Phenomenology of neutrino oscillations

Patrick Huber

Virginia Tech

ν TheME

CERN, September 14, 2010

Neutrinos are massive – so what?

Neutrinos in the Standard Model (SM) are strictly massless, therefore the discovery of neutrino oscillation, which implies non-zero neutrino masses requires the addition of new degrees of freedom.

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, in principle, the most sensitive probe for new physics at high scales

Weinberg

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 → no Majorana mass term
- lepton number may be approximately conserved → 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
- 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

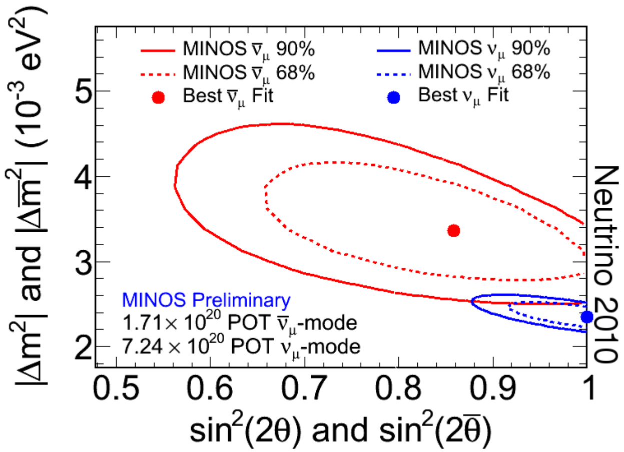
In the context of neutrino oscillation experiments

- $\sin^2 2\theta_{13}$
- 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

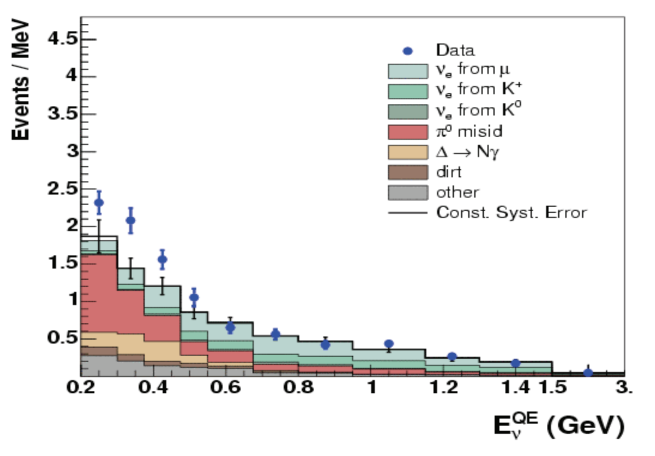
This year we have seen a number of exotic animals

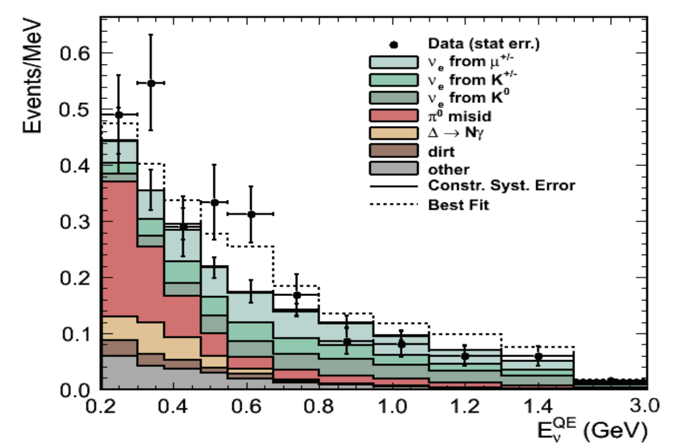


MINOS

- CPT violations at 2.5 sigma?
- Will be resolved by T2K and NOνA

New additions to the Zoo

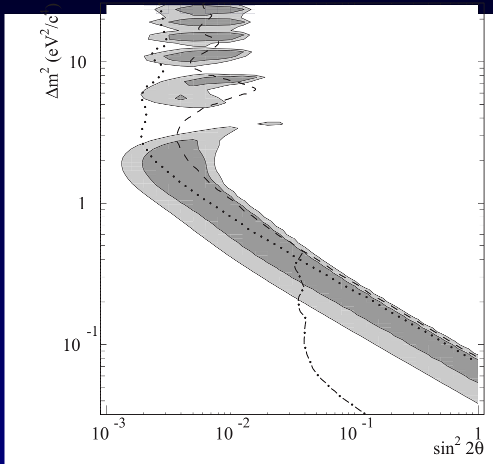




MiniBooNE

- 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

Long term exhibits



LSND

- Statistically quite significant, $> 3\,\sigma$
- Nearly tested by Karmen
- Oscillation interpretation not supported by global data

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

Theory

Phenomenology

Nature

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 $|\Delta m^2_{31}| \Rightarrow$ $\mathcal{T}_s := \Delta m^2_{31} \to -\Delta m^2_{31}$
- Disappearance determines only $\sin^2 2\theta_{23} \Rightarrow$ $\mathcal{T}_t := \theta_{23} \to \pi/2 - \theta_{23}$
- 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 $P(\nu_\mu \rightarrow \nu_e)$, $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$, $P(\nu_e \rightarrow \nu_\mu)$ and $P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)$
- 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

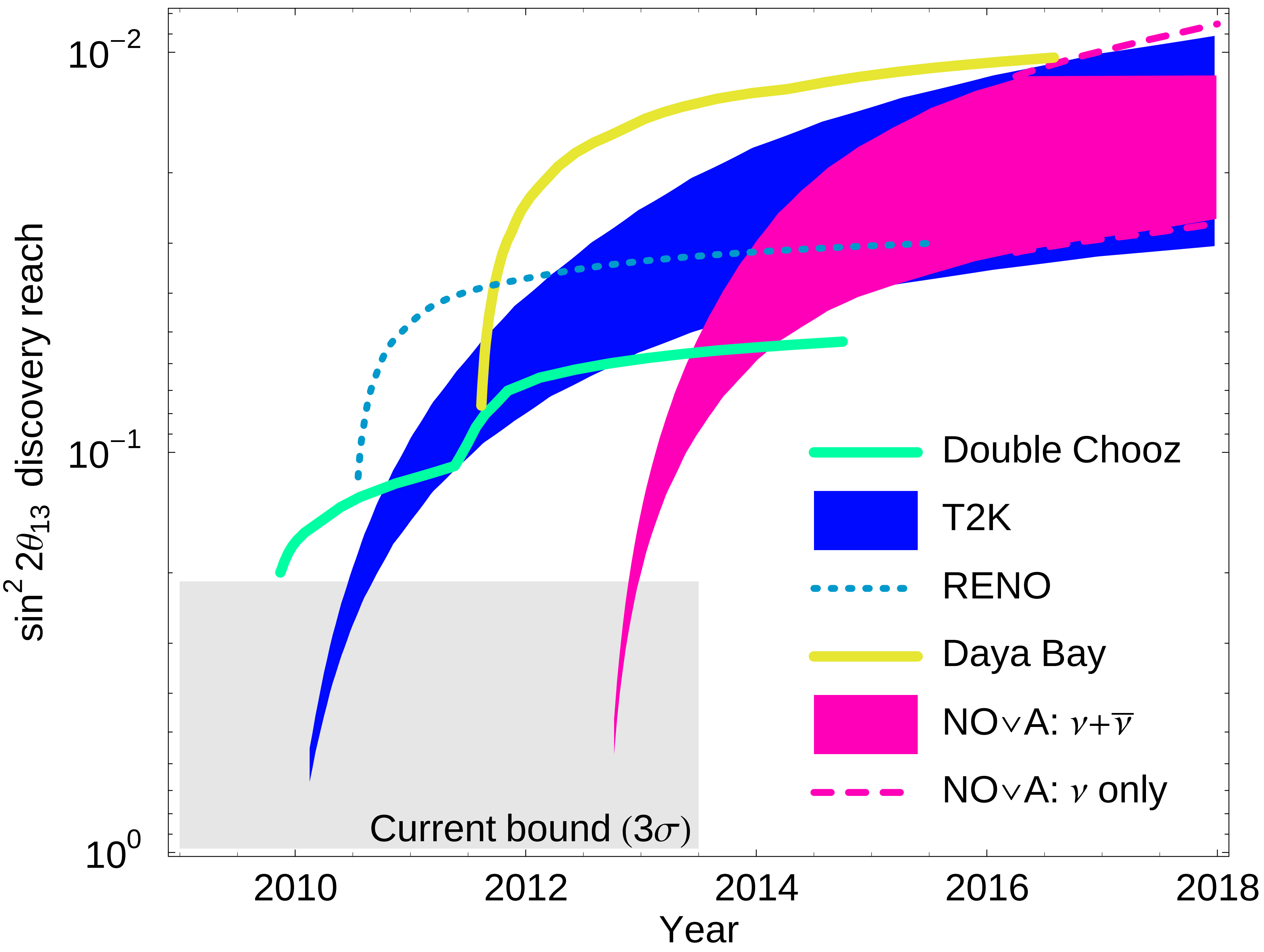
As a rule of thumb, the best experiments we currently can think of, would have

