

Large θ_{13} Challenge and Opportunity

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θ_{13} is large!

The Daya Bay result is

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

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

NB – a year ago we had only 2σ indications.

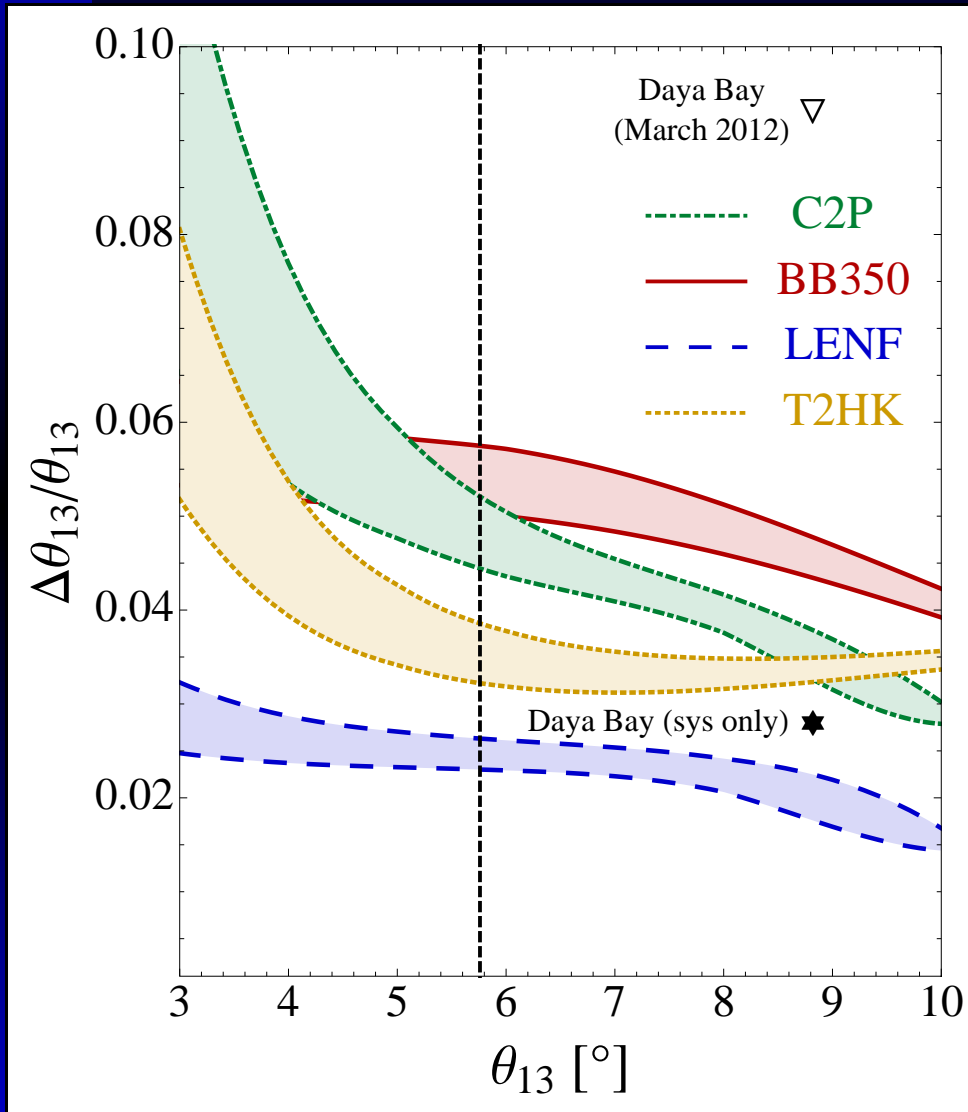
Implications

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 NO ν A and T2K necessary to discover CP violation?
- Are superbeams sufficient for precision neutrino physics?

Any of these 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

Large θ_{13} and new physics

In looking for new physics (NP) we generally have

$$P = |A_{\text{SM}} + A_{\text{NP}}|^2 = A_{\text{SM}}^2 + 2A_{\text{SM}}A_{\text{NP}} + A_{\text{NP}}^2$$

With large θ_{13} we have $A_{\text{SM}} \gg A_{\text{NP}}$ and thus

$$P \simeq A_{\text{SM}}^2 + 2A_{\text{SM}}A_{\text{NP}}$$

which depends linearly on the new physics amplitude, A_{NP}

Note, there is not reason to expect the NP to be CP conserving.

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.

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

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

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

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

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

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

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

- lepton number may be conserved \rightarrow no Majorana mass term
- lepton number may be approximately conserved \rightarrow 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**

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

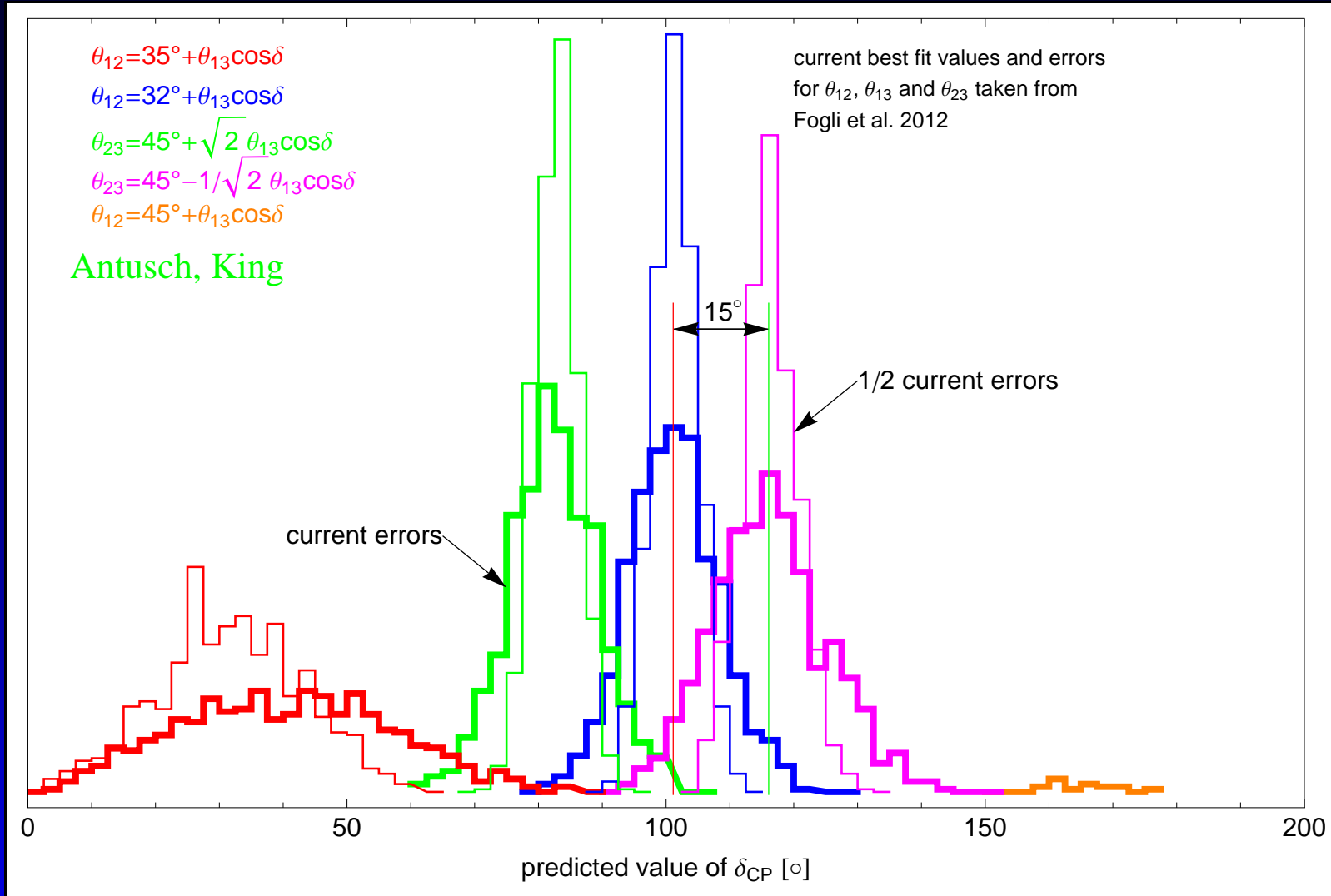
predicts flat distribution in δ_{CP}

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 σ 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 – not covered in this talk
- 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

