Systematics in Neutrino Oscillation Experiments

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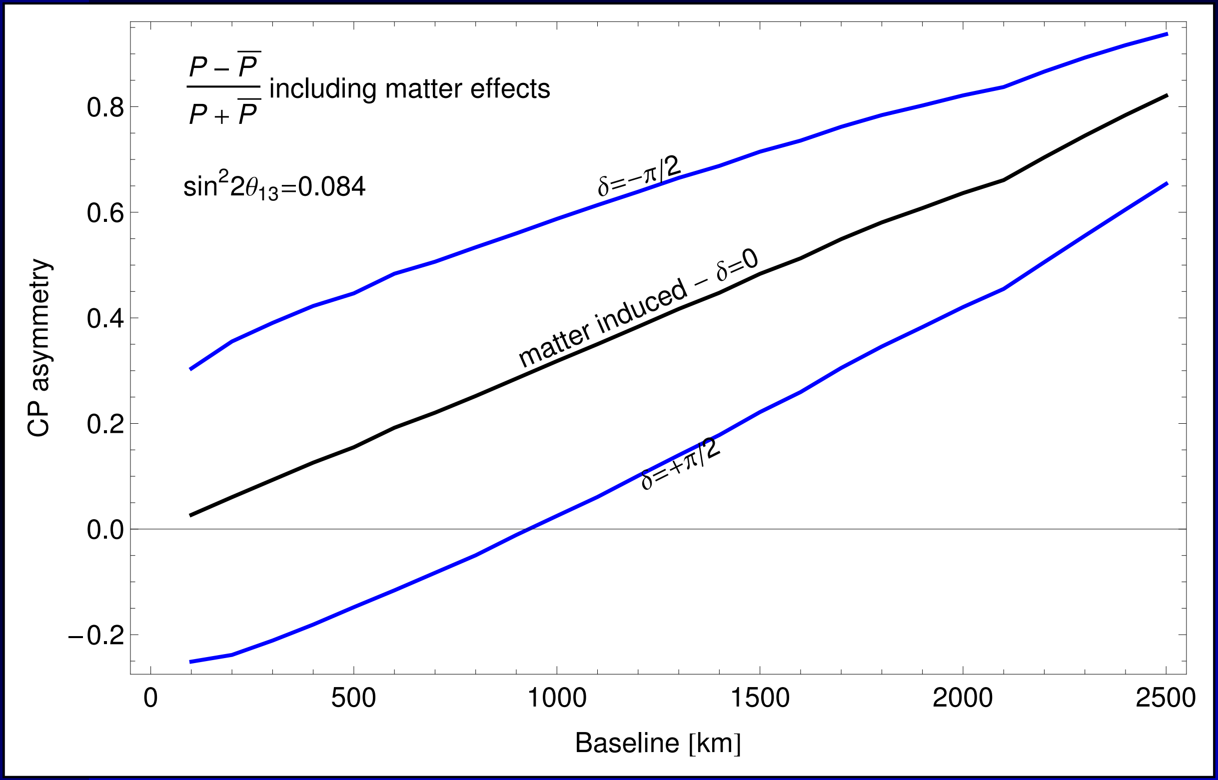
How much precision?