- 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

Setup	t_ν [yr]	$t_{\bar{\nu}}$ [yr]	P_{Th} or P_{Target}	L [km]	Detector	m_{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)

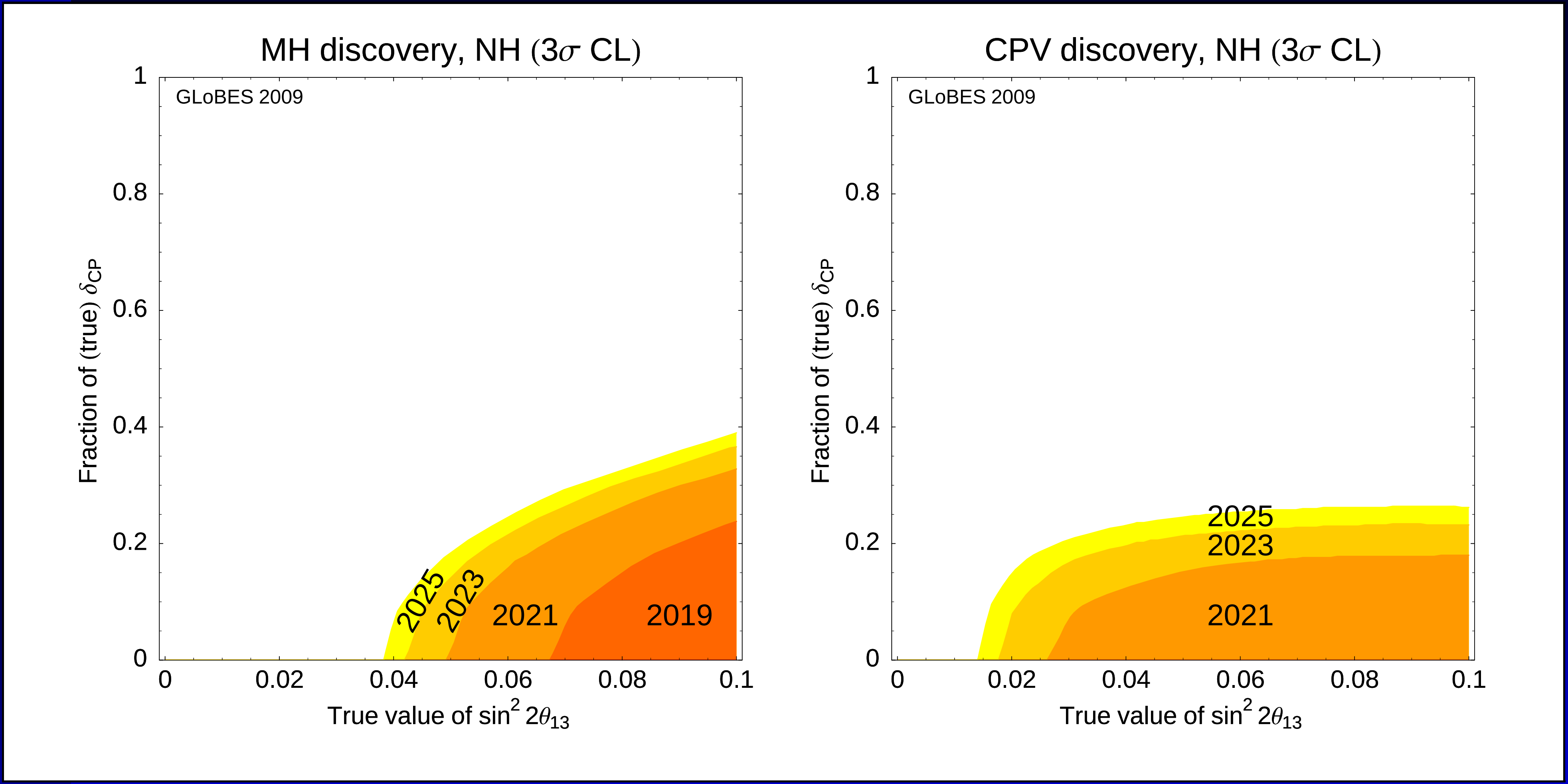


PH, M. Lindner, T. Schwetz, W. Winter, arXiv:0907.1896.

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, M. Lindner, T. Schwetz, W. Winter, arXiv:0907.1896.

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

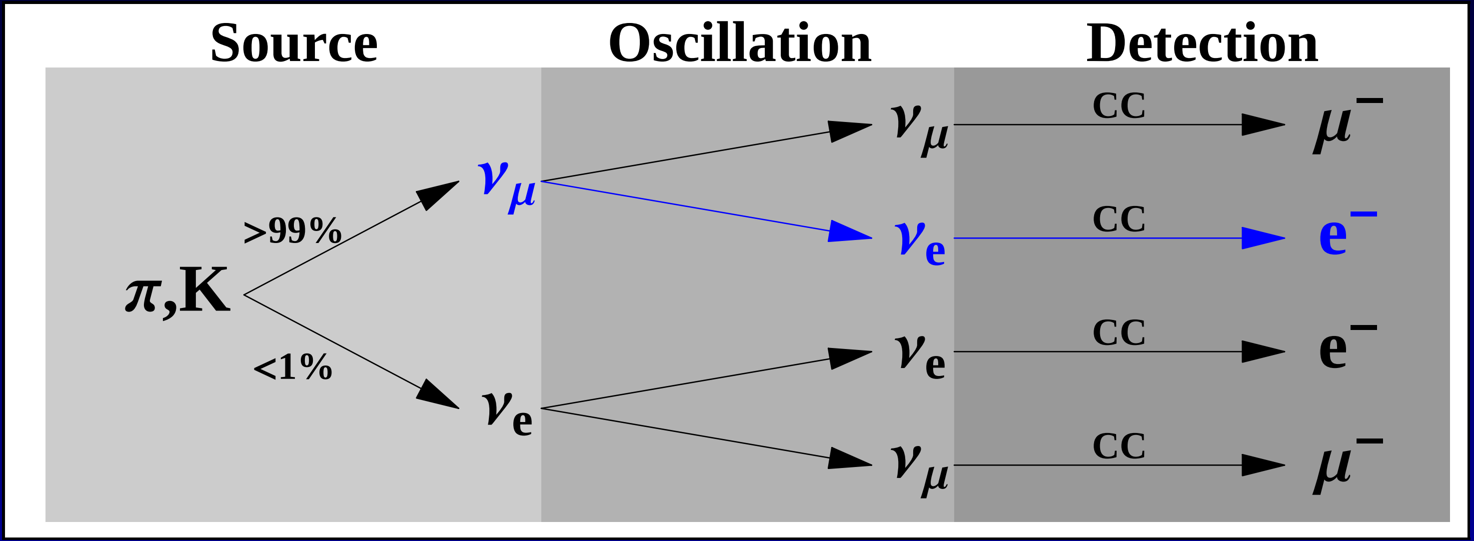
- $\theta_{23} = \pi/4$ – for maximal mixing $45° \pm 4°$
- size of θ_{13} – if $\sin^2 2\theta_{13} > 0.01$
- mass hierarchy – if $\sin^2 2\theta_{13} > 0.04$ for at most 30% of all CP phases
- CP violation in leptons – if $\sin^2 2\theta_{13} > 0.02$ for at most 20% of all CP phases
- MINOS anomaly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

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

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 by the end of this year.

