NNN08

Neutrino factory with a non-magnetic detector

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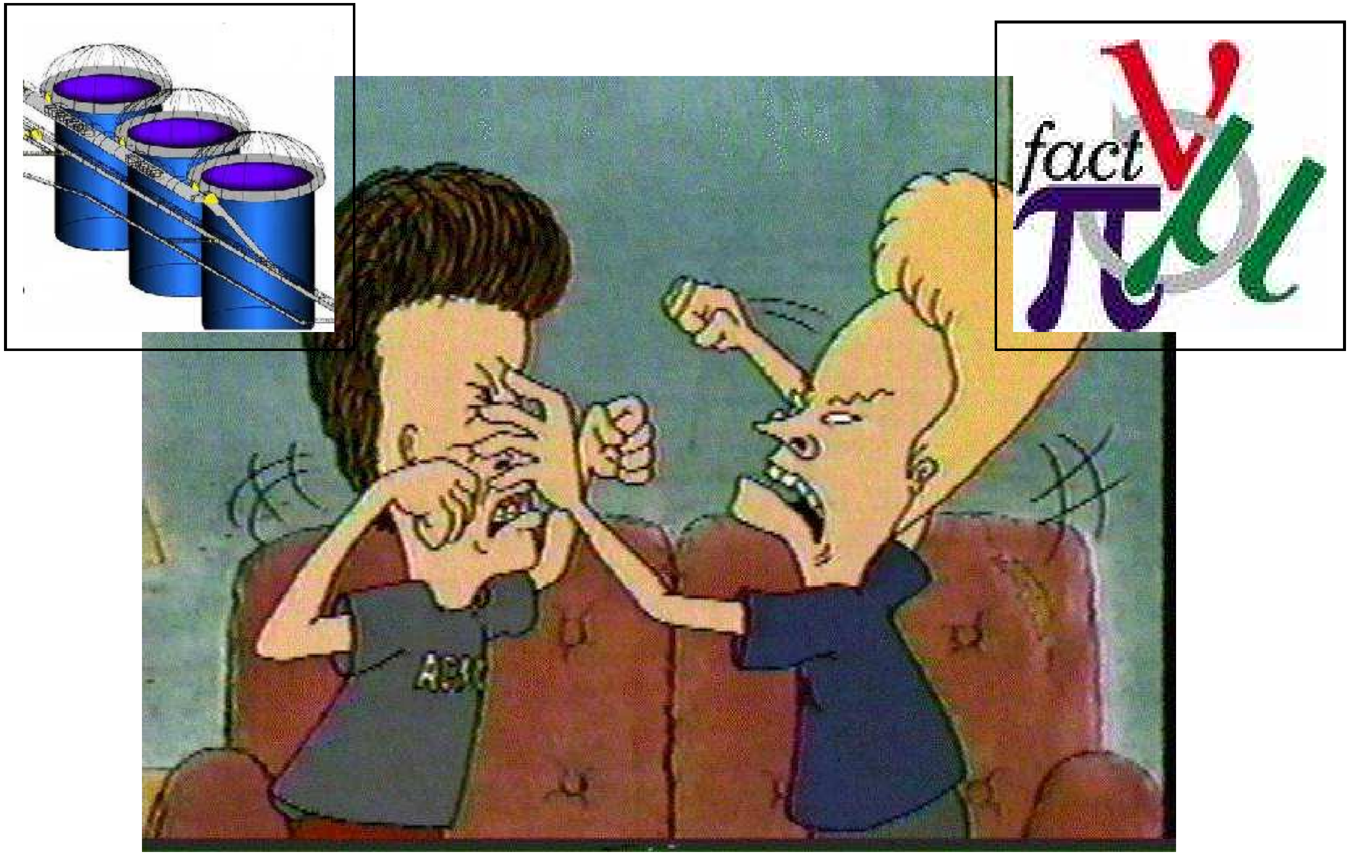
based on P. Huber and TS, arXiv:0805.2019

