Neutrino Oscillations

Neutrino oscillations depend from

- 3 mixing angles, $\theta_{12}, \theta_{23}, \theta_{13}$
- 2 mass differences: Δm^2_{12}, Δm^2_{23}
- 1 CP phase δ

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_3 \\ \nu_3 \end{pmatrix}$$

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

In vacuum:

$$P(\nu_\alpha \rightarrow \nu_\beta) = -4 \sum_{k>j} Re[W^{jk}_{\alpha\beta}] \sin^2 \frac{\Delta m^2_{jk} L}{4E_\nu} \pm 2 \sum_{k>j} Im[W^{jk}_{\alpha\beta}] \sin^2 \frac{\Delta m^2_{jk} L}{2E_\nu}$$

$$\alpha = e, \mu, \tau$$
$$j = 1, 2, 3$$
$$W^{jk}_{\alpha\beta} = U_{\alpha j} U^*_{\beta j} U^*_{\alpha k} U_{\beta k}$$

$$2\,\text{neutrinos} : \quad P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \cdot \sin^2 \left(1.27 \Delta m^2_{\alpha\beta}[eV^2] L[km]/E[GeV]\right)$$

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

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

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

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

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

If you are skeptical about that ....

Experimental articles with more than 500 cites in the last 15 years in the QSPIRES database (at 04/04/03):

1	SK	Evidence for Oscillation of Atmospheric Neutrinos.	1705
2	SCP	Measurements of Ω and Λ from 42 High Redshift SN.	1311
3	SST	Observational Evidence from SuperNovae for an Accelerating Universe and a Cosmological Constant.	1293
4	COBE	Structure in the COBE DMR First Year Maps.	1036
5	CDF	Observation of TOP Quark Production in $\overline{p} - p$ Collisions.	930
6	D0	Observation of the Top Quark.	889
7	SK	Atmospheric ν_μ / ν_e Ratio in the MultiGeV Energy Range.	751
8	Chooz	Initial Results from CHOOZ.	683
9	Boomerang	A Flat Universe from High Resolution Maps of the CMB.	644
10	Chooz	Limits on Neutrino Oscillations from the CHOOZ Experiment.	635
11	Kamiokande	Observation of a Small Atmospheric ν_μ / ν_e Ratio.	628
12	CLEO	First Measurement of the Rate for the Inclusive $b \rightarrow s\gamma$.	618
13	SNO	Measurement of the rate of ν_e + d –> p + p + e- ...	592
14	Homestake	Measurement of the Solar ν_e Flux ...	565
15	LSND	Evidence for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ Oscillations from LSND.	563
16	SK	Measurement of a Small Atmospheric ν_μ / ν_e Ratio.	561
17	CDF	Evidence for TOP Quark Production in $\overline{p} - p$	550
18	SK	Study of the Atm. ν Flux in the MultiGeV Energy Range.	547
19	IMB	The ν_e and ν_μ Content of the Atmospheric Flux.	535
20	SK	Solar Neutrino Data Covering Solar Cycle 22.	504
21	LSND	Neutrino Oscillations from LSND.	500

Most of the parameters are waiting to be measured

δm^2_{12} ✔ — SOLARS+KAMLAND: $5\,10^{-5} < \delta m^2_{12} < 3\,10^{-4}\,eV^2$

θ_{12} ✔ — SOLARS+KAMLAND: $0.2 < \sin^2(\theta_{12}) < 0.5$

Addressed by a SuperBeam/Nufact experiment

δm^2_{23} ✔ — ATMOSPHERICS: $\delta m^2_{23} = 2.6 \pm 0.4\ eV^2$

θ_{23} ✔ — ATMOSPHERICS: $0.9 < \sin^2 2(\theta_{23}) < 1$

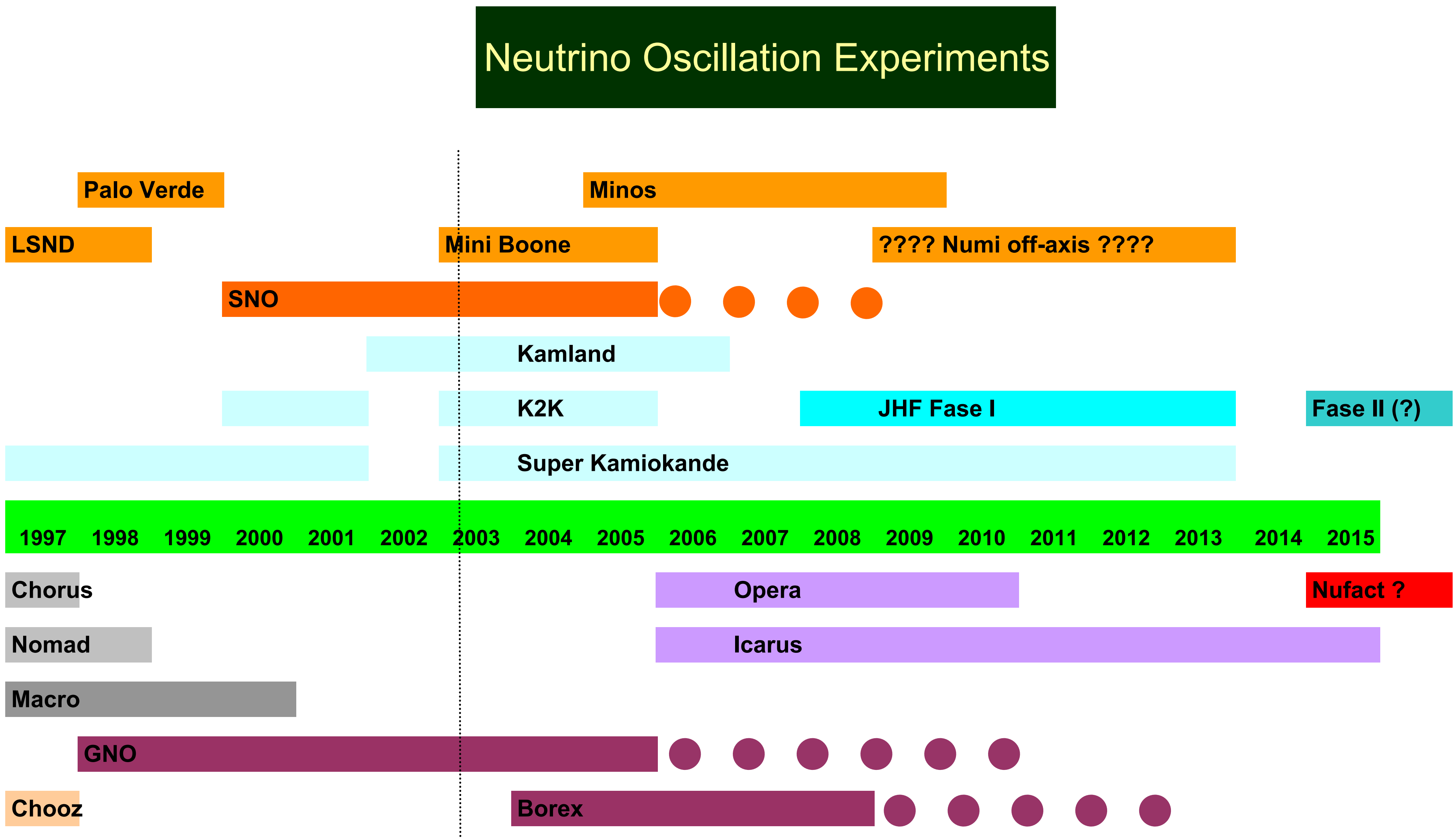
θ_{13} ☐ — CHOOZ LIMIT: $\theta_{13} < 14^0$

δ_{CP} ☐

Mass hierarchy ☐

Σm_ν ☐ — BETA DECAY END POINT: $\Sigma m_\nu < 6.6$ eV

Dirac/Majorana ☐



Neutrino Oscillation Experiments
Palo Verde
Minos
LSND
Mini Boone
???? Numi off-axis ????
SNO
Kamland
K2K
JHF Fase I
Fase II (?)
Super Kamiokande
1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015
Chorus
Opera
Nufact ?
Nomad
Icarus
Macro
GNO
Chooz
Borex

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!)

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

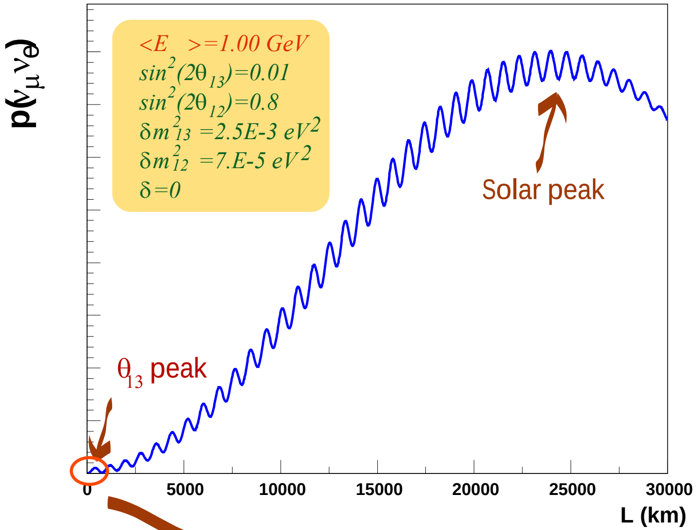
$\theta_{13} \rightarrow 0 \quad \Rightarrow$ The 3x3 matrix is a trivial product of two 2x2 matrixes.

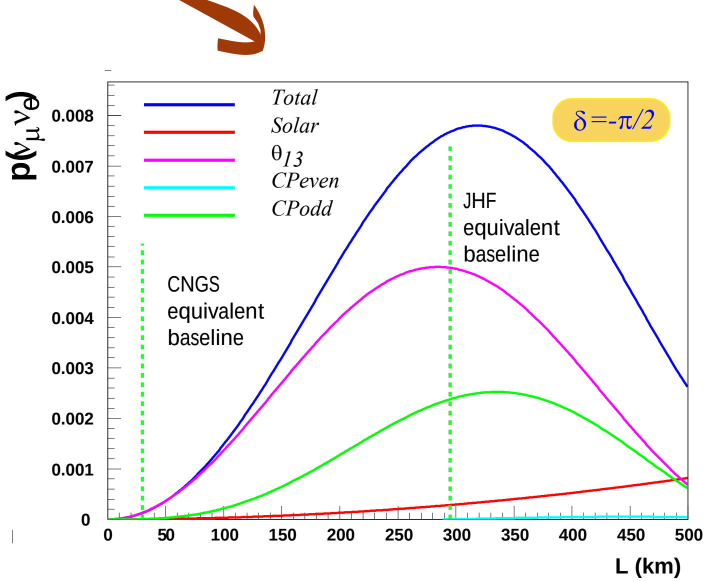
θ_{13} drives $\nu_\mu \rightarrow \nu_e$ subleading transitions $\Rightarrow$

the necessary milestone for any subsequent search:

neutrino mass hierarchy and leptonic CP searches.

Subleading $\nu_\mu - \nu_e$ oscillations





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

$$p(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\frac{\Delta m_{13}^2 L}{4E} \qquad \theta_{13} \text{ driven}$$

$$+ 8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\frac{\Delta m_{23}^2 L}{4E}\sin\frac{\Delta m_{13}^2 L}{4E}\sin\frac{\Delta m_{12}^2 L}{4E} \quad \text{CPeven}$$

$$- 8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\frac{\Delta m_{23}^2 L}{4E}\sin\frac{\Delta m_{13}^2 L}{4E}\sin\frac{\Delta m_{12}^2 L}{4E} \qquad \text{CPodd}$$

$$+ 4s_{12}^2 c_{13}^2\{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta\}\sin\frac{\Delta m_{12}^2 L}{4E} \qquad \text{solar driven}$$

$$- 8c_{12}^2 s_{13}^2 s_{23}^2 \cos\frac{\Delta m_{23}^2 L}{4E}\sin\frac{\Delta m_{13}^2 L}{4E}\frac{aL}{4E}(1-2s_{13}^2) \qquad \text{matter effect (CP odd)}$$

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

The hunting for θ_{13}

- Possibilities of the next Long Baseline experiments.
- Possible experimental approaches.
- Proposals for new initiatives

Possible experimental approaches to θ_{13}, Part I

Long Baseline Experiments

Detect $\nu_\mu \rightarrow \nu_e$ transitions via ν_e appearance in a not so pure ν_μ beam.

Experimental backgrounds:

- Beam ν_e contamination ($\sim 0.5\%$)
- π° production in NC ν_μ interactions.
- $\nu_\mu \rightarrow \nu_\tau \rightarrow \tau \rightarrow e^- \overline{\nu}_e \, \nu_\tau$
  (N.B. ν_τ production $\propto (\Delta m^2_{23})^2$, very difficult to normalize in absence of a precise measure of Δm^2_{23})

MINOS

Twice the Chooz sensitivity, limited by the coarse granularity of the detector and by the systematics.

ICARUS

Five times the Chooz sensitivity in 8 years of data taking with a 3 kton detector. Computed neglecting systematic errors (but no close detector in the CNGS beam).

Upgrade CHOOZ

(Mikaelyan et al. `hep-ph/0109277`, D. Nicoló at NO-VE 2001)

The cleanest approach to θ_{13} is

$p(\nu_e \rightarrow \nu_e) \propto 1 - \sin^2 2\theta_{13} \, \sin^2 \frac{\Delta m^2_{atm} L}{4E}$,

not influenced by δ or MSW effects.

Chooz can be improved by a factor 5 if:

- Use a detector as big as 10$\times$ the Chooz detector.
- Use a close detector, to be placed underground $\Rightarrow$ $\sigma_{sys} \simeq 0.5\%$
- Measure backgrounds at reactor off $\Rightarrow$ $\sigma_{stat} \simeq 0.5\%$

Possible experimental approaches to θ_{13}, Part II

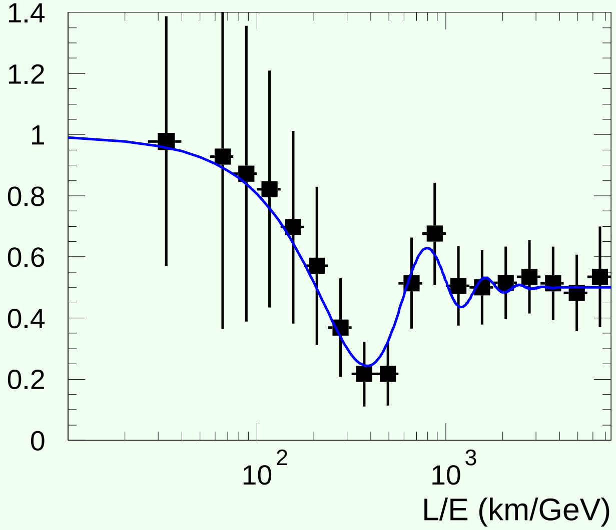
Atmospheric Neutrino MSW resonance in the Earth

(Bernabeu et al. hep-ph/0102184, Monolith internal notes)

The resonance is described by

- $E_R = \pm \cos 2\theta_{13} \frac{\Delta m^2_{13}}{2\sqrt{2} G_F N_e}$
- $\Gamma_R = 2 \sin 2\theta_{13} \frac{\Delta m^2_{13}}{2\sqrt{2} G_F N_e}$.

This latter can measure θ_{13} , having a detector with a good L/E resolution, as for instance Monolith.



200 kton/year $\Rightarrow$ 2$\times$ Chooz

400 kton/year $\Rightarrow$ 4$\times$ Chooz (scales with $\sin 2\theta_{13}$)

SuperNovae neutrinos MSW in the Earth

(Smirnov-Lunardini. hep-ph/01006149)

Three big Supernovae detectors are running: SK, SNO, LVD in three different contintents.