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

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

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

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

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

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

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

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

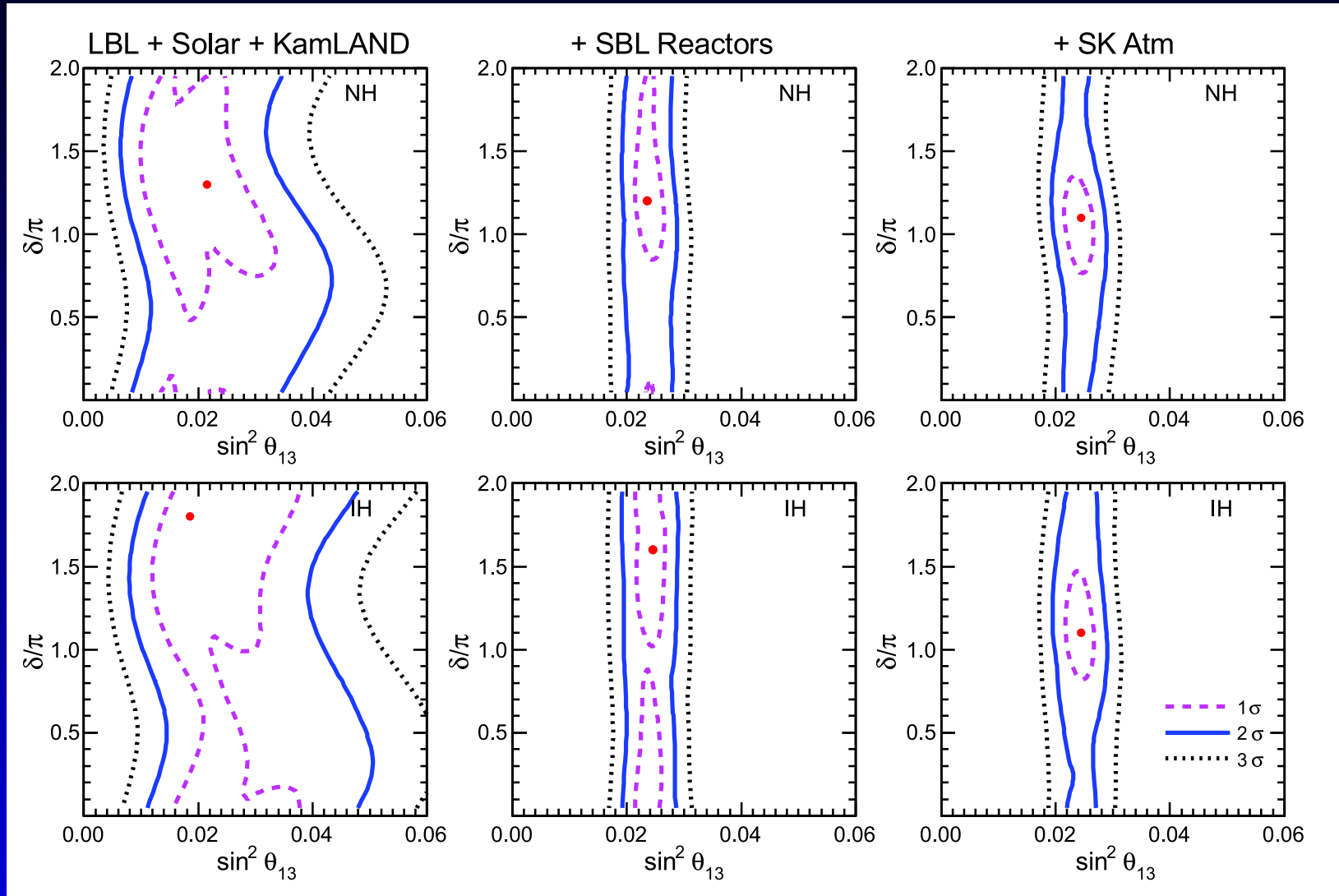
	ν	$\bar{\nu}$
$\Delta m^2 > 0$	MSW	-
$\Delta m^2 < 0$	-	MSW

Consequences for experiments

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

Are new experiments still necessary?

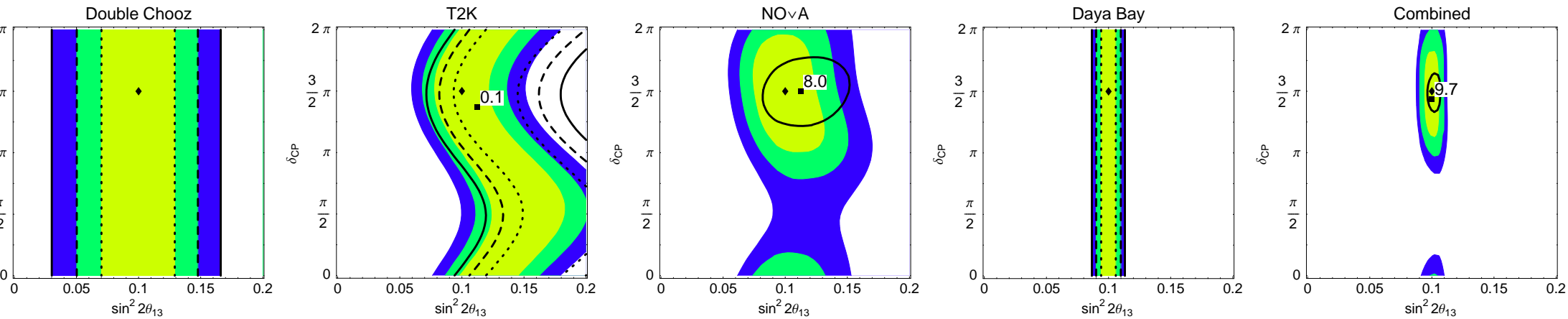
Status quo



Fogli, *et al.*, arXiv:1205.5254

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

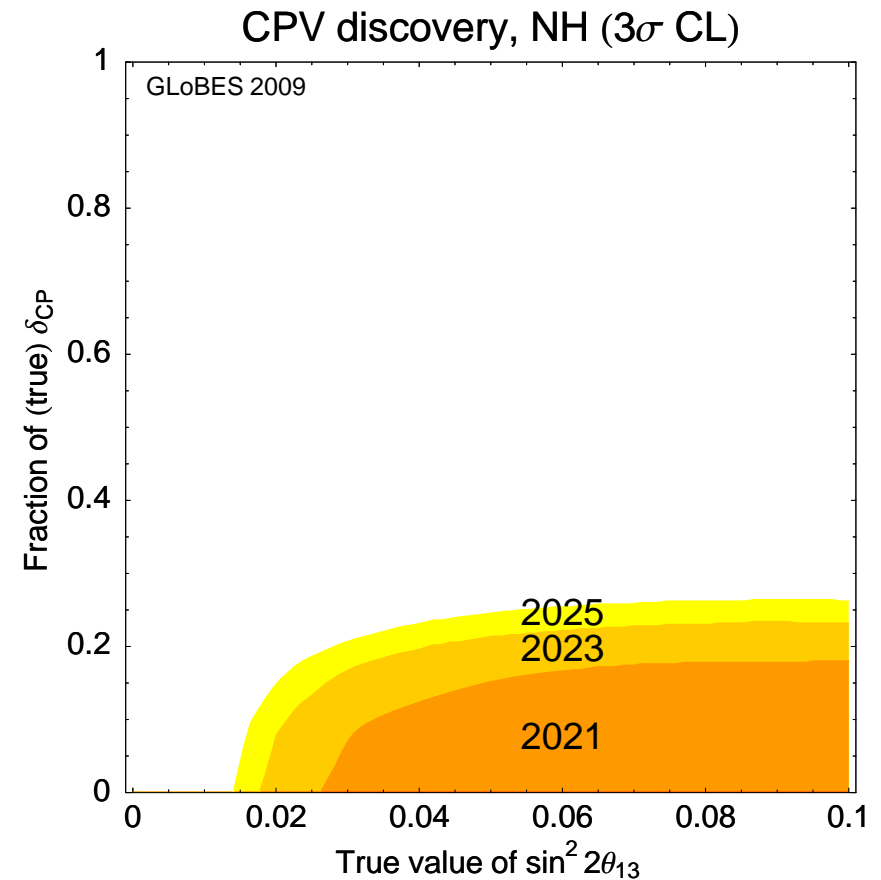
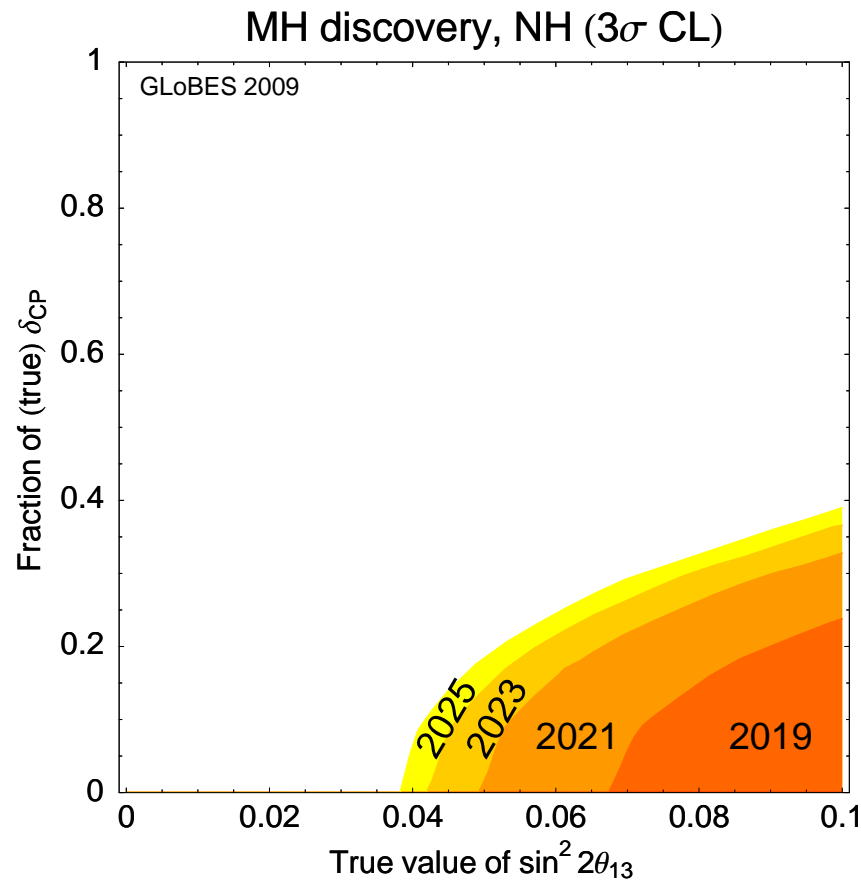
CPV without new experiments?



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

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

CPV without new experiments?



