Neutrino Phenomenology

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Outline

- Status quo
- Why neutrinos?
- Current experiments
- US options for the future
- Summary

Status Quo

A common, minimal framework for all the neutrino data is oscillation

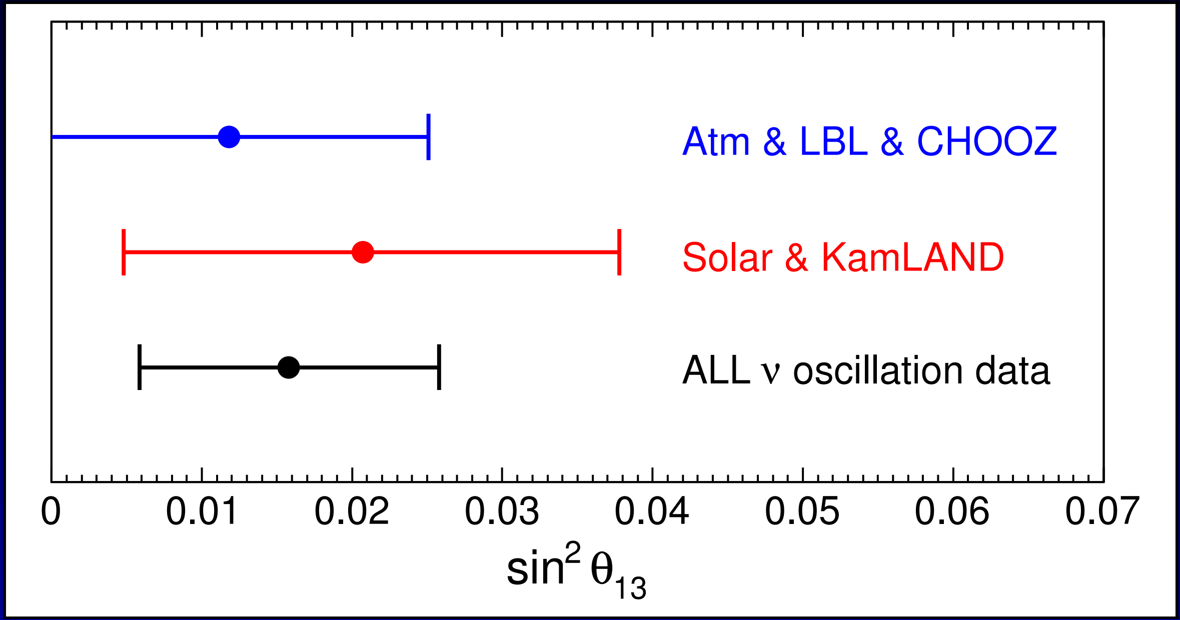
- $\Delta m^2_{21} = 7.6^{+0.5}_{-0.3} \cdot 10^{-5}\,\mathrm{eV}^2$ and $\sin^2\theta_{12} = 0.32^{+0.05}_{-0.04}$
- $\Delta m^2_{31} = 2.4^{+0.3}_{-0.3} \cdot 10^{-3}\,\mathrm{eV}^2$ and $\sin^2\theta_{23} = 0.5^{+0.13}_{-0.12}$
- $\sin^2\theta_{13} \leq 0.033$

This implies a lower bound on the mass of the heaviest neutrino

$$\sqrt{2.4 \cdot 10^{-3}\,\mathrm{eV}^2} \sim 0.04\,\mathrm{eV}$$

from hep-ph/0405172v6

Hints for $\theta_{13} \neq 0$



E. Lisi, *et al.*, arXiv:0806.2649.

- weak hint in atmospheric data was already there
- more KamLAND data
- more SNO NC data

$$\sin^2\theta_{13} = 0.016 \pm 0.010 \text{ or } \sin^2 2\theta_{13} = 0.06 \pm 0.04$$

Hints for $\theta_{13} \neq 0$

However, other authors pointed out that the atmospheric contribution is not robust and thus the hint resides solely in KamLAND and solar data.

In that case result is

$\sin^2\theta_{13} = 0.01^{+0.016}_{-0.01}$ or $\sin^2 2\theta_{13} = 0.04^{+0.06}_{-0.04}$

T. Schwetz, J.W.F. Valle, M. Tortola, arXiv:0806.2016. M. Maltoni, T. Schwetz, arXiv:0806.3161.

Hints for $\theta_{13} \neq 0$ – MINOS

MINOS' first ν_e appearance results

35 events seen vs $27 \pm 5 \pm 2$ expected for $3.14 \cdot 10^{20}$ pot

The odds that this is a fluctuation are, depending on the size of the systematic error

27 ± 0	1:13
27 ± 2	1:10
27 ± 4	1:8

Their best fit $\sin^2 2\theta_{13} \simeq 0.1 - 0.15$ or $\sin^2 \theta_{13} \simeq 0.03 - 0.04$

M. Sanchez, FNAL Wine & Cheese 27. Feb 2009.

Neutrinos are massive – so what?

Neutrinos in the Standard Model (SM) are strictly massless, *i.e.* there is no way to write a mass term for neutrinos with only SM fields which is gauge invariant and renormalizable.

Neutrinos are massive in reality – thus neutrino mass requires physics beyond the standard model.

We always knew they are . . .

The SM is an effective field theory, *i.e.* at some high scale Λ new degrees of freedom will appear

$$\mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \ldots$$

The first operators sensitive to new physics have dimension 5. It turns out there is only one dimension 5 operator

$$\mathcal{L}_5 = \frac{1}{\Lambda}(LH)(LH) \rightarrow \frac{1}{\Lambda}(L\langle H\rangle)(L\langle H\rangle) = m_\nu \nu\nu$$

Thus studying neutrino masses is the most sensitive probe for new physics at high scales

Effective theories

The problem in effective theories is, that there are *a priori* unknown pre-factors for each operator

$$\mathcal{L}_{SM} + \frac{\#}{\Lambda}\mathcal{L}_5 + \frac{\#}{\Lambda^2}\mathcal{L}_6 + \dots$$

Typically, one has $\# = \mathcal{O}(1)$, but there may be reasons for this being wrong

- lepton number may be conserved $\longrightarrow$ no Majorana mass term
- lepton number may be approximately conserved $\longrightarrow$ small pre-factor for $\mathcal{L}_5$

Therefore, we do not know the scale of new physics responsible for neutrino masses.

What we want to learn

- Majorana?
- Absolute mass scale
- Size of θ_{13}
- mass hierarchy?
- $\theta_{23} = \pi/4$?
- CP violation in leptons?