In case of a galactic (~ 10 Mpc) SuperNova explosion, it's very likely that one detector can measure the SN neutrino spectrum undistorted, while another can measure the ν after they have crossed the Earth's Core. **The first one normalizes the spectrum, the second can directly measure the MSW distortion to the spectrum.**

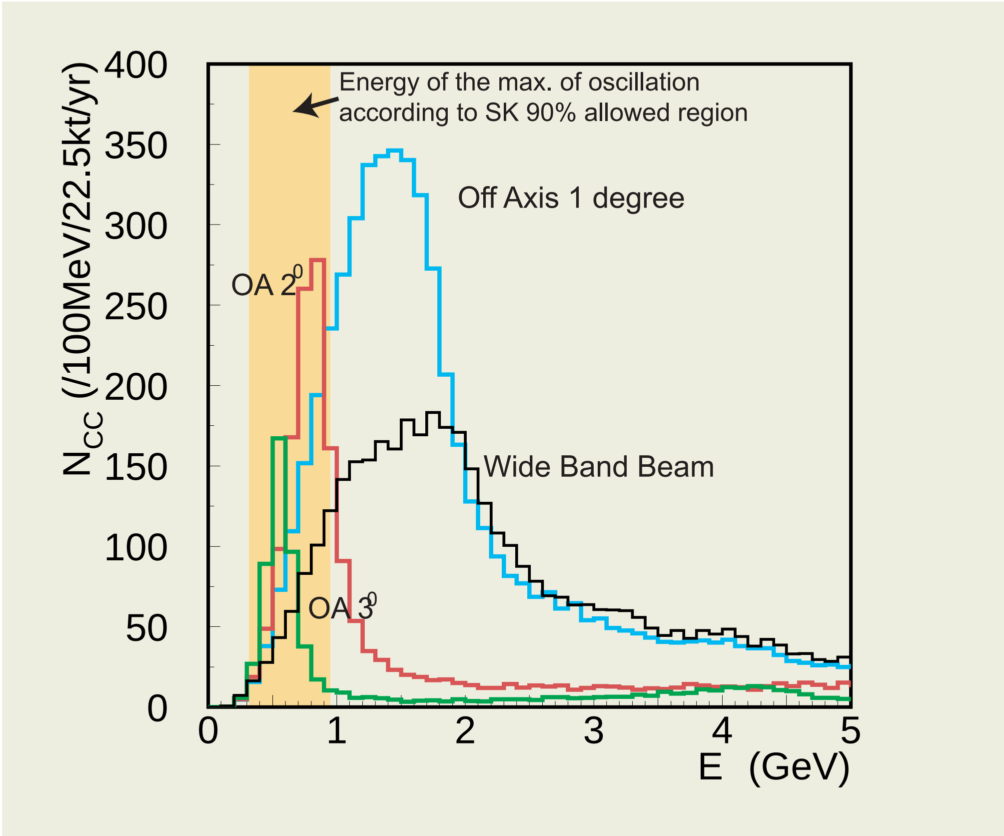
Model independent measurement of sign(Δm^2_{12}) at 2-3 σ and a verification that $\sin^2 2\theta_{13} \geq 10^{-5}$ (otherwhile the transition cannot happen).

JHF-Japan Hadron Facility at Jaeri

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

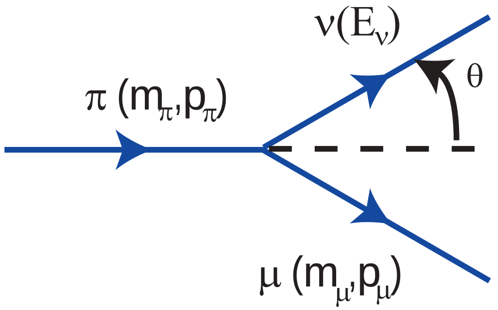
Taken off-axis to better match the oscillation maximum at the SuperKamiokande location (295 km).

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



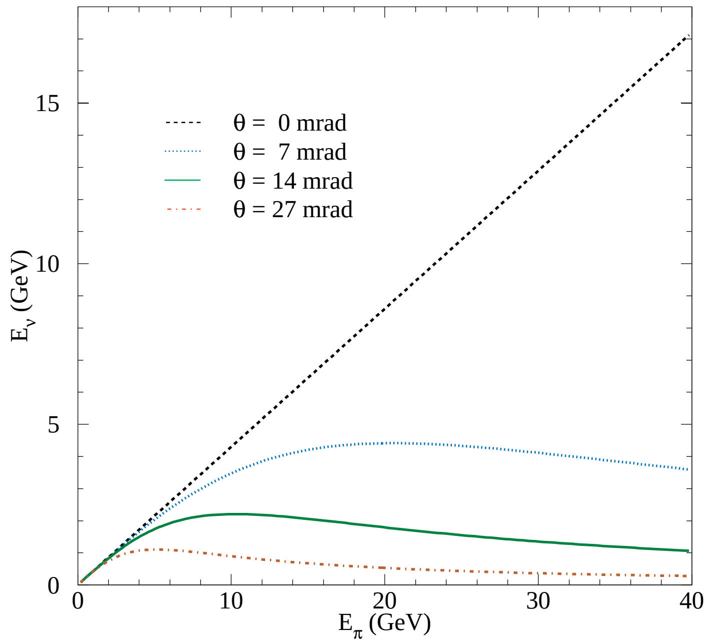
Off Axis Neutrino Beams. BNL-E889 proposal: http://minos.phy.bnl.gov/nwg/papers/E889

Decay Kinematics

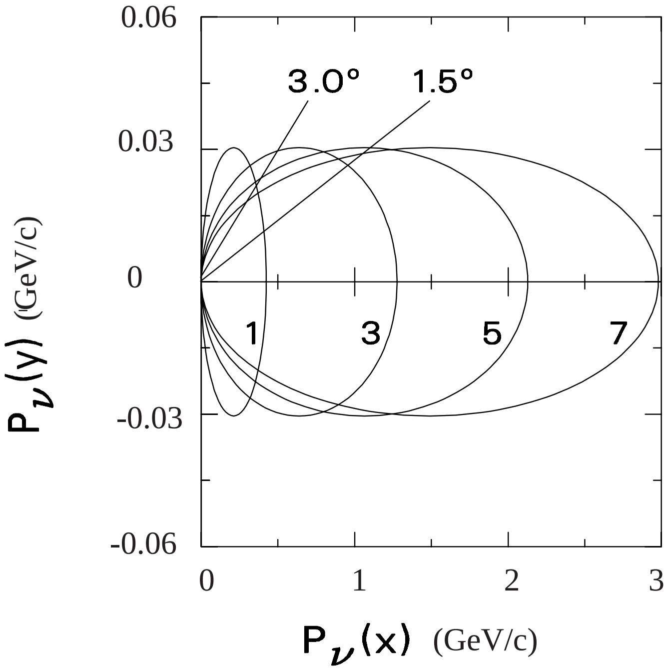


From momentum energy conservation:

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi cos\theta)}$$



A qualitative argument:



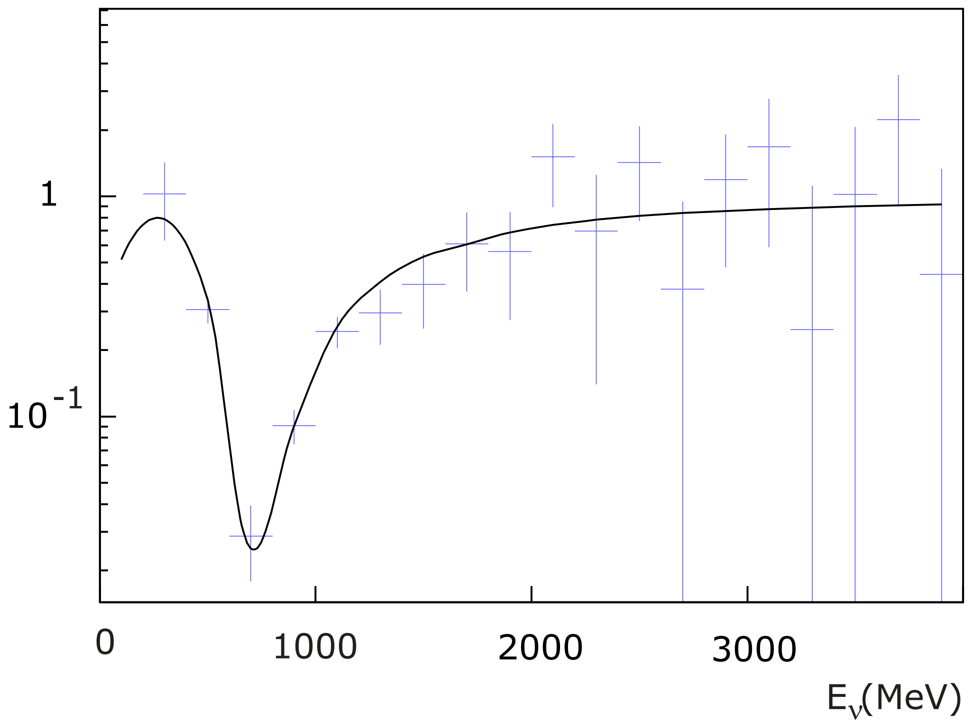
- Transverse momentum, Lorentz invariant: $m_\pi - m_\mu$.
- Longitudinal momentum is Lorentz boosted.
- At an angle θ there is an accumulation of lower energies neutrinos

- **Maximum neutrino flux at $0°$.**
- **Off axis is the most efficient way to have a narrow band beam.**
- ν_e **come from 3 body decays (kaons or muons) while off-axis is optimized on the pion 2 body decay$\Rightarrow$ the** ν_e **contamination below the peak is reduced.**

JHF (continued)

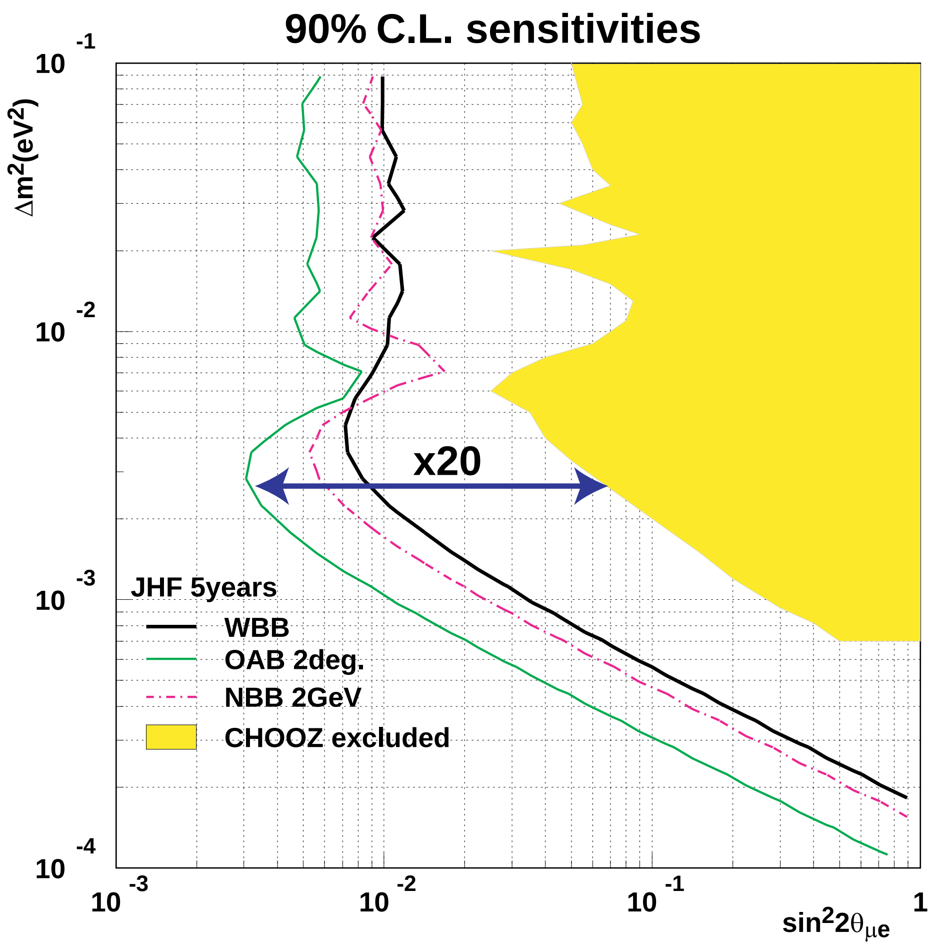
Precision measure of the atmospheric parameters:

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



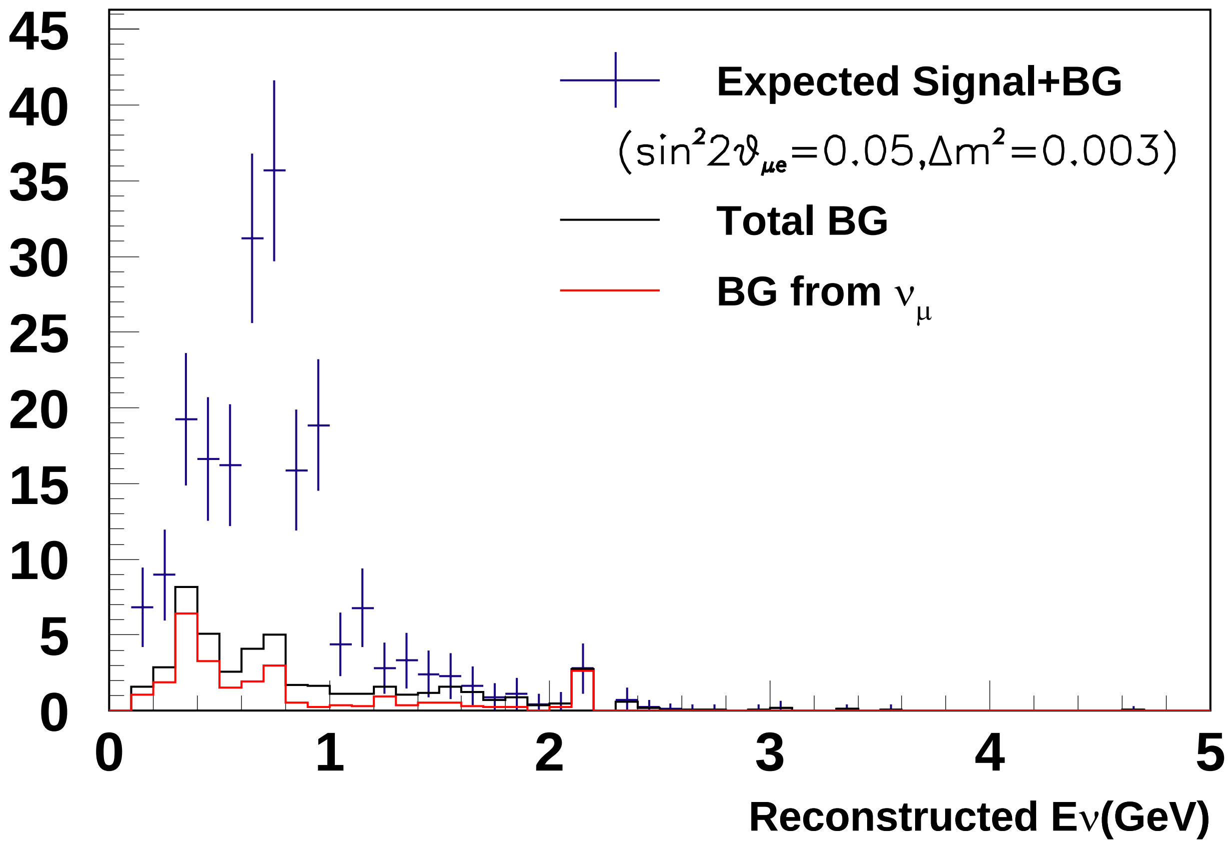
Ratio of the measured ν_μ spectrum with respect to the non-oscillation prediction in case of oscillation (5 years).

