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“ Discussion on Future Neutrino Beams”

Part of the material of this talk comes from A. Guglielmi, M. Mezzetto, P. Migliozzi, F. Terranova, paper in preparation.

LNGS, 11 may 2005.

The importance of ν oscillations.

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.

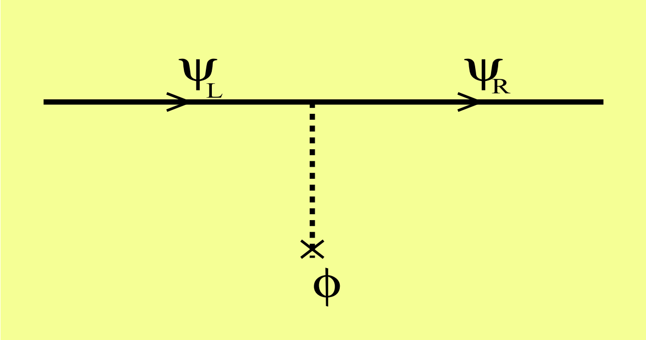
They open the perspective of the measure of **leptonic CP violation.**

Leptons are VERY different from quarks. (I)

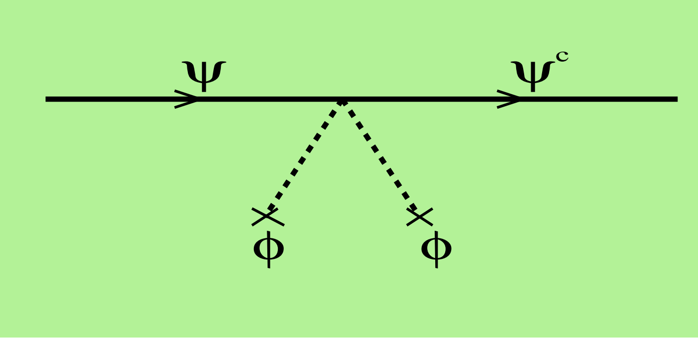
$$u \sim 5\ \mathrm{MeV} \quad c \sim 1\ \mathrm{GeV} \quad t \sim 175\mathrm{GeV}$$
$$d \sim 8\ \mathrm{MeV} \quad s \sim 0.1\ \mathrm{GeV} \quad b \sim 5\mathrm{GeV}$$

$$e \sim 0.5\ \mathrm{MeV} \quad \mu \sim 0.1\ \mathrm{GeV} \quad \tau \sim 2\mathrm{GeV}$$
$$\nu_e \leq \mathcal{O}(1\,eV) \quad \nu_\mu \leq \mathcal{O}(1\,eV) \quad \nu_\tau \leq \mathcal{O}(1\,eV)$$

How can the same model generate mass ratio so different?



$$\lambda_\nu \overline{\Psi}_R \Phi \Psi_L + h.c.$$
$$m_f = \lambda_f v$$
$$L$$



$$\frac{\alpha_\nu}{M} \nu_L^T C \tilde{\Phi}^T \tilde{\Phi} \nu_L + h.c.$$
$$m_f = \alpha_\nu \frac{v^2}{M}$$
$$\not{L}$$

A new physics scale, M, can explain the new hierarchy (if at the GUT scale) and is associated to the breaking of a global symmetry of the SM: total lepton number L.

Leptons are VERY different from quarks. (II)

Solar+Atmospherics indicate a quasi bi-maximal mixing matrix, **VERY DIFFERENT from CKM matrix (almost diagonal)!**

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

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

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

the necessary milestone for any subsequent search:

neutrino mass hierarchy and leptonic CP searches.

Most of the parameters are waiting to be measured

δm^2_{12} ☑

SOLARS+KAMLAND

$\delta m^2_{12} = (7 +/- 1)\ 10^{-5}\ \mathrm{eV}^2$

θ_{12} ☑

SOLARS+KAMLAND

$0.2 < \sin^2(\theta_{12}) < 0.5$

Addressed by a SuperBeam/Nufact experiment

δm^2_{23} ☑

ATMOSPHERICS

$\delta m^2_{23} = (2.0 +/- 0.4)\ 10^{-3}\ \mathrm{eV}^2$

θ_{23} ☑

ATMOSPHERICS

$0.9 < \sin^2 2(\theta_{23}) < 1$

θ_{13} ☐

CHOOZ LIMIT

$\theta_{13} < 14^0$

δ_{CP} ☐

Mass hierarchy ☐

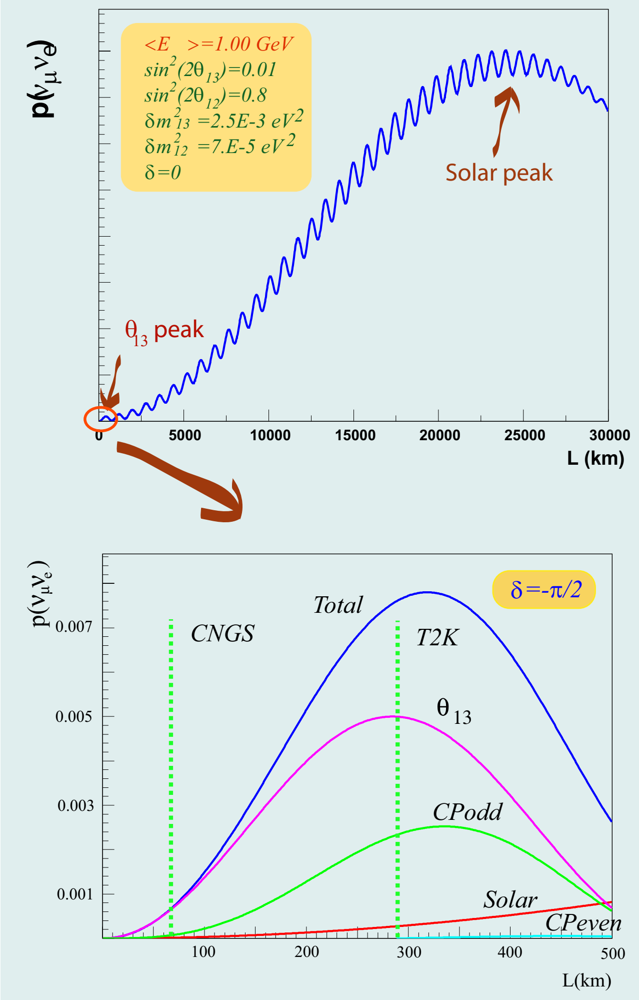
Σm_ν ☐

BETA DECAY END POINT

$\Sigma m_\nu < 6.6$ eV

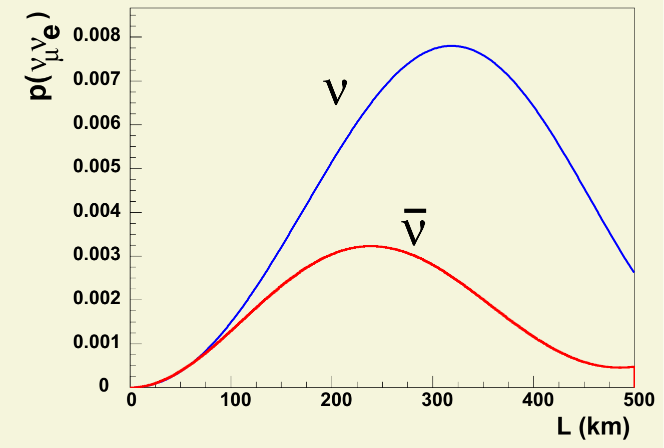
Dirac/Majorana ☐

Sub leading $\nu_\mu - \nu_e$ oscillations



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

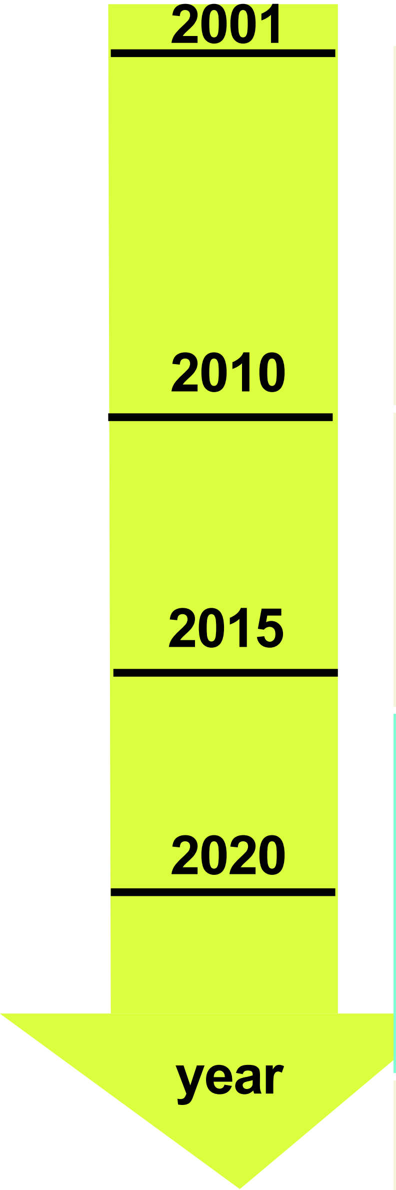
θ_{13} discovery requires total probability greater than solar driven probability



Leptonic CP discovery requires

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} \neq 0$$

At least 4 phases of Long Baseline experiments



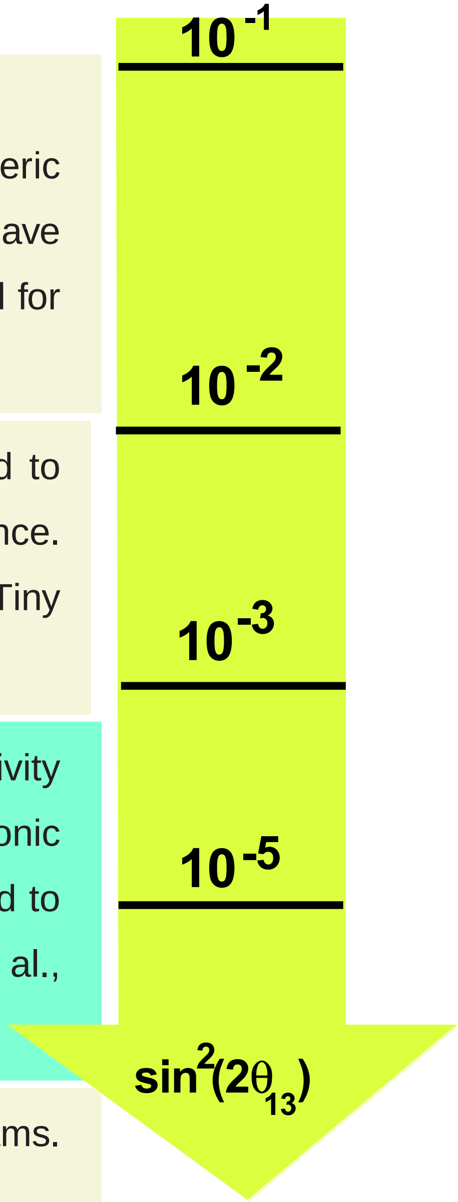
1) 2001-2010. K2K, Opera, Icarus, Minos.

Optimized to confirm the SuperK evidence of oscillation of atmospheric neutrinos through ν_μ disappearance or ν_τ appearance. They will have limited potential in measuring oscillation parameters. Not optimized for $\nu_e$appearance (θ_{13} discovery).

2) 2009-2015. T2K (approved), Noνa, Double Chooz. Optimized to measure θ_{13} (Chooz $\times$ 20) through $\nu_e$appearance or $\nu_e$disappearance. Precision measure of the atmospheric parameters (1 % level). Tiny discovery potential for CP phase δ, even combining their results.

3) 2015 - 2025. SuperBeams and/or Beta Beams. Improved sensitivity on θ_{13} (Chooz $\times$ 200). They will have discovery potential for leptonic CP violation and mass hierarchy for $\theta_{13} \geq 1^\circ$. In any case needed to remove any degeneracy from Nufact results (see P. Hernandez et al., hep-ph/0207080)

4) Ultimate facility: Neutrino Factories or high energy Beta Beams. Ultimate sensitivity on the CP phase δ, θ_{13} , mass hierarchy.



Status after the first and secong generation: θ_{13}

Computed with:

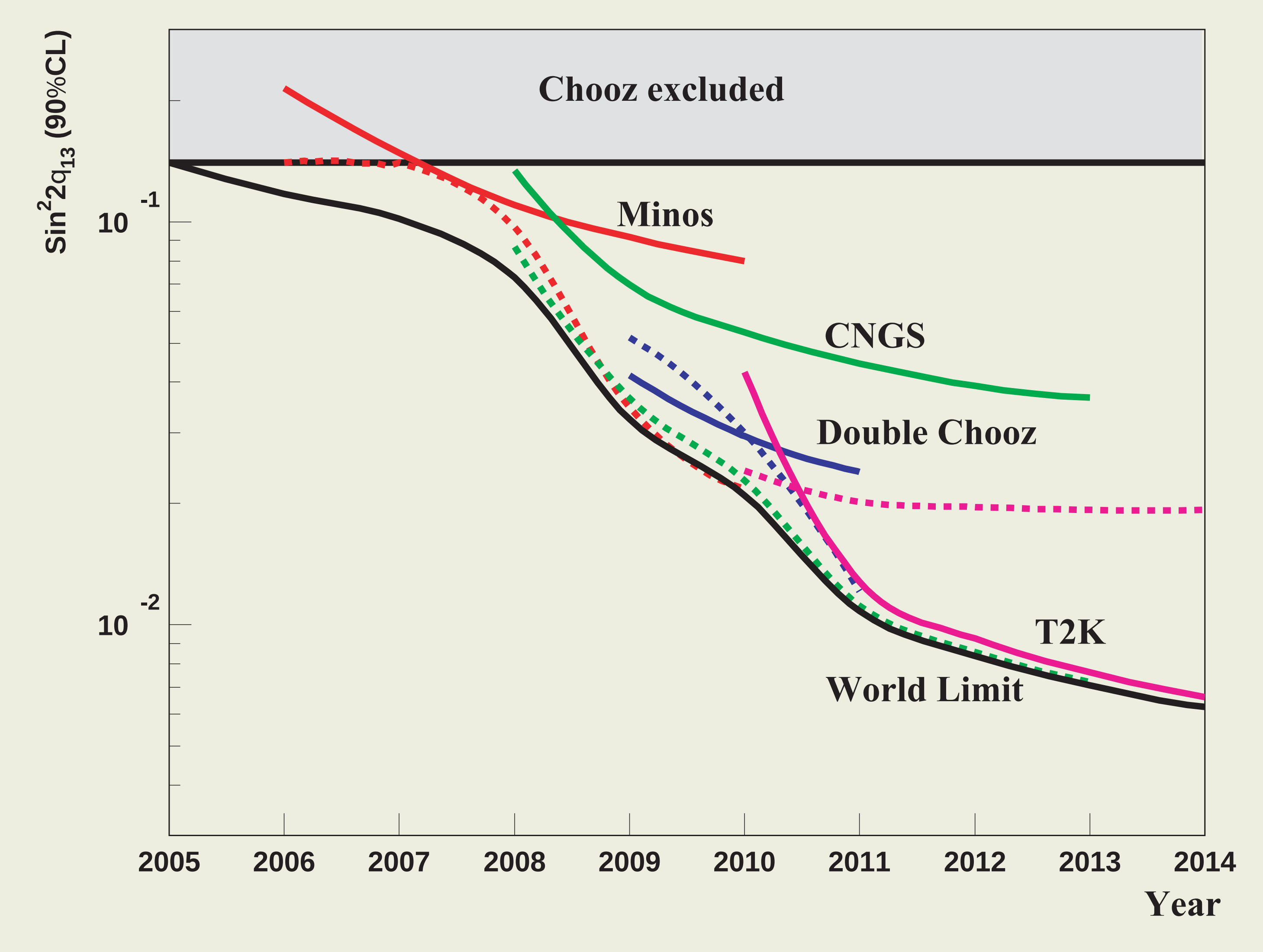
MINOS: Start in 2005, 5 years integrating $14 \cdot 10^{21}$ pot

OPERA: Full detector since 2007

ICARUS: Full detector (3 kton) since 2008

Double Chooz: start in 2008

T2K: start in 2009, first year at 10% of nominal luminosity.



