Neutrino measurements needed for systematics

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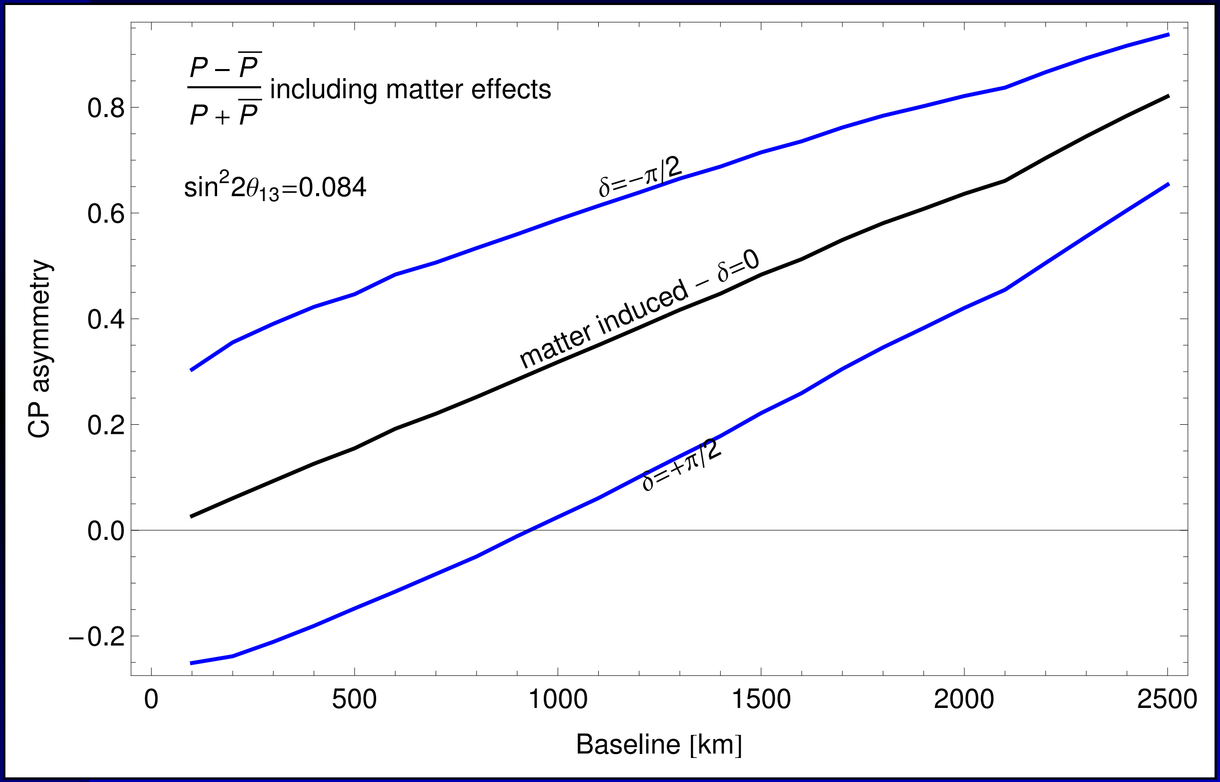
How much precision?

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.

Disclaimer

The goal is clear – we need 1%-level systematics for the $P - \bar{P}$ difference.

The need for specific measurements to improve systematics is driven by an extrapolation of what the systematic errors would be in the future in comparison to the 1% goal.

Predicting systematic errors of experiments is difficult, in particular, since there are many completed experiments for which we are not quite sure what the systematics are.

Notation

When I speak of some quantity is ’known’ in the following I mean, known at a level of percent or better from an actual measurement or a theoretical calculation†

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† *i.e.* from a controlled approximation, where the error term can be bounded reliably from above

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!

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

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. Real world example: Daya Bay.

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.* MINOS.

But . . .

