Simulations of Long-Baseline Neutrino Oscillation Experiments in LAGUNA

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Talk outline

- Overview of neutrino oscillation physics.
- Review of previous LAGUNA LBL studies.
- Current studies - super-beams.
- Optimisation studies:

  Exposure times

  Quasi-elastic event detection

  Neutral-current backgrounds

  Intrinsic backgrounds.
- Comparison of all detectors.
- Summary.

Neutrino oscillation physics

Neutrino oscillations are evidence for Beyond the Standard Model physics.

They are controlled by the mixing parameters

θ_{12}, θ_{23}, θ_{13}, δ, Δm^2_{21}, Δm^2_{31}.

We still need to measure θ_{13}, δ and the sign of Δm^2_{31} $(\pm)$ which tells us the mass hierarchy.

$\Rightarrow$ Next-generation long-baseline (LBL) experiments with high statistics and low systematic errors are required.

LBL experiments in LAGUNA

A LBL experiment requires a beam, baseline and detector.

Using a beam from CERN, LAGUNA has 7 possible baselines...

Location	Distance from CERN
Fréjus	130 km
Canfranc	630 km
Umbria	665 km
Sierozsowice	950 km
Boulby	1050 km
Slanic	1570 km
Pyhäsalmi	2300 km

A. Rubbia, arXiv:1003.1921.

LBL experiments in LAGUNA

… and 3 possible detectors

- 100 kton liquid argon (GLACIER)
- 50 kton liquid scintillator (LENA)
- 440 kton water Čerenkov (MEMPHYS).

We need to quantitatively compare the performances of different combinations of baselines and detectors.

Previous LAGUNA LBL studies - SB and NF

The following super-beam and neutrino factory setups have been studied:

- Super-beam with liquid argon, $L > 950$ km

  A. Rubbia, arXiv:1003.1921.

- Super-beam with LENA, $L = 950$ km

  TL, S. Pascoli.

- Wide-band beam with LENA, $L = 2300$ km

  J. Peltoniemi, arXiv:0911.4876 [hep-ex].

- Low energy NF with magnetised LENA, $L = 2300$ km

  J. Peltoniemi, arXiv:0912.2611 [hep-ph].

- Low energy NF with magnetised liquid argon, $L = 2300$ km

  TL, S. Pascoli.

Previous LAGUNA LBL studies - β-beams

The following β-beam setups have been studied:

- 100γ β-beam with MEMPHYS, L = 130 km

  J. Campagne, M. Maltoni, M. Mezzetto, T. Schwetz, JHEP 0704 (2007) 003.

- 450γ β-beam with LAr, L = 1050 km

  D. Meloni, O. Mena, C. Orme, S. Palomares-Ruiz and S. Pascoli, HEP 0807 (2008) 115.

- $570/350\gamma$ β-beam with LAr, L = 1570 km or 2300 km

  C. Orme, arXiv:1004.0939.

Previous LAGUNA studies

These studies tell us the following:

- The length of the baseline has a critical effect on the performance of the setup - in particular to sensitivity to the mass hierarchy.
- The best results are obtained by setups with high statistics and long baselines.
- A neutrino factory has the best physics reach of any experiment but is technically very challenging to construct.

Current LAGUNA studies - super-beams

Currently we are studying super-beam setups (using GLoBES).

A super-beam is a more powerful version of a conventional neutrino beam.

Neutrinos and anti-neutrinos are produced from the decay of hadrons (mainly $\pi^{\pm}$ and $K^{\pm}$).

Performance is limited by the cross-section and flux errors, and by backgrounds.

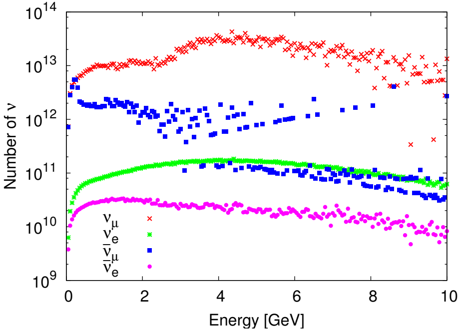
Super-beam backgrounds

In addition to the main ν_μ ($\bar{\nu}_\mu$) content, a neutrino (anti-neutrino) beam also contains

$\sim$ 10% contamination from $\bar{\nu}_\mu$ (ν_μ).

