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Long-Baseline Neutrino Oscillations

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Introduction

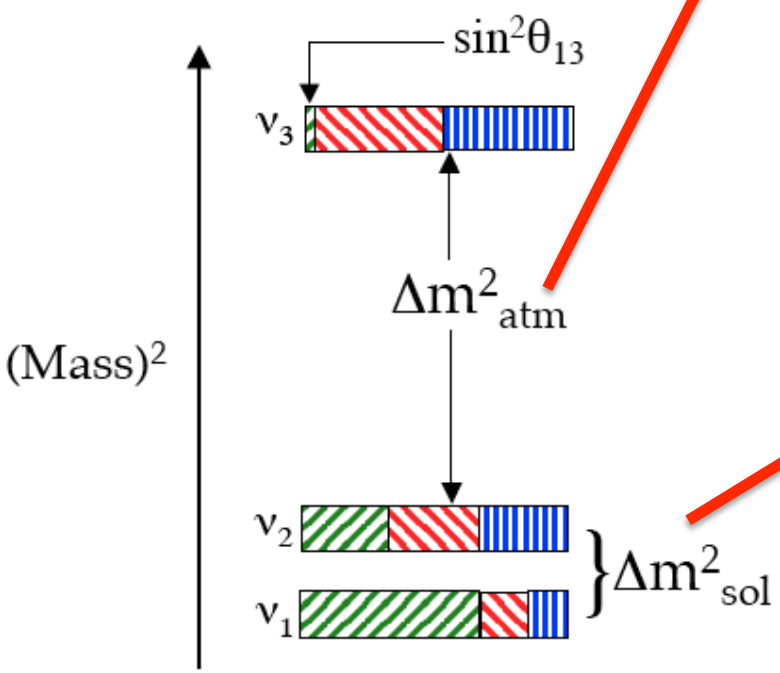
- Theory overview
- Where we stand experimentally
- Results:
  - Solar sector: Solar + KamLAND
  - Atmospheric sector: MINOS + SK
  - Subdominant sector: Chooz + MINOS
- Future:
  - Reactor expts (Double Chooz, Daya Bay and RENO)
  - Accelerator expts (NOvA)
    - T2K and LBNE (see following talks)

Theory Overview

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Subdominant term



$\Delta m^2_{31} = m_3^2 - m_1^2$, L/E≅500 km/GeV

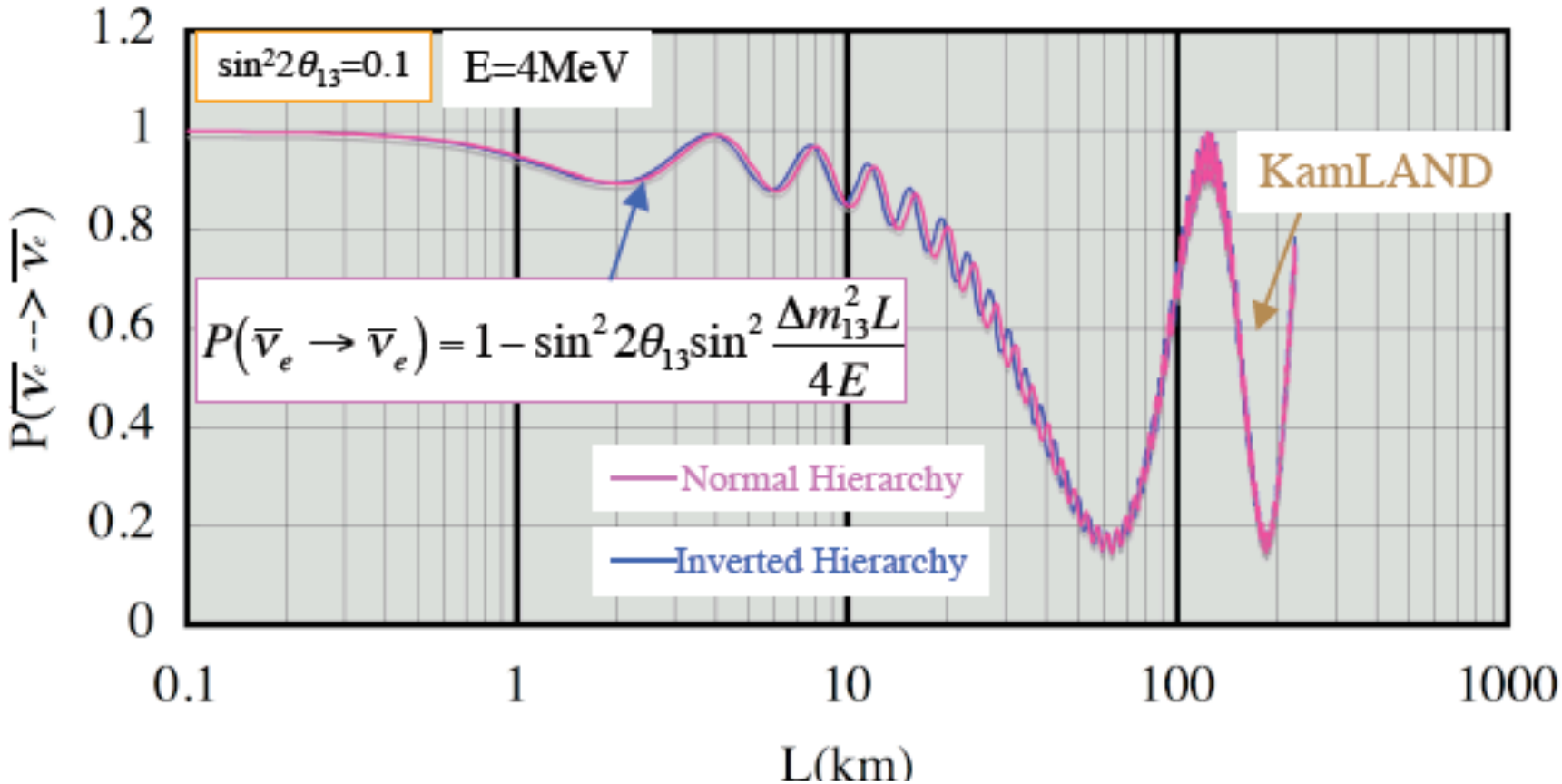
$\Delta m^2_{32} = m_3^2 - m_2^2$, L/E≅500 km/GeV

(≅0.5 km/MeV)

$\Delta m^2_{21} = m_2^2 - m_1^2$, L/E≅15000 km/GeV

Two Examples of Oscillation Probability

1



$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2(\theta_{23})\sin^2\left(1.27\Delta m^2_{31}\frac{L}{E}\right) +$$

2

$$\sin^2(2\theta_{12})\cos^2(\theta_{23})\sin^2\left(1.27\Delta m^2_{21}\frac{L}{E}\right) +$$

$$\sin(2\theta_{13})\sin(2\theta_{23})\sin(2\theta_{12})\sin\left(1.27\Delta m^2_{31}\frac{L}{E}\right)\sin\left(1.27\Delta m^2_{21}\frac{L}{E}\right)\cos\left(1.27\Delta m^2_{32}\frac{L}{E} \pm \delta_{CP}\right)$$

Where we stand experimentally

	bf ± 1σ	acc.@3σ	
Δm^2_{21}	$(7.7\pm0.2)\ 10^{-5}\ eV^2$	(8%)	KamLAND
$\sin^2\theta_{12}$	0.31 ± 0.015	(18%)	SNO
$\lvert\Delta m^2_{32}\rvert$	$(2.4\pm0.1)\ 10^{-3}\ eV^2$	(20%)	MINOS
$\sin^2\theta_{23}$	0.46 ± 0.045	(38%)	SK atm
$\sin^2\theta_{13}$	< 0.044 @ 3σ		CHOOZ

δ_{CP}, θ_{23} quadrant, mass hierarchy (?)

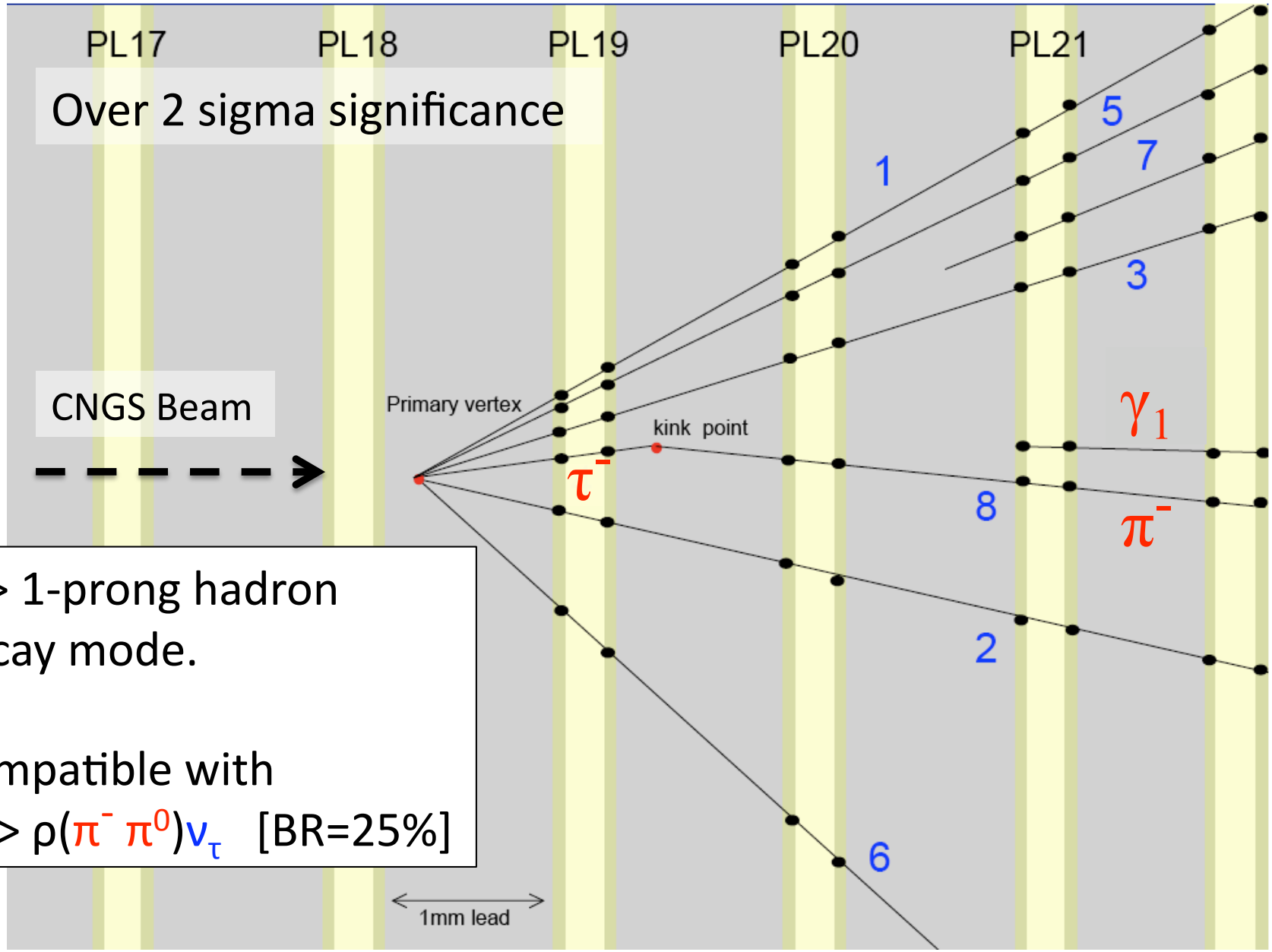
[Lisi, Nu2010]

First direct observation of a neutrino flavour appearing due to oscillations

(neglecting LSND/MiniBooNE)

Verifying the oscillation model…

Opera's 1st ν_τ Candidate Event



τ -> 1-prong hadron decay mode.

Compatible with
τ -> ρ(π^- π^0)ν_τ [BR=25%]

[Sato, Nu2010]

Results breakdown

Solar sector: Solar+KamLAND

Atmospheric sector: MINOS+SK

Subdominant sector: Chooz + MINOS

Solar Sector

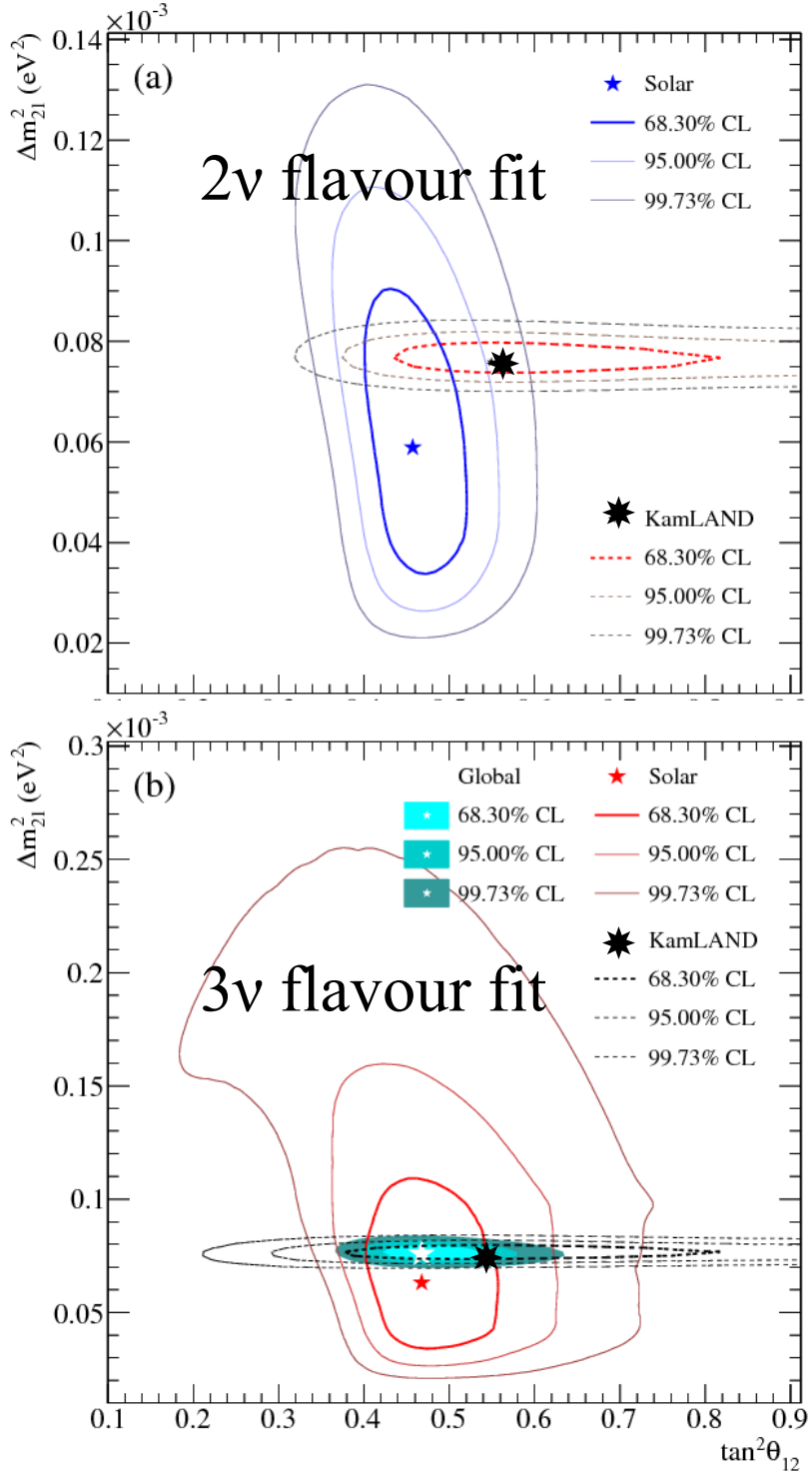
Solar + KamLAND

- SNO Low Energy Threshold Analysis (LETA)
  - some improvements to come
- SK, Chlorine, Gallium, Borexino expts included
- KamLAND (data: 2002-2007)
  - wont double again until 2013(?)
  - Δm^2 largely systematically limited