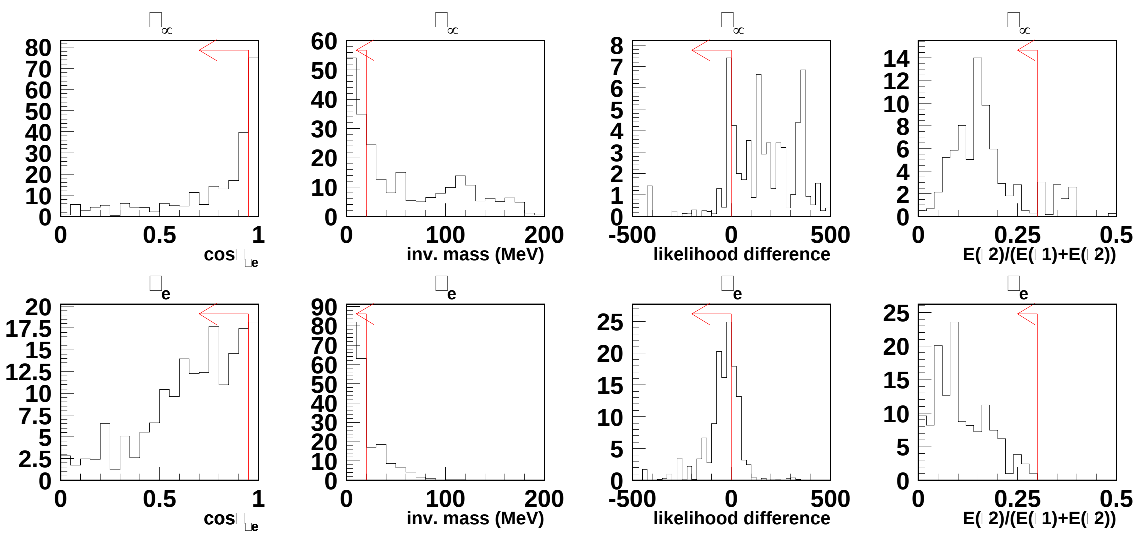
Sensitivity to θ_{13}



5 ears $\delta m^2 = 3 \times 10^{\ 3}$ e ^{2} and $\sin^2 2\theta_{\mu e} = 0.05$

2	ν_μ C C	ν_μ C	eam ν_e	scillated ν_e
1) enerated in F	10713 6	4080 3	292 1	301 6
2) 1 e li e	14 3	247 1	68 4	203 7
3) e π^0 se aration	3 5	23 0	21 9	152 2
4) 0 4 e $E_{\ ec}$ 1.2 e	1 8	9 3	11 1	123 2





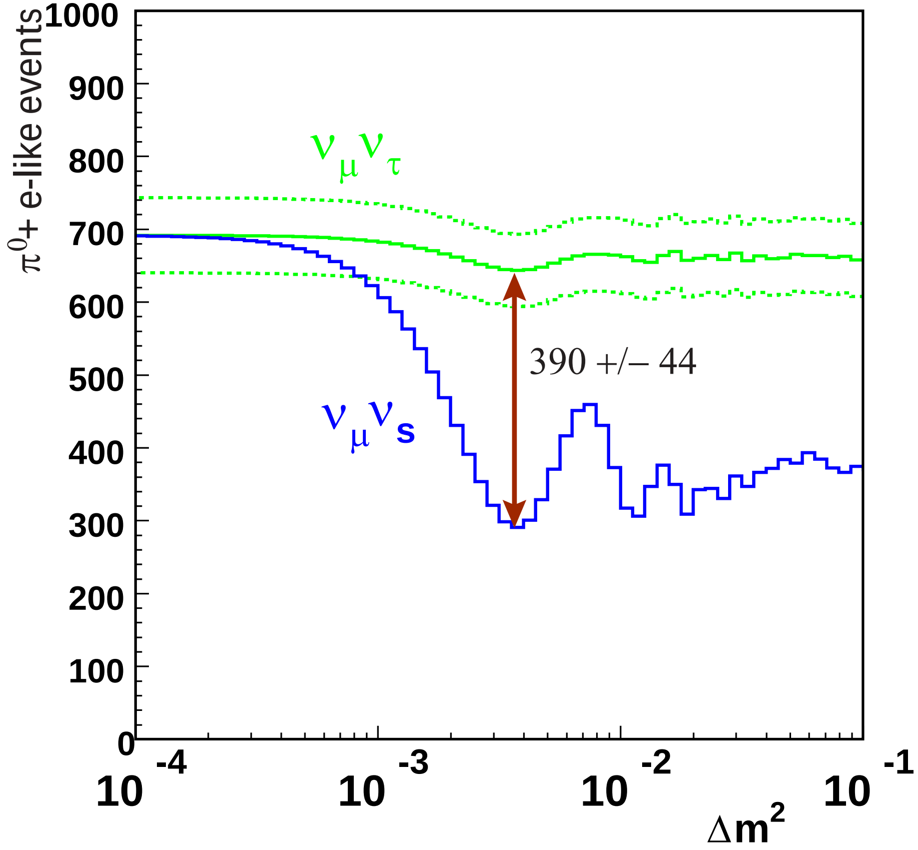
Fi ure 9: istri tions o t e an tities sed in t e $e/\ ^0$ separation e eam is t e o 2 de ree eam and events are a ter t e sin le rin e li e selection pper isto rams corresponds to $_\mu$ ac ro nds events and t e lo er isto rams correspond to t e $_e$ si nal events e arro s in t e re s o t e c t positions sed in t e anal sis

Separazione $\nu_\tau - \nu_{\rm sterili}$

Tag delle correnti neutre con i π° (metodo Vissani-Smirnov), usato anche in SK ($\nu + N \to \nu + N + \pi^\circ$)

Le sistematiche sulla sezione d'urto di produzione risonante di π° in eventi di NC verranno fortemente ridotte dal close detector di K2K e dai close detectors di JHF.

Limite alla frazione di ν_s a circa 0.1 (90% CL).



What about Numi and CNGS off-axis?

NuMi off-axis (LoI of 05/06/2002)

- Use NuMi Medium Energy beam
- Place a detector at ~ 730 km, 9 km off-axis (0.7°), that means NOT deep underground.
- The far detector is not yet well specified however it should be:
  - 20 kton, fiducial = 85% of total.
  - Good π° rejection in the 1-3 GeV energy range (π° bacground must be reduced below the level of beam ν_e contamination)
  - Cost below 100 M$
  - Ready in 2008 (the JHF clock!)

Under these conditions it could have a θ_{13} sensitivity similar to JHF.

CNGS off-axis (Dydak's talk at Neutrino 2002)

- Modify the CNGS in order to have a mean energy of 3.5 GeV (renouncing to any tau appearance experiment at LNGS or waiting for 2011).
- Place a detector underwater, off-axis, in the Gulf of Taranto, in TWO positions corresponding to the SECOND oscillation maximum and minimum.
- The detector should be made by 4000 PMTS, in a grid of 6m side, equipping a cone of 1 Mton of water (radius 110m, height 25 m).
- With a coverage of 2% of the surface (SK has 40%) it should reduce the π° background to less than 1% of the ν_μ^{CC} (SK has 2.5% of π° with not optimized algorithms).
- It should cost 100 M$ (???)
- It should be ready in 2008 to compete with JHF

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.

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.

Are CP-odd effects detectable?

$$A_{CP} = \frac{P(\overline{\nu}_e \to \overline{\nu}_\mu) - P(\nu_e \to \nu_\mu)}{P(\overline{\nu}_e \to \overline{\nu}_\mu) + P(\nu_e \to \nu_\mu)} \simeq \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \cdot \sin \delta \cdot \sin \frac{\Delta m^2_{12} L}{4E}$$

A_{CP} vanishes in the limit $\Delta m^2_{12} \to 0$

$$A_{CP} \propto \sin 2\theta_{12}$$

Only the solar LMA solution allows a detectable Δ_{CP}

Latest SNO results are very much in favor of LMA, but the final worlds will come from the Kamland experiment, that's running.

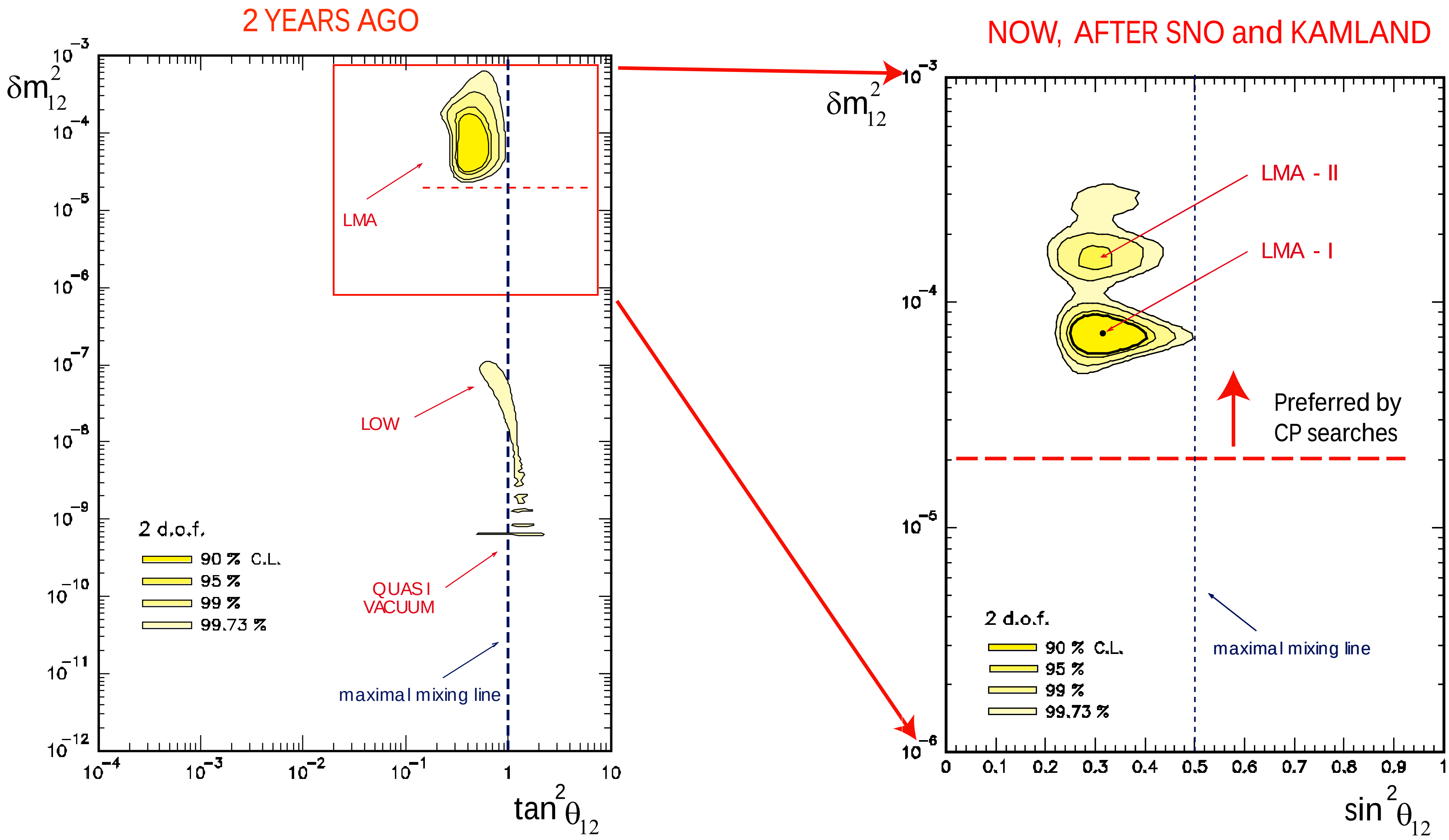
LSND scenario: CP violation arises from interference between:

- LSND frequency $\sim 0.3 \, \text{to} \, 2 \, eV^2$.
- Atmospheric frequency $\sim 3 \cdot 10^{-3} \, eV^2$.

Amplitudes comparable at atmospheric baseline

Near 100% CP asymmetry is possible

The delightful news from solar neutrino experiments



δ and θ_{13} interplay.

$P(\nu_\mu \to \nu_e) \propto \sin^2 2\theta_{13}$ $\quad A_{CP} \propto \frac{1}{\sin\theta_{13}}$

$\Downarrow$

$\sin^2 2\theta_{13} \leq 10^{-3}$ $\Rightarrow$ practically impossible to detect CP through $\nu_\mu \to \nu_e$ transitions (see later).

$\sin^2 2\theta_{13}$ small $\Rightarrow$ small statistics but big asymmetry.

$\sin^2 2\theta_{13}$ big $\Rightarrow$ high statistics but small asymmetry

$\Downarrow$

The two effects tend to balance BUT detector requirements are very different in the two cases: high mass and reduced resolution against "small" mass but high resolution.

Very risky to start a CP search without knowing the real value of θ_{13}, certainly without knowing that $\sin^2 2\theta_{13} \geq 10^{-3}$

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

To detect $\nu_\mu \to \nu_e$ transitions with high sensitivity are needed:

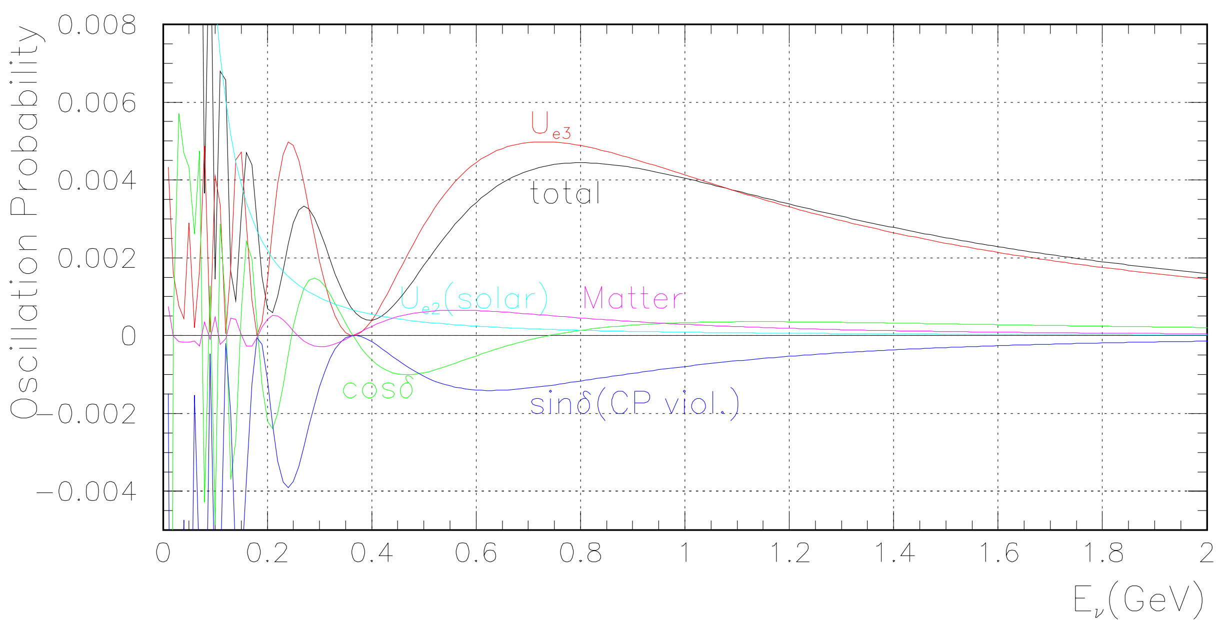
Very clean neutrino beams.

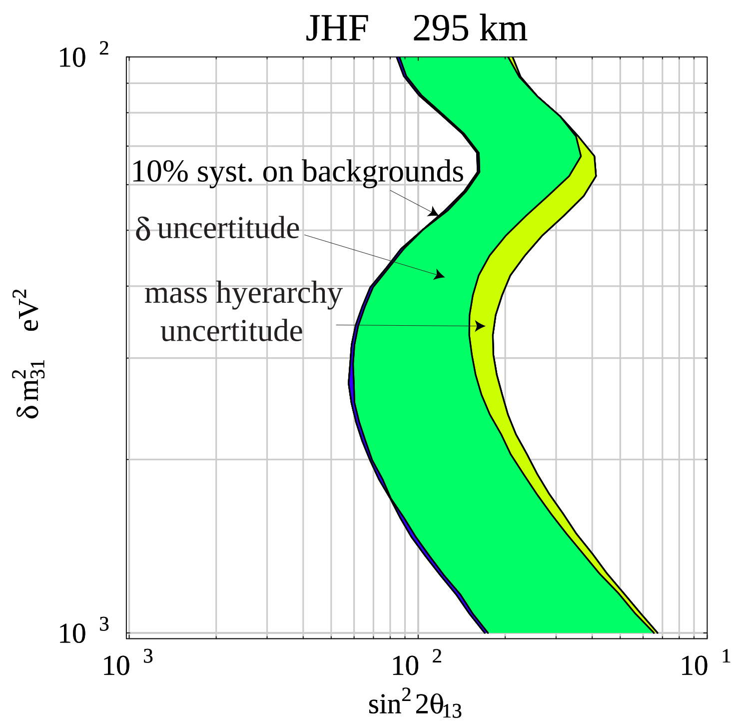
Very intense neutrino beams:
The CNGS beam intensity is about two orders of magnitude smaller to what needed to run a CP search at the appropriate baseline ($\sim 8000\,km$) with enough statistics in a 50 kton detector.

δ and θ_{13} interplay (II).

On the other hand any θ_{13} experiment not sensitive to CP can see the effect but cannot precisely measure θ_{13} .

