Large θ_{13}
Challenge and Opportunity

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Experimental Seminar

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θ_{13} is large!

The Daya Bay result is

$$\sin^2 2\theta_{13} = 0.089 \pm 0.010(\mathrm{stat}) \pm 0.005(\mathrm{syst})\,,$$

which translates into a more than $5\,\sigma$ exclusion of $\theta_{13} = 0$, confirmed by RENO.

NB – a 1.5 years ago we had only $2\,\sigma$ indications.

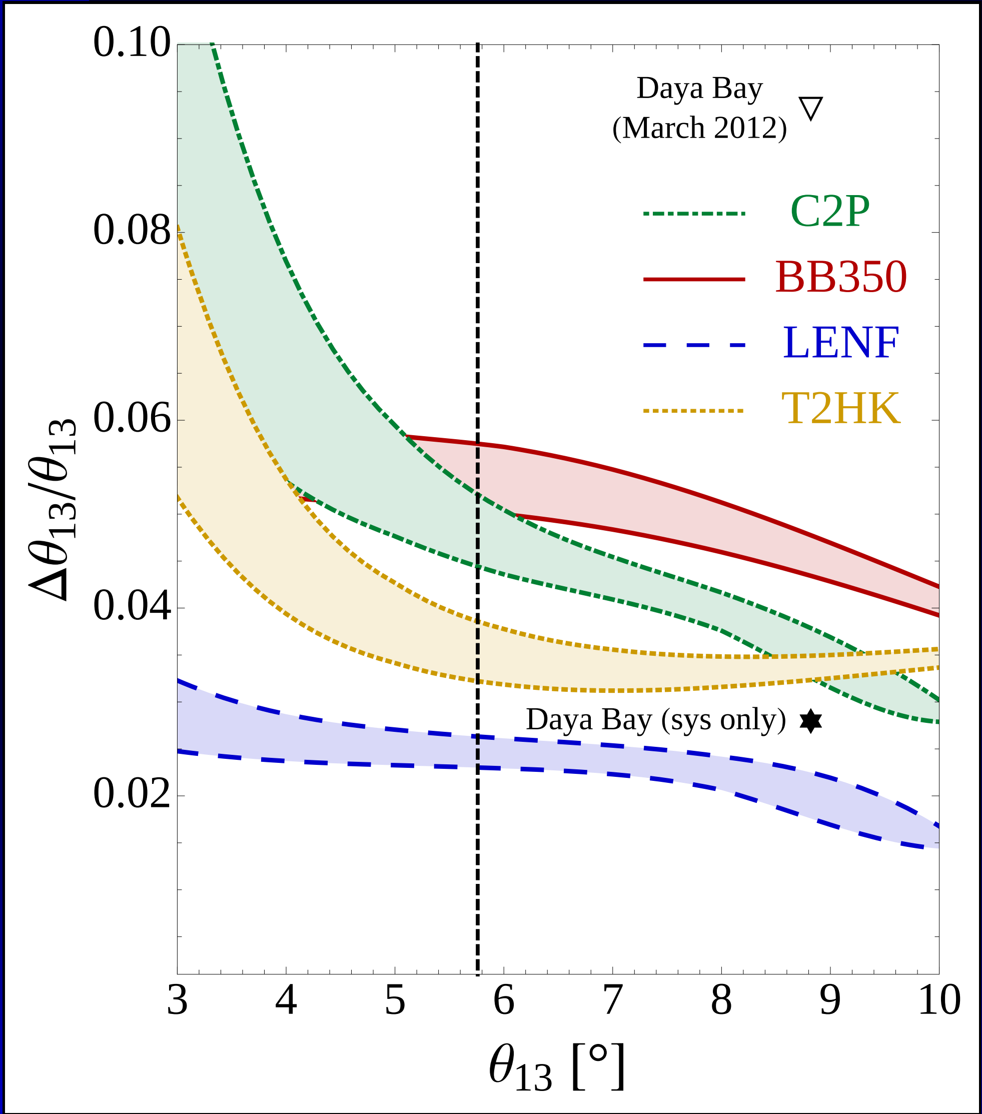
Implications

In general, this raises the following questions

- Is neutrino physics essentially done?
- Will the mass hierarchy have been determined before the next generation of long-baseline experiments?
- Are new experiments beyond NOνA and T2K necessary to discover CP violation?
- Are superbeams sufficient for precision neutrino physics?

Any of this questions is both a challenge and opportunity!

The future of θ_{13}



FAPP θ_{13} will be known to very high accuracy

At $\sin^2 2\theta_{13} = 0.1$ the measurement error at T2K will be 10%

At $\sin^2 2\theta_{13} = 0.1$ the measurement error at Daya Bay will be <5%

Agreement of values of θ_{13} from reactors (disappearance) and beams (appearance) constitutes a critical test of the 3 flavor framework

P. Coloma, A. Donini, E. Fernandez-Martinez, P. Hernandez, arXiv:1203.5651

Neutrinos are massive – so what?

Neutrinos in the Standard Model (SM) are strictly massless, therefore the discovery of neutrino oscillation, which implies non-zero neutrino masses requires the addition of new degrees of freedom.

The discovery of a light sterile neutrino could well be the most significant piece of BSM physics in the last 30 years.

We always knew they are . . .

The SM is an effective field theory, *i.e.* at some high scale Λ new degrees of freedom will appear

$$\mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \ldots$$

The first operators sensitive to new physics have dimension 5. It turns out there is only one dimension 5 operator

$$\mathcal{L}_5 = \frac{1}{\Lambda}(LH)(LH) \to \frac{1}{\Lambda}(L\langle H\rangle)(L\langle H\rangle) = m_\nu \nu\nu$$

Thus studying neutrino masses is, in principle, the most sensitive probe for new physics at high scales
Weinberg

Effective theories

The problem in effective theories is, that there are *a priori* unknown pre-factors for each operator

$$\mathcal{L}_{SM} + \frac{\#}{\Lambda}\mathcal{L}_5 + \frac{\#}{\Lambda^2}\mathcal{L}_6 + \ldots$$

Typically, one has $\# = \mathcal{O}(1)$, but there may be reasons for this being wrong

- lepton number may be conserved $\to$ no Majorana mass term
- lepton number may be approximately conserved $\to$ small pre-factor for $\mathcal{L}_5$

Therefore, we do not know the scale of new physics responsible for neutrino masses.

Flavor models

Simplest un-model – anarchy Murayama, Naba, DeGouvea

$$dU = ds_{12}^2\, dc_{13}^4\, ds_{23}^2\, d\delta_{CP}\, d\chi_1\, d\chi_2$$

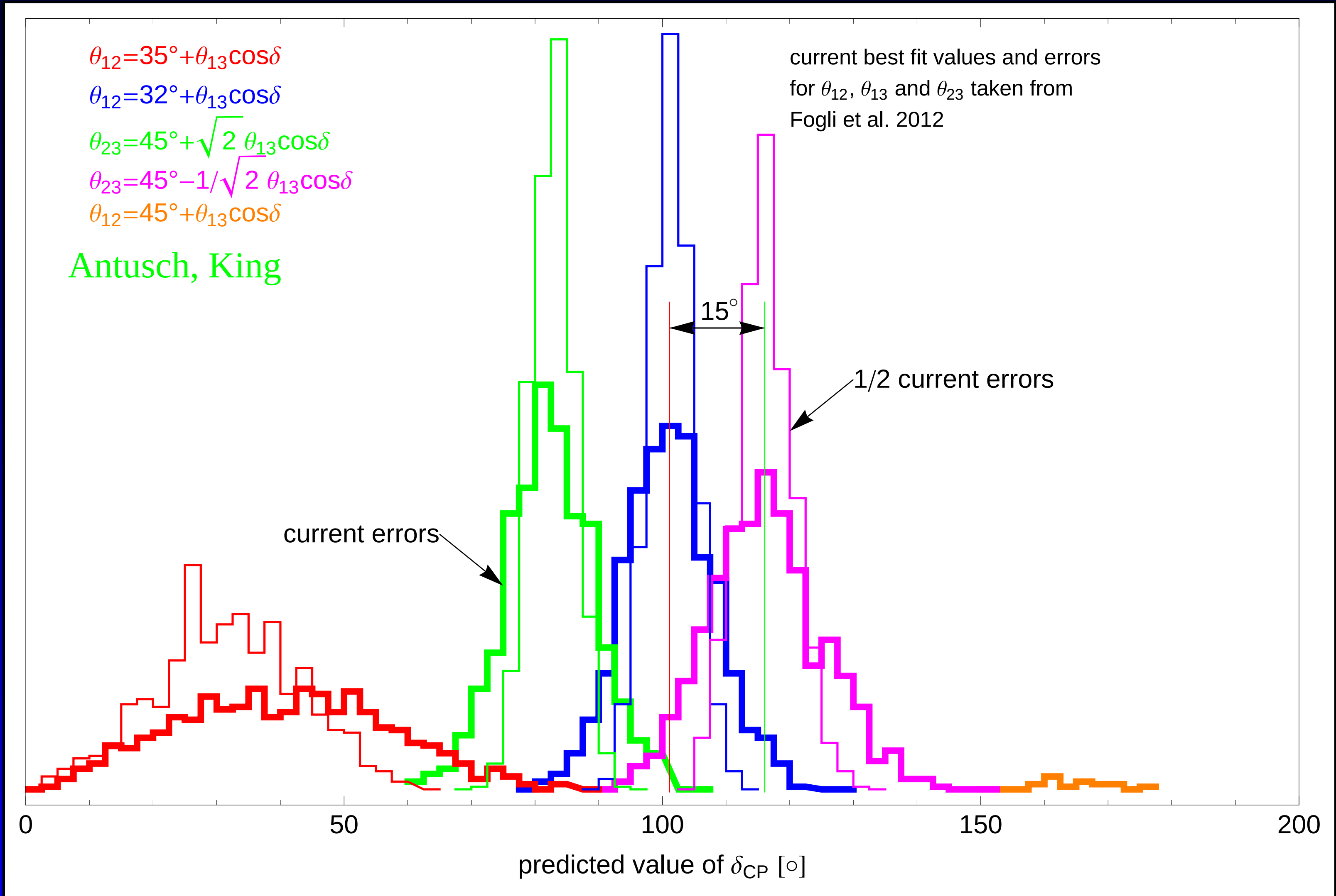
predicts flat distribution in δ_{CP}

Simplest model – Tri-bimaximal mixing Harrison, Perkins, Scott

$$\begin{pmatrix} \sqrt{\frac{1}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

to still fit data, obviously corrections are needed – predictivity?

Sum rules



$3\,\sigma$ resolution of 15° distance requires 5° error. NB – smaller error on θ_{12} requires dedicated experiment like Daya Bay II

What we want to learn

In the context of neutrino oscillation experiments

- δ_{CP}
- mass hierarchy
- $\theta_{23} = \pi/4$, $\theta_{23} < \pi/4$ or $\theta_{23} > \pi/4$?
- Resolution of LSND and the other short-baseline anomalies
- New physics?

Given the current state of the theory of neutrinos we can not say with confidence that any one quantity is more fundamental than any other.

Phenomenology of 3×3 active oscillations

CP violation

Like in the quark sector mixing can cause CP violation

$$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq 0$$

The size of this effect is proportional to

$$J_{CP} = \frac{1}{8} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin\delta$$

but the asymmetry

$$\frac{P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)}{P(\nu_\alpha \to \nu_\beta) + P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)} \propto \frac{1}{\sin 2\theta_{13}}$$

The experimentally most suitable transition to study CP violation is $\nu_e \leftrightarrow \nu_\mu$.

Matter effects

The charged current interaction of ν_e with the electrons creates a potential for ν_e

$$A = \pm 2\sqrt{2} G_F \cdot E \cdot n_e$$

where $+$ is for ν and $-$ for $\bar{\nu}$.
This potential gives rise to an additional phase for ν_e and thus changes the oscillation probability. This has two consequences

$$P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq 0$$

even if $\delta = 0$, since the potential distinguishes neutrinos from anti-neutrinos.

