Hadronic FS effects on neutrino oscillations

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Final Sate Nucleons for Neutrino-Nucleus Interactions

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P5 dixit

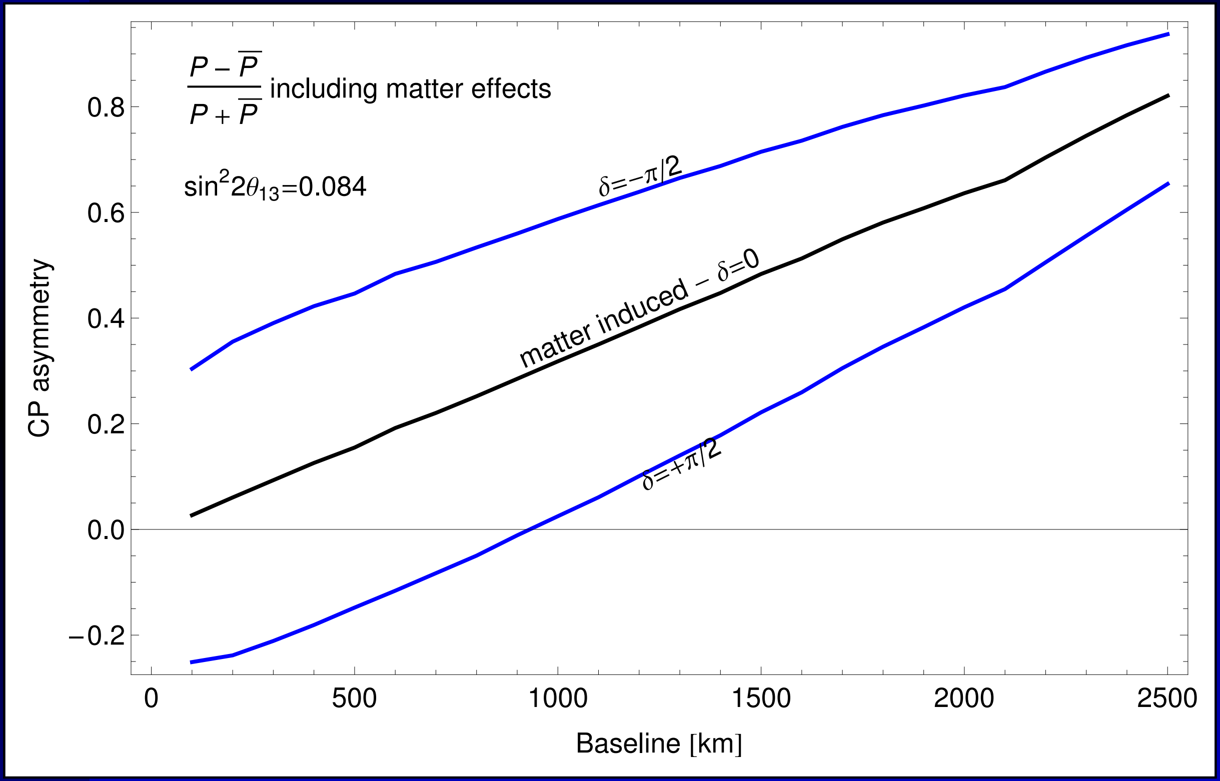
Recommendation 12: In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.

For a long-baseline oscillation experiment, based on the science Drivers and what is practically achievable in a major step forward, we set as the goal a mean sensitivity to CP violation[2] of better than 3σ (corresponding to 99.8% confidence level for a detected signal) over more than 75% of the range of possible values of the unknown CP-violating phase δ_{CP}. By current esti-

P5 stands for Particle Physics Project Prioritization Panel and is a sub-panel of HEPAP, the High-Energy Physics Advisory Panel. P5 has released a report in 2014 based on a year-long community study (aka SNOWMASS) which sets the priorities for the U.S. program for the next 5-10 years.

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 a specific support program 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.

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)

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

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

And the error on $\frac{N_\mathrm{far}}{N_\mathrm{near}}$ 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 . . .

