Long-baseline neutrino oscillation experiments for large θ_{13}

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Inνisibles pre-meeting
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Talk outline

- Neutrino oscillations.
- θ_{13} - measured!
- What next? Plans for future experiments.
- LAGUNA-LBNO: a ν oscillation experiment in Europe.
- Summary.

ν oscillations - summary

- Neutrinos are observed to **oscillate** between flavours.
- This is a quantum-mechanical phenomena which occurs because the ν flavour states and mass states are **not aligned**.
- The ν flavour states are related to the ν mass states via a mixing matrix, U_{PMNS}:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino mixing parameters

U_{PMNS} depends on 6 independent* (?) parameters:
* May be related by sum rules.

e.g. S. Antusch, S. King, arXiv:hep-ph/0508044.

- 3 mixing angles, θ_{12}, θ_{23}, and θ_{13}
- 1 Dirac phase, δ
  ($\delta \neq \{0, \pi\}$ AND all 3 angles $\neq 0 \Rightarrow$ CP violation).
- 2 Majorana phases, α_1 and α_2 (not relevant to ν oscs.)

  Only visible in processes with L-number violation, but oscillations only violate L-flavour.

The frequency of the oscillation depends on the mass-squared differences, $\Delta m^2_{ij} = m^2_i - m^2_j$ ($i, j = 1, 2, 3$) and the ratio L/E.

L is the 'baseline' = distance travelled by the ν.

ν physics = new physics!

The ν oscillations observed by Super-Kamiokande, KamLAND, SNO etc. indicate that

Δm^2_{21}, Δm^2_{31}, $\Delta m^2_{32} \neq 0 \Rightarrow$ At least 2 ν masses are non-zero.

$\Rightarrow$ First (and only!) experimental evidence for BSM physics.

ν oscillations	$\Rightarrow$	BSM physics
Low-energy phenomena	$\Rightarrow$	High-energy physics.

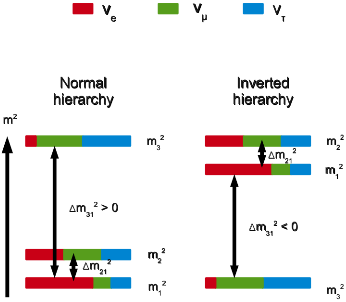
ν oscillation experiments (MeV to GeV energies) can provide complementary information to TeV collider experiments.

Unknown parameters

Up to ~ 1 year ago, there were 3 unknown oscillation parameters:

- δ - Is there CPV in the leptonic sector?
  Low-energy CPV ⇒ High-energy CPV ⇒ Leptogenesis?

- Mass hierarchy -
  normal (NH) $\Delta m^2_{31} > 0$ or
  inverted (IH) $\Delta m^2_{31} < 0$?



- θ_{13} - is it zero?
  Important theoretically
  and phenomenologically.

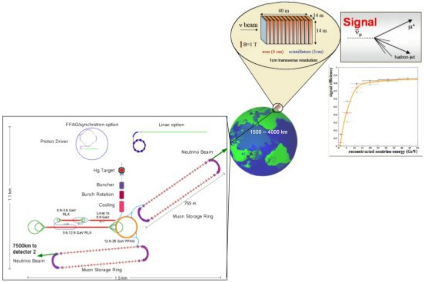
Measuring the unknown parameters

We knew that $\sin^2 2\theta_{13} <\sim 0.1$ from the CHOOZ experiment.

CHOOZ Collaboration, arXiv:hep-ex/9907037.

But exactly how small...? 10^{-2}? 10^{-4}? 10^{-10}?

Designed experiments which could detect $\sin^2 2\theta_{13} \gtrsim 10^{-5}$:



www.ids-nf.org

- Neutrino factories

S. Geer, arXiv:hep-ph/9712290.

- β-beams

P. Zucchelli, Phys. Lett. B532 (2002) 166.

These have:

very powerful beams +

very large detectors +

very low backgrounds +

very low systematic errors.

Recent θ_{13} bounds

But lately...

