What future atmospheric & LBL experiments can teach us ?

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What we want to learn

- Majorana?
- Absolute mass scale
- Size of θ_{13}
- Mass hierarchy
- $\theta_{23} = \pi/4$?
- CP violation in leptons
- Anomalies (LSND, MiniBooNE ...)

Ultimately, we want to understand the physics of neutrino mass generation and we hope, that this will shed light onto the flavor puzzle.

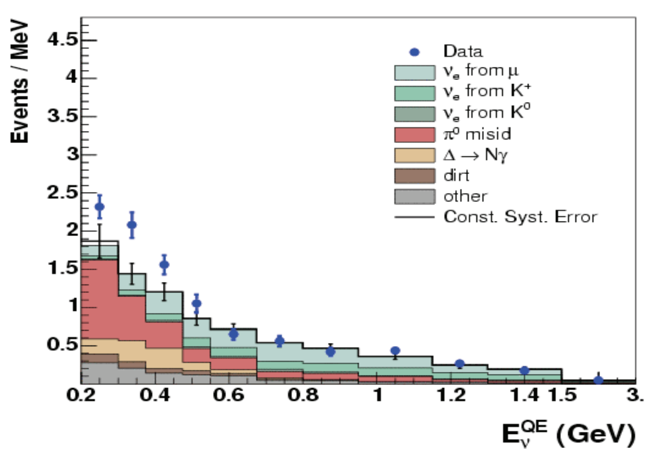
What we can learn

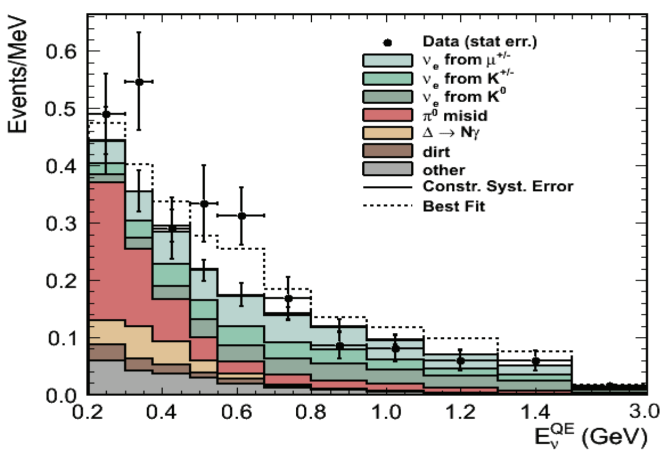
In the context of neutrino oscillation experiments

- $\sin^2 2\theta_{13}$
- δ_{CP}
- mass hierarchy
- $\theta_{23} = \pi/4$, $\theta_{23} < \pi/4$ or $\theta_{23} > \pi/4$?
- Exotica (NSI, sterile neutrinos, CPT violation)

It is very difficult to rank those measurements in their relative importance, with exception of $\sin^2 2\theta_{13}$ since its size has practical implications beyond theory.

Welcome to the Zoo





MiniBooNE

- LSND confirmed? refuted? both?
- Other oscillation data, *cf.* Bugey and CDHS?
- Low energy excess?
- 3+2 neutrinos + NSI?
- + a long list of proposals to finally hunt down this specimen

The Hunting of the Snark

All “animals” have in common that they are less than $5\,\sigma$ effects and they may be all due to the extraordinary difficulty of performing neutrino experiments, if not:

- Improving the bound on $P_{\nu_e\nu_e}$: LENS-sterile, zoned Gallium experiment, beta beams, short range reactor experiments
- Direct tests of LSND using stopped pion sources: OscSNS, LSND reloaded
- Indirect tests using neutrino beams: BooNE, new detectors in the NuMI beamline, beta beams, neutrino factories

Neutrino oscillation

CP violation

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.

Matter effects

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.

Matter effects

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

$$\Delta m^2 \simeq A \quad \Leftrightarrow \quad E_{\mathrm{res}}^{\mathrm{Earth}} = 6 - 8\,\mathrm{GeV}$$

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

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 $|\Delta m^2_{31}| \Rightarrow$ $\mathcal{T}_s := \Delta m^2_{31} \rightarrow -\Delta m^2_{31}$
- Disappearance determines only $\sin^2 2\theta_{23} \Rightarrow$ $\mathcal{T}_t := \theta_{23} \rightarrow \pi/2 - \theta_{23}$
- 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.

Consequences for experiments

To study three flavor oscillation we need

- to measure 2 out of $P(\nu_\mu \to \nu_e)$, $P(\bar{\nu}_\mu \to \bar{\nu}_e)$, $P(\nu_e \to \nu_\mu)$ and $P(\bar{\nu}_e \to \bar{\nu}_\mu)$
- more than 1 energy and 1 baseline
- matter resonance at $6 - 8\,\mathrm{GeV}$
- matter effects sizable for $L > 1\,000\,\mathrm{km}$
- magic baseline $L \simeq 7,500\,\mathrm{km}$ allows for a clean measurement of the mass hierarchy

Consequences for experiments

To study physics beyond three flavor oscillation we need

- to measure 2 out of $P(\nu_\mu \to \nu_e)$, $P(\bar{\nu}_\mu \to \bar{\nu}_e)$, $P(\nu_e \to \nu_\mu)$ and $P(\bar{\nu}_e \to \bar{\nu}_\mu)$
- a good and large (!) near detector
- ideally ν_τ detection in a (large?) near detector
- magic baseline $L \simeq 7,500\,\mathrm{km}$ allows for a clean measurement of NSI in propagation (NC like interactions)