Solid lines:

Experimental sensitivity of the single experiment

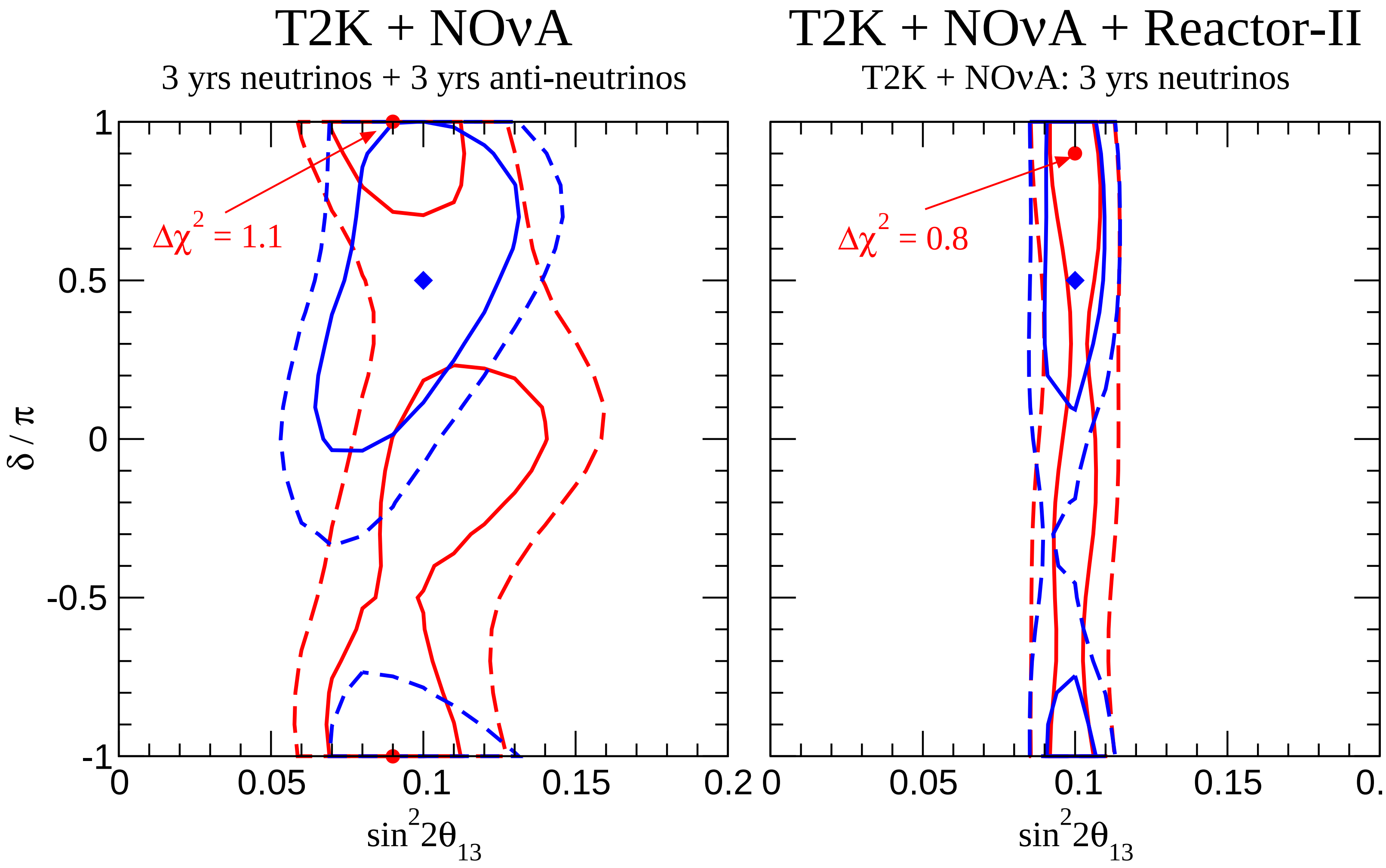
Dotted lines:

World limit without the single experiment

Status after the first and second generation: δ_{CP}

From P. Huber, M. Lindner, M. Rolinec, T. Schwetz and W. Winter, hep-ph/0412133.

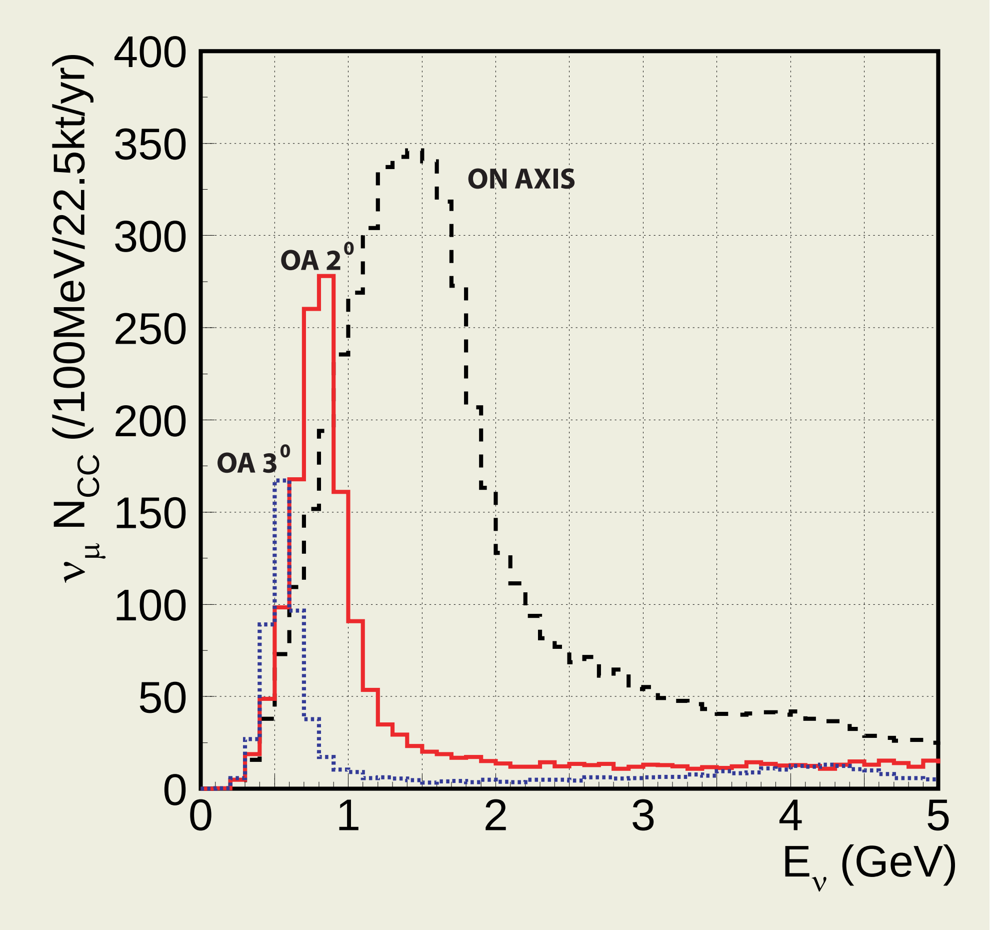
No hope to see any CP signal at 3σ (dotted lines, solid are 90%CL)



JHF-Japan Hadron Facility at Jaeri

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

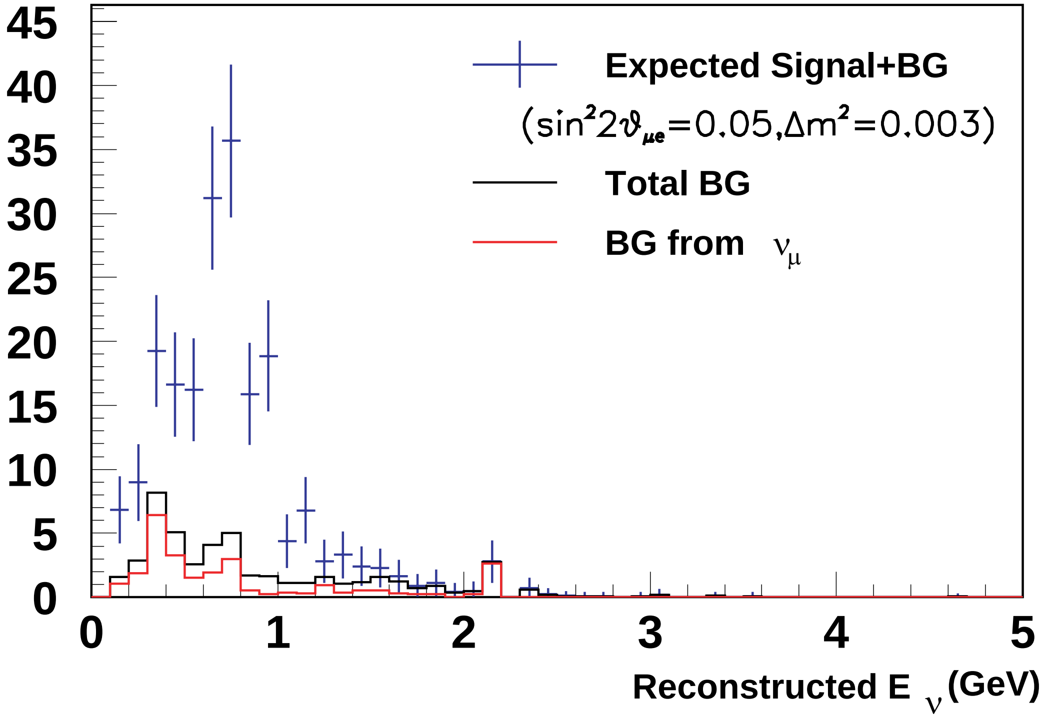
Taken off-axis to better match the oscillation maximum at the SuperKamiokande location (295 km).



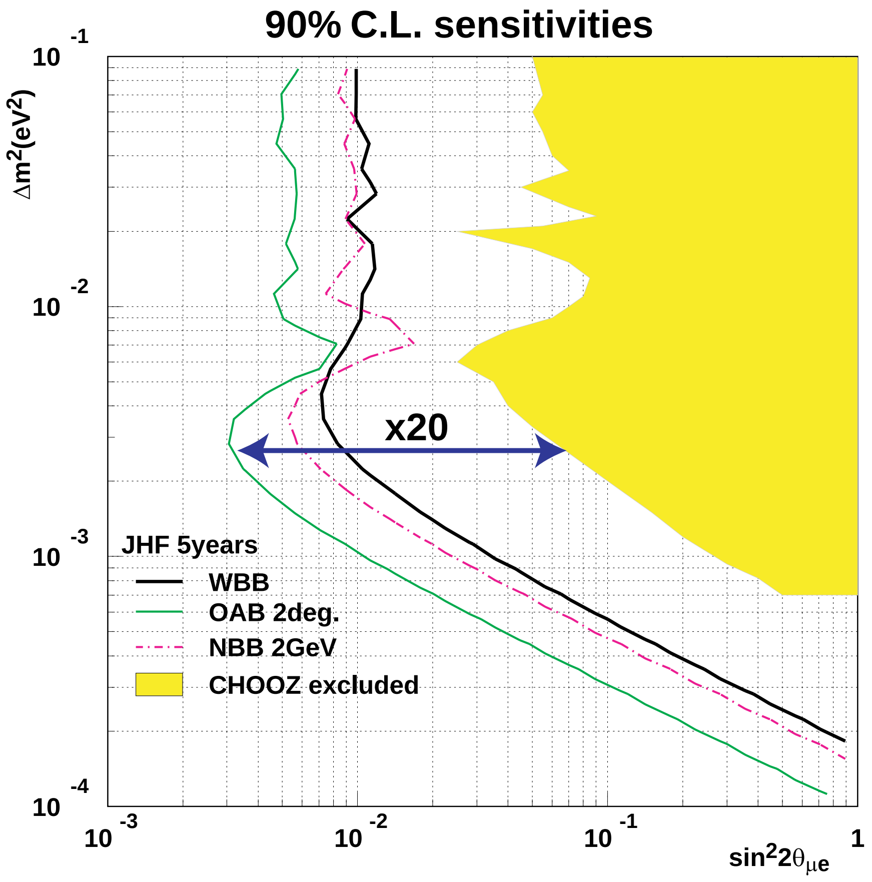
K2K		T2K
$6 \cdot 10^{12}$	Protons per pulse	$3 \cdot 10^{14}$
2.2 s	Cycle	3.4 s
12 GeV	Proton energy	50 GeV
40	Events in SK per year (no osc.)	2200
1.5	Mean neutrino energy	0.8

T2K ν_e appearance

OAB 2°	ν_μ CC	ν_μ NC	ν_e CC	Osc. ν_e
Generated in F.V.	10713.6	4080.3	292.1	301.6
1R e-like	14.3	247.1	68.4	203.7
e/π^0 separation	3.5	23.0	21.9	152.2
0.4 GeV$< E_{rec} < 1.2$ GeV	1.8	9.3	11.1	123.2

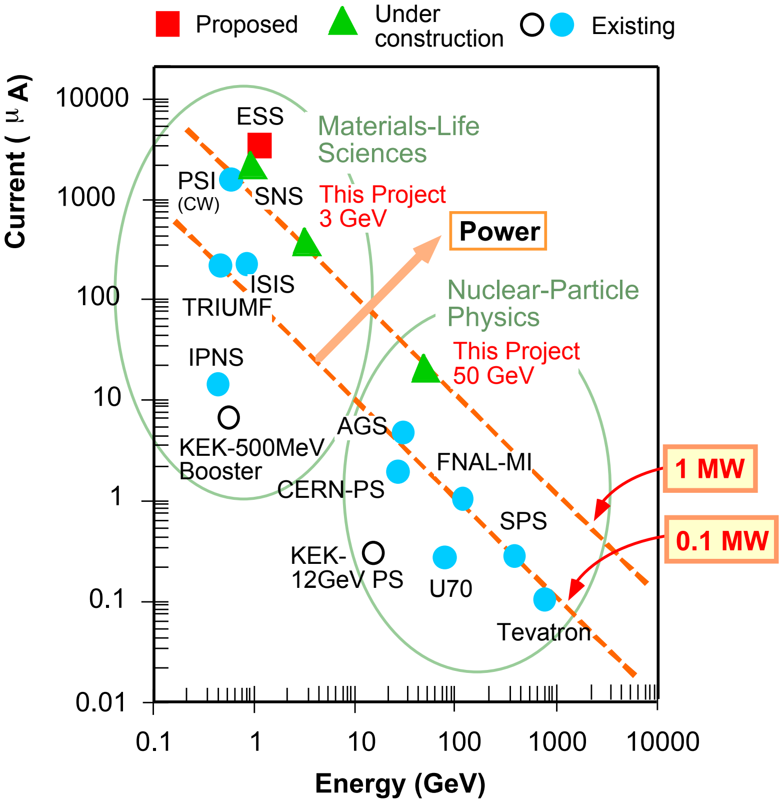


Sensitivity to θ_{13}



After T2K, in the standard scenario

	Mass (kton)	Start	Energy range (GeV)
Water Cerenkov	50	1996	0.005 - 10
Iron calo.	5.4	2004	> 0.5
Nucl. Emulsions	1.8	2006	1-100
Liquid Argon	0.6 $\rightarrow$ 3.0	2001	0.001-100
Low Z calo.	30	2011	0.1-10



Any major improvement of T2K will be extremely expensive:

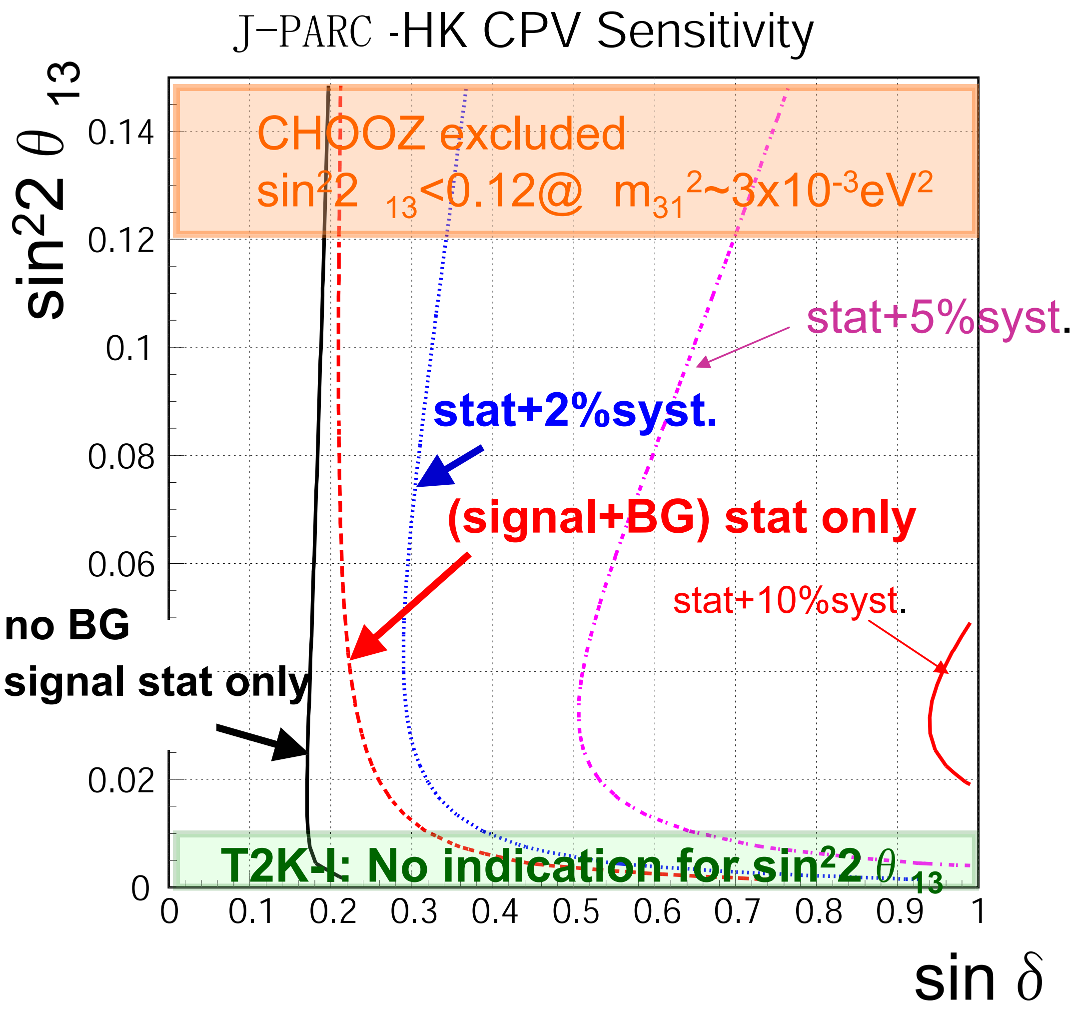
- θ_{13} **sensitivity roughly scales as** $\sqrt{N_\nu}$
- The proton driver is a next generation machine
- The detector is 10 times bigger of the second biggest: Minos.
- The design of close detectors system is challenging, but T2K will provide a very valuable first setup.

The knowledge of θ_{13} is necessary to guarantee the conditions to measure δ and to optimize the facility.

Any future initiative should have enough physics potential besides neutrino oscillations to justify the risk of starting the Leptonic CP violation searches without any guarantee.

SuperBeams - J-PARC phase 2

T. Kobayashi, J.Phys.G29:1493(2003)



Upgrade the proton driver from 0.75 MW to 4 MW

Upgrade SuperKamiokande by a factor $\sim 20 \Longrightarrow$ HyperKamiokande

Both upgrades are necessary to address leptonic CP searches.

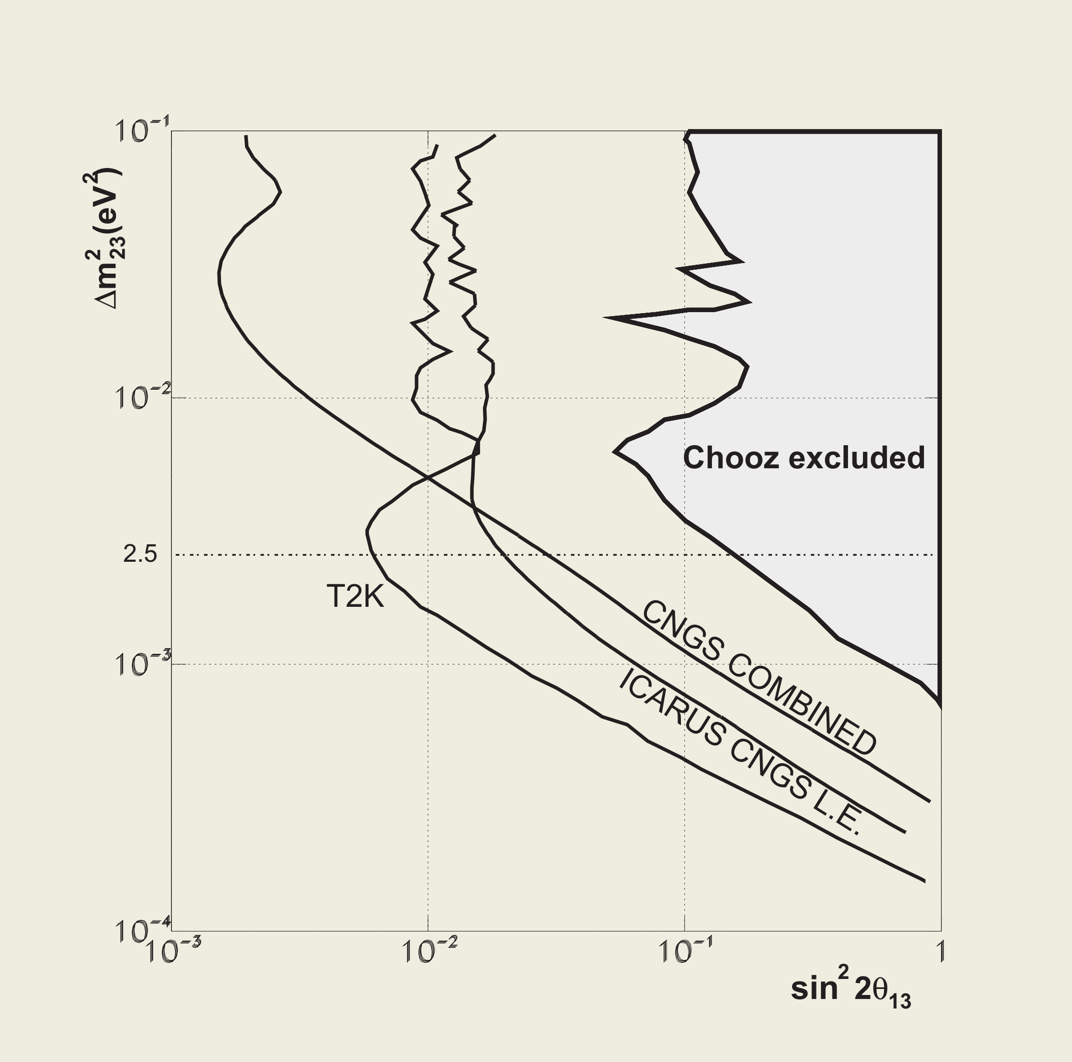
Systematics at 2% are tight

4 MW at 50 GeV/c are tight

Target and optics at 4 MW are tight and will probably require some compromise

CNGS Low Energy

A. Rubbia and P. Sala, JHEP **0209** (2002) 004, hep-ph/0207084.



Tune the CNGS to lower energies, to optimize it for $\nu_\mu \rightarrow \nu_e$transitions.

Change the optics, shorten the decay length (from 1 km to 350 m), enlarge the decay tunnel (from $\phi = 122$ cm to 350 cm).

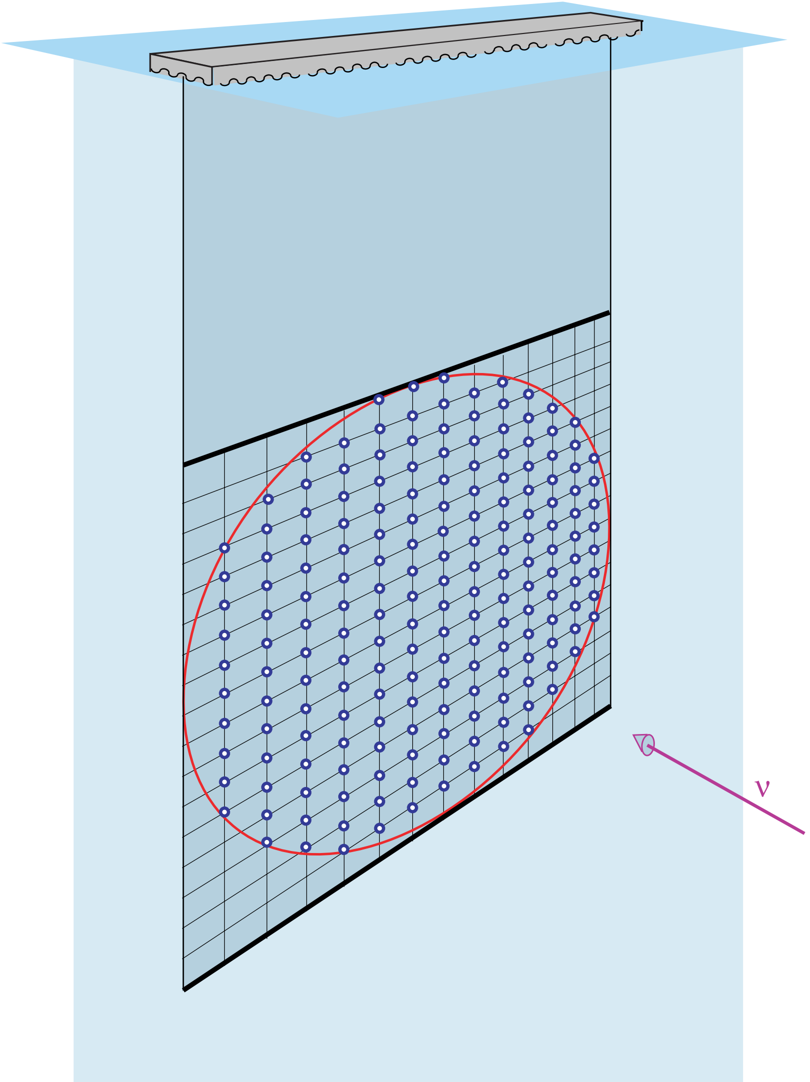
Not compatible with CNGS. Operations in the beam line require “radioactive cooling” (3 years ?). Alternatively build a new beam line.

Mean neutrino energy: ~ 1.5 GeV. Opera useless at these energies.

CNGT (Cern to Golfo di Taranto)

A.E.Ball et al., CERN-SPSC-2004-025,SPSC-M-723, 21 September, 2004.

- Use the low energy CNGS beam.
- Place a detector 1000 m underwater, 2° off-axis, in the Gulf of Taranto, moving it in TWO positions corresponding to the SECOND oscillation maximum and minimum.
- The detector should be made by 44000 PMTS, in a grid of 5m side, equipping a cone of 2 Mton of water.
- Impossible to design a close detector and very difficult to extimate the fiducial volume with tiny systematic errors.
- Sensitivity would be marginally worse than T2K, in a 5 years data taking.



PS ++

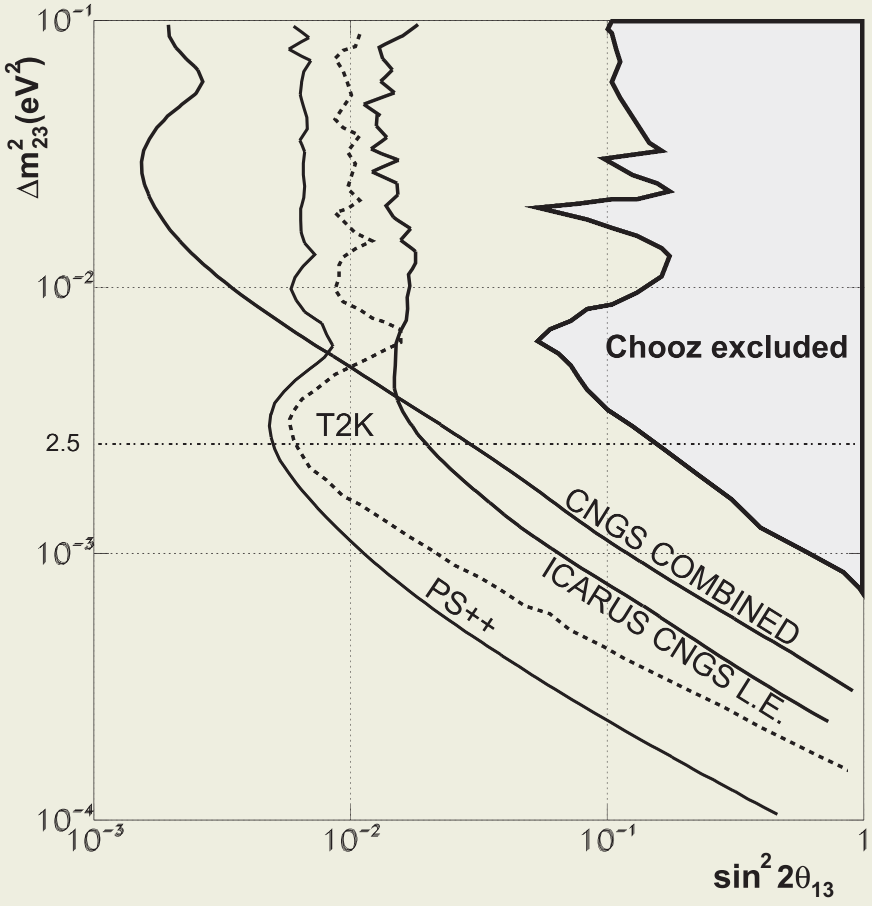
A. Ferrari, A. Rubbia, C. Rubbia and P. Sala, New J. Phys. **4** (2002) 88, hep-ph/0208047.

- Study the optimal proton driver and the optimal baseline for the Icarus detector at LNGS.
- Best option: 20 GeV PS at CERN.
- Sensitivity computed for 5 years at $2 \cdot 10^{22}$ p.o.t./year: 100 times the PS and corresponding to 6.5 MW in a 10^7 s standard year.
- Icarus 3 kton as detector.

