A MINDless neutrino factory?

Patrick Huber

CERN

Virginia Tech

based on

PH and T.Schwetz, arXiv:0805.2019

IDS Plenary Meeting

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mind·less \ˈmīndlə̇s, *rapid* -nl-\ *adj* [ME *myndles*, fr. OE *gemyndlēas* foolish, senseless, fr. *gemynd* mind, memory + *-lēas* -less — more at MIND] **1 a :** destitute of mind or consciousness : characterized by or exhibiting a lack of consciousness ⟨hatred toward the sea as though it were not a ~ force but a conscious one —C.B.Nordhoff & J.N.Hall⟩ ⟨fell into a ~ sleep —Mary Austin⟩ **b :** lacking or held to be without intellectual powers : STUPID, UNINTELLIGENT ⟨become more than friendly with . . . a gorgeous ~ creature who teaches riding —*New Yorker*⟩ ⟨his white hair crested like a wave over his ~ face —Edith Sitwell⟩ **c :** characterized by or displaying no use of the powers of the intellect : UNTHINKING ⟨that deep ~ sympathy —Douglas Stewart⟩ **d :** out of one's mind : MAD

from Webster's 3rd edition

Outline

- The MIND paradigm
- Oscillation helps
- Neutrinos are not their own anti-particles†
- Size matters
- Outlook

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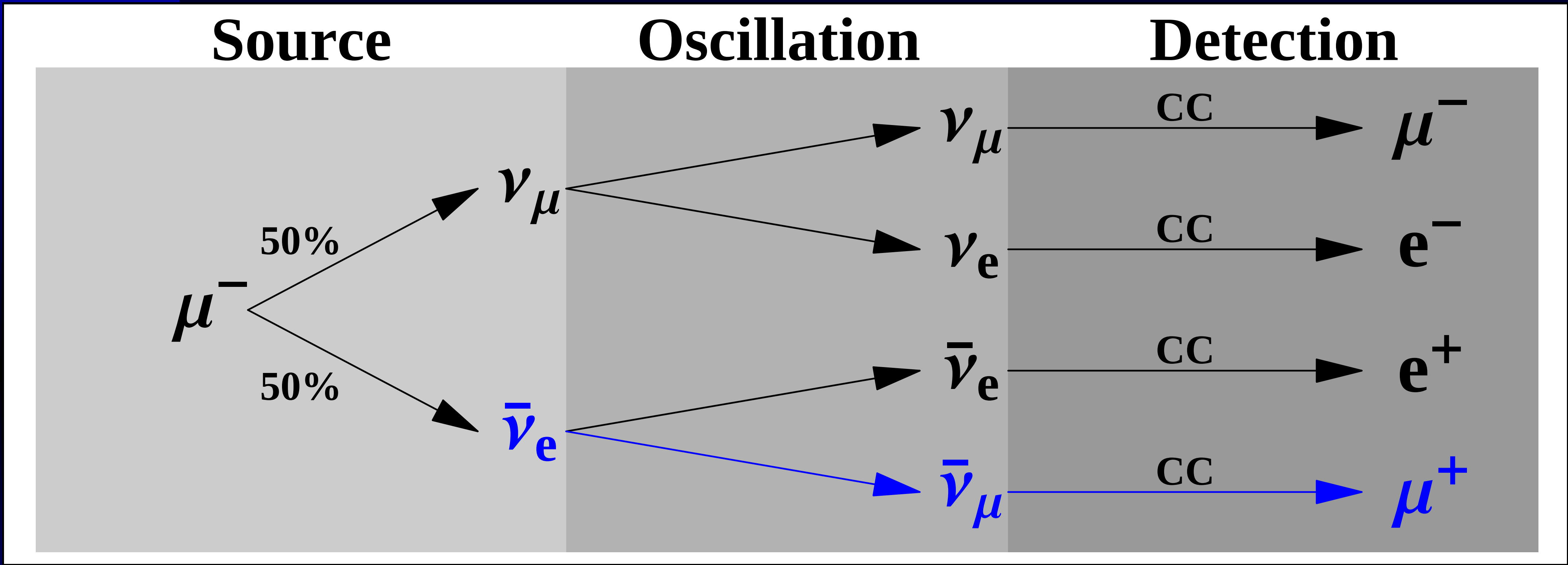
† I am not claiming they are Dirac particles.

