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Physics Potential of SPL Part I: Super Beam

Summary:

- **Introduction.**
- **SPL-Super Beam.**
- **Sensitivity to θ_{13}**
- **Sensitivity to the CP phase δ.**

In collaboration with the CERN working group on Super Beams:

A. Blondel, M. Donegà, S. Gilardoni Universitè de Geneve

D. Casper University of California, Irvine

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P. Hernández CERN

Nufact 02, London, July 1-6 ,2002

Can the SPL-SuperBeam compete with JHF?

Certainly NOT

- The proton driver is not there
- The far detector is not there
- The CERN is in crisis

So why to study the SPL - SuperBeam?

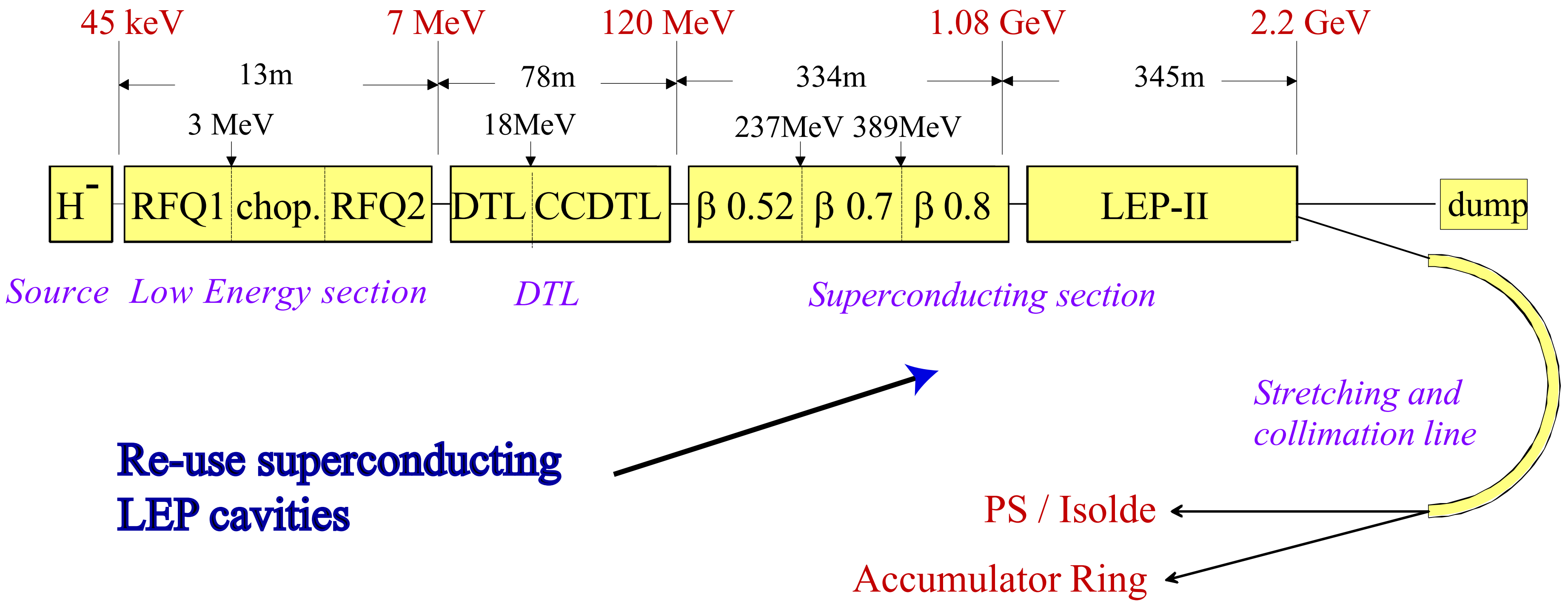
The SPL is a device necessary to CERN independently from any neutrino beam. It's mandatory to exploit all its physics capabilities.

Depending from the result of JHF, after 2010, will be necessary a completely new facility either to explore Leptonic CP (in case a $\nu_\mu \rightarrow \nu_e$ discovery at JHF) or to further search for $\nu_\mu \rightarrow \nu_e$ transitions increasing the sensitivity to θ_{13} .

The SPL is the first stage of any long term neutrino beam at CERN: either a Neutrino Factory and/or a Beta Beam.

The results of a neutrino oscillation experiment at the SPL-SuperBeam can be combined with the results of a Neutrino Factory experiment to solve any ambiguity (Olga Mena talk " New study about the degeneracies of the neutrino factory", tomorrow), or can be combined with a Beta Beam experiment (Part II of this talk, this afternoon).

MW-Linac: SPL (Superconducting Proton Linac)



