Mauro Mezzetto

Istituto Nazionale di Fisica Nucleare,

Sezione di Padova

Physics Potential of SPL Part II: Beta Beam

Summary:

- **Beta Beam.**
- **Sensitivity to θ_{13} and δ**
- **Combined sensitivity to δ with the SPL Super Beam.**

In collaboration with M. Campanelli, D. Casper, P. Zucchelli.

Nufact 02, London, July 1-6 ,2002

CP phase is well hidden in the mixing matrix

In principle CP terms could be extracted with oscillations from the first and the third generation ($\nu_e \rightarrow \nu_\tau$), in practice this experimental approach seems non viable: too difficult to detect ν_τ in very massive detectors.

Best possibility: $\nu_\mu \rightarrow \nu_e$ transitions.

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

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

At the first order, neglecting matter effects and CP:

$$P(\nu_\mu \rightarrow \nu_e) \propto \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \frac{\Delta m_{23}^2 L}{4E}$$

Recalling the Beta Beam

- Beta Beam produces just one neutrino flavour, $\overline{\nu}_e$ if running with ^{6}He or ν_e if running with ^{18}Ne.
- The neutrino energy is controlled by the Lorentz boost γ of the parent ions.
- The only possible backgrounds are
  - Detector backgrounds: single π's from NC and electrons (positrons) mis-identified as muons.
  - Atmospheric neutrinos collected in the neutrino gate.

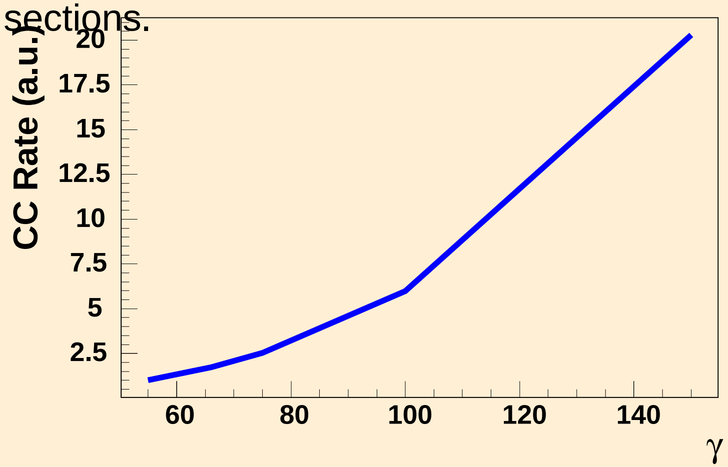
In the following Beta Beam will be normalized to $2.9 \cdot 10^{18}$ ^{6}He useful decays/year and $3.6 \cdot 10^{17}$ ^{18}Ne decays/year.

A full simulation of neutrino events in water have been performed with the NUANCE MonteCarlo code.
The events are then fully reconstructed and analyzed.
An optimization of the selection criteria is still underway

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

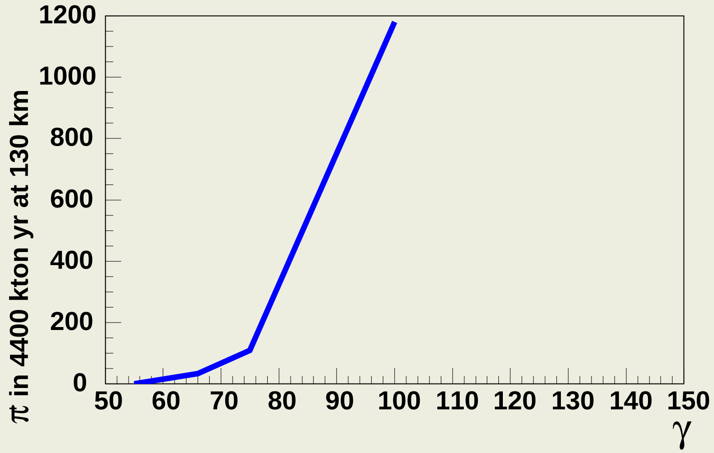
Higher γ produce more CC interactions

More collimated neutrino production and higher cross sections.