Outline

- Introduction:
  Why NNN and Neutrino Factory do not like each other



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- I’ll try to convince you that this is not justified:
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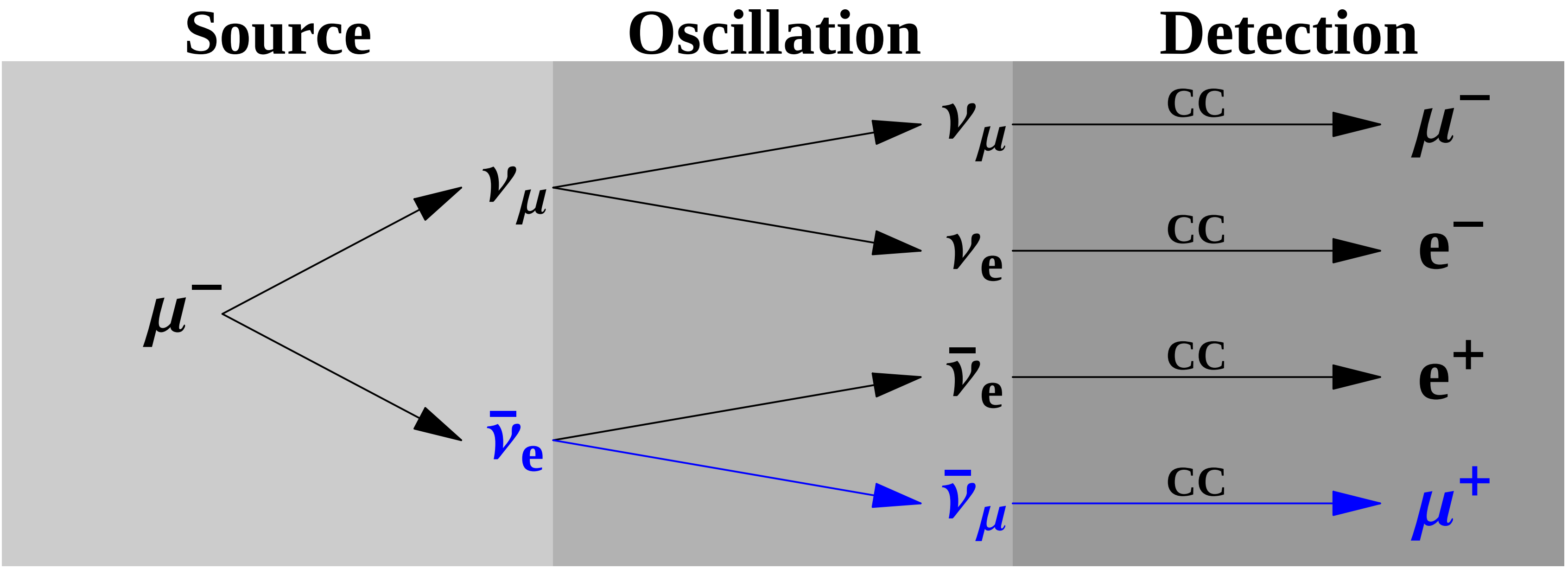
- I’ll try to convince you that this is not justified:
  they should speak to each other...
- What are the requirements that a non-magnetic (but huge) detector can be useful also for a Neutrino Factory beam

The signal from a neutrino factory



Need to distinguish wrong-sign from right-sign muon events in the detector in order to separate

the appearance signal $\bar{\nu}_e \to \bar{\nu}_\mu$ from

the disappearance signal $\nu_\mu \to \nu_\mu$

The common solution is...

use a magnetic field (~ 1 T) to identify the charge of the muon with an efficiency of $\lesssim 10^{-4}$ $\Rightarrow$

- “standard” NuFact: MIND (Magnetized Iron Neutrino Det.)

  required length of muon track puts constraint on neutrino energy threshold, energy resolution is poor, ~ 50 kt

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  lower energy neutrinos, good energy resolution, air core magnet (superconducting LHC type magnet), ~ 20 kt

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compared to the NNN scale these are relatively “small” special purpose detectors

Can we learn something by using a Neutrino Factory beam on a Mt scale non-magnetized detector?

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YES!

- oscillation itself helps to suppress the right-sign muons
- there are other means to distinguish neutrino from anti-neutrino events (at least statistically)

