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Beta Beam

Summary:

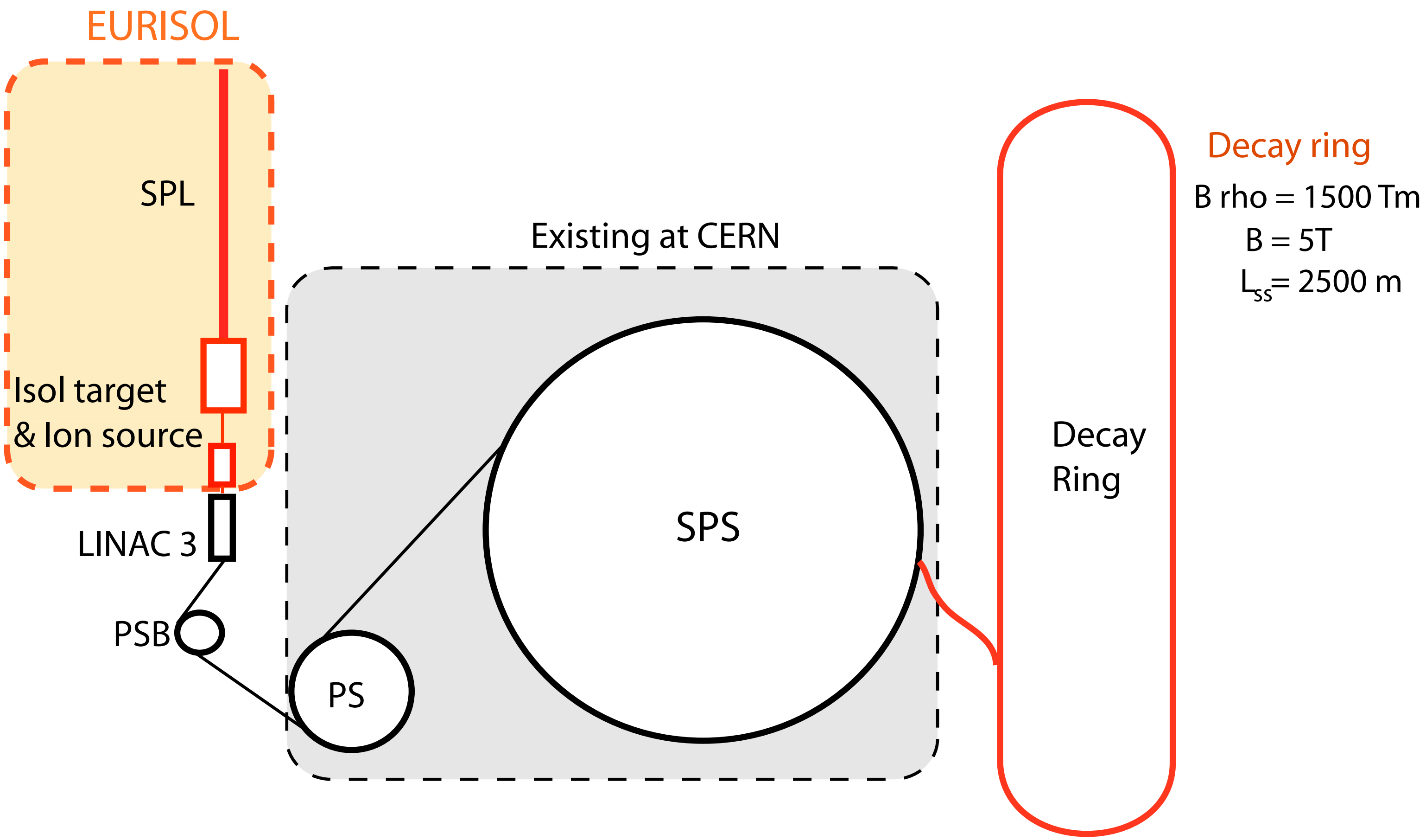
- **Optimization.**
- **Sensitivity to θ_{13} and δ**
- **Comparison with the Neutrino Factory.**

Thanks to: P. Zucchelli, M. Lindroos, J. Bouchez, P. Hernandez, JJ Gomez-Cadenas, J. Burguet-Castell, O. Mena, D. Casper, A. Blondel, M. Campanelli, S. Gilardoni

