Neutrino Physics Perspectives

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see also arXiv:1411.0629

MAP 2014 Winter Meeting

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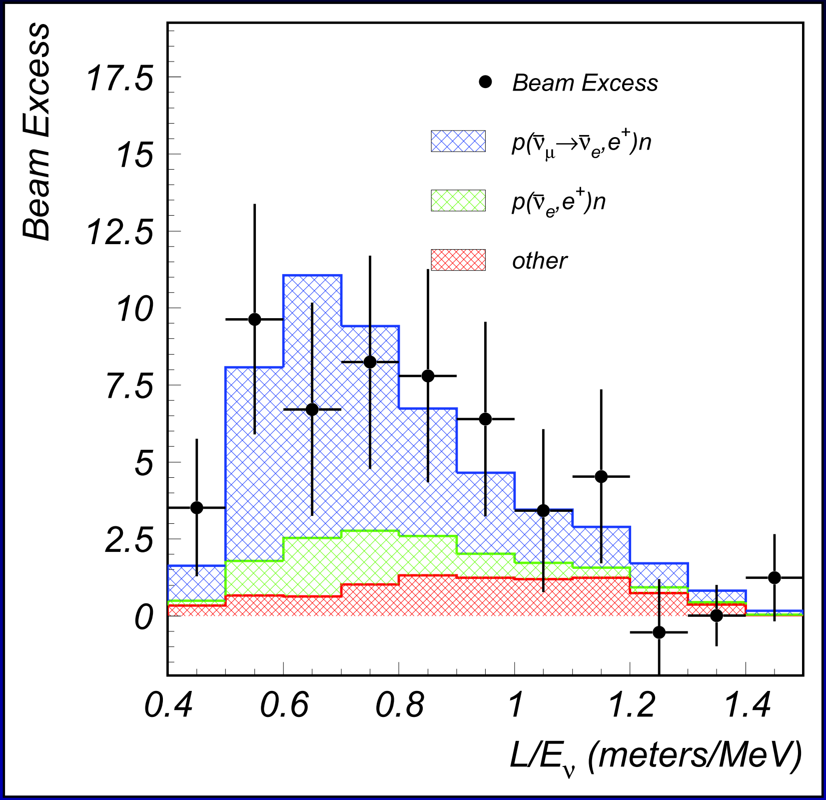
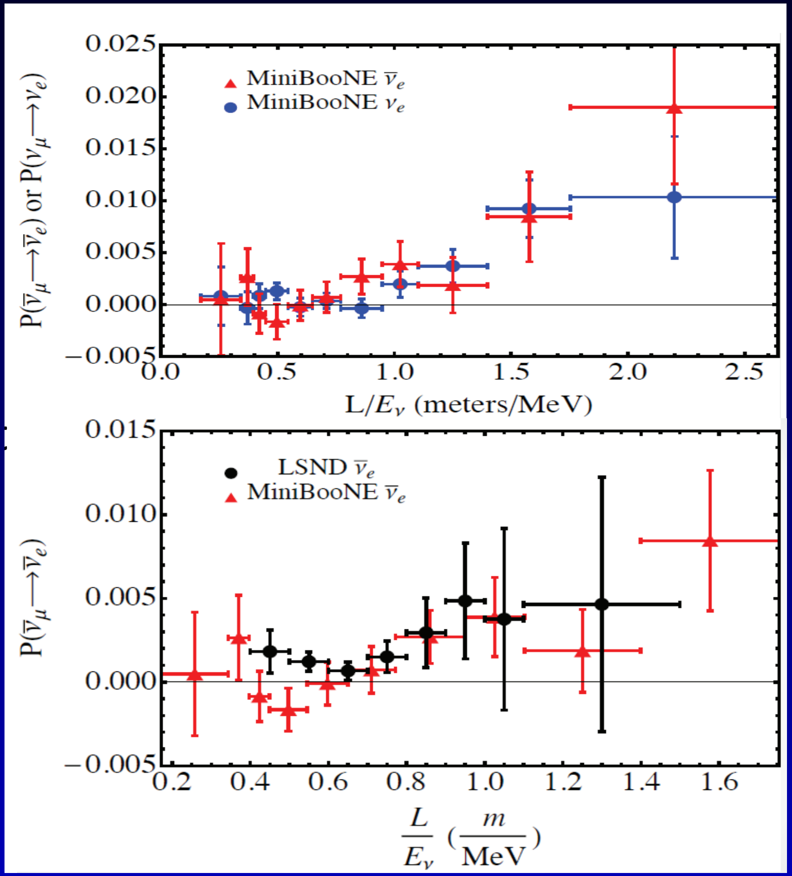
Short-baseline Physics

