Motivation for neutrino cross-section measurements at nuSTORM

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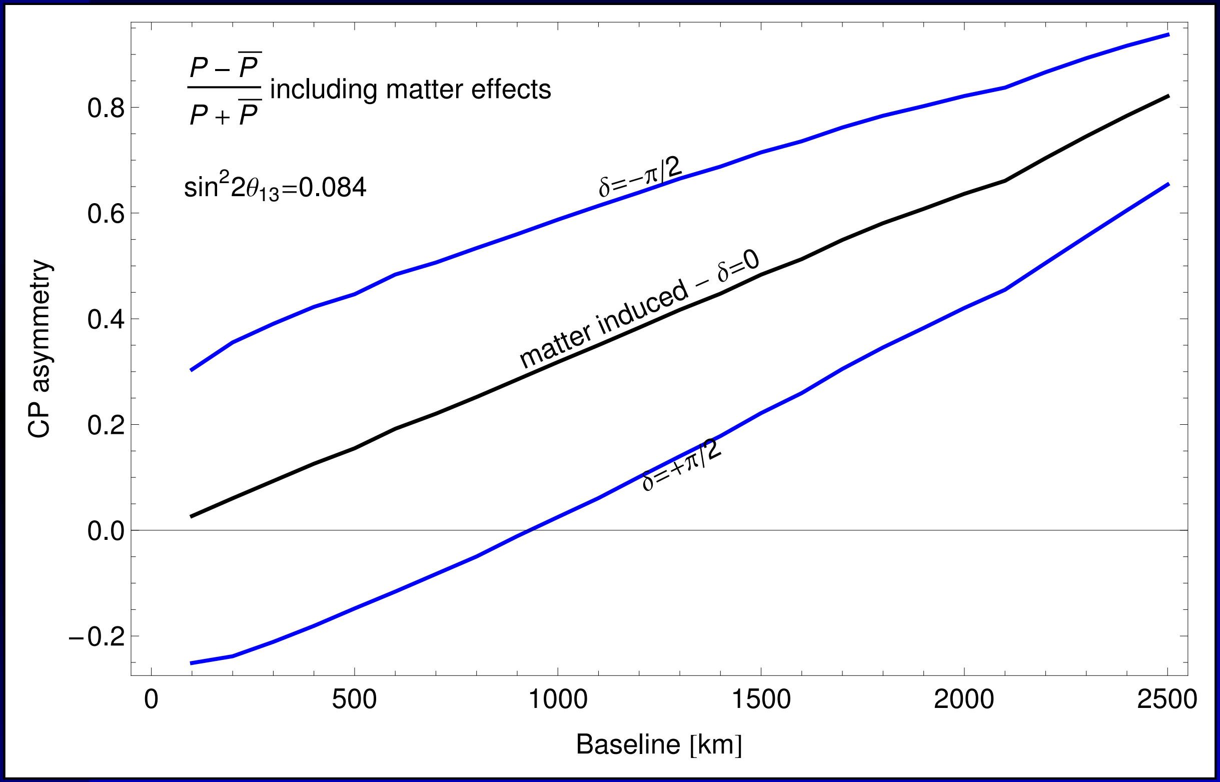
How much precision?

1st oscillation maximum



For baselines below 1500 km, the genuine CP asymmetry is at most $\pm 25\%$

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

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.

