Mauro Mezzetto

Istituto Nazionale di Fisica Nucleare,

Sezione di Padova

“ Physics with BetaBeams and SuperBeams from CERN to a Frejus based Megaton Detector ”

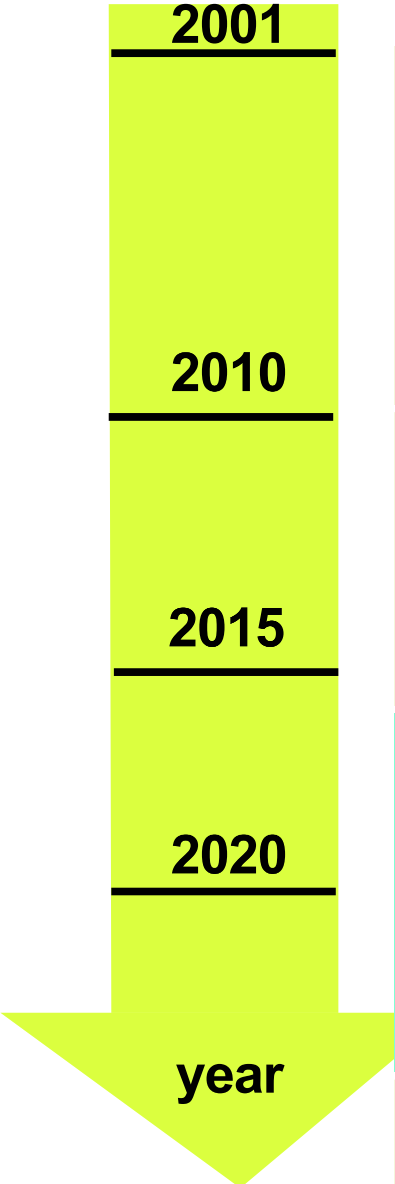
The CERN-Frejus scenario is still evolving very fast.

From the 2.2 GeV SPL SuperBeam and the $\gamma = 60, 100$ Beta Beam scenario of six months ago (Villars)

To the 3.5 GeV SPL SuperBeam and a $\gamma = 100, 100$ Beta Beam in phase of definition (Aussois).

NNN05, Aussois, 7-9 April 2005.

At least 4 phases of Long Baseline experiments

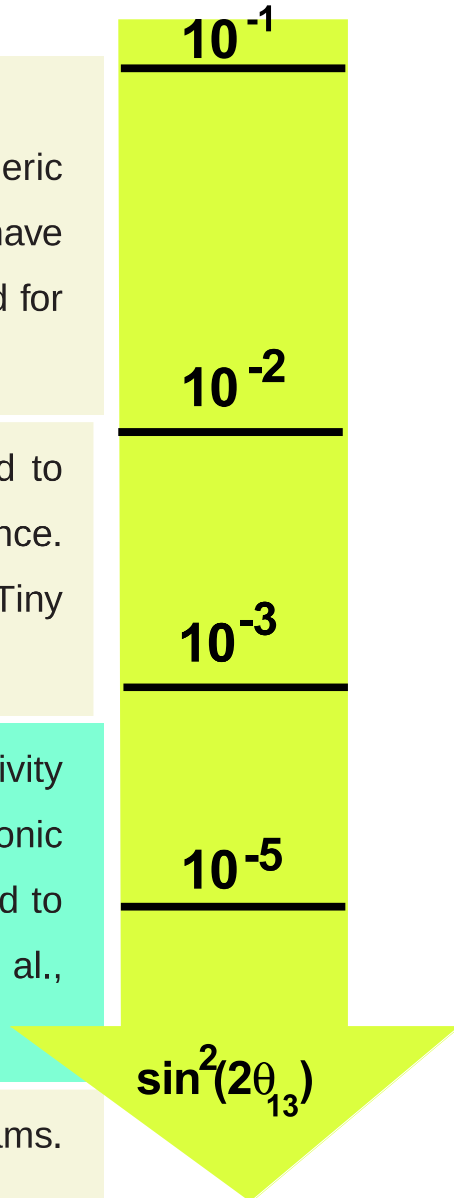


1) 2001-2010. K2K, Opera, Icarus, Minos.
Optimized to confirm the SuperK evidence of oscillation of atmospheric neutrinos through ν_μ disappearance or ν_τ appearance. They will have limited potential in measuring oscillation parameters. Not optimized for $\nu_e$appearance (θ_{13} discovery).

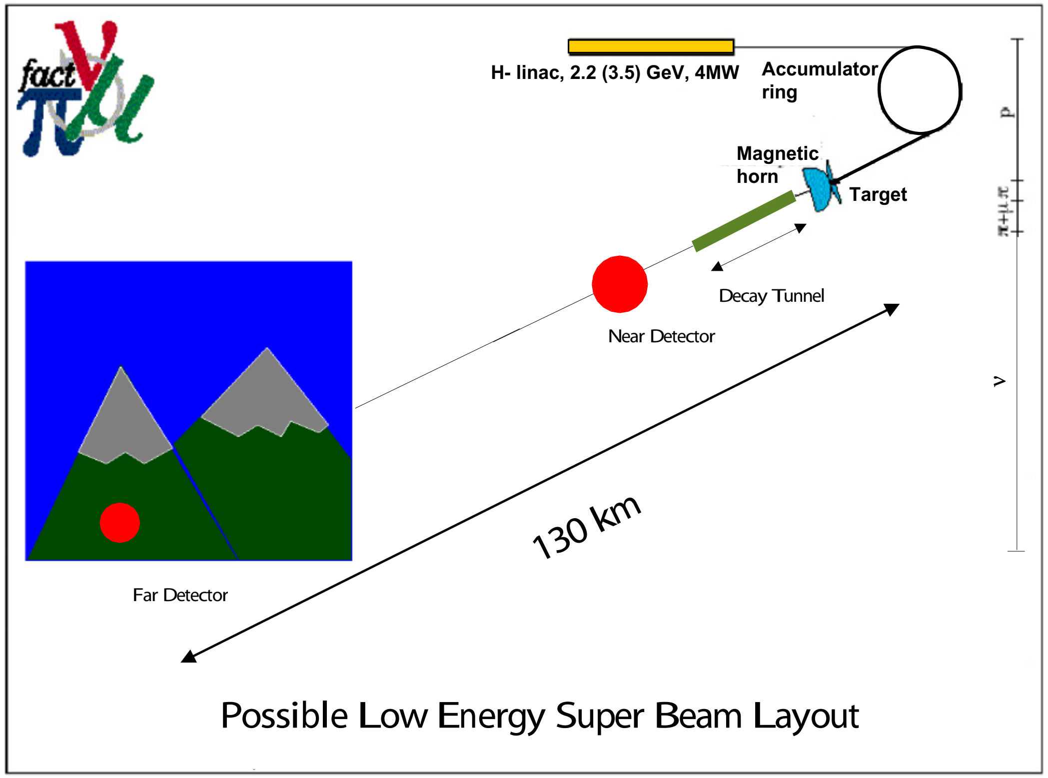
2) 2009-2015. T2K (approved), Noνa, Double Chooz. Optimized to measure θ_{13} (Chooz $\times$ 20) through $\nu_e$appearance or $\nu_e$disappearance. Precision measure of the atmospheric parameters (1 % level). Tiny discovery potential for CP phase δ, even combining their results.

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.

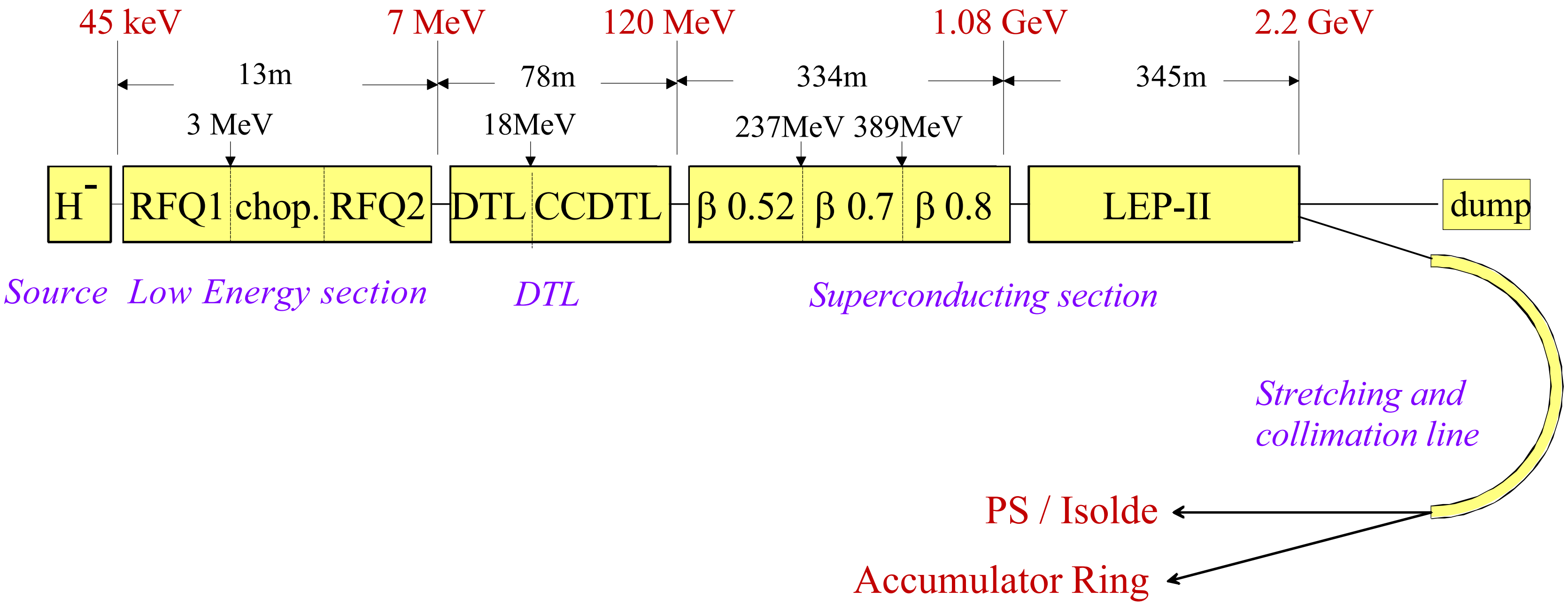


SuperBeams - SPL ν beam at CERN



- 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

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: 42 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 much better