Exposure

Everyone has different assumptions about

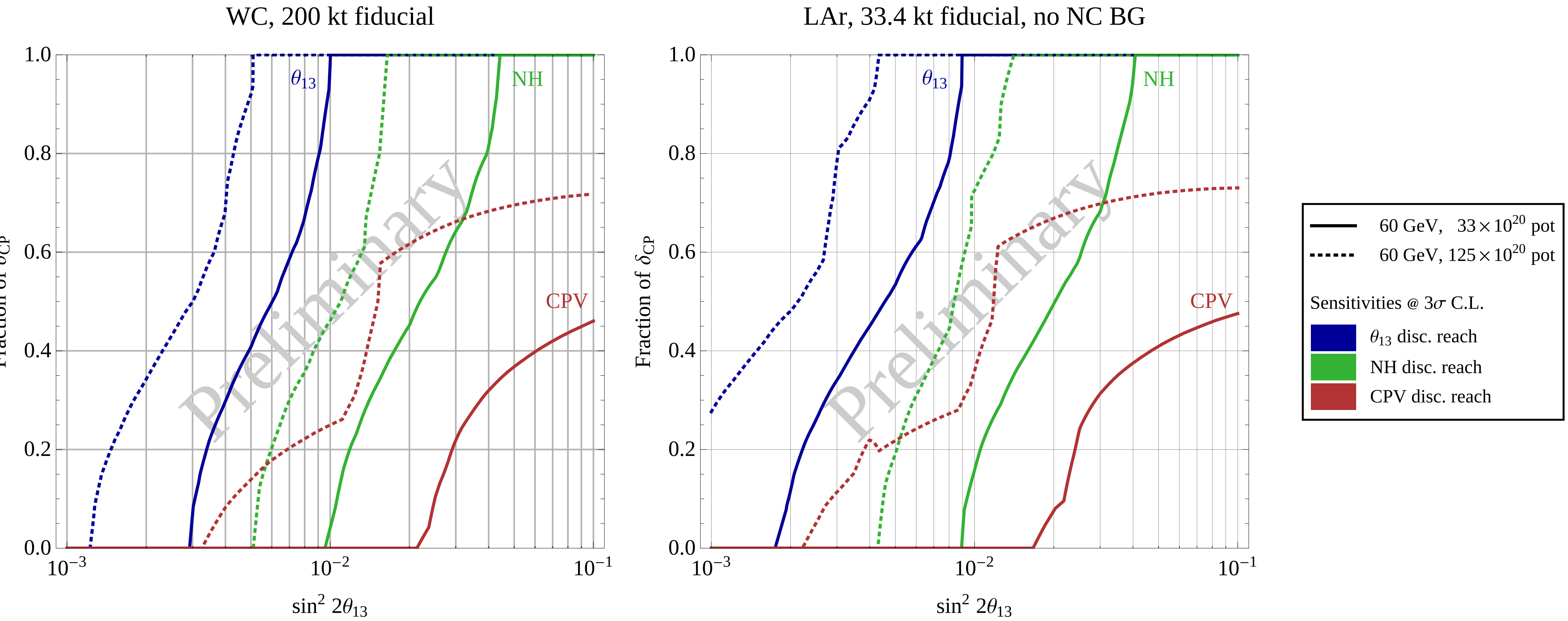
- seconds in a year
- number of years
- detector size
- beam power (or pot)