Matter effects

The second consequence of the matter potential is that there can be a resonant conversion – the MSW effect. The condition for the resonance is

$$\Delta m^2 \simeq A \quad \Leftrightarrow \quad E_{\mathrm{res}}^{\mathrm{Earth}} = 6 - 8\,\mathrm{GeV}$$

Obviously the occurrence of this resonance depends on the signs of both sides in this equation. Thus oscillation becomes sensitive to the mass ordering

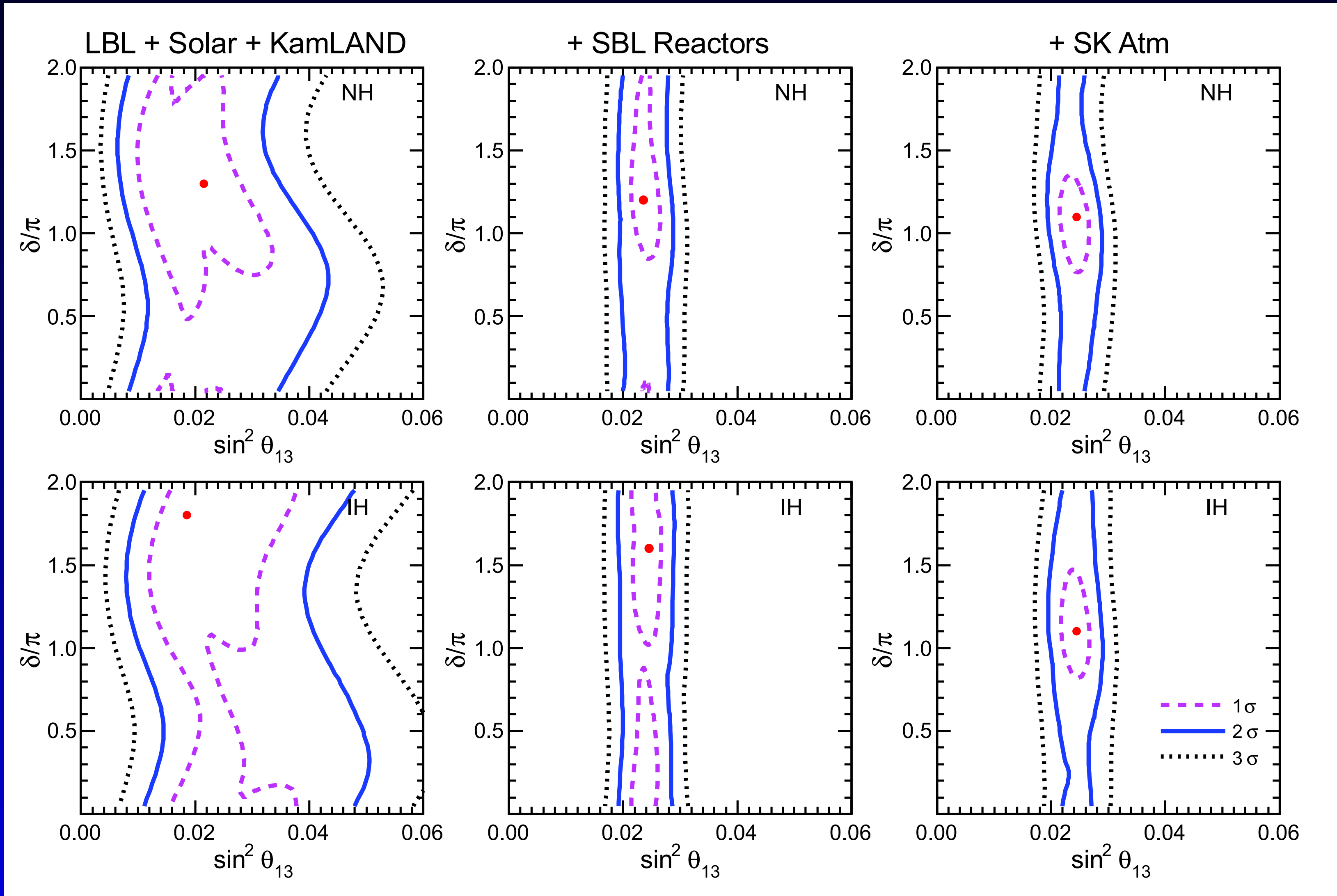
	ν	$\bar{\nu}$
$\Delta m^2 > 0$	MSW	-
$\Delta m^2 < 0$	-	MSW

Consequences for experiments

- need to measure 2 out of $P(\nu_\mu \to \nu_e)$, $P(\bar{\nu}_\mu \to \bar{\nu}_e)$, $P(\nu_e \to \nu_\mu)$ and $P(\bar{\nu}_e \to \bar{\nu}_\mu)$
- need more than 1 energy and/or 1 baseline
- matter resonance at $6 - 8\,\mathrm{GeV}$
- matter effects sizable for $L > 1\,000\,\mathrm{km}$
- large θ_{13} implies small CP asymmetries
  $\Rightarrow$ need for small systematics

Are new experiments still necessary?

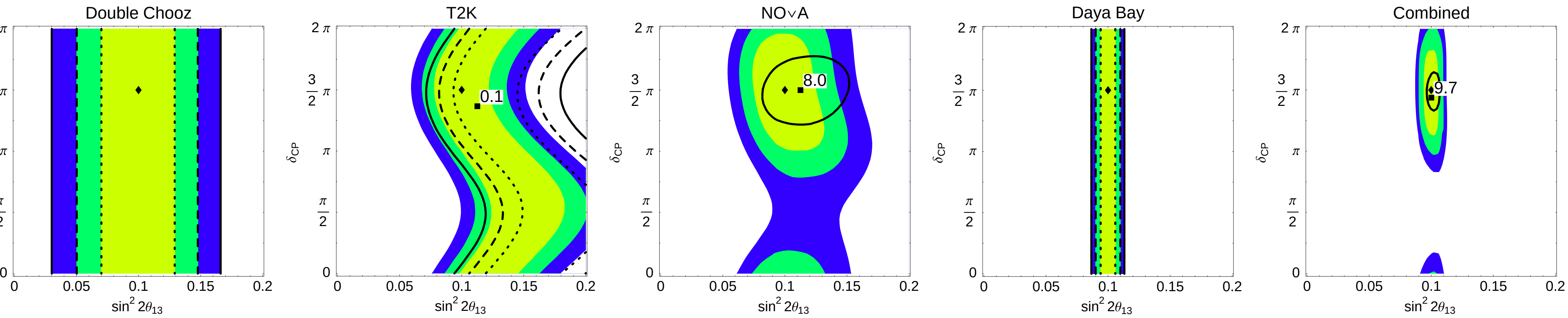
Status quo



Fogli, *et al.*, arXiv:1205.5254

NB – 1 σ range for $\delta = 30 - 35^\circ$

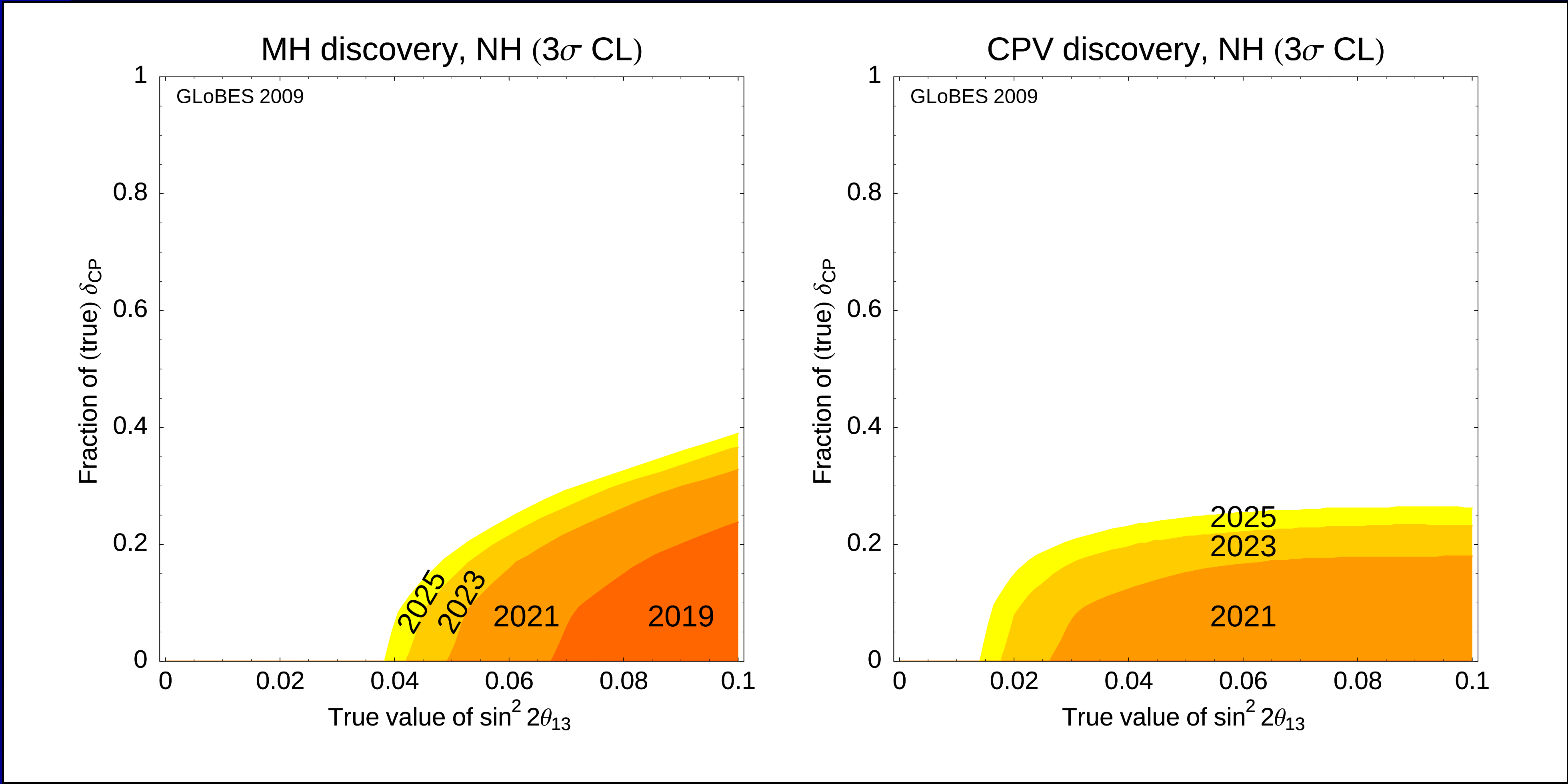
CPV without new experiments?



PH, M. Lindner, T. Schwetz, W. Winter, JHEP 11 044 (2009), arXiv:0907.1896.

Barely reaches $3\,\sigma$ for mass hierarchy, and this is the most favorable δ_{CP}!

CPV without new experiments?

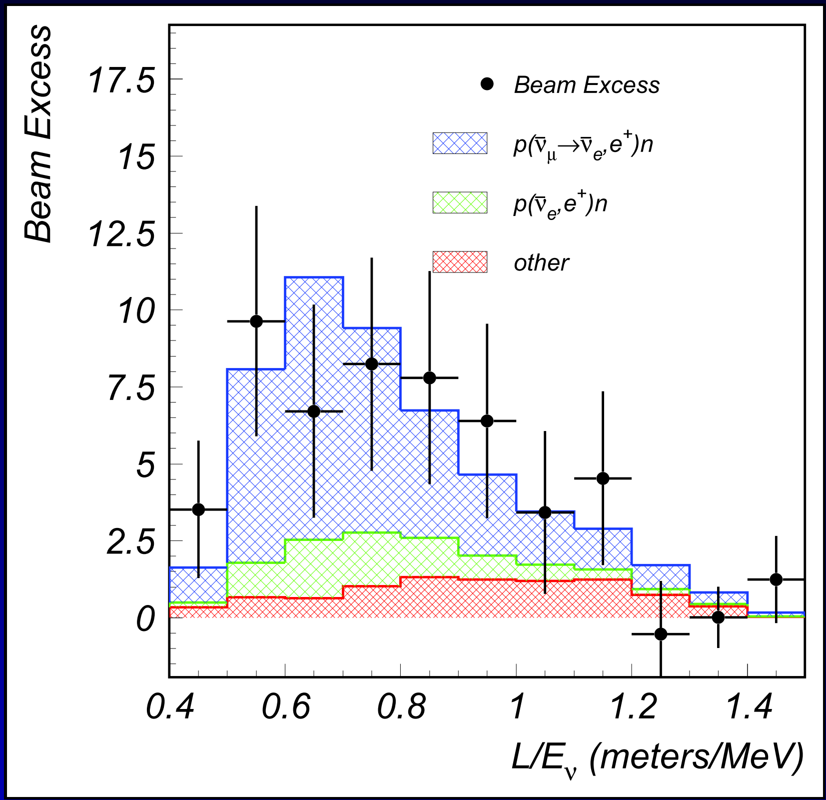


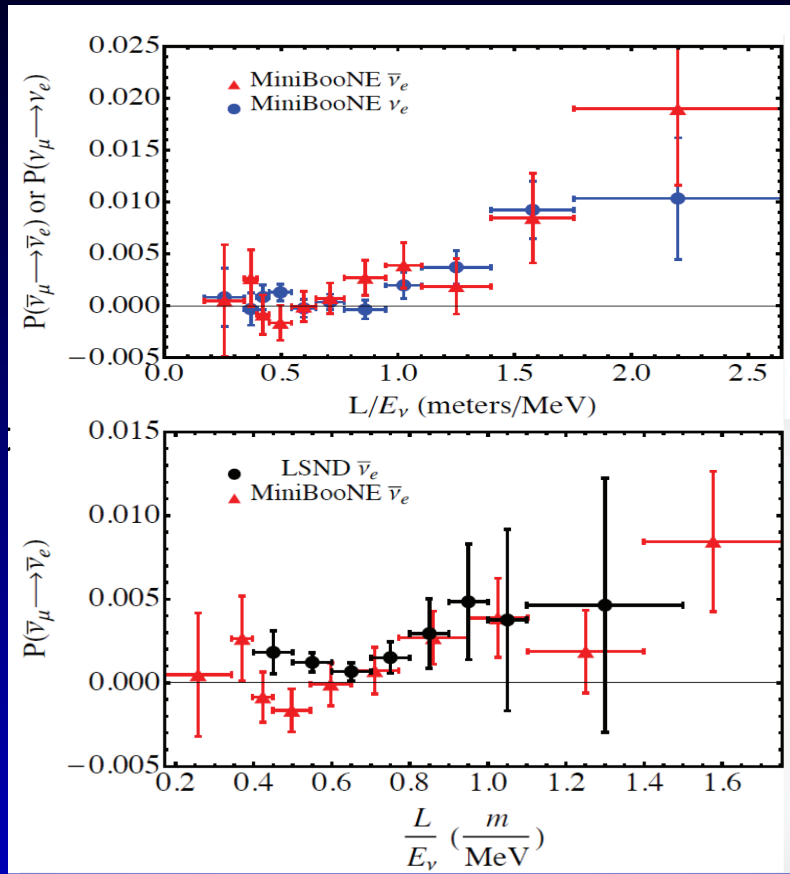
PH, M. Lindner, T. Schwetz, W. Winter, JHEP 11 044 (2009), arXiv:0907.1896.

