Mauro Mezzetto

Istituto Nazionale di Fisica Nucleare,

Sezione di Padova

“Future Neutrino Oscillations ”

- **Introduction.**
- **The hunting for θ_{13}**
- **Leptonic CP violation**
- **Neutrino Factories, SuperBeams, Beta Beams**

Les Arcs, March 17, 2003

ν oscillations are the most important discovery in hep of the last 15 years.

They measure foundamental parameters of the standard model. Mixing angles, neutrino masses and the CP phase δ_{CP} are foundamental constants of the standard model.

They are a probe of the GUT scales . The smallness of neutrino masses is connected to the GUT scale trhough the see-saw mechanism.

They are directly linked to many fields in astrophysics and cosmology : bariogenesis, leptogenesis, galaxies formation, dynamic of supernovae explosion, power spectrum of energy anisotropies, etc.

They open the perspective of the measure of **leptonic CP violation.**

Most of the parameters are waiting to be measured

δm^2_{23} ☑

δm^2_{12} ☑

θ_{13} ☐

δ_{CP} ☐

Mass hierarchy ☐

Dirac/Majorana ☐

θ_{23} ☑

θ_{12} ☑

Σm_ν ☐

The capital importance of θ_{13}

Present limit from CHOOZ: $\sin^2 2\theta_{13} \leq 0.1$. Both solar and atmospheric results are compatible with $\theta_{13} = 0$.

Solar+Atmospherics favor a near bi-maximal mixing matrix (VERY DIFFERENT from CKM matrix!)

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

$\theta_{13} \rightarrow 0 \quad \Rightarrow$ The 3x3 matrix is a trivial product of two 2x2 matrixes.

θ_{13} drives $\nu_\mu \rightarrow \nu_e$ subleading transitions $\Rightarrow$

the necessary milestone for any subsequent search:

neutrino mass hierarchy and leptonic CP violation searches.

Subleading $\nu_\mu - \nu_e$ oscillations

$p(\nu_\mu \to \nu_e)$ developed at the first order of matter effects

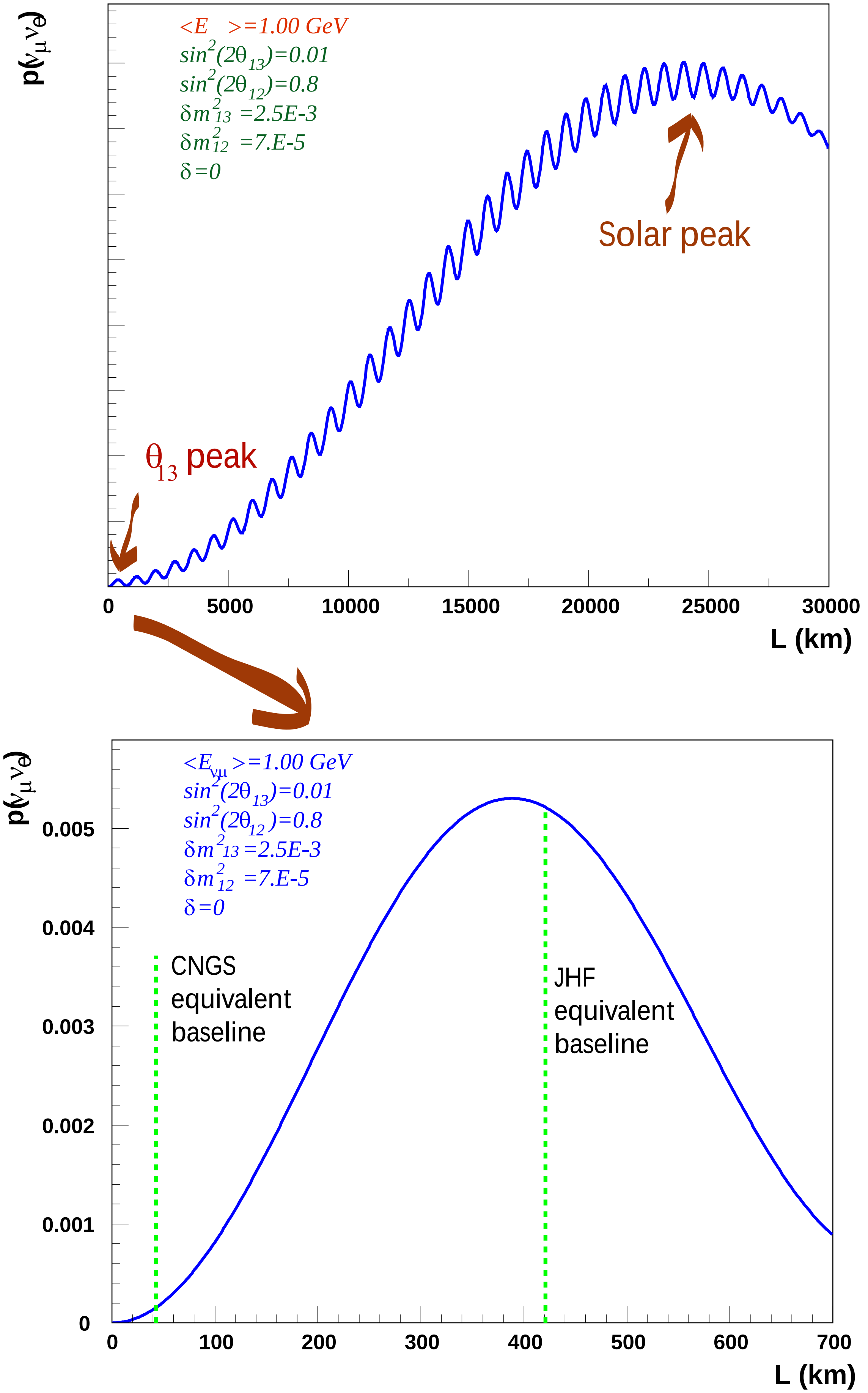
$$
\begin{aligned}
p(\nu_\mu \to \nu_e) = \\
& 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} && \theta_{13} \text{ driven} \\
& + 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} cos\delta - s_{12} s_{13} s_{23}) \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} && \text{CP} - \text{even} \\
& - 8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} && \text{CP} - \text{odd} \\
& + 4s_{12}^2 c_{13}^2 \{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} cos\delta\} \sin \frac{\Delta m_{12}^2 L}{4E} && \text{solar driven} \\
& - 8c_{12}^2 s_{13}^2 s_{23}^2 \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E} (1 - 2s_{13}^2) && \text{matter effect (CP odd)}
\end{aligned}
\tag{1}
$$

where $a = \pm 2\sqrt{2} G_F n_e E_\nu = 7.6 \cdot 10^{-5} \rho[g/cm^3] E_\nu [GeV] \quad [eV^2]$

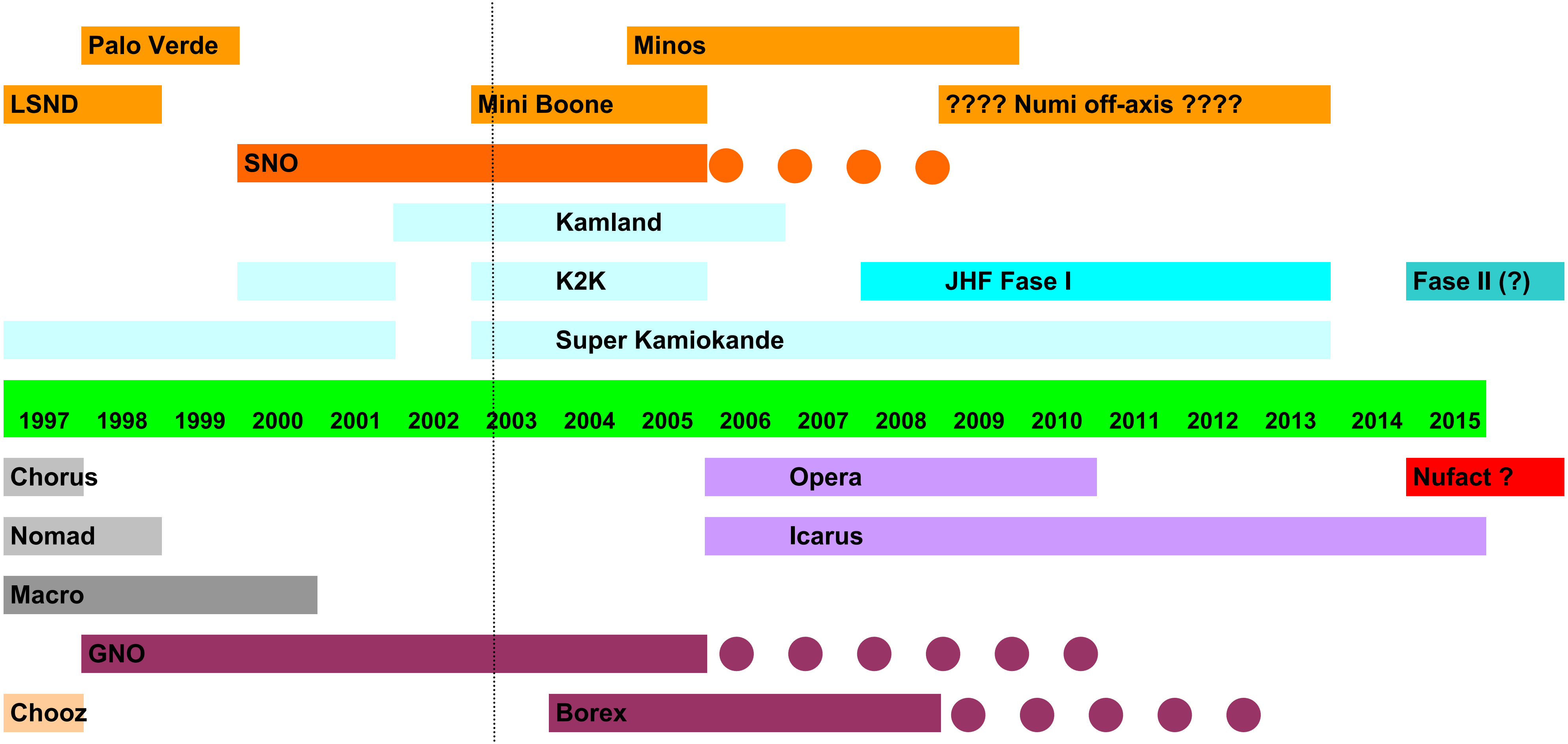
At the first order, neglecting matter effects and CP:

$$P(\nu_\mu \to \nu_e) \propto \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \frac{\Delta m_{23}^2 L}{4E}$$

Why subleading transitions?