LSND and MiniBooNE

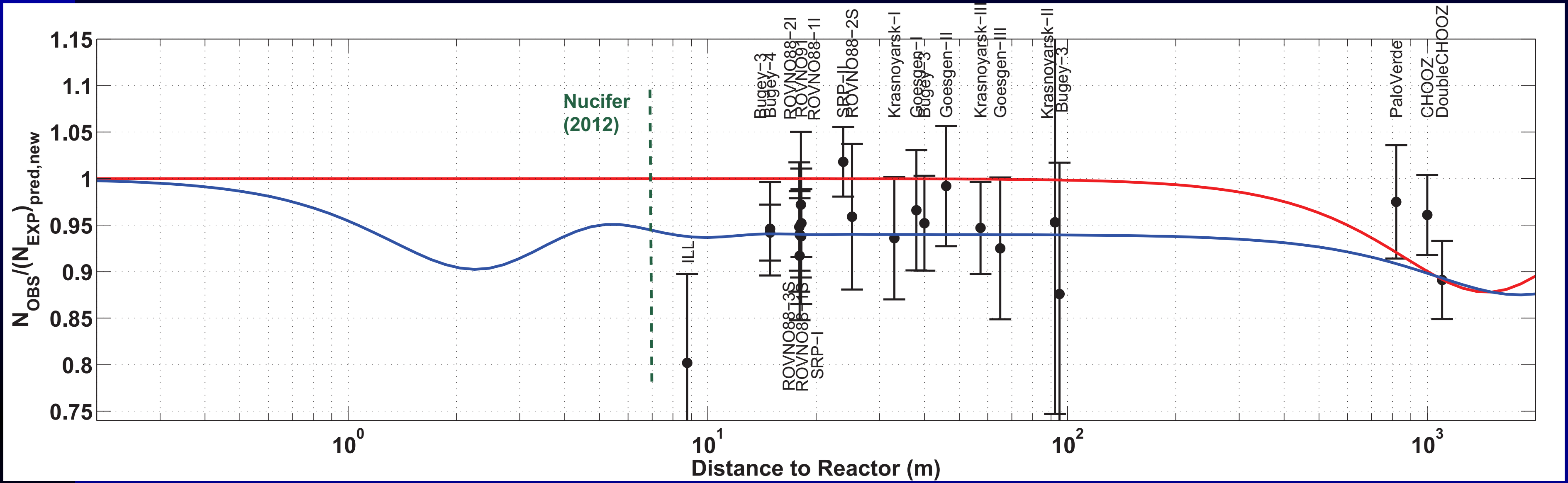




$$P(\bar\nu_\mu \rightarrow \bar\nu_e) \simeq 0.003$$

Tension between neutrino and antineutrino signals?

and the reactor anomaly



6% deficit of $\bar{\nu}_e$ from nuclear reactors at short distances

- In combination they all point to a eV scale sterile neutrino
- But there is strong tension in global fits with disappearance data

Sterile oscillation

In general, in a 3+N sterile neutrino oscillation model one finds that the energy averaged probabilities obey the following inequality

$$P(\nu_\mu \to \nu_e) \leq 4[1 - P(\nu_e \to \nu_e)][1 - P(\nu_\mu \to \nu_\mu)]$$

independent of CP transformations. Therefore, a stringent test of the model is to measure (assuming CPT holds)

- $P(\nu_\mu \to \nu_e)$ or $P(\bar{\nu}_e \to \bar{\nu}_\mu)$ – appearance
- $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ or $P(\nu_e \to \nu_\mu)$ – appearance
- $P(\nu_\mu \to \nu_\mu)$ or $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$ – disappearance
- $P(\nu_e \to \nu_e)$ or $P(\bar{\nu}_e \to \bar{\nu}_e)$ – disappearance

P5 recommendation

Recommendation 15: Select and perform in the short term a set of small-scale short-baseline experiments that can conclusively address experimental hints of physics beyond the three-neutrino paradigm. Some of these experiments should use liquid argon to advance the technology and build the international community for LBNF at Fermilab

Without nuSTORM?