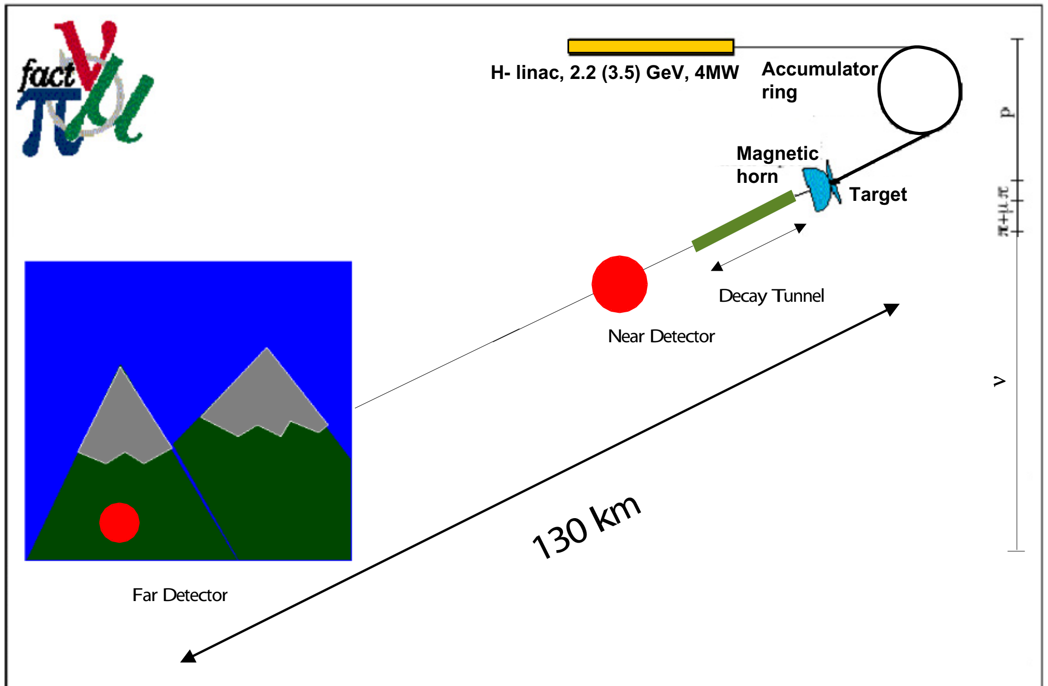
Sensitivity $\propto \sqrt{N_\nu}$.

Icarus numbers are computed with $\epsilon = 100\%$, background rejection=100%, no systematic errors.

Difficult to foresee a SuperBeam experiment capable to significantly improve the T2K sensitivity being hosted inside a LNGS hall.



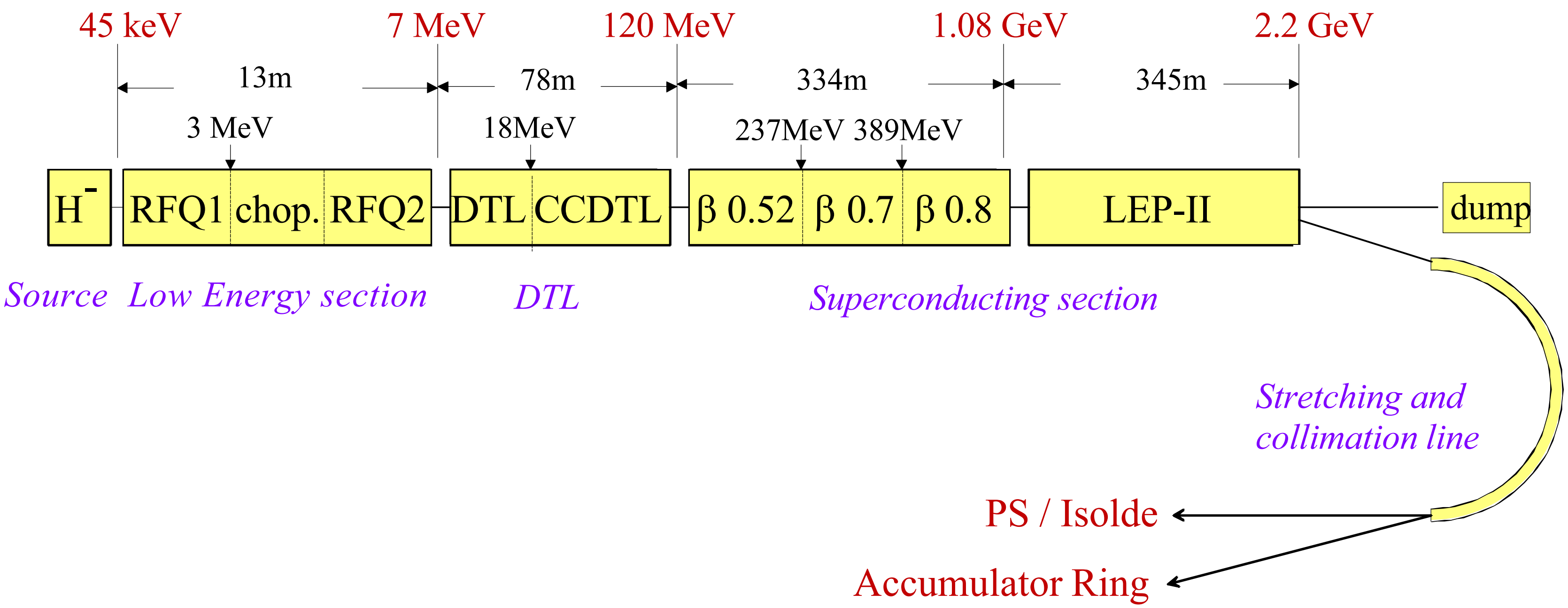
SuperBeams - SPL ν beam at CERN



Possible Low Energy Super Beam Layout

- A 2.2 or 3.5 GeV (kinetic energy) Linac, 4 MW.
- An accumulator (hosted in the ISR tunnel) to keep the duty cycle small. Necessary to keep low the atmospheric neutrino background.
- A liquid mercury target station capable to manage the 4 MW proton beam. R&D required.
- A conventional neutrino beam optics capable to survive to the heat, radiation and mercury. Already prototyped.
- Up to here is the first stage of a neutrino factory complex.
- A sophisticated close detector to measure at 2% signal and backgrounds.
- A megaton class detector under the Frejus, L=130 km

MW-Linac: SPL (Superconducting Proton Linac)



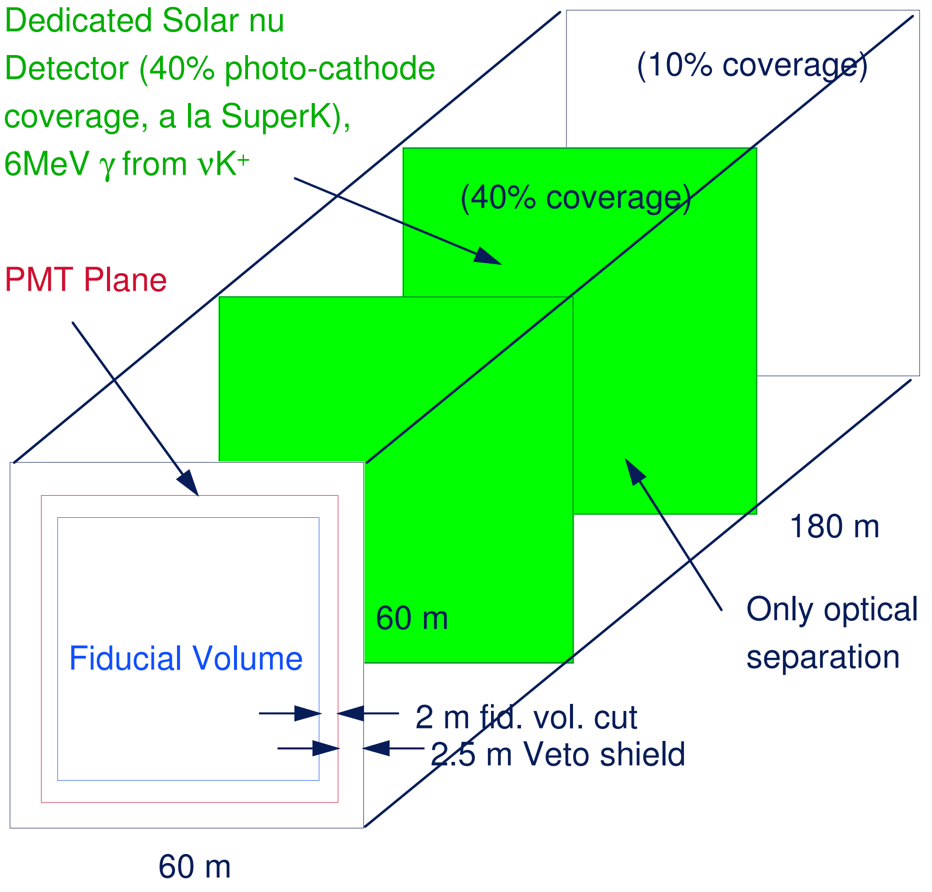
EKIN = 2.2 GeV
Power = 4 MW
Protons/s = 10^{16}

→

10^{23} protons/year

2 ma current
100 μa needed by Beta-Beam targets
It can accomodate both a conventional ν beam (SPL-SuperBeam) and a Beta Beam

UNO/HyperK detector



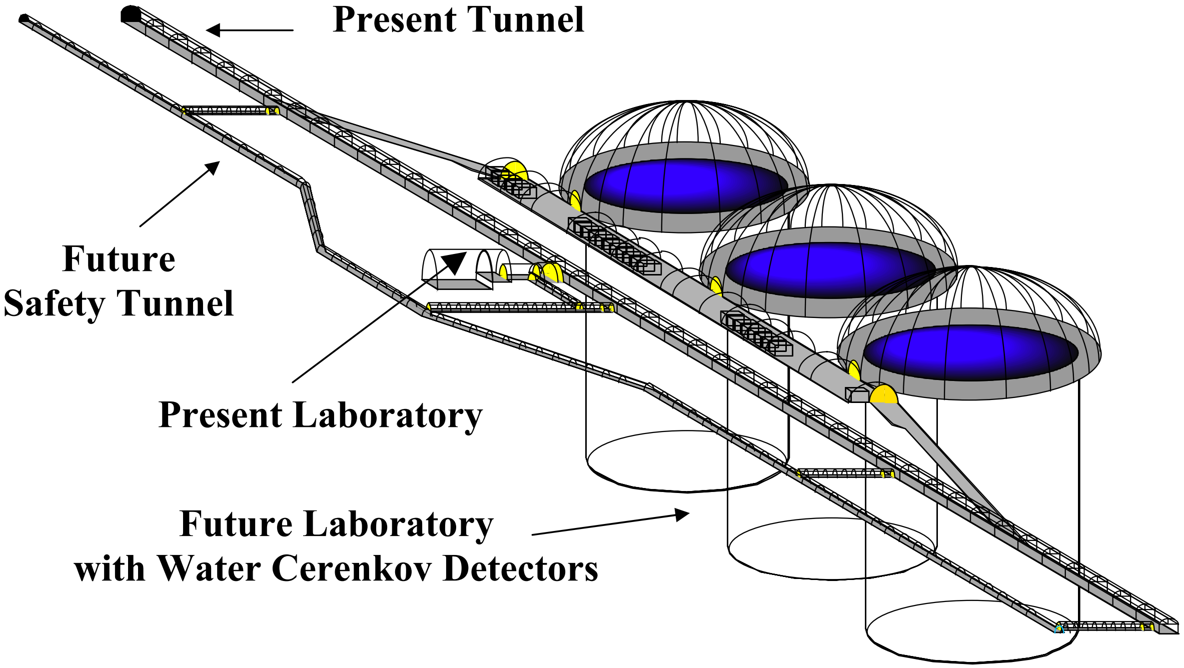
- Fiducial volume: 440 kton (HyperK has 540 kton): 20 times SuperK.
- 60000 PMTs (20") in the inner detector, 15000 PMTs in the outer veto detector.
- Energy resolution is poor for multi track events but quite adequate for sub-GeV neutrino interactions.
- Roughly quoted at 500M$ (including excavation). Timescale: 10 years.

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

The Frejus project

- The rock caracteristics and the distance to CERN make Frejus a unique opportunity to build a megaton detector.
- The only possibility to build such a detector is to have a worldwide collaboration, including japanese and americans from SuperKamiokande. (only one detector of this size is reasonable in the world)
- The second Frejus highway tunnel excavation will be finished in 2008
- This opens the possibility to dig the laboratory at a very reduced price
- 5+5 years since then is the (optimistic) schedule to have the detector ready.

-> a **very large Laboratory** to allow the installation of a **Megaton**-scale **Cerenkov** Detector (10^6 m^3)



Some comments about SPL SuperBeam

- Initially proposed as the first stage of the CERN neutrino factory (Nufact 01)
- Now seen as the first stage of the CERN Beta Beam (Nufact 02), with which could share the same detector.
- NOT very efficient in producing neutrinos: 37 events/kton/year at the optimal baseline, for 4 MW power, to be compared with the T2K ~ 100 events/kton/year at the optimal baseline (off axis), 0.75 MW power.
- The best option as far as concerns $\nu_e$contamination, being the protons below the kaon production threshold.
- When combined with the Beta Beam it improves CP sensitivity and allows for T and CPT searches in appearance mode.

A recent SPL SuperBeam optimization: 3.5 GeV is better

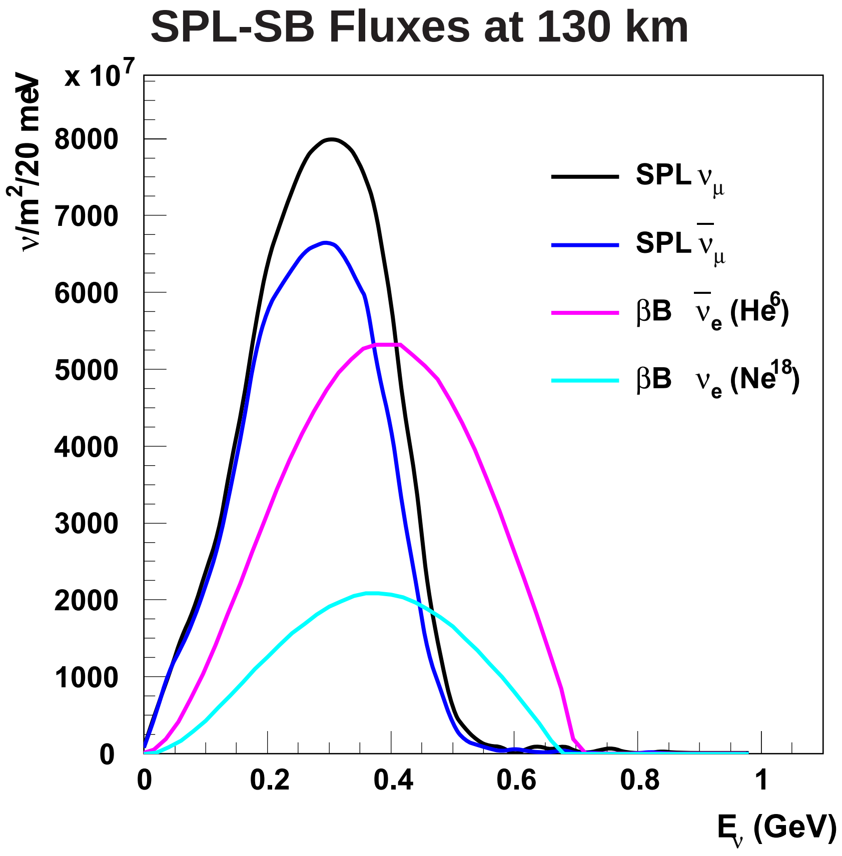
The 2.2 GeV kinetic energy of SPL was due to the re-use of the LEP RF cavities.

More recent RF cavities could increase the energy for the same Linac length.

This triggered a reoptimization of the SPL energy having in mind the SuperBeam physics reach.