Oscillation helps

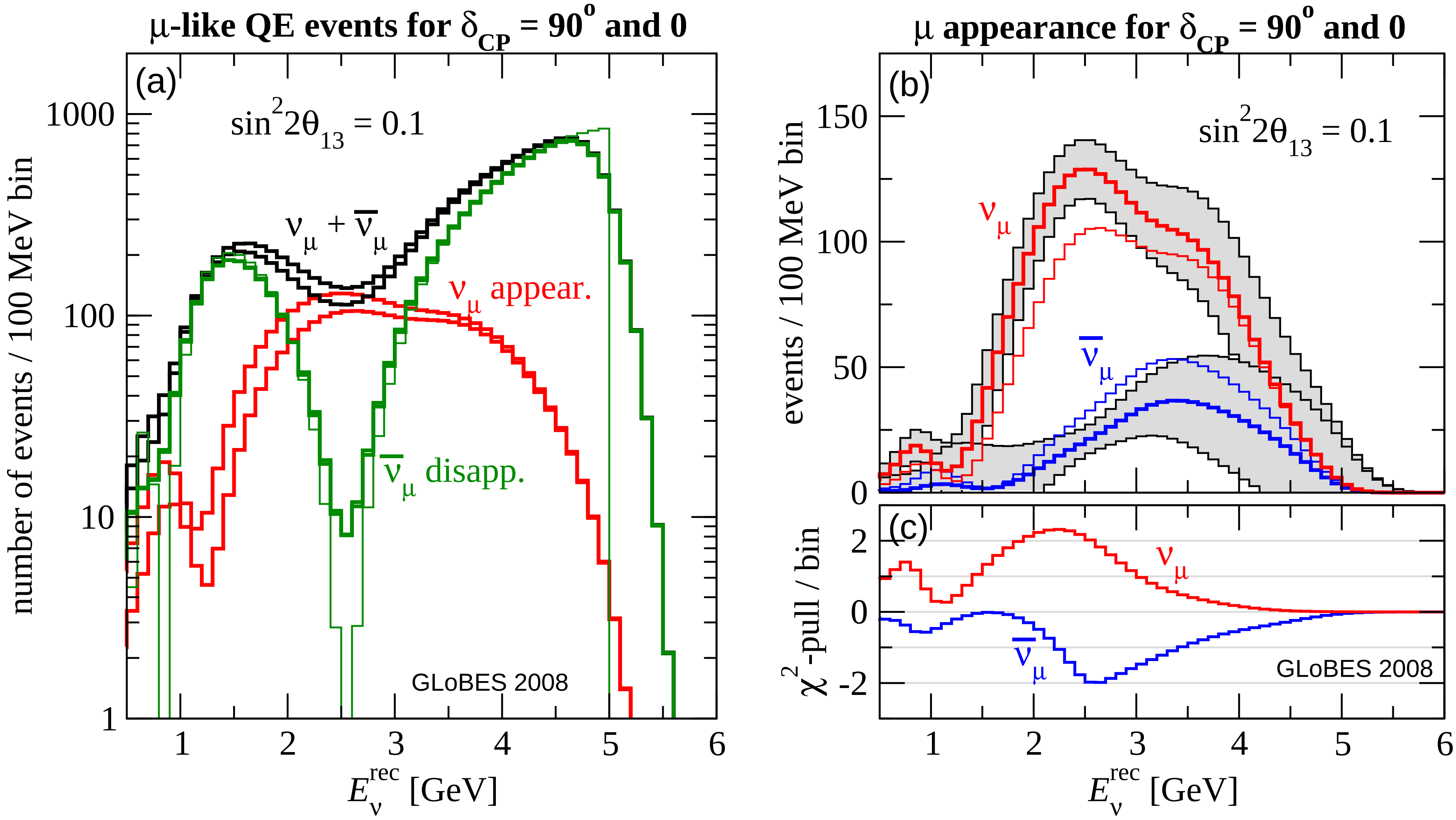
$$P_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2 \Delta + \mathcal{O}(\Delta m^2_{21}, \theta_{13})$$

$$\begin{aligned} P_{e\mu} &\approx 4 s^2_{13} s^2_{23} \sin^2 \Delta + c^2_{23} \tilde{\alpha}^2 \\ &\quad + 2 \tilde{\alpha} s_{13} \sin 2\theta_{23} \sin \Delta \cos(\Delta \mp \delta) \end{aligned}$$

here $\Delta \equiv \Delta m^2_{31} L/(4E)$, $\tilde{\alpha} \equiv \sin 2\theta_{12}\, \Delta m^2_{21} L/(4E)$

at the first oscillation maximum $\Delta = \pi/2$, $P_{\mu\mu}$ (right-sign) goes to zero for $\sin^2 2\theta_{23} = 1$, whereas $P_{e\mu}$ (wrong-sign) peaks

