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“Physics Potential of existing and future LBL ν beams”

NBI 2002 , March 14-18,2002, - CERN

The golden era of Neutrino Beams

The evidence of atmospheric neutrinos oscillations opened the golden era of neutrino beams: 4 new projects to confirm the result and precisely measure the parameters + the Fermilab main injector neutrino beam to test LSND. (With only one bad surprise: a slightly too low δm^2)

K2K at KEK, to SuperKamiokande detector, running.

Numi from Fermilab to Minos, expected by 2003 (?)

CNGS from CERN to Opera and Icarus, expected by 2005 (?)

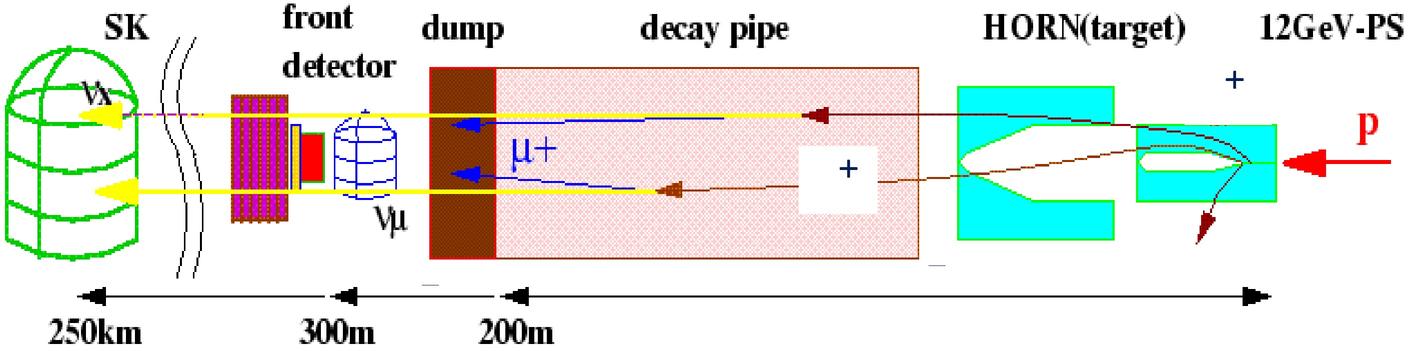
JHF neutrino beam, from JHF (Jaeri) to SuperKamiokande, to be approved end of this year, first neutrino beam expected for 2007 (?)

Main Injector neutrino beam, from Fermilab to MiniBoone, to check the LSND evidence for oscillations, expected for this year.

Top cited experimental articles in the last 10 years in the QSPIRES database:

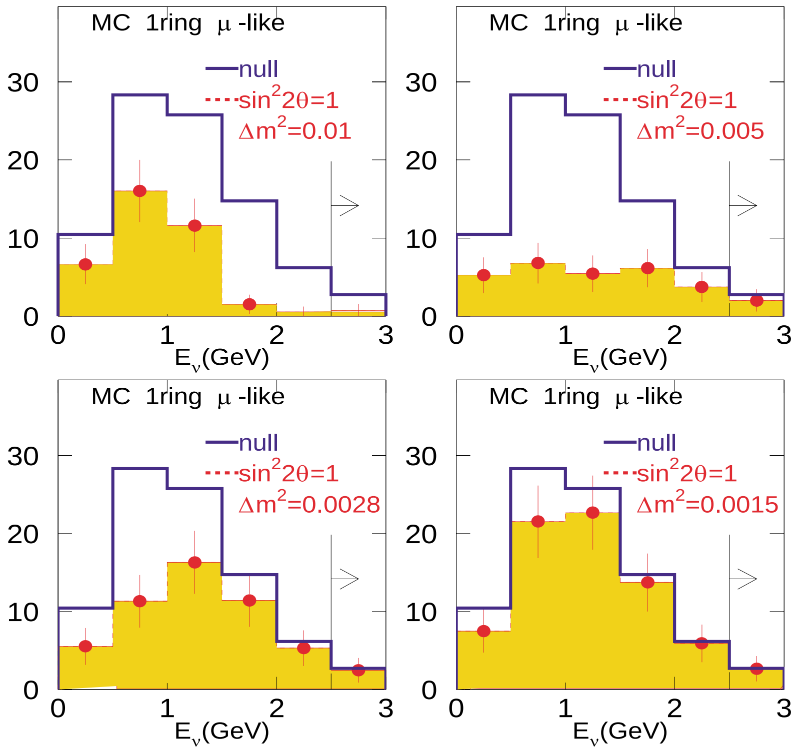
1	SuperKamiokande evidence of atmospheric ν oscillation	1258
2	Top discovery at CDF	889
3	Top Discovery at D0	849
4	Measurement of Ω and Λ from 42 high redshifts SuperNovae	657
5	Kamiokande evidence of atmospheric ν oscillation	654
7	Chooz initial results	561

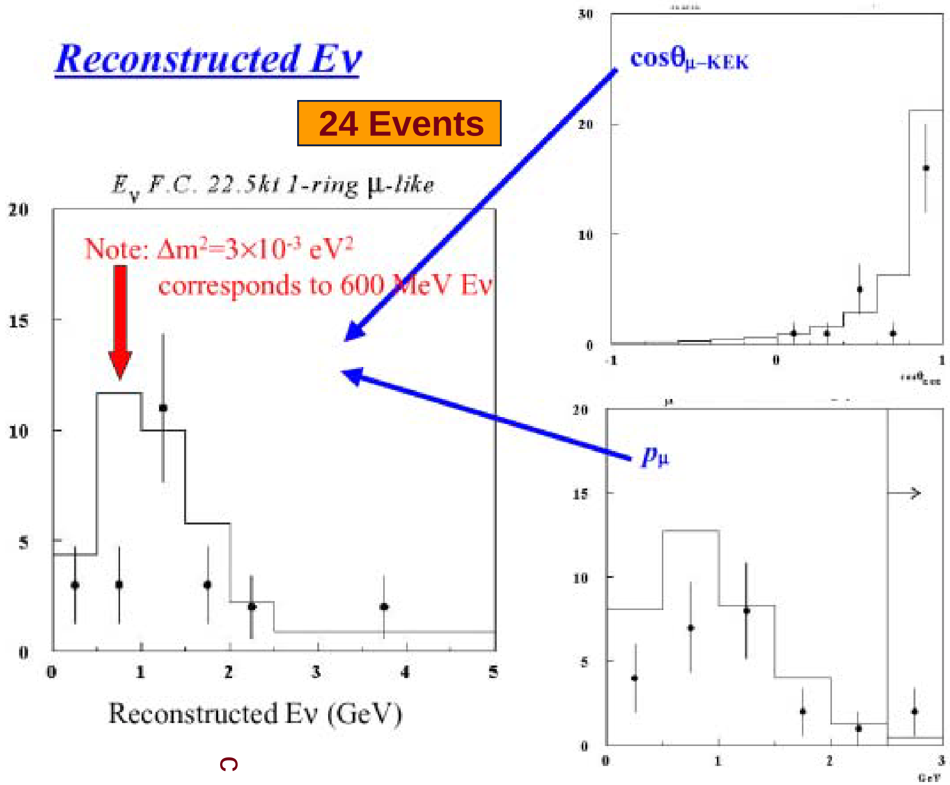
K2K



Perhaps not the conclusive answer alone, but of tremendous impact when analyzed together SuperKamiokande.