Includes Project X and T2K running at 1.7 MW.

Short baseline anomalies

LSND and MiniBooNE

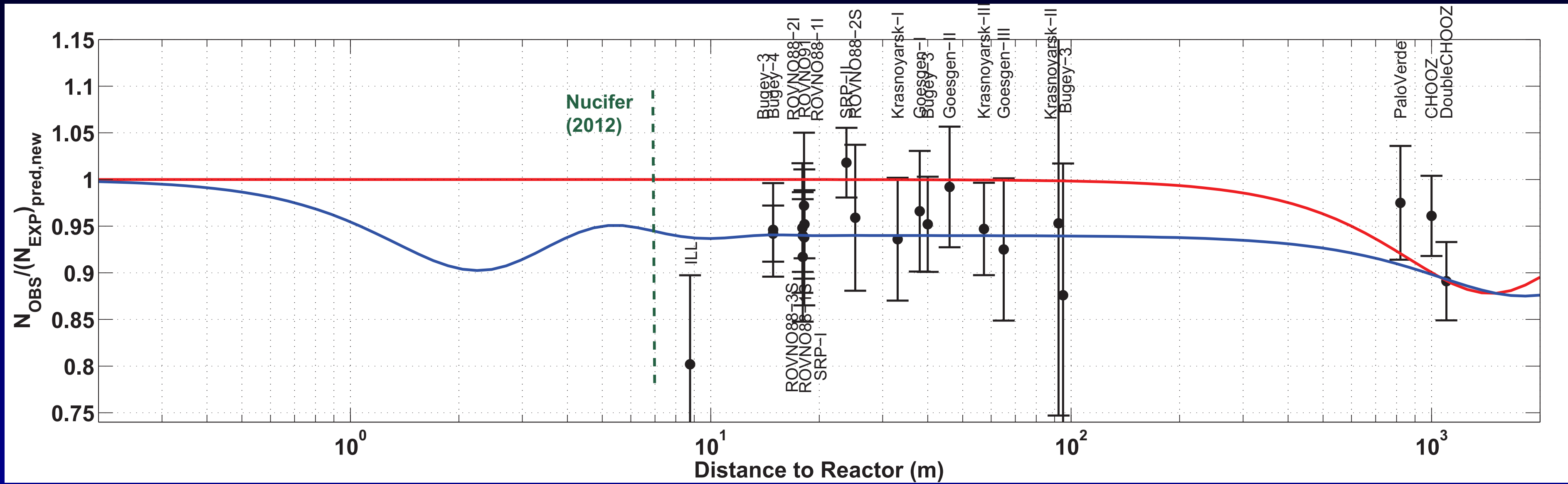




$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \simeq 0.003$$

Tension between neutrino and antineutrino signals?

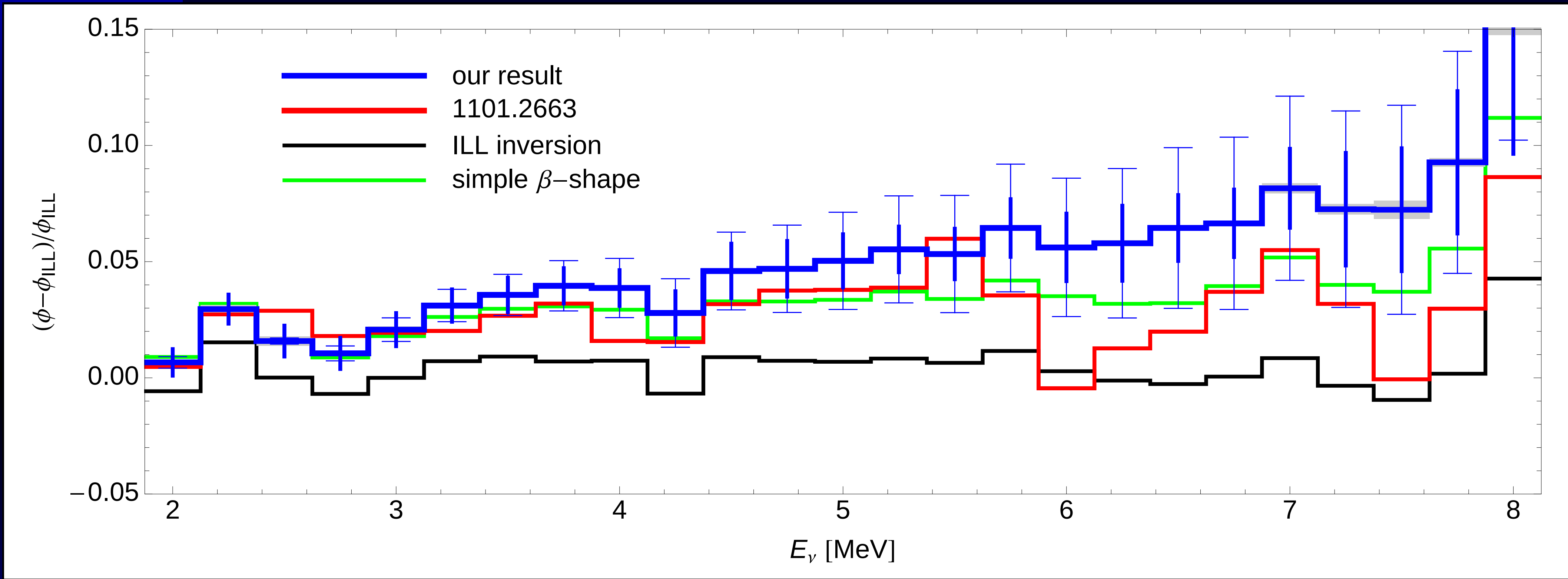
Reactor anomaly



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

- 3% increase in reactor neutrino fluxes
- decrease in neutron lifetime
- inclusion of long-lived isotopes (non-equilibrium correction)

Reactor antineutrino fluxes

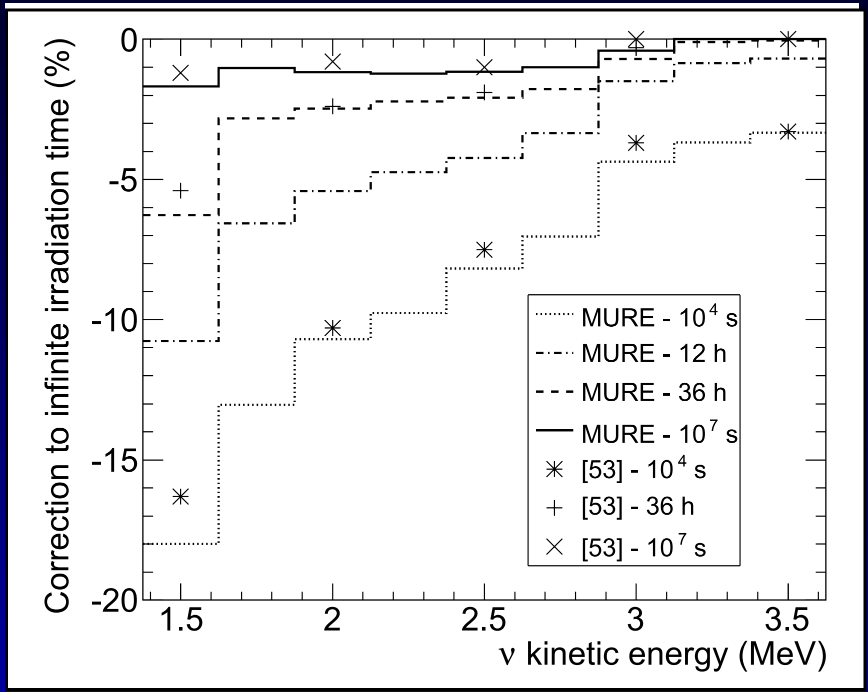


Shift with respect to ILL results, due to

a) different effective nuclear charge distribution

b) branch-by-branch application of shape corrections

Non-equilibrium corrections



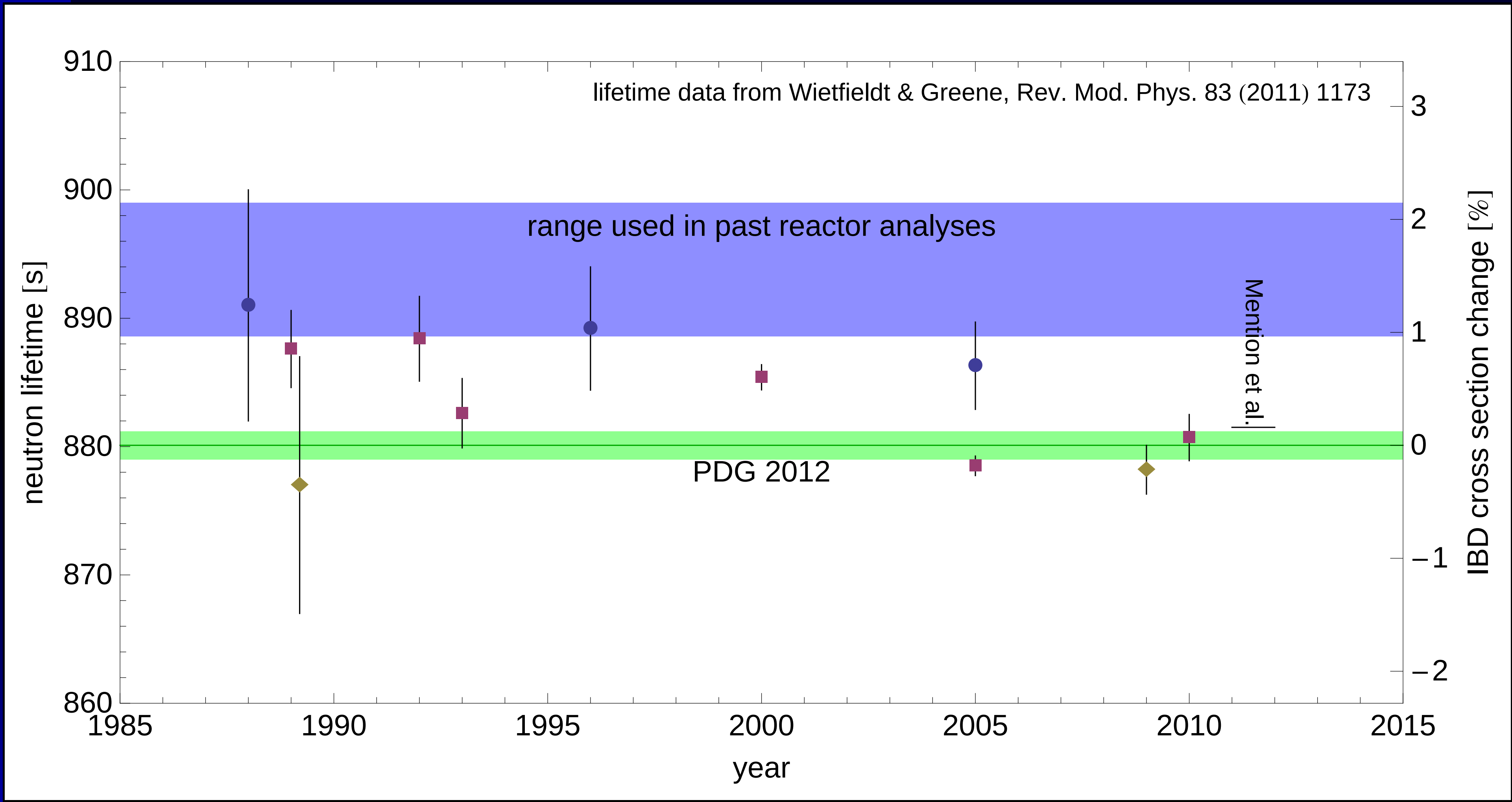
Mueller, *et al.*, RRC 83 (2011) 054615

only 2 dozen isotopes with $t_{1/2} > 12\,\mathrm{h}$ above inverse β-decay threshold

Extra shift due to long-lived isotopes

a) small nuclear physics uncertainty in β-decay
b) depends on detailed fuel history

Neutron lifetime



Gallium anomaly

	GALLEX		SAGE	
k	G1	G2	S1	S2
source	^{51}Cr	^{51}Cr	^{51}Cr	^{37}Ar
R_B^k	0.953 ± 0.11	$0.812^{+0.10}_{-0.11}$	0.95 ± 0.12	$0.791 \pm ^{+0.084}_{-0.078}$
R_H^k	$0.84^{+0.13}_{-0.12}$	$0.71^{+0.12}_{-0.11}$	$0.84^{+0.14}_{-0.13}$	$0.70 \pm ^{+0.10}_{-0.09}$
radius [m]	1.9		0.7	
height [m]	5.0		1.47	
source height [m]	2.7	2.38	0.72	

25% deficit of ν_e from radioactive sources at short distances

- effect depends on nuclear matrix element
- interpretation as sterile neutrino is in conflict with large scale structure neutrino mass bounds over a large fraction of the parameter space