Therefore, it is useful to introduce the concept of exposure

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

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

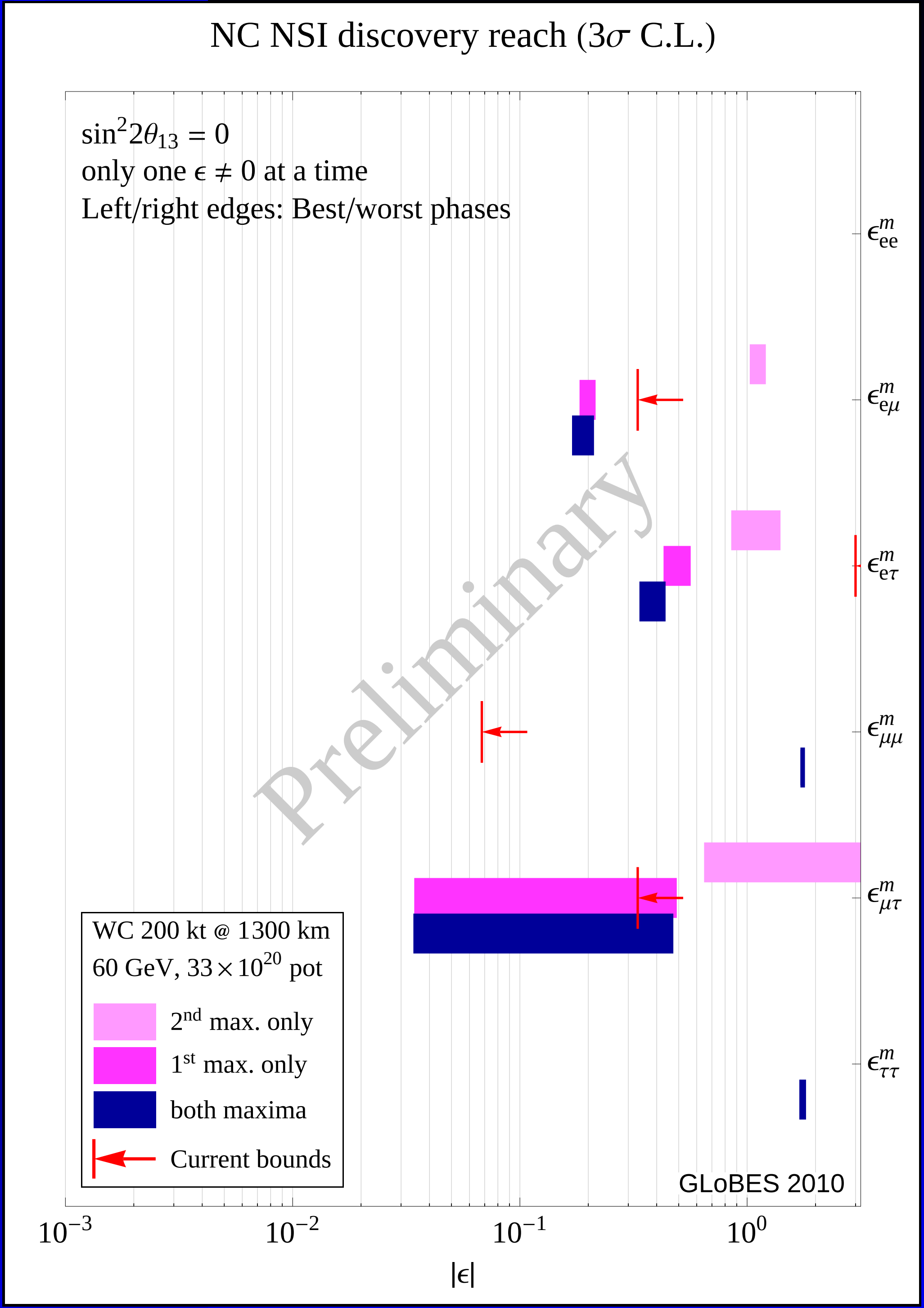
Sensitivities


WC, 200 kt fiducial

LAr, 33.4 kt fiducial, no NC BG

PH and J. Kopp, work in progress

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

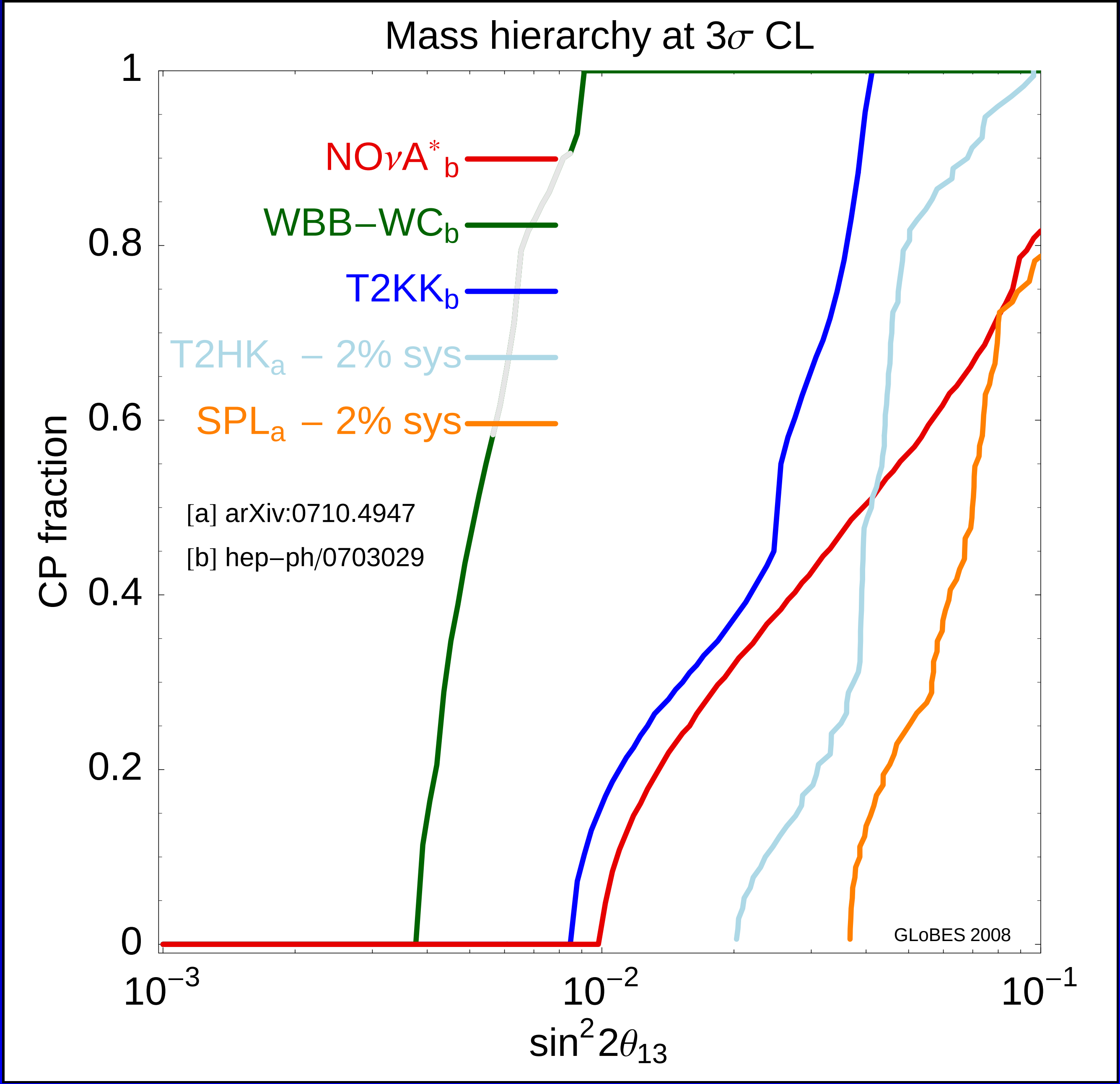


Sensitivity to NC like non-standard interactions

- Only 1 NSI parameter at a time varied
- Current bounds improved for τ-involving NSI
- Includes near detector (w/o ν_τ detection)

PH and J. Kopp, work in progress

Alternatives?

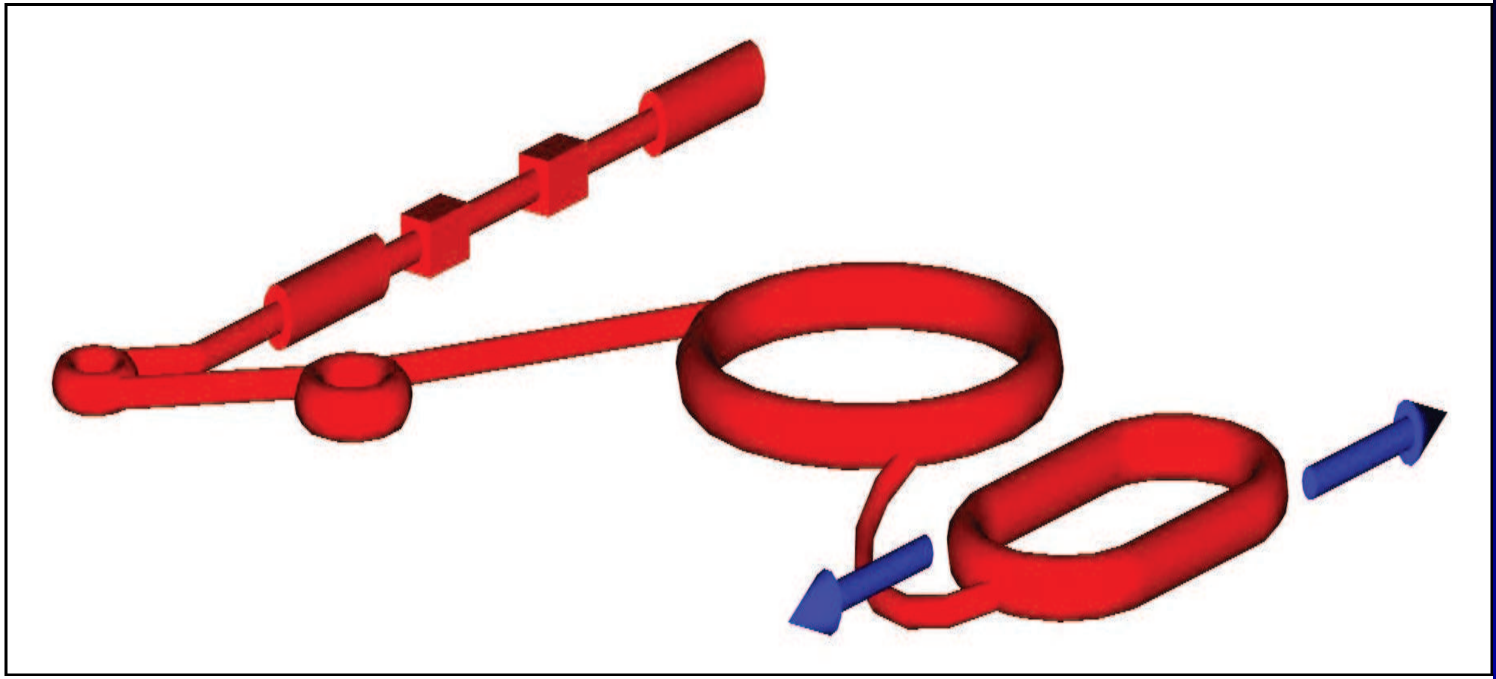


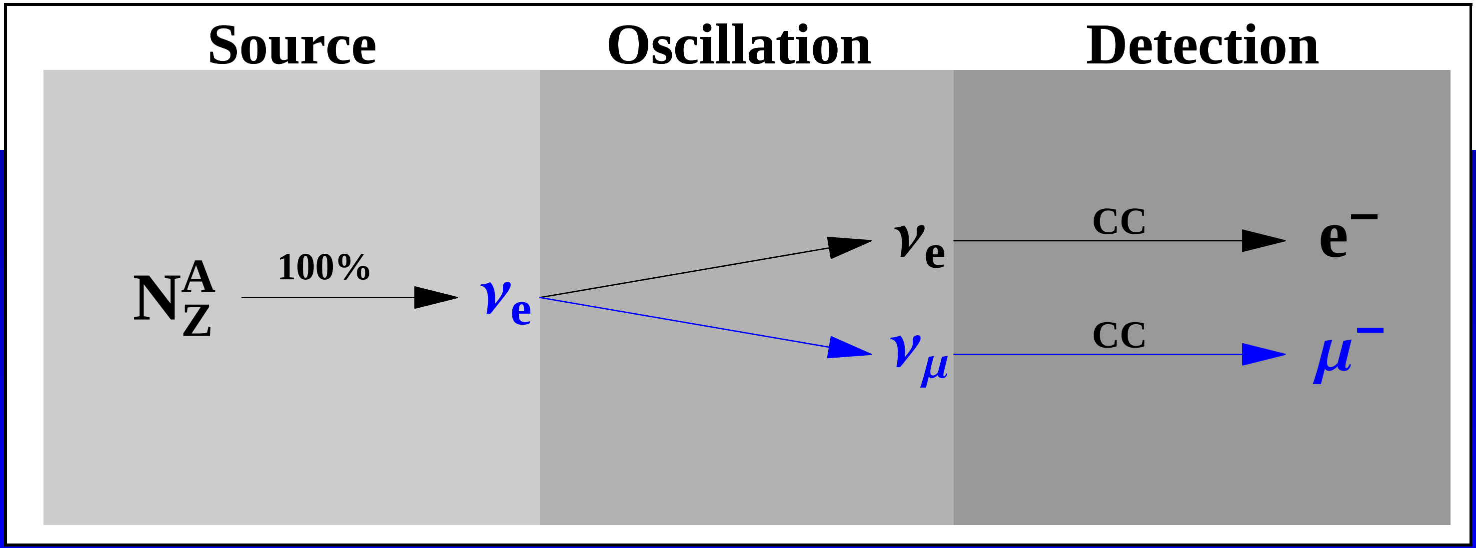
1st maximum at longer L
→ higher E_ν:
- WBB-WC

2nd maximum
→ second detector:
- NOνA*
- T2KK

Beta beam

β-beams





Source **Oscillation** **Detection**

$N_Z^A \xrightarrow{100\%} \nu_e$

$\nu_e \rightarrow \nu_e \xrightarrow{CC} e^-$

$\nu_e \rightarrow \nu_\mu \xrightarrow{CC} \mu^-$

Candidate ions

	A/Z	half life [s]	Q value [MeV]	production rate
^{6}He	3.0	0.8	3.5	OK
^{8}Li	2.7	0.8	13.0	OK?
^{18}Ne	1.8	1.7	3.4	unsolved
^{8}B	1.6	0.8	13.9	OK?

For a beam peak energy of 1 GeV, Lorentz boosts of $\gamma \sim 150$ (^{8}Li and ^{8}B) or of $\gamma \sim 570$ (^{6}He and ^{18}Ne) are required.