SPL SB optimization has been computed by J.E. Campagne and A. Cazes, LAL, hep-ex/0411062

- Scan the proton driver energies from 2.2 to 8 GeV (4MW fixed).
- Keep the baseline fixed to 130 km
- From 3.5 GeV to above explore the possibility to focus higher momentum pions.
- The 3.5 GeV energy, with a neutrino beam with $\langle E_\nu \rangle \simeq 300 MeV$, decay length of 40 m and decay tunnel diameter of 2 m greatly improves the 2.2 GeV performances: ν_μ CC rate at 130 km from 37 to 122 events/kton/year

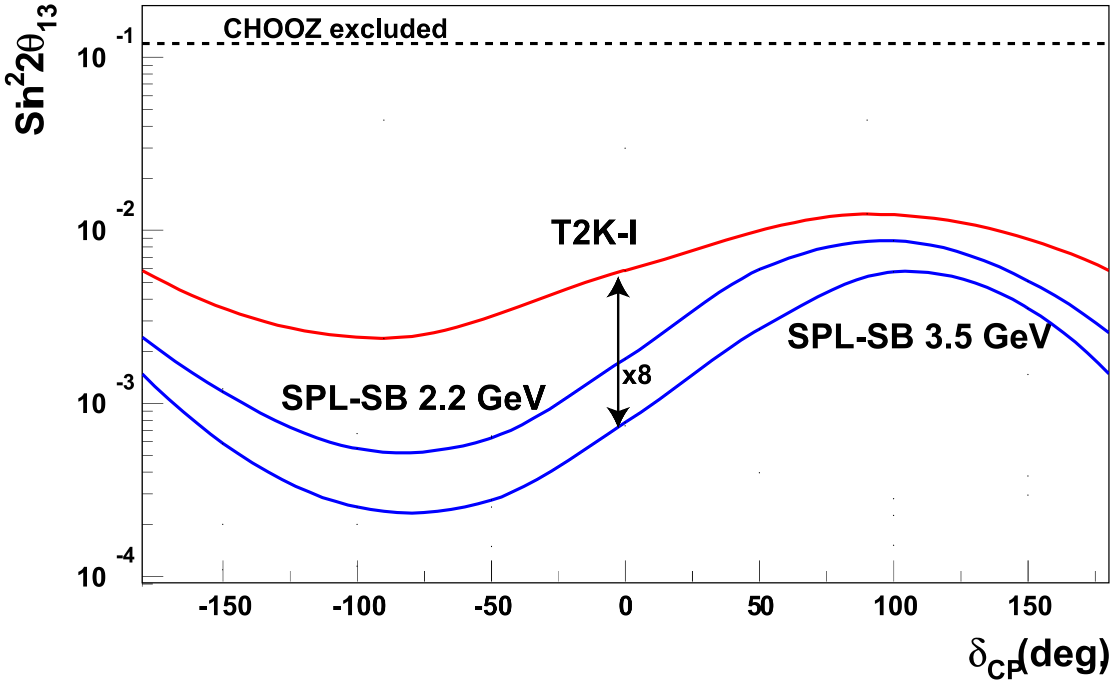


SPL SuperBeam Performances

Computed introducing neutrino energy reconstruction in 200 MeV energy bins.

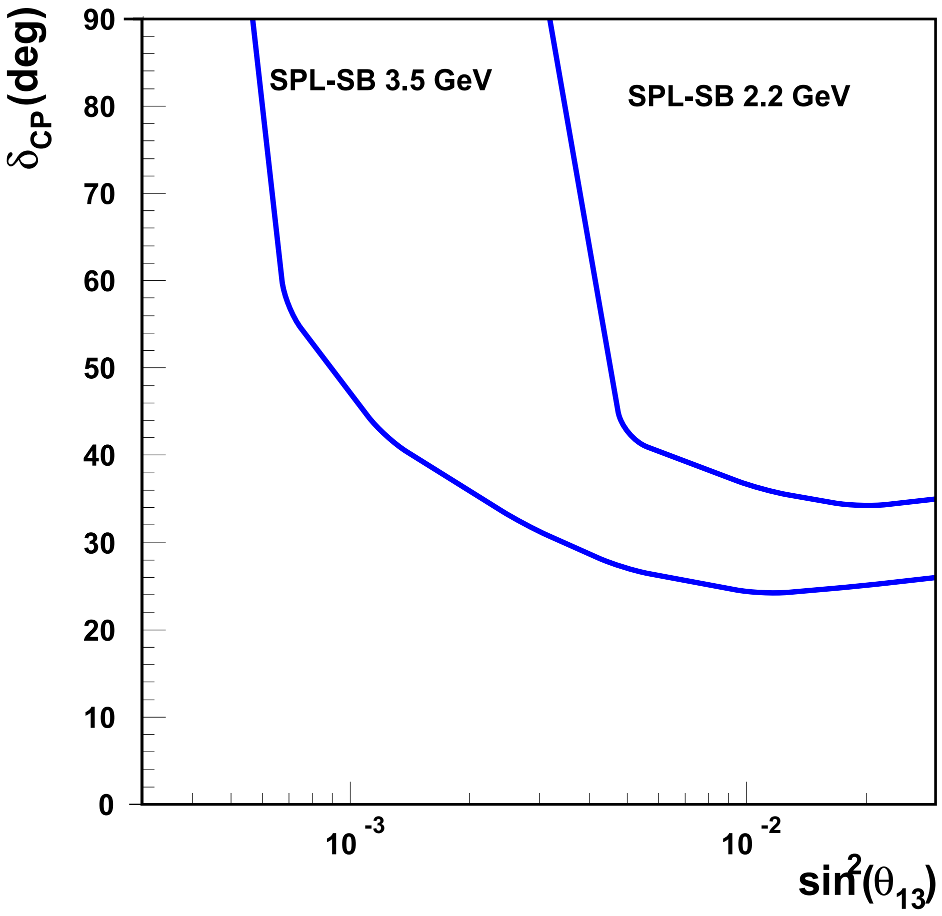
θ_{13} sensitivity (90% CL)

5 years, ν_μ run

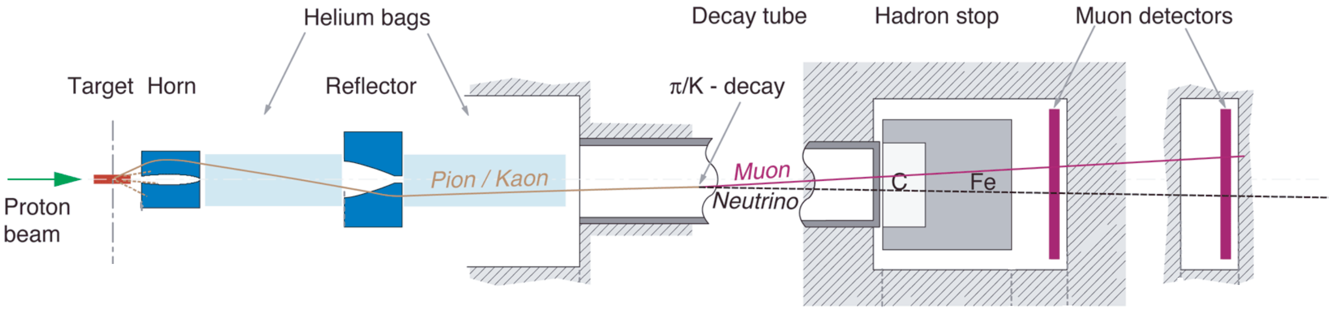


$\delta_{\rm CP}$ discovery potential (3σ)

10 years, 2 ν_μ + 8 $\overline{\nu}_\mu$



Conventional neutrino beams are going to hit their ultimate limitations.



In a **conventional neutrino beam**, neutrinos are produced SECONDARY particle decays (mostly pions and kaons). 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.

- Besides the main component (ν_μ) at least 3 other neutrino flavors are present ($\overline{\nu}_\mu$, ν_e, $\overline{\nu}_e$), generated by wrong sign pions, kaons and muon decays. $\nu_e$contamination is a background for θ_{13} and δ, $\overline{\nu}_\mu$contamination dilutes any CP asymmetry.
- Hard to predict the details of the neutrino beam starting from the primary proton beam, the problems being on the secondary particle production side.
- Difficult to tune the energy of the beam in case of ongoing optimizations.

All these limitations are overcome if secondary particles become primary

Collect, focus and accelerate the neutrino parents at a given energy. This is impossible within the pion lifetime, but can be tempted within the muon lifetime **(Neutrino Factories)** or within some radioactive ion lifetime **(Beta Beams)**:

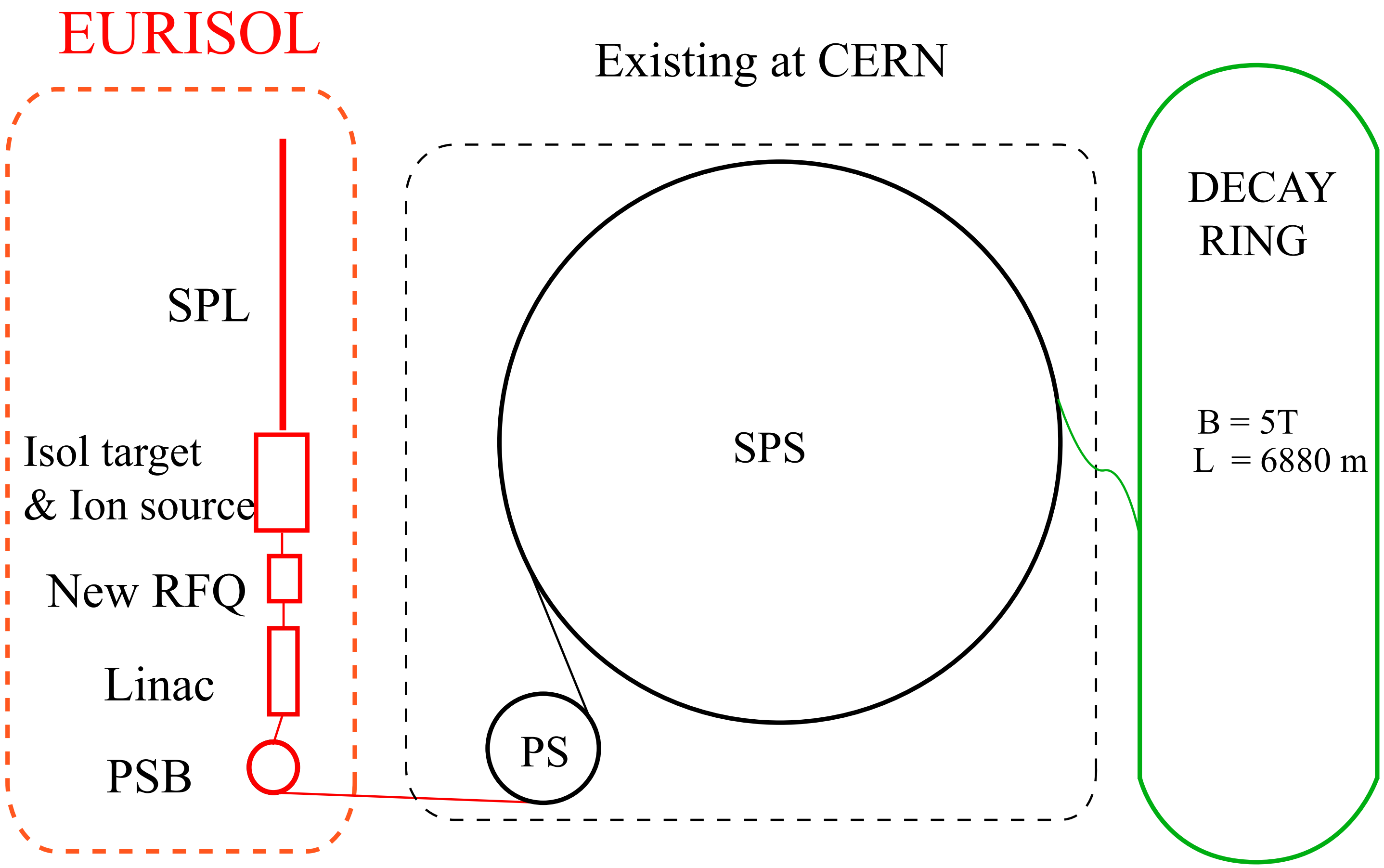
- Just one flavor in the beam
- Energy shape defined by just two parameters: the endpoint energy of the beta decay and the γ of the parent ion.
- Flux normalization given by the number of ions circulating in the decay ring.
- Beam divergence given by γ.

The full ^{6}He flux MonteCarlo code

```
Function Flux(E)
Data Endp/3.5078/
Data Decays /2.9E18/
ye=me/EndP
c ...For ge(ye) see hep-ph0312068
ge=0.0300615
2gE0=2*gamma*EndP
c ...  Kinematical Limits
If(E.gt.(1-ye)*2gE0)THEN
   Flux=0.
   Return
Endif
c ...Here is the Flux
Flux=Decays*gamma**2/(pi*L**2*ge)*(E**2*(2gE0-E))/
+ 2gE0**4*Sqrt((1-E/2gE0)**2-ye**2)
Return
```

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

M. Lindroos et al., see http://beta-beam.web.ch/beta-beam



- 1 ISOL target to produce He^6, 100 μA, $\Rightarrow 5.8 \cdot 10^{18}$ ion decays/straight session/year. $\Rightarrow \overline{\nu}_e$.
- 3 ISOL targets to produce Ne^{18}, 100 μA, $\Rightarrow 2.4 \cdot 10^{18}$ ion decays/straight session/year. $\Rightarrow \nu_e$.
- These fluxes apply if the two ions are run separately

The SuperBeam - BetaBeam synergy

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

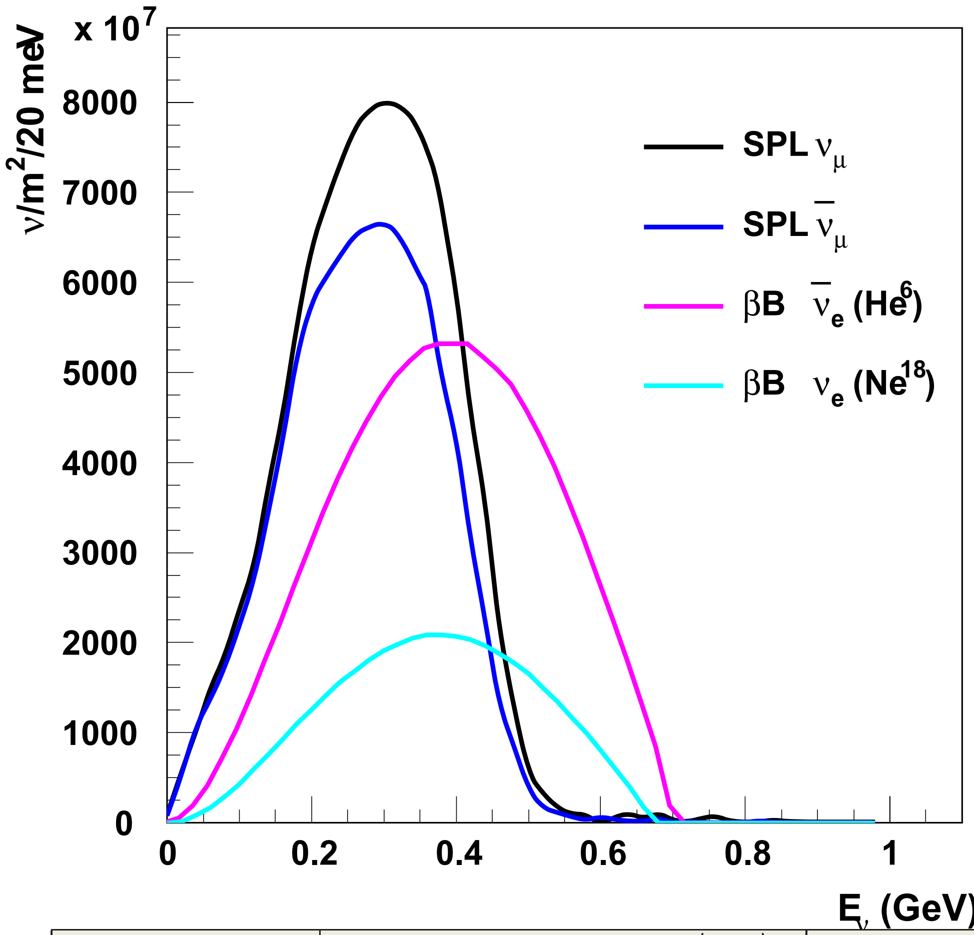
Both beams need a Linac, but the BetaBeam requires at most 12% of the SPL protons $\longrightarrow$ the two beams can run together.