Experimental limitations

As a rule of thumb, the best experiments we currently can think of, would have

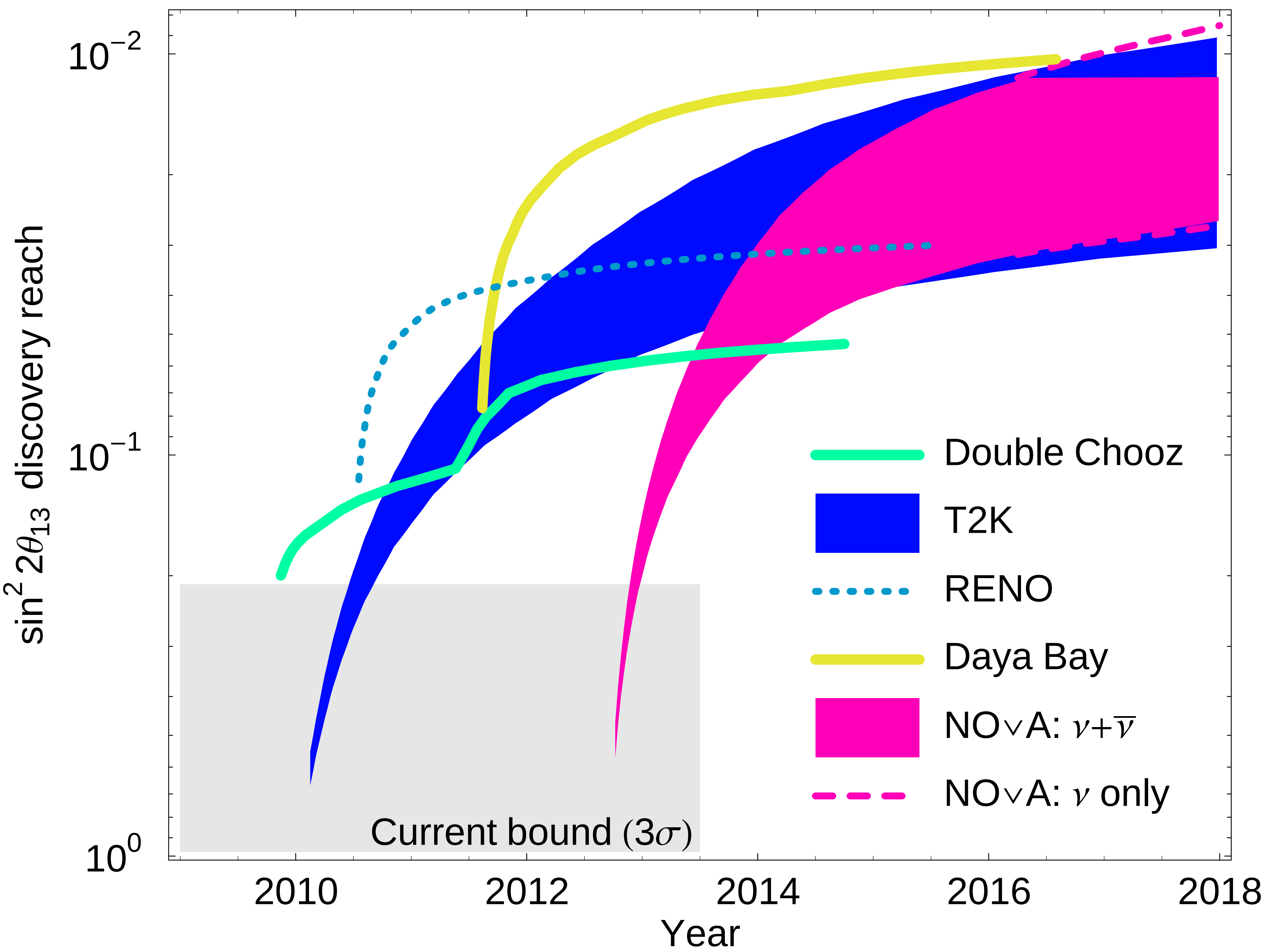
- Total CC rate uncertainty of 5%
- Relative (between near and far detectors) CC rate uncertainty of 1%, with the notable exception of low energy, <10MeV, experiments like Double Chooz and Daya Bay
- Total NC rate uncertainty of 10%
- Neutrino energy resolution of 5%
- 10-20% τ detection efficiency in a small mass <kt
- 1 million events in their best detection mode, typically $\nu_\mu \to \nu_\mu$

The Next Generation

The Experiments

Setup	t_ν [yr]	$t_{\bar{\nu}}$ [yr]	$P_{\rm Th}$ or $P_{\rm Target}$	L [km]	Detector	$m_{\rm Det}$
Double Chooz	-	3	8.6 GW	1.05	L. scint.	8.3 t
Daya Bay	-	3	17.4 GW	1.7	L. scint.	80 t
RENO	-	3	16.4 GW	1.4	L. scint.	15.4 t
T2K	5	-	0.75 MW	295	Water	22.5 kt
NOνA	3	3	0.7 MW	810	TASD	15 kt

$\sin^2 2\theta_{13}$ discovery potential (NH, 3σ CL)

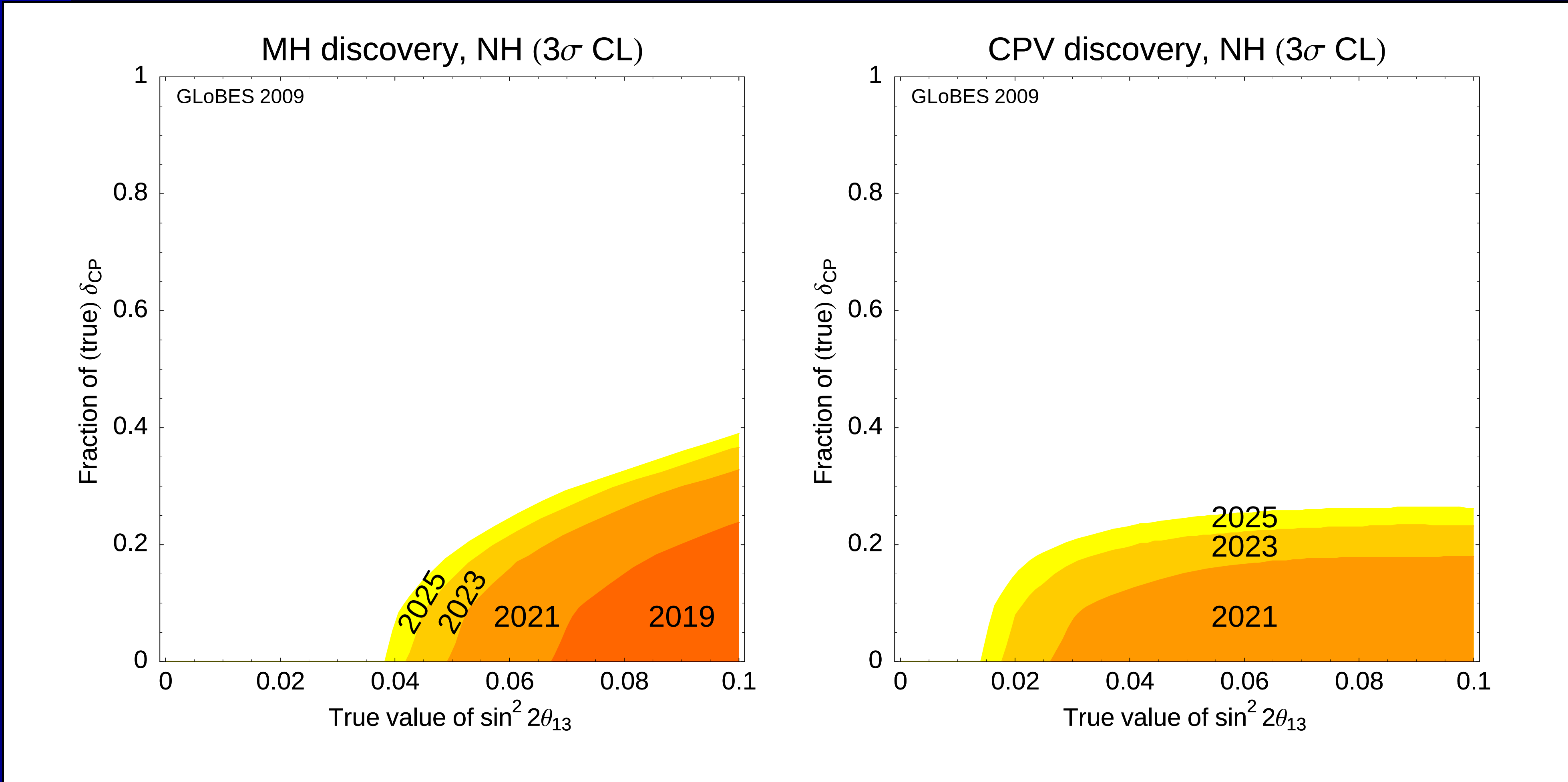


PH, Lindner, Schwetz, Winter, JHEP 11 044 (2009).