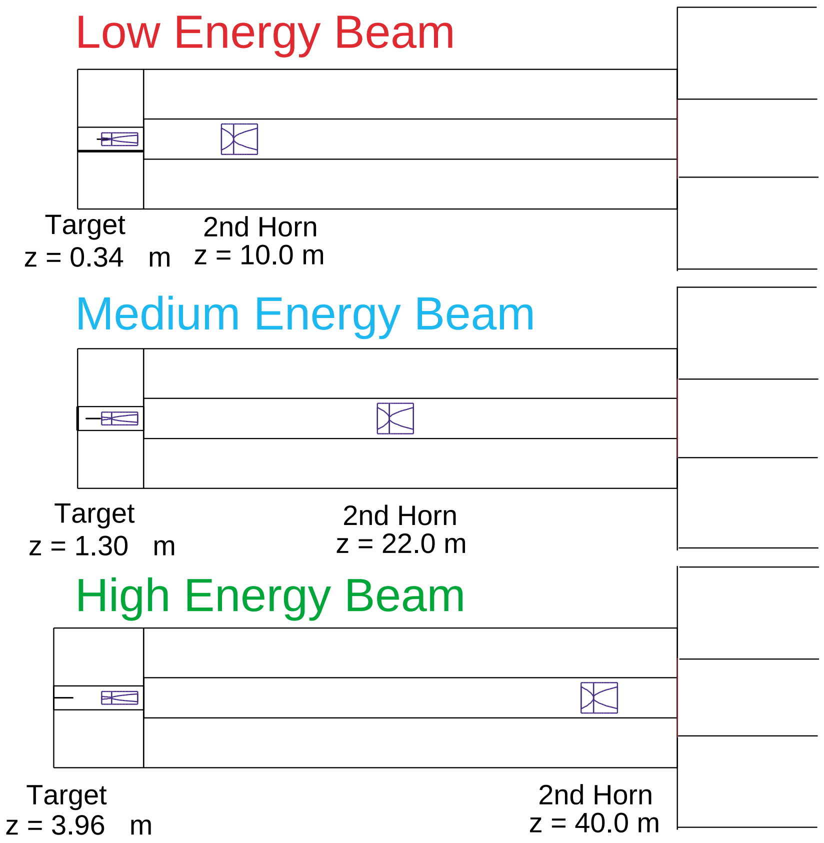
Reconstructed Neutrino Energy (MC, end of data taking)

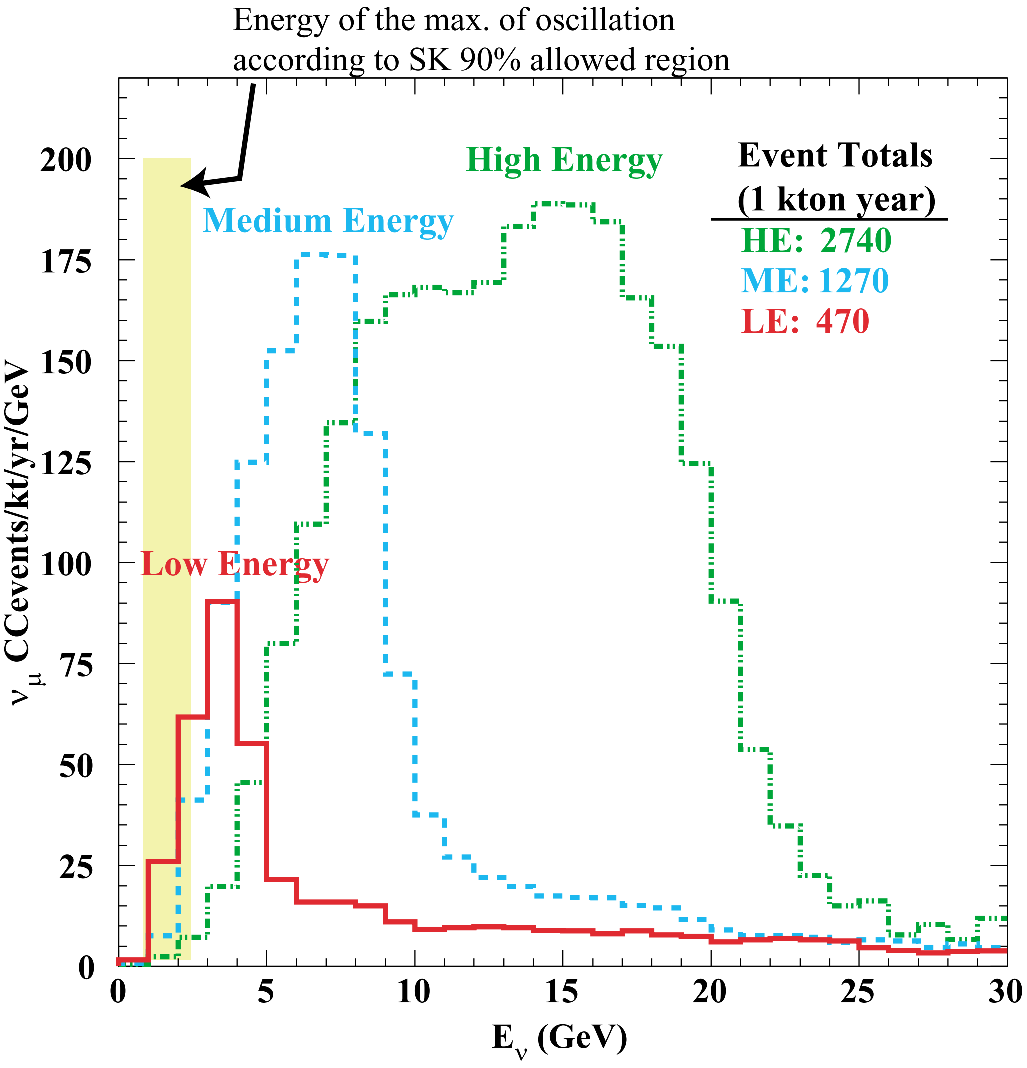




Numi to MINOS

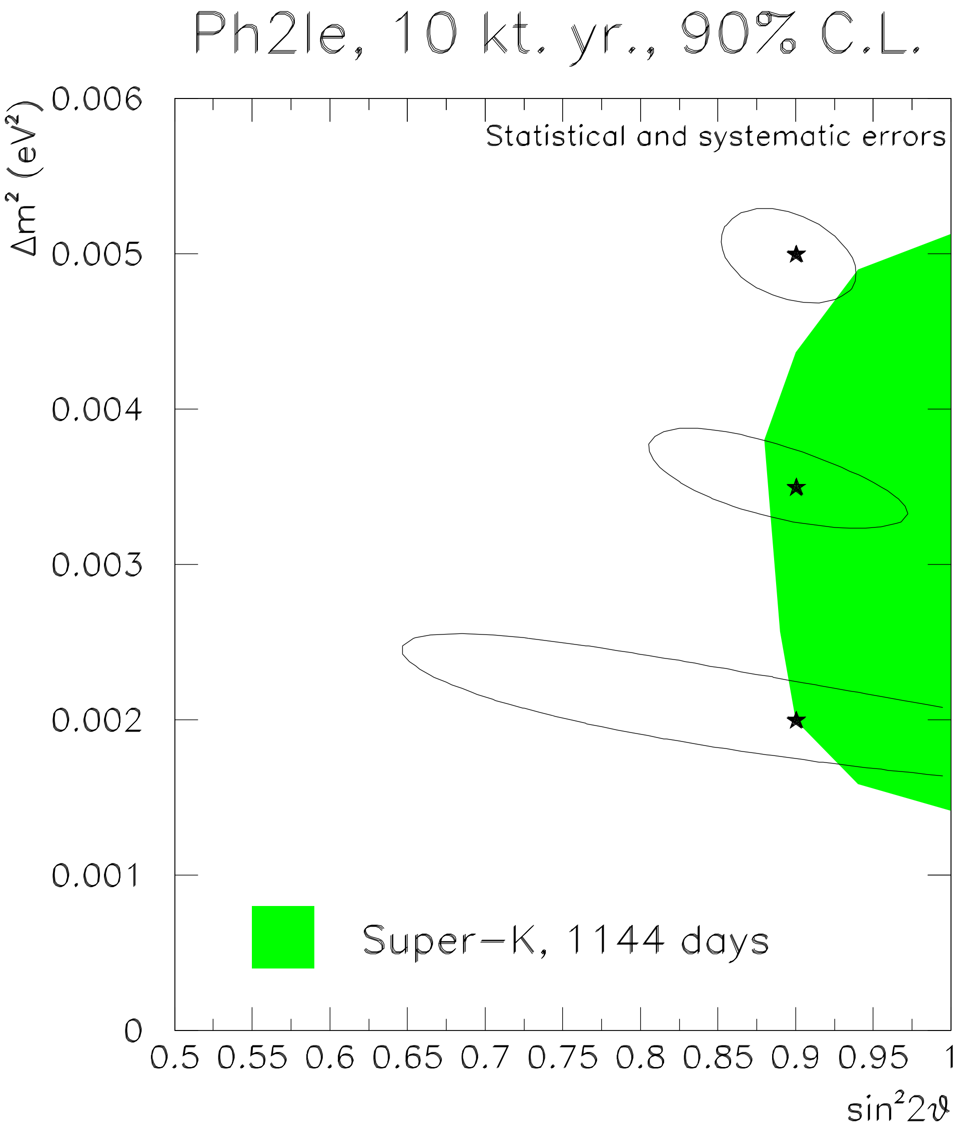
Sacrifice neutrino flux to fit the expected energy of oscillated events.