Contributes to $p(\nu_e \rightarrow \nu_\mu)$ in the case of the JHF experiment, from `hep-ex/0106019`



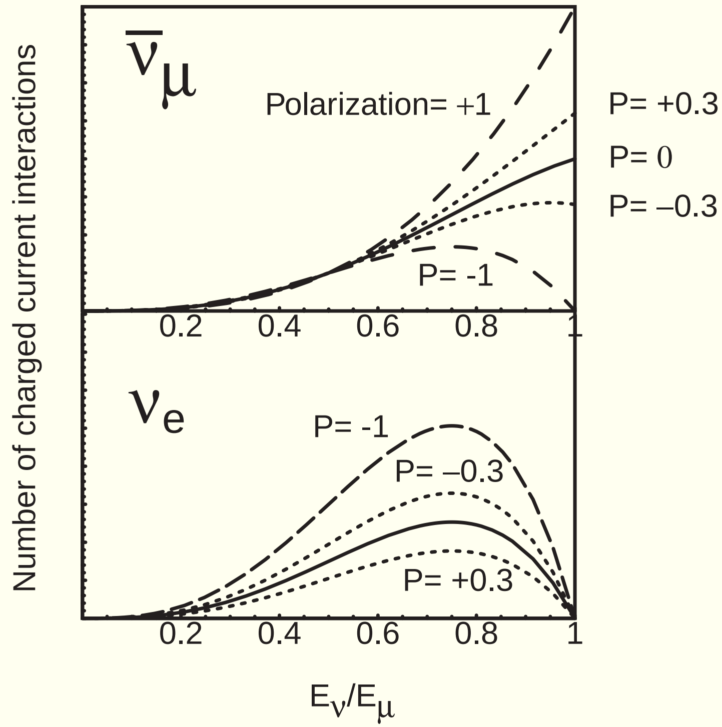


Neutrino Factories

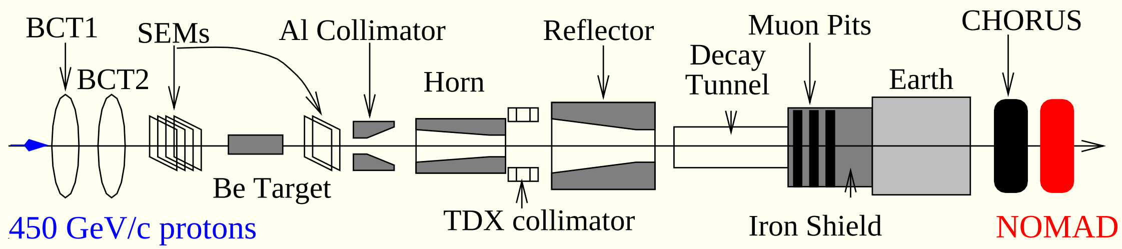
- The dream beam of every neutrino physicist.
- The first case in which the whole neutrino production chain, including proton acceleration, is accounted on the budget of the neutrino beam construction.
- Oscillated events N_{osc} at a distance L:

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

  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 ($\overline{\nu}_e$ ν_μ or ν_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.**



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.

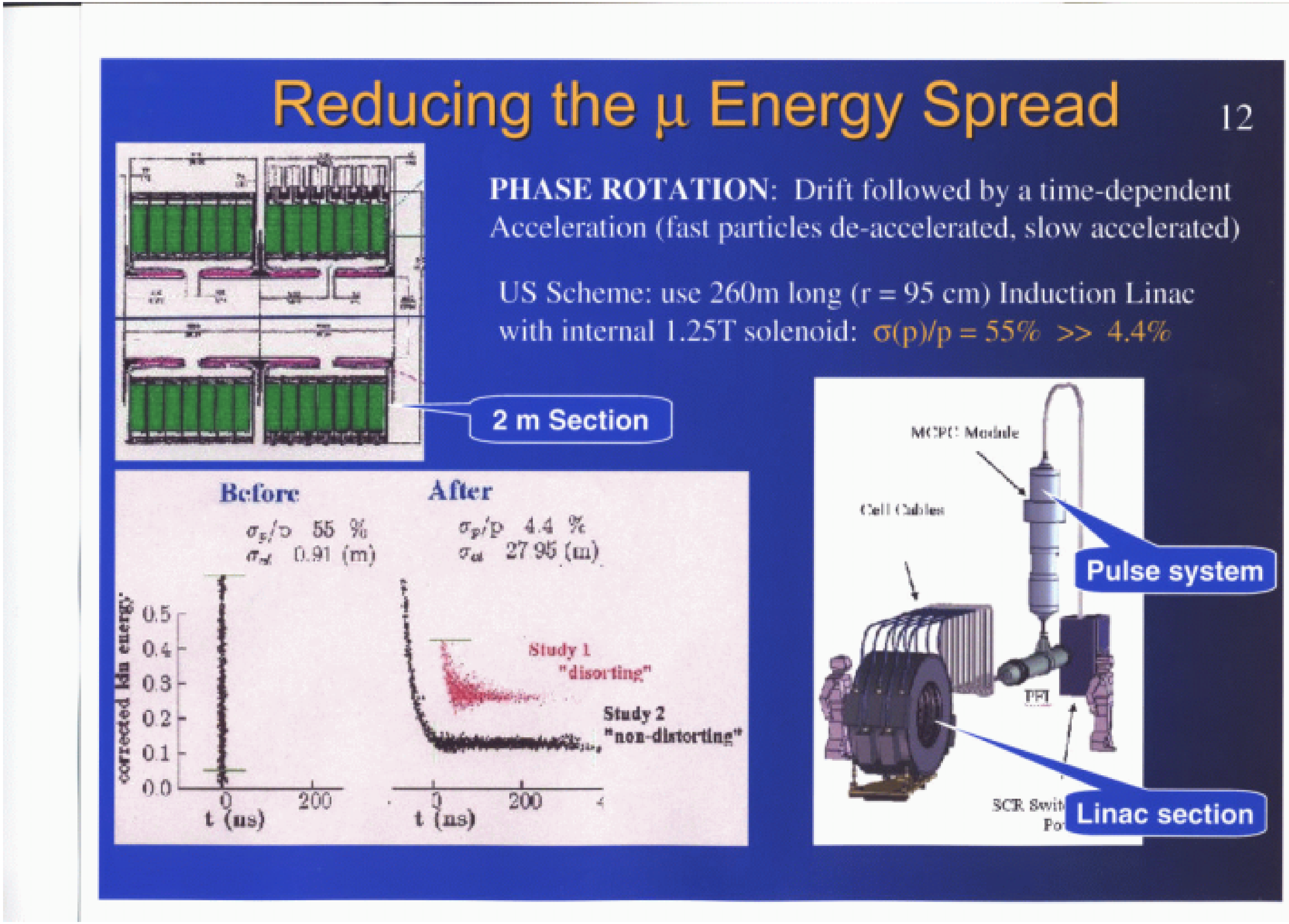
Much more efficient way to produce neutrinos BUT a real challenge to accelerate, in a very short time, particles generated with a large emittance .

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


Reducing the μ Energy Spread
12
PHASE ROTATION: Drift followed by a time-dependent Acceleration (fast particles de-accelerated, slow accelerated)
US Scheme: use 260m long (r = 95 cm) Induction Linac with internal 1.25T solenoid: σ(p)/p = 55% >> 4.4%
2 m Section
Before
After
Study 1 "disorting"
Study 2 "non-distorting"
t (ns)
corrected kin energy
MCPC Module
Cell Cables
Pulse system
Linac section

Reducing the Transverse Phase Space 13

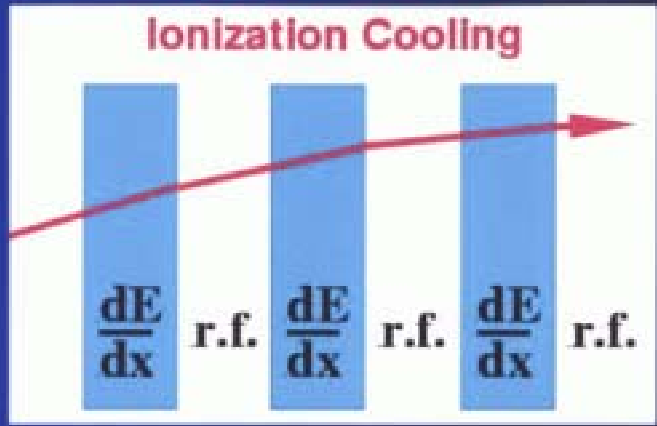
Transverse phase space too large to fit within normal accelerator

Must "cool" the beam fast – Before muons decay

Electron cooling & stochastic Cooling too slow
>> USE IONIZATION COOLING

An ionization cooling channel Can be thought of as a LINAC Filled with material

Need high gradient RF to keep the muons captured



Coulomb scattering tries to heat beam

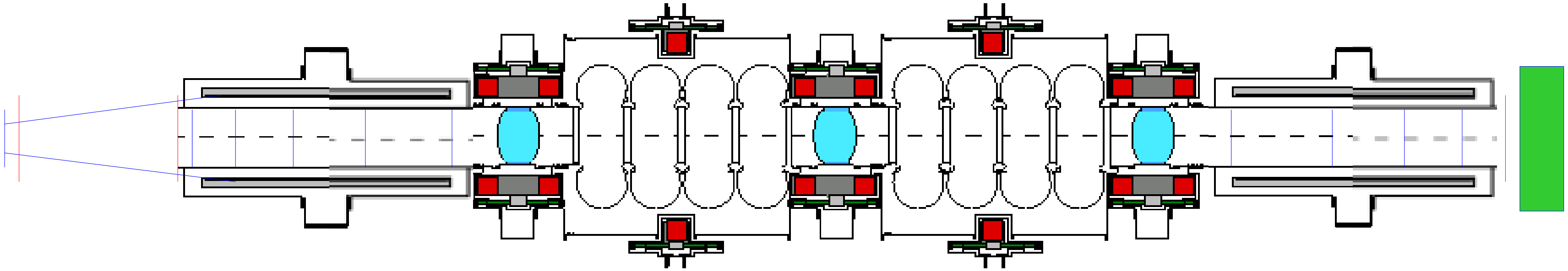
Use Liquid Hydrogen absorbers

Use strong radial focusing
>> high field solenoid channel

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**

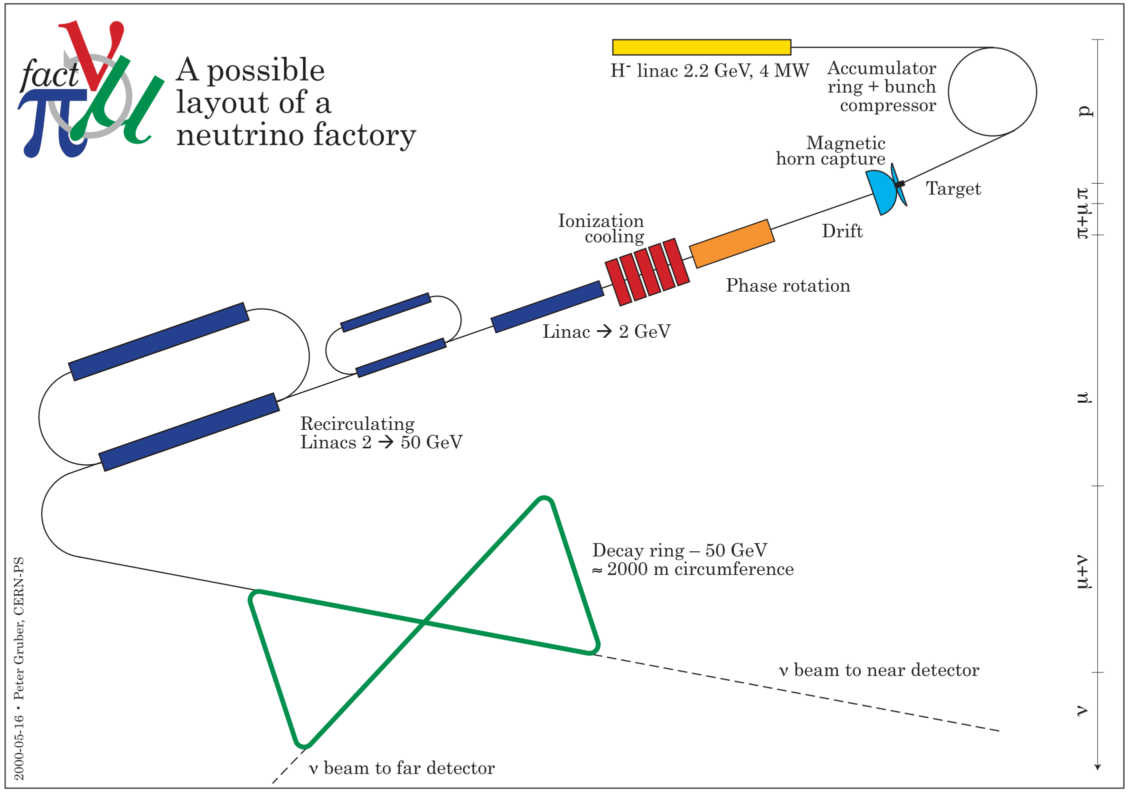
Edgecock

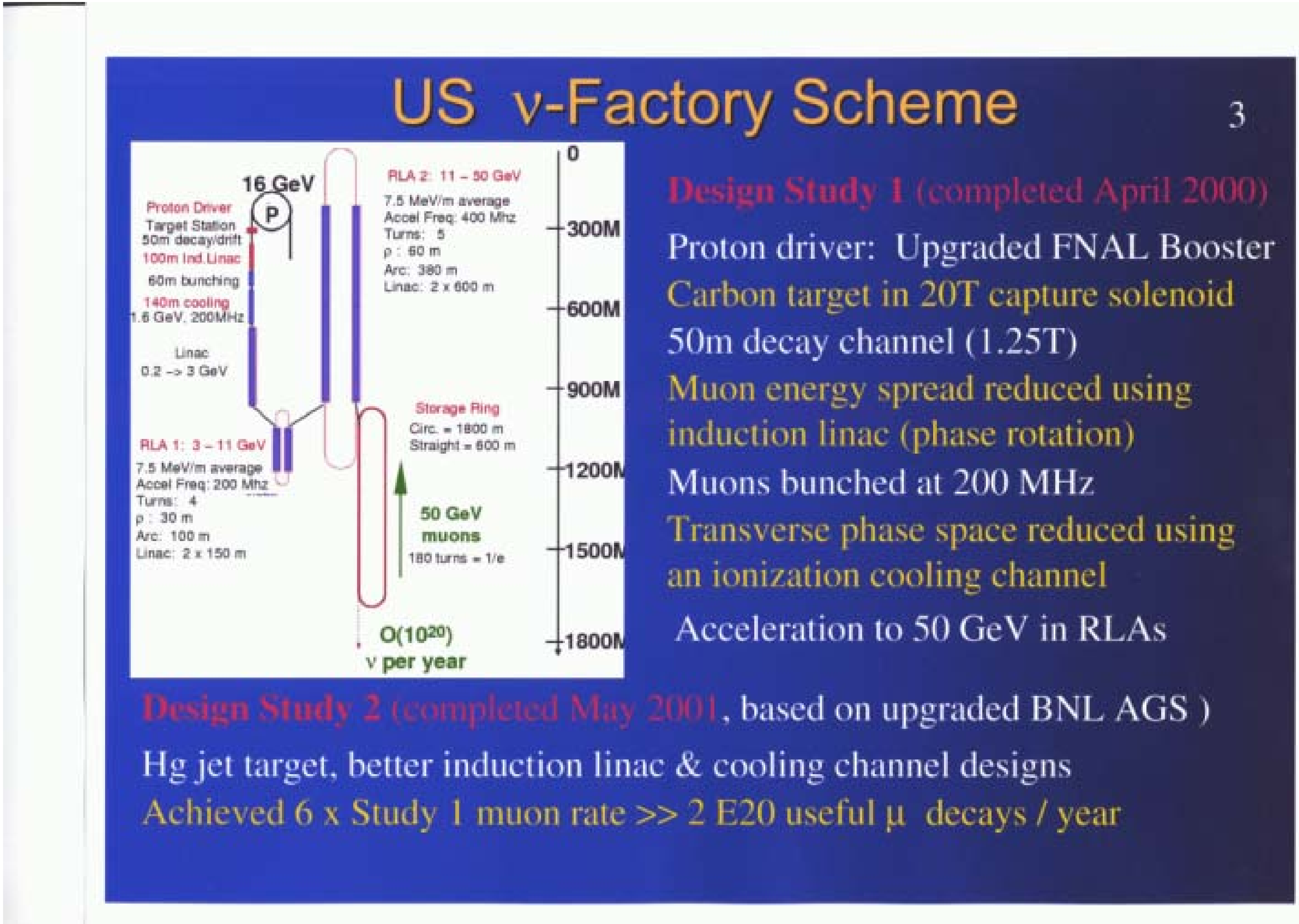


- **Construction: 2002-2004**
- **First beam: 2004/5**
- **New collaborators welcome!**