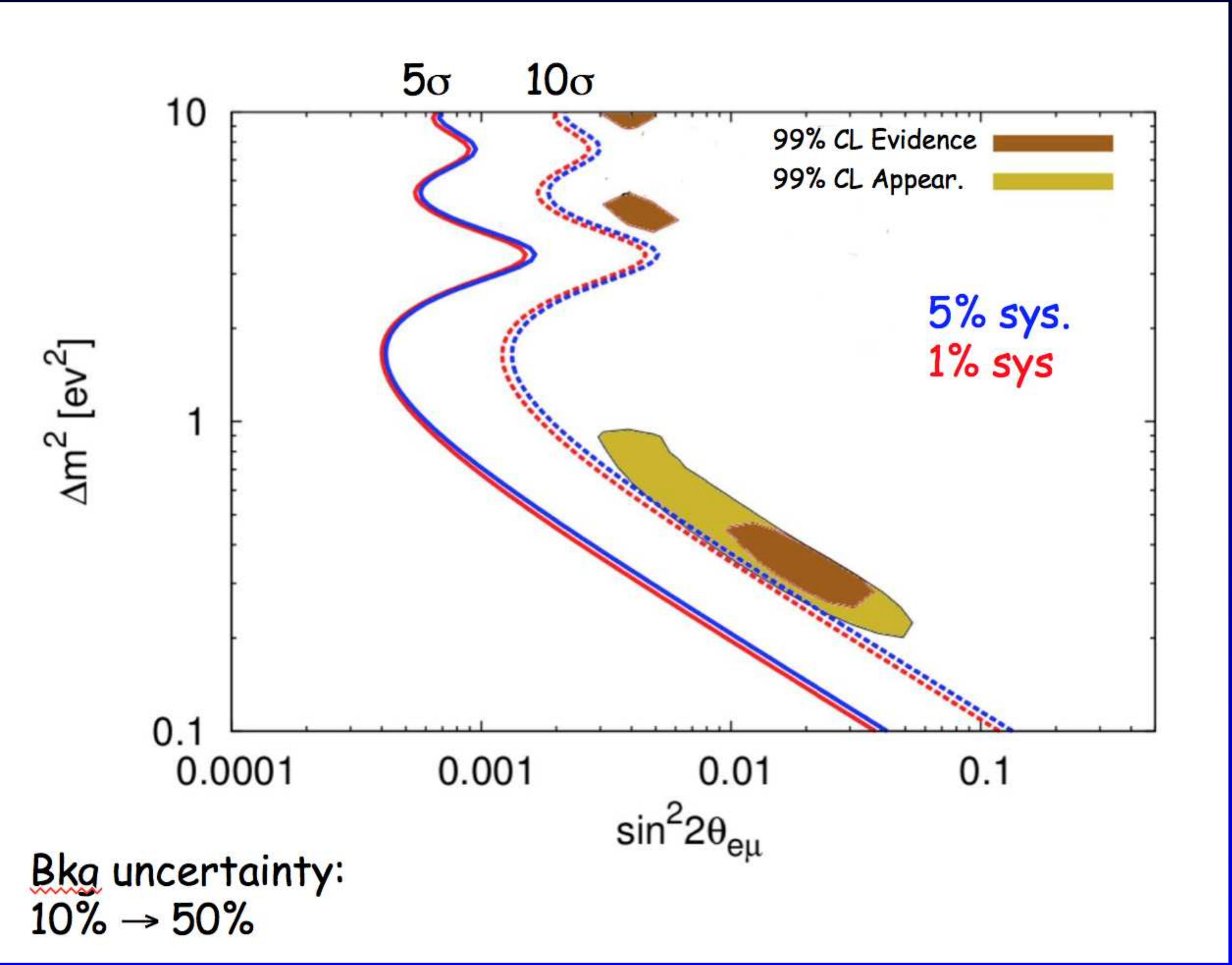
$\nu_\mu \to \nu_\mu$	atmospheric, SBL	$\nu_\mu \to \nu_e$	SBL
$\bar\nu_\mu \to \bar\nu_\mu$	atmospheric, SBL	$\bar\nu_\mu \to \bar\nu_e$	SBL, OscSNS
$\nu_e \to \nu_e$	SOX	$\nu_e \to \nu_\mu$	?
$\bar\nu_e \to \bar\nu_e$	PROSPECT, isoDAR, SOX	$\bar\nu_e \to \bar\nu_\mu$	?

SBL refers to anything put into a conventional neutrino beam at a baseline <2 km

The appearance searches in conventional beams suffer from a S/N$\sim$0.1 and neutral current backgrounds to a ν_e search.

The disappearance searches with SOX and PROSPECT can access only a limited L/E range

Sensitivity of nuSTORM



nuSTORM

nuSTORM delivers a beam with absolute normalization better than 1%

μ^- and μ^+ runs provide precisely CP-conjugate beams

nuSTORM is the only facility which can access all eight channels

And does so with percent-level or better accuracies

The combination of what P5 calls small scale projects: ICARUS++, IsoDAR, LAr1-ND, MicroBooNE, OscSNS and PROSPECT totals at least $200M with overall lesser capabilities than nuSTORM.