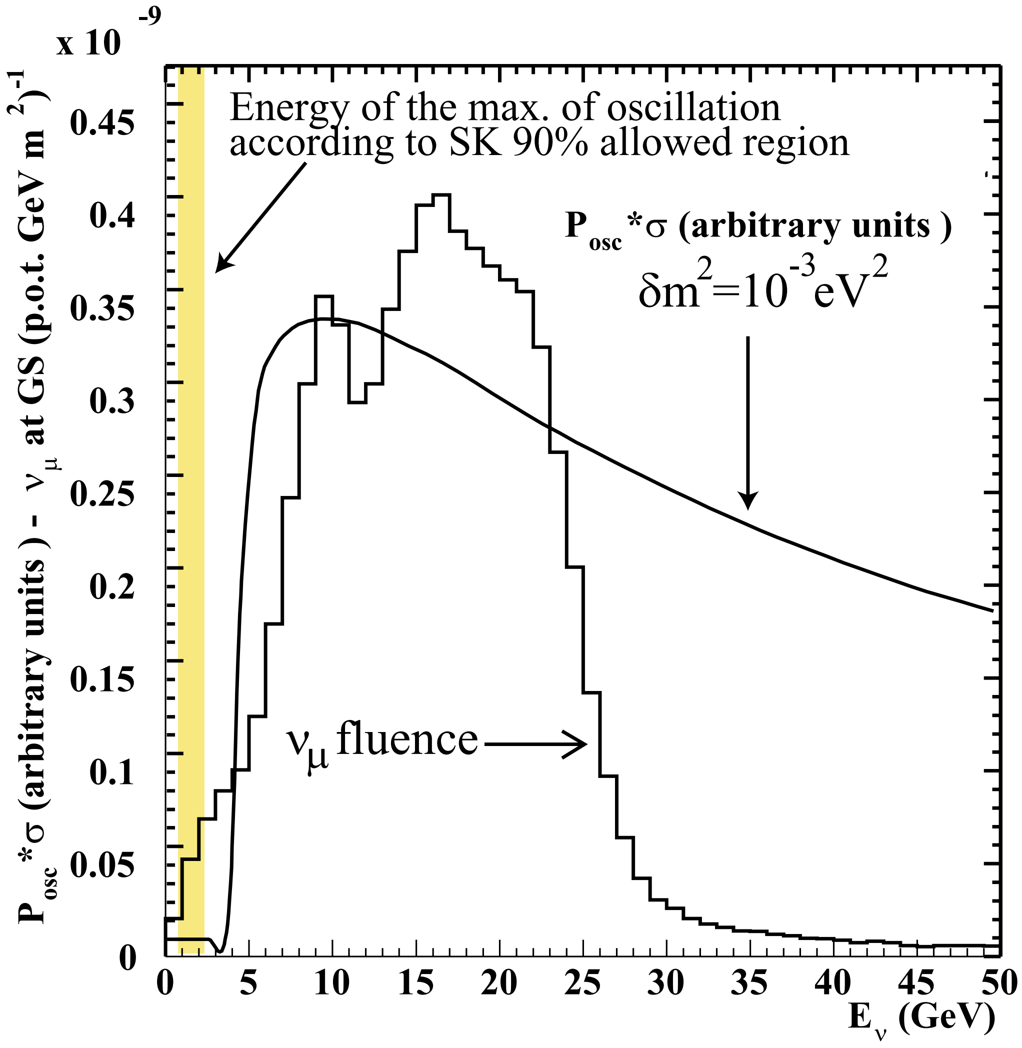
Numi to MINOS (continued)

Aimed to measure oscillation parameters through ν_μ disappearance.



CNGS

Optimized to τ appearance searches, the forced choice given the initial proton energy and the baseline



CNGS

A positive result would be:

- The final proof of $\nu_\mu \longrightarrow \nu_\tau$ oscillation
- The first appearance signal in neutrino oscillations (if LSND will not be confirmed).

OPERA

Decay Mode	Signal $1.6 \times 10^{-3}\, eV^2$	Signal $2.5 \times 10^{-3}\, eV^2$	Signal $4.0 \times 10^{-3}\, eV^2$	BG
e^- Long	1.4	3.4	8.6	0.15
μ^- Long	1.3	3.2	8.1	0.29
h^- Long	1.6	3.7	9.4	0.23
e^- Short	0.4	1.0	2.5	0.03
μ^- Short	0.2	0.5	1.3	0.04
TOTAL	4.9	11.8	30.0	0.74

ICARUS

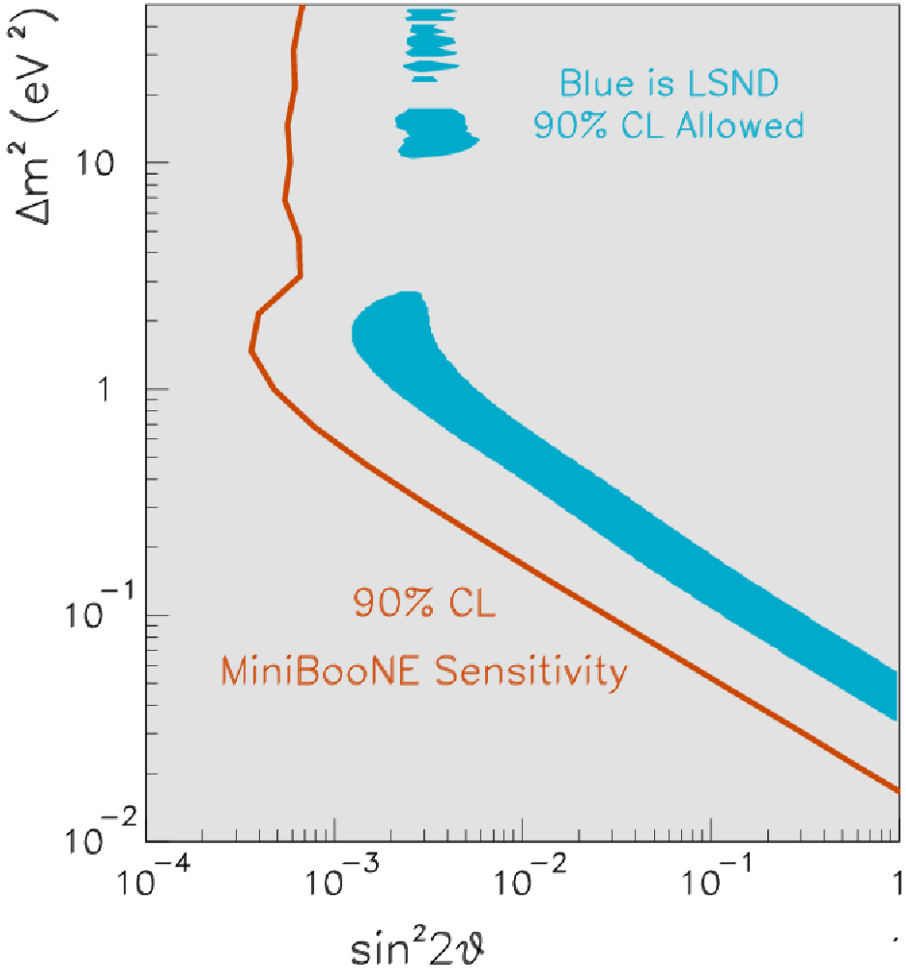
Decay Mode	Signal $1.6 \times 10^{-3}\, eV^2$	Signal $2.5 \times 10^{-3}\, eV^2$	Signal $4.0 \times 10^{-3}\, eV^2$	BG
$\tau \longrightarrow e$	3.7	9	23	0.7
$\tau \longrightarrow \rho$ DIS	0.6	1.5	3.9	< 0.1
$\tau \longrightarrow \rho$ QEL	0.6	1.4	3.6	< 0.1
TOTAL	4.9	11.9	30.5	0.7

MiniBoone

The MiniBoone experiment at the Fermilab Main Injector Neutrino Beam will be able to firmly proof or discard the LSND evidence of $\overline{\nu}_\mu \longrightarrow \overline{\nu}_e$ oscillations.

A positive result would be of tremendous impact:

- The confirmation of the first appearance result in neutrino oscillation experiments.
- If also the solar and atmospheric neutrinos oscillations would be confirmed it will require additional neutrino(s) $\Rightarrow$ STERILE NEUTRINOS.
- The whole picture of neutrino mixing matrix should be put in discussion again.



Will these experiments the end of the story?