Nufact 03, New York, July 5-11 ,2003

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

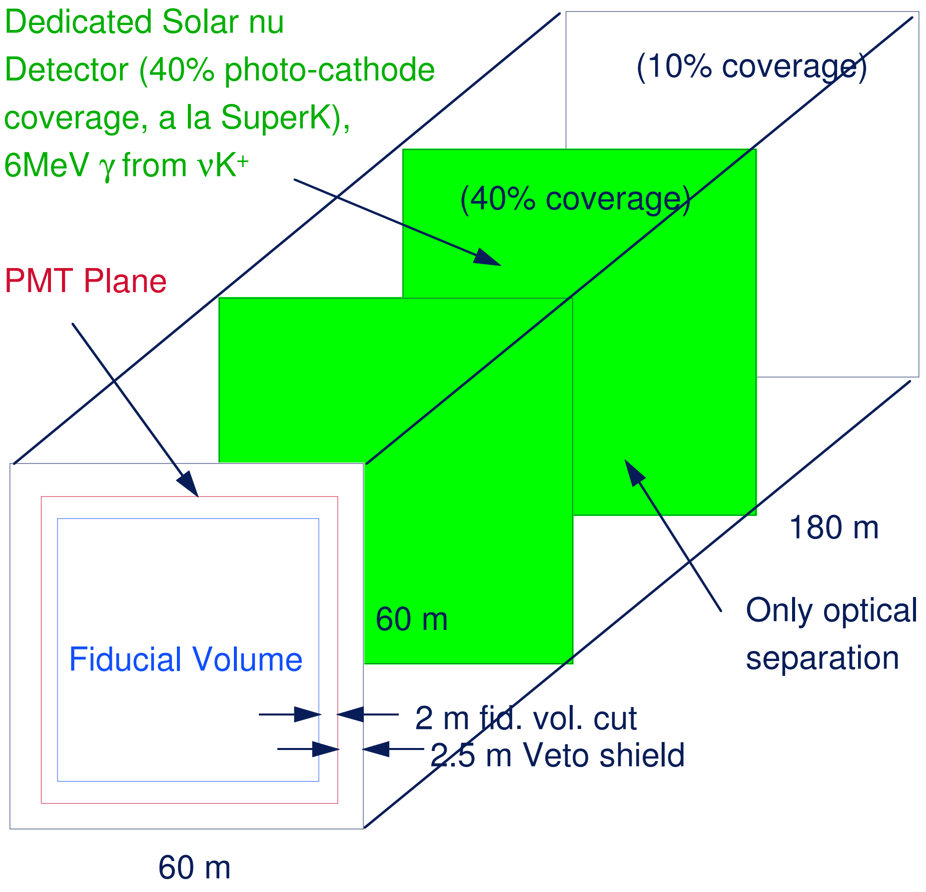
M. Lindroos and collaborators, see http://beta-beam.web.ch/beta-beam



- 1 ISOL target to produce He^6, 100 μA, $\Rightarrow 2.9 \cdot 10^{18}$ ion decays/straight session/year. $\Rightarrow \overline{\nu}_e$.
- 3 ISOL targets to produce Ne^{18}, 100 μA, $\Rightarrow 1.2 \cdot 10^{18}$ ion decays/straight session/year. $\Rightarrow \nu_e$.
- The 4 targets could run in parallel, but the decay ring optics requires:

$$\gamma(\boldsymbol{Ne^{18}}) = \mathbf{1.67} \cdot \gamma(\boldsymbol{He^{6}}).$$

