Long-baseline neutrino oscillation experiments in LAGUNA

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Talk outline

- Introduction to LAGUNA.
- Long-baseline neutrino oscillations.
- Optimising the LAGUNA beam.
- Choosing the baseline.
- Comparison of LAGUNA detectors.
- Summary.

LAGUNA-LBNO

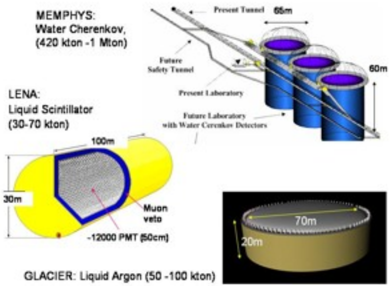
Large **A**pparatus for **G**rand **U**nification and **N**eutrino **A**strophysics/

Long-**B**aseline **N**eutrino **O**scillations

http://www.laguna-science.eu/

LAGUNA detectors

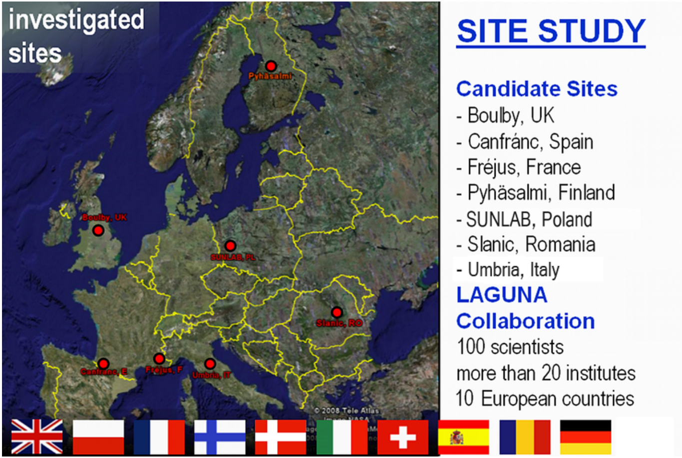
The LAGUNA design study assesses the feasibility and potential of 3 different detectors...



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

LAGUNA sites

... and 7 different sites...



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LAGUNA-LBNO physics goals

... to perform the following physics:

- Search for proton decay (grand unification).
- Study astrophysical neutrinos - solar and supernovae.
- Study terrestrial and atmospheric neutrinos.
- Couple to a next-generation neutrino beam from CERN to study long-baseline neutrino oscillations.

LAGUNA baselines

⇒ 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.

Why study long-baseline neutrino oscillations?

- Neutrino oscillations are the only evidence we have for non-zero neutrino masses.

  $\Rightarrow$Physics Beyond the Standard Model.

- Neutrino oscillation experiments can probe physics at high-energy scales, in a low-energy experiment.

- Measure the neutrino 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.

Future LBL experiments

- T2K, DoubleChooz, Daya Bay, RENO can discover if $\sin^2 2\theta_{13} \gtrsim 10^{-2}$ in the next $\sim$ 5 to 10 years.

- Then what?

  - If we discover non-zero $\theta_{13} \Rightarrow$ search for CP violation and identify the mass hierarchy.

  - If we don't discover $\theta_{13} \Rightarrow$ carry on searching...

- Need a new generation of long-baseline experiments, such as LAGUNA.

How to measure oscillation parameters

Super-beam experiments search for the $\nu_\mu \to \nu_e$ channel:

$$
\begin{aligned}
P_{\nu_\mu \to \nu_e} &= s_{213}^2 s_{23}^2 \sin^2\left(\frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2}\right) \\
&+ s_{213}\, \alpha\, s_{212}\, s_{223} \frac{\Delta m_{31}^2 L}{2EA} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E} - \frac{AL}{2}\right) \\
&\quad \times \cos\left(\delta + \frac{\Delta m_{31}^2 L}{4E}\right) \\
&+ \alpha^2 c_{23}^2 s_{212}^2 \left(\frac{\Delta m_{31}^2 L}{2EA}\right)^2 \sin^2\left(\frac{AL}{2}\right).
\end{aligned}
$$

We need:

- High statistics (suppression by θ_{13})
- Good energy resolution (to reconstruct the energy spectrum)
- Long baseline (to determine mass hierarchy).

