NOνA and beyond

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Extreme Beam Lecture

FNAL

April 16th 2009

Outline

- Why neutrinos?
- Neutrino oscillation
- Multiple solutions
- Current experiments
- Options at FNAL
- 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

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

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

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

The Seesaw

One plausible explanation of the smallness of neutrino masses would be the that the scale of new physics Λ is very large, this in essence is the seesaw mechanism.

In typical realizations Λ is close to the GUT scale, which allows to use the heavy right handed neutrino for leptogenesis.

On the other hand, it is not straightforward to create large lepton mixing angles and small quark mixing angles in a GUT context. Moreover, to make all these things work quantitatively at the same time is not easy!

Effective theories

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

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

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.

Low energy observables

- Majorana vs Dirac mass – $0\nu\beta\beta$
- Absolute m_ν – Katrin, Cosmology
- How large is θ_{13}? – Oscillation
- Which one is the heaviest neutrino? –$0\nu\beta\beta$, Katrin, Oscillation
- Is θ_{23} maximal? – Oscillation
- Is there leptonic CP violation? – Oscillation
- Are there only 3 light neutrinos? – Oscillation
- Do neutrinos have non-standard interactions? – Oscillation, Scattering

What we want to learn

- 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.

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†at least with sufficient accuracy/ parameter reach

Neutrino oscillations

The mass eigenstates are related to flavor eigenstates by U_ν, thus a neutrino which is produced as flavor eigenstate is a superposition of mass eigenstates. These mass eigenstates propagate with different velocity and a phase difference is generated. This phase difference gives rise to a finite transition probability

$$P_{\nu_\alpha\to\nu_\beta} = \sum_{ij} U_{\alpha j}U^*_{\beta j}U^*_{\alpha i}U_{\beta i}e^{-i\frac{\Delta m^2_{ij}L}{2E}} \sim \sin^2 2\theta \sin^2 \frac{\Delta m^2_{ij}L}{4E}$$

Neutrino oscillation is a quantum mechanical interference phenomenon and therefore it is uniquely sensitive to extremely tiny effects.

Neutrino oscillations – CP viol.

Like in the quark sector mixing can cause CP violation

$$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq 0$$

The size of this effect is proportional to

$$J_{CP} = \frac{1}{8} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin\delta$$

The experimentally most suitable transition to study CP violation is $\nu_e \leftrightarrow \nu_\mu$, which is only available in beam experiments.

Neutrino oscillation – matter

The charged current interaction of ν_e with the electrons creates a potential for ν_e

$$A = \pm 2\sqrt{2} G_F \cdot E \cdot n_e$$

where $+$ is for ν and $-$ for $\bar{\nu}$.
This potential gives rise to an additional phase for ν_e and thus changes the oscillation probability. This has two consequences

$$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq 0$$

even if $\delta = 0$, since the potential distinguishes neutrinos from anti-neutrinos.

Neutrino oscillation – matter

The second consequence of the matter potential is that there can be a resonant conversion – the MSW effect. The condition for the resonance is

$$\Delta m^2 \simeq A$$

Obviously the occurrence of this resonance depends on the signs of both sides in this equation. Thus oscillation becomes sensitive to the mass ordering

	ν	$\bar{\nu}$
$\Delta m^2 > 0$	MSW	-
$\Delta m^2 < 0$	-	MSW

$P(\nu_\mu \to \nu_e)$

Two-neutrino limit – $\Delta m^2_{21} = 0$

$$\approx \quad \sin^2 2\theta_{13} \qquad \sin^2 \theta_{23} \qquad \frac{\sin^2((\hat{A}-1)\Delta)}{(\hat{A}-1)^2}$$

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

Three flavors – $\Delta m^2_{21} \neq 0$

$$\approx \quad \sin^2 2\theta_{13} \quad \sin^2\theta_{23} \quad \frac{\sin^2((\hat{A}-1)\Delta)}{(\hat{A}-1)^2}$$

$$\pm \quad \alpha\sin 2\theta_{13} \quad \sin\delta\sin 2\theta_{12}\sin 2\theta_{23} \quad \frac{\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})}$$

$$+ \quad \alpha\sin 2\theta_{13} \quad \cos\delta\sin 2\theta_{12}\sin 2\theta_{23} \quad \frac{\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})}$$

$$+ \quad \alpha^2 \quad \cos^2\theta_{23}\sin^2 2\theta_{12} \quad \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

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

Small quantities – $\alpha := \Delta m^2_{21}/\Delta m^2_{31}$ and $\sin 2\theta_{13}$

$$\approx \quad \sin^2 2\theta_{13} \quad \sin^2\theta_{23} \quad \frac{\sin^2((\hat{A}-1)\Delta)}{(\hat{A}-1)^2}$$

$$\pm \quad \alpha \sin 2\theta_{13} \quad \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \quad \frac{\sin(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})}$$

$$+ \quad \alpha \sin 2\theta_{13} \quad \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \quad \frac{\cos(\Delta)\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})}$$

$$+ \quad \alpha^2 \quad \cos^2\theta_{23} \sin^2 2\theta_{12} \quad \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

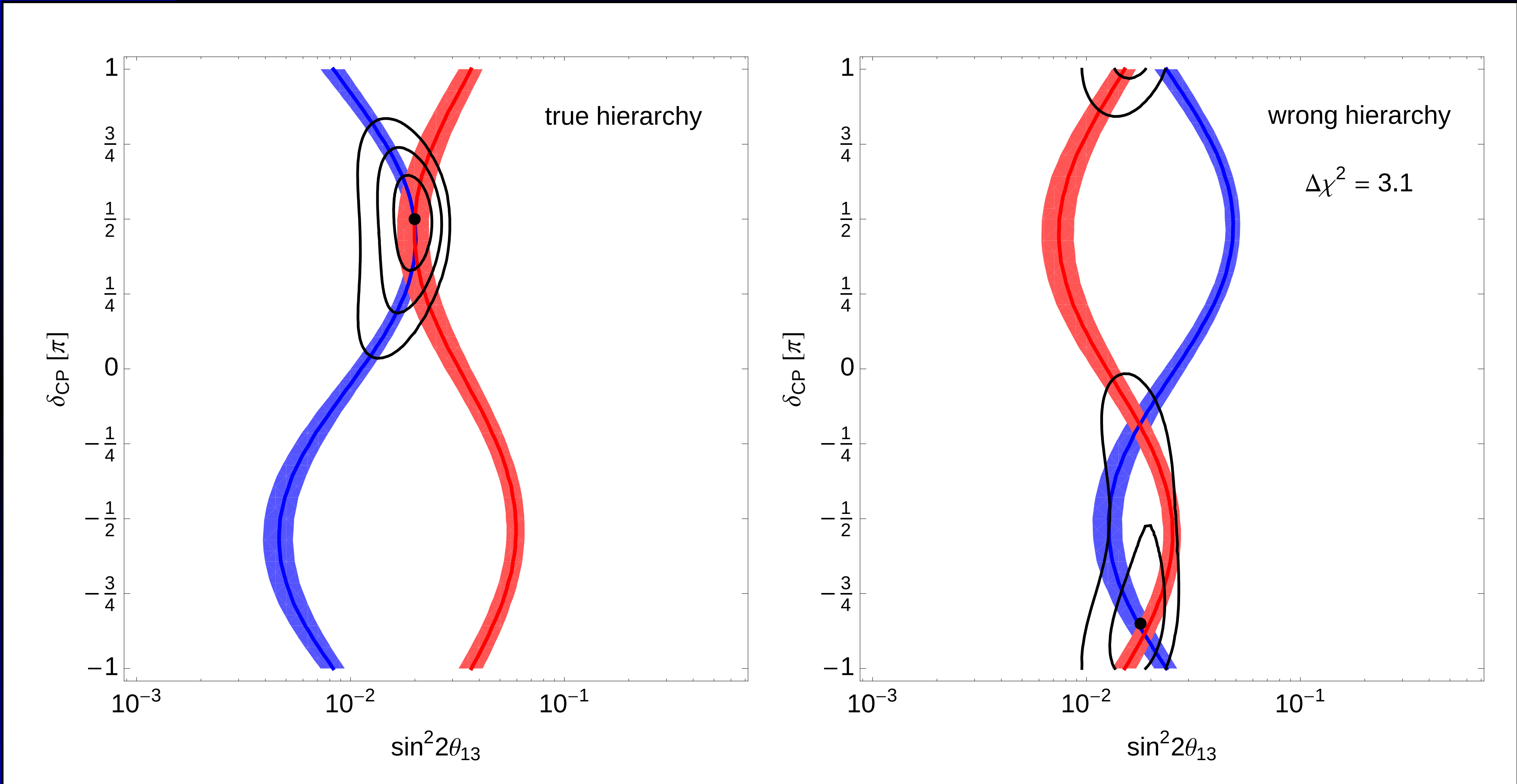
Eight-fold degeneracy

By measuring only two numbers n_ν and $n_{\bar{\nu}}$, the following solutions remain

- intrinsic ambiguity for fixed α
- Disappearance determines only $|\Delta m^2_{31}| \Rightarrow$ $\mathcal{T}_s := \Delta m^2_{31} \longrightarrow -\Delta m^2_{31}$
- Disappearance determines only $\sin^2 2\theta_{23} \Rightarrow$ $\mathcal{T}_t := \theta_{23} \longrightarrow \pi/2 - \theta_{23}$
- Both transformations $\mathcal{T}_{st} := \mathcal{T}_s \oplus \mathcal{T}_t$

