The main motivation for this study is to answer to the following question:

“Are the 2-5% overall systematic errors claimed by future SuperBeam experiment credible? Their sensitivities depend very much from this value”

Furthermore:

- Are the close detectors sufficient to this task?
- What are the improvements from hadroproduction experiments and from better measurements of neutrino cross sections?
- What are the most critical quantities to be measured?
The study concentrated on the T2HK experiment, for the simple reason that it’s the experiment for which is available the most complete experimental information and the close detectors are already designed for T2K. We concentrated more on general development of the method than on precise definition of all the aspects of the T2HK experiment. Some information about T2KK are given.

- Describe the T2HK (T2K) experiment in Globes.
- Make an educated guess of which systematics you’d have without any close detector.
- Add the 2 km water Čerenkov detector and study the performances of a two detector setup: SK + 2 km;
- Compute sensitivity and study which are the most important systematics.
- Quantitatively define:
  - The overall level of systematics
  - The most promising areas of improving, in particular
    - The impact of a second (more performant) close detector
    - The impact of a dedicated hadroproduction experiment
    - The impact of ancillary measurements on cross-sections
The general problem of close detectors in a SB experiment

**SuperBeams**

$$N_{\text{events}}^{\text{far}} = \left( \sigma_{\nu_e} \epsilon_{\nu_e} P_{\nu_\mu \nu_e} + \sigma_{\nu_\mu}^{\text{NC}} \epsilon_{\text{NC}} + \sigma_{\nu_\mu}^{\text{CC}} \epsilon_{\text{CC}} P_{\nu_\mu \nu_\mu} \right) \phi_{\nu_\mu} + \sigma_{\nu_e}^{\text{CC}} \epsilon_{\nu_e} \phi_{\nu_e}$$

$$N_{\text{events}}^{\text{close}} = \left( \sigma_{\nu_\mu}^{\text{NC}} \epsilon_{\text{NC}}' + \sigma_{\nu_\mu}^{\text{CC}} \epsilon_{\text{CC}}' \right) \phi_{\nu_\mu}' + \sigma_{\nu_e}^{\text{CC}} \epsilon_{\nu_e} \phi_{\nu_e}'$$

- The close detector measures the product of fluxes × cross section × efficiency
- Reduced $\nu_e$ flux: small statistics to determine the cross section
- NC backgrounds must be separated from beam $\nu_e$.

**Beta Beams**

$$N_{\text{events}}^{\text{far}} = \left( \sigma_{\nu_\mu} \epsilon_{\nu_\mu} P_{\nu_e \nu_\mu} + \sigma_{\nu_e}^{\text{NC}} \epsilon_{\text{NC}} + \sigma_{\nu_e}^{\text{CC}} \epsilon_{\text{CC}} P_{\nu_e \nu_e} \right) \phi_{\nu_e}$$

$$N_{\text{events}}^{\text{close}} = \left( \sigma_{\nu_e}^{\text{NC}} \epsilon_{\text{NC}}' + \sigma_{\nu_e}^{\text{CC}} \epsilon_{\text{CC}}' \right) \phi_{\nu_e}'$$

Flux known at priori, no intrinsic contamination (direct measure of NC backgrounds), no problems with the close-far extrapolation BUT no events to measure signal ($\nu_\mu$) cross sections.
Description of T2K inside Globes

- Publically available from the Globes web site
- Flux file from the 50 GeV beam configuration of the 2001 proposal
- Cross section file obtained by Nuance v3.0 (QE and not-QE cross sections are kept separated)
- Efficiency for signal detection from 2001 LoI
- Background rates from the 2001 LoI
- Definition of systematic errors and of their correlations (public file has only the basic information).
- 8 migration matrixes connecting true neutrino energies with reconstructed neutrino energies. They are built for QE and not-QE interactions of $\nu_\mu$, $\nu_e$, $\bar{\nu}_\mu$, $\bar{\nu}_e$. Nuance MC + SK parametrization of resolution of energy measurement of electrons and muons have been used.
Migration matrixes (adding QE + non-QE)
**Systematic errors and their pulls**