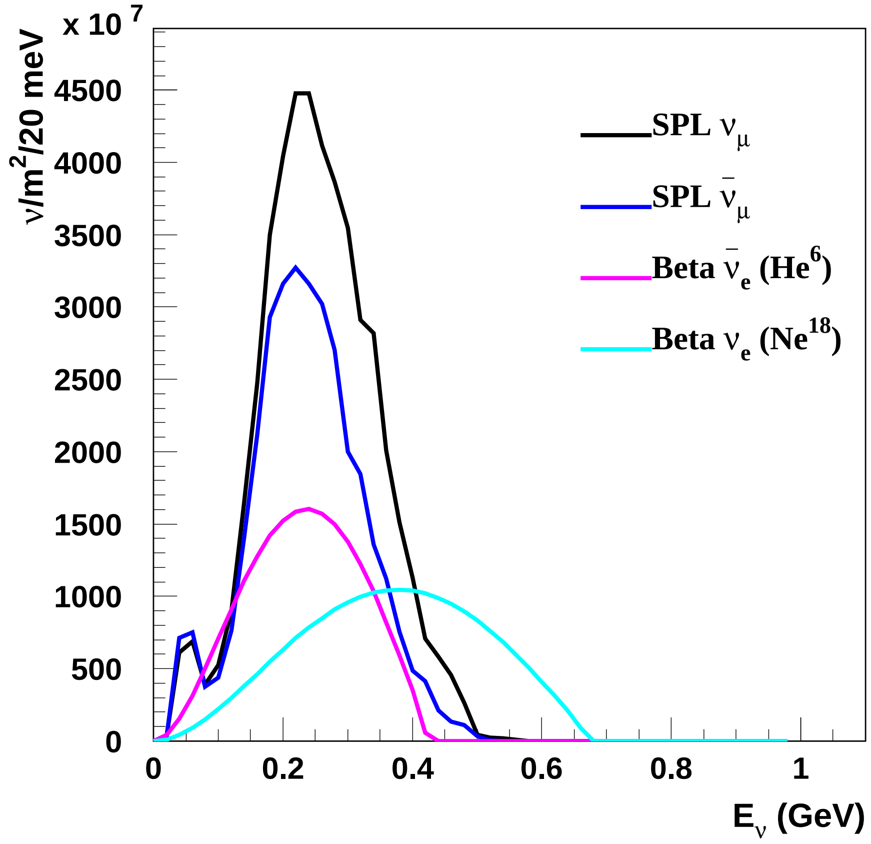
UNO detector



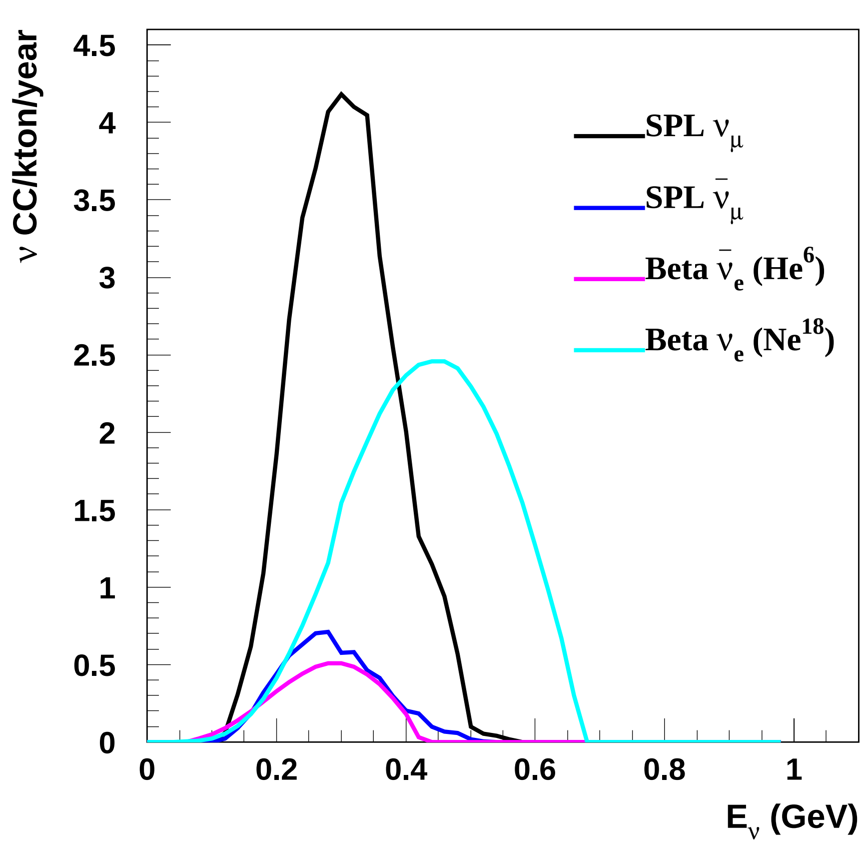
- Fiducial volume: 440 kton: 20 times SuperK.
- 60000 PMTs (20") in the inner detector, 15000 PMTs in the outer veto detector.
- Energy resolution is poor for multitrack events but quite adequate for sub-GeV neutrino interactions.
- It would be hosted at the Frejus laboratory, 130 km from CERN, in a $10^6\ m^3$ cavern to be excavated.

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

Fluxes



CC Rates



	Fluxes @ 130 km $\nu/m^2/yr$	$< E_\nu >$ (GeV)	CC rate (no osc) events/kton/yr	$< E_\nu >$ (GeV)	Years	Integrated events (440 kton $\times$ 10 years)
SPL Super Beam						
ν_μ	$4.78 \cdot 10^{11}$	0.27	41.7	0.32	2	36698
$\overline{\nu}_\mu$	$3.33 \cdot 10^{11}$	0.25	6.6	0.30	8	23320
Beta Beam						
$\overline{\nu}_e \ (\gamma = 60)$	$1.97 \cdot 10^{11}$	0.24	5.2	0.28	10	28880
$\nu_e \ (\gamma = 100)$	$1.88 \cdot 10^{11}$	0.36	39.2	0.43	10	172683

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 $\simeq 400$ MeV.

Angular cuts have not be considered.

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

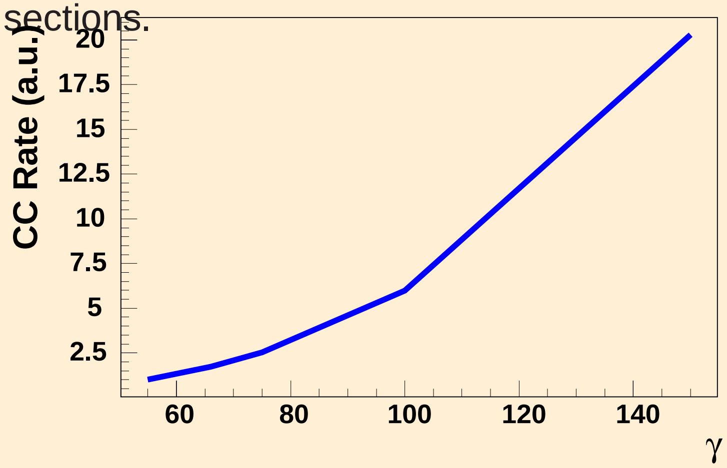
Atmospheric neutrino background can be kept low only by a very short duty cycle of the Beta Beam. A reduction factor bigger than 10^3 is needed.

This is achieved by building 10 ns long Ion bunches.