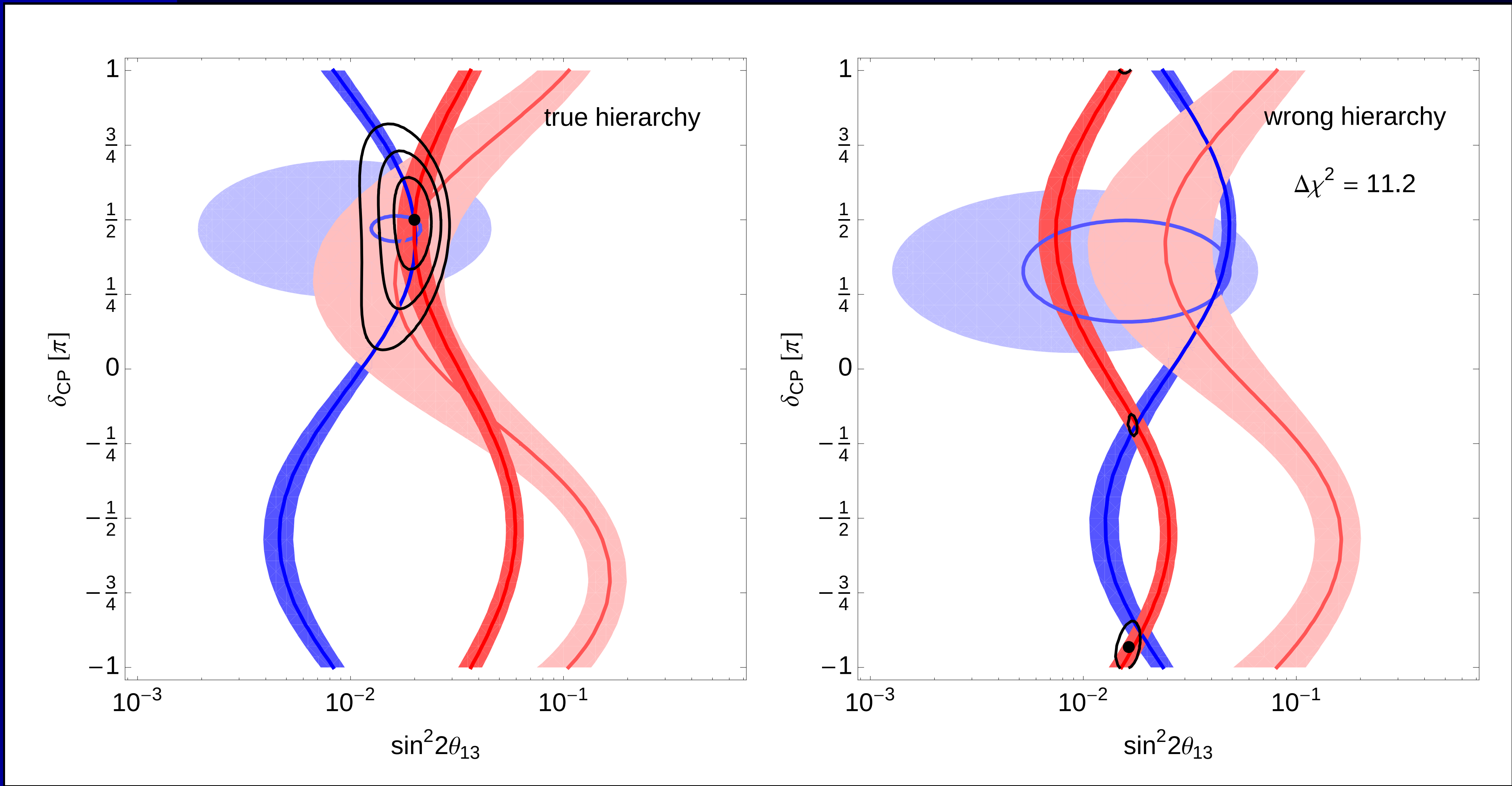
For studies of CP violation the sign ambiguity $\mathcal{T}_s$ poses the most severe problems.

The sign ambiguity



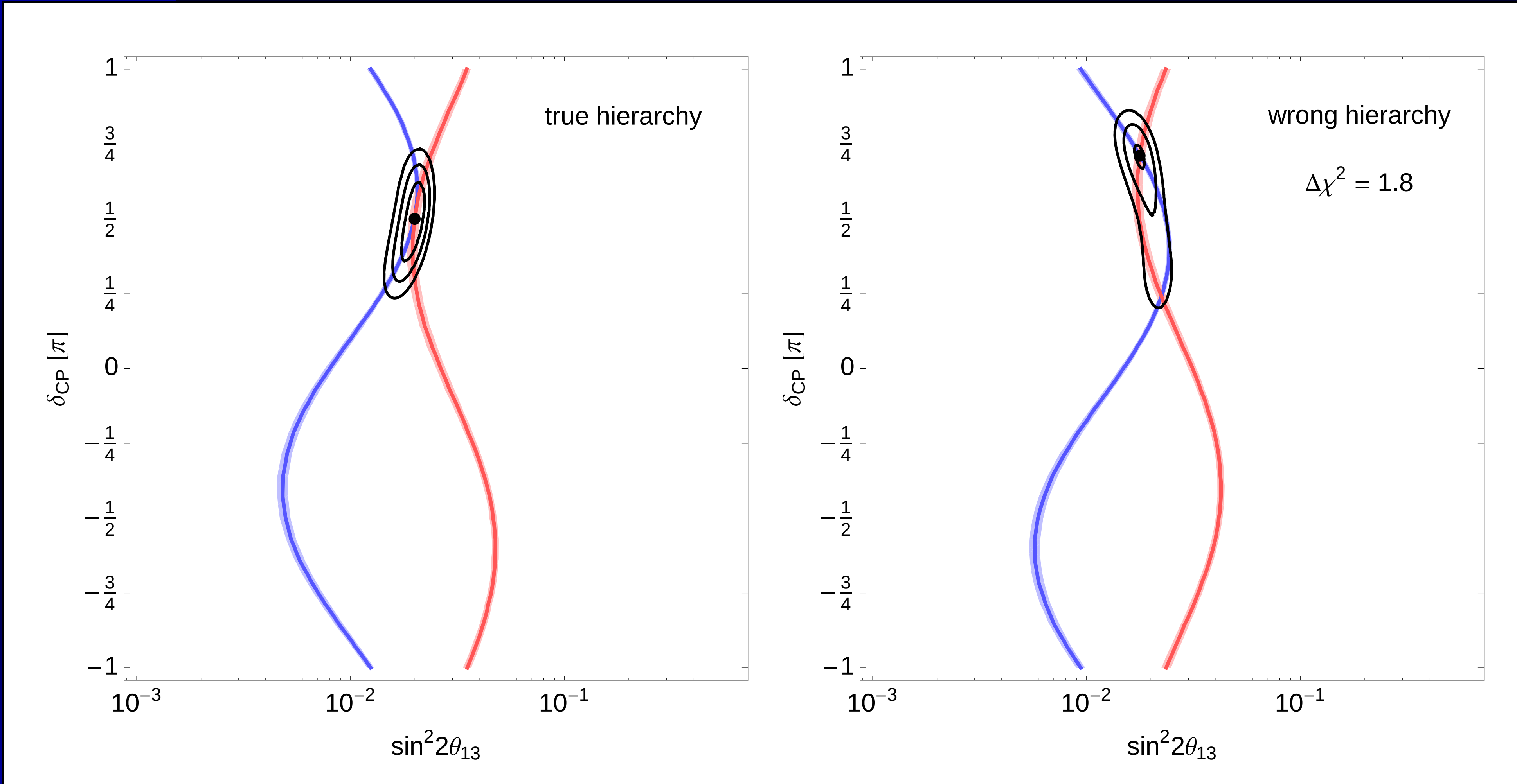
1300 km baseline, 1st oscillation maximum.

The sign ambiguity



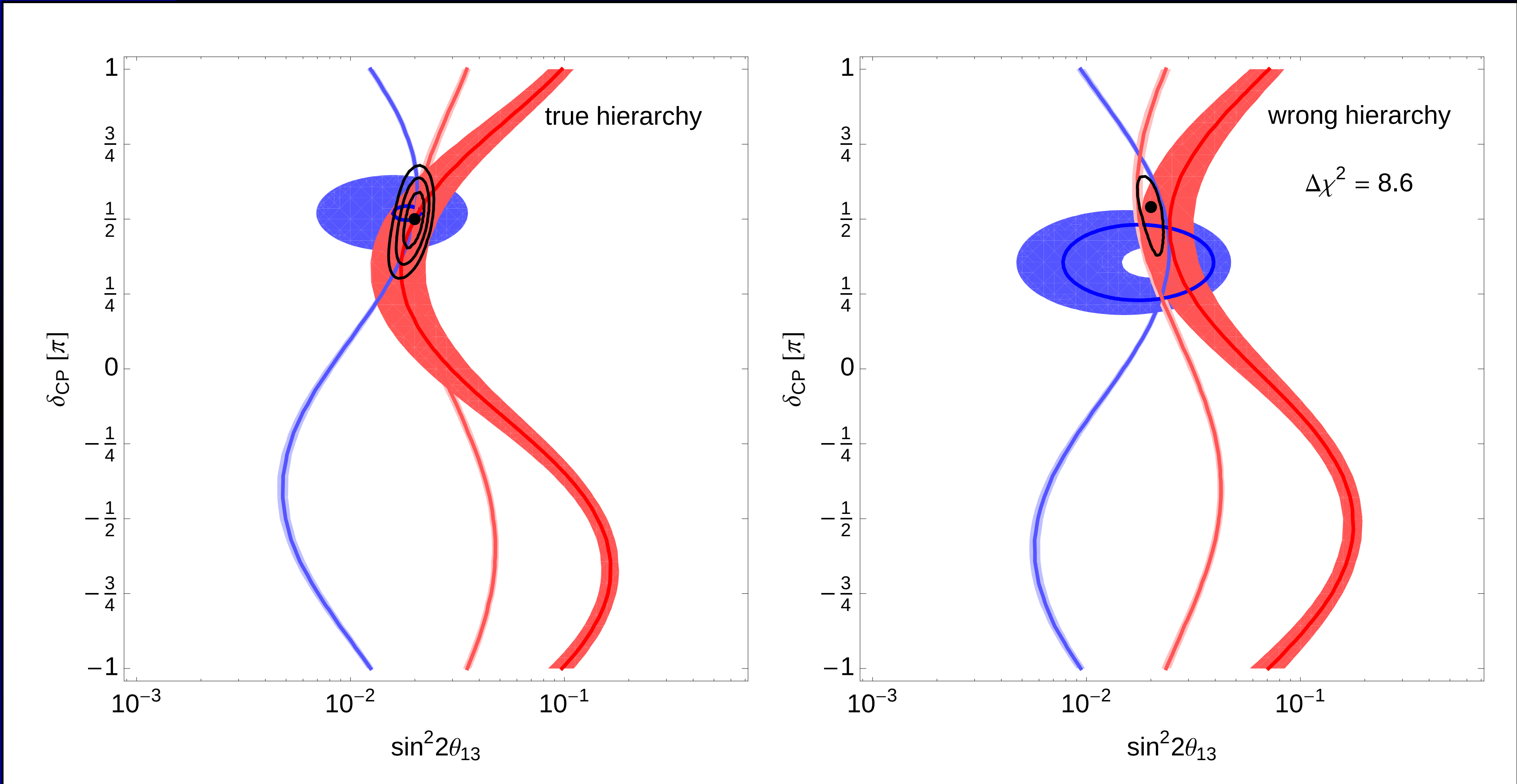
1300 km baseline, 1st & 2nd oscillation maximum.

The sign ambiguity



295 km baseline, 1st oscillation maximum.