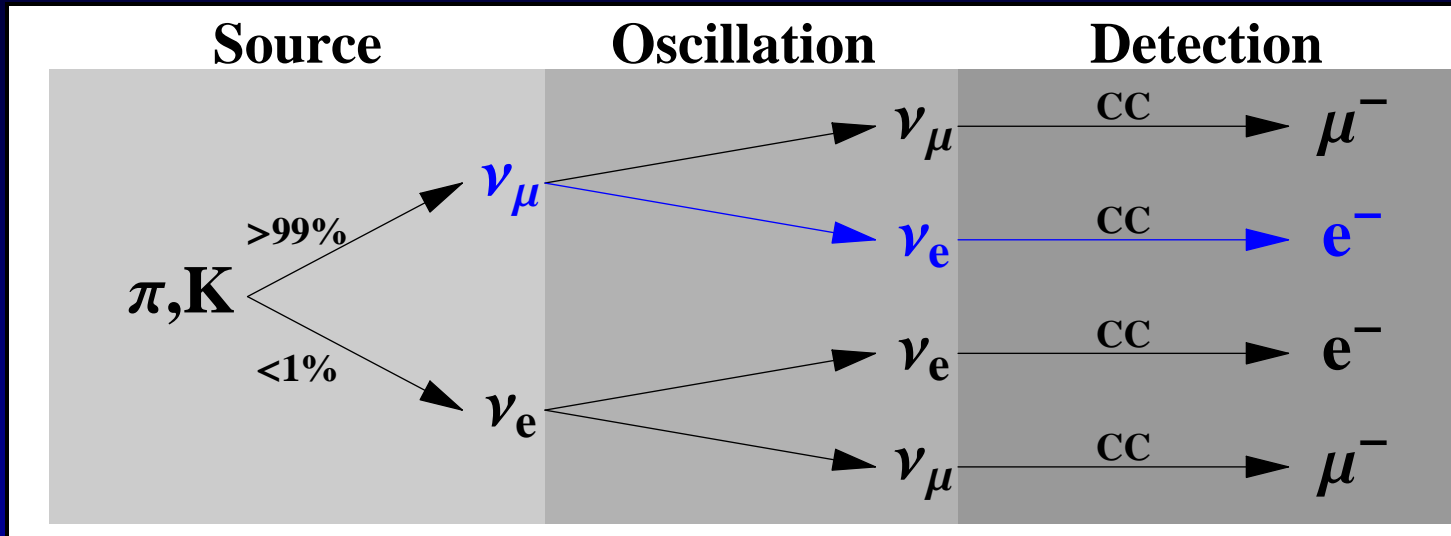
PH, M. Lindner, T. Schwetz, W. Winter, JHEP 11 044 (2009),
arXiv:0907.1896.

Includes Project X and T2K running at 1.7 MW.

Neutrino sources

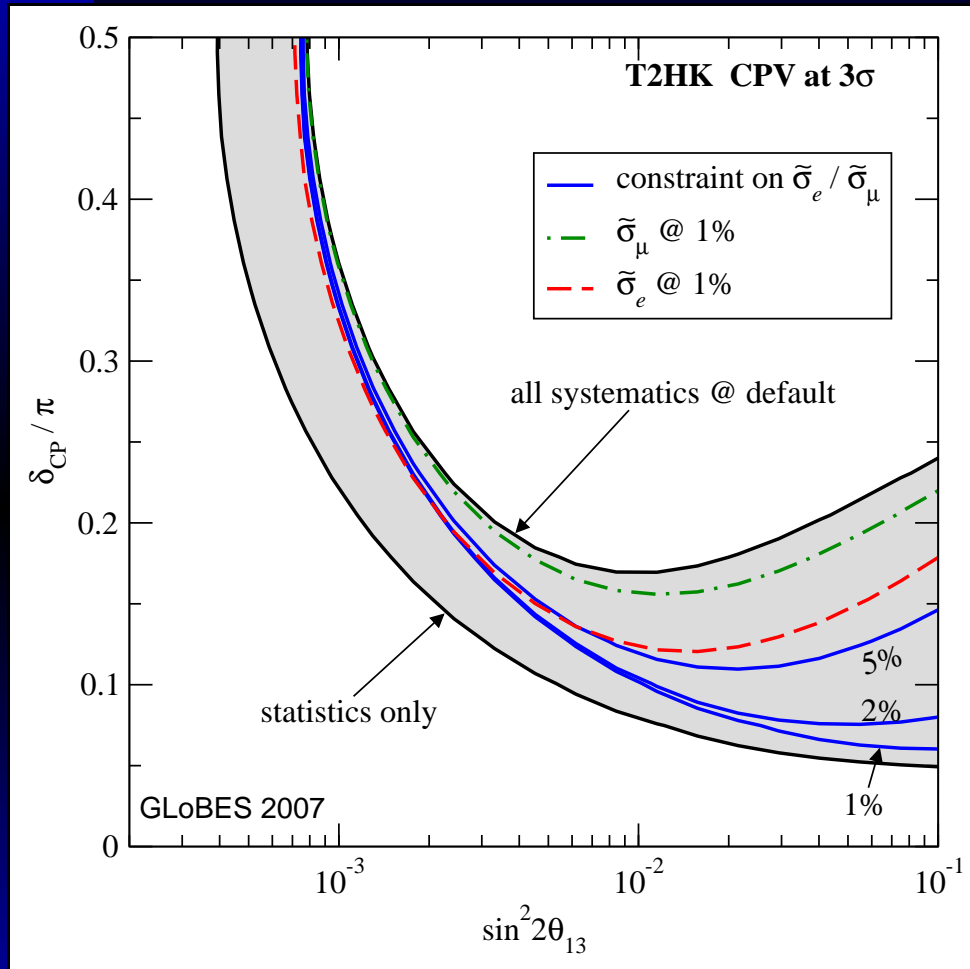
Traditional beam

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

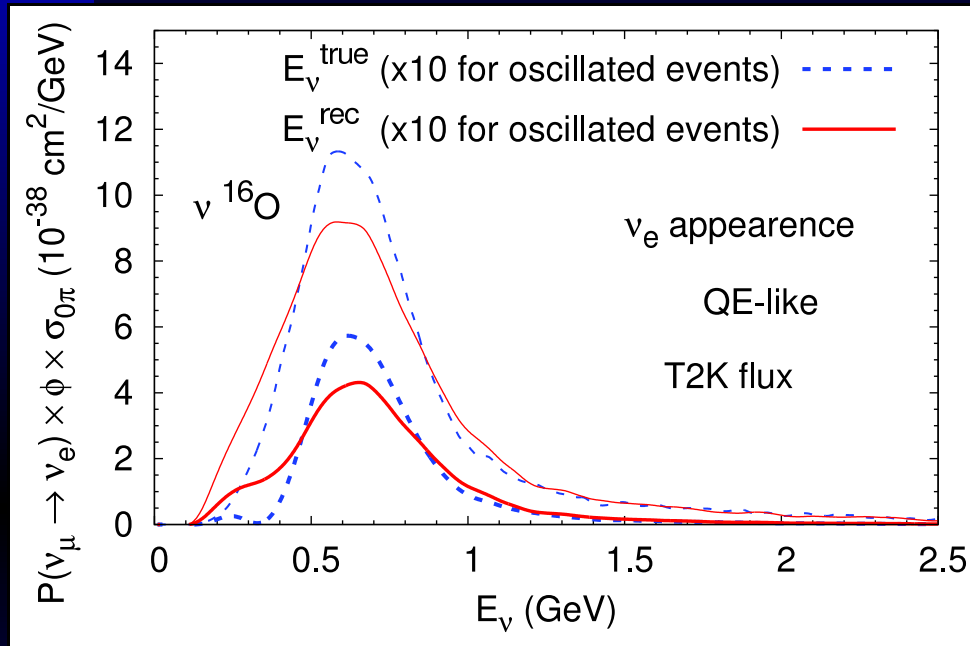


Appearance experiments using a (nearly) flavor pure beam can **not** rely on a near detector to predict the signal at the far site!

Large θ_{13} most difficult region.

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

QE energy reconstruction



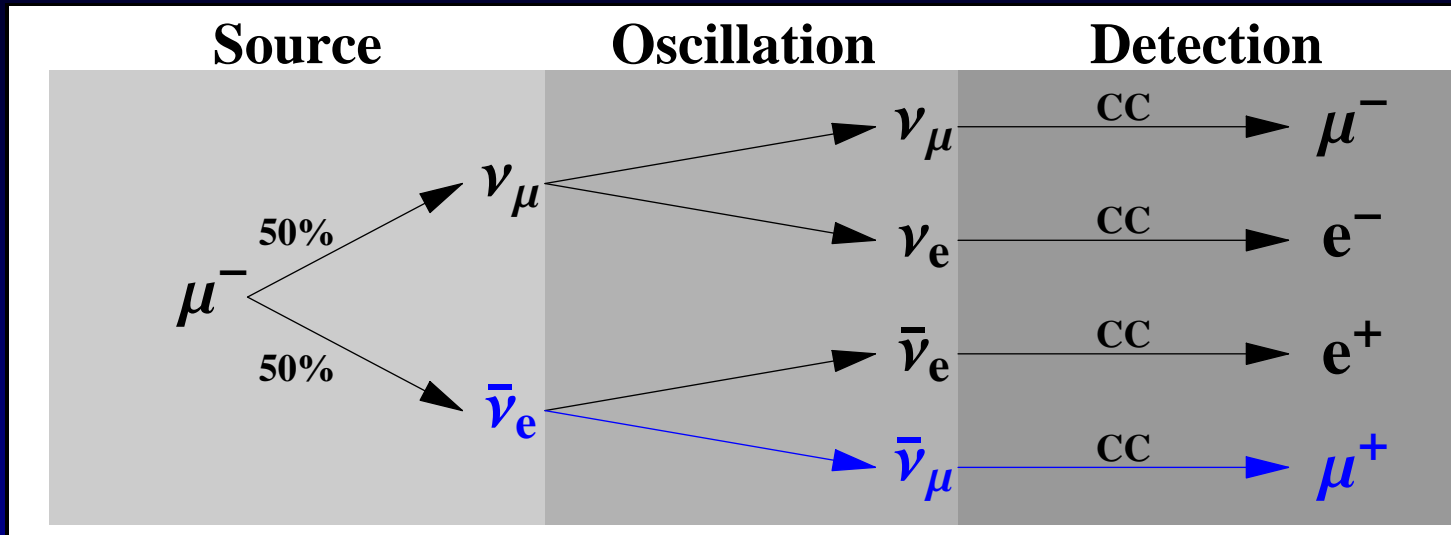
Nuclear effects change the relation between true neutrino energy and lepton energy

Lalakulich, Mosel, arXiv:1208.3678.