Astrophysics

Model	Data	N_{eff}	Ref.
N_{eff}	W-5+BAO+SN+H_0	$4.13^{+0.87(+1.76)}_{-0.85(-1.63)}$	[347]
	W-5+LRG+H_0	$4.16^{+0.76(+1.60)}_{-0.77(-1.43)}$	[347]
	W-5+CMB+BAO+XLF+f_{gas}+H_0	$3.4^{+0.6}_{-0.5}$	[350]
	W-5+LRG+maxBCG+H_0	$3.77^{+0.67(+1.37)}_{-0.67(-1.24)}$	[347]
	W-7+BAO+H_0	$4.34^{+0.86}_{-0.88}$	[339]
	W-7+LRG+H_0	$4.25^{+0.76}_{-0.80}$	[339]
	W-7+ACT	5.3 ± 1.3	[344]
	W-7+ACT+BAO+H_0	4.56 ± 0.75	[344]
	W-7+SPT	3.85 ± 0.62	[345]
	W-7+SPT+BAO+H_0	3.85 ± 0.42	[345]
	W-7+ACT+SPT+LRG+H_0	$4.08^{(+0.71)}_{(-0.68)}$	[351]
	W-7+ACT+SPT+BAO+H_0	3.89 ± 0.41	[352]
$N_{eff}+f_\nu$	W-7+CMB+BAO+H_0	$4.47^{(+1.82)}_{(-1.74)}$	[353]
	W-7+CMB+LRG+H_0	$4.87^{(+1.86)}_{(-1.75)}$	[353]
$N_{eff}+\Omega_k$	W-7+BAO+H_0	4.61 ± 0.96	[352]
	W-7+ACT+SPT+BAO+H_0	4.03 ± 0.45	[353]
$N_{eff}+\Omega_k+f_\nu$	W-7+ACT+SPT+BAO+H_0	4.00 ± 0.43	[352]
	W-7+CL+SPT+BAO+H_0	(< 3.74)	[354]
$N_{eff}+f_\nu+w$	W-7+CMB+BAO+H_0	$3.68^{(+1.90)}_{(-1.84)}$	[353]
	W-7+CMB+LRG+H_0	$4.87^{(+2.02)}_{(-2.02)}$	[353]
$N_{eff}+\Omega_k+f_\nu+w$	W-7+CMB+BAO+SN+H_0	$4.2^{+1.10(+2.00)}_{-0.61(-1.14)}$	[355]
	W-7+CMB+LRG+SN+H_0	$4.3^{+1.40(+2.30)}_{-0.54(-1.09)}$	[355]

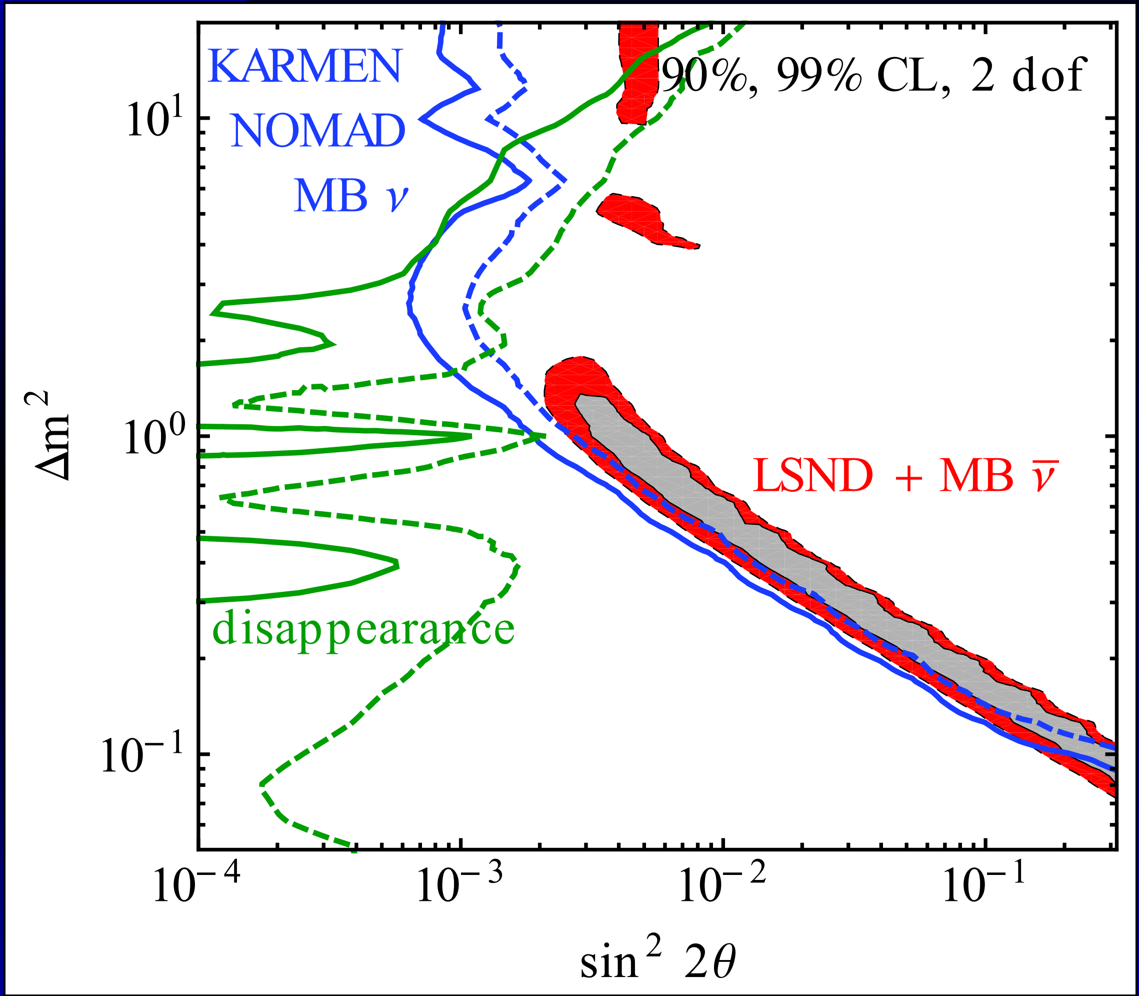
$N_{\rm eff} \simeq 4$ from relativistic energy density

BUT

$m_s \lesssim 1\,\mathrm{eV}$ from large scale structure

future data (PLANCK) will help to address this tension

Disappearance constraints



Absence of effects in

- atmospheric
- Bugey
- CDHS
- MINOS
- …

data creates considerable tension in 3+N sterile neutrino models

More details can be found in the sterile neutrino white paper, arXiv:1204.5379.

Sterile oscillation

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

$$P(\nu_\mu \to \nu_e) \leq 4P(\nu_e \to \nu_e)P(\nu_\mu \to \nu_\mu)$$

independent of CP transformations. Therefore, a stringent test of the model is to measure

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

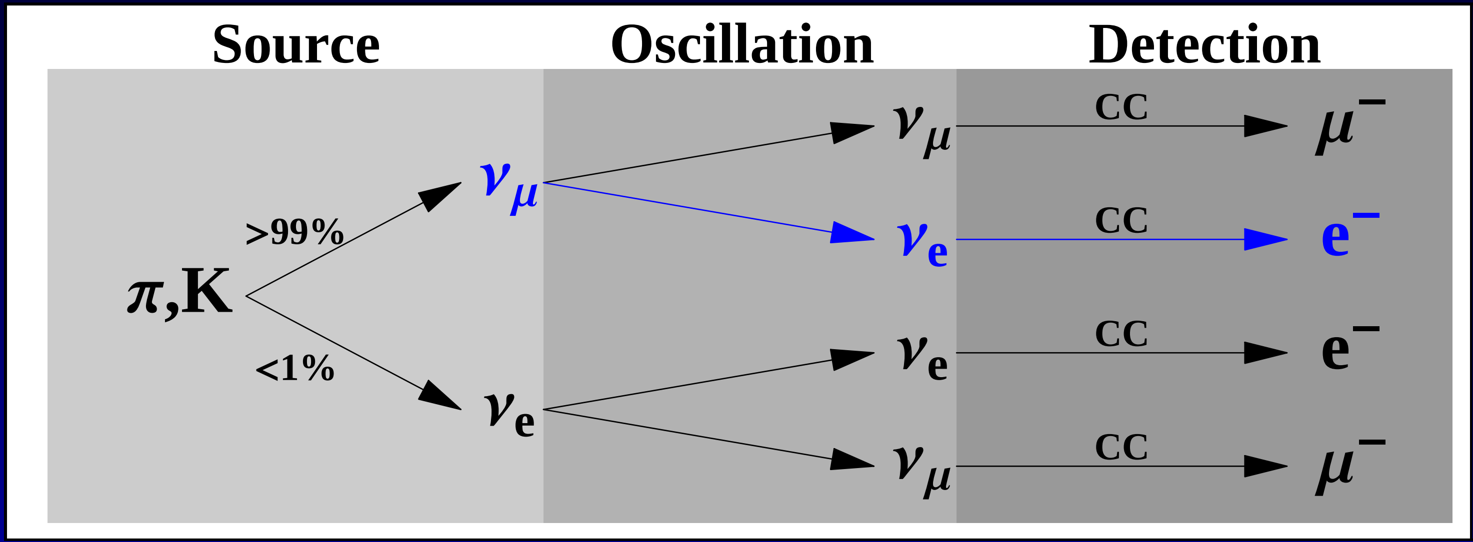
SBL anomalies – corollary

- All current hints are $3\,\sigma$-ish
- A lot of hidden, hard to control systematics and theory errors
- Tension in global fits
- Need for new experiments
- What would be the consequence of a discovery for LBL physics?

Neutrino sources

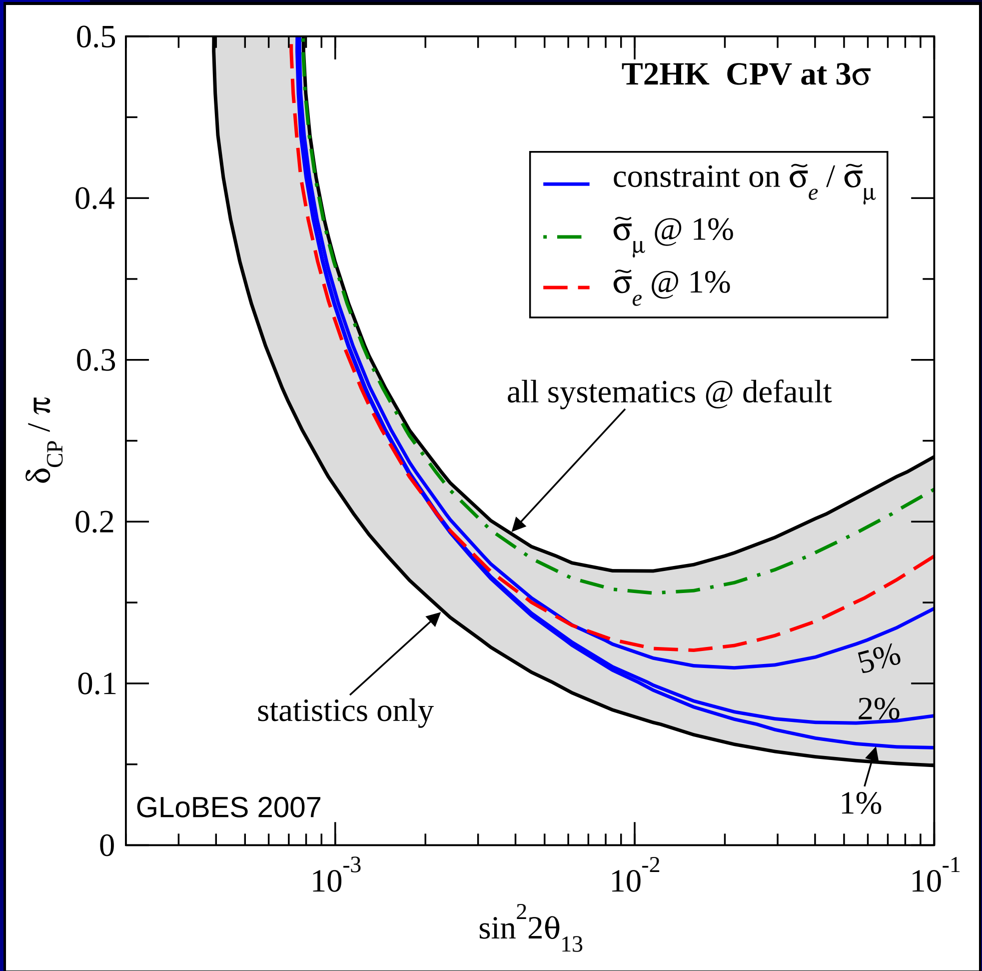
Traditional beam

Neutrino beam from π-decay



- primary ν_μ flux constrained to 5-15%
- ν_e component known to about 20%
- anti-neutrino beam systematically different – large wrong sign contamination
- ν_e difficult to distinguish from NC events

ν_e/ν_μ x-sections

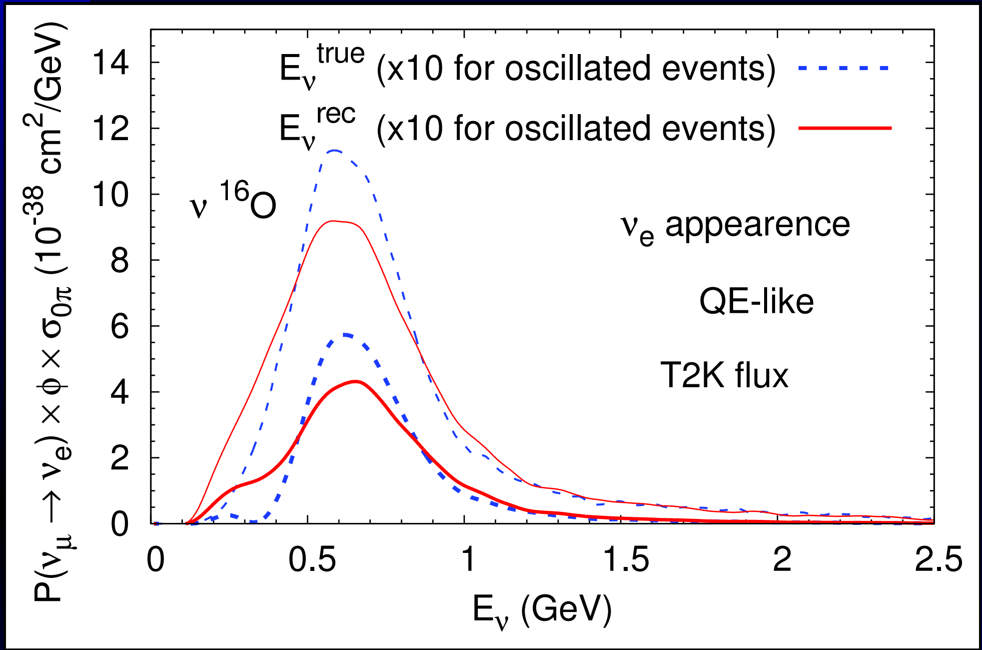


PH, M. Mezzetto, T. Schwetz
arXiv:0711.2950

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.