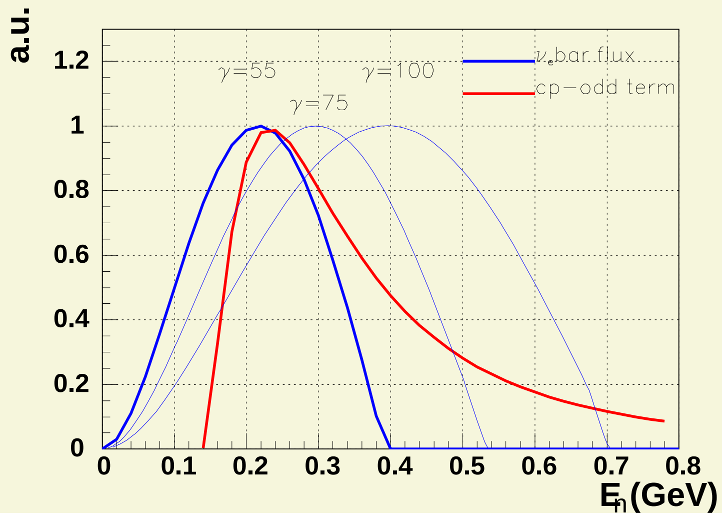


Background rate rises much faster than CC interactions

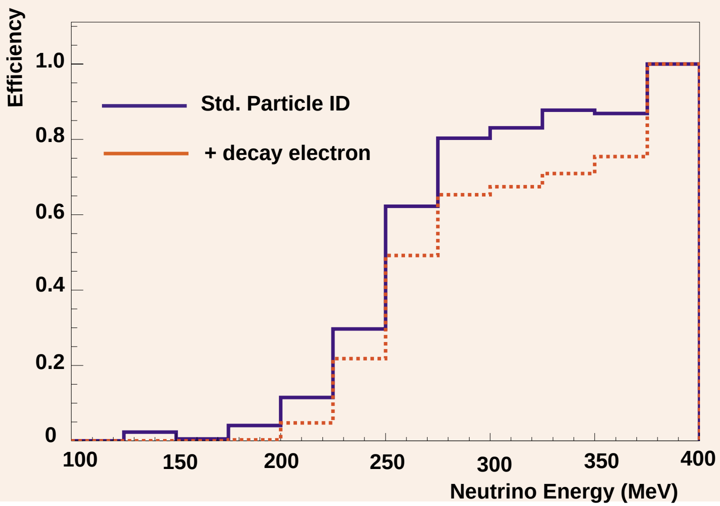
From resonant pion production in $\overline{\nu}_e$ NC interactions



ν flux must match the CP-odd oscillating term



Detection efficiency as function of ν energy



Beta Beam Backgrounds

Computed with a full simulation and reconstruction program.

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.

The threshold for this process in $\simeq 400$ MeV.

Angular cut 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 a likelihood function.
- 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.

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.
- The limiting factor would be the knowledge of the number of ions 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

$p(\nu_\mu \rightarrow \nu_e)$ 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 a few % 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.

Sensitivity to θ_{13} with a UNO like detector (^{6}He)