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



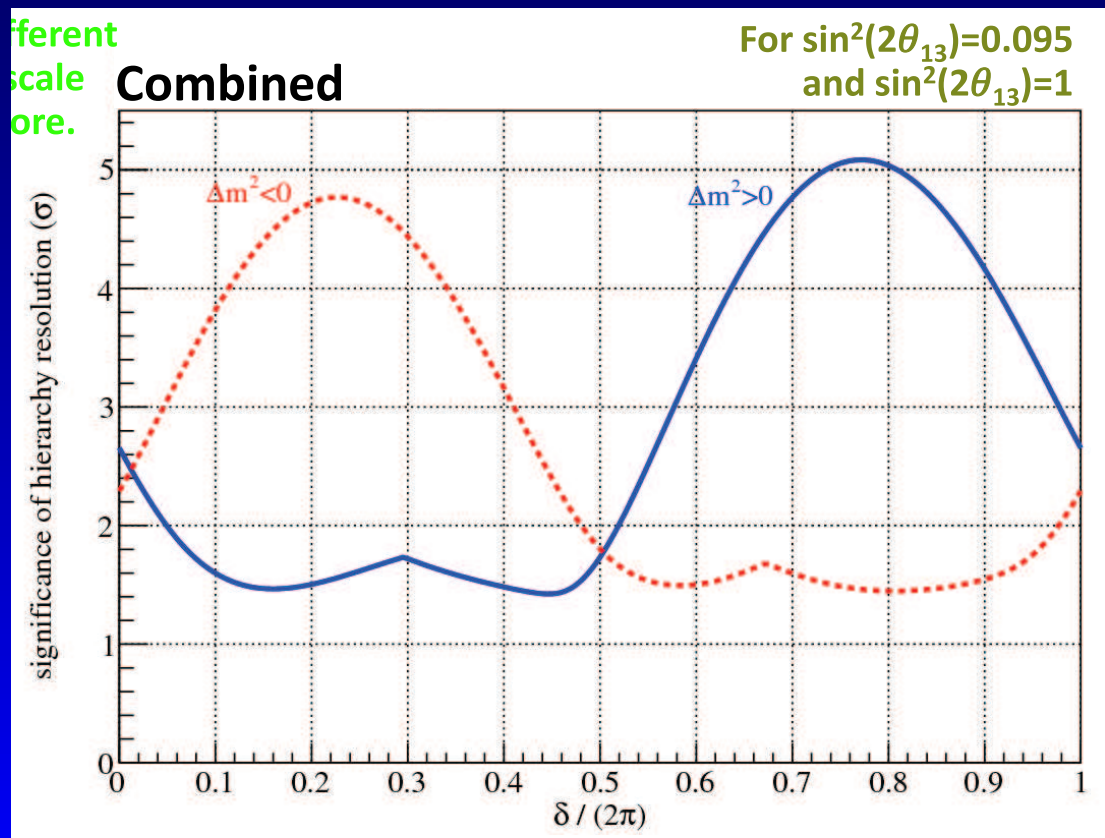
This requires a detector which can distinguish μ^+ from $\mu^- \Rightarrow$ magnetic field of around 1T

- 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

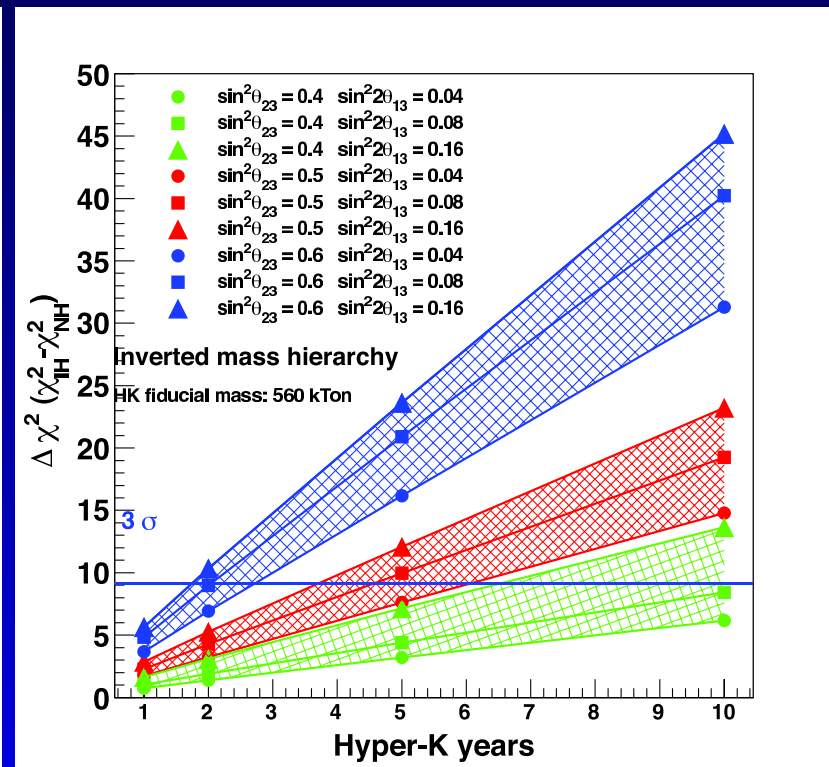
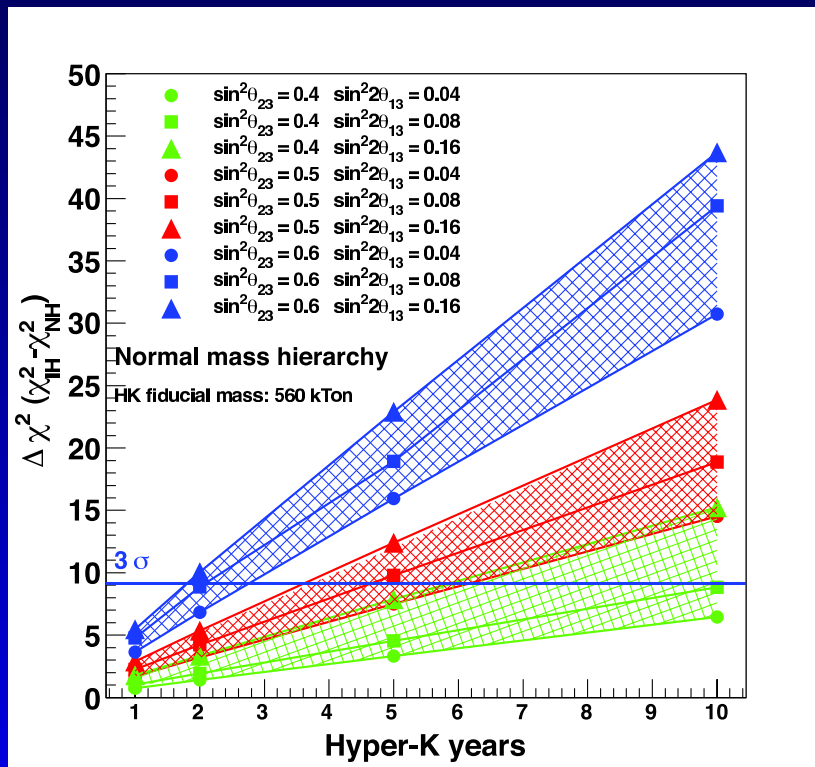
Hyper-K