The need for a magnetic field



The most reliable way to distinguish a μ^- from a μ^+ is by measuring its charge sign and this is done by bending the muon track in a magnetic field.

The MIND

The use of a magnetic field $\sim 1\,\mathrm{T}$ has following consequences

- iron core magnet
- high target density
- short muon tracks
- most of the detector mass is passive

this results in

- requires a relative long muon track
- puts a severe constraint on the lowest neutrino energy
- mediocre energy resolution
- target mass limited to $\sim 100\,\mathrm{kt}$

The TASD

To overcome the low energy constrain:

- air core magnet
- lower target density
- longer muon tracks
- all of the detector is active

this results in

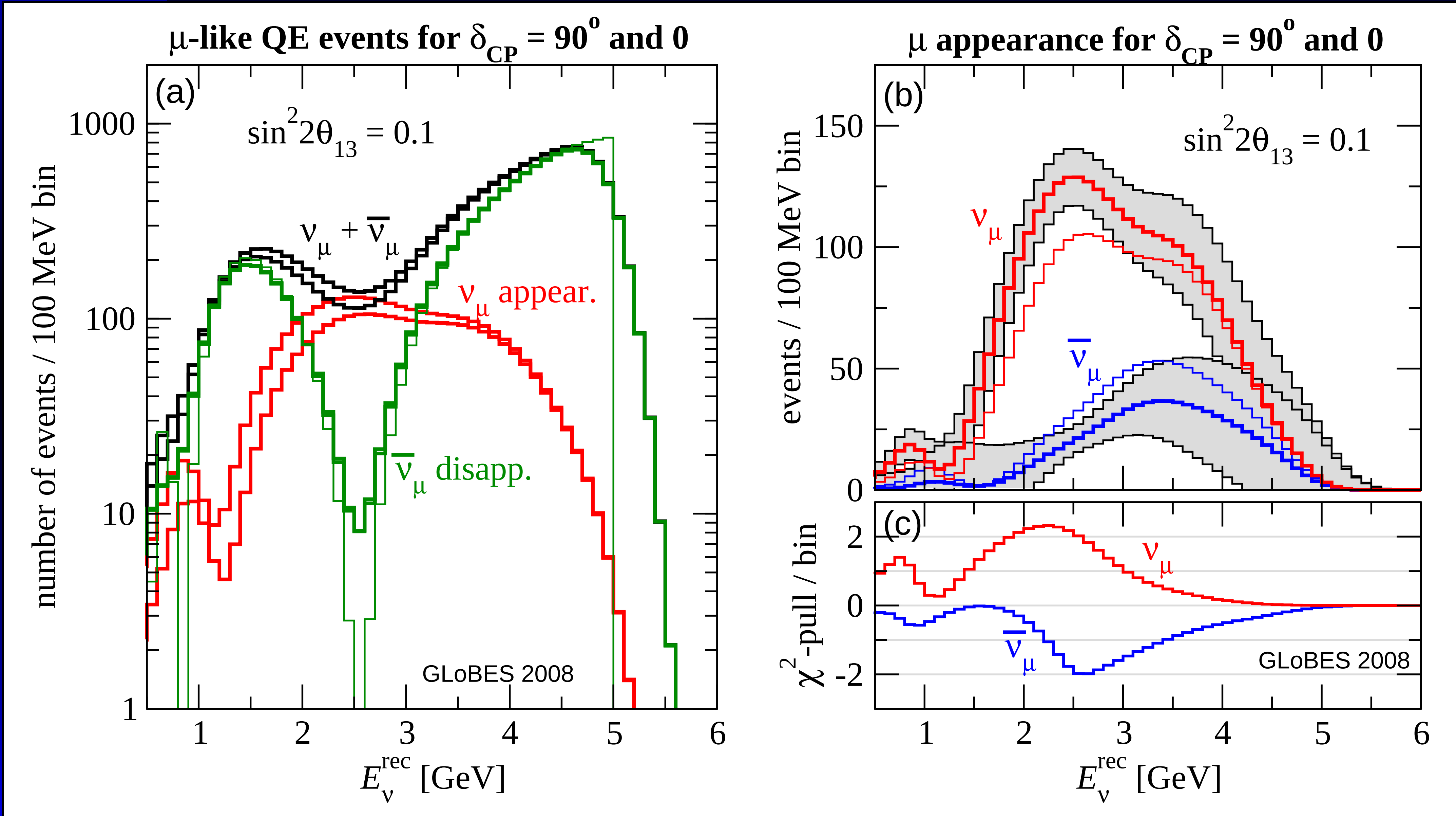
- requires a relatively short muon track
- low energy neutrinos can be used as well
- very good energy resolution
- target mass limited to $\sim 20\,\mathrm{kt}$
- high luminosity, low energy $5\,\mathrm{GeV}$ neutrino source