Beam upgrades

- T2K: 2015 - 2016: 0.75 MW - 1.66 MW linear
  Talk by K. Hasegawa, NNN 2008
- NOvA: 03/2018-03/2019: 0.7 MW - 2.33 MW linear, Project X Project X: resource loaded schedule

Optimal sensitivities



PH, Lindner, Schwetz, Winter, JHEP 11 044 (2009).

This includes data from T2K with a 1.66MW beam, NOvA with Project X, Daya Bay, RENO and Double Chooz.

2025

Knowledge in 2025 without new facilities at $3\,\sigma$ CL

- $\theta_{23} = \pi/4$ – for maximal mixing $45^\circ \pm 4^\circ$
- size of θ_{13} – if $\sin^2 2\theta_{13} > 0.01$
- mass hierarchy – if $\sin^2 2\theta_{13} > 0.04$ for at most 30% of all CP phases
- CP violation in leptons – if $\sin^2 2\theta_{13} > 0.02$ for at most 20% of all CP phases
- MINOS anomaly will be resolved

Even for the largest currently allowed θ_{13} more than 70% of parameter space are not accessible.

Atmospheric Neutrinos

Physics with atm. neutrinos

- Δm^2_{31} measurement – MINOS hint for CPT violation?
- θ_{23} measurement – octant resolution? CPT violation?
- mass hierarchy for large θ_{13}
- non-standard neutrino interaction (large L/E range)
- combination of beam data with atmospheric neutrinos
- sterile neutrinos?
- $\ldots$

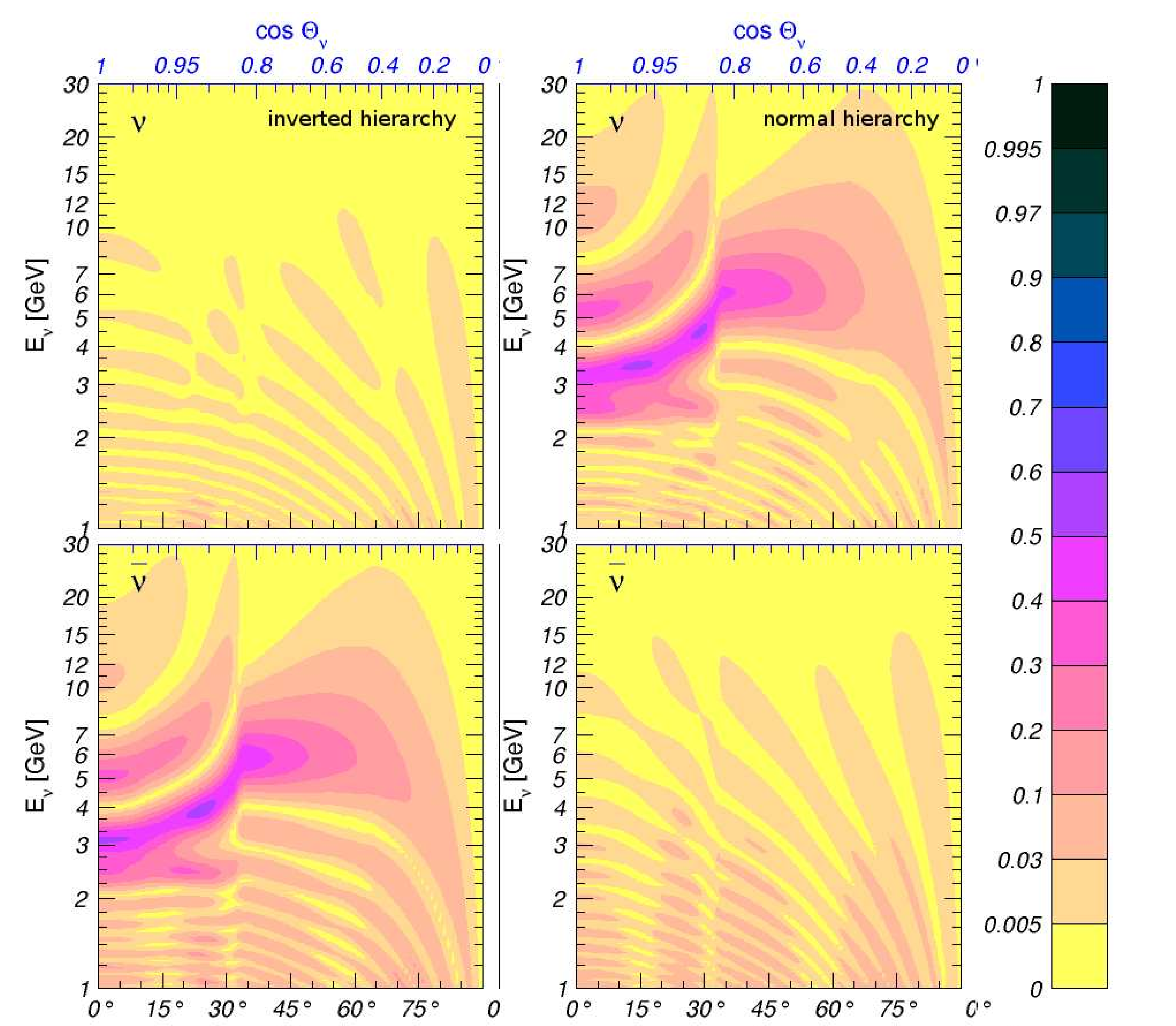
Atm. neutrino experiments

- Most effects are energy and baseline dependent therefore, energy and angular (= baseline) resolution for the neutrino, *viz.* lepton, are crucial
- Atmospheric neutrino fluxes

$$\nu_\mu \simeq \bar{\nu}_\mu \quad \nu_\mu + \bar{\nu}_\mu \simeq 2(\nu_e + \bar{\nu}_e) \quad \bar{\nu}_e < \nu_e$$