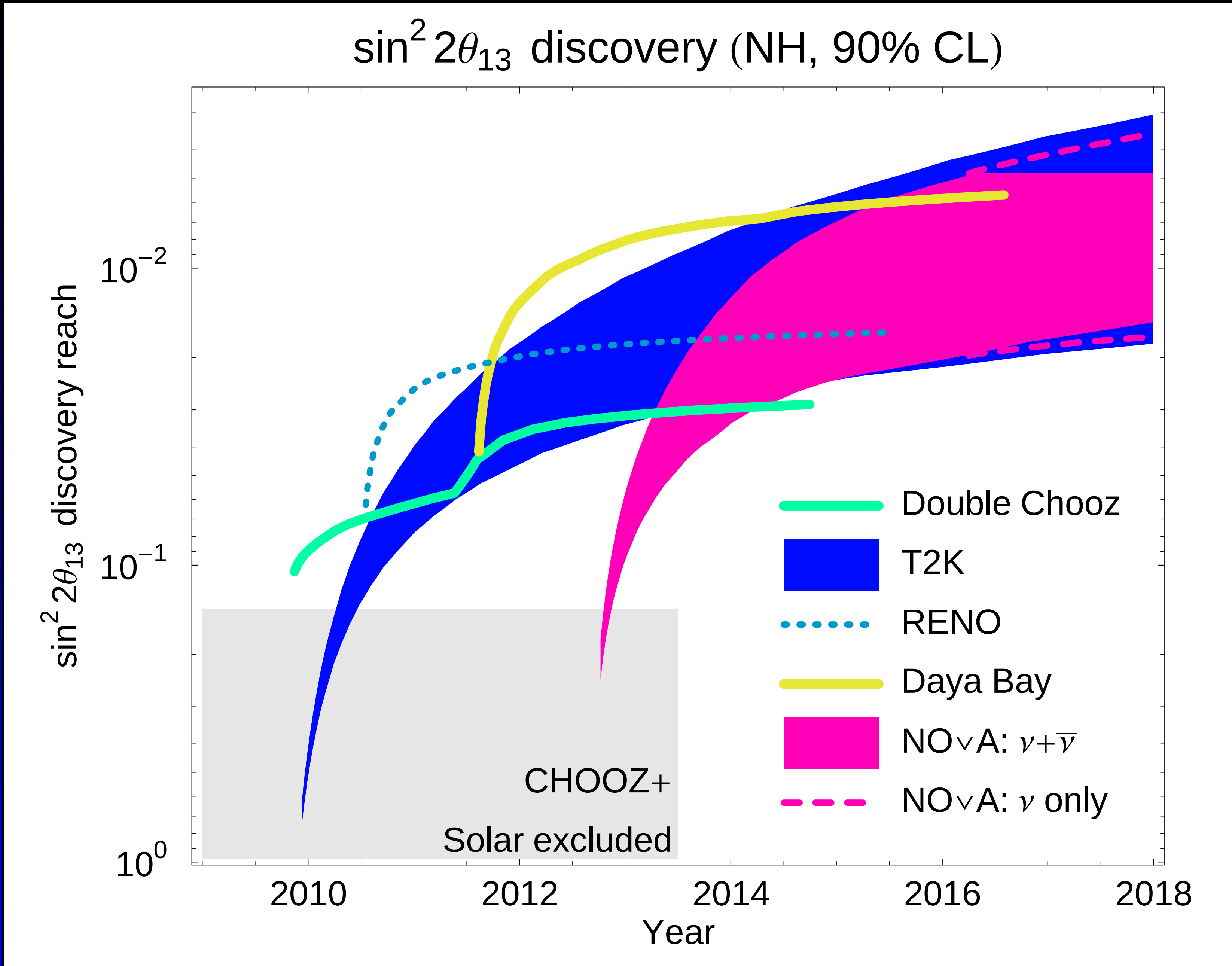
The latter three cannot be addressed† by currently running (MINOS, OPERA) or planed experiments like DoubleChooz, Reno, Daya Bay, T2K or NOνA.

Hence, the need for a new generation of neutrino oscillation experiments.

From hints to the hunt for θ_{13}

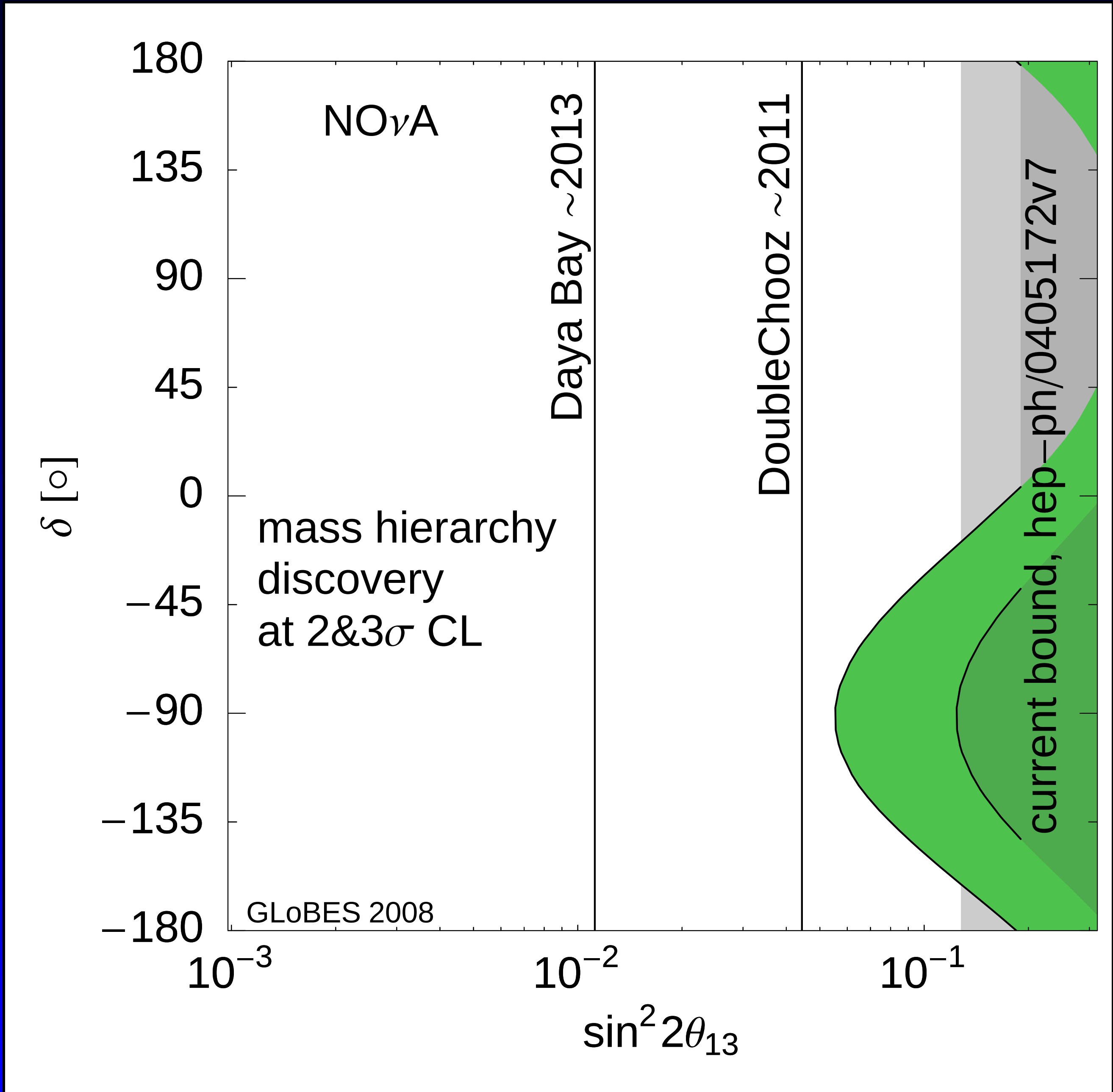
Timeline

- T2K: 09/2009 - 12/2012: 0 MW - 0.75 MW linear, Talk by Kakuno, NOW 2008
- Double Chooz: Start 09/2009, 1.5 yr with FD only, then ND+FD, Talk by S. Peeters, NOW 2008
- RENO, 06/2010 all modules Talk by Y. Kim, Rencontres de Physique, 2008
- Daya Bay: 7/2011 all modules, Talk by J. Napolitano at UC Davies
- NOvA: 08/2012 - 01/2014: 2.5 kt - 15 kt linear, Talk by M. Messier, ICHEP08