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

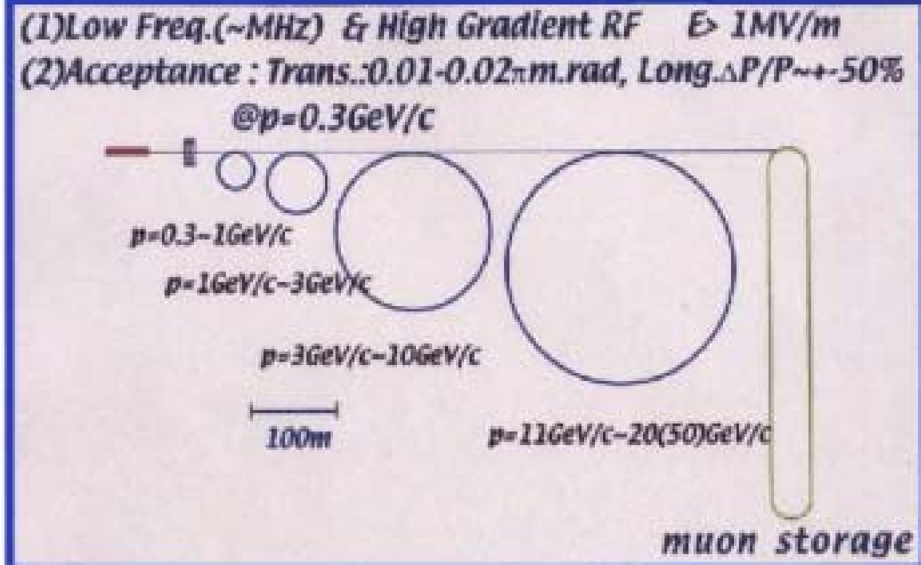
- High power (4 MW) proton beam onto a liquid mercury target.
- System for collection of the produced pions and their decay products, the muons.
- Energy spread and transverse emittance have to be reduced: "phase rotation" and ionization cooling
- Acceleration of the muon beam with a LINAC and Recirculating 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: $\geq 10^{20}$ μ decays per straight section per year**




US ν-Factory Scheme
3
16 GeV
Proton Driver
P
Target Station
50m decay/drift
100m Ind.Linac
60m bunching
140m cooling
1.6 GeV, 200MHz
Linac
0.2 -> 3 GeV
RLA 1: 3 – 11 GeV
7.5 MeV/m average
Accel Freq: 200 Mhz
Turns: 4
ρ : 30 m
Arc: 100 m
Linac: 2 x 150 m
RLA 2: 11 – 50 GeV
7.5 MeV/m average
Accel Freq: 400 Mhz
Turns: 5
ρ : 60 m
Arc: 380 m
Linac: 2 x 600 m
Storage Ring
Circ. = 1800 m
Straight = 600 m
50 GeV
muons
180 turns = 1/e
O(10^20)
ν per year
0
300M
600M
900M
1200M
1500M
1800M
Design Study 1 (completed April 2000)
Proton driver: Upgraded FNAL Booster
Carbon target in 20T capture solenoid
50m decay channel (1.25T)
Muon energy spread reduced using
induction linac (phase rotation)
Muons bunched at 200 MHz
Transverse phase space reduced using
an ionization cooling channel
Acceleration to 50 GeV in RLAs
Design Study 2 (completed May 2001, based on upgraded BNL AGS)
Hg jet target, better induction linac & cooling channel designs
Achieved 6 x Study 1 muon rate >> 2 E20 useful μ decays / year

Japanese ν-Factory Scheme

5



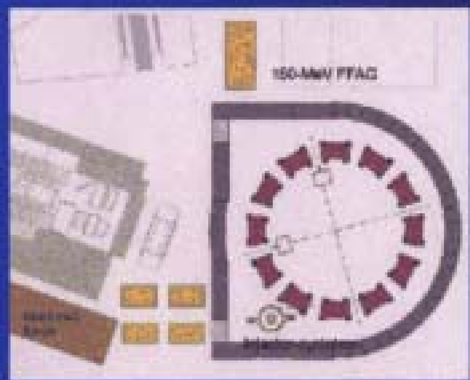
NO PHASE ROTATION OR COOLING
(would benefit from some cooling)

USE LARGE ACCEPTANCE ACCELERATORS - FFAGs

R&D Issues: RF, Injection/extraction, magnet design, dynamic aperture

GOAL: 1.E20 >> 4.4E20 USEFUL muon DECAYS / YEAR @ 20 GeV >> 50 GeV

Proof of Principle (POP) FFAG tested at KEK in June 2000



NEXT STEP
150 MeV FFAG
Under construction
At KEK

RF R&D: US/Japan collaboration

Detector

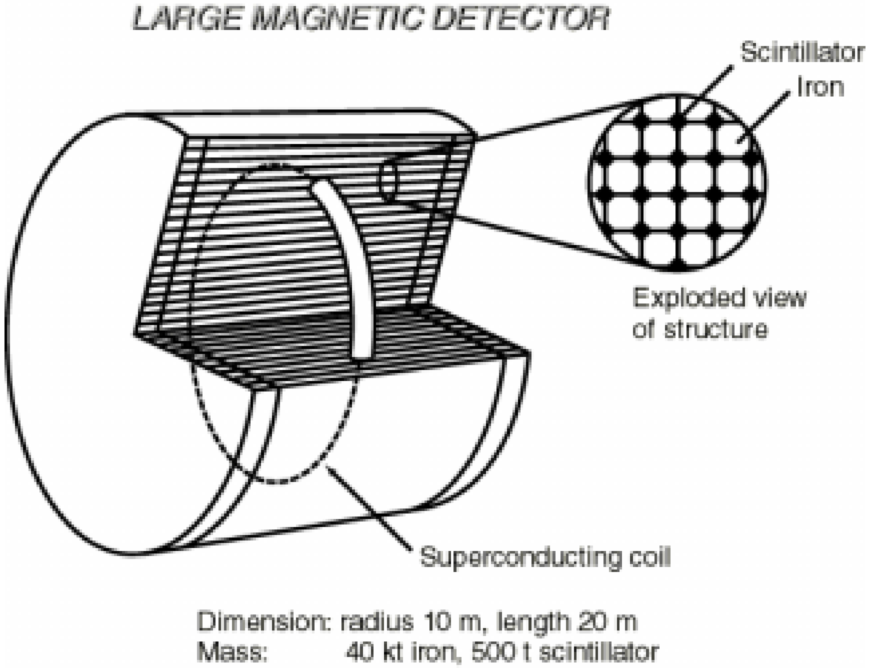
Iron calorimeter

Magnetized

- Charge discrimination
- B = 1 T

R = 10 m, L = 20 m

Fiducial mass = 40 kT



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

Events for 1 year

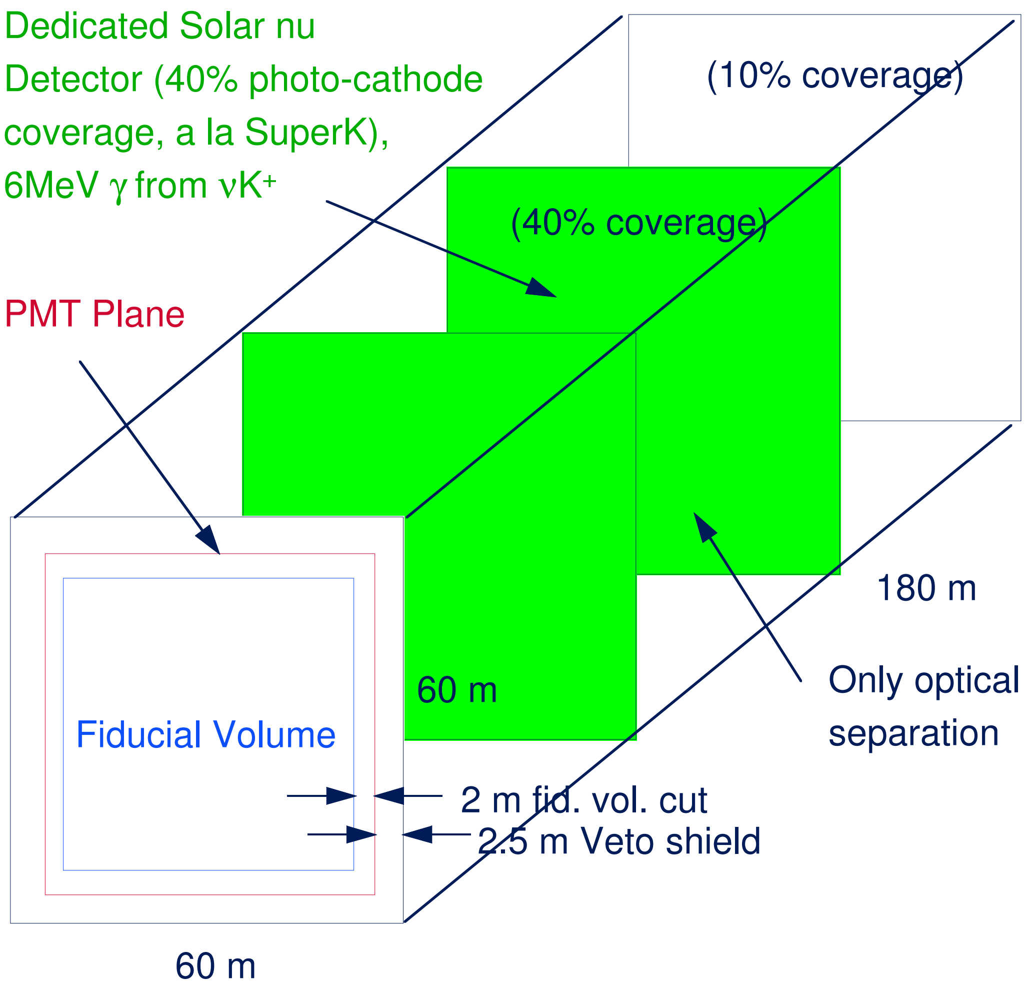
Baseline	‾ CC	$_e$ CC	signal $(\sin^2\ _{13}=0.01)$
732 Km	3.5×10^7	5.9×10^7	1.1×10^5
3500 Km	1.2×10^6	2.4×10^6	1.0×10^5 (cf 40 in JHF-SK)

Alain Blondel, Venice, March 2003

Possible detectors 2): Liquid Argon TPC

- The first 300 ton module is operational.
- Excellent energy resolution, tracking, particle identification.
- Difficult to scale to a multi-10kton detector.
- Non trivial implementation of magnetic field: downstream spectrometers. The possibility to magnetize large, multikiloton volume of Argon is under study.
- Conceptual possibility to measure the charge of electrons if the full volume is magnetized at 1 Tesla.
- The best solution if redundant searches of oscillations are needed to overconstrain the mixing matrix.

UNO detector



- Fiducial volume: 440 kton: 20 times SuperK.
- The killer detector for proton decay, atmospheric neutrinos, supernovae neutrinos.
- Energy resolution is poor for multitrack events but quite adequate for sub-GeV neutrino interactions.
- Difficult implementation of magnetic field: downstream spectrometers.

A problem ...

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. $\Rightarrow$ **Optimal energy: as high as possible**.

$$\Downarrow$$

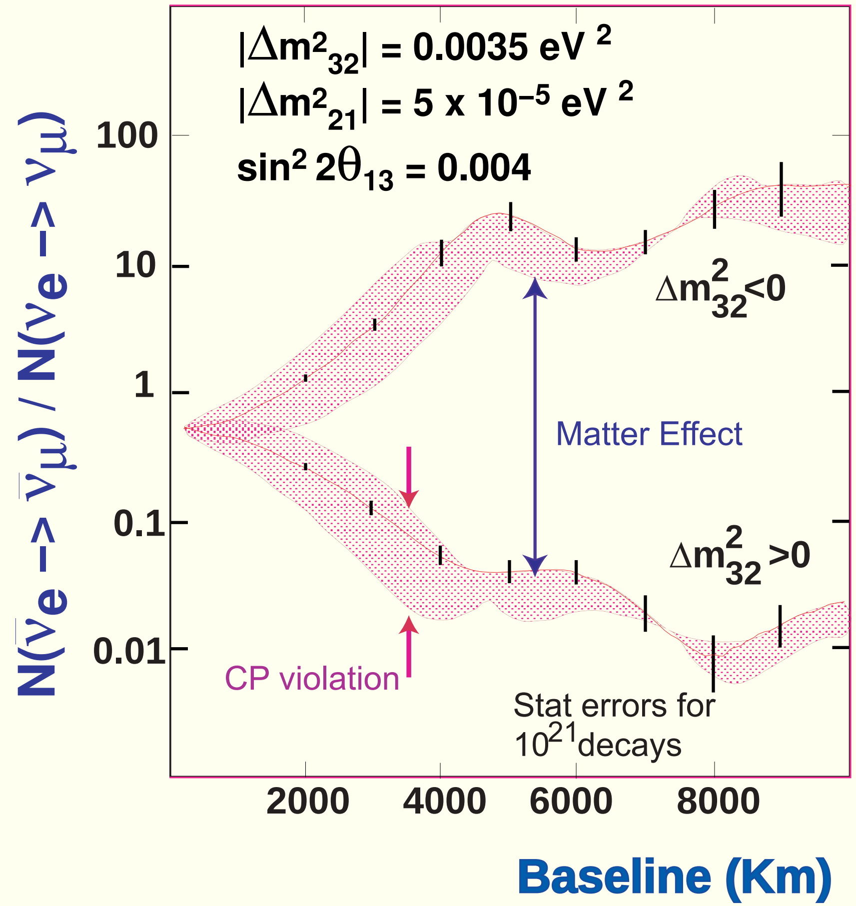
High Neutrino Energies $\Rightarrow$ Long Baselines $\Rightarrow$ Matter Effects

Can genuine CP effects be separated from matter effects?

Genuine CP-odd, δ driven effects can be decoupled from matter effects, but paying a high price:

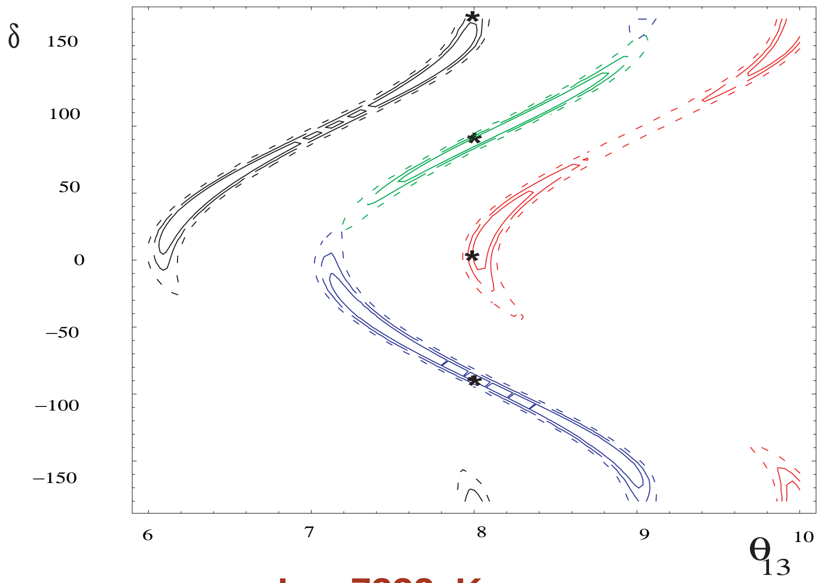
1. The experiment must be run at a baseline much shorter than the optimal one.
2. A strong correlation between δ and θ_{13} .
3. The experimental result is affected by the uncertitude on the other parameters of the mixing matrix and by the uncertitude on the matter density along the beam line.

From V. Barger et al., hep-ph/0003184.