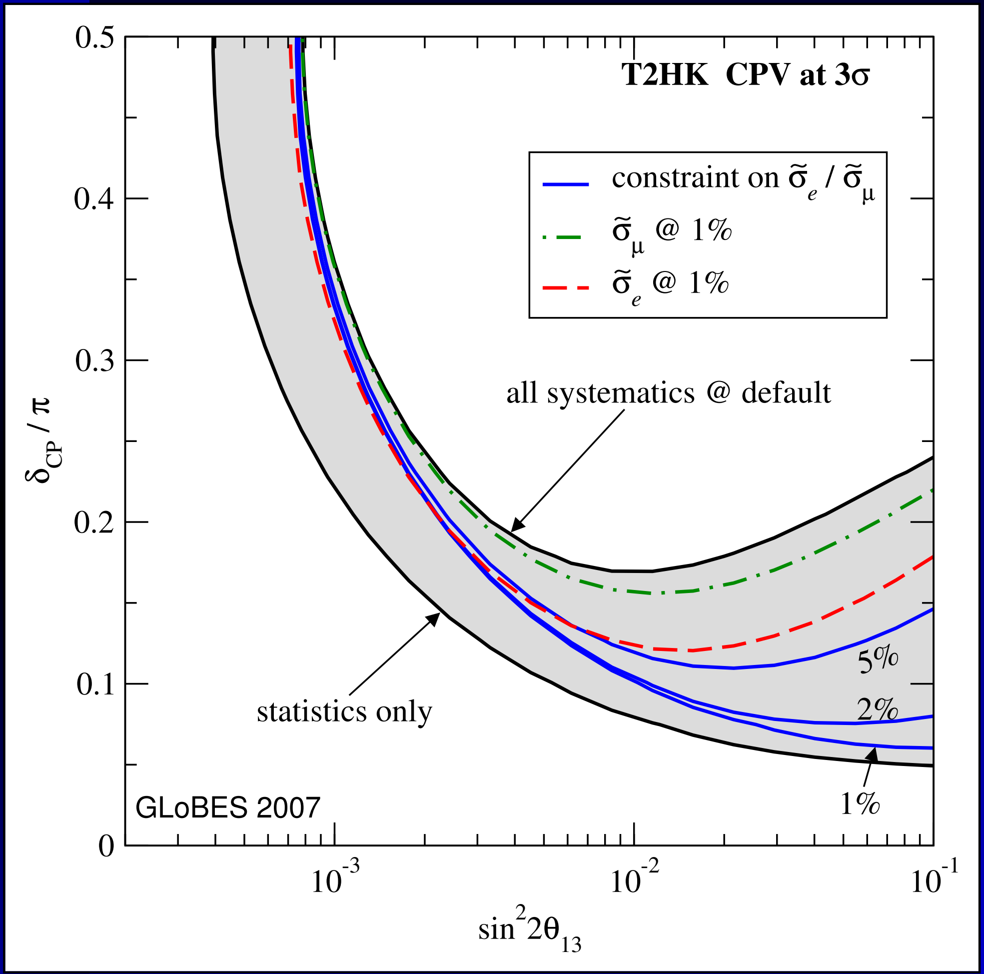
This all works only for disappearance measurements!

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

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

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 e.g. Day, McFarland, 2012

A simple analysis

Numbers before using a near detector

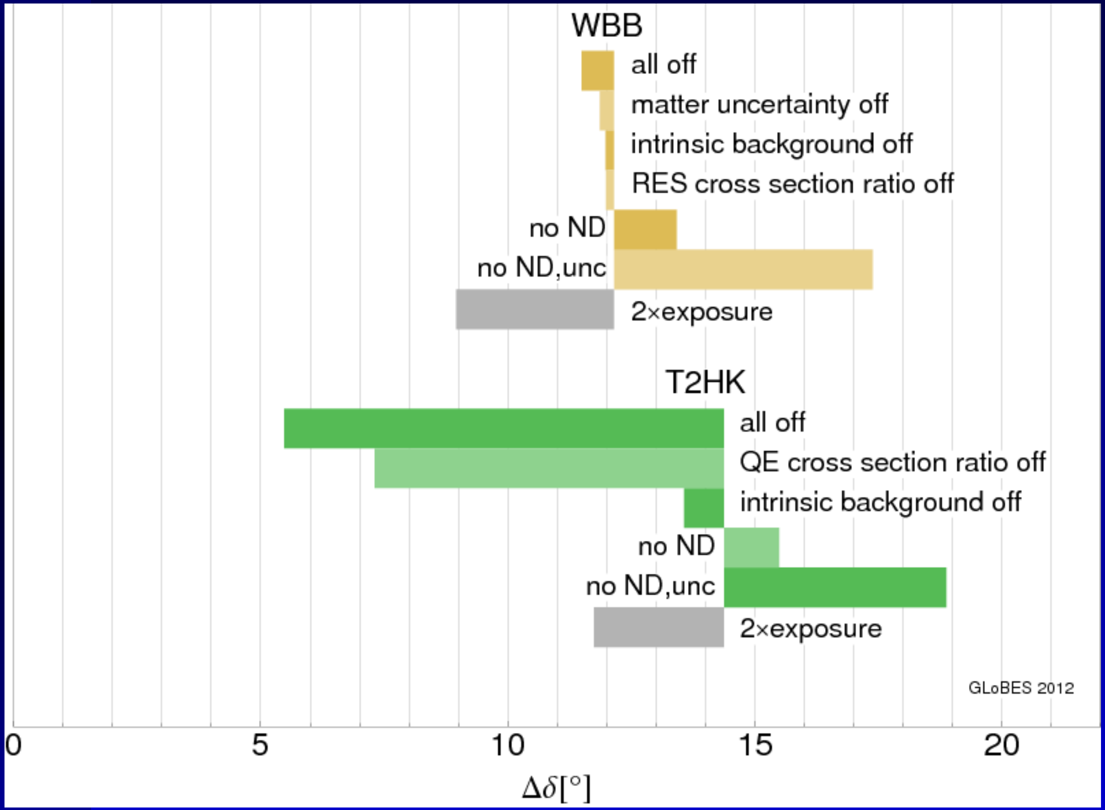
Systematics	SB Opt.	SB Def.	SB Cons.	BB Opt.	BB Def.	BB Cons.	NF Opt.	NF Def.	NF Cons.
Fiducial volume ND	0.2%	0.5%	1%	0.2%	0.5%	1%	0.2%	0.5%	1%
Fiducial volume FD	1%	2.5%	5%	1%	2.5%	5%	1%	2.5%	5%
(incl. near-far extrap.)									
Flux error signal ν	5%	7.5%	10%	1%	2%	2.5%	0.1%	0.5%	1%
Flux error background 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 × eff. QE†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs × eff. RES†	10%	15%	20%	10%	15%	20%	10%	15%	20%
Cross secs × 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