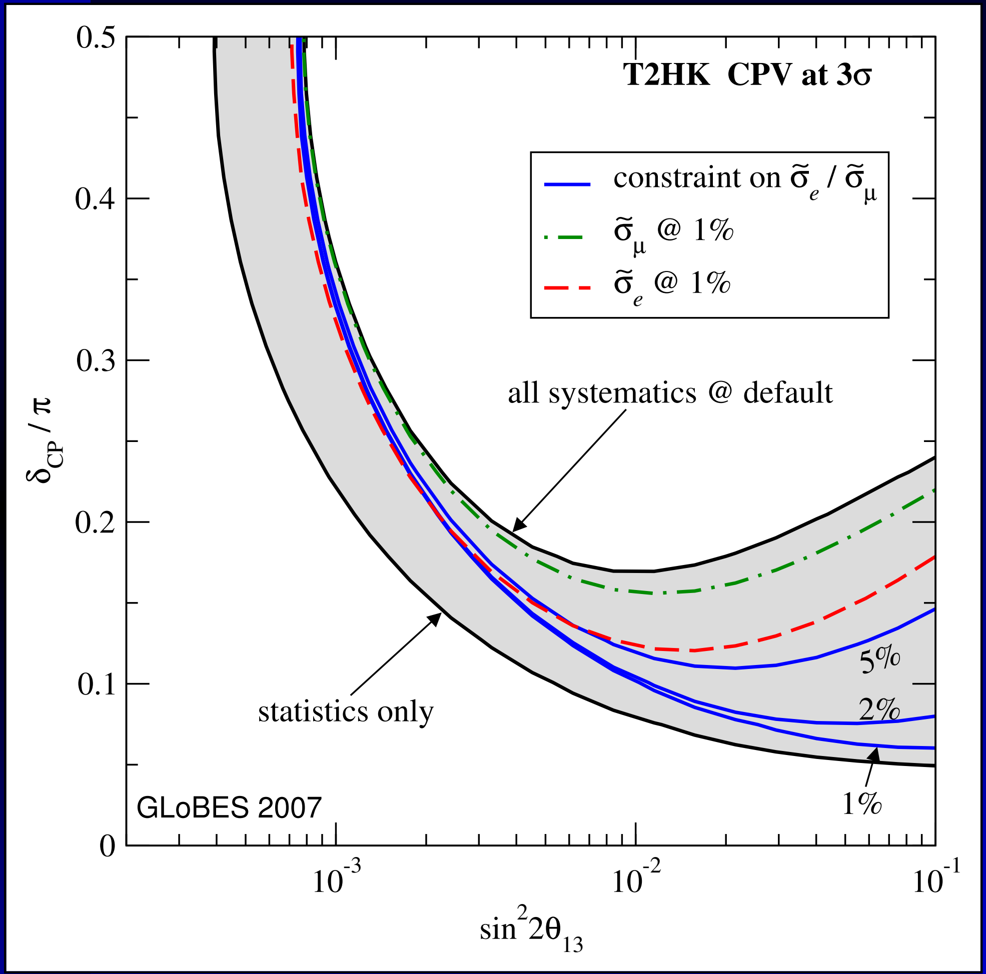
This all works only for disappearance measurements!