Certainly NOT. Probably they will be only the starting point.

The two most important parameters in the neutrino mixing matrix would be still to be measured:

- θ_{13}.
- The CP phase δ.

In case of a positive result from MiniBoone the experimental issues would be much more and the roadmap for the future experiment to be re-thought.

The capital importance of θ_{13}

Solar and atmospherics oscillations are compatible with $\theta_{13} = 0$.

Present limit on θ_{13} comes from CHOOZ: $\sin^2 2\theta_{13} \leq 0.1$.

Solar LMA + Atmospheric $\Rightarrow$ A closely bimaximal 3x3 mixing matrix (VERY different from the CKM quark mixing matrix)

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

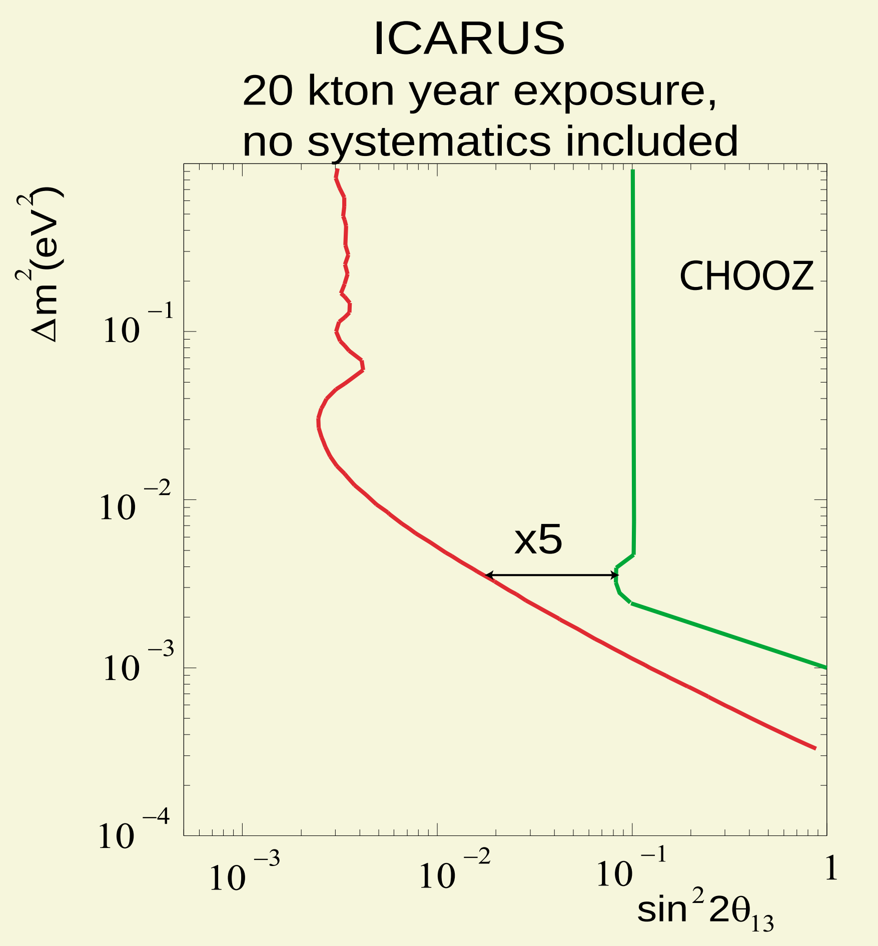
In other words Solar and Atmospherics can be described by two simple 2×2 mixing matrixes $\Rightarrow$ no experimental evidence of the presence of a 3×3 mixing matrix! $\Rightarrow$ The experiment that will establish $\theta_{13} \neq 0$ will claim to have demonstrated the existence of the 3×3 mixing matrix!.

θ_{13} is crucial to measure the unitariety of the mixing matrix.

θ_{13} regulates sub-leading $\nu_\mu \rightarrow \nu_e$ transitions $\Rightarrow$ the fundamental parameter to define the experimental approach to the Leptonic CP (see after).

Could the next generation long-baseline experiments measure θ_{13} ?

- θ_{13} controls sub-leading $\nu_\mu \longrightarrow \nu_e$ transitions in the atmospheric regime.
- Minos will improve the Chooz sensitivity by a factor 2 (limited by systematics and by its low efficiency in detecting electrons)
- Icarus could have a better sensitivity ($\times 5$), but what about the systematics (without the close detector)?



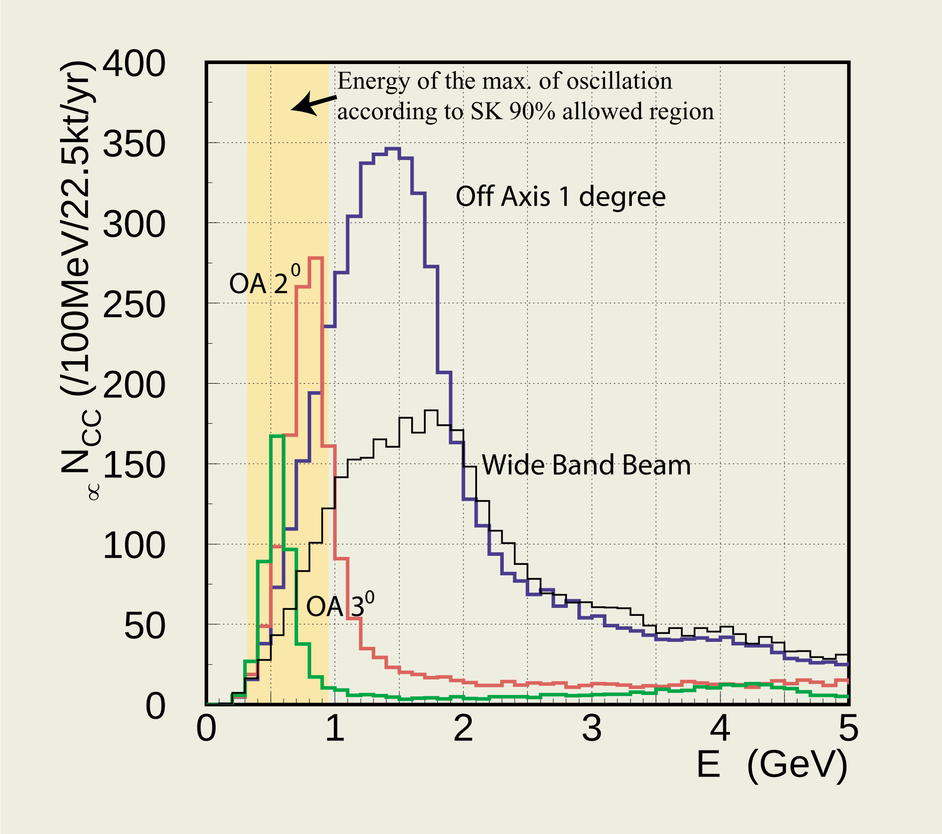
JHF-Japan Hadron Facility at Jaeri

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.

The neutrino beam line is not yet approved. Approval is expected by the end of this year.

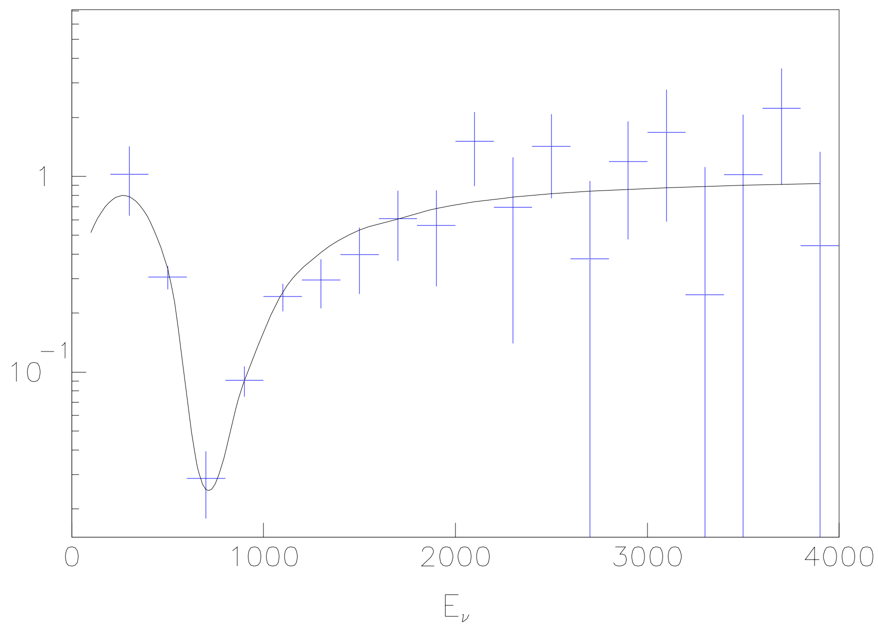
K2K		JHF
$6 \cdot 10^{12}$	Protons per pulse	$3 \cdot 10^{14}$
2.2 s	Cycle	3.4 s
12 GeV	Proton energy	50 GeV
40	Events in SK per year (no osc.)	2200
1.5	Mean neutrino energy	0.8