**Computed for T2HK sensitivity on LCPV at \( \sin^2 2\theta_{13} = 0.03 \)**

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<td>total νe cross section ( \times ) efficiency – 10%</td>
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<td>total νµ cross section ( \times ) efficiency – 10%</td>
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<td>ratio of QE/NQE cross sections – 20%</td>
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<td>NC cross section ( \times ) efficiency in FD – 10%</td>
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<td>ratio of ( \bar{\nu}/\nu ) NC cross sections ( \times ) efficiencies in FD – 5%</td>
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<td>NC cross section ( \times ) efficiency for ν–beam in ND – 10%</td>
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<td>NC cross section ( \times ) efficiency for ( \bar{\nu} )–beam in ND – 10%</td>
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<td>error on muon miss–identification in ND for ν–beam – 10%</td>
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<td>error on muon miss–identification in ND for ( \bar{\nu} )–beam – 10%</td>
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**RED:** Systematic error switched off.  **BLUE:** Systematic error multiplied by 5
Also introduced combinations of systematics constrained at 2%

\[ \tilde{\sigma}_{\nu_\alpha} := \sigma_{\nu_\alpha} \epsilon_{\nu_\alpha} \]

\[ \sin^2 2\theta_{13} = 0.03 \]

GLoBES 2007
$\theta_{13}$ vs. luminosity

3 $\sigma$ sensitivity to $\theta_{13}$, $\nu_\mu$ and $\bar{\nu}_\mu$, running time: 1 : 3.

sensitivity to $\sin^2 2\theta_{13}$ at 3$\sigma$

luminosity [kt MW yr]

GLoBES 2007

all systematics @ default

statistics only

$\delta_{CP} = \pi$

$\delta_{CP} = \pi/2$

$\bar{\sigma}_e$ and $\Phi_e$ fixed

$+$ NC in FD fixed
Allowed $\theta_{13}$ regions

In case of signal the impact of systematics is more important.

Disappearance channel is taken into consideration, in case of T2K anyway it is not enough to eliminate the sizable decrease of sensitivity once the errors on the other oscillation parameters are taken into account. In T2HK the effect almost disappears.
$3 \sigma$ LCPV Sensitivity

T2HK CPV at $3\sigma$

- constraint on $\tilde{\sigma}_e / \tilde{\sigma}_\mu$
- $\tilde{\sigma}_\mu @ 1\%$
- $\tilde{\sigma}_e @ 1\%$

- all systematics @ default
- statistics only

GLoBES 2007

$\delta_{CP} / \pi$

$\sin^2 2\theta_{13}$
Computed for \( \sin^2 2\theta_{13} = 0.03 \)

Smallest \( \delta_{CP} \) in \([0, \pi/2]\) for which CPV can be established at \( 3\sigma \)

\( \sin^2 2\theta_{13} = 0.03 \)

all systematics @ default

statistics only

\( \delta_{CP} / \pi \)

\( \sigma_{\mu} @ 1\% \)

\( \sigma_{e} @ 1\% \)

constraint on \( \sigma_{e} / \sigma_{\mu} \)

T2K

GLoBES 2007
3 $\sigma$ LCPV Sensitivity without Close Detectors

Spectral information is important to reduce systematics.
**Fluxes in the close detector**  
(LCPV at $\sin^2 2\theta_{13} = 0.03$)

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**Several non trivial quantitative consequences:**

- A detector capable of disentangling NC from intrinsic beam $\nu_e$ is needed.
- For ultimate $\theta_{13}$ sensitivities the statistics of 1kton (0.1 kton fiducial) water Cerenkov detector (4 MW of beam intensity) is not optimal.
- A hadroproduction experiment capable of determining fluxes better than 5% is very important.
Does T2KK help in term of systematic errors?

A particular cancellation of systematics beyond that already present between near and far detector is not observed. Having two baselines helps at large $\theta_{13}$
The 2 km close detector implementation is equivalent to overall systematic errors of 10% on signal and 3.5% on backgrounds.
Conclusions

- The method demonstrated to be very powerful in quantitatively study the impact of systematic errors.
- Globes can describe multi-detector setups, combine different oscillation channels and describe a complex system of correlated systematic errors.
- The impact of hadroproduction experiments and ancillary experiments to measure neutrino cross sections has been quantitively computed.
- The 2 km close detector implementation is equivalent to overall systematic errors of 10% on signal and 3.5% on backgrounds.