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

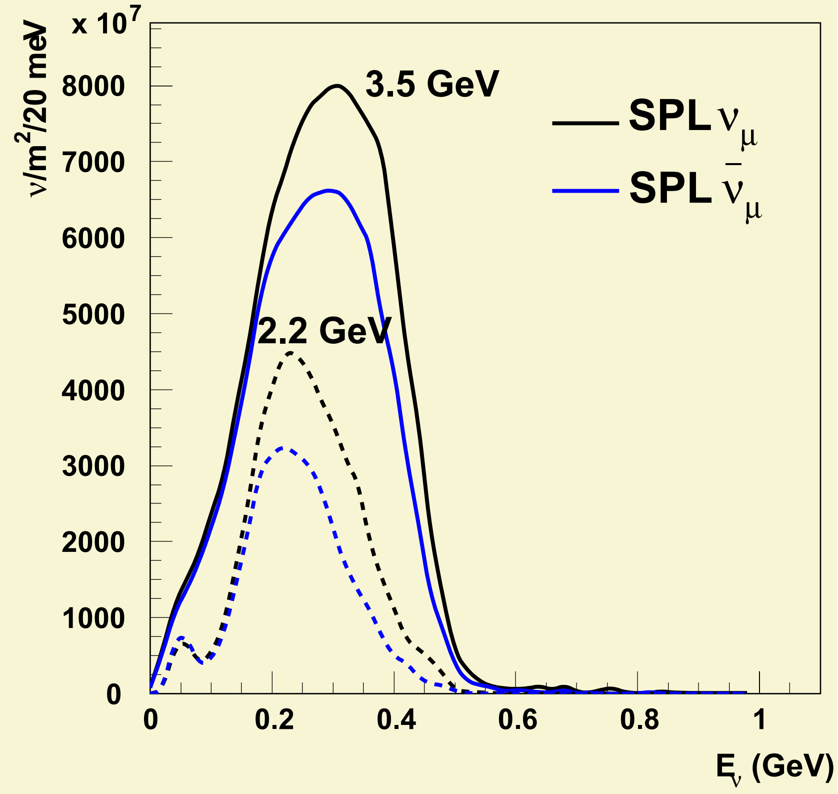
More recent RF cavities could increase the energy for the same Linac length.

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

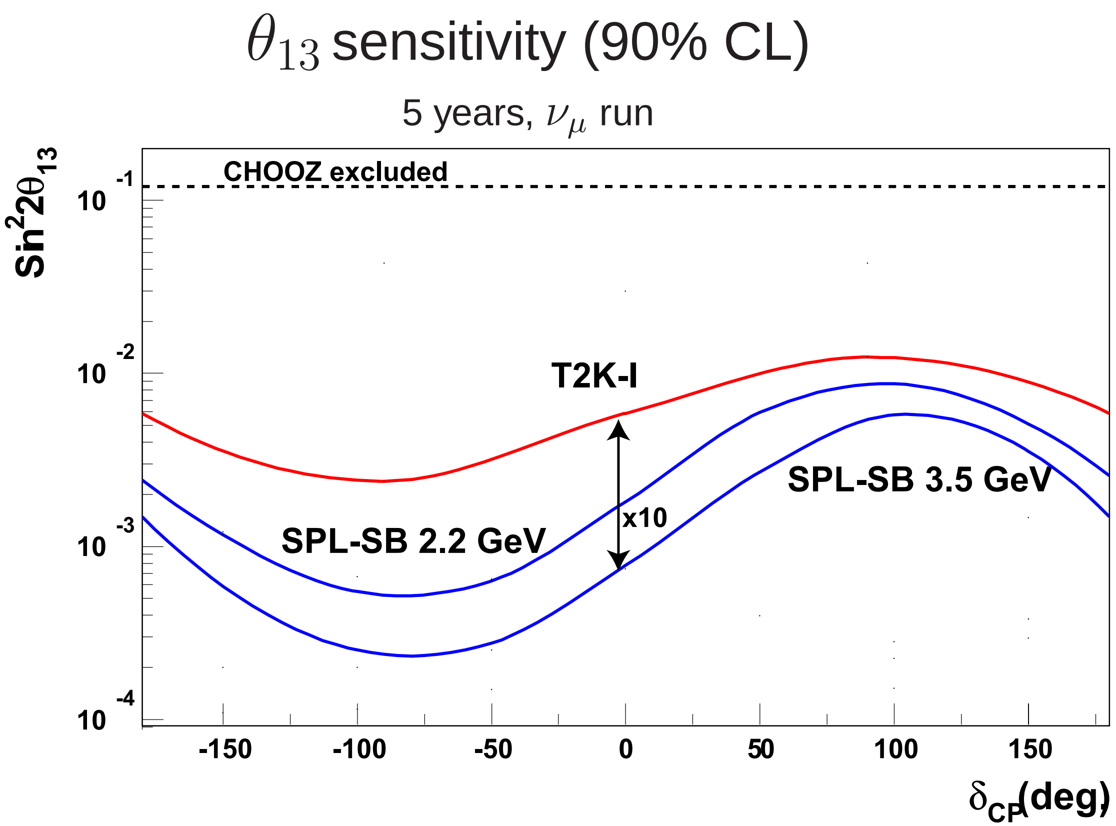
- Scan the proton driver energies from 2.2 to 8 GeV (4MW fixed).
- Keep the baseline fixed to 130 km
- From 3.5 GeV to above explore the possibility to focus higher momentum pions.
- The 3.5 GeV energy, with a neutrino beam with $\langle E_\nu \rangle \simeq 300 MeV$, decay length of 40 m and decay tunnel diameter of 2 m greatly improves the 2.2 GeV performances: ν_μ CC rate at 130 km from 42 to 122 events/kton/year

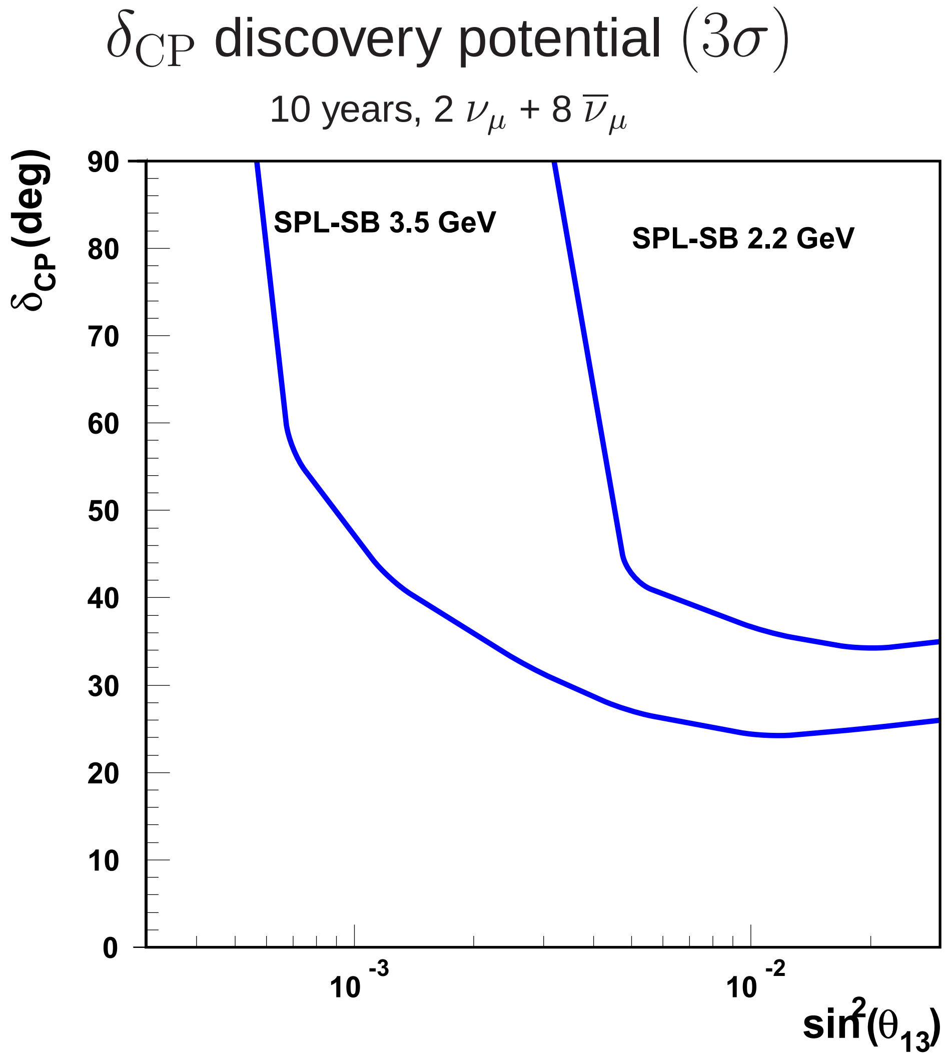
SPL-SB Fluxes at 130 km



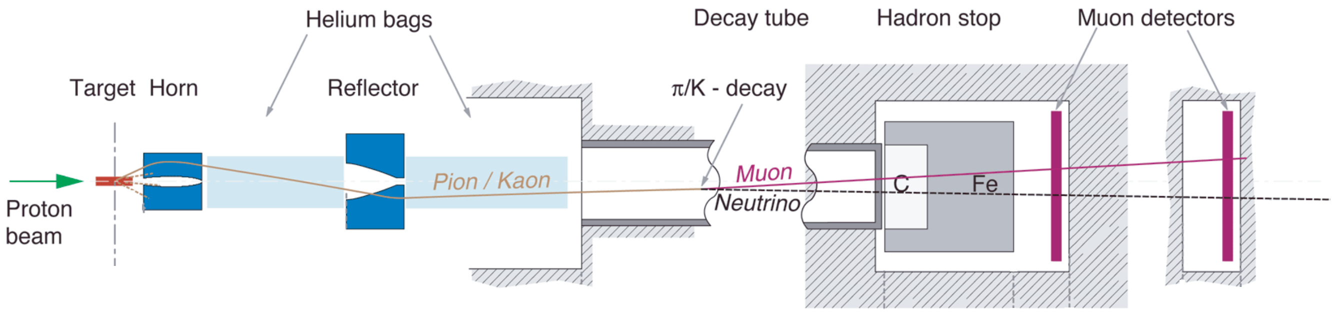
SPL SuperBeam Performances

Computed introducing neutrino energy reconstruction in 200 MeV energy bins.