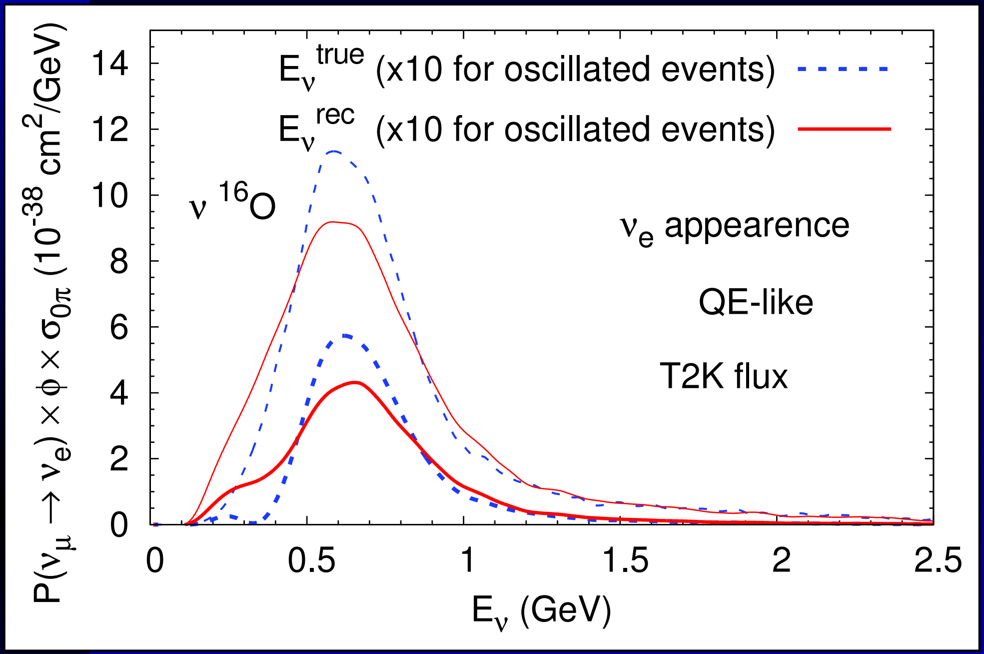


Disappearance data can play the role of near detector if three flavor framework is assumed

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

QE energy reconstruction



Lalakulich, Mosel, 2012

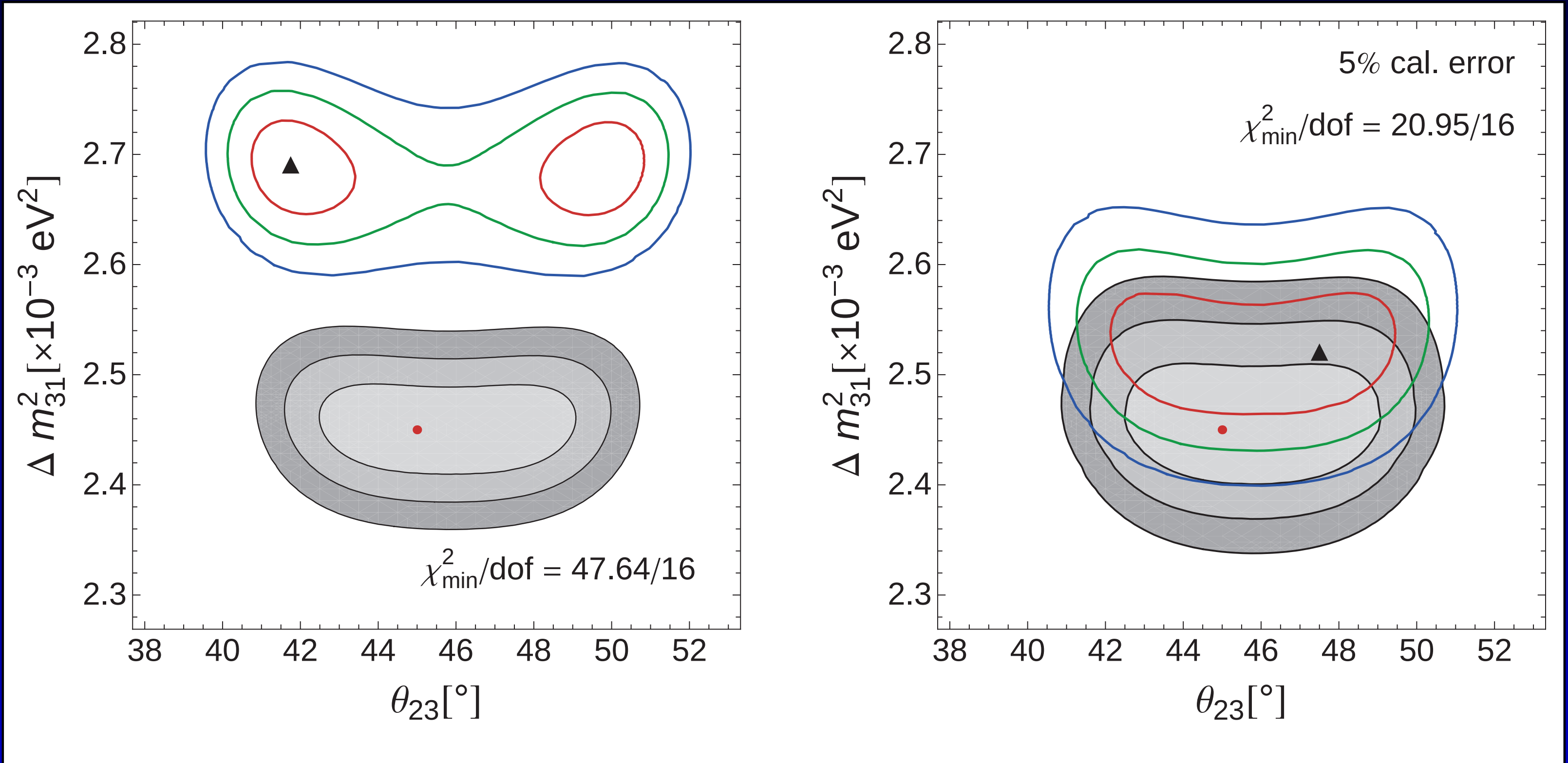
Nuclear effects change the relation between true neutrino energy and lepton energy

