB, K2K, MINOS, T2K, NOvA

$P(\nu_\mu \rightarrow \nu_\tau)$ (Opera)

$$\theta_{13} = 8.4 \pm 0.2^{o}$$

$P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ Daya-Bay, RENO, Double Chooz

$P(\nu_\mu \rightarrow \nu_e)$ T2K, NOvA

$$\delta_{CP} = [0, 2\pi]$$

T2K, NOvA

THE KNOWNS AND THE UNKNOWNS

from NuFit 2016

Solar parameters

$$\theta_{12} = 33.6 \pm 0.8^{o}$$

$$\Delta m^2_{21} = +(7.5 \pm 0.2) \times 10^{-5} \mathrm{eV}^2$$

$P(\nu_e \rightarrow \nu_{\mu,\tau})$ SNO , SK, BOREXINO, GALLEX, SAGE..

$P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ KamLAND

Atmospheric parameters

$$\theta_{23} = (38 - 50)^{o} (3\sigma)$$

Octant

$$|\Delta m^2_{32}| \approx (2.5 \pm 0.4) \times 10^{-3} \mathrm{eV}^2$$

Mass Hierarchy

$P(\nu_\mu \rightarrow \nu_\mu)$ Kamiokande, SK, IMB, K2K, MINOS, T2K, NOvA

$P(\nu_\mu \rightarrow \nu_\tau)$ (Opera)

$$\theta_{13} = 8.4 \pm 0.2^{o}$$

$P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ Daya-Bay, RENO, Double Chooz

$P(\nu_\mu \rightarrow \nu_e)$ T2K, NOvA

$$\delta_{CP} = [0, 2\pi]$$

CP violation

T2K, NOvA

THE KNOWNS AND THE UNKNOWNS

Accelerator- based experiments

- $P(\nu_\mu \to \nu_\mu) \sim 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23})\sin^2\Delta m^2_{31}\frac{L}{4E}$

- $$P(\nu_\mu \to \nu_e) \sim \begin{array}{lll} \sin^2 2\theta_{13} & \times \sin^2\theta_{23} & \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2} \\ -\alpha\sin\delta & \times \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} & \times \sin\Delta\frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)} \\ +\alpha\cos\delta & \times \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} & \times \cos\Delta\frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)} \\ +\mathcal{O}(\alpha^2) & & \end{array}$$

matter effects

$$\alpha = \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{31}L}{4E} \qquad x \equiv \frac{2\sqrt{2}G_F N_e E}{\Delta m^2_{31}}$$

M. Freund, Phys.Rev. D64 (2001) 053003

Reactor- based experiments

- $$P(\bar\nu_e \to \bar\nu_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right)$$

HOW DO WE MEASURE δ_{CP}?

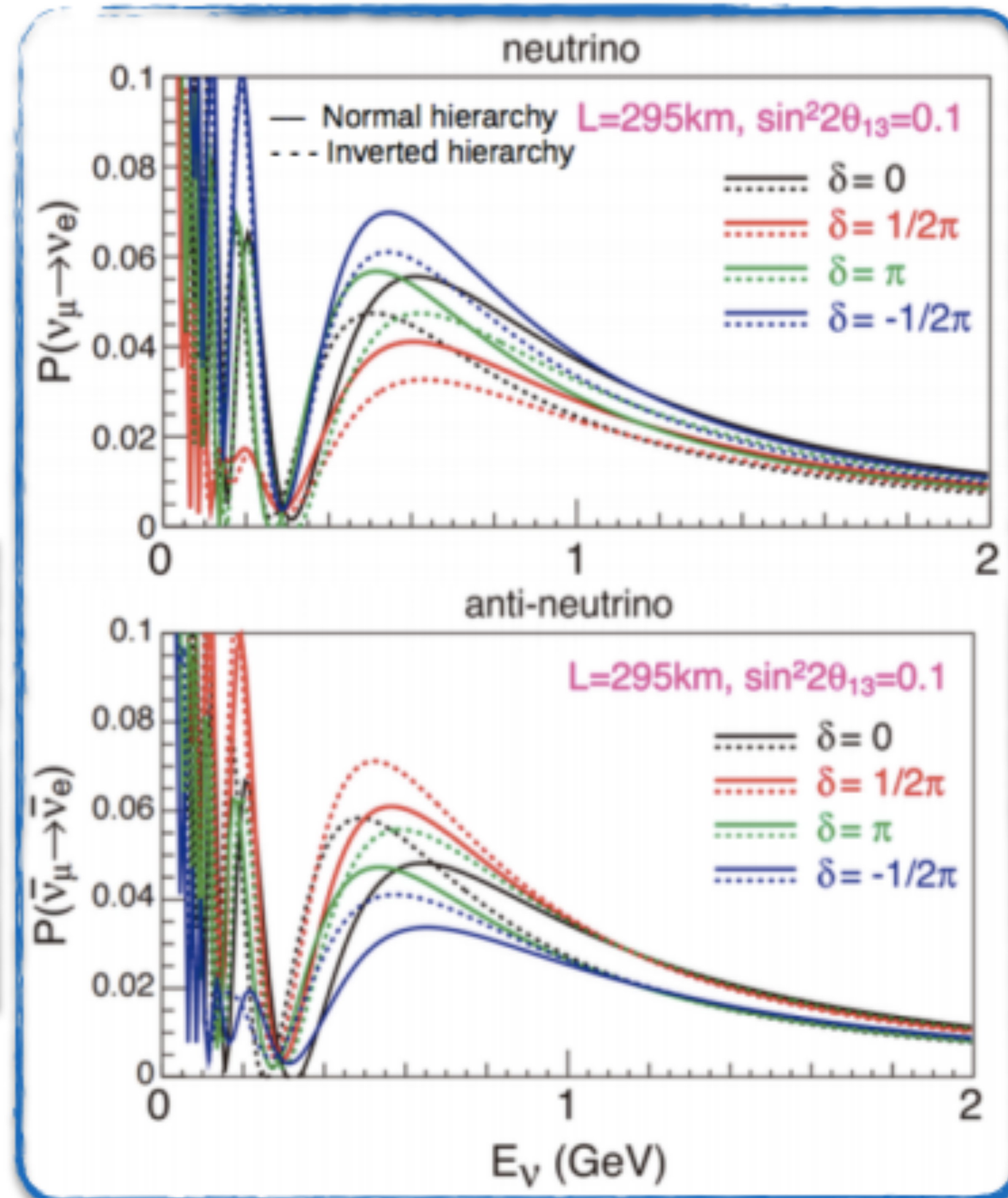
- δ_{CP} **can be measured only by accelerator-based LBL experiment.** Reactor experiments do NOT have access to this parameter

- The measurement is (in principle) simple: looking for a **different behaviour (shape and normalisation) between neutrino and anti-neutrino oscillations**

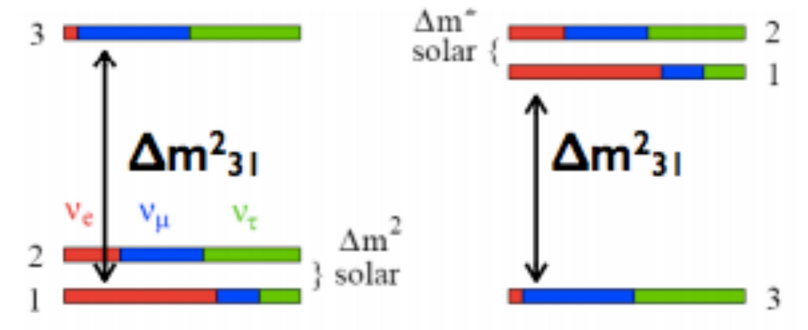
  e.g. if δ_{CP} = :
  - 0 , π : no CP violation $P(\nu_\mu \rightarrow \nu_e) = P(\overline{\nu_\mu} \rightarrow \overline{\nu_e})$
  - $-\pi/2$: enhance $P(\nu_\mu \rightarrow \nu_e)$ suppress $P(\overline{\nu_\mu} \rightarrow \overline{\nu_e})$
  - $+\pi/2$: suppress $P(\nu_\mu \rightarrow \nu_e)$ enhance $P(\overline{\nu_\mu} \rightarrow \overline{\nu_e})$

  - **Matter effects,** if significative, **make the measurement more complicate**

- δ_{CP} strongly correlated with θ_{13}. δ_{CP} **can be extracted using reactor constraints**



HOW DO WE MEASURE THE MASS HIERARCHY?



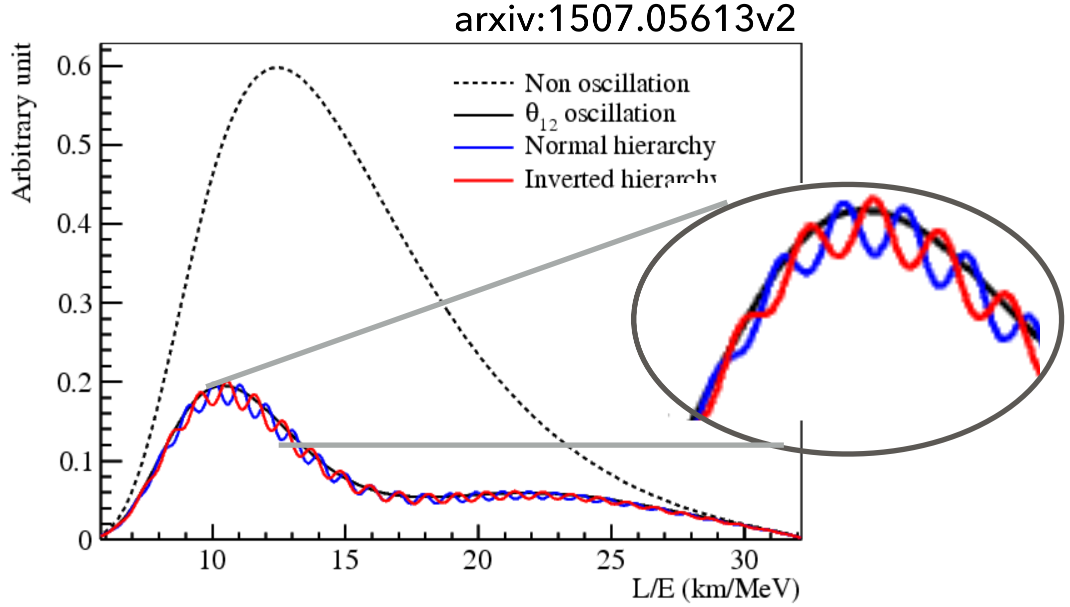
Two approaches :

Oscillation interference:

Spectral distortion on medium baseline reactor experiment (3% effect)

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}\left(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right)$$

arxiv:1507.05613v2



JUNO

Matter effect:

ν/anti-ν oscillations enhanced depending from the MH (need LBL)

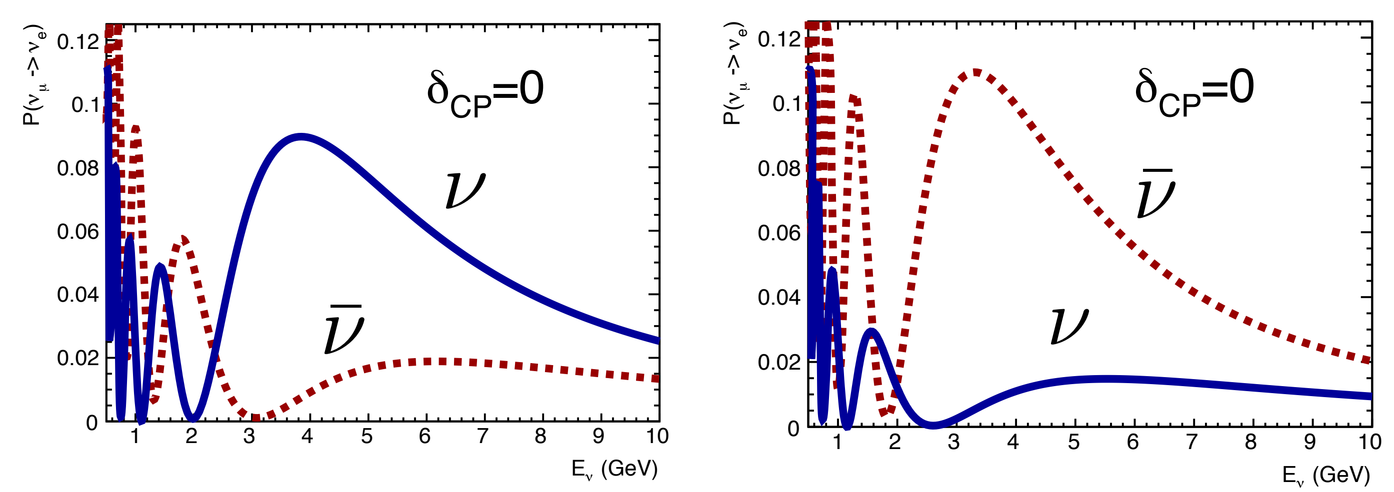
$$A = \pm\frac{2\sqrt{2}G_F N_e E}{\Delta m^2}$$

+ for ν

- for anti-ν

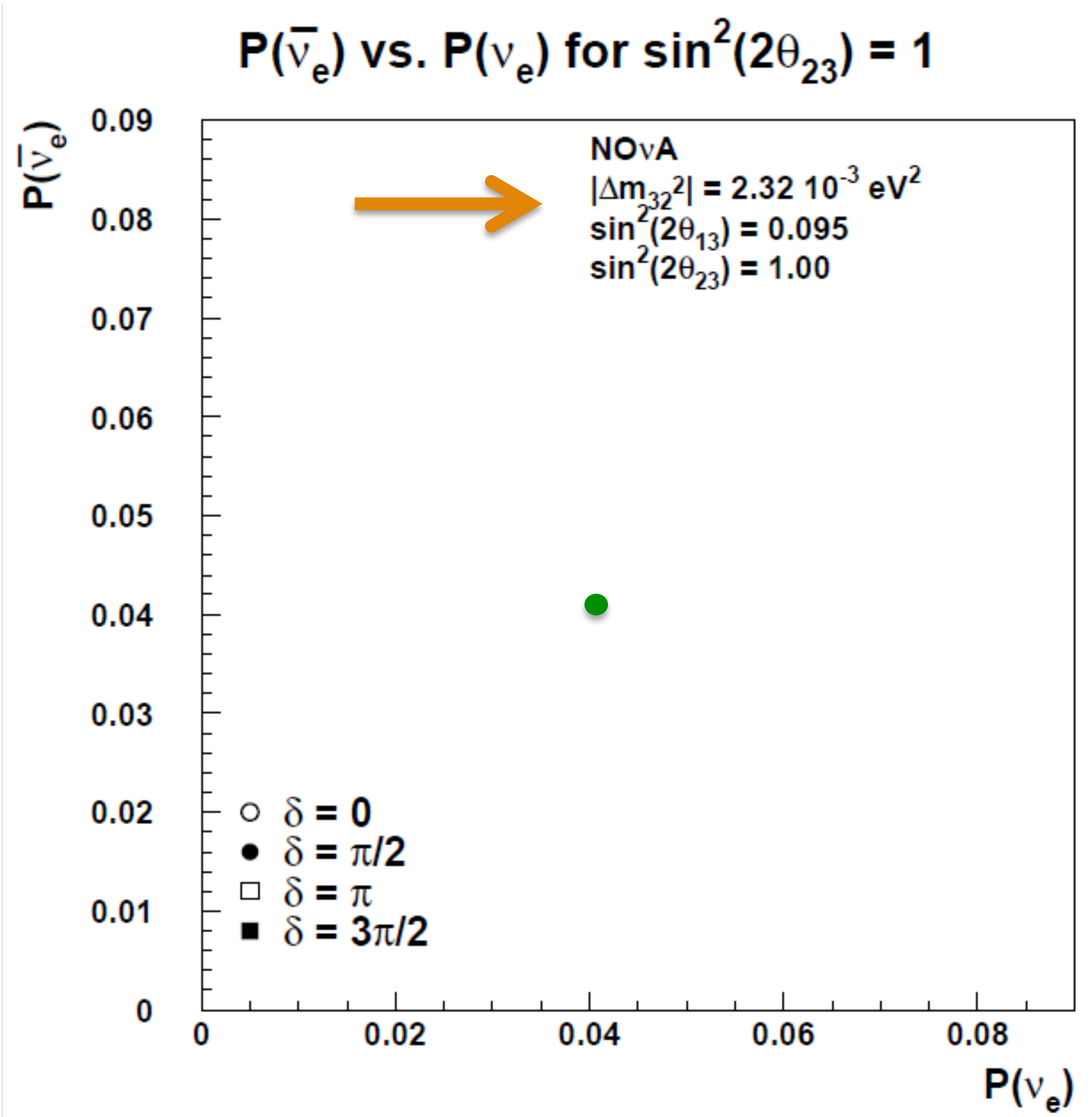
Normal Hierarchy

Inverted Hierarchy



NOvA, DUNE, HK ..

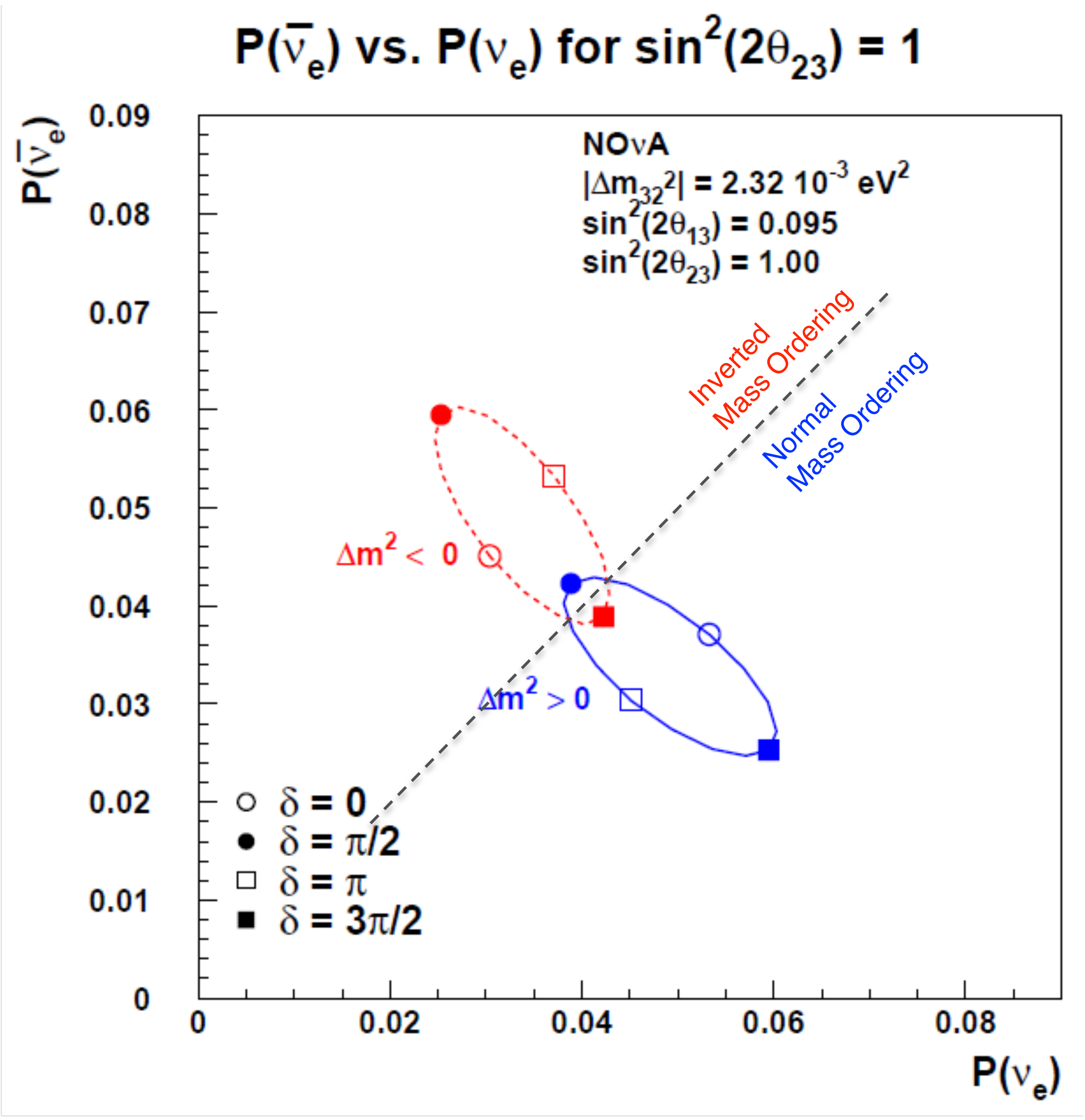
EFFECT ON OSCILLATIONS MEASUREMENTS



Considering:

- no matter effects
- no CP violation
- maximal mixing (θ_{23}=45°)

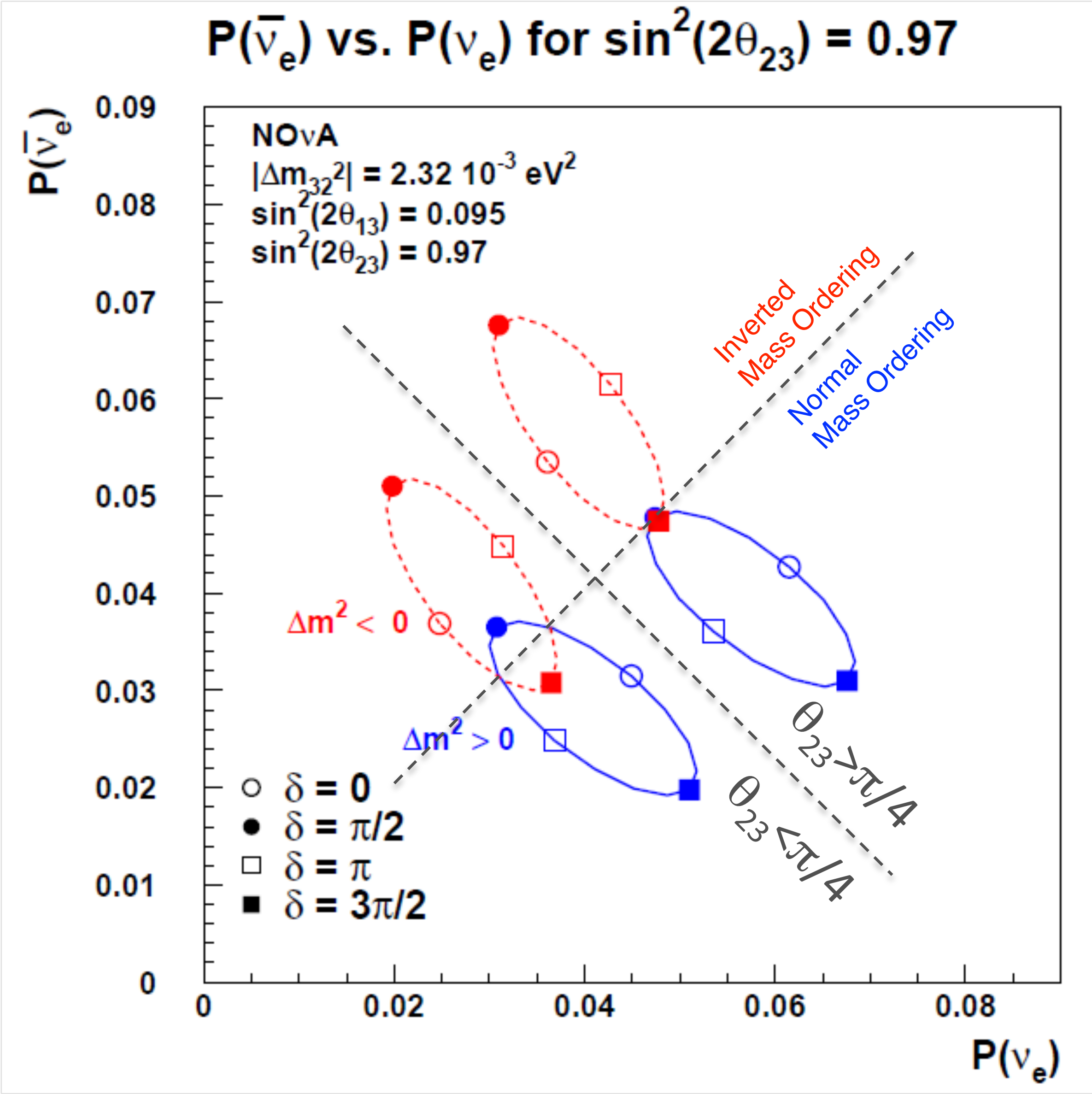
EFFECT ON OSCILLATIONS MEASUREMENTS



Considering:

- **Matter effect** → move measurement wrt **diagonal**
- **CP violation** → move the measurement along one **ellipse**

EFFECT ON OSCILLATIONS MEASUREMENTS



Considering:

- **Matter effect**: move measurement wrt **diagonal**
- **CP violation** : move the measurement along one **ellipse**
- **Octant** : move measurement on the **other diagonal**