EKIN = 2.2 GeV
Power = 4 MW
Protons/s = 10^{16}

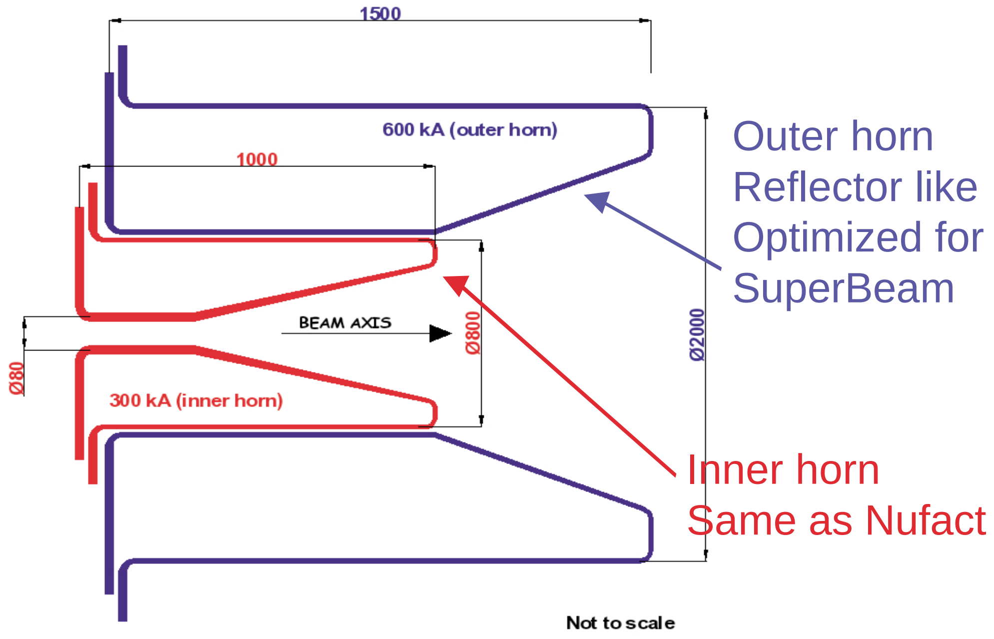
→ **10^{23} protons/year**

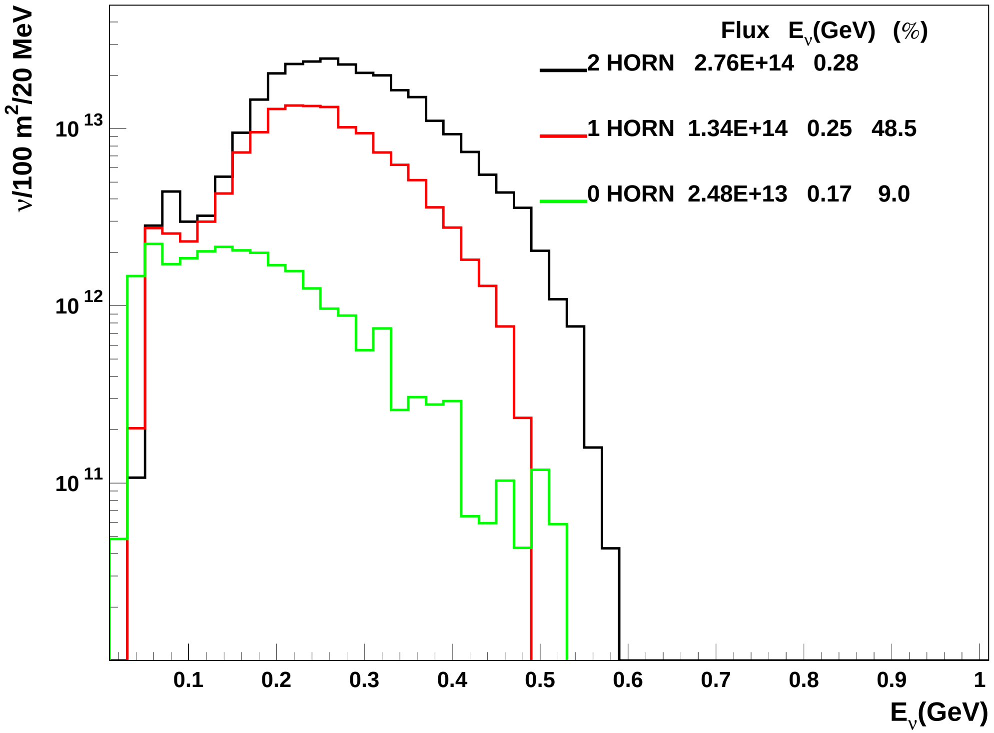
An improved optics for the SPL-SuperBeam

S. Gilardoni "Horn for a neutrino factory", this afternoon

- Full simulation using MARS. Polarization effects are taken into account
- Optimal performances compromised with the need to survive to the 4 MW proton beam.

New horn design





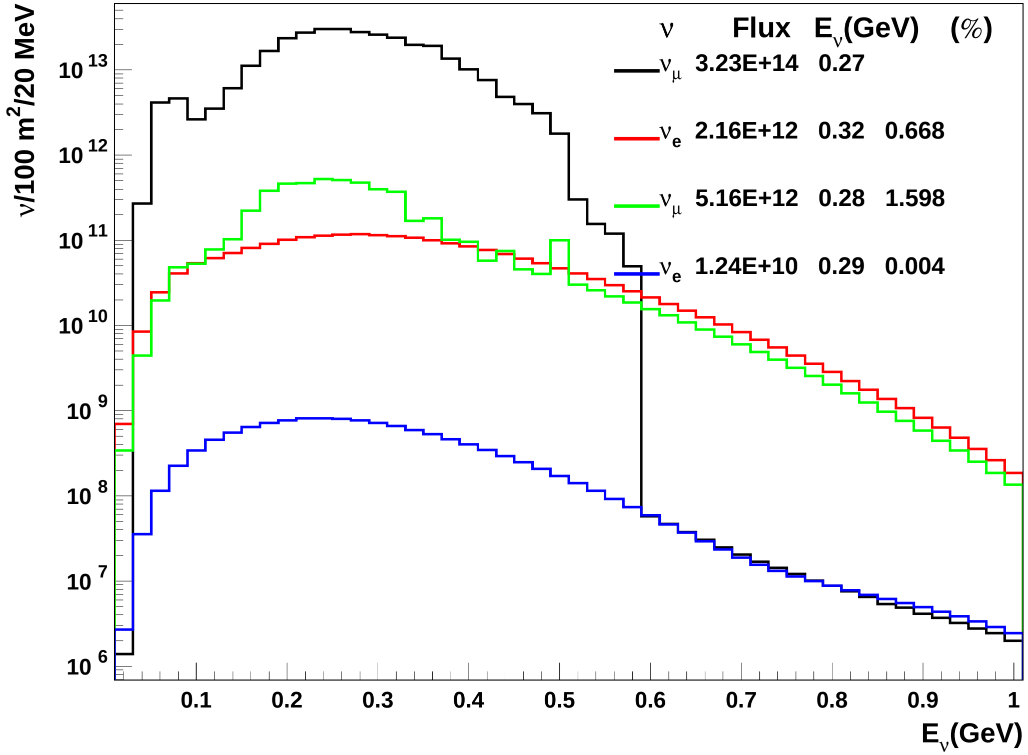
Optimizing the decay tunnel length.

The length of the decay tunnel is a compromize between a higher flux and a lower ν_e contamination.

A longer decay tunnel decreases the antineutrino contamination, a useful feature for the CP searches.