Neutrino Oscillation Experiments



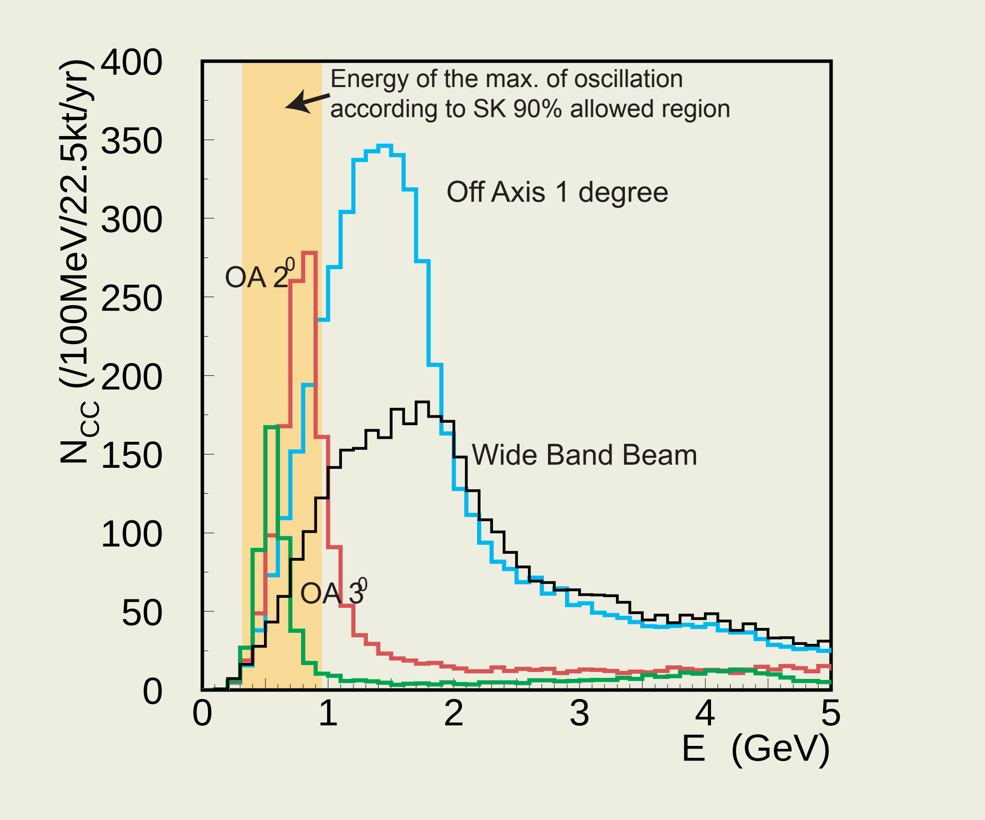
JHF-Japan Hadron Facility at Jaeri

Neutrino beam from the 50 GeV - 0.75 MW proton beam at the Hadron Facility at Jaeri, Japan.

Taken off-axis to better match the oscillation maximum at the SuperKamiokande location (295 km).

The neutrino beam line is not yet approved. Approval is expected by mid 2003. Start of data taking expected by 2007.

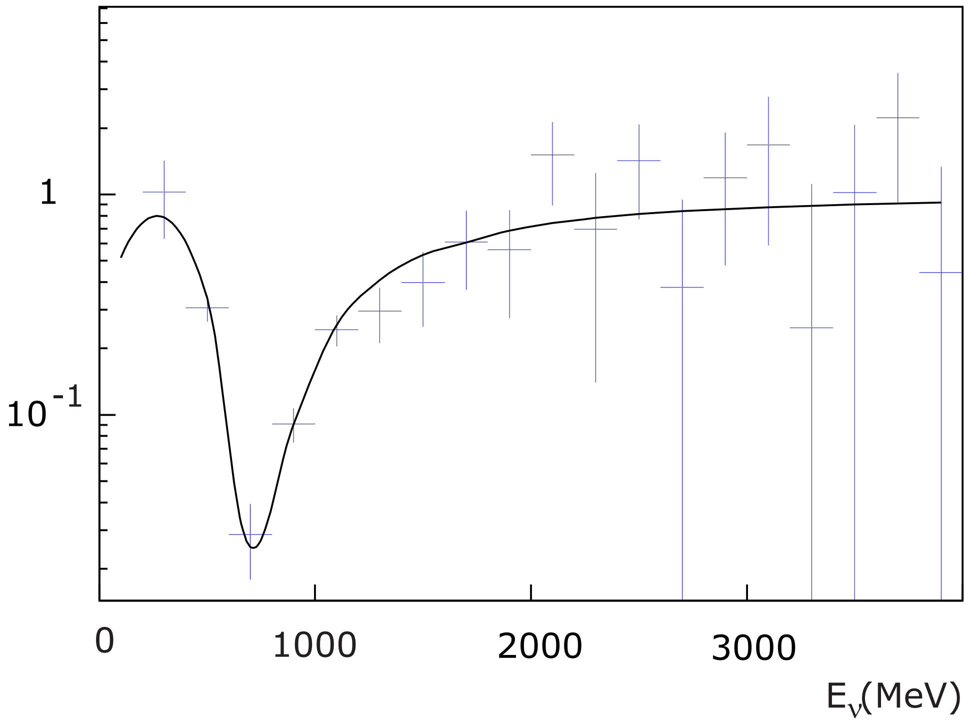
K2K		JHF
$6 \cdot 10^{12}$	Protons per pulse	$3 \cdot 10^{14}$
2.2 s	Cycle	3.4 s
12 GeV	Proton energy	50 GeV
40	Events in SK per year (no osc.)	2200
1.5	Mean neutrino energy	0.8



JHF (continued)

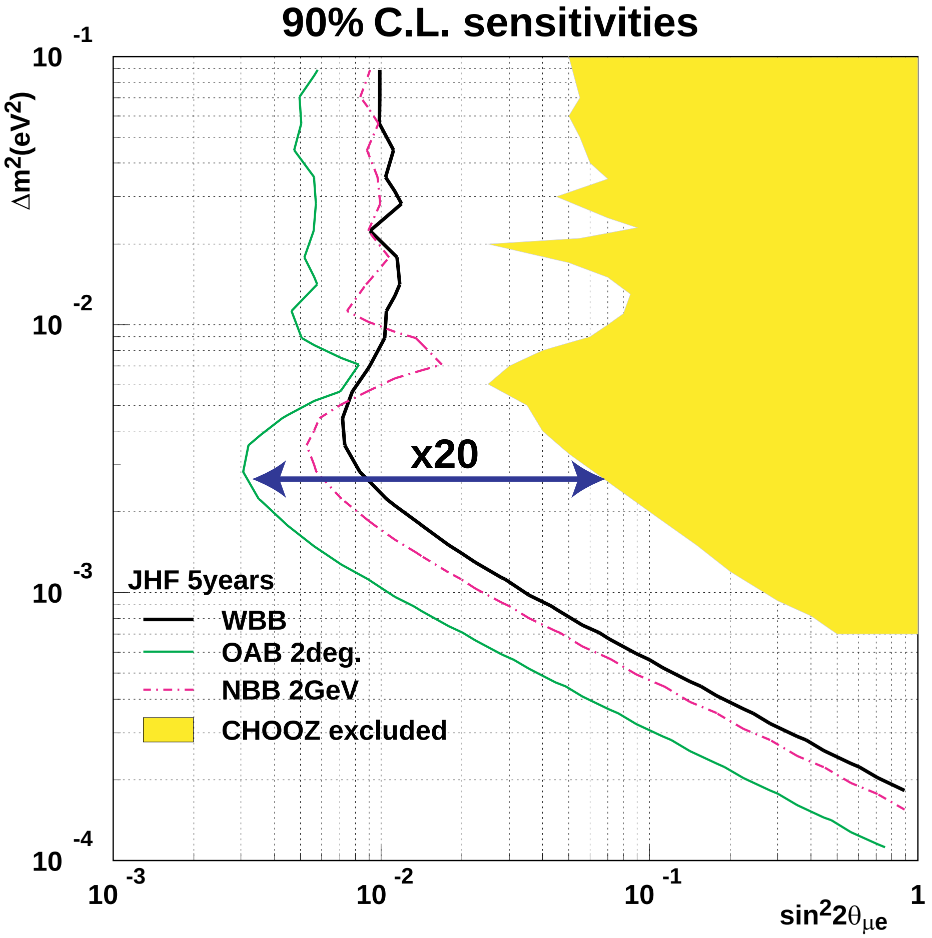
Precision measure of the atmospheric parameters:

- δm^2_{23} with a resolution of 10^{-4} eV^2.
- $\sin^2 2\theta_{23}$ at $1 \div 2$ %.