Detector choice depends on neutrino energy: water Cerenkov and liquid Argon for low energy, iron calorimeter for high energy

Lorentz boost

^{6}He is the most difficult isotope since $A/Z = 3$.

size of storage ring			
γ	rigidity [Tm]	ring length [m] B=5 T & f=36%	dipole field [T] L=7 km
100	938	4916	3.1
150	1404	6421	4.7
200	1867	7917	6.2
350	3277	12474	10.9
500	4678	17000	15.6

Optimized beta beam

In view of the difficulties associated with large values of γ, an optimized, 2 baseline, four isotope setup has been proposed:

- Upgraded CERN SPS as accelerator
- He/Ne at $\gamma = 350$ aimed at 500kt water Cerenkov, baseline 650km
- Li/B at $\gamma = 656/390$ aimed at 50kt iron detector, baseline 7000km
- 2.5 years running for each isotope
- Shortened decay ring, 8.3 T dipole field , 3-4km long and dips 700m below ground

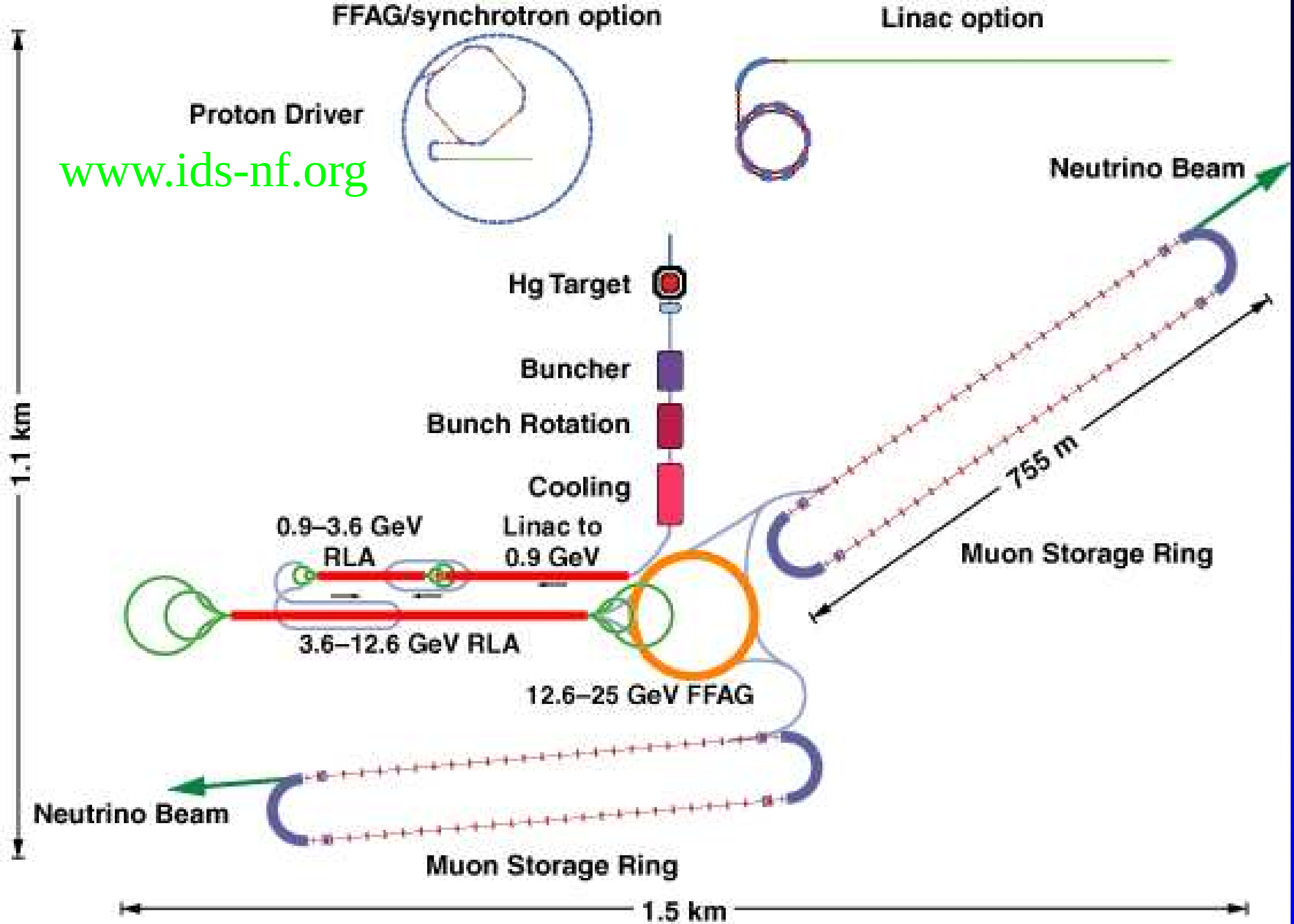
Choubey, Coloma, Donini, Fernandez-Martinez, arXiv:0907.2379

Challenges

- Isotope production
- Acceleration – sufficiently high neutrino energies
- Radioactive beams – activation of equipment
- Storage ring – high ion densities, size
- No ν_μ disappearance, thus no θ_{23} measurement
- Community support?

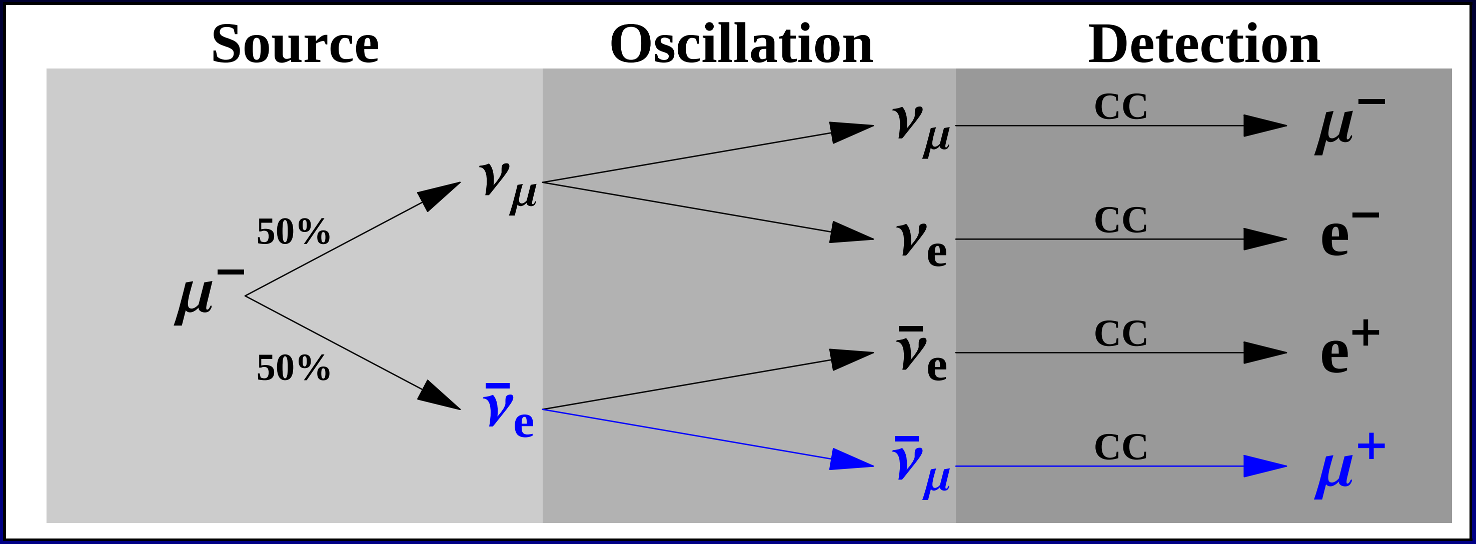
Neutrino factory

Neutrino Factory



www.ids-nf.org

Signal



This requires a detector which can distinguish μ^+ from μ^- $\Rightarrow$ magnetic field of around 1T

- above 3 GeV – iron calorimeter like MINOS
- below 3 GeV – magnetized, totally active, fine grained scintillator