$\sim$ 1% contamination from ν_e and $\bar{\nu}_e$.

ν beam flux from A. Longhin:



Backgrounds - intrinsic ν_e background

Our primary channel is the $\nu_\mu \to \nu_e$ channel.

It is impossible to distinguish between a ν_e which is the product of an oscillated ν_μ and one which is an unoscillated ν_e.

This background is strongly detrimental to the results (more later).

Background reduction

The only way to reduce this background (and also that arising from $\bar{\nu}$ (ν) in the ν ($\bar{\nu}$) beam) is to accurately predict the original content of the beam by

- Performing dedicated experiments
- Using a near detector.

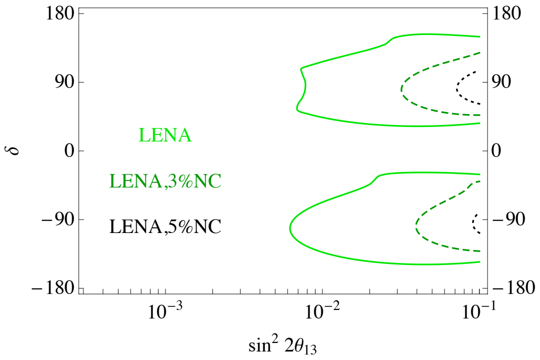
In any case, it is important to have an accurate estimate of these backgrounds in order to perform realistic simulations.

Backgrounds - neutral-current events

We can only identify the flavour of a neutrino from a charged-current interaction, not a neutral-current interaction.

So we need to distinguish these two types of interaction - misidentified NC events are a background.

Effect on CP sensitivity in LENA:

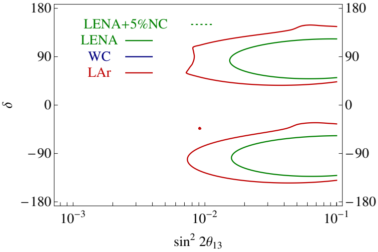


Latest simulations - beam

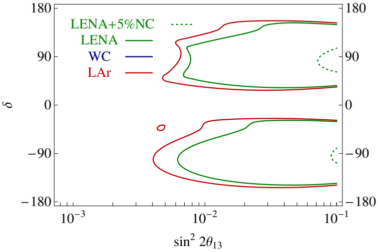
For each of the LAGUNA baselines, we have beam fluxes optimised for each baseline from A. Longhin.

Latest optimisation based on generating maximum number of events at first oscillation maximum.

Old fluxes:



New fluxes:



⇒ Large improvement, especially for CP sensitivity.

Latest simulations - detectors

Our detector simulations are based on information from the following sources.

- Liquid argon: V. Barger *et al.*, arXiv:0705.4396 [hep-ph]; migration matrices from L. Esposito and A. Rubbia.
- Liquid scintillator: J. Peltoniemi, R. Mollënberg.
- Water Čerenkov: V. Barger *et al.*, arXiv:0705.4396 [hep-ph]; B. Choudhary; N.Vassilopoulos.

Latest detector simulations

	ϵ_{CC}	ϵ_{QE}	E_{res}	E (GeV)
LAr	90%	80%	Migration matrices	[0.1, 10]
LENA	90%	70% (e) 85% (μ)	$\sigma_{CC}^{e,\mu} = 0.05E$ $\sigma_{QE}^{e,\mu} = 0.10E$	[0.5, 7]
WC	15%	[20, 40] %[1]	$\sigma_{QE}^{e} = 1.4/\sqrt{E} + 1.4$ $\sigma_{QE}^{\mu} = 1.8/\sqrt{E}$ $\sigma_{CC}^{e,\mu} = [0.05, 0.2]\ E$	[0.1, 10]

[1] We have interpolated the diagonal elements of the migration matrices used for the simulation of a WC exposed to a high-γ β-beam in GLoBES.

