Systematics in Neutrino Oscillation Experiments

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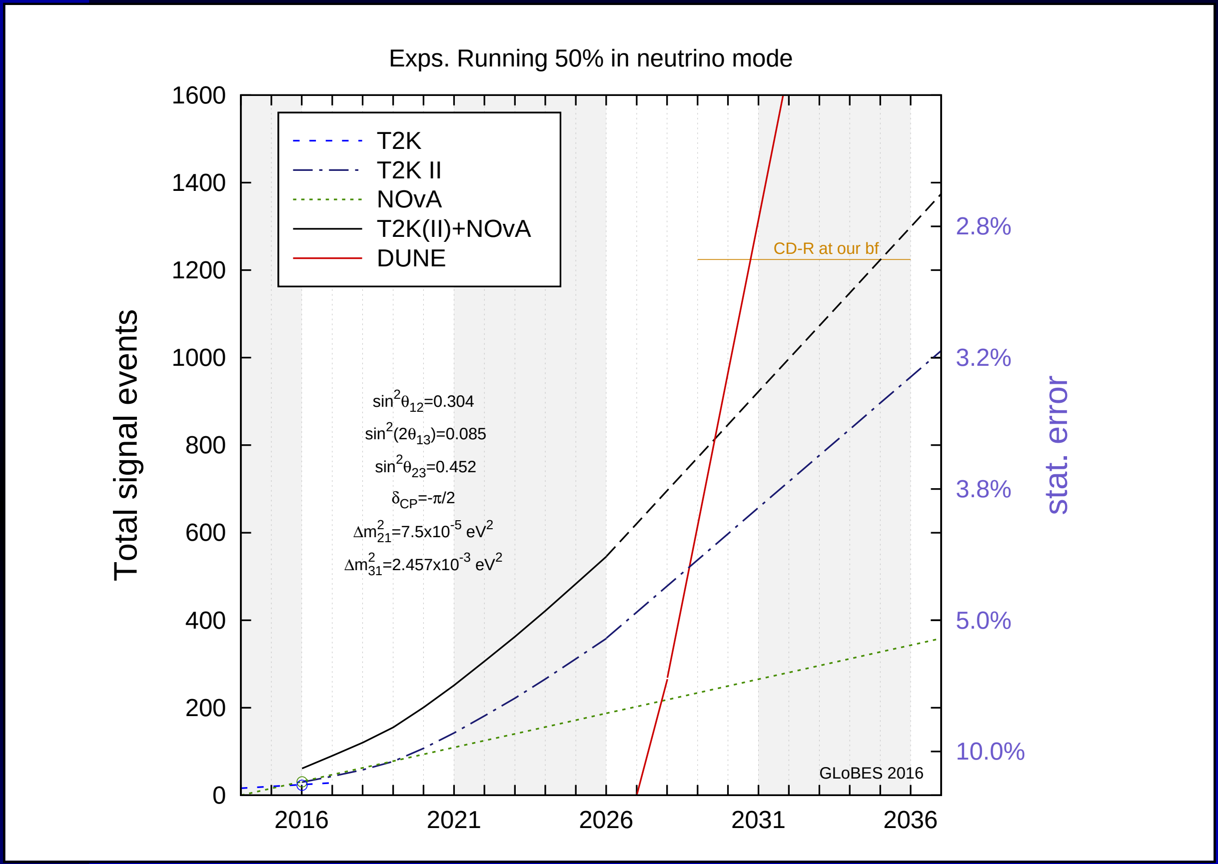
Statistical errors



Clearly, we are on the (slow) road towards 3% measurements of the event rates

Translating this into a 3% measurements of the oscillation probability is very difficult

Note, T2HK would reach 1000 ν_e signal events very quickly.

The Idea

In order to measure CP violation we need to reconstruct one out of these

$$P(\nu_\mu \to \nu_e) \text{ or } P(\nu_e \to \nu_\mu)$$

and one out of these

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \text{ or } P(\bar{\nu}_e \to \bar{\nu}_\mu)$$

and we'd like to do that at the percent level accuracy

The Reality

We do not measure probabilities, but event rates!

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

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)

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

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

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

But . . .