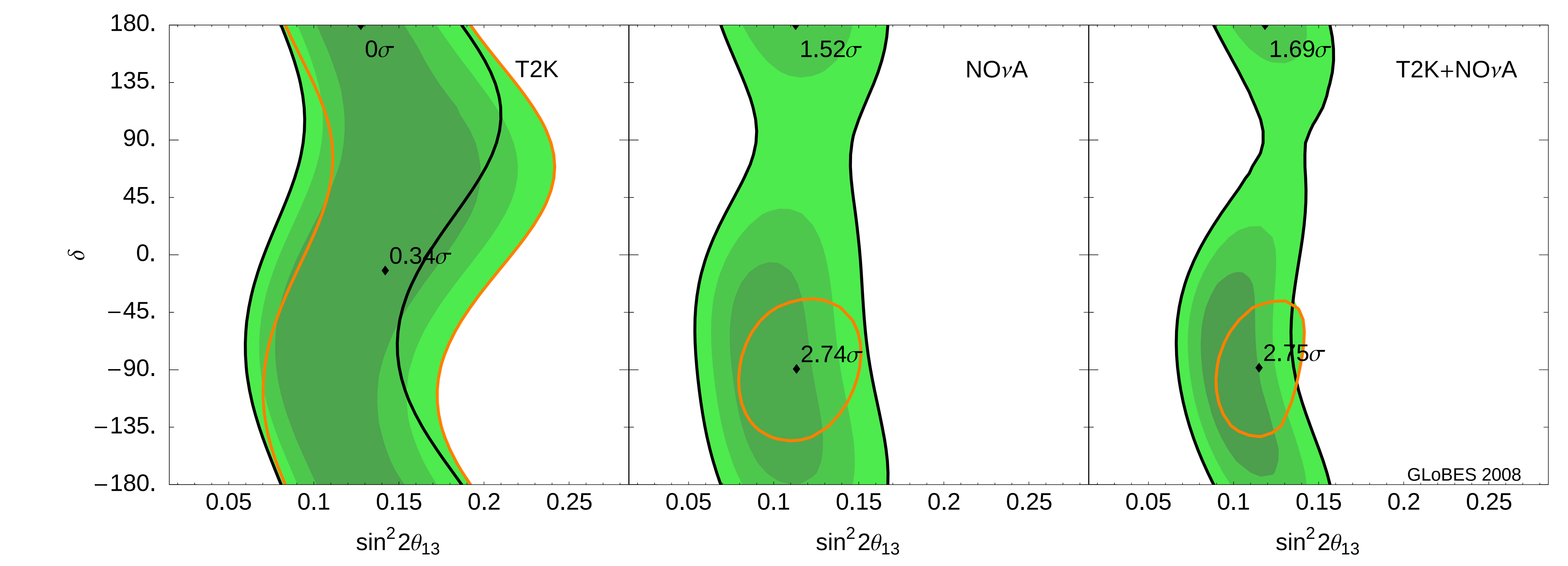


PH, M. Lindner, T. Schwetz and W. Winter, work in progress

Mass hierarchy

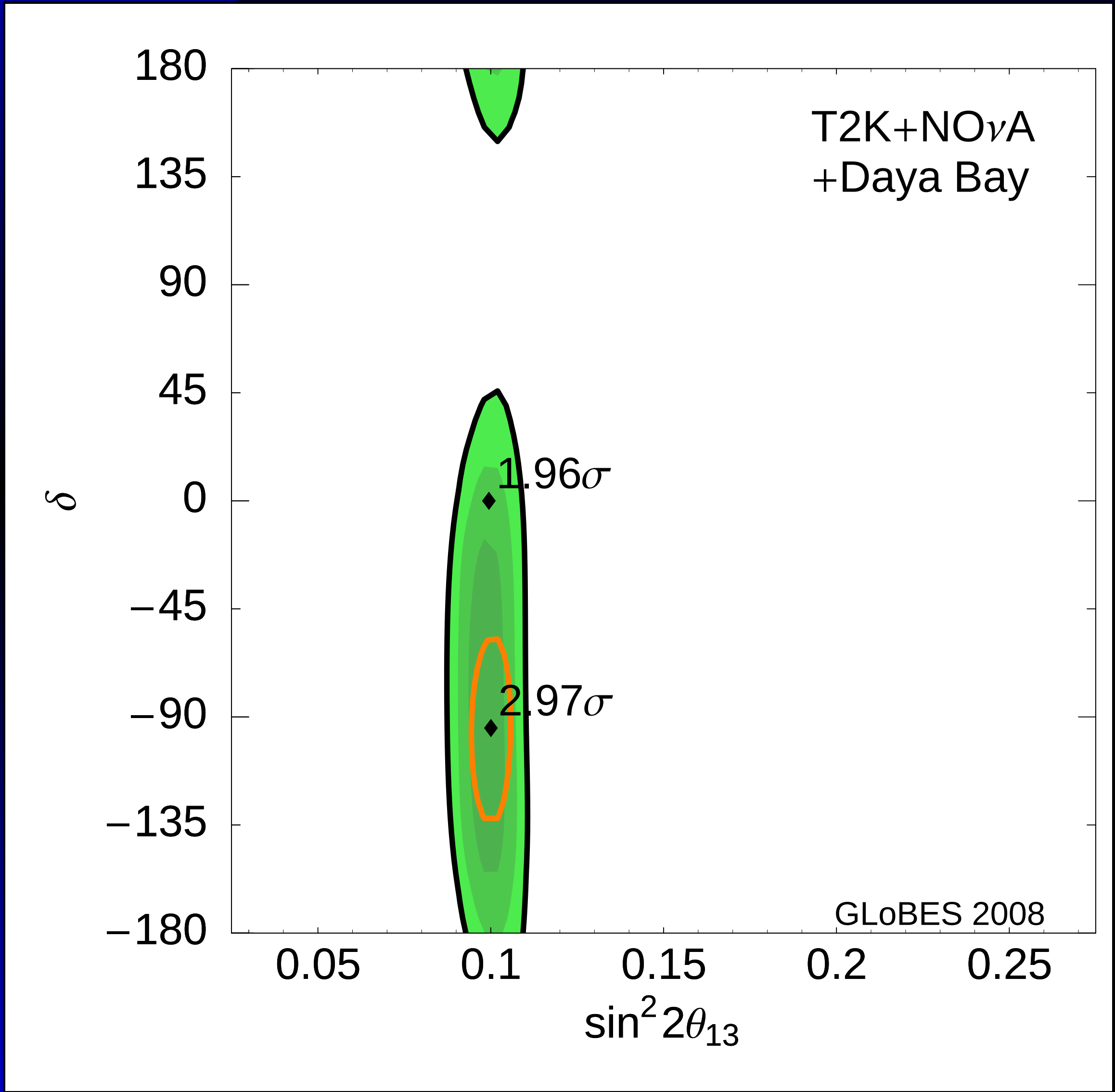


CP violation



- input values $\sin^2 2\theta_{13} = 0.1$ and $\delta = -90^\circ$
- at most a $1.7\,\sigma$ hint for CPV
- no value of δ excluded at $3\,\sigma$
- this is already the best case

Reactors help



- input values $\sin^2 2\theta_{13} = 0.1$ and $\delta = -90^\circ$
- about 130° of δ excluded at $3\,\sigma$, 36% of parameter space

CP violation and mass hierarchy

To precisely measure δ_{CP} and the to determine the mass hierarchy, following ingredients are needed

- large detectors, mass 100kt and up
- powerful neutrino and anti-neutrino beams, proton power 1 MW and up
- exquisite control of systematics, 5% and better
- more than two numbers to break degeneracies
  - at least one baseline longer than 1000 km
  - 1st and 2nd oscillation maximum at one baseline
  - or two baselines (either same or different L/E)


NuMI
0.3 MW
ANU
0.7 MW
SNuMI
1.2 MW
Project X
2.3 MW

Detector options

- water Cerenkov, 300 kt fiducial, needs to be deep underground $\longrightarrow$ needs to be sited in DUSEL $\longrightarrow$ baseline of 1300 km, new beamline
- liquid Argon TPC, 100kt fiducial, works at the surface (or at least with minimal overburden), thus can go either into the existing NuMI beamline or into DUSEL

Detector performances taken from the Report of the US long baseline neutrino experiment study, arXiv:0705.4396

Beam options

- NuMI beamline – currently used for MINOS. 675m long and 2m diameter decay tunnel. Baseline is 735km pointed to the Sudan mine.
- DUSEL beamline – new construction required. 380m long and 4m diameter decay tunnel. Baseline is 1290km pointed to the Homestake mine (DUSEL).

Resulting beam fluxes taken from Report of the US long baseline neutrino experiment study, arXiv:0705.4396, we use 6 years total running time.