Optimisation studies

Using this updated information we have studied the following:

- Quasi-elastic event detection efficiencies
- Exposure times
- Intrinsic background
- Neutral-current backgrounds.

We use the CERN-Pyhäsalmi baseline (2285 km) but the results are qualitatively similar for the other baselines.

Quasi-elastic events

- Quasi-elastic (QE) and non-quasi-elastic (nQE) events have different topologies

  $\Rightarrow$ different detection properties.

- QE events in WC detectors are well-understood, but are not so well-known in LAr and LS.

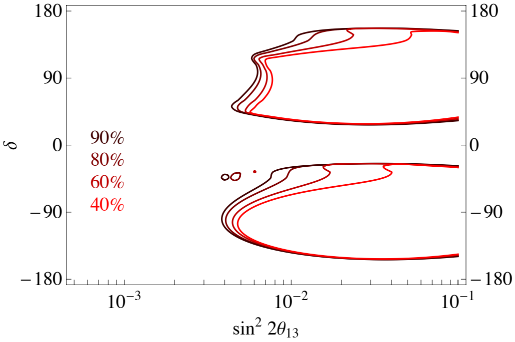
- Most QE events occur at low energies $\lesssim 1.5$ GeV (although there are still QE events at higher energies).

- Low energy events are most important for CP sensitivity.

Quasi-elastic events

If we don't accurately know the values of the QE efficiencies, we can't accurately predict the CP sensitivity.

Effect on CP sensitivity of different QE efficiencies in LAr detector:



ν and $\bar{\nu}$ running times

The CERN HP-PS2 configuration assumes 50 GeV protons, 3×10^{21} PoT per year.

A. Rubbia, arXiv:1003.1921 [hep-ph].

The running time is 2 years' $\nu + 8$ years' $\bar{\nu}$.

The running time is asymmetric because $\bar{\nu}$'s have a smaller cross-section than ν's

$\Rightarrow 2 + 8$ years gives an approximately equal number of ν and $\bar{\nu}$ interactions.

What happens if this running time is different?

ν and $\bar{\nu}$ running

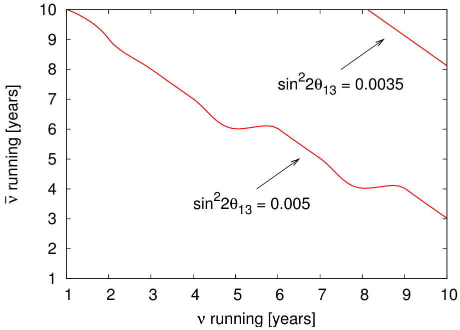
We show:

- That different combinations of $\nu/\bar{\nu}$ running give similar results.
- Which running times are necessary to reach a specific precision.

The most interesting case is CP sensitivity since this requires both ν and $\bar{\nu}$ events.

The next plot shows the running times for which the min. value of $\sin^2 2\theta_{13}$ at which we have CP sensitivity is 0.005 or 0.0035.

ν and $\bar{\nu}$ running

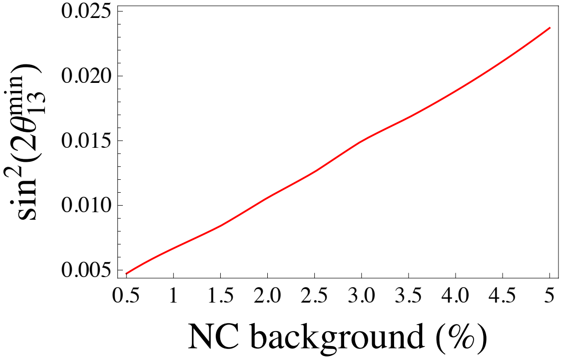


- A running time of $\sim 4 + 6$ years is similar to $\sim 2 + 8$ years.
- To obtain CP sensitivity at $\sin^2 2\theta_{13} = 0.005$ you need to run for e.g. $3 + 8$ years.
- To obtain CP sensitivity at $\sin^2 2\theta_{13} = 0.0035$ you need to run for e.g. $10 + 8$ years.