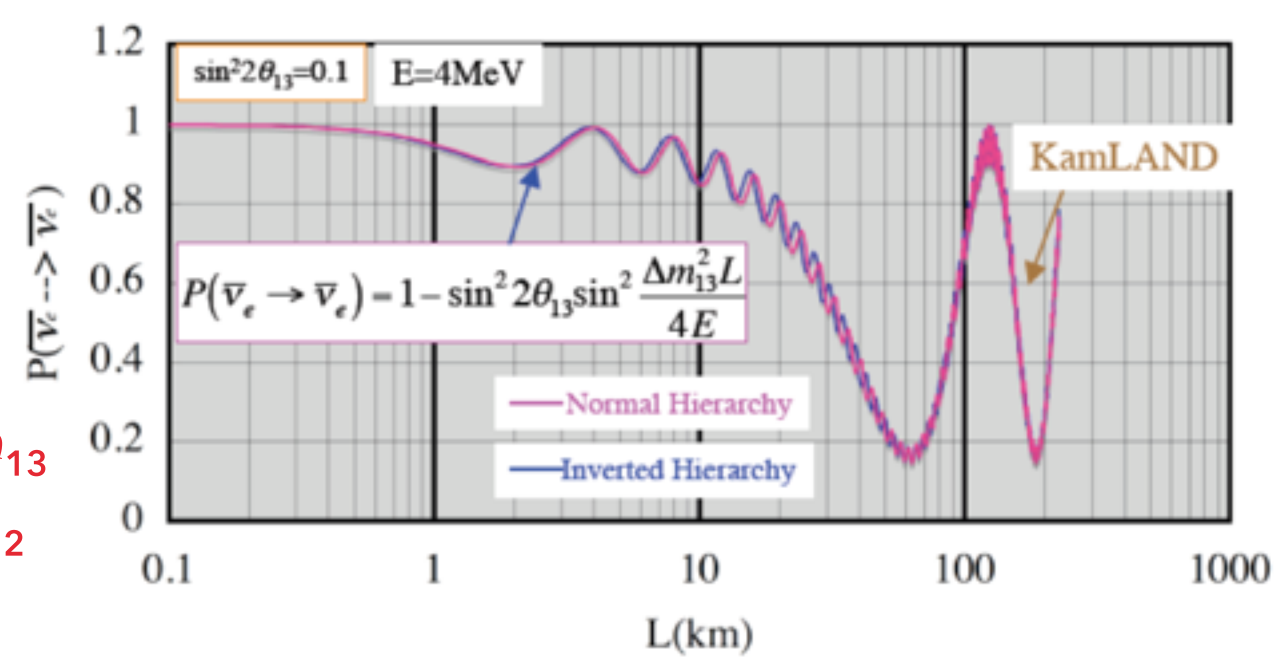
ANALYSIS STRATEGY

- Estimation of the flux is complicated for both accelerator and reactor experiments
- Big uncertainties to take into account (e.g. number of ß-decay from fission products for reactors, hadron production for beams..)
- 2 detectors :
  - **Near Detector :** estimate the incoming neutrino flux before the oscillation occurs
  - **Far Detector :** measure the distortions due to oscillations

NB: Depending on where the detector are located, the experiment can be sensible to different parameters

e.g. ***Reactor experiments :***

- if short baseline (~ few km), sensitivity to Δm^2_{atm} and ϑ_{13}
- if long baseline (~100s km) sensitivity to Δm^2_{sol} and ϑ_{12}

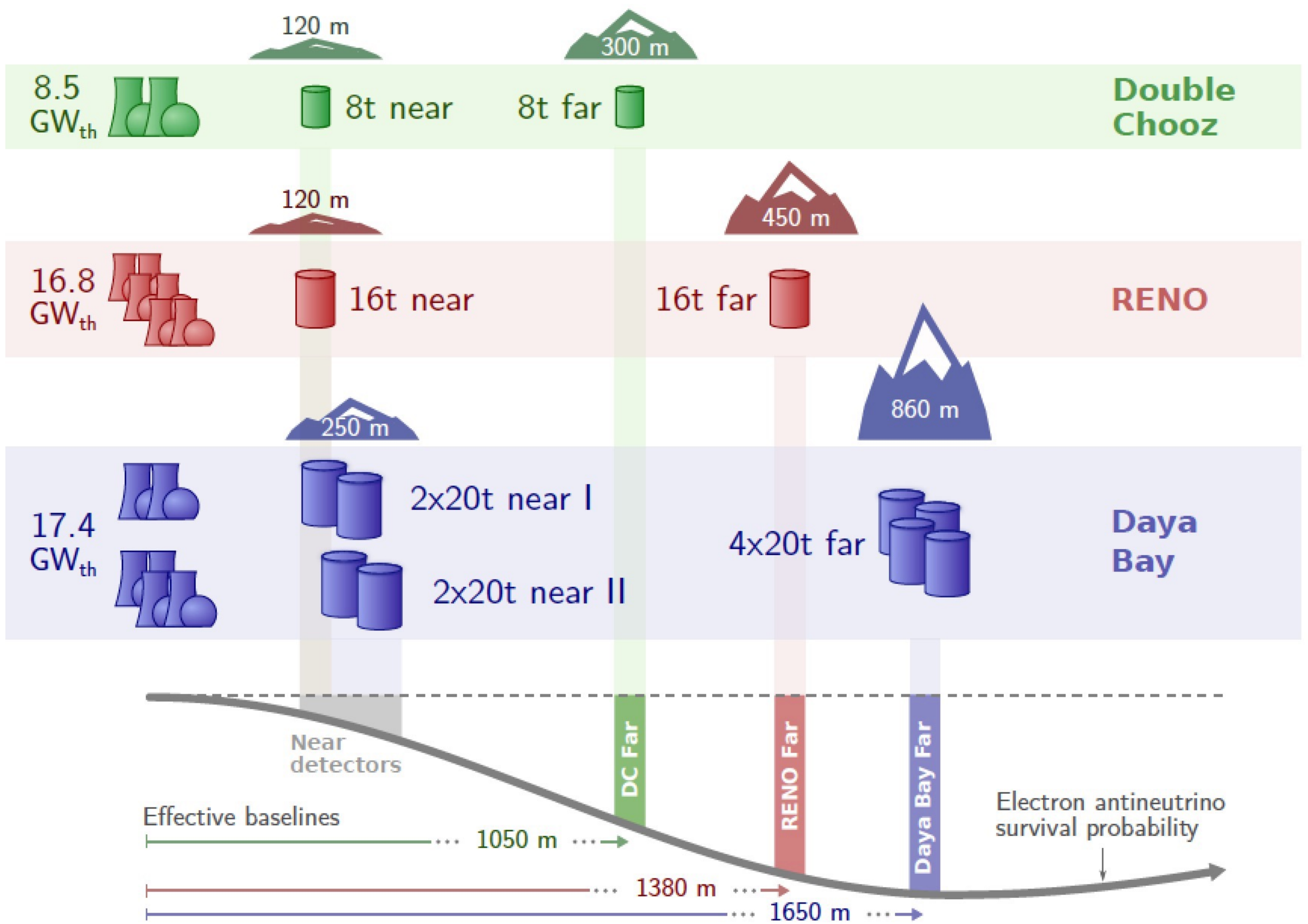


REACTOR EXPERIMENTS

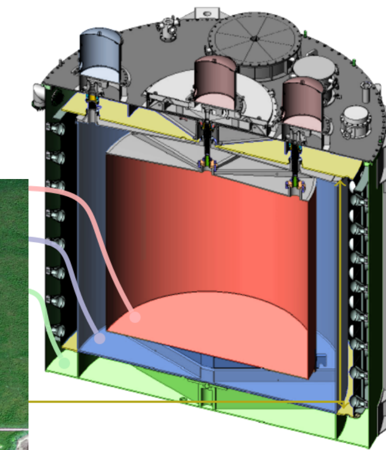
CURRENT REACTOR EXPERIMENTS

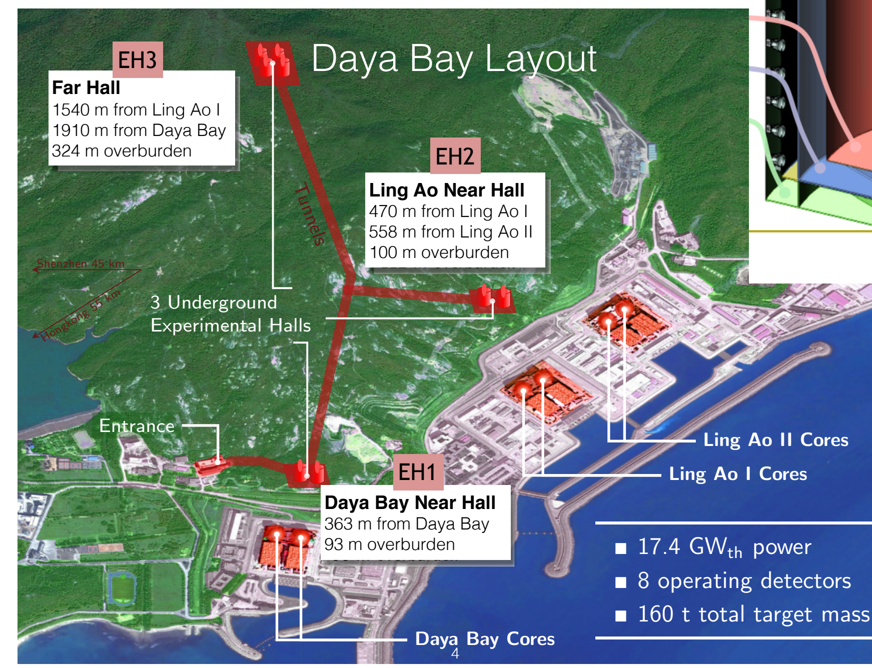
2012: not only Higgs boson discovery..

year of reactor experiments: **measurement of the last mixing angle ϑ_{13}**



CURRENT REACTOR EXPERIMENTS: DAYA-BAY



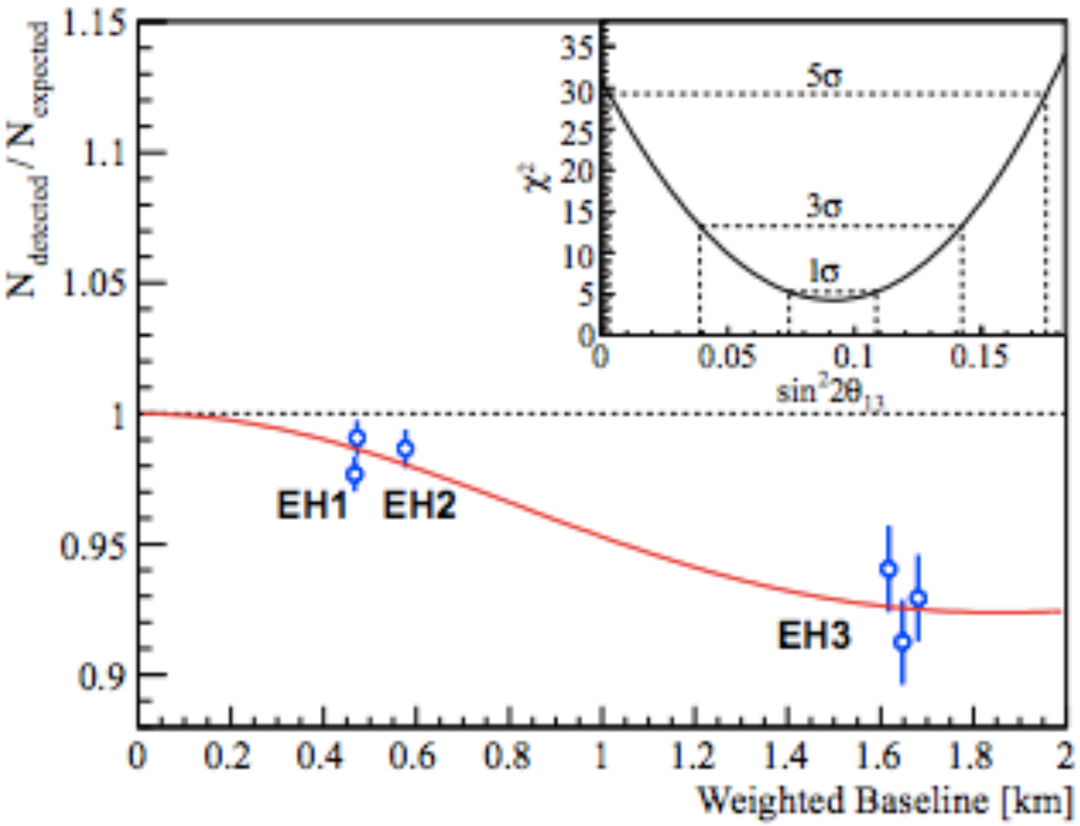


- **First experiment measuring θ_{13} and world leading**

  March 2012 :

  $\theta_{13} \neq 0$ with a significance of 5.2σ

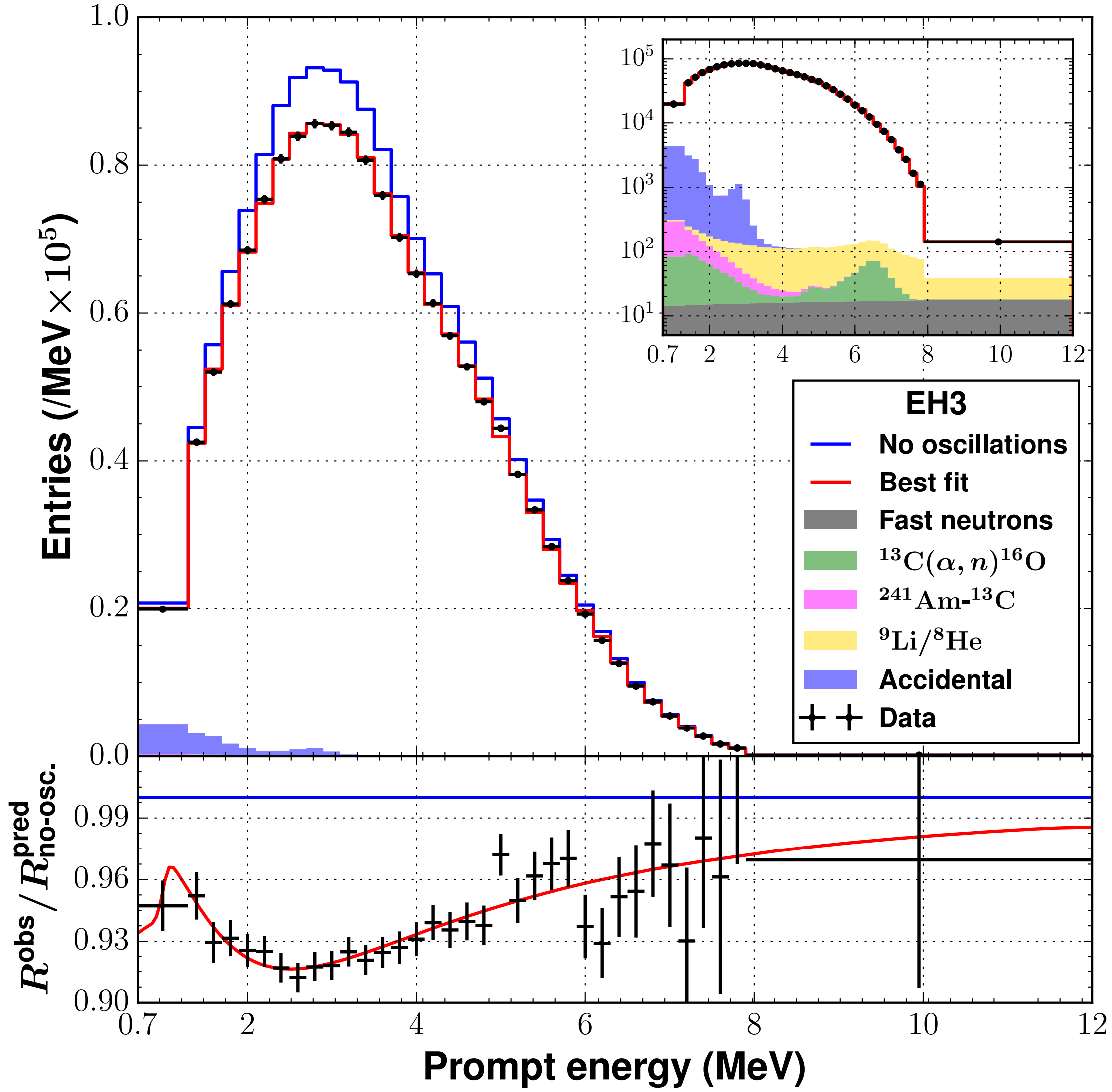
Phys.Rev.Lett. 108:171803 (2012)

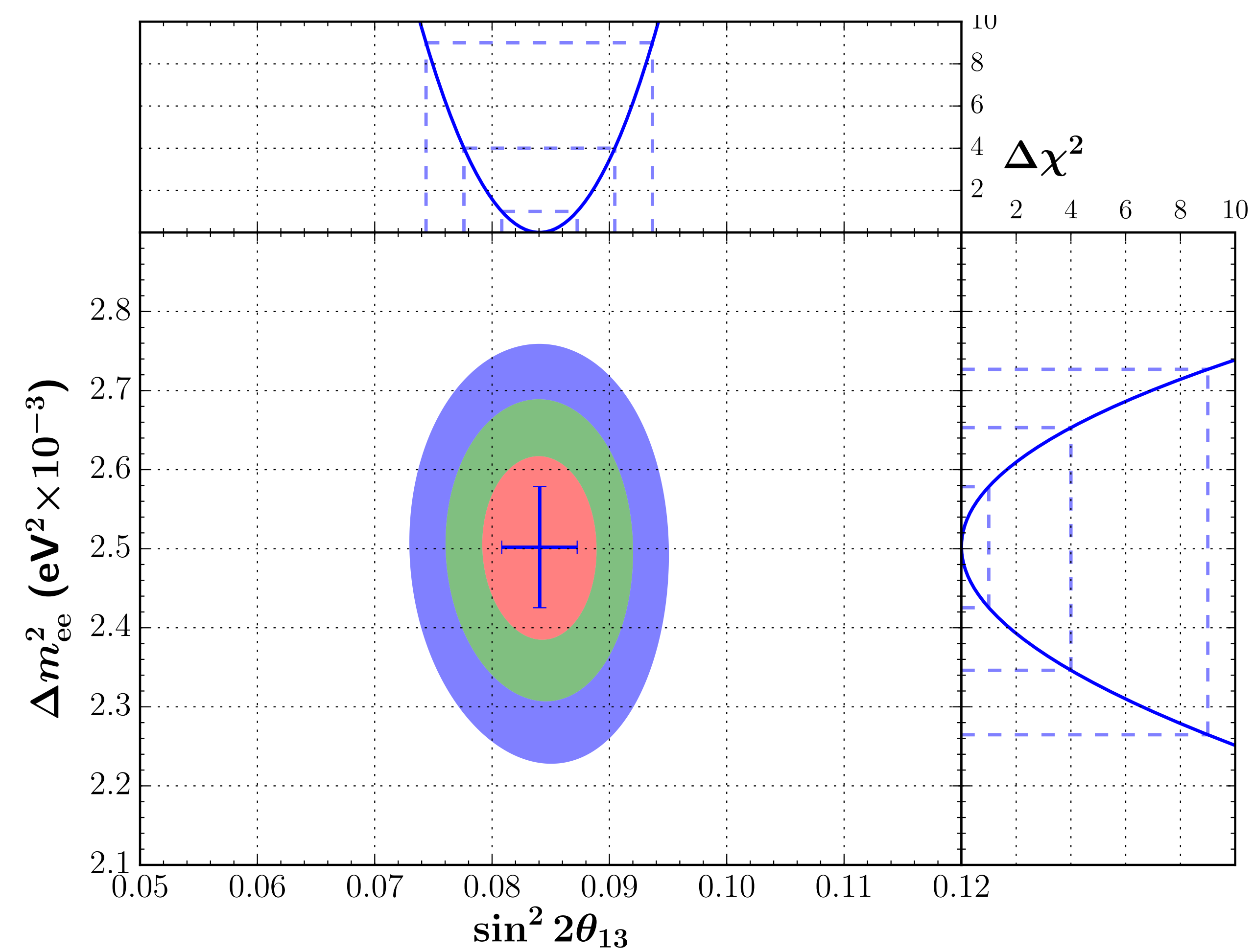


Far detector hall

CURRENT REACTOR EXPERIMENTS: DAYA-BAY

World's most precise determination of Δm^2_{ee} and ϑ_{13}





$\sin^2 2\theta_{13}$ = [8.41±0.27 (stat.)±0.19(syst.)]×10^{-2}

Δm^2_{ee} = [2.50±0.06(stat.)±0.06(syst.)]×10^{-3} eV^2

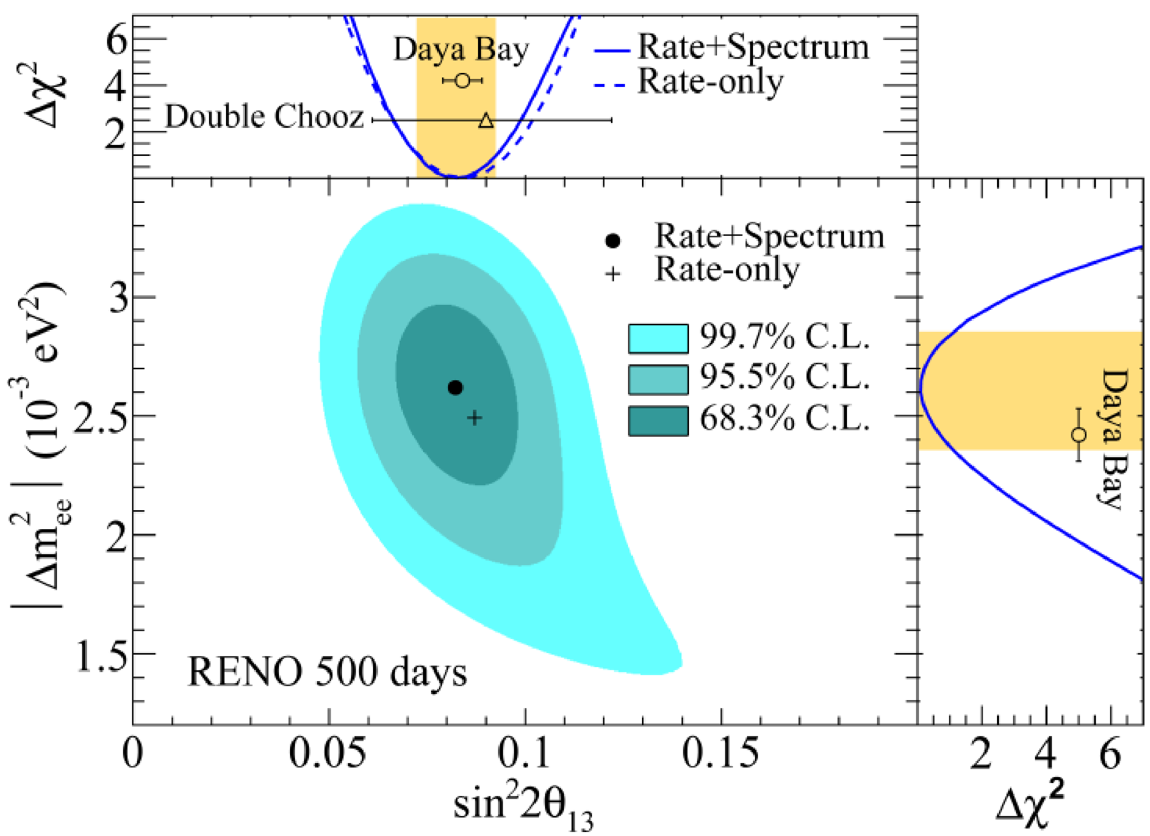
χ^2/ndf = 232.6/263

still statistics dominated!