The MIND paradigm

Using a magnetic field a neutrino factory can achieve the ultimate sensitivities to very small probabilities.

- using MIND – severe constraints on the minimum usable energy
- for both MIND & TASD – relatively small, special purpose detector

Oscillation helps

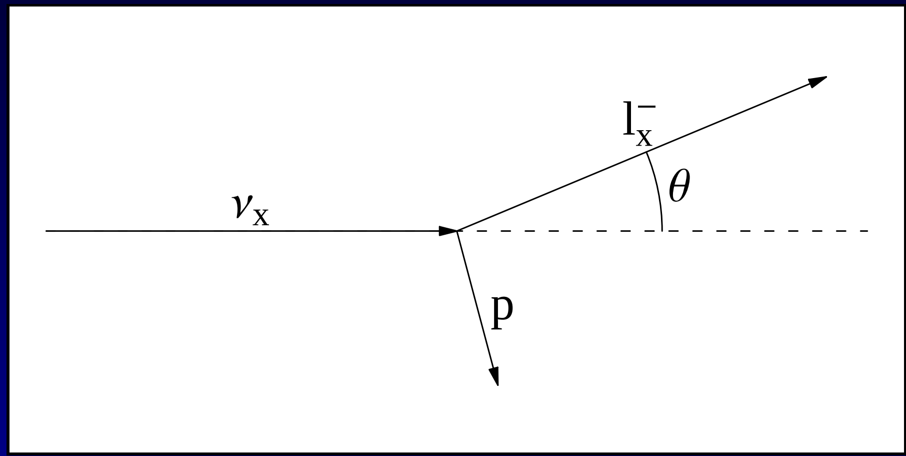


baseline 1290 km and $\Delta E = 0.05\sqrt{E} + 0.085\,\mathrm{GeV}$

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

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

$\nu \neq \bar{\nu}$ – muon lifetime

A μ^- can be caught by the positively charged nuclei in the target and will undergo muon capture.

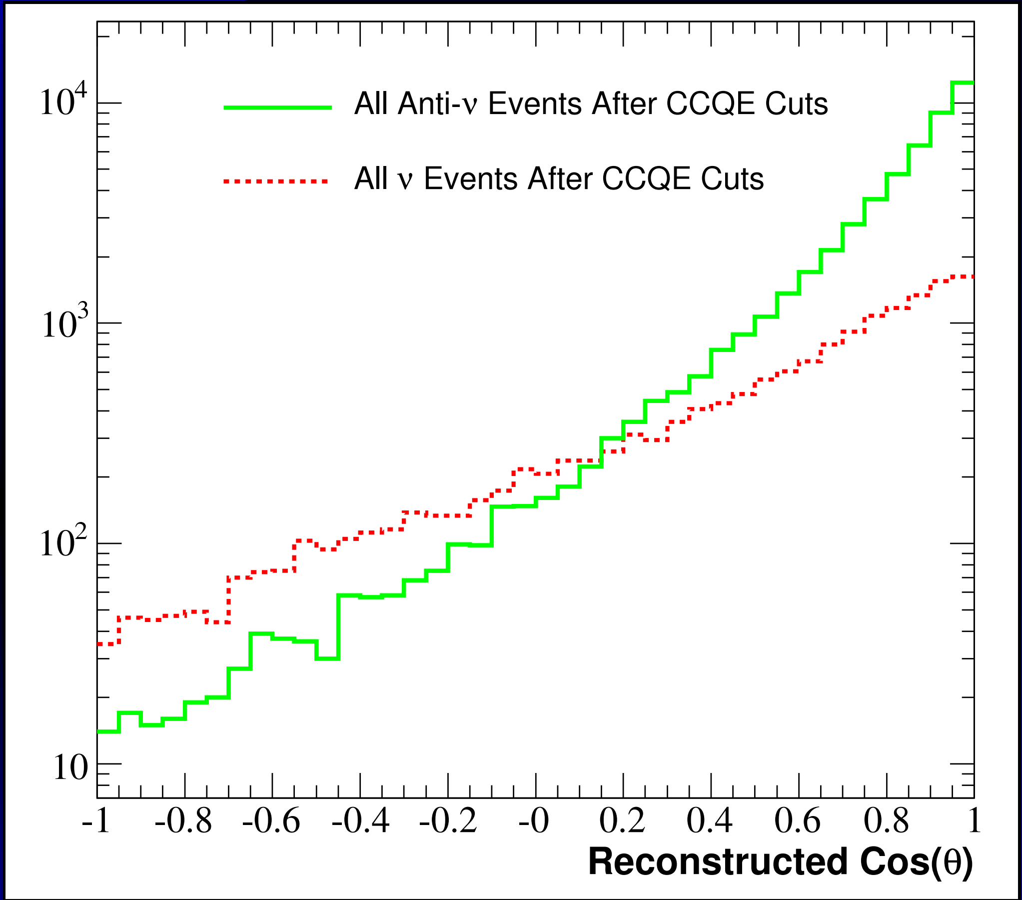
Since this opens and additional channel for muon decay, the resulting life time will be shorter than the one in vacuum.