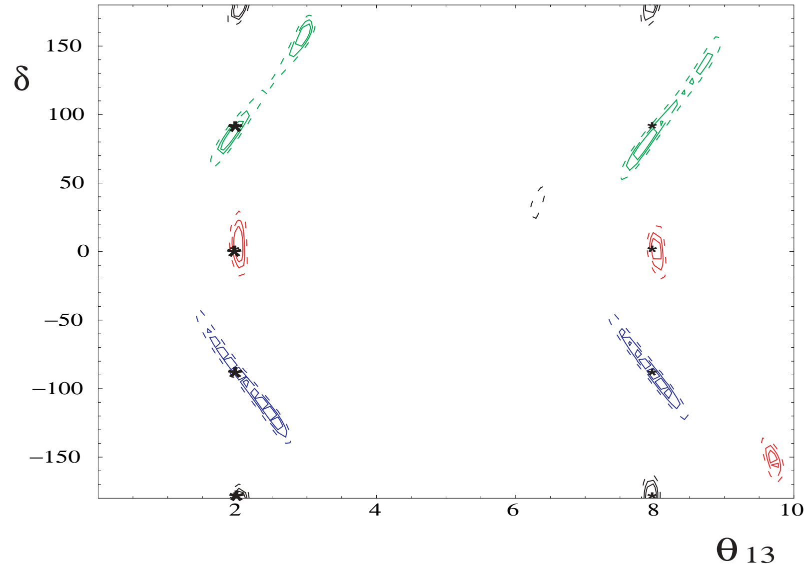


Simultaneous fits at δ e θ_{13} (from Nucl.Phys. B608(2001)301)

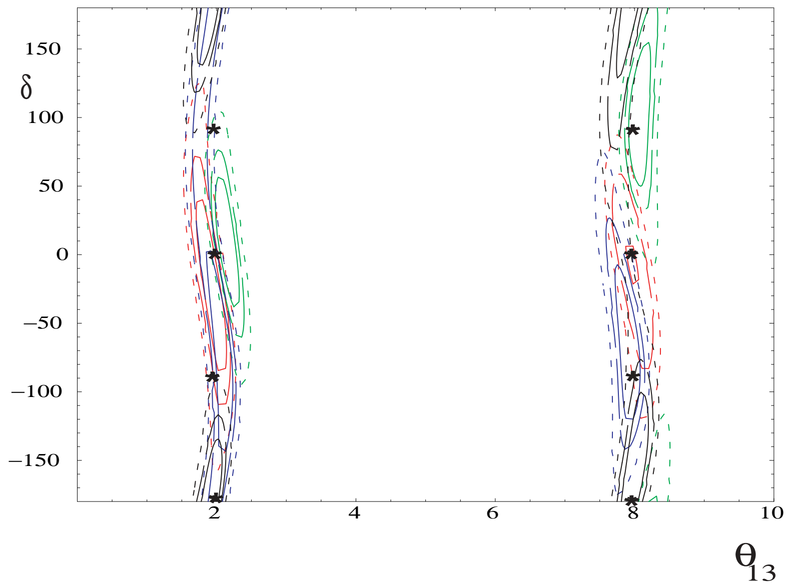
L = 732 Km



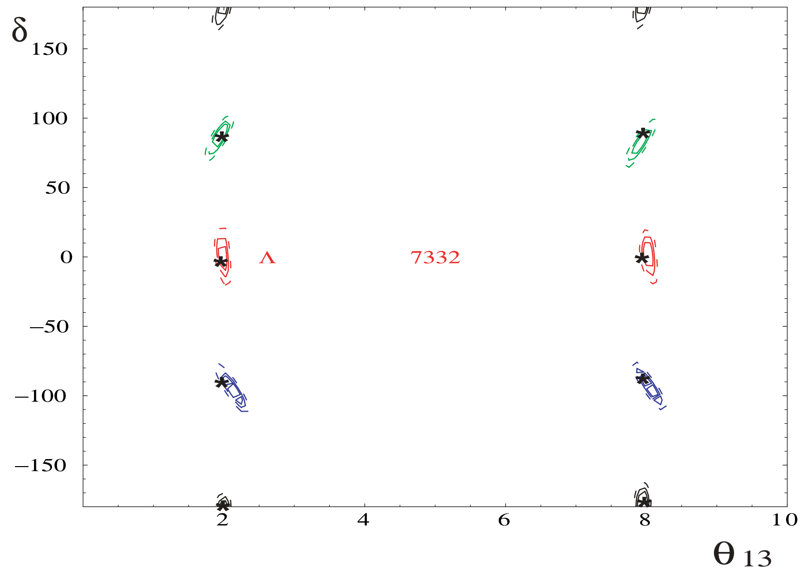
L = 2810 Km



L = 7332 Km

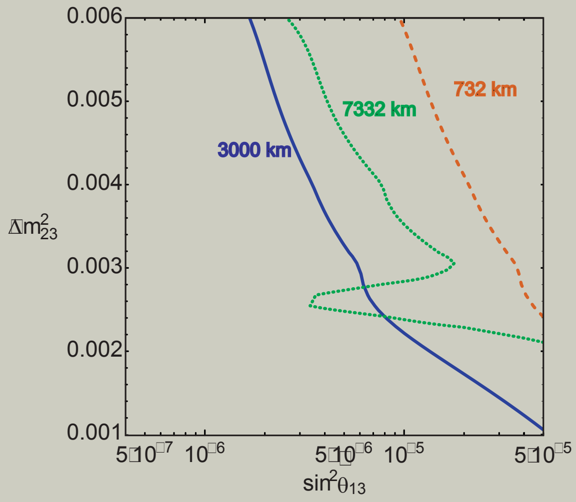


L = 2810 Km + L = 7332 Km

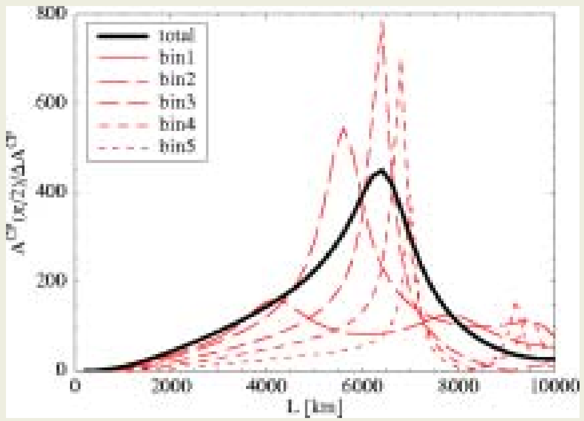


Precision measurements at the Neutrino Factories

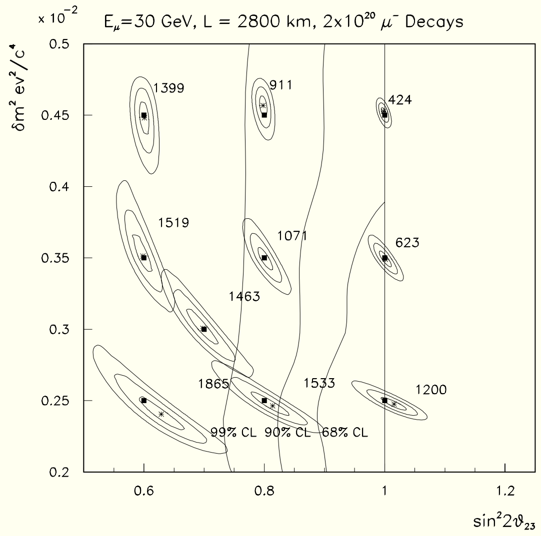
Improve up to 4 orders of magnitude the Chooz sensitivity on θ_{13}



Measure the Δm^2_{23} sign



Measure the atmospheric parameters at 1%.

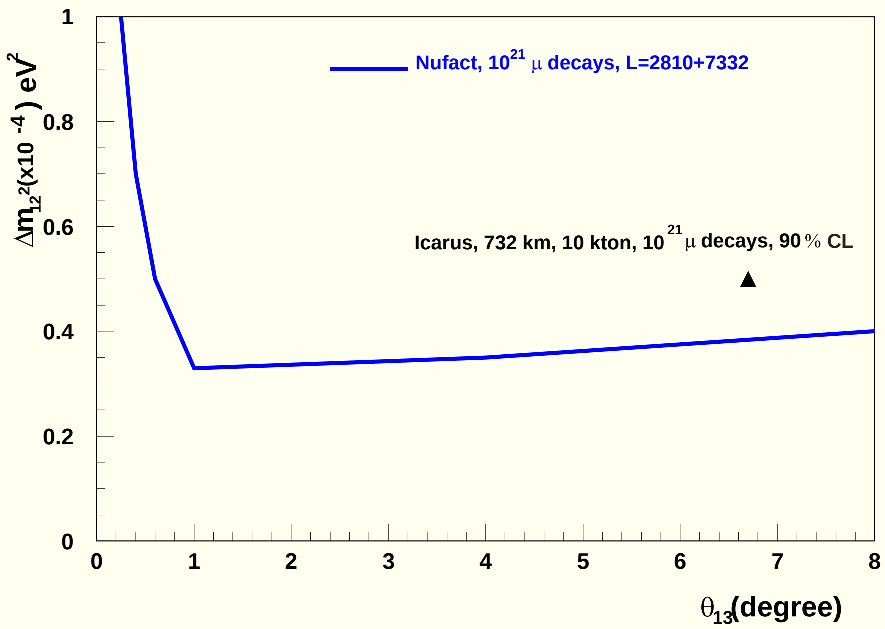


Final Sensitivity

- 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.

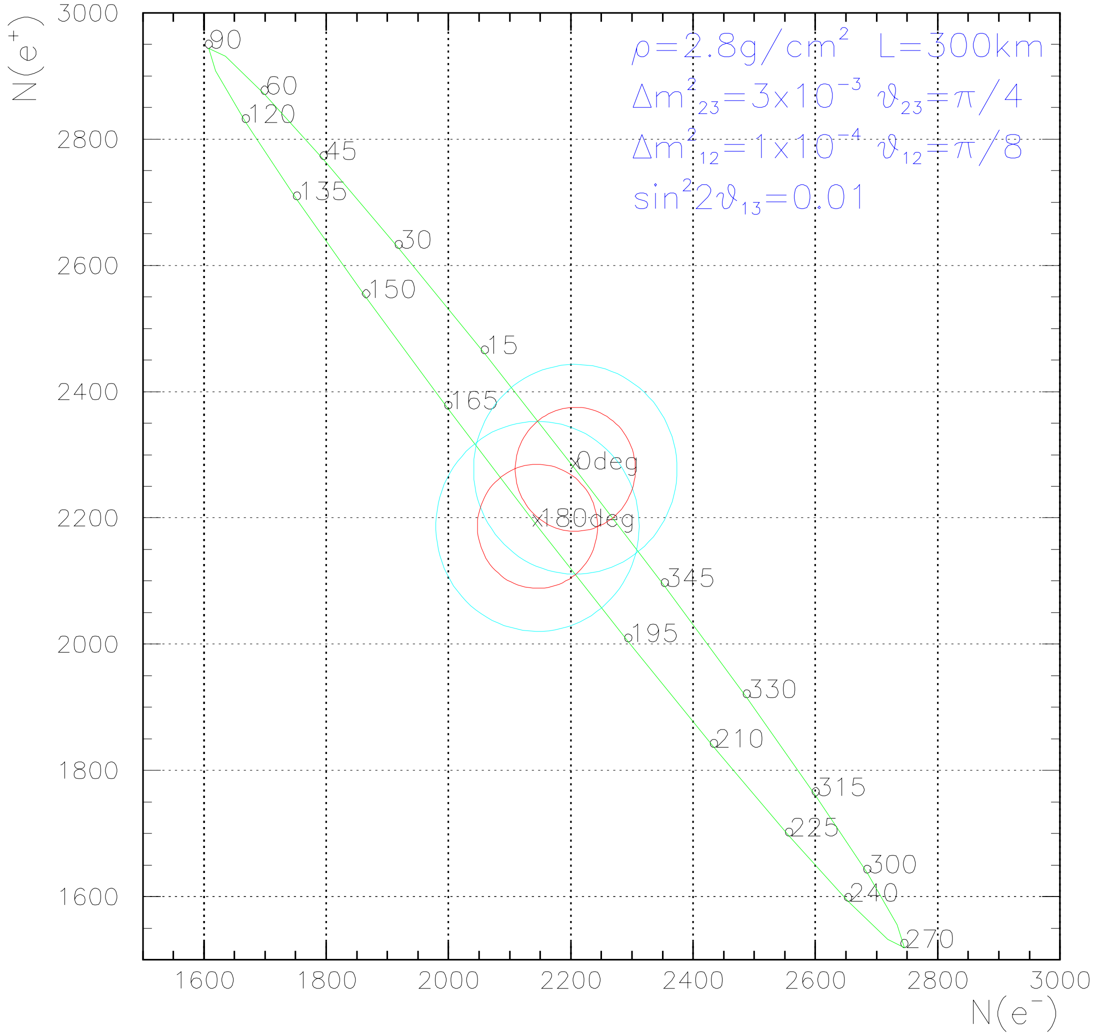
CP sensitivity, defined as the capacity to separate at 99%CL max CP ($\delta = \pi/2$) from no CP ($\delta = 0$) computed as function of the two critical parameters θ_{13} and δm^2_{12}



SuperBeams (1) - JHF phase 2

Upgrade the proton driver from 0.75 MW to 4 MW

Upgrade SuperKamiokande by a factor 40 $\Longrightarrow$ HyperKamiokande



Interesting features of a low energy conventional neutrino beam.

ν beam:

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

ν_e in the beam come only from μ decays.

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

$\Rightarrow$ 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

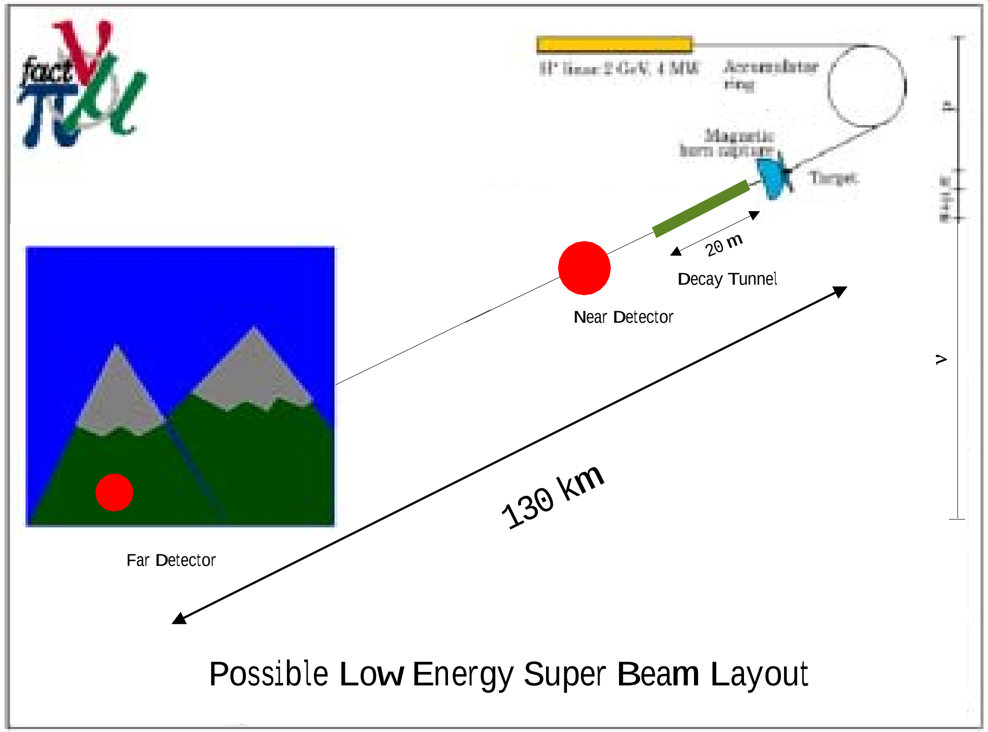
- Good e/π^0 separation following the large $\pi^0 \rightarrow \gamma\gamma$ opening angle
- Good e/μ separation in a Čerenkov detector because μ are produced below or just above the Čerenkov threshold.
- Charm and τ production below threshold.

