SuperBeam studies at CERN

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As a rapporteur from the CERN working group on Super Beams:

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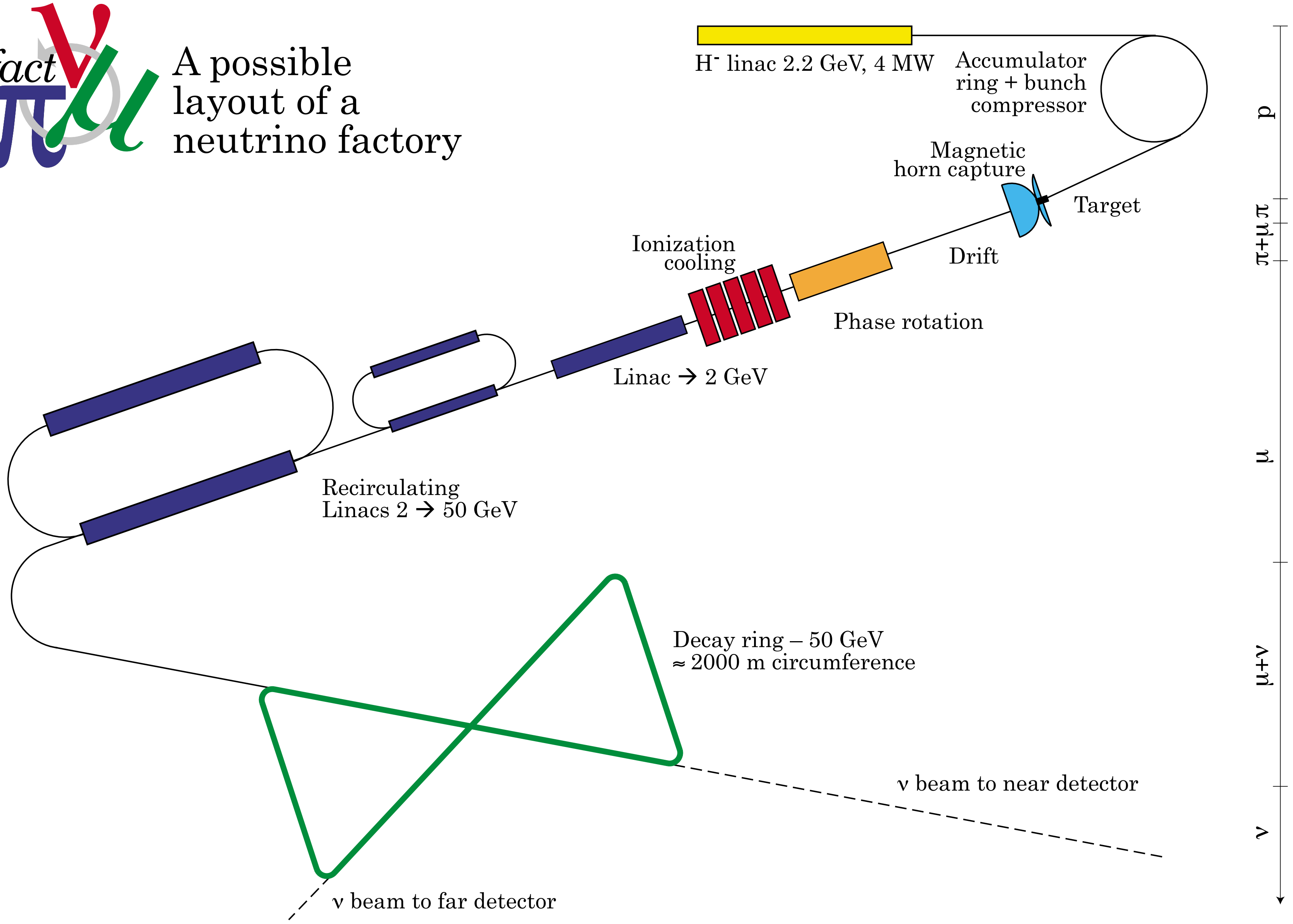
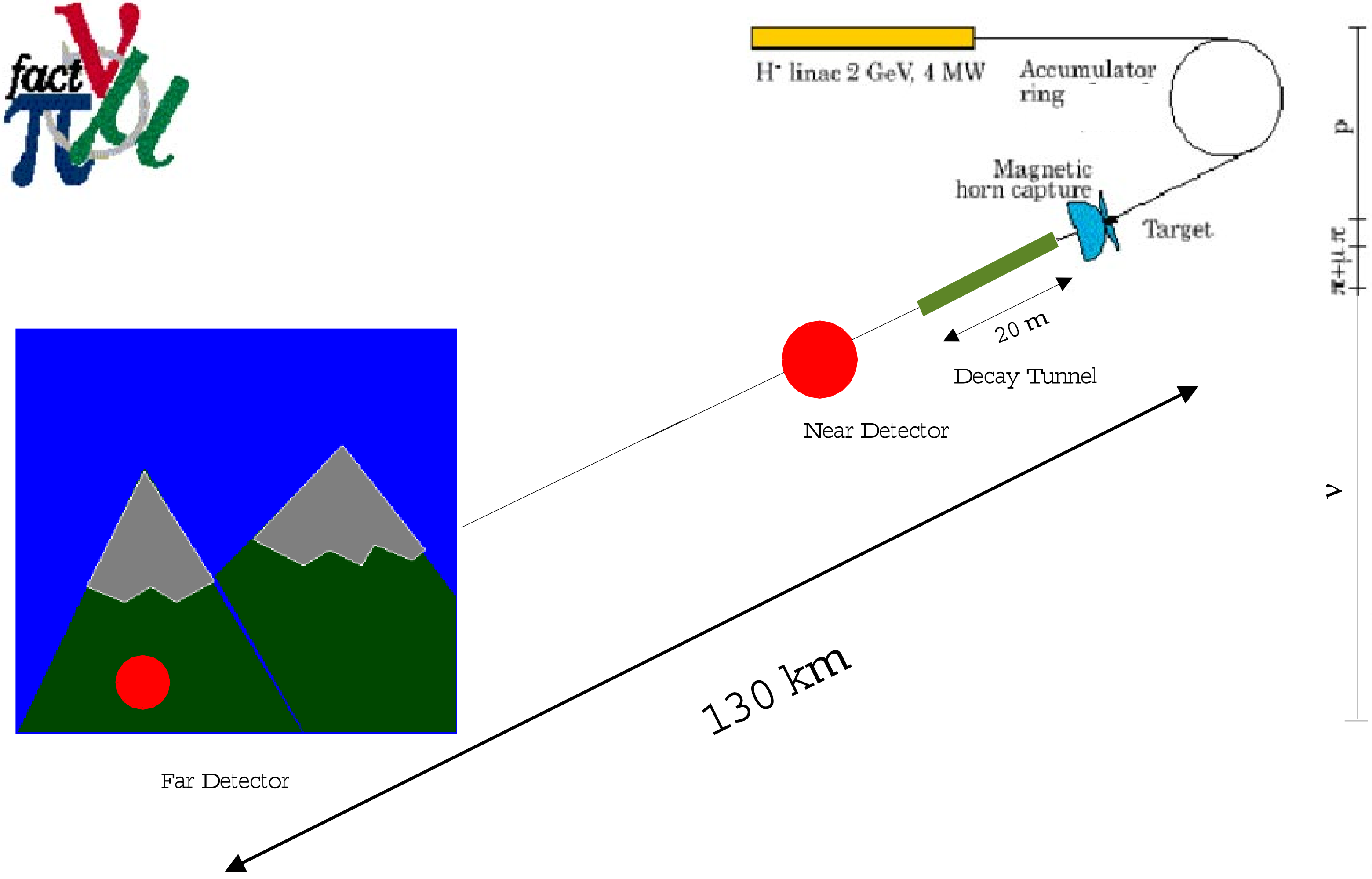
A possible layout of a neutrino factory