3ν flavour best-fit:

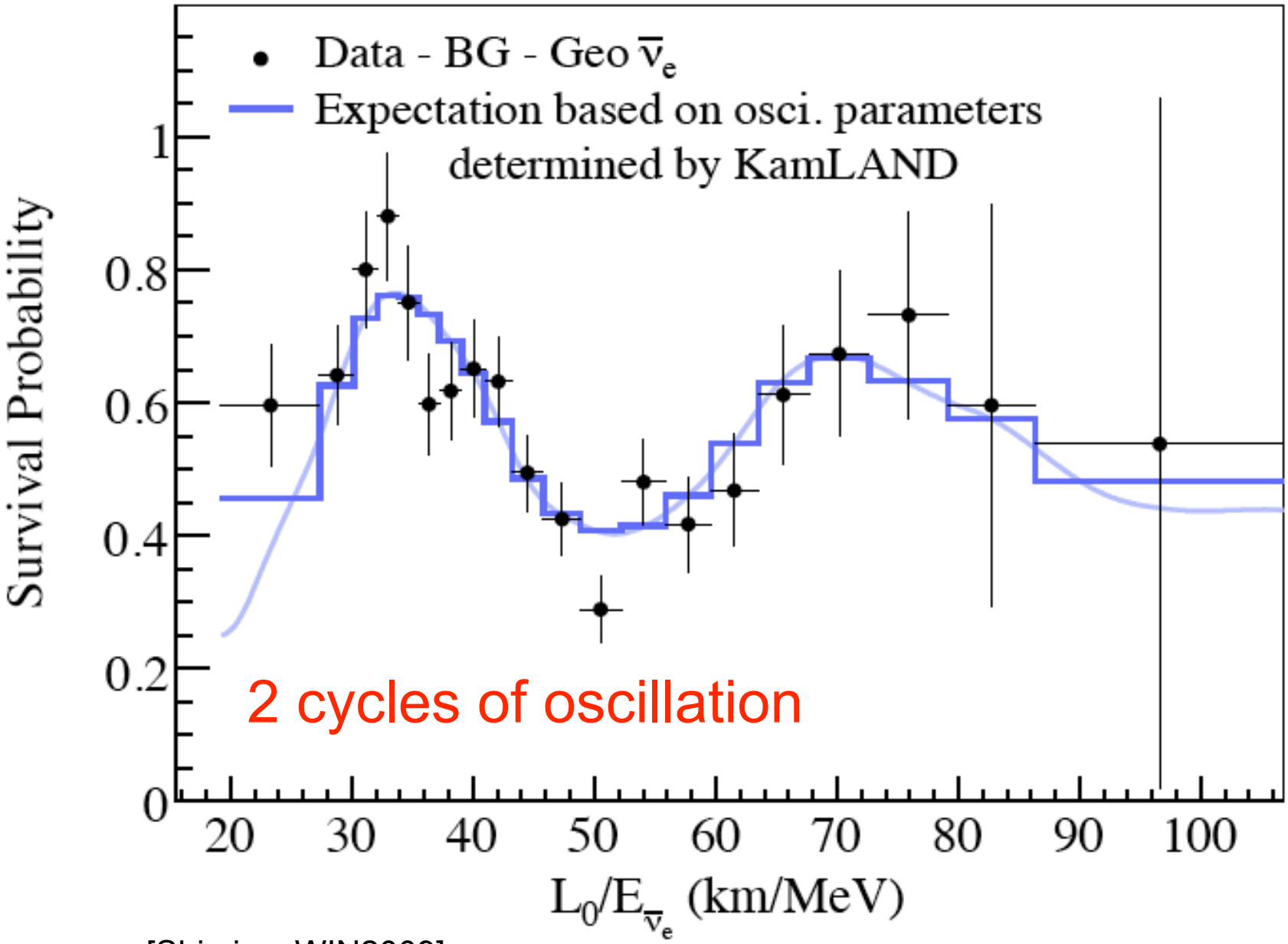
$\sin^2\theta_{13}=0.020\ ^{+0.021}_{-0.016}$

$\sin^2\theta_{13} < 0.057$ (95% C.L.)



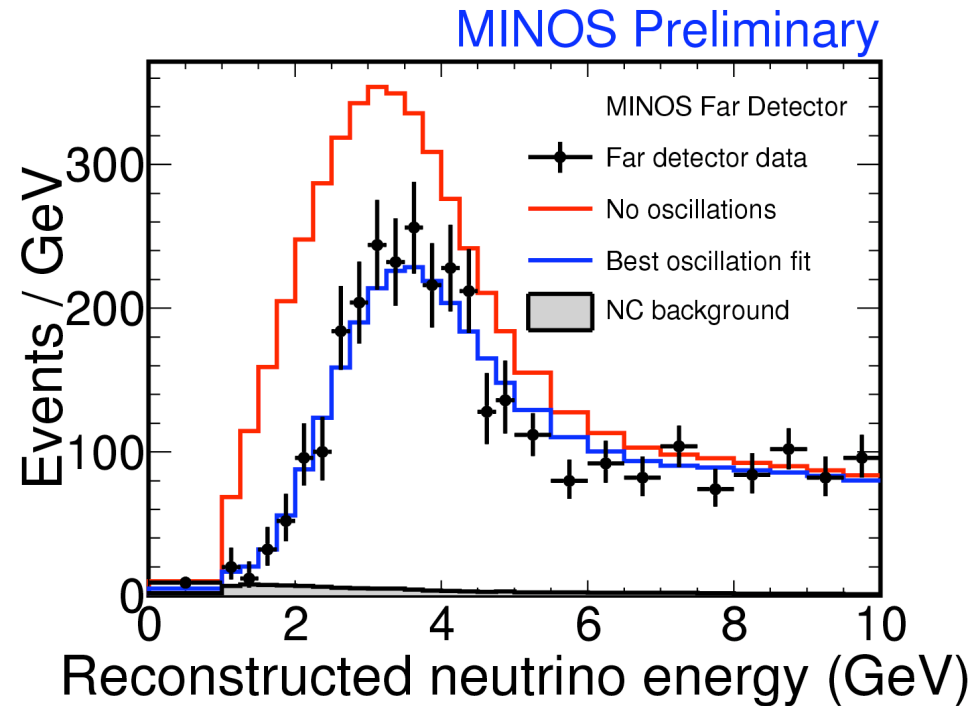
[Klein, Nu2010]

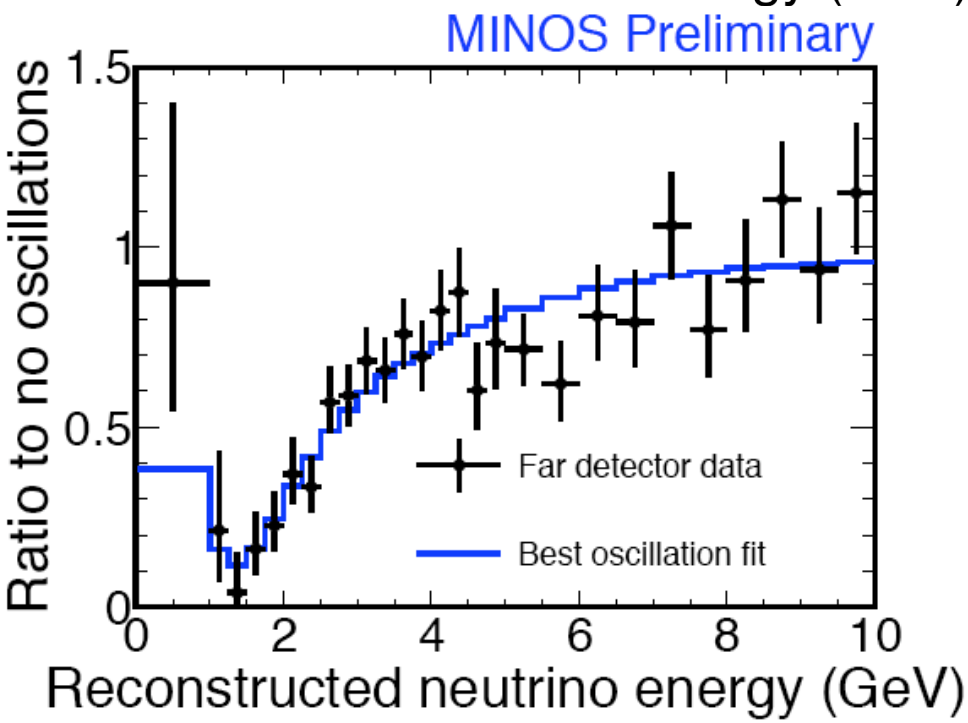
KamLAND's Beautiful Data

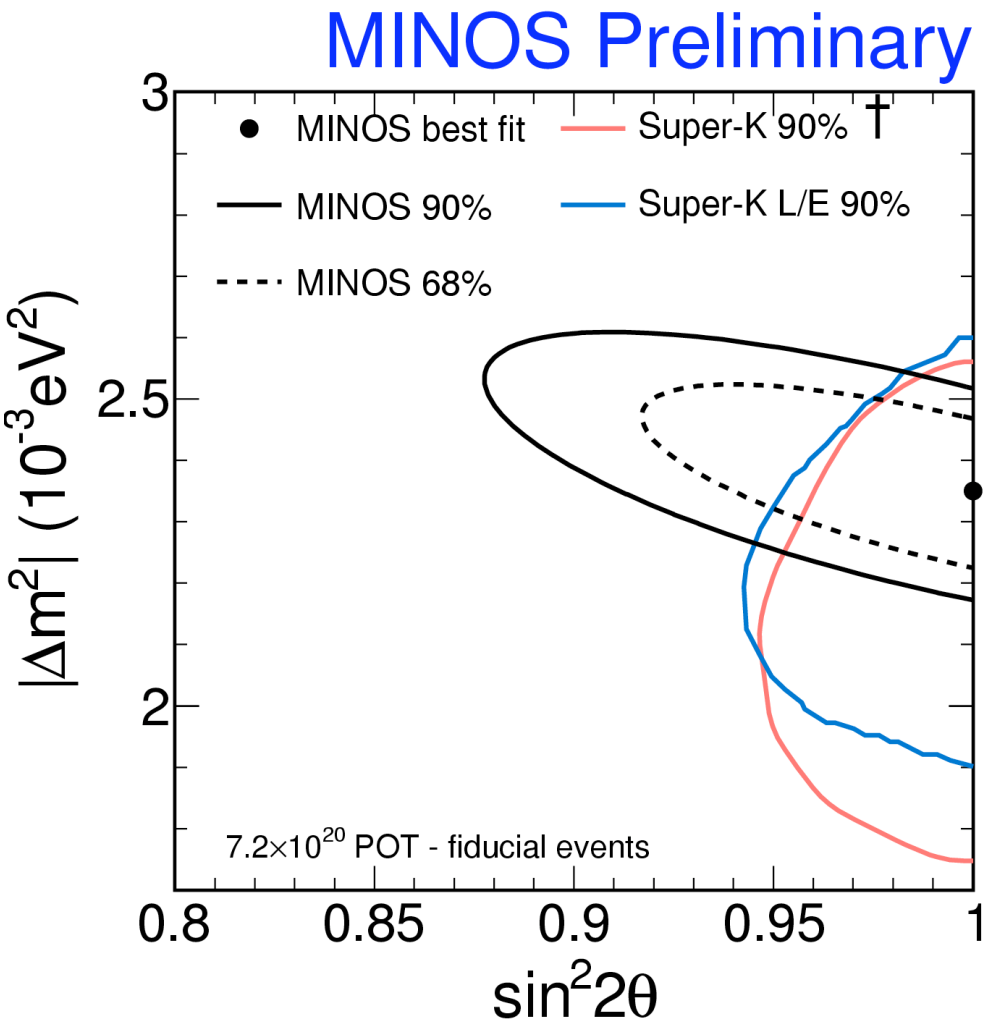


[Shimizu, WIN2009]

Atmospheric Sector







$$\left|\Delta m^2\right| = 2.35^{+0.11}_{-0.08} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\theta) > 0.91\ (90\%\ \mathrm{C.L.})$$

†Super-Kamiokande 2-flavour (preliminary)

[Vahle, Nu2010]