JHF (continued)

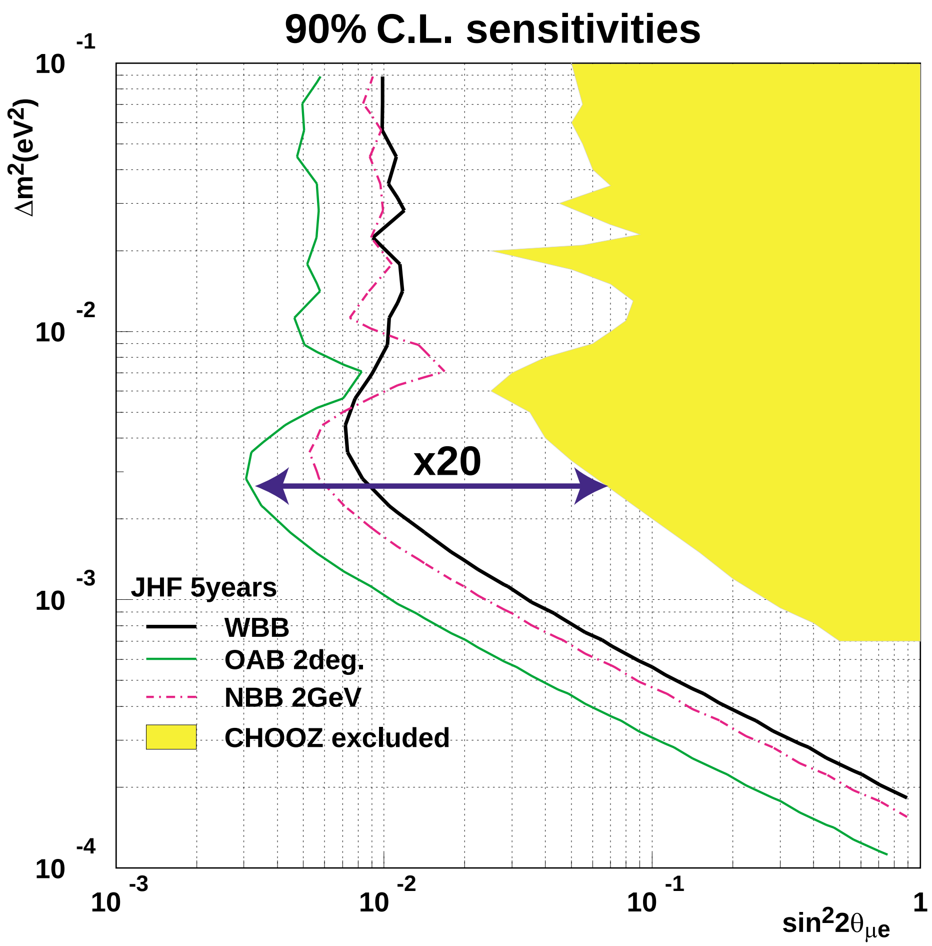
Precision measure of the atmospheric parameters:

- 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}



What about off-axis Numi or CNGS ?

- The direction of these beams cannot be changed $\Longrightarrow$ the detector would be outside the underground laboratory and to be built from scratch.
- A quantitative approach for NuMi can be found in `hep-ex/0110032` or in D.Harris' talk at NNN02.
- Some ideas are circulating about CNGS ...

Leptonic CP

Two conditions to make Leptonic CP detectable:

- Solar LMA confirmed
- $\theta_{13} \geq 0.5^0$ (see the following).

A big step from a θ_{13} search:

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

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 $\Rightarrow$ Dedicated experiments on neutrino cross-section, hadron production, particle ID.

CP phase is well hidden in the mixing matrix

In principle CP terms could be extracted with oscillations from the first and the third generation ($\nu_e \rightarrow \nu_\tau$), in practice this experimental approach seems non viable: too difficult to detect ν_τ in very massive detectors.

Best possibility: $\nu_\mu \rightarrow \nu_e$ transitions.

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

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

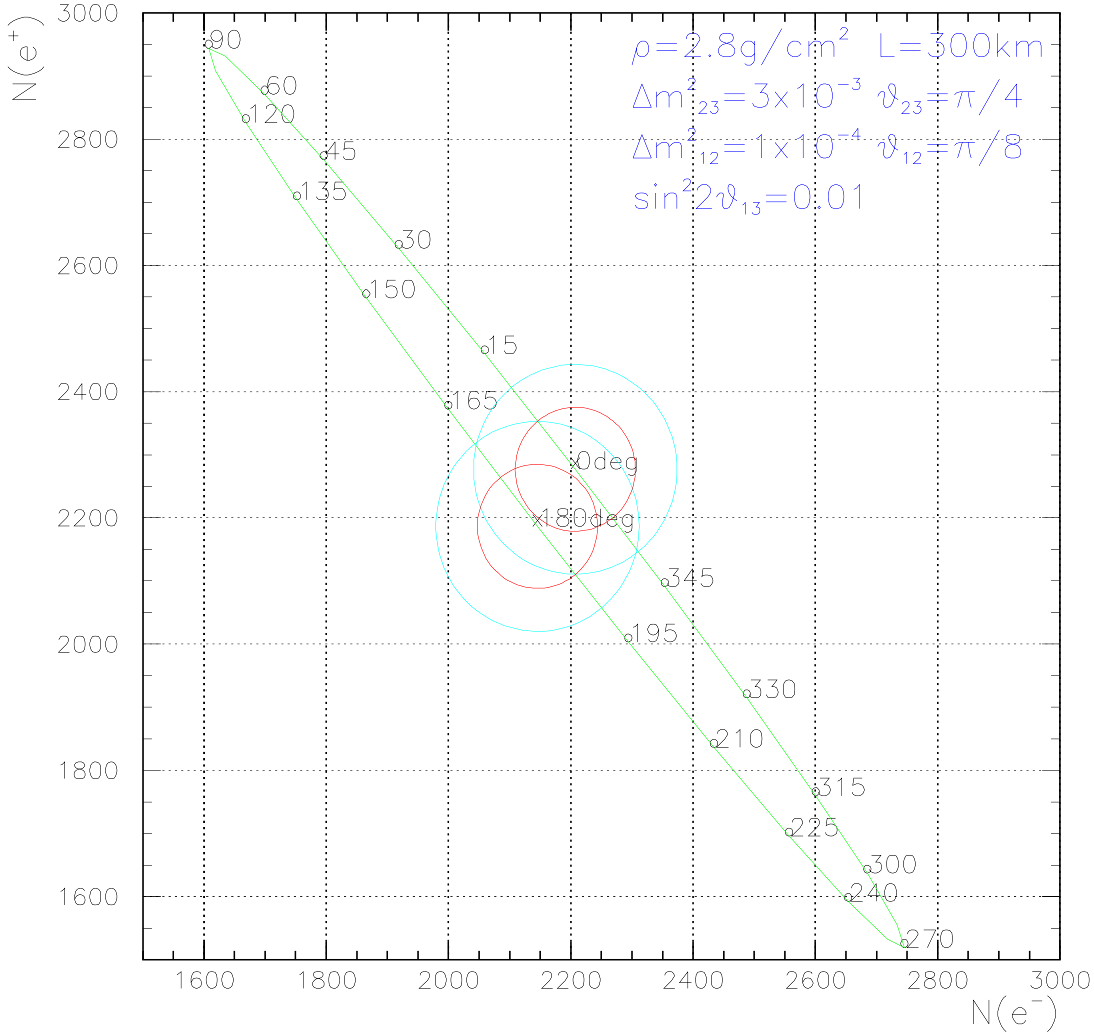
At the first order, neglecting matter effects and CP:

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

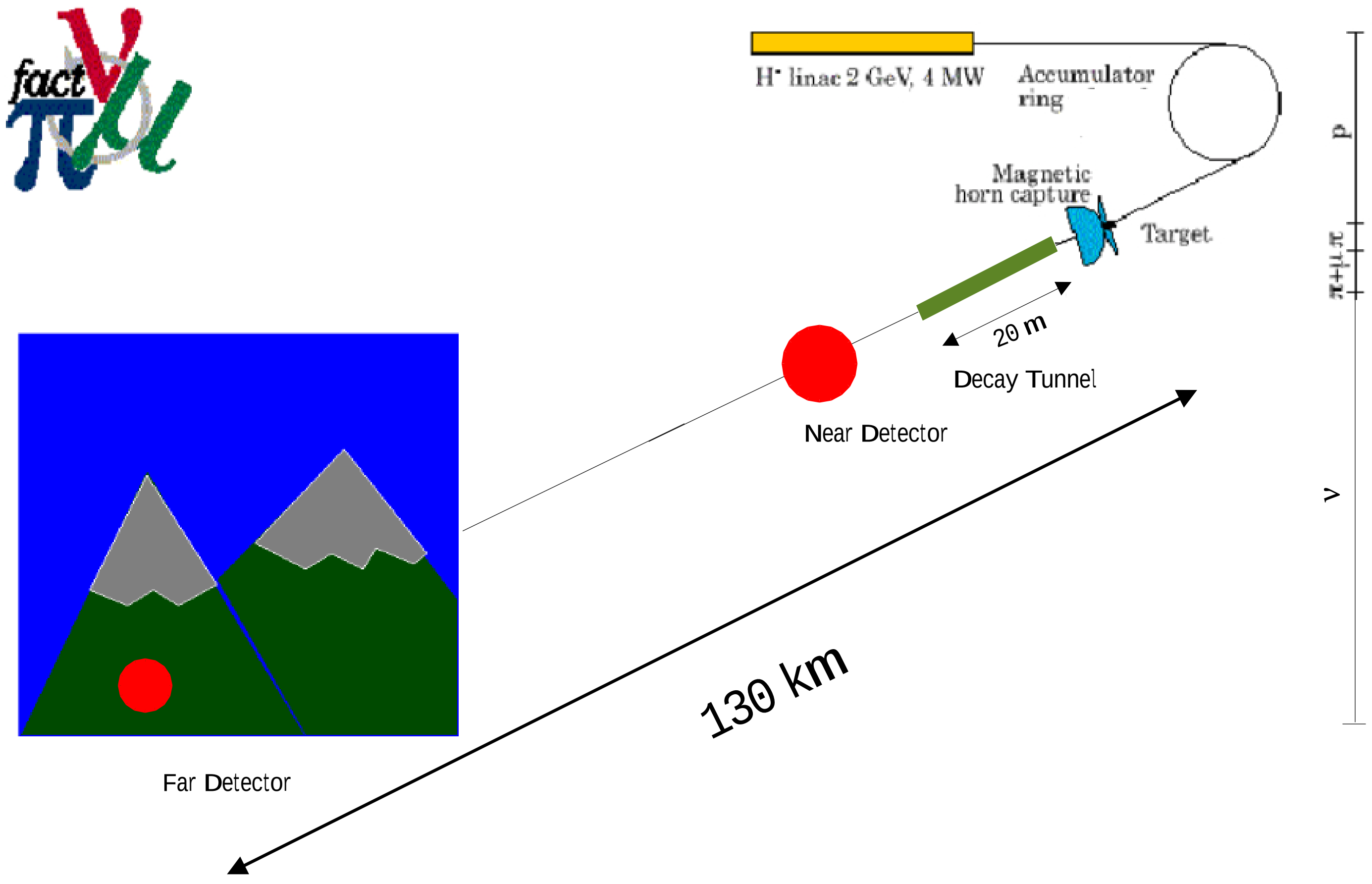
SuperBeams (1) - JHF phase 2

Upgrade the proton driver from 0.75 MW to 4 MW

Upgrade SuperKamiokande by a factor 40 $\Longrightarrow$ HyperKamiokande

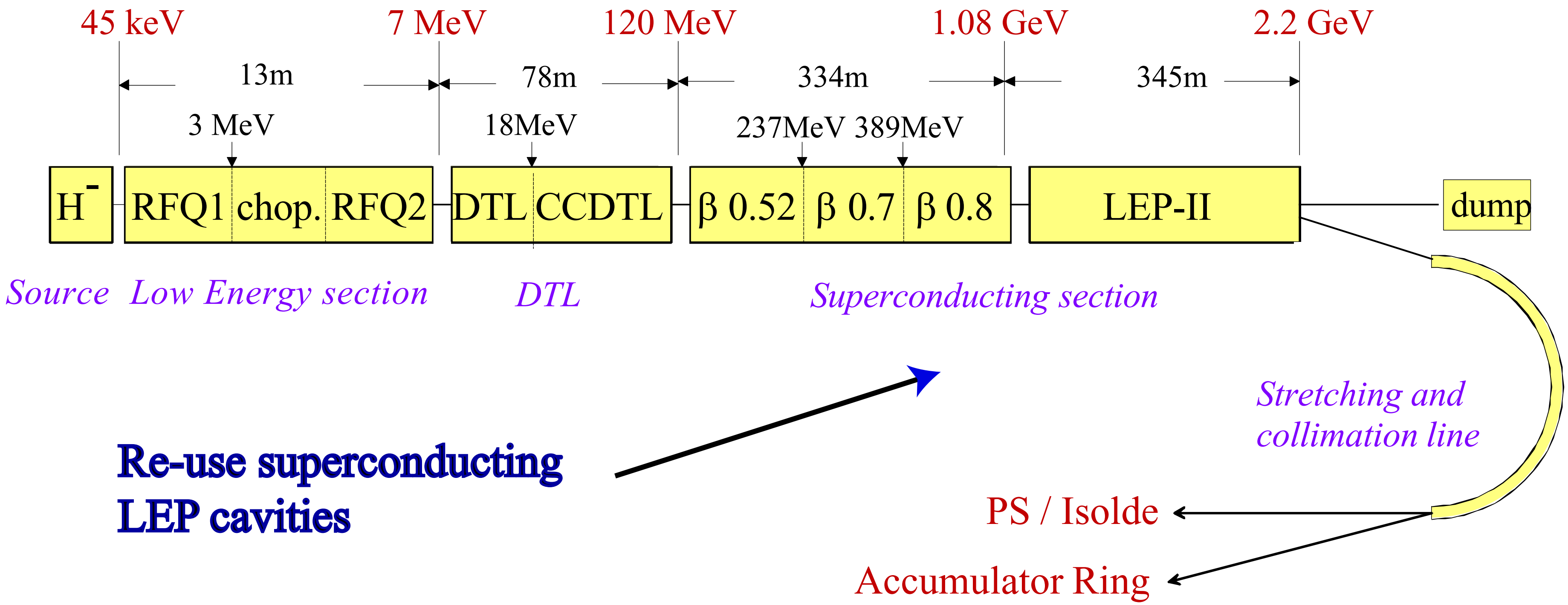


CERN SPL SuperBeam



Possible Low Energy Super Beam Layout

MW-Linac: SPL (Superconducting Proton Linac)