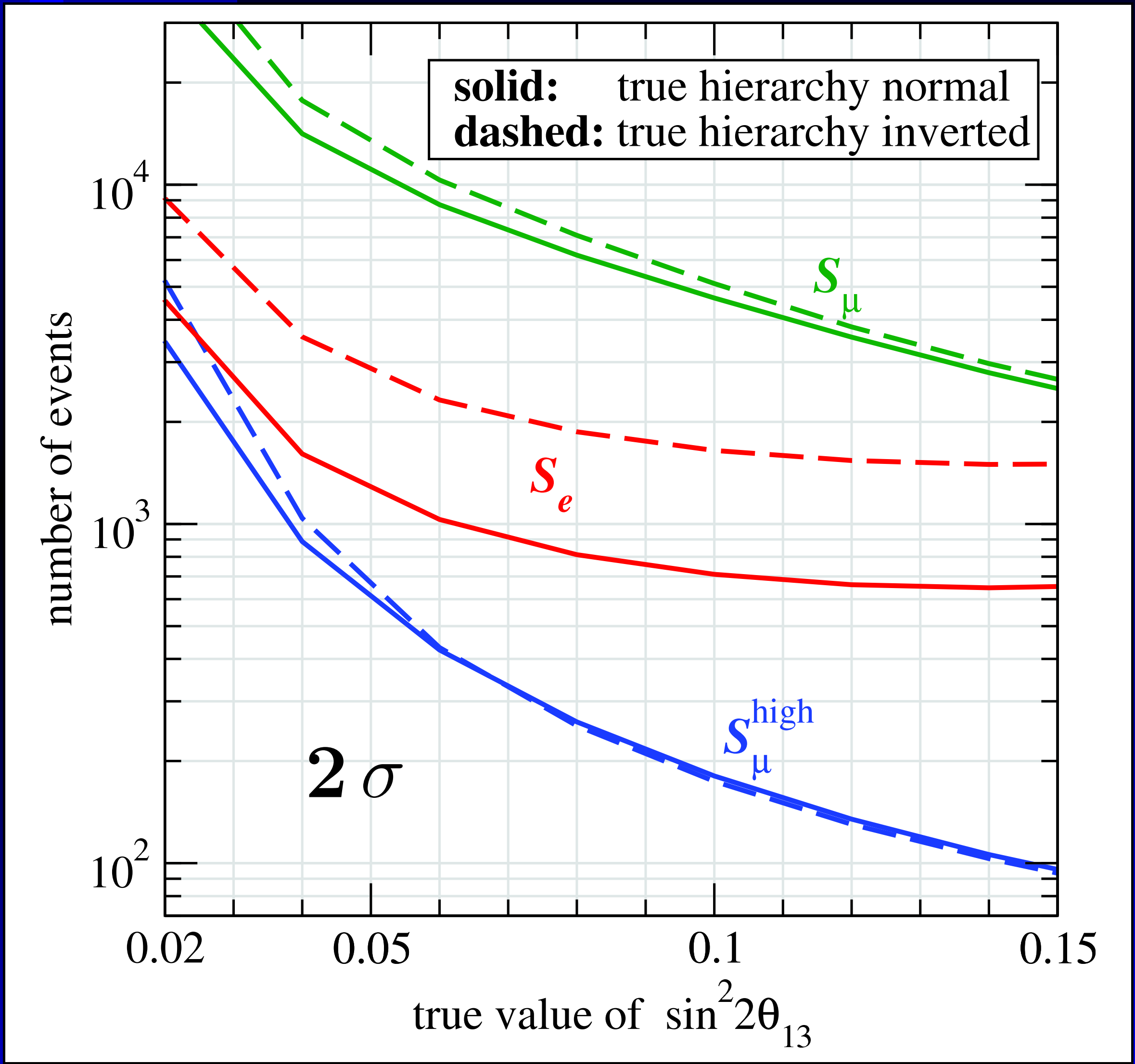
but many effects require flavor separation and the ability to distinguish $\nu/\bar{\nu}$.

Therefore, water Cerenkov detectors are sensitive mostly to θ_{23} related effects, only.



adapted from Akhmedov *et al.*,JHEP 0806:072,2008.

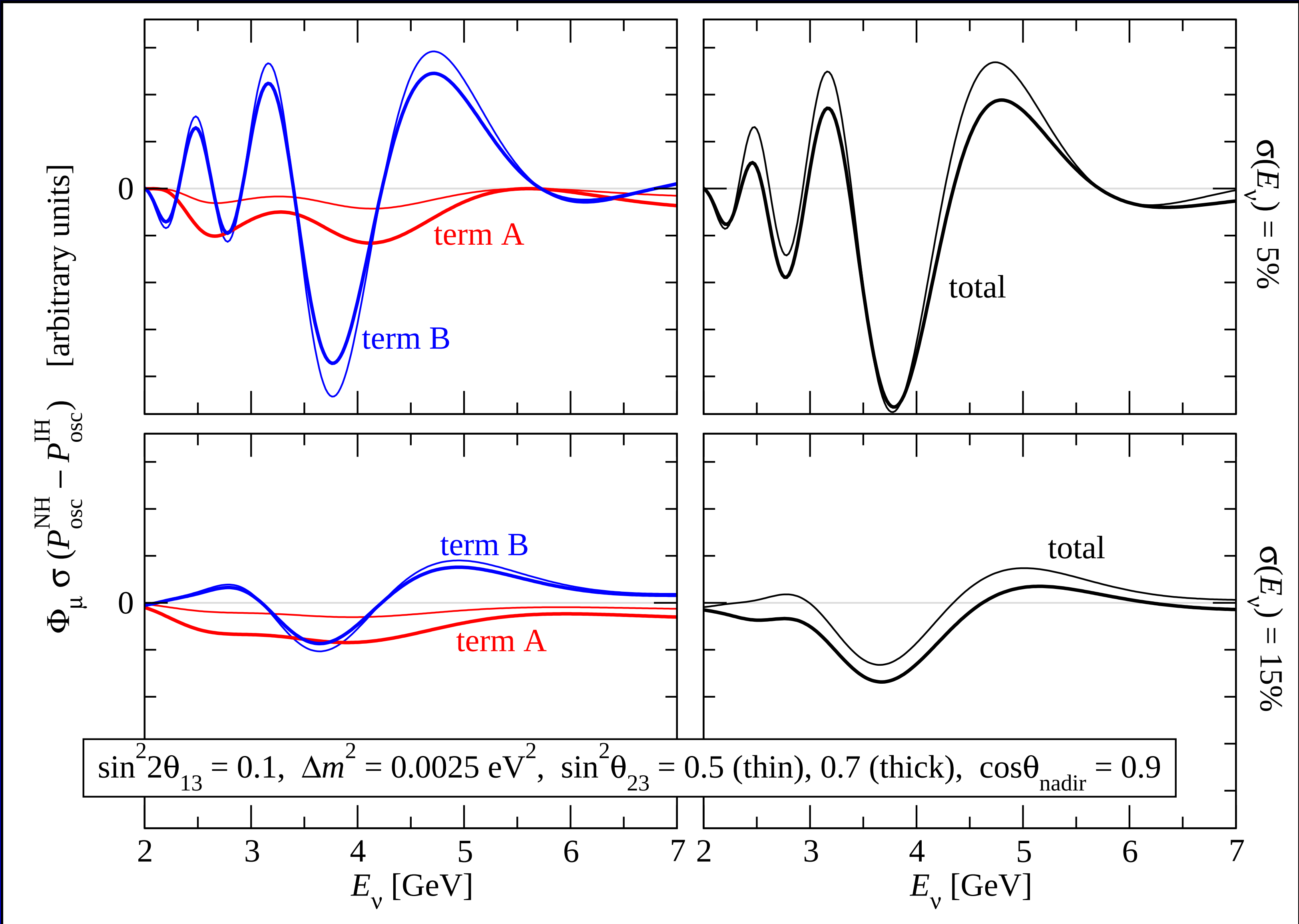
Mass hierarchy



Petcov, Schwetz, NPB 740:1-22,2006.