The competition

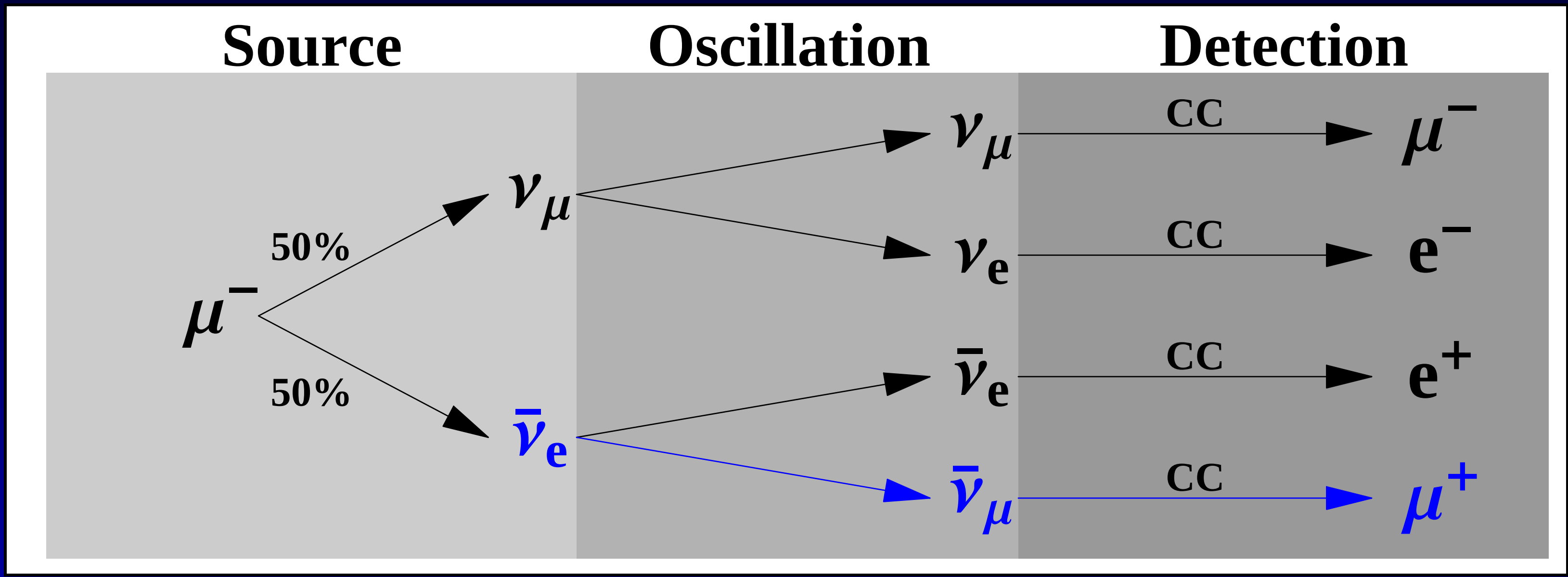
Japanese program to upgrade T2K

- Proton intensity upgrade to 1.66 MW around 2015
- New detector(s)
  - 540 kt water Cerenkov at 295km (T2HK)
  - 270 kt water Cerenkov at 295km and 270kt at 1050km (T2KK)
- 8 years running time

It turns out that T2KK has a consistently superior performance compared to T2HK, which therefore will not be considered further.
From NNN08, talk by T. Hasegawa

A neutrino factory

Put muons in a storage ring and let them decay

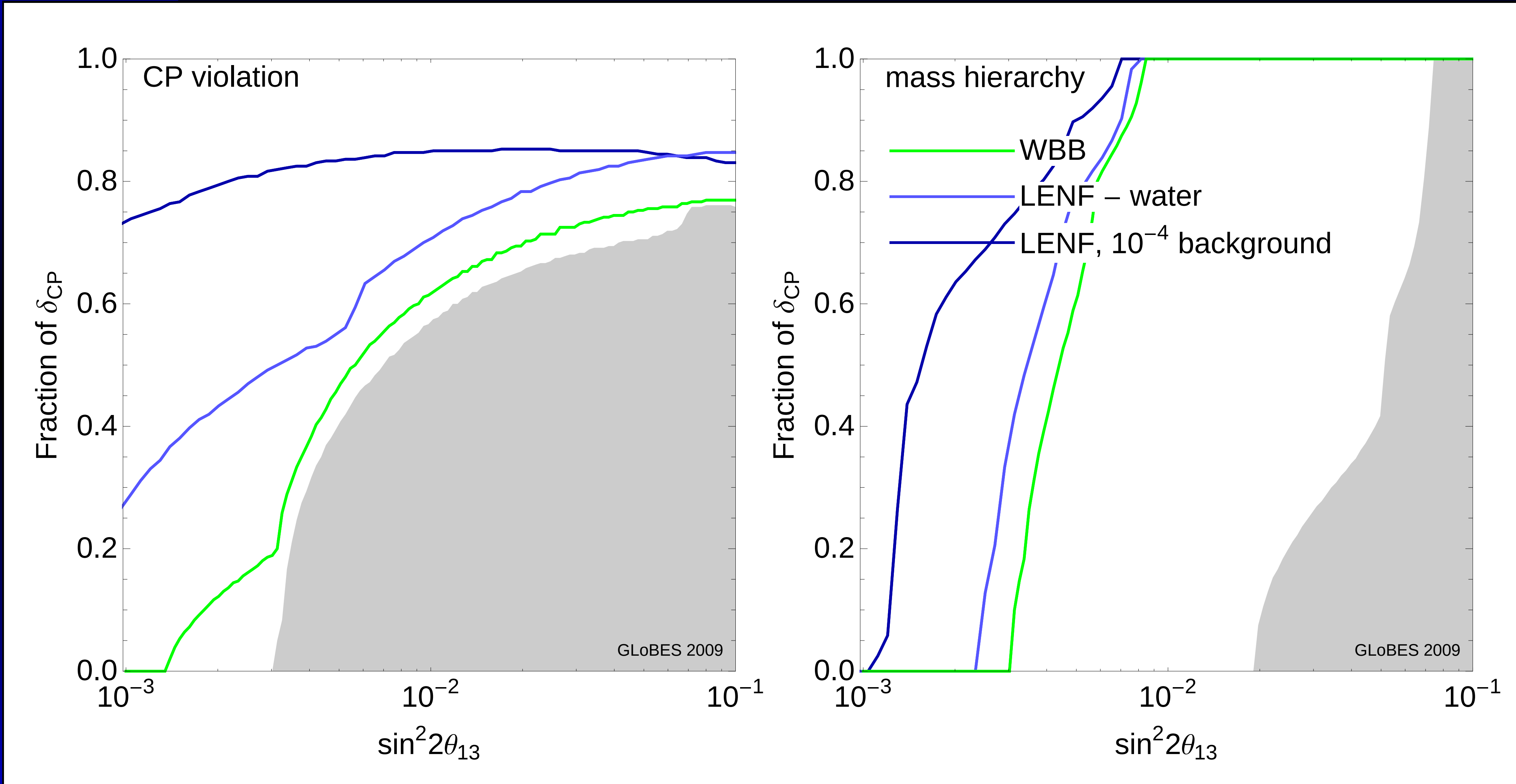


We assume $1.4 \cdot 10^{21}$ useful muon decays per year and polarity, two polarities simultaneously, 10 years and 20kt (fiducial) magnetized TASD in DUSEL