CURRENT REACTOR EXPERIMENTS

RENO

presented at Neutrino 2016

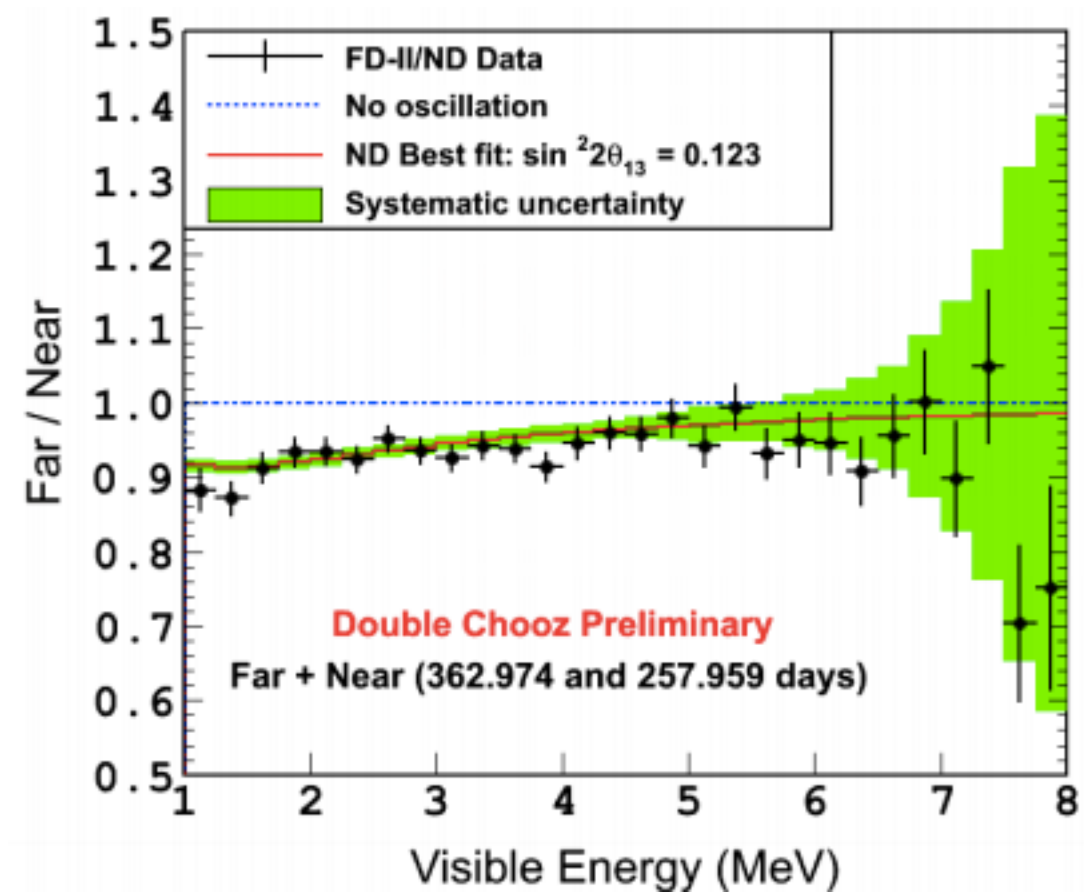


$$\sin^2 2\theta_{13} = 0.082 \pm 0.009(\text{stat.}) \pm 0.006(\text{syst.})$$

$$\left|\Delta m^2_{ee}\right| = 2.62^{+0.21}_{-0.23}(\text{stat.})^{+0.12}_{-0.13}(\text{syst.}) \ \ (\times 10^{-3} eV^2)$$

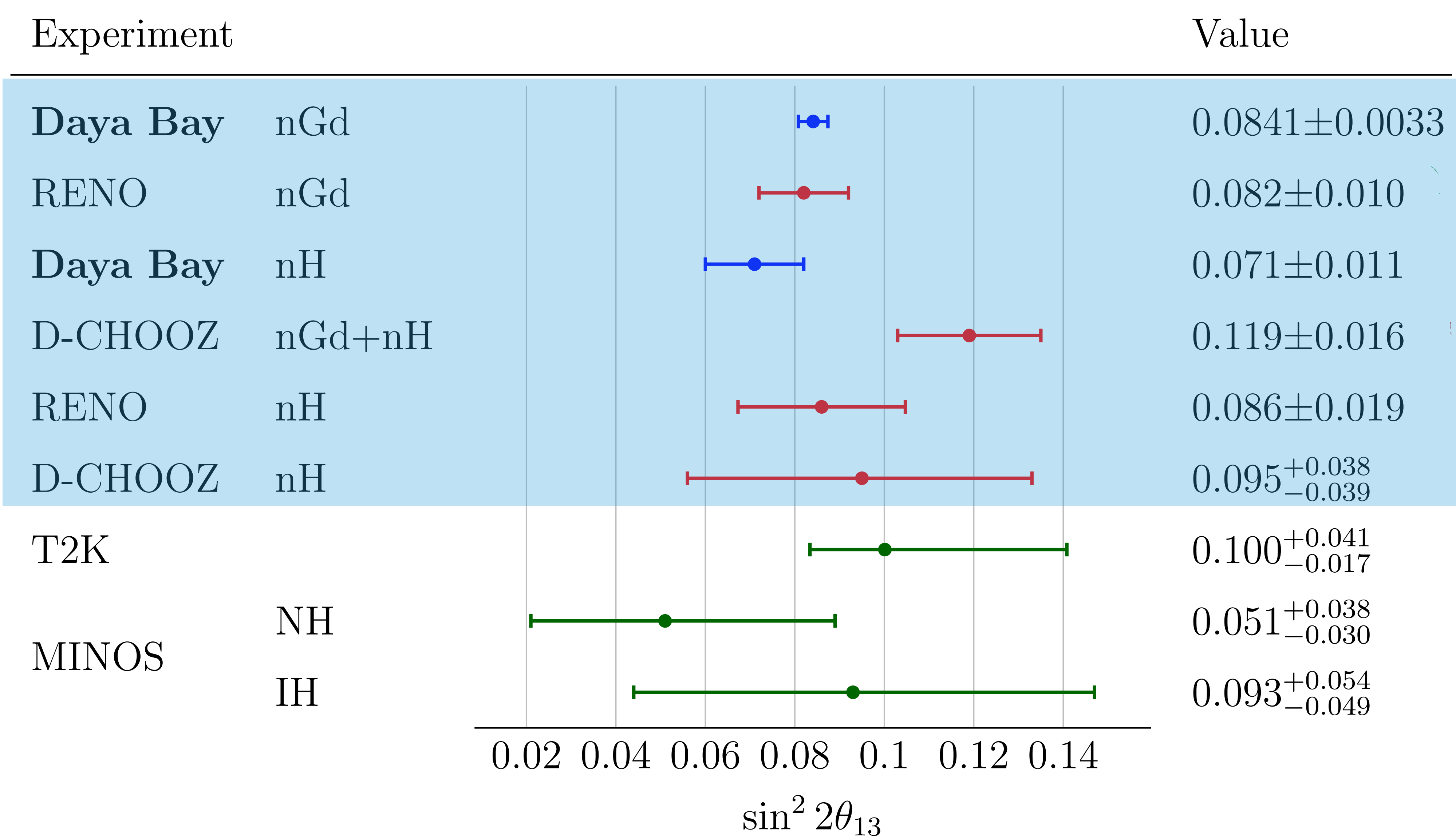
Double Chooz

presented at CERN, September 2016



$\sin^2(2\theta_{13})^{R+S}$=(0.116±0.017)
[FD-II:ND⊕FD-I]
χ^2 / ndf: 97.5 / 76

SUMMARY OF THE θ_{13} MEASUREMENTS

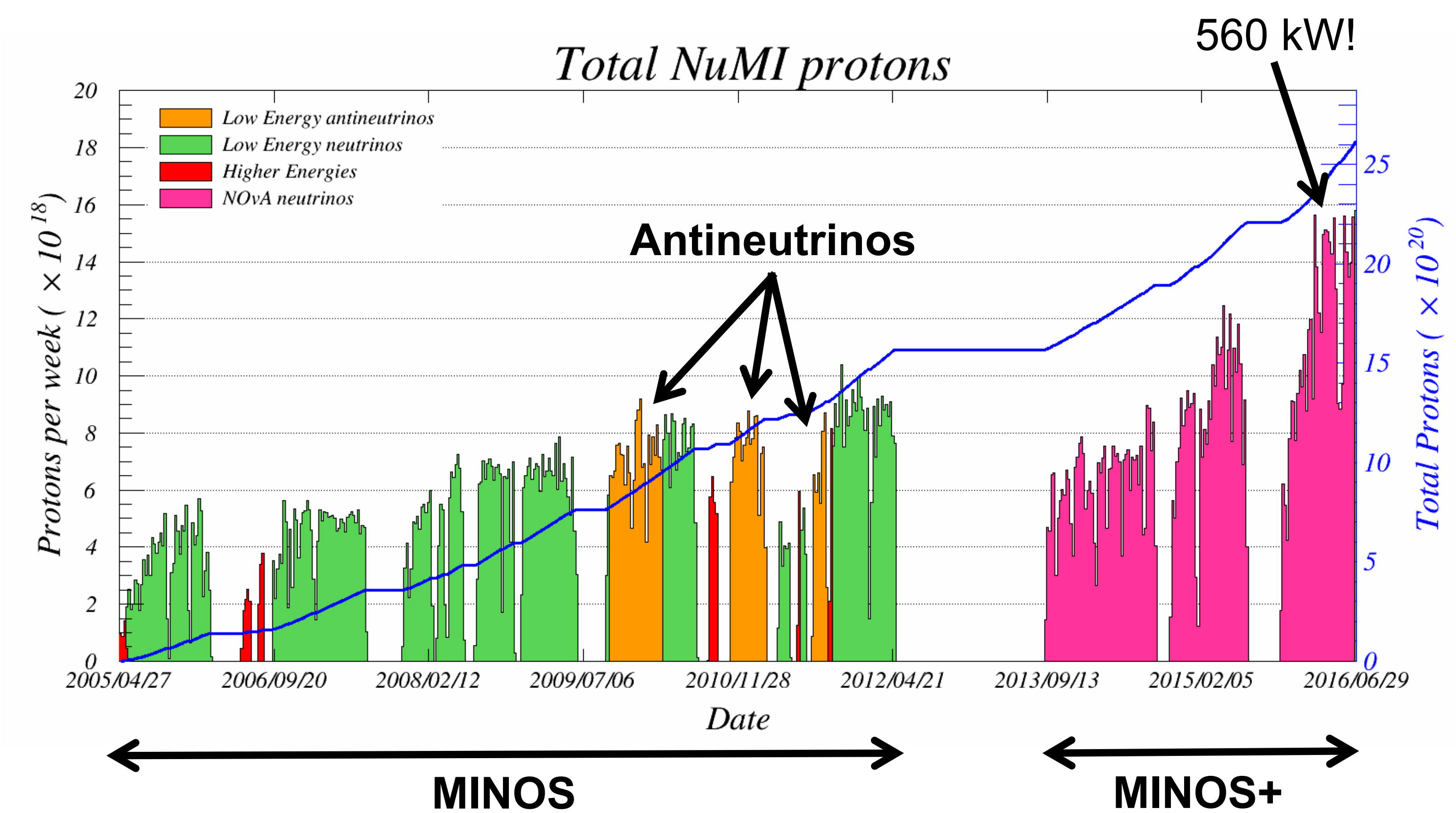


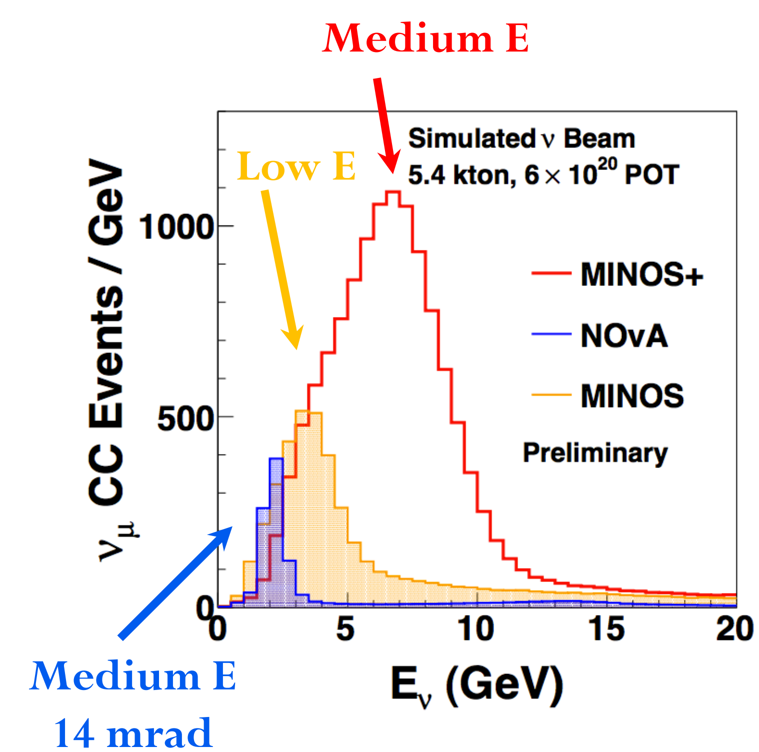
from Daya-Bay CERN seminar, Feb 2017

ACCELERATOR-BASED EXPERIMENTS

LBL EXPERIMENTS : MINOS / MINOS+

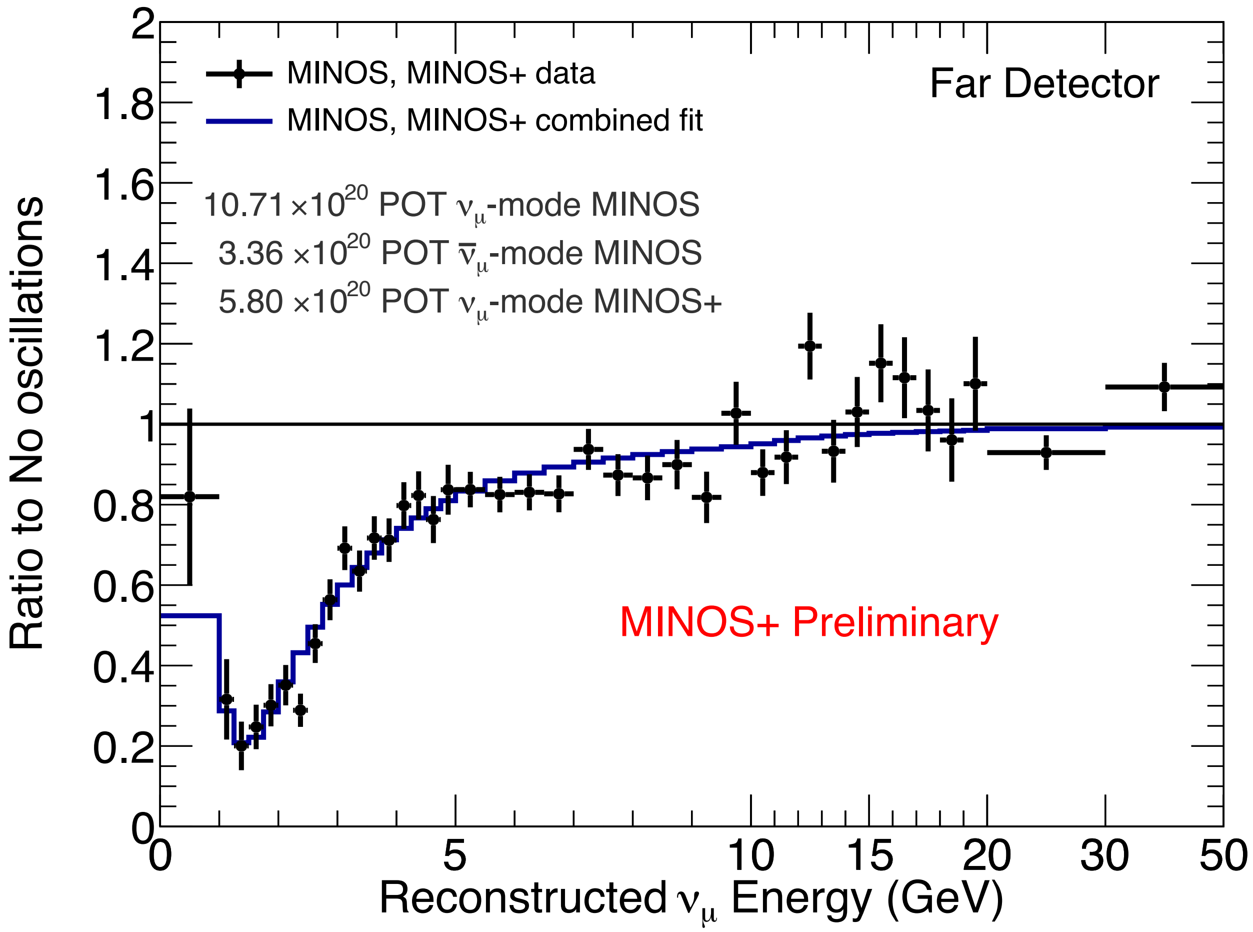
- Long baseline accelerator experiment in US 2003 - 2016
- baseline ~ **735 km**
- on axis, **<E$_\nu$> ≃ 2 GeV** (MINOS), **<E$_\nu$> ≃ 6-7 GeV** (MINOS+)
- data in both neutrino and anti-neutrino modes

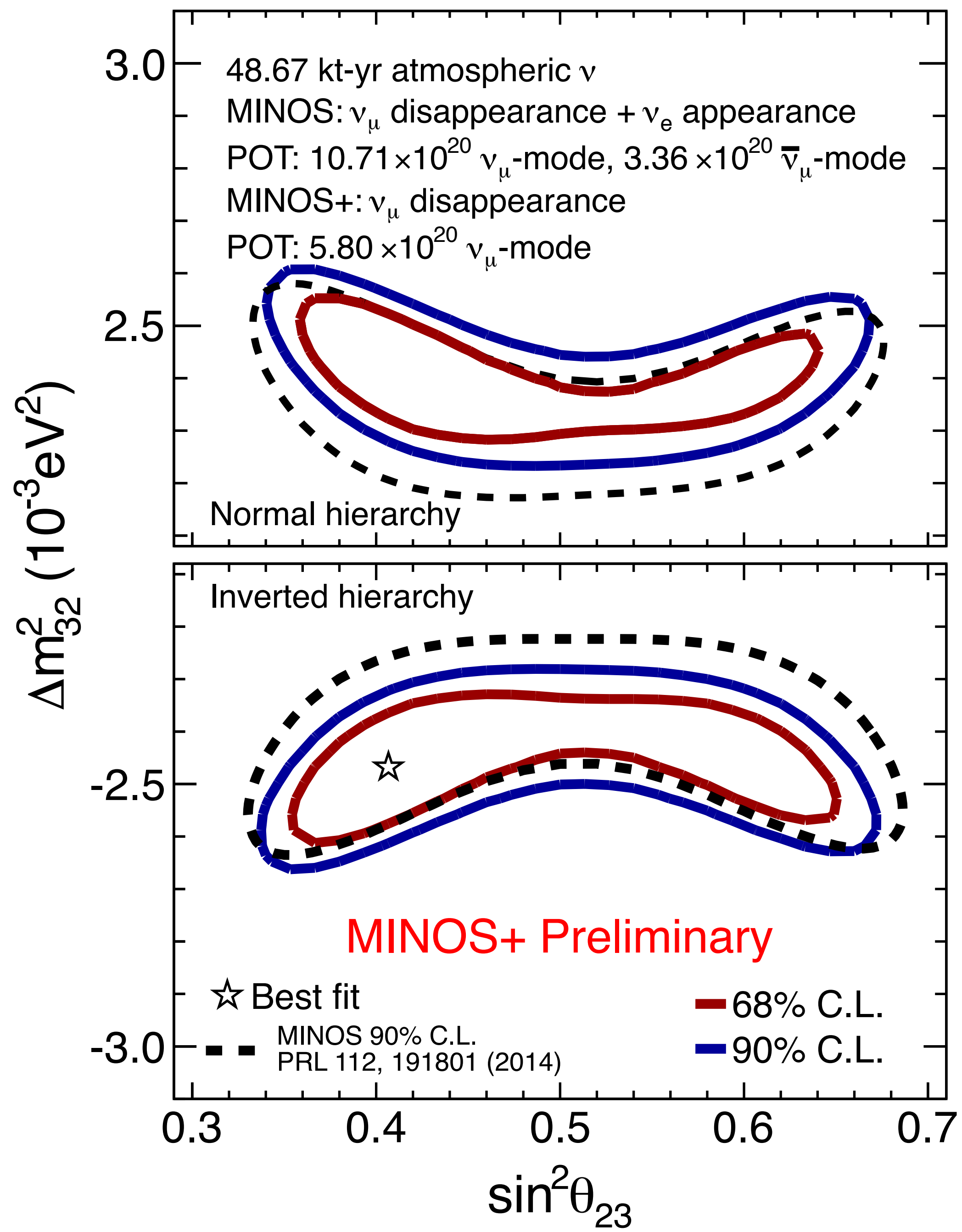




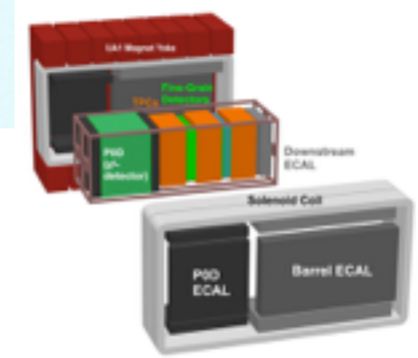
LBL EXPERIMENTS : MINOS / MINOS+

Latest MINOS+ results: combining MINOS+ and MINOS data

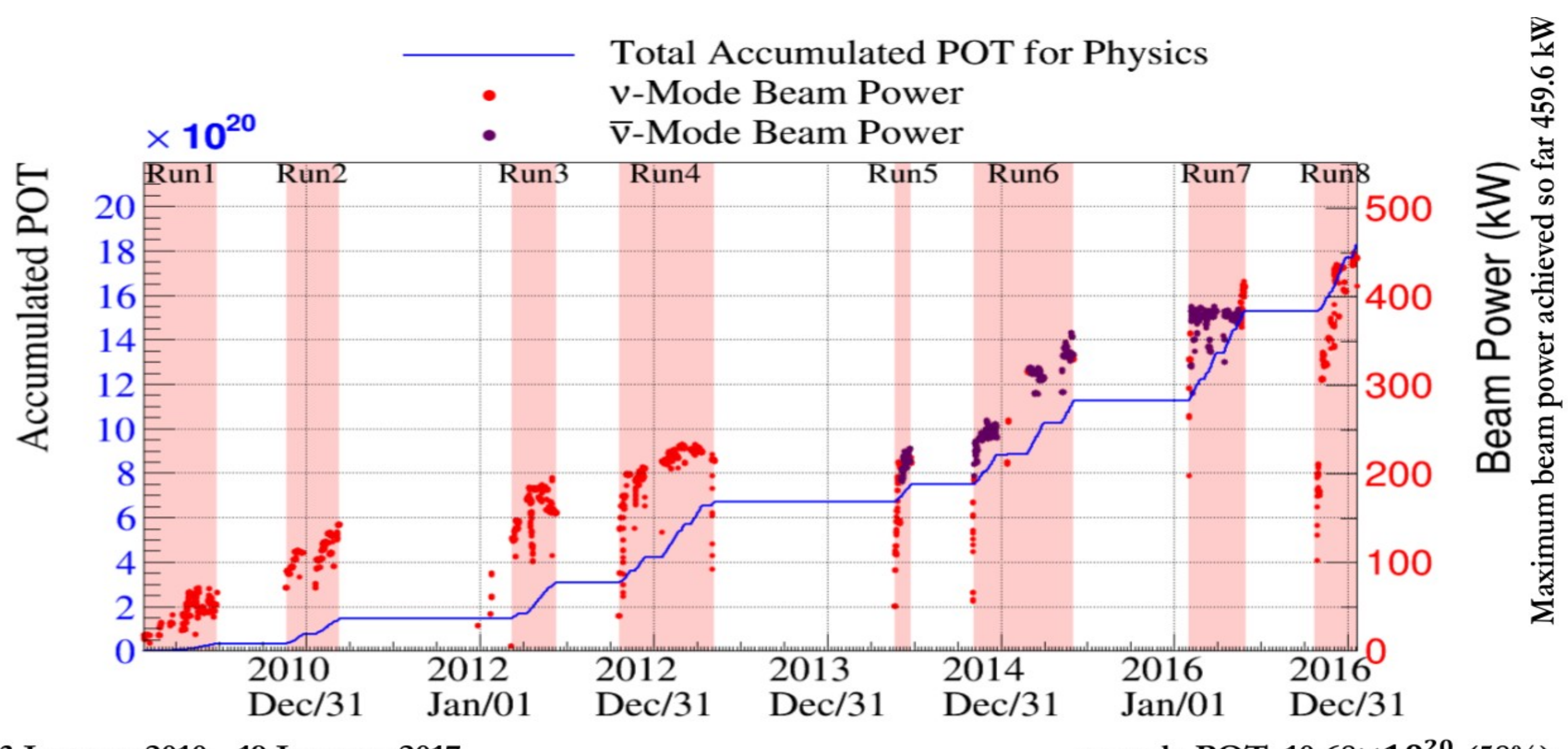




LBL EXPERIMENTS : T2K

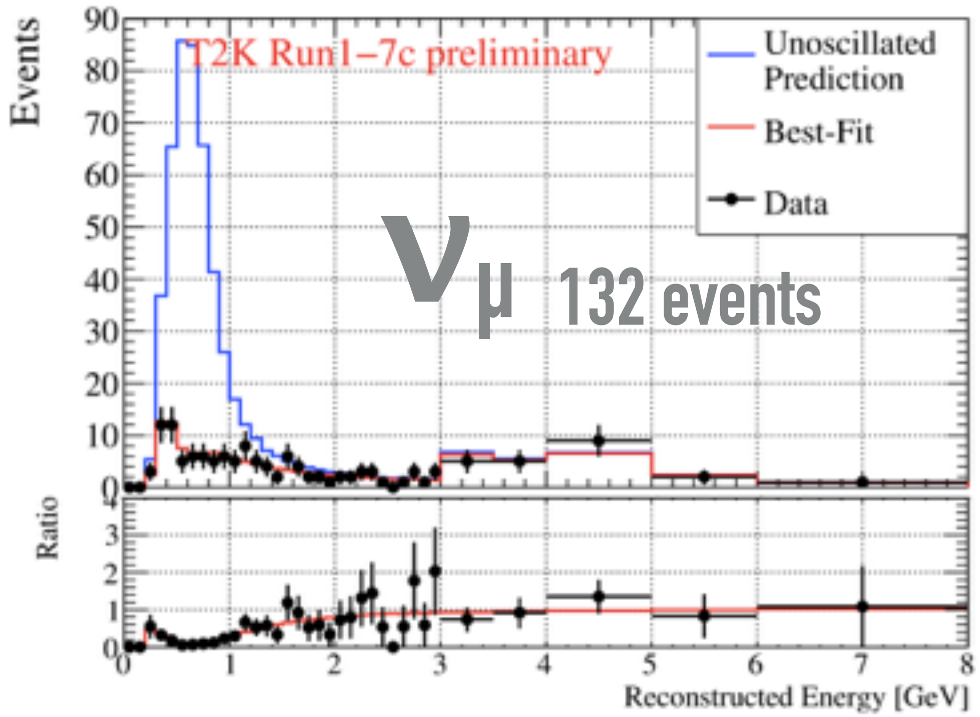


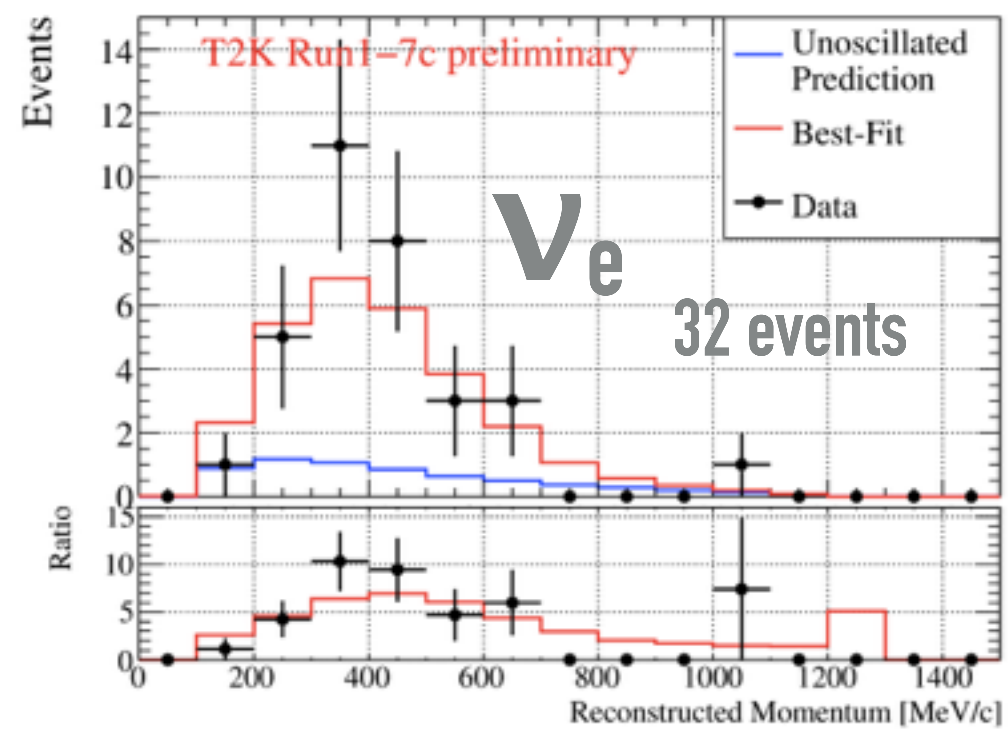
- LBL experiment in Japan since 2010
- baseline ~**300km**
- first experiment with off-axis technique. **<E$_\nu$> ≃ 0.6 GeV**
- data collected in both neutrino and anti-neutrino modes
- Kinematic approach