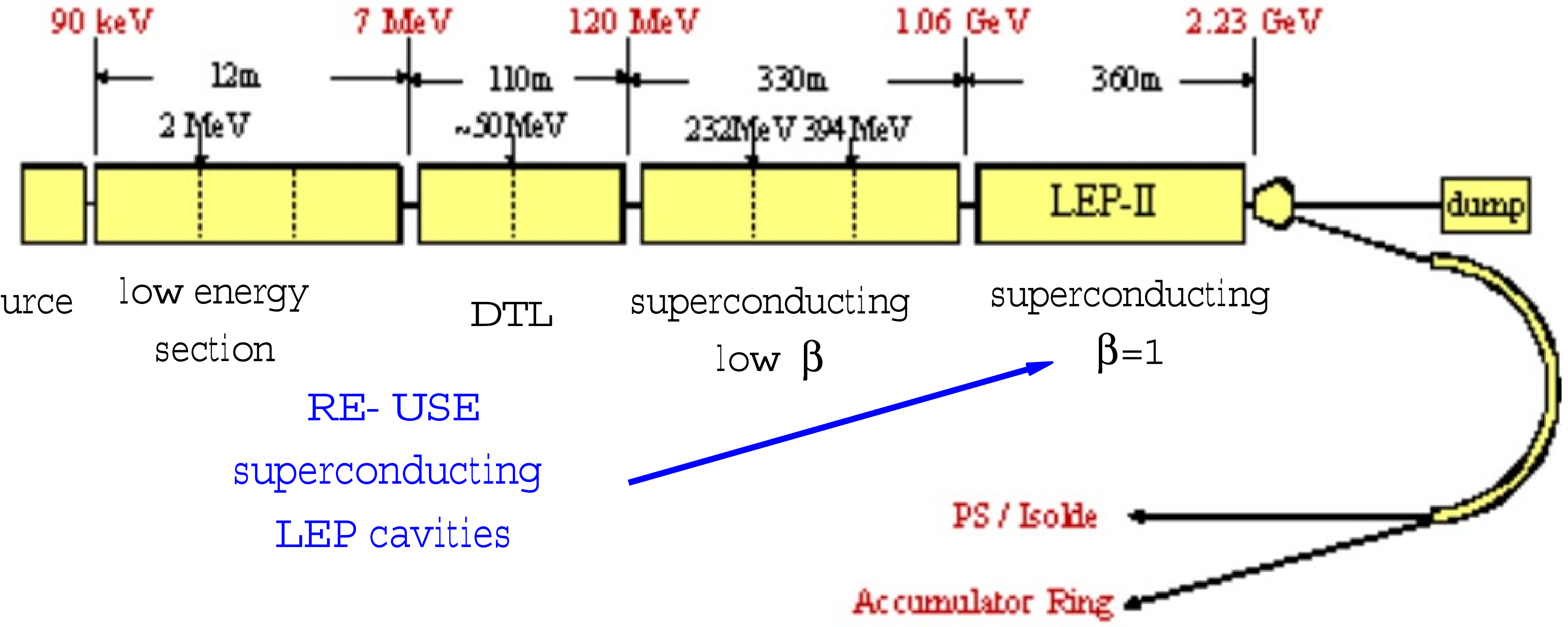


2000-05-16 • Peter Gruber, CERN-PS



Possible Low Energy Super Beam Layout

MW- linac: SPL (Superconducting Proton Linac)



source

low energy section

DTL

superconducting low β

superconducting β=1

RE- USE superconducting LEP cavities

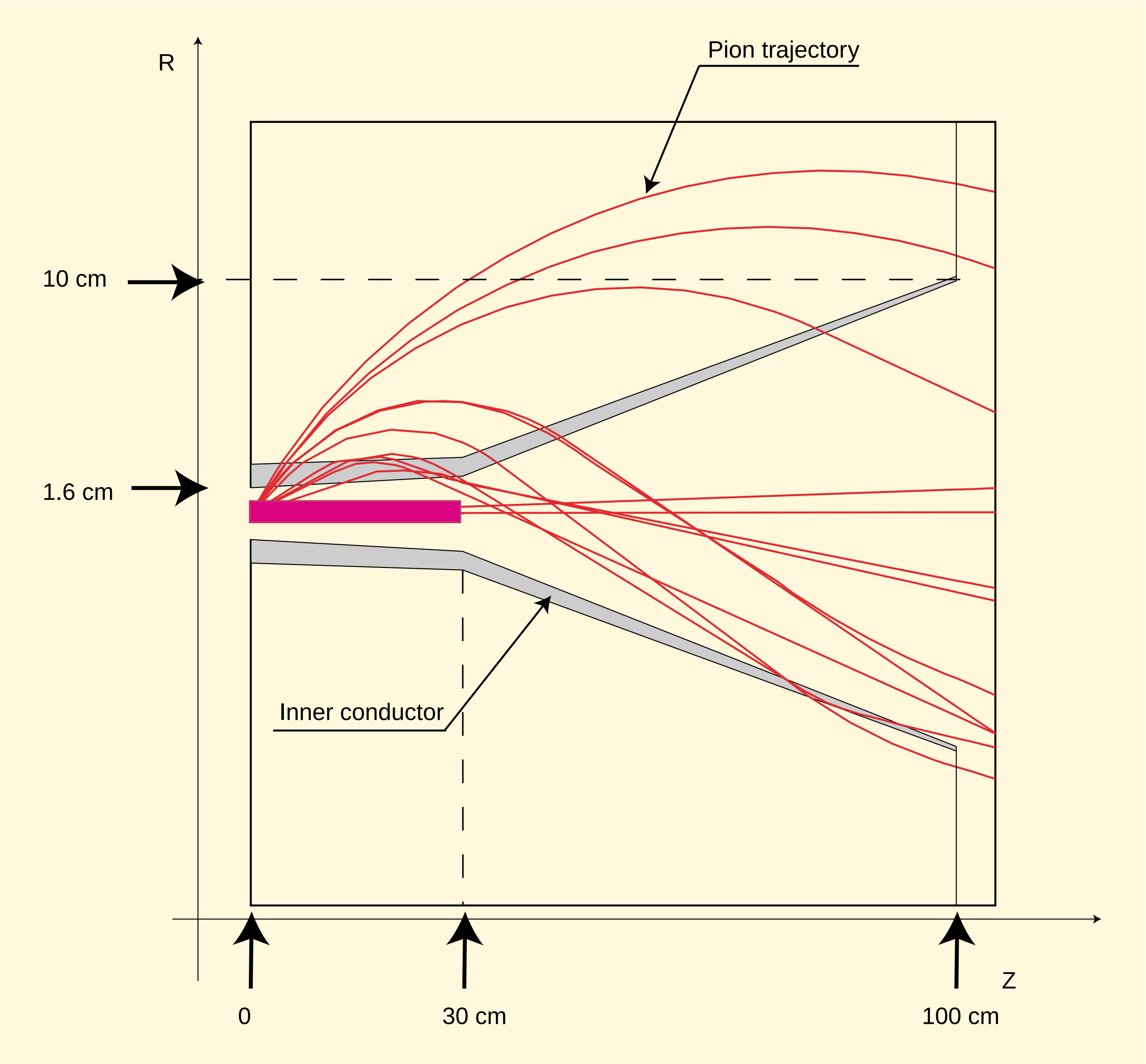
E_{kin} = 2.2 GeV

Power = 4 MW

Protons/s = 10^{16}

10^{23} protons/year

Target and focusing system



Liquid target:

- Mercury
- $L = 30\ cm$
- $R = 0.75\ cm$
- Speed$=$ 20m/s

Magnetic Horn:

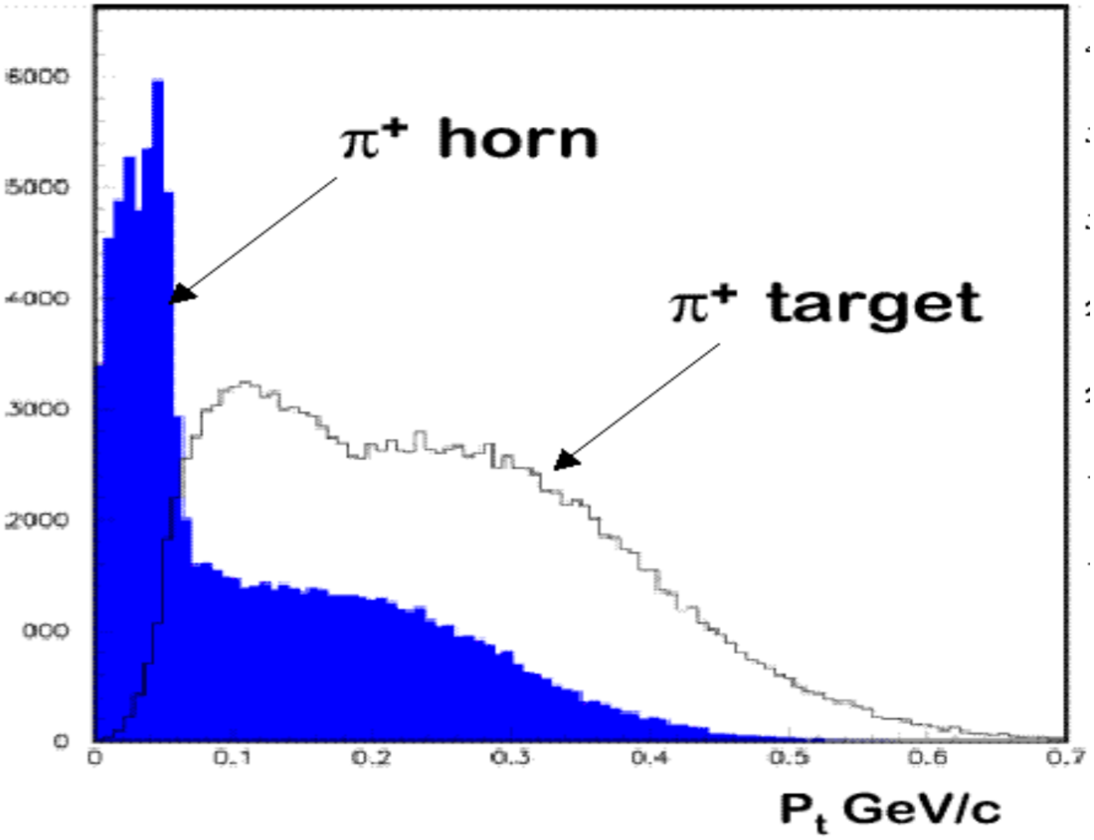
- $I = 300$ kA
- Toroidal magnetic field
- Charge selective

Future:

- Optimization for the SuperBeam
- Reflector
- Mechanical/Radiation R&D

A full beam simulation

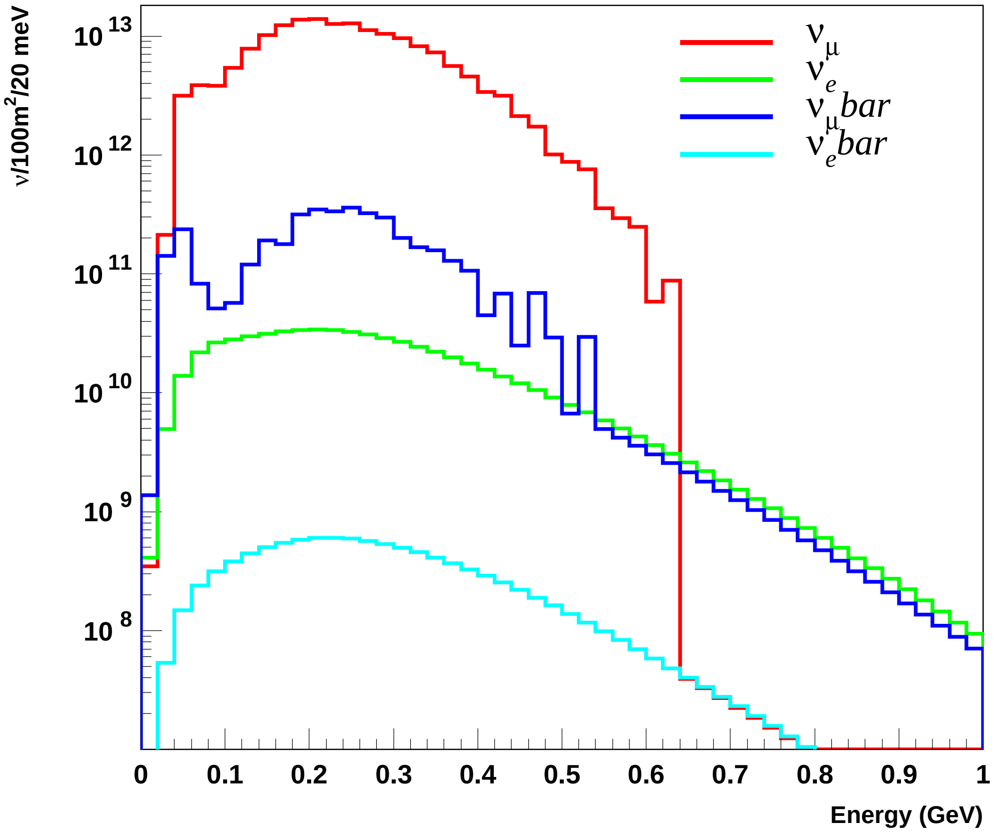
Decay tunnel: length=20 m, radius=1 m



- Proton interaction on target simulated by MARS
- Secondaries followed by GEANT.
- Polarization effects are taken into account

HARP results strongly needed to reduce systematic errors in secondary particles production !!!

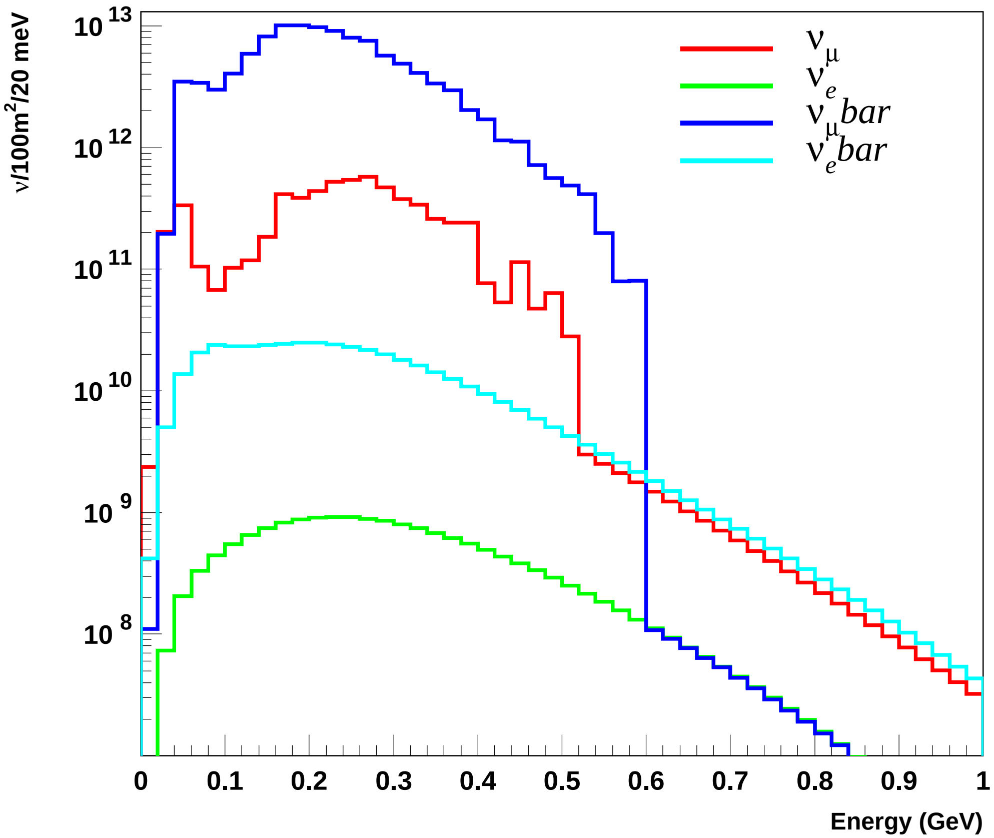
SPL SuperBeam (π^+ focused)



Flux intensities at 50 km from the target

Flavour	Absolute Flux $(\nu/10^{23}\mathrm{pot}/10^2\mathrm{m}^2)$	Rel. Flux	$\langle E_\nu \rangle$ (GeV)
ν_μ	$1.7 \cdot 10^{14}$	1	0.26
$\overline{\nu}_\mu$	$4.1 \cdot 10^{12}$	2.4%	0.24
ν_e	$6.1 \cdot 10^{11}$	0.36%	0.24
$\overline{\nu}_e$	$1.0 \cdot 10^{10}$	0.006 %	0.29

SPL SuperBeam (π^- focused)