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

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

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 e.g. Day, McFarland, 2012

A simple analysis

Numbers before using a near detector

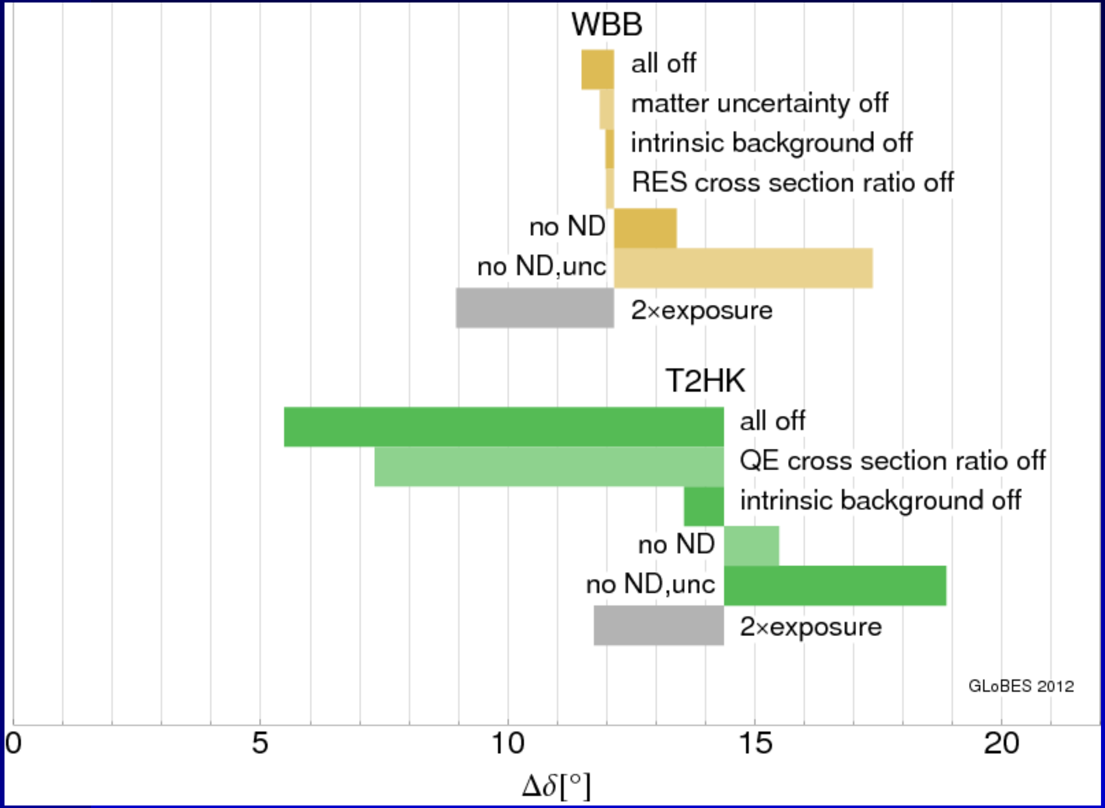
Systematics	SB Opt.	SB Def.	SB Cons.	BB Opt.	BB Def.	BB Cons.	NF Opt.	NF Def.	NF Cons.
Fiducial volume ND	0.2%	0.5%	1%	0.2%	0.5%	1%	0.2%	0.5%	1%
Fiducial volume FD (incl. near-far extrap.)	1%	2.5%	5%	1%	2.5%	5%	1%	2.5%	5%
Flux error signal ν	5%	7.5%	10%	1%	2%	2.5%	0.1%	0.5%	1%
Flux error background ν	10%	15%	20%	correlated			correlated		
Flux error signal $\bar{\nu}$	10%	15%	20%	1%	2%	2.5%	0.1%	0.5%	1%
Flux error background $\bar{\nu}$	20%	30%	40%	correlated			correlated		
Background uncertainty	5%	7.5%	10%	5%	7.5%	10%	10%	15%	20%
Cross secs $\times$ eff. QE†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs $\times$ eff. RES†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs $\times$ eff. DIS†	5%	7.5%	10%	5%	7.5%	10%	5%	7.5%	10%
Effec. ratio ν_e/ν_μ QE*	3.5%	11%	–	3.5%	11%	–	–	–	–
Effec. ratio ν_e/ν_μ RES*	2.7%	5.4%	–	2.7%	5.4%	–	–	–	–
Effec. ratio ν_e/ν_μ DIS*	2.5%	5.1%	–	2.5%	5.1%	–	–	–	–
Matter density	1%	2%	5%	1%	2%	5%	1%	2%	5%

Coloma *et al.* 2012

Even at a rate-only level for systematics there is a large number of inputs required, many of which are best guesses only.