Length (m)	ν_μ $(\nu/m^2/yr)$ (@50 km)	ν_e (%)	$\overline{\nu}_\mu$ (%)	$\overline{\nu}_\mu$ $(\nu/m^2/yr)$ (@50 km)	$\overline{\nu}_e$ (%)	ν_μ (%)	θ_{13} (90%CL) (2200 kton/yr)
20	2.43 $\cdot 10^{+12}$	0.383	1.731$\cdot 10^{+12}$	1.71	0.41	3.9	1.20
30	2.81 $\cdot 10^{+12}$	0.490	1.636	1.97$\cdot 10^{+12}$	0.52	3.6	1.23
60	3.23 $\cdot 10^{+12}$	0.668	1.598	2.25$\cdot 10^{+12}$	0.695	3.3	1.25
100	3.35 $\cdot 10^{+12}$	0.763	1.618	2.33$\cdot 10^{+12}$	0.786	3.28	1.30
20 (old)	1.71$\cdot 10^{+12}$	0.36	2.41	1.12$\cdot 10^{+12}$	0.382	5.62	1.47

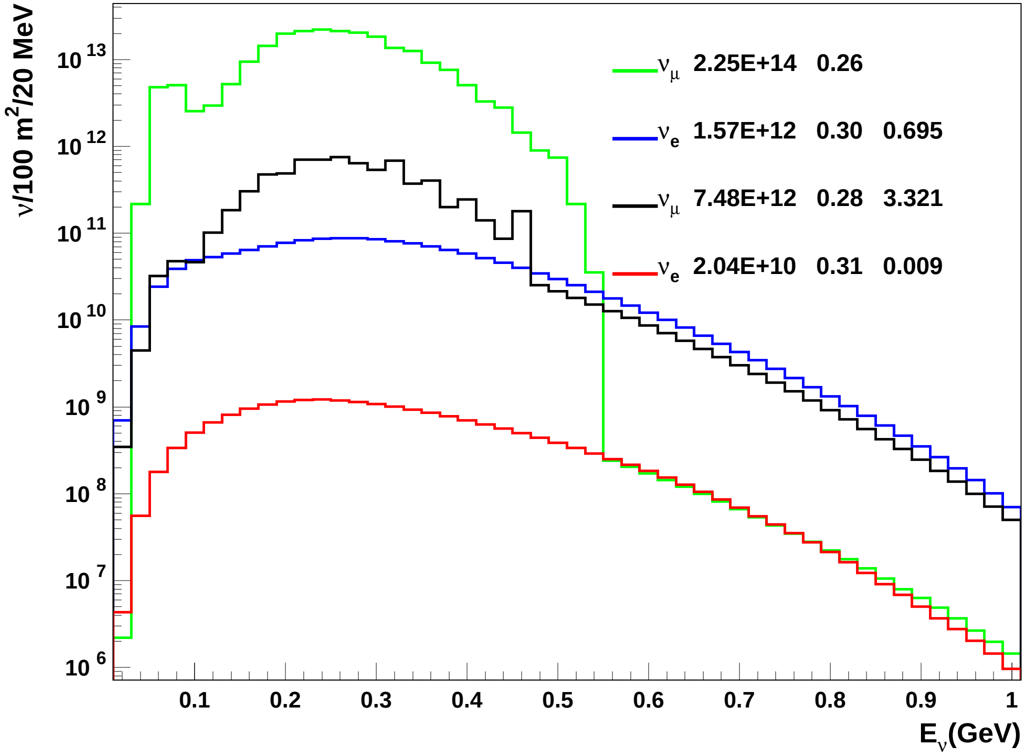
SPL SuperBeam (π^+ focused)



Flux 50 km from the target

Flavour	Absolute Flux ($\nu/10^{23}\mathrm{pot}/\mathrm{m}^2$)	Rel. Flux (%)	$\langle E_\nu \rangle$ (GeV)
ν_μ	$3.2 \cdot 10^{12}$	100	0.27
$\overline{\nu}_\mu$	$2.2 \cdot 10^{10}$	1.6	0.28
ν_e	$5.2 \cdot 10^{9}$	0.67	0.32
$\overline{\nu}_e$	$1.2 \cdot 10^{8}$	0.004	0.29

SPL SuperBeam (π^- focused)



Flux at 50 km from the target

Flavour	Absolute Flux ($\nu/10^{23}\mathrm{pot}/\mathrm{m}^2$)	Rel. Flux (%)	$\langle E_\nu \rangle$ (GeV)
$\overline{\nu}_\mu$	$2.2 \cdot 10^{12}$	100	0.26
ν_μ	$7.5 \cdot 10^{10}$	3.3	0.28
$\overline{\nu}_e$	$1.6 \cdot 10^{9}$	0.70	0.30
ν_e	$2.0 \cdot 10^{8}$	0.009	0.31

Interesting features of a low energy conventional neutrino beam.

ν beam:

- $\langle E_{\nu_\mu} \rangle \simeq 0.25$ GeV $\Rightarrow L \simeq 100$ km $\Rightarrow$ Matter effects suppressed.
- ν_e production by kaons largely suppressed by threshold effects.

ν_e in the beam come only from μ decays.

$$\begin{array}{ccc} \pi^+ & \longrightarrow & \mu^+\nu_\mu \\ & & \downarrow \\ & & e^+\nu_e\overline{\nu}_\mu \end{array}$$

they can be predicted from the measured ν_μ CC spectrum both at the close and at the far detector **with a small systematic error of $\sim 2\%$.**

Detector Backgrounds

- Good e/π^0 separation following the large $\pi^0 \rightarrow \gamma\gamma$ opening angle
- Good e/μ separation in a Čerenkov detector because μ are produced below or just above the Čerenkov threshold.
- Charm and τ production below threshold.

Less exiting aspects of a low energy neutrino beam

- Cross sections are small $\Rightarrow$ large detectors are necessary in spite of the very intense neutrino beam.
- $\overline{\nu}_\mu$ production is disfavored for two reasons:
  - Smaller π^- multiplicity at the target.
  - $\overline{\nu}_\mu / \nu_\mu$ cross section ratio is at a minimum (1/5).
- Visible energy is smeared out by Fermi motion

CERN-Frejus

The underground Modane laboratory at Frejus, 5000 m^3, hosting among the others the Nemo and Edelweiss experiments, is at the right distance from CERN: 130 km.