QE energy reconstruction



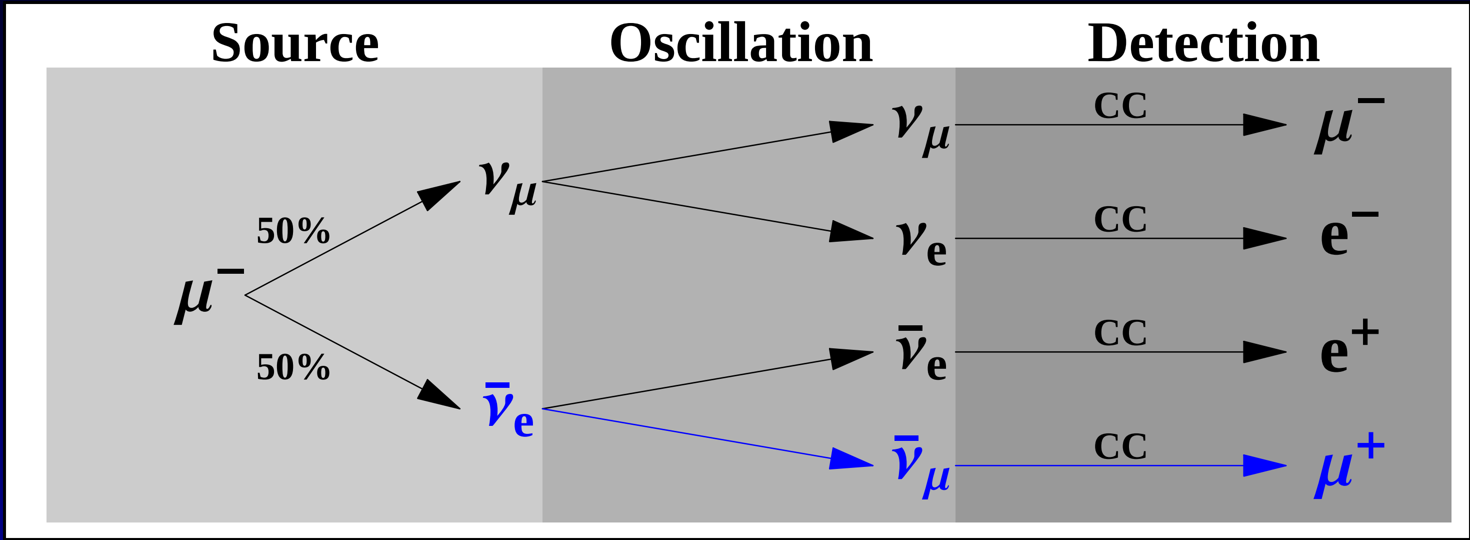
Lalakulich, Mosel, arXiv:1208.3678.

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

Inferring the CP phase from QE spectrum seems quite difficult – no quantitative analysis with respect to oscillation physics, yet.

Not obvious that near detectors alone can solve this problem.

Neutrino factory beam



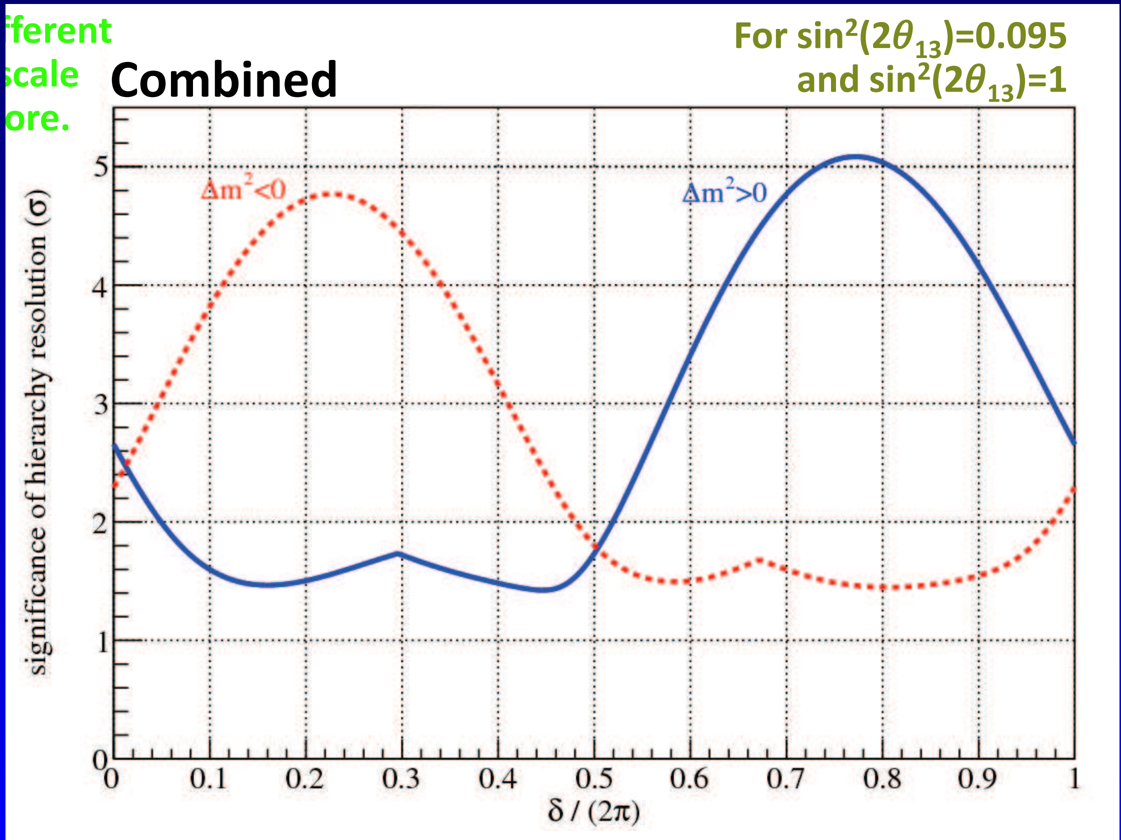
This requires a detector which can distinguish μ^+ from μ^- $\Rightarrow$ magnetic field of around 1T

- beam known to %-level or better
- muon detection very clean
- multitude of channels available

Long-baseline oscillations

MH from existing experiments

- NOvA continues running at 14 kton and 700 kW to 2025
- T2K continues running at 22.5 kton with 700 kW to 2025
- NOvA achieves a further 20% sensitivity gain
- T2K achieves a further 10% sensitivity gain

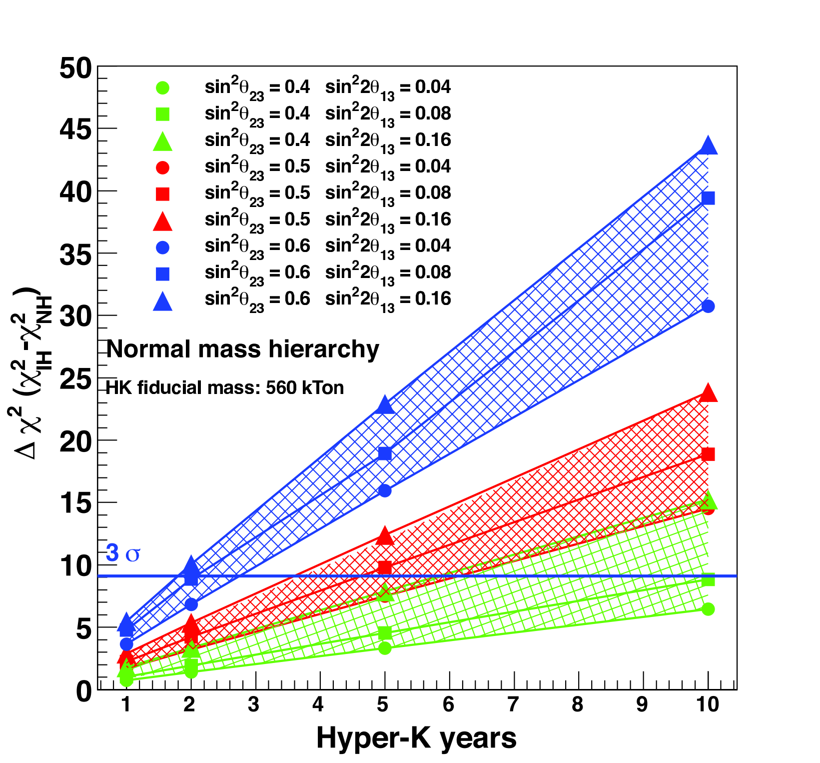


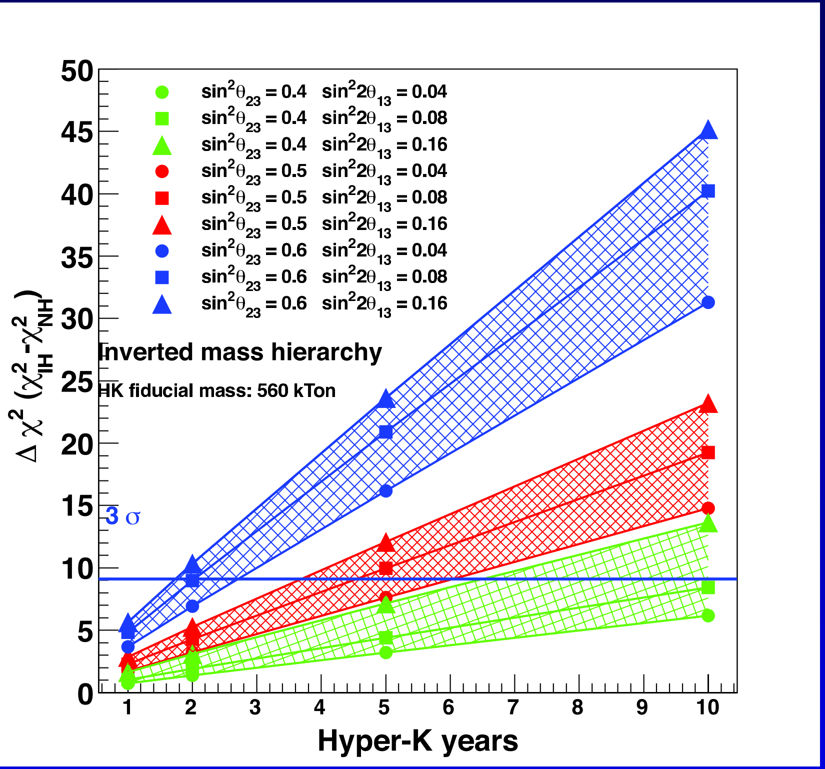
Includes Daya Bay projected final error

R. Patterson, NuFact 12

Hyper-K

Atmospheric data only
Assumes θ_{13} known from reactors
Assumes θ_{23} known from beam
Leaves δ free

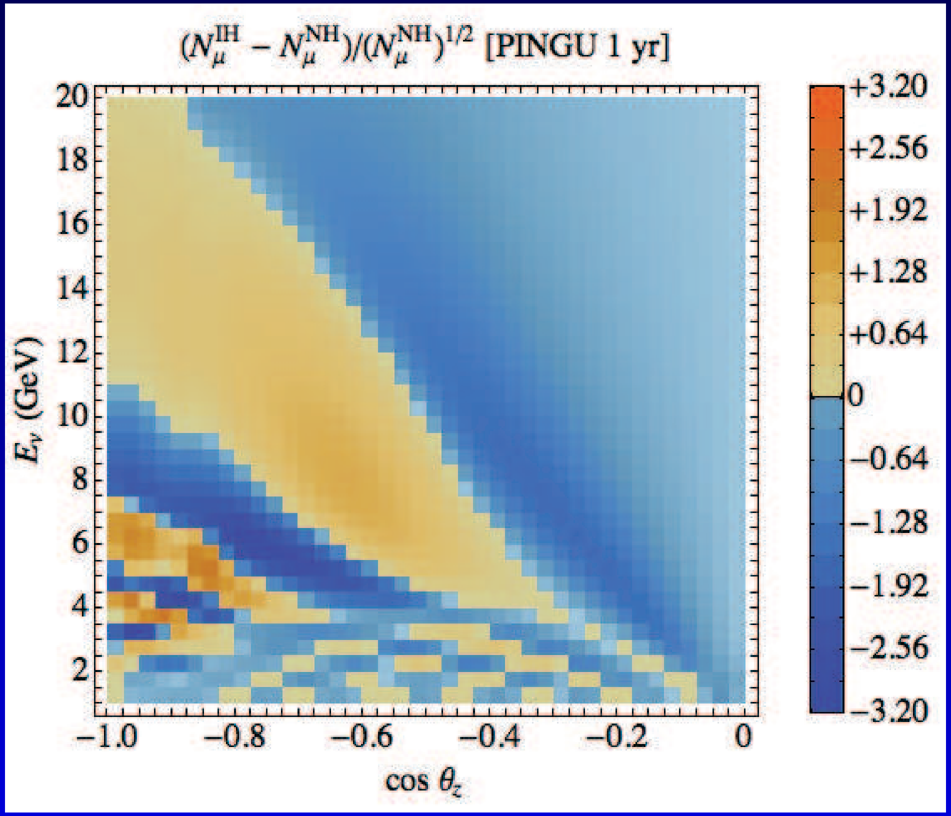




Hyper-K LOI, arXiv:1109.3262

PINGU

Phased IceCube Next Generation upgrade
20 strings with $\sim$1000 optical modules
Energy threshold of around 1 GeV