Moreover, there will be no Michel electron.

	Vacuum	Carbon	Oxygen	Argon
lifetime μs	2.197	2.026	1.795	0.537
capture prob.	-	8%	18%	76%

Has been used by MiniBooNE (neutrinos) and Kamiokande (cosmic ray muons).

$\nu \neq \bar{\nu} - \cos\theta$



from MiniBooNE, hep-ex/0602051.

- $\bar{\nu}$ produce more forward leptons
- effect largest around $1\,\mathrm{GeV}$

Has been used by MiniBooNE.

$\nu \neq \bar{\nu}$ – 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.

$\nu \neq \bar{\nu}$ – parametrization

In absence of the necessary dedicated MC studies, we parametrize $\nu/\bar{\nu}$ separation by assuming that we sort each event into either the $\bar{\nu}$-like sample N_1 or the ν-like sample N_2.

$$
\begin{aligned}
N_1^i &= \frac{1-p}{2} N_\nu^i + \frac{1+p}{2} N_{\bar{\nu}}^i \\
N_2^i &= \frac{1+p}{2} N_\nu^i + \frac{1-p}{2} N_{\bar{\nu}}^i
\end{aligned}
$$

The efficiency is given by $(1+p)/2$ and the contamination with the other type by $(1-p)/2$, with $p=0$ corresponding to no separation at all and $p=1$ is perfect separation.

The beam

- 5GeV neutrino factory
- 10^{21} useful decays per year
- 5 years μ^-
- 5 years μ^+
- baseline 1290km

Note: this luminosity requires 4MW for 10^7s per year, which is about the same than FNAL's Project X which would deliver 2.3MW for $1.7 \cdot 10^7$s a year.

Detector parametrization

	TASD	WC	LAr
fiducial mass [kt]	20	500	100
efficiency	0.73	0.9[a]	0.8
magnetized	yes	no	no
ΔE at $2.5\,\mathrm{GeV}$ [MeV]	165	300[b]	165
p for muons	0.999	$0-0.7$	$0.7-0.9$
p for electrons	0	0	$0.7-0.9$

[a] on top of the single ring selection efficiency and an efficiency of 82% for ν_μ events

[b] equivalent Gaußian width

A word about backgrounds

The statistical error in a bin i of sample N_2 is given by

$$\sigma^2_{\text{stat}} = \frac{1+p}{2} N^i_\nu + \frac{1-p}{2} N^i_{\bar\nu} + \frac{B_i}{2}$$

In the limit of vanishing signal, this error is determined by the background of 'right sign' events plus any other background B_i

$$\sigma^2_{\text{stat}} \overset{N^i_\nu \to 0}{=} \frac{1-p}{2} N^i_{\bar\nu} + \frac{B_i}{2}$$

Thus the permissible background B_i will depend on $1-p$.