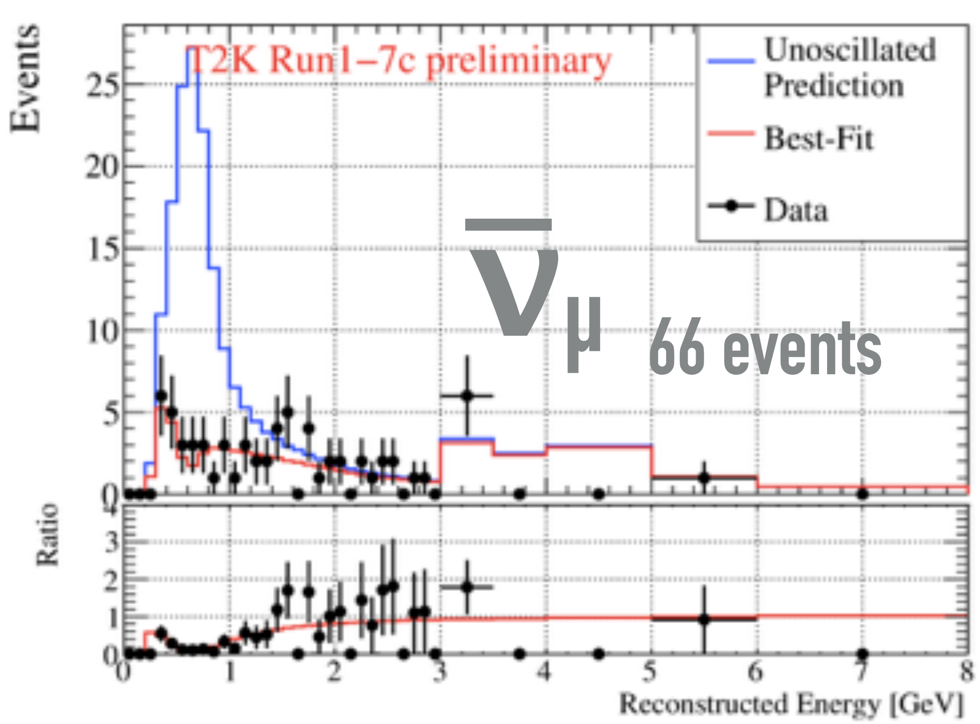


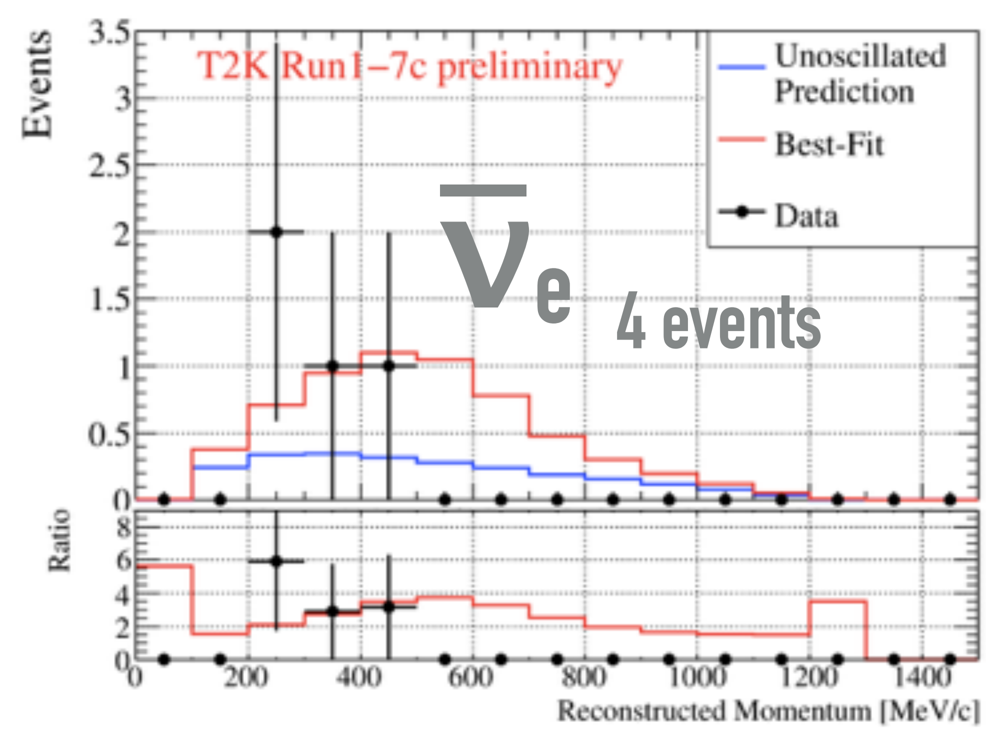
Stable operation at ~ 450 kW !

LBL EXPERIMENTS : T2K





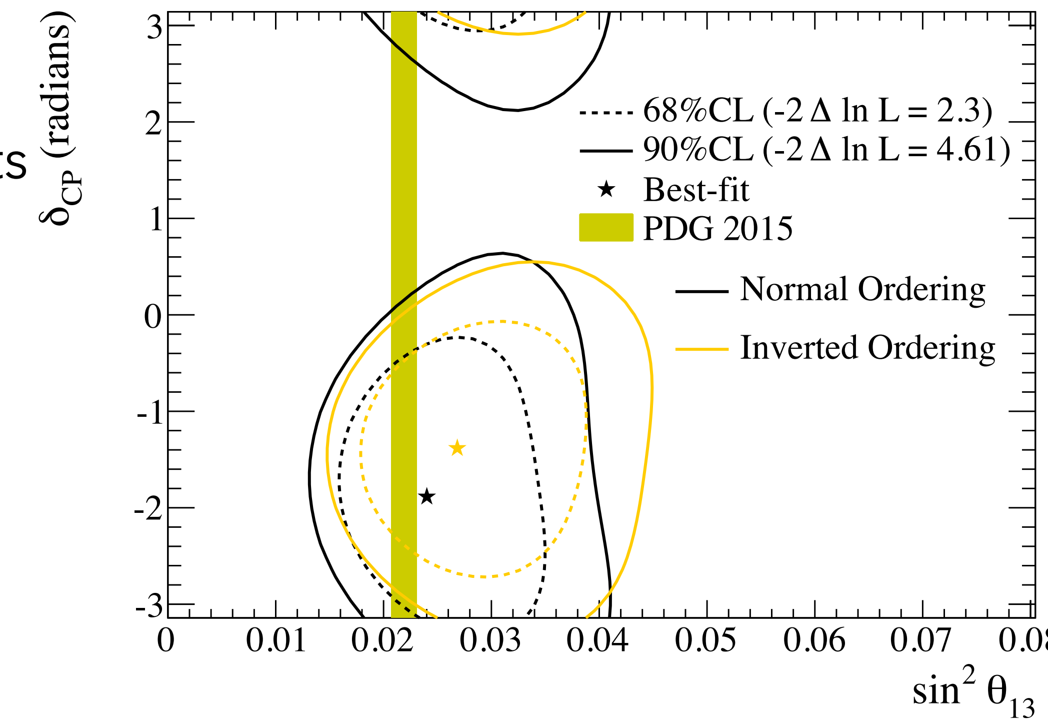




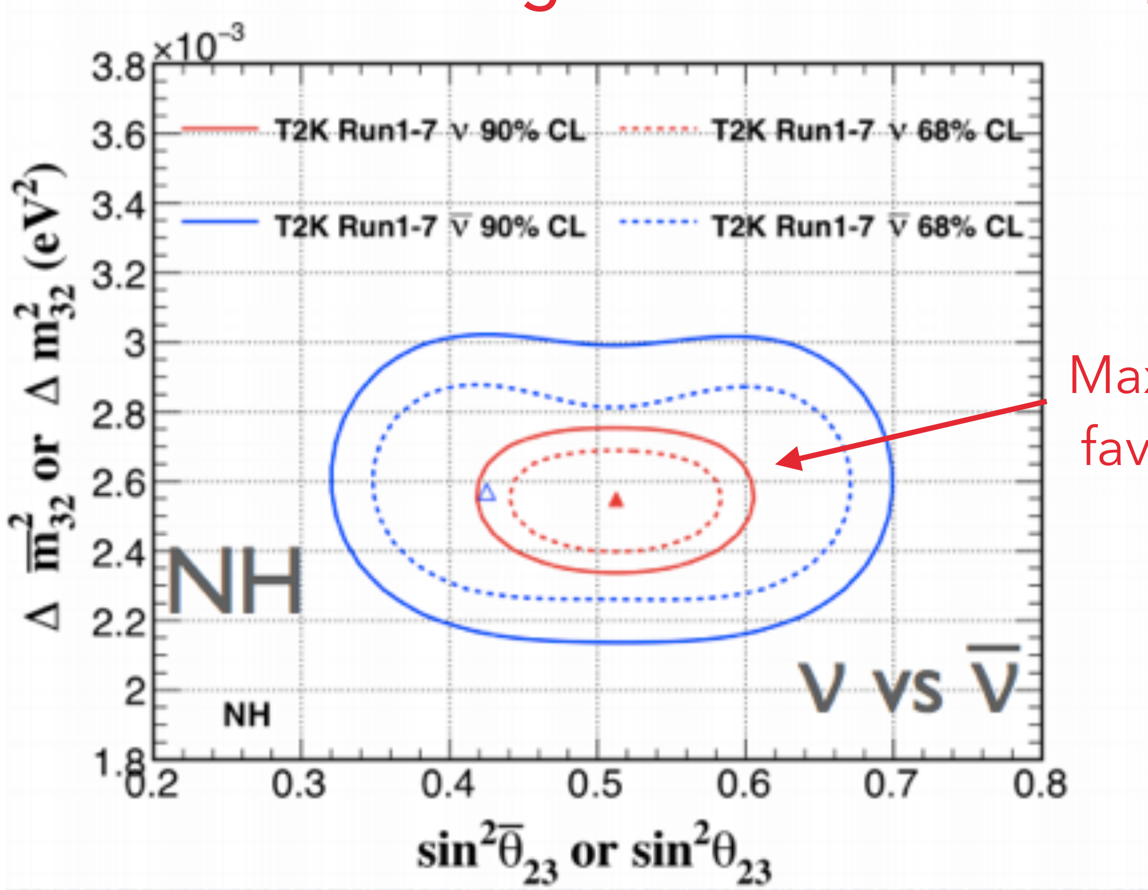
LBL EXPERIMENTS : T2K

arXiv[hep-ex] 1701.00432

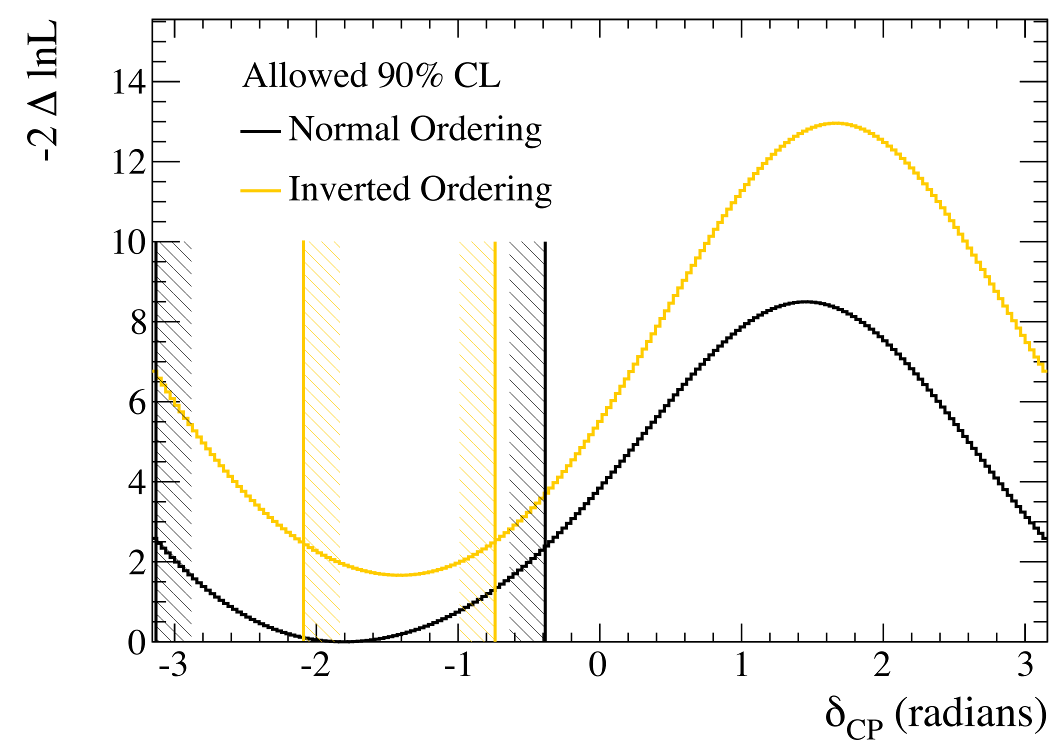
- Joint neutrino anti-neutrino analysis
- Extraction of constraints on δ_{CP} from ν_e appearance results
- Reactor constraints on θ_{13} can be used to resolve the degeneracy with this parameter



World's leading measurement on θ_{23}

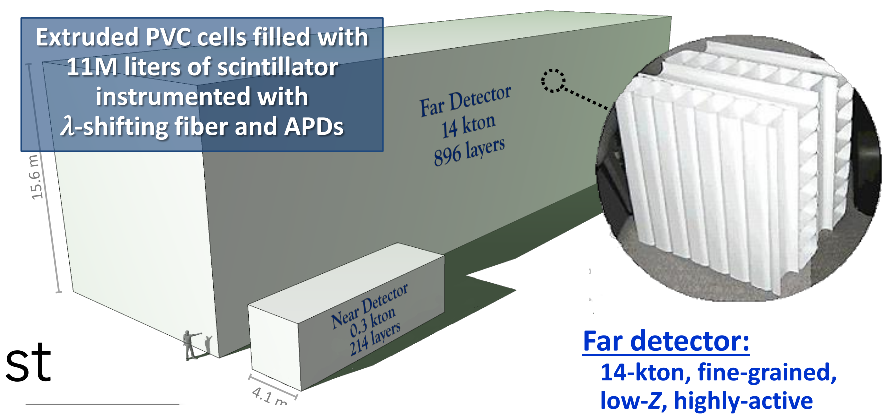


Maximal mixing favoured



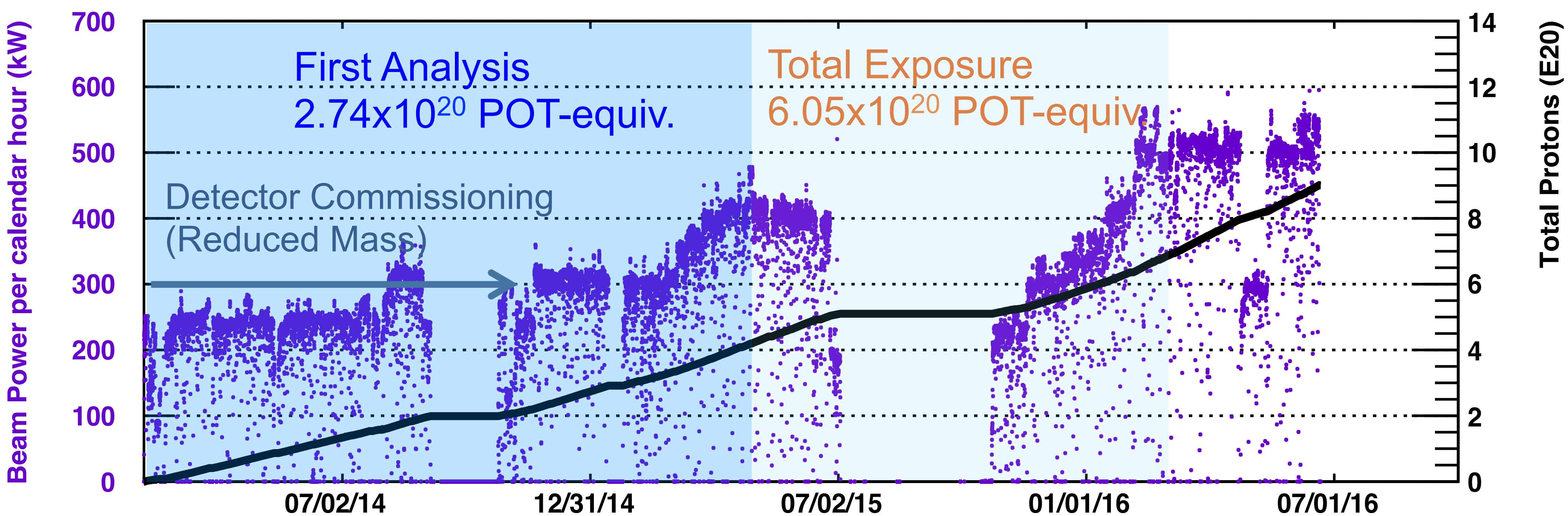
LBL EXPERIMENTS : NOVA

- Long baseline accelerator experiment in US started in 2013
- baseline ~ 810 km
- Using off-axis technique. <E_ν> ≃ 2 GeV
- calorimetric approach
- results on only neutrino mode so far. Anti-neutrino runs just started!

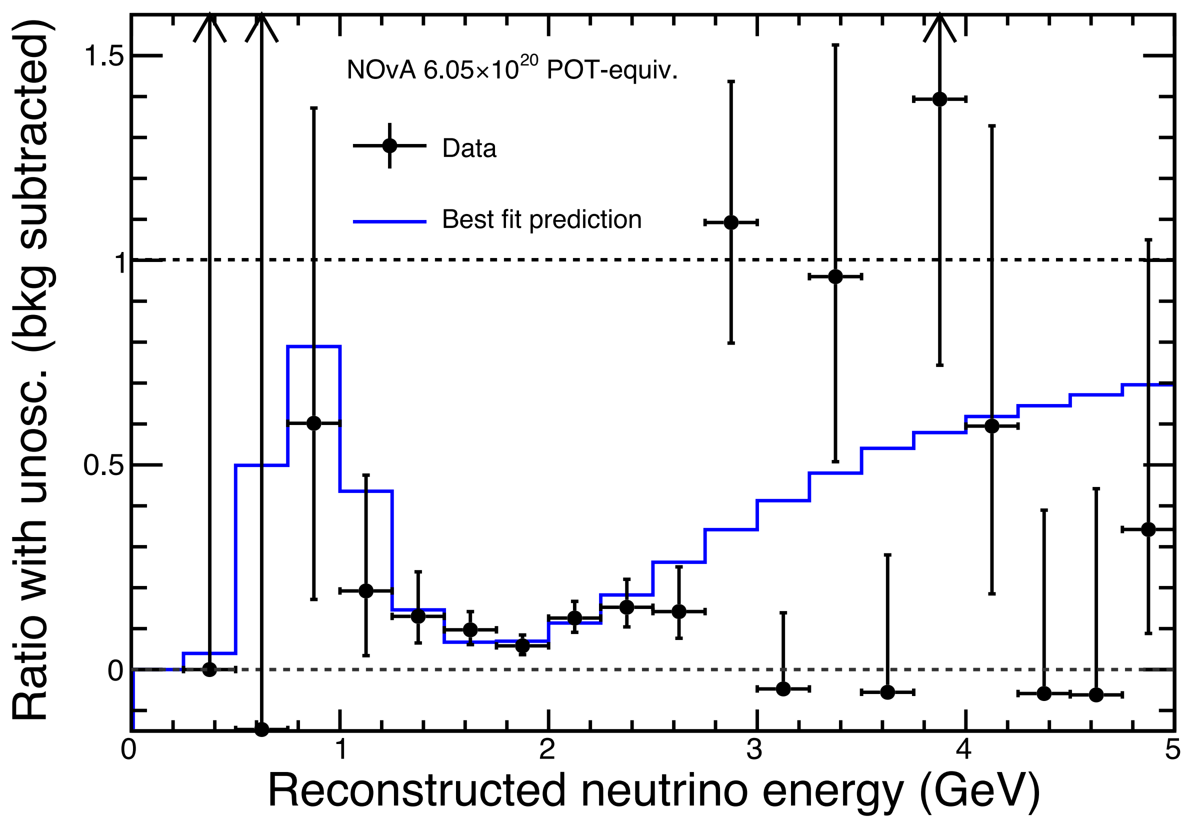


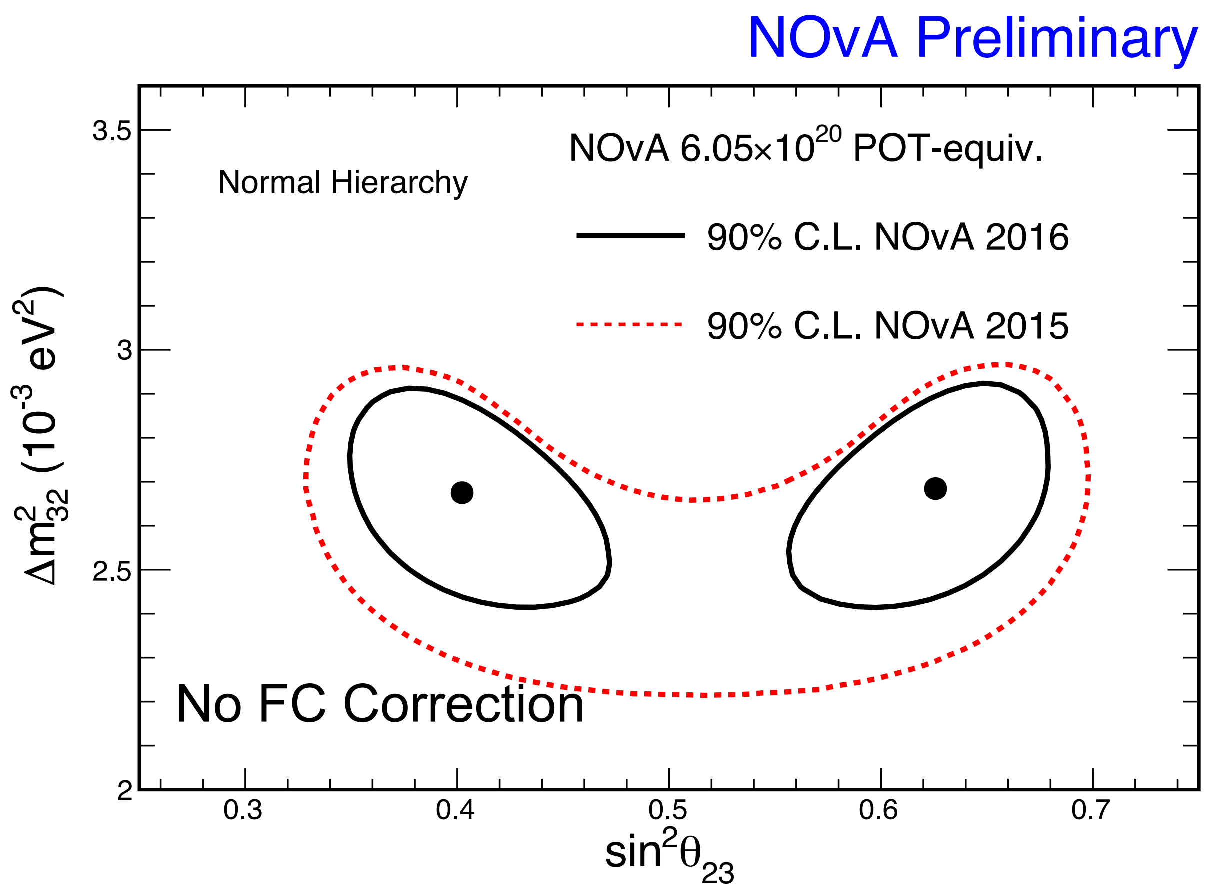
Far detector:
14-kton, fine-grained, low-*Z*, highly-active tracking calorimeter
→ *344,000 channels*