Oscillation helps



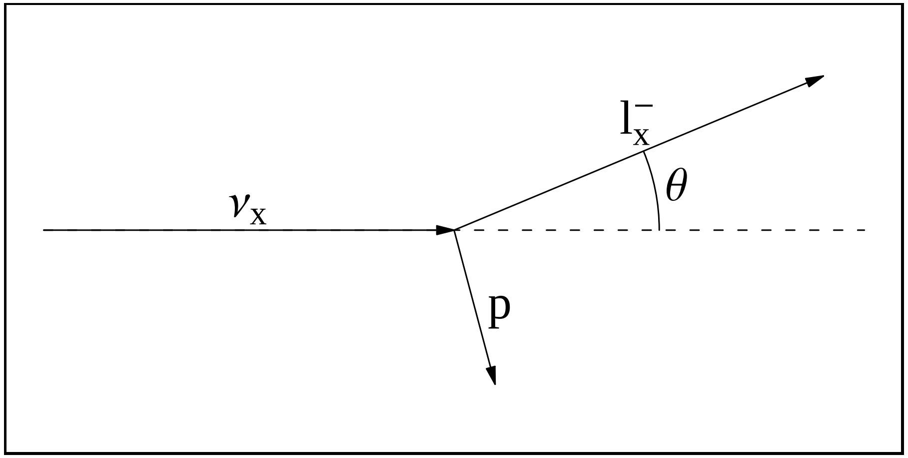
5 GeV NuFact, 100 kt LAr @ 1290 km,

$$\Delta E = 0.05\sqrt{E} + 0.085\,\mathrm{GeV}$$

$\nu/\bar{\nu}$ separation without magn. field

QE reactions

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



There are (at least) 3 differences between ν and $\bar{\nu}$ events:

- muon lifetime due to μ^- capture
- $\cos\theta$ distribution
- 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.

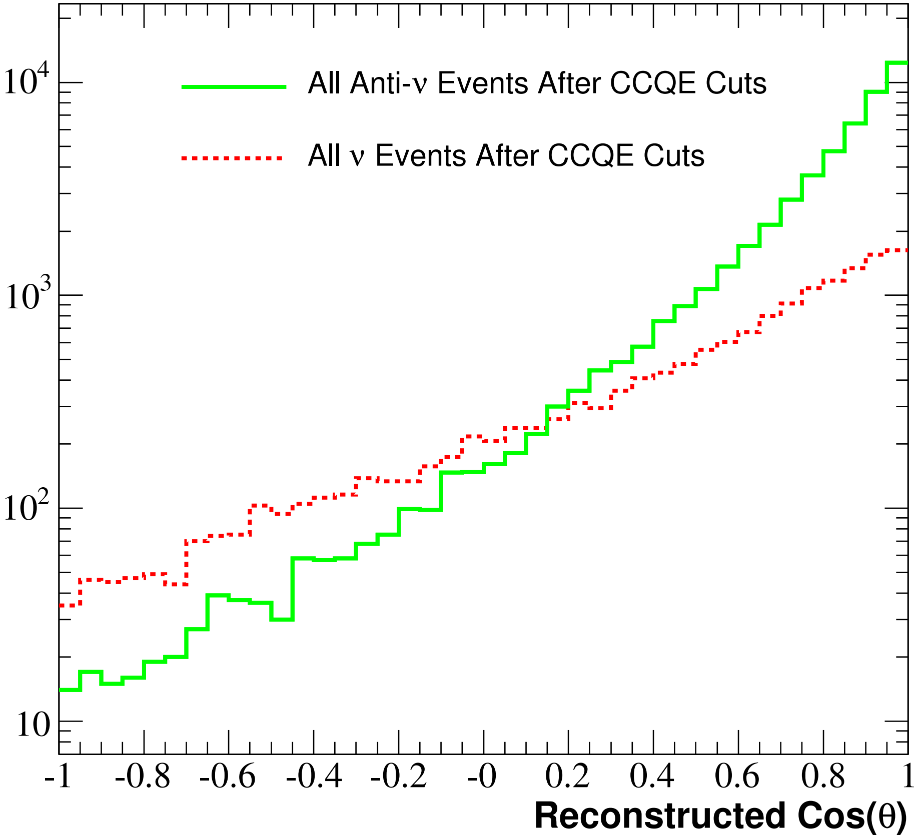
Since this opens and additional channel for muon decay, the resulting life time will be shorter than the one in vacuum.

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).

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



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 either the proton or the neutron, ideally both.

There are two sources of mis-ID:

- the tag is not 100% efficient
- the event produced the wrong nucleon because
  - there were more than 1 nucleon
  - 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: Cerenkov threshold $p_p \gtrsim 1.07$ GeV

talk by M. Fechner: “neutrino sample” with $\nu/\bar{\nu} \sim 9$

Neutron tagging 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.

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

Sensitivity calculations

Parametrization of statistical $\nu/\bar\nu$ separation

In absence of dedicated MC studies we parametrize $\nu/\bar\nu$ separation by assuming that we sort each event into either a $\bar\nu$-like sample N_1 or a 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 $(1-p)/2$

$p = 0$: no separation at all, $p = 1$: perfect separation.