The sign ambiguity



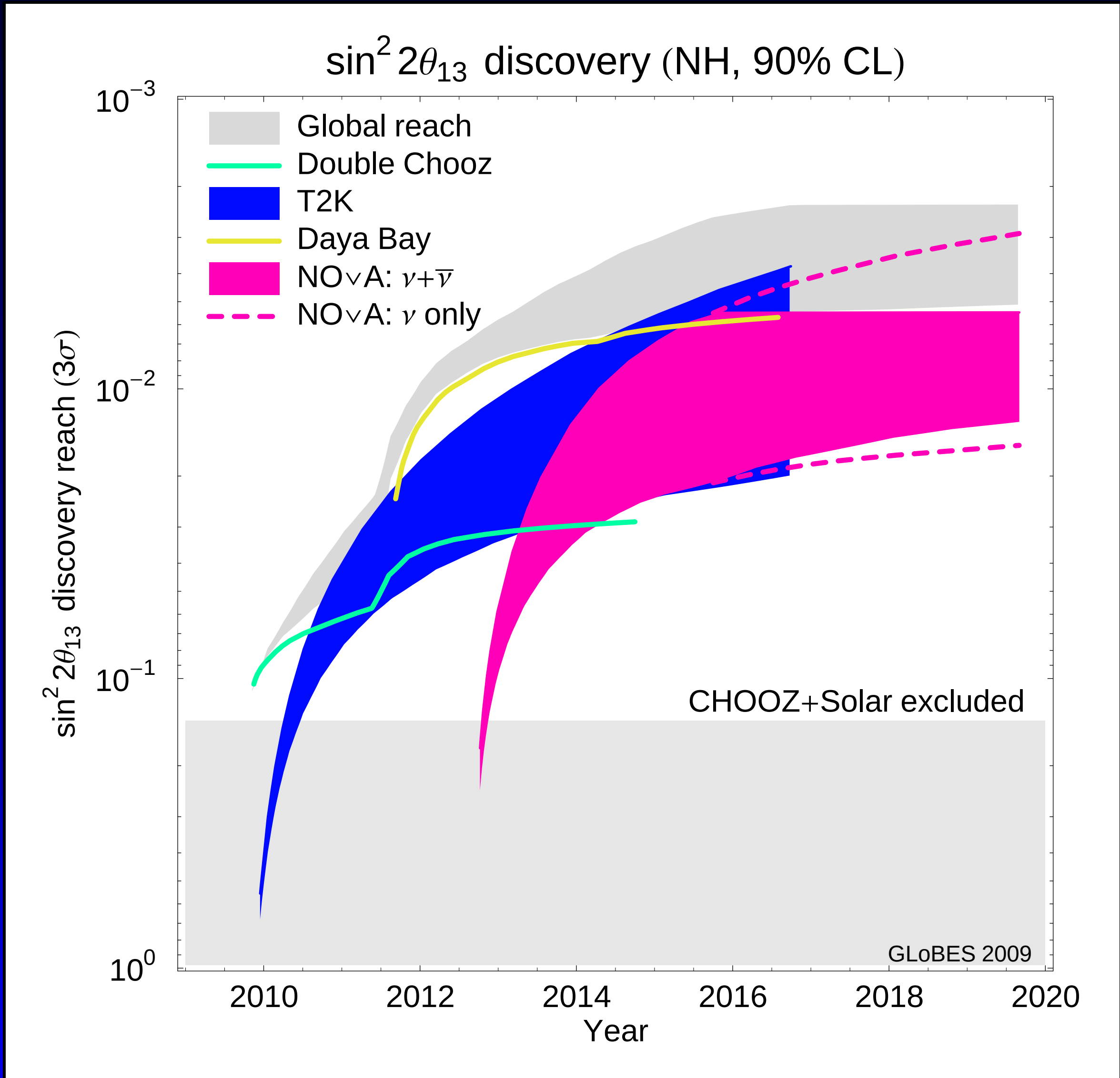
295 km baseline, 1st oscillation maximum & 1050 km baseline, 2nd oscillation maximum

From hints to the hunt for θ_{13}

Timeline

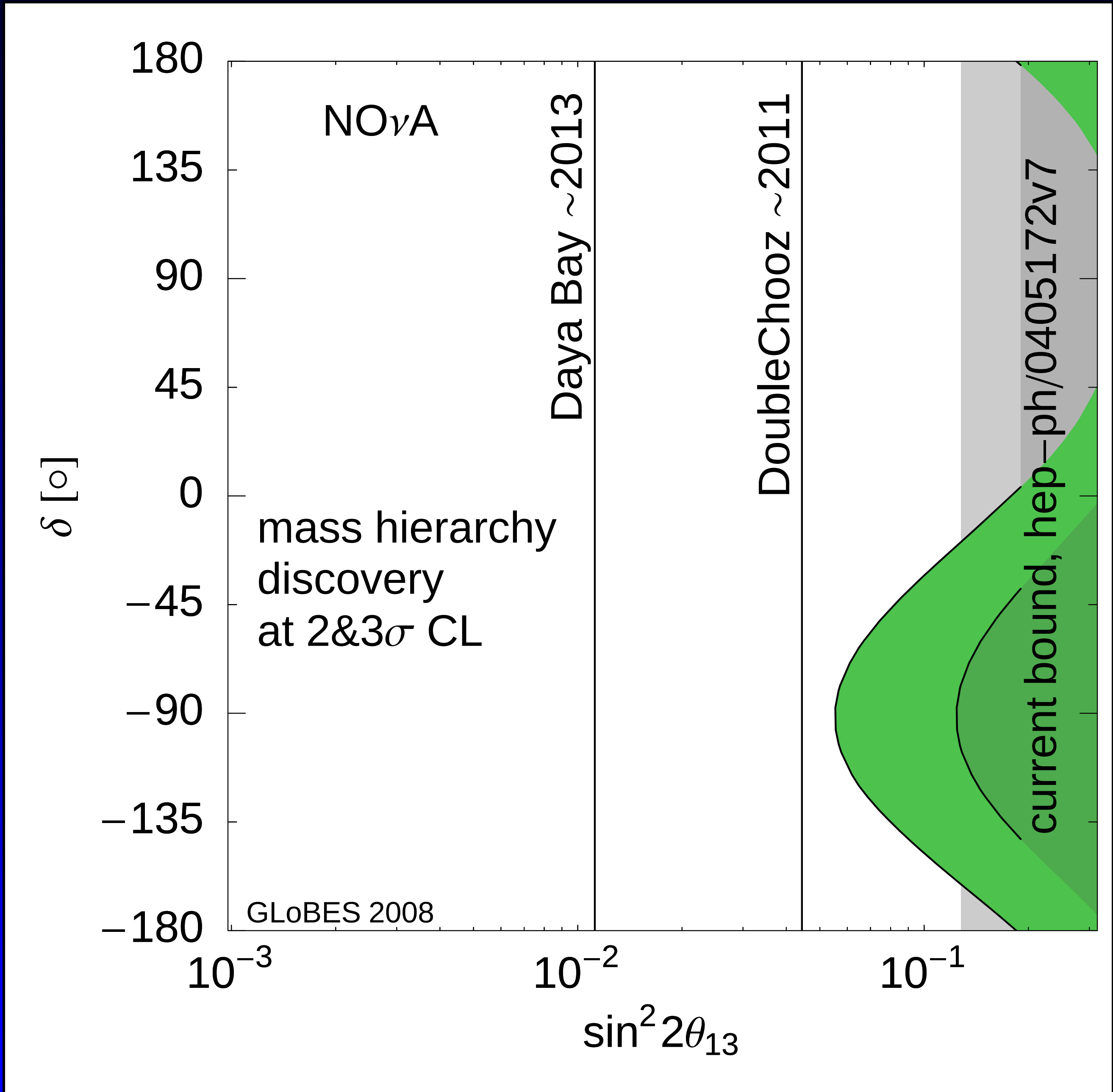
- T2K: 09/2009 - 12/2012: 0 MW - 0.75 MW linear, Talk by Kakuno, NOW 2008
- Double Chooz: Start 09/2009, 1.5 yr with FD only, then ND+FD, Talk by S. Peeters, NOW 2008
- Daya Bay: 7/2011 all modules, Talk by J. Napolitano at UC Davies
- NOvA: 08/2012 - 01/2014: 2.5 kt - 15 kt linear, Talk by M. Messier,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