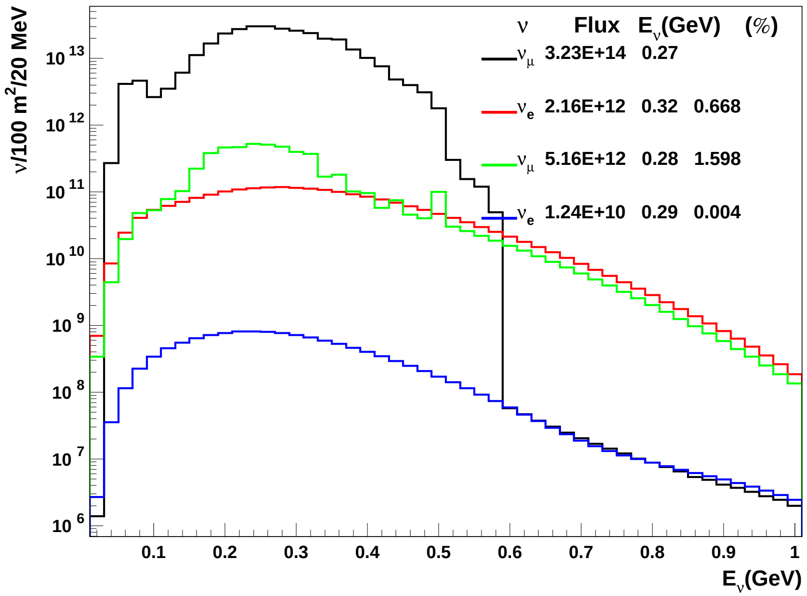
Less exiting aspects of a low energy neutrino beam

- 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

SPL-SuperBeam at CERN

A feasibility study of the CERN possible developments

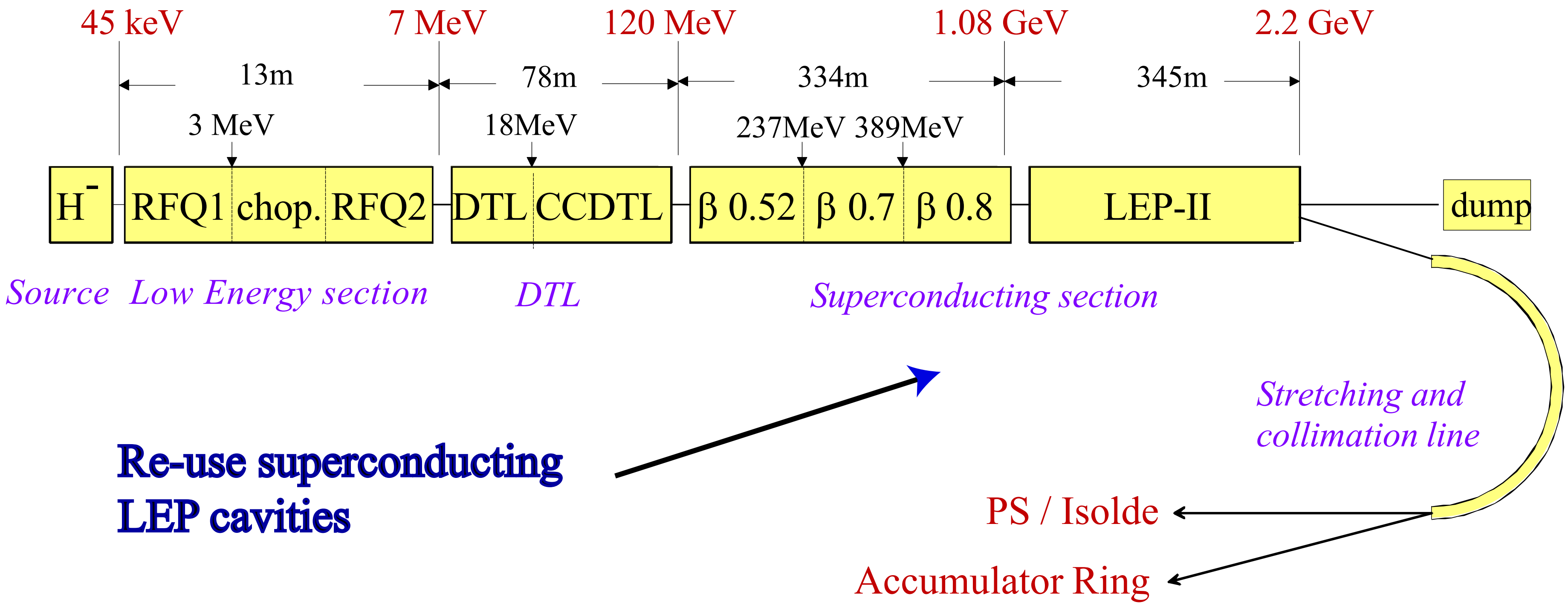




Flux intensities at 50 km from the target

Flavour	Absolute Flux $(\nu/10^{23}\text{pot}/\text{m}^2)$	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

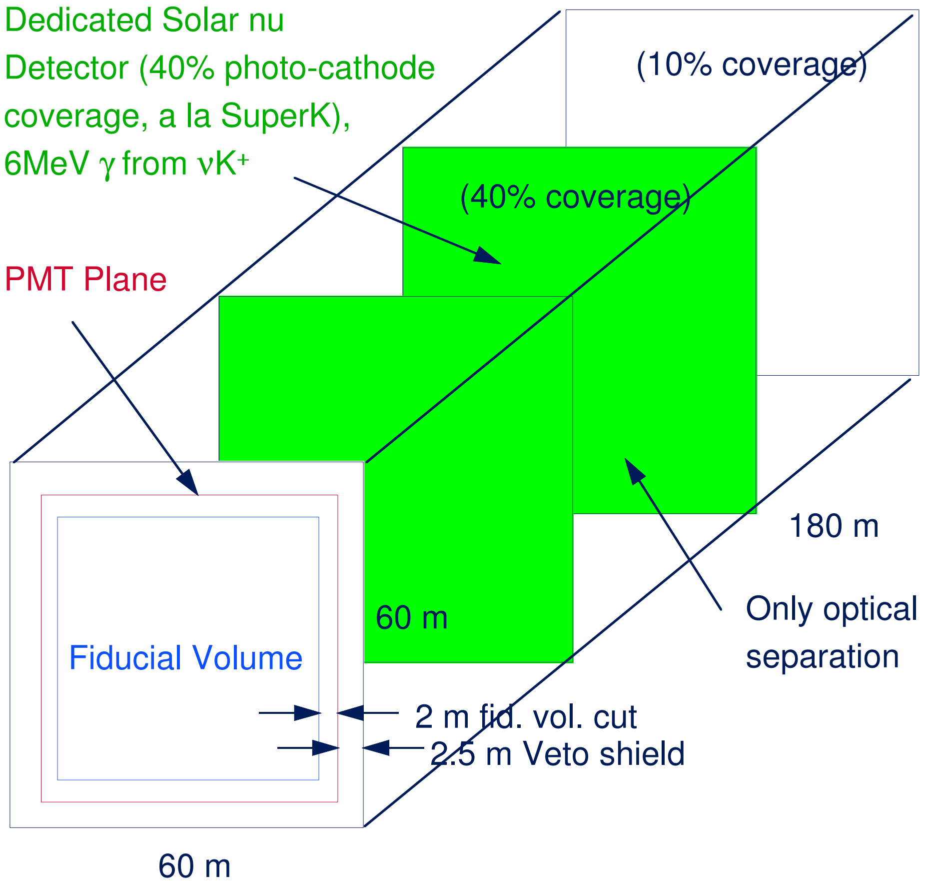
MW-Linac: SPL (Superconducting Proton Linac)



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

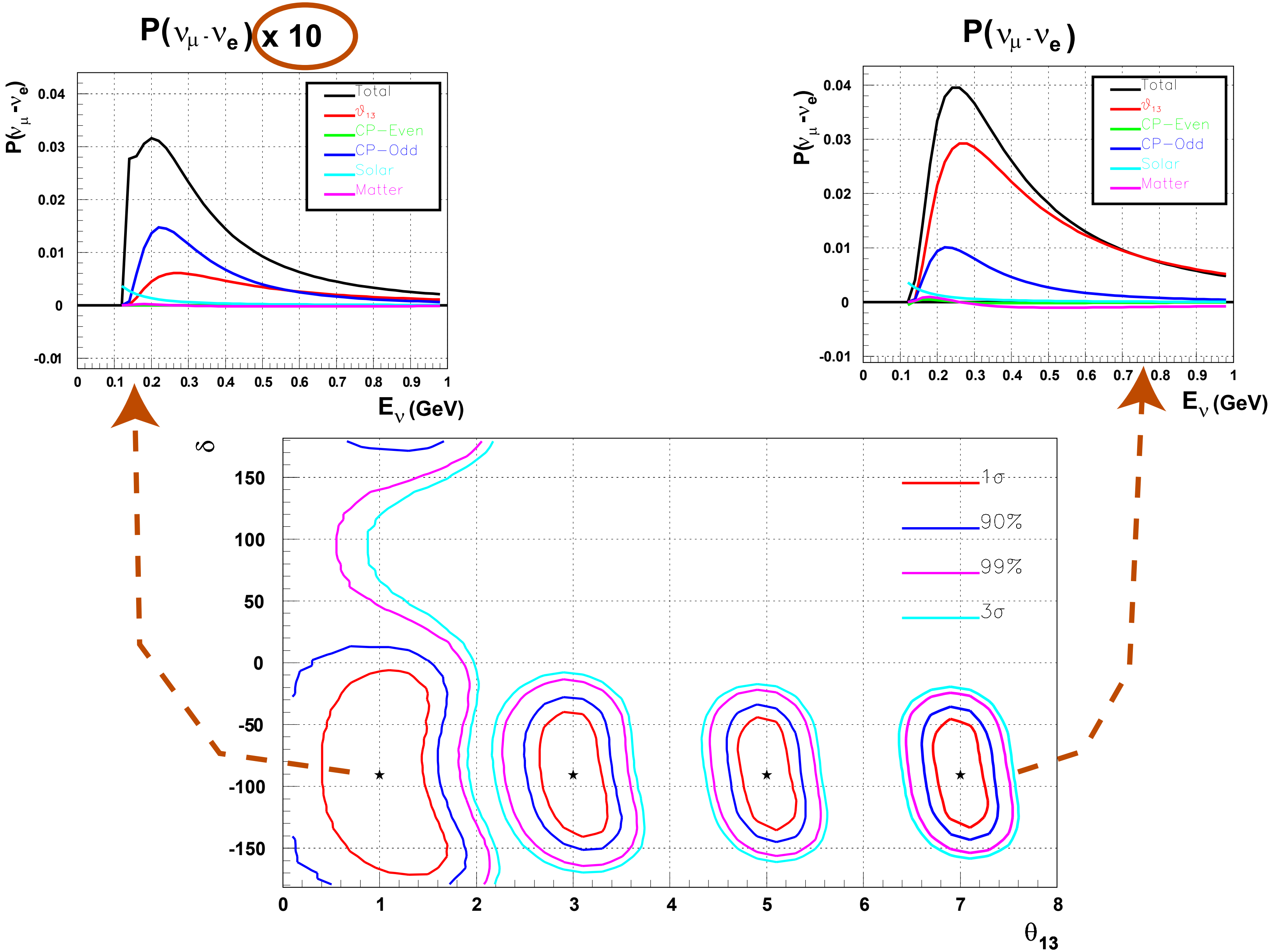
→ **10^{23} protons/year**

UNO detector

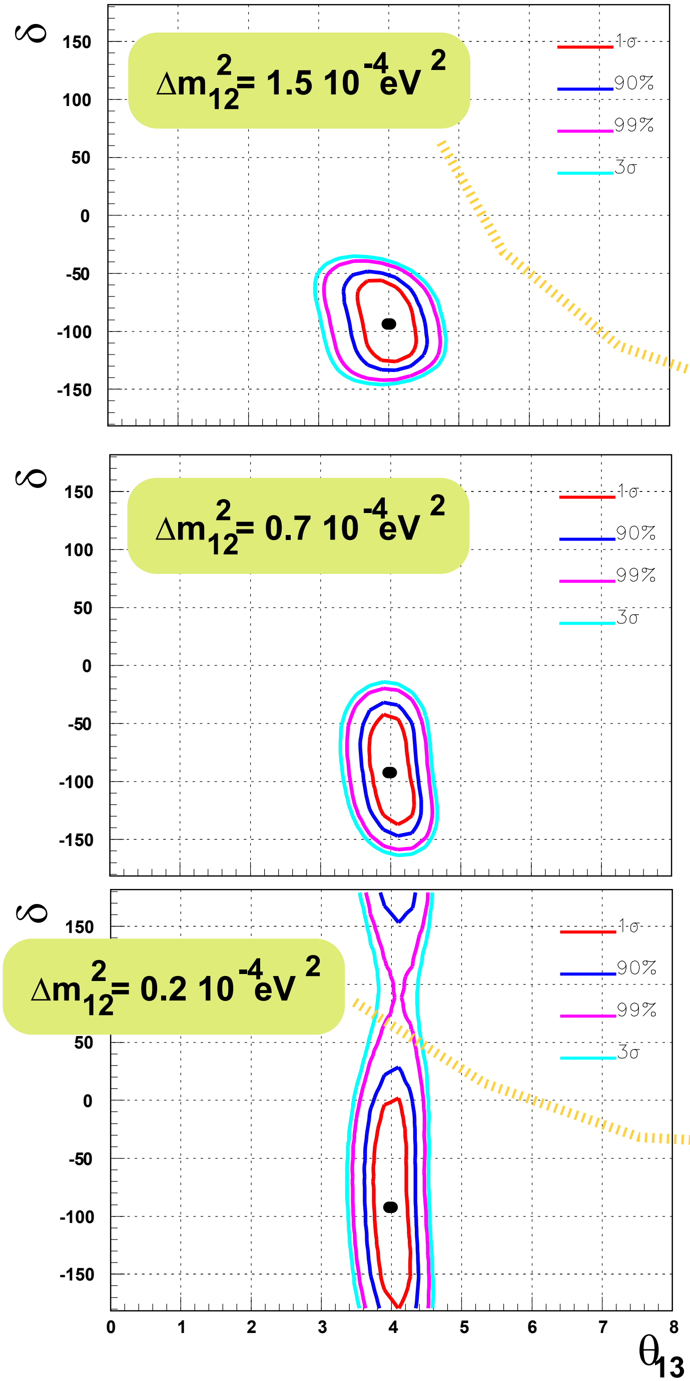


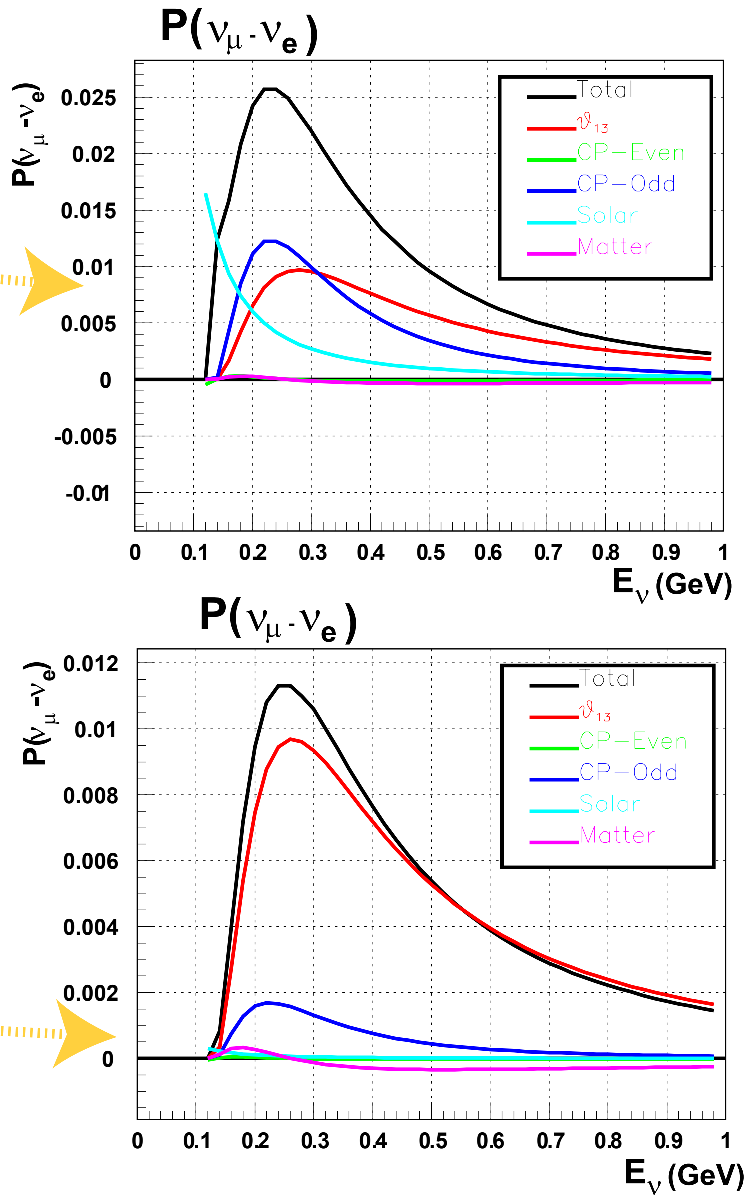
- Fiducial volume: 440 kton: 20 times SuperK.
- 60000 PMTs (20”) in the inner detector, 15000 PMTs in the outer veto detector.
- **The killer detector for proton decay, atmospheric neutrinos, supernovae neutrinos.**
- Energy resolution is poor for multitrack events but quite adequate for sub-GeV neutrino interactions.
- It would be hosted at the Frejus laboratory, 130 km from CERN, in a $10^6\ m^3$ cavern to be excavated.
- Quoted at 500M$ (including excavation)

δ and θ_{13} interplay: $P(\nu_\mu \to \nu_e) \propto \sin^2 2\theta_{13}$ $\quad A_{CP} = \frac{N(e^+)-N(e^-)}{N(e^+)+N(e^-)} \propto \frac{1}{\sin\theta_{13}}$



Sensitivity depends also by Δm^2_{12} (solars)

