Thoughts about systematics

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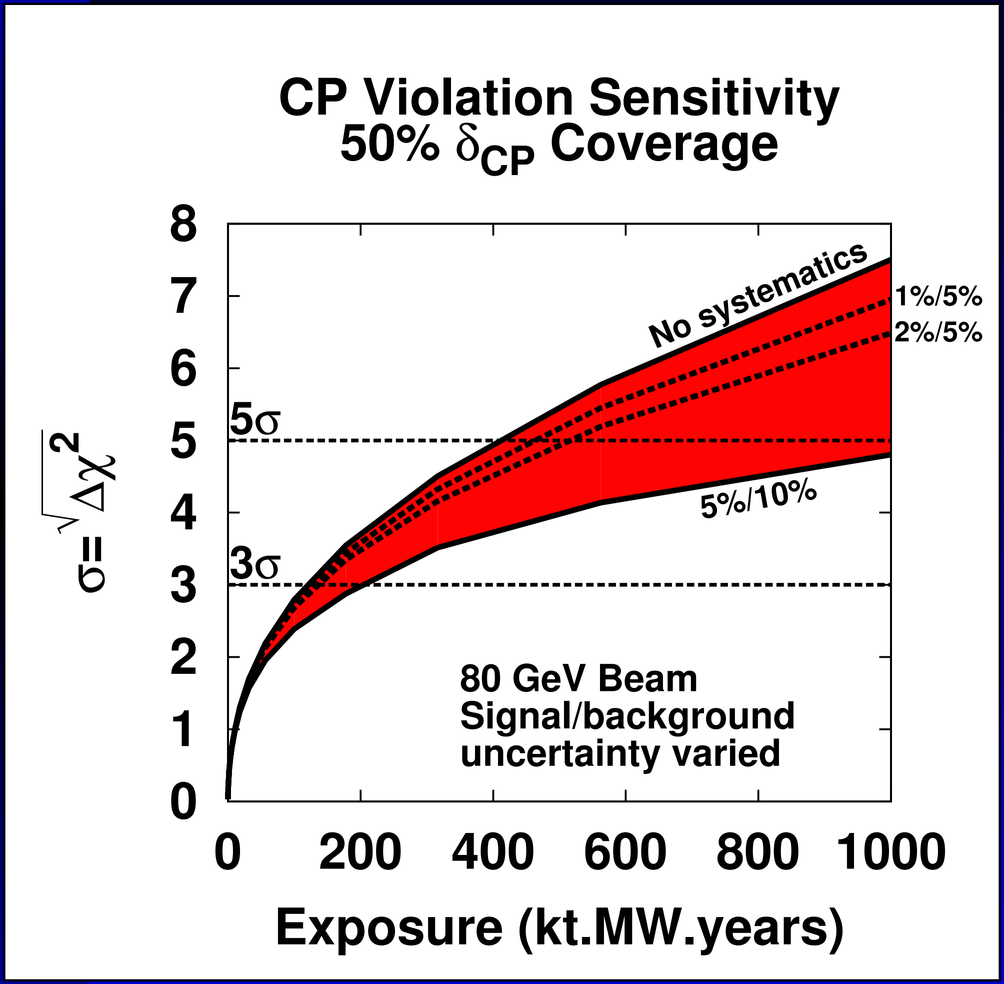
Physics of CPV

$$\frac{P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}{P(\nu_\alpha \to \nu_\beta) + P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)} \propto \frac{1}{\sin 2\theta_{13}}$$

- 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 $P(\bar{\nu}_e \to \bar{\nu}_\mu)$
- need more than 1 energy and/or 1 baseline
- large θ_{13} implies small CP asymmetries
  $\Rightarrow$ need for small systematics

Ultimately, the combination of large exposure $\gg 100\,\mathrm{kt\,MW\,yr}$ with percent-level systematics will be needed.

Luminosity scaling



arXiv:1307.7335

Extrapolating super-beam performances beyond several 100 kt MW years is entirely dependent on the assumptions on systematics!