Optimizing the Lorentz Boost γ (L=130 km): preferred values: $\gamma = 55 \div 75$

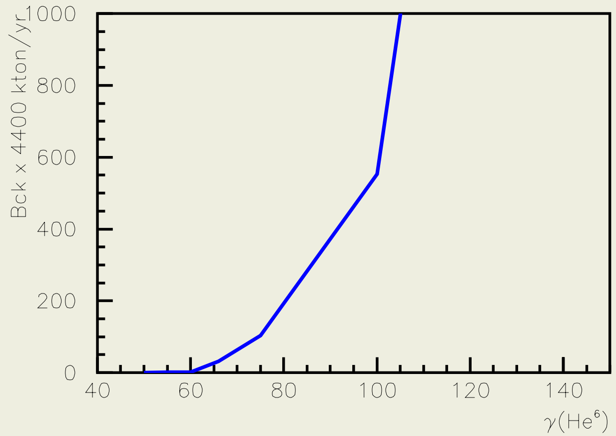
Higher γ produce more CC interactions

More collimated neutrino production and higher cross sections.

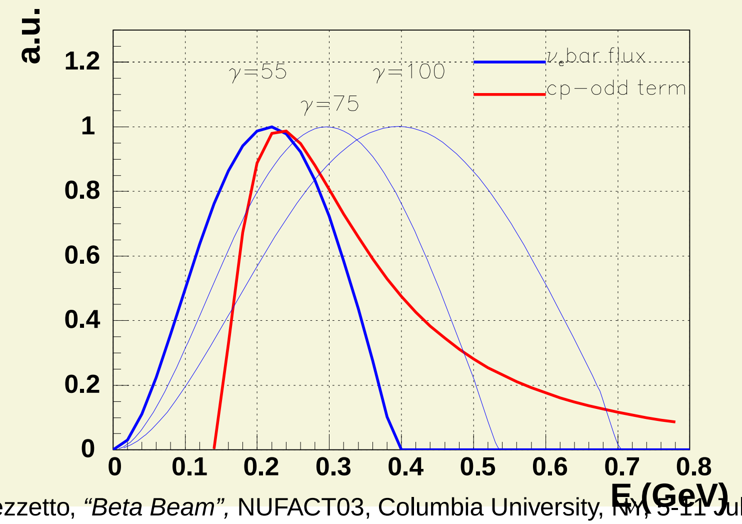


Background rate rises much faster than CC interactions

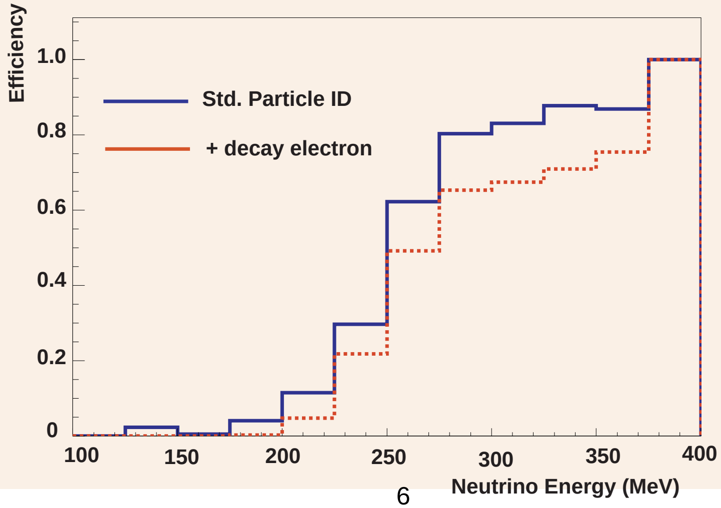
From resonant pion production in $\overline{\nu}_e$ NC interactions



ν flux must match the CP-odd oscillating term



Detection efficiency as function of ν energy



Other sources of errors

Systematic errors: 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.
- Only one neutrino flavour in the beam. in the storage ring.
- 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% uncertitude level on the systematics will be assumed in the following.

Errors on the other parameters

$p(\nu_\mu \to \nu_e)$ depends from all the mixing matrix parameters: errors on parameters influence the sensitivity of a CP search.

At the time of BetaBeam

- JHF will have measured δm^2_{23} with a $\sim 10\%$ resolution and $\sin^2 2\theta_{23}$ with $1 \div 2$ % resolution.
- Solar LMA parameters measured at $\sim 10\%$ precision level by Kamland (after 3 years, see hep-ph/0107277).

Only diagonal contributions from δm^2_{23}, δm^2_{12} and $\sin^2 \theta_{12}$ will be taken into account. Their contribution is anyway marginal.

Statistical method

If the number of events is greater than 12 use the classical gaussian chi2 with all the systematics included. If lower use the Poisson chi2, no systematic included. Given the above errors this approximation is largely acceptable.