Time evolution of physics reach

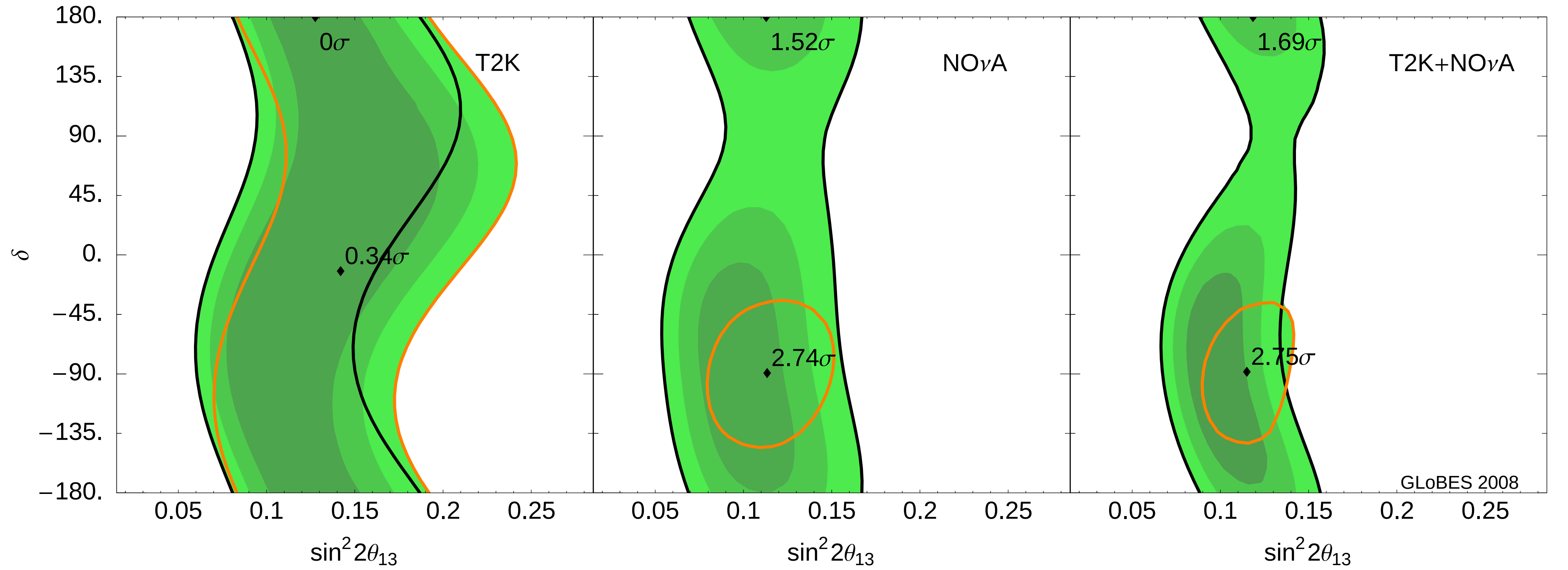


PH, M. Lindner, T. Schwetz and W. Winter, work in progress

Mass hierarchy

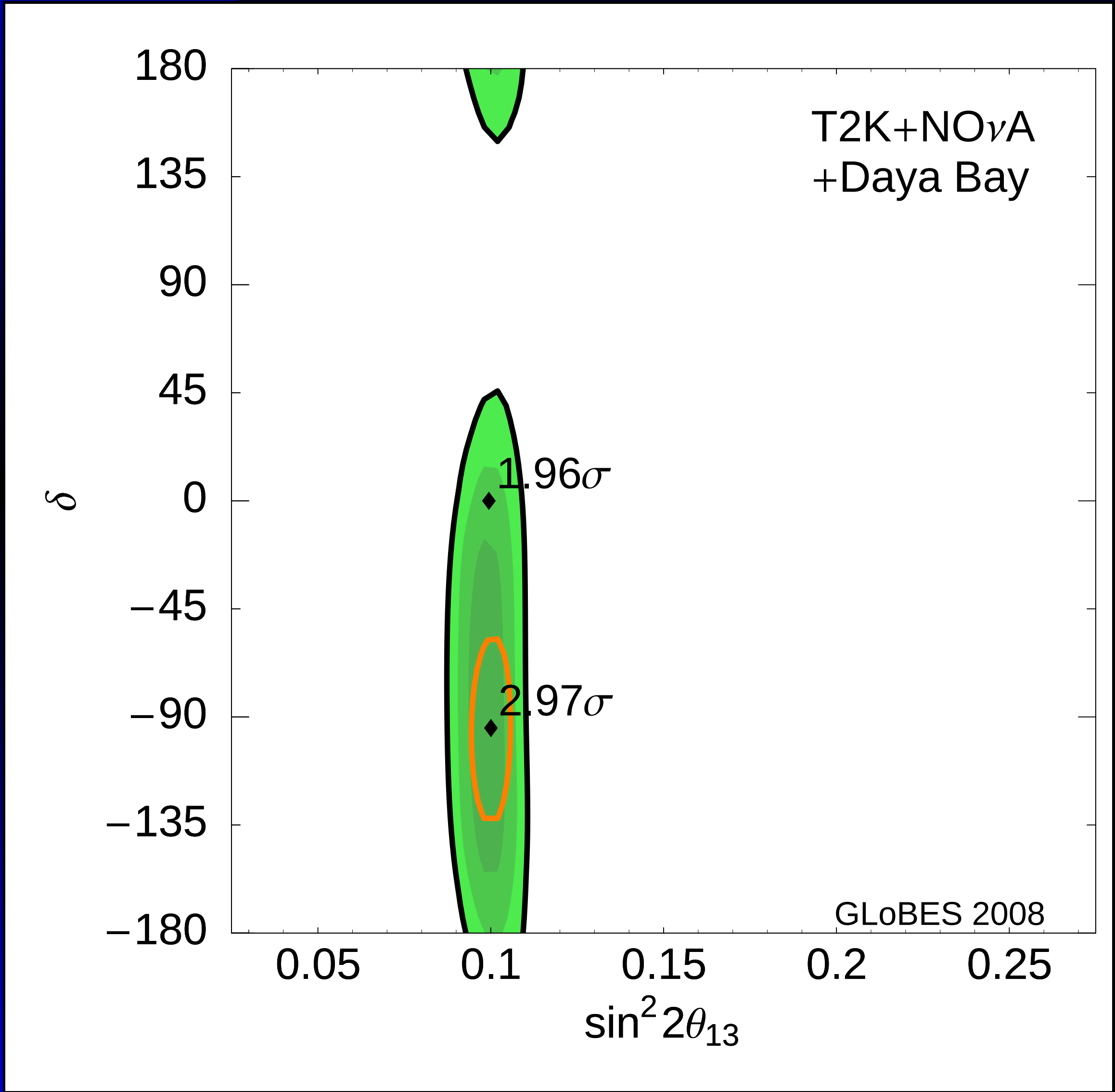


CP violation



- input values $\sin^2 2\theta_{13} = 0.1$ and $\delta = -90°$
- 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.

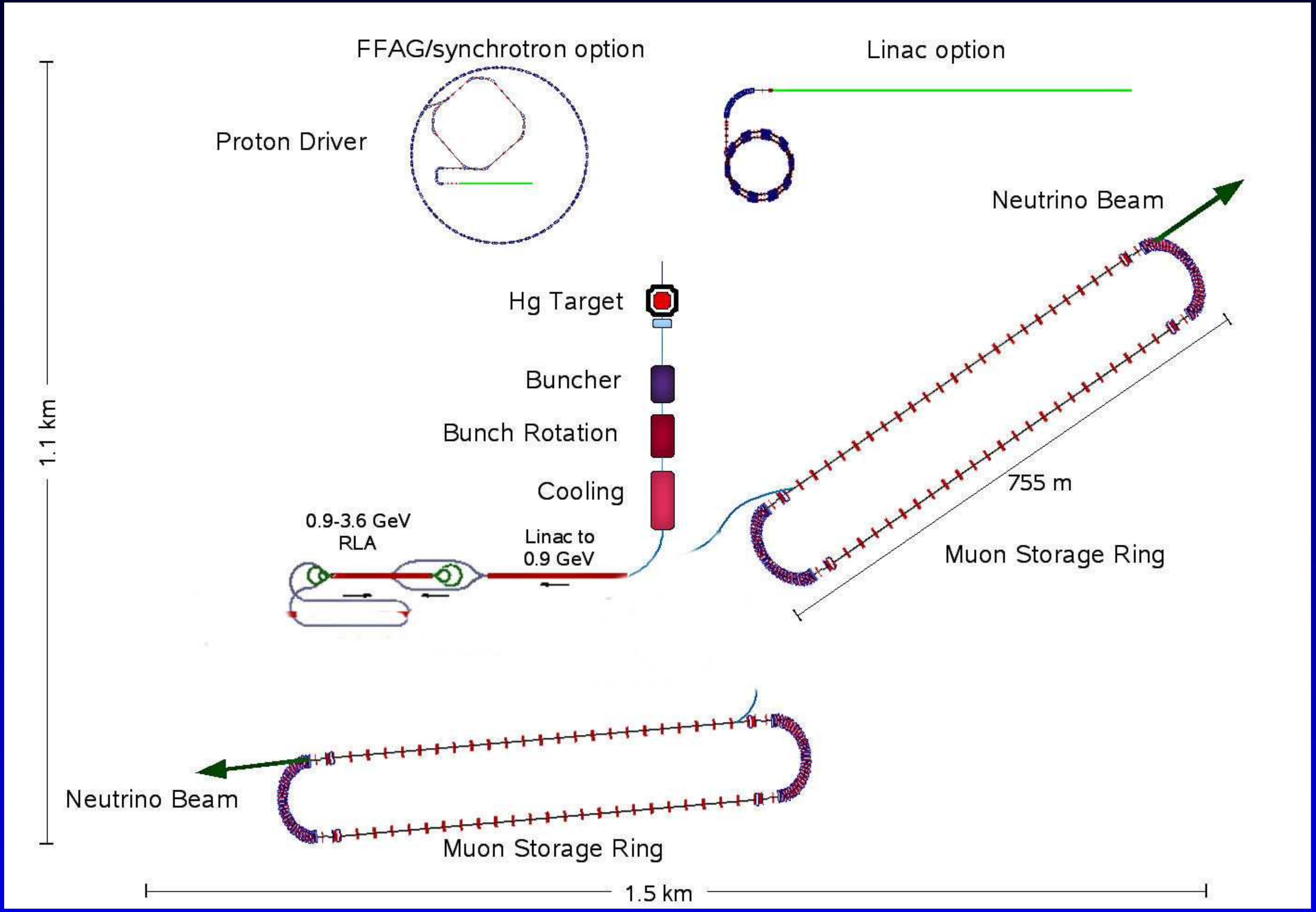
The competition

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

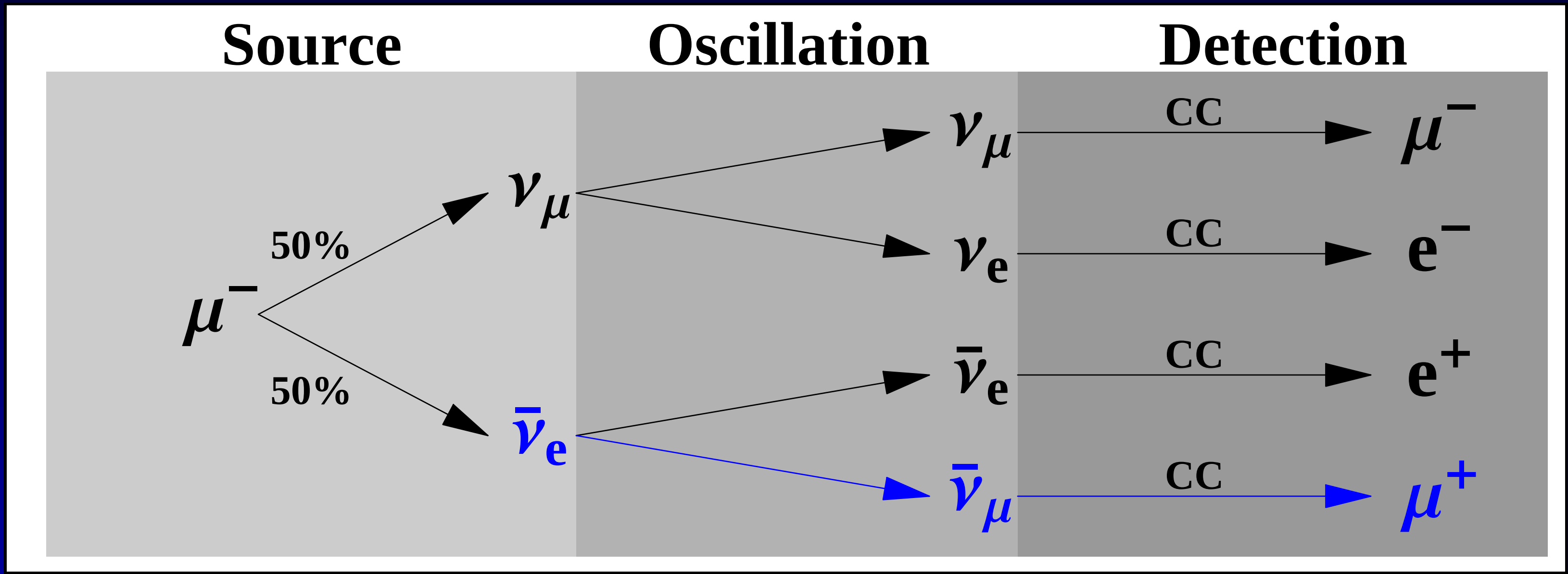
It turns out that T2KK has a consistently superior performance compared to T2HK, which therefore will not be considered further.
From NNN08, talk by T. Hasegawa