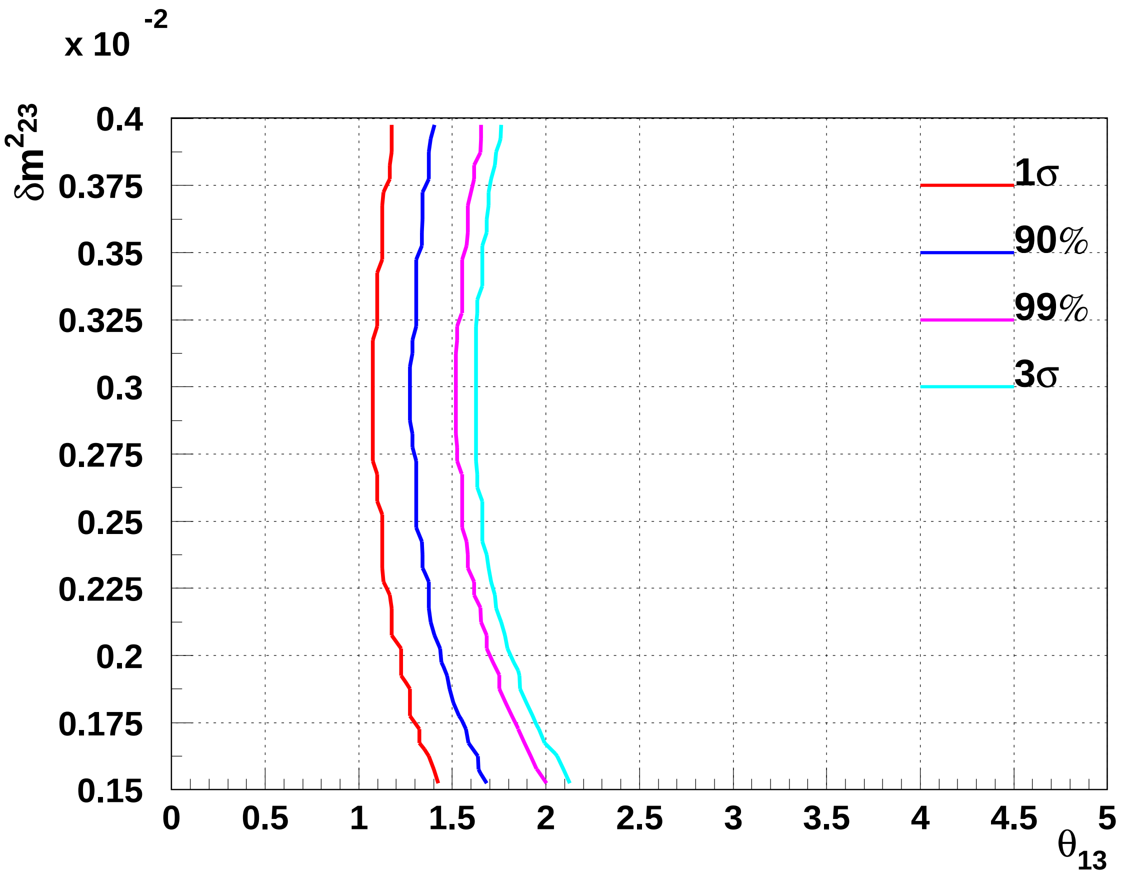
For the JHF limit: $\sin^2 2\theta_{13} = 0.006$ ($\delta m^2_{23} = 2.5 \cdot 10^{-3} eV^2$, solar SMA solution):

$\overline{\nu}_e$ (no osc.)	76782
Detector bkgds	66
Signal	94 ($> 7\sigma$)