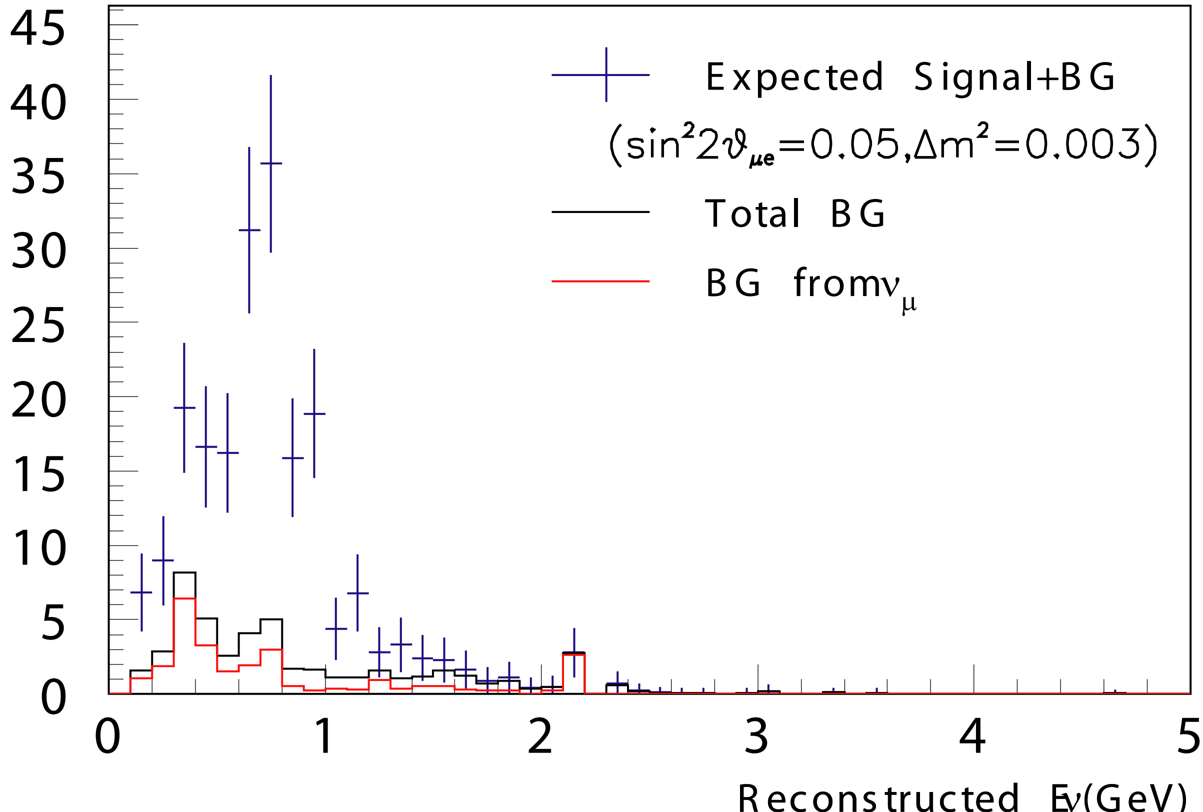
Ratio of the measured ν_μ spectrum with respect to the non-oscillation prediction in case of oscillation (5 years).

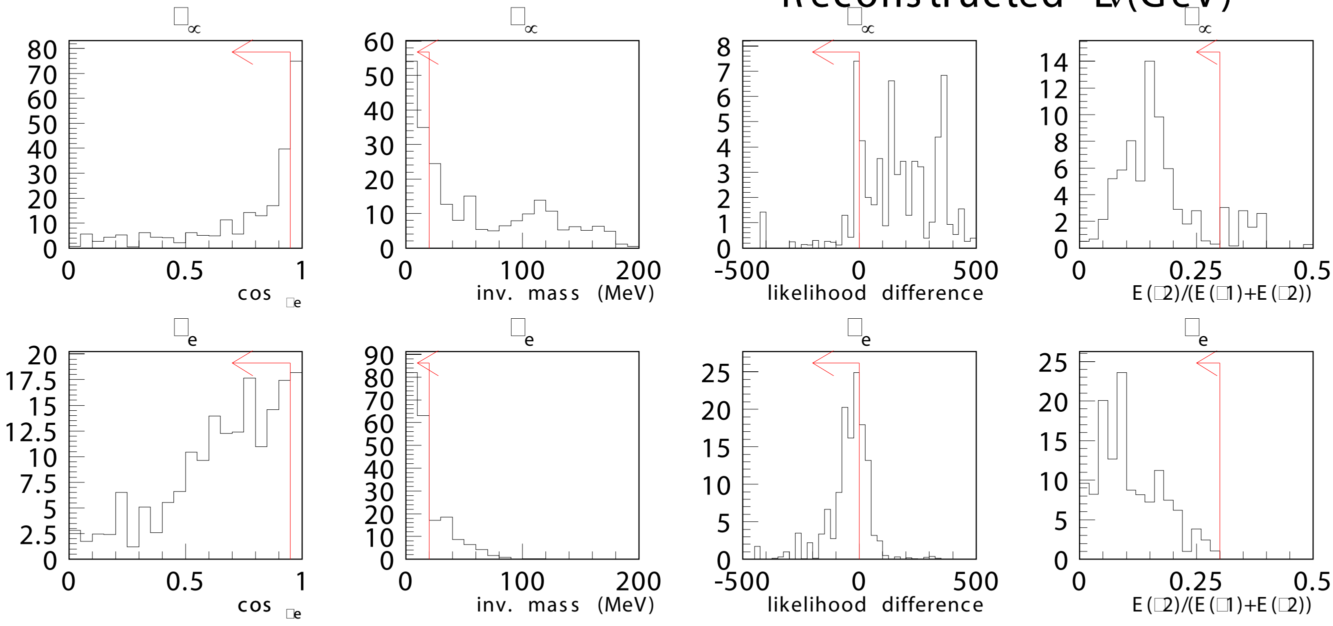
Sensitivity to θ_{13}



5 years, $\delta m^2 = 3 \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{\mu e} = 0.05$

OAB 2□	ν_μ C.C.	ν_μ N.C.	Beam ν_e	Oscillated ν_e
1) Generated in F.V.	10713.6	4080.3	292.1	301.6
2) 1R e-like	14.3	247.1	68.4	203.7
3) e/ π^0 separation	3.5	23.0	21.9	152.2
4) 0.4 GeV< E_{rec} < 1.2 GeV	1.8	9.3	11.1	123.2





Leptonic CP

Two conditions to make Leptonic CP detectable:

- Solar LMA confirmed (DONE by Kamland !)
- $\theta_{13} \geq 0.2^0$ (see the following).

A big step from a θ_{13} search:

$$\text{from } p(\nu_\mu \rightarrow \nu_e) \neq 0 \text{ to } \begin{cases} p(\nu_\mu \rightarrow \nu_e) \neq p(\overline{\nu}_\mu \rightarrow \overline{\nu}_e) & \text{(direct CP)} \\ p(\nu_\mu \rightarrow \nu_e) \neq p(\nu_e \rightarrow \nu_\mu) & \text{(T search)} \end{cases}$$

This will require:

1. Neutrino beams of novel conception.

Super Beams

Neutrino Factory

Beta Beams

2. Detectors of unprecedent mass
3. Improved control of systematics ⇒ Dedicated experiments on neutrino cross-section, hadron production, particle ID.

Detecting the δ phase at the Neutrino Factories

$$A_\delta = [P(\nu_e \to \nu_\mu, \delta = +\pi/2) - P(\nu_e \to \nu_\mu, \delta = 0)]/[P(\delta = +\pi/2) + P(\delta = 0)]$$

Compare the measured $\nu_e \to \nu_\mu$ oscillation probability, as a function of the neutrino energy E_ν, to a “Monte-Carlo” prediction of the spectrum in absence of δ-phase.

Problems: it’s model dependent, requires a precise knowledge of the other oscillation parameters, possible degeneracy between solutions and strong correlation with the θ_{13} parameter.

$$A_{CP}(\delta) = [P(\nu_e \to \nu_\mu, \delta) - P(\overline{\nu}_e \to \overline{\nu}_\mu, \delta)]/[P(\nu_e \to \nu_\mu, \delta) + P(\overline{\nu}_e \to \overline{\nu}_\mu, \delta)]$$

Compare the appearance of ν_μ ($\overline{\nu}_\mu$) in a beam of stored μ^+(μ^-)decays as a function of the neutrino energy E_ν.

Problems It must compete with the fake CP from matter effects. Run time is more than doubled: $\overline{\nu}$ cross sections are half the ν cross section and matter effects disfavor $\overline{\nu}$ oscillations.

$$A_T(\delta) = [P(\nu_e \to \nu_\mu, \delta) - P(\nu_\mu \to \nu_e, \delta)]/[P(\nu_e \to \nu_\mu, \delta) + P(\nu_\mu \to \nu_e, \delta)]$$

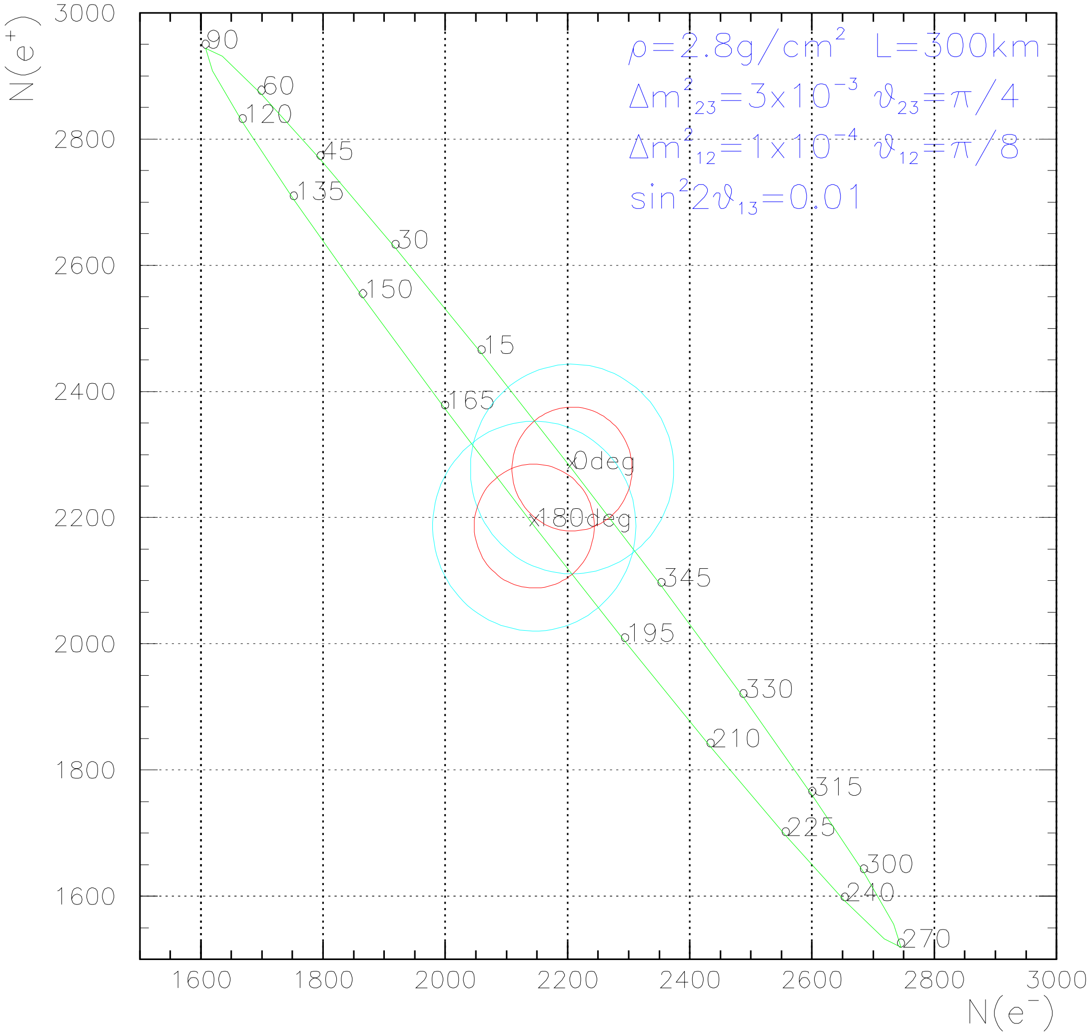
Compare the appearance of ν_μ in a ν_e beam AND ν_e in a ν_μ beam as a function of the neutrino energy E_ν.