A neutrino factory



A neutrino factory

Put muons in a storage ring and let them decay

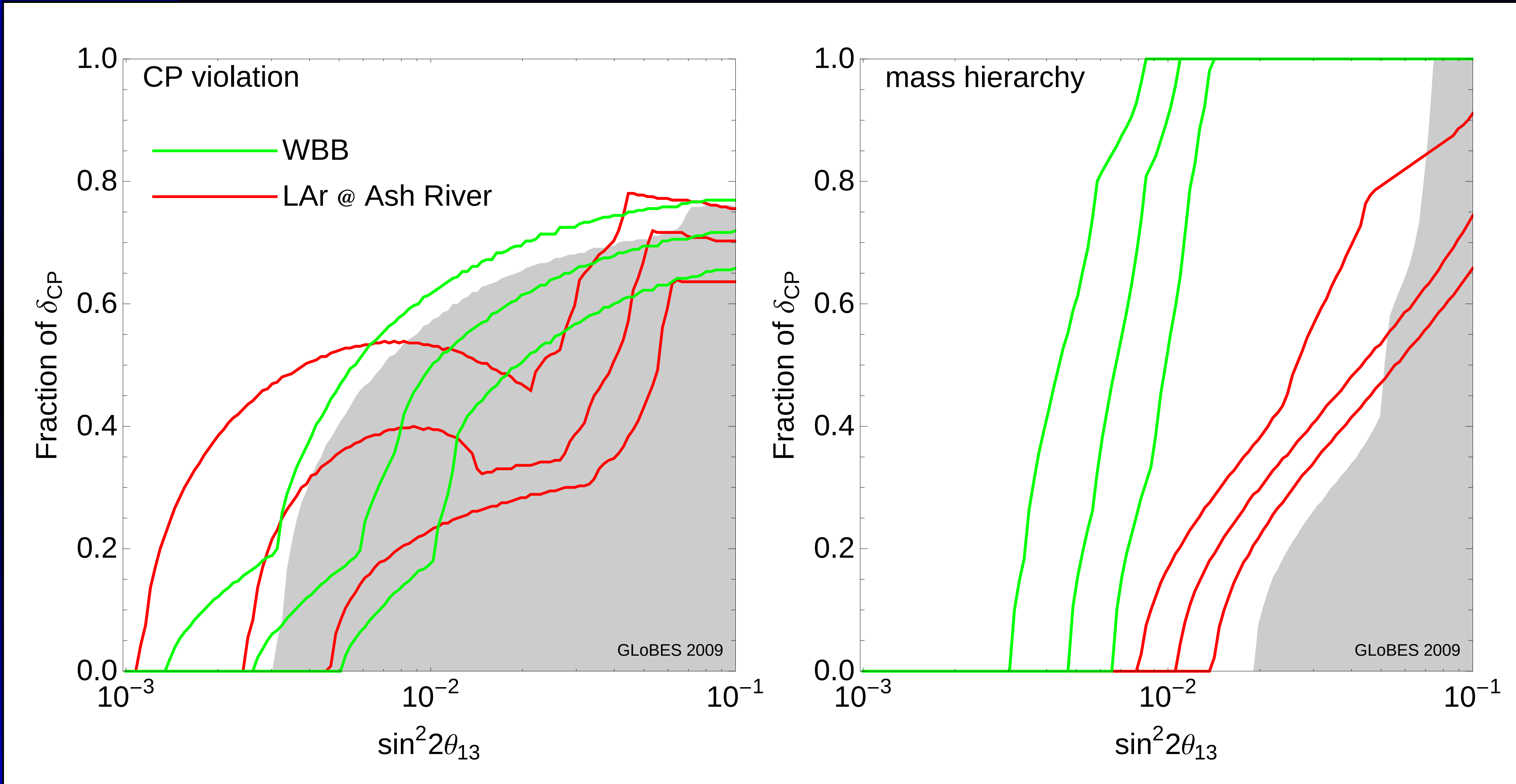


We assume $1.4 \cdot 10^{21}$ useful muon decays per year and polarity, two polarities simultaneously, 10 years and 20kt (fiducial) magnetized TASD in DUSEL

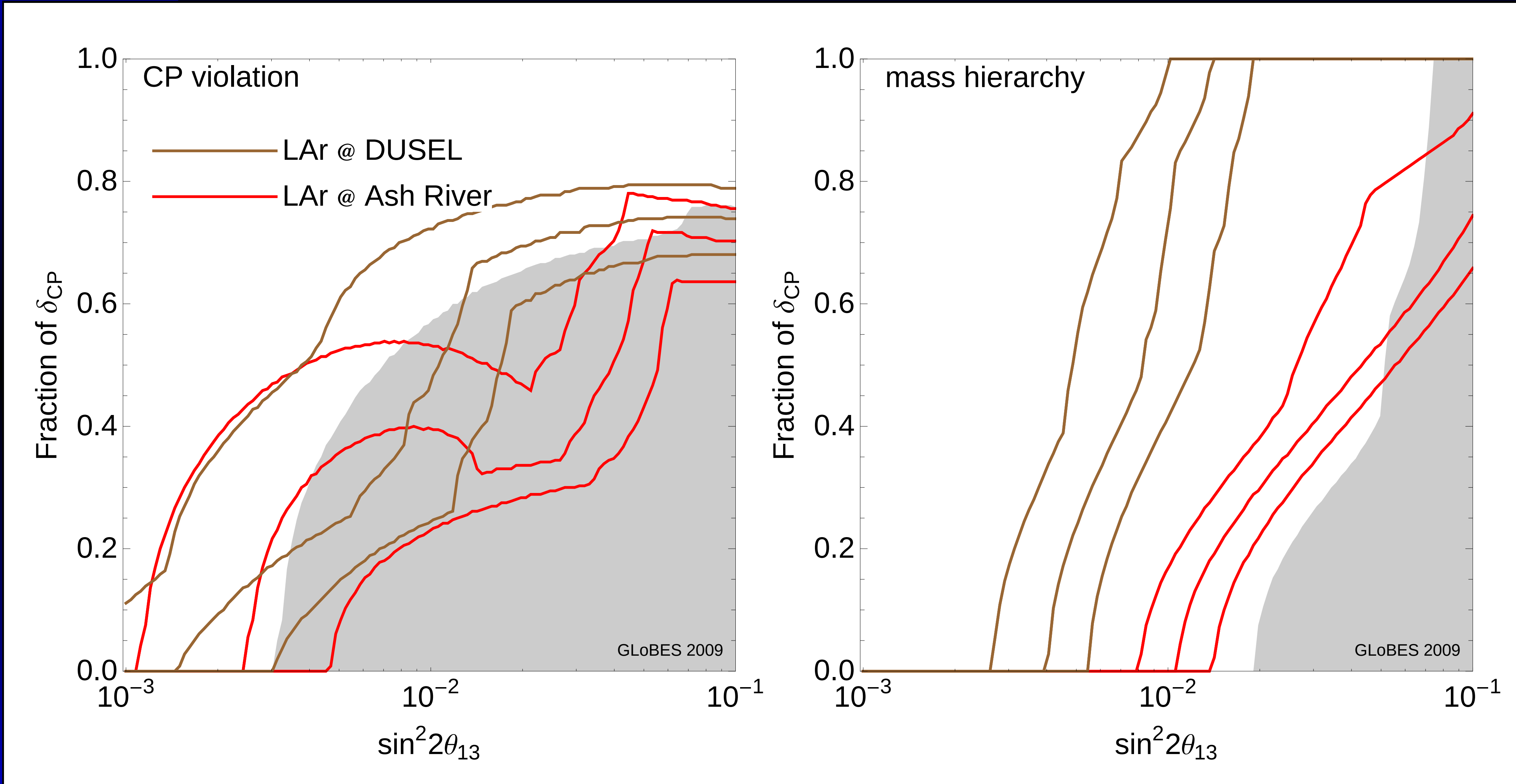
From IDS-NF plenary meeting 2009 at CERN, talk by A. Bross

- the following results are all at $3\,\sigma$ CL (1 dof)
- if there are three lines of the same color, remember
  - tall – 0.7MW
  - grande – 1.2MW
  - venti – 2.3MW