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

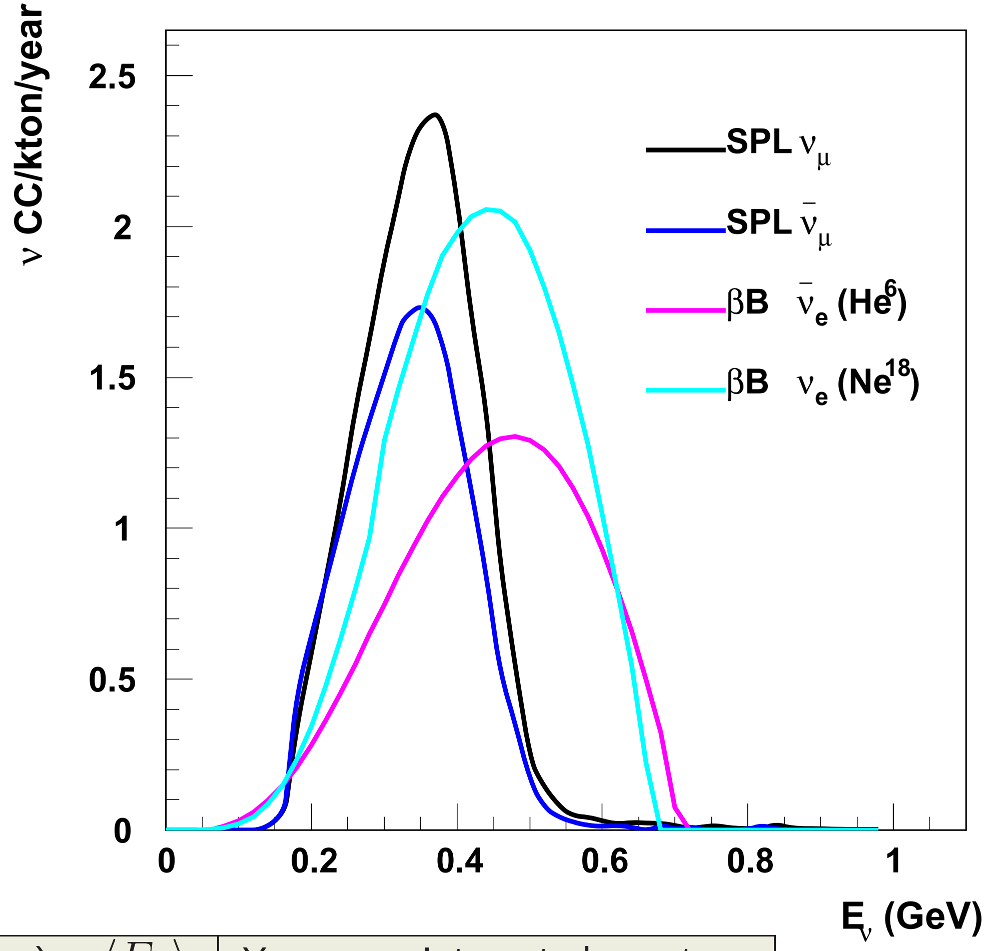
Explore CP violation in two different channels with different backgrounds and systematics.

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

Yearly Fluxes



Averaged yearly CC rates in a 10 years run for CP



	Fluxes @ 130 km $\nu/m^2/yr$	$\langle E_\nu \rangle$ (GeV)	CC rate (no osc) events/kton/yr	$\langle E_\nu \rangle$ (GeV)	Years	Integrated events (440 kton × 10 years)
SPL Super Beam						
ν_μ	$11.80 \cdot 10^{11}$	0.29	121.7	0.36	2	107127
$\overline{\nu}_\mu$	$9.66 \cdot 10^{11}$	0.28	23.1	0.35	8	81164
Beta Beam						
$\overline{\nu}_e(\gamma = 100)$	$10.92 \cdot 10^{11}$	0.40	46.0	0.46	5	101262
$\nu_e(\gamma = 100)$	$4.06 \cdot 10^{11}$	0.38	65.4	0.44	5	143887

Beta Beam Backgrounds

Computed with a full simulation and reconstruction program. (Nuance + Dave Casper).

π from NC interactions

The main source of background comes from pions generated by resonant processes (Δ^+ production) in NC interactions.

Pions cannot be separated from muons.

However the threshold for this process is $\simeq 450$ MeV, and the pion must be produced above the Cerenkov threshold.

Angular cuts have not be considered yet.

e/μ mis-identification

The full simulation shows that they can be kept well below 10^{-3} applying the following criteria:

- One ring event.
- Standard SuperK particle identification with likelihood functions.
- A delayed decay electron.

Atmospheric neutrinos

Atmospheric neutrino background can be kept low only by a very short duty cycle of the Beta Beam. A reduction factor bigger than 10^3 is needed.

This is achieved by building 10 ns long Ion bunches.

Distinctive features of the Beta Beam

Just one neutrino flavor in the beam.

Short baseline: no subtraction of the fake CP violating MSW effects.

No intrinsic background and very few detector backgrounds (with a different energy than signal).

Neutrino fluxes virtually systematics free. Excellent control of systematic errors and a powerful measure of neutrino cross-sections in the close detector.

The ν_e and $\overline{\nu}_e$ beams allow for the disappearance channel with a very good control of the systematics and a direct access to θ_{13}. The comparison of these two disappearance channels allows for CPT tests.

Furthermore when combined with the SPL-SuperBeam

Comparing the ν_μ and $\overline{\nu}_\mu$ SPL beams with the ν_e and $\overline{\nu}_e$ Beta Beams: access to CP, T, and CPT searches.

However

- Cross sections are small $\Rightarrow$ very massive detectors.
- $\overline{\nu}_\mu/\nu_\mu$ cross section ratio at a minimum (1/4).
- Visible energy smeared out by Fermi motion.
- No way to measure sign(Δm^2).

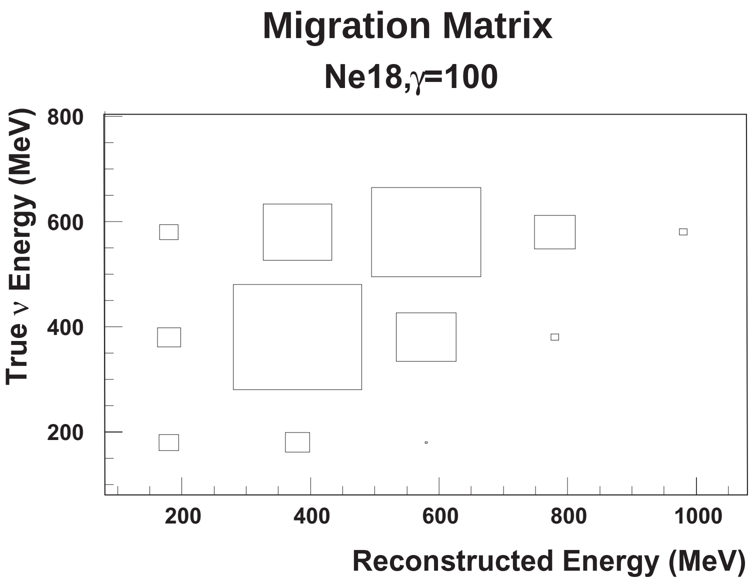
The $\gamma = 100, 100$ option

The physics potential of the baseline Beta Beam has been computed in J. Bouchez, M. Lindroos, M.M., AIP Conf. Proc. **721** (2004) 37 [hep-ex/0310059]; see A. Donini et al., Nucl. Phys. B **710** (2005) 402 and hep-ph/0411402 for computations aware of all the possible degeneracies.

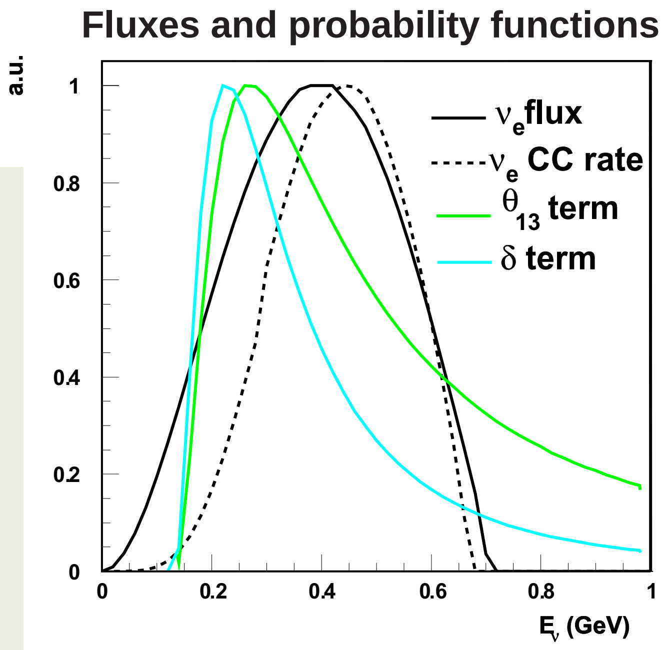
Computed for $\gamma(^6\mathrm{He}) = 60$, $\gamma(^{18}\mathrm{Ne}) = 100$. This γ ratio was intended to fully exploit Beta Beam ions by running $^6\mathrm{He}$ and $^{18}\mathrm{Ne}$ at the same time in the machine.

New developments show that the two ions can be run separately keeping constant their overall fluxes, this allows a better optimization.

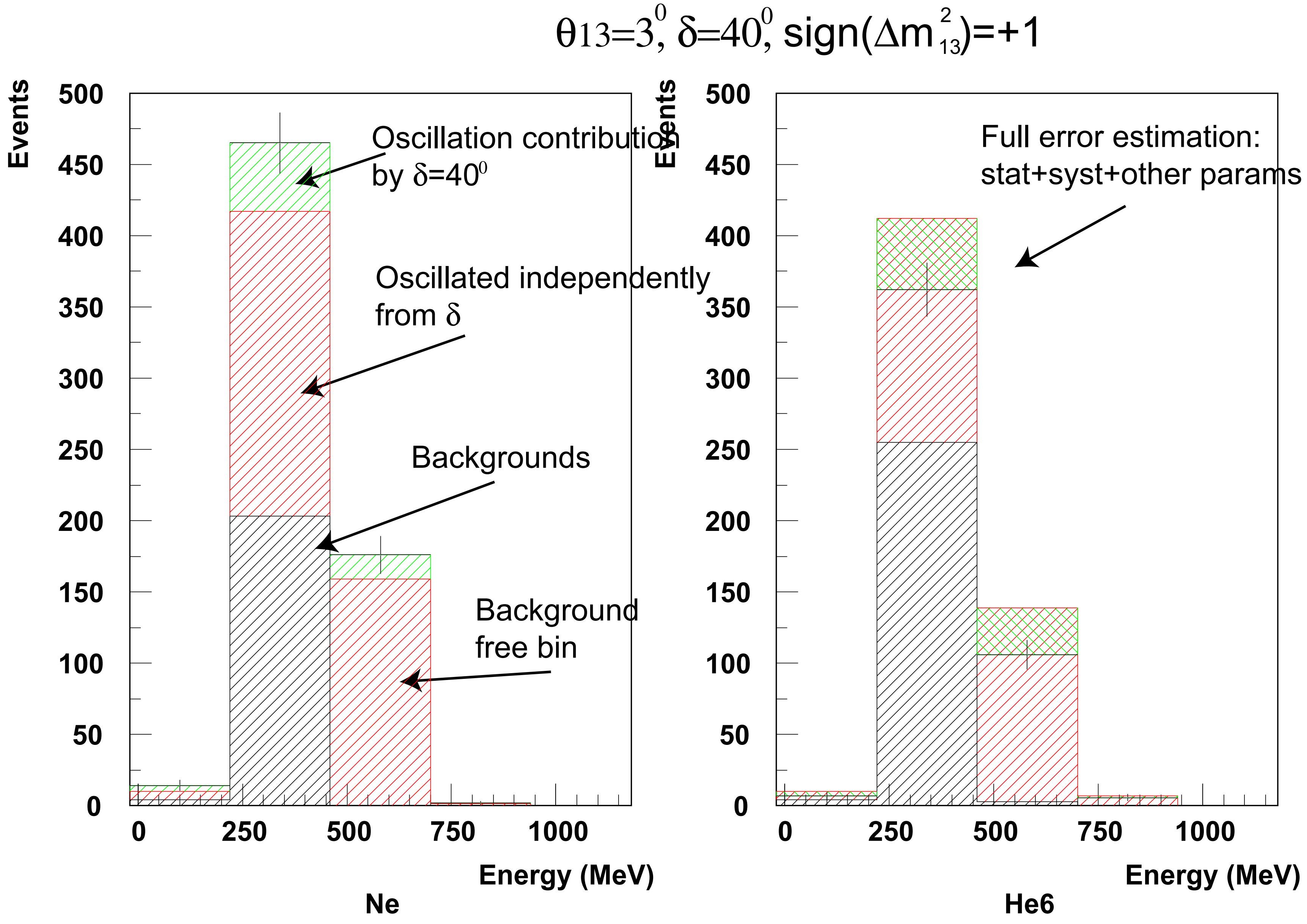
- $^6\mathrm{He}$ and $^{18}\mathrm{Ne}$ have similar end point energy, keep their γs equal.
- At higher γ better energy reconstruction and smaller ratio of atmospheric neutrino backgrounds to signal.
- Events are binned in 200 MeV bins. A. Blondel et al. paper: NIM A535 (2004)665 paper suggests a MC based method to further improve energy resolution at those energies.
- The $\gamma = 100, 100$ option results to be the best one for L=130 km.


Migration Matrix

Ne18,γ=100


Fluxes and probability functions

As an example: events for $\theta_{13} = 3^\circ, \delta = 40^0$



$\theta_{13}=3^0, \delta=40^0$, sign($\Delta m^2_{13}$)=+1

Oscillation contribution by $\delta=40^0$

Oscillated independently from δ

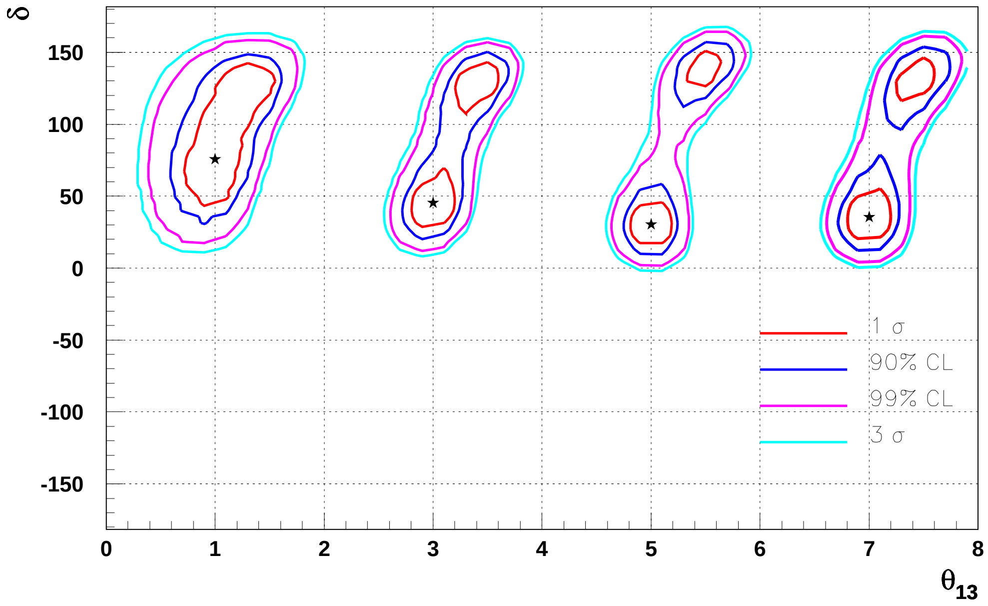
Backgrounds

Background free bin

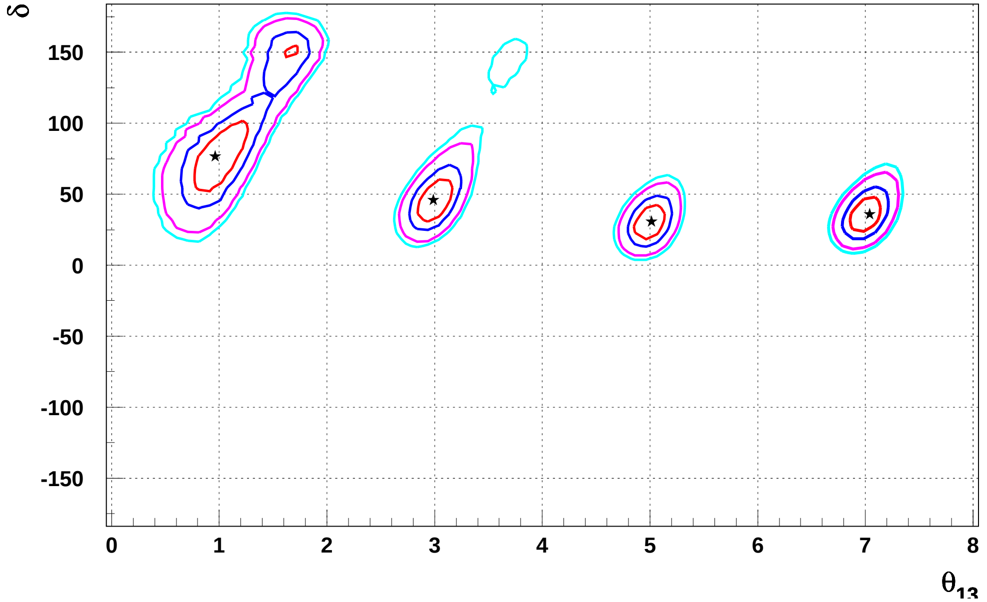
Full error estimation: stat+syst+other params