Excavating works to dig a safety tunnel have recently been approved, this potentially dramatically reduces the costs to prepare a gigantic experimental hall.

The biggest cavern than can be excavated at Frejus is $10^6\ m^3$: $60 \times 30 \times 600\ m^3$ at 2500 m.w.e. or $50 \times 25 \times 800\ m^3$ at 4400 m.w.e.

A strong interest for a SuperBeam-proton decay massive deep underground detector is fast rising in Europe, following the UNO and HyperK initiatives.

Details can be found in the transparencies of the international workshop “Large Detectors for Proton Decay, Supernovae and Atmospheric Neutrinos and Low Energy Neutrinos from High Intensity Beams”, CERN 18-20 January 2002. `http://muonstoragerings.cern.ch/NuWorkshop02/`

The benchmark: θ_{13} sensitivity with a SuperKamiokande like detector

Full simulation and full reconstruction of the events (D. Casper)

$f_B(\nu_e) = 3.8 \cdot 10^{-3}$

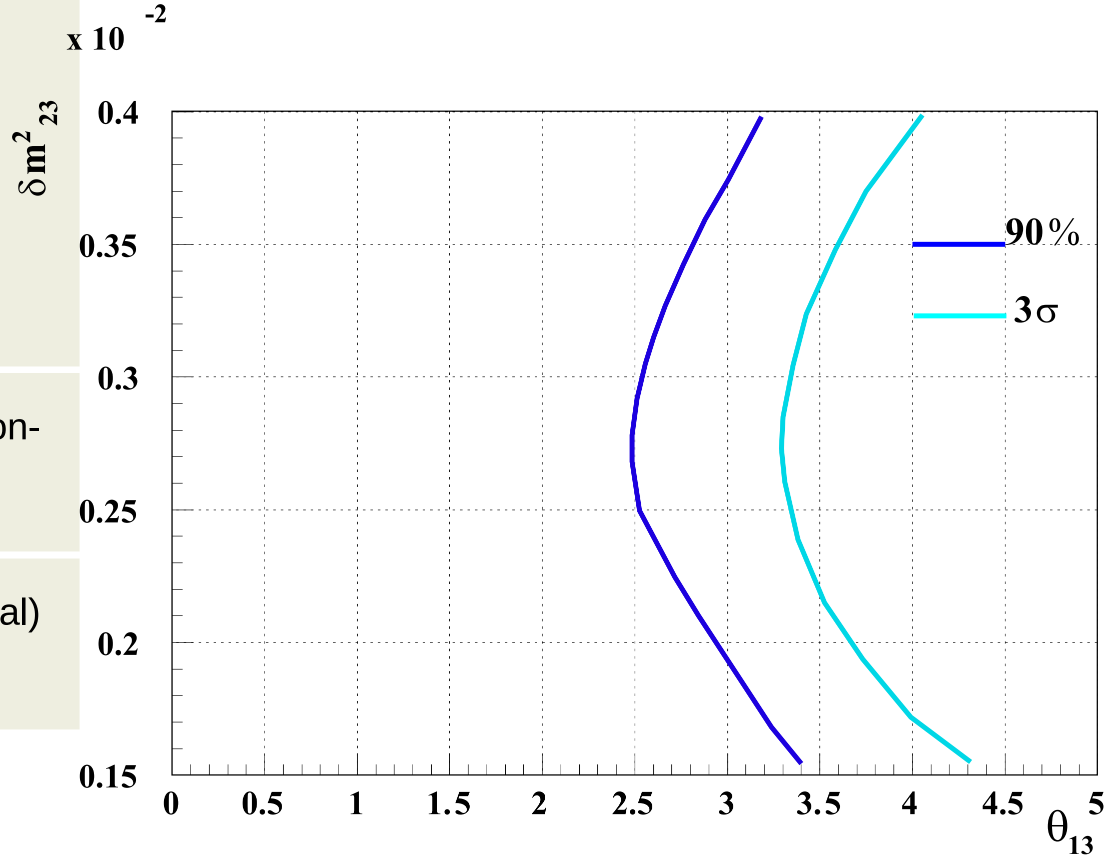
$f_B(\pi^\circ) = 2.0 \cdot 10^{-3}$

$f_B(\mu/e) \leq 10^{-3}$

$\epsilon(\nu_e) = 70.5\%$

Counting experiment: ν energy is poorly reconstructed mostly because of the Fermi motion.

5 years of ν_μ exposure on a 22.5 kton (fiducial) water Cerenkov detector



For $\sin^2 2\theta_{13} = 0.01$ ($\delta m^2_{23} = 2.5 \cdot 10^{-3} eV^2$,
solar SM

ν_μ^{CC} (no osc.)	3926
Beam ν_e	15
NC	8
μ/e	4
Signal	39

θ_{13} sensitivity: $\theta_{13} \leq 2.5^\circ$ (90% CL)