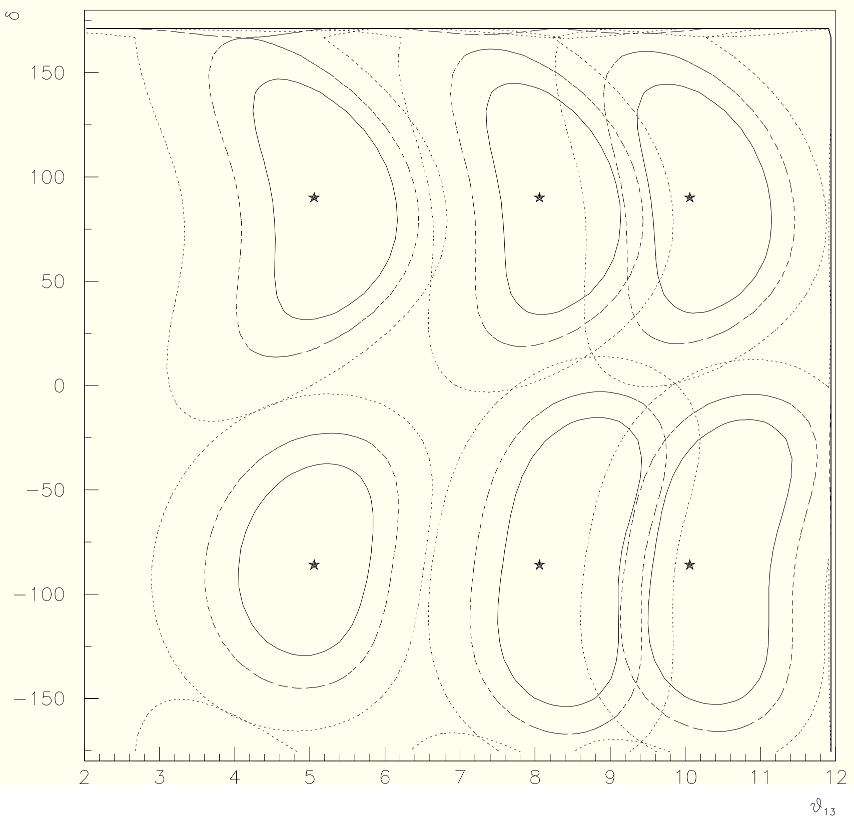
Re-use superconducting LEP cavities

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

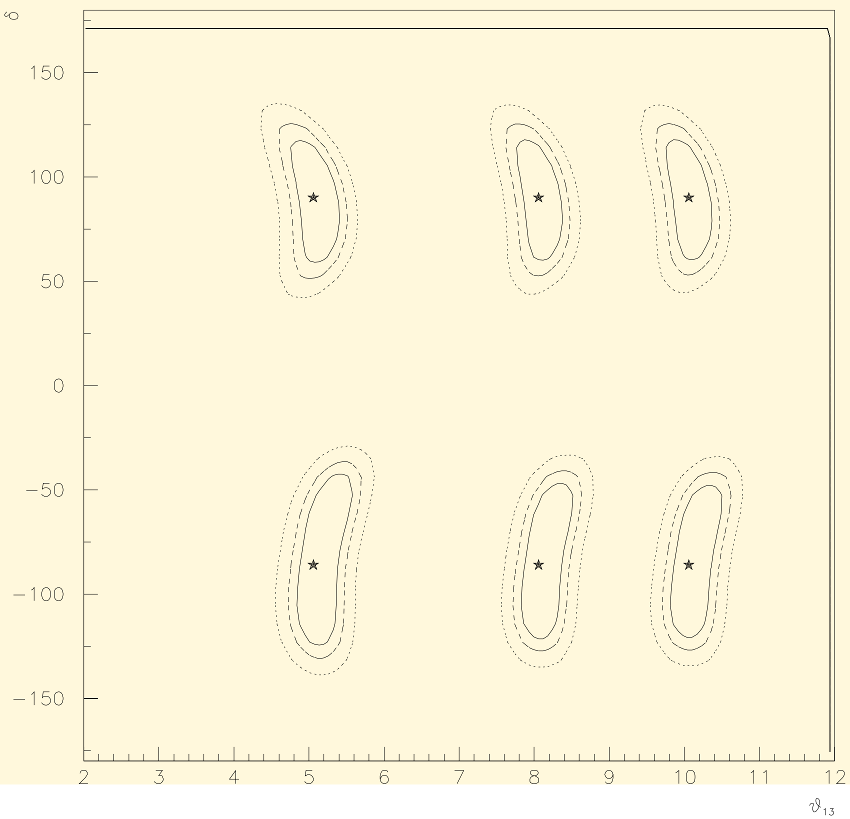
10^{23} protons/year

SPL SuperBeam CP sensitivity

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



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

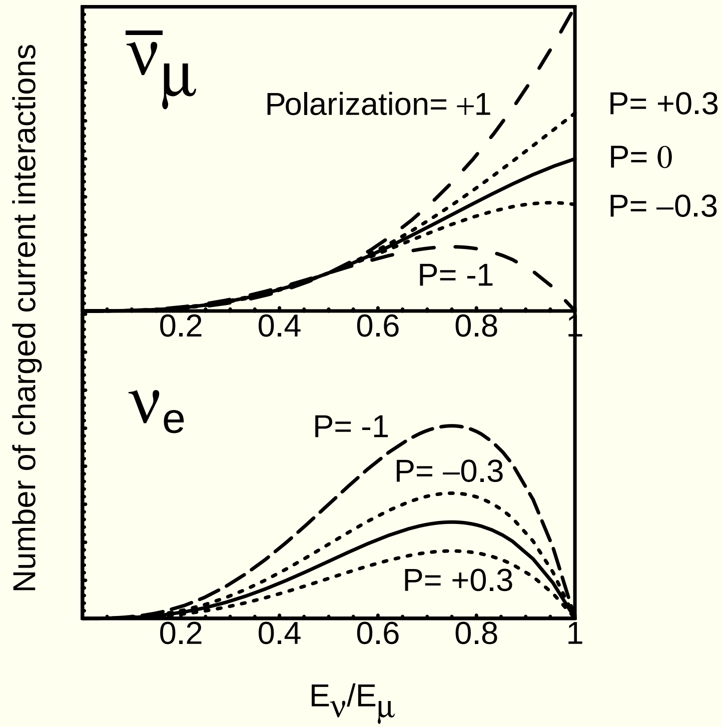


Neutrino Factories

- 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.
- Oscillated events N_{osc} at a distance L:

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

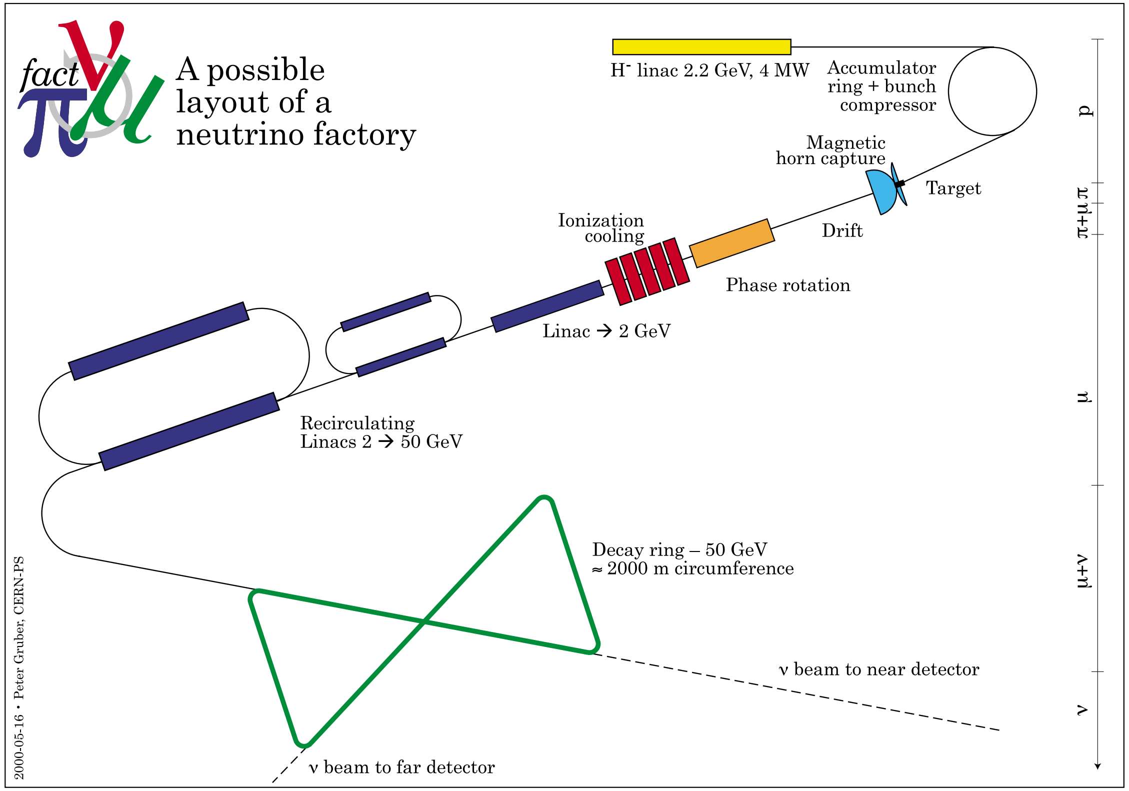
  N_{osc} increases linearly with the beam energy. Optimal energy: as high as possible.
- Beam intensities predicted to be two orders of magnitude higher than in traditional neutrino beams.
- No hadronic MonteCarlos to predict neutrino fluxes.
- Neutrino beams from muon decays contain ONLY two types of neutrinos of opposite helicities ($\overline{\nu}_e\ \nu_\mu$ or $\nu_e\ \overline{\nu}_\mu$). **It is possible to search for $\nu_\mu \rightarrow \nu_e$ transitions characterized by the appearance of WRONG SIGN MUONS, without intrinsic beam backgrounds.**



The basic concept of a neutrino factory

- High power proton driver (4MW) 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:** $\geq 10^{20}$ μ **decays per straight section per year**

Working groups in Europe, USA and Japan



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:** $\boldsymbol{\nu_e}$ **or** $\boldsymbol{\overline{\nu}_e}$**.**

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.