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)**:

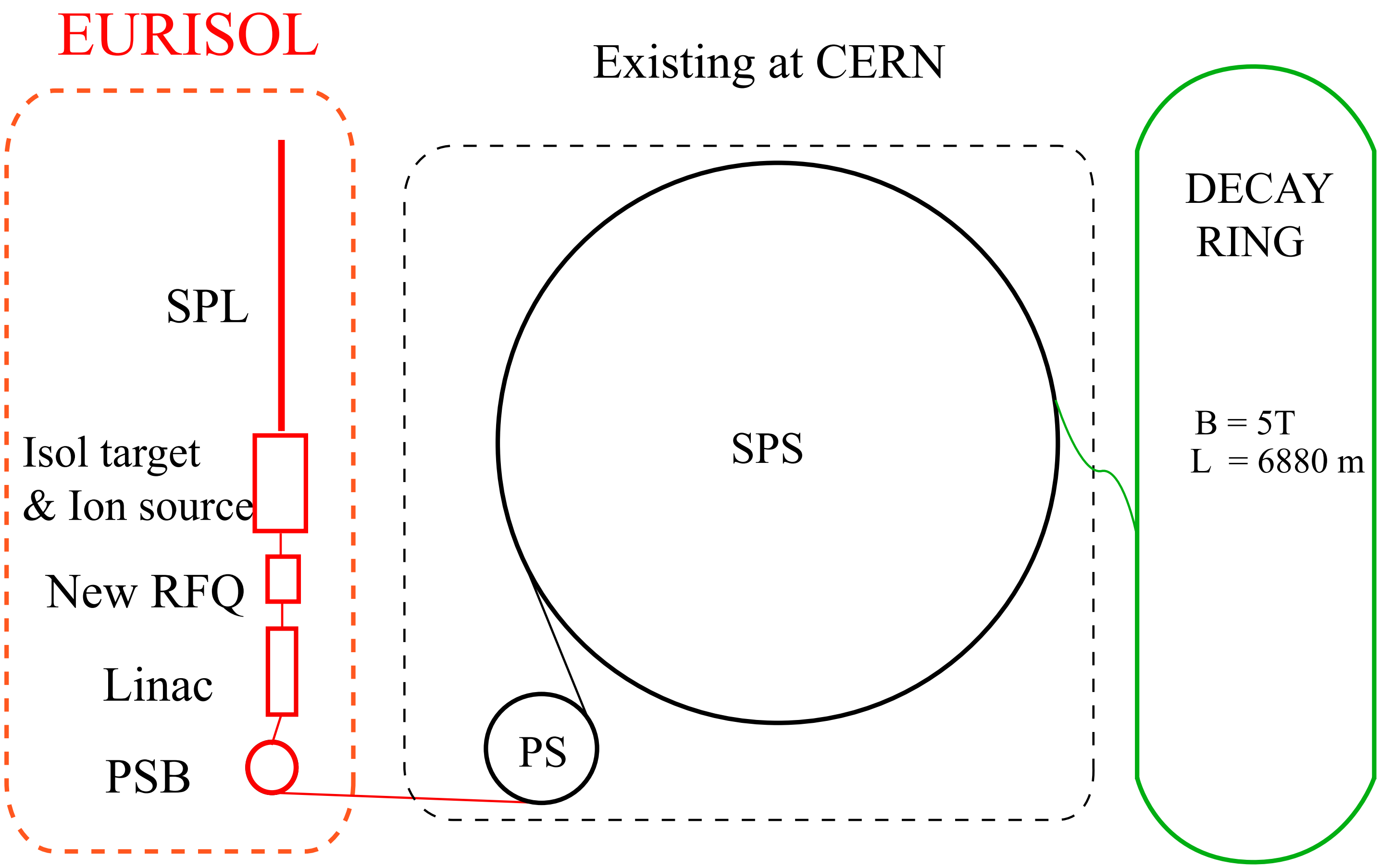
- Just one flavor in the beam
- Energy shape defined by just two parameters: the endpoint energy of the beta decay and the γ of the parent ion.
- Flux normalization given by the number of ions circulating in the decay ring.
- Beam divergence given by γ.

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.

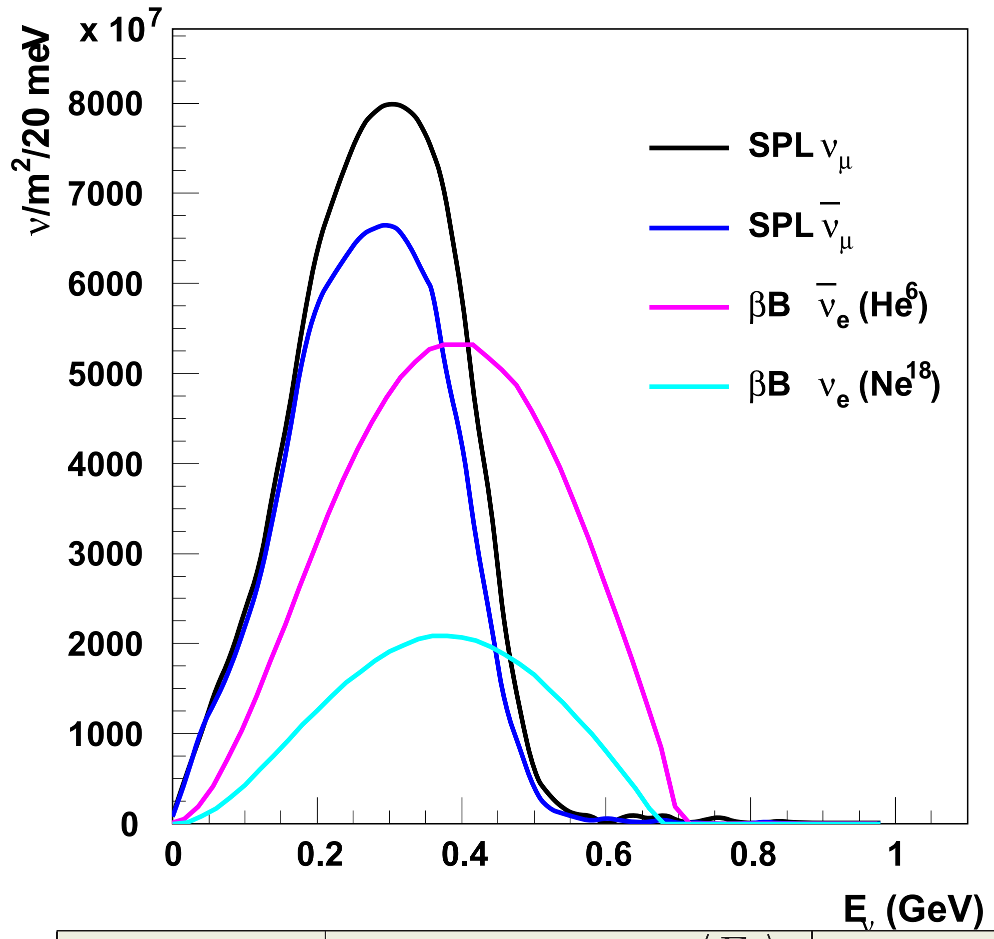
Both beams need a Linac, but the BetaBeam requires at most 12% of the SPL protons $\longrightarrow$ the two beams can run together.

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

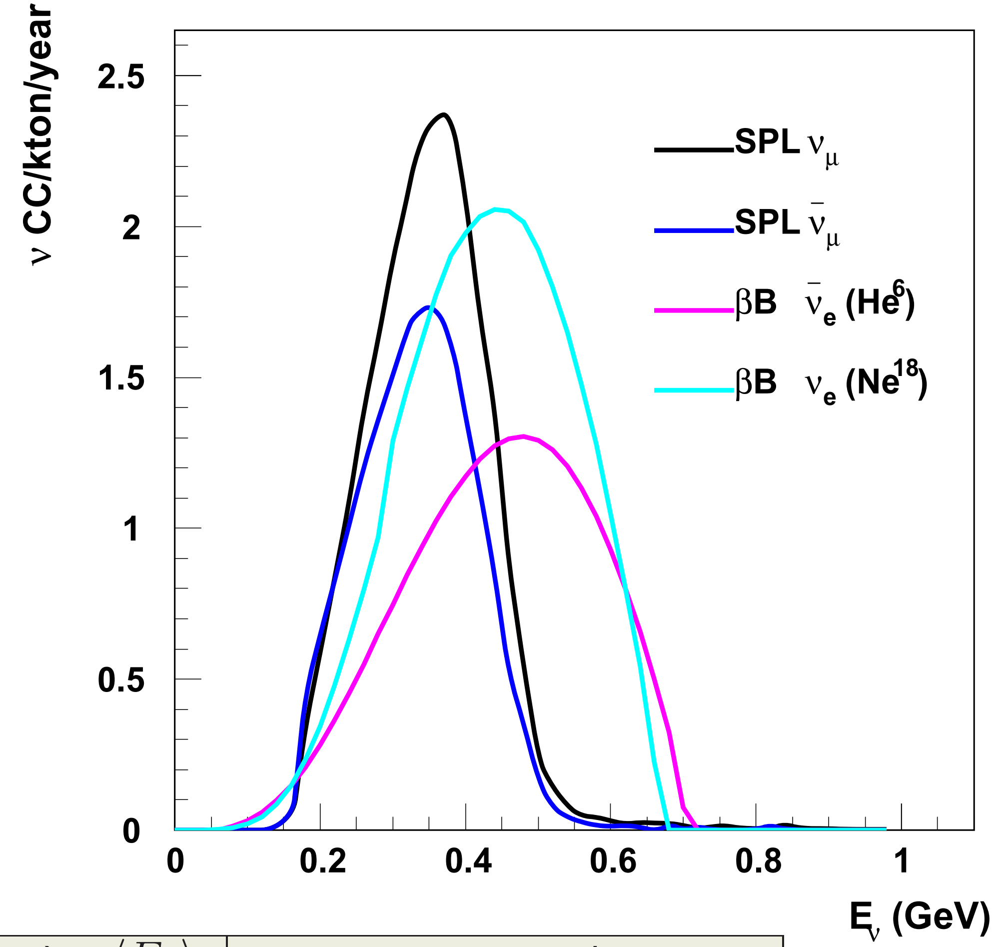
Explore CP violation in two different channels with different backgrounds and systematics.