Problems Electron charge must be measured in case of a neutrino factory experiment. Systematics of muon and electron efficiencies must be kept to very small values.

SuperBeams and Leptonic CP (1) - JHF phase 2

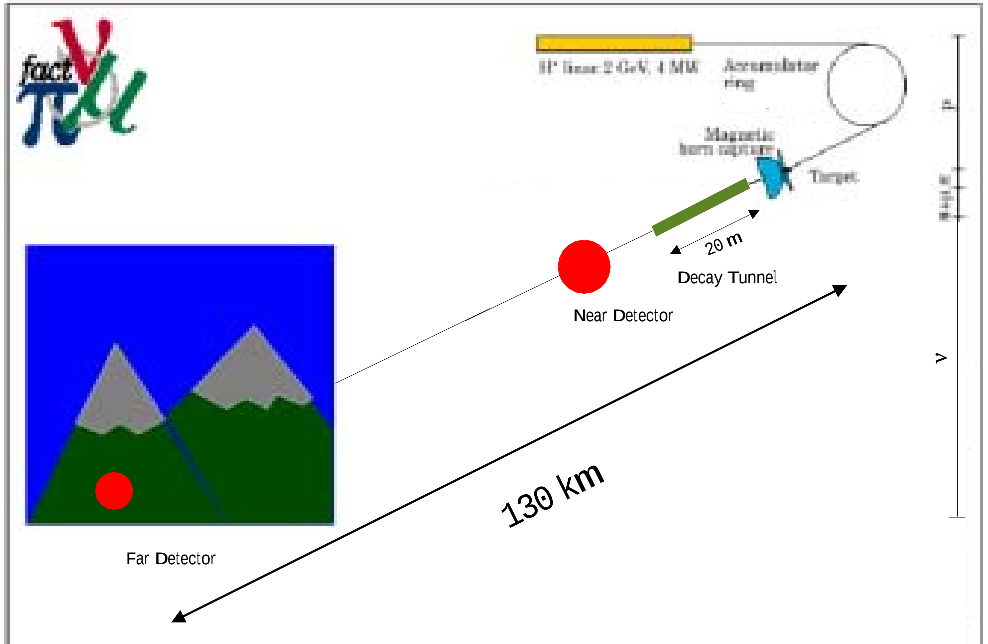
Upgrade the proton driver from 0.75 MW to 4 MW

Upgrade SuperKamiokande by a factor 40 $\Longrightarrow$ HyperKamiokande

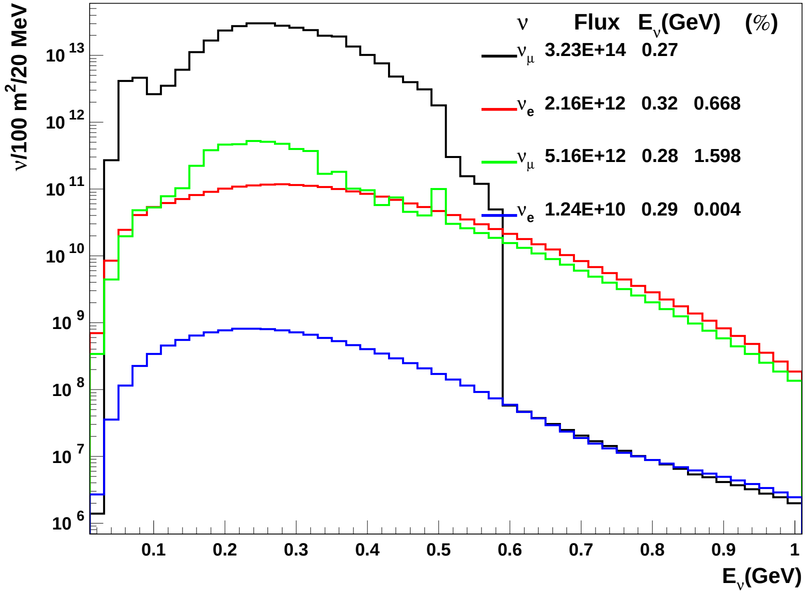


SuperBeams (2) SPL-SuperBeam at CERN

A feasibility study of the CERN possible developments



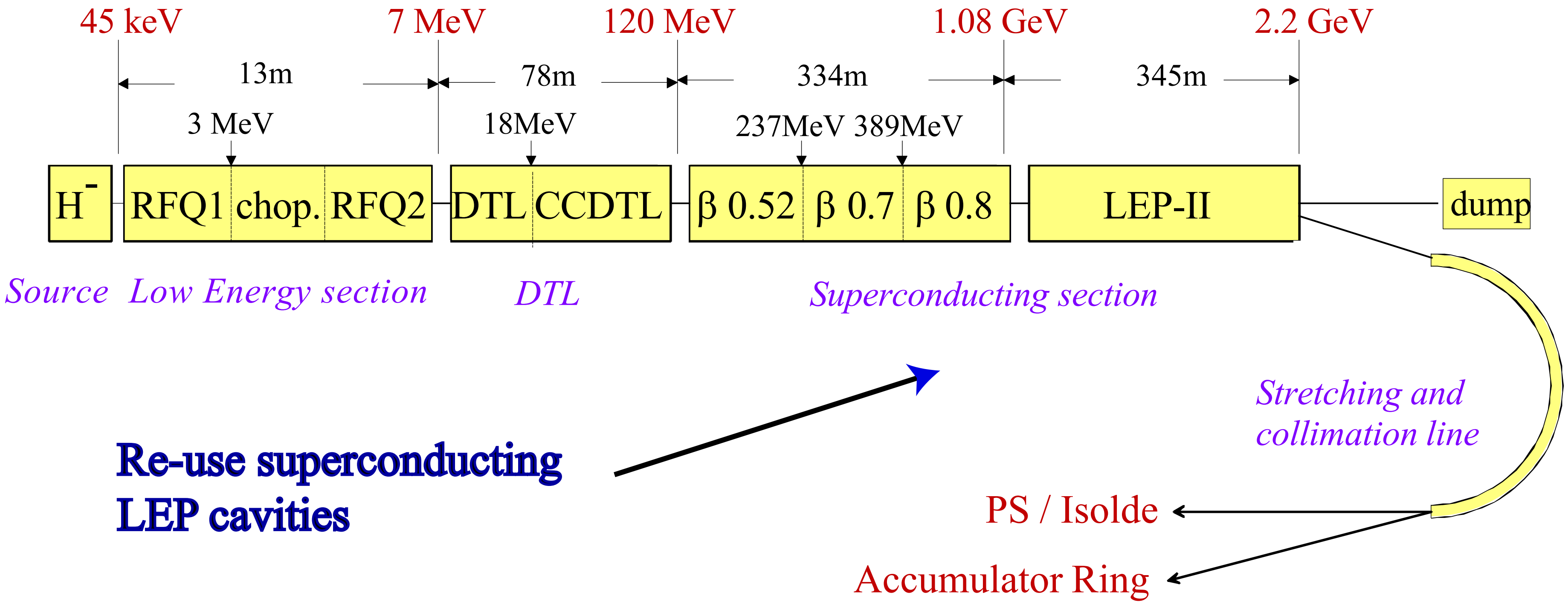
Possible Low Energy Super Beam Layout



Flux intensities at 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

MW-Linac: SPL (Superconducting Proton Linac)