The Neutrino Factory beam

- 5 GeV muons (low-energy 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.

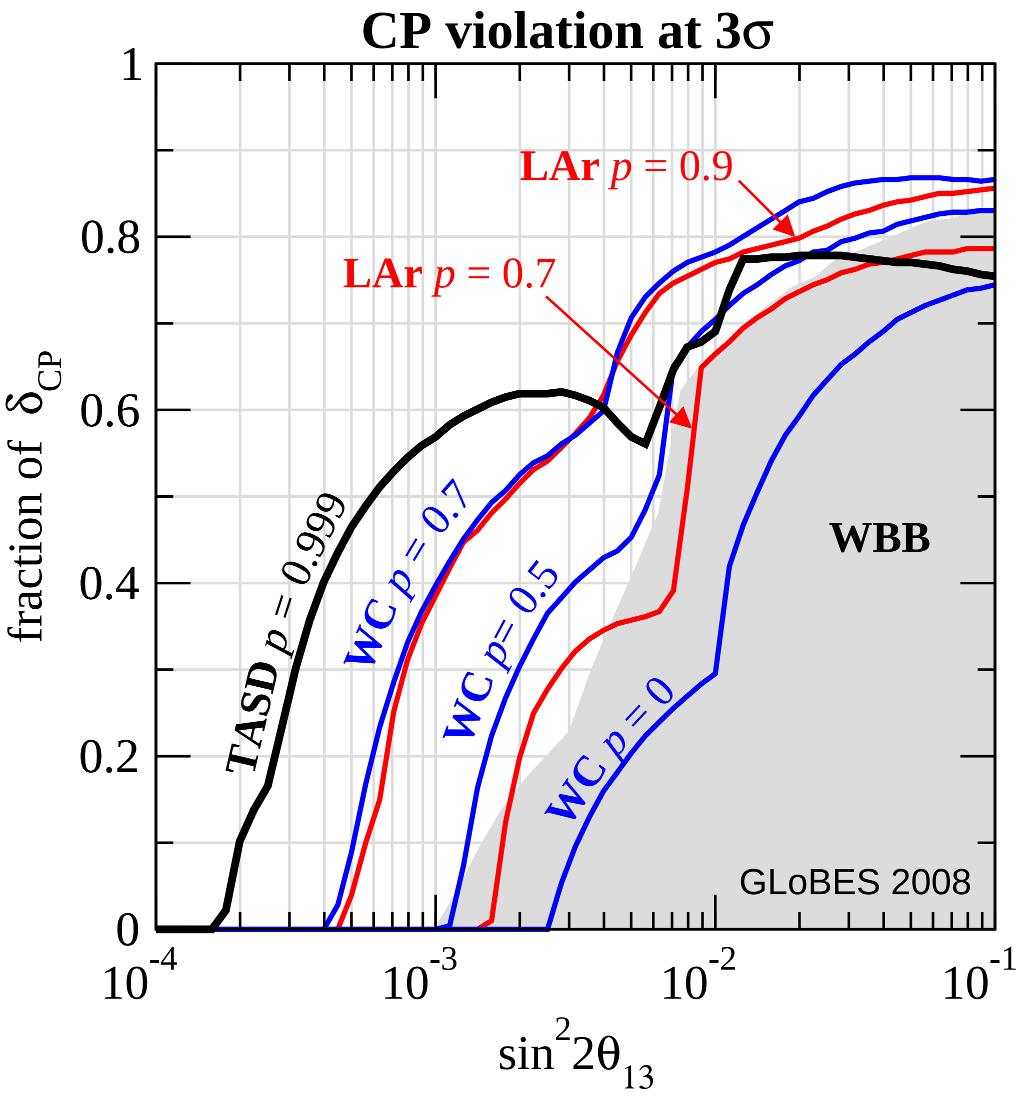
Detector parameterization

	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

CP sensitivity



WBB: 120 GeV proton beam from FNAL to WC@DUSEL

$\sin^2 2\theta_{13} > 0.03$

WBB better than NF with TASD

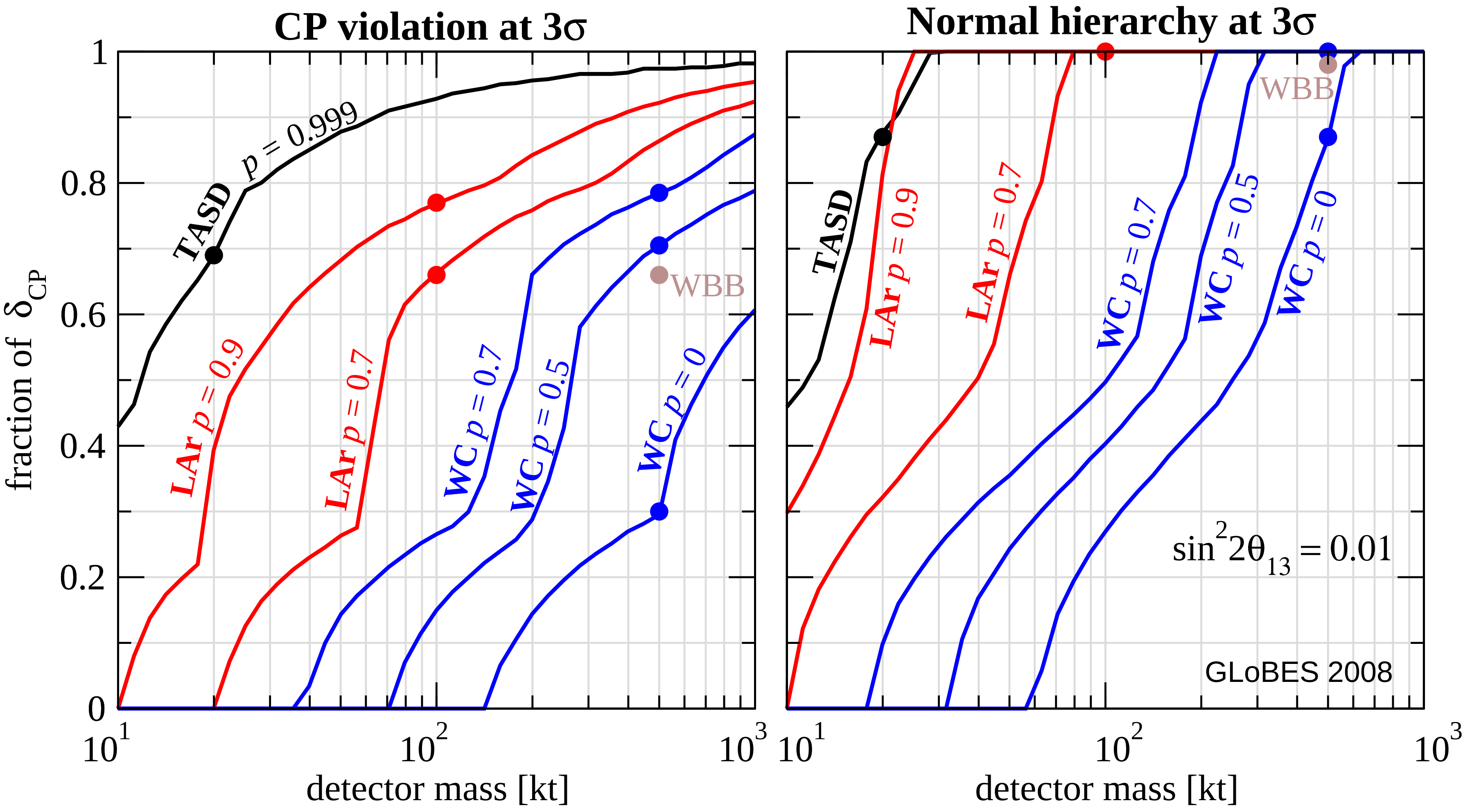
$\sin^2 2\theta_{13} > 0.004$

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

Size matters!



Concluding remarks

Summary

A large non-magnetized detector IS interesting also in the context of a (low-energy) Neutrino Factory

- Oscillation provides a right sign muon suppression of $1:10$ down to $1:100$, depending on energy resolution
- Statistical $\nu/\bar{\nu}$ separation:
  muon lifetime, $\cos\theta$ distribution, nucleon tagging
- separation efficiencies and purities of 50%-90% allow to use NNN detectors for $\sin^2 2\theta_{13} \gtrsim 0.004$