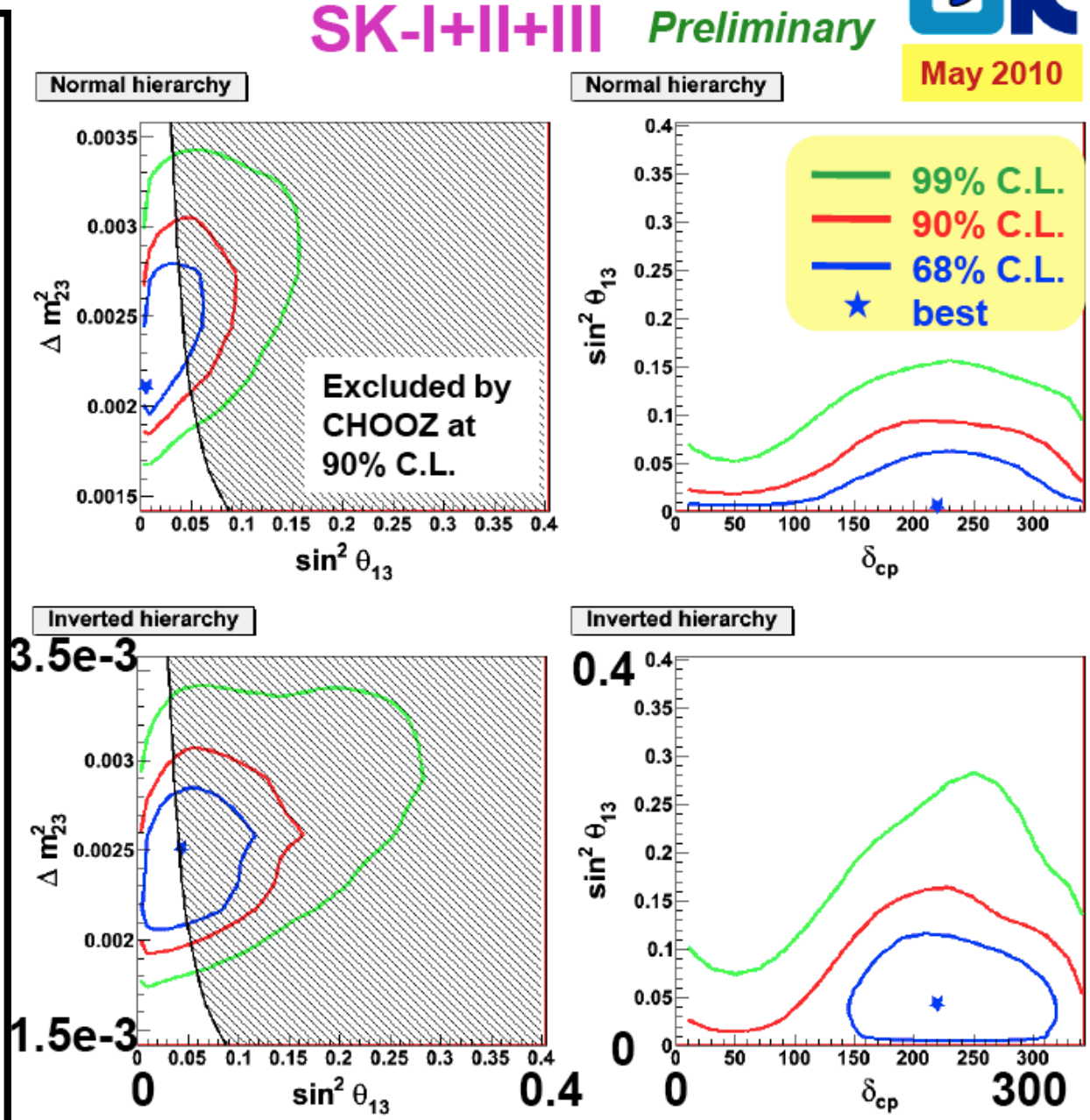
Full 3-flavor oscillation results

Super-K has extended from 2-flavour fit to 3-flavour, includes
-- δ_{CP}
-- θ_{13}
-- matter effect
-- fixed solar osc. (Δm^2_{21}, θ_{12})

SK is sensitive due to:
-- mixed flux of ν_e ν_μ $\bar{\nu}_e$ $\bar{\nu}_\mu$
-- large range of L, E and L/E

PRD81, 092004, 2010
Considers only matter and solar terms individually (neglects interference term between the two)

New FULL 3-flavour analysis this summer
-- No significant preferences on θ_{13}, mass hierarchy or δ_{CP}



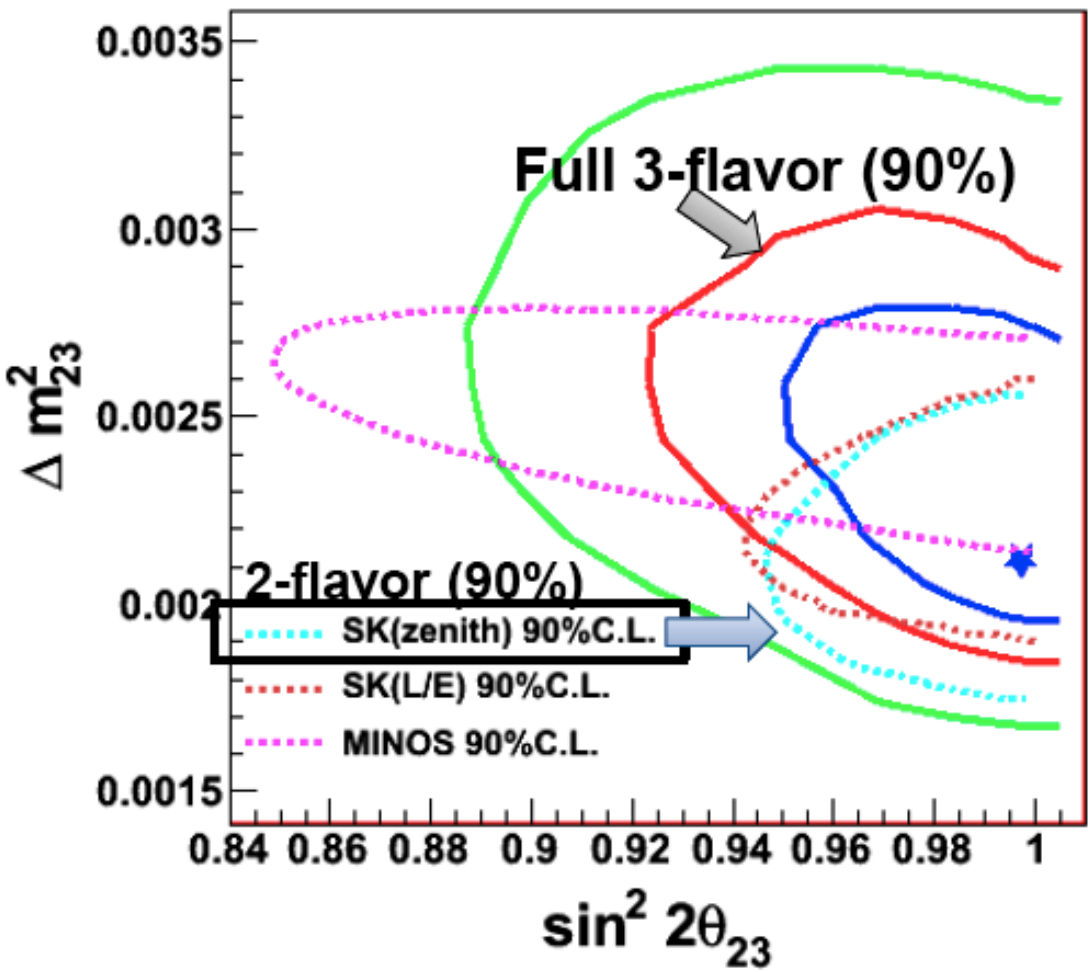
[Takeuchi, Nu2010]

Comparing 3-flavour with 2-flavour

Including δ_{CP}, θ_{13} and matter effect weakens SK constraints on the "2-flavour parameters"

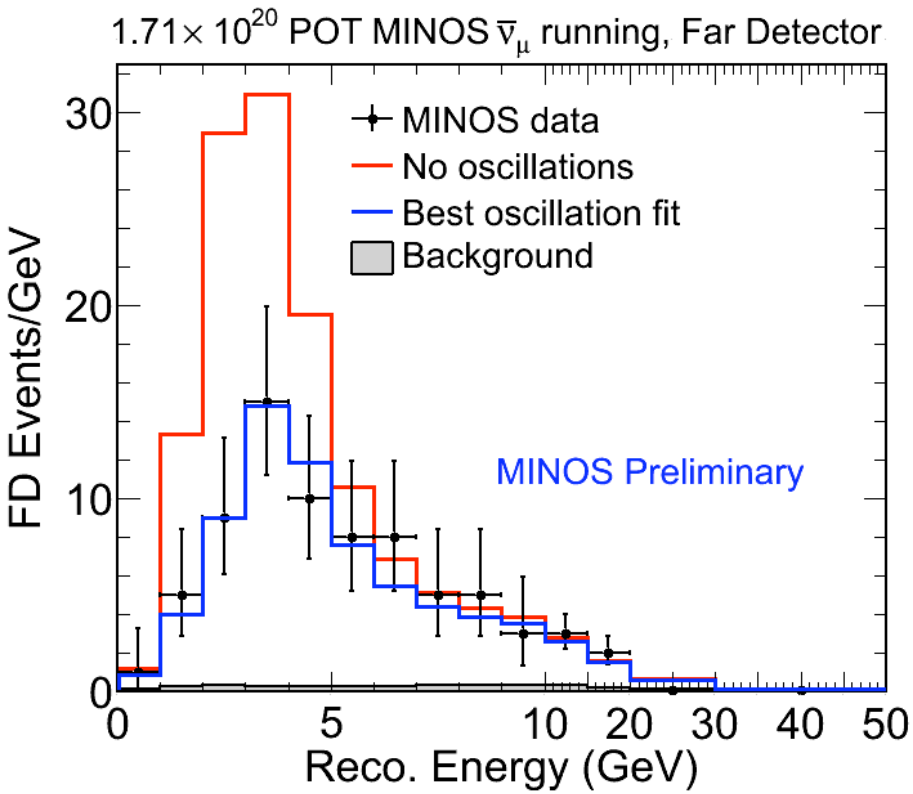
Naively, not expected to make a large difference to MINOS contour (note: old contour shown)

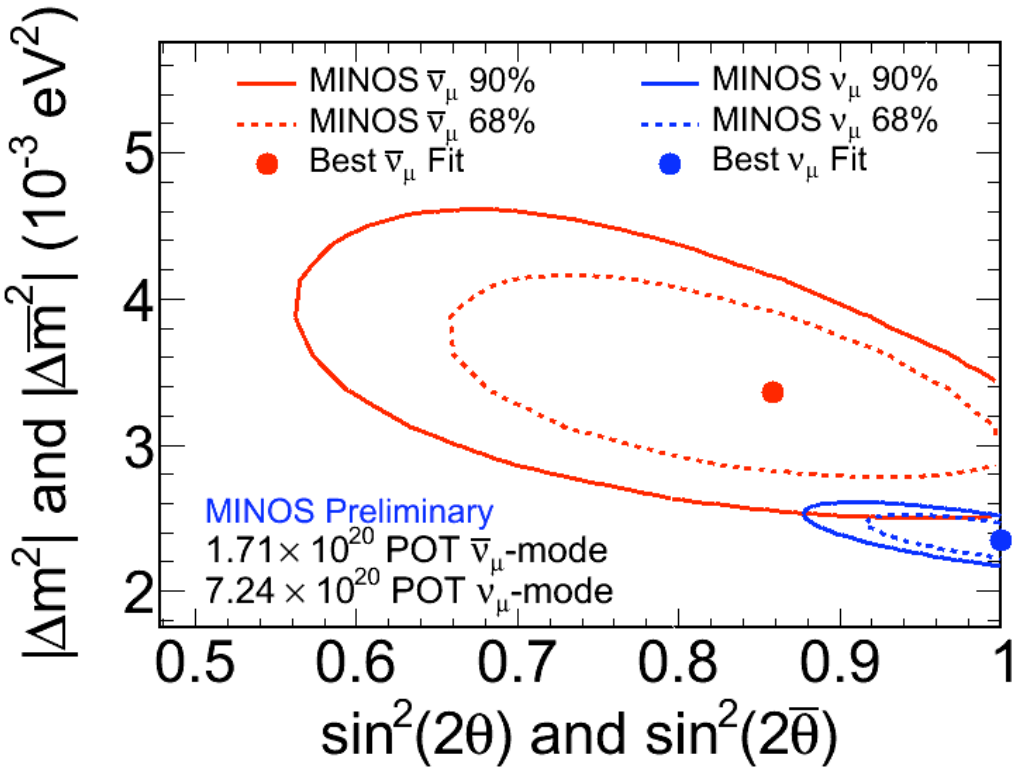
Normal hierarchy



[Takeuchi, Nu2010]

Comparison of ν_μ and $\bar{\nu}_\mu$





6.3 σ rejection of $\bar{\nu}_\mu$ null-oscillation hypothesis

$$\left|\overline{\Delta m^2}\right| = 3.36^{+0.45}_{-0.40} \times 10^{-3}\,\mathrm{eV}^2$$

$$\sin^2(2\bar{\theta}) = 0.86 \pm 0.11$$

[Vahle, Nu2010]