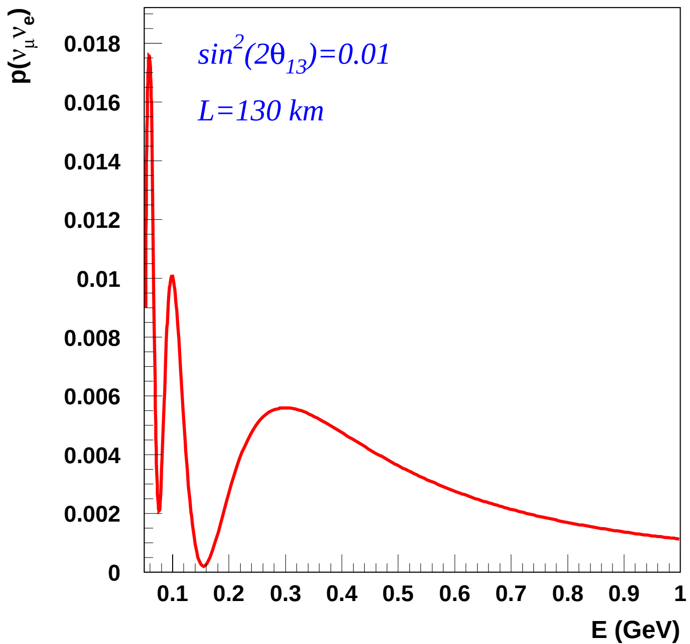
Flux intensities at 50 km from the target

Flavour	Absolute Flux $(\nu/10^{23}\text{pot}/10^2\text{m}^2)$	Rel. Flux	$\langle E_\nu \rangle$ (GeV)
$\overline{\nu}_\mu$	$1.1 \cdot 10^{14}$	1	0.23
ν_μ	$6.3 \cdot 10^{12}$	5.7%	0.25
$\overline{\nu}_e$	$4.3 \cdot 10^{11}$	3.9 %	0.25
ν_e	$1.6 \cdot 10^{10}$	0.15%	0.29

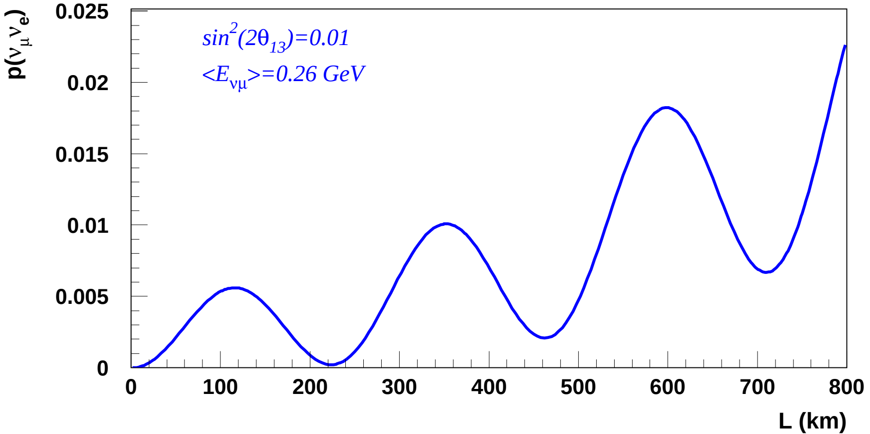
Measuring θ_{13}

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

$$\begin{aligned} p(\nu_\mu \rightarrow \nu_e) = & -4Ue(1)Ue(2)U_\mu(1)U_\mu(2)\sin^2(1.27 \cdot \delta m^2_{12} \cdot L/E) \\ & -4Ue(1)Ue(3)U_\mu(1)U_\mu(3)\sin^2(1.27 \cdot \delta m^2_{23} \cdot L/E) \\ & -4Ue(2)Ue(3)U_\mu(2)U_\mu(3)\sin^2(1.27 \cdot (\delta m^2_{23} + \delta m^2_{12}) \cdot L/E) \end{aligned} \tag{1}$$



$p(\nu_\mu \nu_e)$ vs. E

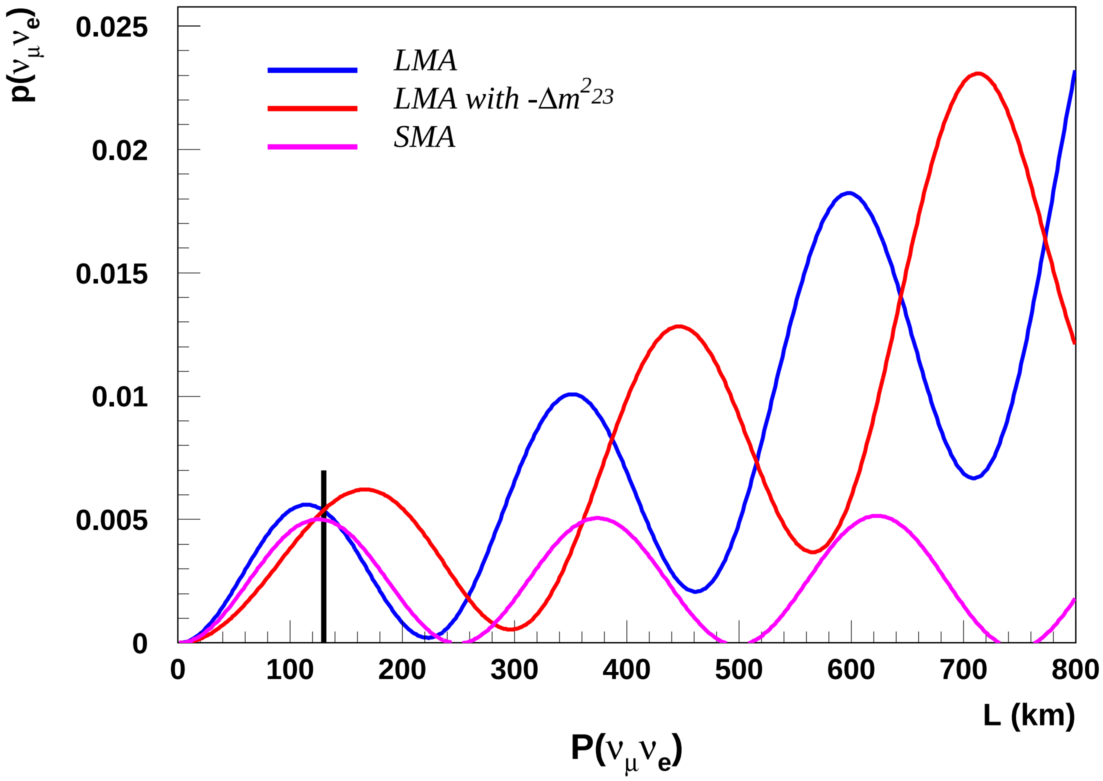


$p(\nu_\mu \nu_e)$ vs. L

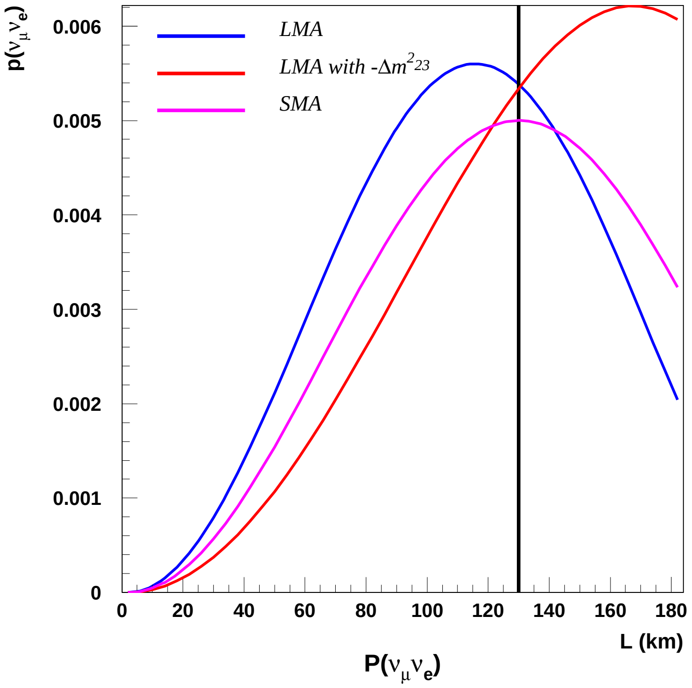
- $sin^2 2\theta_{23} = 1,$
- $sin^2 2\theta_{12} = 0.8,$
- $\delta m^2_{23} = 2.5 \cdot 10^{-3}\ eV^2$,
- $\delta m^2_{12} = 5 \cdot 10^{-5}\ eV^2,$
- hierarchical mass model
- hotly waiting for MiniBoone and Kamland.

Regarding the parameters’ choice.