Long-baseline Physics

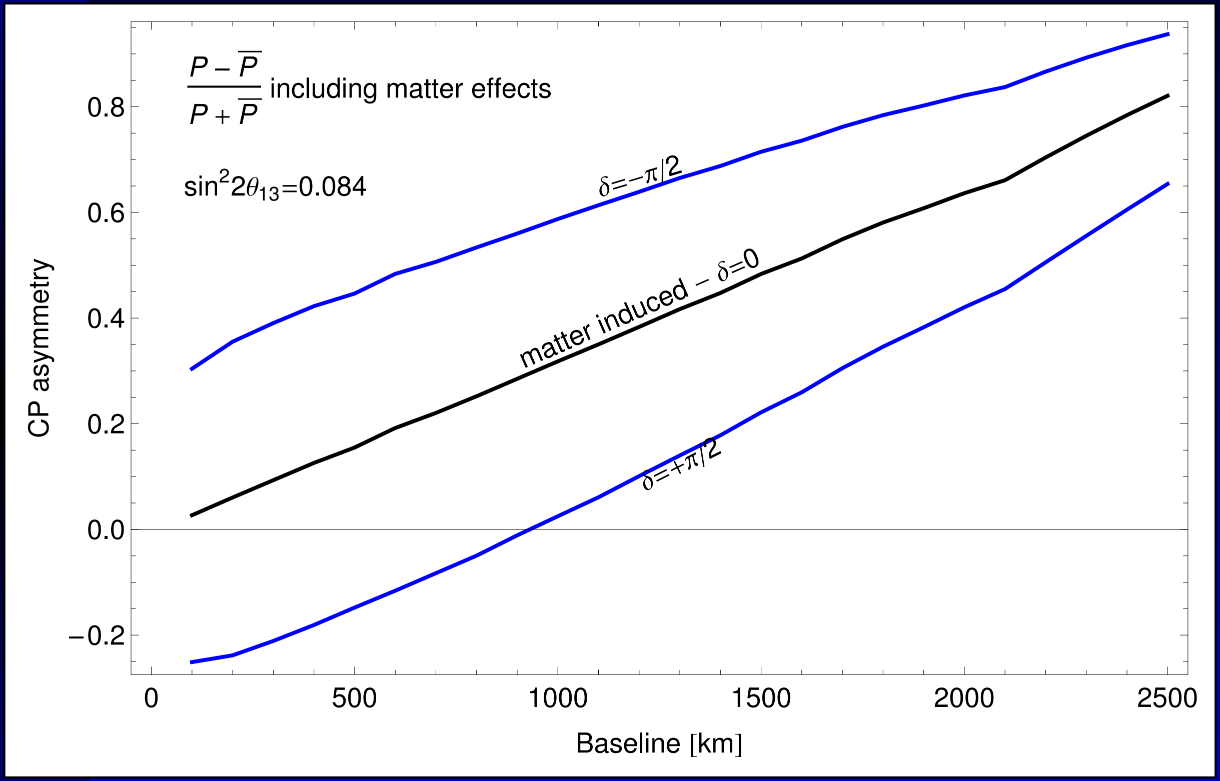
P5 recommendation

Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest-priority large project in its timeframe.

The minimum requirement is to have a sensitivity to discover CP violation for at least 75% of all CP phases at $3\,\sigma$ confidence level.

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

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 . . .