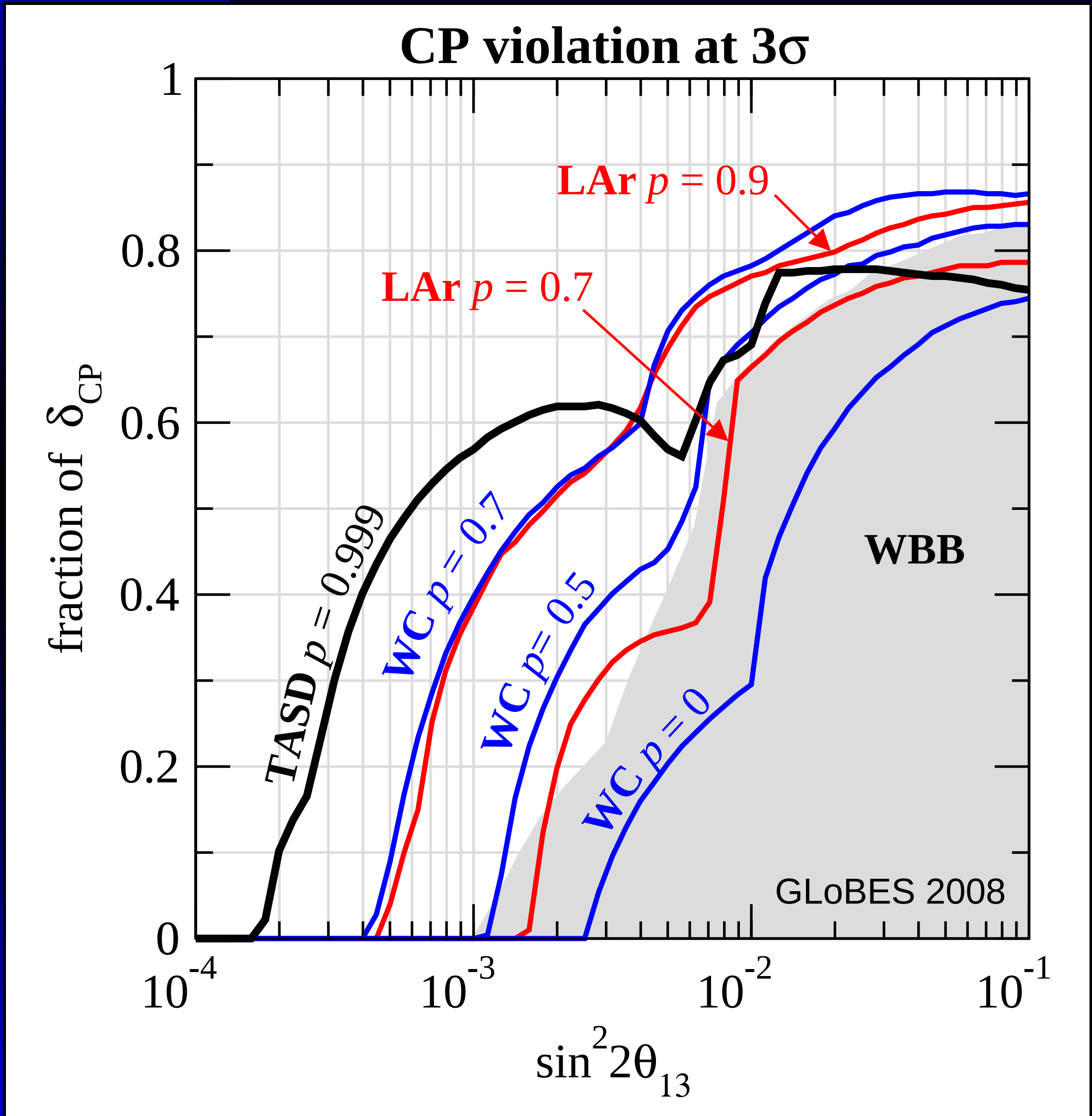
A word about backgrounds

The worst case is when events from the peak of the right sign event distribution migrate into its minimum. We call the ratio between the events in the minimum to the events in the maximum r. Depending on the energy resolution we have $r = 1/100 - 1/10$.
Thus whenever

$$f = B_i/N_\nu \lesssim r(1-p)$$

we safely can neglect B_i. Thus we obtain $f \lesssim 0.001$ for LAr and $f \lesssim 0.03$ for WC, which seems to be fulfilled in both cases.
Note: Muons from ν_τ events also do not play a role for a 5GeV NF.