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

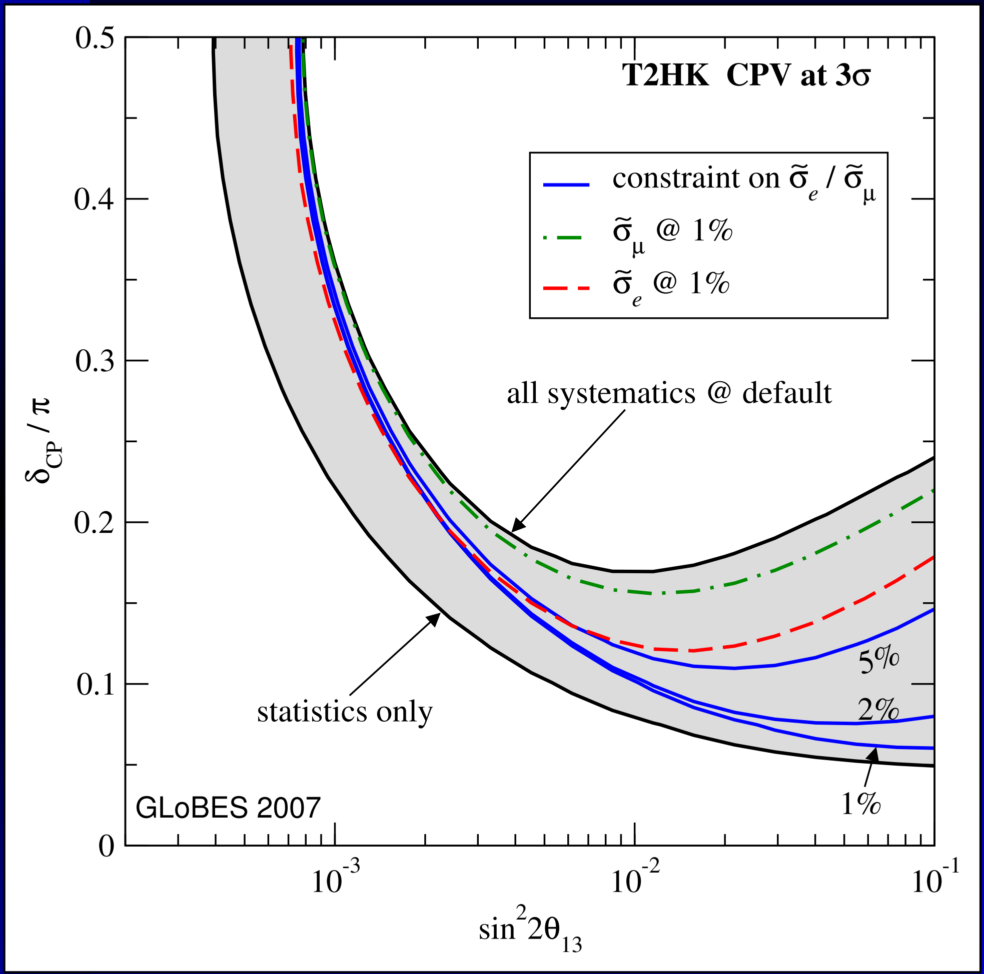
$$\frac{\Phi_\alpha}{\Phi_{\bar{\alpha}}} \quad \text{or} \quad \frac{\Phi_\alpha}{\Phi_\beta}$$

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

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 e.g. Day, McFarland, 2012

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.

Theory and cross sections

Theory is cheap, but multi-nucleon systems and their dynamic response are a hard problem. Currently, there are two major approaches

Greens function Monte Carlo: numerically "exact" solutions for light nuclei ($A \leq 12$) and non-relativistic kinematics.

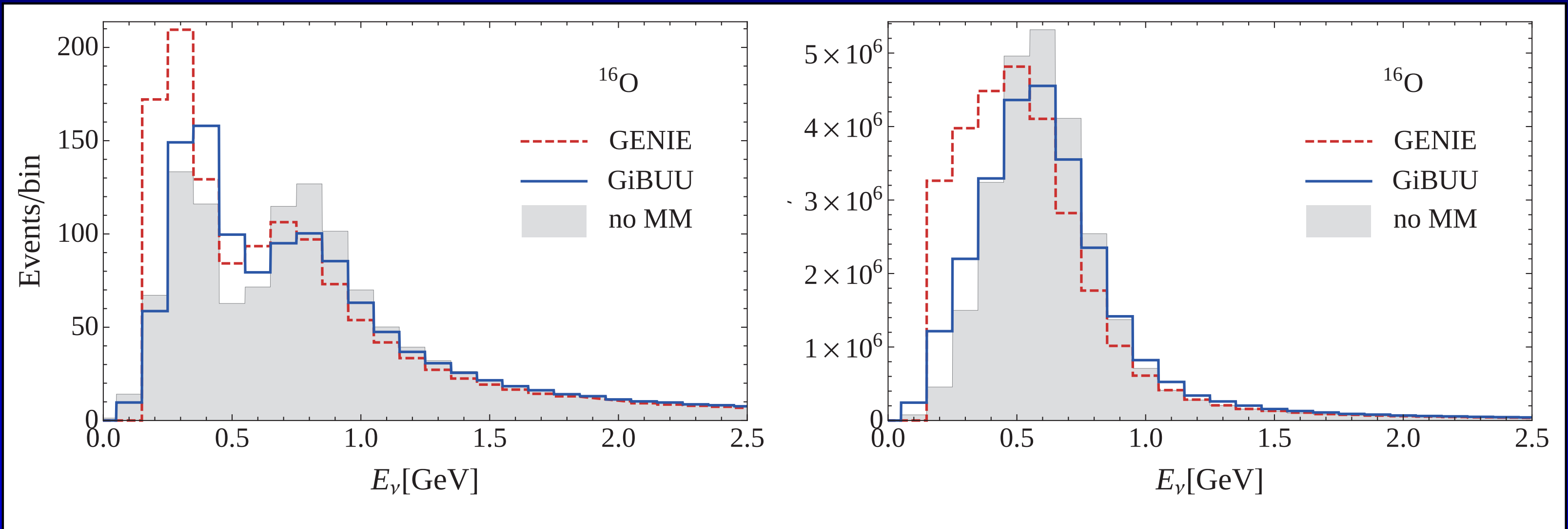
Spectral functions: use information on the initial state from electron-scattering data.