Atmospheric data only

Assumes θ_{13} known from reactors

Assumes θ_{23} known from beam

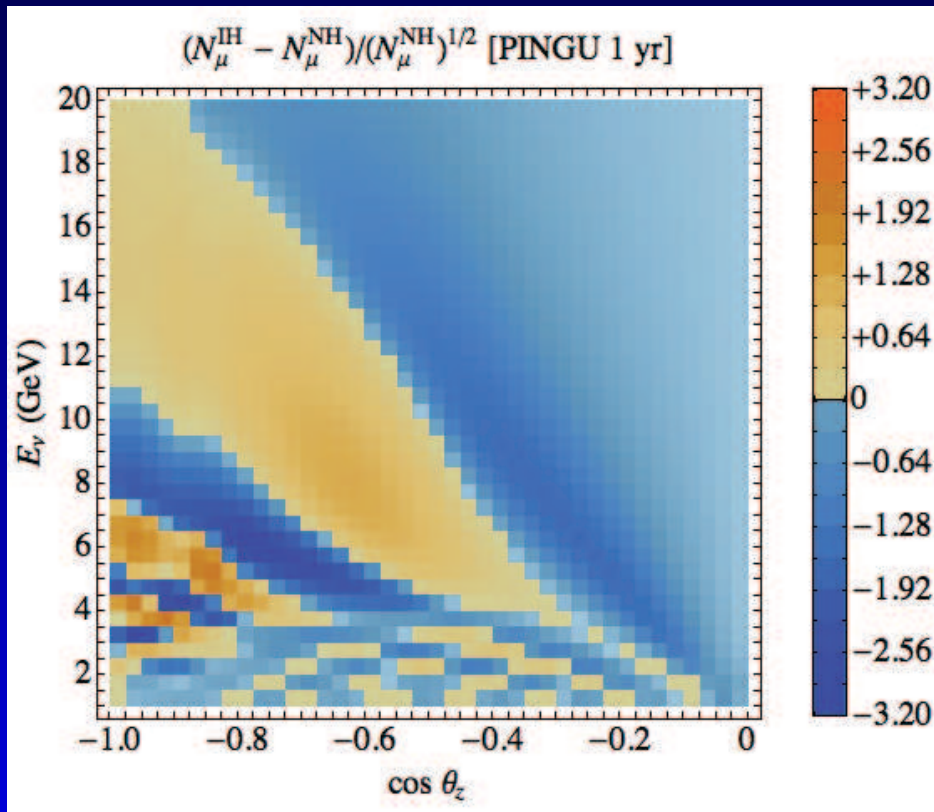
Leaves δ free



Hyper-K LOI, arXiv:1109.3262

PINGU

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



5-10 σ for all CP phases

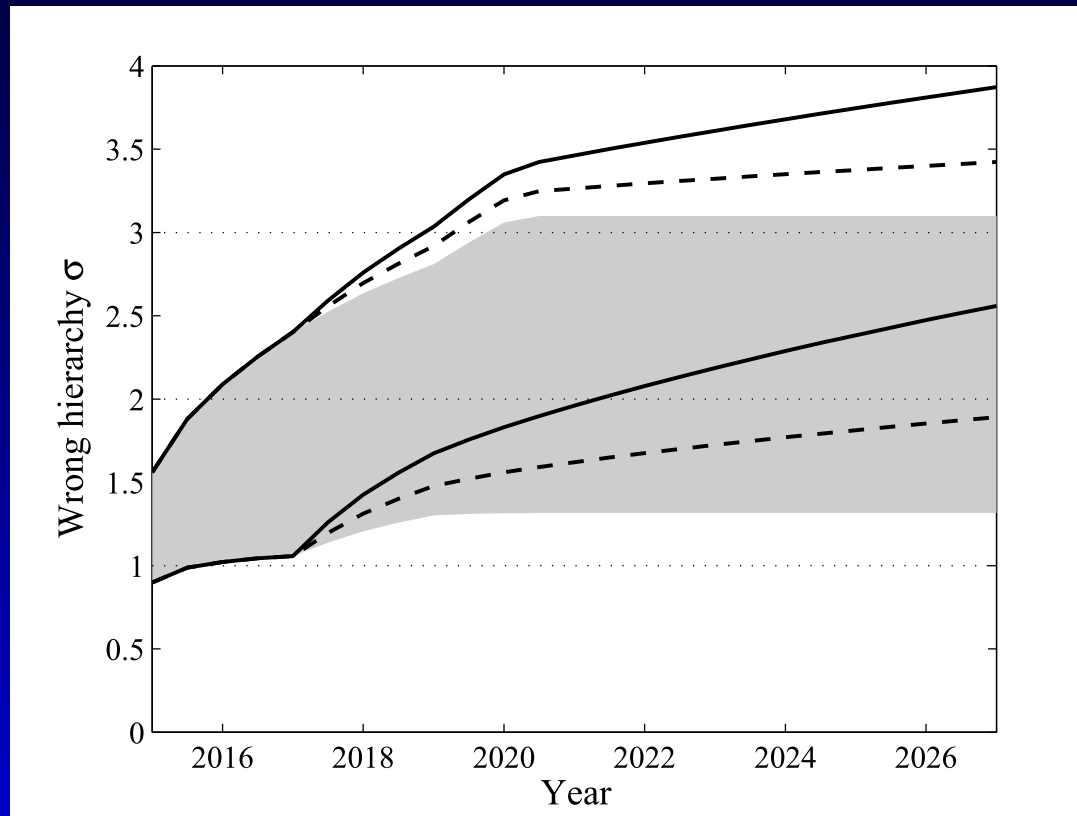
Cheap & fast

Feasibility under study
by the IceCube collaboration

Akhmedov, Razzaque, Smirnov
arXiv:1205.7071

Indian Neutrino Observatory

40 kt magnetized iron detector (like MONOLITH)



Improved angular and
energy resolution in
the multi-GeV range
neutrino/antineutrino
separation from muon
charge

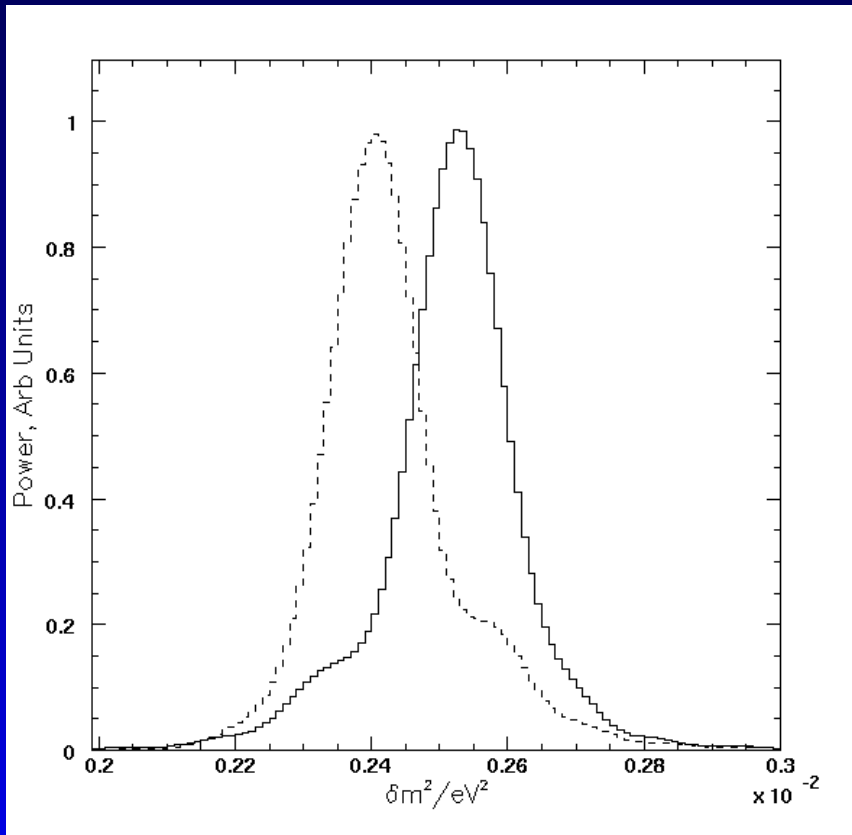
Blennow, Schwetz, arXiv:1203.3388

MH from reactors

Interference of the two mass scales

Choubey, Petcov, Piai, 2003

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



Daya Bay II

Question of systematics
control – energy scale

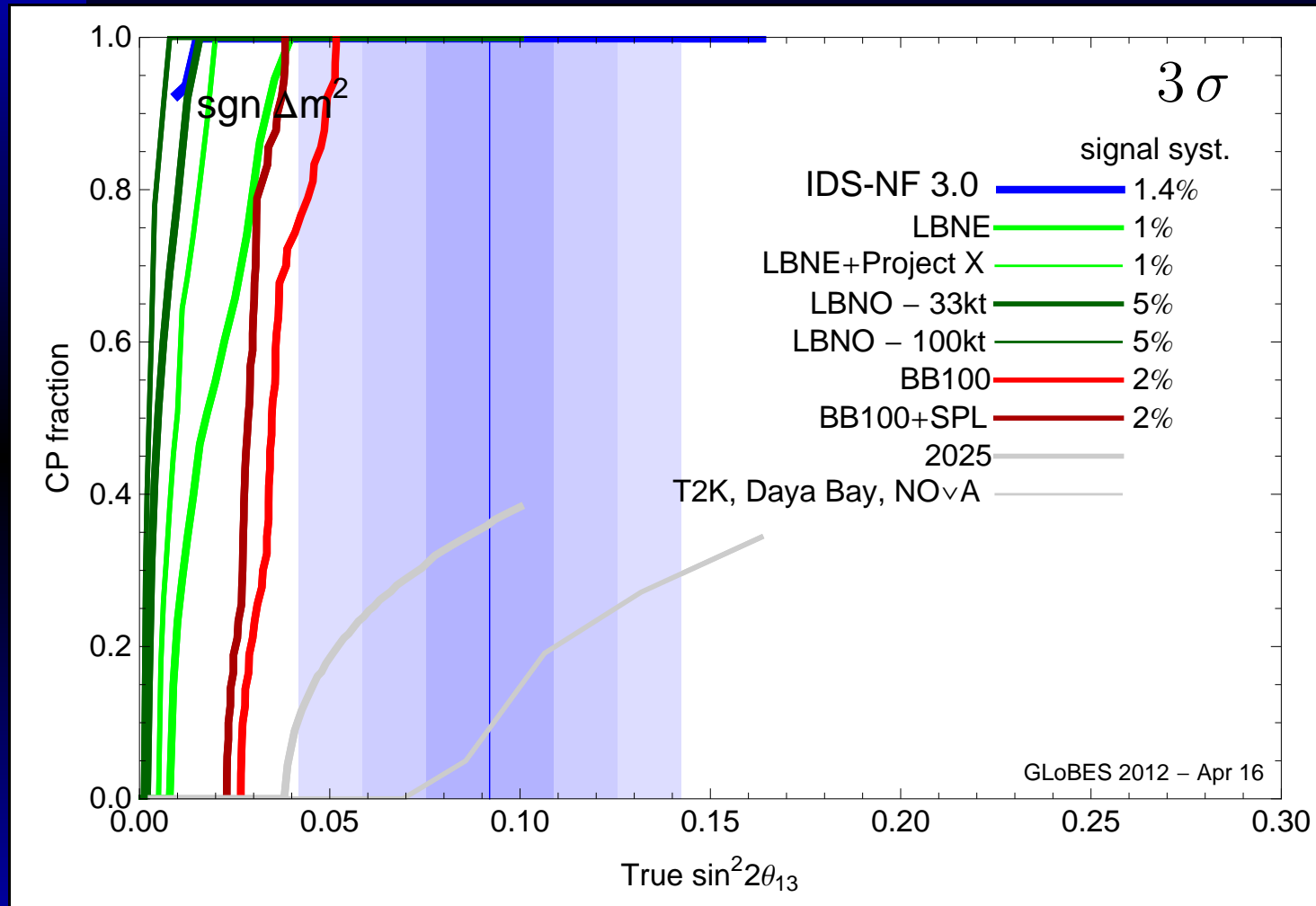
Qian *et al.*, 2012

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

Mass hierarchy corollary

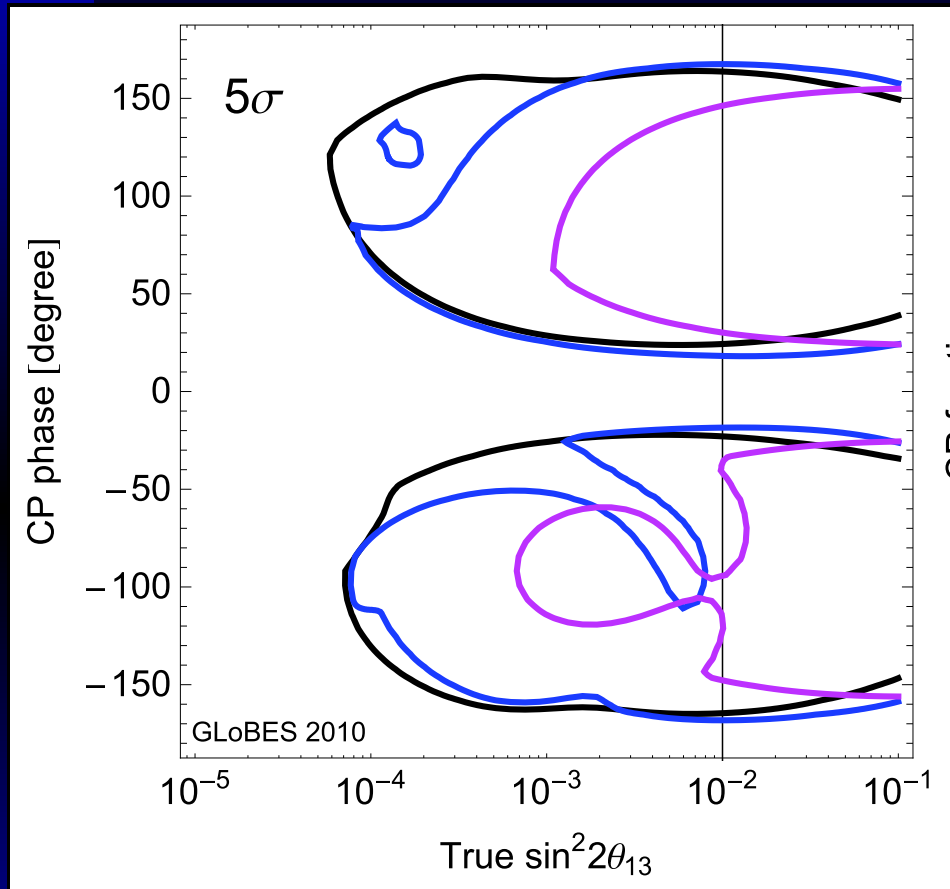
- Given the large value of θ_{13} mass hierarchy can be done in many different ways
- PINGU, ICAL, Daya Bay 2, HK atmospheric data, ...
- It therefore seems very likely that the mass hierarchy will be determined at some level w/o a new long baseline experiment