IDS-NF plenary meeting 2009 at CERN, talk by A. Bross

A. Bross, *et al.*, arXiv:0709.3889

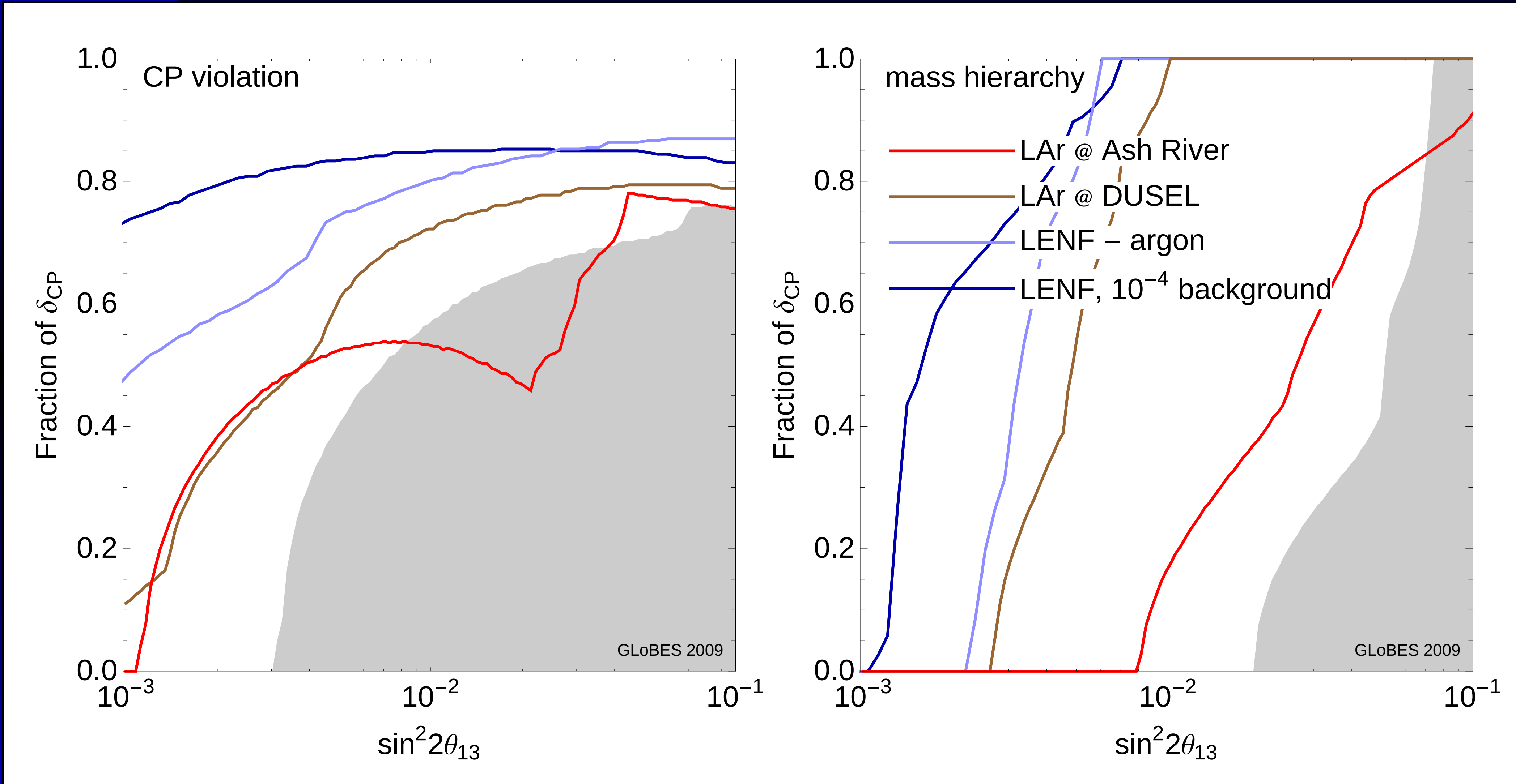
Road map with Water



non magnetized option is taken from

PH, T.Schwetz, arXiv:0805.2019

Road map with Argon



non magnetized options is taken from

PH, T.Schwetz, arXiv:0805.2019

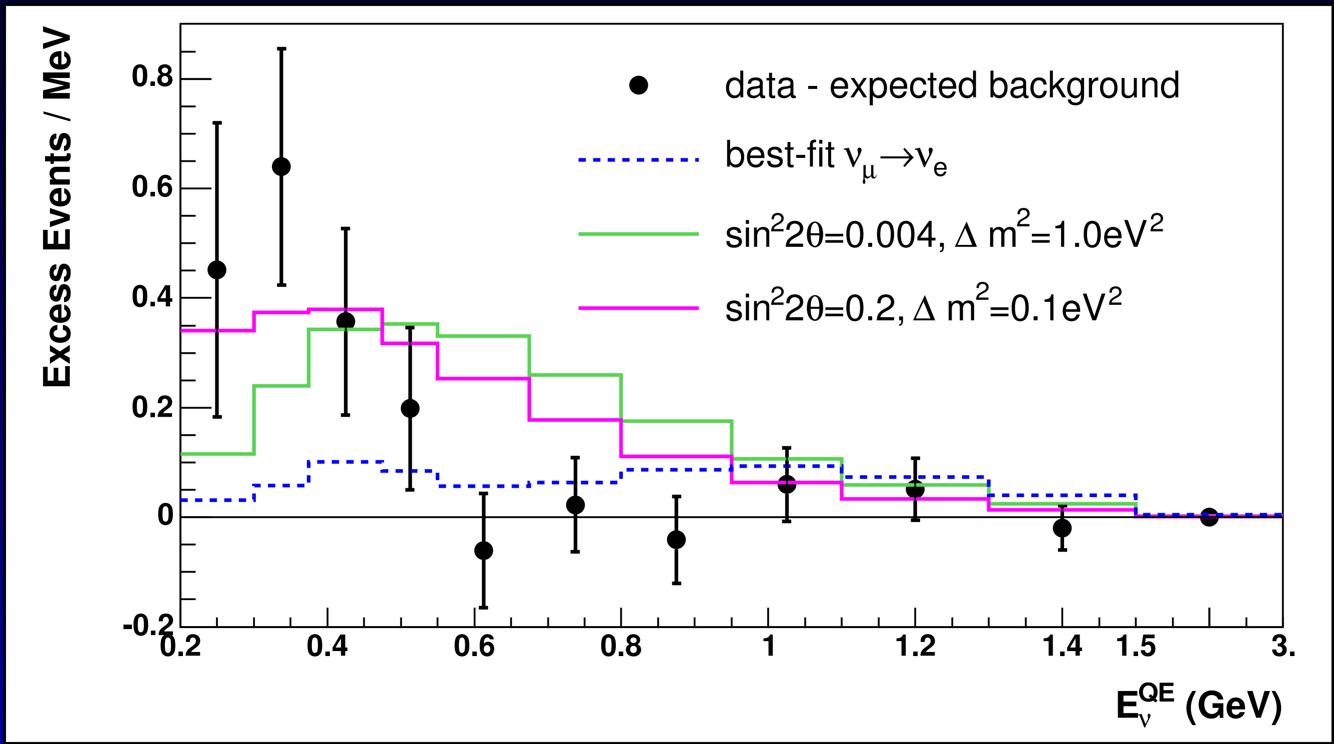
Summary

- Precision neutrino physics is possible
- Studying neutrinos is complementary to LHC
- High intensity proton source is key
- Project X & large detector(s) at DUSEL allow for a competitive long term program
- This program ultimately can prepare the ground for a return to the high energy frontier (neutrino factory $\longrightarrow$ muon collider)

Backup slides

On Sterile Neutrinos

MiniBooNE – neutrino mode

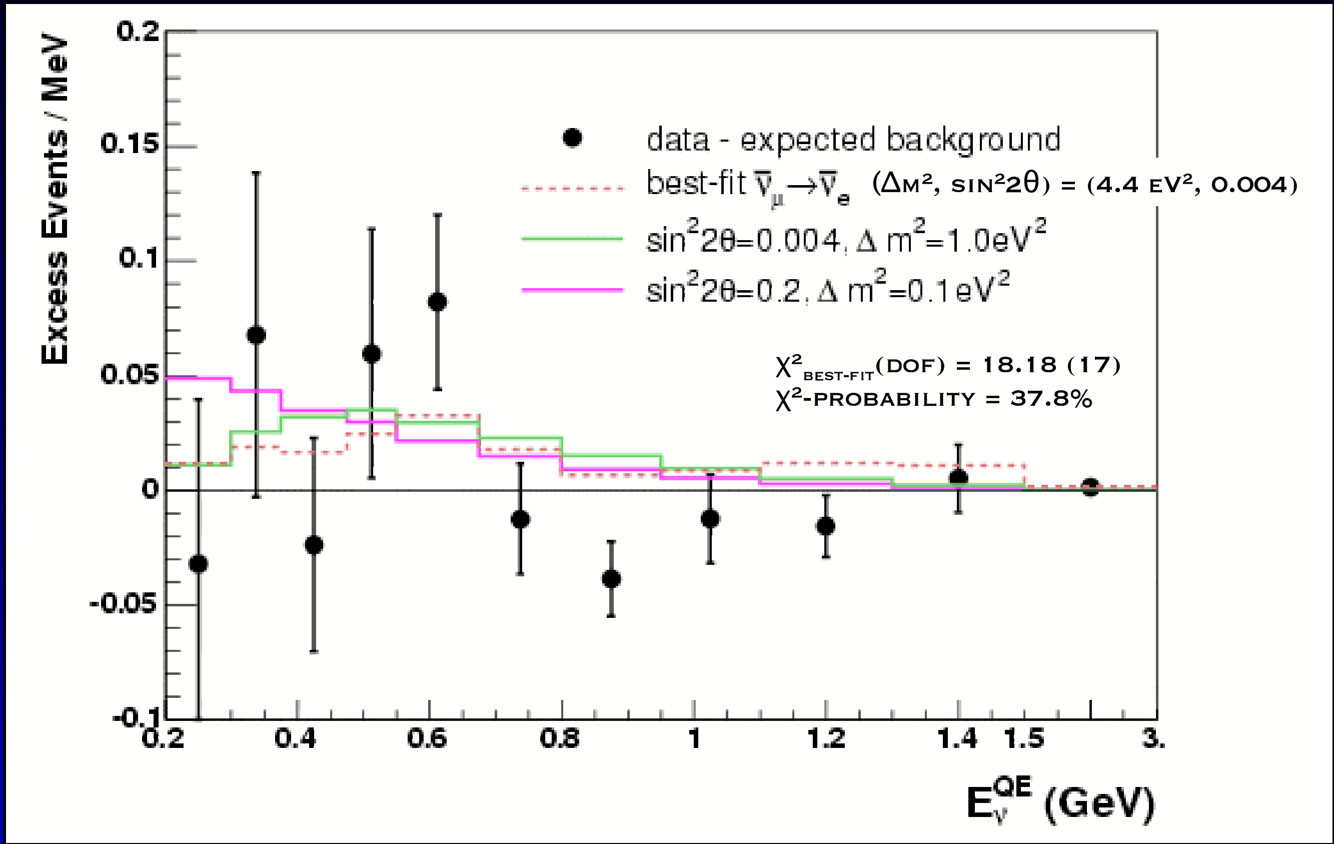


Below 475 MeV: 544 events seen vs 415.2 ± 43.4 expected

Above 475 MeV: 408 events seen vs 385.9 ± 35.7 expected

from MiniBooNE collaboration, arXiv:0812.2243v2.