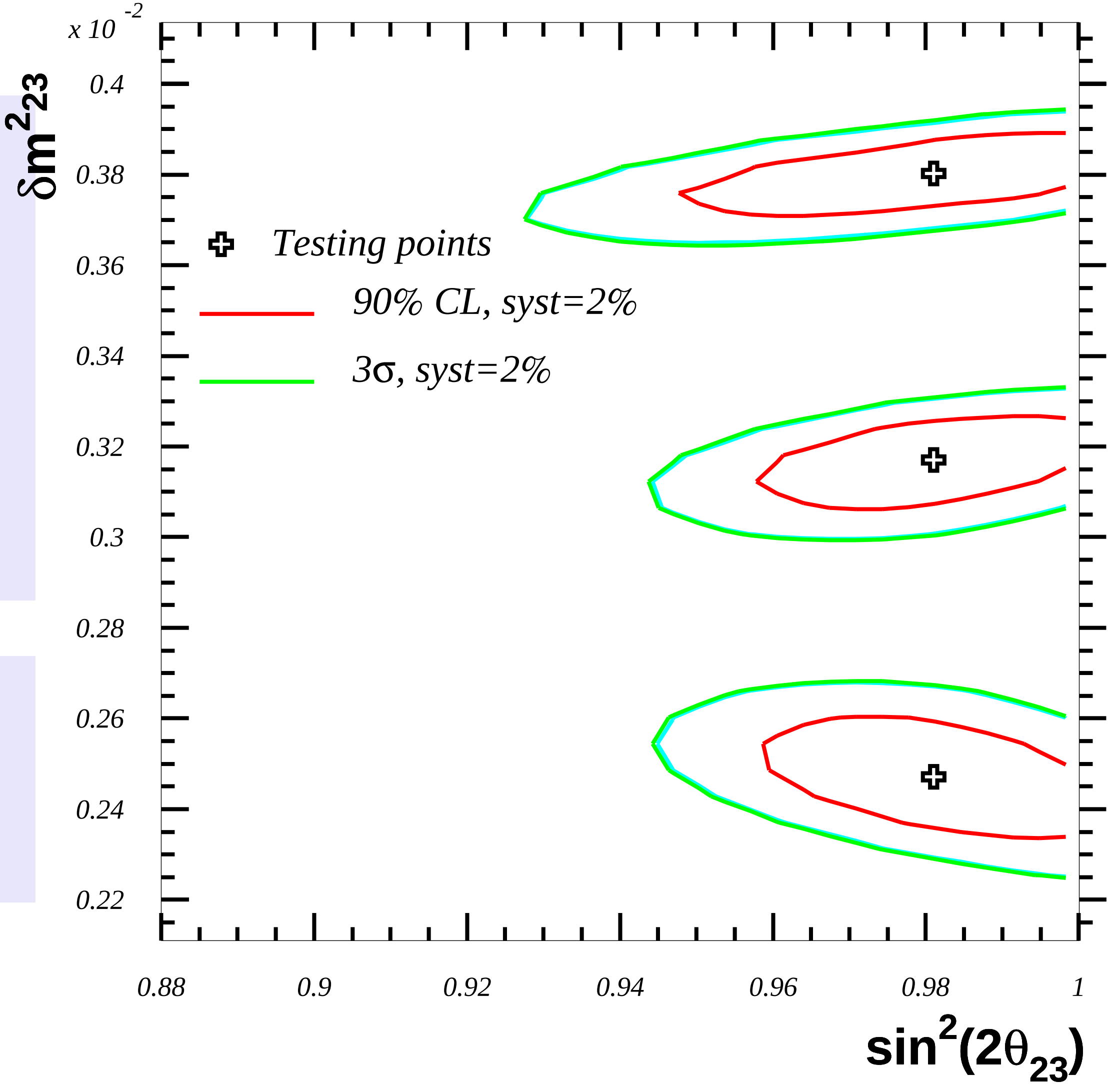
JHF sensitivity: $\theta_{13} \leq 2.3^\circ$ (90% CL)

Sensitivity to δm^2_{23} and $sin^2(2\theta_{23})$

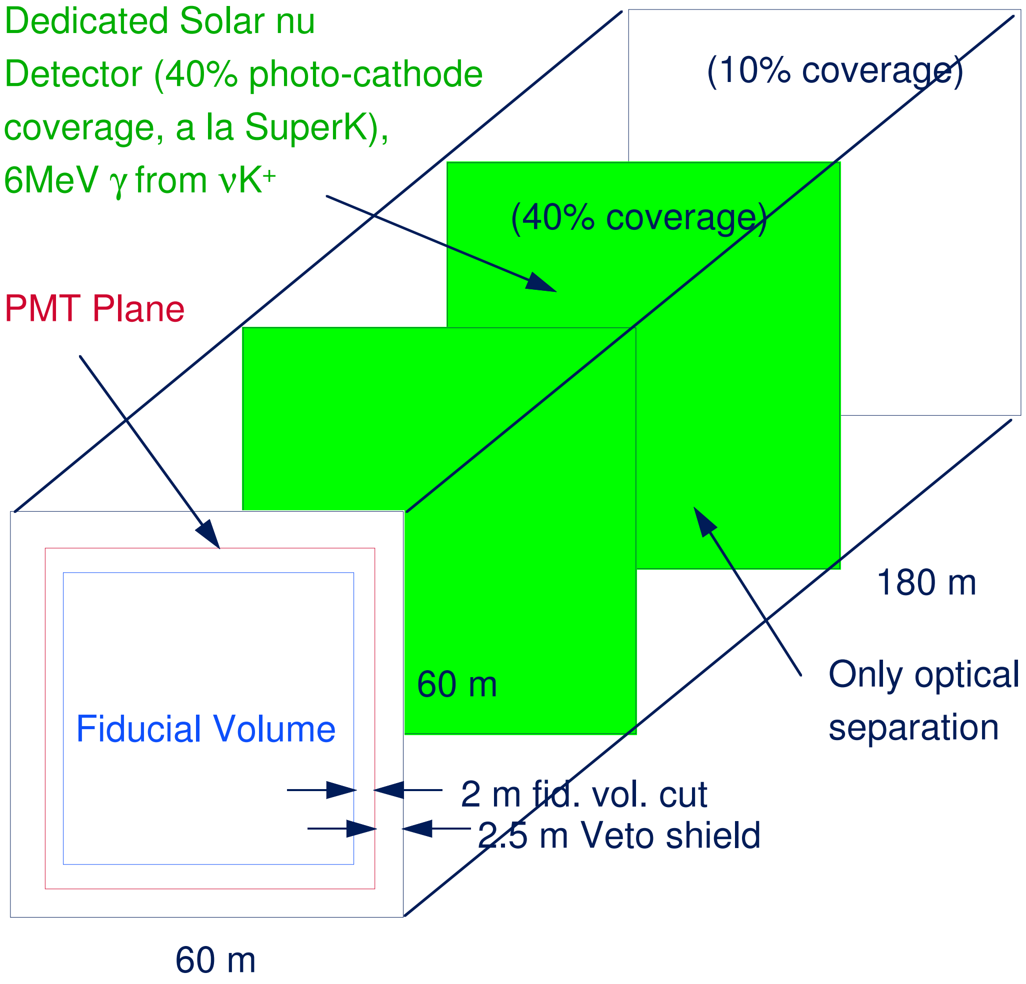
- Take three testing points at
  $\sin^2 2\theta_{23} = 0.98$,
  $\delta m^2_{23} = 3.8,\ 3.2,\ 2.5\ \cdot 10^{-3}\,\mathrm{eV}^2$
- 120 kton-year exposure
- Assume 3 energy bins in the 0.25-0.7 GeV range.
- 2% systematic errors

$\Downarrow$

- $\sin^2 2\theta_{23}$ measured at 1.5%
- δm^2_{23} measured with $\sim 1.5 \cdot 10^{-4}$ resolution



UNO detector



The optimal detector for sub-GeV neutrinos is a water Čerenkov detector:

- The only viable solution for a $>> 100$ kton detector.
- Good energy resolution.
- Good e/π° rejection.
- Excellent e/μ separation.