Subdominant Sector

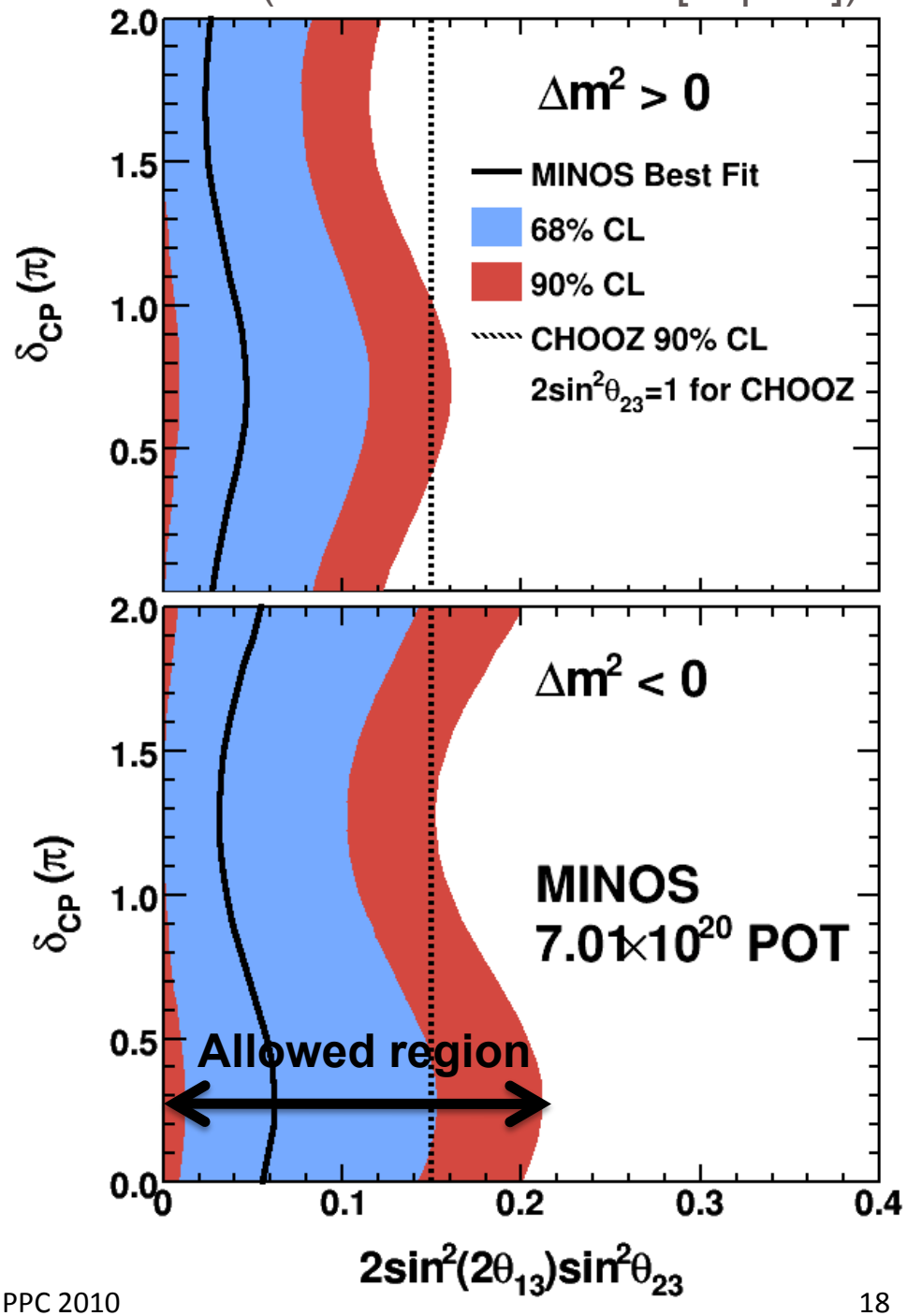
MINOS ν_e Appearance and CHOOZ $\bar{\nu}_e$ Disappearance

Accelerator and reactor experiments are complementary

Accelerator searches for ν_e appearance are sensitive to 4 parameters:
θ_{13}, mass hierarchy, δ_{CP} and $\sin^2\theta_{23}$

Reactor experiments just sensitive to θ_{13}

(arXiv:1006.0996v1 [hep-ex])



[Vahle, Nu2010]

The Future

Hottest topic:

$$\theta_{13}$$

If not too small, provides a potential door to

leptonic CP violation

(and determines future experimental program)

Dedicated experiments

Accelerator:

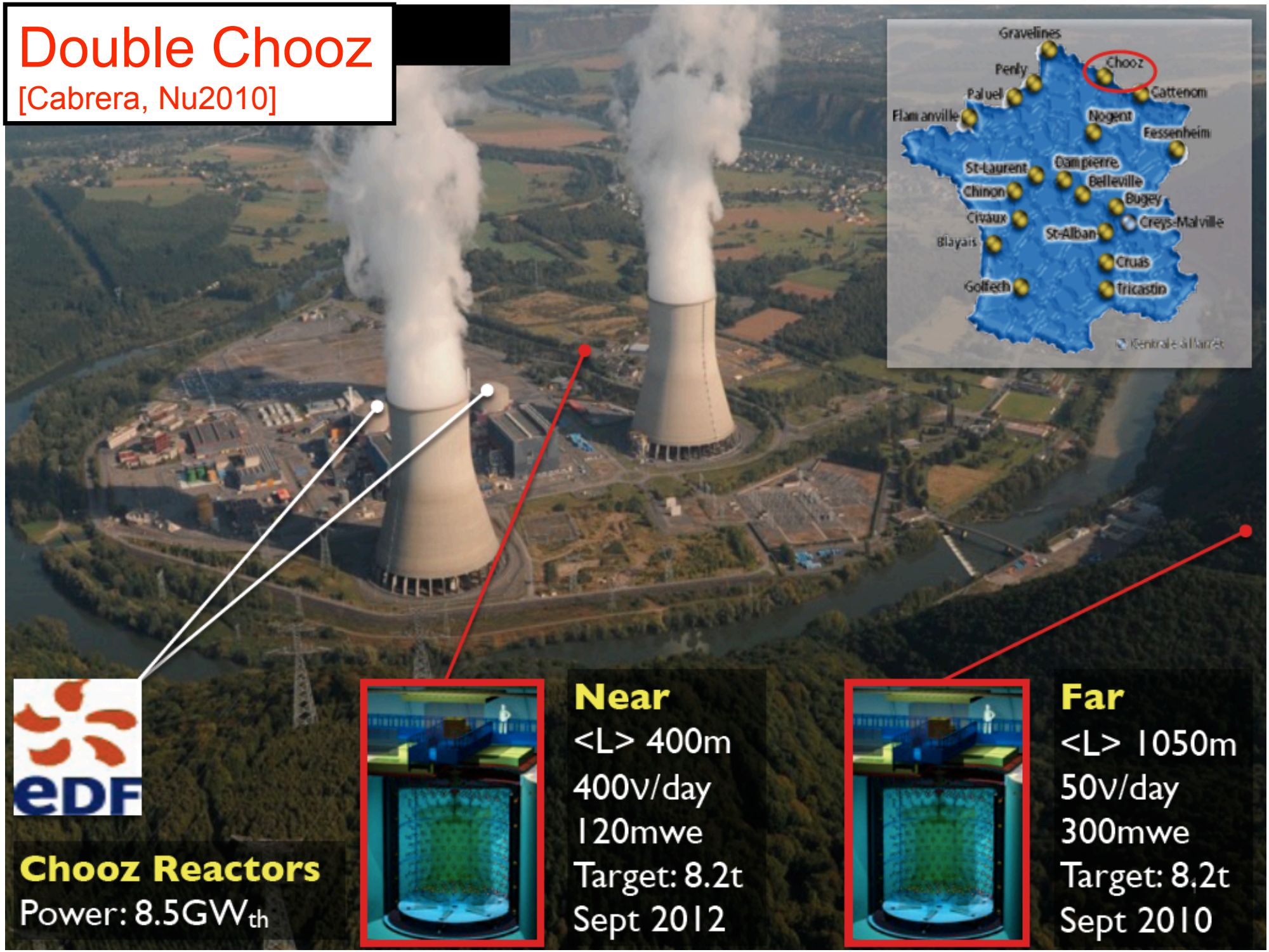
T2K, NOvA, (LBNE)

Reactor:

Double Chooz, Daya Bay, RENO

Double Chooz

[Cabrera, Nu2010]



Chooz Reactors

Power: 8.5GW$_{th}$

Near

<L> 400m

400ν/day

120mwe

Target: 8.2t

Sept 2012

Far

<L> 1050m

50ν/day

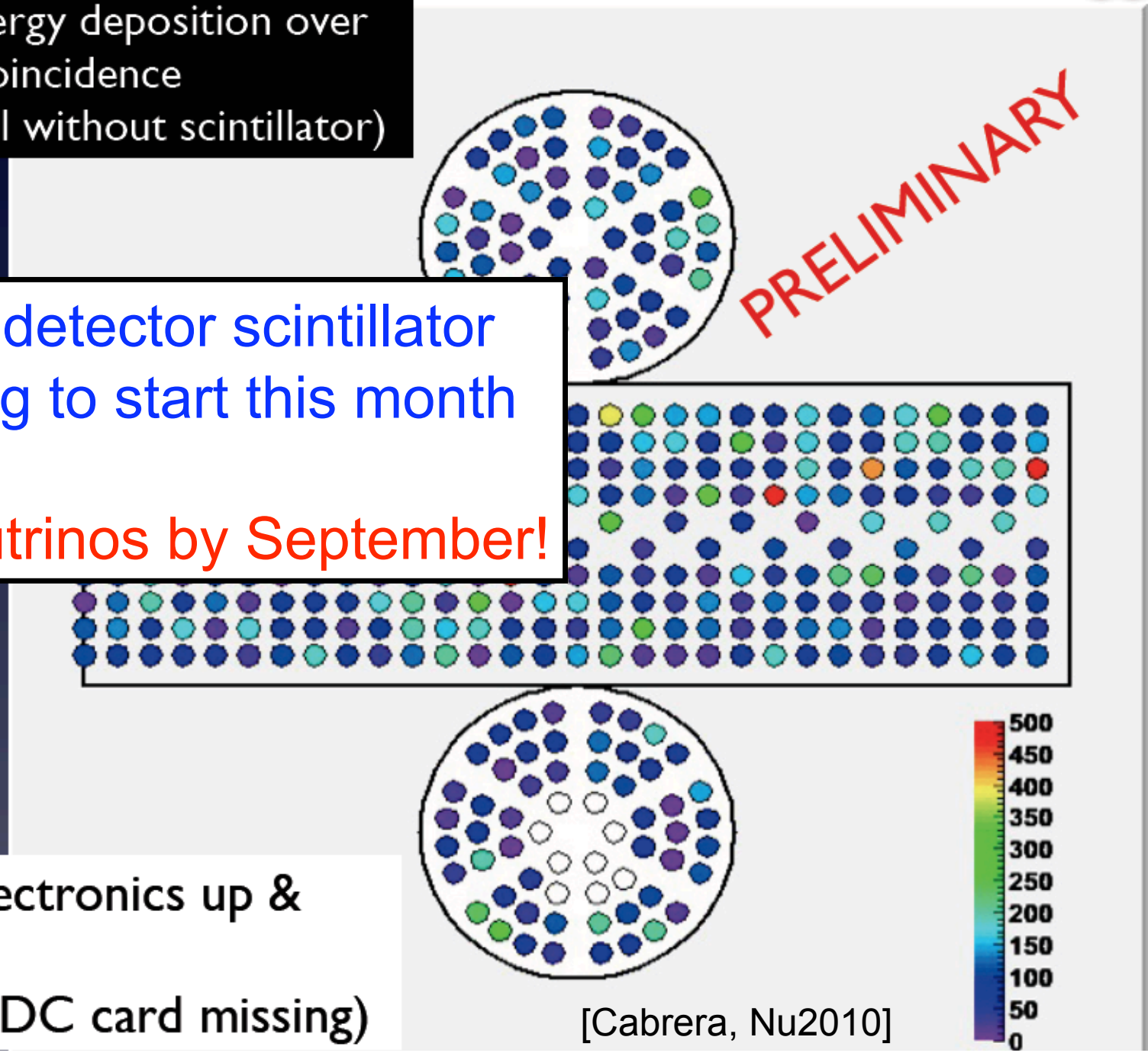
300mwe

Target: 8.2t

Sept 2010

first internal triggers…

Energy-Trigger
large energy deposition over ~70ns coincidence
(now still without scintillator)



Far detector scintillator filling to start this month

Neutrinos by September!

Most electronics up & running!
(one FADC card missing)

[Cabrera, Nu2010]

A look ahead…

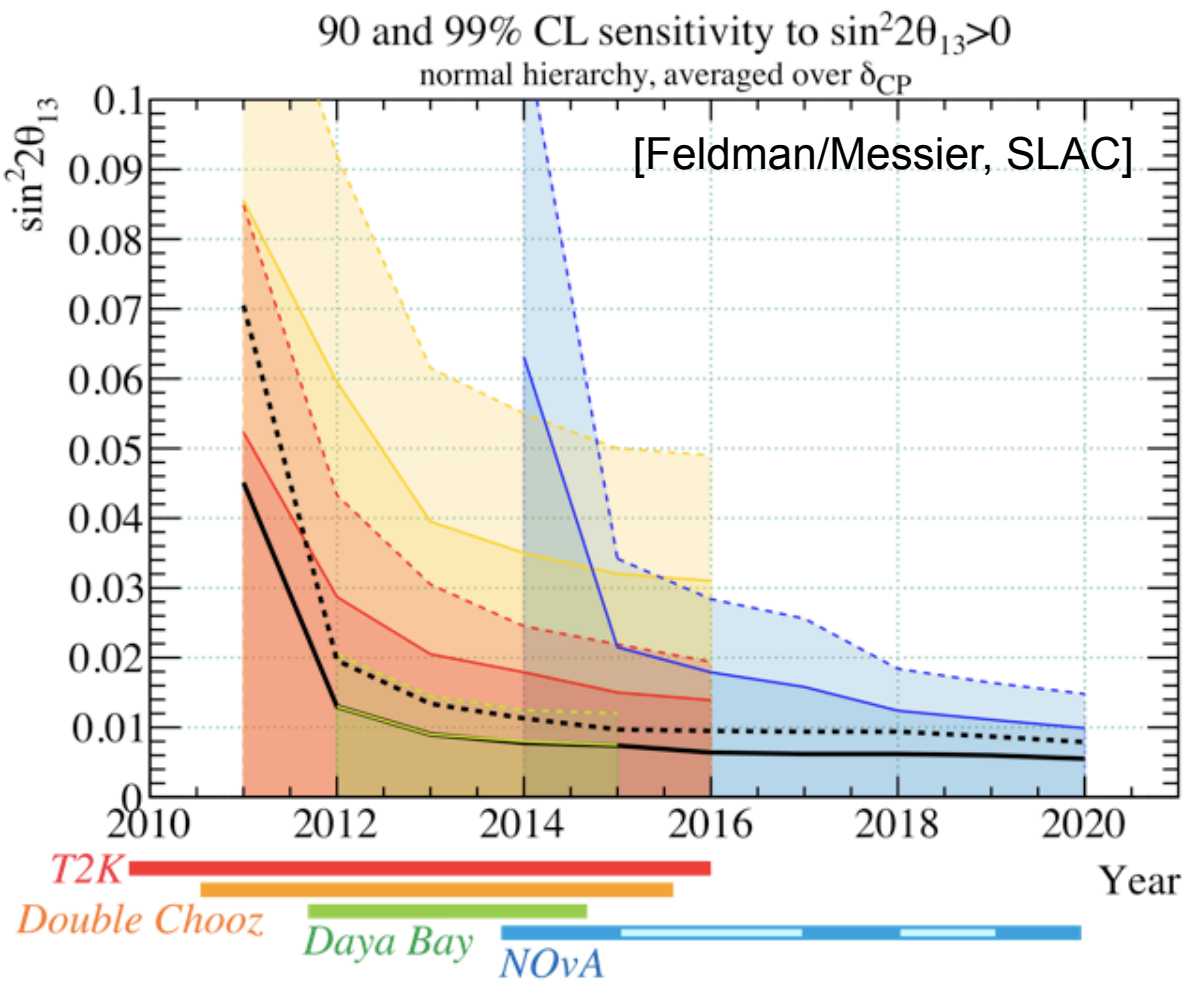
“Predictions are always hard, especially about the future” (anon)

All these experiments could potentially be delayed by a year or more in getting their results out: who knows!