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

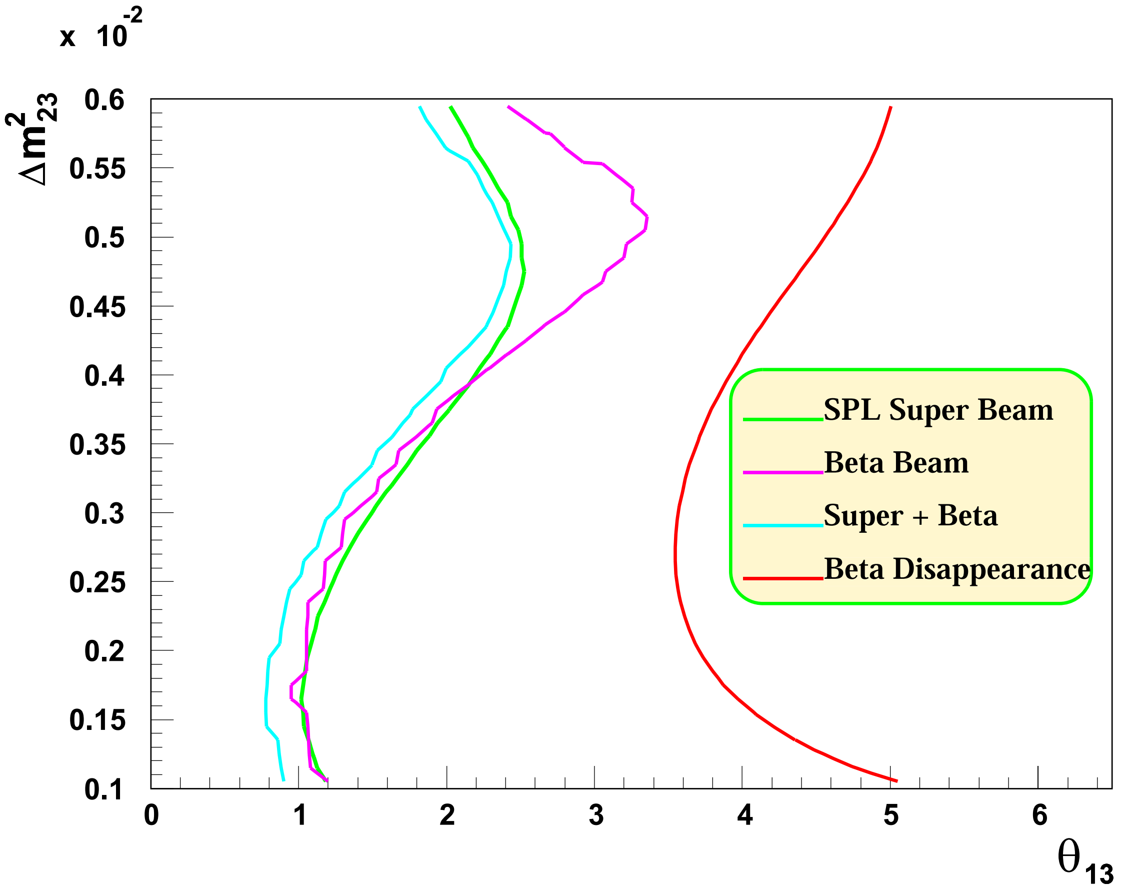
CPT searches

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

The SuperBeam - BetaBeam synergy: a benchmark on θ_{13} sensitivity

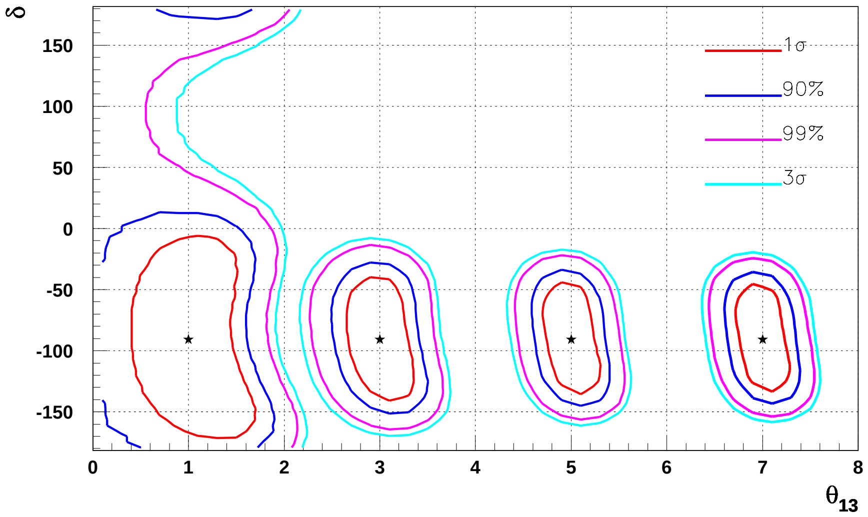
Computed for $\delta_{CP} = 0$ and 5 years running.