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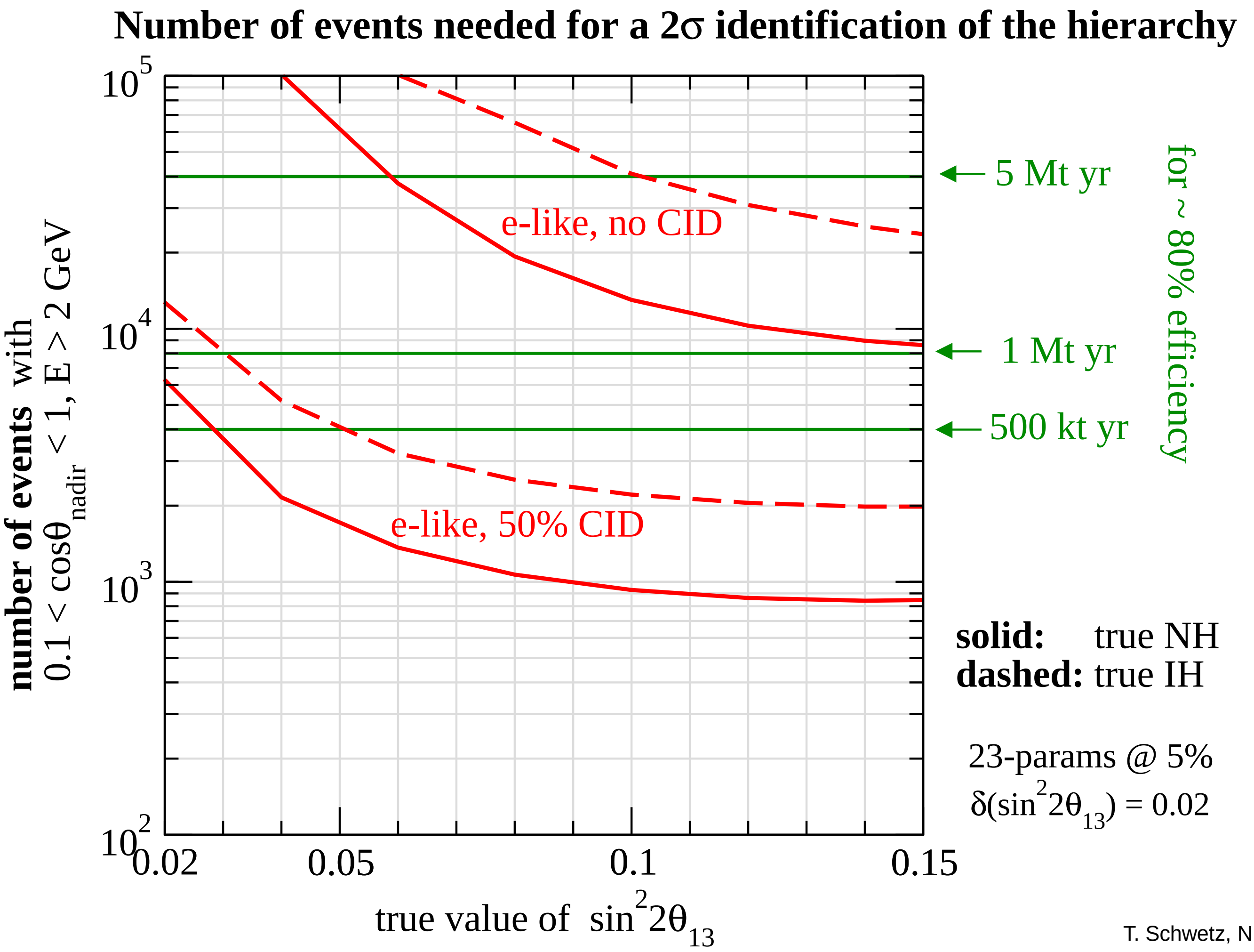
All of this requires detailed simulations and a precise understanding of nuclear effects, detector effects...!