- Amplitude is driven by $\sin^2(2\theta_{13})$
- Wavelength is driven by δm^2_{23}
- But also δm^2_{12}, its sign, δ, $\sin^2 2\theta_{23}$, $\sin^2 2\theta_{12}$ have sizable effects



$P(\nu_\mu \nu_e)$



$P(\nu_\mu \nu_e)$

ν_e Appearance Experiment

Aim of the experiment: detect $\boldsymbol{\nu_e}$ generated by $\boldsymbol{\nu_\mu \rightarrow \nu_e}$ transitions with $\boldsymbol{p(\nu_\mu \rightarrow \nu_e) \leq 5 \cdot 10^{-3}}$

- It's a counting experiment: ν energy is poorly reconstructed mostly because of the Fermi motion and does not allow to subdivide energy distribution in bins.
- **Detector Backgrounds**
  - μ mis-identified
  - π^0 production in Neutral Current
- **Irreducible $\boldsymbol{\nu_e}$ beam background**: slightly below $4 \cdot 10^{-3}$.
- **Atmospheric neutrino background**: negligible, thanks to the accumulator.
- **Close Detector**: A 0.5 kton detector at 1 km from the target will normalize the backgrounds with a 2% statistical accuracy.

Two reference values for L:

- The optimal one (depending from oscillation parameters and f_B): $L \simeq 90$ km
- The practical one: CERN-Modane: $L \simeq 130$ km.

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.

$$\begin{tikzcd}
\pi^+ \arrow[r] & \mu^+\nu_\mu \arrow[d] \\
& e^+\nu_e\overline{\nu}_\mu
\end{tikzcd}$$

$\Rightarrow$ 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 disfavoured 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

Three detectors scenario

Water Čerenkov detector á la SuperK (40% PMT coverage) with 40 kton fiducial mass

- $\epsilon_s \sim 70\%$ (from a full simulation + analysis)
- $f_B(\pi^0\ /e) \sim 0.002$ (full simulation + analysis using energy flow fitter to identify π^0)
- $f_B(\mu/e) \sim 0.001$ (full simulation)
- $f_B\ (\mathrm{Beam}) \sim 0.003$ (full simulation of beam)

f_B are normalized to the ν_μ CC rate

Liquid scintillator á la MiniBoone (10% PMT coverage) with 40 kton fiducial mass

- $\epsilon_s \sim 50\%$ (using MiniBoone numbers)
- $f_B(\pi^0\ /e) \sim 0.001$ (using MiniBoone numbers)
- $f_B(\mu/e) \sim 0.001$ (using MiniBoone numbers)
- $f_B\ (\mathrm{Beam}) \sim 0.003$ (full simulation of beam)

Water Čerenkov detector á la SuperK with 400 kton fiducial mass

- Extrapolated from the 40 kton detector

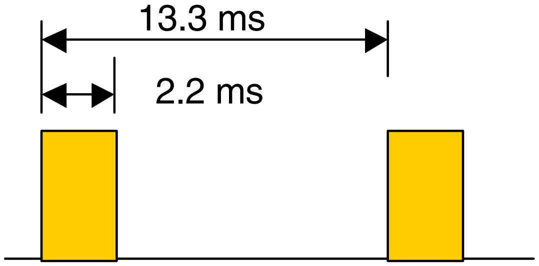
Reducing atmospheric neutrino background with the accumulator

SubGeV nue like events forward, 200 kton year ≈ 1500 events

SuperBeam≈ 10 events

Reduction needed: 150

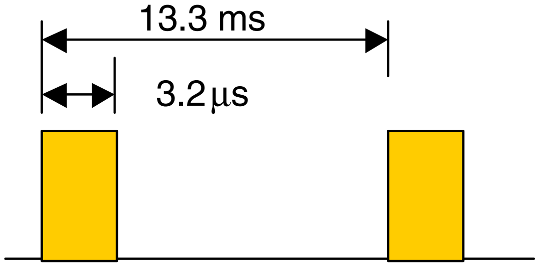
From SPL



13.3 ms/2.2 ms = **6**

NOT enough!

After NuFact accumulator



13.3 ms/3.2 10^{3-} ms = **4000**

Bunch Compressor

Could provide and additional reduction factor 30

Water Čerenkov: Particle Identification Cut

Use Čerenkov light pattern (including opening angle, if possible) as primary μ rejection

Tighten cut to reduce miss-ID further

ν_e CC efficiency: 94%

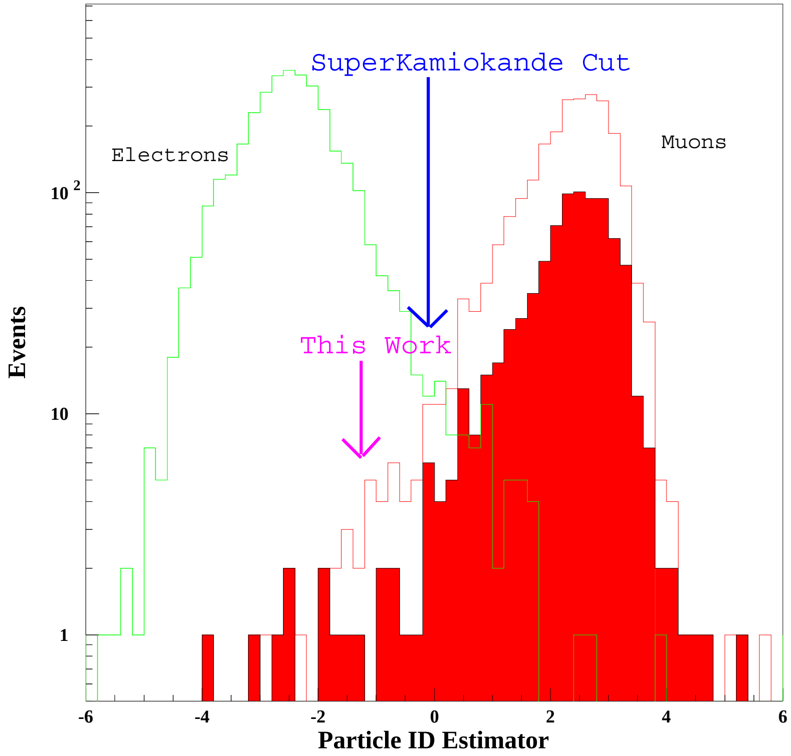
ν_μ CC efficiency: $\sim 1\%$

Muon decay identification using delayed coincidence

Only $\sim 22\%$ of μ^- absorbed before decay.

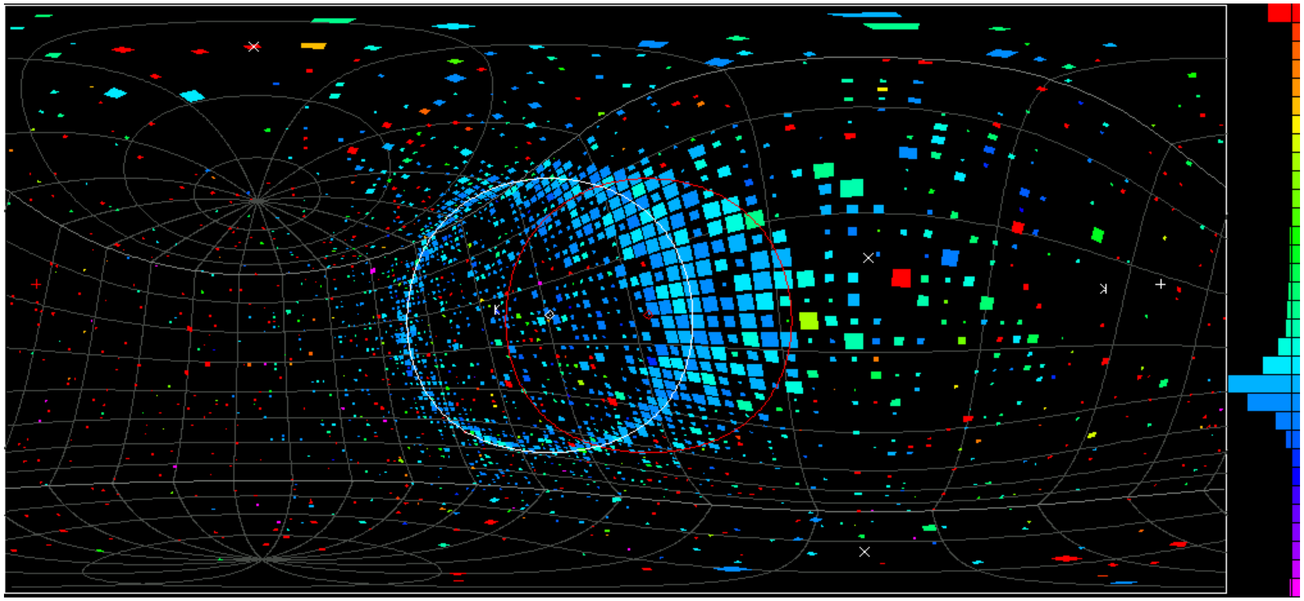
Visible energy cut:

$\mathrm{E_{vis}} > 100\ MeV \Rightarrow \nu_\mu$ CC efficiency: $\sim 0.1\%$



π°/e background rejection based on sophisticated energy flow fitter

When the standard SuperK algorithm finds a single electron-like ring, a special algorithm is started that always identifies second candidate. Electron is identified if $m_{\gamma\gamma} < 45\ MeV$.