Mass hierarchy forecast



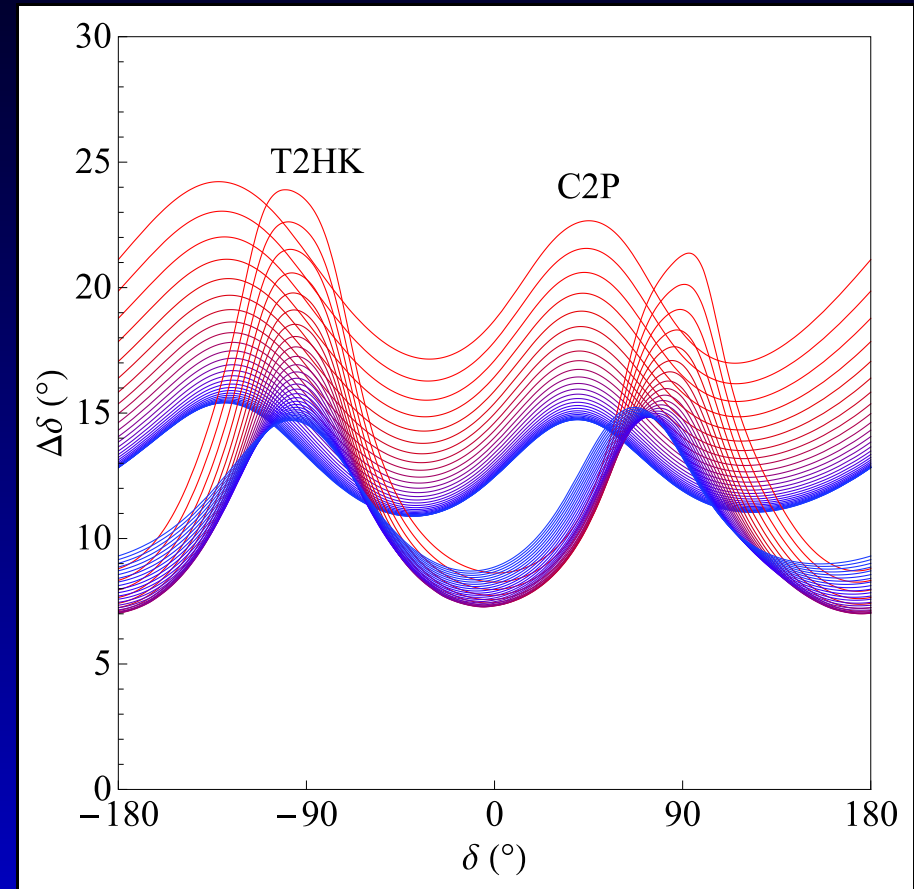
Mass hierarchy is no longer a distinguishing feature!

CP violation vs CP precision



IDS-NF IDR

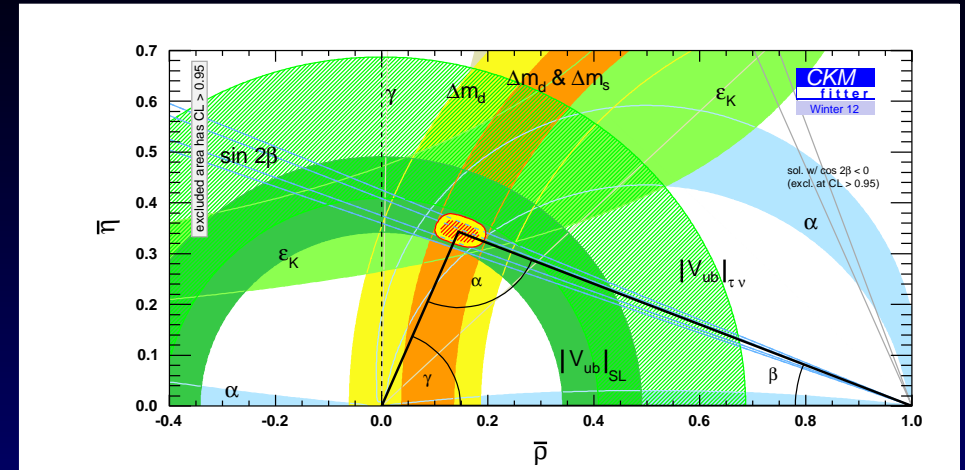
- + can show θ_{13} dependence
- + naturally include degeneracies
- region of no sensitivity



Coloma *et al.* 2012

- + can show δ dependence
- + no gaps in sensitivity
- hard to include degeneracies

Figure of merit



How to compare facilities?

- θ_{13} is measured
- mass hierarchy likely will be measured

I will use CP precision as figure of merit

- experimentally most challenging – high bar
- directly related to the unitarity triangle
- most susceptible to new physics

The following slides contain results
obtained in collaboration with
P. Coloma, J. Kopp and W. Winter.
A preprint will appear soon.

CP precision 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

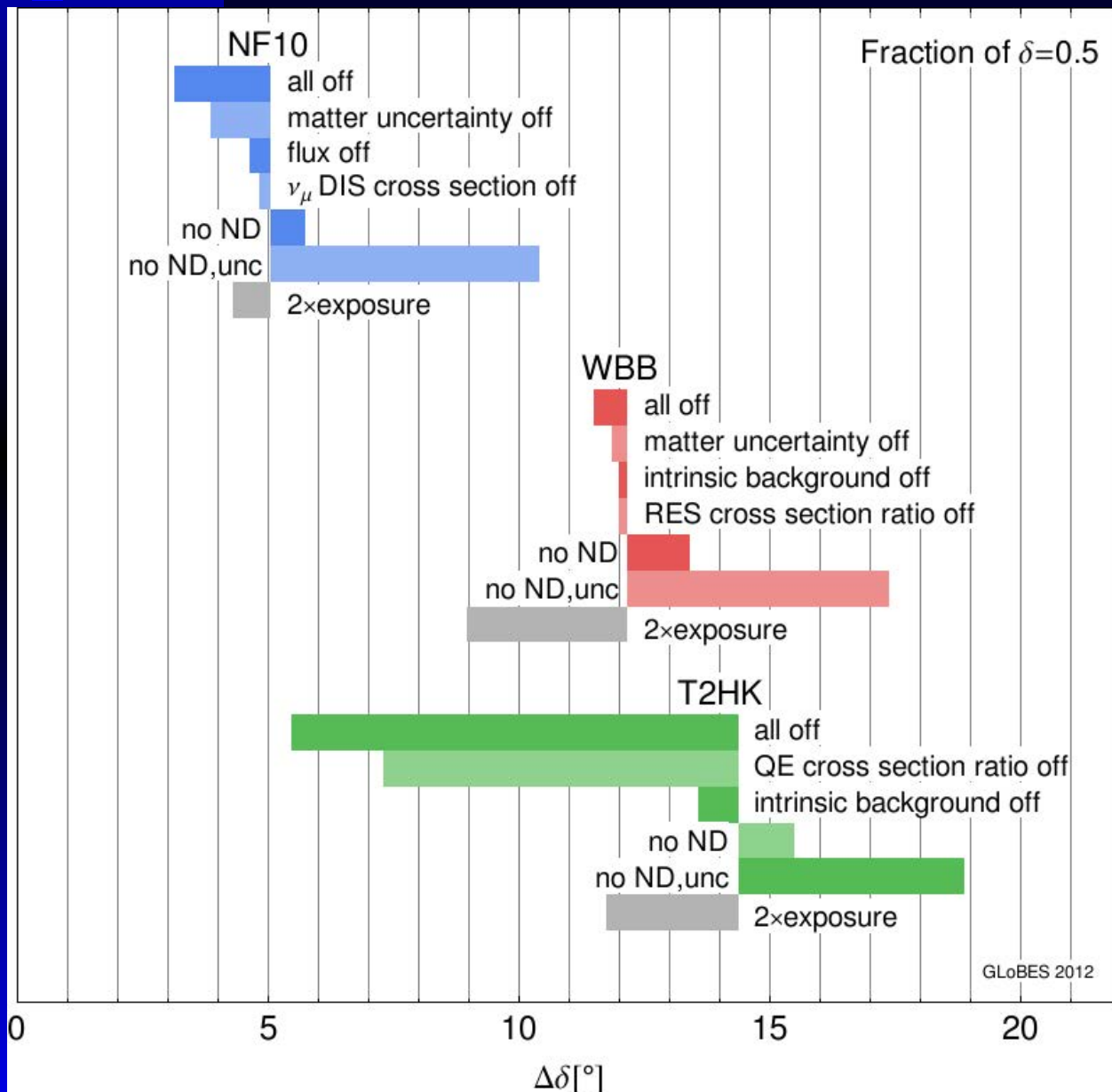
- fluxes
- beam backgrounds
- detector backgrounds