1st oscillation maximum

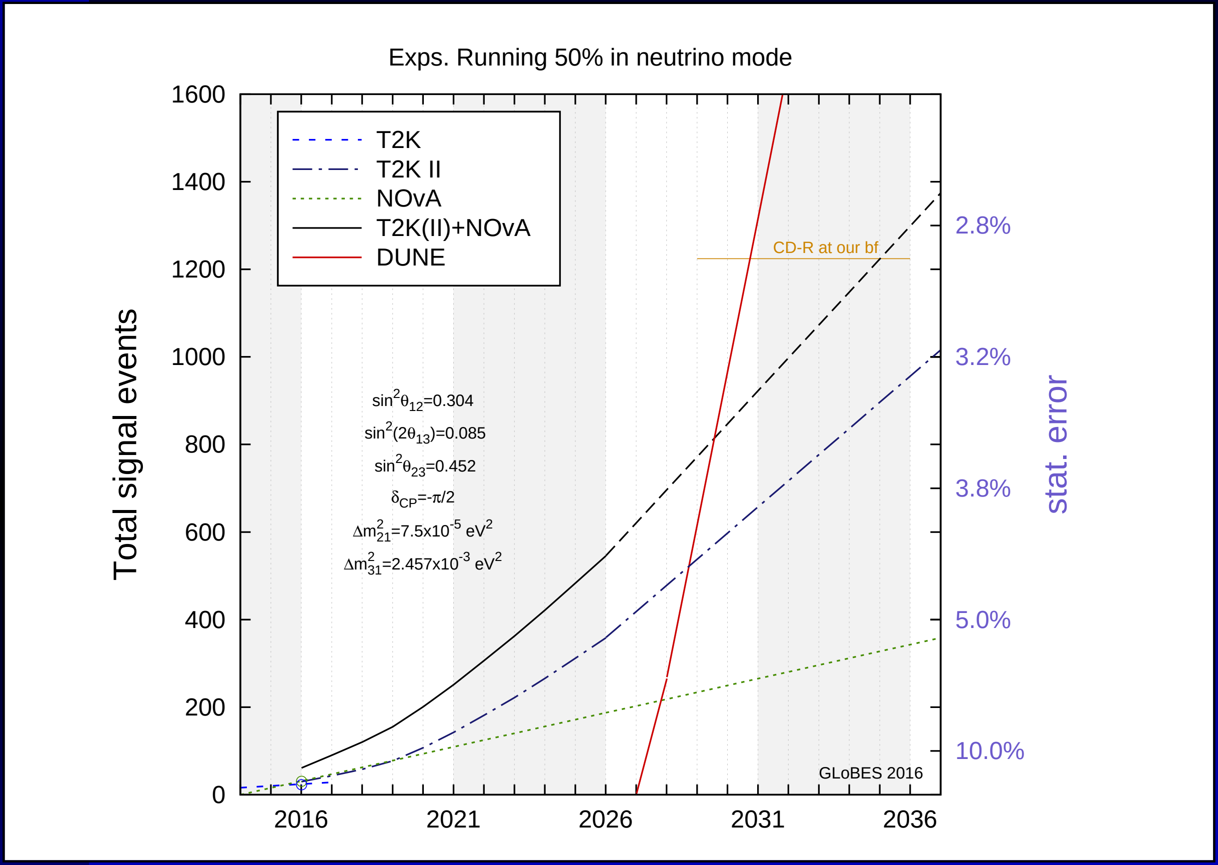


For baselines below 1500 km, the genuine CP asymmetry is at most ±25%

For 75% of the parameter space in δ, the genuine CP asymmetry is as small as ±5%

That is, a 3σ evidence for CP violation in 75% of parameter space requires a $\sim 1.5\%$ measurement of the $P-\bar{P}$ difference, and thus a 1% systematic error.

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)

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

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

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

But . . .