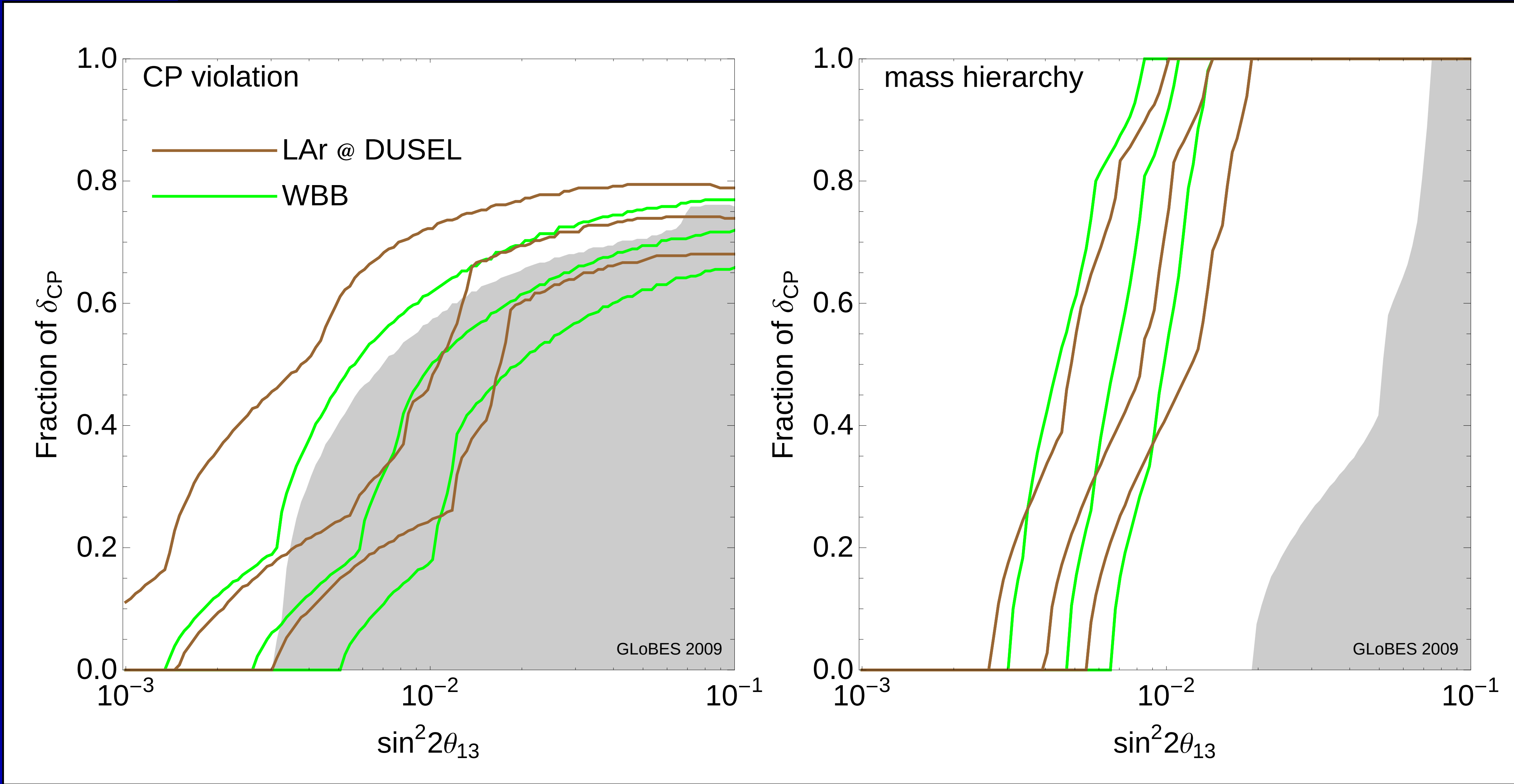
NuMI vs DUSEL beamline



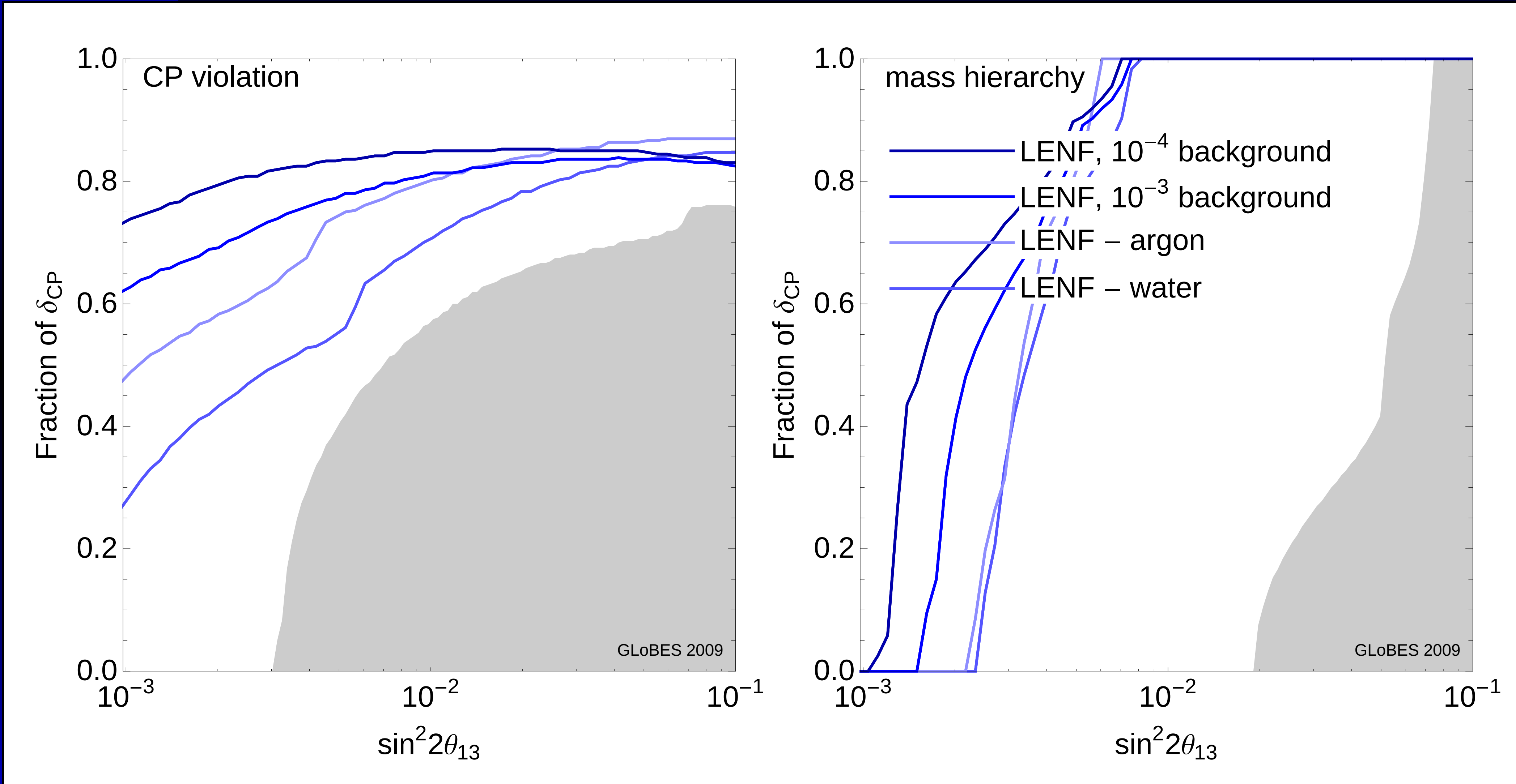
NuMI vs DUSEL beamline



Water vs Argon



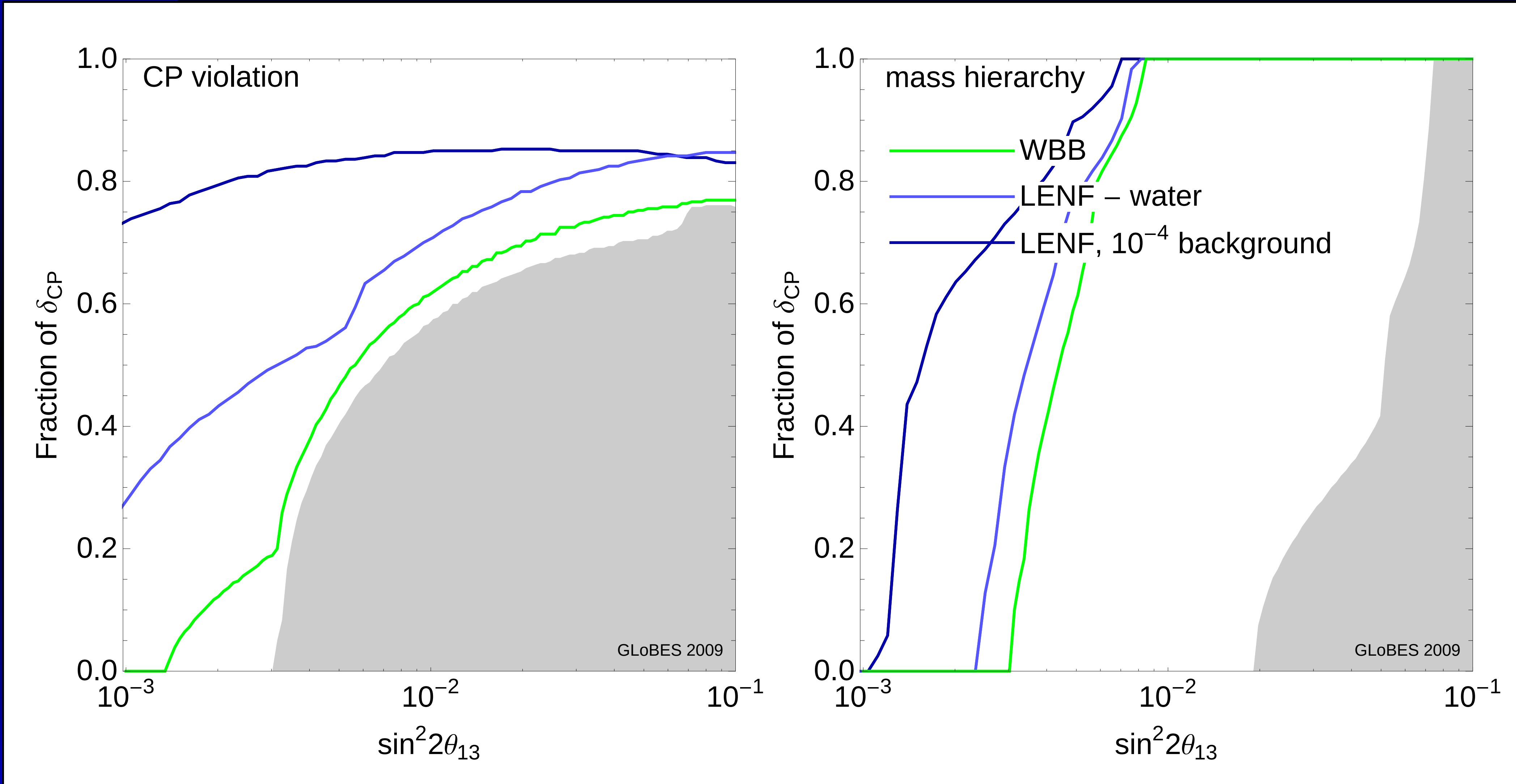
Low energy Neutrino Factory



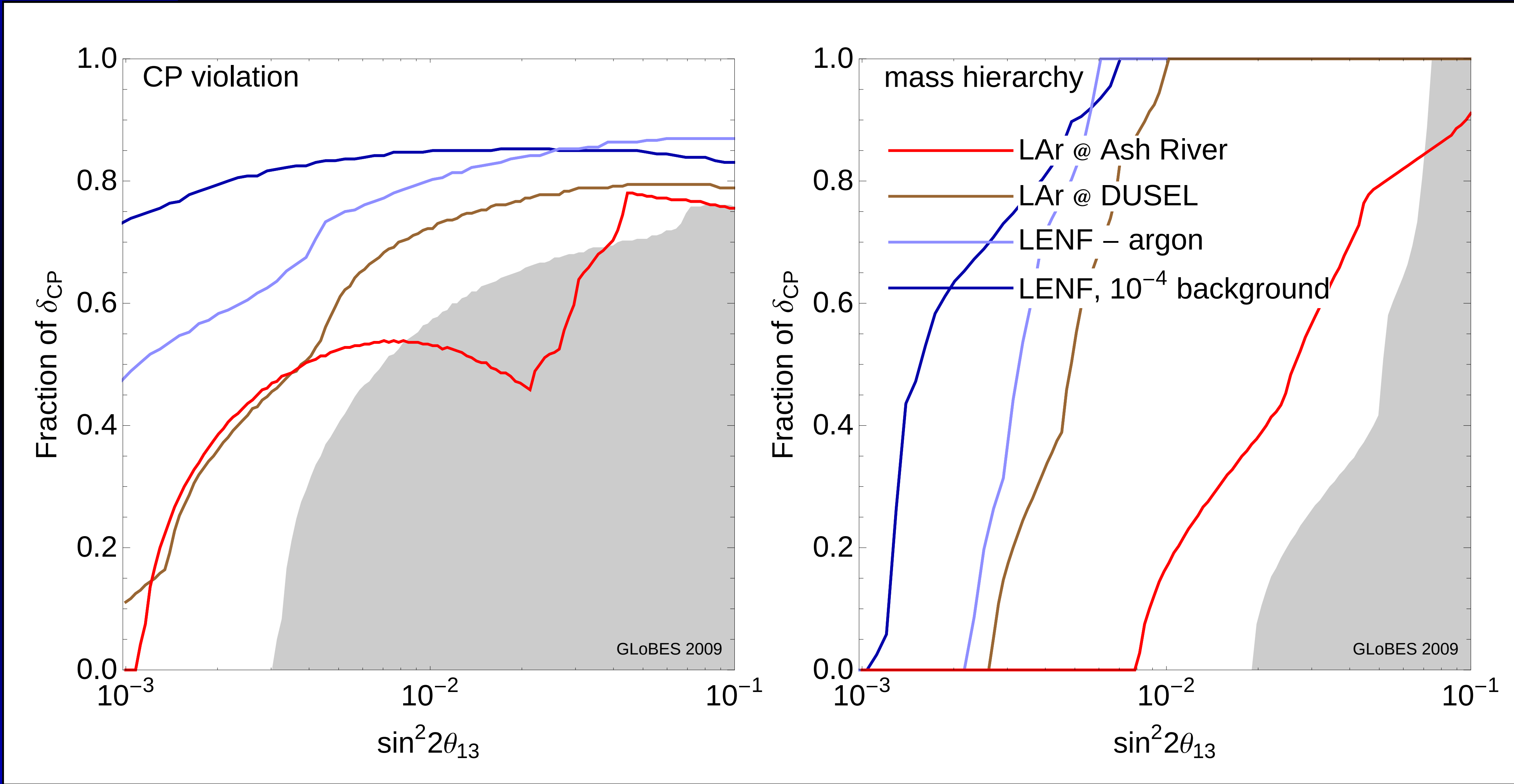