Final comment

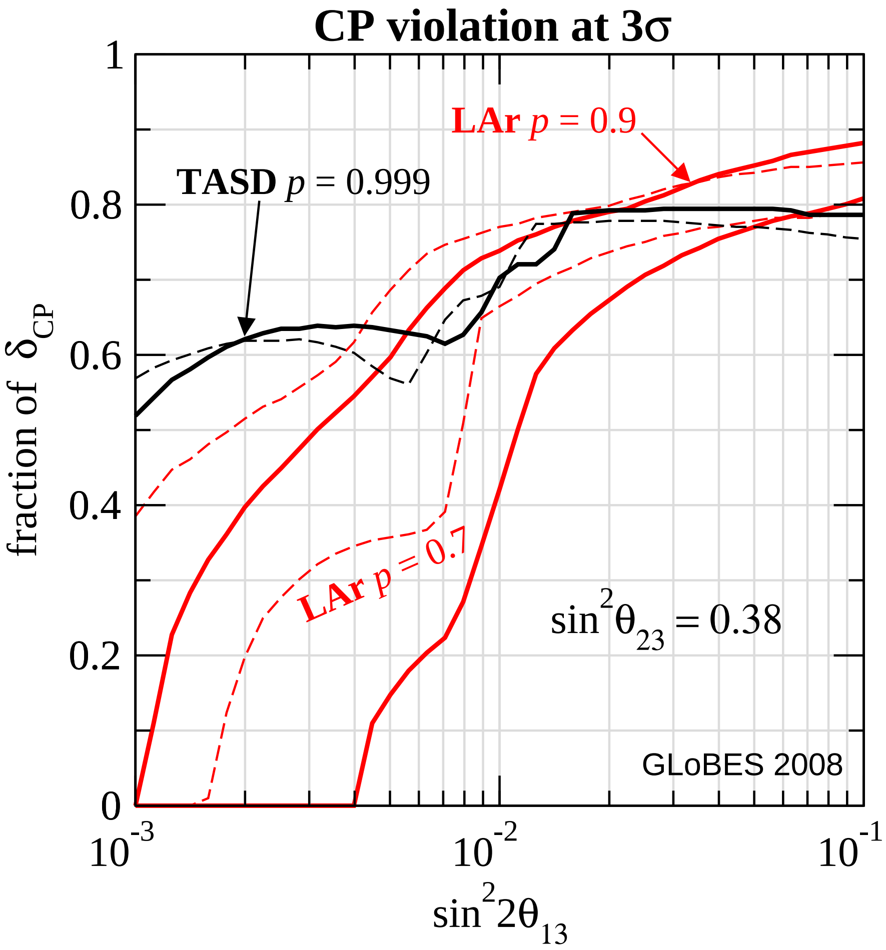
Statistical $\nu/\bar{\nu}$ separation is very useful also for atmospheric neutrinos:

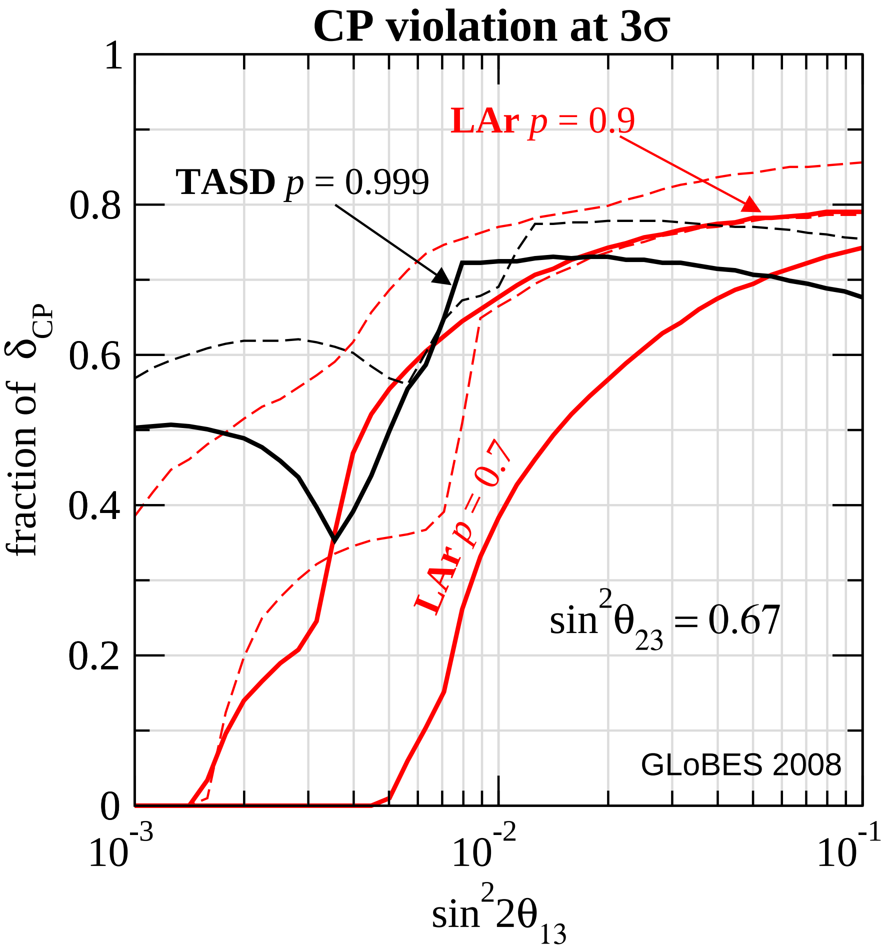


Thank you for your attention!

Backup Slides

Non-maximal θ_{23}





Small θ_{13}