Final Background Rejection

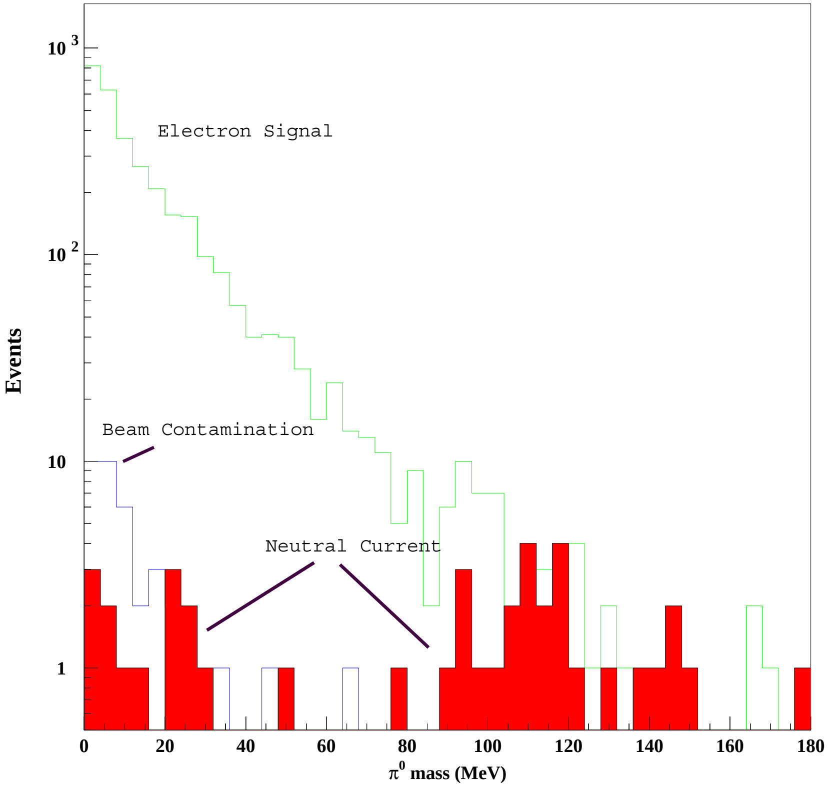
Apply energy flow fitter to surviving events

Accept events if $m_{\gamma\gamma} < 45 MeV$

π^0 /e at 0.1% level

μ/e at 0.1% level

Signal efficiency very high $(\sim 70\%)$



Final event rates for a 200 kton-year exposure

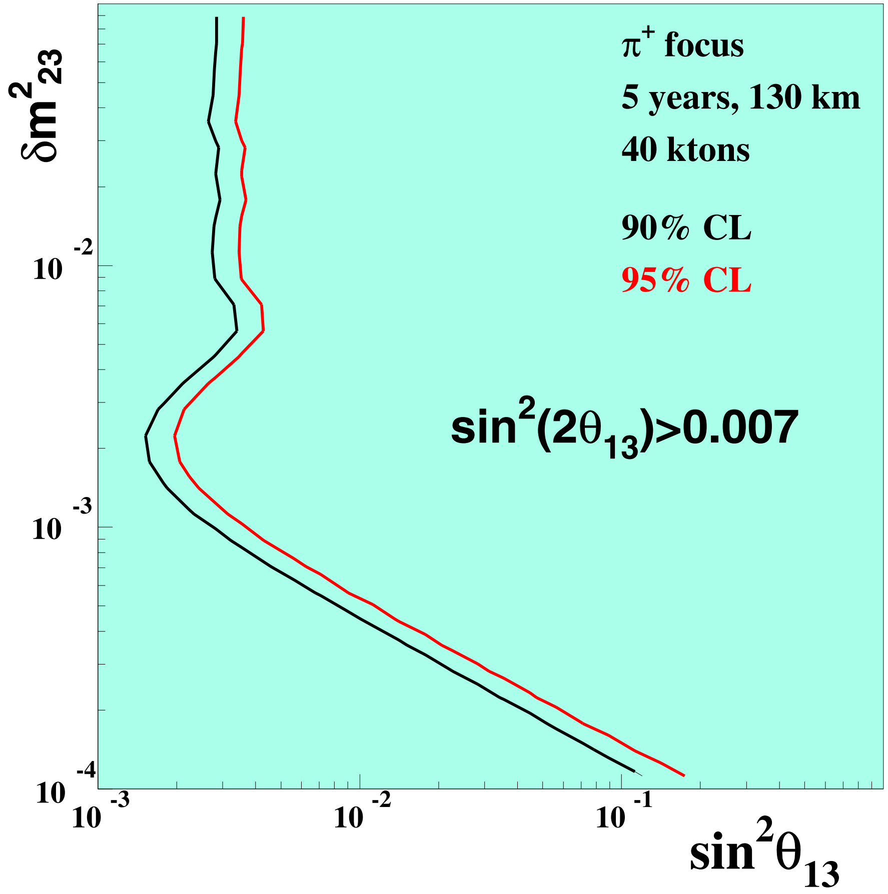
ν_μ CC are computed NEGLECTING $p(\nu_\mu \to \nu_\mu)$. ν_μ disappearance reduces ν_μ background by an additional factor 5.

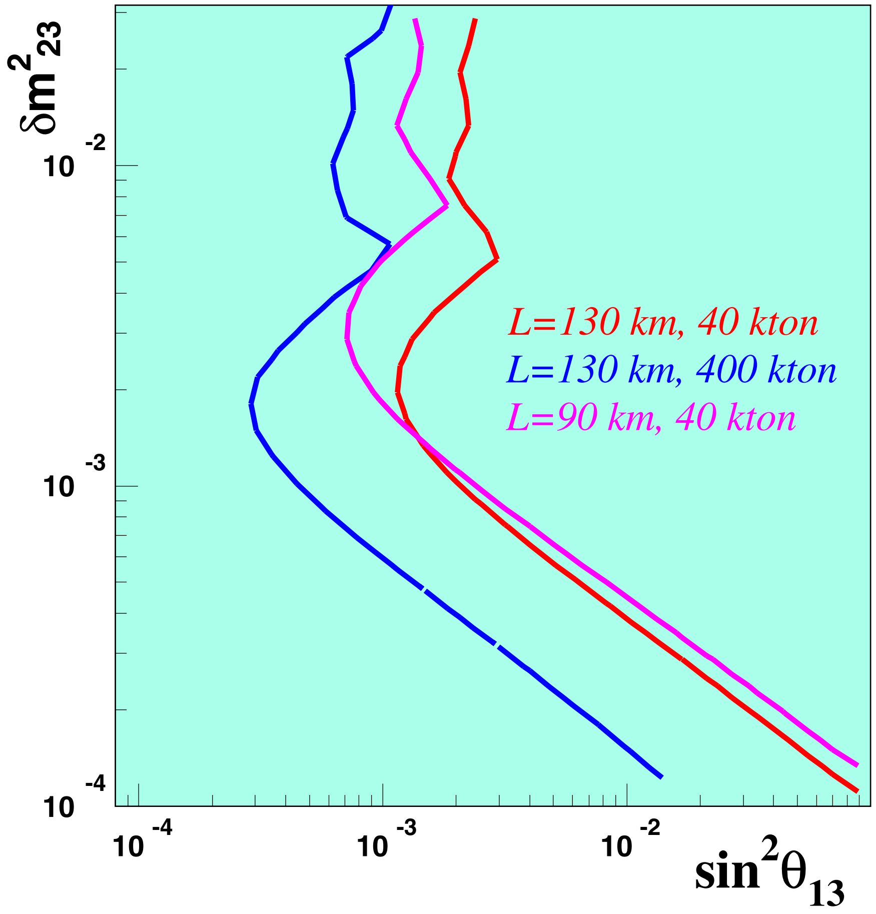
Water Čerenkov, π^+ focused beam						
Channel	Initial sample	Visible events	Single-ring $100 - 450\ MeV$	Tight PID	No $\mu \to$ e	$m_{\gamma\gamma} < 45$ (MeV/c^2)
ν_μ CC	3250	887	578	5.5	2.5	1.5
ν_e CC	18	12	8.2	8.0	8.0	7.8
NC	2887	37	8.7	7.7	7.7	7.5
$\nu_\mu \to \nu_e$		82.4%	77.2%	76.5%	70.7%	70.5%
Water Čerenkov, π^- focused beam						
ν_μ CC	539	186	123	2.3	0.7	0.7
ν_e CC	4	3.3	3.	2.7	2.7	2.7
NC	687	11.7	3.3	3.	3.	0.3
$\overline{\nu}_\mu \to \overline{\nu}_e$		79.3%	74.1%	74.0%	67.1%	67.1%