Maximum useful exposure depends strongly on systematics

The Reality

We do not measure probabilities, but event rates!

$$R^\alpha_\beta = N \int dE \, \Phi_\alpha(E) \, \sigma_\beta(E) \, \epsilon_\beta(E) \, P(\nu_\alpha \to \nu_\beta, E)$$

In order the reconstruct P, we have to know

- N – overall normalization (fiducial mass)
- Φ_α – flux of ν_α
- σ_β – x-section for ν_β
- ϵ_β – detection efficiency for ν_β

Note: $\sigma_\beta \epsilon_\beta$ always appears in that combination, hence we can define an effective cross section $\tilde{\sigma}_\beta := \sigma_\beta \epsilon_\beta$

The Problem

Even if we ignore all energy dependencies of efficiencies, x-sections *etc.*, we generally can not expect to know any ϕ or any $\tilde{\sigma}$. Also, we won't know any kind of ratio

$$\frac{\Phi_\alpha}{\Phi_{\bar{\alpha}}} \quad \text{or} \quad \frac{\Phi_\alpha}{\Phi_\beta}$$

nor

$$\frac{\tilde{\sigma}_\alpha}{\tilde{\sigma}_{\bar{\alpha}}} \quad \text{or} \quad \frac{\tilde{\sigma}_\alpha}{\tilde{\sigma}_\beta}$$

Note: Even if we may be able to know σ_e/σ_μ from theory, we won't know the corresponding ratio of efficiencies ϵ_e/ϵ_μ

The Solution

Measure the un-oscillated event rate at a near location and everything is fine, since all uncertainties will cancel, (provided the detectors are identical and have the same acceptance)

$$\frac{R^\alpha_\alpha(\mathrm{far})L^2}{R^\alpha_\alpha(\mathrm{near})} = \frac{N_{\mathrm{far}}\Phi_\alpha\,\tilde{\sigma}_\alpha\,P(\nu_\alpha \to \nu_\alpha)}{N_{\mathrm{near}}\Phi_\alpha\,\tilde{\sigma}_\alpha 1}$$

$$\frac{R^\alpha_\alpha(\mathrm{far})L^2}{R^\alpha_\alpha(\mathrm{near})} = \frac{N_{\mathrm{far}}}{N_{\mathrm{near}}}P(\nu_\alpha \to \nu_\alpha)$$

And the error on $\frac{N_{\mathrm{far}}}{N_{\mathrm{near}}}$ will cancel in the ν to $\bar{\nu}$ comparison.

But . . .

This all works only for disappearance measurements!

$$\frac{R_\beta^\alpha(\mathrm{far})L^2}{R_\beta^\alpha(\mathrm{near})} = \frac{N_{\mathrm{far}}\Phi_\alpha\,\tilde\sigma_\beta\,P(\nu_\alpha\to\nu_\beta)}{N_{\mathrm{near}}\Phi_\alpha\,\tilde\sigma_\alpha\,1}$$

$$\frac{R_\beta^\alpha(\mathrm{far})L^2}{R_\beta^\alpha(\mathrm{near})} = \frac{N_{\mathrm{far}}\,\tilde\sigma_\beta\,P(\nu_\alpha\to\nu_\beta)}{N_{\mathrm{near}}\,\tilde\sigma_\alpha\,1}$$

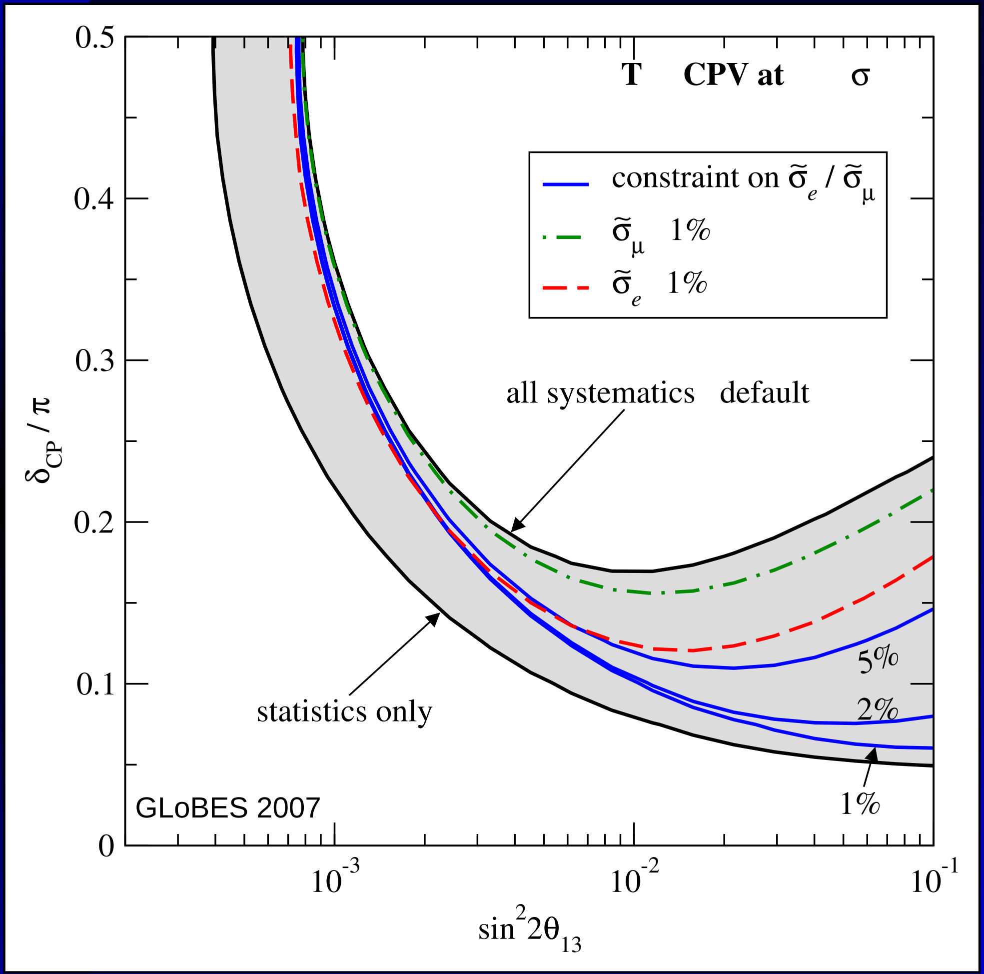
Since $\tilde\sigma$ will be different for ν and $\bar\nu$, this is a serious problem. And we can not measure $\tilde\sigma_\beta$ in a beam of ν_α.