Backgrounds - neutral-current events

NC backgrounds have different effects on each detector.

Here we show how the NC background level affects the minimum value of $\sin^2 2\theta_{13}$ which can be detected by the WC detector.

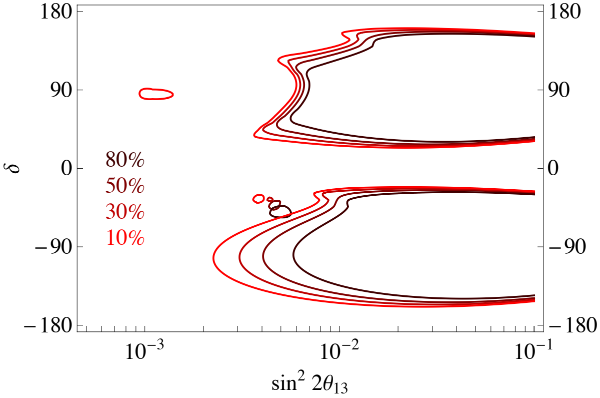


It's important to minimise this background!

Intrinsic ν_e background

The value of the intrinsic ν_e background also limits the experimental sensitivity.

CP sensitivity in LAr:

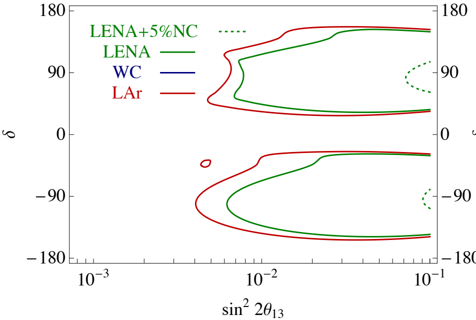


Need to minimise this background too!

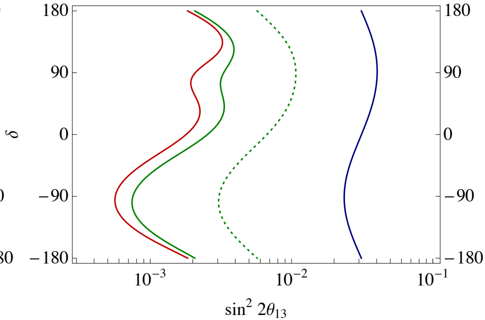
Comparison of all 3 detectors

Finally, we compare the performance of all the detectors, at the baseline of 2285 km (this will vary with different baselines).

CP discovery

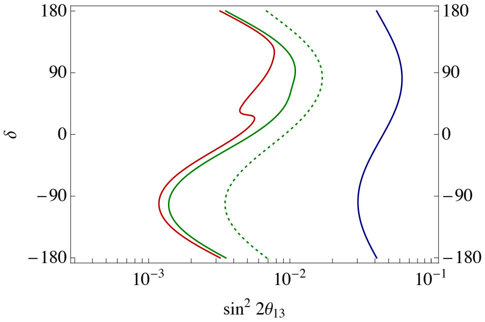


θ_{13} discovery



Comparison of the detectors

Hierarchy sensitivity



- The LAr detector performs best at this baseline.
- A LS detector, if NC backgrounds are negligible, is similar to LAr.
- A WC detector is not ideal for this baseline.
- NC backgrounds have a large effect on the results.

Summary

- LAGUNA has the potential to be a next-generation long-baseline neutrino oscillation experiment, with sensitivity to θ_{13}, δ and the mass hierarchy.
- Previous studies tell us that the best setups are those with a long baseline (> 1000 km) and high statistics.
- We are currently studying super-beam setups using optimal beam fluxes and the most recent detector information.
- Optimisation studies show that backgrounds have a critical effect on the results.
- We have also studied the importance of quasi-elastic events, and running times.
- For a baseline of 2285 km, we find that a LAr detector has the best performance, or a LS detector if the NC backgrounds can be eliminated.