Near detector:
0.3-kton version of the same
→ *20,000 channels*



LBL EXPERIMENTS : NOVA





78 events observed at FD

430 +/- 30 expected w/ no oscillation

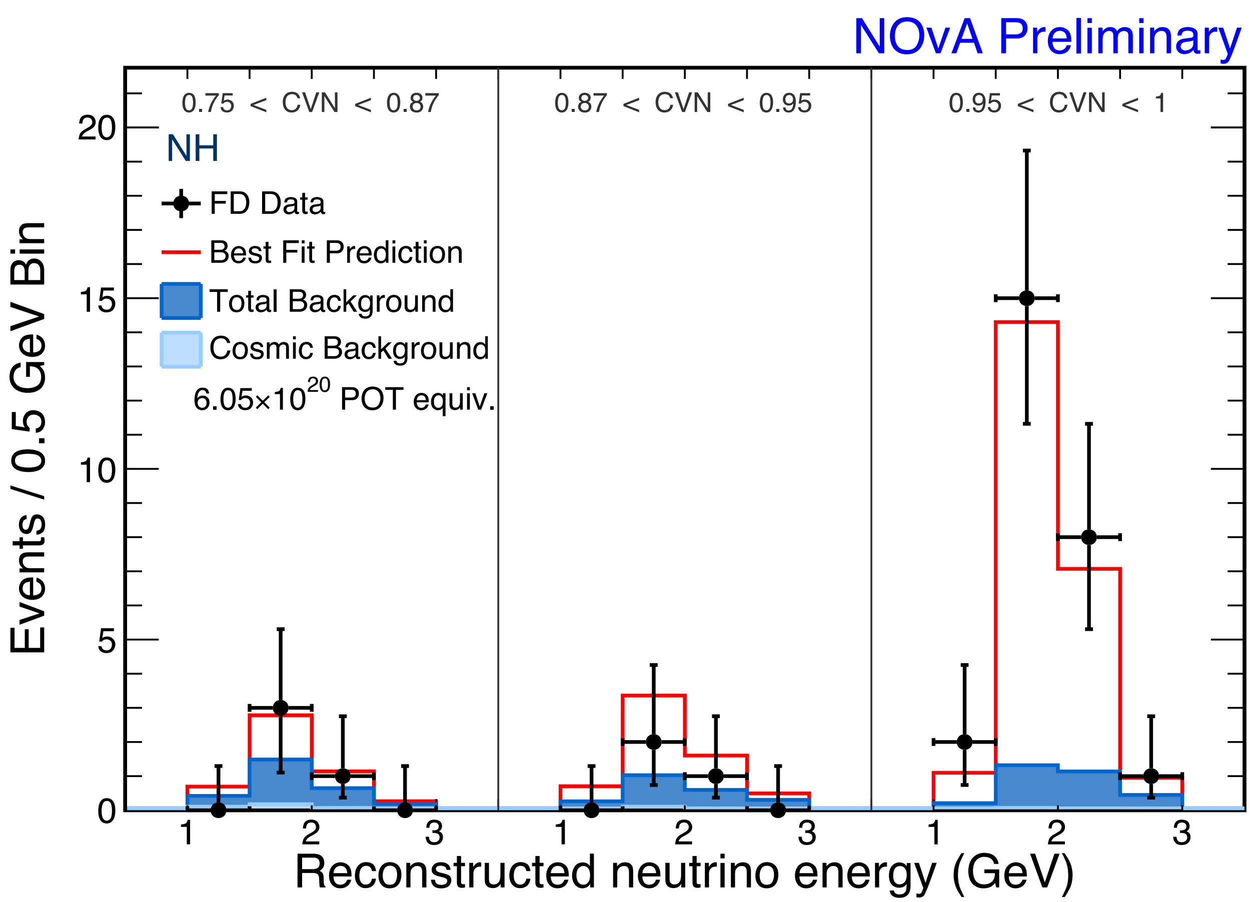
Best Fit (in NH):

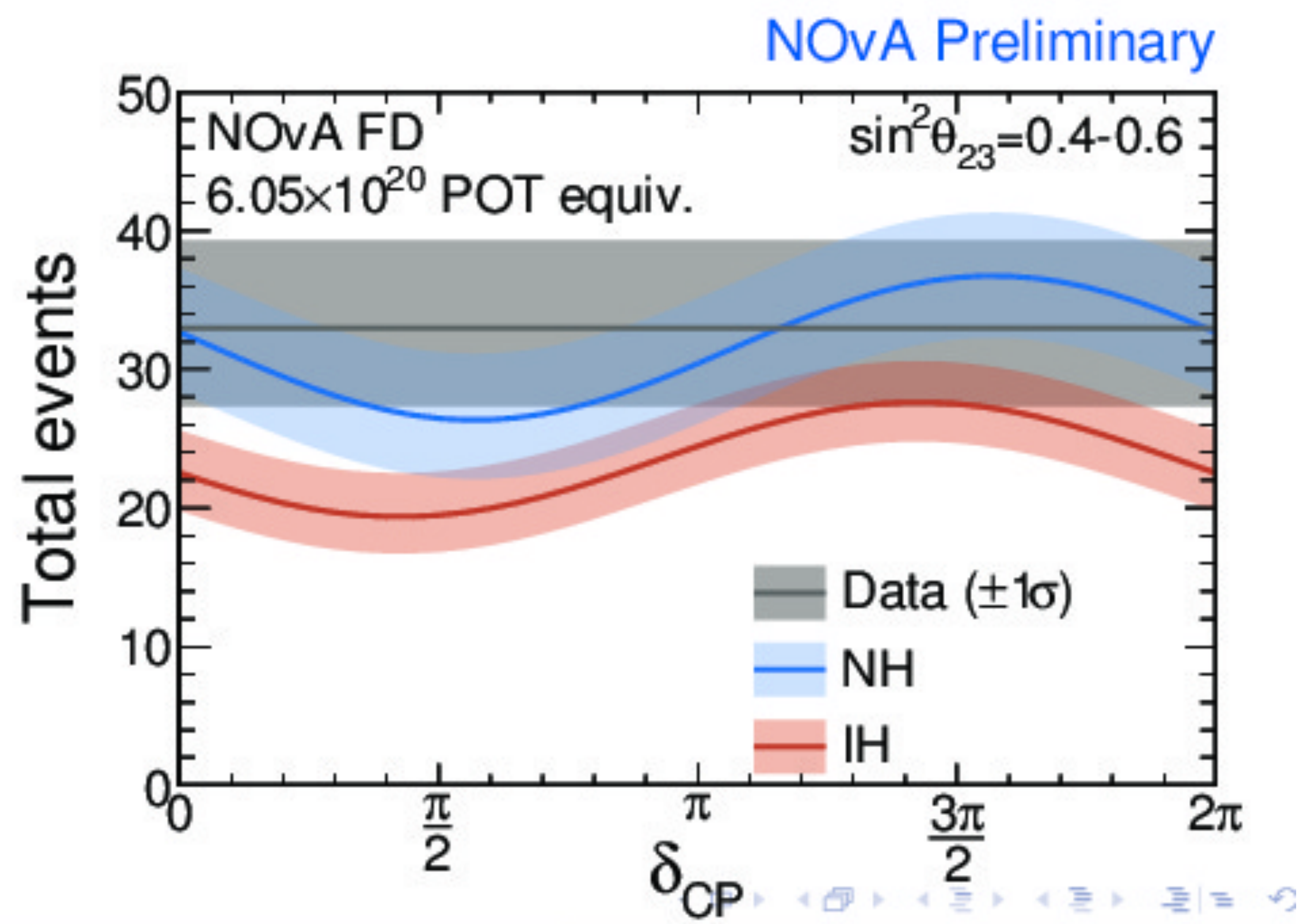
$$|\Delta m^2_{32}| = 2.67 \pm 0.12 \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}(0.63^{+0.02}_{-0.03})$$

Maximal mixing excluded at 2.5σ

LBL EXPERIMENTS : NOVA





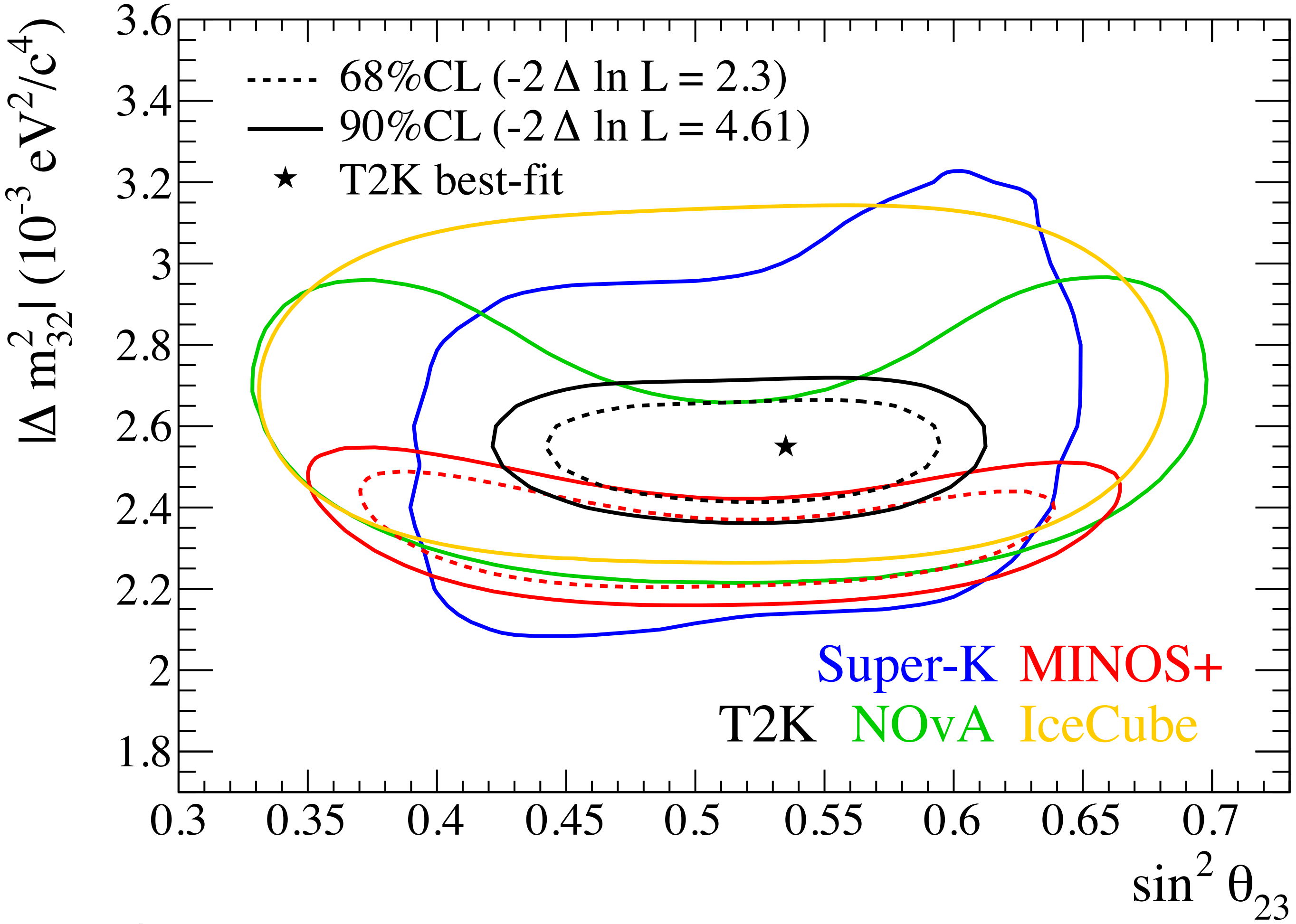
33 events observed

8.2 +/- 0.8 expected background

ν_e appearance signal @ > 8σ

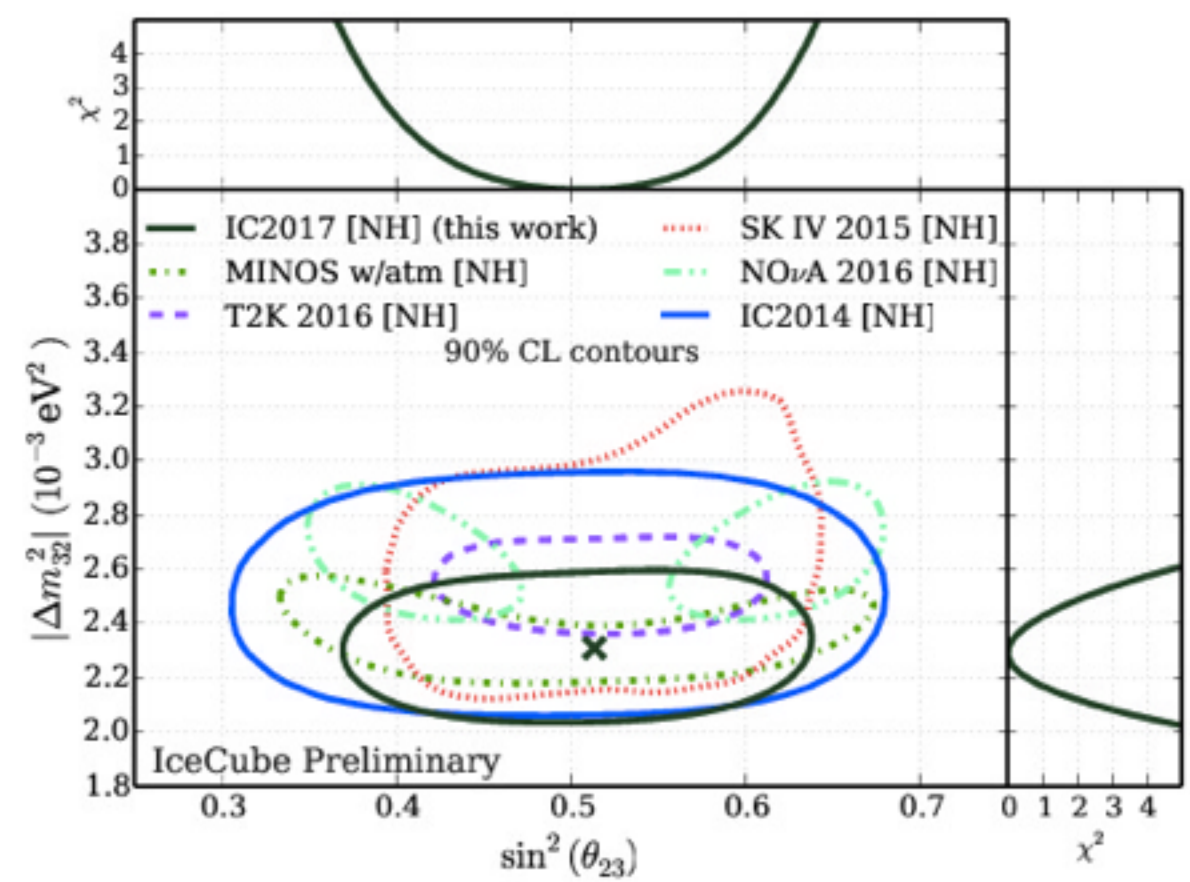
SOME COMPARISONS

Latest results of T2K



arXiv[hep-ex] 1701.00432

Latest results of NOvA and IceCube

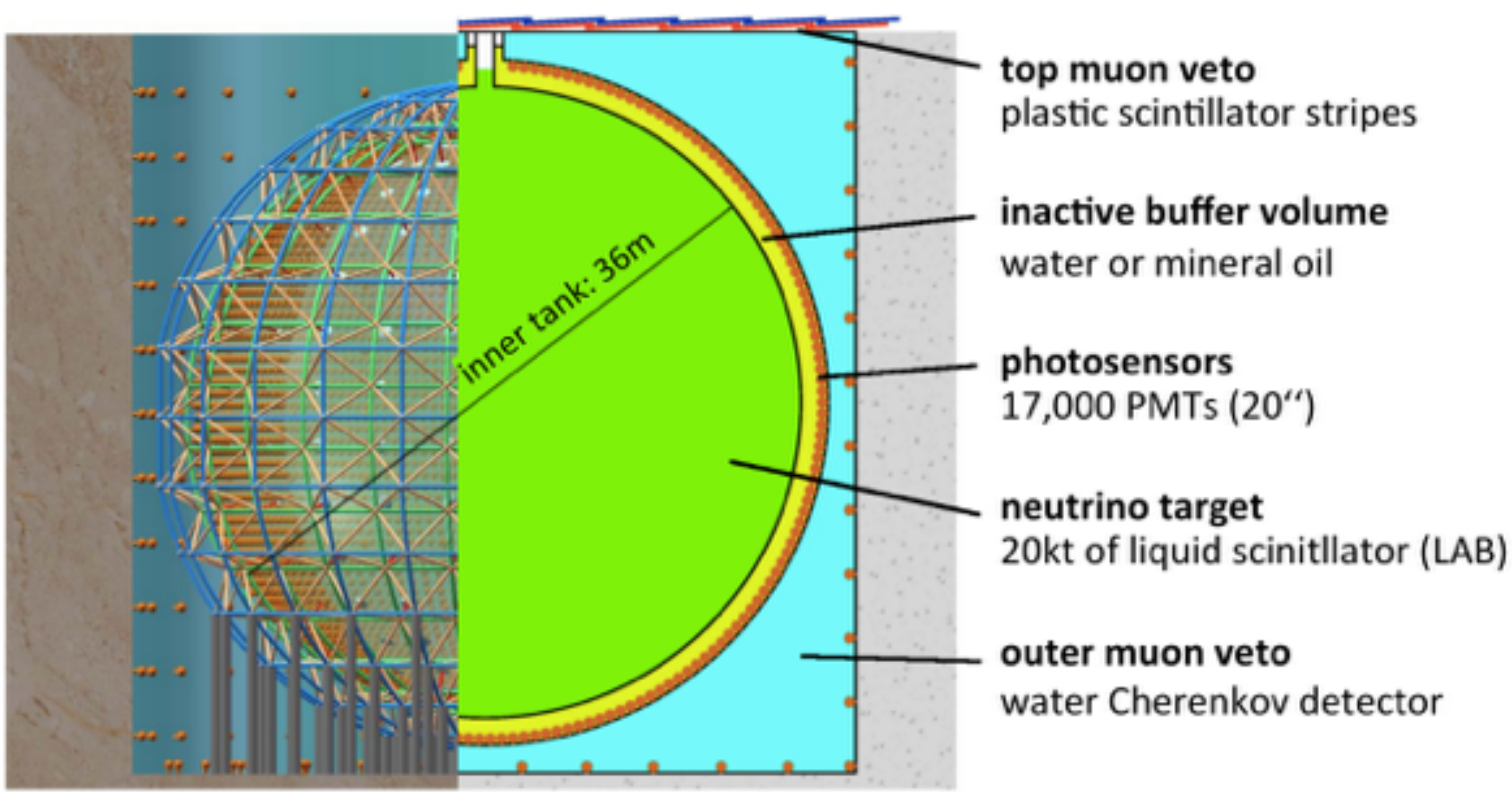


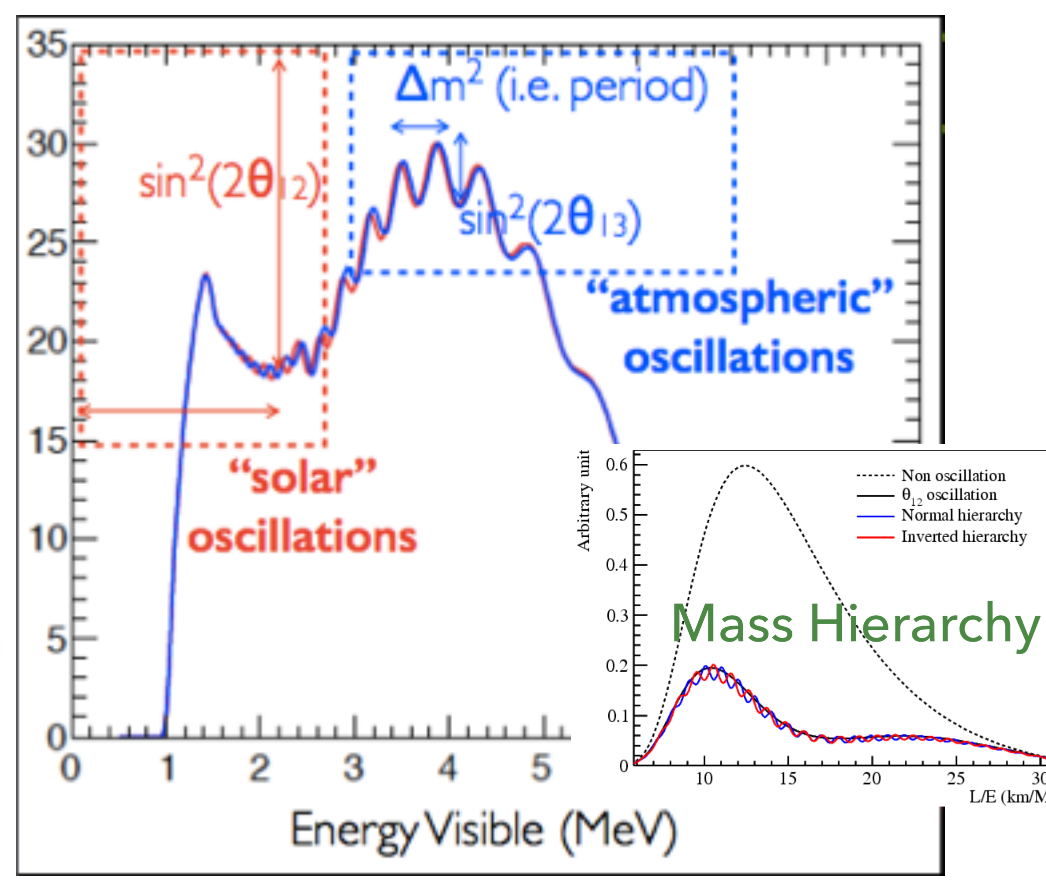
presented at APS meeting 2017

WHAT'S NEXT?

FUTURE REACTOR EXPERIMENT ?