The improvement

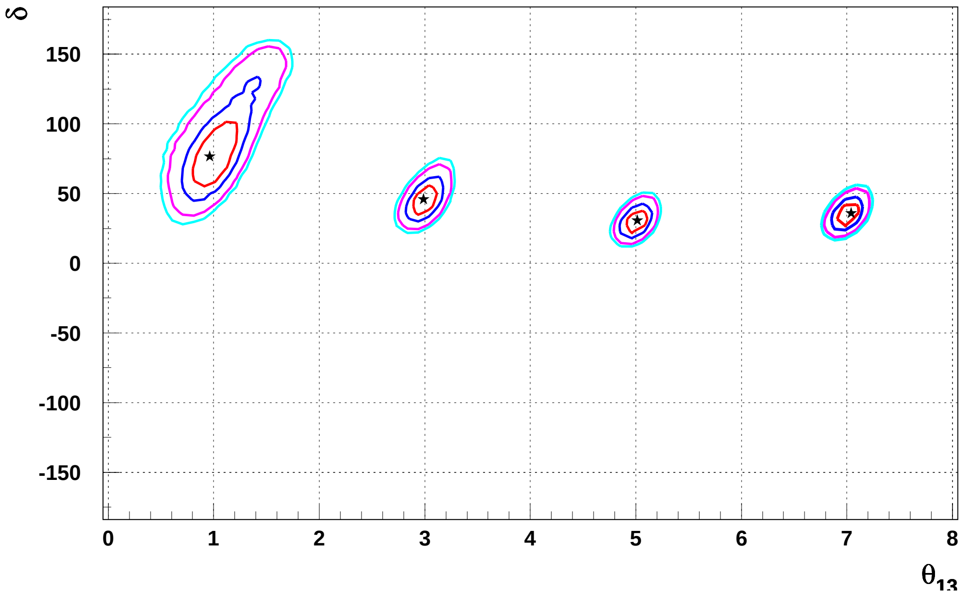
$\gamma = 60, 100$



$\gamma = 100, 100$ with the new bck evaluation



$\gamma = 100, 100$ + SPL-SB 3.5 GeV



$\delta m^2_{12} = 7 \cdot 10^{-5}\ eV^2, \theta_{13} = 1^\circ, \delta = \pi/2$, sign$(\Delta m^2) = +1$

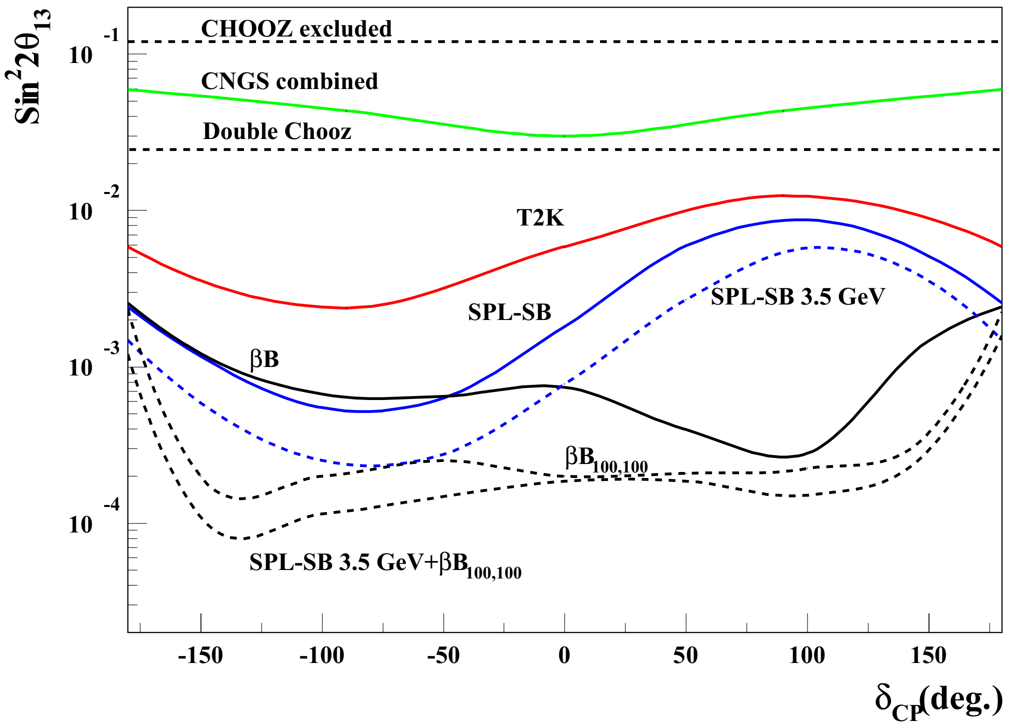
	^{6}He $(\gamma = 100)$	^{18}Ne $(\gamma = 100)$
CC events (no osc, no cut)	101263	144784
Oscillated	7	118
δ oscillated	-38	54
Beam background	0	0
Detector backgrounds	262	206

δ-oscillated events indicates the difference between the oscillated events computed with $\delta = 90^\circ$ and with $\delta = 0$

Beta Beam ($\gamma = 100, 100$) performances

θ_{13} sensitivity (90% CL)

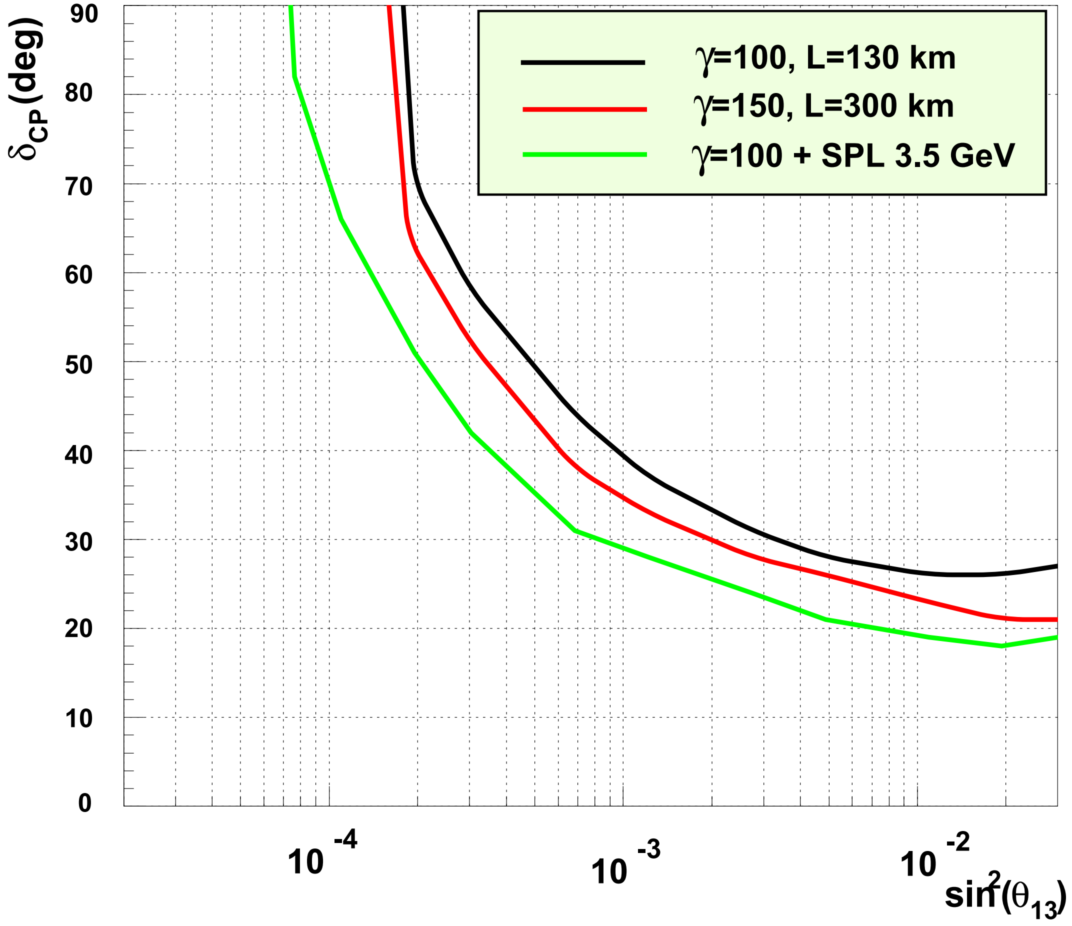
5 years run

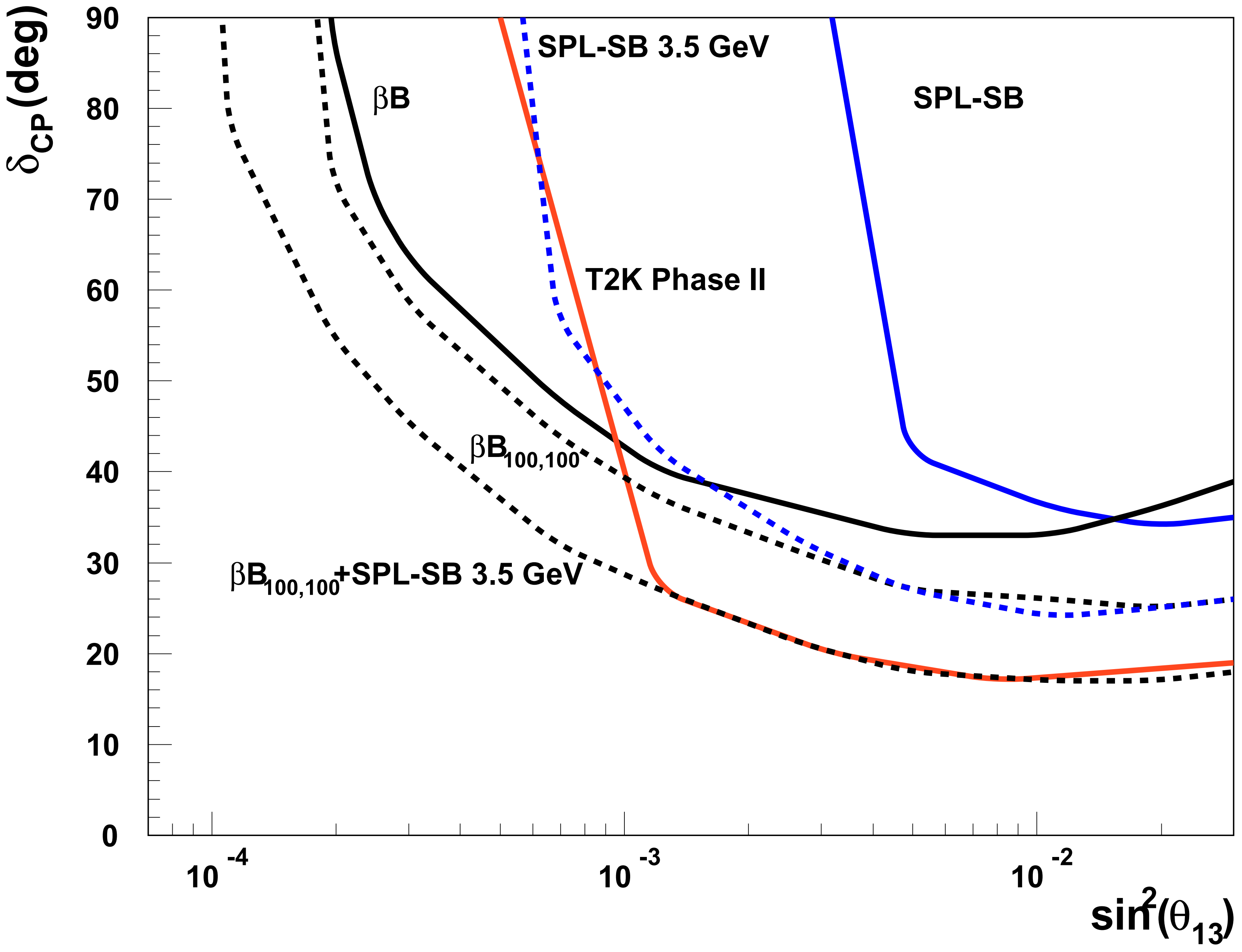


δ_{CP} discovery potential (3σ)

10 years, 5 ν_e+ 5 $\overline{\nu}_e$

$\gamma = 150$ curve with the tentative new γ-flux relation

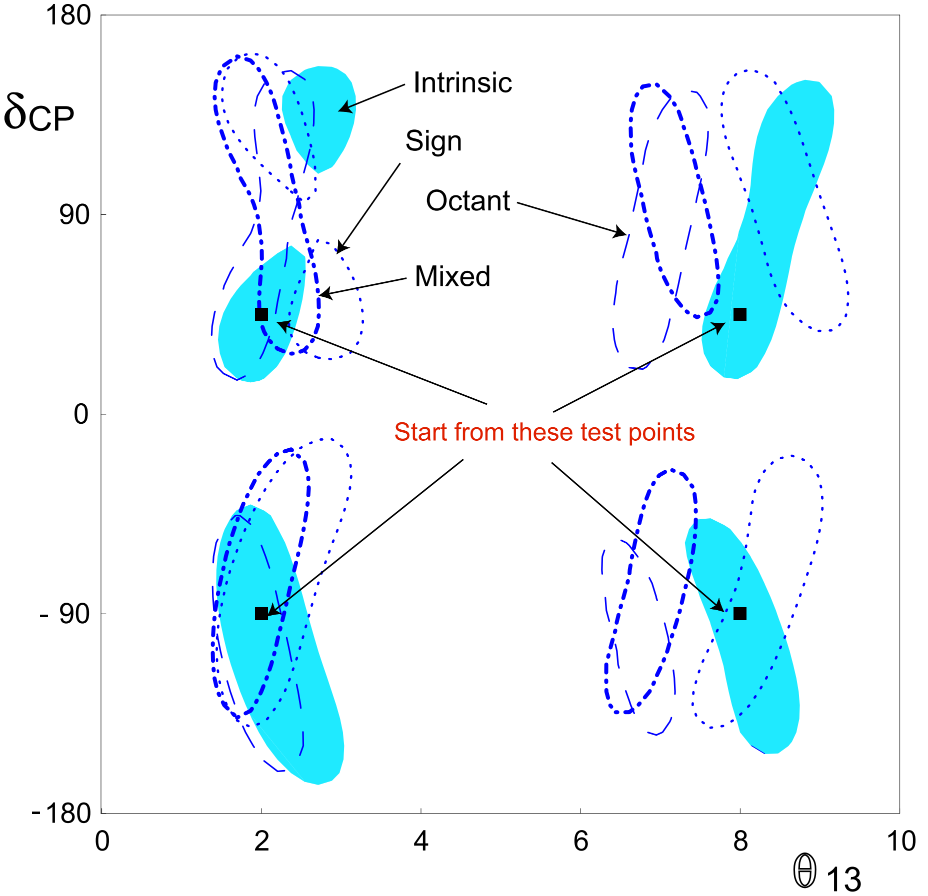



δ_{CP}(deg)
90
80
70
60
50
40
30
20
10
0
10^{-4}
10^{-3}
10^{-2}
$\sin^2(\theta_{13})$
SPL-SB 3.5 GeV
SPL-SB
βB
T2K Phase II
$\beta B_{100,100}$
$\beta B_{100,100}$+SPL-SB 3.5 GeV