Accelerator searches tend to be optimistic and quote the best or average limit on θ_{13}

Reactor experiments have a clean measurement of θ_{13}

Safe to say that 2011-2015 will be an exciting time...
By the end of it we will know if $\sin^2(2\theta_{13})$ > few-%

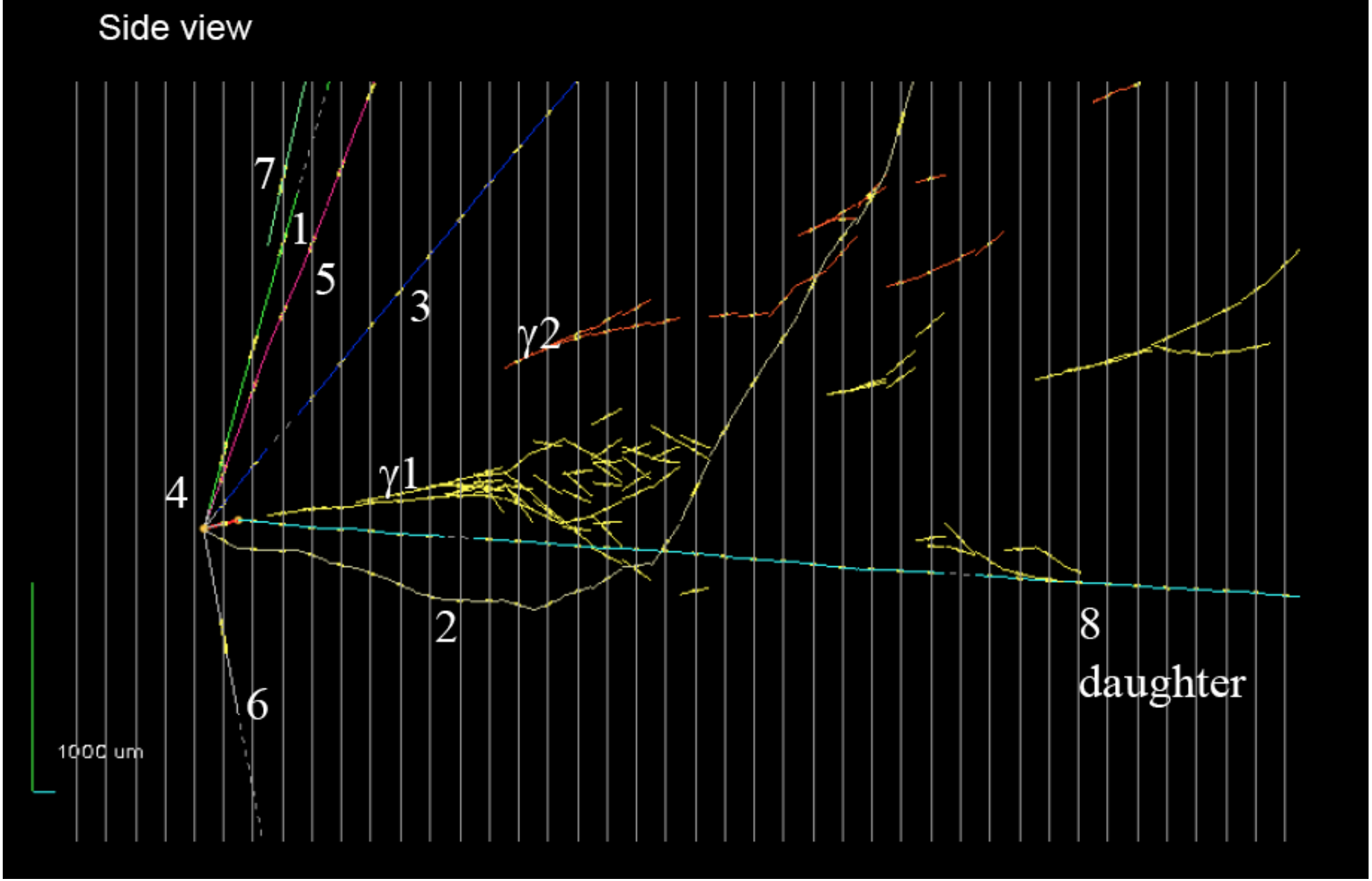


Conclusions

- Diverse neutrino sources + detectors have produced beautiful data
- Precision (~%) measurements of some osc. pars.
  - Reaching the need for full 3-flavour analyses, often can't rely on accidental bifurcation of oscillations into solar and atmospheric sectors
  - yet several parameters remain undiscovered
- Keep testing assumptions: new surprises!?
- Hunt for subdominant osc. (θ_{13}) fast ramping up as dedicated experiments come online
  - Next 5 years will provide a results deluge
    - it's going to be very exciting!

Backup slides

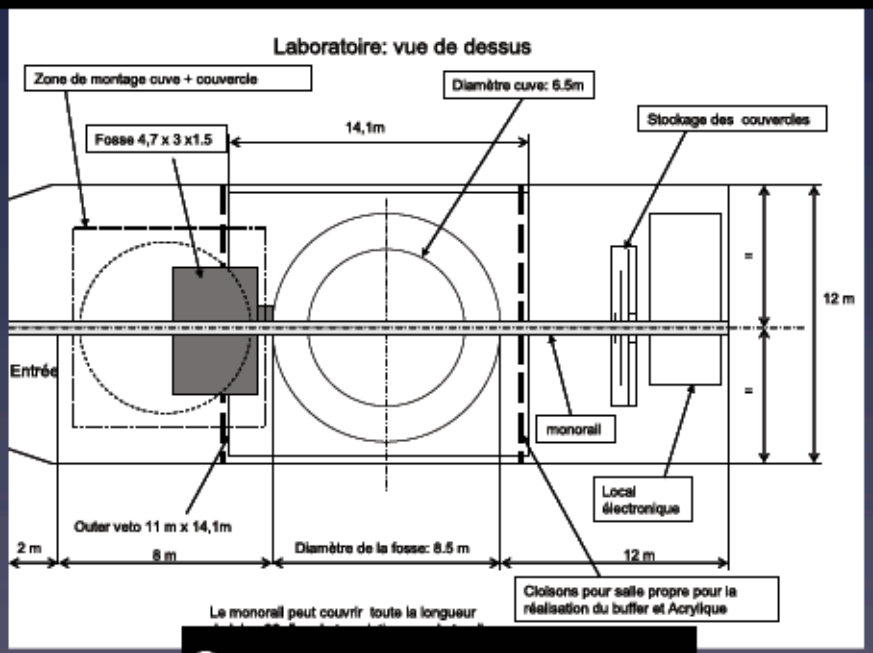
Event topological features (side view)



ND status…

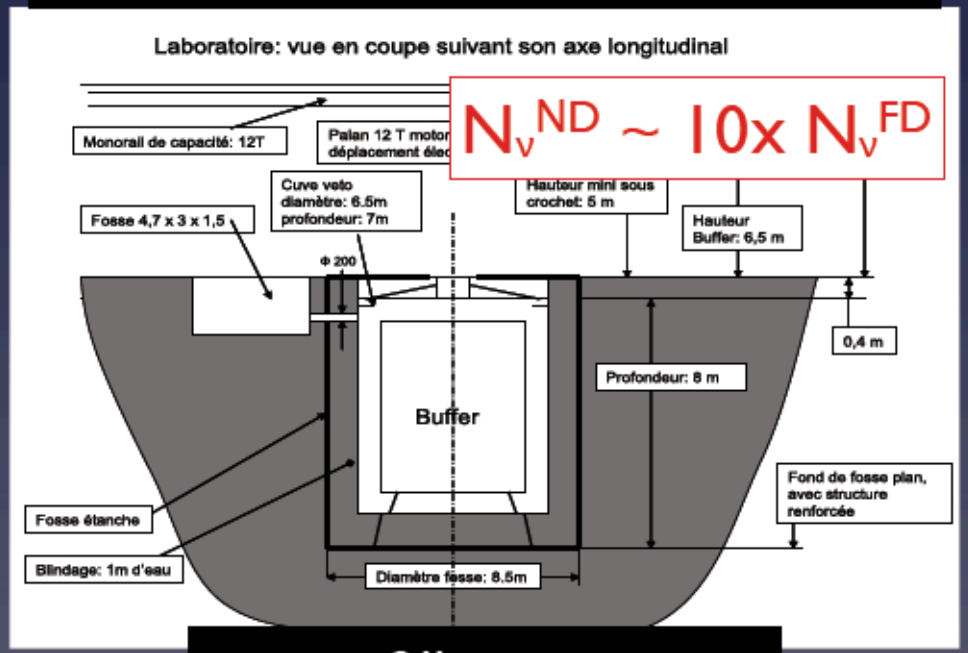
- **all authorisations & funding secured…**
  - ground studies completed since end of 2009
  - involvement of EDF on the construction
- tendering over summer ⟹ **digging from November 2010**
- lab available fall 2011
- ND construction ⟹ 30 weeks (many lessons learned from FD)
- goal: **data taking by towards 2012**

ND Lab designed for building ND



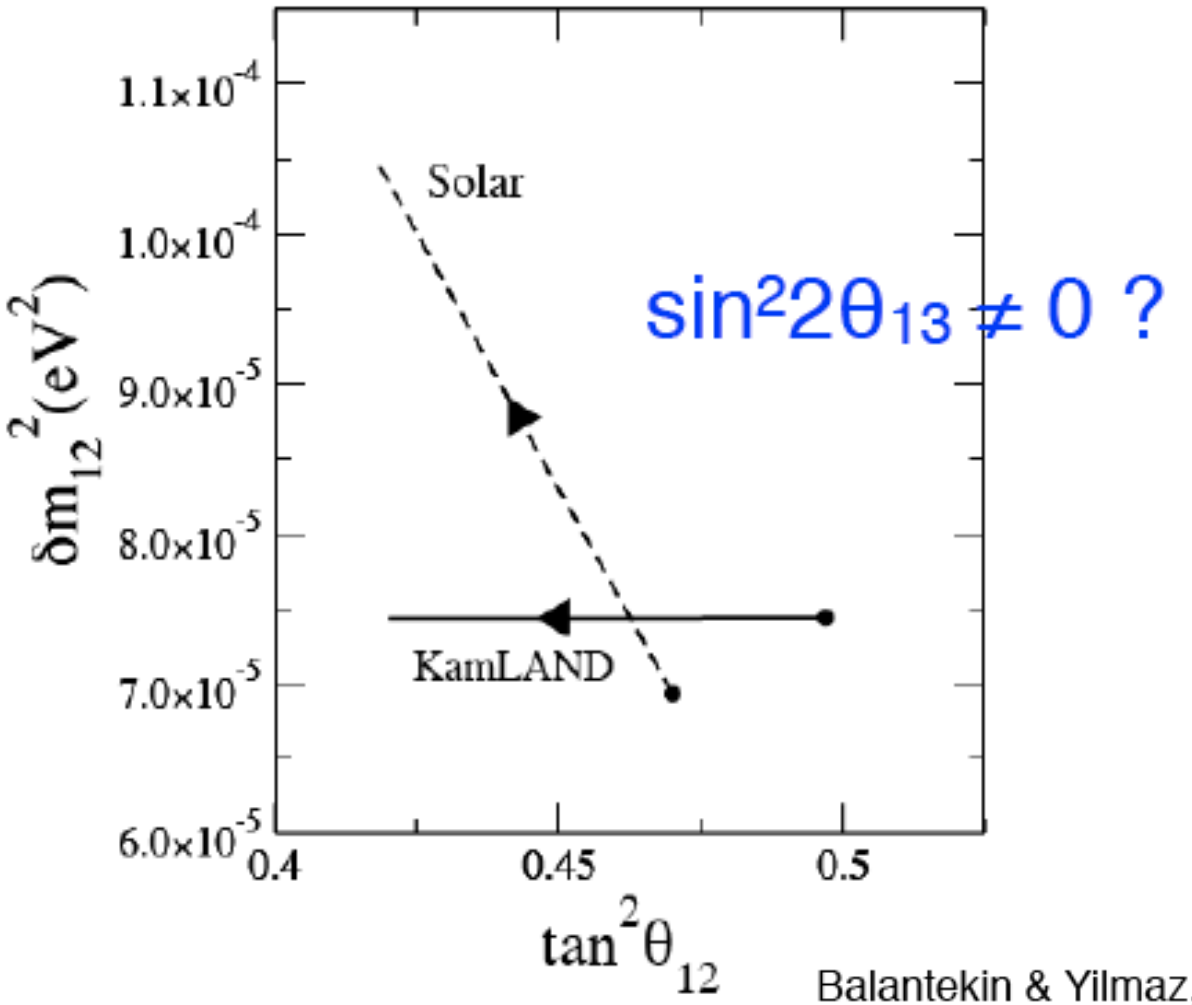
3x zones concept

1m water shield to radioactivity



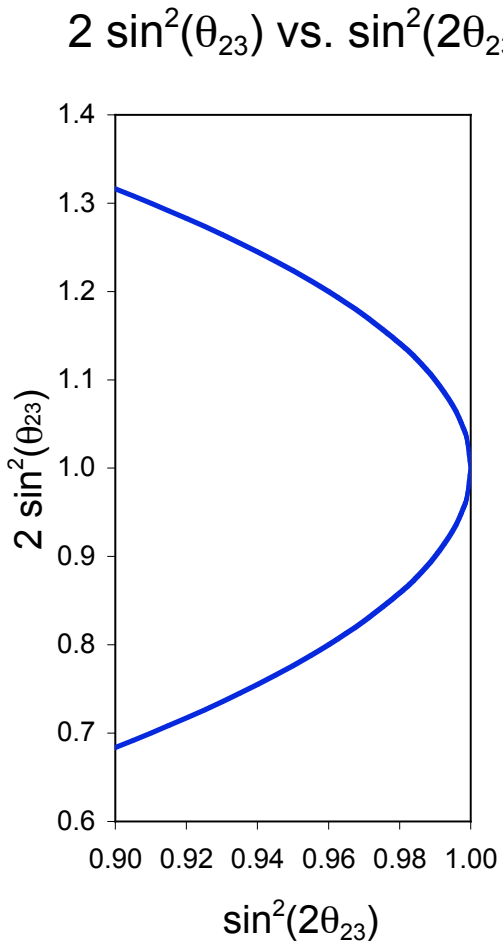
easier filling concept

Solar vs. Reactor Tension: effect of theta13



Balantekin & Yilmaz, J. Phys. G **35**, 075007 (2008) (arXiv:0804.3345 [hep-ph]).