Liquid Scintillator

π^+ focused beam			π^- focused beam		
Channel	Initial sample	Final sample	Channel	Initial sample	Final sample
$\nu_\mu{}^{CC}$	2538	2	$\overline{\nu}_\mu{}^{CC}$	451	0.5
$\nu_e{}^{CC}$	12	6	$\overline{\nu}_e{}^{CC}$	2.3	1
NC (visible)	48	0.5	NC	10	0.1
$\nu_\mu \to \nu_e$	100%	50%	$\overline{\nu}_\mu \to \overline{\nu}_e$	100%	50 %

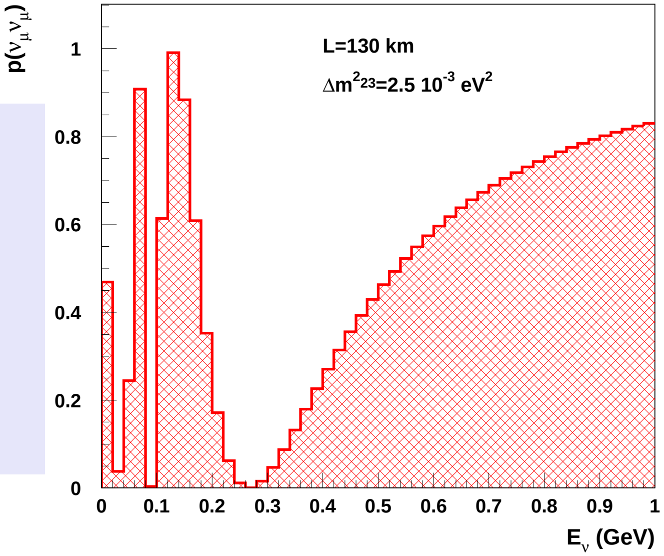
Sensitivity curves



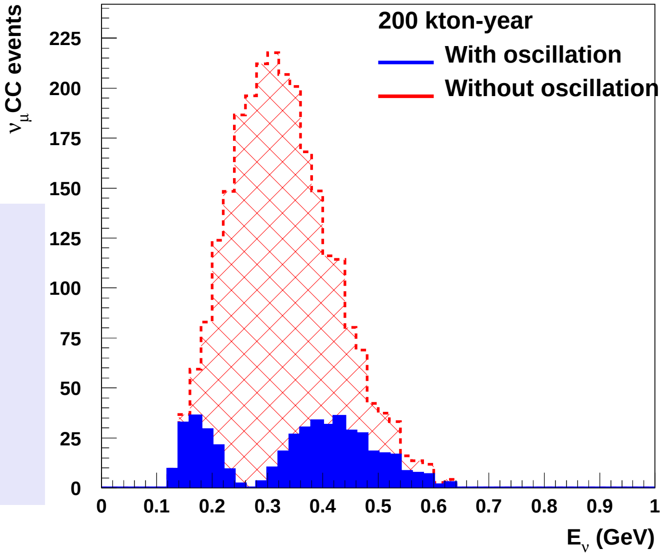


ν_μ disappearance experiment (liquid scintillator detector).

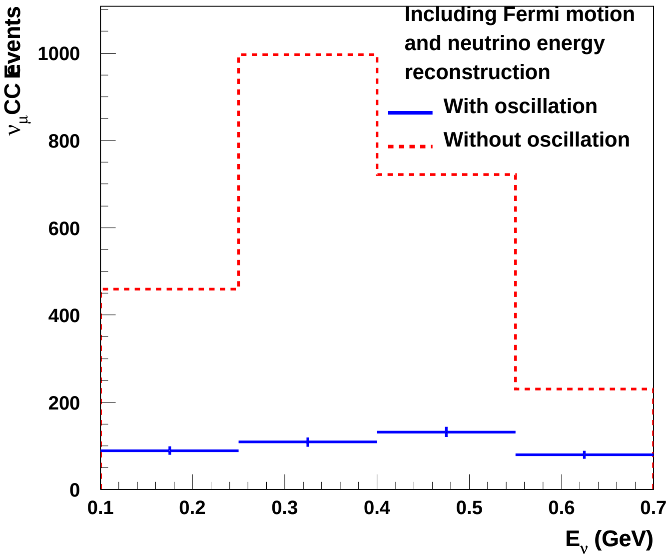
At $L \sim 130$ km the far detector is just above the first minimum of $p(\nu_\mu \rightarrow \nu_\mu)$



The potentiality of a ν_μ disappearance experiment is spectacular.



ν_μ CC distribution having included Fermi motion and detector resolution.

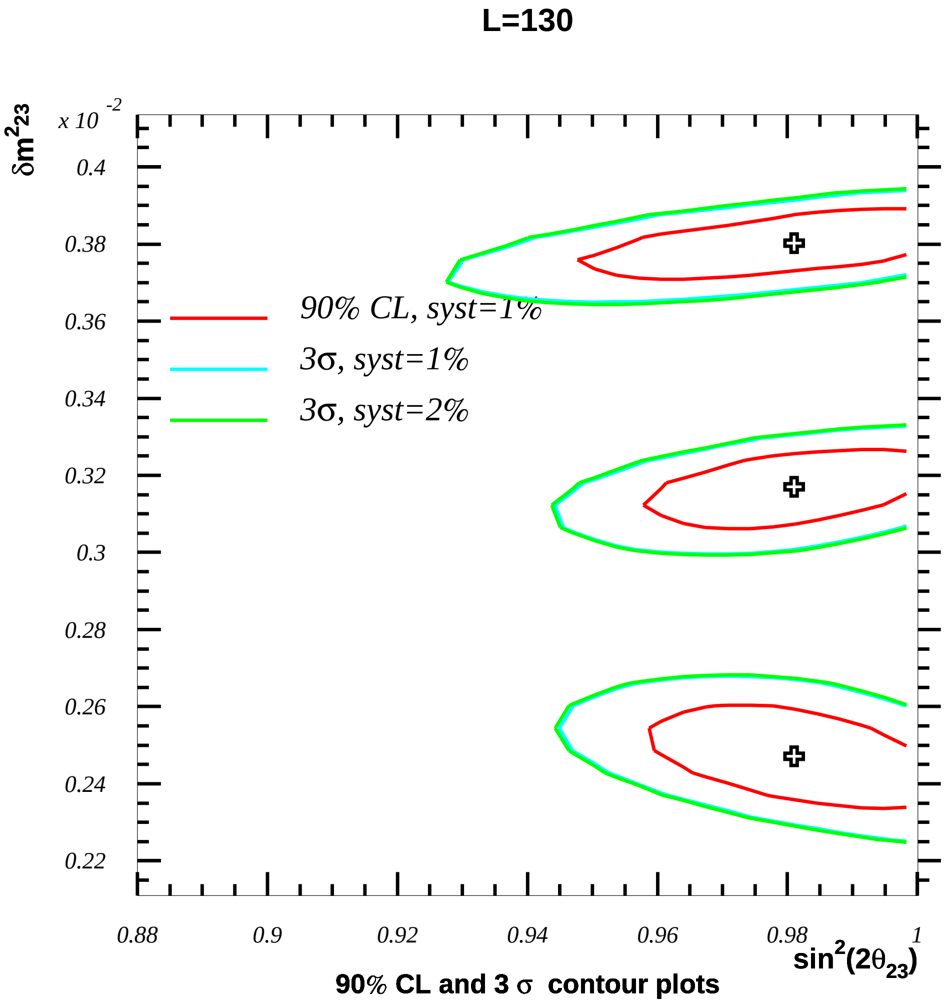


Sensitivity on δm^2_{23} and $sin^2(2\theta_{23})$

- Take three testing points at $\sin^2 2\theta_{23} = 0.98$, $\delta m^2_{23} = 3.8,\ 3.2,\ 2.5 \cdot 10^{-3}\,\mathrm{eV}^2$
- 200 kton-year exposure
- 2% systematic errors