Re-use superconducting LEP cavities

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

10^{23} protons/year

Super Beams and Leptonic CP (2) SPL SuperBeam

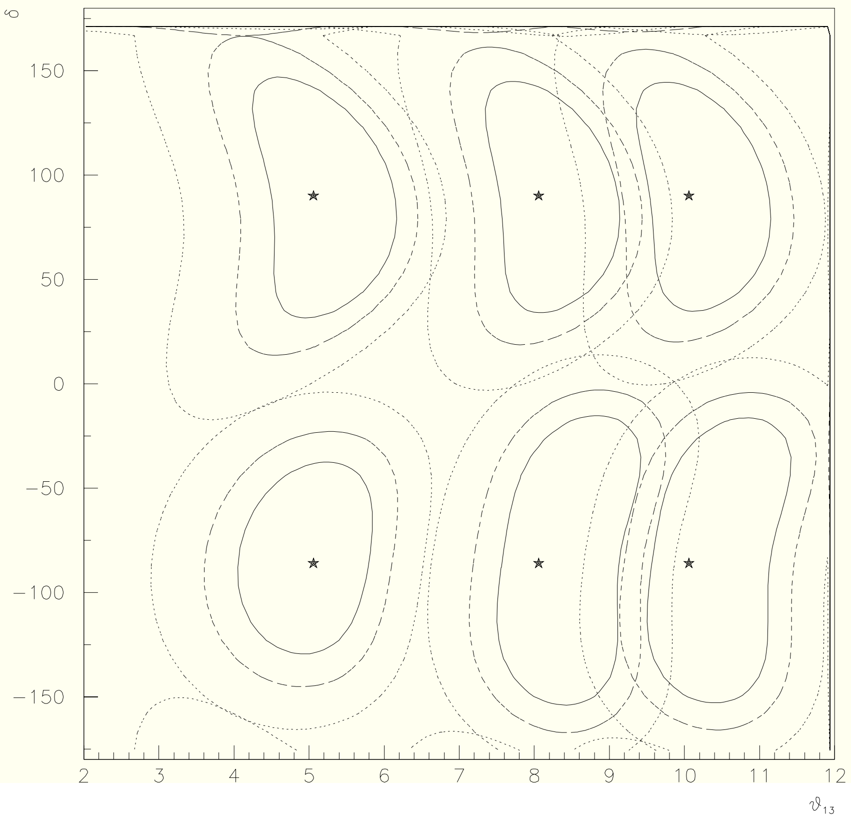
- Assume the upper value of LMA: $\delta m^2_{12} = 10^{-4}\ eV^2$
- The CP violating observable is $\frac{N(e^+)-N(e^-)}{N(e^+)+N(e^-)}$, corrected for the different fluxes and cross sections. Here $e^-(e^+)$ indicates all the e-like events selected with the $\pi^+(\pi^-)$ focused beam.
- Run for 2 years with the π^+ focused beam and 10 years with the π^- focused beam, to compensate the unfavorable ($\overline{\nu}_e\ /\nu_e$) cross section ratio
- Fit simultaneously δ and θ_{13} on N(e$^+$) and N(e$^-$) separately.
- Take $\theta_{13} = 5°, 8°, 10°$ ($sin^2(2\theta_{13}) = 0.03,\ 0.08,\ 0.12$) and a maximally violating CP phase, $\delta = \pm 90°$

$\Downarrow$ (see figure)

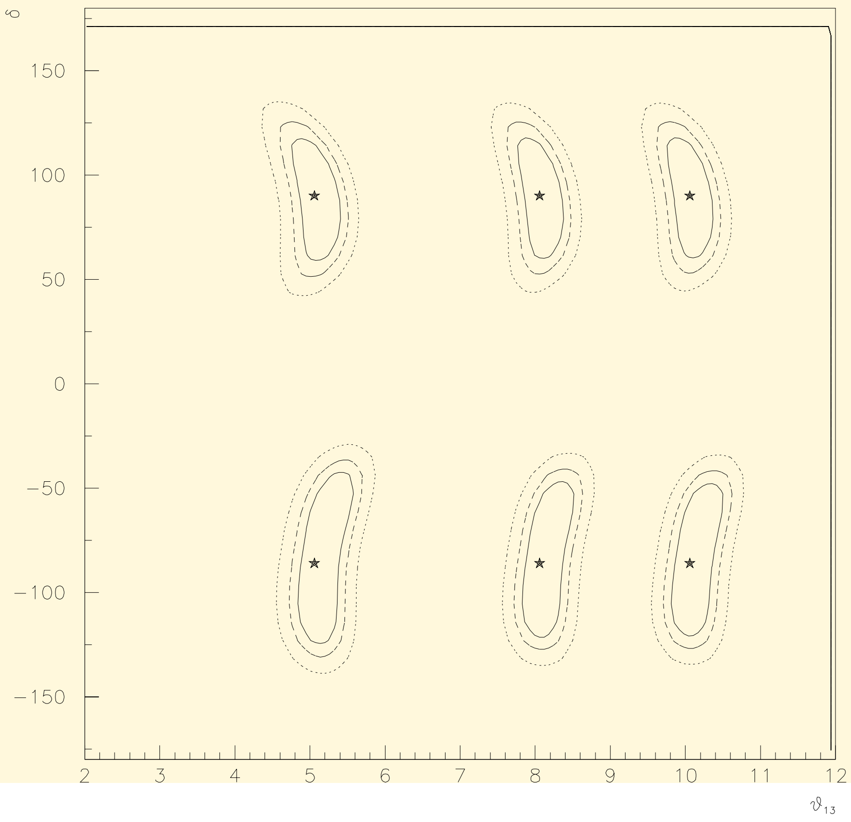
- CP sensitivity does not worsen very much with θ_{13}.
- In the 40 kton detector, 90% CL, a maximally violating CP phase ($\delta = \pm 90°$) would be just distinguishable from a non violating CP phase ($\delta = 0°$).
- With the 400 kton detector the prospects to observe CP violation are much improved.

Preliminary CP sensitivity

40 kton water detector 1σ, 90%CL, 99%CL lines



400 kton water detector 1σ, 90%CL, 99%CL lines

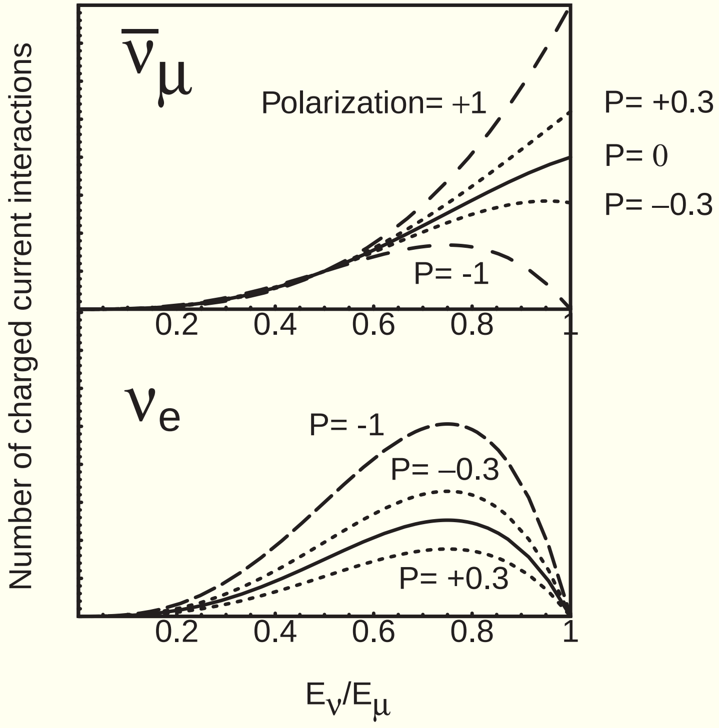


Introducing Neutrino Factories

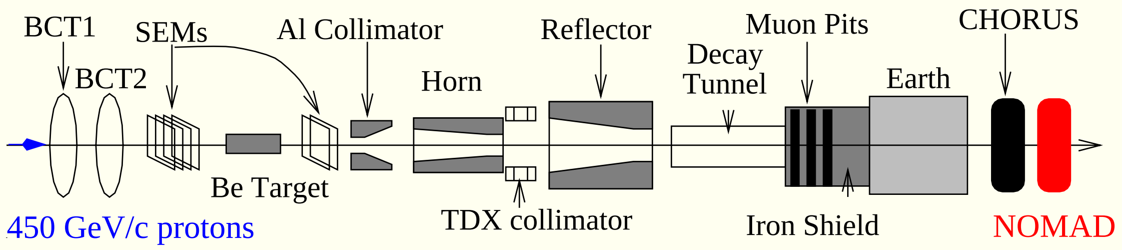
- The dream beam of every neutrino physicist.
- The first case in which the whole neutrino production chain, including proton acceleration, is accounted on the budget of the neutrino beam construction.
- Beam intensities predicted to be two orders of magnitude higher than in traditional neutrino beams.
- No hadronic MonteCarlos to predict neutrino fluxes.
- Oscillated events N_{osc} at a distance L:

$$N_{\rm osc} \sim {\rm Flux} \times \sigma_\nu \times P_{\rm osc} \sim \frac{E_\nu^3}{L^2} \sin^2 \frac{L}{E_\nu} \propto E_\nu$$

  N_{osc} increases linearly with the beam energy. Optimal energy: as high as possible.
- Neutrino beams from muon decays contain ONLY two types of neutrinos of opposite helicities ($\overline{\nu}_e$ ν_μ or ν_e $\overline{\nu}_\mu$). **It is possible to search for $\nu_\mu \longrightarrow \nu_e$ transitions characterized by the appearance of WRONG SIGN MUONS, without intrinsic beam backgrounds.**



Why a Neutrino Factory is far more efficient of a conventional neutrino beam ?



In a **conventional neutrino beam**, neutrinos are produced by pions (and kaons) generated by the proton beam interaction on the target. Given the short life time of the pions ($2.6 \cdot 10^{-8}$s), they can only be focused (and charge selected) by means of magnetic horns. Then they are let to decay in a decay tunnel, short enough to prevent most of the muon decays.

Hard to predict the details of the neutrino beam, since it derives from hadronic interactions. At least four neutrino flavours are present (ν_μ , $\overline{\nu}_\mu$, ν_e , $\overline{\nu}_e$)

In a **neutrino factory** pions decay inside a solenoid, and most of the muons are collected. Muons are longeval enough ($2.2 \cdot 10^{-6}$s) to open the possibility to collimate and accelerate them to the desired momentum.

Much more efficient way to produce neutrinos BUT a real challenge to accelerate, in a very short time, particles generated with a large emittance .