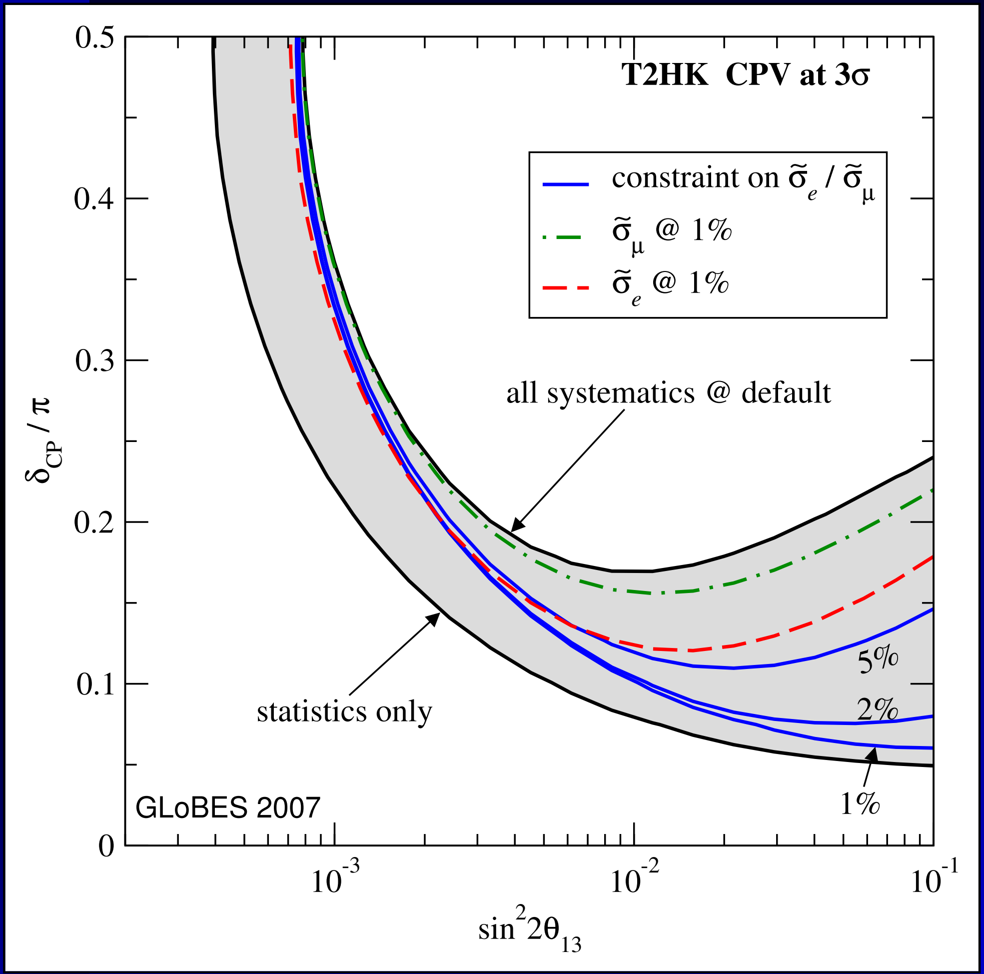
This all works only for disappearance measurements!

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

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

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



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.

PH, Mezzetto, Schwetz, 2007

Differences between ν_e and ν_μ are significant below 1 GeV, see e.g. Day, McFarland, 2012

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
- Nuclear excitations
- Reaction products have to leave the nucleus
- Higher order interactions appear

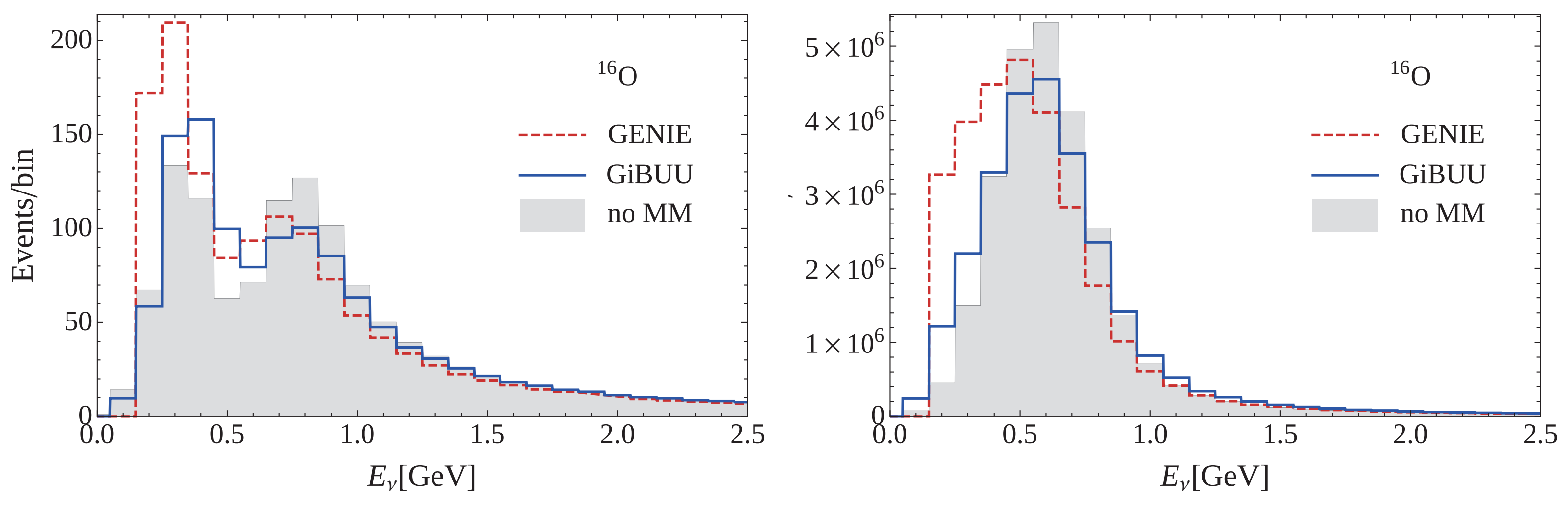
As a function of Q^2 these effects are flavor blind, but we do NOT measure Q^2.