Effect of not knowing the theta23 quadrant



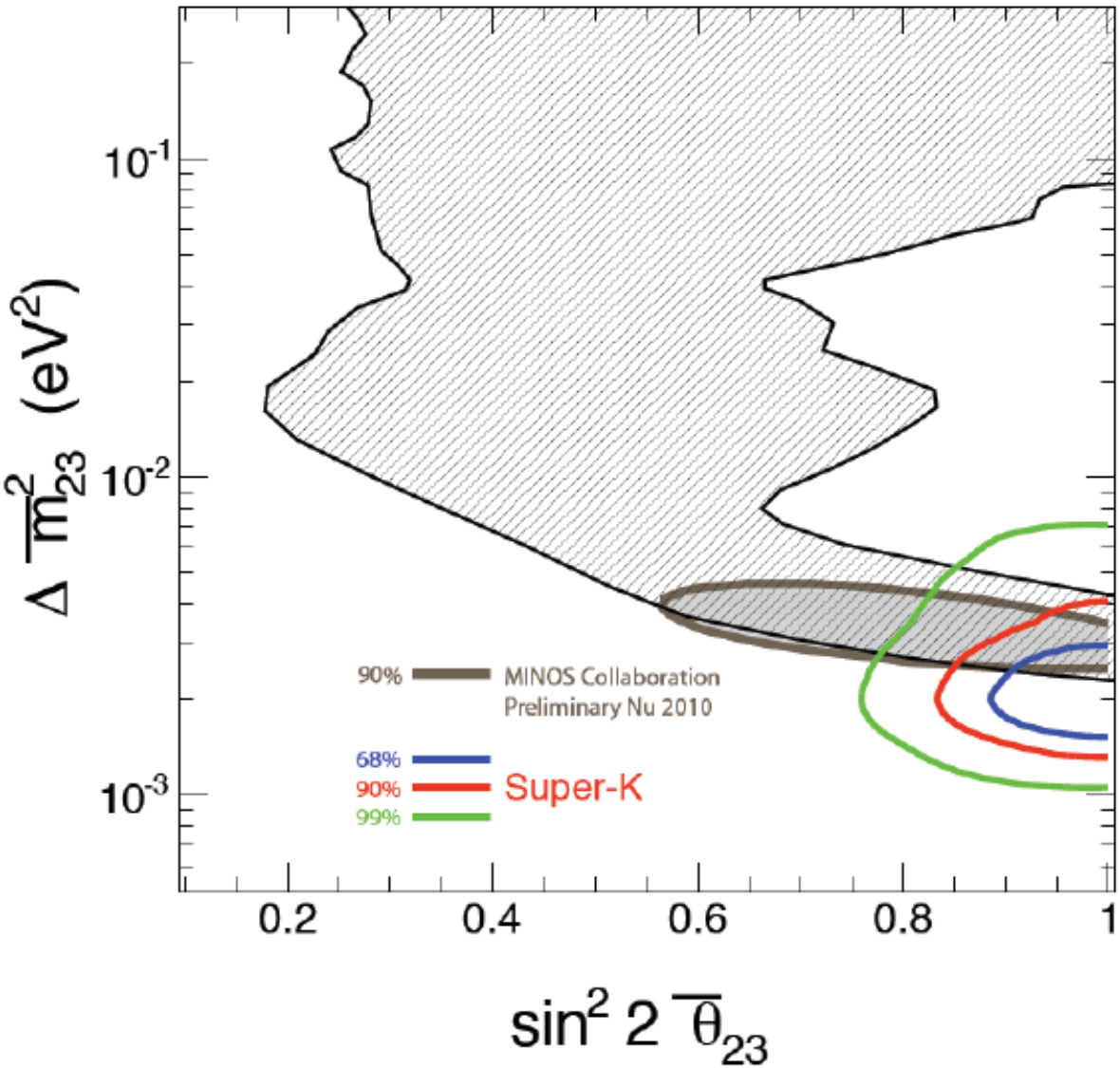
Search for CPT violation in atm. ν

Jun 2009

- Under the CPT theorem, P(ν→ ν) and P($\bar{\nu}$→ $\bar{\nu}$) should be same.
- Test ν oscillation or $\bar{\nu}$ oscillation separately.

SK-I+II+III

Preliminary



Neutrino:

$\Delta m_{23}^2 = 2.2 \times 10^{-3} eV^2$

$\sin^2 2\theta_{23} = 1.0$

Anti-neutrino:

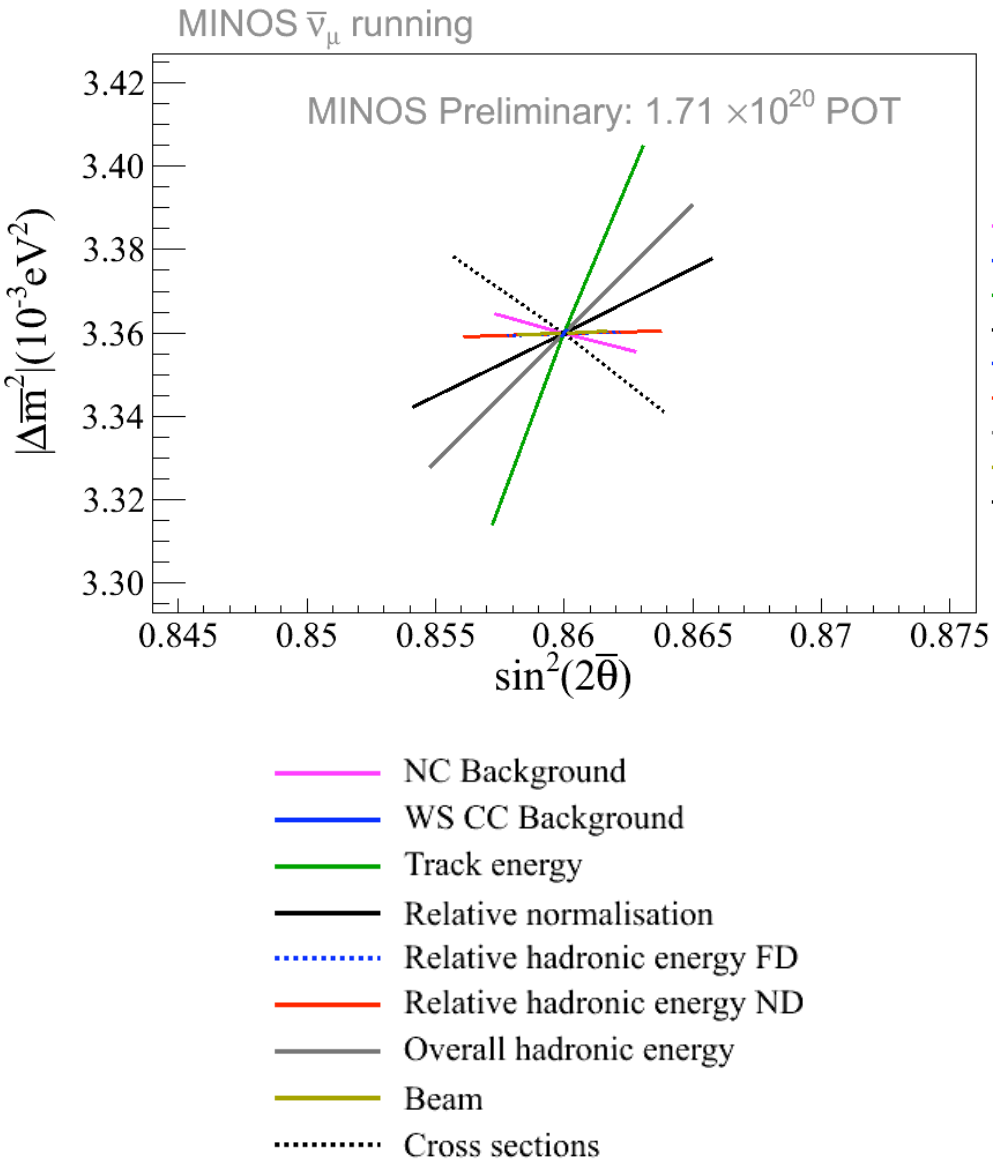
$\Delta \overline{m}_{23}^2 = 2.0 \times 10^{-3} eV^2$

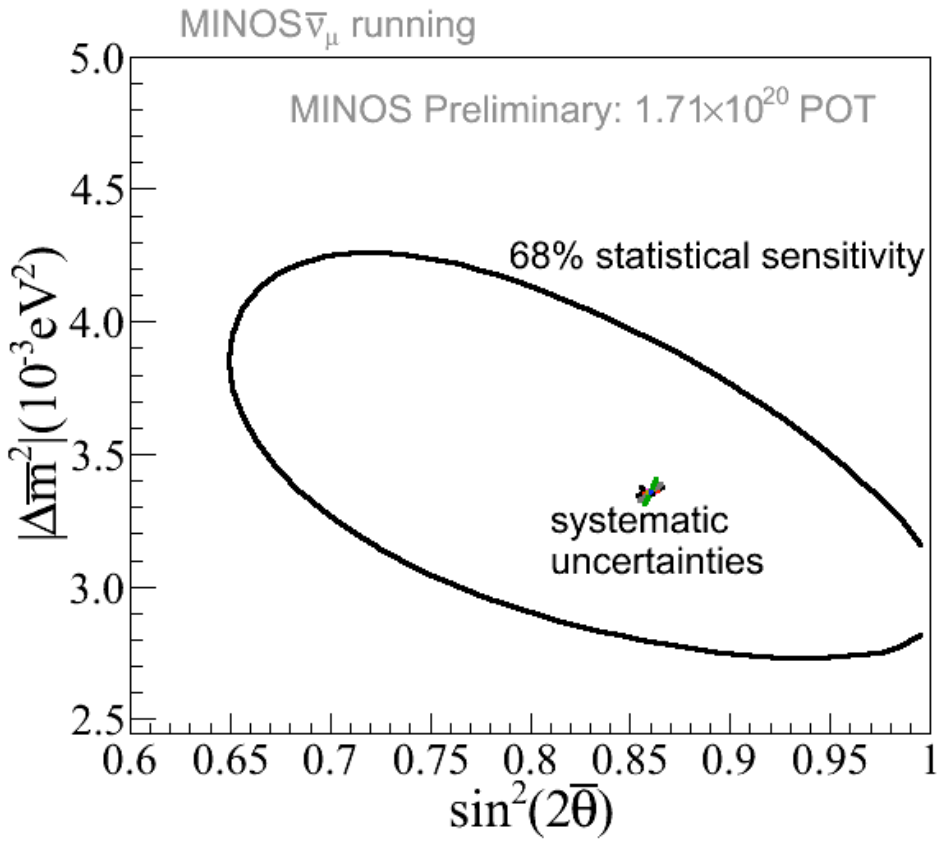
$\sin^2 2\overline{\theta}_{23} = 1.0$

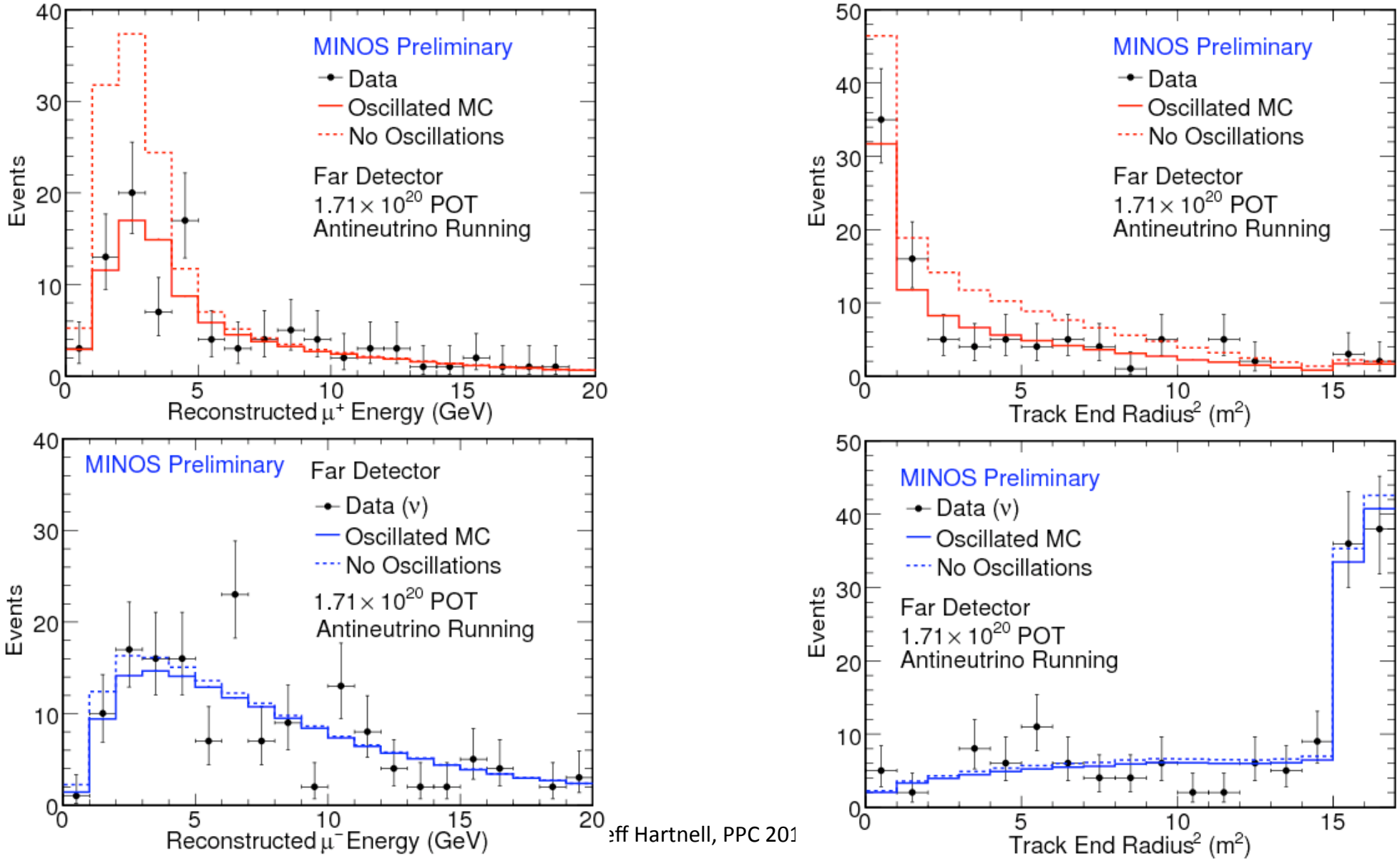
No evidence for CPT violating oscillations is found