Two possible solutions,

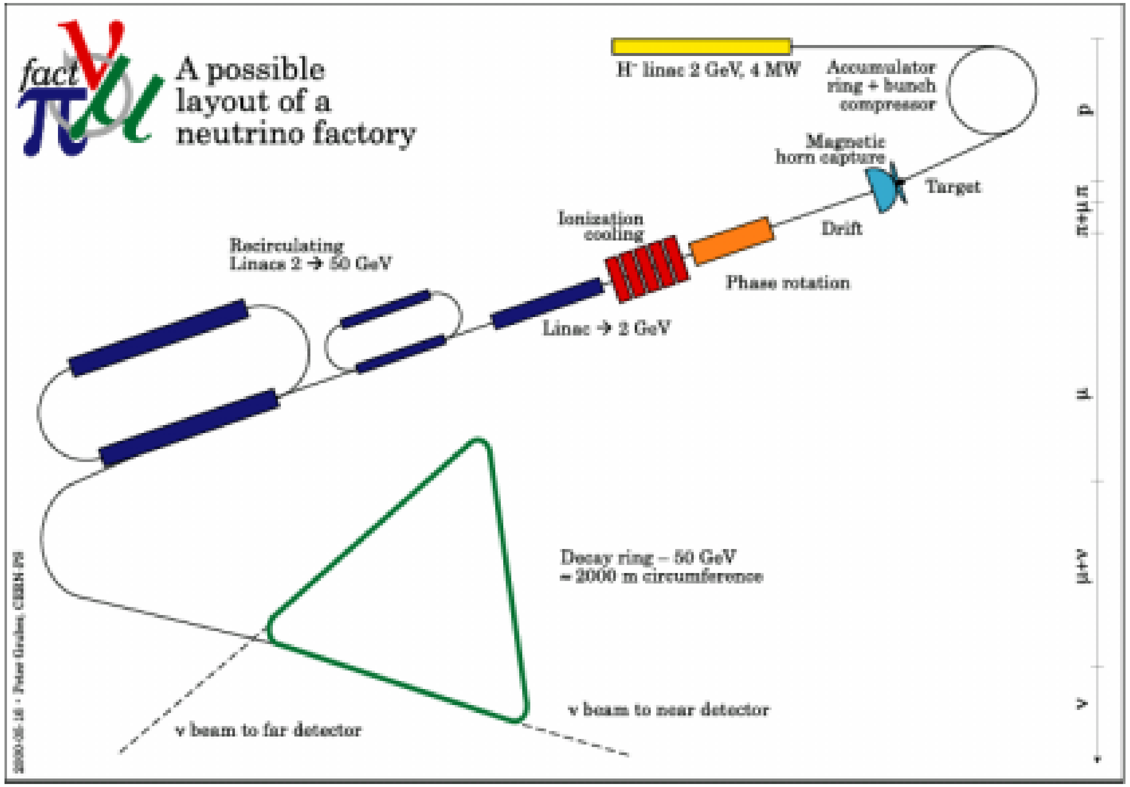
- Ionization cooling (stochastic cooling is too slow).
- Very large aperture accelerators (FFAG)

Both solutions have never been implemented and require R&D.

No need of hadronic MC to predict the fluxes and only two ν flavours in the beam

The basic concept of a neutrino factory (the CERN scheme)

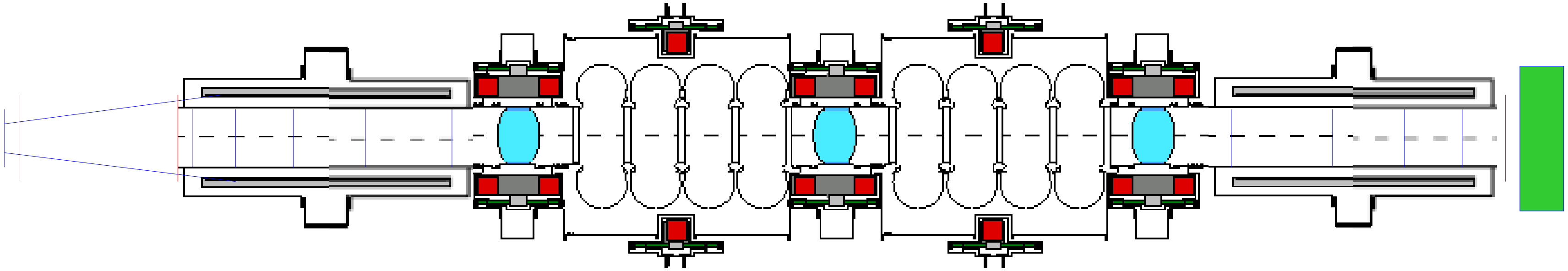
- High power (4 MW) proton beam onto a liquid mercury target.
- System for collection of the produced pions and their decay products, the muons.
- Energy spread and transverse emittance have to be reduced: “phase rotation” and ionization cooling
- Acceleration of the muon beam with a LINAC and Recirculating Linear Accelerators.
- Muons are injected into a storage ring (decay ring), where they decay in long straight sections in order to deliver the desired neutrino beams.
- **GOAL:** $\geq\ 10^{20}\ \ \mu$ **decays per straight section per year**



MICE

- **Muon Ionisation Cooling Experiment**
- **Collaboration of 40 institutes from Europe, Japan, US**
- **LOI recently reviewed by international panel at RAL**
- **Enthusiastically supported MICE**
- **Asked for a proposal by end 2002**

Edgecock



- **Construction: 2002-2004**
- **First beam: 2004/5**
- **New collaborators welcome!**

Detector

Iron calorimeter

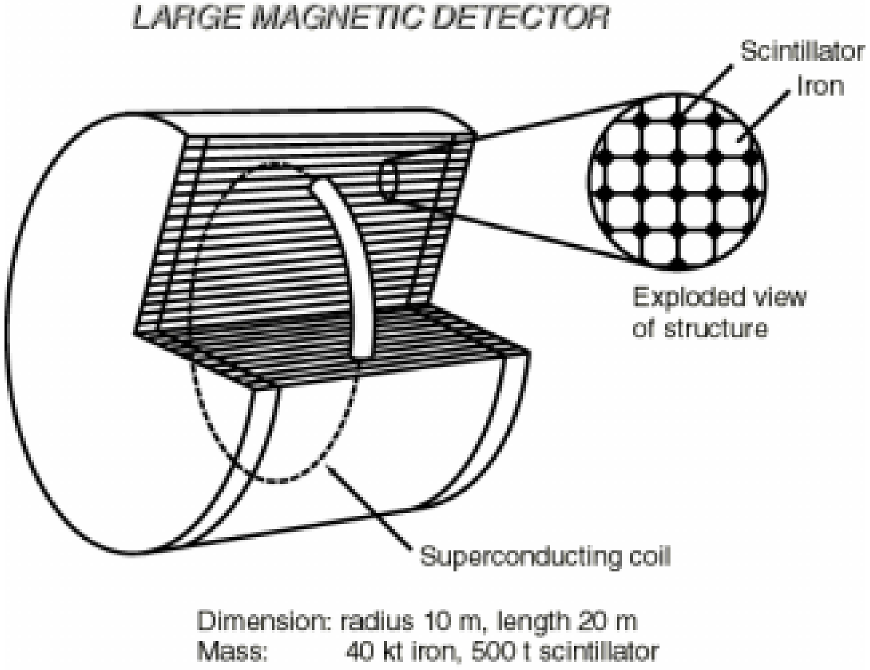
Magnetized

Charge discrimination

B = 1 T

R = 10 m, L = 20 m

Fiducial mass = 40 kT



Dimension: radius 10 m, length 20 m
Mass: 40 kt iron, 500 t scintillator

Also: L Arg detector: magnetized ICARUS
Wrong sign muons, electrons, taus and NC evts

Events for 1 year

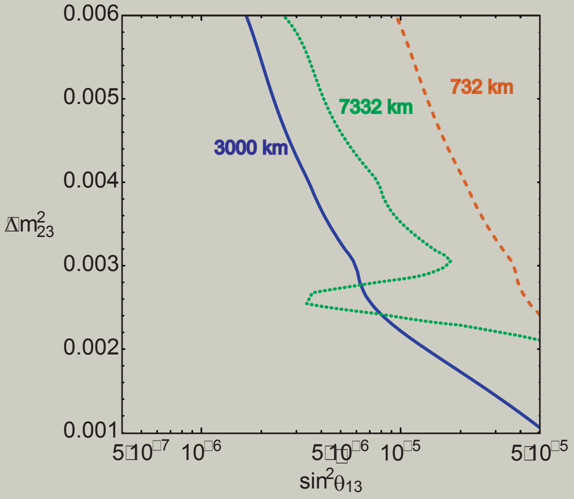
Baseline	— CC	$_e$ CC	signal (sin^2 $_{13}$=0.01)
732 Km	3.5 x 10^7	5.9 x 10^7	1.1 x 10^5
3500 Km	1.2 x 10^6	2.4 x 10^6	1.0 x 10^5

(cf 40 in JHF-SK)

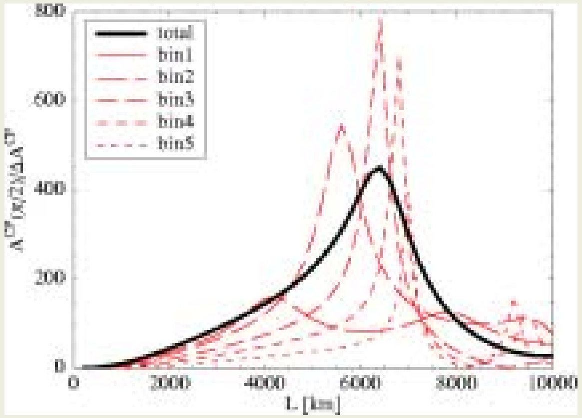
Alain Blondel, Venice, March 2003

Precision measurements at the Neutrino Factories

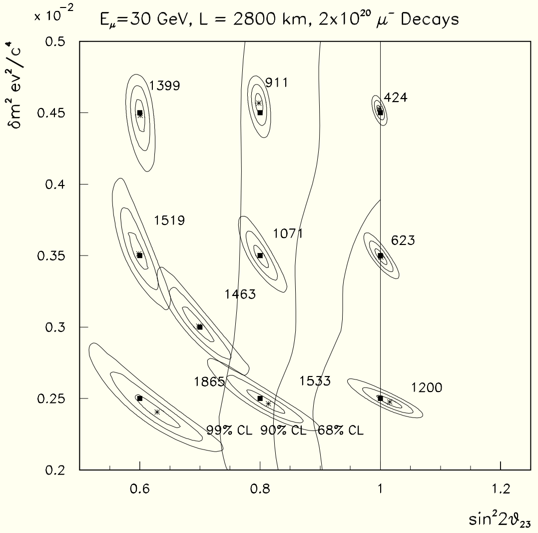
Improve up to 4 orders of magnitude the Chooz sensitivity on θ_{13}



Measure the Δm^2_{23} sign



Measure the atmospheric parameters at 1%.