$\Downarrow$

- $\sin^2 2\theta_{23}$ measured at 1%
- δm^2_{23} measured with $\sim 1 \cdot 10^{-4}$ resolution



90% CL and 3 σ contour plots

A preliminary exercise on CP sensitivity

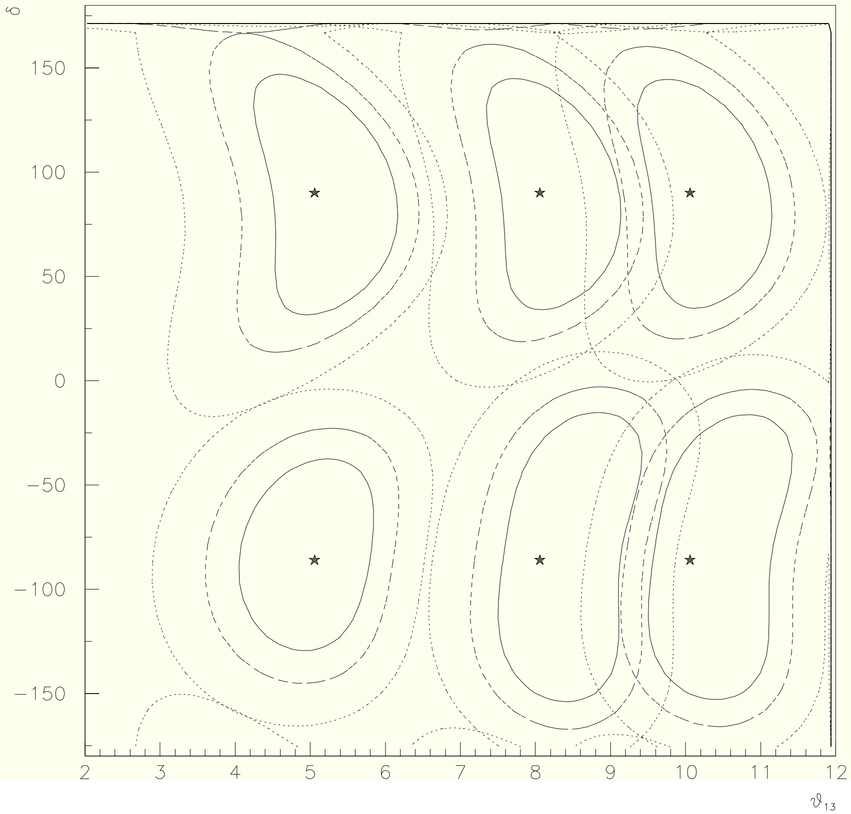
- Assume the upper value of LMA: $\delta m^2_{12} = 10^{-4}\ eV^2$
- The CP violating observable is $\frac{N(e^+)-N(e^-)}{N(e^+)+N(e^-)}$, corrected for the different fluxes and cross sections. Here $e^-(e^+)$ indicates all the e-like events selected with the $\pi^+(\pi^-)$ focused beam.
- Run for 2 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 $\theta_{13} = 5^\circ, 8^\circ, 10^\circ$ ($sin^2(2\theta_{13}) = 0.03,\ 0.08,\ 0.12$) and a maximally violating CP phase, $\delta = \pm 90^\circ$

$\Downarrow$ (see figure)

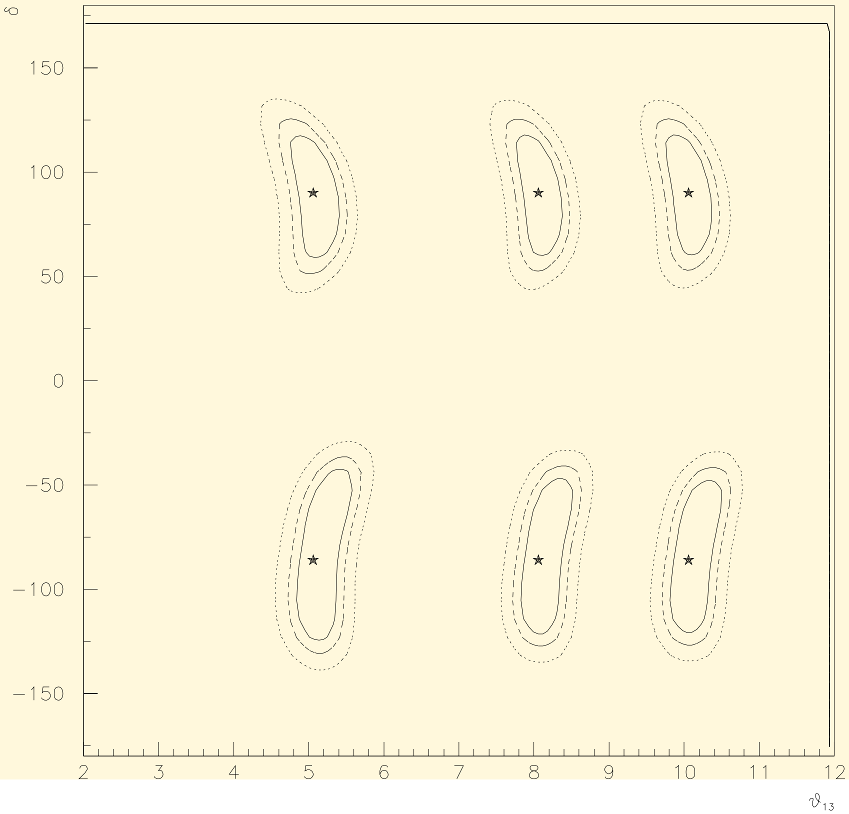
- CP sensitivity does not worsen very much with θ_{13}.
- In the 40 kton detector, 90% CL, a maximally violating CP phase ($\delta = \pm 90^\circ$) would be just distinguishable from a non violating CP phase ($\delta = 0^\circ$).
- With the 400 kton detector the prospects to observe CP violation are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



CERN-Modane

Two very good reasons to put the far detector deep underground:

- A detector 300 (3000) times bigger than LSND but with the same signal event rate cannot tolerate the sea-level througoing muon rate.
- It's well known that a 40 (400) kton detector deep underground would have outstanding capabilities on other themes like proton decay, atmospheric neutrinos, supernovae neutrinos, possibly solar neutrinos.

Two long highway tunnels exist at about 100 km from CERN: Monte Bianco (90 km) and Frejus (130 km), both tunnels connect Italy to France. In the Monte Bianco tunnel the Nusex experiment was performed, the underground Modane laboratory at Frejus, 5000 m^3, hosts the Nemo and Edelweiss experiments.

Excaving works to dig a safety tunnel will probably start at Frejus.

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 $50 \times 25 \times 800\ m$ 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.

An international workshop will be organized at CERN by the end of the year: "Workshop on large detector for ν SuperBeam, p decay and atmospheric ν's", jointly with the UNO collaboration and hopefully with HyperK.

Conclusions

- A full simulation of the beam line and neutrino events together with real analysis of the events have been performed.
- Low energy is the best option for SuperBeams as far as concern backgrounds.
- Very MASSIVE detectors are needed
- Čerenkov detectors guarantee the necessary performances $\Rightarrow$ SuperBeam + proton decay+ atmospheric and supernovae neutrinos at the same time.
- A 40 kton (fiducial) detector can:
  - Detect $\sin^2(2\theta_{13})$ if $\sin^2(2\theta_{13}) \geq 0.007\,(90\%\,CL)$
  - Measure $\sin^2(2\theta_{23})$ with 1-2% resolution
  - Measure δm^2_{23} with $10^{-4}\,eV^2$ resolution.
  - Detect CP violating effects at 90%CL in a small region of parameters space.
- A 400 kton (fiducial) detector can:
  - Detect $\sin^2(2\theta_{13})$ if $\sin^2(2\theta_{13}) \geq 10^{-3}\,(90\%\,CL)$
  - Detect CP violating effects at more than 3σ in a wider range of parameters space.