Inferring the CP phase from QE spectrum seems quite difficult

Not obvious that near detectors alone can solve this problem.

Impact on oscillation

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



(a) No calibration error

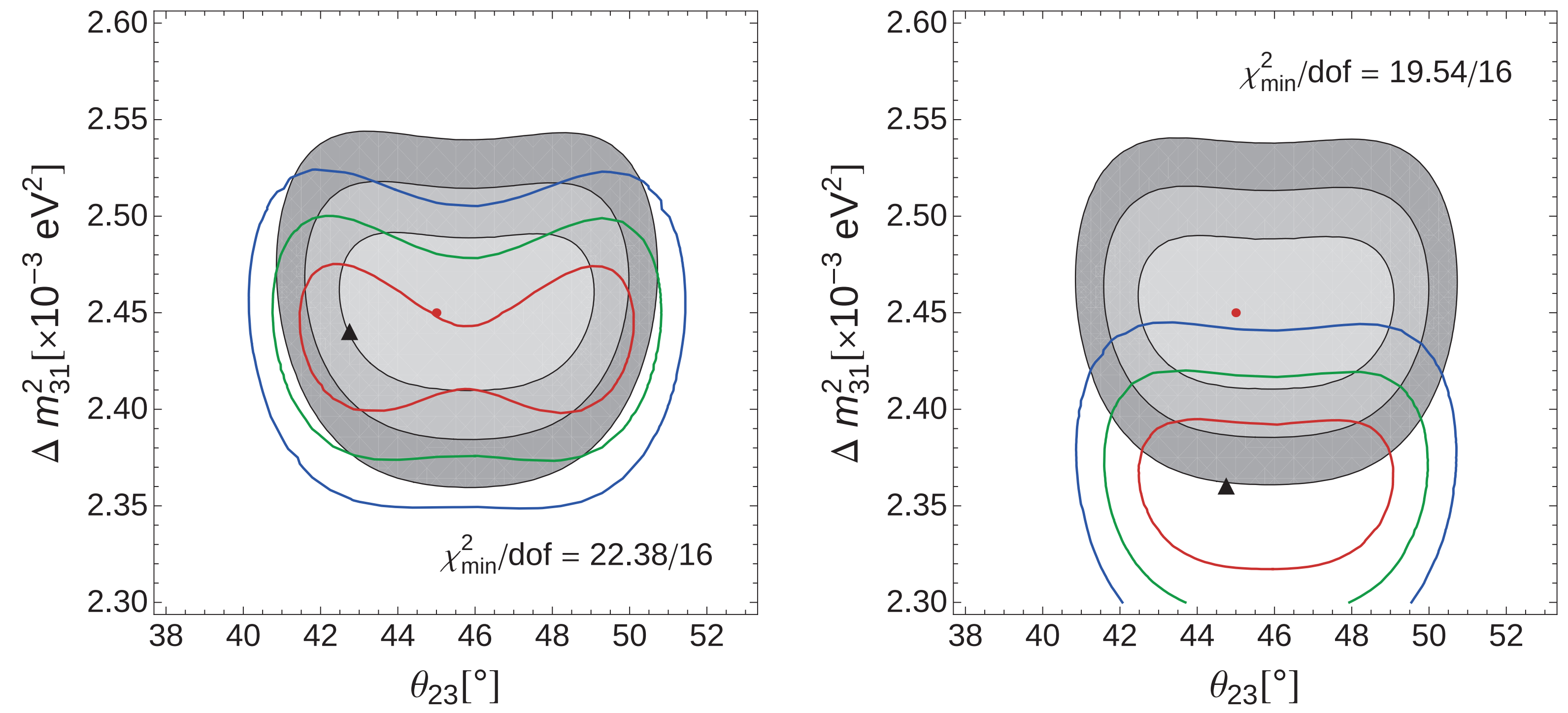
(b) 5% calibration error

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



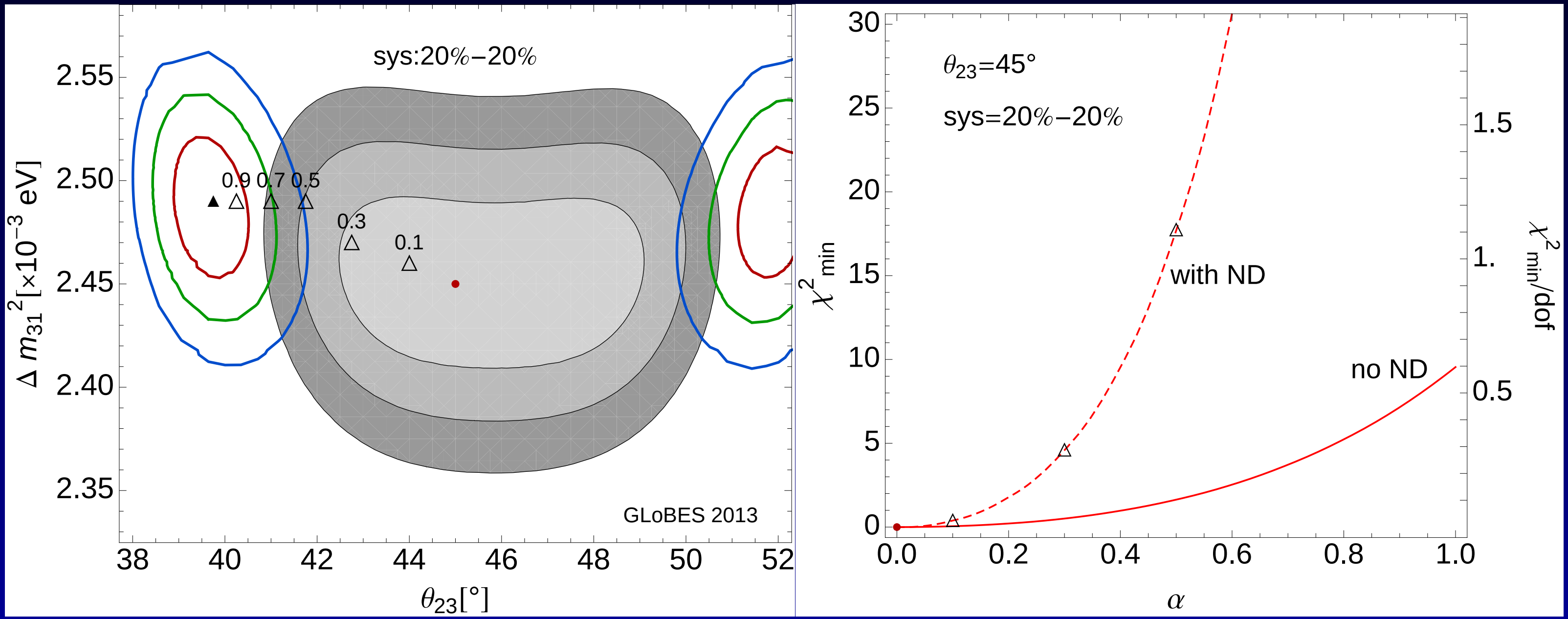
(a) Results using GiBUU matrices and cross sections

(b) Results using GENIE matrices and cross sections

Coloma *et al.* 2013

Different generators make very different predictions

Nuclear effects in QE



Coloma *et al.* 2013

$$N_i^{\text{test}}(\alpha) = \alpha \times N_i^{QE} + (1-\alpha) \times N_i^{QE-like}$$

where $\alpha = 0$ corresponds to perfectly know nuclear effects and $\alpha = 1$ to entirely unknown nuclear effects in the fit.