Both techniques are not controlled approximations and thus to trust theory at x% we have to experimentally test the theory at x% – ultimately, precision cross section measurements are unavoidable.

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.



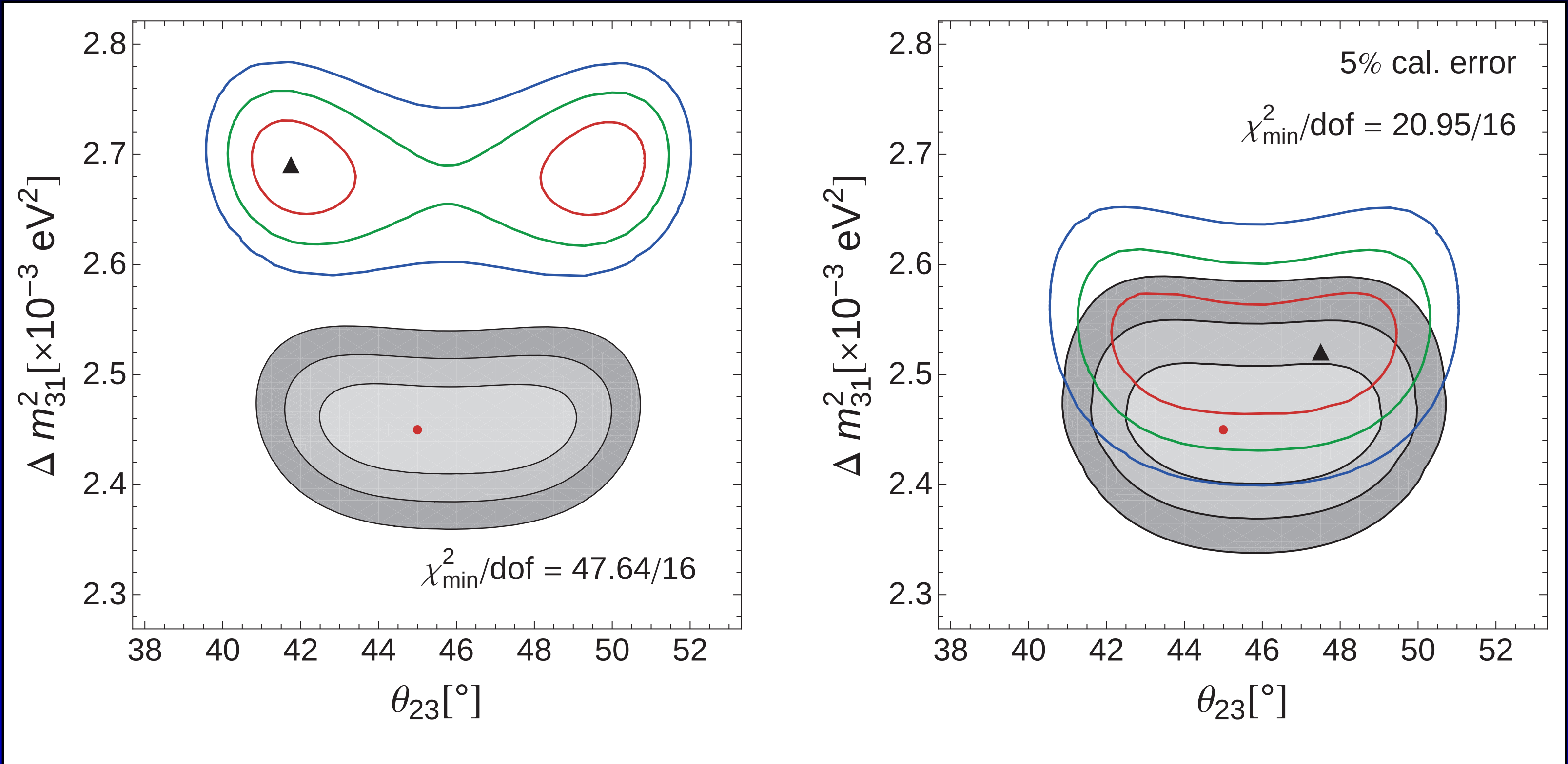
(a) Expected events at the far detector

(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.