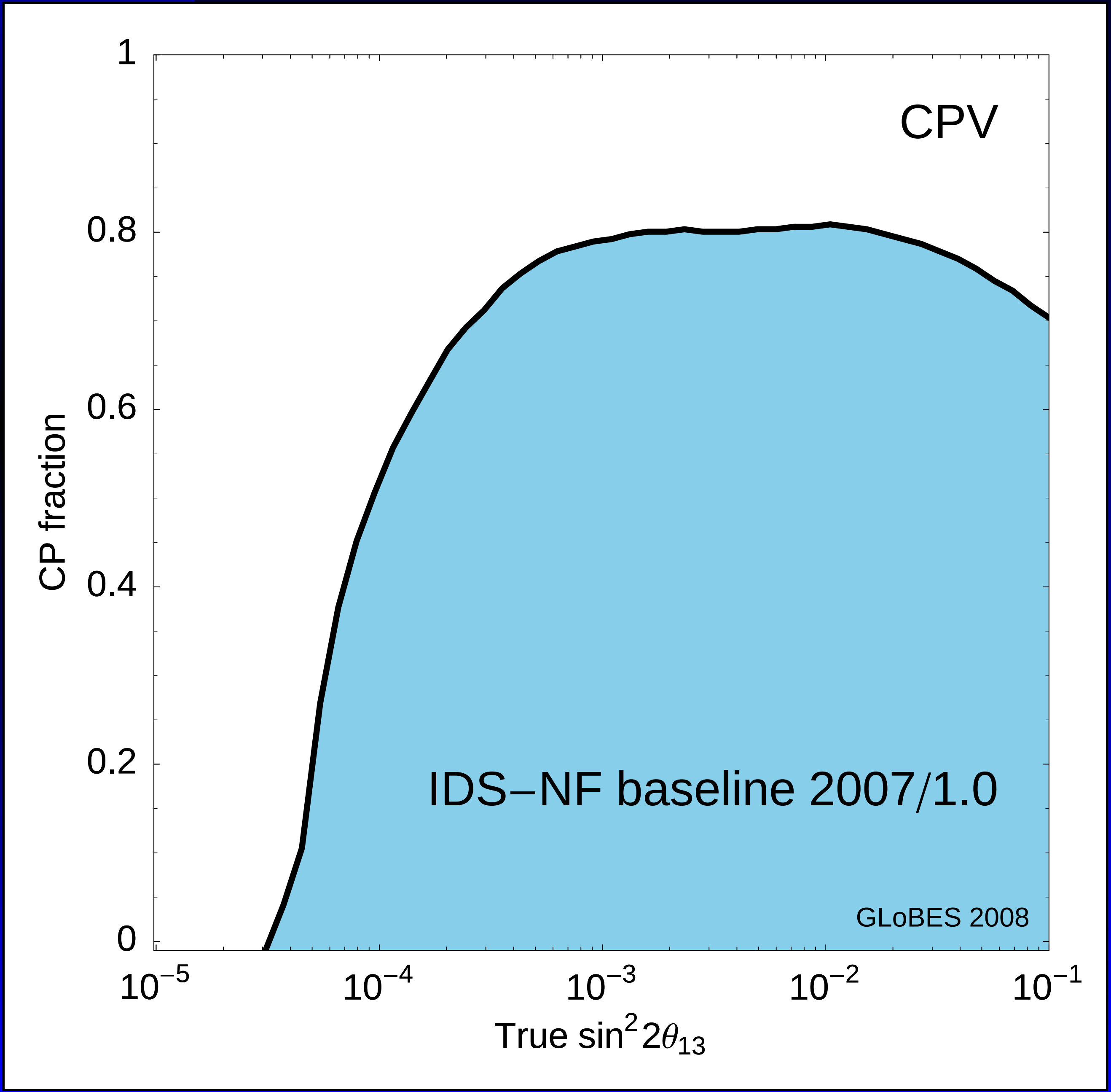
Challenges

- muon production (MERIT)
- muon cooling (MICE, MuCool)
- muon acceleration (EMMA)

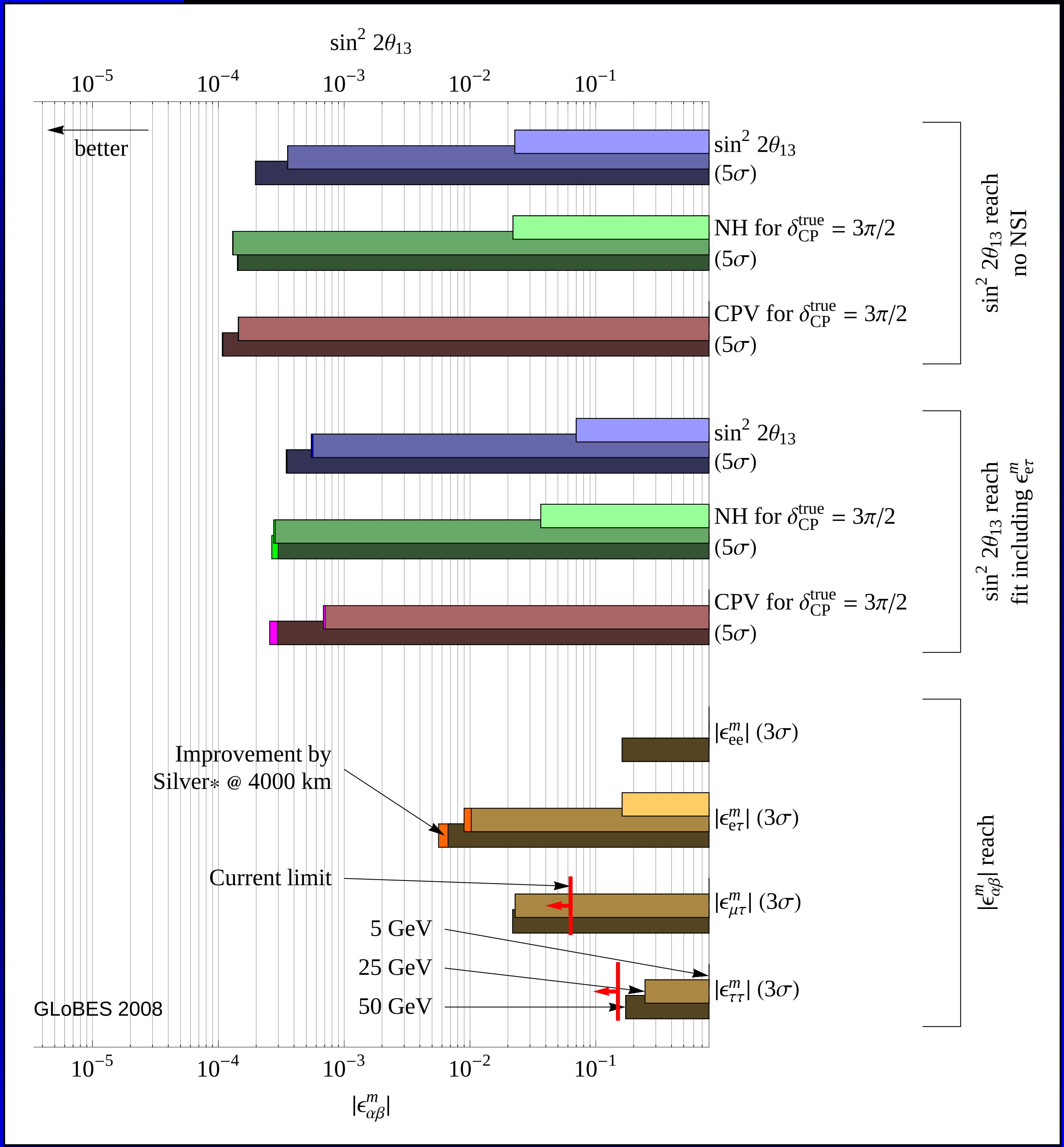
All these step are necessary for a muon collider, too. Active R&D effort, which will yield a reference design report by 2012.

International Design Study for a Neutrino Factory (IDS-NF): www.ids-nf.org

IDS-NF baseline



- $E_\mu = 25\,\mathrm{GeV}$
- 10^{21} useful muon decays per year
- 2 baselines: 4000 and 7500 km
- 2 mag. iron detector with $m_f = 50\,\mathrm{kt}$
- $10\,\mathrm{kt}$ OPERA-like detector at 4000km



Sensitivity to NC like non-standard interactions.