- JUNO: New reactor experiment in China: anti-ν_e from Daya Bay power plant
- 20 kton of liquid scintillator with wide physics program
- MH determination towards oscillation interference
  - big challenge in calorimetry! Need energy resolution better than 3% ($\delta m^2/\Delta m^2$ ~3%)
- Data taking foreseen for > 2020

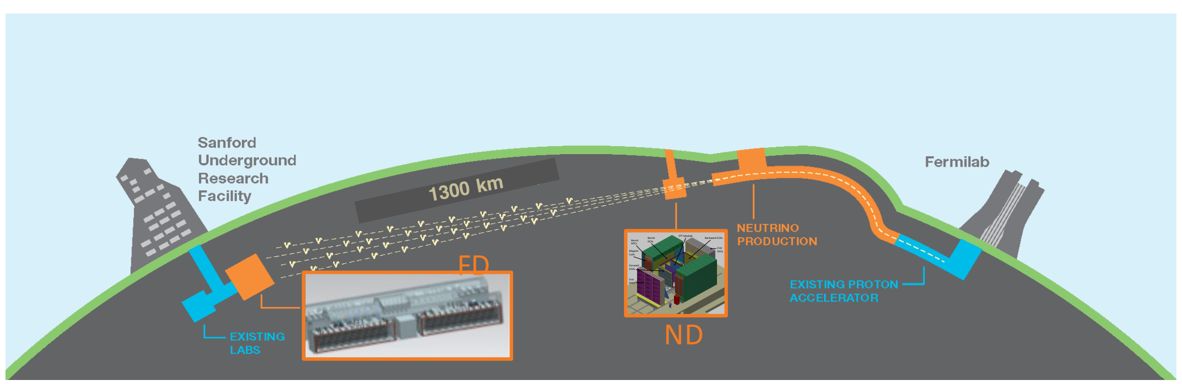


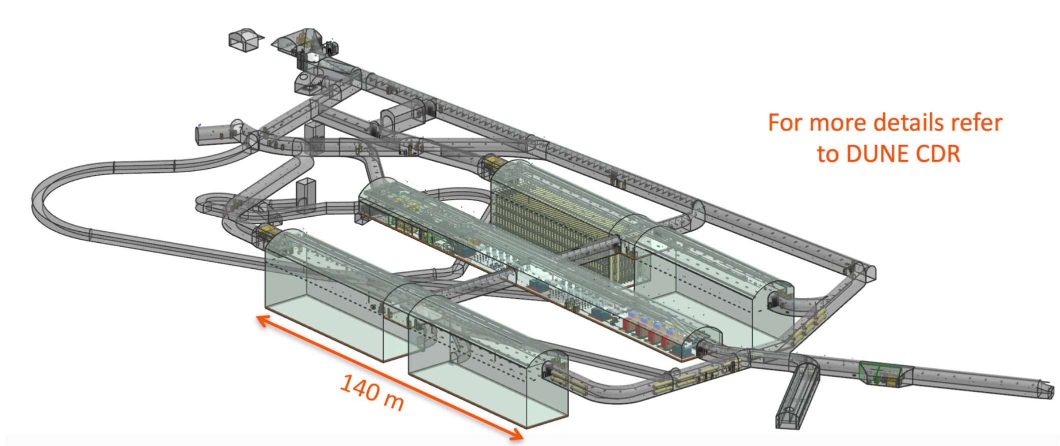


FUTURE LONG BASELINE EXPERIMENTS

DUNE

- 4 modules Liquid Ar-TPC ~10kton each
- SURF, Homestake mine (US) ~2400mwe
- On-axis beam from Fermilab (1.2-2.4 MW)
- baseline ~**1300km**
- $\langle E_\nu \rangle$ ~**3GeV**

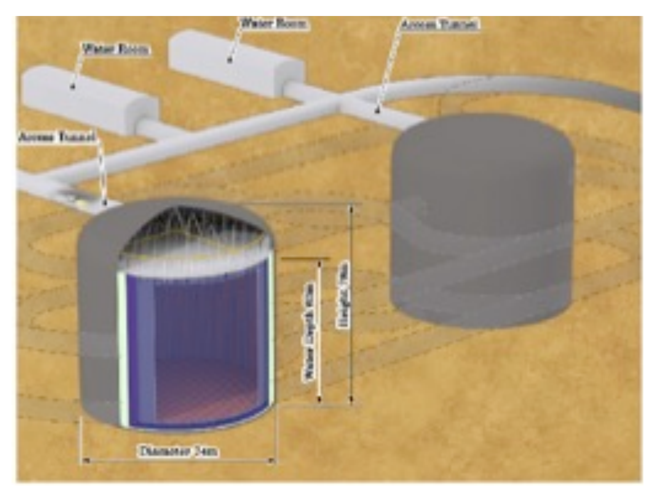


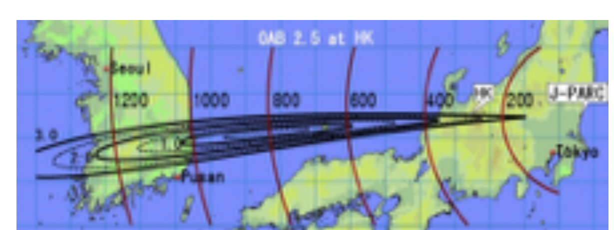


For more details refer to DUNE CDR

HYPER-KAMIOKANDE

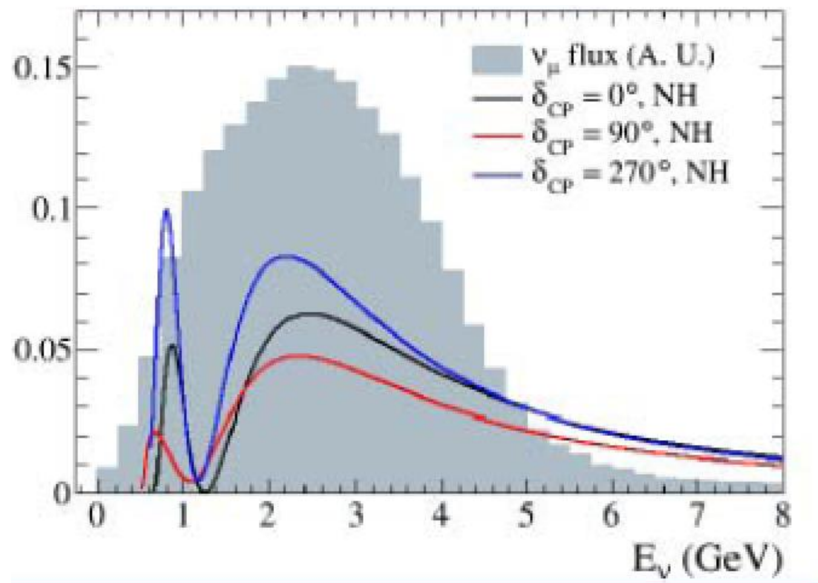
- 2 water Cherenkov of ~260 ton each
- Tochibora, near Kamioka (Japan),~1750mwe
- Off-axis beam from Tokai (1.3 MW)
- baseline ~**300km** (1100km if T2HKK)
- $\langle E_\nu \rangle$ ~**0.6GeV**



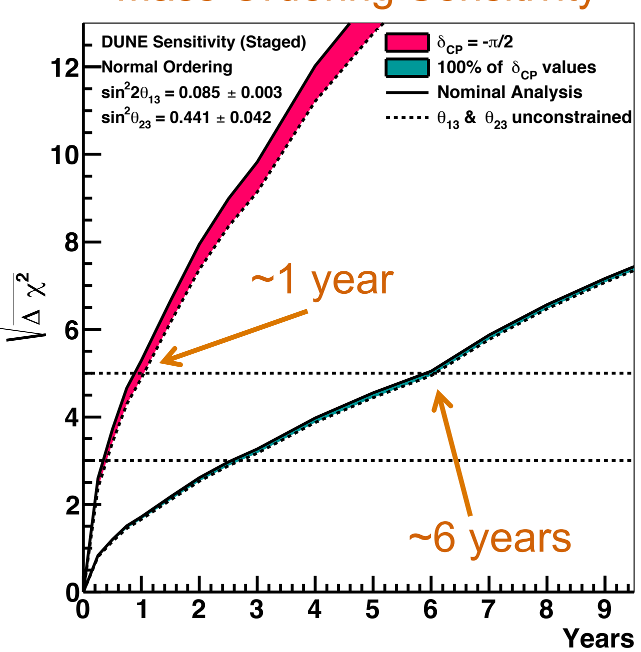


FUTURE LONG BASELINE EXPERIMENT

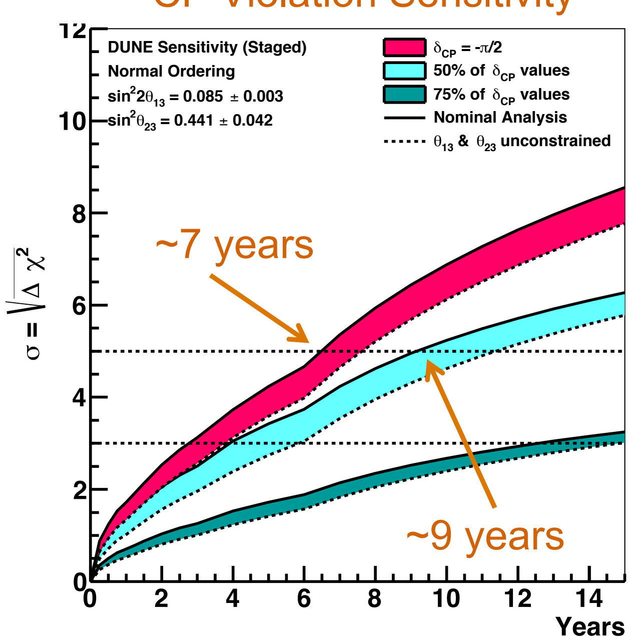
DUNE



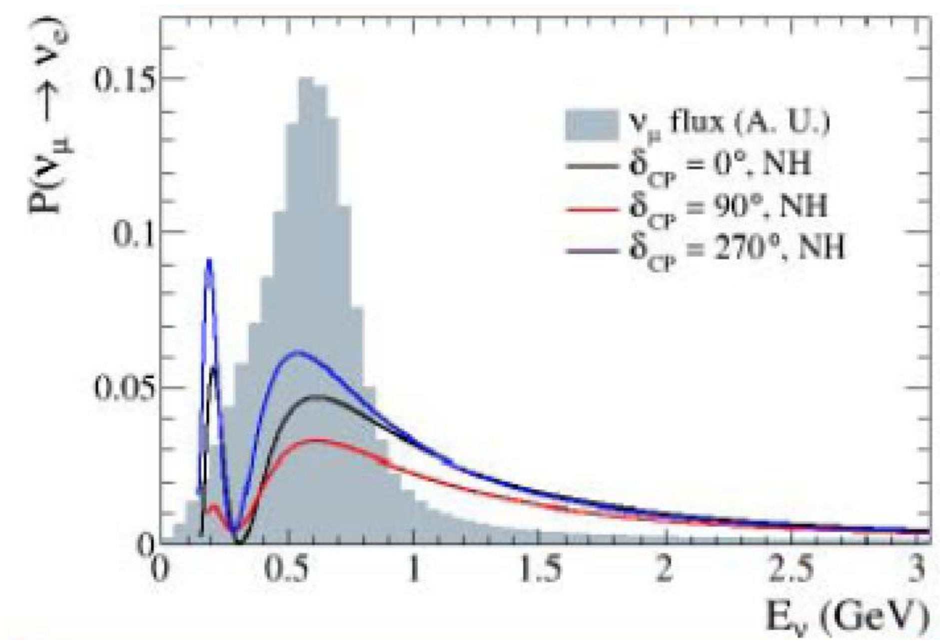
Mass Ordering Sensitivity



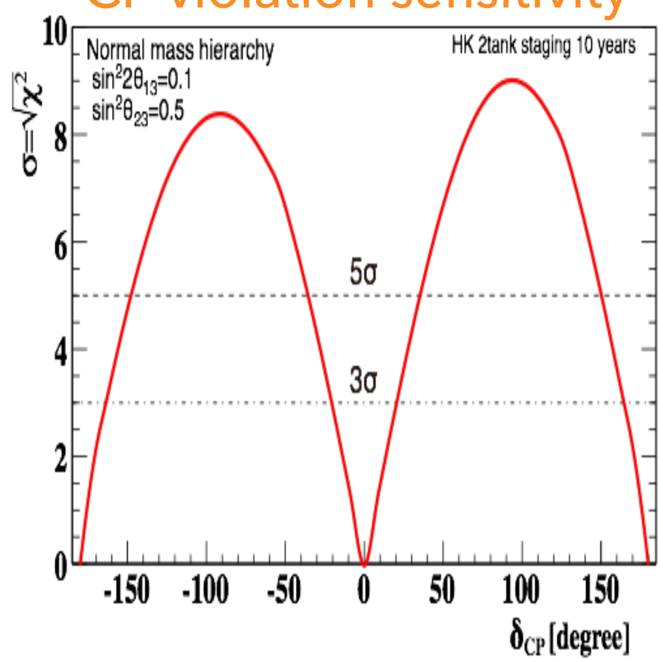
CP Violation Sensitivity



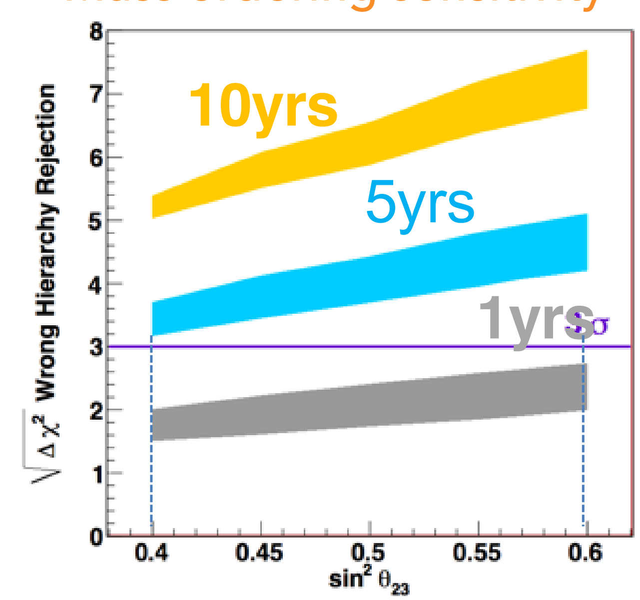
HYPER-KAMIOKANDE



CP violation sensitivity



Mass ordering sensitivity



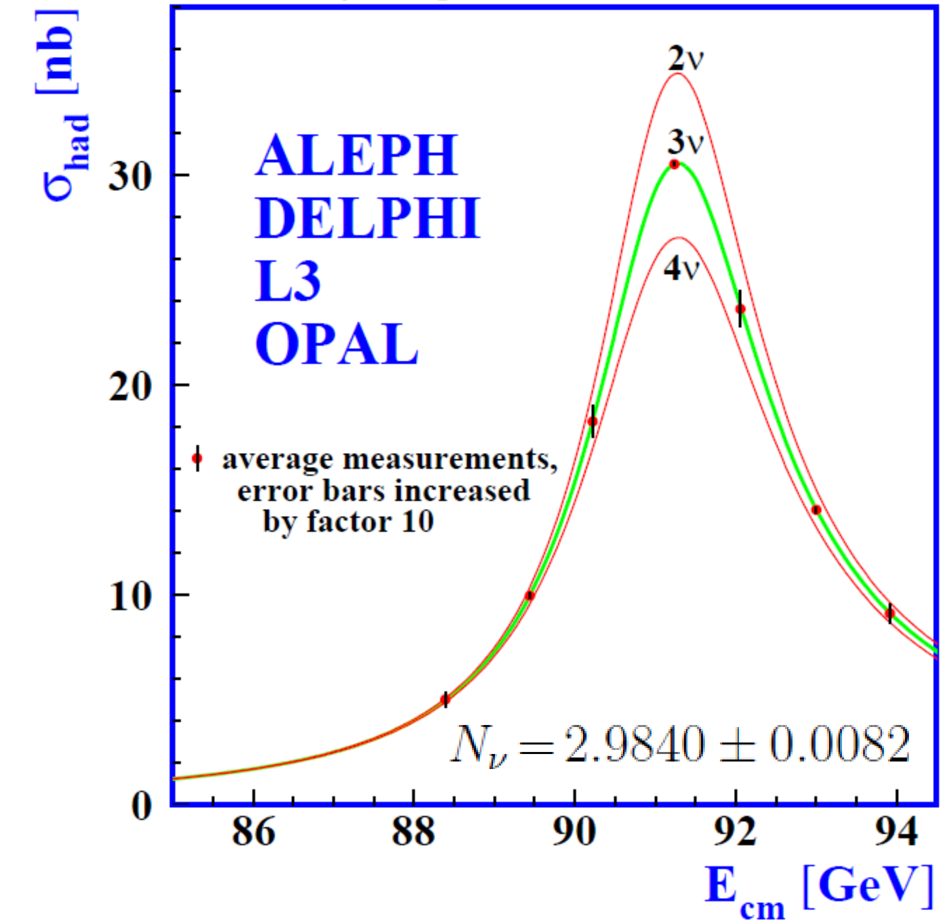
HOW MANY NEUTRINOS?

3 FAMILIES OR MORE?

- LEP measurements of the invisible Z^0 width are consistent with 3 families of light neutrinos
- If other neutrinos exist, they should be "sterile" : not coupling with the Z boson
- The only way to detect sterile neutrinos is towards the possible missing to active neutrinos

from Symmetry magazine

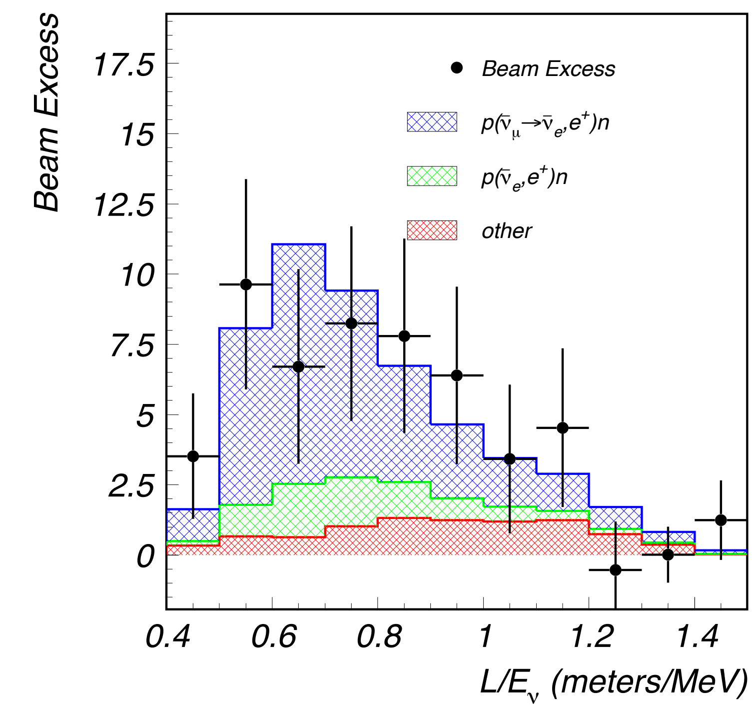
Phys.Rept. 427, 257 (2006)



THE EARLY HISTORY: ν_e APPEARANCE AT 1m/MeV

LSND (1993 -1998) baseline 30 m   (**L/E ~ m/MeV**)

- **excess in the anti-ν_μ → anti-ν_e** compatible with $\Delta m^2 \simeq 0.2$ eV^2

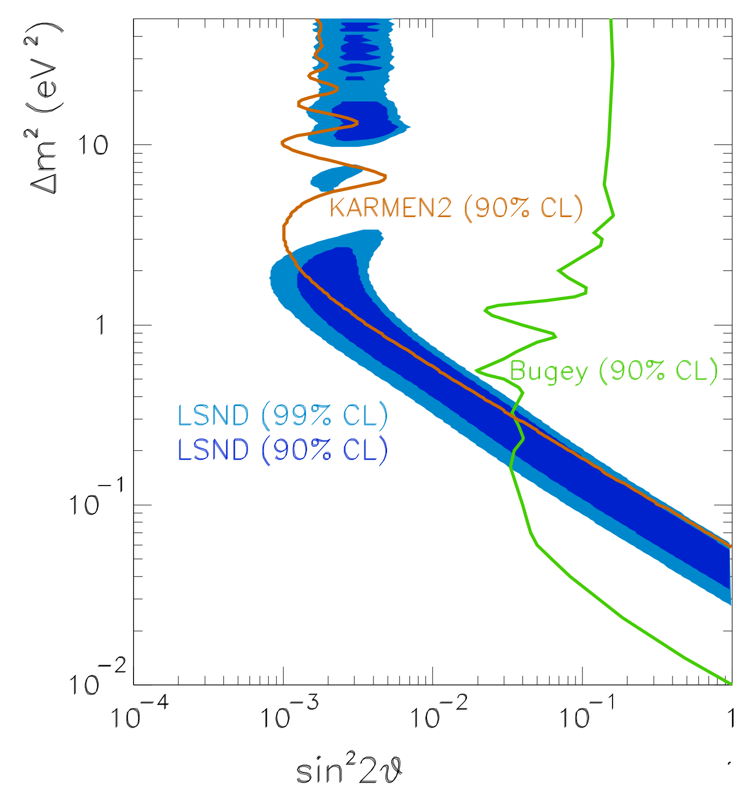


KARMEN (1993 -1998) baseline 18 m (**L/E ~ m/MeV**)

- very similar experiment to LSND
- **no excess in the anti-ν_μ → anti-ν_e**

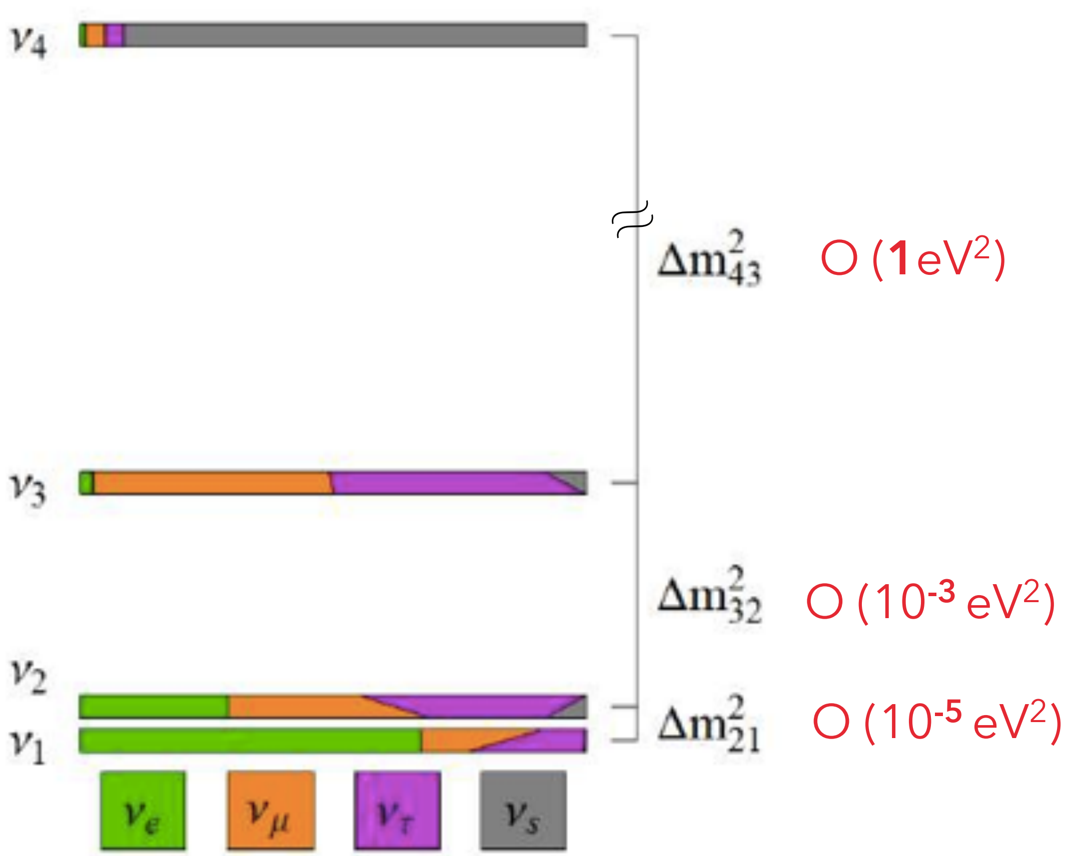
Bugey (80's-90's) baseline 15, 40 and 95 m

- reactor experiment
- **no excess in the anti-ν_e → anti-ν_e**



STERILE NEUTRINOS

- The LSND anomaly (i.e. possible short baseline oscillations) suggest a third independent $\Delta m^2 \sim 1$ eV^2
- This might be explained by introducing 4th neutrino but it should be ***sterile***
  - not interaction via weak force or too massive for the Z to decay to (not visible at LEP)
  - mixing with the active neutrinos
  - large mass splitting (Δm^2) ~ 1 eV^2



how many sterile? 1, 2 . . . . N ?