Setups

	Setup	E_ν^{peak}	L	OA	Detector	kt	MW	Decays/yr	$(t_\nu, t_{\bar{\nu}})$
Benchmark	BB350	1.2	650	–	WC	500	–	$1.1(2.8) \times 10^{18}$	(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	–	$1.1(2.8) \times 10^{18}$	(5,5)
	+ SPL			–			4	–	(2,8)
	NF5	2.5	1 290	–	MIND	100	–	7×10^{20}	(10,10)
	LBNE _{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

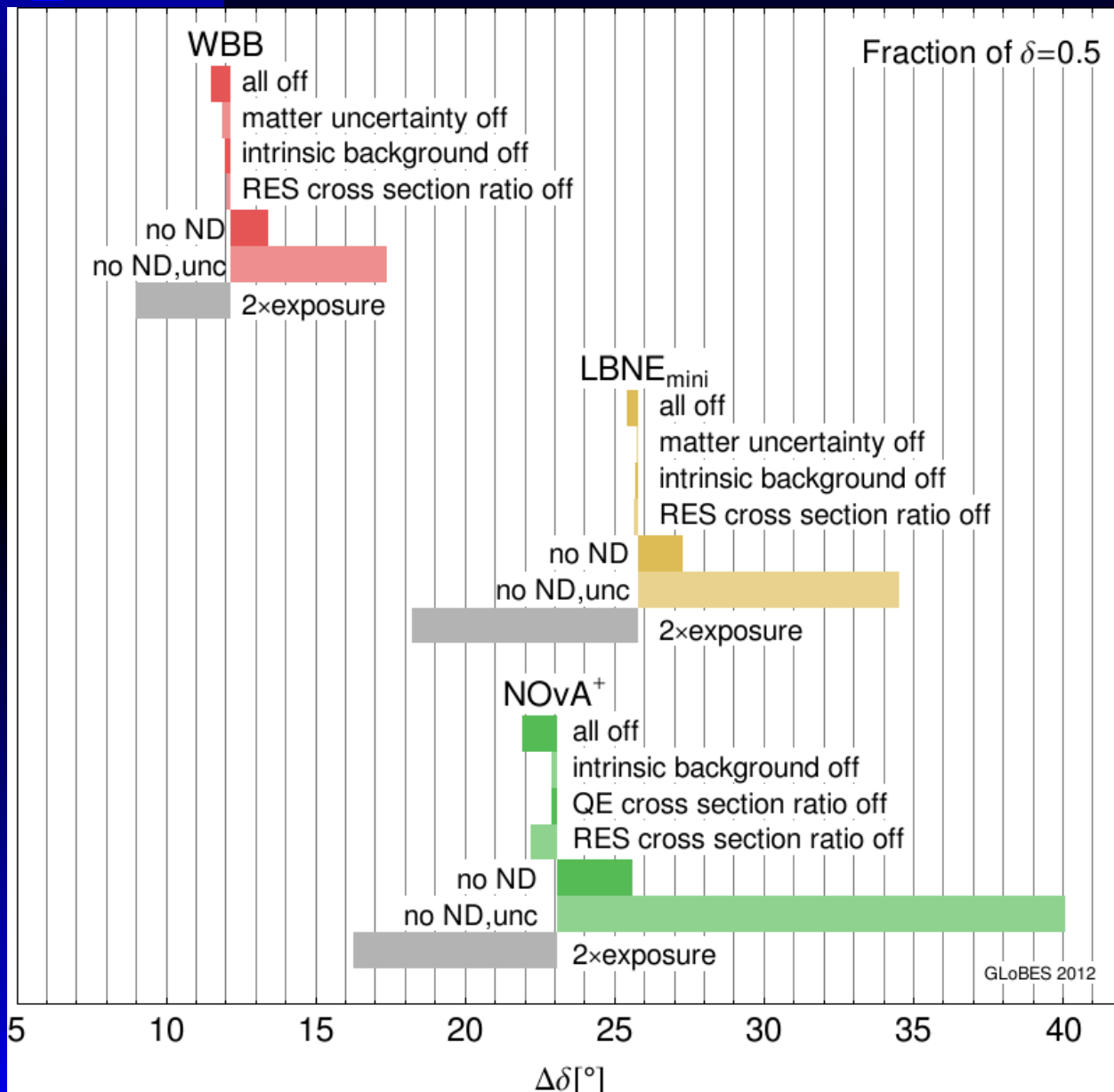
Systematics I



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

NF10 clearly outperforms all other options

Systematics II

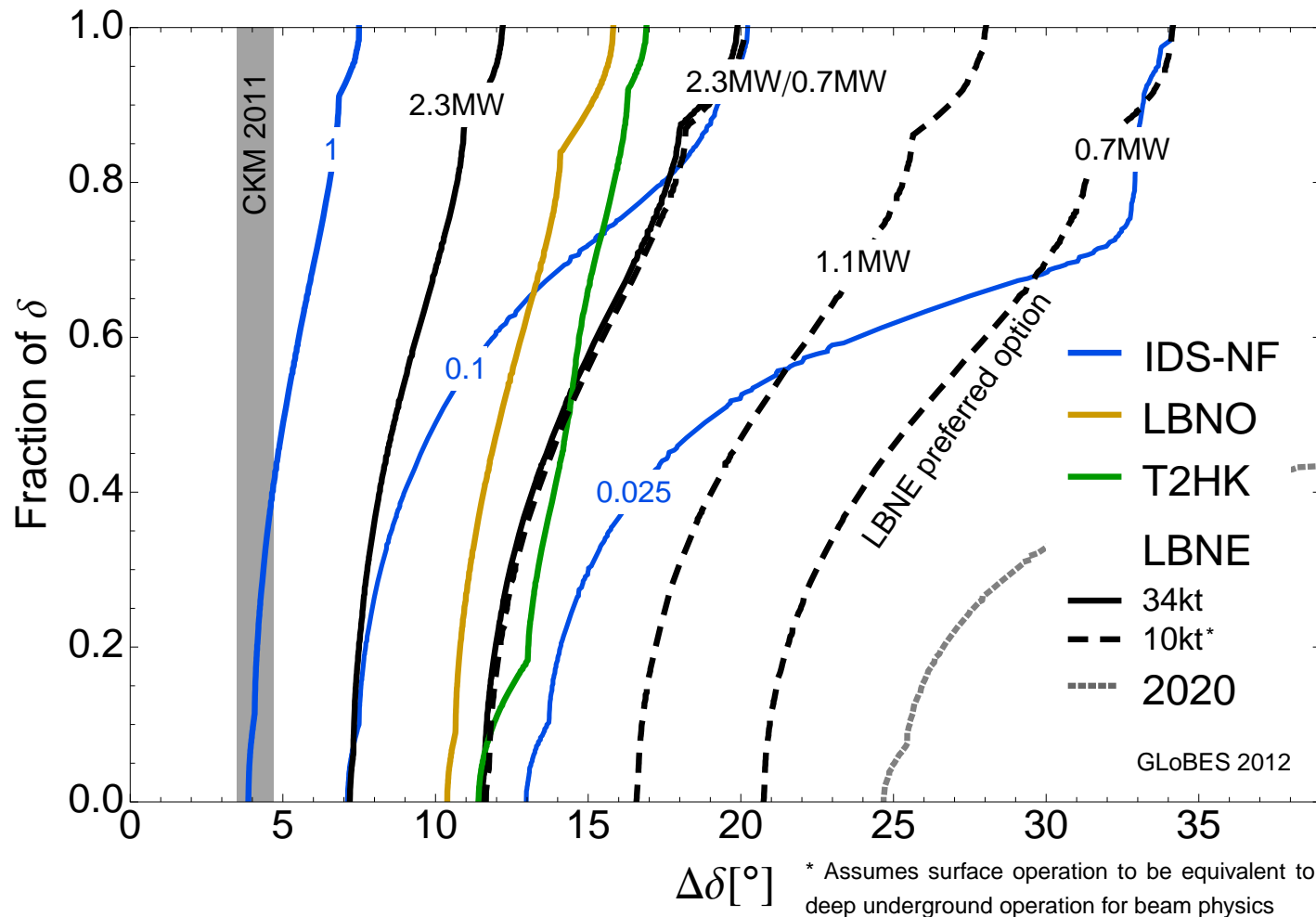


Near detector crucial
for new physics searches

NOvA⁺ higher risk
from systematics

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

CP precision



2020 – T2K, NO ν A and Daya Bay nominal runs

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

LBNO – 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

P. Coloma, PH, J. Kopp, W. Winter, in preparation

0.025 IDS-NF – 700kW, no cooling, 2×10^8 s running time, 10-15 kt detector

Summary – but not finished yet

- 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 – ν STORM, low luminosity neutrino factory, full neutrino factory, ...

A comment on staging –

a tale from German history

Konrad von
Hochstaden
Archbishop of
Cologne



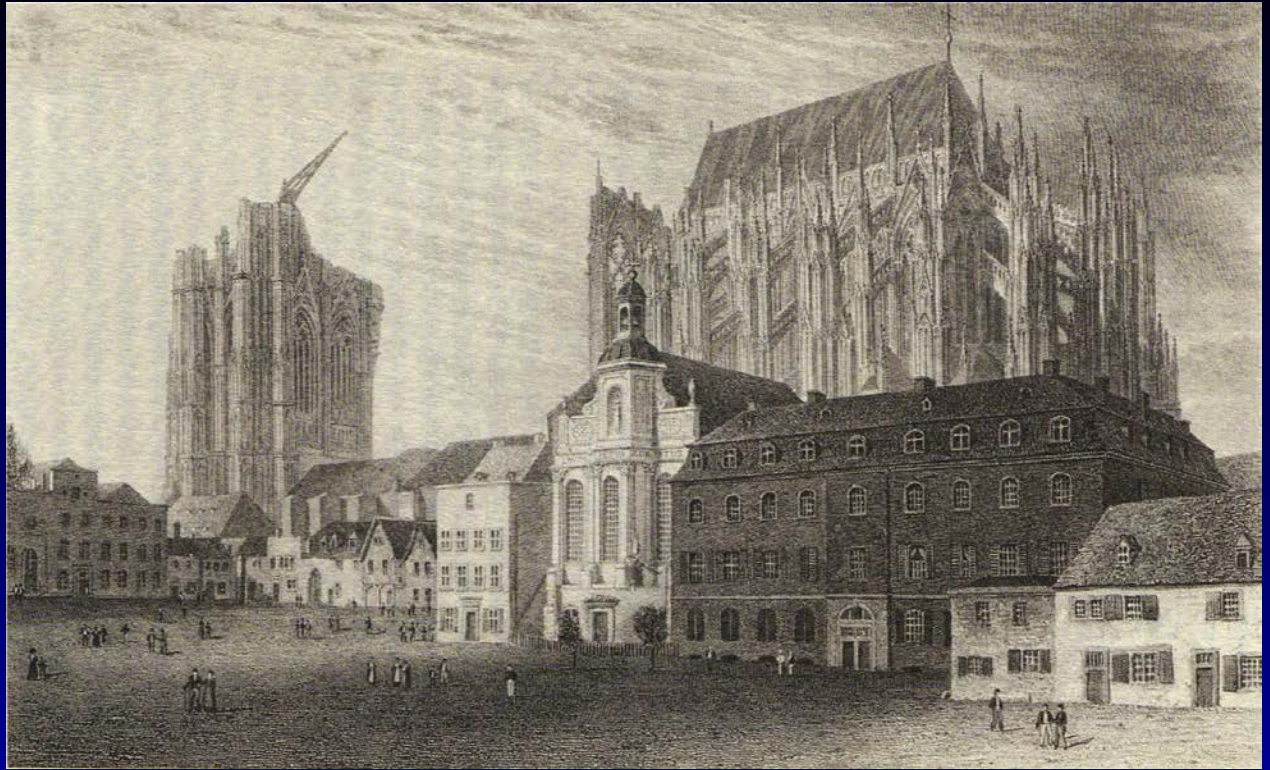
1248 A.D. Konrad inaugurated a civil engineering project to build a Gothic cathedral...