Narrow vs broad

T2HK – 4600 MW kton years WC at 295 km
WBB – 800 MW kton years LAr at 2300 km



Disappearance data can play the role of near detector if three flavor framework is assumed

Coloma *et al.*, 2012

The difference in systematics dependency is largely due to the difference between narrow and broad band beams – LBNF very similar to WBB

Remarks

- Measuring a cross section at 1% in a beam which is known to 5% seems difficult
- Not clear that ν_e component of a superbeam will help much, since Φ_μ/Φ_e is not well known and statistics will be low
- And we really need to know the ratio (at least)
- Most crucially, we have not yet talked about the energy dependence of the cross section and the relation between true neutrino energy and the energy visible in the detector

Neutrino cross sections

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

- Initial state momentum distribution (e.g. Fermi gas, spectral functions)
- Nuclear excitations
- Reaction products have to leave the nucleus (aka final state interaction)
- Higher order interactions appear (aka 2p2h, meson exchange current)

As a function of Q^2 these effects are flavor blind but are NOT the same for neutrinos and antineutrinos.

Event generators vs nuclear theory

In impulse approximation a consistent computation of nuclear cross sections appears feasible – however there are many different schemes to perform the calculation and no complete calculation exists to date.

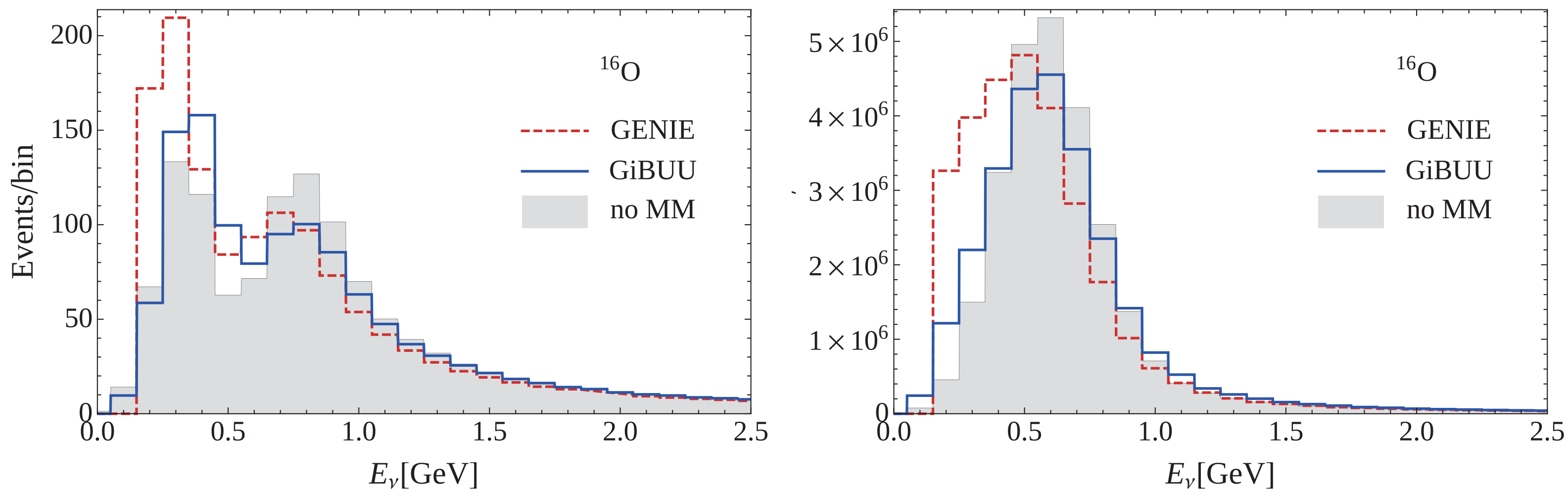
Inputs are derived from electron scattering data, which fixes most of the nuclear structure related parts – NB, there is currently no such data for argon

Event generators are lagging behind nuclear theory by 1-2 decades and are not consistent amongst themselves

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.