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

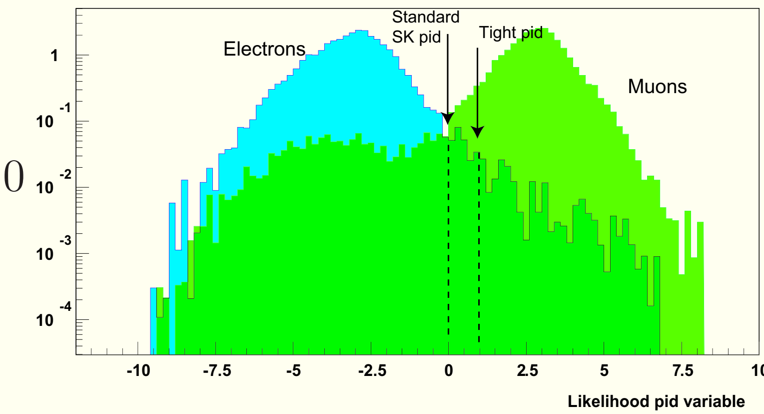
Atmospheric neutrino background can be kept low only by a very short duty cycle of the Beta Beam. A reduction factor bigger than 10^3 is needed.

This is achieved by building 10 ns long Ion bunches.

Particle identification and signal efficiency

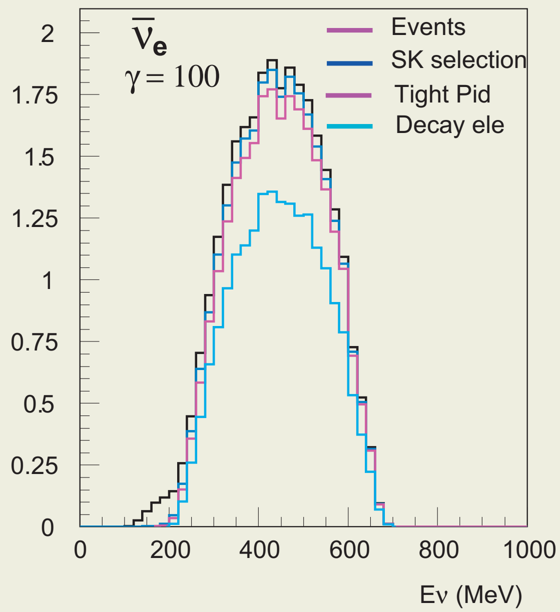
Electron/muon misidentification must be suppressed much more than in standard SK analysis to guarantee a negligible background level.

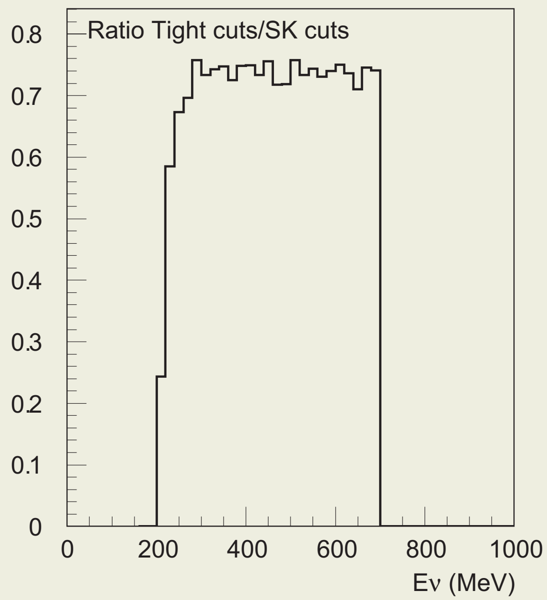
Pid in SK is performed through a Likelihood, $Pid > 0$ identifies muons. Use $Pid > 1$



To further suppress electron background ask for the signal of the Michel electron from μ decay.

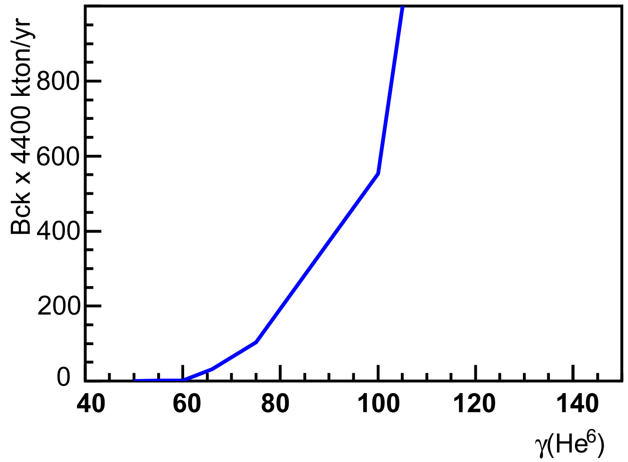
Final efficiency for positive muons. Negative muons have an efficiency smaller by $\sim 22\%$ because can be absorbed before decaying. Electron background suppressed to $\sim 10^{-5}$.



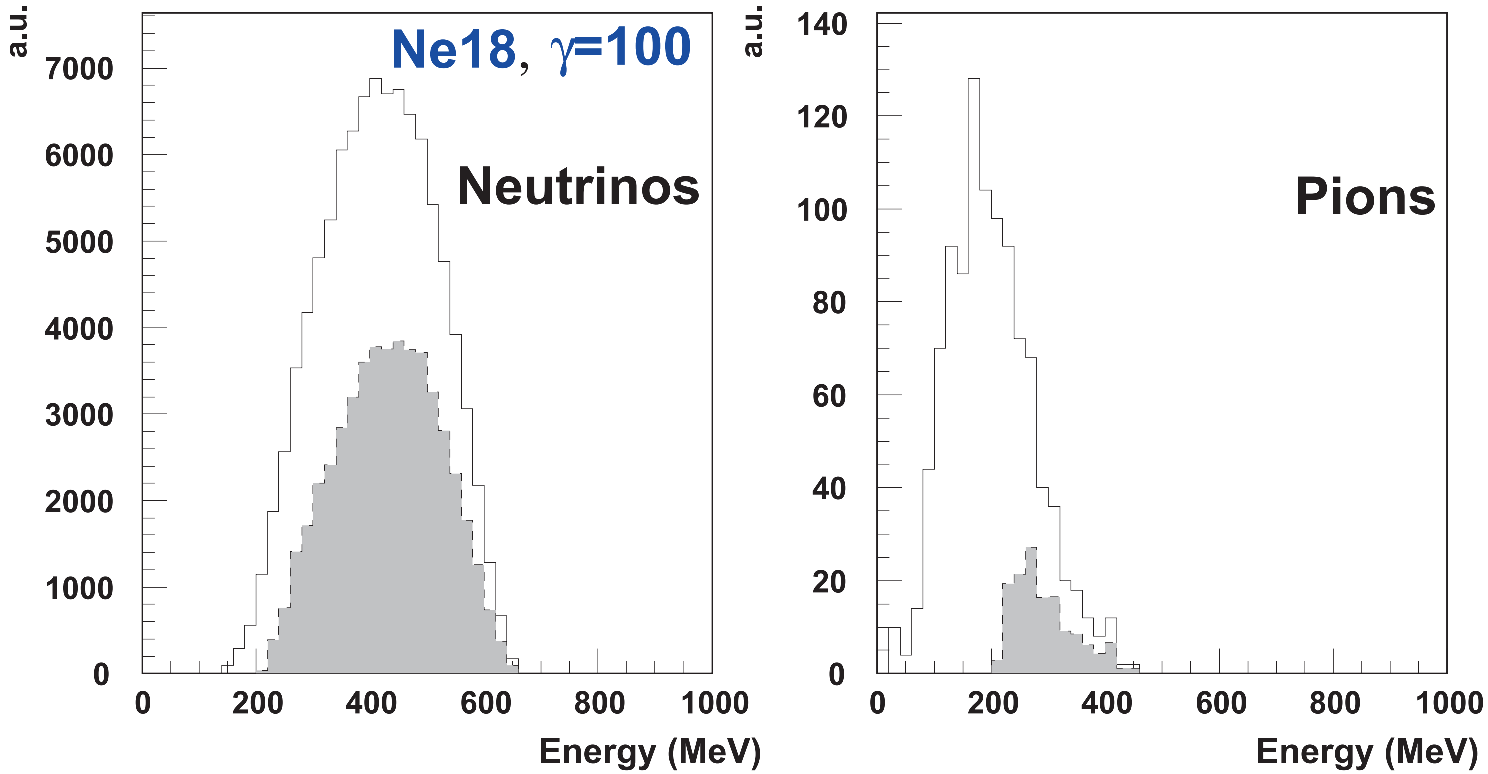


The pion background (the main concern at the higher gammas)

The efficiency function is computed by Nuance by asking a single ring event, one track above the Cerenkov threshold and the signature of the muon through the detection of the Michel electron. For $^{18}\mathrm{Ne}$ events the efficiency is smaller because of the muon absorption in water.



Effect on signal and background events:

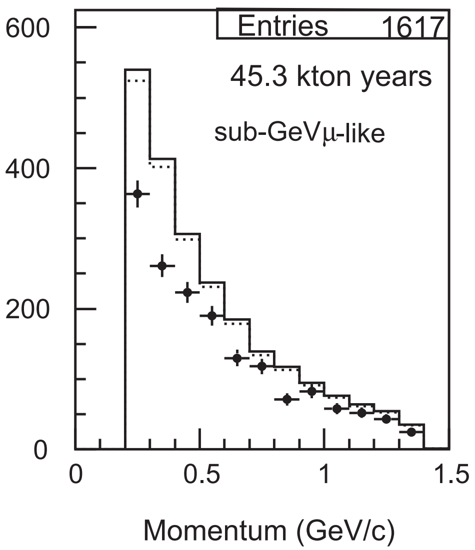


Not yet implemented:

Pion reinteractions in water. These would miss the tight pid criteria.