- Super Beam $\longrightarrow 96\times$ CHOOZ.
- Super Beam + Beta Beam $\longrightarrow 160\times$ CHOOZ.
- **Beta Beam can measure θ_{13} both in appearance and in disappearance mode. All the ambiguities can be removed for $\theta_{13} \geq 3.4°$**

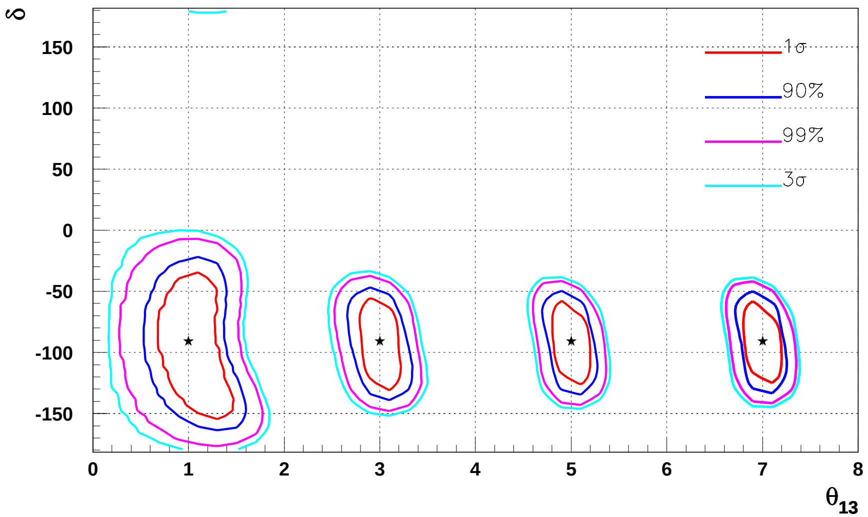


Beta Beam - Super Beam synergy: CP sensitivity

SUPER BEAM ONLY

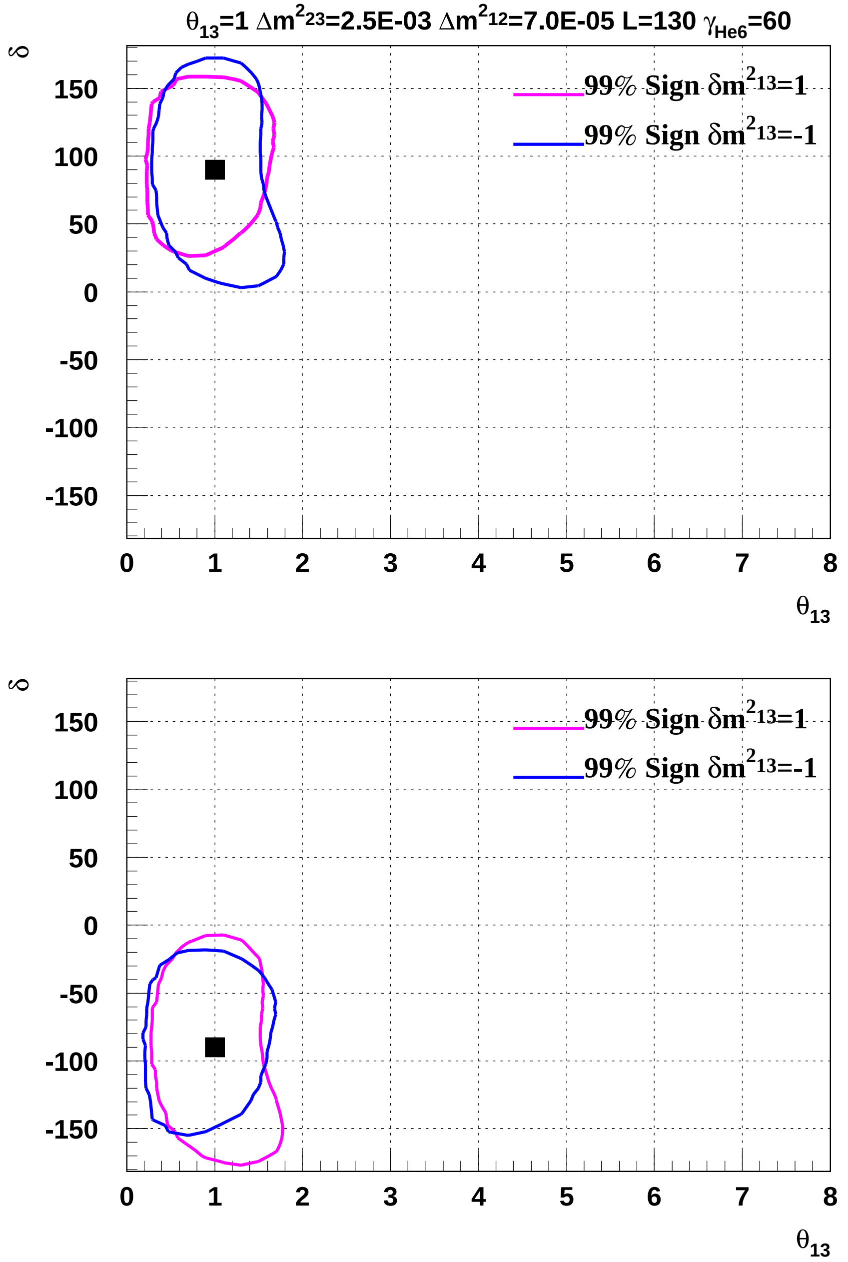


SUPER BEAM + BETA BEAM



$\delta m^2_{12} = 7 \cdot 10^{-5}\ eV^2, \quad \theta_{13} = 1^\circ, \quad \delta_{CP} = \pi/2$