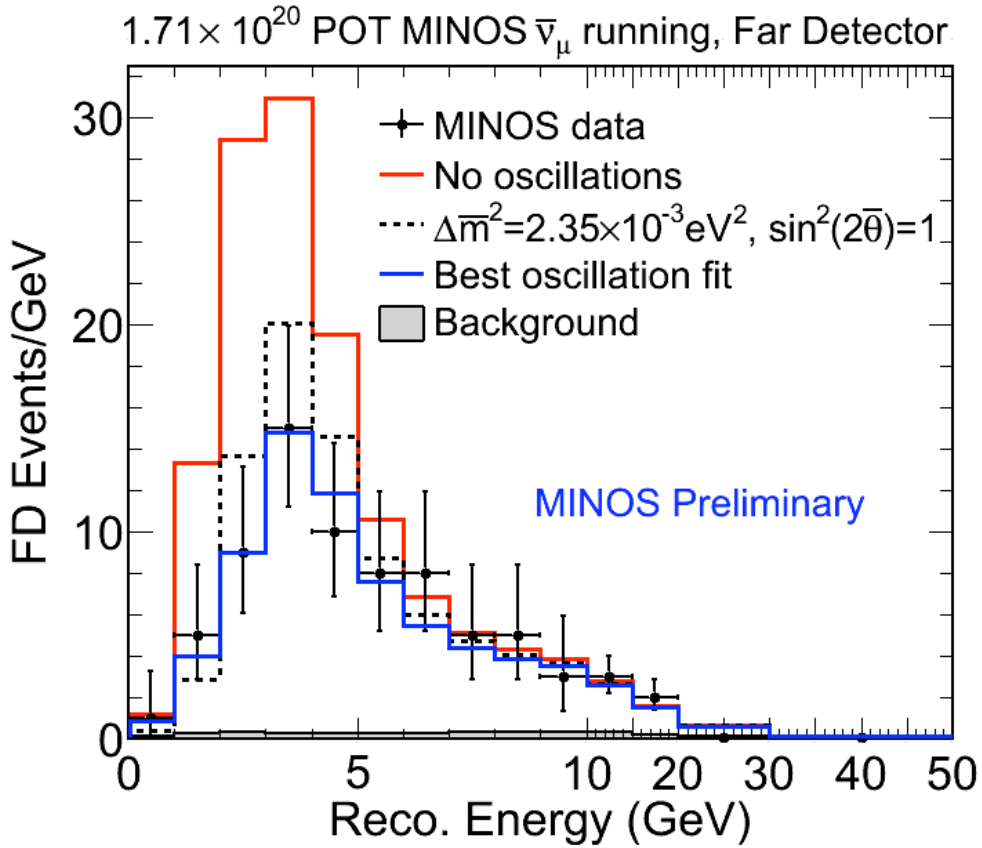
⇨ **Poster-79 by Roger Wendell**

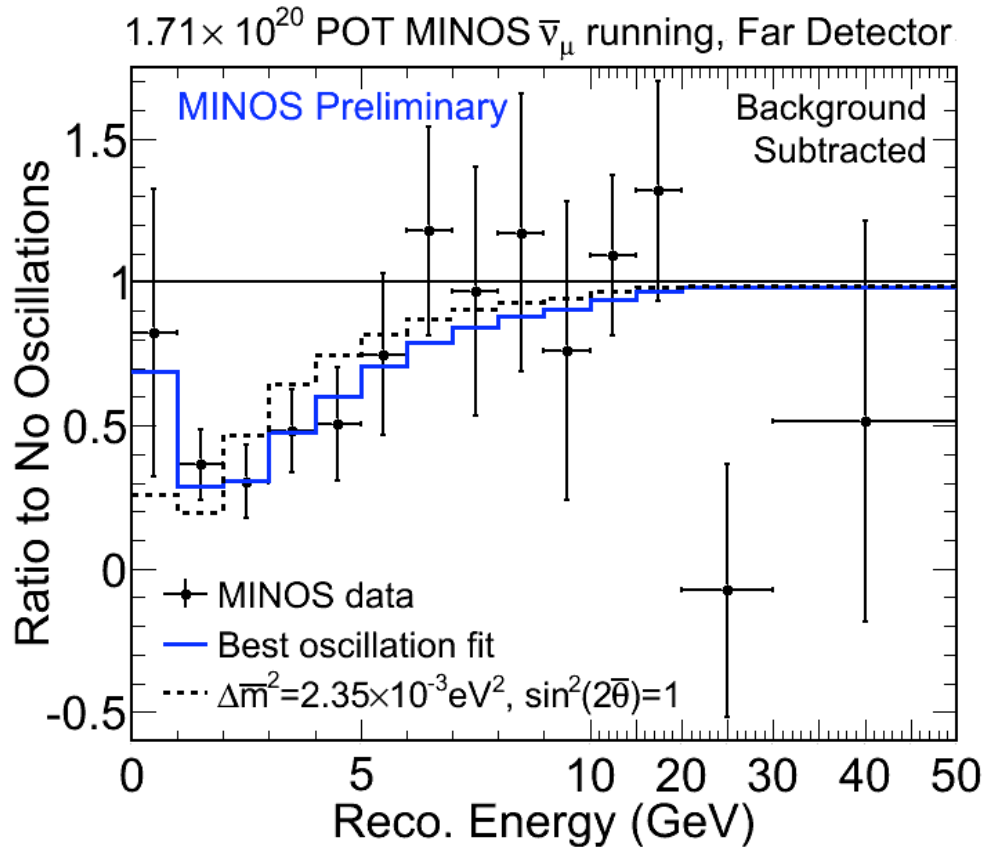
[Takeuchi, Nu2010]


MINOS $\bar{\nu}_\mu$ running
MINOS Preliminary: 1.71 $\times 10^{20}$ POT
$|\Delta\overline{m}^2|(10^{-3}eV^2)$
$\sin^2(2\bar{\theta})$
NC Background
WS CC Background
Track energy
Relative normalisation
Relative hadronic energy FD
Relative hadronic energy ND
Overall hadronic energy
Beam
Cross sections

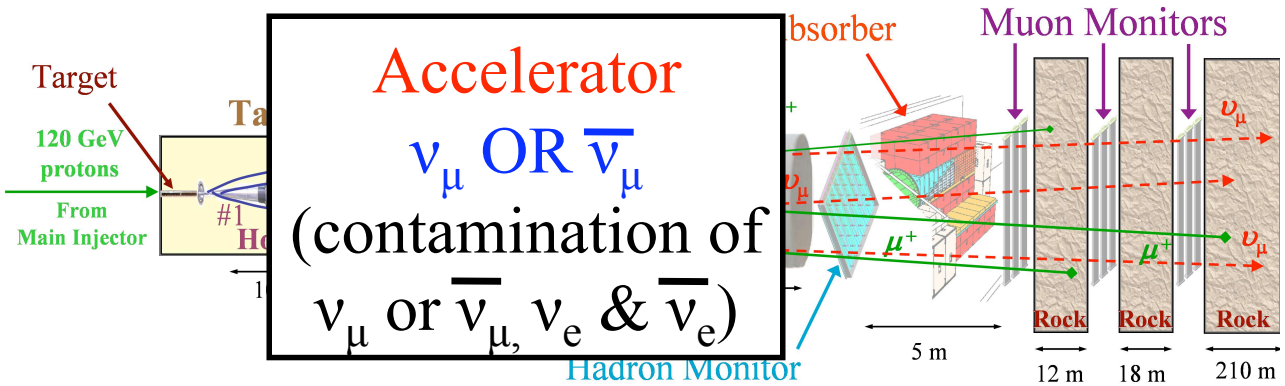

MINOS $\bar{\nu}_\mu$ running
MINOS Preliminary: 1.71$\times 10^{20}$ POT
68% statistical sensitivity
systematic uncertainties
$|\Delta\overline{m}^2|(10^{-3}eV^2)$
$\sin^2(2\bar{\theta})$


MINOS Preliminary
Data
Oscillated MC
No Oscillations
Far Detector
1.71× 10^20 POT
Antineutrino Running
Events
Reconstructed μ+ Energy (GeV)
Track End Radius² (m²)
Data (ν)
Reconstructed μ− Energy (GeV)


1.71× 10^20 POT MINOS $\bar{\nu}_\mu$ running, Far Detector
MINOS data
No oscillations
$\Delta\bar{m}^2$=2.35×10^-3 eV^2, sin^2(2$\bar{\theta}$)=1
Best oscillation fit
Background
MINOS Preliminary
FD Events/GeV
Reco. Energy (GeV)


1.71× 10^20 POT MINOS $\bar{\nu}_\mu$ running, Far Detector
MINOS Preliminary
Background Subtracted
MINOS data
Best oscillation fit
$\Delta\bar{m}^2$=2.35×10^-3 eV^2, sin^2(2$\bar{\theta}$)=1
Ratio to No Oscillations
Reco. Energy (GeV)

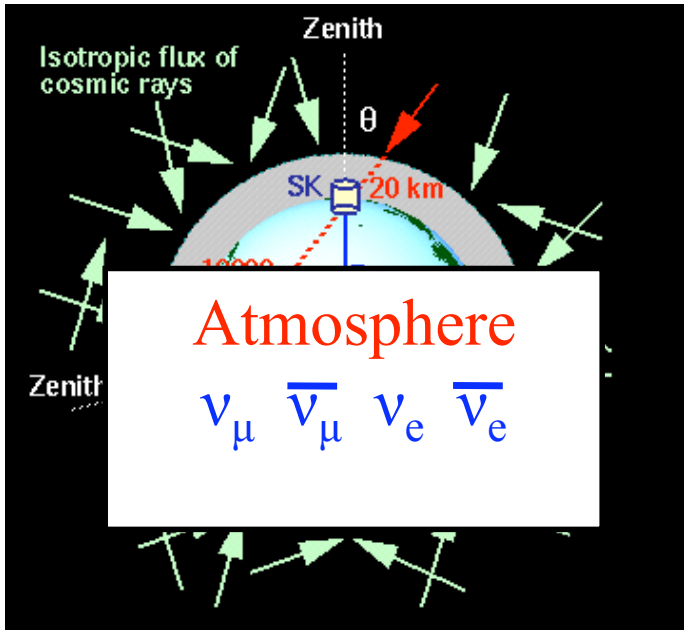
Neutrino Sources



Accelerator

ν_μ OR $\overline{\nu}_\mu$

(contamination of ν_μ or $\overline{\nu}_\mu$, ν_e & $\overline{\nu}_e$)