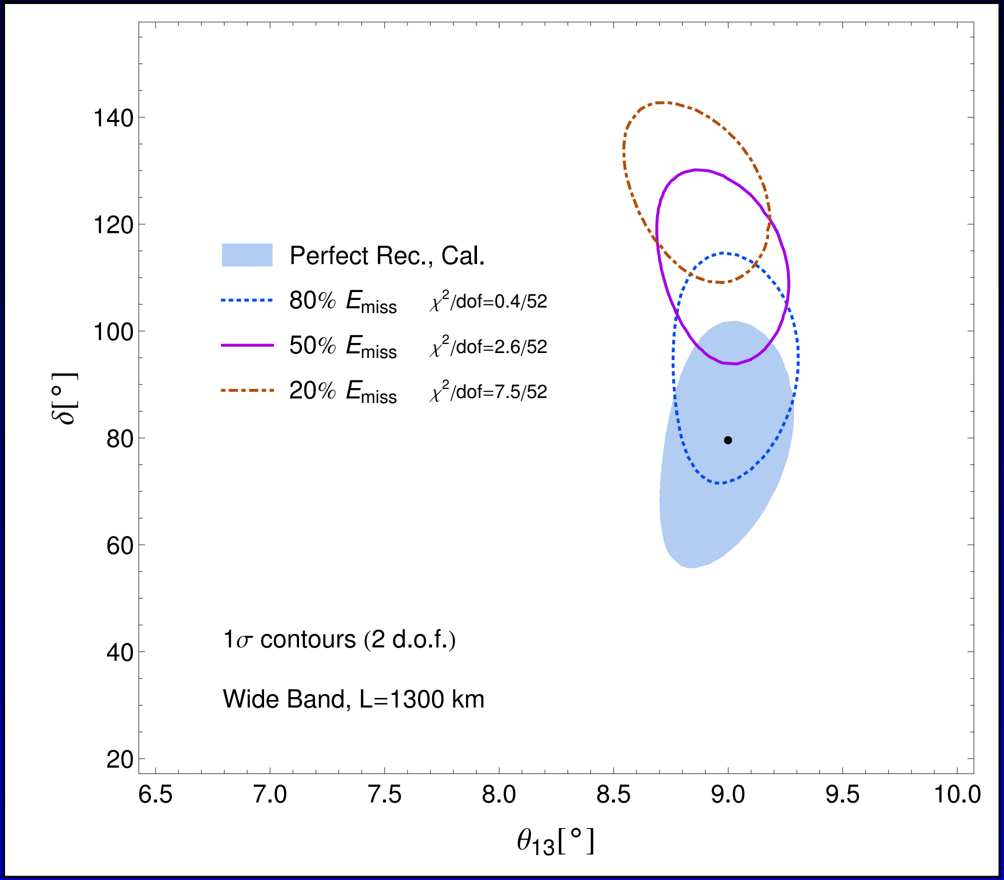


(a) No calibration error (b) 5% calibration error

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



Ankowski *et al.*, 2015

In elastic scattering a certain number of neutrons is made

Neutrons will be largely invisible even in a liquid argon TPC

$\Rightarrow$ missing energy

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.

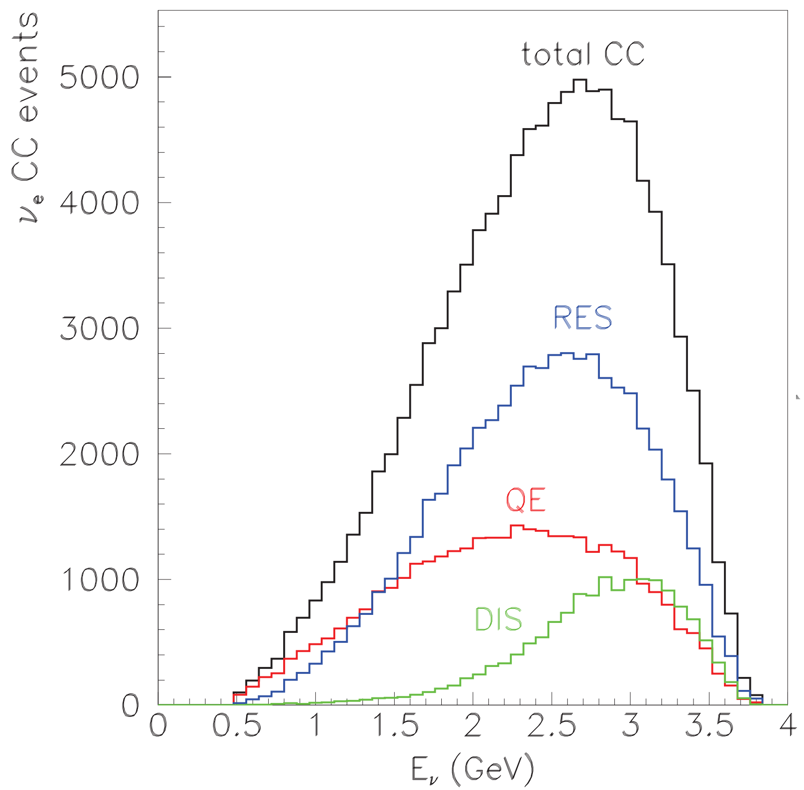
- Sub-percent beam flux normalization
- Very high statistics needed to map phase space
- Neutrinos and antineutrinos
- ν_μ and ν_e