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.



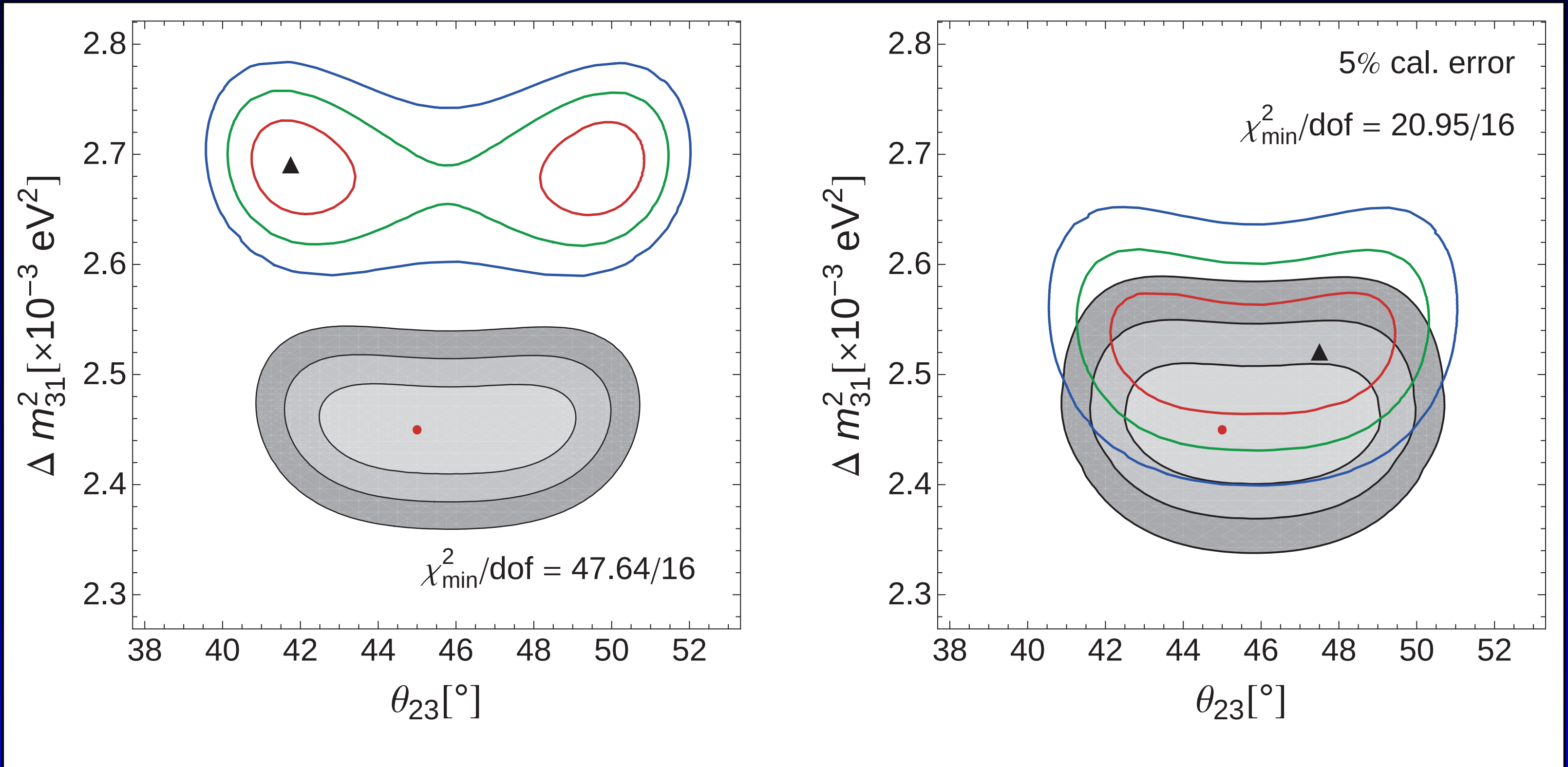
(a) Expected events at the far detector

(b) Expected events at the near detector

Coloma *et al.* 2013

Impact on oscillation

$\nu_\mu \rightarrow \nu_\mu$ 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

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 an approved experiment at Jefferson Lab to collect data on argon
- 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.