CP sensitivity



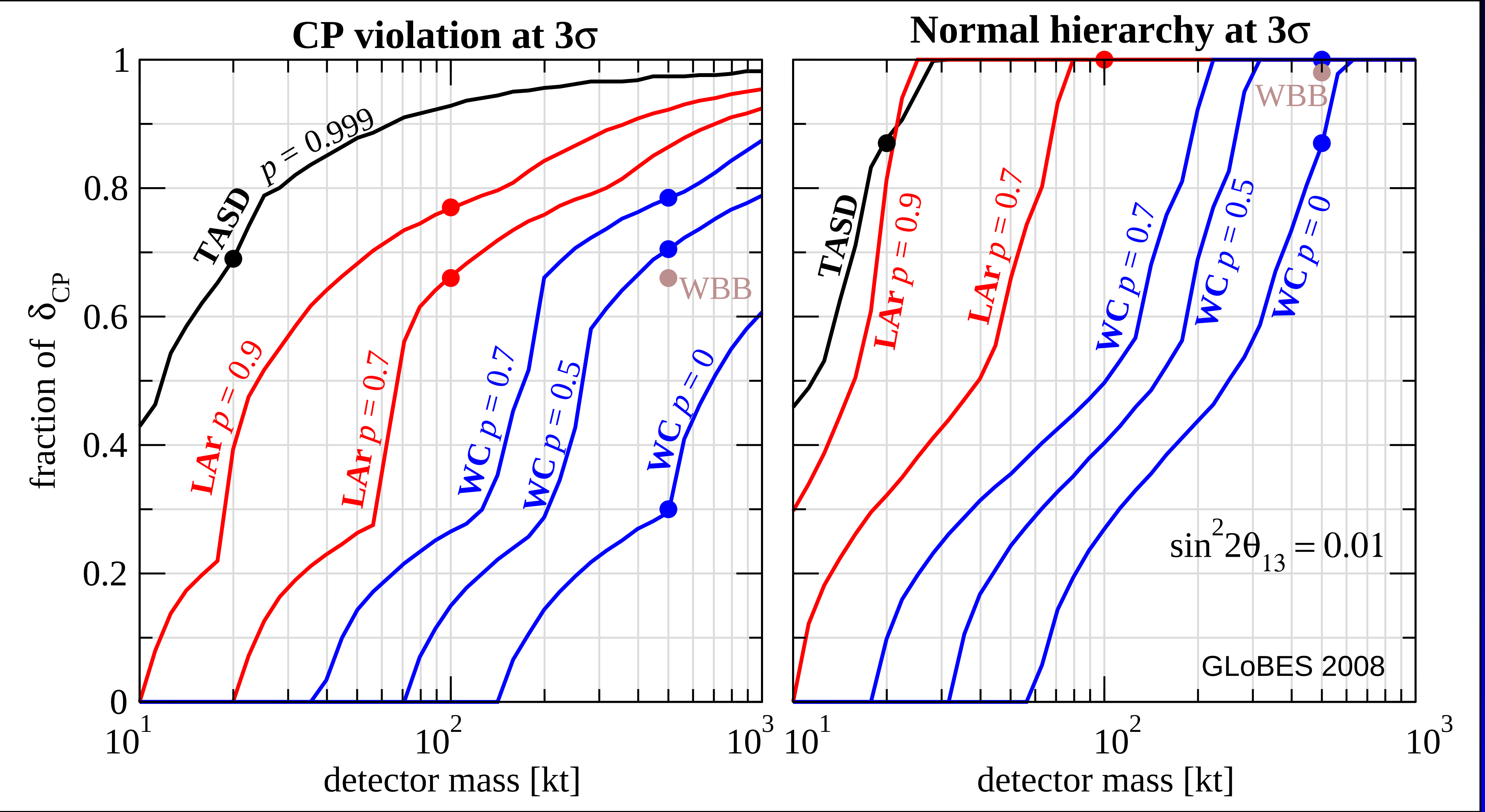
$\sin^2 2\theta_{13} > 0.03$
WBB better than NF with TASD

$\sin^2 2\theta_{13} > 0.004$
WC and LAr with some $\nu/\bar{\nu}$ separation equivalent or better than TASD