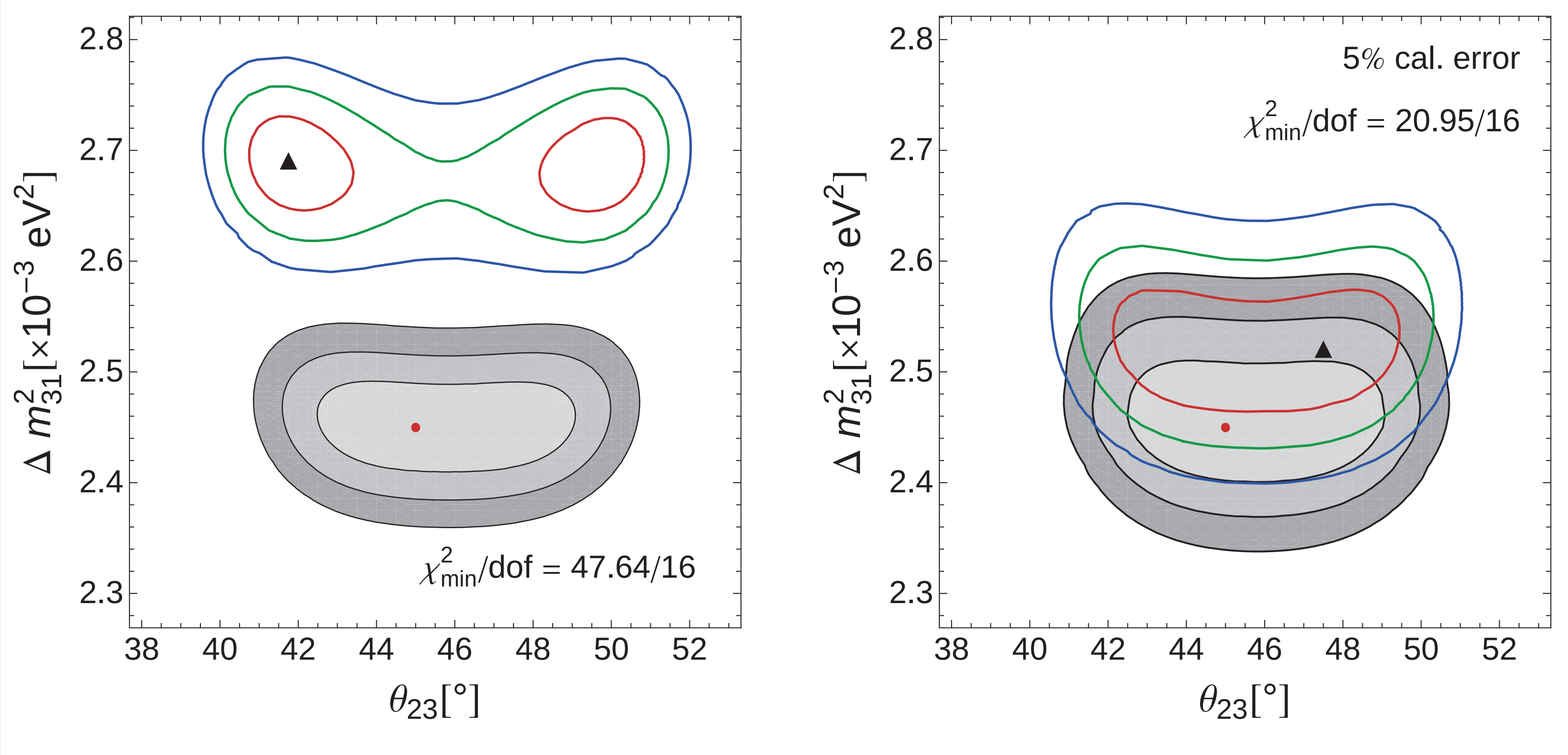


(a) Expected events at the far detector (b) Expected events at the near detector

Coloma *et al.* 2013

Impact on oscillation

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



(a) No calibration error

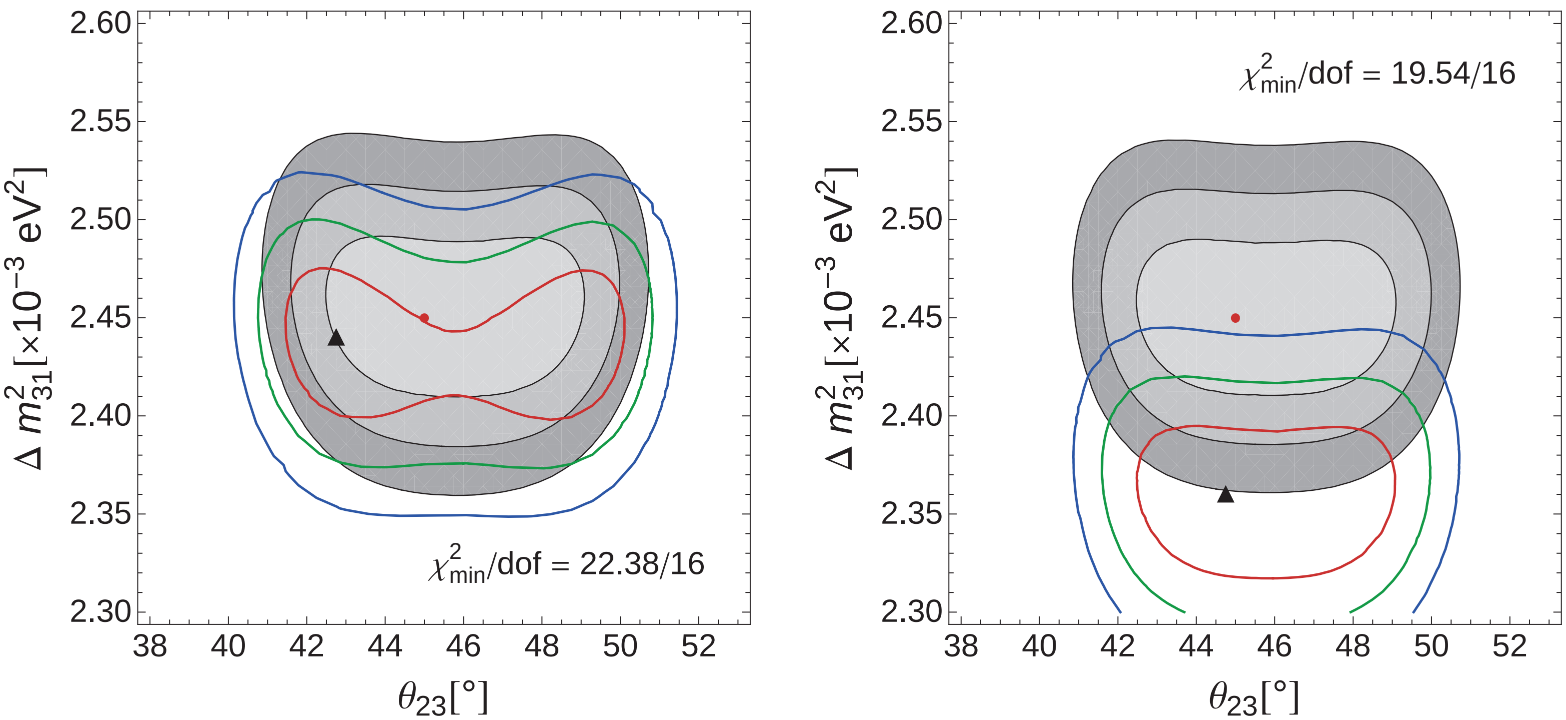
(b) 5% calibration error

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

Higher order effects

Including effects like 2p2h or MEC



(a) Results using GiBUU matrices and cross sections (b) Results using GENIE matrices and cross sections

Coloma *et al.* 2013

Different generators make very different predictions

Calorimetry

In some detectors, like LAr, there will be calorimetry

- Calorimetric resolution significantly worse than leptonic resolution, but by how much?
- Neutral particles will give rise to missing energy, can we compute that?
- Missing energy dependent on detector size, near/far comparison?