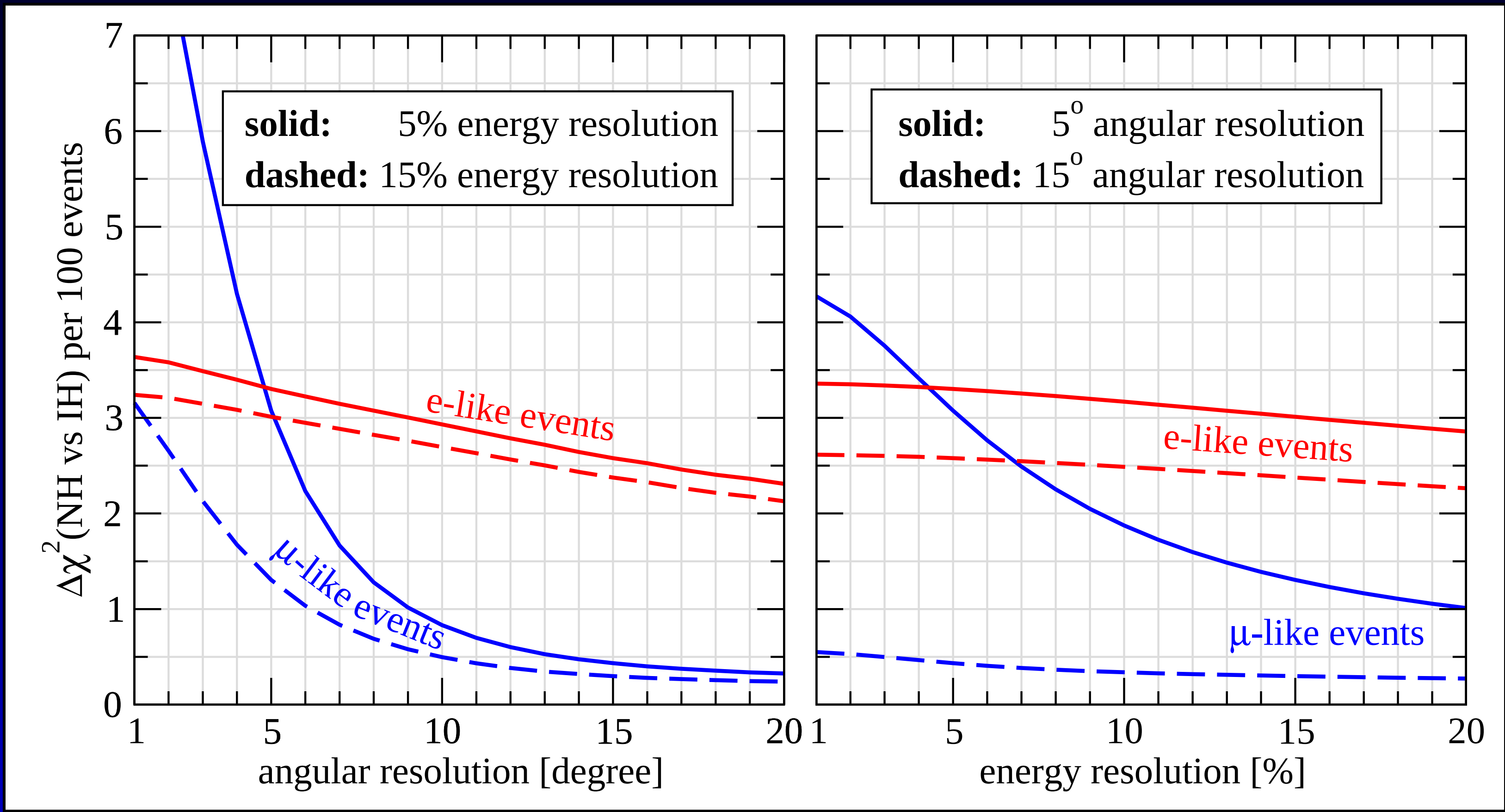
- magnetized calorimeter
- $\phi \propto E_\nu^{-3}$, low statistics at few GeV
- 5 events per kt and year
- S_μ/S_e – 15% energy res., 15° angular res.
- S_μ^{high} – 5% energy res., 5° angular res.
- $S_\mu^{\text{high}} \to$ ATLAS
Kopp, Linder, PRD 76 093003 (2007).

Importance of resolution – I



Petcov, Schwetz, NPB 740:1-22,2006.

Importance of resolution – II



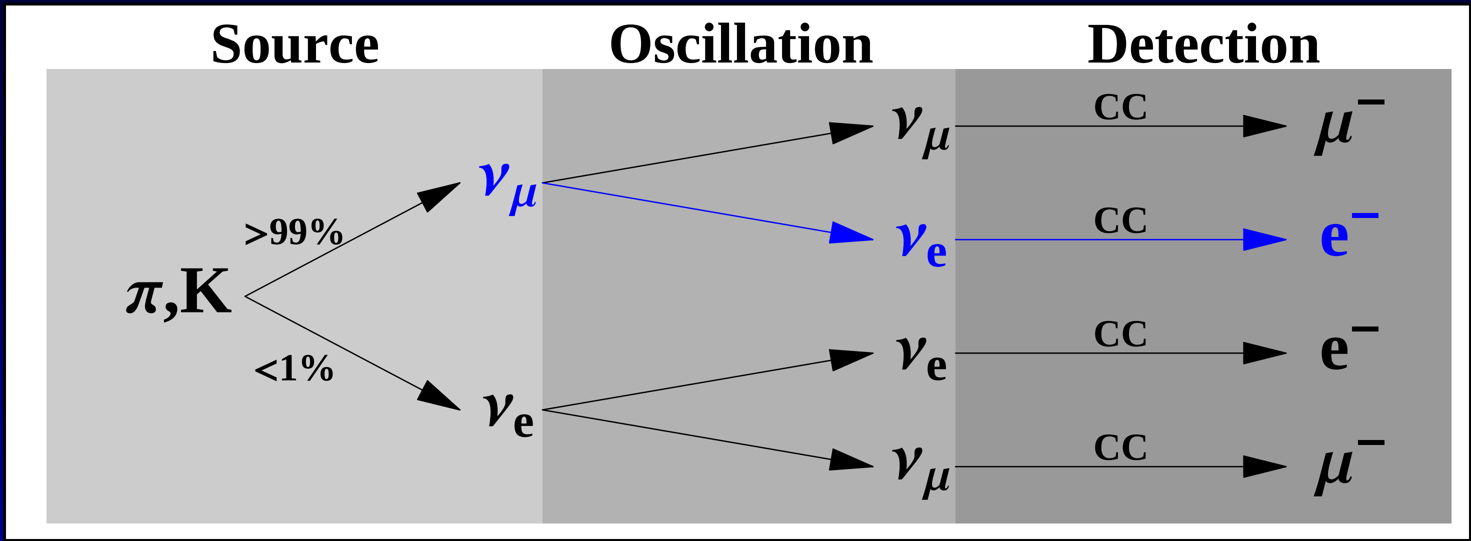
Petcov, Schwetz, NPB 740:1-22,2006.