Akhmedov, Razzaque, Smirnov
arXiv:1205.7071

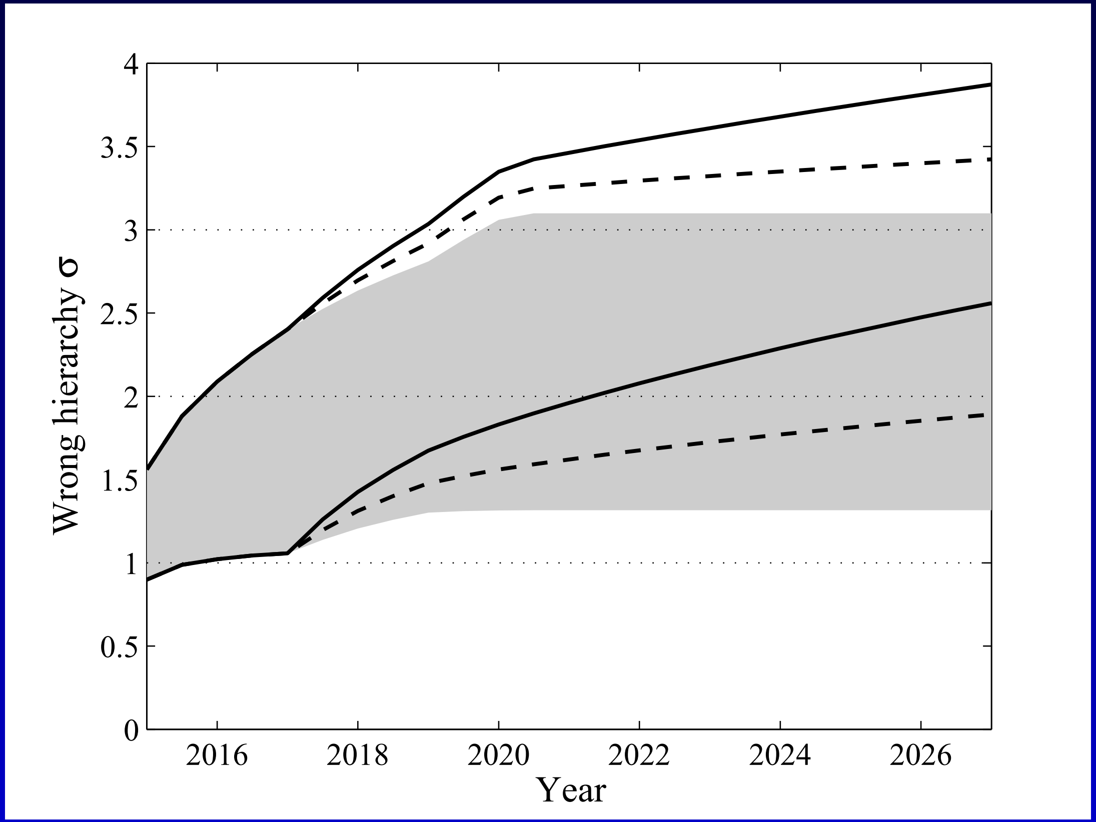
5-10 σ for all CP phases

Cheap & fast

Feasibility under study by the IceCube collaboration

Indian Neutrino Observatory

40 kt magnetized iron detector (like MONOLITH)



Blennow, Schwetz, arXiv:1203.3388

Improved angular and energy resolution in the multi-GeV range

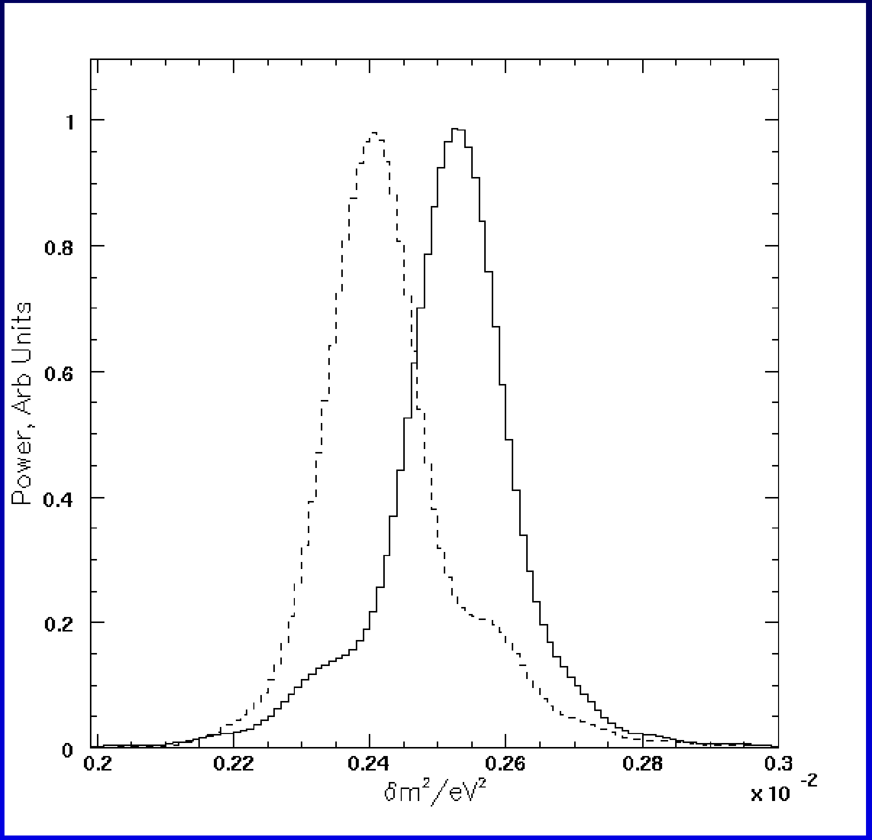
neutrino/antineutrino separation from muon charge

MH from reactors

Interference of the two mass scales

Choubey, Petcov, Piai, 2003

Baseline of $\sim$60 km and exposure of $\mathcal{O}(100)$ kt years



Learned *et al.*, hep-ex/0612022

Daya Bay II

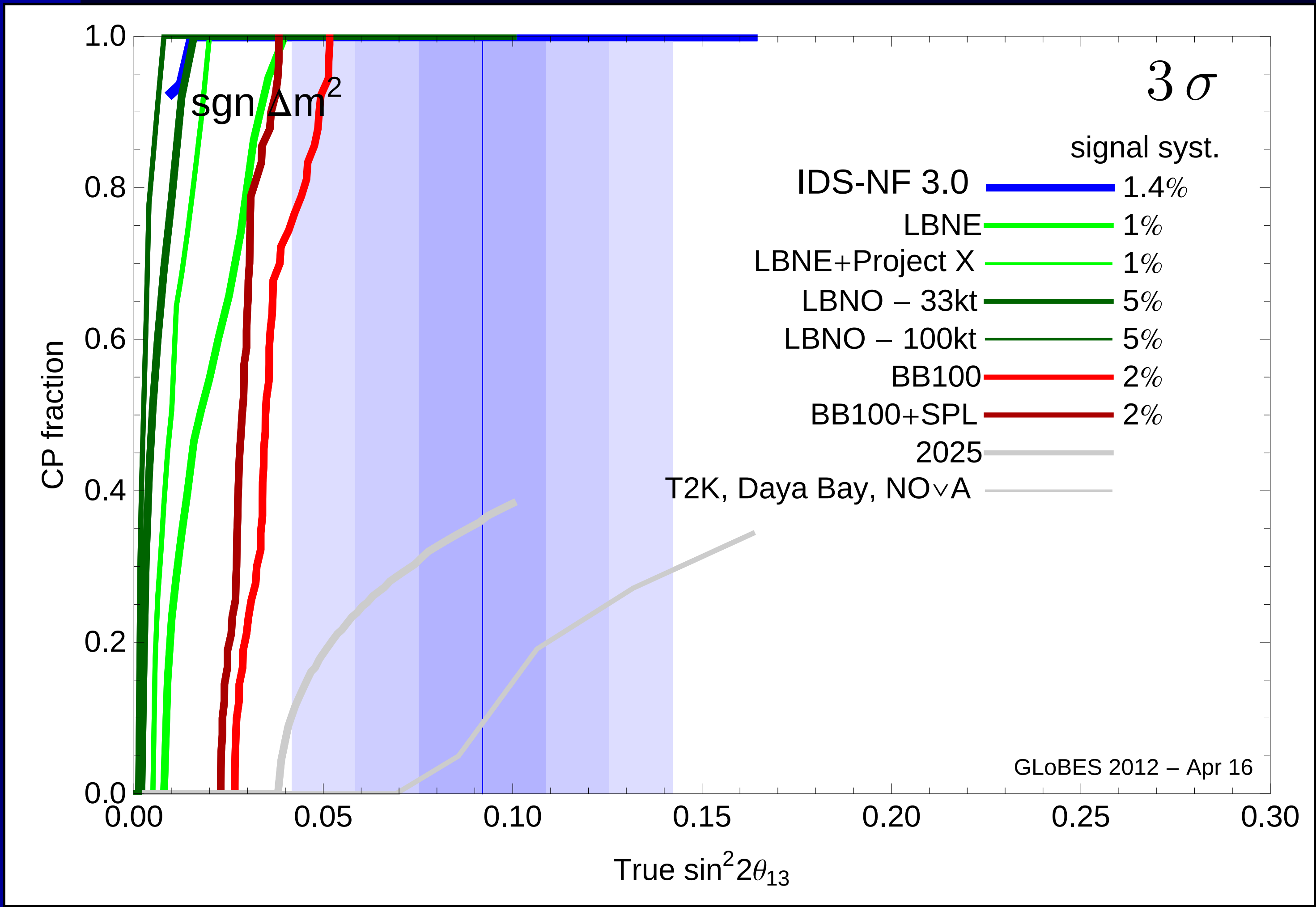
Question of systematics control – energy scale

Qian *et al.*, 2012

Mass hierarchy corollary

- Given the large value of θ_{13} mass hierarchy can be done in many different ways
- PINGU, ICAL, Daya Bay 2, HK atmospheric data, ...
- It therefore seems very likely that the mass hierarchy will be determined at some level w/o a new long baseline experiment

Mass hierarchy forecast



Mass hierarchy is no longer a distinguishing feature!

CP and systematics

We specifically simulate near and far detectors

We use common assumptions for all experiments on

- cross sections split into QE, RES and DIS for each flavor and neutrinos and antineutrinos
- cross section ratios between e and μ flavors for QE, RES and DIS and neutrinos and antineutrinos
- fiducial volume and near/far extrapolation errors