Optimising LBNO

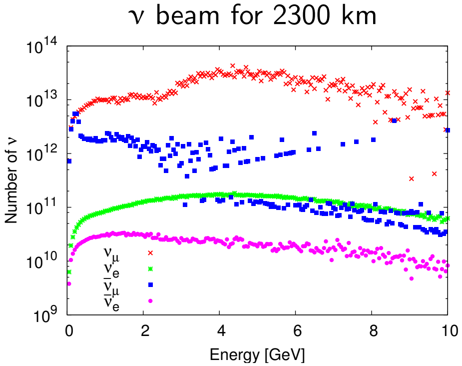
We have to assess all three parts of the experiment:

- The beam
- The baseline
- The detectors.

LBNO beam

We use optimised beam fluxes provided by Andrea Longhin.

These peak at the first oscillation maximum - maximises statistics.

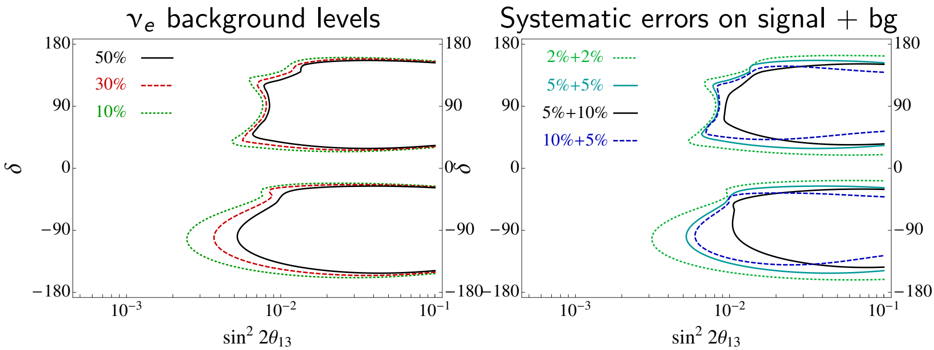


Intrinsic backgrounds:

- $\sim 1\%$ contamination from ν_e (bkgd to $\nu_\mu \to \nu_e$ channel)
- $\sim 10\%$ contamination from $\bar{\nu}_\mu$ (inhibits CP sensitivity).

LBNO beam

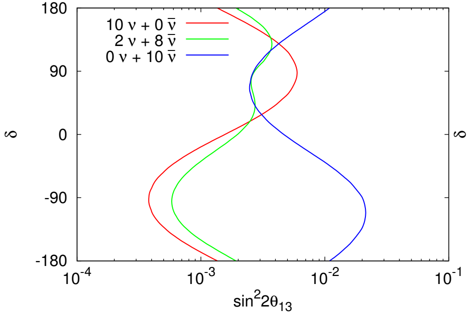
It is very important that we can accurately predict the beam content (dedicated experiments or use a near detector).



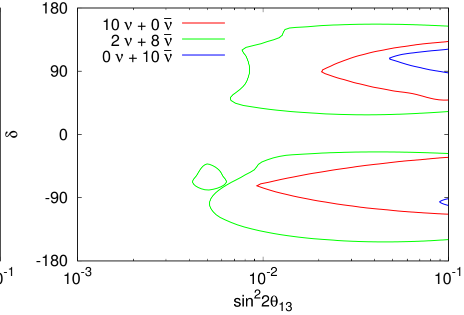
The standard HP-PS2 setup (A. Rubbia, arXiv:1003.1921) assumes 2 years' ν + 8 years' $\bar{\nu}$.

Do we need both ν's and $\bar{\nu}$'s? Yes!

θ_{13} discovery



CP discovery



Choosing the baseline

We assess the performance primarily in terms of the sensitivities to θ_{13}, δ and the mass hierarchy.

In theory: enhancing matter effects with a long baseline enables us to determine the mass hierarchy and thus reduce degeneracies.