Fraction of hadronic energy very different for neutrinos and antineutrinos

The relative robustness of LBNF with respect to rate-based systematics derives from the precise reconstruction of the energy dependence of the oscillation pattern!

Solutions

There are two distinct problems: ν_e/ν_μ ratios in a narrow band beam and energy response for both WC and LAr detectors.

- Better theory – some room for improvement, in particular, closing gap between generators and theory
- More electron scattering data – there is a proposal at Jefferson Lab to collect Ar data
- High resolution near detector – very important, but flavor effects and energy containment?
- Better flux predictions – unlikely to reach percent level accuracy

Expectations

Source of Uncertainty	MINOS Absolute/ν_e	T2K ν_e	LBNE ν_e	Comments
Beam Flux after N/F extrapolation	3%/0.3%	2.9%	2%	MINOS is normalization only. LBNE normalization and shape highly correlated between ν_μ/ν_e.
		Detector effects		
Energy scale (ν_μ)	7%/3.5%	included above	(2%)	Included in LBNE ν_μ sample uncertainty only in three-flavor fit. MINOS dominated by hadronic scale.
Absolute energy scale (ν_e)	5.7%/2.7%	3.4% includes all FD effects	2%	Totally active LArTPC with calibration and test beam data lowers uncertainty.
Fiducial volume	2.4%/2.4%	1%	1%	Larger detectors = smaller uncertainty.
		Neutrino interaction modeling		
Simulation includes: hadronization cross sections nuclear models	2.7%/2.7%	7.5%	$\sim 2\%$	Hadronization models are better constrained in the LBNE LArTPC. N/F cancellation larger in MINOS/LBNE. X-section uncertainties larger at T2K energies. Spectral analysis in LBNE provides extra constraint.
Total	**5.7%**	**8.8%**	**3.6 %**	**Uncorrelated ν_e uncertainty in full LBNE three-flavor fit = 1-2%.**

LBNE collab. 2013

- Near/far cancellations already included
- Mostly rate-only effects
- Relies on 3-flavor framework being valid
- Assumes excellent hadron calorimetry

Even on paper, barely reaches the required 1% goal.

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.

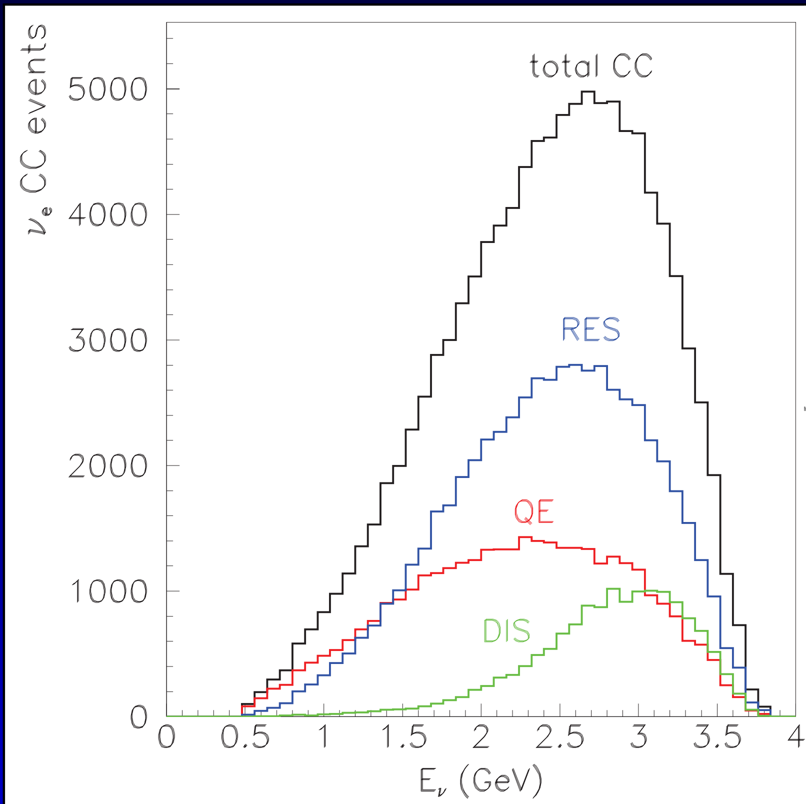
- Sub-percent beam flux normalization
- Very high statistics needed to map phase space
- Neutrinos and antineutrinos
- ν_μ and ν_e