- T2K (Jun 2011):
  $\sin^2 2\theta_{13} = 0.03 - 0.34$ (90% CL).

  T2K Collaboration, arXiv:1106.2822 [hep-ex].

- MINOS (July 2011):
  $\sin^2 2\theta_{13} \neq 0$ at 89% CL.

  MINOS Collaboration, arXiv:1108.0015 [hep-ex].

- Double CHOOZ (Dec 2011):
  $\sin^2 2\theta_{13} = 0.017 - 0.16$ (90% CL).

  Double CHOOZ Collaboration, arXiv:1112.6353 [hep-ex].

- Daya Bay (Mar 2012):
  $\sin^2 2\theta_{13} \neq 0$ at 5.2σ (!),
  best-fit $= 0.092$.

  Daya Bay Collaboration, arXiv:1203.1669 [hep-ex].

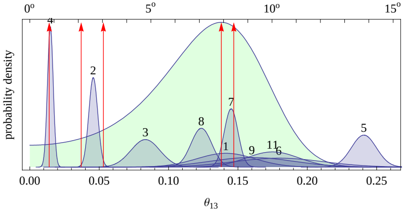
http://dayawane.ihep.ac.cn/

$\sin^2 2\theta_{13} \sim 10^{-1}$.

θ_{13} is 'large' - so what?!

Theory

- "θ_{13} prediction contest" - testing flavour models.


A. Strumia, F. Vissani, arXiv:hep-ph/0606054.

Daya Bay results can begin to exclude some models.

- δ is only physical if all 3 angles $\neq 0$
$\Rightarrow$ CPV possible.

Experiment

- δ and mass hierarchy may be measured sooner than we thought.
- Can use a smaller experiment than a ν factory or β-beam

  $\Rightarrow$ '**superbeam**' (like a normal ν beam but BIGGER).
- Different experimental strategy required than for small θ_{13}.

What next?

Requirements for a future ν oscillation experiment:

- Measure the mass hierarchy
  (relatively easy because it's a 'binary' measurement).
- Measure δ
  (harder - continuous parameter and maybe $\delta \simeq \{0, \pi\}$).
- Begin to make precision measurements
  (ideally comparable to CKM precision).
- Search for non-standard physics
  (i.e. anything other than 3-flavour oscillations).

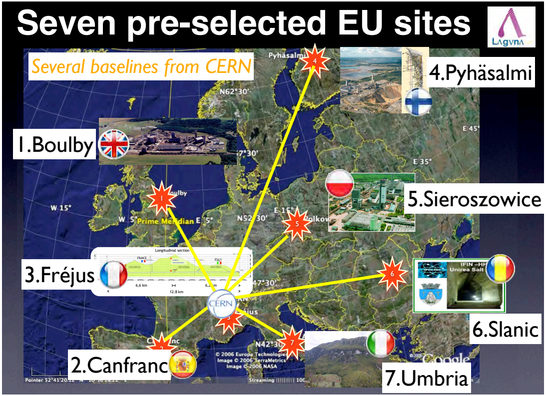
And also: **be technologically and financially feasible**
(Boring but necessary...).

‘LAGUNA’ - a long-baseline ν experiment in Europe

There is a European Design Study, LAGUNA-LBNO,

Large **A**pparatus for **G**rand **U**nification and **N**eutrino **A**strophysics/ **L**ong-**B**aseline **N**eutrino **O**scillations

to build an underground Mton-scale multi-purpose particle detector somewhere in Europe. There are 7 possible sites:



CERN could produce a **superbeam**.

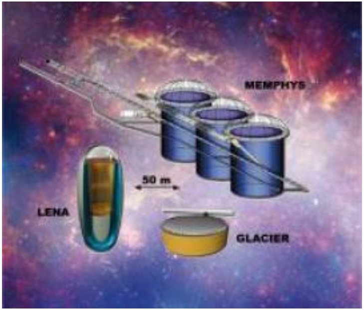
Baselines range from 130 km - 2300 km.