Calorimetry

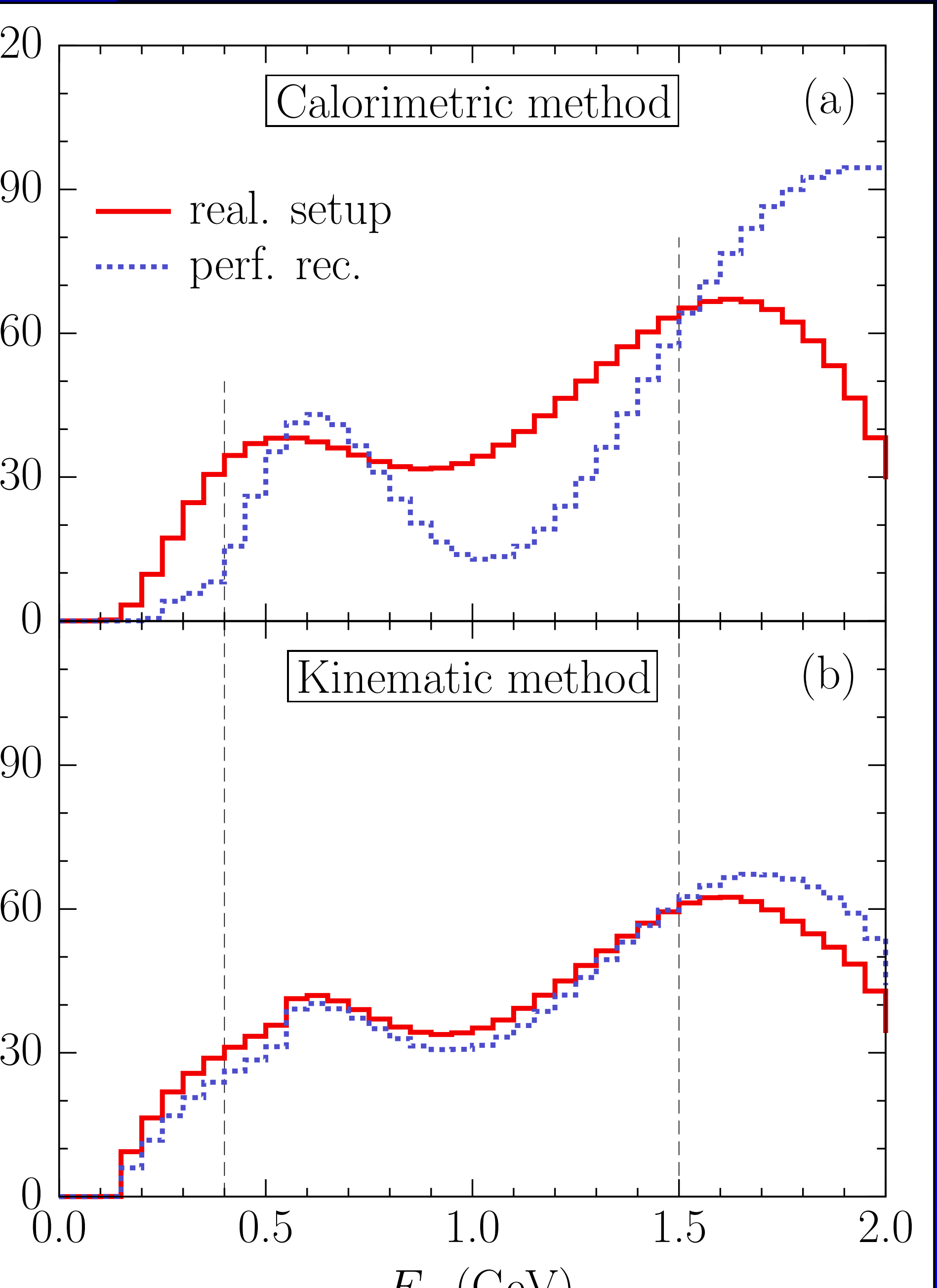
In some detectors, like LAr, there will be calorimetry

- 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!

Calorimetry – an example



PRELIMINARY Ankowski, Benhar, Coloma, Huber, Jen, Mariani, Vagnoni

LAGUNA beam and baseline is 550 km

Hypothetical detector (all active with magnetic field)

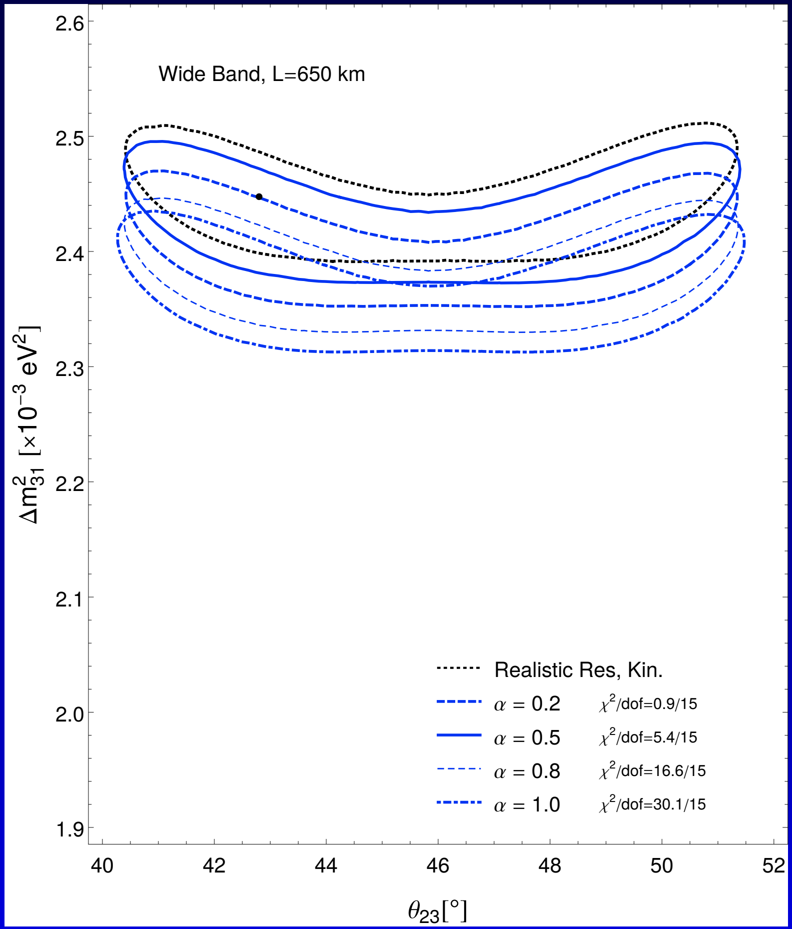
Selecting events with at least one particle beyond the leading muon