$\sin^2 2\theta_{13} < 0.004$
TASD is the best solution

WBB – 120 GeV proton beam from FNAL to DUSEL at 0.5mrad

Size matters – detector mass



Outlook

- 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

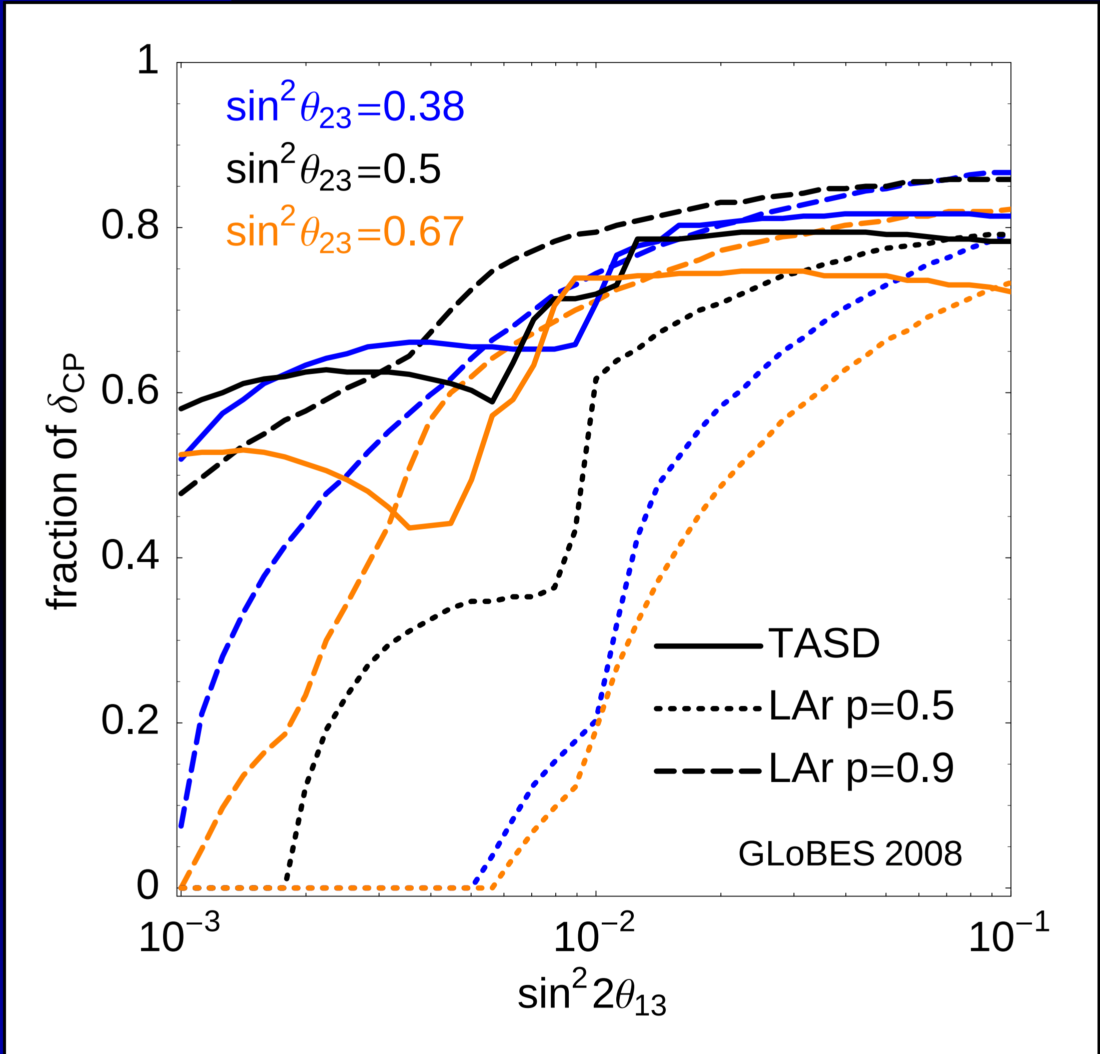
CAVEAT EMPTOR: all of this requires detailed simulations and a precise understanding of nuclear effects.

A neutrino factory may be mindless –

but still can be reasonable.

Backup Slides

Non-maximal θ_{23}



Variation of the true θ_{23} within its current 3σ range.

Small θ_{13}