MiniBooNE – anti-neutrino mode



Below 475 MeV: 61 events seen vs 61.5 ± 11.7 expected
Above 475 MeV: 61 events seen vs 57.8 ± 10.0 expected

from talk by H. Ray

MiniBooNE vs LSND

Any interpretation of LSND as solely due to neutrino oscillation is very strongly disfavored for any number of neutrinos, by the lack of evidence for neutrino disappearance at short distances.

MiniBooNE basically only adds a few units of $\Delta\chi^2$ in a fit with more than 100 degrees of freedom

M. Maltoni, T. Schwetz, arXiv:0705.0107.

Light sterile neutrinos?

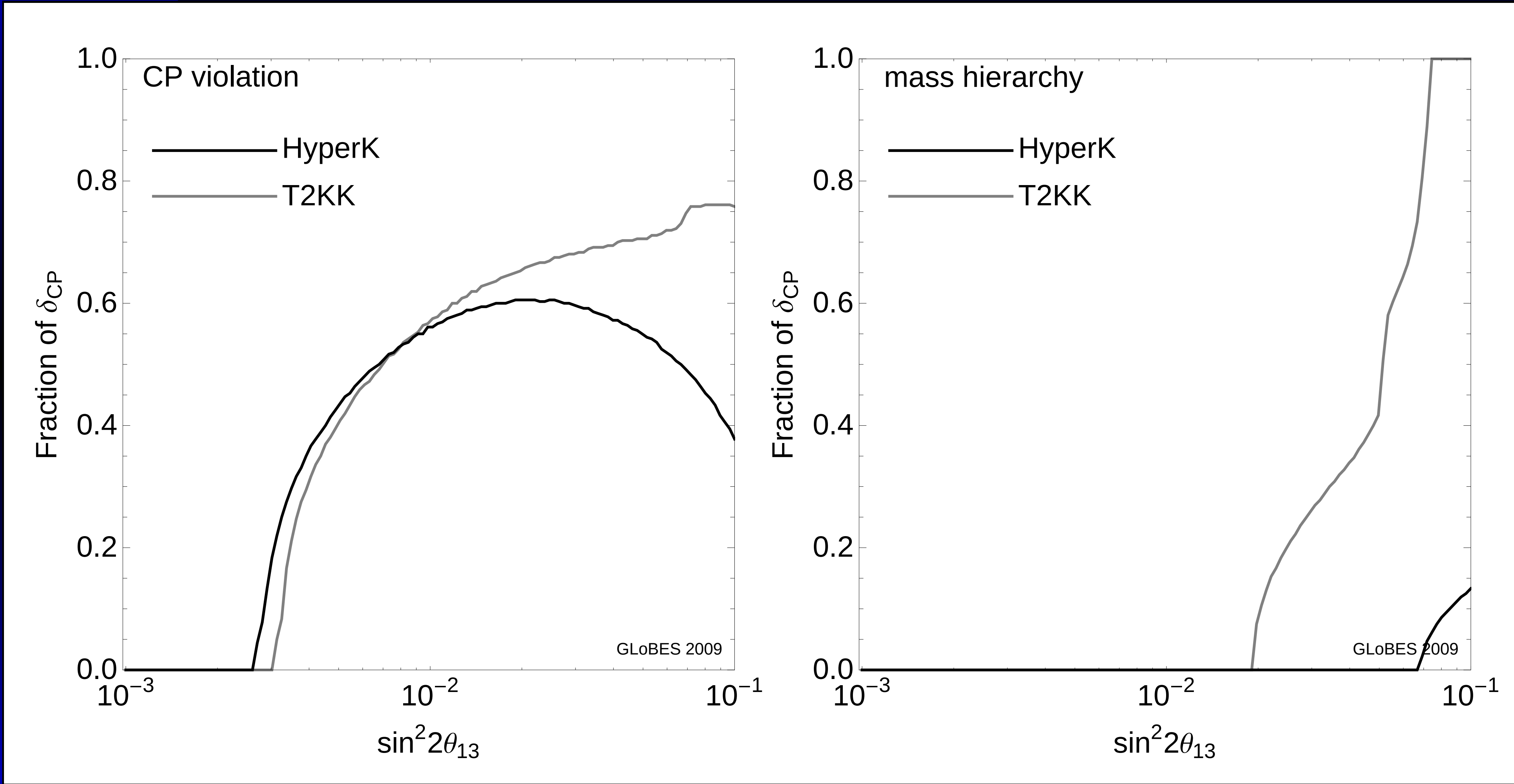
Does this imply that that we no longer need to look for light sterile neutrinos?

NO

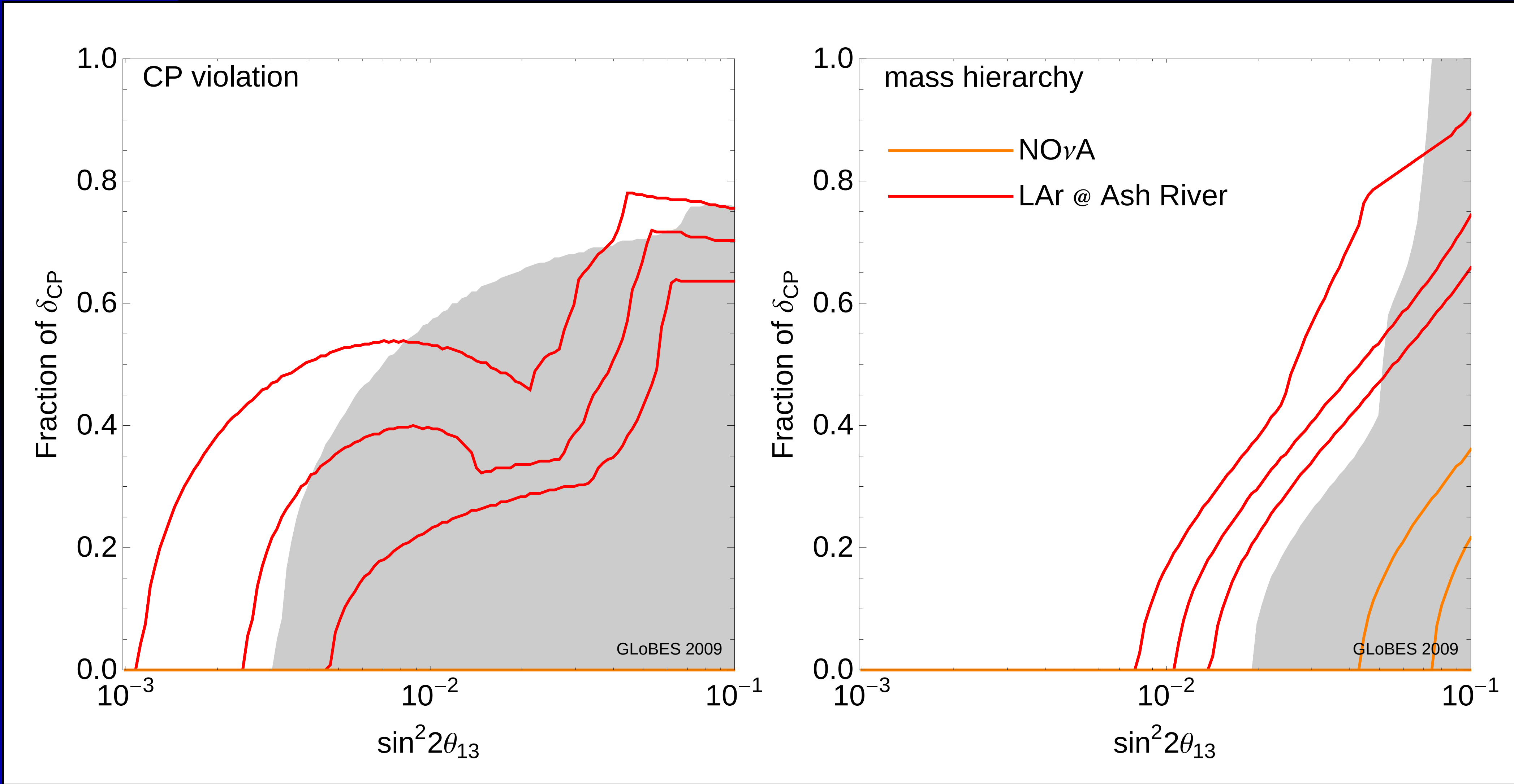
- The seesaw scale is essentially unknown see *e.g.*, A. de Gouvea, J. Jenkins, N. Vasudevan, hep-ph/0608147.
- Even with $m_R \sim 10^{15}$ GeV, the resulting neutrino mass matrix can have more than 3 small eigenvalues.
- eV scale sterile neutrinos can play a role in certain astrophysical contexts, like *e.g.* r-process nucleosynthesis