The degeneracy problem

The sub-leading $\nu_\mu \rightarrow \nu_e$formula leaves room for clone solutions of the fit to θ_{13} and $\delta_{\rm CP}$. The eightfold degeneracies arise from

- $\boldsymbol{{\rm sign}(\Delta m^2)}$. Changing ${\rm sign}(\Delta m^2)$ the $P(\nu_\mu \rightarrow \nu_e)$terms $\propto$ $\sin(\Delta m^2_{23})$ change sign. Two separate solutions can be created by $(\theta_{13}\,,\delta_{\rm CP}\,,{\rm sign}(\Delta m^2)\,)$ and by $(\theta_{13}{}',\delta_{\rm CP}{}',-{\rm sign}(\Delta m^2)\,)$.
- $\boldsymbol{\pi/2-\theta_{23}}$ (octant) . ν_μ disappearance measures $\sin^2 2\theta_{23}$ but some terms in the oscillation formula depend from $\sin\theta_{23}$ .At present the experimental best fit is $\sin^2 2\theta_{23} = 1$ allowing no ambiguity, but the experimental not excluded values smaller than unity allow for a twofold $\pi/2-\theta_{23}$ ambiguity.
- **Mixed** The product of the above two

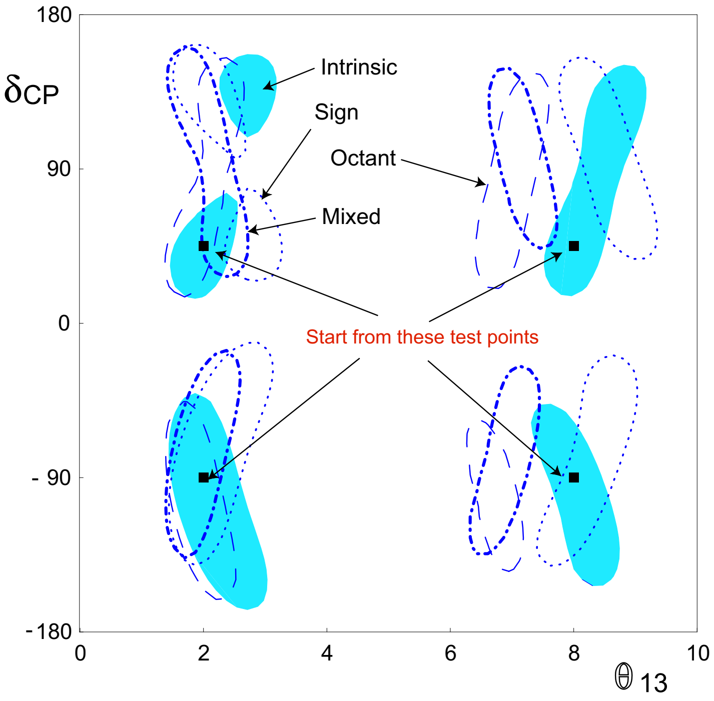


These eightfold discrete degeneracies (or twofold in case $\sin^2 2\theta_{23} \simeq 1$) can be solved by combining information of different experiments running at different energies or looking to different processes (i.e. combining $\nu_\mu \rightarrow \nu_e$ transitions with $\nu_e$disappearance or with $\nu_e \rightarrow \nu_\tau$ transitions). A single experiment cannot solve all these degeneracies by itself.

Good news for the degeneracies

“I would left the degeneracy problem to theoreticians and invite experimentalists to concentrate in design better and better experiments” H. Minakata, Win04.

- For a long period several authors focused on how clones and degeneracies can destroy SB+BB discovery potential.
- A couple of very recent papers shed a light on the possibility to solve this problem



- **A. Donini et al., hep-ph/0411402:** The sign and octant clones disappear if the $\nu_e$appearance signal is combined with a good quality ν_μ disappearance data. This because clone solution appear with a different δm^2_{23} value. Beta Beam cannot have ν_μ disappearance data, SPL-SB can (as computed in the paper), but T2K phase I data would be enough!

- **P. Huber et al., hep-ph/0501037**: The sign and octant clones can disappear AND $\mathrm{sign}(\Delta m^2)$ **can be measured** by combining SuperBeam data (they took T2K phase II data) with atmospheric neutrino data measured in the megaton detector:
  - **Octant** e-like events in the Sub-GeV data is $\propto \cos^2\theta_{23}$
  - **Sign** e-like events in the Multi-GeV data, thanks to matter effects, especially for zenith angles corresponding to neutrino trajectories crossing the mantle and core where a resonantly enhancement occurs.

The BetaBeam high energy options

Several papers explored the physics potential of higher energy beta beams:

- J. Burguet-Castell et al., Nucl. Phys. B **695**, 217 (2004): $\gamma = 350$
- F. Terranova et al., Eur. Phys. J. C **38** (2004) 69: $\gamma = 2500, \gamma = 4158$
- J. Burguet-Castell et al., hep-ph/0503021: $\gamma = 150$

All these papers computed sensitivities assuming constant ion fluxes at higher gammas.

This assumption needs to be confirmed by deeper studies.

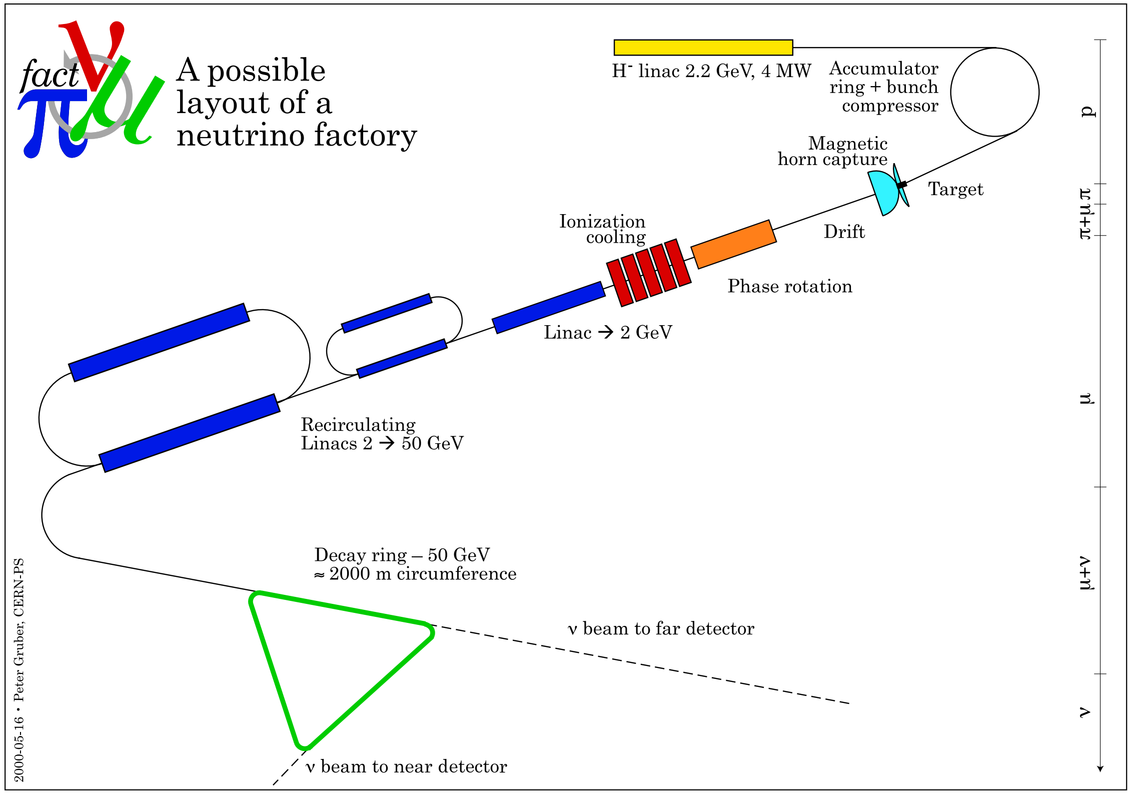
To be noted that the decay tunnel length is directly proportional to γ, for $\gamma = 150$ the decay tunnel length is $\simeq 7000$ m (36% useful straight session, 5 T magnets).

Two high energy options foresee a detector under Gran Sasso:

- $\gamma = 350$ with a 40 kton tracking calorimeter. Aiming at measuring both θ_{13} and δ_{CP} . $\gamma = 350$ can be obtained if the "Super-SPS" will be built at CERN in the LHC luminosity upgrade programme.
- $\gamma = 4158$ with a muon counting detector, aiming at measuring θ_{13} (no δ_{CP} sensitivity). This γ corresponds to the maximum possible by LHC.

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**



Oscillation signals at the neutrino factory

μ^- (μ^+) decay in (ν_μ , $\overline{\nu}_e$) (($\overline{\nu}_\mu$, ν_e)).

Golden channel: search for $\nu_e \longrightarrow \nu_\mu$ ($\overline{\nu}_e \longrightarrow \overline{\nu}_\mu$) transitions by detecting wrong sign muons.

Ideal detector: 40-100 kton iron magnetized calorimeter (Monolith like)

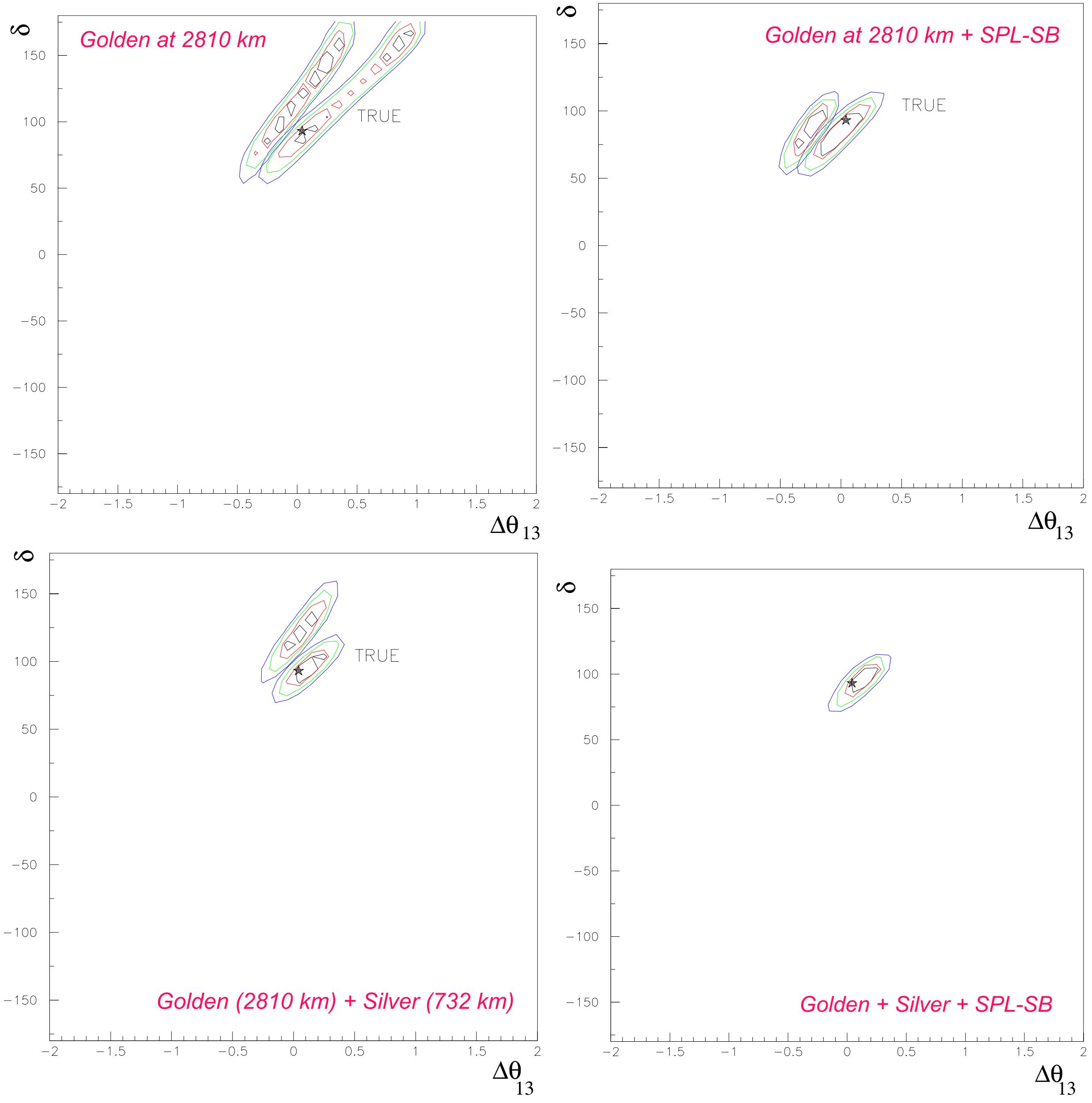
Silver channel: search for $\nu_e \longrightarrow \nu_\tau$ transitions by detecting ν_τ appearance.

Ideal detector: Super-Opera with 2-4 times the mass of Opera

Both detectors can be accomodate at LNGS. Ideal baseline for a 50 GeV Neutrino Factory is ~ 3000 km.

Golden and Silver channel complementarity

D. Autiero *et al.*, Eur. Phys. J. C **33** (2004) 243, hep-ph/0305185.



A summary table of SuperBeam and BetaBeam experiments

		T2K	J-Parc II	NOνA	BNL	PS$++$	SPL (3.5)	βB (βB$_{100,100}$)
p-driver	(MW)	0.75	4	0.8 (2)	1	6.5	4	0.4
p beam energy	(GeV)	50	50	120	28	20	2.2 (3.5)	1-2.2
$\langle E(\nu_\mu)\rangle$	(GeV)	0.7	0.7	2	1.5	1.6	0.27 (0.29)	0.3 (0.4)
L	(Km)	295	295	810	2540	732	130	130
Off-Axis		2°	2°	0.8°	-	-	-	-
ν_μ (ν_e)CC	(/Kt/yr)	100	500	80	11	730	37 (122)	38 (56)
ν_e^{CC}/ν_μ^{CC}	%	0.4	0.4	0.5	0.5	1.2	0.4 (0.7)	0
Fiducial Mass	(Kt)	22.5	540	30	440	2.4	440	440
Material		H_2O	H_2O	LScint	H_2O	LAr	H_2O	H_2O
Signal efficiency	%	40	40	24	25	100	70	60 (70)
π°/ν_e (π/ν_e)	%	80	80	60	100	0	30	0.2
$\sin^2 2\theta_{13}\cdot 10^4$	(90% CL)	60	6	38 (27)	30	50	18 (8)	7 (2)

Conclusions

- The neutrino oscillation roadmap predicts several ten years and several complementary experiments to be completed in the simplest scenario (no steriles).
- The easy things ($P_{\rm osc} \simeq 1$) have already been done. New projects appear to be very expensive and demanding. We are in the explorative phase of defining the different approaches and comparing their merits.
- A high intensity proton source is anyway the driver of every foreseen facility.
- EU (and INFN) supports these studies through the network BENE.