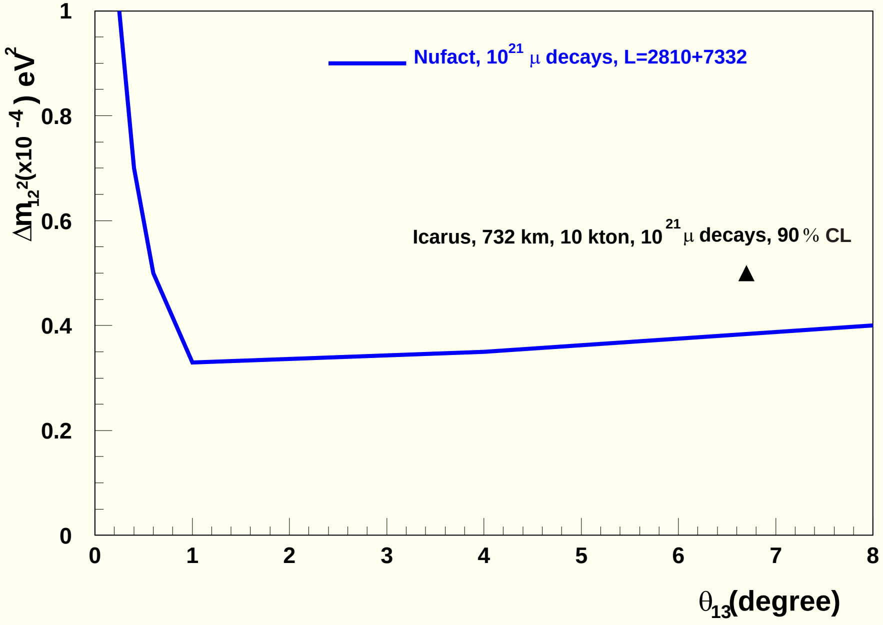


Final Sensitivity

- Matter effects must be separated from genuine CP-odd effects.
- Strong correlations in the simultaneus fit of θ_{13} and δ.
- The errors of all the other mixing matrix parameters influence the precision of the measure of δ. On the other hand a νF can measure θ_{23} e Δm^2_{23} at 1% through the ν_μ disappearance.
- Backgrounds ed efficiencies computed for a 40 kton large magnetic detector (full simulation, full reconstruction).
- (J. Burguet-Castell et al., Nucl. Phys. B **608** (2001) 301)

Two detectors at two different baselines are the optimal solution for the Leptonic CP detection. Best combination: 3000+7000 km.

CP sensitivity, defined as the capacity to separate at 99%CL max CP ($\delta = \pi/2$) from no CP ($\delta = 0$) computed as function of the two critical parameters θ_{13} and δm^2_{12}



SuperBeam vs. Nufact

PROS

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

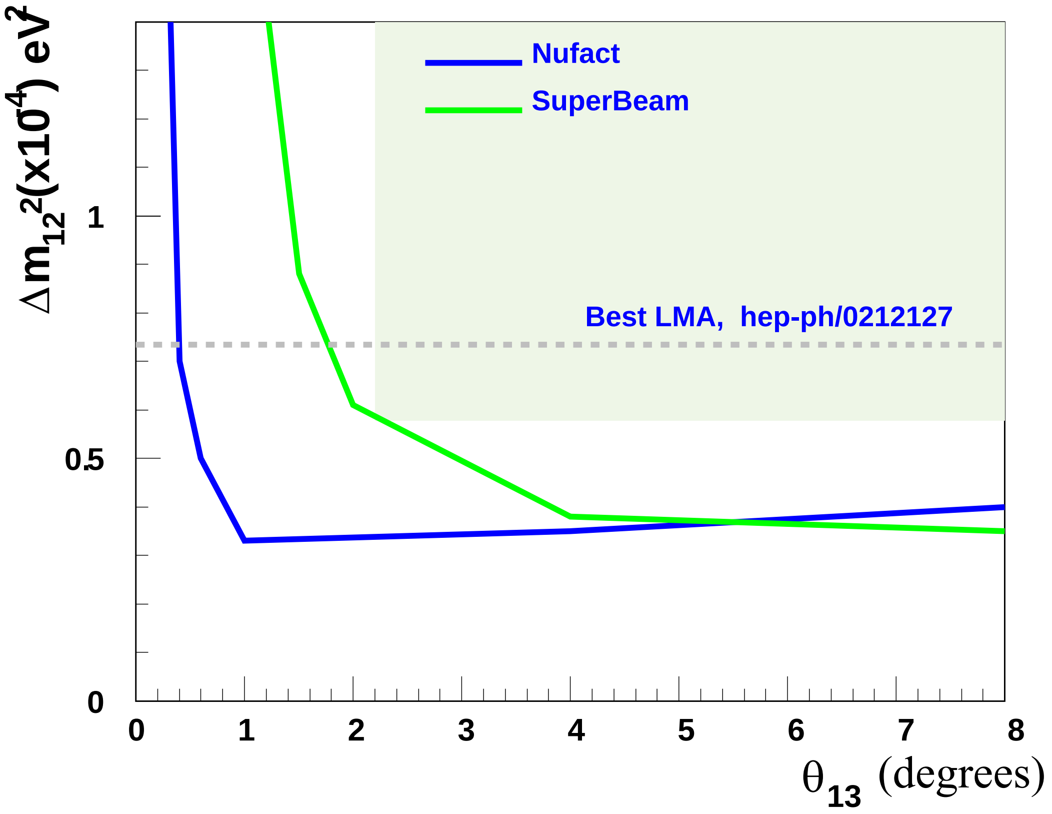
CONS

- Smaller CC rate
- Higher systematic errors
- Intrinsic beam contamination

A comparison of CP sensitivities of 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 and SPL-SuperBeam sensitivities computed with the same conditions.



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°, $\delta m^2_{12} = 0.7 \cdot 10^{-4}\, eV^2$, $\sin^2 2\theta_{12} = 0.8$:

	ν_μ beam 2 years	$\overline{\nu}_\mu$ beam 8 years
μCC (no osc)	36698	23320
Oscillated events (total)	45	133
Oscillated events (cp-odd)	-84	53
Intrinsic beam background	140	101
Detector backgrounds	36	49

Can the SuperBeam+UNO combination be upgraded?

YES
with a novel concept of neutrino beam: BETA BEAM.

Beta Beam (P.Zucchelli hep-ex/0107006)

Muons are not the only unstable particles that decay into neutrinos, there are also β emitter nuclei.

As for the neutrino factory the neutrino spectrum is completely defined by the parent decay properties and by the Lorentz boost γ.

To produce a Beta Beam:

1. Produce β radioactive ions with a lifetime of the order of ~ 1s. Best candidate: ^{6}He, β^- emitter ($E_0 \simeq 3.5\,MeV\,, T/2 \simeq 0.8\,s$).
2. Accelerate them to high energies in a conventional way (PS).
3. Accumulate them in a decay ring with long straight sections (SPS like).
4. **Just ONE neutrino flavour is produced: ν_e or $\overline{\nu}_e$.**

CERN ISOLDE, if injected by SPL, could produce $7 \cdot 10^{13}\ ^6He/s$ by using 1/8 of the SPL duty cycle.

PS + SPS (modified to have 2.5 km long straight sections). Today they are already accelerating heavy ions up to $\gamma = 150$.

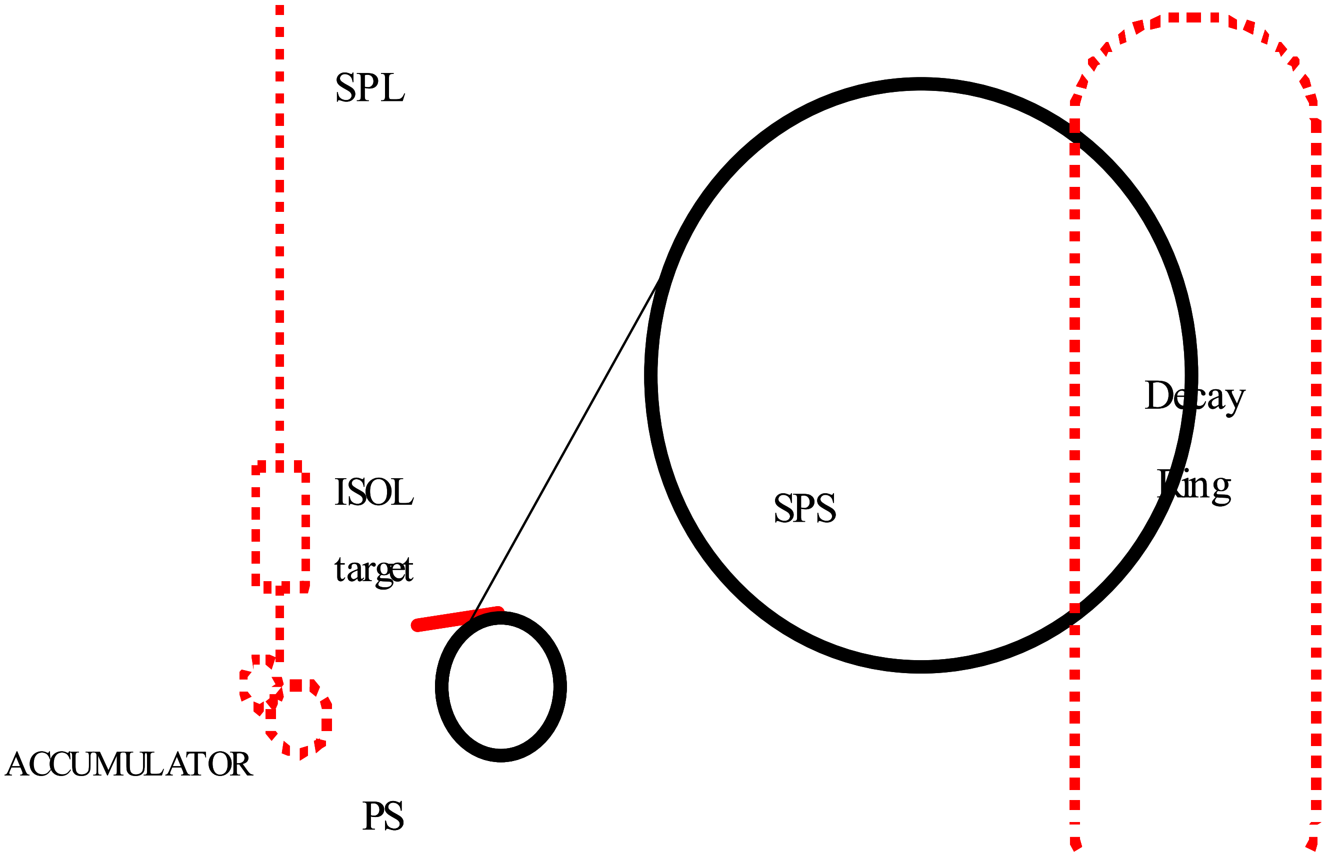
The complexity of the FAST muon acceleration is absent (simply 4×10^5 more time).