Only 1 NSI parameter at a time varied

Fernandez-Martinez, *et al.*, IDS-NF interim report

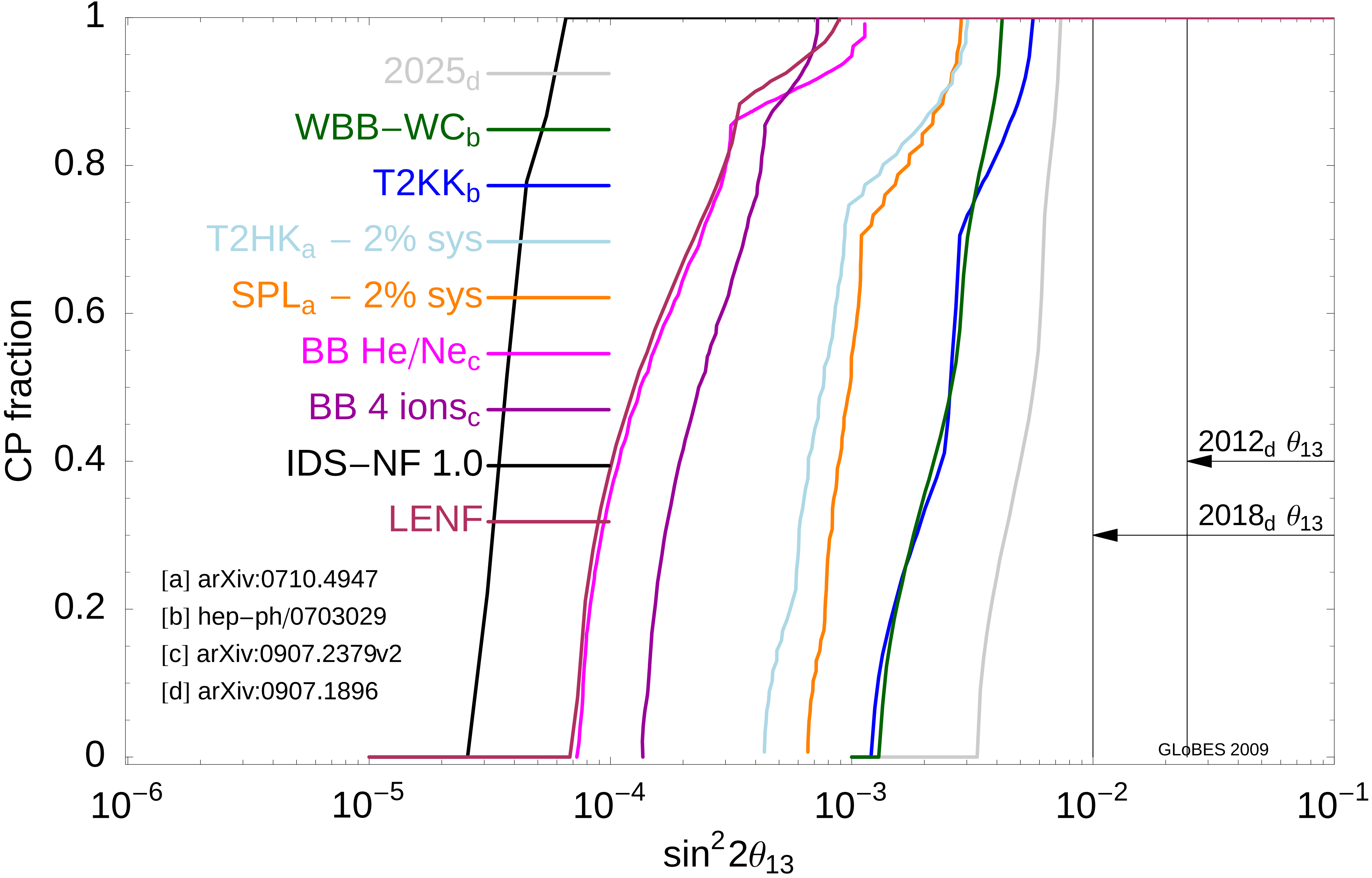
Low energy neutrino factory

- $E_\mu = 4.12\,\mathrm{GeV}$
- much of accelerator infrastructure is no longer required (one stage of RLA and the FFAG ring)
- one baseline of 1300km
- one compact (250m) storage ring
- $1.4 \cdot 10^{21}$ useful muon decays per year and polarity
- 10 years of running
- fine grained magnetic detector, either totally active scintillator (like Minerva) or liquid Argon TPC, we take 20kt as fiducial mass