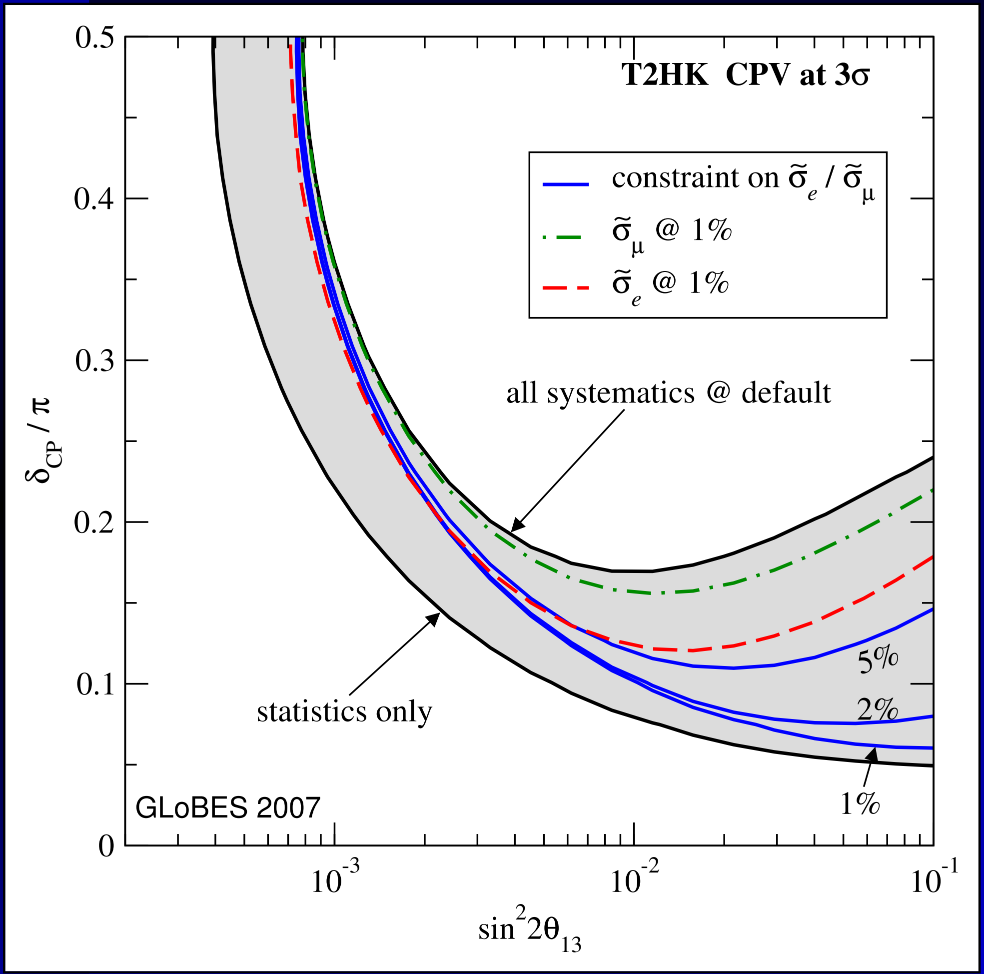
This all works only for disappearance measurements!

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

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

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.

ν_e/ν_μ total x-sections



PH, Mezzetto, Schwetz, 2007

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.

Differences between ν_e and ν_μ are significant below 1 GeV, see K. McFarland's talk

Neutrino cross sections

Our detectors are made of nuclei and compared to a free nucleon, the following differences arise

- Initial state momentum distribution
- Nuclear excitations
- Reaction products have to leave the nucleus
- Higher order interactions appear

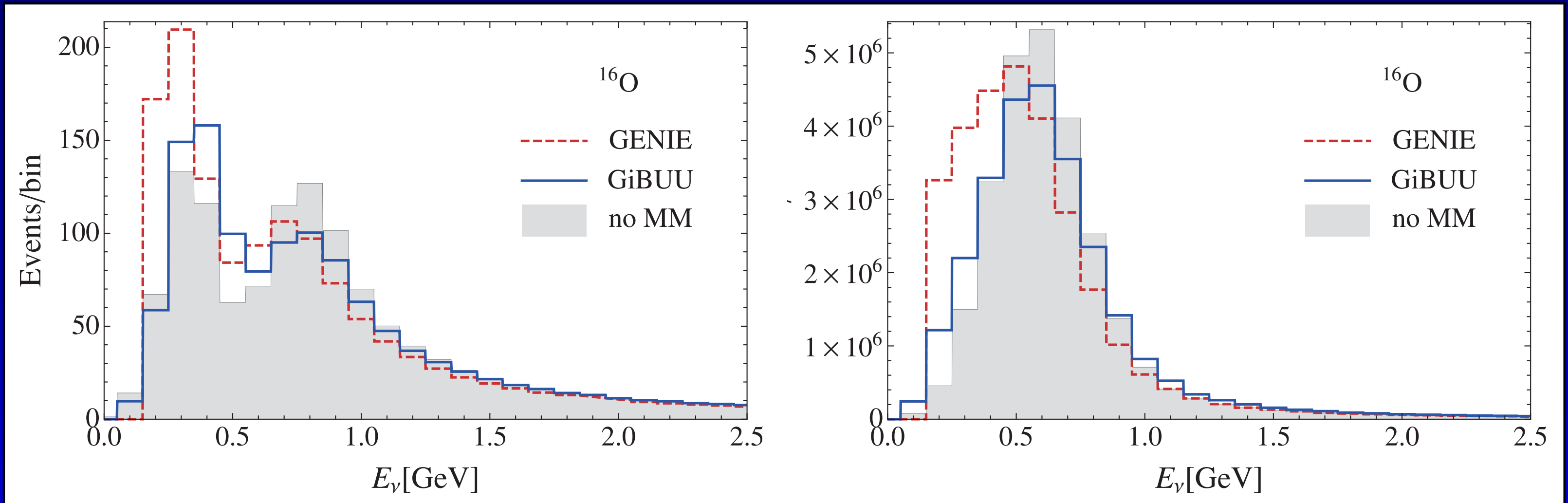
As a function of Q^2 these effects are flavor blind, but we do NOT measure Q^2.