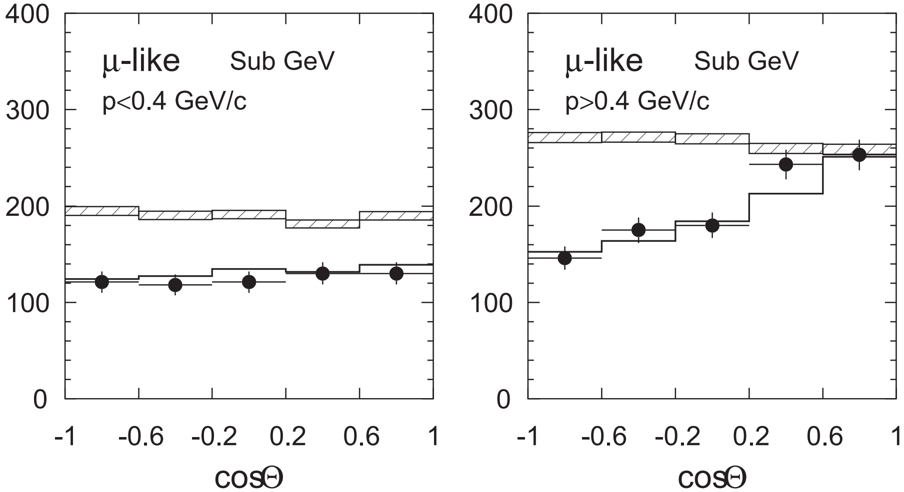
Pion/muon separation through the Cerenkov opening angle in the 200-300 MeV/c range.

Atmospheric neutrino background

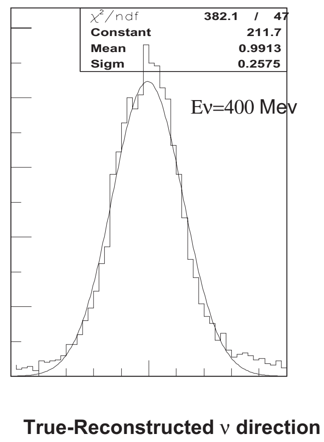


Sub-GeV μ-like events in SK integrated over the solid angle. 45.3 kton year exposure

Sub-GeV μ-like events zenithal distribution



Event direction resolution at 400 MeV. Take $\pm 2\sigma$ as acceptance, equivalent to $\pm 40^\circ$. Solid angle reduced to 1/8



Kamioka to Frejus flux correction: + 20%

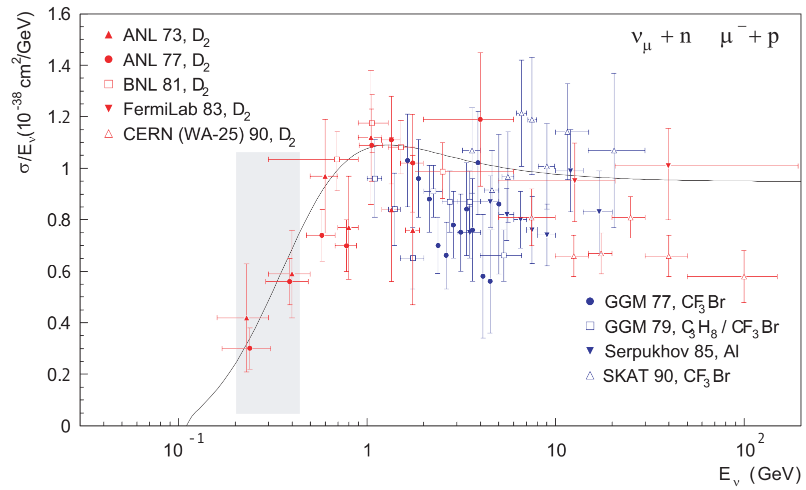
Signal efficiency with respect to standard SK algorithms: 54% (flat in energy)

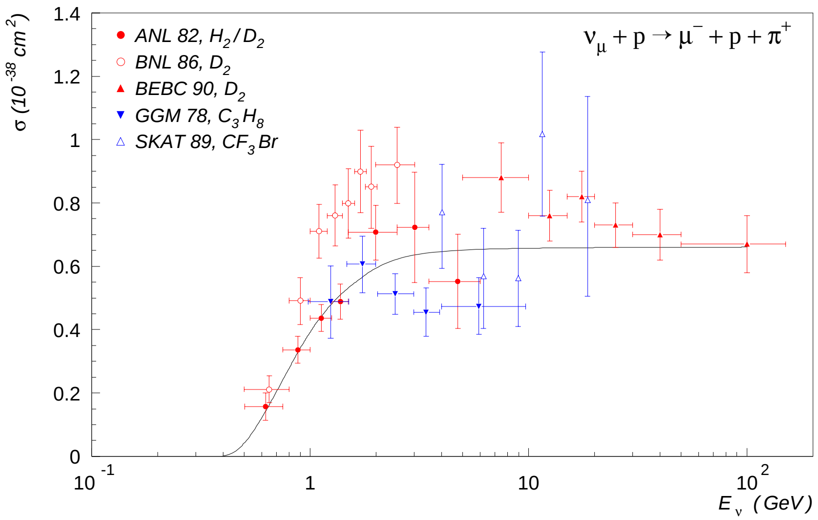
Duty cycle: 4 packets 10 ns long in the 7 km long decay ring: $1.7 \cdot 10^{-3} \times \mathrm{bunch\,length}[10\mathrm{ns}]$

10 events per ion specie in 4400 kton year exposure for 10 nsec long packets

The cross sections problem

V.V. Lyubushkin et al., internal NOMAD memo





Neutrino cross-sections are badly measured around 300 MeV.

Nuclear effects are very important at these energies.

No surprise that different MonteCarlo codes predict rates with a 50% spread.

On the other hand: Beta Beam is the ideal place where to measure neutrino cross sections

- Neutrino flux and spectrum are completely defined by the parent ion characteristics and by the Lorentz boost γ.
- Just one neutrino flavor in the beam.
- You can scan different γ values starting from below the Δ production threshold.
- A close detector can then measure neutrino cross sections with unprecedent precision.

A 2% systematic error both in signal and backgrounds is used in the following

Distinctive features of the Beta Beam

Just one neutrino flavor in the beam.

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

In the proposed scheme the $\overline{\nu}_e$channel is completely background free!

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

The $\nu_e$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.

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).

Furthermore when combined with the SPL-SuperBeam

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

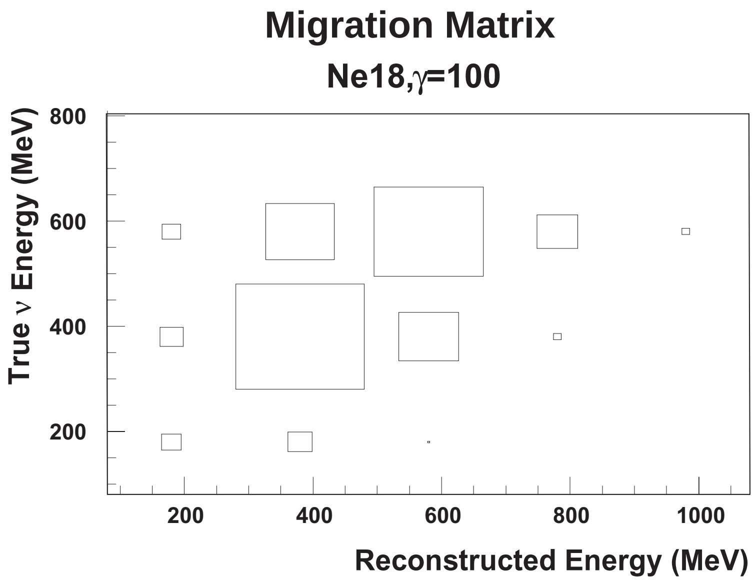
The $\gamma = 100, 100$ option

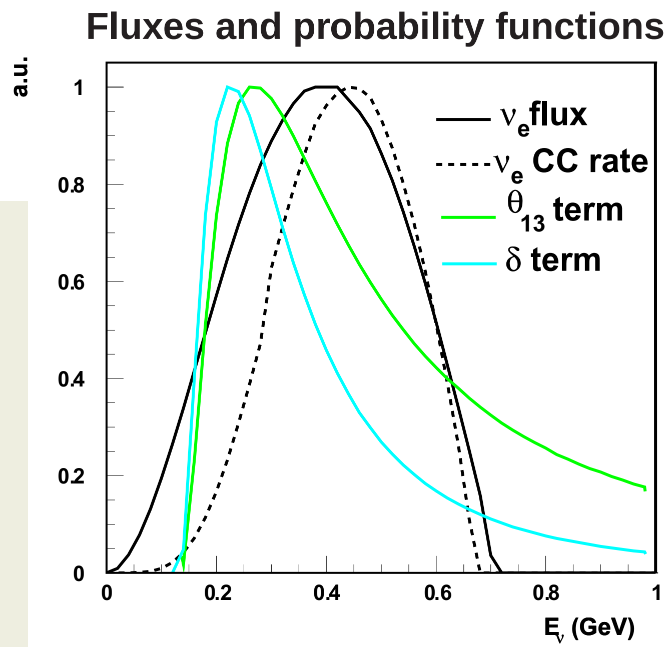
The physics potential of the baseline Beta Beam has been computed in J. Bouchez, M. Lindroos, M.M., AIP Conf. Proc. **721** (2004) 37 [hep-ex/0310059]; see A. Donini et al., Nucl. Phys. B **710** (2005) 402 and hep-ph/0411402 for computations aware of all the possible degeneracies.

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.