10 yrs (4400 kton/yr)	SuperBeam		Beta Beam	
	ν_μ	$\overline{\nu}_\mu$	$\overline{\nu}_e$ (He^6)	ν_e (Ne^{18})
	(2 yrs)	(8 yrs)	$\gamma = 60$	$\gamma = 100$
CC events (no osc, no cut)	36698	23320	28880	172683
Total oscillated	1.7	33.3	0.5	84.2
CP-Odd oscillated	-25.5	16.9	-11.9	41
Beam backgrounds	141	113	/	/
Detector backgrounds	37	50	1	299
Statistical Error	13.4	13.6	1.5	21.9
Error on θ_{23}	2.1	1.7	0.5	4.7
Error on δm^2_{12}	2.8	1.9	0.3	8.1
Total Error	13.9	14.6	1.7	25.7



Ambiguities

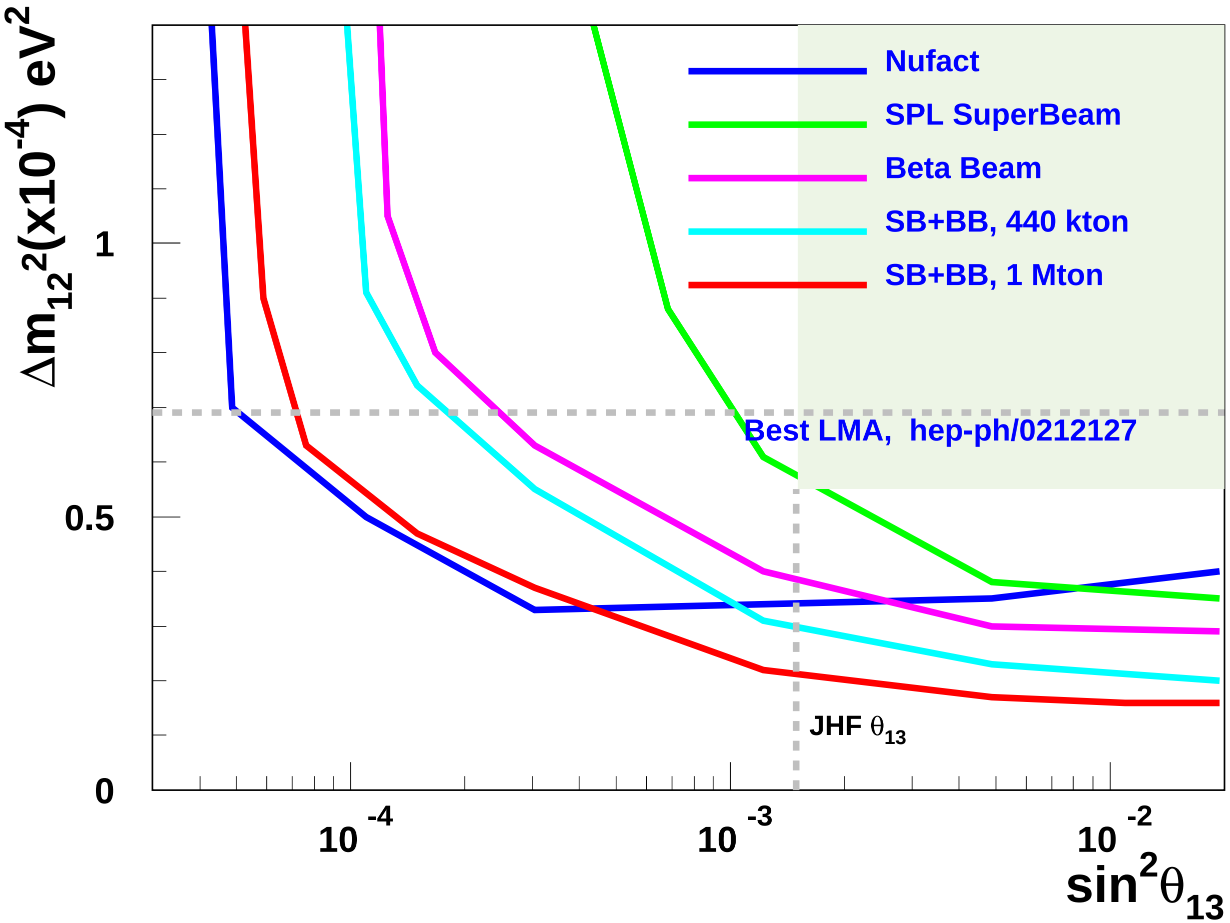
- The asymmetric statistics and background rates in the ν_e and $\overline{\nu}_e$ beams produce an asymmetric response to the positive and negative values of δ.
- Even if the matter effects are negligible, the $p(\nu_\mu \rightarrow \nu_e)$ formula contains odd $\mathrm{sign}(\delta \mathrm{m}^2_{13})$ terms .
- The change of $\mathrm{sign}(\delta m^2_{13})$ produces non negligible changes in the oscillation formula. No attempt made so far to fit $\mathrm{sign}(\delta m^2_{13})$, θ_{13} and δ at the same time.
- Results are shown in the following for positive values of δ and $\mathrm{sign}(\delta m^2_{13})$.
  - $\sin^2 2\theta_{23} = 1.0$
  - $\delta m^2_{23} = 2.5 \cdot 10^{-3}$ eV^2.
  - $\sin^2 2\theta_{12} = 0.8$

A comparison of CP sensitivities: Beta Beam vs. Nufact

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

Nufact sensitivity as computed in J. Burguet-Castell et al., Nucl. Phys. B **608** (2001) 301:

- 50 GeV/c μ.
- $2 \cdot 10^{20}$ useful μ decays/year.
- 5+5 years.
- 2 iron magnetized detectors, 40 kton, at 3000 and 7000 km.
- Full detector simulation, including backgrounds and systematics.