These effects are NOT the same for neutrinos and antineutrinos.

Quasi-elastic scattering

QE events allow for a simple neutrino energy reconstruction based on the lepton momentum.

Nuclear effects will make some non-QE events appear to be like QE events ⇒ the neutrino energy will not be correctly reconstructed.



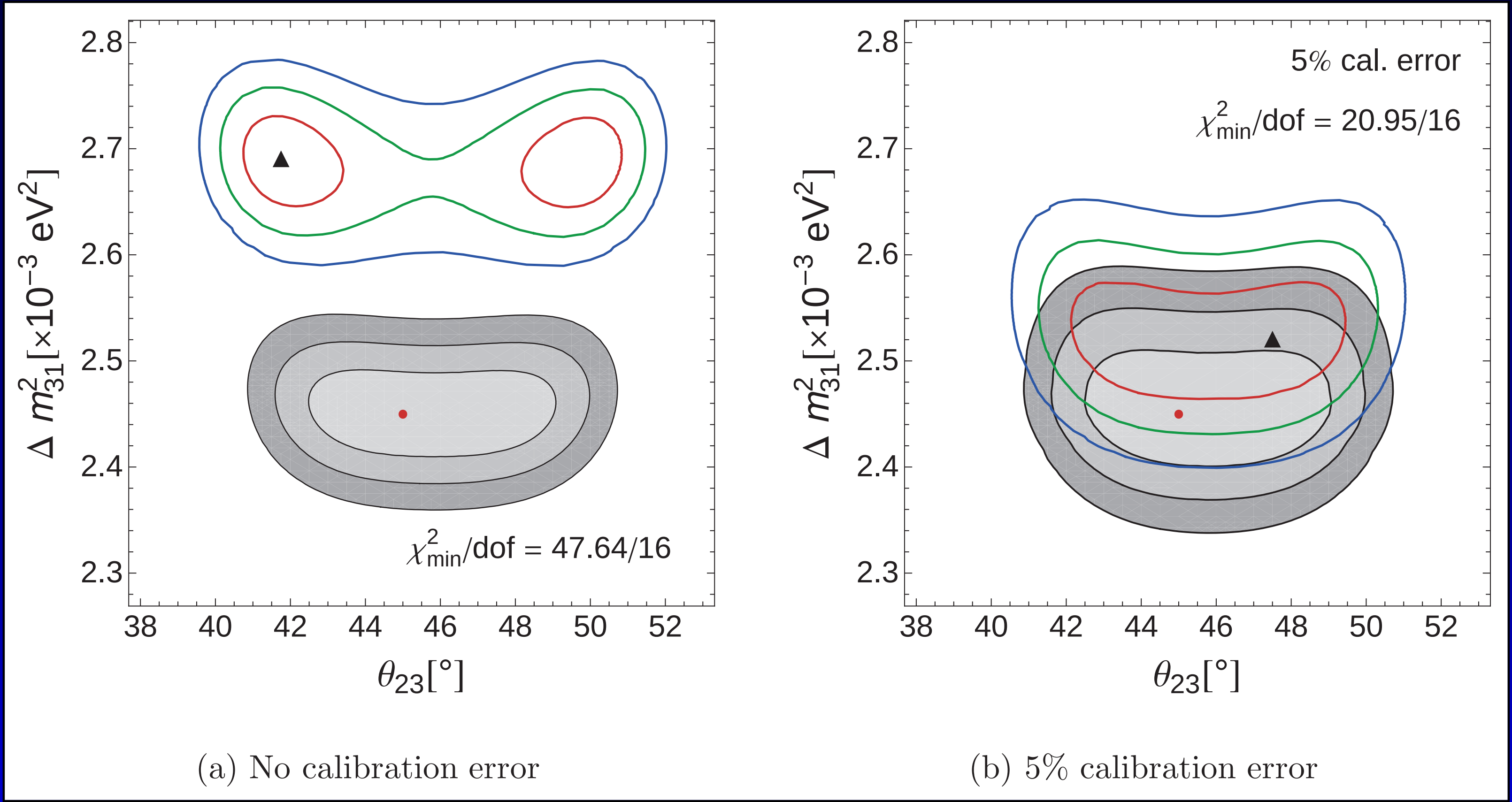
(a) Expected events at the far detector

(b) Expected events at the near detector

Coloma *et al.* 2013

Impact on oscillation

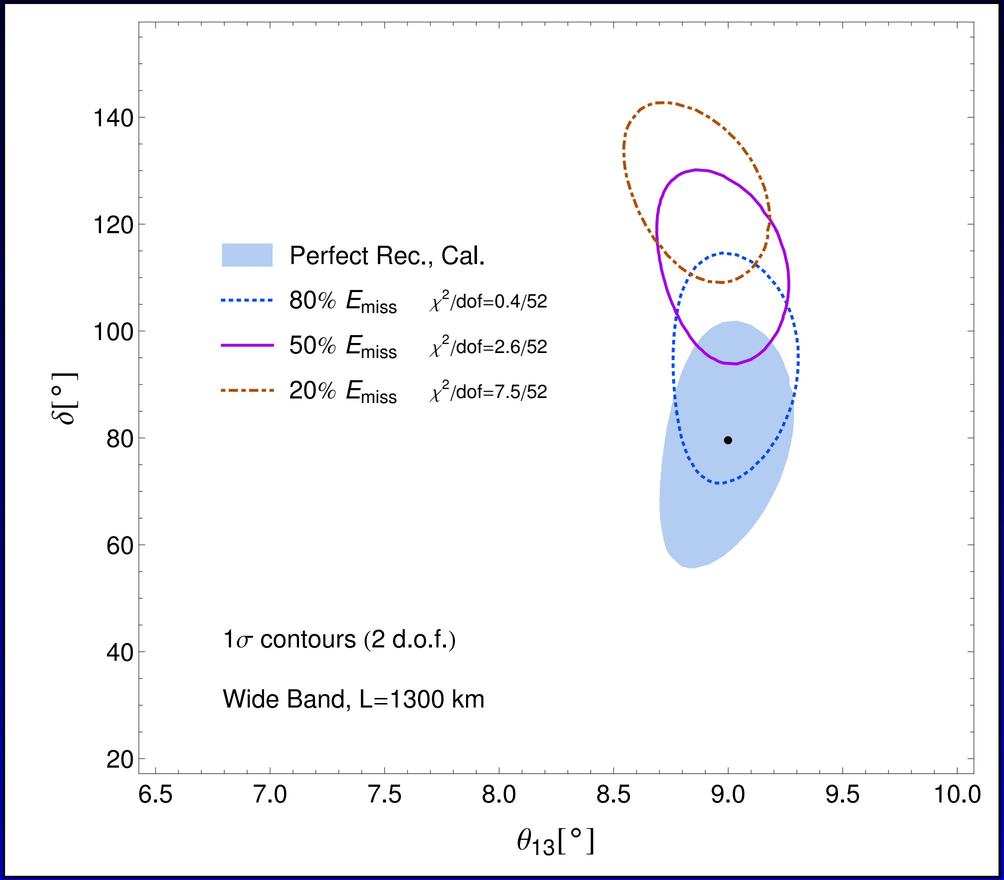
$\nu_\mu \to \nu_\mu$ in a T2K-like setup with near detector.



Coloma *et al.* 2013

If the energy scale is permitted to shift, tension and bias are reduced, but effects very hard to spot from χ^2

Missing energy



In elastic scattering a certain number of neutrons is made

Neutrons will be largely invisible even in a liquid argon TPC

$\Rightarrow$ missing energy

Ankowski *et al.*, 2015

We can correct for the missing energy IF we know the mean neutron number and energy made in the event. . .

Towards precise cross sections

This will require better neutrino sources, since a cross section measurement is about as precise as the accuracy at which the beam flux is known.

- Percent beam flux normalization
- Very high statistics needed to map phase space
- Neutrinos and antineutrinos
- ν_μ and ν_e

A (the only?) source which can deliver all that is a muon storage ring, aka nuSTORM.