A smaller but better detector may ultimately provide the better physics!

Superbeams

Superbeams

Neutrino beam from π-decay



They are called 'super'

- beam power $\sim 1\,\mathrm{MW}$
- detectors mass $\sim 100\,\mathrm{kt}$
- running time of the experiment $\sim$ 10 years
- price

LBNE

LBNE short for Long Baseline Neutrino Experiment

- 700kW from Fermilab
- 200kt water Cerenkov equivalent (WCE) detector, where WCE can be either 200kt of water Cerenkov or 33kt of liquid argon or a combination thereof
- Far detector at Homestake mine aka DUSEL
- Potential upgrade of beam power to >2MW by Project X

LBNE has DOE CD0 approval and will go for DOE CD1 review in the spring of 2011.

Exposure

Everyone has different assumptions about

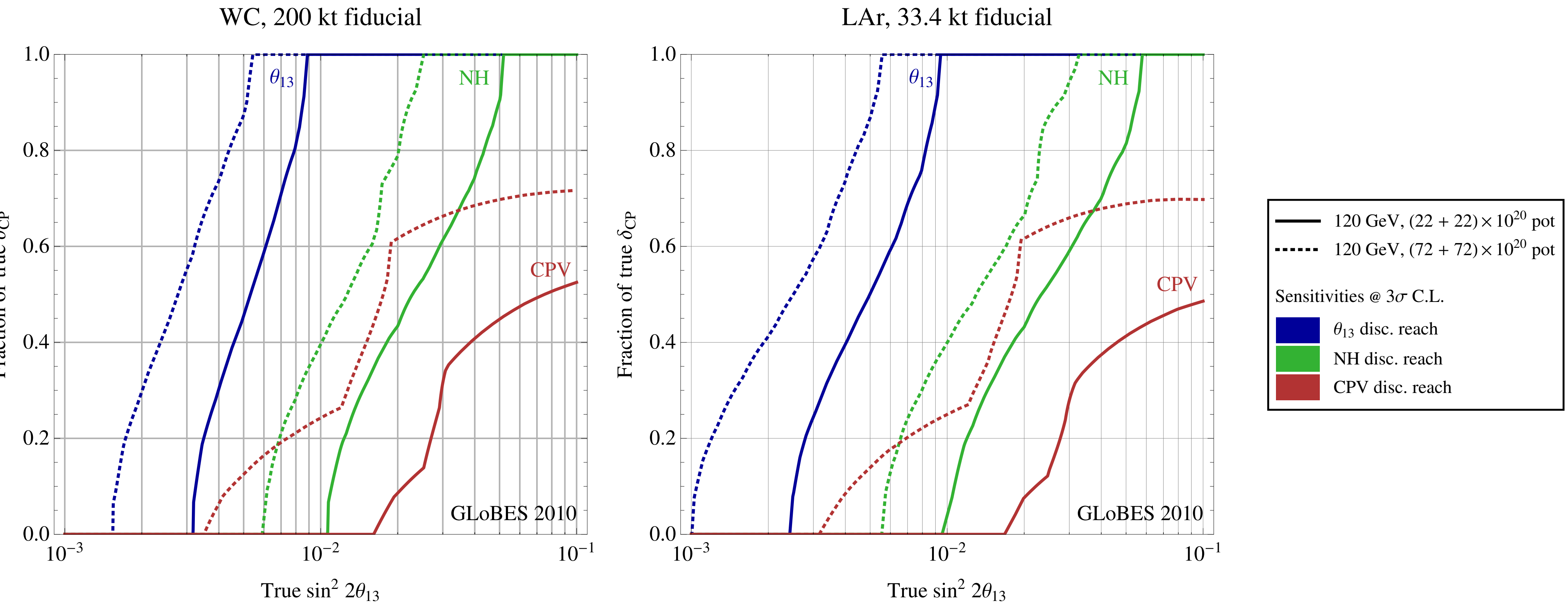
- seconds in a year
- number of years
- detector size
- beam power (or pot)

Therefore, it is useful to introduce the concept of exposure

$$\text{detector mass}\,[\text{Mt}] \times \text{target power}\,[\text{MW}] \times \text{running time}\,[10^7\,\text{s}]\,.$$

Much of the difference between the various superbeam proposals stems from different assumptions about the exposure.

Sensitivities



PH, Kopp, arXiv:1010.3706

6 tons of water $\simeq$ 1 ton of liquid argon.