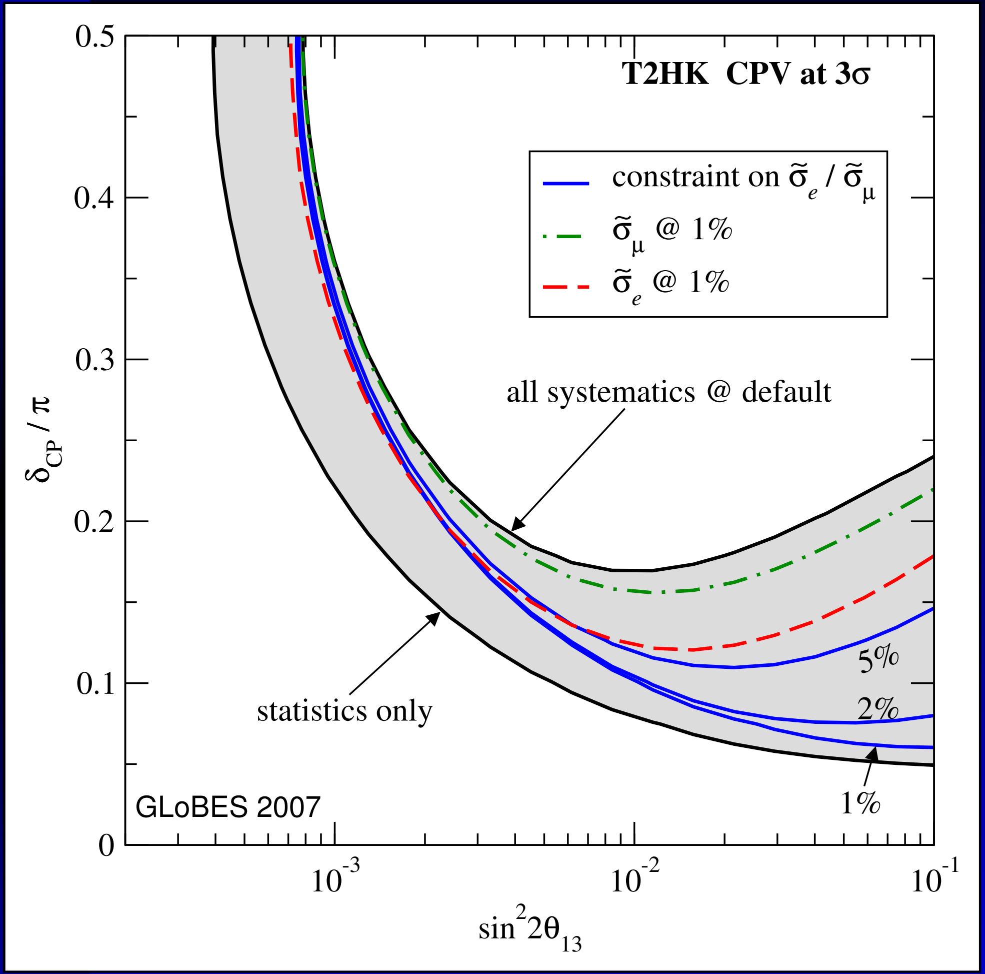
This all works only for disappearance measurements!

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

$$\frac{R^\alpha_\beta(\text{far})L^2}{R^\alpha_\beta(\text{near})} = \frac{N_\text{far}\,\tilde\sigma_\beta\,P(\nu_\alpha\rightarrow\nu_\beta)}{N_\text{near}\,\tilde\sigma_\alpha\,1}$$

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

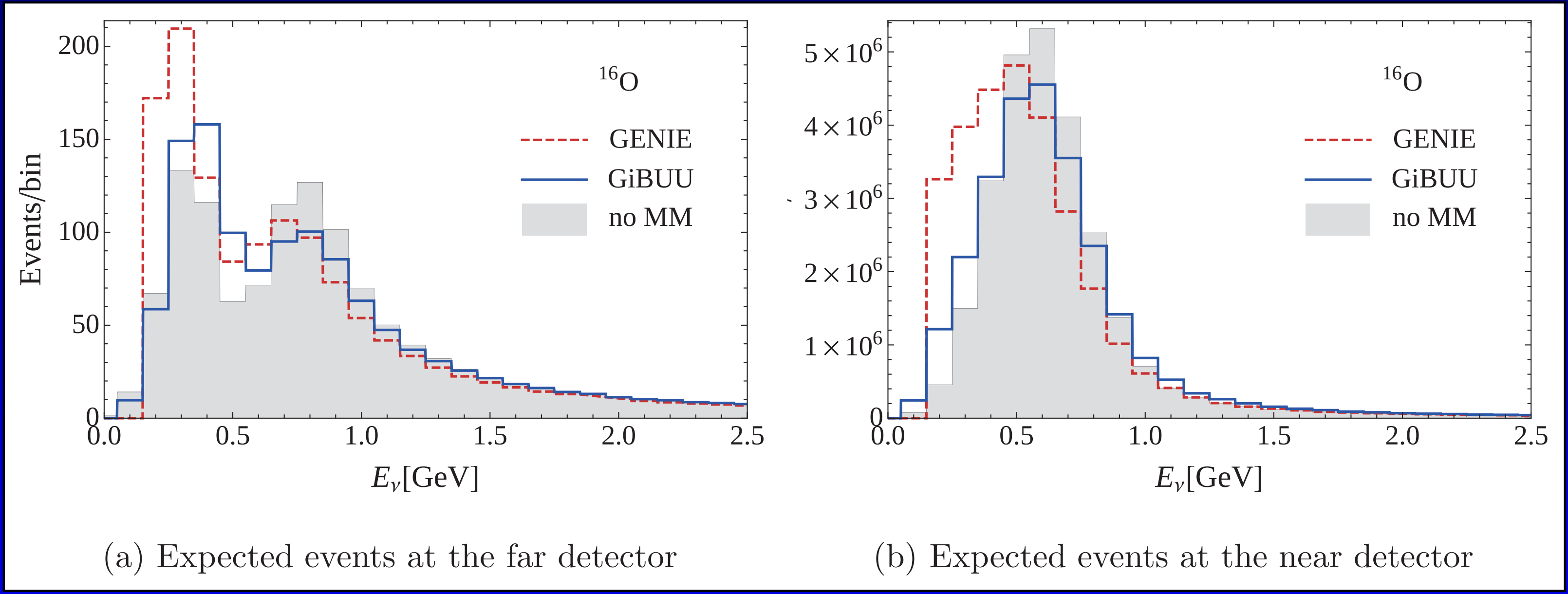
As a function of Q^2 these effects are flavor blind, but we do NOT measure Q^2.