The killer detector for proton decay, atmospheric neutrinos, supernovae neutrinos.

Sensitivity to θ_{13} with a UNO like detector

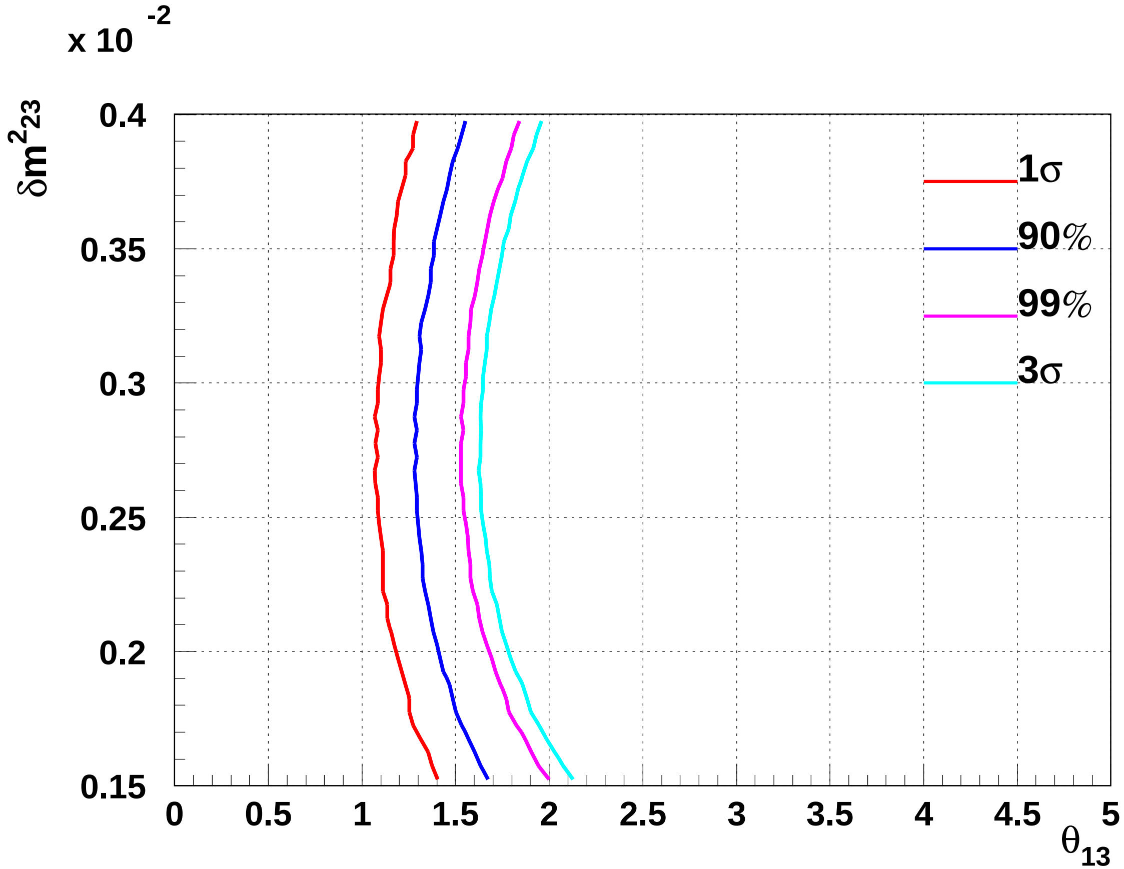
For the JHF limit: $\sin^2 2\theta_{13} = 0.006$ ($\delta m^2_{23} = 2.5 \cdot 10^{-3} eV^2$, solar SMA solution):

ν_μ^{CC} (no osc.)	76782
Beam ν_e	294
NC	153
μ/e	71
Signal	138 ($> 5\sigma$)