We use experiment type specific errors for

- fluxes
- beam backgrounds
- detector backgrounds

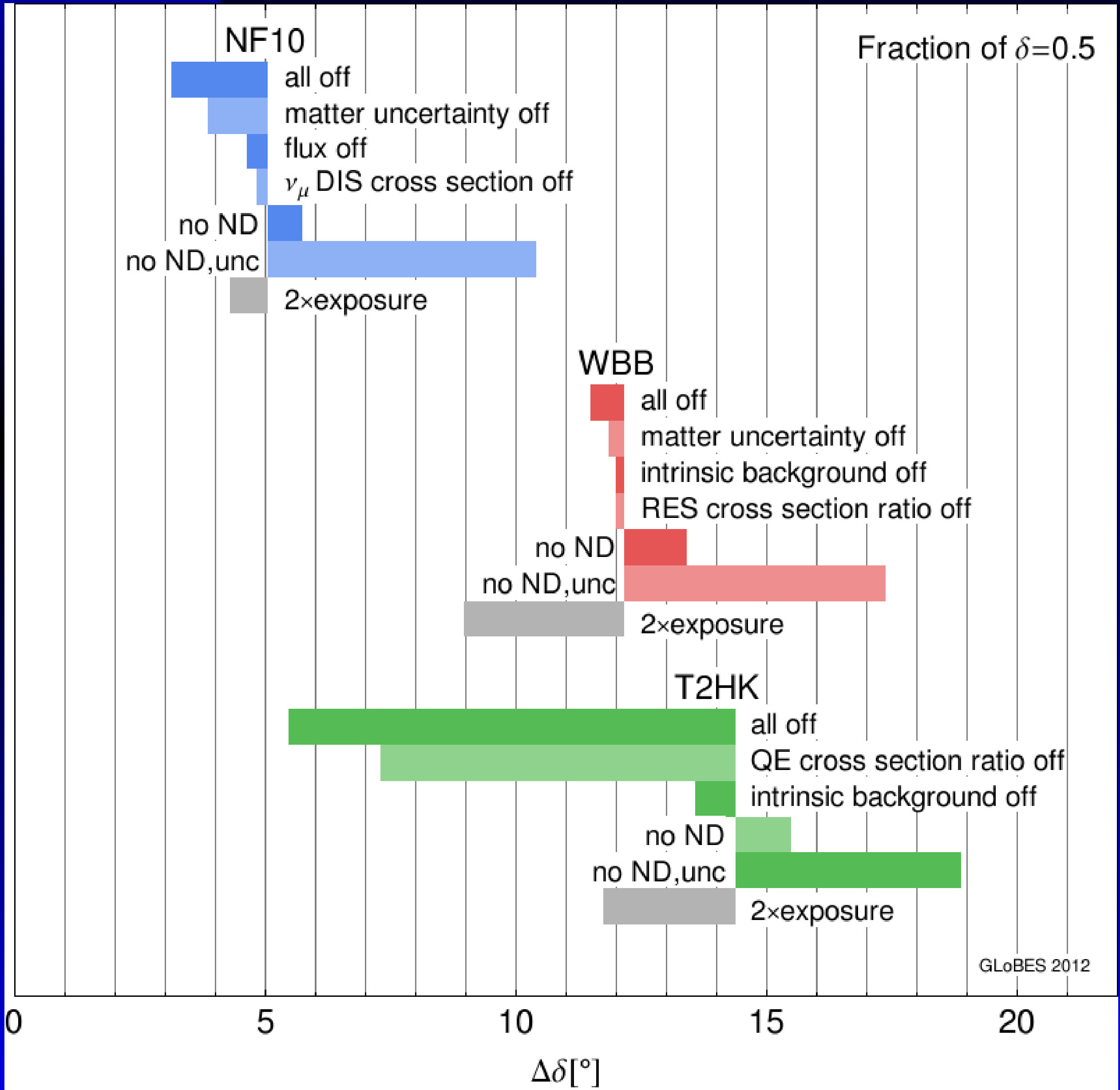
Setups

	Setup	E_ν^{peak}	L	OA	Detector	kt	MW	Decays/yr	$(t_\nu,t_{\bar\nu})$
Benchmark	BB350	1.2	650	–	WC	500	–	$1.1(2.8)\times10^{18}$	(5,5)
	NF10	5.0	2 000	–	MIND	100	–	7×10^{20}	(10,10)
	WBB	4.5	2 300	–	LAr	100	0.8	–	(5,5)
	T2HK	0.6	295	2.5°	WC	560	1.66	–	(1.5,3.5)
Alternative	BB100	0.3	130	–	WC	500	–	$1.1(2.8)\times10^{18}$	(5,5)
	+ SPL			–			4	–	(2,8)
	NF5	2.5	1 290	–	MIND	100	–	7×10^{20}	(10,10)
	LBNE$_{\text{mini}}$	4.0	1 290	–	LAr	10	0.7	–	(5,5)
	NOvA$^+$	2.0	810	0.8°	LAr	30	0.7	–	(5,5)

NB – neutrino/antineutrino running at NF10/NF5 is simultaneous

The following results are taken from
Coloma, PH, Kopp, Winter, arXiv:1209.5973.

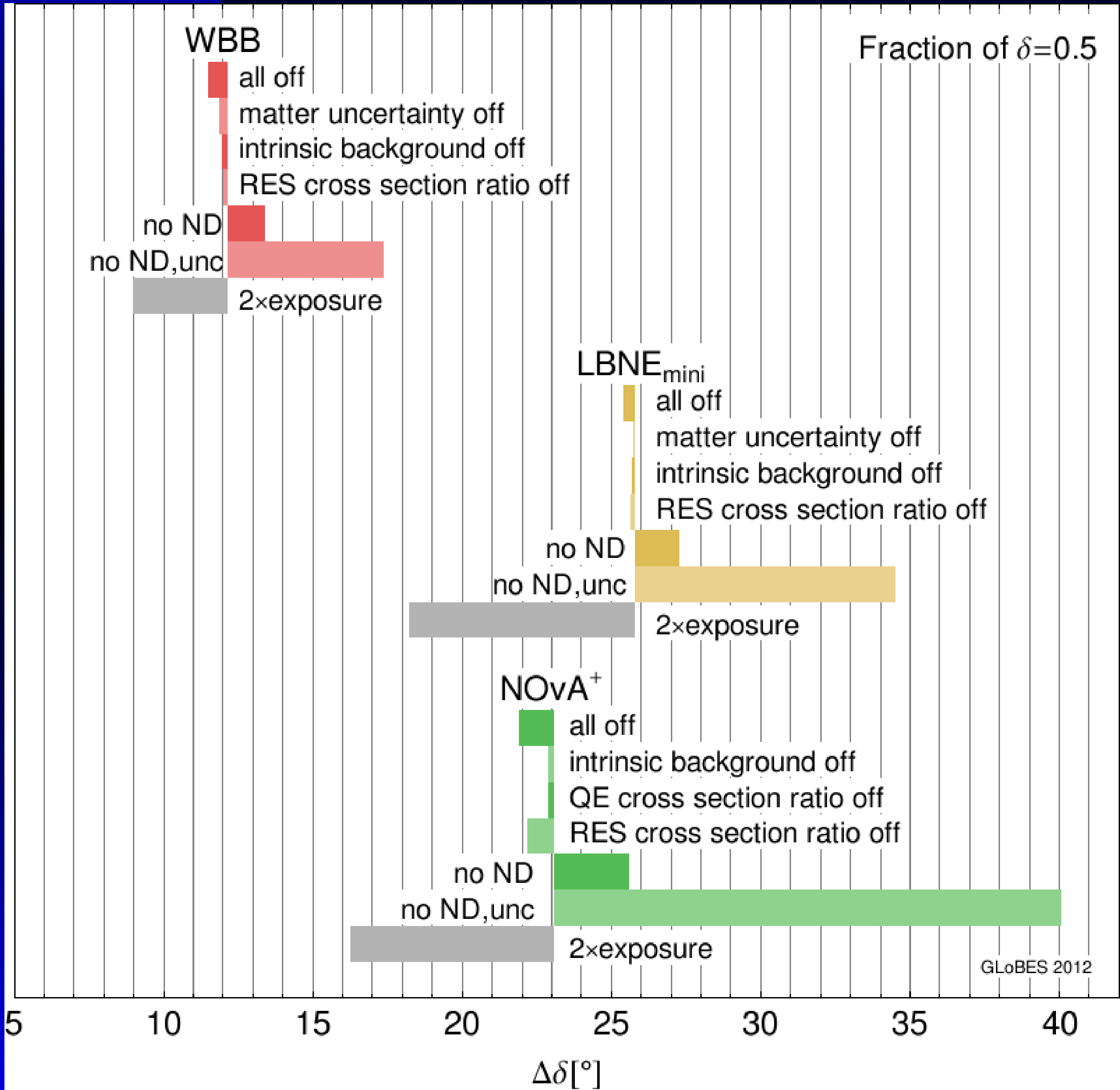
Systematics I



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

NF10 clearly out-performs all other options

Systematics II

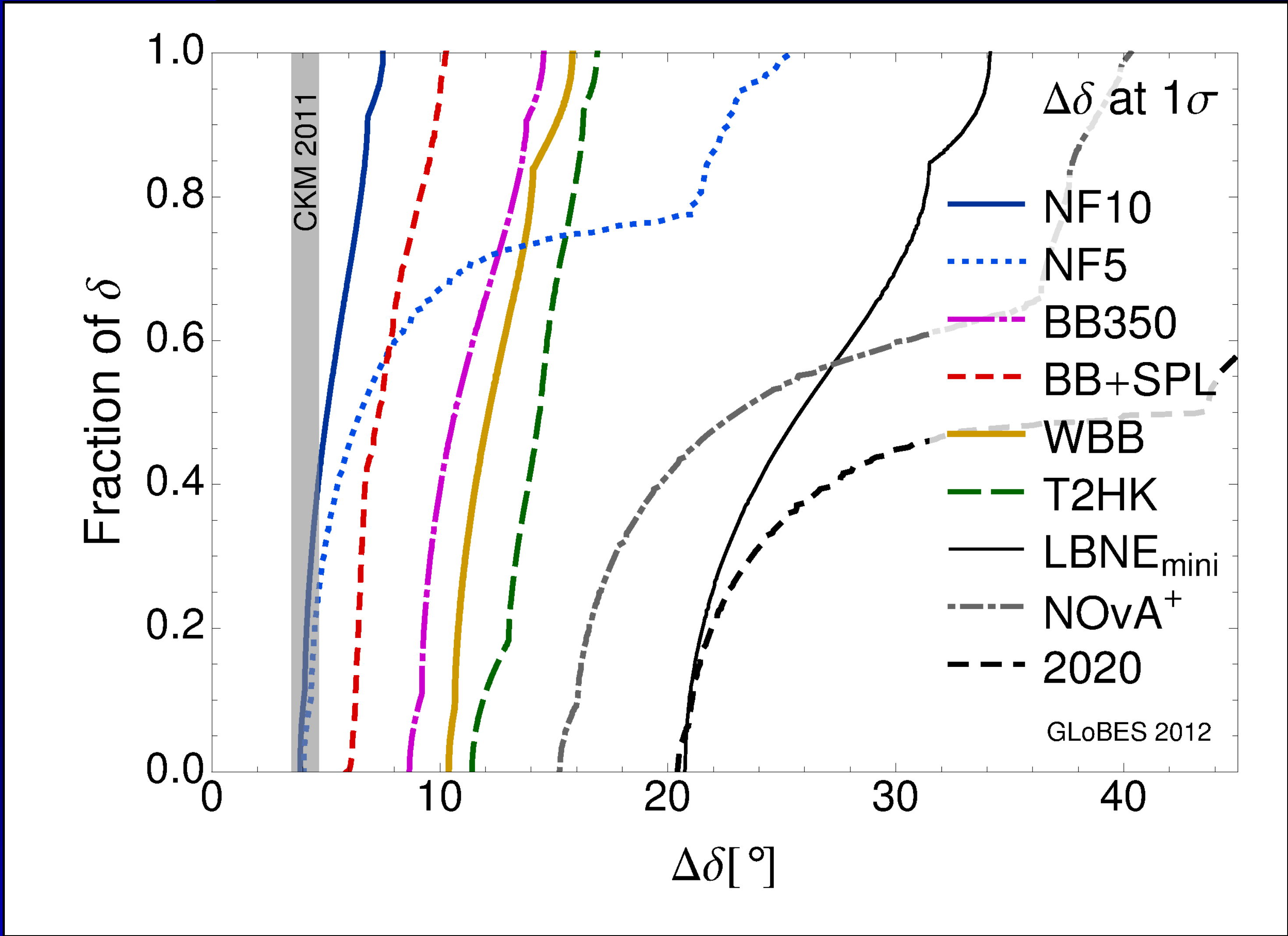


Near detector crucial for new physics searches

NOvA^{+} higher risk from systematics

Current $\Delta\delta$ is 30-35° Fogli *et al.*, 2012

CP precision



2020 – T2K, NOνA and Daya Bay nominal runs

LBNE – 1300 km, 34 kt
0.7 MW, 2×10^8 s

WBB – 2300 km, 100 kt
0.8 MW, 1×10^8 s

T2HK – 295 km, 560 kt
0.7 MW, 1.2×10^8 s

all masses are fiducial

LBNO EOI submitted to CERN – 20 kt LAr + MIND, similar beam power to above, but Finish government will not support Pyhäsalmi lab

One way forward

A staged, muon based program

- νSTORM – resolve the SBL anomalies and if discovery, precise measurements of NP, necessary to control systematics in superbeam experiments
- Low luminosity neutrino factory (700kW beam, no cooling, 10 kt detector) – better than mini-LBNE
- Full neutrino factory – ultimate precision

provides excellent, unique physics in each phase!

νSTORM

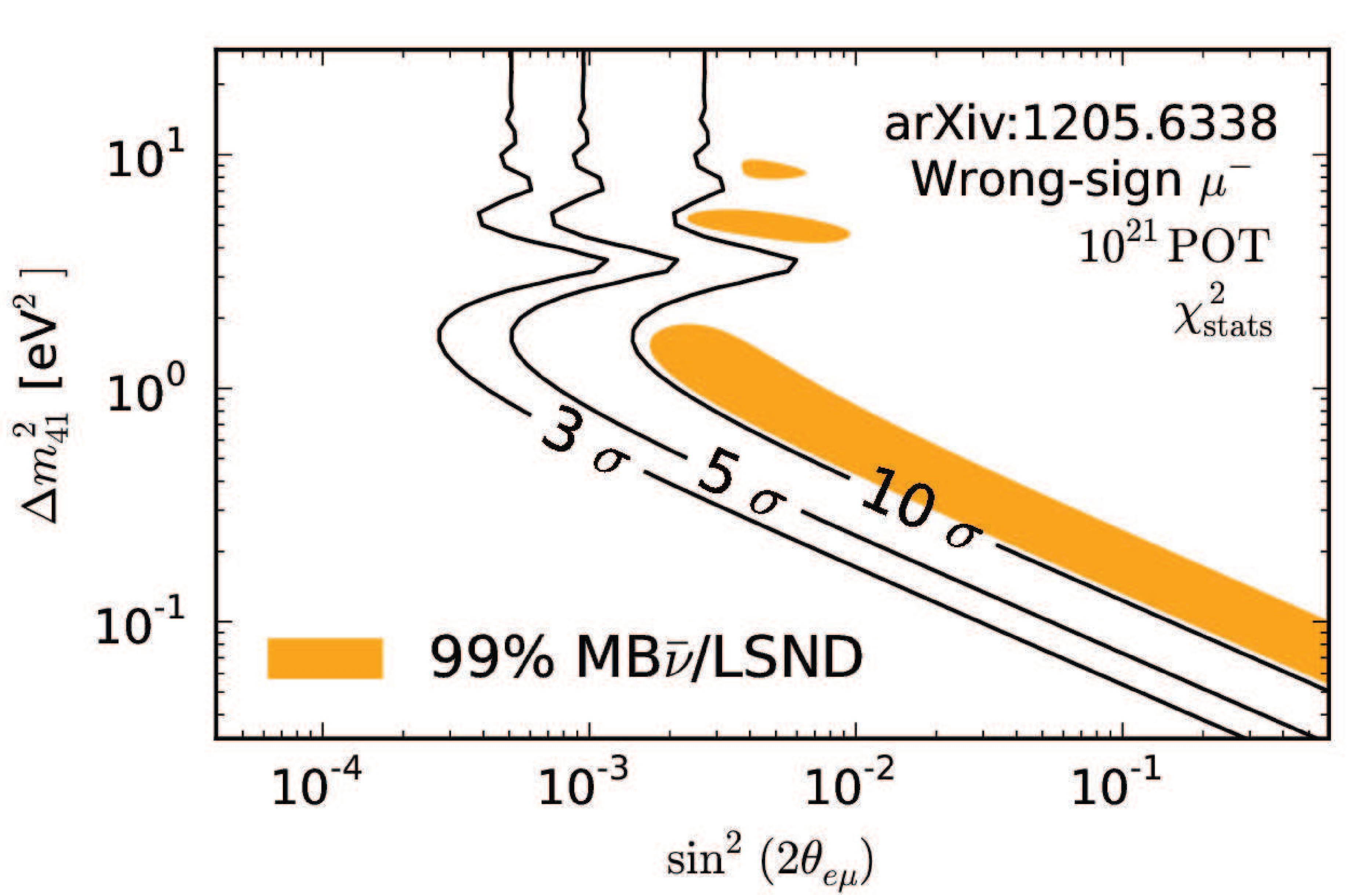
Low energy, low luminosity muon storage ring, based on existing technology. Provides with 1.7×10^{18} μ^+ stored, the following oscillated event numbers