Hadronic reconstruction: $E_{rec} = E_\mu + E_{had}$

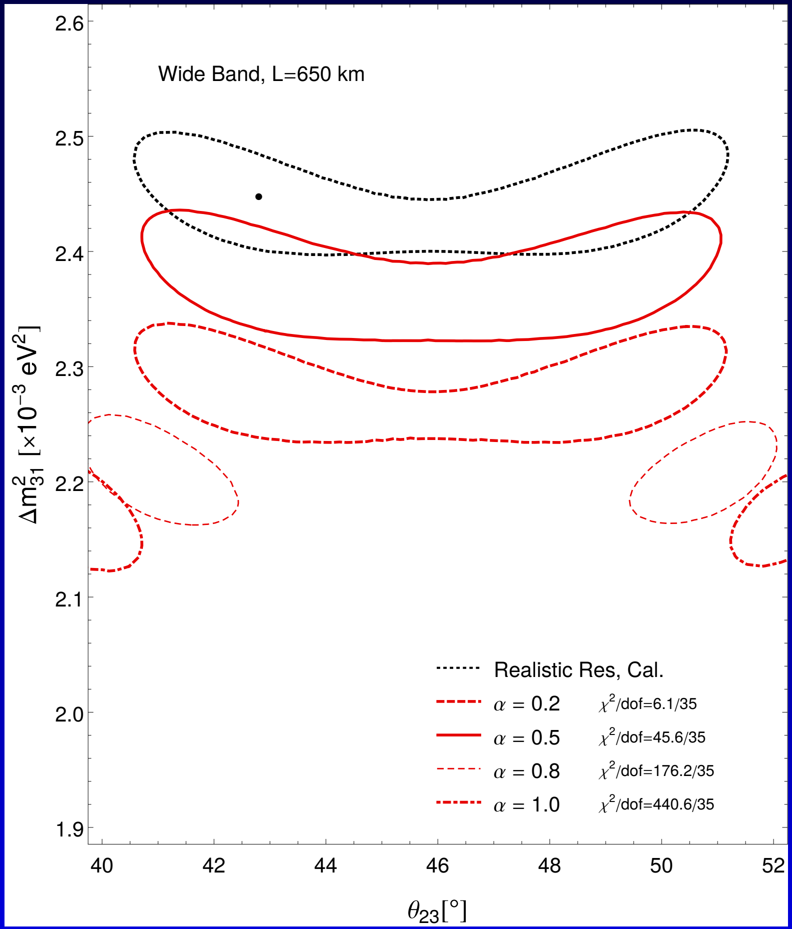
Kinematic reconstruction: based on muon energy and angle

Impact on oscillations

Introduce α parameter interpolating between ideal and "realistic" cases



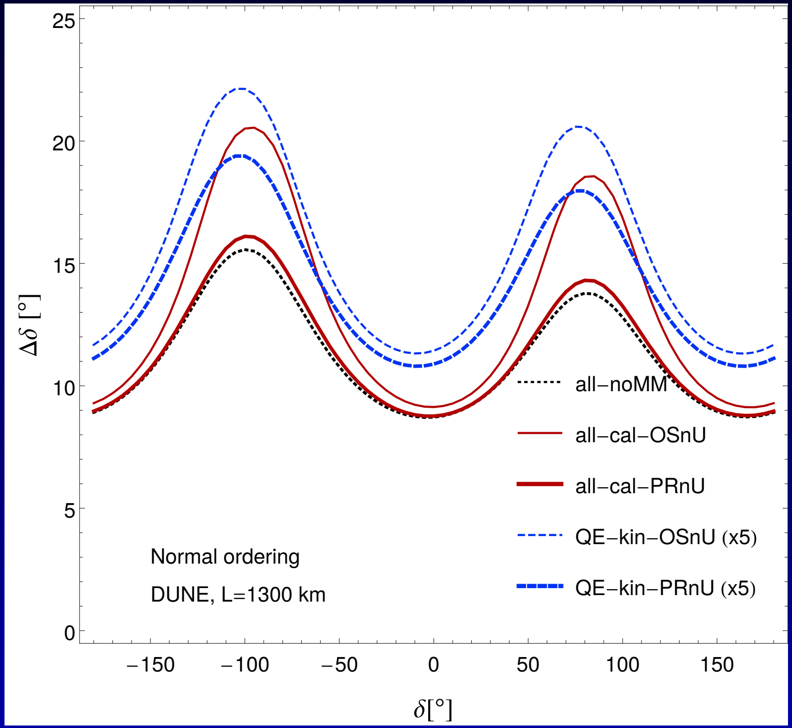
Kinematic analysis



Calorimetric analysis

PRELIMINARY

What about CP violation?



MORE PRELIMINARY

At this stage: all detector effects, mostly detection thresholds.

Clearly, the question is: what happens if you look at variations of the underlying nuclear physics.

Theory and cross sections

Theory is cheap, but multi-nucleon systems and their dynamic response are a hard problem. Currently, there all major approaches have in common that they rely on assumptions which are not guaranteed to be fulfilled in the experiment in question.

Thus to trust theory at x% we have to experimentally test the theory at x% – ultimately, precision cross section measurements are unavoidable.