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.

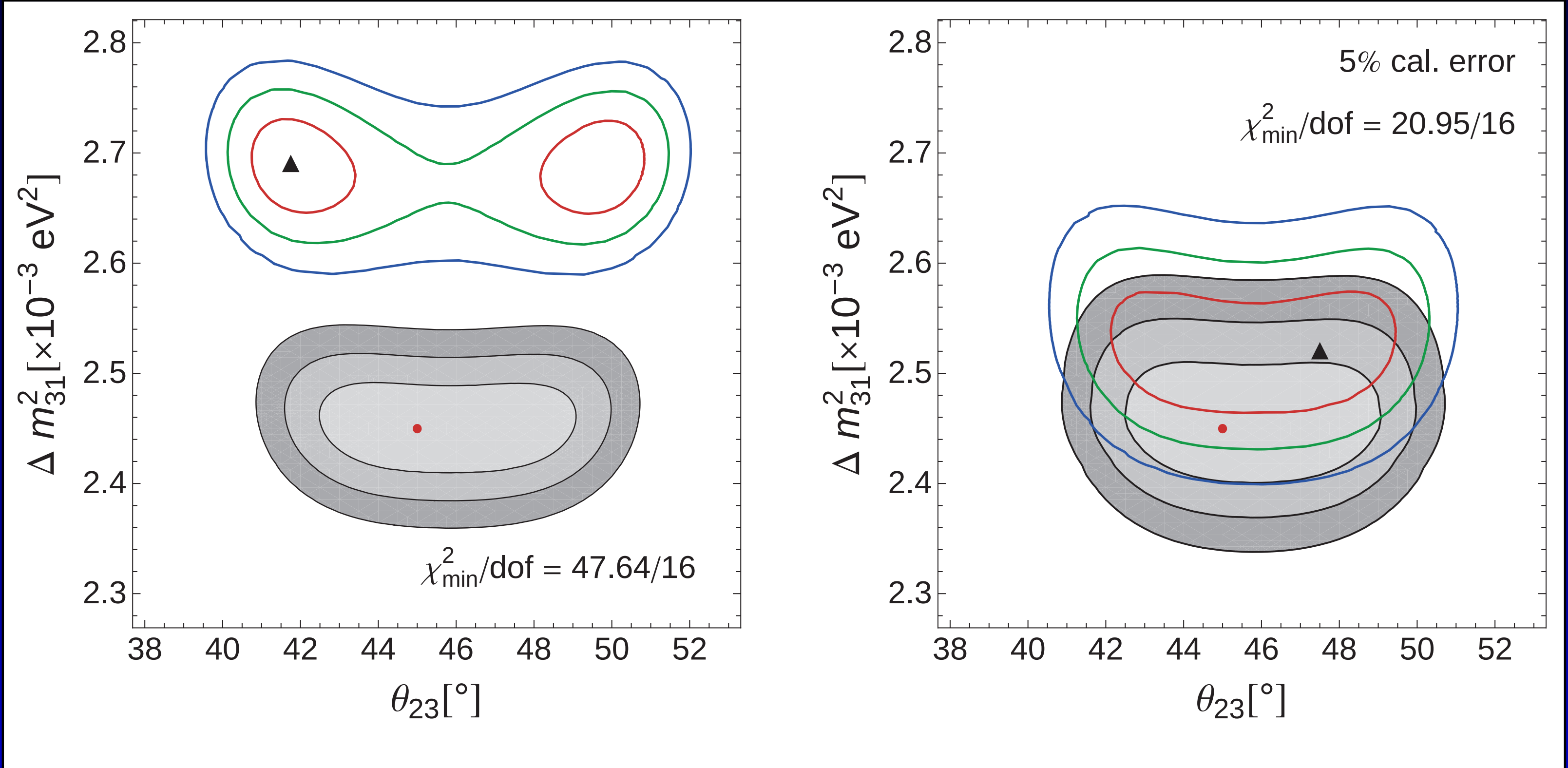


(a) Expected events at the far detector (b) Expected events at the near detector

Coloma *et al.* 2013

Impact on oscillation

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