θ_{13} 90%CL sensitivity: θ_{13} =$1.2°$

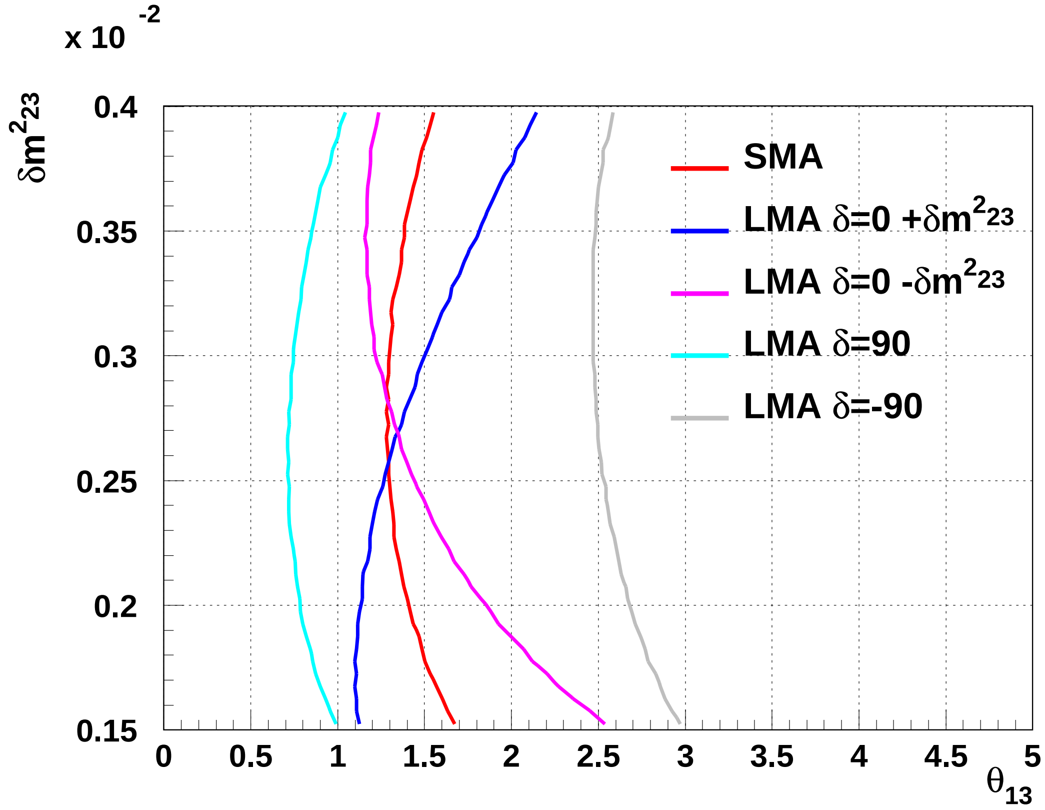
JHF 90%CL sensitivity: θ_{13} =$2.3°$

(Factor 3.7 better on $\sin^2 2\theta_{13}$)

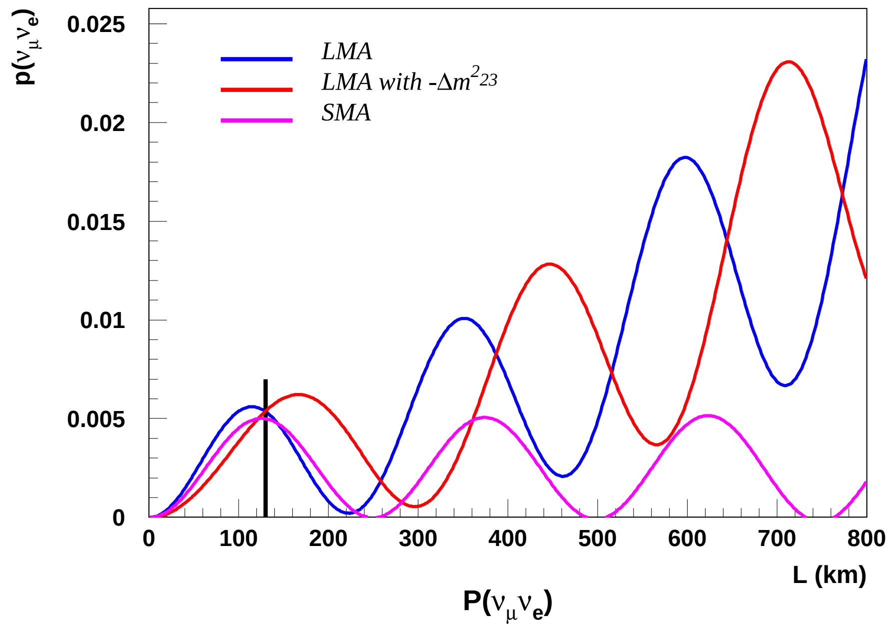


A precise measurement of θ_{13} requires antineutrino runs

- Exclusion plots vary with the solar solution and with the sign of δm^2_{23}.
- Exclusion plots vary if the (unknown) value of the CP phase δ is fixed at $\pm 90°$.



Evolution of $p(\nu_\mu \rightarrow \nu_e)$ as function of the baseline under different solar solutions.



Hunting for Leptonic CP: SuperBeam vs. Nufact

From $p(\nu_\mu \to \nu_e) \neq 0$ **to** $p(\nu_\mu \to \nu_e) \neq p(\overline{\nu}_\mu \to \overline{\nu}_e)$

PROS

- Negligible matter effects: it can be run at the optimal baseline
- Negligible matter effects: reduced correlations between θ_{13} and δ
- Counting experiment: less influenced by uncertainties on the other mixing matrix parameters

CONS

- Smaller CC rate
- Intrinsic beam contamination (not in the case of Beta Beam).

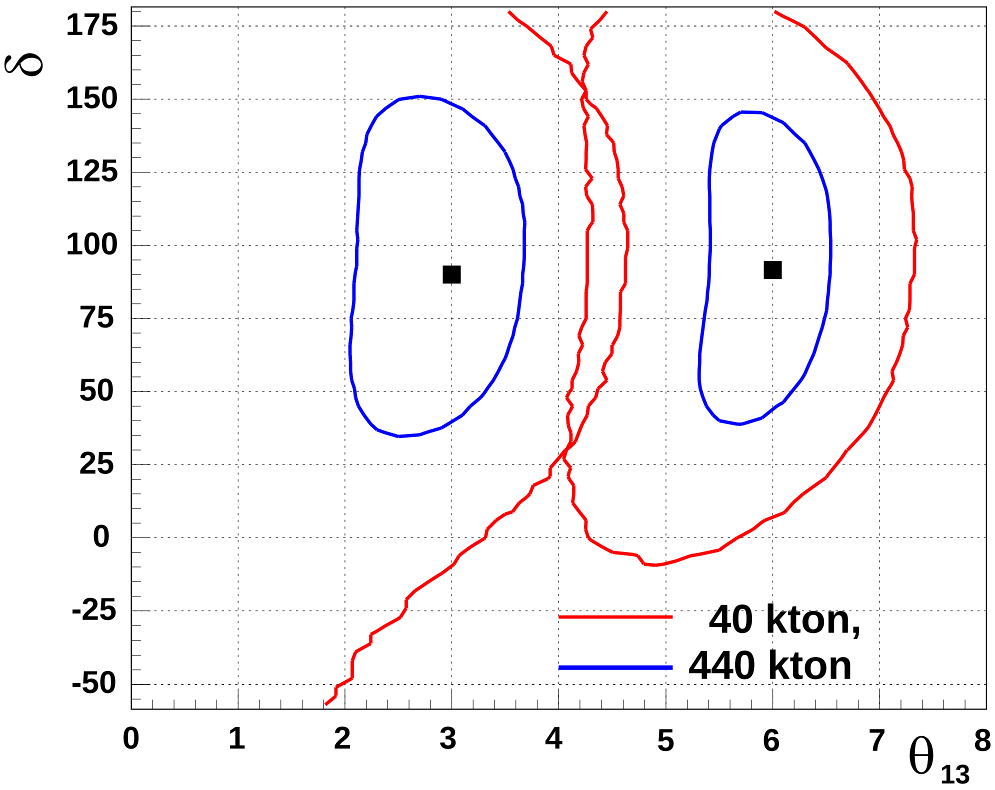
The checking list for the fits to δ

- Full simulation and full reconstruction
- Proper statistical analysis
- Systematic errors
- Errors on the other parameters of the neutrino mixing matrix
- Ambiguities and degeneracies
- Publish it !!!