non magnetized options are taken from

PH, T.Schwetz, arXiv:0805.2019

Road map with Water



Road map with Argon



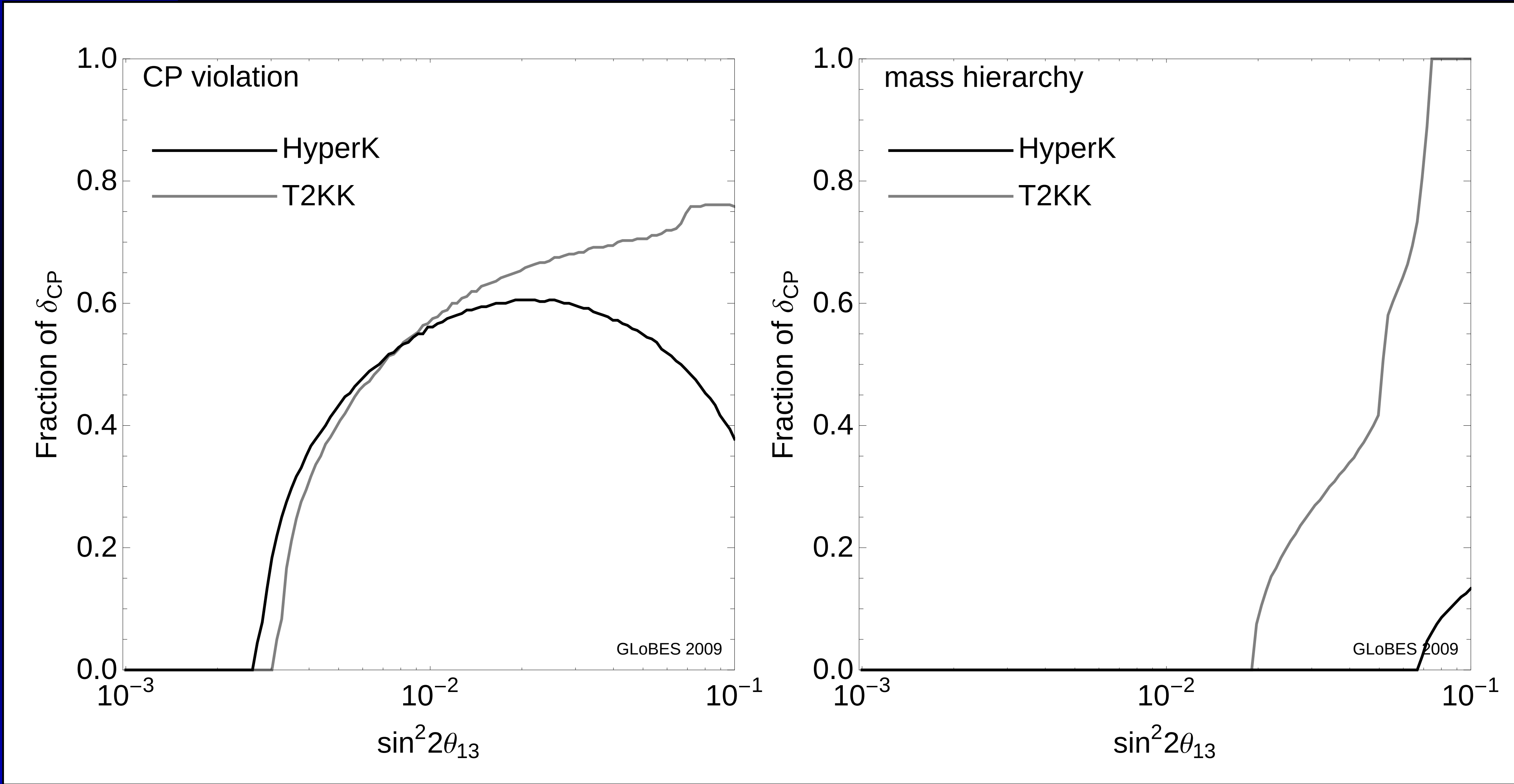
Summary

- 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 $\rightarrow$ muon collider)