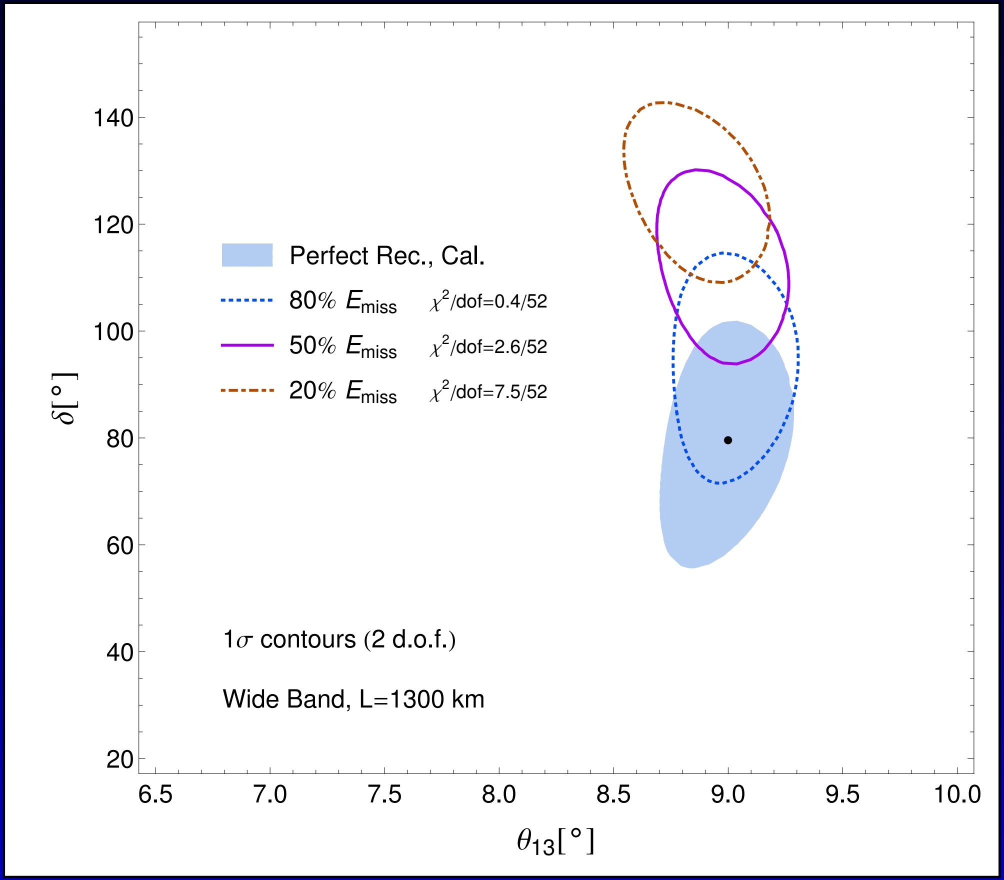
(a) No calibration error

(b) 5% calibration error

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

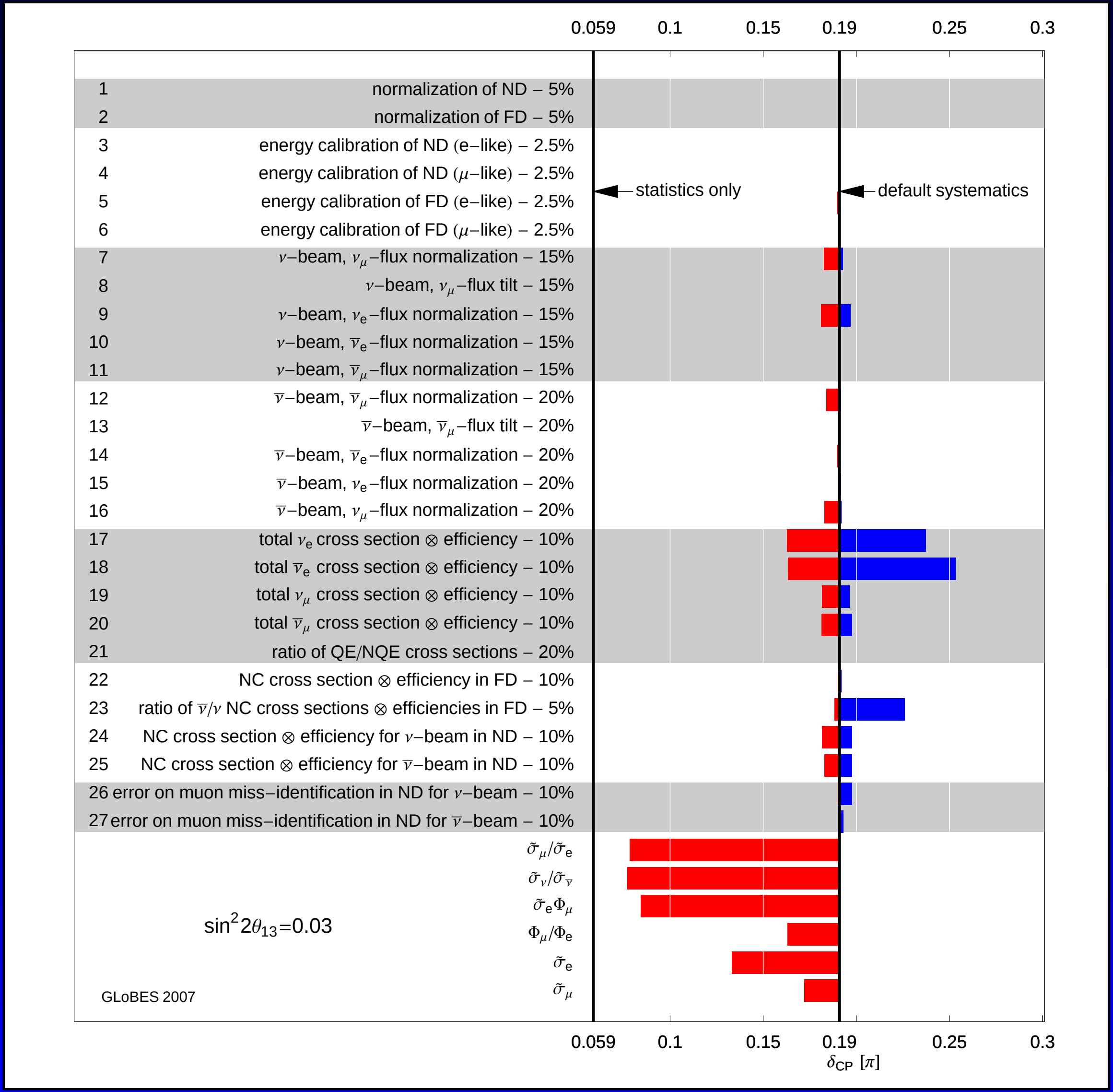
⇒ missing energy

Ankowski *et al.*, 2015

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

Known unknowns

All studies somehow use a table like this



Two great philosophers

“[...] that is to say we know there are some things we do not know. But there are also unknown unknowns — there are things we do not know we don’t know.”