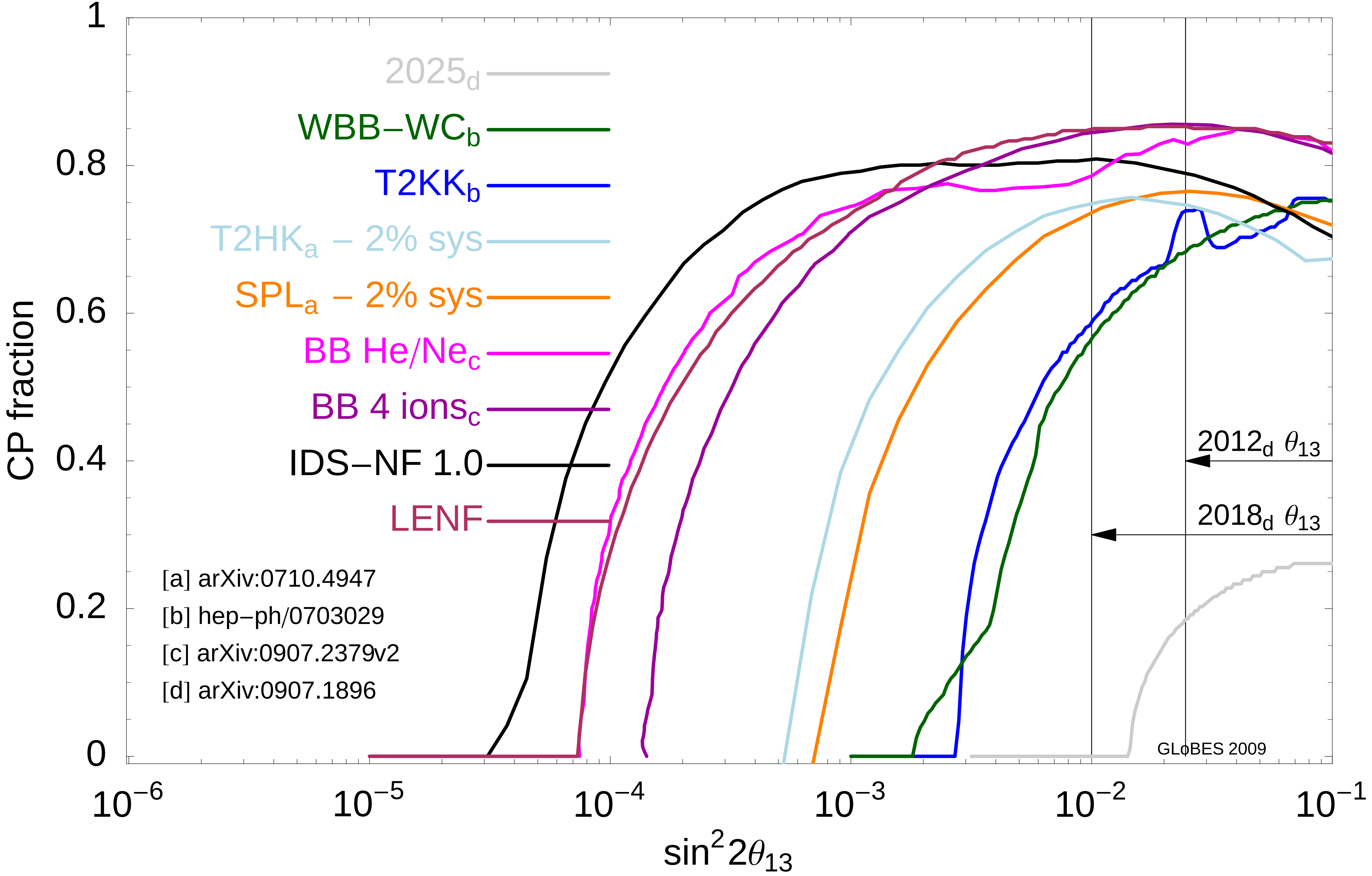
Bross, *et al.* arXiv:0709.3889

Summary

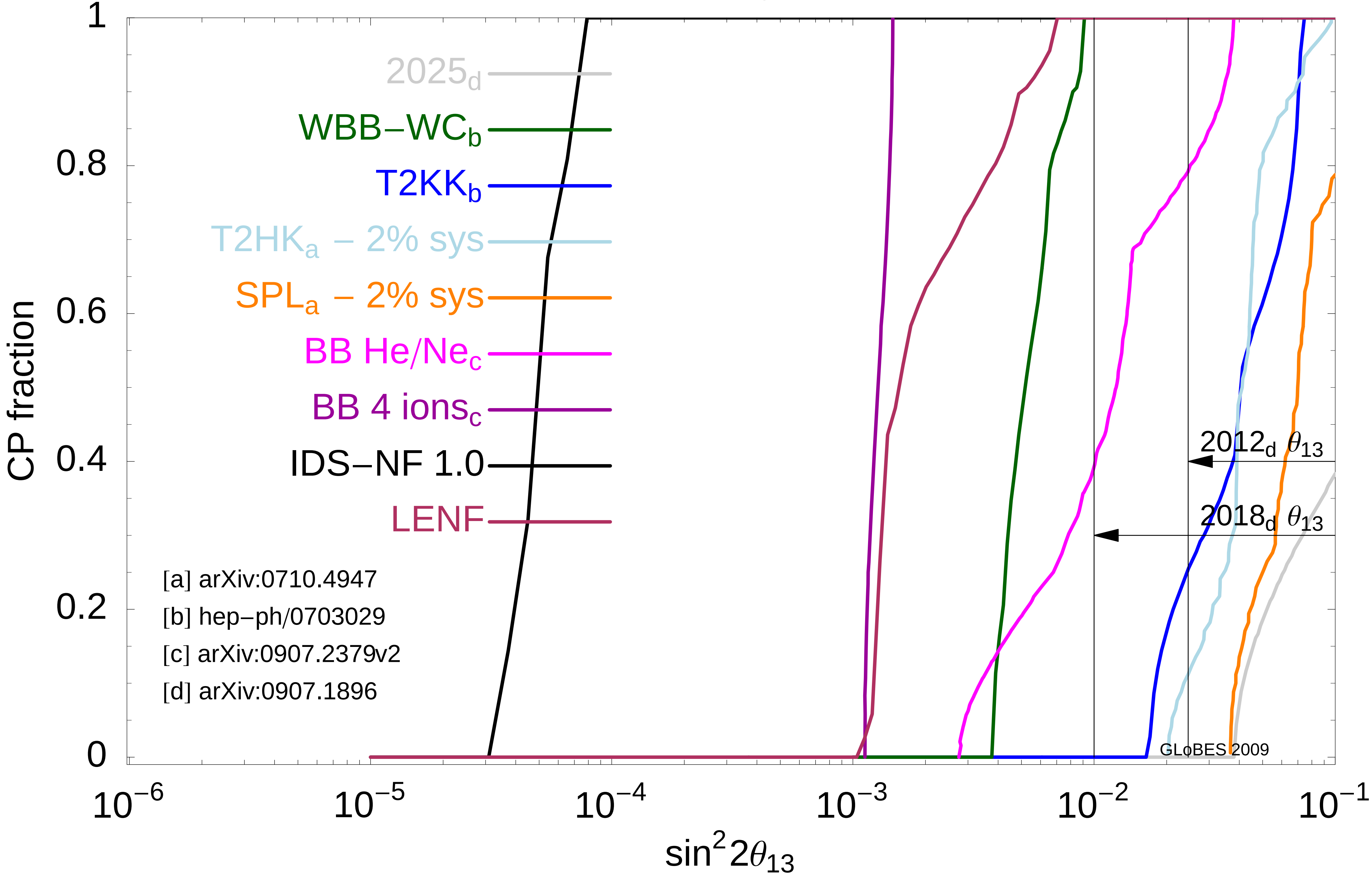
$\sin^2 2\theta_{13}$ discovery at 3σ CL



CP violation at 3σ CL



Mass hierarchy at 3σ CL



Three technologies

- Superbeams – for large $\sin^2 2\theta_{13} > 0.01$, require true MW beams and Mt detectors
- Beta beams – large experiments, with somewhat limited physics: no ν_μ disappearance, difficulties with mass hierarchy
- Neutrino factories – the ultimate tool, technologically moderately more difficult, can be built in steps (low energy option), gateway to muon collider
- New physics searches can be performed at the same facilities with only slight modifications and many cases strengthen the robustness of the other measurements

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 beams

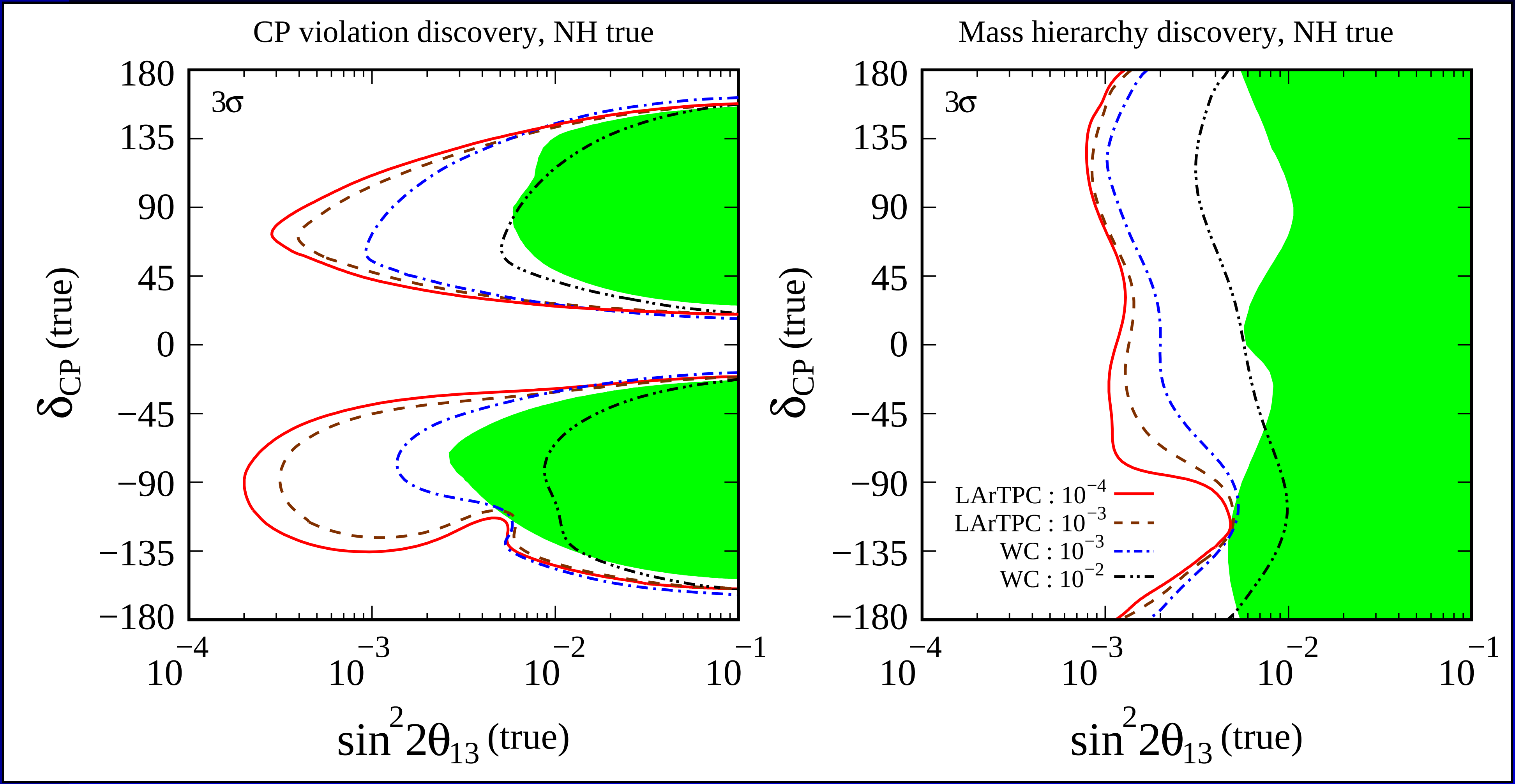
Given sufficient resources, it seems likely that neutrino mixing can be quantitatively understood at a level similar to the quark sector.

Backup Slides

Fermilab beta beam

- Tevatron can accelerate the ions up to $\gamma_{\mathrm{Ne}} = 585$ and $\gamma_{\mathrm{He}} = 350$
- Beam is sent to DUSEL, baseline is 1300km
- Two possible detector technologies
  - 300kt water Cherenkov detector
  - 100kt liquid Argon TPC
- Decay ring with 5T magnets is 14km circumference – will not fit on FNAL site, at least 10T magnets required

Fermilab beta beam – continued



Agarwalla, PH, arXiv:0909.2257

Green shaded regions: superbeam with P=1.1MW

Stopped pion sources – I

Conrad and Shaevitz (arXiv:0912.4079) propose to use stopped pion neutrino sources (more than a dozen) to study CP violation in a Gd doped, 300kt water Cerenkov detector. In the meantime, the DAEDALUS collaboration formed and has posted an EOI arXiv:1006.0260.

The crucial assumption is that each of these sources would be cheap due to advances in accelerator technology.

Stopped pion sources – II

If we believe this assumption, then with N sources, we have the following possibilities

- $N = 4$, at 20km replaces the anti-neutrino run at LBNE and increases LBNE’s potential to discover CP violation S. Agarwalla, *et al.*, arXiv:1005.4055
- $N = 2$, at 20m can provide EW precision physics (weak mixing angle), S. Agarwalla, PH, arXiv:1005.1254
- $N = 1$, at 20m from Super-K can settle LSND,

  S. Agarwalla, PH arXiv:1007.3228