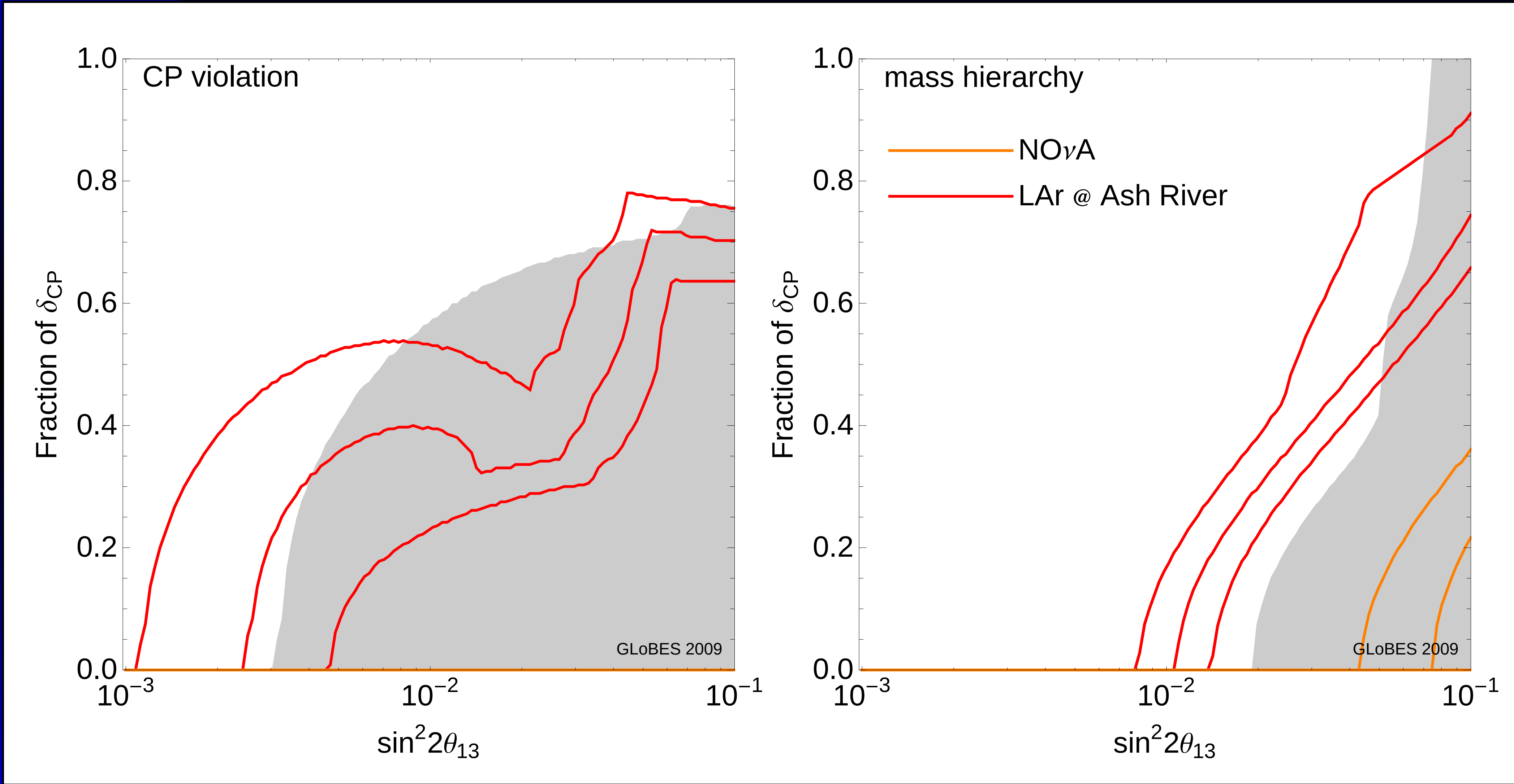
Backup slides

More on FNAL options

One vs two detectors for the JAERI beam

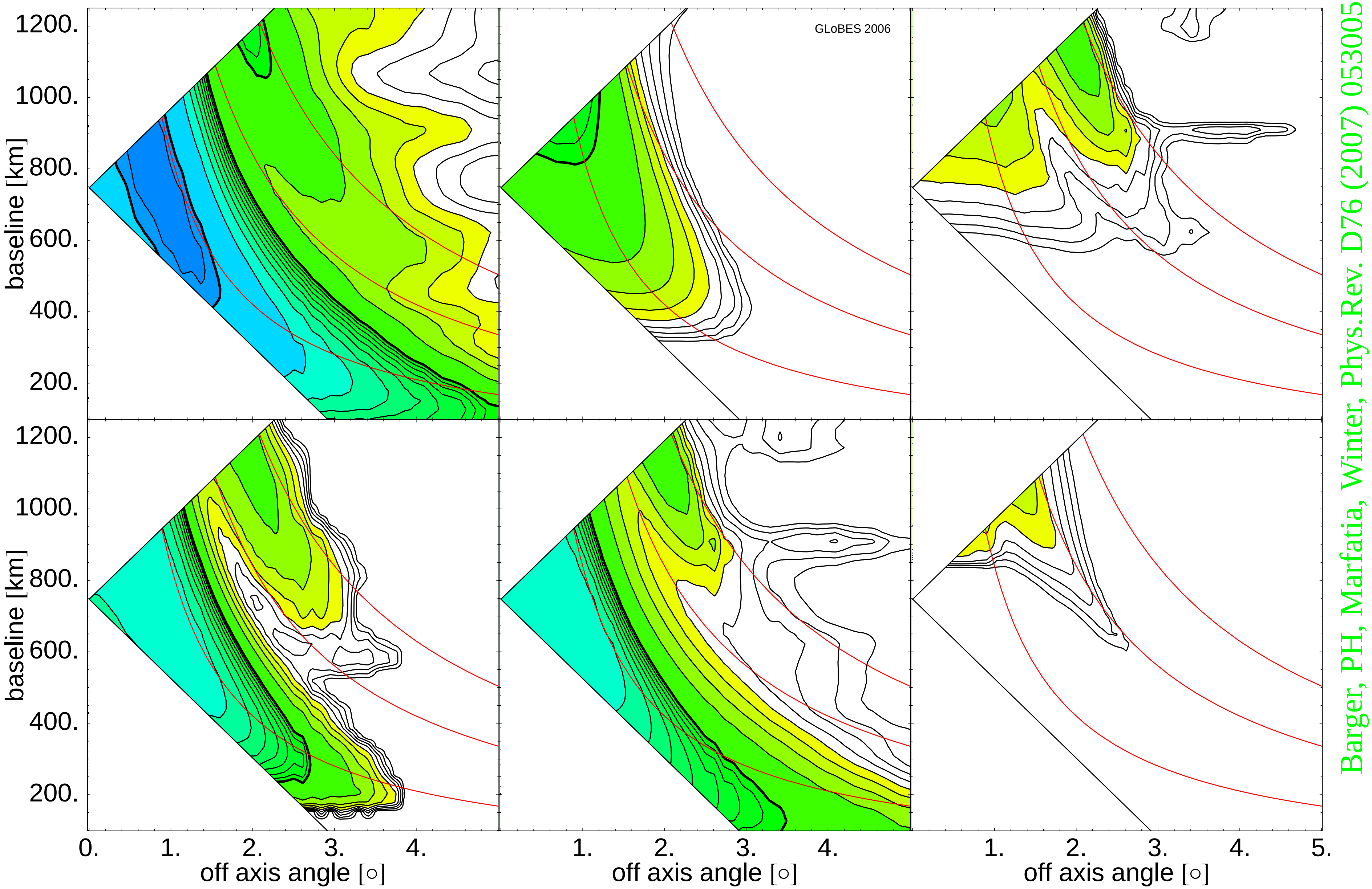


NOνA and proton intensity

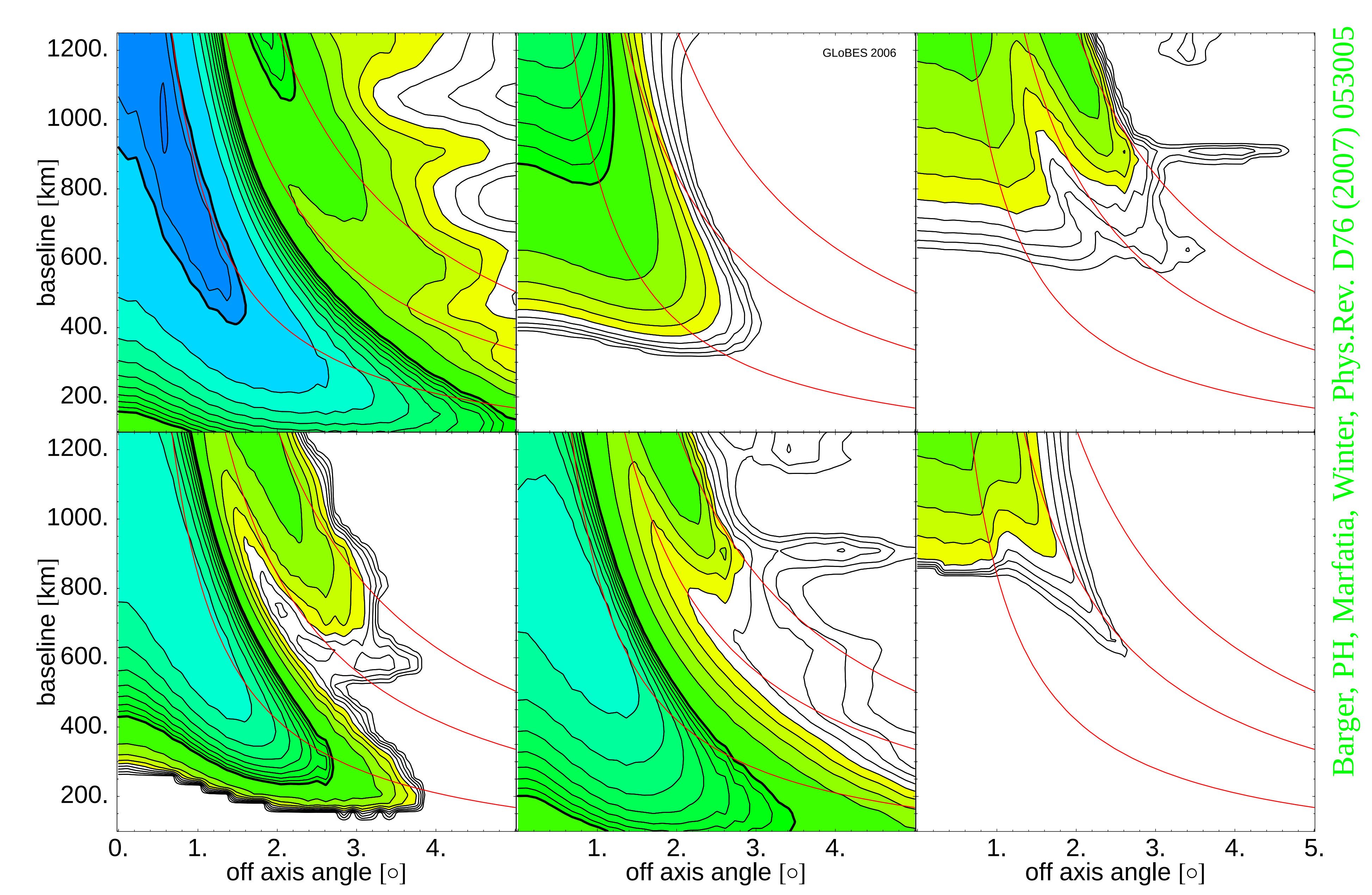


On vs off-axis

On vs off-axis

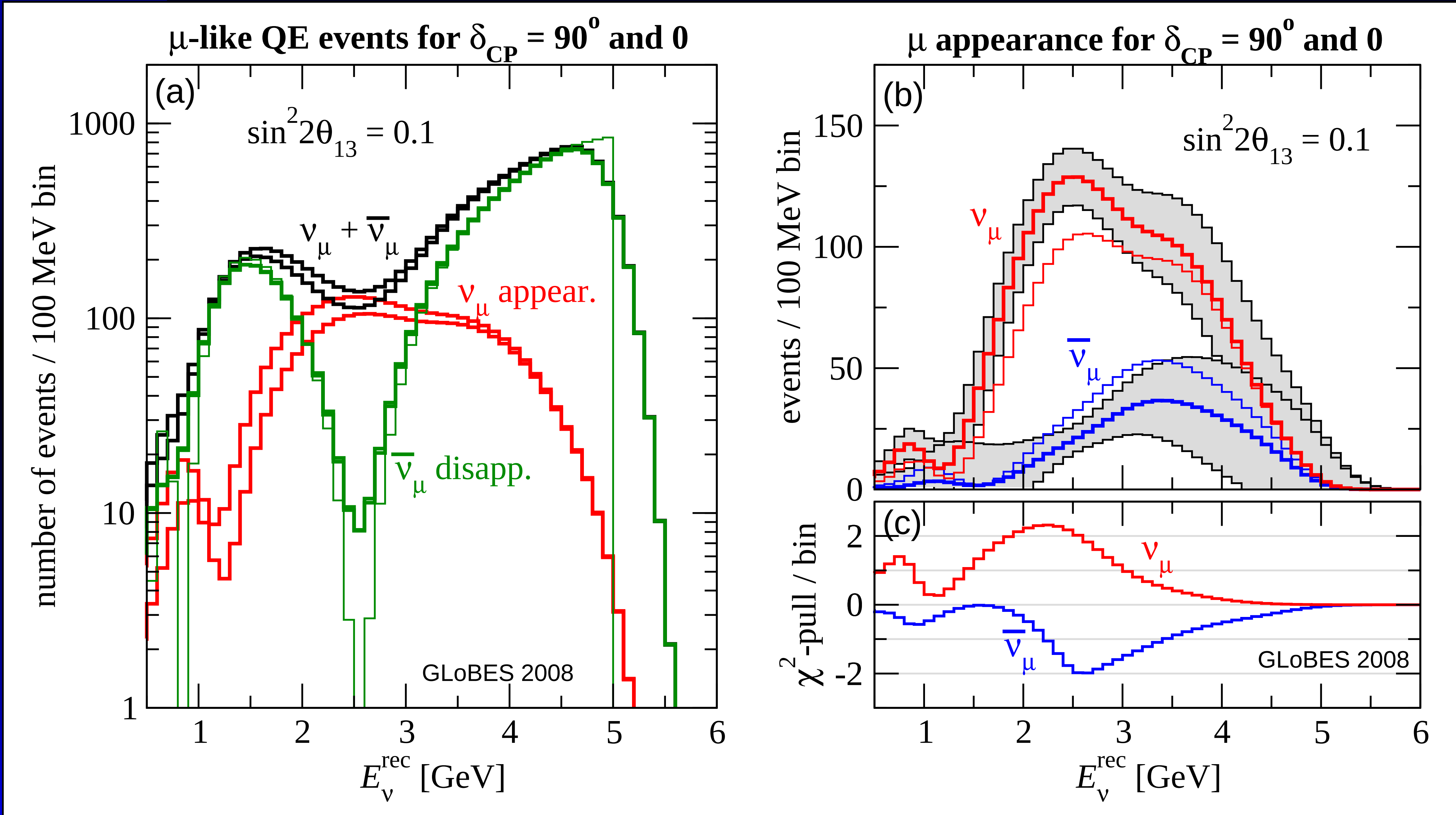


On vs off-axis



Non-magnetized detectors for LENF

Oscillation helps

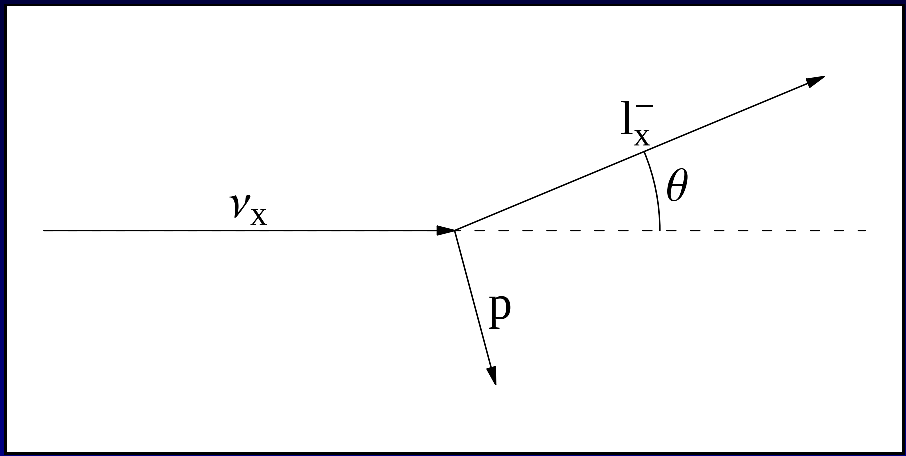


baseline 1290 km and $\Delta E = 0.05\sqrt{E} + 0.085\,\mathrm{GeV}$

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

QE reactions

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



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.