The only source which can deliver all that is a muon storage ring, aka nuSTORM.

NONE of the other solutions has been shown to be able deliver sufficient improvements in systematics!

nuSTORM in numbers

Beam flux known to better than 1%



μ^+ Channel	N_{evts}	μ^- 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

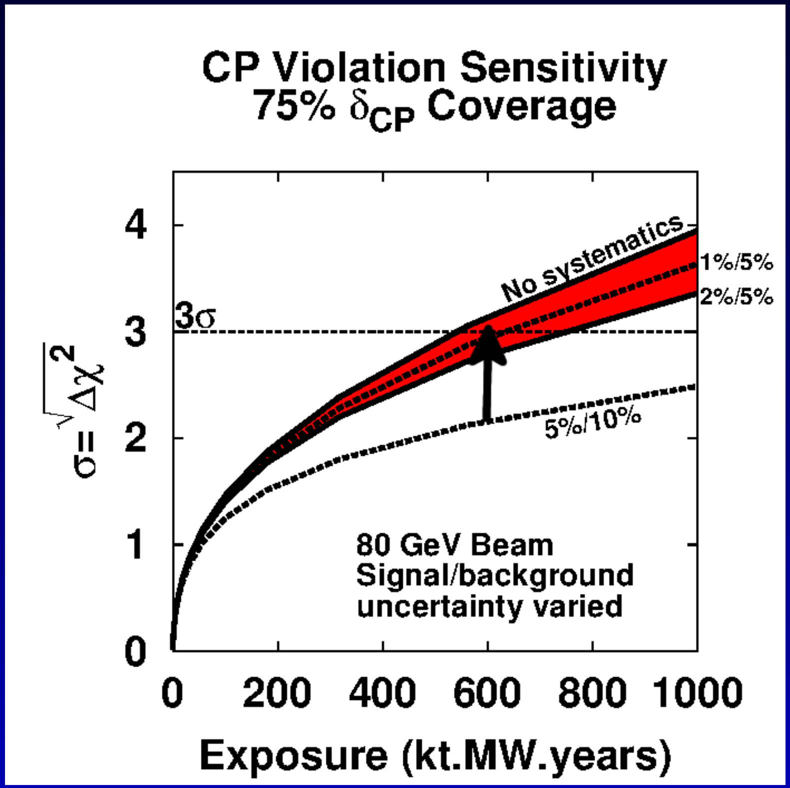
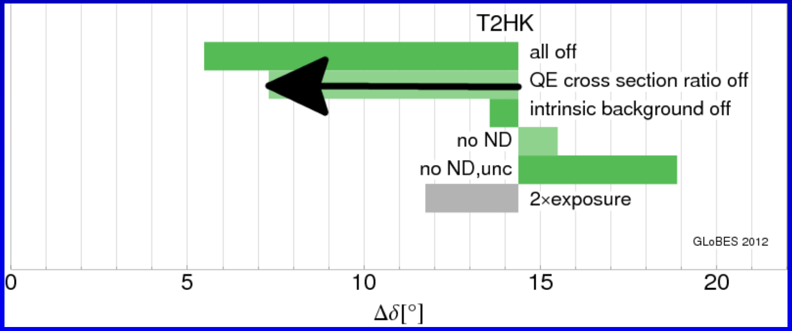


figure courtesy M. Bass, 2014



Systematics at the 1% level is necessary for a successful future LBL program

The range of 1 – 5% systematics corresponds to an exposure difference of about 200-300% in a very non-linear fashion

Given the \$1-2B scale of LBL experiments, investing in precise cross section measurements provides a very good return on investment!