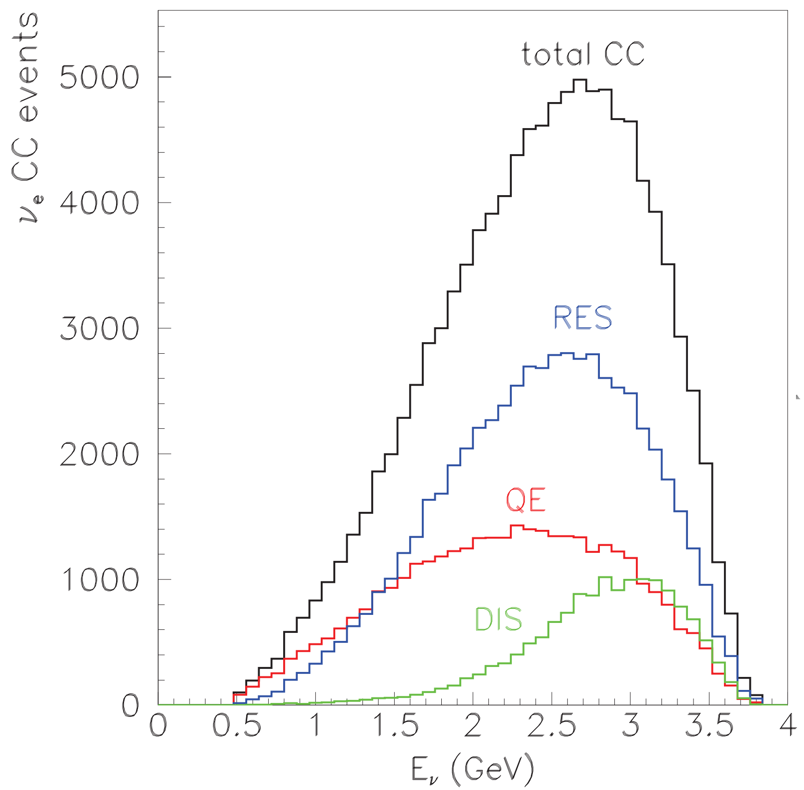
- Sub-percent beam flux normalization
- Very high statistics needed to map phase space
- Neutrinos and antineutrinos
- ν_μ and ν_e

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^+		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

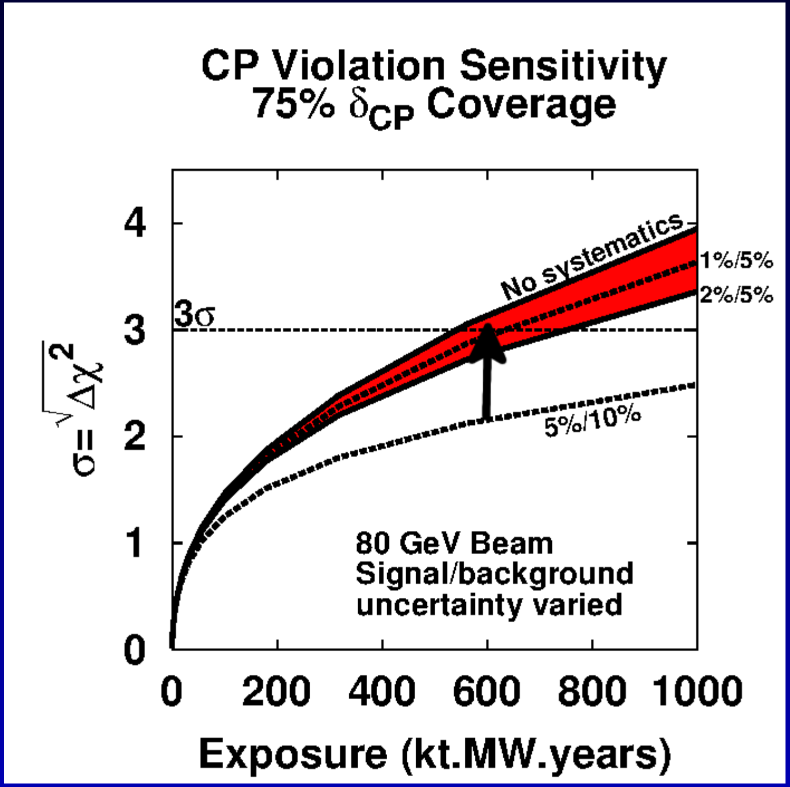
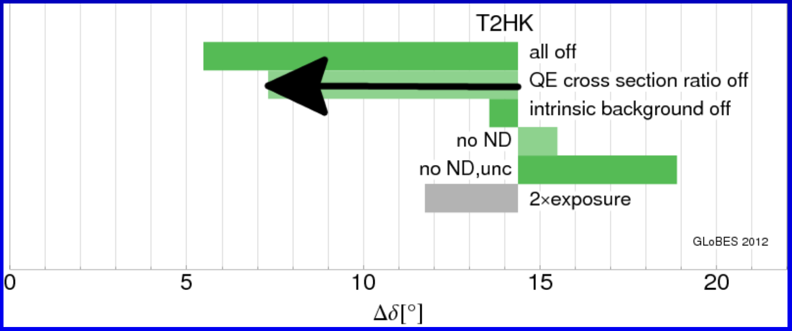