CP violation

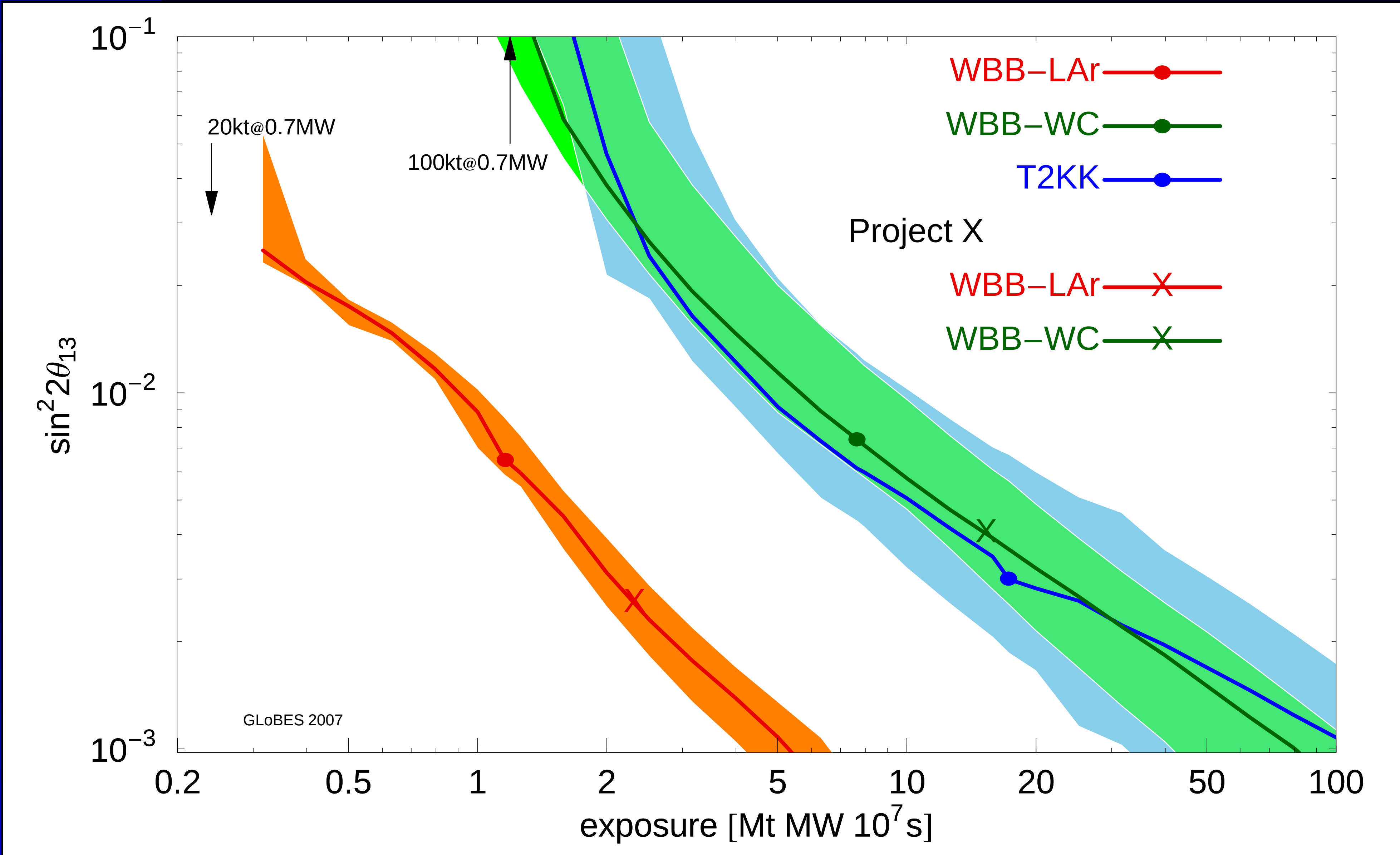


figure adapted from Barger, PH, Marfatia, Winter, Phys.Rev. D76 (2007) 053005

Mass hierarchy

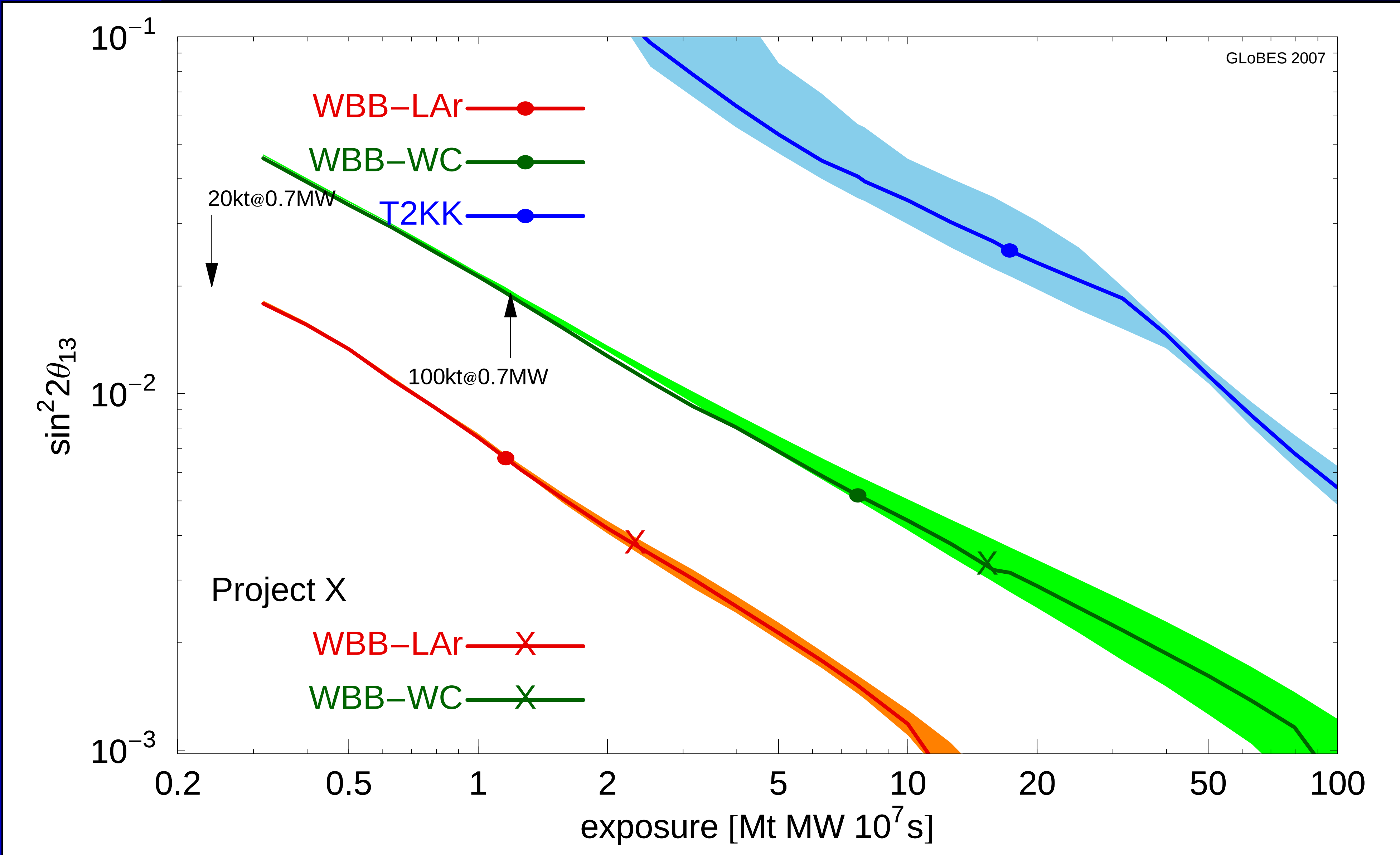
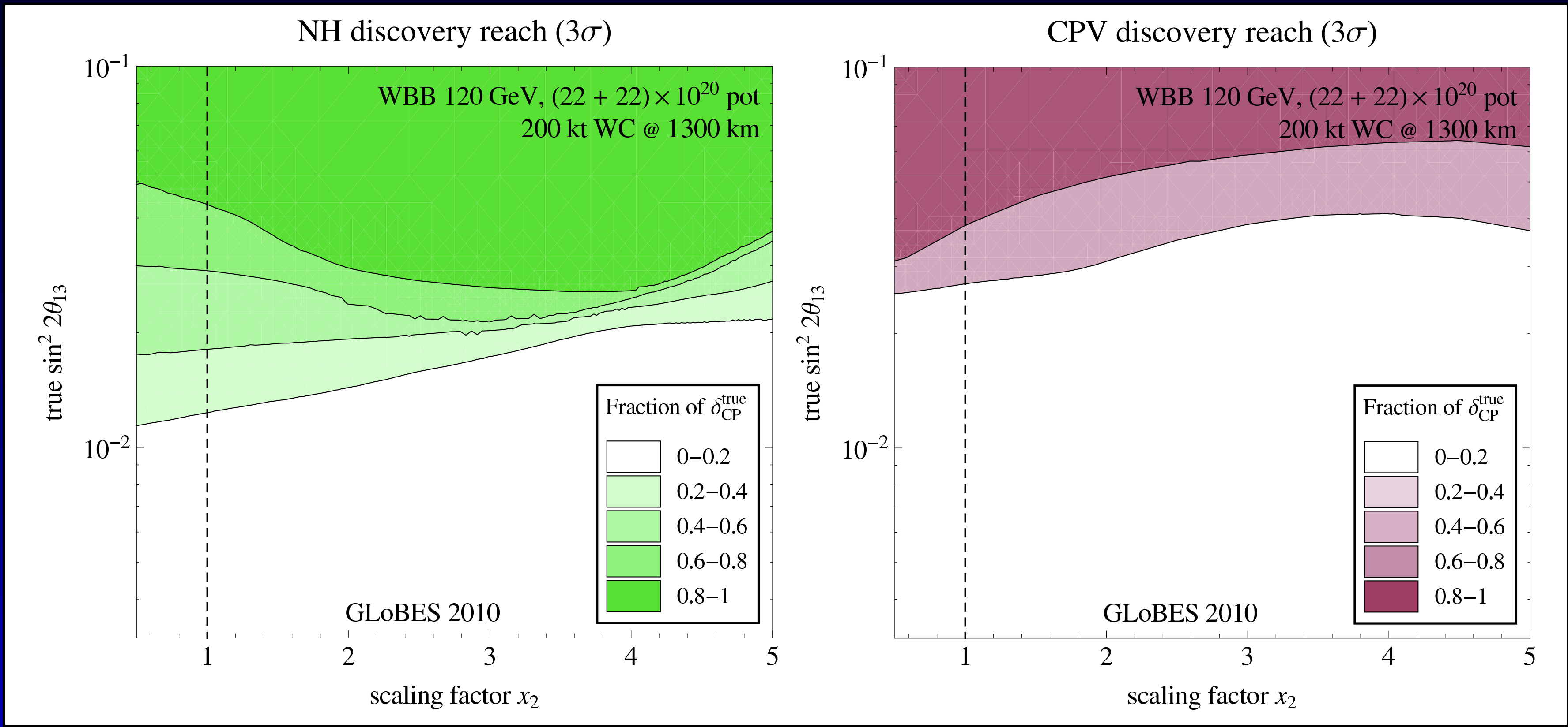