More on FNAL options

One vs two detectors for the JAERI beam

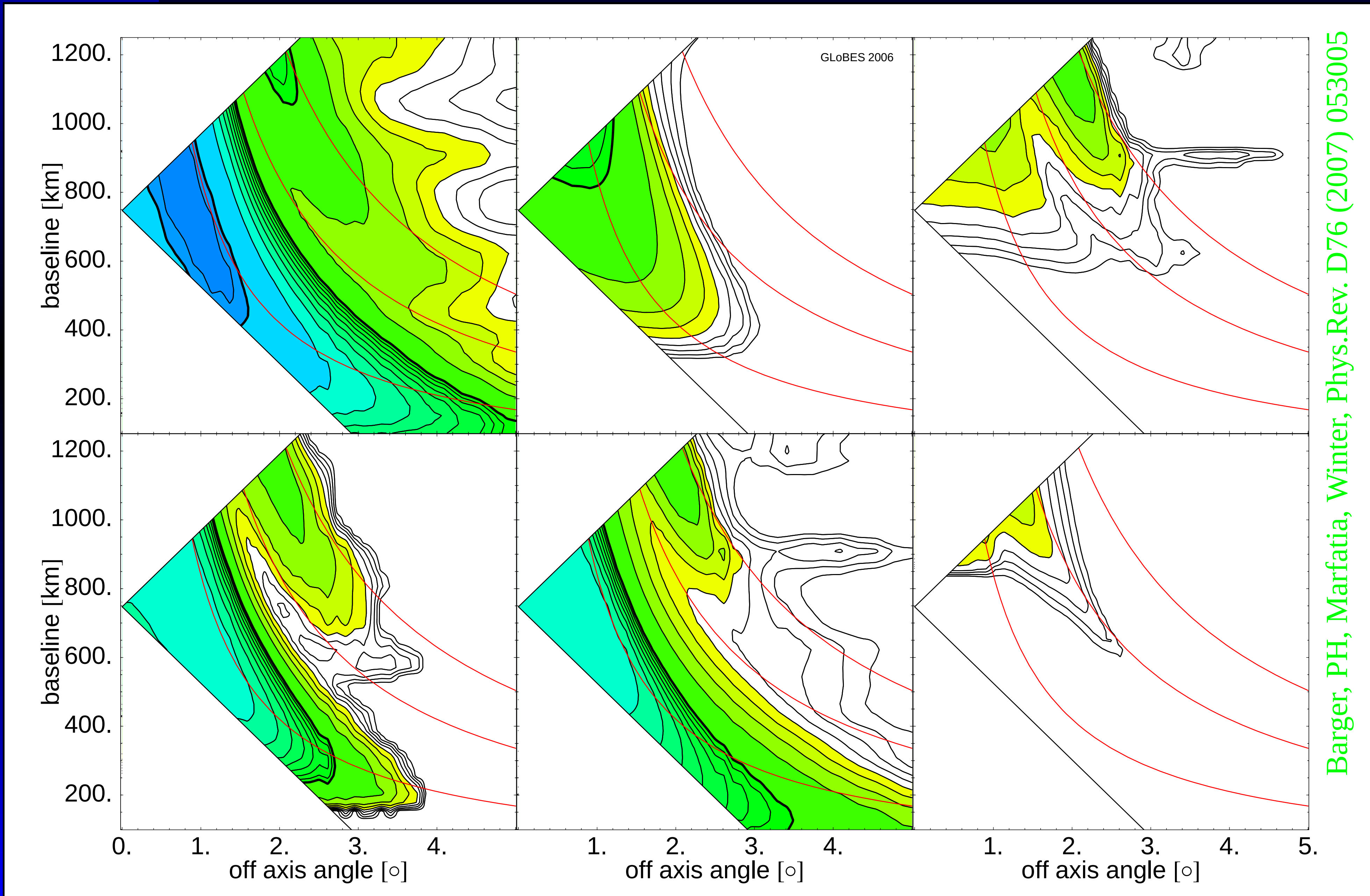


NOνA and proton intensity

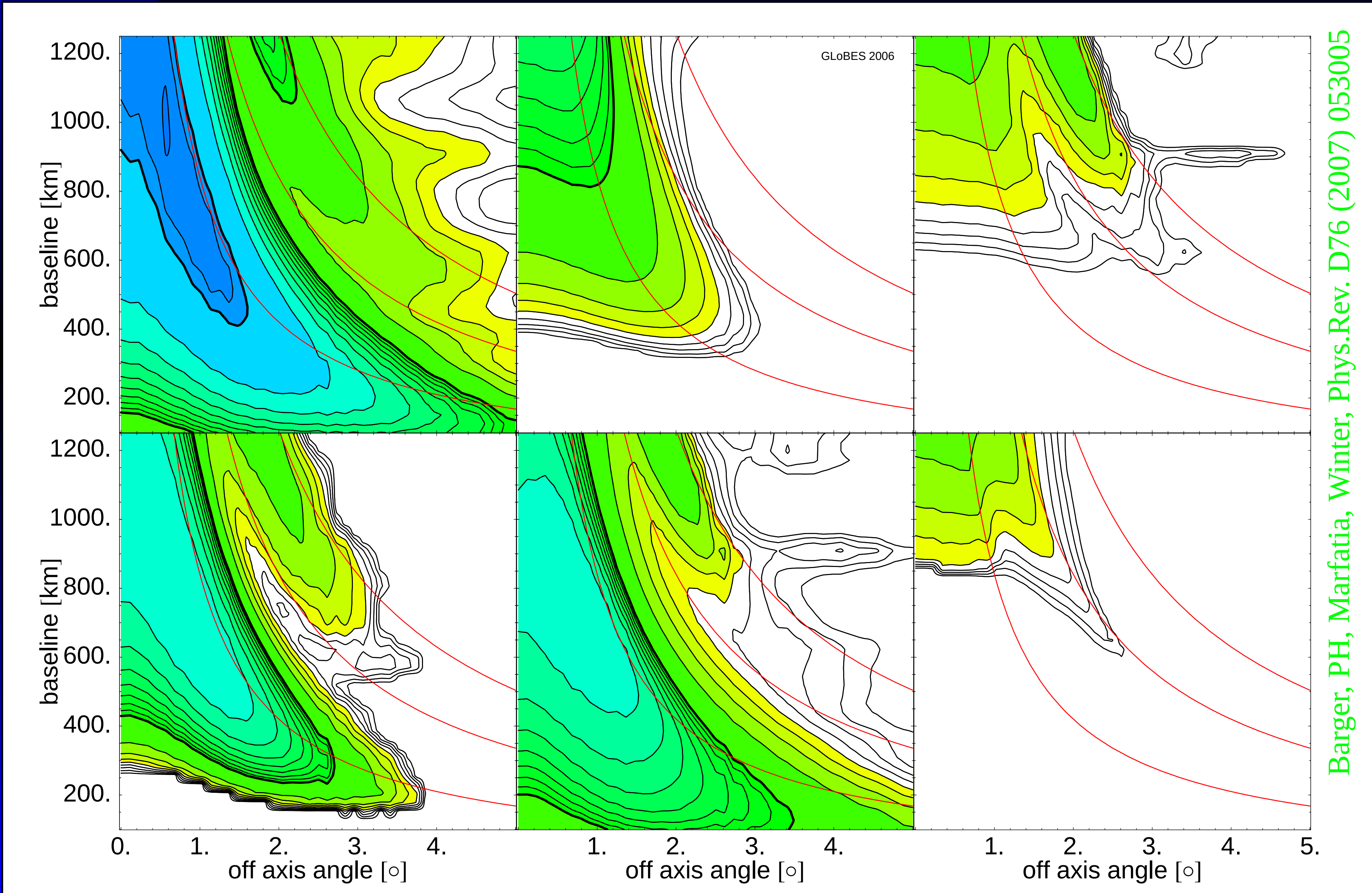


On vs off-axis

On vs off-axis

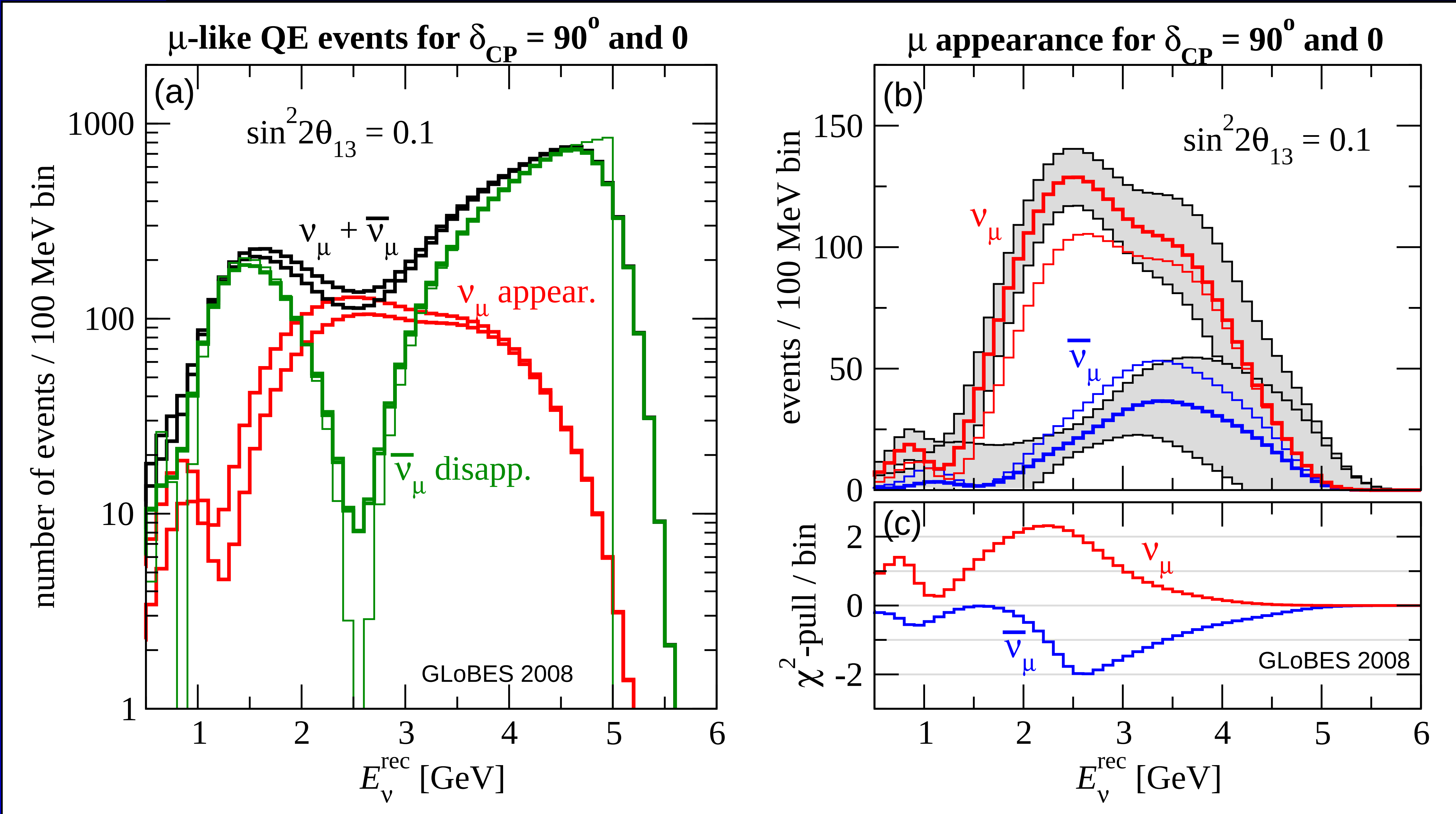


On vs off-axis



Non-magnetized detectors for LENF

Oscillation helps

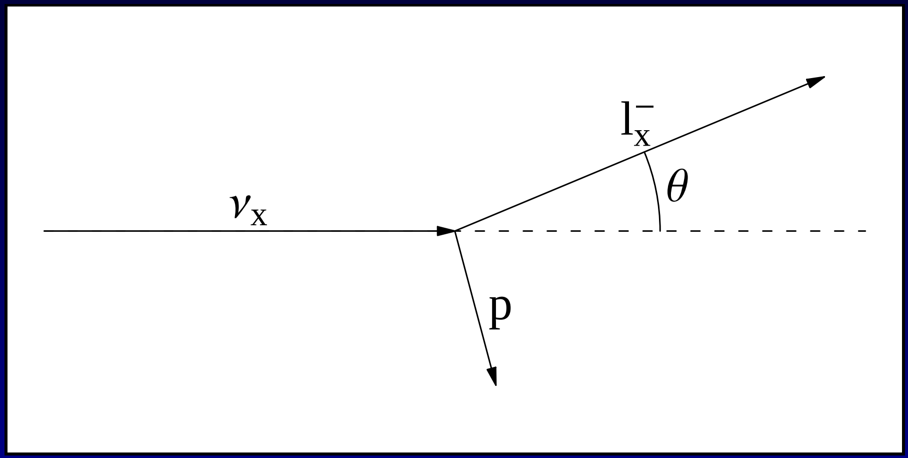


baseline 1290 km and $\Delta E = 0.05\sqrt{E} + 0.085\,\mathrm{GeV}$

$\nu \neq \bar{\nu}$!

QE reactions

$$\nu_x + N \to l_x^- + p + N'$$
$$\bar{\nu}_x + N \to l_x^+ + n + N'$$



There are 3 basic differences between ν and $\bar{\nu}$ events

1. muon lifetime due to μ^- capture
2. $\cos\theta$ distribution
3. outgoing nucleon, either a proton or a neutron

$\nu \neq \bar{\nu}$ – proton vs neutron

Identifying the outgoing nucleon requires the ability to tag at least either the proton or the neutron, ideally both.

Assuming, we have a tag for the proton or neutron, we get two sources of mis-ID

- the tag is not 100% efficient
- the event produced the wrong nucleon
  - because there were more than 1 nucleon
  - because the initial nucleon underwent a charge exchange reaction

Initial estimates indicate, that efficiencies larger than 90% maybe possible and, that charge exchange affects less than 15% of events.

Nucleon tagging

Water Cerenkov

Proton tagging very inefficient due to Cerenkov threshold. However, neutron tagging is possible by adding 0.2% Gadolinium. The neutron will predominantly capture on Gd and the Gd then will emit about $8\,\mathrm{MeV}$ of γs. GADZOOKS project is underway to study feasibility in large scale detector. J. Beacom and M. Vagins, hep-ph/0309300.

Liquid Argon

Has demonstrated its ability to see low energy protons in a prototype. F. Arneodo, *et al.*, physics/0609205.

Non-magnetized detectors summary

- Oscillation provides a right sign muon suppression of $1:10$ down to $1:100$, depending on energy resolution
- Neutrinos are not anti-neutrinos: muon lifetime, $\cos\theta$ and nucleon tagging
- moderate separation efficiencies and purities of 50%-90% allow to use very large general purpose detectors down to $\sin^2 2\theta_{13} \simeq 0.004$
- this may be very useful in the context of staging

CAVEAT EMPTOR: all of this requires detailed simulations and a precise understanding of nuclear effects.