A. Rubbia, talk at EUCARD meeting, CNRS, Paris, May 10th 2011.

LAGUNA-LBNO

There are 3 possible detector options:

- 100 kton liquid argon (LAr, GLACIER)
- 50 kton liquid scintillator (LSc, LENA)
- 440 kton Water Čerenkov (WC, MEMPHYS).



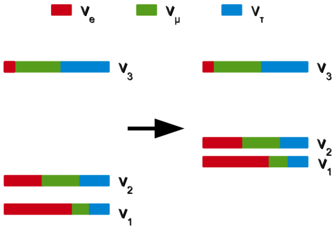
http://pprc.qmul.ac.uk/.

Different detectors have very different properties: optimal for different energies, particles, interaction types...

Which baseline + detector configuration performs best?

Best baseline? Matter matters

- ν's are 'refracted' by their interactions with matter.
- All ν flavours: NC interactions; only ν_e: CC interactions
$\Rightarrow$ ν_e's acquire larger effective mass and become 'heavier'.
- ν_1 and ν_2 have largest ν_e content, so for a NH these states get heavier:



- Energy gap is decreased
$\Rightarrow$ oscillations enhanced.
- For an IH, oscillations are suppressed.

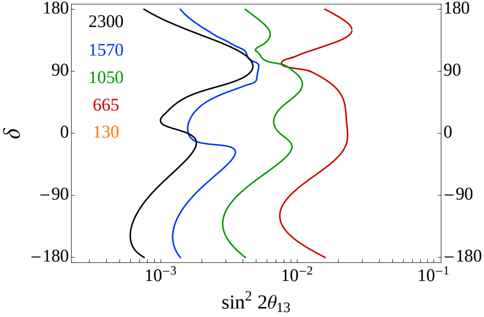
This is the key to determining the mass hierarchy...

Mass hierarchy → long baseline needed

Larger matter effects ⇒ easier to distinguish NH and IH.

In a ν beam experiment, achieve this by using a long baseline (the ν's travel through the Earth to reach the detector).

These are the hierarchy sensitivities for the LAGUNA baselines (assuming maximum beam power):



For Daya Bay value, can choose any baseline ⩾ 665 km (only for max beam power).

Matter effects more important than detector choice.

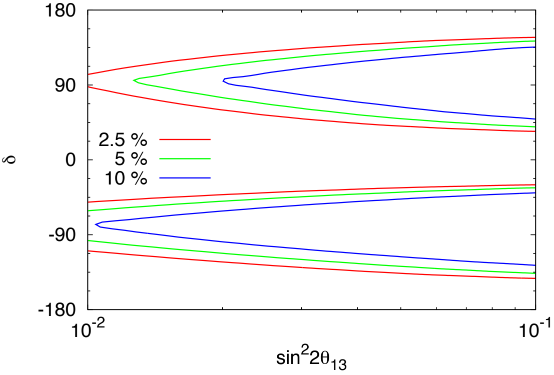
P. Coloma, TL, S. Pascoli, in preparation.

Optimal detector for CP violation

Detecting CPV is more complicated...

For large θ_{13}, some important factors are systematic errors and **backgrounds**:

Different background levels in LSc



Systematics ∼ same for all detectors.

But backgrounds in LSc are higher than in LAr or WC.

⇒ LSc good for low-E ν astrophysics, but not ∼ GeV oscillation physics.

P. Coloma, TL, S. Pascoli, in preparation.

Precision measurements

“ν oscillation physics is entering the precision era.”

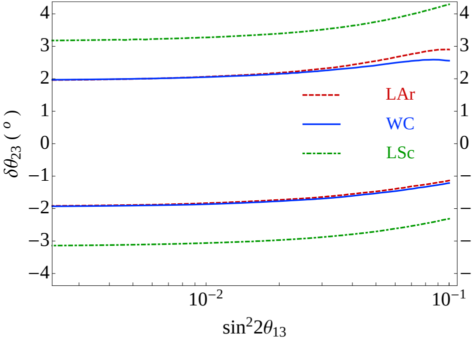
- To obtain measurements of the ν mixing parameters to within $\sim 1\%$ precision, need a ν factory (or β-beam).
- A superbeam cannot give high enough statistics/ low enough backgrounds or systematic errors.
- But it can begin to improve upon current measurements.
- e.g. The current best-fit value for θ_{23} is 45° (Super-K, MINOS).