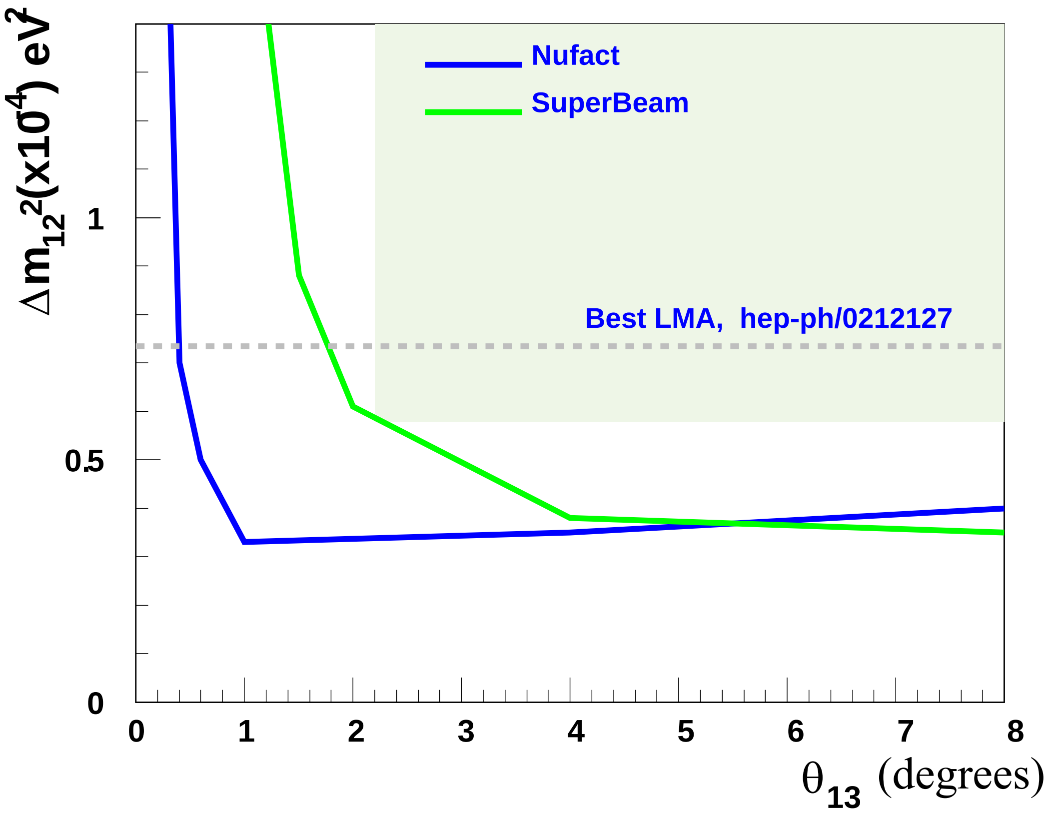




A comparison of CP sensitivities: Nufact vs. SuperBeam

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

Nufact 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

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
- Counting experiment: less influenced by uncertitudes on the other mixing matrix parameters

CONS

- Smaller CC rate
- Intrinsic beam contamination

Can the SuperBeam+UNO combination be upgraded?

YES

with a novel concept of neutrino beam: BETA BEAM.

(P. Zucchelli: Phys. Lett. B532:166, 2002)

Beta Beam (P. Zucchelli: Phys. Lett. B532:166, 2002)

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).

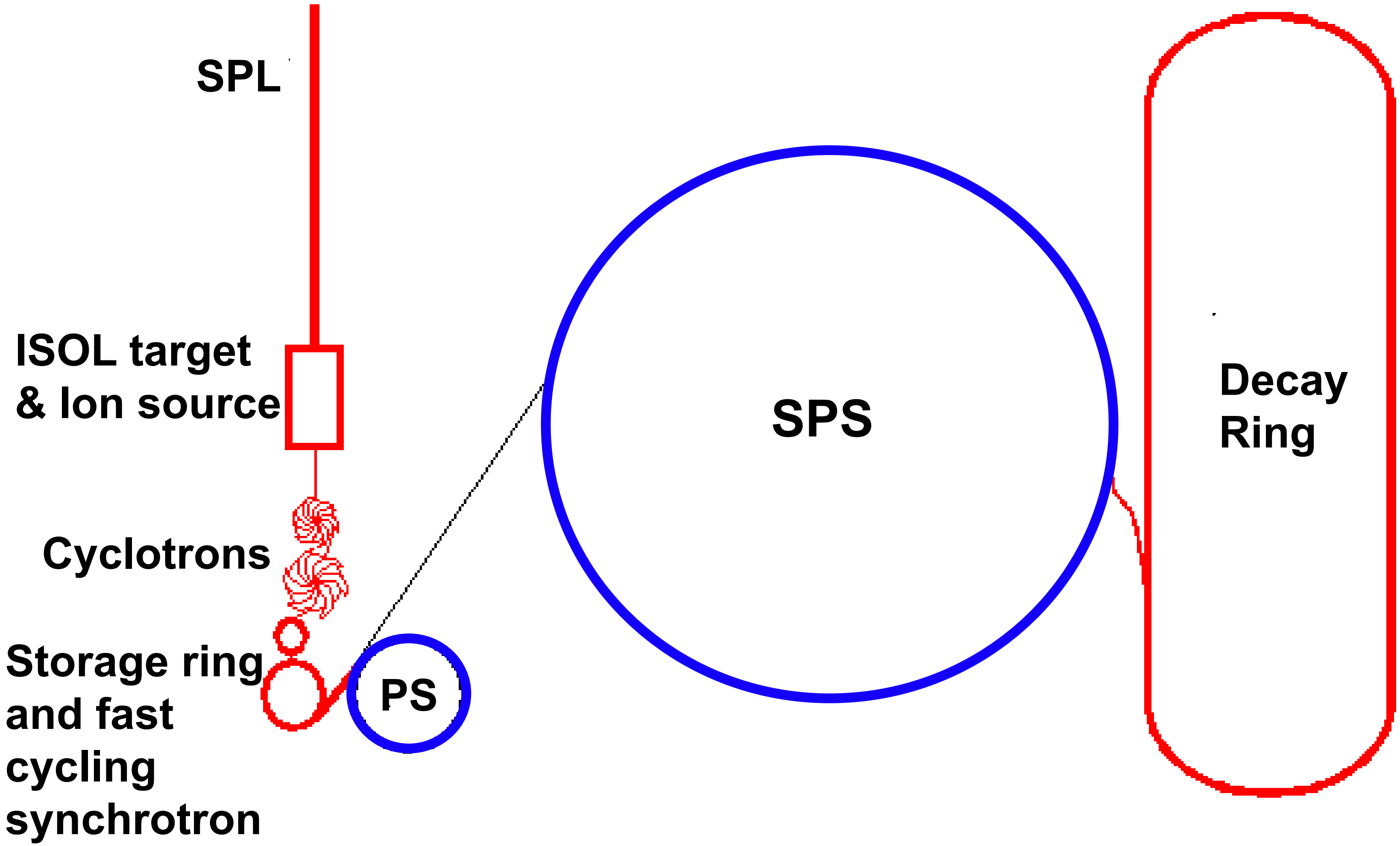
It is technologically feasible to build neutrino beams with intensities comparable with SuperBeams.

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

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

A Beta Beam sketch

M. Lindroos and collaborators, see http://beta-beam.web.ch/beta-beam

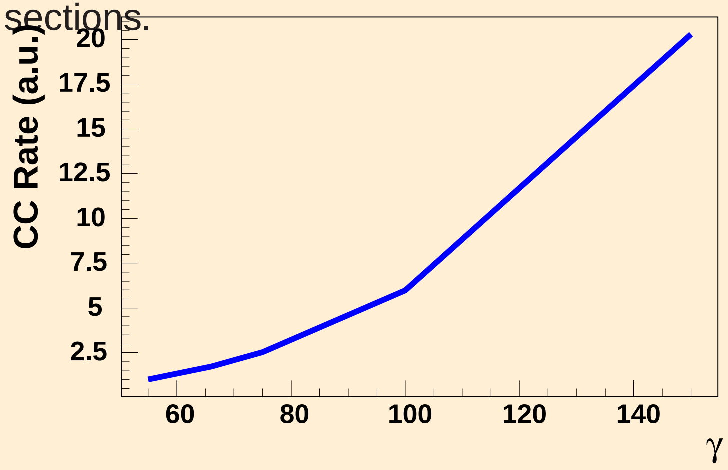


- 1 ISOL target to produce HE^6, 100 μA, $\Rightarrow 2.9 \cdot 10^{18}$ ion decays/straight session/year. Source of $\overline{\nu}_e$.
- 3 ISOL targets to produce Ne^{18}, 100 μA, $\Rightarrow 1.1 \cdot 10^{18}$ ion decays/straight session/year. Source of ν_e .
- The 4 targets could run in parallel.

Optimizing the Lorentz Boost γ (L=130 km): preferred value: $\gamma = 75$

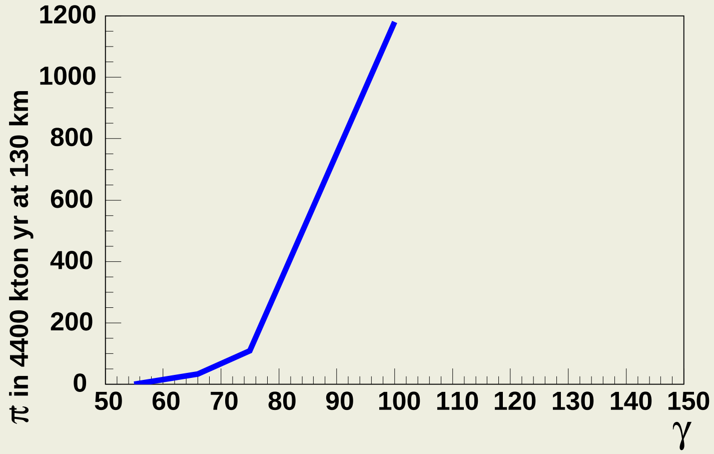
Higher γ produce more CC interactions

More collimated neutrino production and higher cross sections.

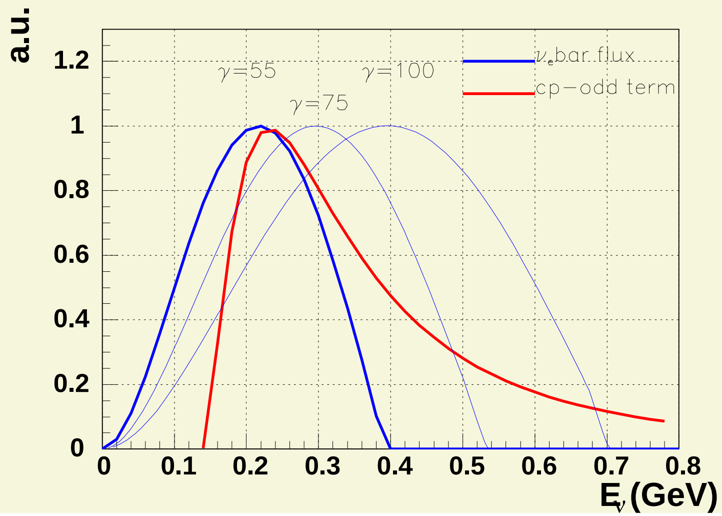


Background rate rises much faster than CC interactions

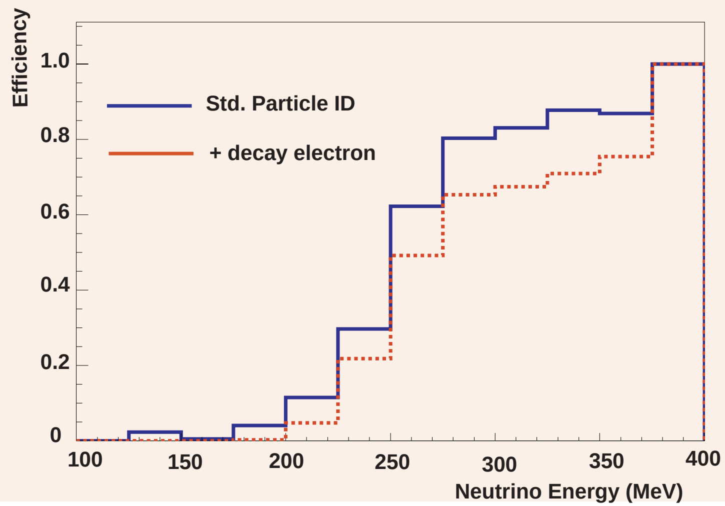
From resonant pion production in $\overline{\nu}_e$ NC interactions



ν flux must match the CP-odd oscillating term



Detection efficiency as function of ν energy



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 12% of the SPL protons $\longrightarrow$ the two beams can run together.

Both beams produce sub-GeV neutrinos $\longrightarrow$ 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 $p(\nu_\mu \rightarrow \nu_e)$ with Beta Beam ^{18}Ne $p(\nu_e \rightarrow \nu_\mu)$
- Compare Super Beam $p(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$ with Beta Beam ^{6}He $p(\overline{\nu}_e \rightarrow \overline{\nu}_\mu)$.

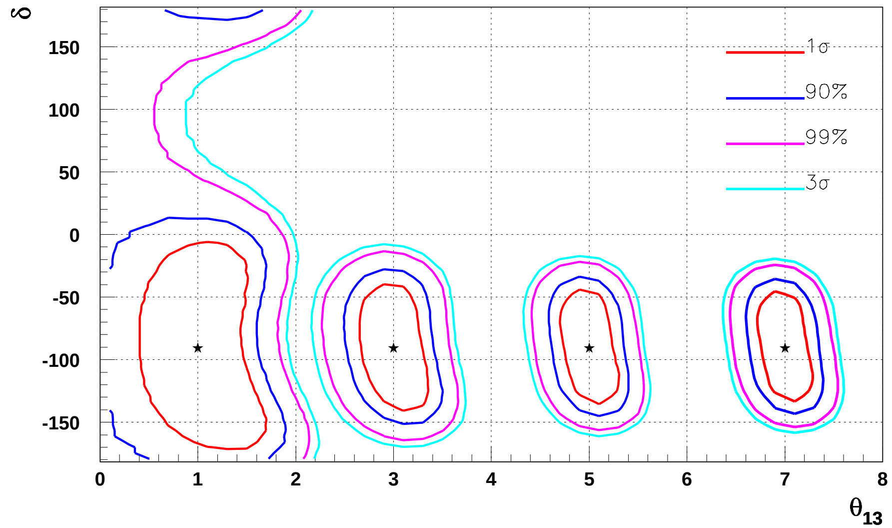
CPT searches

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

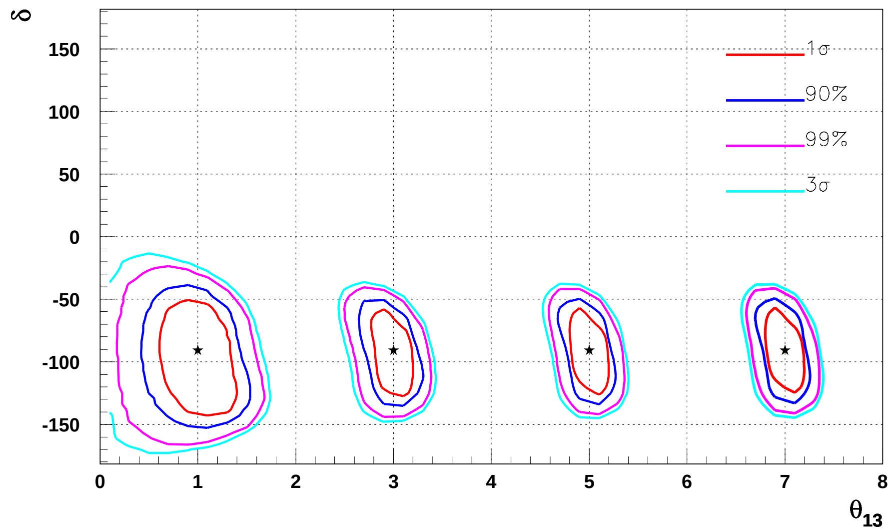
In case of small values of θ_{13} the most powerful combination to discover Leptonic CP would be however a single T search with neutrinos (SuperBeam ν_μ with BetaBeam ν_e).

Beta Beam Super Beam synergy: results

SUPER BEAM ONLY



SUPER BEAM + BETA BEAM



$$\delta m^2_{12} = 7 \cdot 10^{-5}\ eV^2, \quad \theta_{13} = 4^\circ, \quad \delta_{CP} = -\pi/2$$

10 yrs (4400 kton/yr)	SuperBeam		Beta Beam	
	ν_μ	$\overline{\nu}_\mu$	$\overline{\nu}_e$	ν_e
	(2 yrs)	(8 yrs)	(He^6)	(Ne^{18})
CC events (no osc, no cut)	36698	23320	40783	55749
Total oscillated	314	67	193	117
CP-Odd oscillated	102	-64	61	-95
Beam background	141	113	/	/
Detector bkg.	37	50	60	31

Final CP sensitivity.

After Moriond, very preliminary