Some practical issues

- same acceptance may require a not-so-near near detector
- near and far detector cannot be really identical
- some energy dependencies will remain

In principle all those factors can be controlled by careful design and analysis with good accuracy, see *e.g.* T2K see talk by A. Kaboth

ν_e/ν_μ x-sections

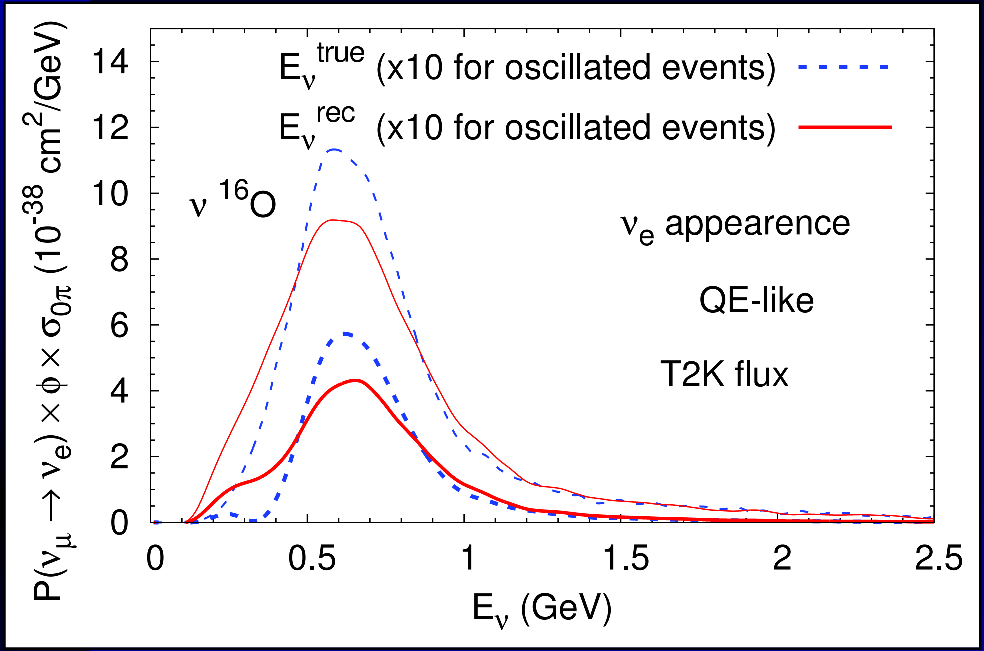


PH, M. Mezzetto, T. Schwetz
arXiv:0711.2950

Appearance experiments using a (nearly) flavor pure beam can not rely on a near detector to predict the signal at the far site!

Large θ_{13} most difficult region.