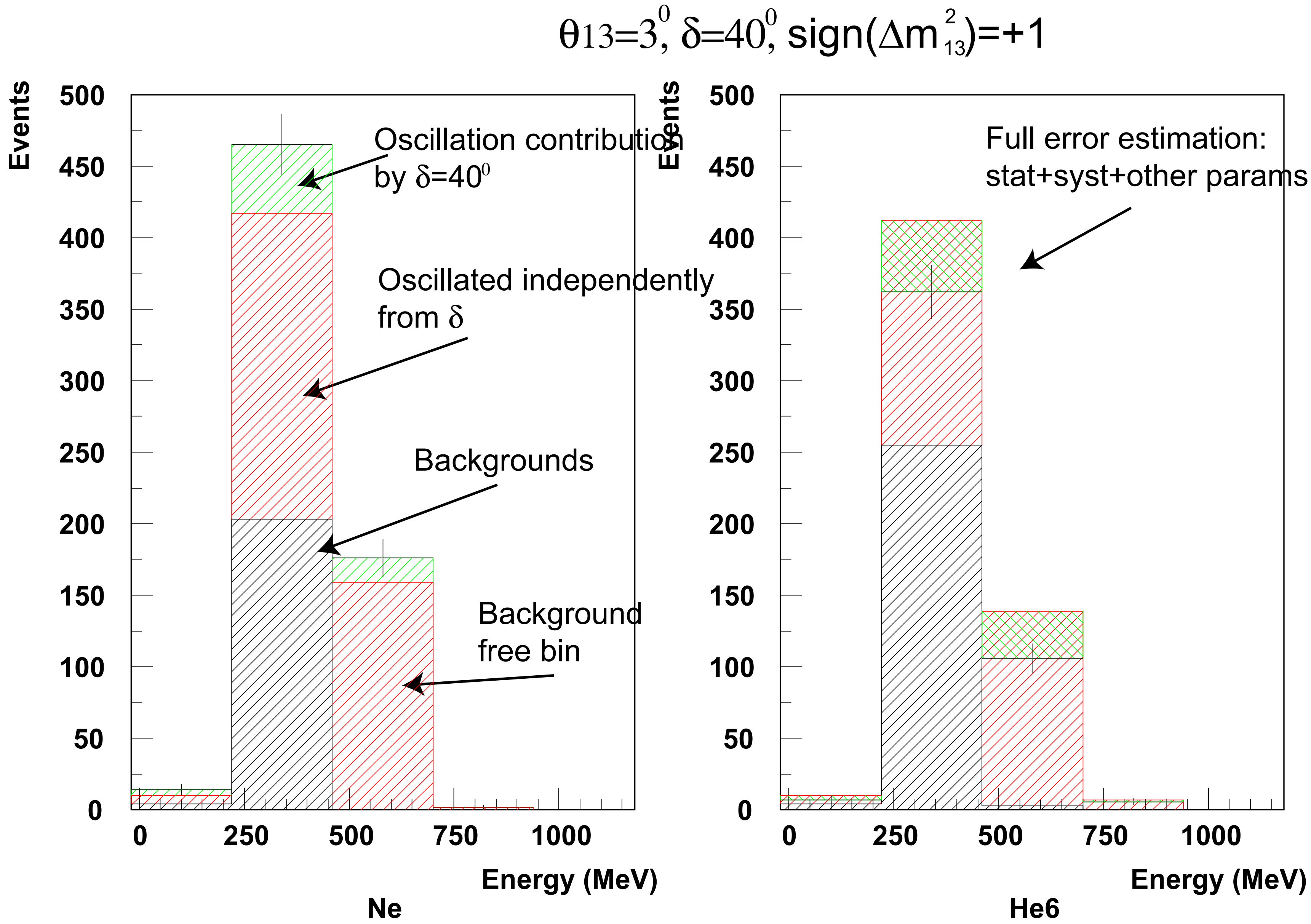
New developments (see M. Lindroos talk) show that the two ions can be run separately keeping constant their overall fluxes, this allows a better optimization.

- $^6\mathrm{He}$ 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.

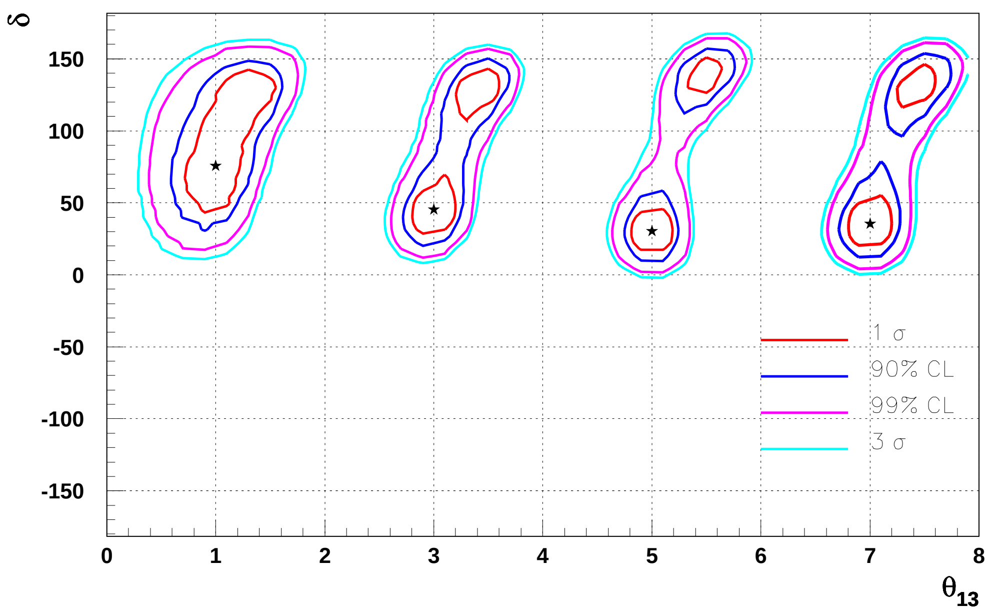




As an example: events for $\theta_{13} = 3^\circ, \delta = 40^0$

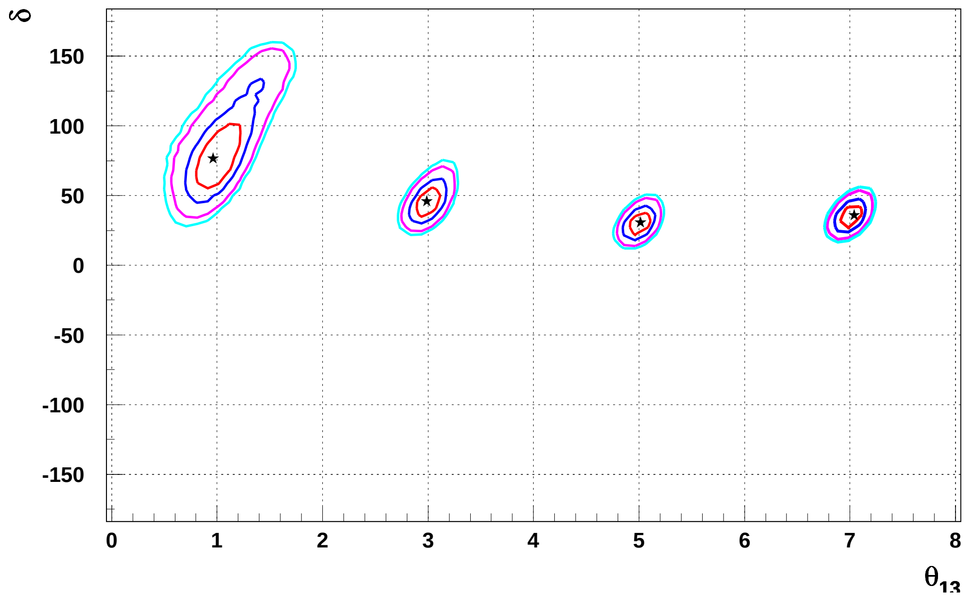


$\gamma = 60, 100$

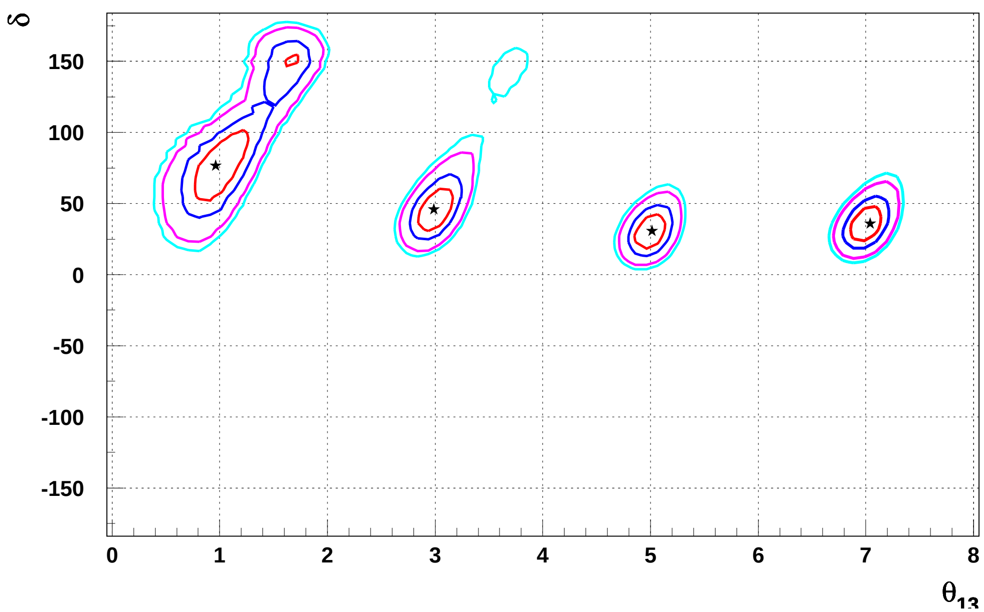


The improvement

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



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



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

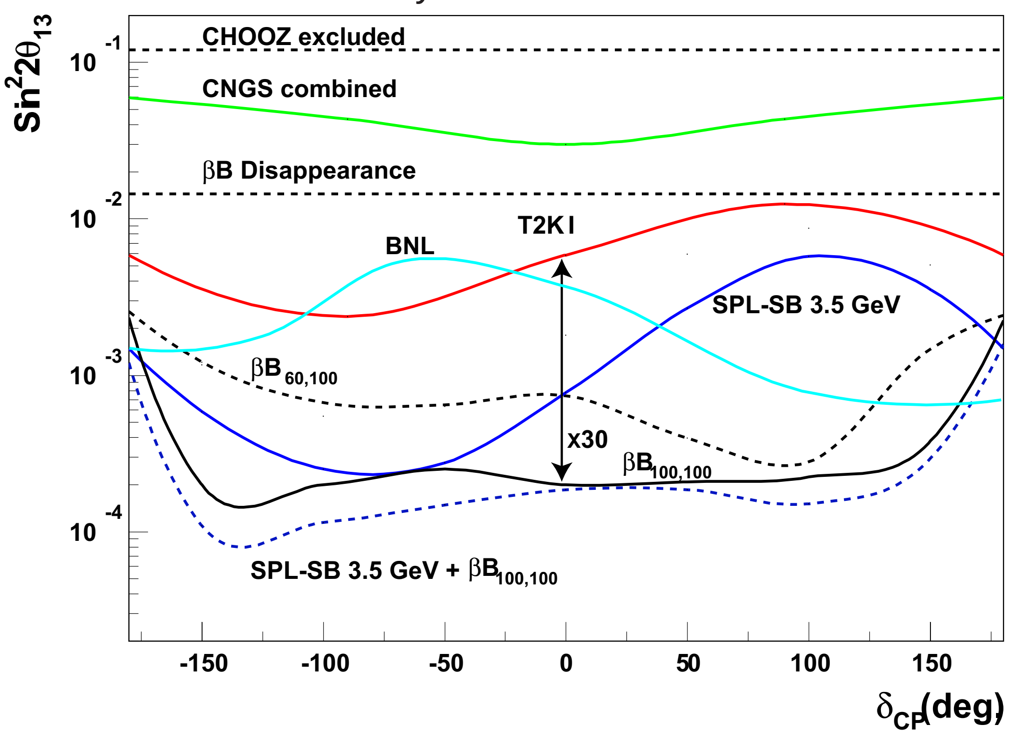
	^6He ($\gamma = 100$)	^{18}Ne ($\gamma = 100$)
CC events (no osc, no cut)	101263	144784
Oscillated	7	118
δ oscillated	-38	54
Beam background	0	0
Detector backgrounds	262	206