figure adapted from Barger, PH, Marfatia, Winter, Phys.Rev. D76 (2007) 053005

2nd maximxum?

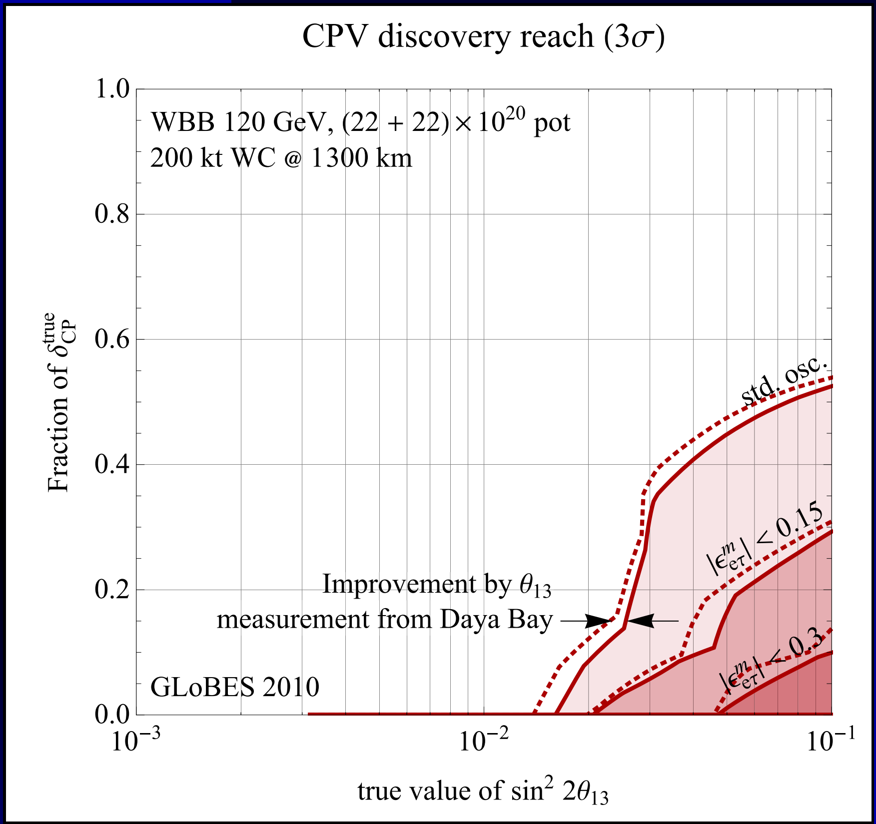


PH, Kopp, arXiv:1010.3706

$$\phi \equiv \phi_1 + \phi_2,\ \ \phi_2 \to x_2\,\phi_2,\ \ \phi_1 \to \phi - x_2\,\phi_2$$

with ϕ_1 flux in 1^{st} and ϕ_2 flux in 2^{nd} maximum

Confusion



PH, Kopp, arXiv:1010.3706

Confusion theorem between NSI and θ_{13} at probability level.
PH, Valle, Schwetz, PRD 66:013006, 2002.

Limited impact at neutrino factory due to muonic τ decays.
Campanelli, Romanino, PRD 66:113001, 2002.

Superbeam experiments have nearly no τ production and hence the confusion theorem applies, including complex NSI also leads to confusion for CPV.

Summary

- New facilities are indispensable to fully exploit the discovery of neutrino oscillation
- CP violation is never easy to measure – even for the largest values of θ_{13}
- Mass hierarchy needs long baseline and multi-GeV neutrinos
- Mass hierarchy is an opportunity for atmospheric neutrinos and magnetized detectors, see D. Indumathi's talk

Given sufficient resources, it seems likely that neutrino mixing can be quantitatively understood at a level similar to the quark sector.