Sensitivity to CP

- The CP violating observable is $\frac{N(e^+)-N(e^-)}{N(e^+)+N(e^-)}$, corrected for the different fluxes and cross sections. Here $e^-(e^+)$ indicates all the e-like events selected with the $\pi^+(\pi^-)$ focused beam.
- Run for 2 years with the π^+ focused beam and 8 years with the π^- focused beam, to compensate the unfavorable ($\overline{\nu}_e$ / ν_e) cross section ratio
- Fit simultaneously δ and θ_{13} on N(e^+) and N(e^-) separately.
- Exercise for $\delta m^2_{12} = 10^{-4}\ eV^2$, $\theta_{13} = 3°, 6°$, $(sin^2(2\theta_{13})$ = 0.01, 0.04) and a maximally violating CP phase, $\delta = \pm 90°$

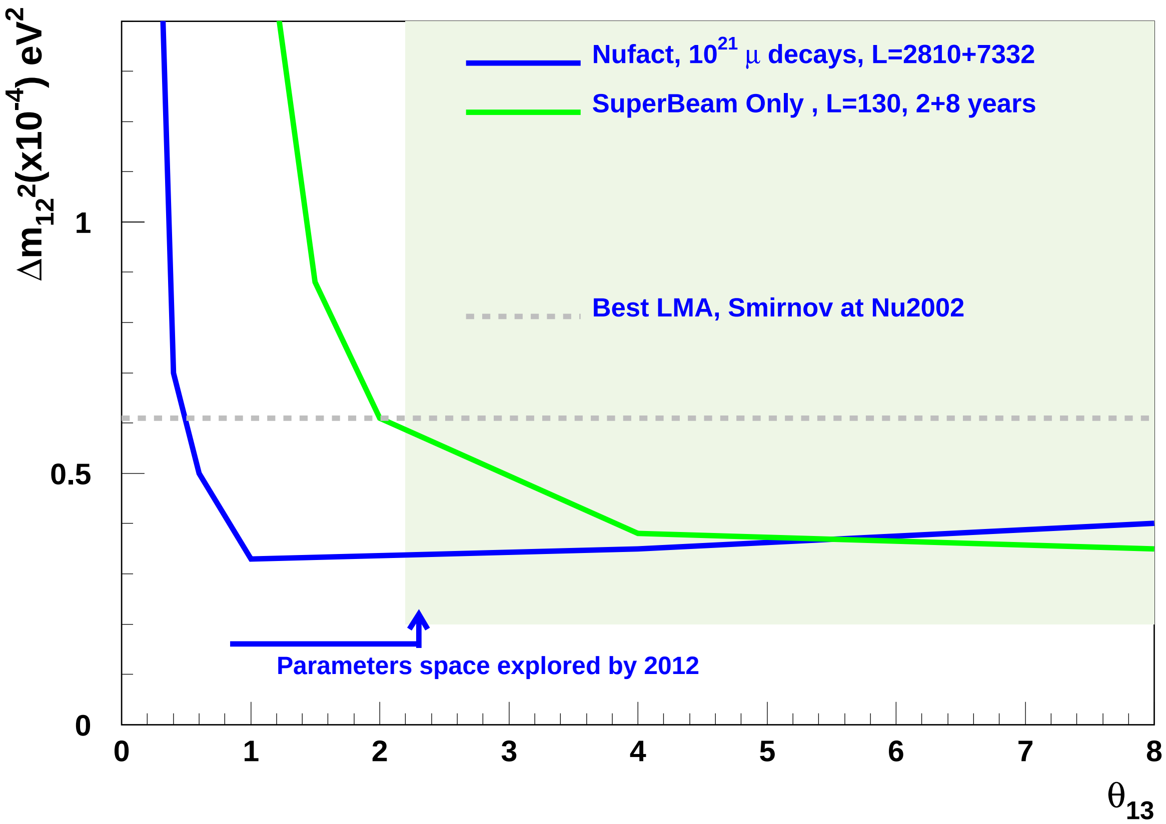
Note the absence of degeneracies between δ and θ_{13}.



A comparison of CP sensitivities: Nufact vs. SuperBeam

CP sensitivity, defined as the capacity to separate at 99%CL max CP ($\delta = \pi/2$) from no CP ($\delta = 0$).

Nufact sensitivity as computed in J. Burguet-Castell et al., Nucl. Phys. B **608** (2001) 301, including background, systematics and using two 40 kton iron magnetized detectors t L=3000 and 7000 km to solve ambiguities.



The limiting factors for the SuperBeam at small θ_{13} values are:

- The low flux of $\overline{\nu}$ and their small cross section. This limits the overall statistic.
- The beam related backgrounds that increase the statistical errors, hiding the CP signal.

As an example for θ_{13} =3°, $\delta m^2_{12} = 0.6 \cdot 10^{-4}\, eV^2$, $\sin^2 2\theta_{12} = 0.8$:

	ν_μ beam 2 years	$\overline{\nu}_\mu$ beam 8 years
ν_μ^{CC} (no osc)	78814	46526
Oscillated events (total)	114	120
Oscillated events (cp-odd)	-154	129
Intrinsic beam background	299	116
Detector backgrounds	236	110

Conclusions

The SPL-SuperBeam, together with a gigantic underground water Cerenkov detector at Frejus, can offer excellent opportunities for the years 2010.

It can offer the possibility to enhance the sensitivity to θ_{13} or, in case of a positive result of JHF, a first sensitive search for Leptonic CP.

These performances can be further improved either firing a neutrino Beta Beam to the same detector or combining its results with a neutrino factory experiment