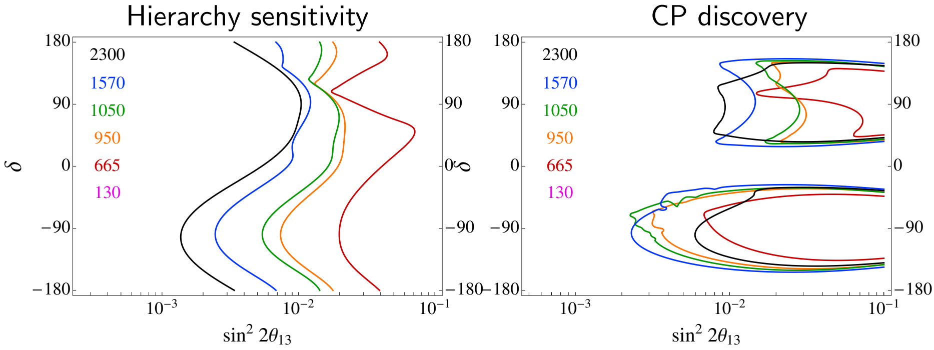
In practice: beam divergence means longer baseline $\Rightarrow$ fewer events.

$\Rightarrow$ **At some baseline, the reduction in statistics is no longer compensated for by the enhanced matter effects.**

Choosing the baseline

In general, the longest baseline will always give the best sensitivity to the mass hierarchy, regardless of the detector.

But this is not true for θ_{13} and CP sensitivity.



Comparing LAGUNA detectors

Basic overview of LAGUNA detectors:

Detector	ϵ_{CC}	ϵ_{QE}	NC bkgd	$\sigma(E)$	E (GeV)
LAr (100 kton)	90%	80%	0.5%	Response matrices	$[0.1, 10]$
LENA (50 kton)	90%	70% (e) 85% (μ)	$[0.5, 5]$ %	$\sigma_{CC} = 0.05E$ $\sigma_{QE} = 0.10E$	$[0.5, 7]$
WC (440 kton)	40%	40%	5%	Response matrices	$[0.1, 10]$

Detectors - references

- Liquid argon:

  - L. Esposito and A. Rubbia

  - LBNE collaboration.

- Liquid scintillator:

  - M. Wurm *et. al*, 1104.5620 (LENA white paper)

  - Private communications from R. Möllenberg and D. Hellgartner.

- Water Čerenkov:

  - LBNE collaboration.

Comparing detector performances

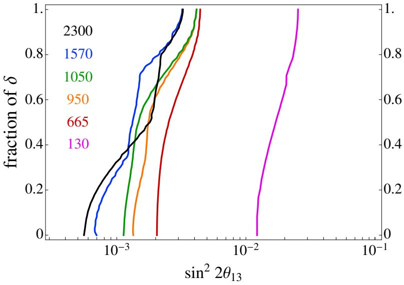
We don't know how well LENA can reject NC background events.

If it does it well, LENA has a similar performance to LAr.

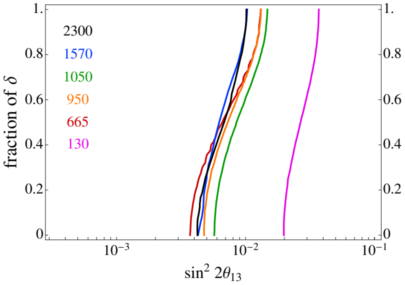
If not, similar to WC (approximately 3x less sensitive than LAr).

θ_{13} discovery potential:

LAr (~ LENA with 0.5% NC)



WC (~ LENA with 5% NC)



Summary

- We are studying the sensitivity of different LAGUNA-LBNO setups.
- The 2300 km baseline has the best reach for the hierarchy, but the 1570 km baseline is optimal for θ_{13} and CP discovery.
- Liquid scintillator with 0.5% NC backgrounds $\simeq$ liquid argon.
- Liquid scintillator with 5% NC background $\simeq$ water Čerenkov.
- The performance is strongly dependent on backgrounds and systematics.
- An optimised LAGUNA-LBNO setup can measure the neutrino oscillation parameters for $\sin^2 2\theta_{13} \gtrsim 10^{-3}$.