figure courtesy M. Bass, 2014

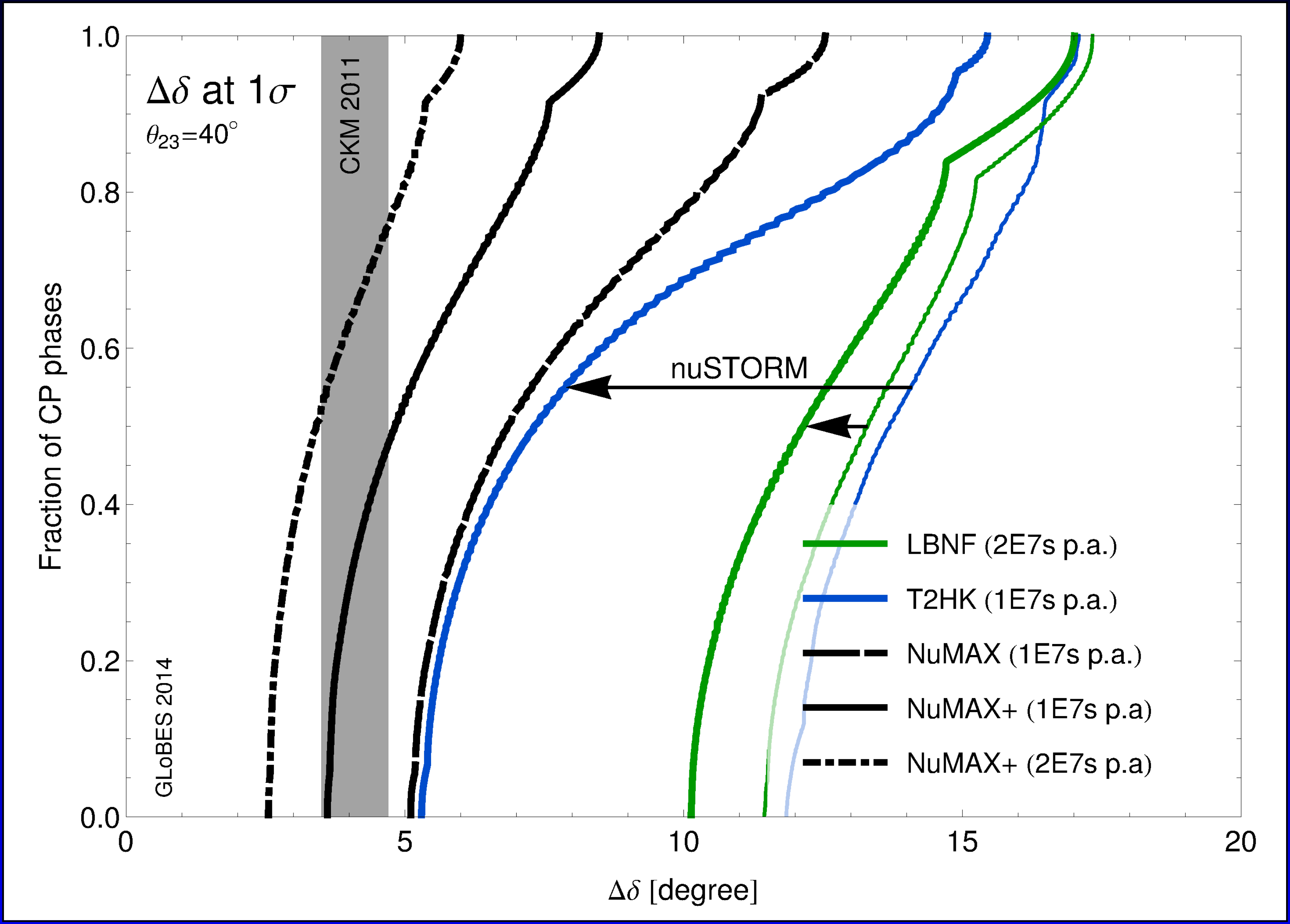


Systematics at the 1% level is necessary for a successful future LBL program

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!

Performance



Summary

- Muon-based neutrino beams deliver on the neutrino-related science drivers as outlined by P5 in a staged program
- They provide internationally competitive physics at each stage
  - nuSTORM – Sterile neutrinos and X-sections, to mitigate the otherwise substantial risk for LBNF to NOT meet the P5 goal on CP violation
  - NuMAX – precision CP phase
  - NuMAX+ – high precision CP phase and unitarity
- MAP is uniquely positioned to deliver these muon-based neutrino beams.