One (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	μ^+ N_{evts}	μ^- Channel	μ^- 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

Conclusion

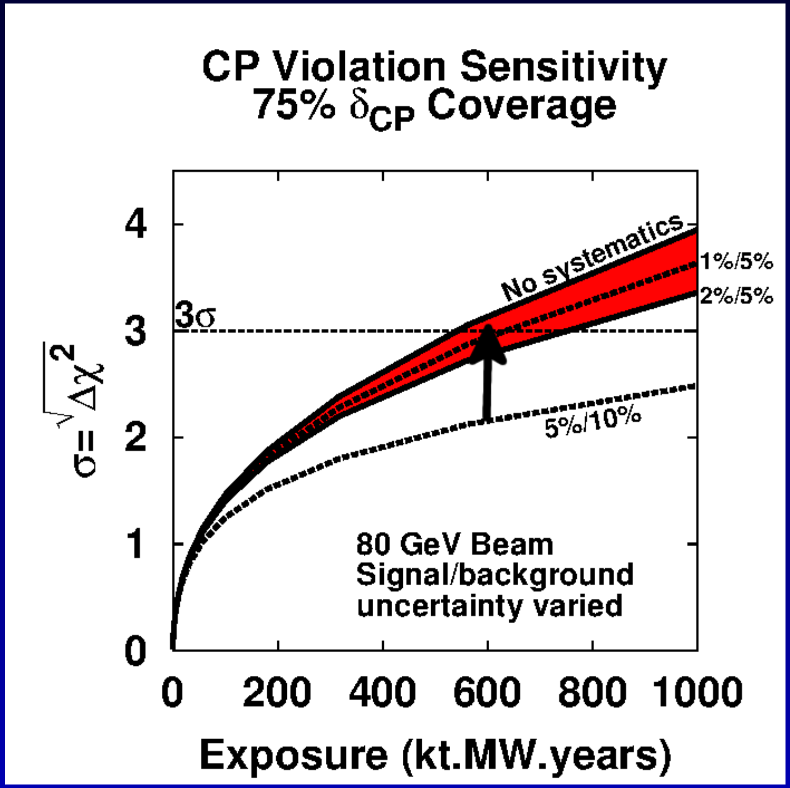
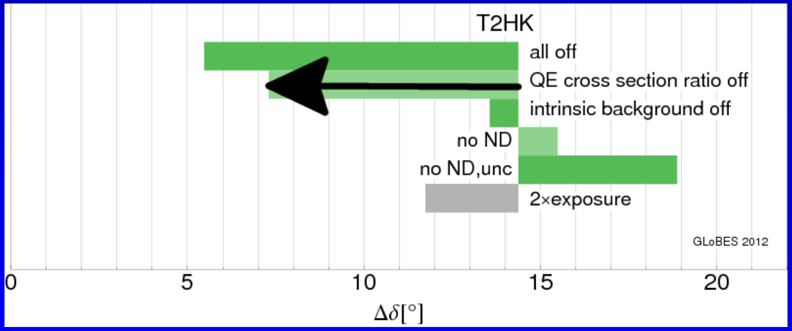


figure courtesy M. Bass, 2014



Systematics at the 1% level is necessary to ensure the success of the future LBL program

The range of 1 – 5% systematics corresponds to an exposure difference of about 200-300%

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