Donald Rumsfeld

“In theory there is no difference between theory and practice. In practice there is.”

Yogi Berra

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.

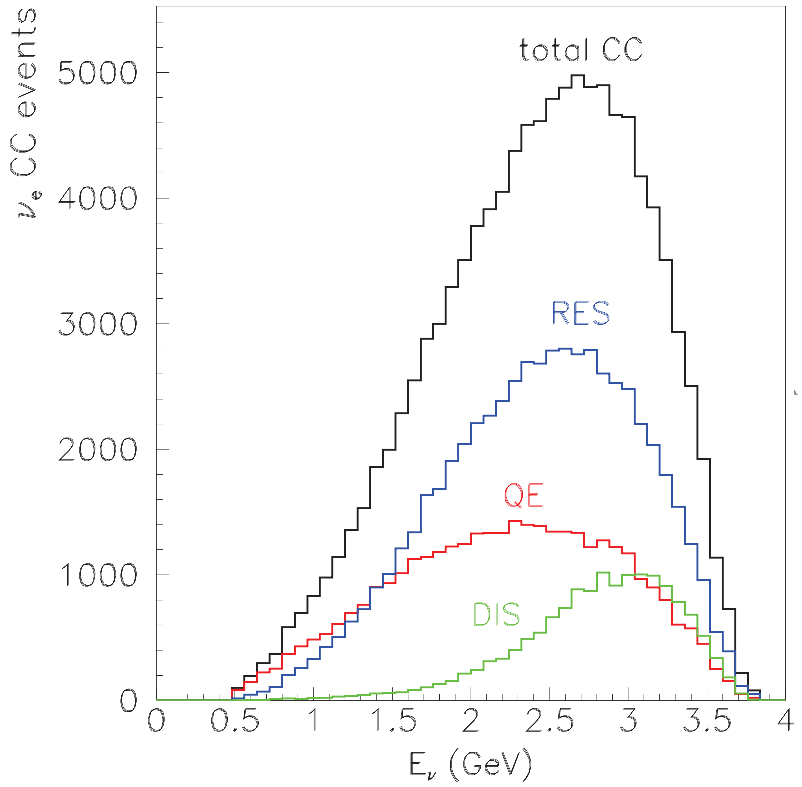
- Percent beam flux normalization
- Very high statistics needed to map phase space
- Neutrinos and antineutrinos
- ν_μ and ν_e

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

see also A. Longhin's talk

nuSTORM in numbers

Beam flux known to better than 1%



	μ^+		μ^-
Channel	N_{evts}	Channel	N_{evts}
$\bar{\nu}_\mu$ NC	1,174,710	$\bar{\nu}_e$ NC	1,002,240
ν_e NC	1,817,810	ν_μ NC	2,074,930
$\bar{\nu}_\mu$ CC	3,030,510	$\bar{\nu}_e$ CC	2,519,840
ν_e CC	5,188,050	ν_μ CC	6,060,580
	π^+		π^-
ν_μ NC	14,384,192	$\bar{\nu}_\mu$ NC	6,986,343
ν_μ CC	41,053,300	$\bar{\nu}_\mu$ CC	19,939,704

nuSTORM collab. 2013

Approximately 3-5 years running for each polarity with a 100 t near detector at 50 m from the storage ring

Systematics for Superbeams

- Already today cross section uncertainties are the leading systematic.
- DUNE and T2HK will reach statistical errors between 1–3% in ν_e-appearance.
- Neutrino energy construction at the few-% level is needed for DUNE.

This calls for a coordinated effort to get the cross section errors into the same ballpark.

Therefore, we need an experimental program beyond MINERνA to measure cross sections.

Hence, we need better (anti-)neutrino sources for both flavors.