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)

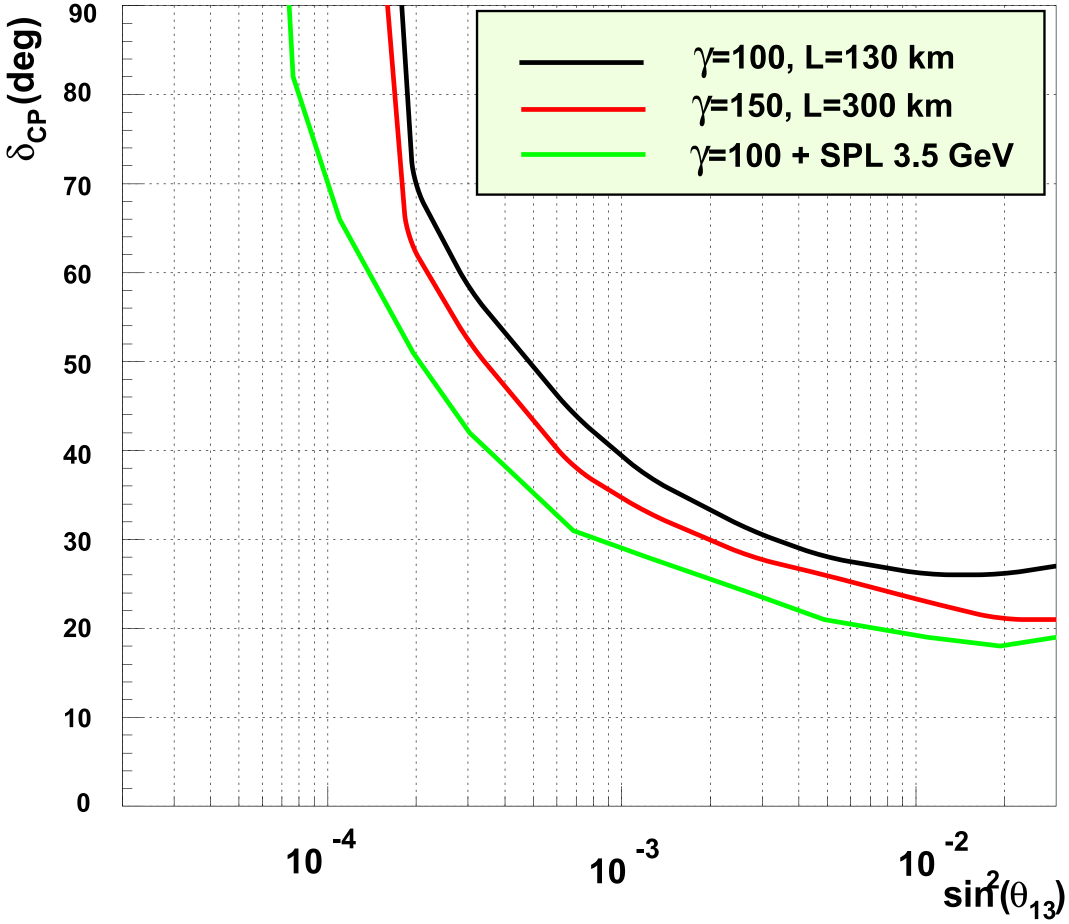
5 years run

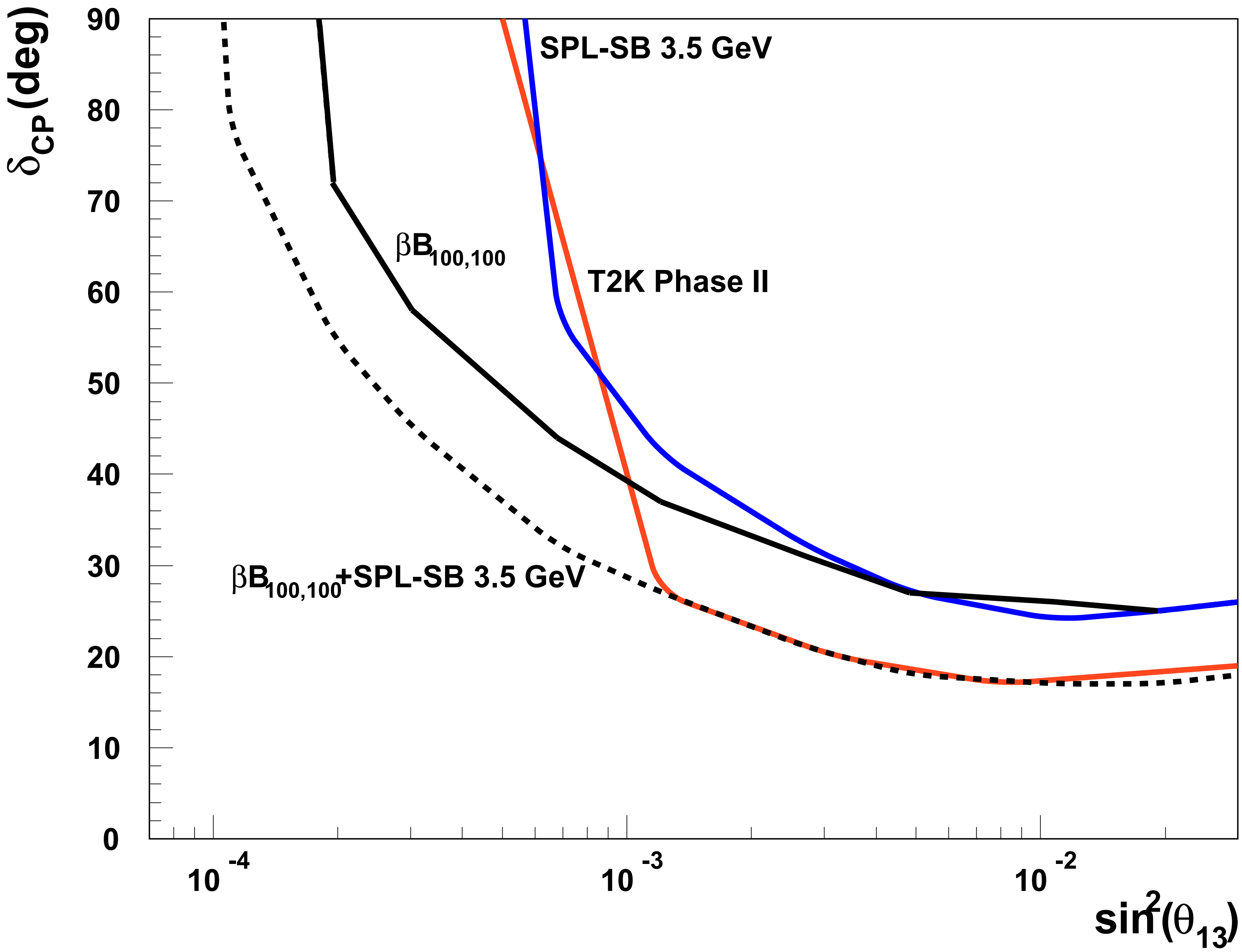


δ_{CP} discovery potential (3σ)

10 years, 5 ν_e+ 5 $\overline{\nu}_e$

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



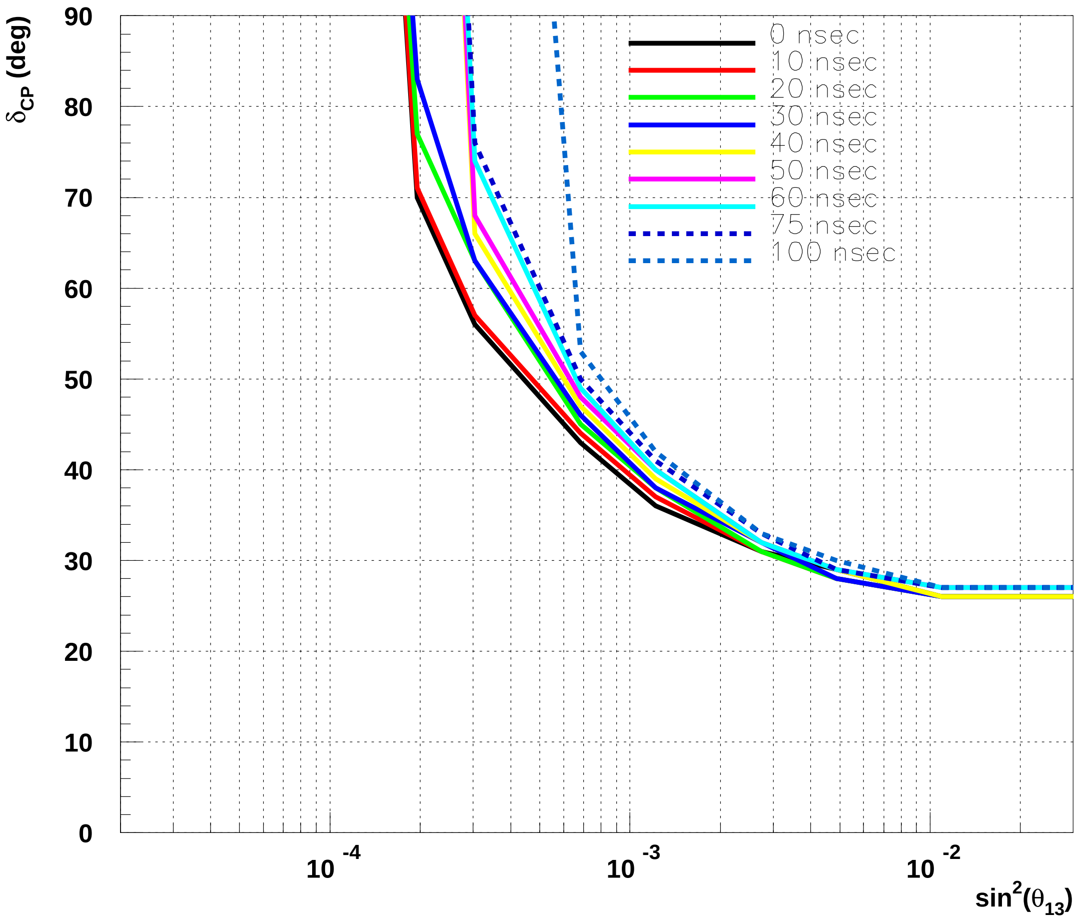


90
80
70
60
50
40
30
20
10
0
δ_{CP}(deg)
SPL-SB 3.5 GeV
$\beta B_{100,100}$
T2K Phase II
$\beta B_{100,100}$+SPL-SB 3.5 GeV
10^{-4}
10^{-3}
10^{-2}
$\sin^2(\theta_{13})$

A technical detail: how long can be the ion batches in the decay tunnel?