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

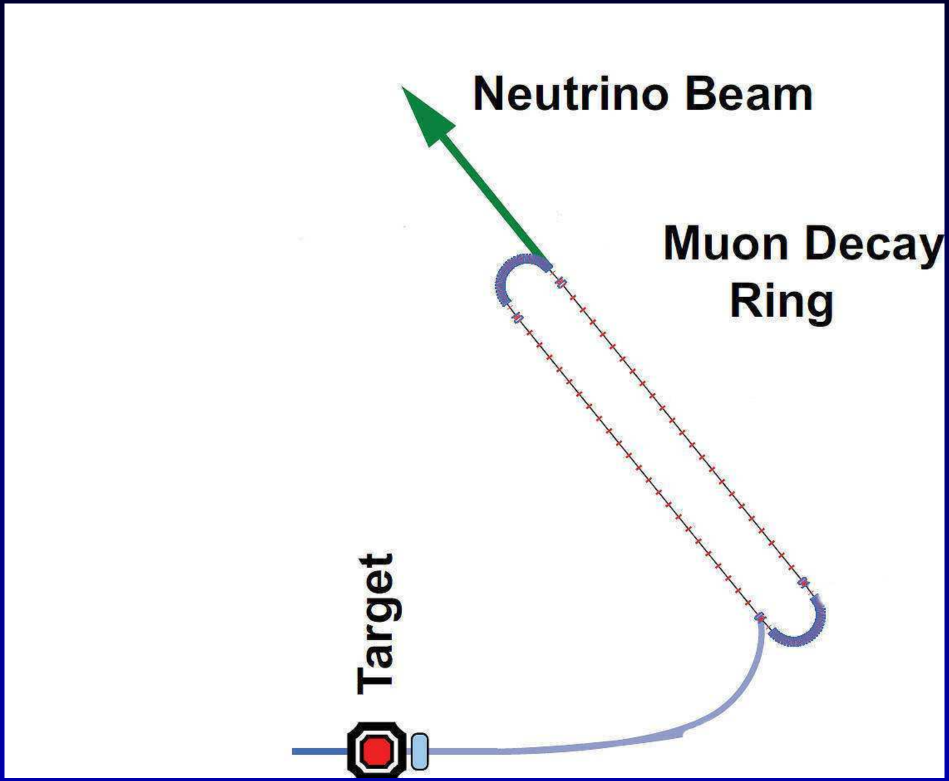
Assumes excellent hadron calorimetry

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

Towards precise cross sections

Needs better neutrino sources

- 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.

Summary

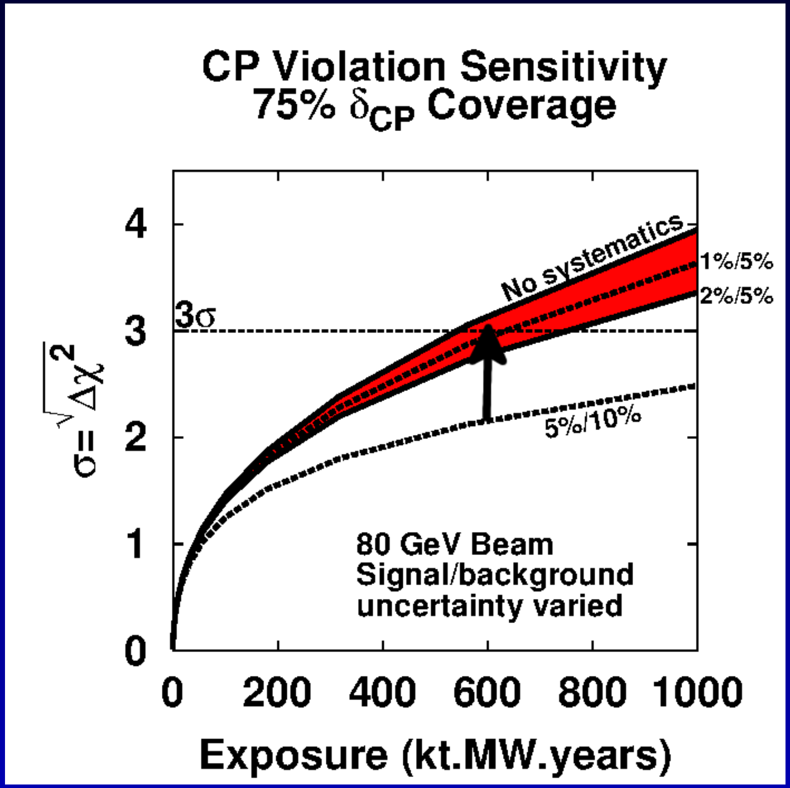
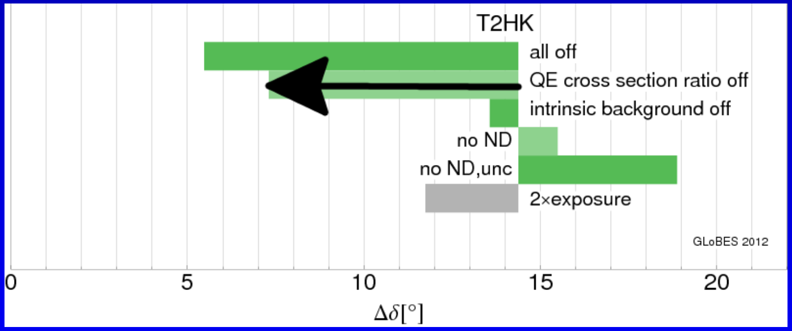


figure courtesy M. Bass, 2014



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!

Conclusions

Neutrino physics has provided us with a number of clues for new physics and the next frontier is CP violation.

- The U.S. has decided to take a leading role
- LBNF presents a unique opportunity for the global community

Realizing the full physics potential and meeting the P5 criteria crucially relies on achieving an unprecedented level of systematics control – a precise understanding of neutrino-nucleus cross sections is necessary.

This will require a significant effort – both in theory and experiment!