- Different models exist to introduce sterile neutrinos : 3+1, 1+3, 3+2, 1+3+1..
- focussing here on the simplest model: 3+1

STERILE NEUTRINOS

- Considering the 3+1 model. Because of the large mass splitting (1eV^2), the other neutrino masses appear degenerate
  - $\Delta m^2_{41} \approx \Delta m^2_{43} \approx \Delta m^2_{24}$
  - approximation to 2 neutrino flavour-mixing

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} \simeq \sin^2 2\vartheta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2$$

$$P^{\text{SBL}}_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\alpha} \simeq 1 - \sin^2 2\vartheta_{\alpha\alpha} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right) \qquad \sin^2 2\vartheta_{\alpha\alpha} = 4|U_{\alpha 4}|^2 \left(1 - |U_{\alpha 4}|^2\right)$$

LBL (usual PMNS matrix)

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

SBL

ν_e DIS
$\sin^2 2\vartheta_{ee} \simeq 4|U_{e4}|^2$

ν_μ DIS
$\sin^2 2\vartheta_{\mu\mu} \simeq 4|U_{\mu 4}|^2$

$\nu_\mu \to \nu_e$ APP
$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu 4}|^2 \simeq \frac{1}{4}\sin^2 2\vartheta_{ee} \sin^2 2\vartheta_{\mu\mu}$

[Okada, Yasuda, IJMPA 12 (1997) 3669; Bilenky, CG, Grimus, EPJC 1 (1998) 247]

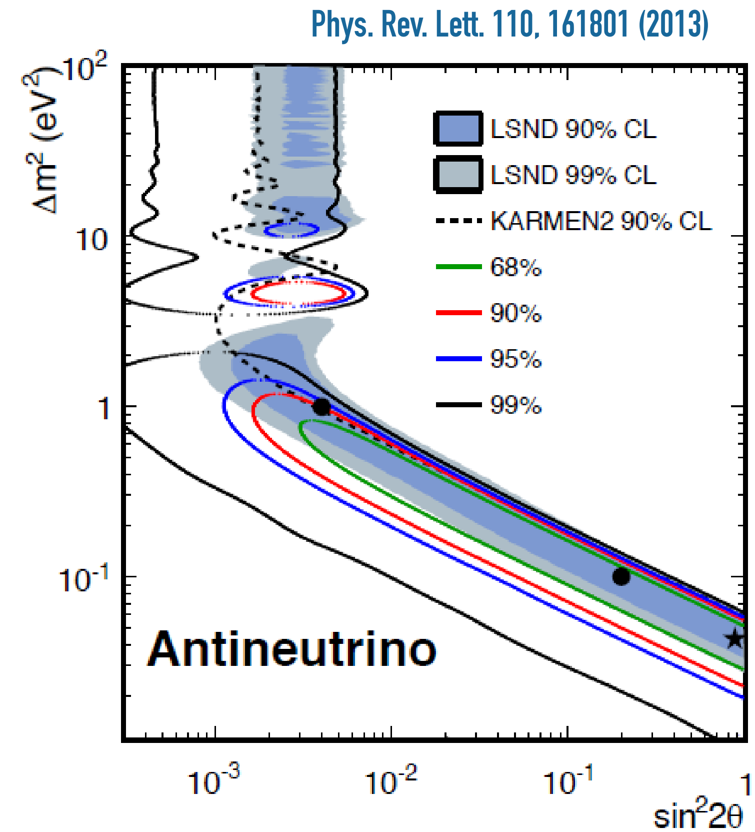
courtesy of C. Giunti

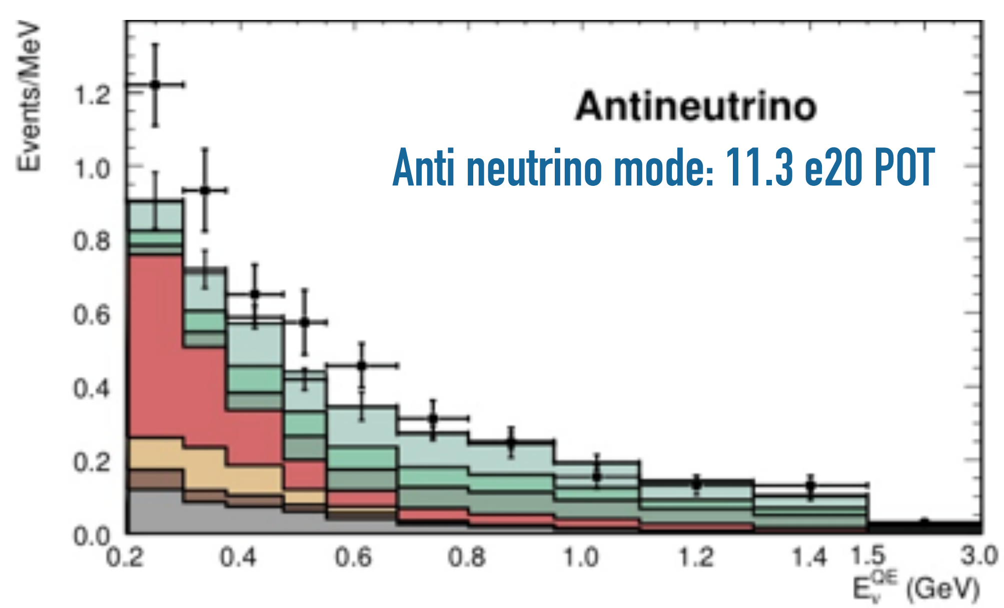
ν_e APPEARANCE AT 1m/MeV

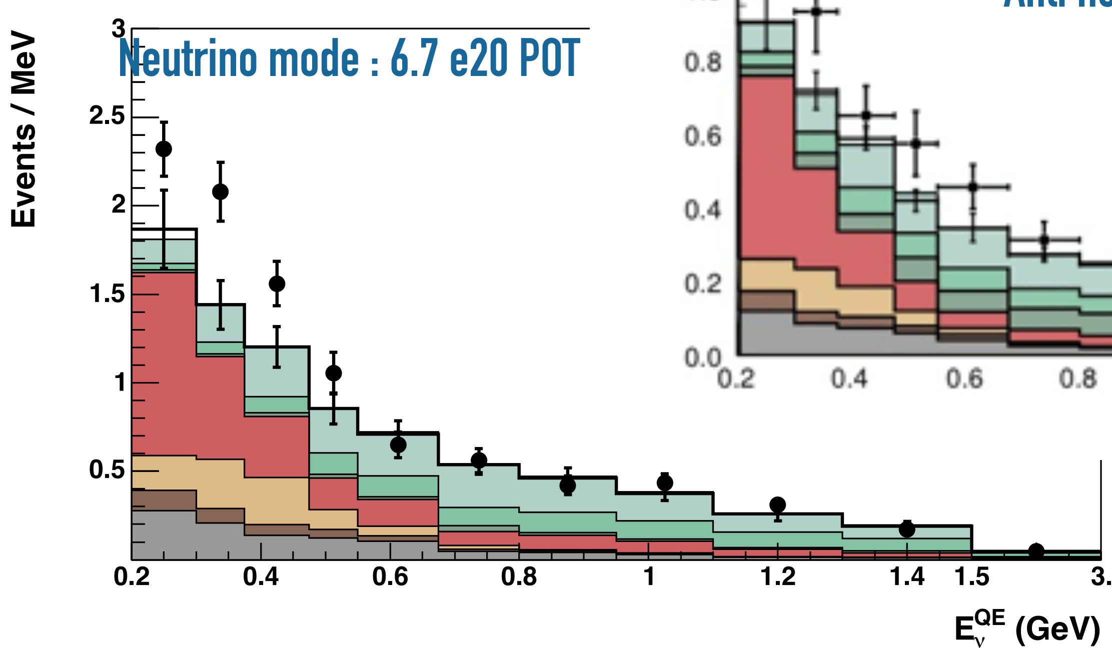
MiniBooNE (2002 -2012) baseline 541 m : L/E ~m/MeV

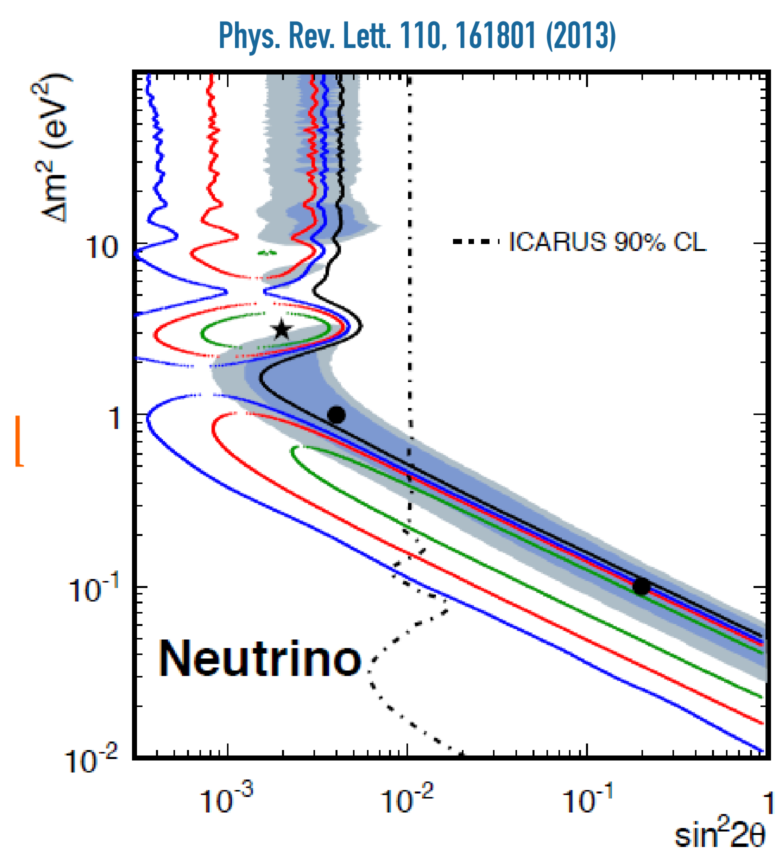
- designed to address the LSND anomaly
- excess in both $\nu_\mu \rightarrow \nu_e$ and anti-$\nu_\mu \rightarrow$ anti-ν_e compatible to the LSND results
- MiniBooNE compatibility is marginal and other experiments exclude large part of LSND region.

Not conclusive measurements!





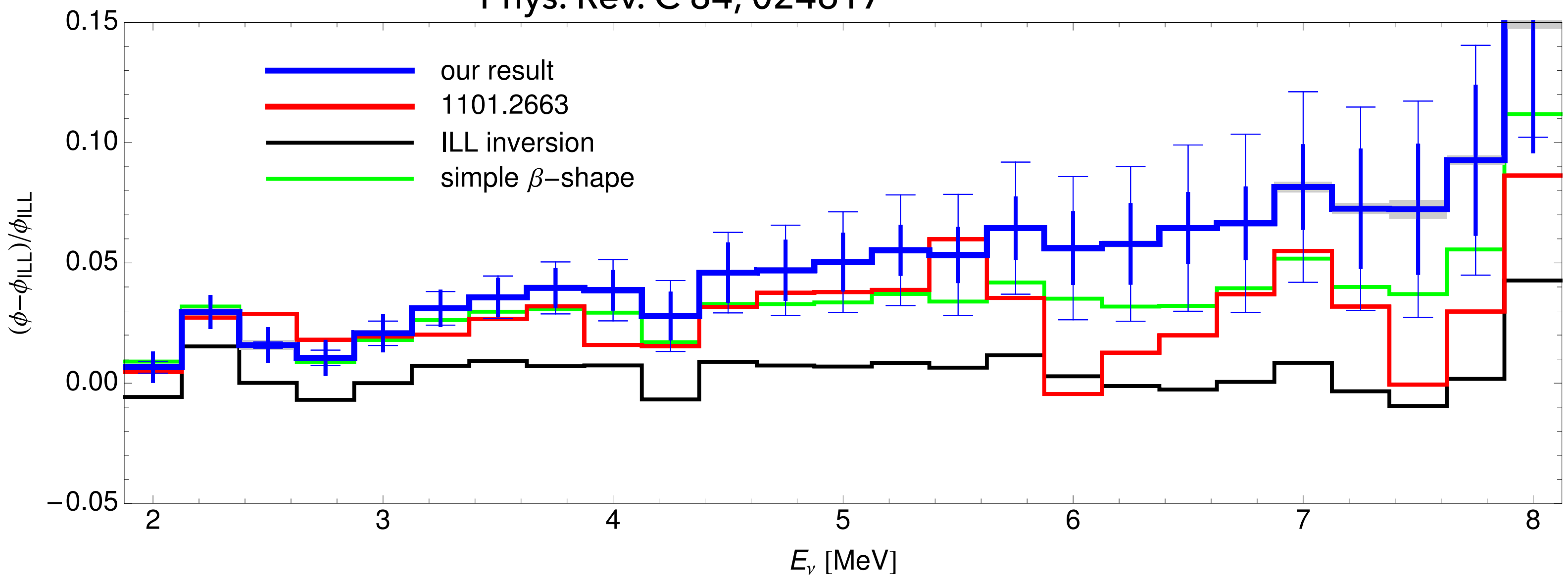




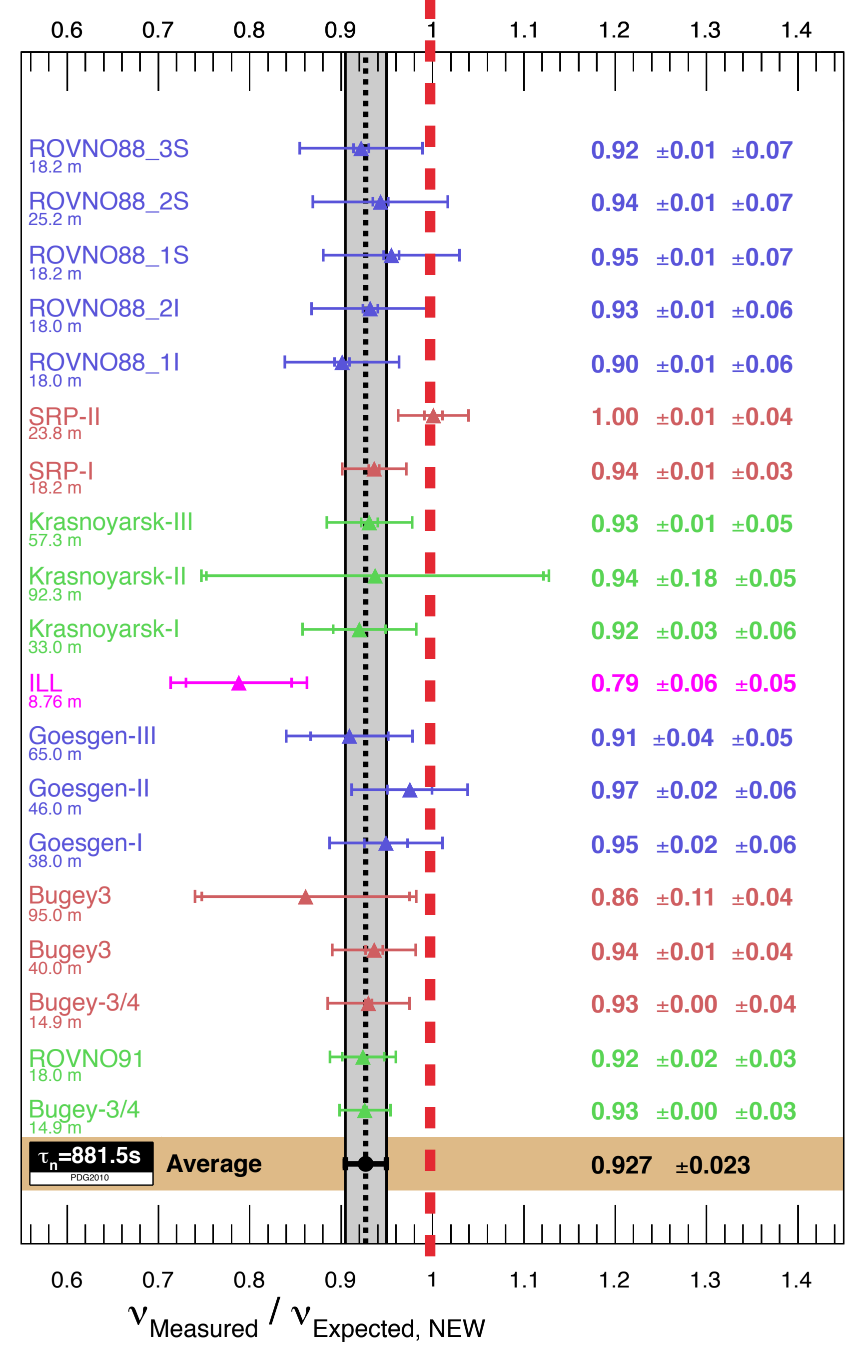
ν_e DISAPPEARANCE AT 1m/MeV

- Reactor neutrino fluxes have been recalculated in 2011
- With the new flux almost all short base reaction have deficits! the so called: *reactor anomaly*

Phys. Rev. C 84, 024617



Phys. Rev. D 83, 073006



R_{avg}= 0.927 ± 0.023

ν_e DISAPPEARANCE AT >1m/MeV

- GALLEX and SAGE experiment (solar neutrino experiments) using radioactive sources ^{51}Cr and ^{37}Ar for calibration purpose

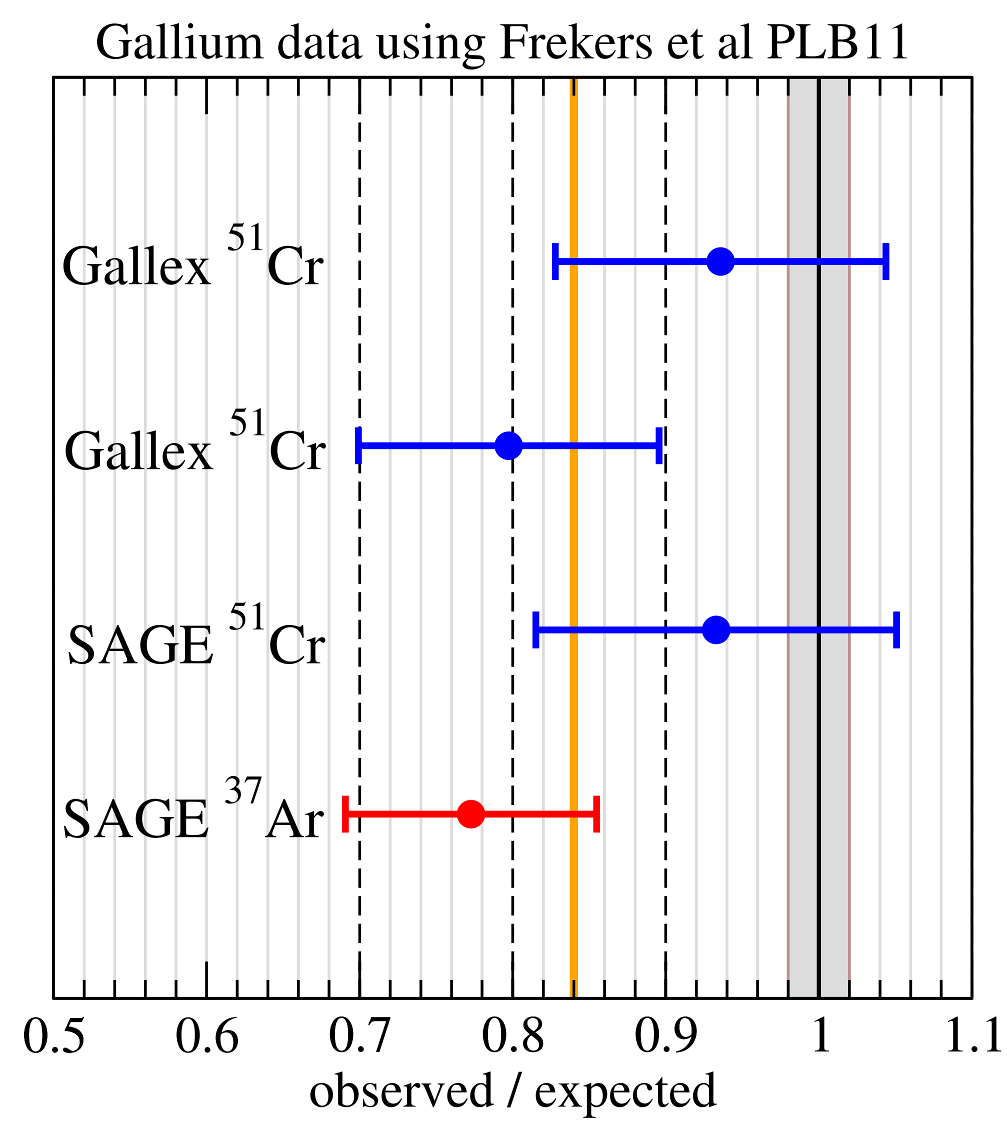
$$e^- + {}^{51}\mathrm{Cr} \to {}^{51}\mathrm{V} + \nu_e\,,$$
$$e^- + {}^{37}\mathrm{Ar} \to {}^{37}\mathrm{Cl} + \nu_e\,,$$

- detection technique as for solar neutrinos

$$\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-$$

- Number of measured events about 2.9σ smaller than expected

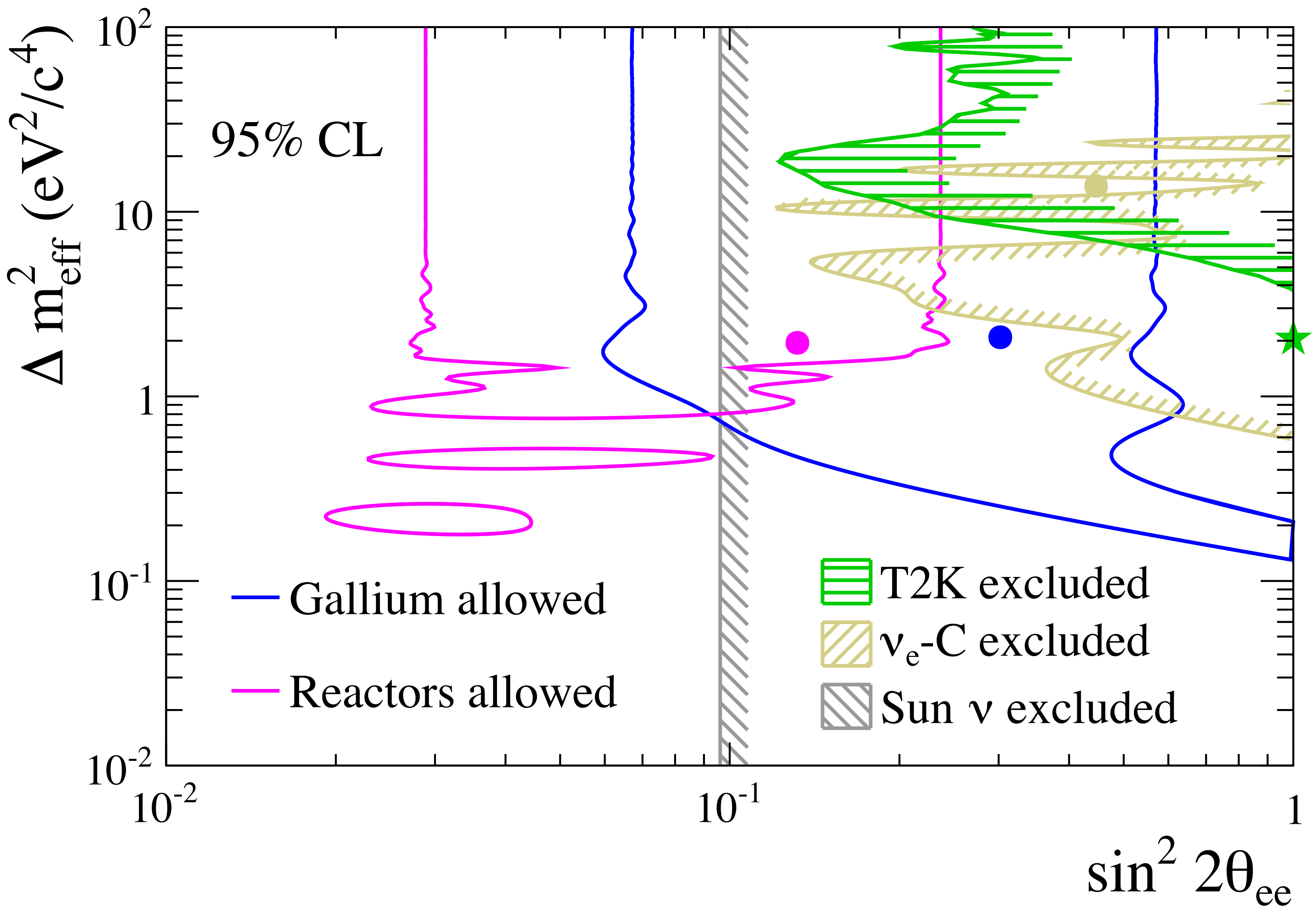
R= 0.84 ± 0.05



ν_e DISAPPEARANCE AT 1m/MeV

- But other experiments did NOT observe any anomaly..

PRD 91, 051102(R) (2015)



SHORT SUMMARY

Some short baseline experiments reported

- hints in ν_e ($\overline{\nu}_e$) appearance
- hints in $\overline{\nu}_e$ disappearance

Reminder:

ν_e DIS
$\sin^2 2\vartheta_{ee} \simeq 4|U_{e4}|^2$

ν_μ DIS
$\sin^2 2\vartheta_{\mu\mu} \simeq 4|U_{\mu4}|^2$

$\nu_\mu \to \nu_e$ APP
$$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4}\sin^2 2\vartheta_{ee}\sin^2 2\vartheta_{\mu\mu}$$
[Okada, Yasuda, IJMPA 12 (1997) 3669; Bilenky, CG, Grimus, EPJC 1 (1998) 247]

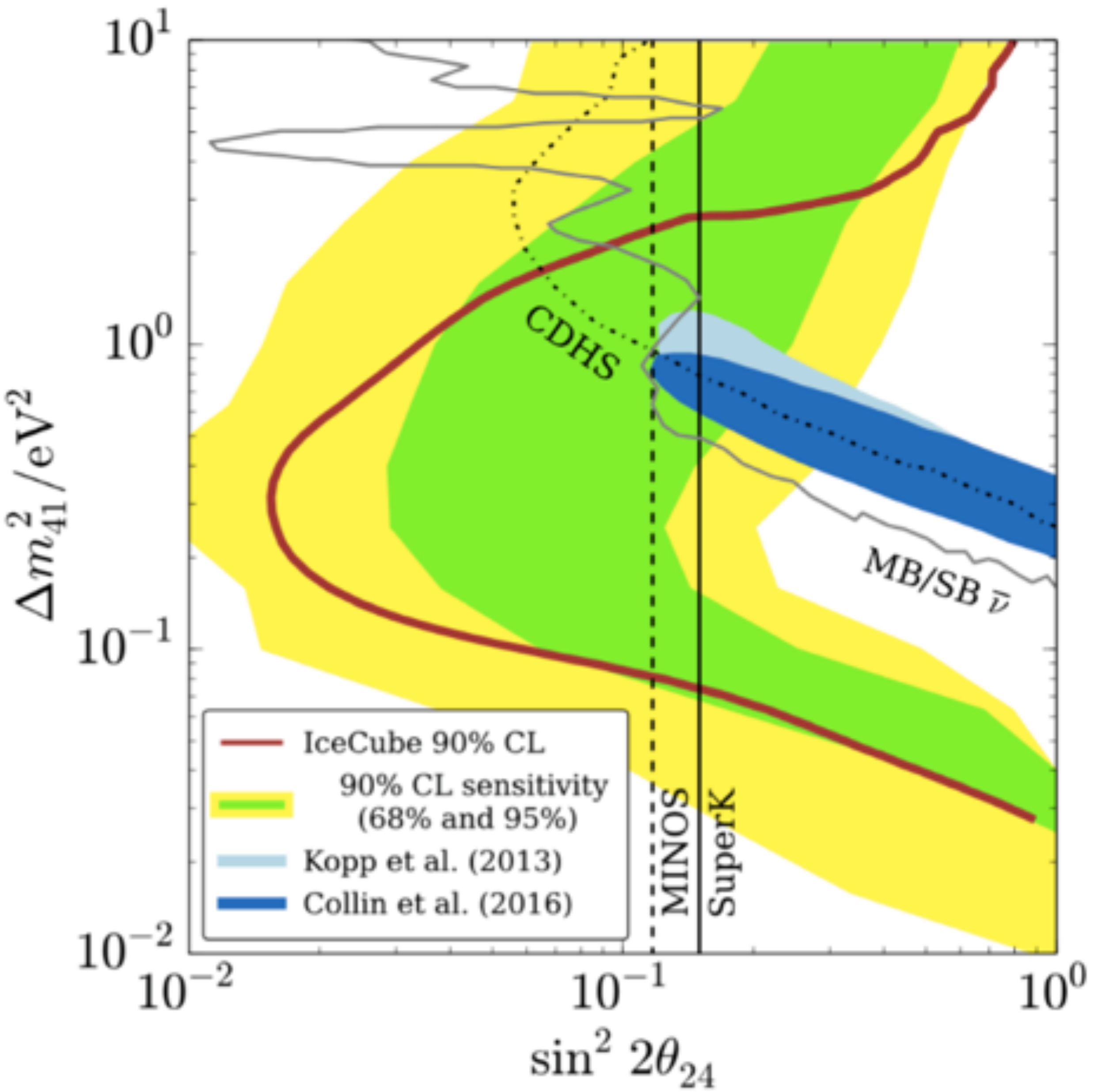
Appearance signal **require both** ν_e and ν_μ **disappearance**!