The 10 ns bunch length in the decay ring is very demanding from the accelerator physicists point of view. Relaxing this bound the ion fluxes could be enhanced.

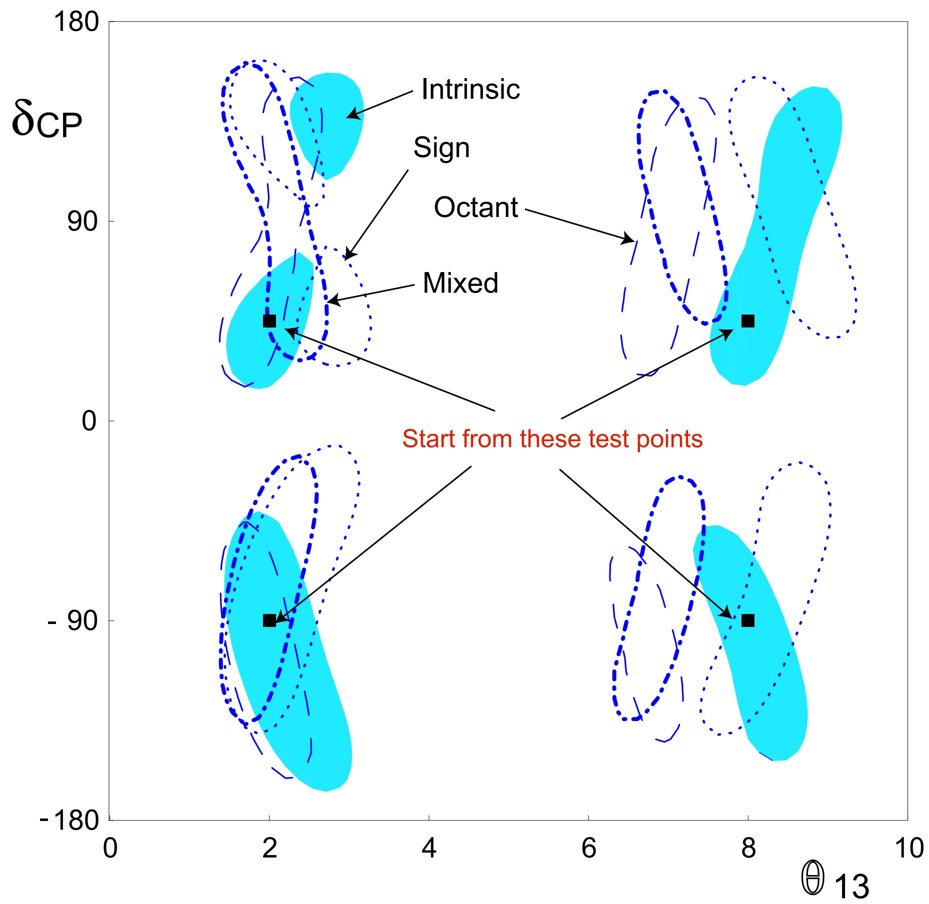
How long the ion bunches can be (keeping the ion fluxes constant)? Look how the $\delta_{\rm CP}$ sensitivity degrades.



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

- $\mathbf{sign(\delta m^2_{23})}$. Changing $\text{sign}(\delta m^2_{23})$ the $P(\nu_\mu \rightarrow \nu_e)$terms $\propto$ $\sin(\delta m^2_{23})$ change sign. Two separate solutions can be created by $(\theta_{13}\,, \delta_{\rm CP}\,, \text{sign}(\delta m^2_{23})\ )$ and by $(\theta_{13}{}', \delta_{\rm CP}{}', -\text{sign}(\delta m^2_{23})\ )$.
- $\boldsymbol{\pi/2 - \theta_{23}}$ (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

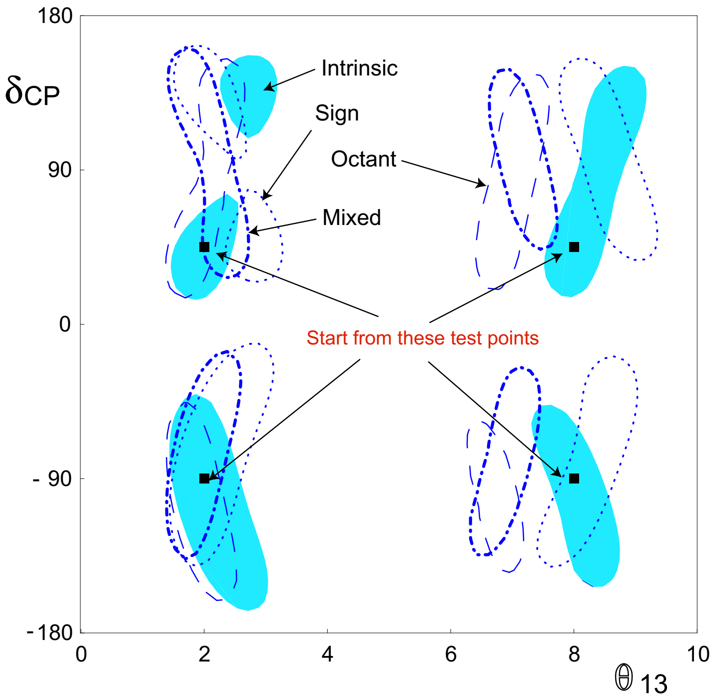


These eightfold discrete degeneracies (or twofold in case $\sin^2 2\theta_{23} \simeq 1$) can be solved by combining information of different experiments running at different energies or looking to different processes (i.e. combining $\nu_\mu \rightarrow \nu_e$ transitions with $\nu_e$disappearance or 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 ν_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 $\mathrm{sign}(\delta m^2_{23})$ **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 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.

Given the latest developments (see M. Lindroos talk), this assumption does not hold, and sensitivities should be recomputed with realistic fluxes.

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).

Electron capture beams

Radioactive ions can produce neutrinos also through electron capture.

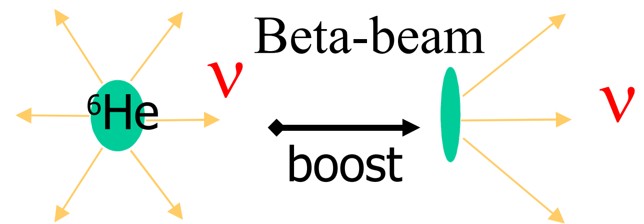
In this case neutrinos would be monochromatic!

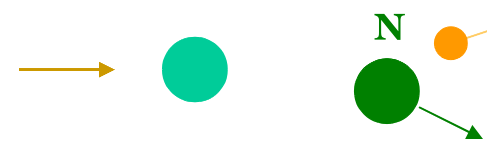
Idea pushed forward by J. Bernabeu and J Burguet Castell (talks at the RAL beta beam meeting 18/1/05 and Nowg meeting 18/3/05) and J. Sato, hep-ph/0503144.

- The same complex could run either beta or electron capture beams.
- No way to have $\overline{\nu}_e$beams (what about ν_μ beams via μ capture (J. Sato)?)
- Ions should be partially (and not fully) stripped. Technologically challenging.
- Ion candidates are much heavier then beta candidates and have much longer lifetimes (no way to stack them in the decay ring)

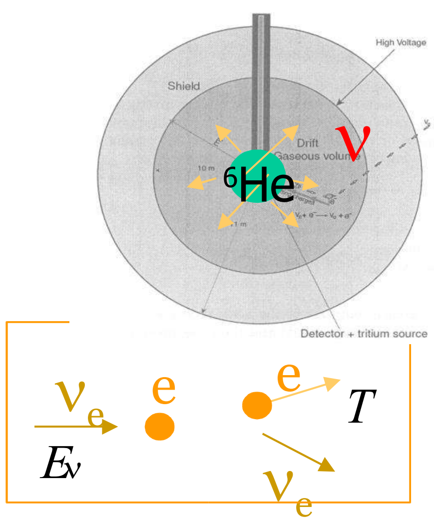
Low energy beta-beam

- The proposal
  - To exploit the beta-beam concept to produce intense and pure low-energy neutrino beams (C. Volpe, Journ. Phys. G. 30(2004)L1, J. Serreau, C.Volpe, hep-ph/0403293, C. Volpe, talk at this conference)
- Physics potential
  - Neutrino-nucleus interaction studies for particle, nuclear physics, astrophysics (nucleosynthesis)
  - Neutrino properties, like n magnetic moment





$^6He \longrightarrow {}^6Li + e + \bar{\nu}_e \quad Q_\beta = 4.\ \text{MeV}$



Conclusions

- The CERN-Frejus project has great physics potential to measure all the missing parameters in neutrino oscillations in a timescale of $\mathcal{O}(10)$ years by combining
  - ν_μ appearance in the Beta Beam ν_e beam, virtually free from intrinsic backgrounds and systematics.
  - ν_e disappearance in the Beta Beam.
  - ν_e appearance in the ν_μ SPL Super Beam, complementing the Beta Beam signals with different backgrounds and systematics. The combinations of Beta Beams and SPL-SB allow for CP, T and CPT searches.
  - ν_μ disappearance in the SPL-SB.
  - Atmospheric neutrinos in the megaton detector. When combined with ν_μ appearance they can solve all the degeneracies and measure $\mathrm{sign}(\delta m^2_{23})$.
- It could profit of very deep synergies with:
  - Nuclear physicists aiming at a very intense source of radioactive ions.
  - A gigantic water Cerenkov detector with great physics potential in its own.
- Additional ideas are growing around this project attracting the interest of more and more physicists.