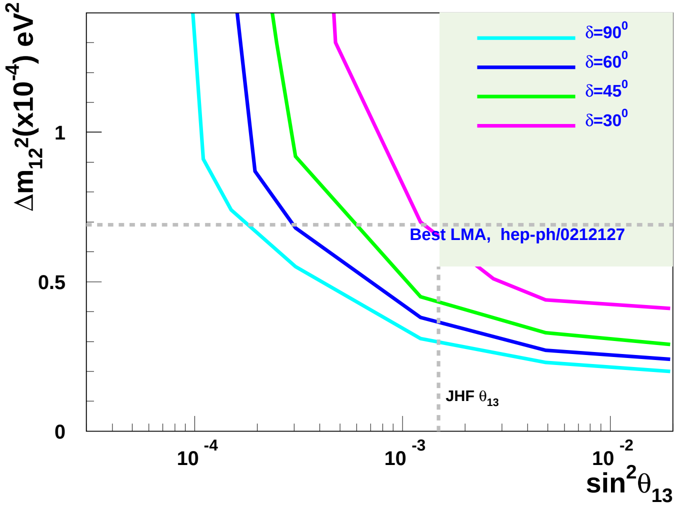


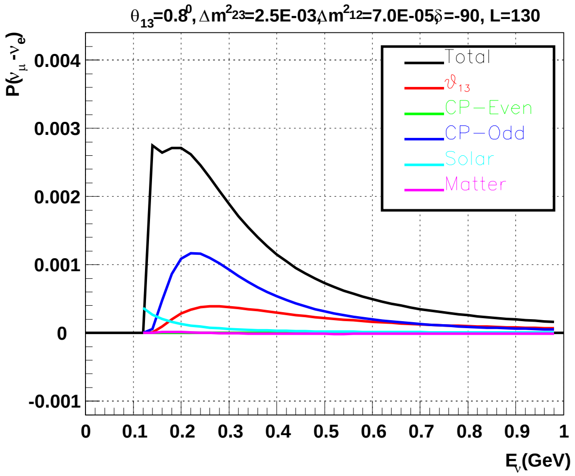
Some comments about the comparison

The sensitivity computation depends from many implicit assumptions, input parameters, degeneracy treatment, statistical methods, tricks, bugs etc.

A fair comparison should be made by the same group using the same methods for the different facilities (a call for collaboration ...)

The plot doesn't tell anything about the fits in a arbitrary $(\theta_{13}\,,\delta)$ point.

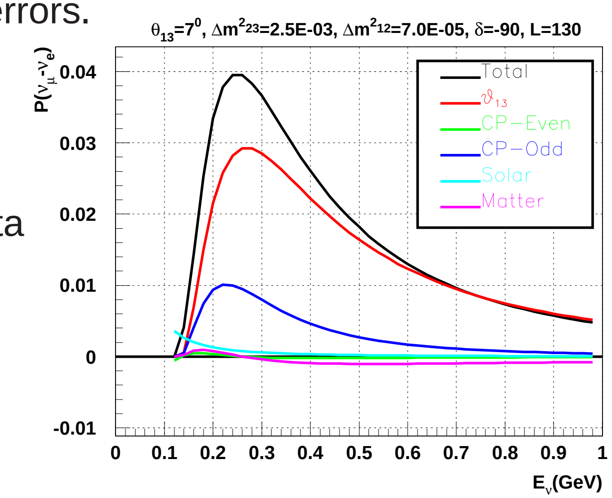




The small θ_{13} region is particularly delicate: going the absolute probabilities down to zero, it's very sensitive to:

- Background levels.
- Statistical treatment of data
- Input parameters and their errors.

In the large θ_{13} region the CP asymmetry is small. This favours the Super-Beta Beams, because they don't have to compete with matter effects.



Conclusions

Beta Beam is a (CERN based) realistic facility that 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.

The Super-Beta Beams combination can address δ_{CP} discovery with a sensitivity similar to the Neutrino Factory having the distinctive possibility of:

- Combine CP, T and CPT searches
- Use ν_e disappearance to solve all the ambiguities for reasonable large values of θ_{13} .

The Super-Beta Beams combination cannot compete with the Neutrino Factory in measuring sign(δm^2_{13}) or matter effects (however, if you are focused in Leptonic CP, this is an advantage.)

If a gigantic water Cerenkov detector will be built in the world, CERN-Frejus could offer it an excellent combination of beams and a very deep site.