1517 A.D. – M. Luther announces a “new theory” and construction came to a halt in the early 16th century



Phase I

Project status
1824 A.D.



The community (= citizens of Cologne) managed to raise $\frac{2}{3}$ of the funds required, about \$1B in today's currency, and construction resumed.

Phase N

1880 A.D. the
cathedral was
finished



a mere 632 years after inception of the project...

Lessons learned

Assuming that our future is in building Gothic cathedrals, ...

- good motivation transcending day-to-day politics
- multi-generational, phased approach
- phase n does not imply that phase $n + 1$ follows (immediately)
- re-assess program based on new developments
- community involvement

As a consequence, each phase will have to be able to stand on its own or on the $n - 1$ previous phases.

Note, that the staff and funding of the cathedral works (Dombauhütte) always shrank and grew in proportion to the actual activities!

One way forward

A staged, muon based program

- ν STORM – 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, 10-20 kt detector) – on par with most superbeams
- Full neutrino factory – ultimate precision
- Higgs factory (s-channel, invisible width)

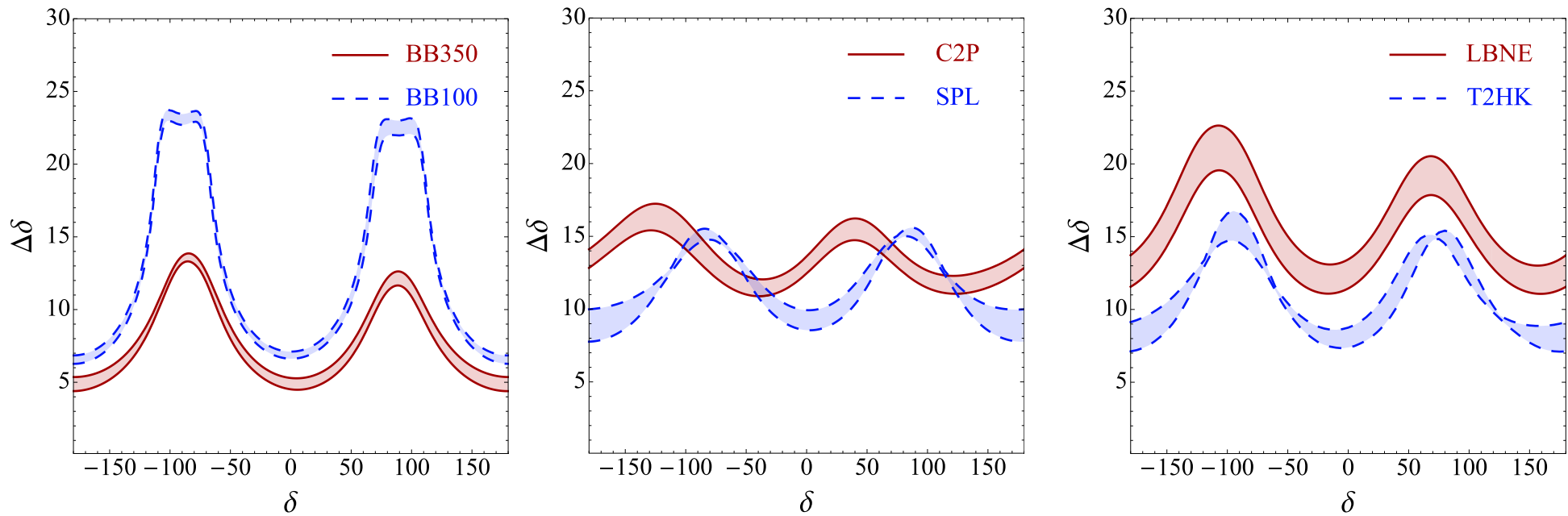
provides excellent, unique physics in each phase!

and if LHC results point to TeV-scale new physics

⇒ Muon Collider

Backup Slides

CP precision – redux



P. Coloma, A. Donini, E. Fernandez-Martinez, P. Hernandez,
[arXiv:1203:5651](https://arxiv.org/abs/1203.5651)

BB100 strongly affected by intrinsic degeneracy –
counting experiment

SPL and T2HK have very similar performances for
similar exposure

ν STORM

Low energy, low luminosity muon storage ring.

Provides with $1.7 \times 10^{18} \mu^+$ stored, the following oscillated event numbers

$$\nu_e \rightarrow \nu_\mu \text{ CC} \quad 330$$

$$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \text{ NC} \quad 47000$$

$$\nu_e \rightarrow \nu_e \text{ NC} \quad 74000$$

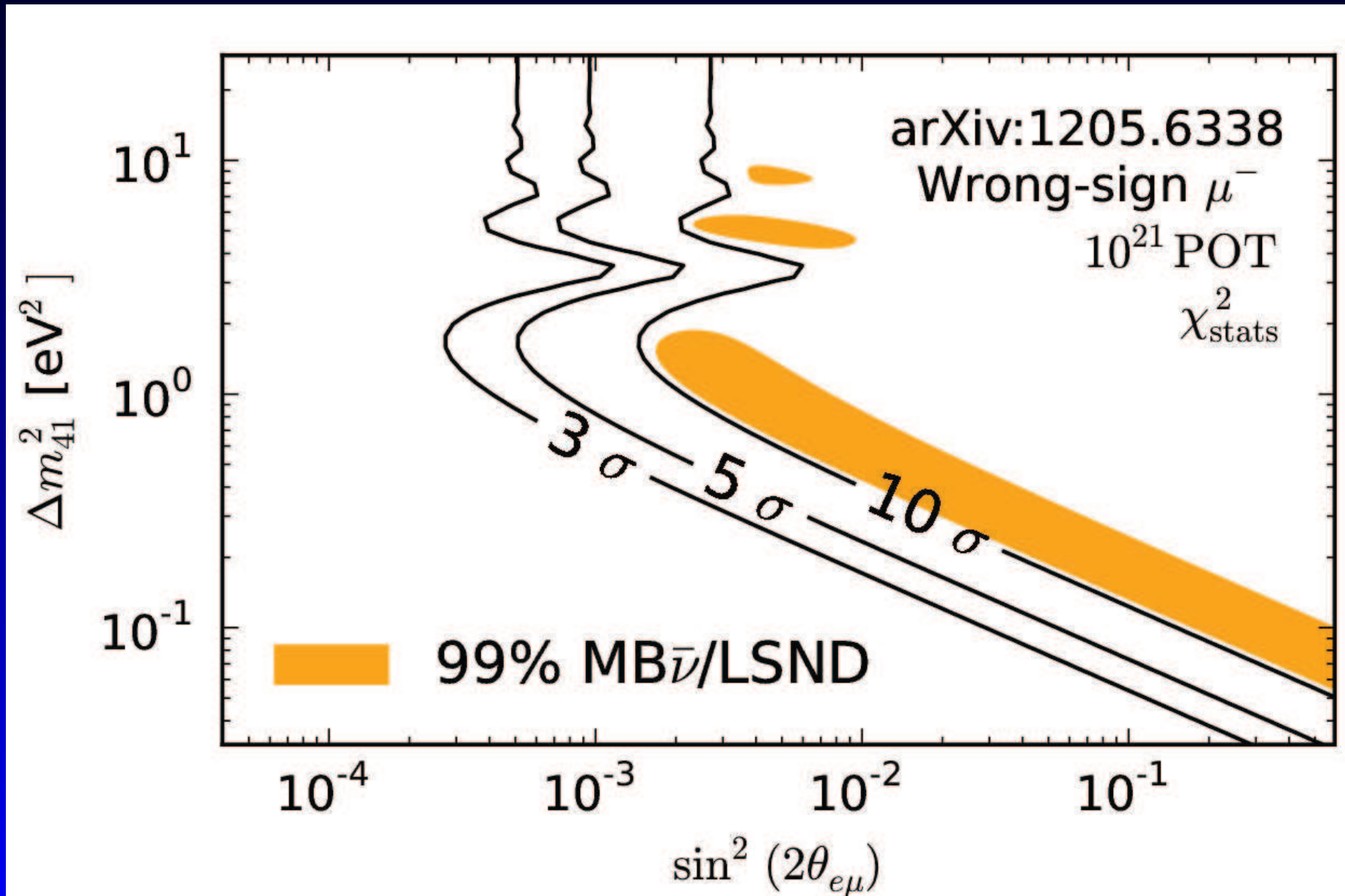
$$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \text{ CC} \quad 122000$$

$$\nu_e \rightarrow \nu_e \text{ CC} \quad 217000$$

and each of these channels has a more than 10σ 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

ν STORM – ν_μ appearance



Systematics – detailed inputs

Systematics	SB			BB			NF		
	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 (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%
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%