It is technologically feasible to build neutrino beams with intensities comparable with SuperBeams.

CERN is the only place with the complete Beta Beam know-how:

- Isotopes production (ISOLDE)
- Ion acceleration (PS+SPS+LHC)
- Neutrino Experiments (EP)

Beta Beam @cern



M. Lindroos et al.

The SuperBeam - BetaBeam synergy

Run two neutrino beams to the same detector at the same time.

Both beams need SPL, but the BetaBeam requires at most 3% of the SPL protons → the two beams can run together.

Both beams produce sub-GeV neutrinos → same baseline and same detector.

CP, T and CPT searches at the same time !!!!

The SuperBeam - BetaBeam synergy: CP, T and CPT

No other realistic scenario can offer CP, T and CPT searches at the same time in the same detector!!!!

CP Searches

- SuperBeam running with ν_μ and $\overline{\nu}_\mu$.
- Beta Beam running with ^{6}He ($\overline{\nu}_e$) and ^{18}Ne (ν_e).

T searches

- Compare Super Beam $p(\nu_\mu \longrightarrow \nu_e)$ with Beta Beam ^{18}Ne $p(\nu_e \longrightarrow \nu_\mu)$
- Compare Super Beam $p(\overline{\nu}_\mu \longrightarrow \overline{\nu}_e)$ with Beta Beam ^{6}He $p(\overline{\nu}_e \longrightarrow \overline{\nu}_\mu)$.

CPT searches

- Compare Super Beam $p(\nu_\mu \longrightarrow \nu_e)$ with Beta Beam ^{6}He $p(\overline{\nu}_e \longrightarrow \overline{\nu}_\mu)$.
- Compare Super Beam p($\overline{\nu}_\mu \longrightarrow \overline{\nu}_e$) with Beta Beam ^{18}Ne $p(\nu_e \longrightarrow \nu_\mu)$

In case of small values of θ_{13} the most powerful combination to discover Leptonic CP would be however a single T search with neutrinos (SuperBeam ν_μ with BetaBeam ν_e).

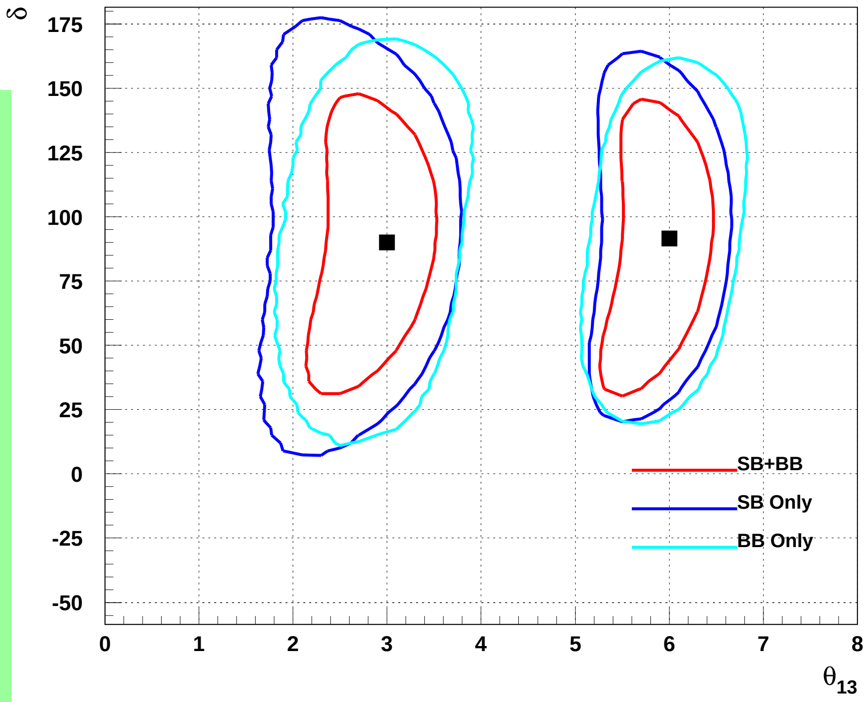
The SuperBeam - BetaBeam synergy: results

A test point running SuperBeam with ν_μ for 10 years and Beta Beam with ν_e for 10 years.

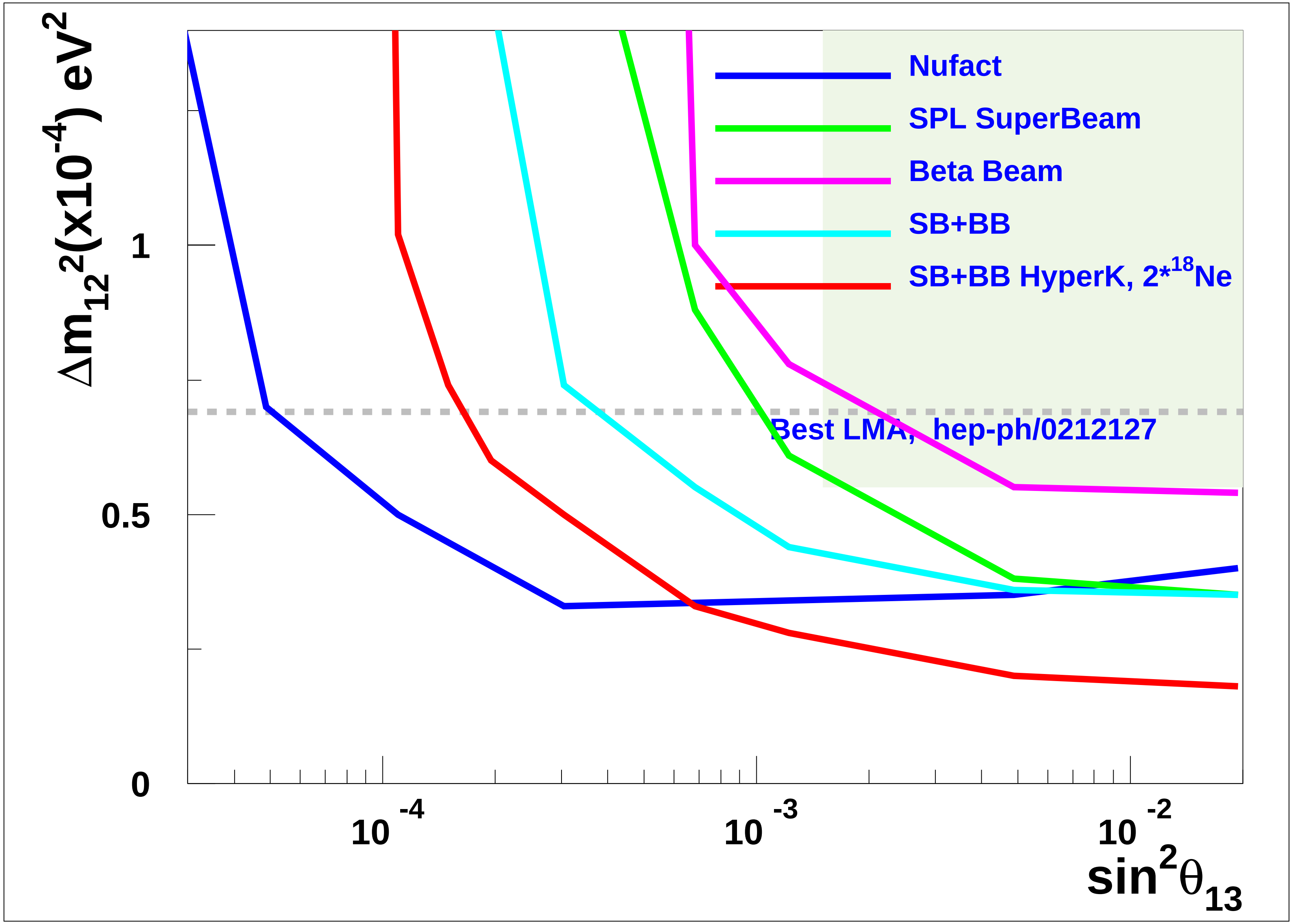
θ_{13} =3°, $\delta m^2_{12} = 0.6 \cdot 10^{-4}\, eV^2$:

10 yrs (4400 kton/yr)	SuperBeam	Beta Beam $\gamma = 75$
CC events (no osc, no cut)	183488	18583
Total oscillated	263	64
CP-Odd oscillated	-360	22
Beam background	705	0
Detector bkg.	181	10

How two particular solutions can be improved by the combination of Super + Beta Beam (99%CL curves)



Final CP sensitivity.



CONCLUSIONS

- Still a long trip to the leptonic CP violation.
- Next generation experiments probably will tell us if the experimental conditions for the search of leptonic CP violation are fullfilled and how difficult the search.
- Neutrino Factories are the most powerful instrument for this searches.
- The first stage of Neutrino Factories, neutrino SuperBeams, could provide the necessary informations for the final searches.
- Beta Beams, a truly new concept, could represent a powerful complementary alternative to Neutrino Factories.
- **If you are interested in Beta Beams you may have a look at the workshop starting tomorrow here at Les Arcs.**