QE energy reconstruction



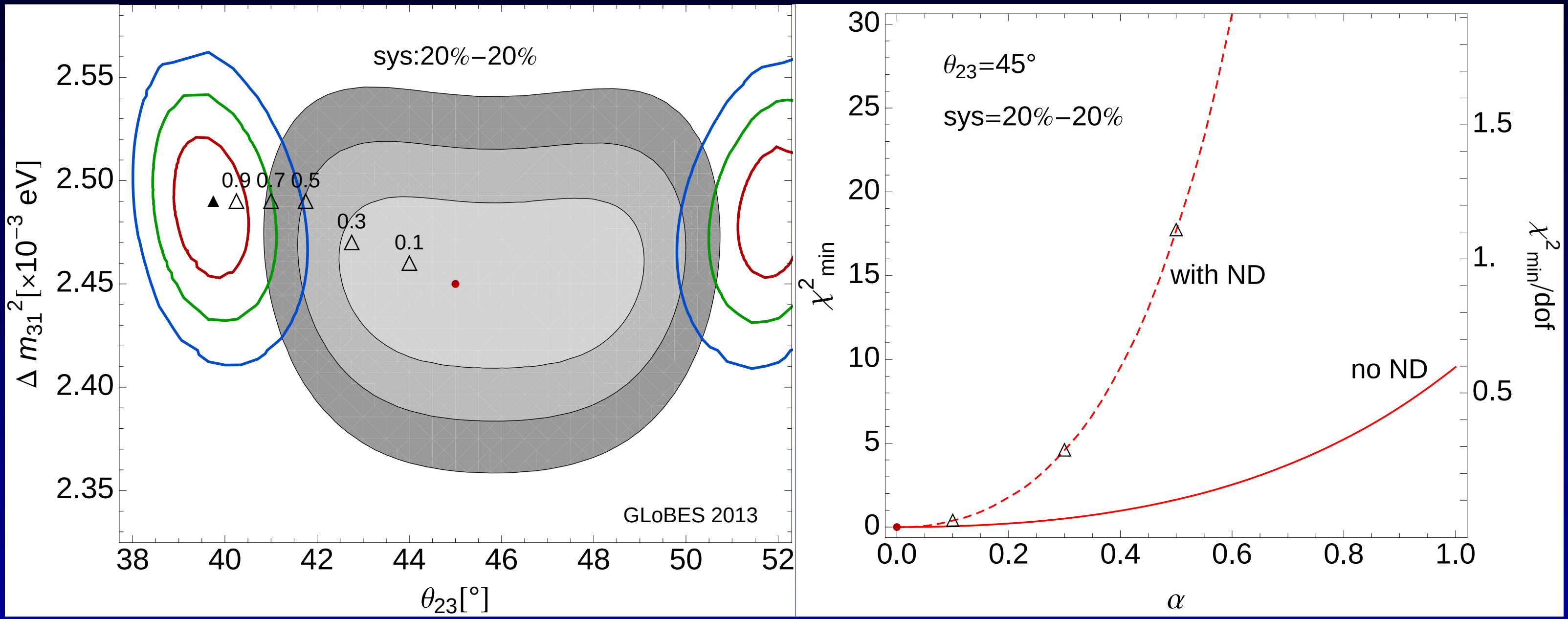
Lalakulich, Mosel, arXiv:1208.3678.

Nuclear effects change the relation between true neutrino energy and lepton energy

Inferring the CP phase from QE spectrum seems quite difficult

Not obvious that near detectors alone can solve this problem.

Nuclear effects



arXiv:1307.1243

$$N_i^{\text{test}}(\alpha) = \alpha \times N_i^{QE} + (1-\alpha) \times N_i^{QE-like}$$

where $\alpha = 0$ corresponds to perfectly known nuclear effects and $\alpha = 1$ to entirely unknown nuclear effects in the fit.

From here to there...

TABLE XVI: Summary of the contributions to the total uncertainty on the predicted number of events, assuming $\sin^2 2\theta_{13}$=0 and $\sin^2 2\theta_{13}$=0.1, separated by sources of systematic uncertainty. Each error is given in units of percent.

Error source	$\sin^2 2\theta_{13}=$ 0	0.1
Beam flux & ν int. (ND280 meas.)	8.5	5.0
ν int. (from other exp.)		
$x_{CCother}$	0.2	0.1
x_{SF}	3.3	5.7
p_F	0.3	0.0
x^{CCcoh}	0.2	0.2
x^{NCcoh}	2.0	0.6
$x^{NCother}$	2.6	0.8
x_{ν_e/ν_μ}	1.8	2.6
$W_{\rm eff}$	1.9	0.8
$x_{\pi-less}$	0.5	3.2
$x_{1\pi E_\nu}$	2.4	2.0
Final state interactions	2.9	2.3
Far detector	6.8	3.0
Total	13.0	9.9

State of the art is T2K: 10% signal systematics, where 7.5% are from interaction physics

We will need 1% to fully exploit our experimental opportunities

What role do phenomenological studies play?

Relation to event generators and nuclear models?

Personal remark

Many experiments, like T2K, have done a fine job with their systematics and developed a large number of tools.

These tools would be very useful to the rest of the community, especially for the purpose of planing future experiments.

We, as a community, would be well advised to share all relevant information and tools freely – instead of reinventing the wheel at every opportunity (see Nuance, GENIE, Neugen, NuWro . . .)