T. Schwetz, M. Tortola, J. Valle, arXiv:1103.0734 [hep-ph].

Theoretically important question: Is θ_{23} *precisely* 45°? (Test flavour models, sum rules).

Precision measurements: $\theta_{23} = 45^\circ$?

This is how well a LAGUNA setup can detect $\theta_{23} \neq 45^\circ$:



P. Coloma, TL, S. Pascoli, in preparation.

- Can obtain a 3σ result for $\theta_{23} \lesssim 44^\circ$ and $\theta_{23} \gtrsim 48^\circ$.
- Best with LAr or WC.
- Need a long-(ish) baseline as this enhances θ_{23}-dependence.

The optimal setup

- To guarantee a measurement of the mass hierarchy (even for lower than expected beam power), need a long baseline.

  ⇒ Optimal detector for this is LAr.

- But for large θ_{13}, it's possible that data from atmospheric ν's can tell us the mass hierarchy.

  e.g. V. Barger, R. Gandhi, P. Ghoshal, S. Goswami, D. Marfatia, W. Prakash, S. Raur, U. Sankar,

  arXiv:1203.6012 [hep-ph].

  ⇒ Could also use a shorter baseline (130 km), for which WC is optimal...

- However, for non-standard physics searches, high energies ∼ long baselines are better.

Starting small

- The latest idea in long-baseline oscillation experiments is the ‘**INCREMENTAL**’ approach:

  Start small and gradually get bigger.

- A Mton-scale detector is non-trivial (!) to build (ATLAS $\sim$ 44m$\times$25m; 100 kton LAr $\sim$ 70m$\times$20m).

  Similarly for a MW-power beam.

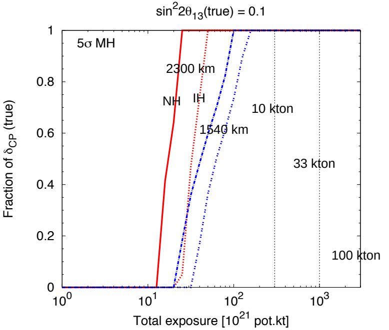
- Start small ⇒ test it works before scaling up ⇒ minimise risk.

- Since θ_{13} is large (statistics not so critical), we can also obtain results if we start with a smaller mass/ beam.

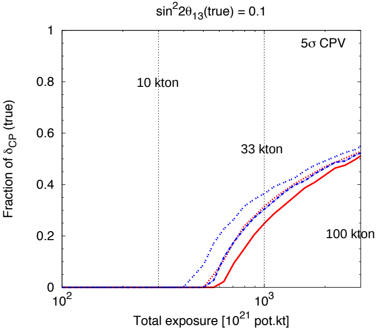
An incremental approach

What if we start with 10 kton $\Rightarrow$ 33 kton $\Rightarrow$ 100 kton?

These are the **5**σ results for mass hierarchy and CPV discovery:



S. Agarwalla, TL, A. Rubbia, arXiv:1109.6526 [hep-ph].



S. Agarwalla, TL, A. Rubbia, arXiv:1109.6526 [hep-ph].

10 kton *guarantees* a 5σ discovery of the mass hierarchy.
33 kton has $\sim$ 30% 5σ coverage for CPV.

Summary

- ν oscillation experiments can provide us with information about new physics.
- θ_{13} has been recently measured by Daya Bay and is (relatively) large.
- Future ν oscillation experiments have to be designed with this in mind.
- The LAGUNA-LBNO project is a prospective candidate for a LBL experiment in Europe.
- The ideal setup has a long baseline $\gtrsim$ 1000 km and a low-background detector.
- Since θ_{13} is large, an incremental approach can yield good physics results at each stage.