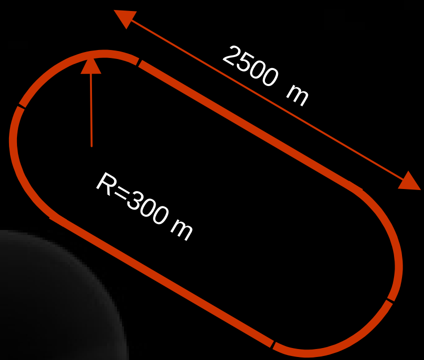
CERN is the only place with the complete Beta Beam know-how:

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

The Acceleration principle

ISOL target → ECR source → Linac 20 MeV/u → Accumulator >~300 MeV/u → PS-21 → SPS 150 GeV/u → Decay ring and compressor

Bunch rotation is the crucial issue for atmospheric background control!



Physics reference numbers:

65%Transmittance into the decay ring
Γ=150 for ^{6}He
Acceleration cycle into the storage ring: 8s

The SuperBeam - BetaBeam synergy

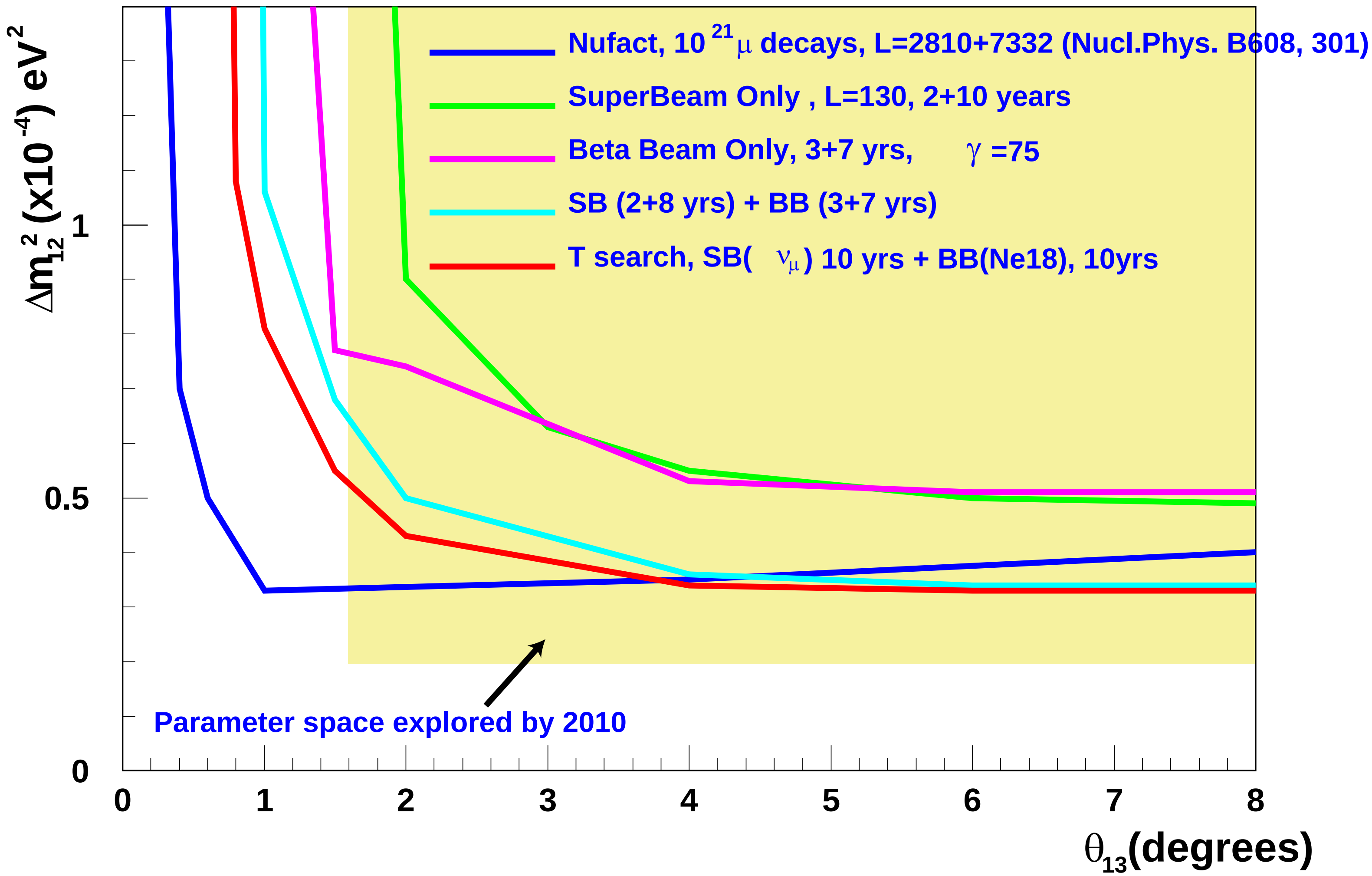
The idea behind is to run two neutrino beams to the same detector at the same time: SPL SuperBeam + Beta Beam.

Both beams need SPL, but the BetaBeam requires only 0.6% of the SPL protons $\longrightarrow$ the two beams can run together.

Both beams produce sub-GeV neutrinos $\longrightarrow$ same baseline and same detector.

- A CP search using SuperBeam running with ν_μ and $\overline{\nu}_\mu$.
- A CP search with Beta Beam running with ^{6}He ($\overline{\nu}_e$) and ^{18}Ne (ν_e).
- Two T searches combining Super Beam neutrinos ($\nu_\mu \longrightarrow \nu_e$) with Beta Beam ^{18}Ne ($\nu_e \longrightarrow \nu_\mu$) and Super Beam antineutrinos ($\overline{\nu}_\mu \longrightarrow \overline{\nu}_e$) with Beta Beam ^{6}He ($\overline{\nu}_e \longrightarrow \overline{\nu}_\mu$).
- A final powerful combination of the CP and the T searches, with redundant physical information and several cross-checks of systematics.
- The most powerful combination would be however a single T search with neutrinos (SuperBeam ν_μ with BetaBeam ν_e).

A comparison of CP sensitivities.



A comparison of neutrino beam intensities

The comparison of neutrino beam intensities is not a trivial task as far as concerns neutrino oscillation experiments.

The optimal baseline to detect sub leading $\nu_\mu \rightarrow \nu_e$ transitions, is $L_{\rm eff} = \frac{\pi}{2} \frac{E_\nu}{1.27 \Delta m^2_{atm}}$.

Beam intensities $CC_{\rm eff}$ (ν CC/kton/yr) are then compared at this optimal baseline $L_{\rm eff}$.

Beam	$\langle E_\nu \rangle$ (GeV)	Flux $(\nu/m^2/\mathrm{yr})$	L (km)	CC ν/kton/yr	$L_{\rm eff}$ (km)	CC$_{\rm eff}$ ν/kton/yr	Ratio
K2K	1.3	$3.9 \cdot 10^9$	250	2	643	0.3	0.02
NuMi(High E)	16	$4.9 \cdot 10^{11}$	730	3100	7916	26.4	1.5
NuMi(Low E)	4	$3.0 \cdot 10^{11}$	730	469	1979	63.8	3.7
CNGS	17.7	$3.5 \cdot 10^{11}$	732	2448	8757	17.1	1.0
JHF (Phase I)	0.7	$1.9 \cdot 10^{11}$	295	95.2	346	69.1	4.0
SPL SuperBeam	0.26	$2.5 \cdot 10^{11}$	130	16.3	129	16.6	1.0
νF^*	30	$2.4 \cdot 10^{12}$	3000	17694	14842	723	42.3
BetaBeam**	0.58	$1.2 \cdot 10^{12}$	130	84	287	17.2	1.0

(*) $E_\mu = 50\ GeV$, $0.2 \cdot 10^{21}$ μ decays/yr, computed for ν_e .

(**) $\gamma = 150$, ^6He ($\overline{\nu}_e$).