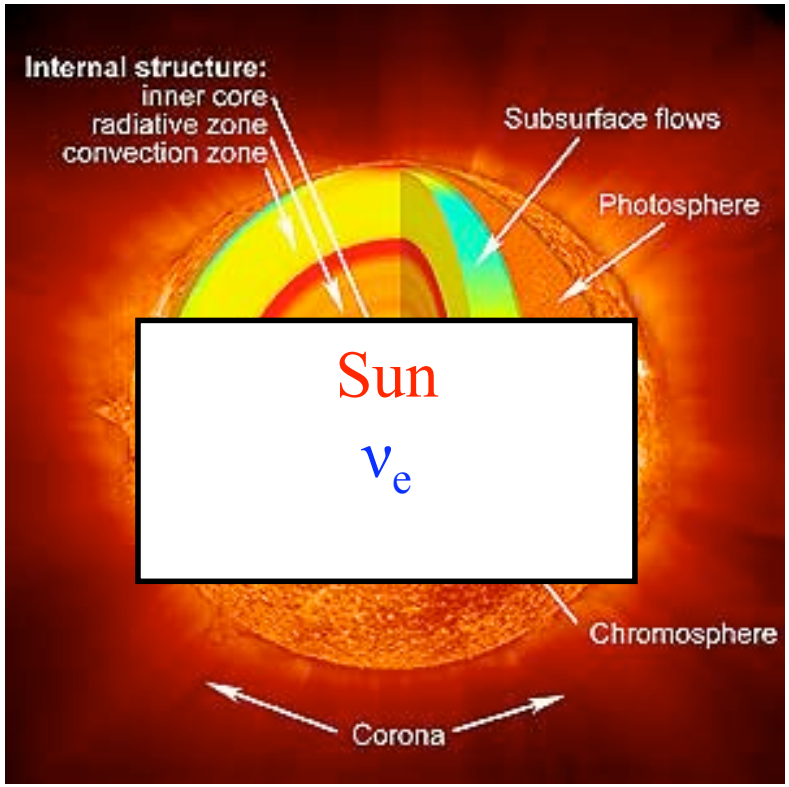


Atmosphere

ν_μ $\overline{\nu}_\mu$ ν_e $\overline{\nu}_e$

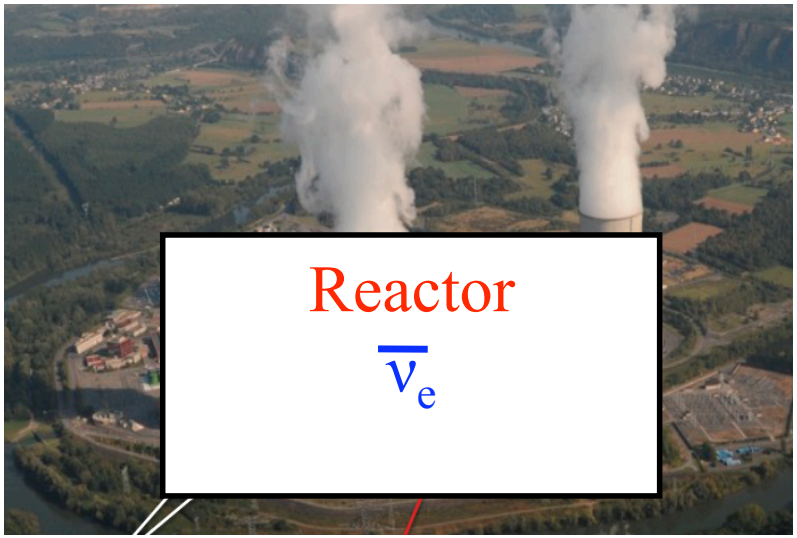
GeV

MeV



Sun

ν_e

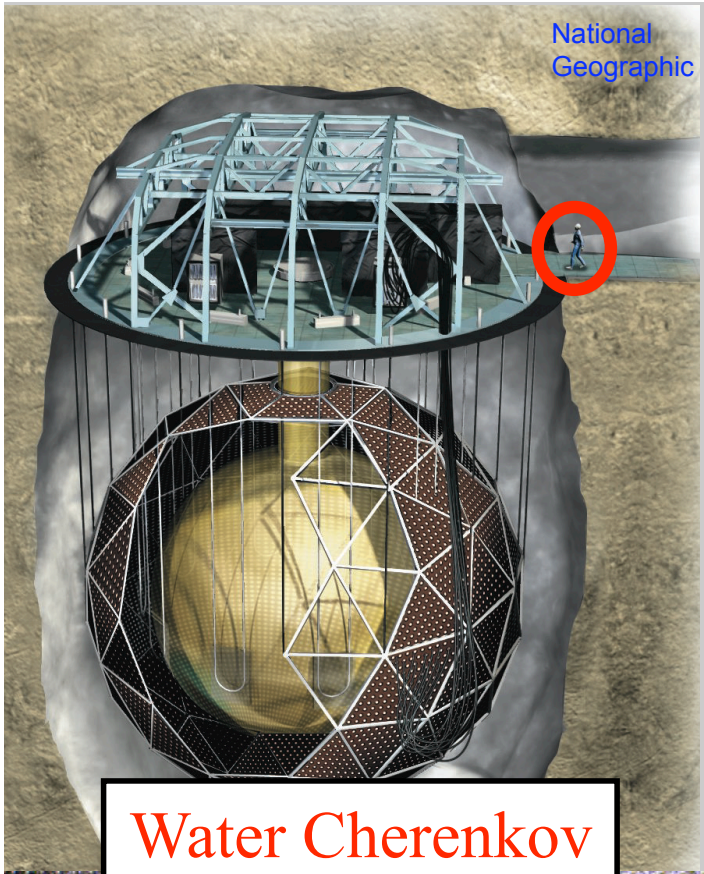


Reactor

$\overline{\nu}_e$

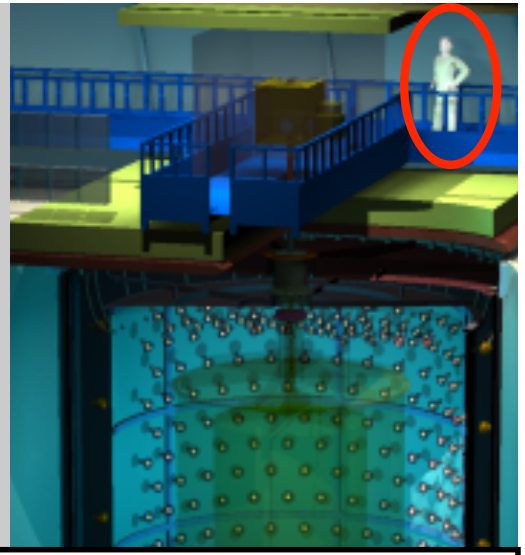
Neutrino Detectors

- Massive (Fiducial volume: 10->22000 tons)
  - Shielded/overburden
- Particle Identification:
  - Distinguish ν-flavours, e.g.:
    - ν_e from ν_μ
    - ν_μ from $\overline{\nu_\mu}$
    - ν_τ from ν_e and ν_μ
    - Exploit being below kinematic thresholds (e.g. reactor experiments, few MeV)
  - Distinguish CC from NC
  - Distinguish charged lepton from hadrons
- Neutrino/visible energy, direction/position

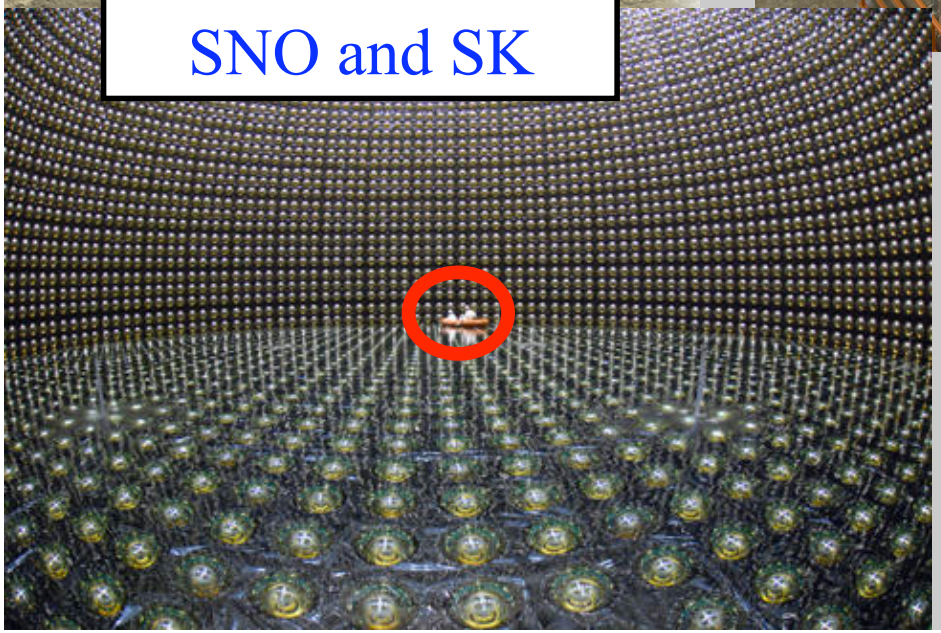


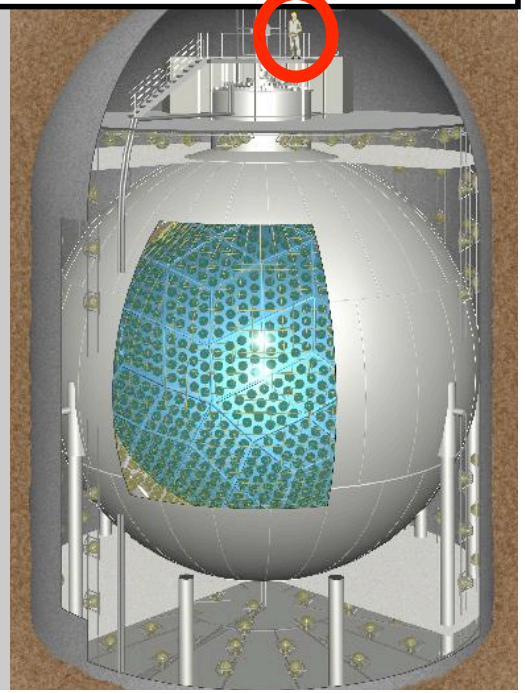
Water Cherenkov
SNO and SK

Iron/Plastic
Scintillator
MINOS



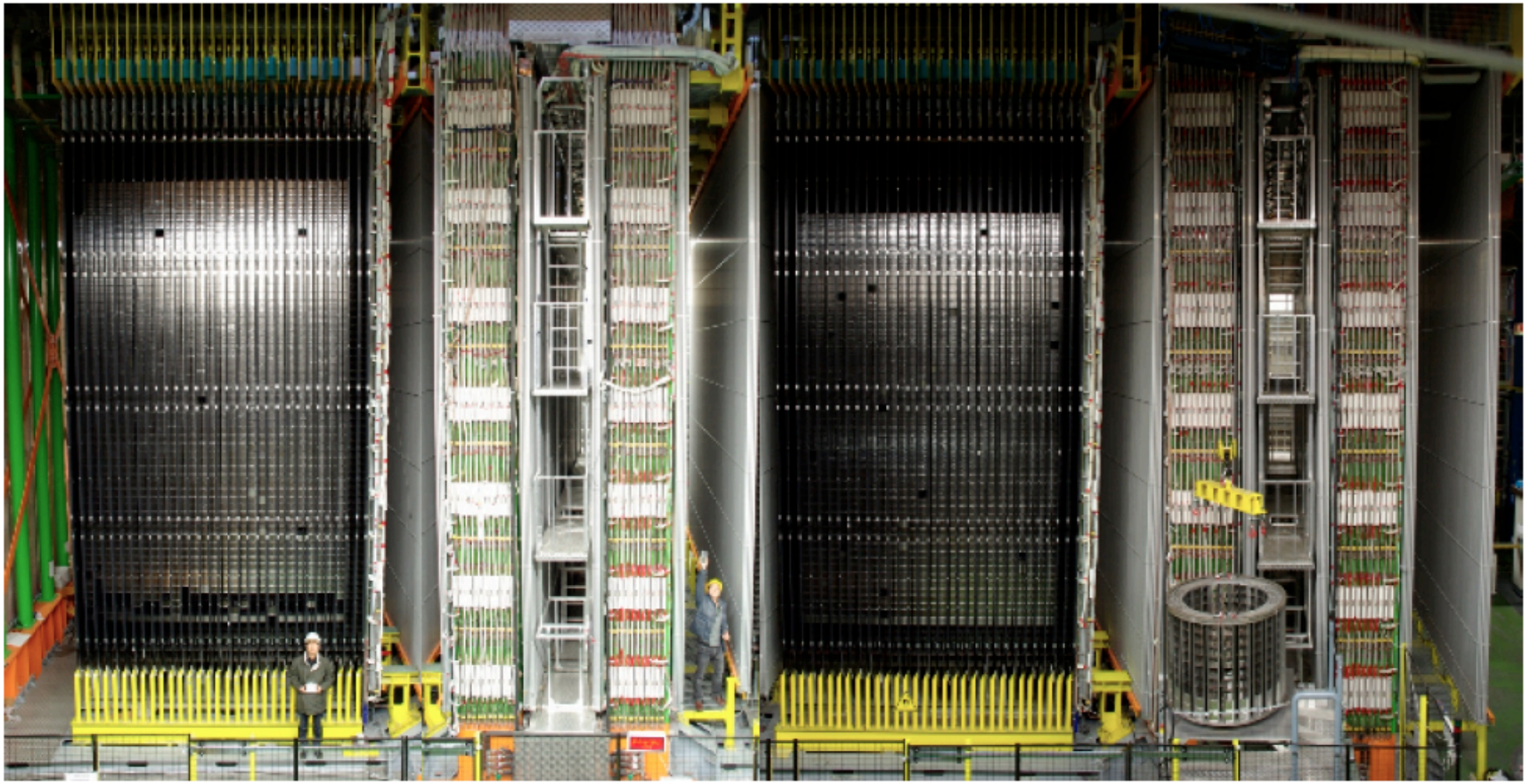
Liquid Scintillator
(Dbl) Chooz and
KamLAND





Neutrino
Detectors

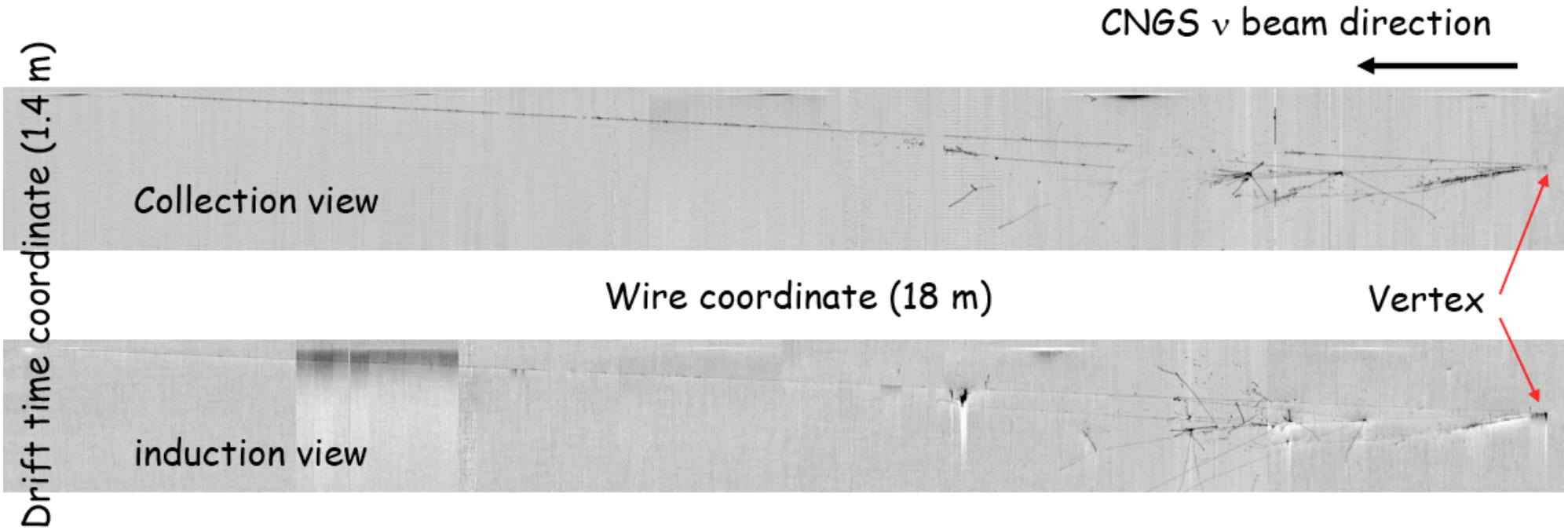
Opera



✧Fine grained “bricks” (1mm thick lead/emulsion).
✧Electronic detectors point back at neutrino vertex.

[Sato, Nu2010]

The first CNGS neutrino interaction in ICARUS T600



- Leading muon (crossing horizontally the whole cryostat)
- Two charged particle tracks undergoing hadronic interactions
- Two γ converting at 14 and 16 cm from vertex (π^0?)
- Vertex not fully visible in collection view, due to locally wrong wire biasing

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