Appearance signal is **quadratically suppressed**

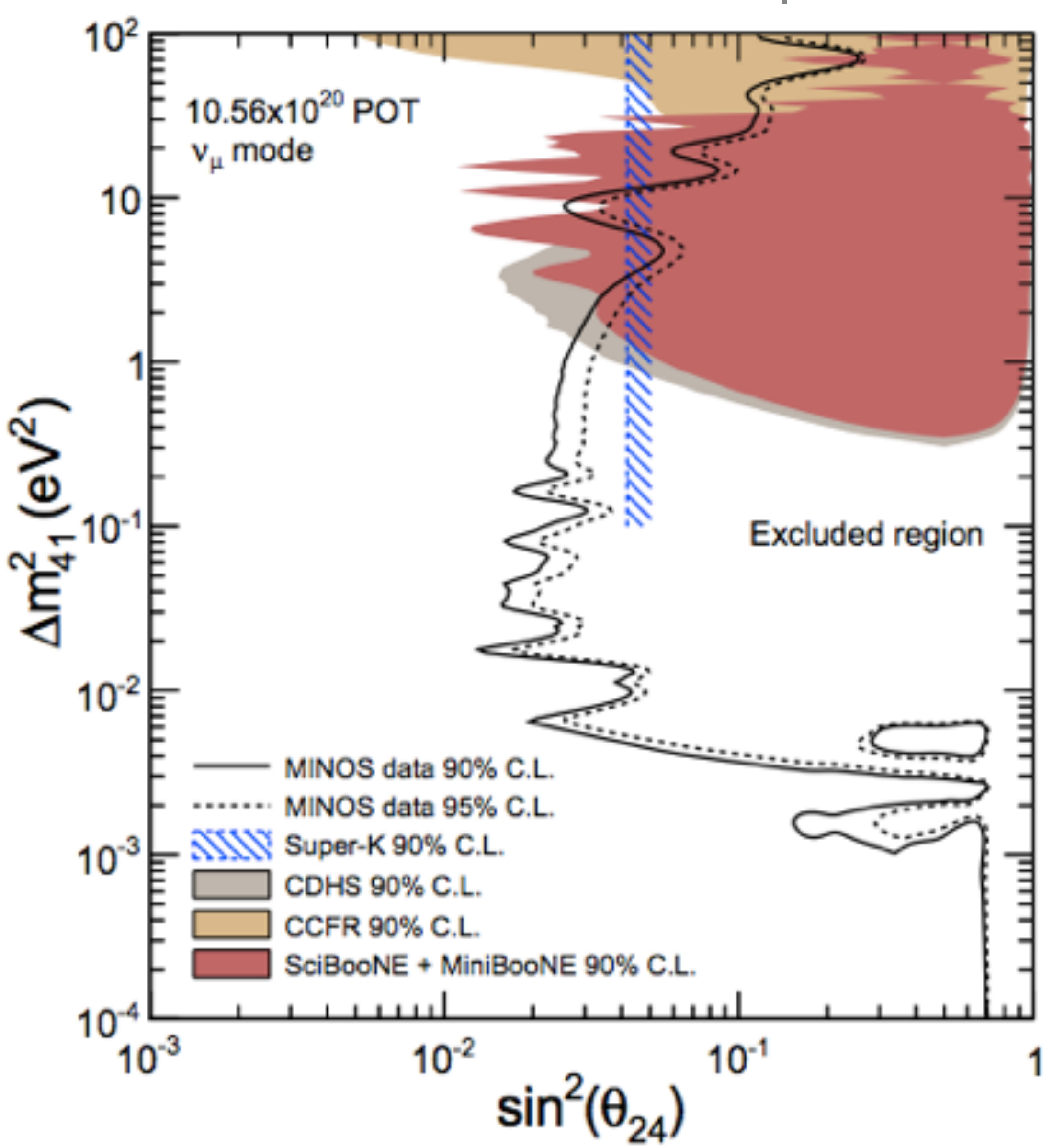
what about ν_μ disappearance ?

SHORT SUMMARY

- No anomaly observed in $\overset{(-)}{\nu}_\mu$ disappearance channel so far..

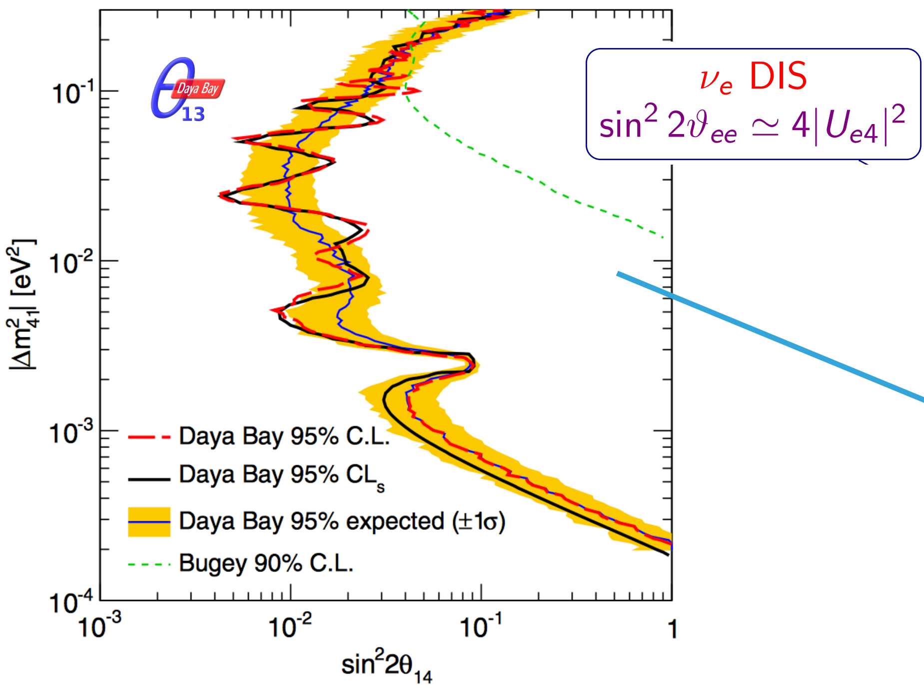


arXiv:1607.01176 [hep-ex]

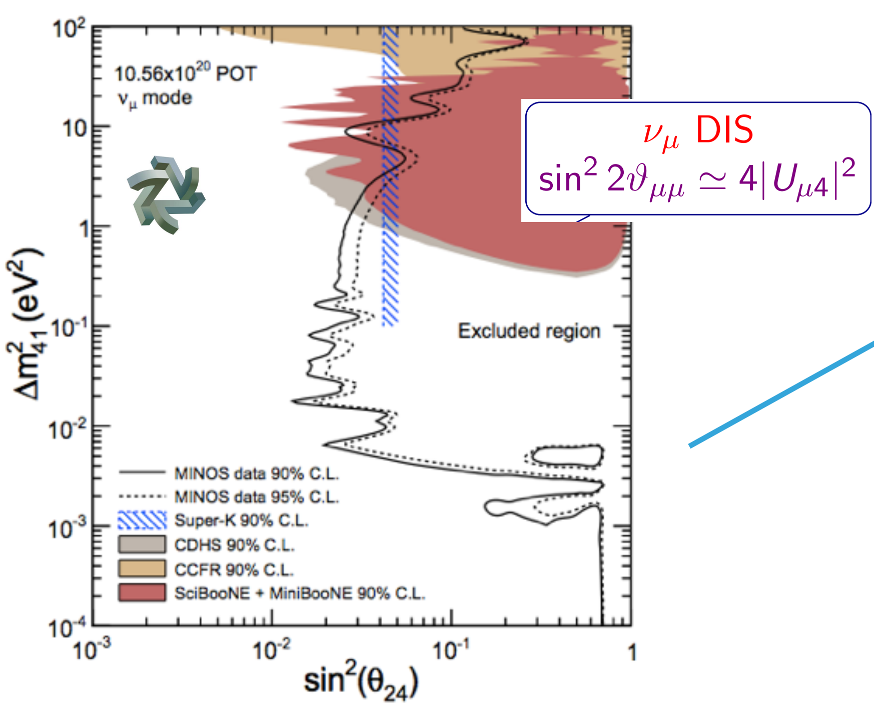


SOME LATEST RESULTS

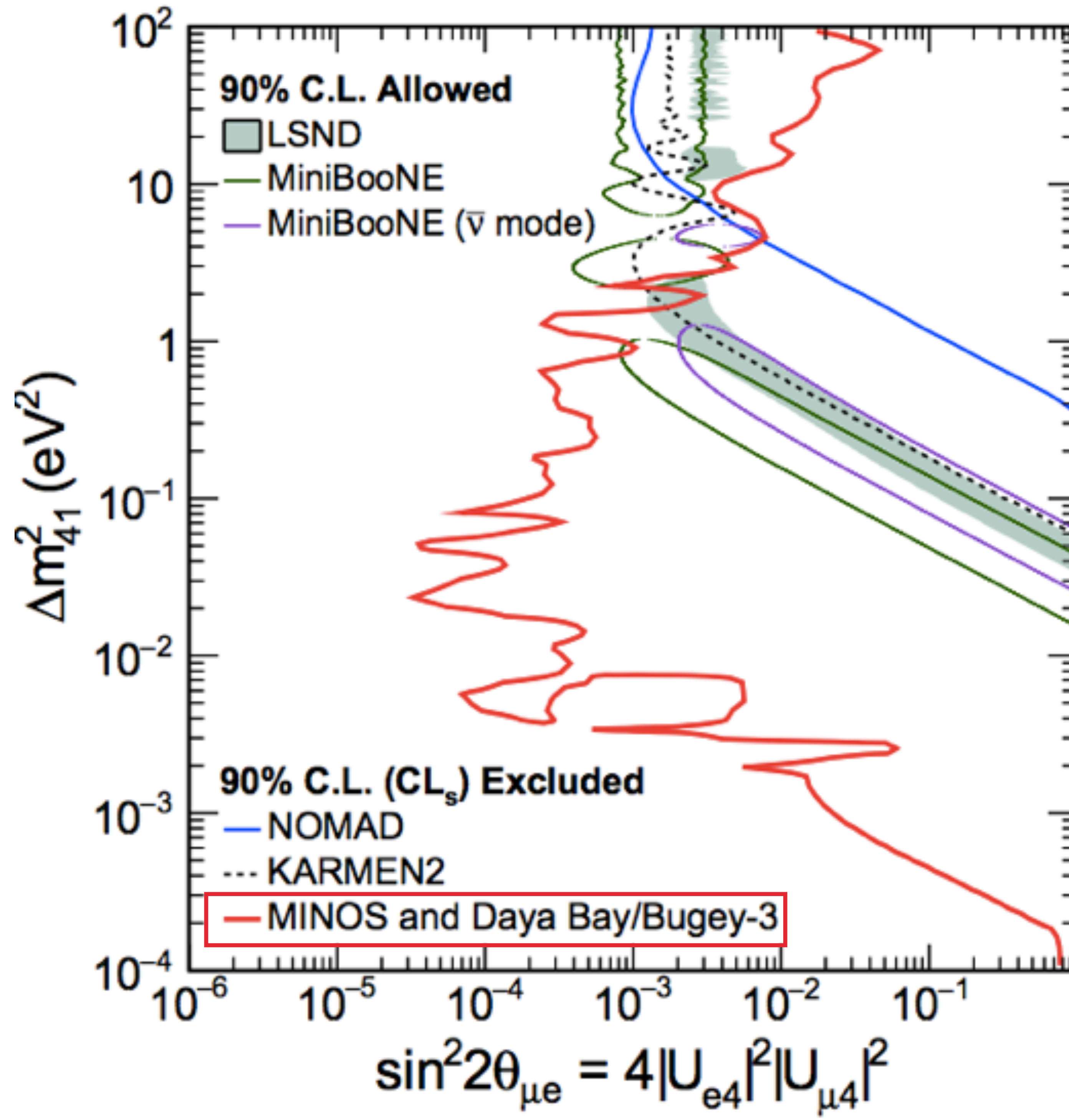
PRL 117, 151802 (2016)



PRL 117, 151803 (2016)

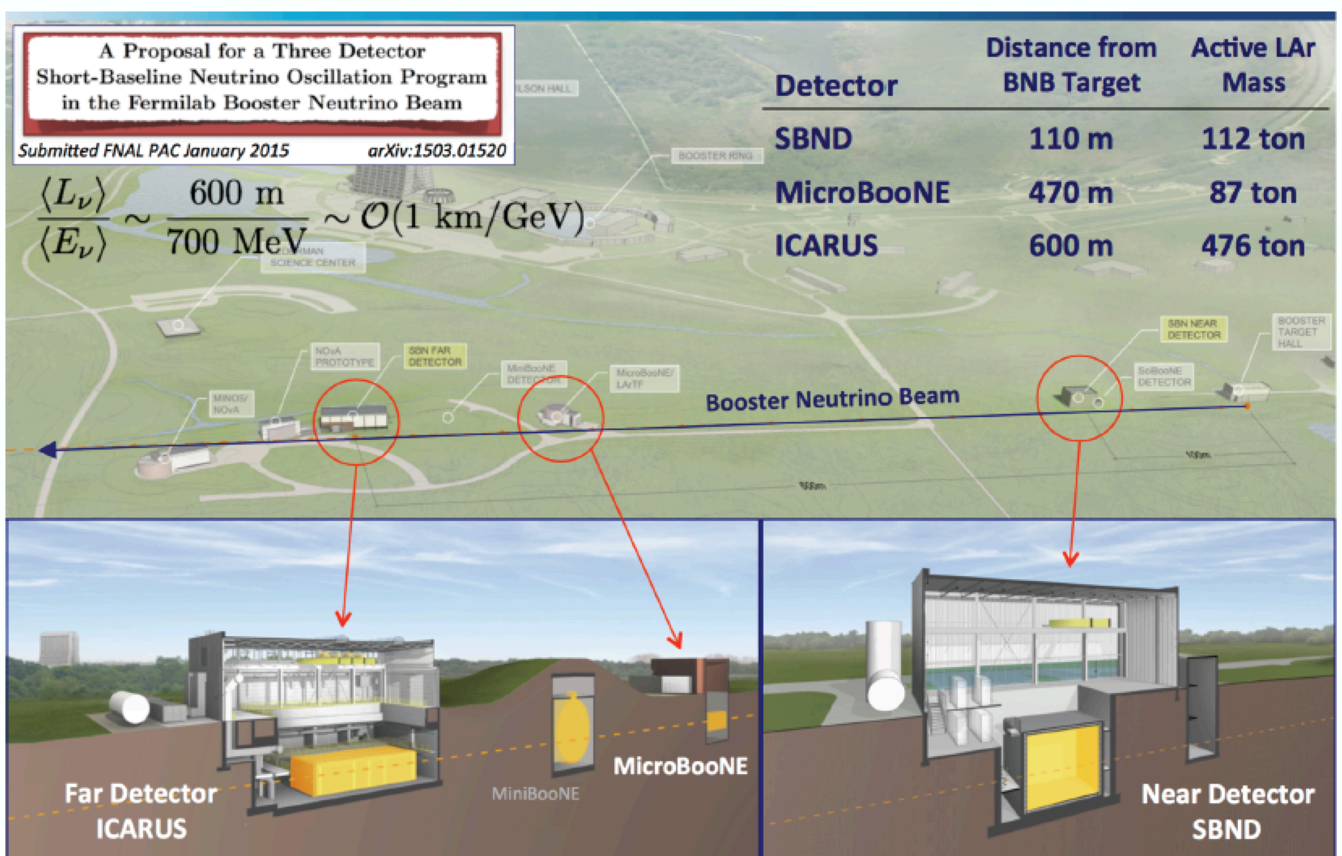


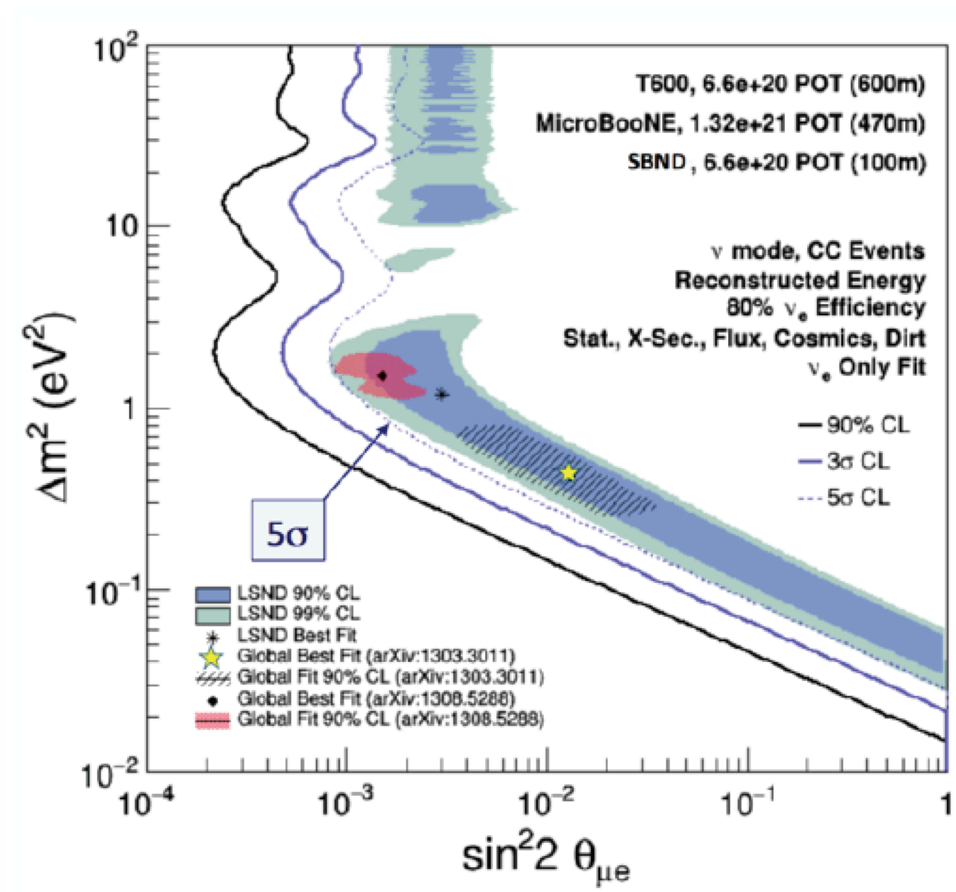
PRL 117, 151801 (2016)



WHAT'S NEXT ? *@ accelerator experiments*

- Short Baseline Program (SBND) at the Booster Beam at Fermilab
- 3 LAr detector on the same beam line at 3 different distances: definitive test of the LSND anomaly
- Complementary measurements on SBL muon disappearance

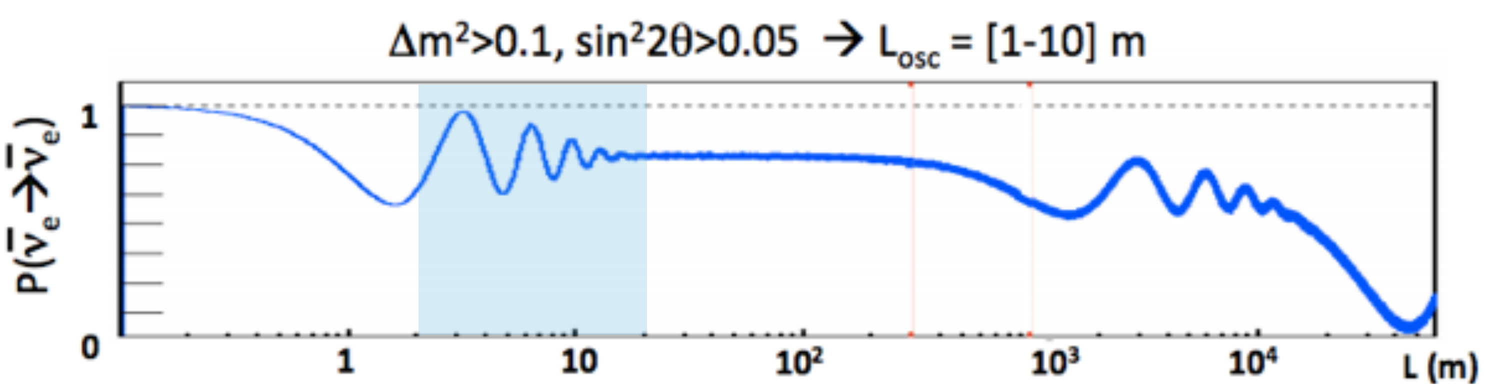


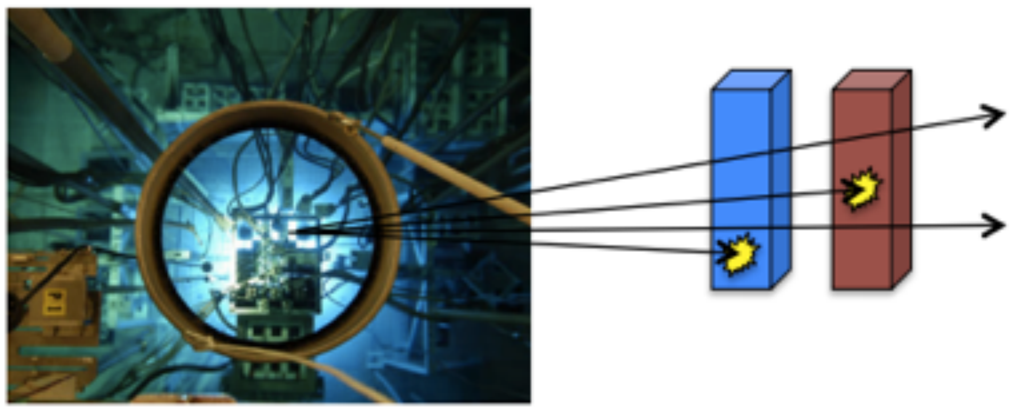


SBN proposal arxiv:1503.01520

WHAT'S NEXT ? *@ reactor experiments*

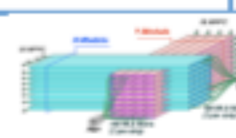
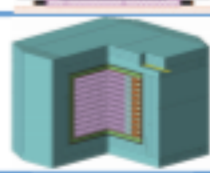
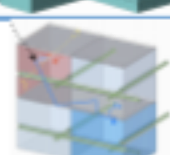
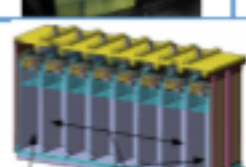
- Very short baseline reactor experiment (5 and 20 m)
- detection based on energy spectrum distortion as a function of the distance
  - extended and (highly) segmented detector to measure **relative distortion among cells** of the same detector
  - **independent from reactor flux estimations**
  - challenging experiment for bkg control (μ, n, ɣ) because on surface





SHORT BASELINE REACTOR EXPERIMENT

from N.Bowden (Neutrino 2016)

Experiment	Reactor Power/Fuel	Overburden (mwe)	Detection Material	Segmentation	Optical Readout	Particle ID Capability
DANSS (Russia) 	3000 MW LEU fuel	~50	Inhomogeneous PS & Gd sheets	2D, ~5mm	WLS fibers.	Topology only
NEOS (South Korea) 	2800 MW LEU fuel	~20	Homogeneous Gd-doped LS	none	Direct double ended PMT	recoil PSD only
nuLat (USA) 	40 MW ^{235}U fuel	few	Homogeneous ^{6}Li doped PS	Quasi-3D, 5cm, 3-axis Opt. Latt	Direct PMT	Topology, recoil & capture PSD
Neutrino4 (Russia) 	100 MW ^{235}U fuel	~10	Homogeneous Gd-doped LS	2D, ~10cm	Direct single ended PMT	Topology only
PROSPECT (USA) 	85 MW ^{235}U fuel	few	Homogeneous ^{6}Li-doped LS	2D, 15cm	Direct double ended PMT	Topology, recoil & capture PSD
SoLid (UK Fr Bel US) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm multiplex	WLS fibers	topology, capture PSD
Chandler (USA) 	72 MW ^{235}U fuel	~10	Inhomogeneous ^{6}LiZnS & PS	Quasi-3D, 5cm, 2-axis Opt. Latt	Direct PMT/ WLS Scint.	topology, capture PSD
Stereo (France) 	57 MW ^{235}U fuel	~15	Homogeneous Gd-doped LS	1D, 25cm	Direct single ended PMT	recoil PSD

CONCLUSIONS

- breakthrough in neutrino physics with the oscillation discovery
- Impressive knowledge acquired in the last 20 years of the oscillation mechanism and the parameter measurement
- New generation of experiments will continue to improve our understanding

- Several anomalies have been reported to the standard 3-neutrino mixing
- Definitive measurements expected in the close future

THANKS!