$\nu_e \to \nu_\mu$ CC	330
$\bar{\nu}_\mu \to \bar{\nu}_\mu$ NC	47000
$\nu_e \to \nu_e$ NC	74000
$\bar{\nu}_\mu \to \bar{\nu}_\mu$ CC	122000
$\nu_e \to \nu_e$ CC	217000

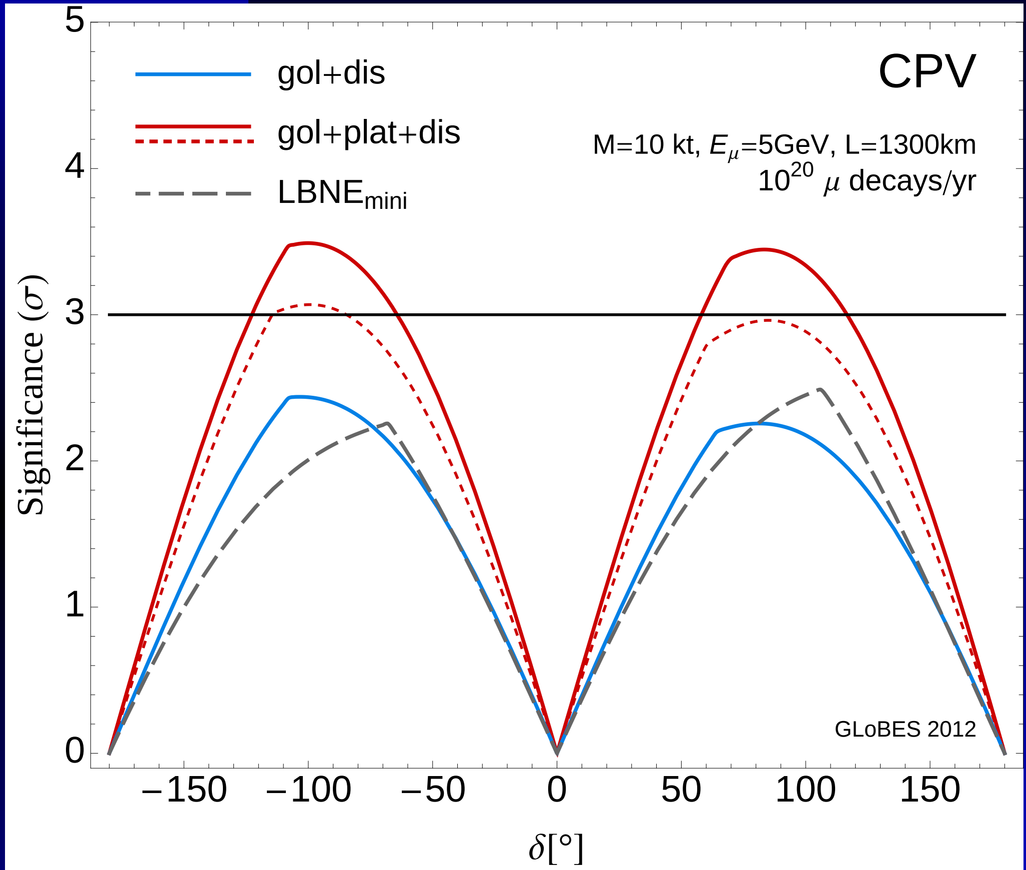
and each of these channels has a more than $10\,\sigma$ difference from no oscillations

With more than 2000 000 ν_e CC events in the near detector a %-level ν_e cross section measurement should be possible

νSTORM – ν_μ appearance



Low energy, low luminosity NF



1300 km baseline
700 kW proton beam power
5 GeV muon storage ring
no muon cooling
10 kt magnetized (!) LAr detector
includes ν_e appearance

NB – LBNE's sensitivity is lower than in the CDR since we use $\theta_{23} = 45°$

Coloma, Christensen, PH, in preparation

L3NF – still all existing technology.

Summary

- New facilities are indispensable to fully exploit the discovery of neutrino oscillation and to study the short-baseline anomalies
- Mass hierarchy at large θ_{13} is no longer a main decision criterion
- CP violation is never easy to measure – especially for the largest values of θ_{13}
- muon based options clearly outperform any other technology both for short- and long-baseline physics
- attractive staging scenario – νSTORM, L3NF, full neutrino factory, $\ldots$

Backup Slides

Systematics – detailed inputs

	SB			BB			NF		
Systematics	Opt.	Def.	Cons.	Opt.	Def.	Cons.	Opt.	Def.	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 $\times$ 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%
Ratio ν_e/ν_μ QE*	3.5%	11%	–	3.5%	11%	–	3.5%	11%	–
Ratio ν_e/ν_μ RES*	2.7%	5.4%	–	2.7%	5.4%	–	2.7%	5.4%	–
Ratio ν_e/ν_μ DIS*	2.5%	5.1%	–	2.5%	5.1%	–	2.5%	5.1%	–
Matter density	1%	2%	5%	1%	2%	5%	1%	2%	5%

L3NF – Detector assumptions

TASD

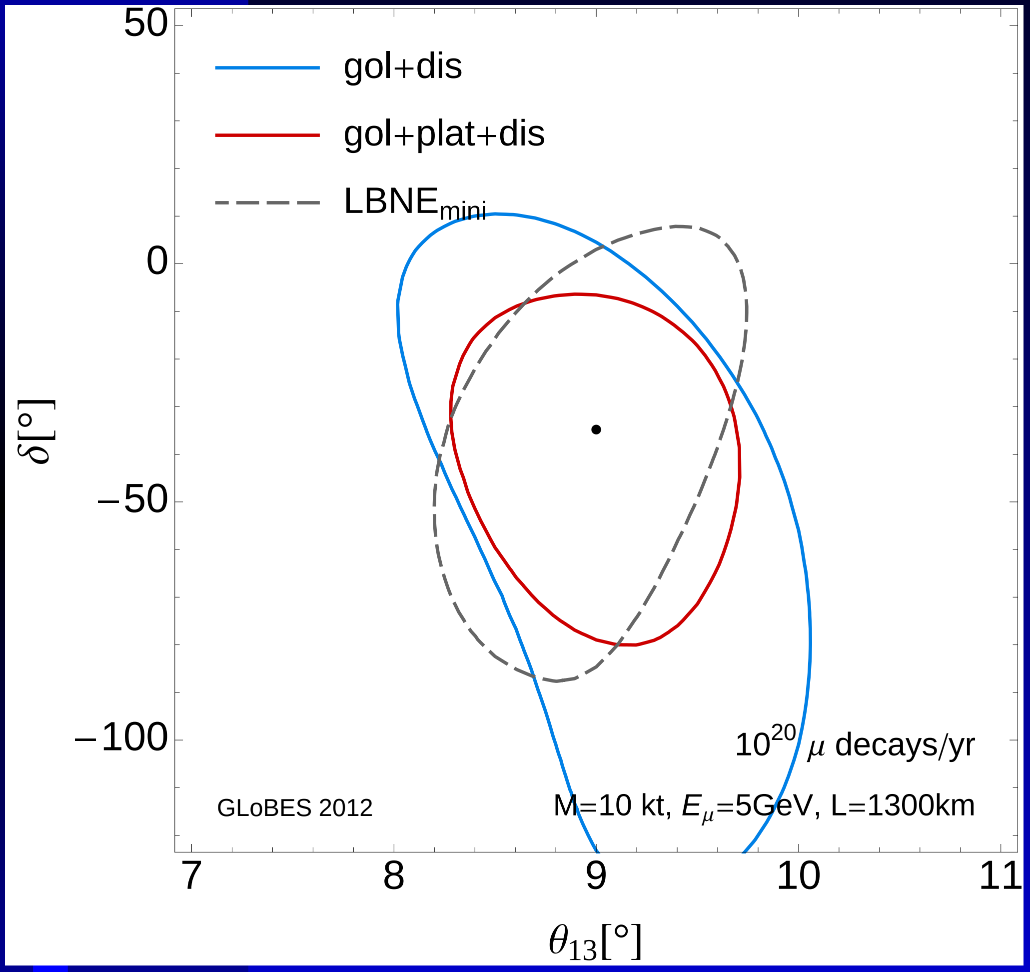
Channel	Effs.	τ Rej.	NC/CID/FID Rej.	$\Delta E/E$
ν_μ app.	73%-94%	0%	99.9%	$0.2/\sqrt{E}$
ν_e app.	37%-47%	0%	99%	$0.15/\sqrt{E}$
ν_μ dis.	73%-94%	0%	99.9%	$0.2/\sqrt{E}$

Magnetized LAr

Channel	Effs.	τ Rej.	NC/CID/FID Rej.	$\Delta E/E$
ν_μ app.	80%	0%	99.9%	$0.2/\sqrt{E}$
ν_e app.	80%	0%	99.9%	$0.15/\sqrt{E}$
ν_μ dis.	80%	0%	99.9%	$0.2/\sqrt{E}$

ν_τ backgrounds included and we use 2E7 s per year for ten years (like LBNE)

L3NF – The Platinum channel



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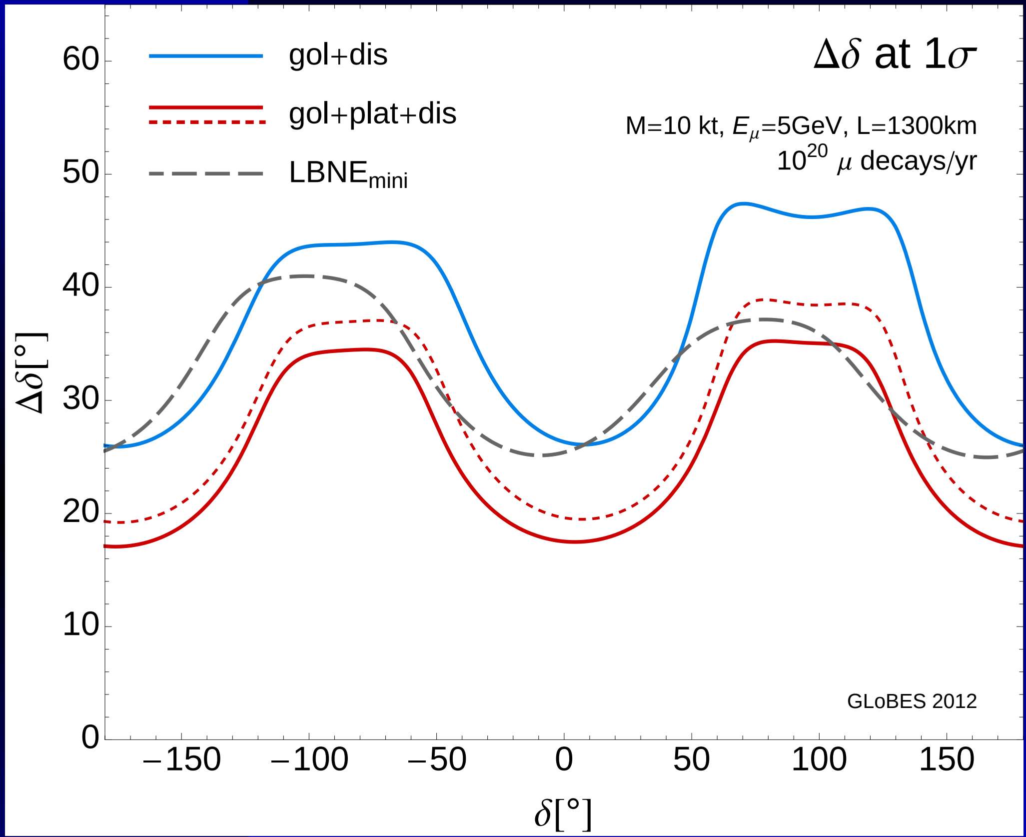
The $\nu_\mu \to \nu_e$ channel is the CPT conjugate of the $\bar{\nu}_e \to \bar{\nu}_\mu$ channel

As a result matter effects effectively cancel

This has been know for quite a while, but the effect is only relevant for large θ_{13}

NB: LBNE-mini corresponds to the LBNE CDR (CD1)

L3NF CP precision



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Solid line – magnetized LAr
Dashed line – magnetized TASD

The obtainable precision is nearly everywhere better than LBNEs by about 9 degrees (1/3)