θ_{13} 90%CL sensitivity: θ_{13} =1.2°

JHF 90%CL sensitivity: θ_{13} =2.3°

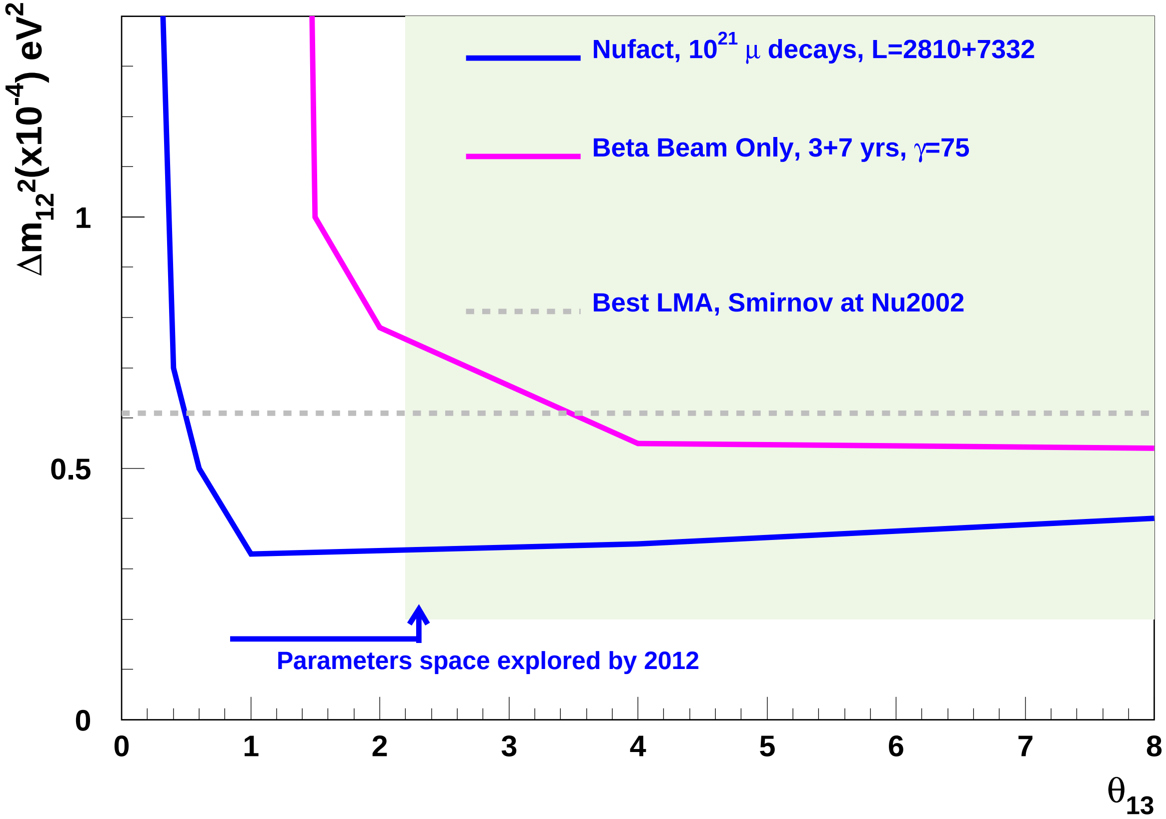
(Factor ~ 4 better on $\sin^2 2\theta_{13}$)



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, including background, systematics and using two 40 kton iron magnetized detectors at L=3000 and 7000 km to solve ambiguities.



Run 3 years with ^6He and 7 years with ^{18}Ne to compensate for the lower ν_e CC rate (in spite of the higher cross-section).

As an example for θ_{13} =4°, $\delta m^2_{12} = 0.6 \cdot 10^{-4}\, eV^2$, $\sin^2 2\theta_{12} = 0.8$:

	$^6He\ (\overline{\nu}_e)$ 3 years	$^{18}Ne\ (\nu_e)$ 7 years
CC events (no osc)	12235	13008
Osc. events (total)	38	70
Osc. events (cp-odd)	-17	46
Detector backgrounds	18	7

The SuperBeam - BetaBeam synergy

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

Both beams need SPL, but the BetaBeam requires at most 3% of the SPL protons $\longrightarrow$ the two beams can run together.

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

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

The SuperBeam - BetaBeam synergy: CP, T and CPT

No other realistic scenario can offer CP, T and CPT searches at the same time in the same detector!!!!

CP Searches

- SuperBeam running with ν_μ and $\overline{\nu}_\mu$.
- Beta Beam running with ^{6}He ($\overline{\nu}_e$) and ^{18}Ne (ν_e).

T searches

- Compare Super Beam $p(\nu_\mu \longrightarrow \nu_e)$ 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 $p(\nu_e \longrightarrow \nu_\mu)$

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

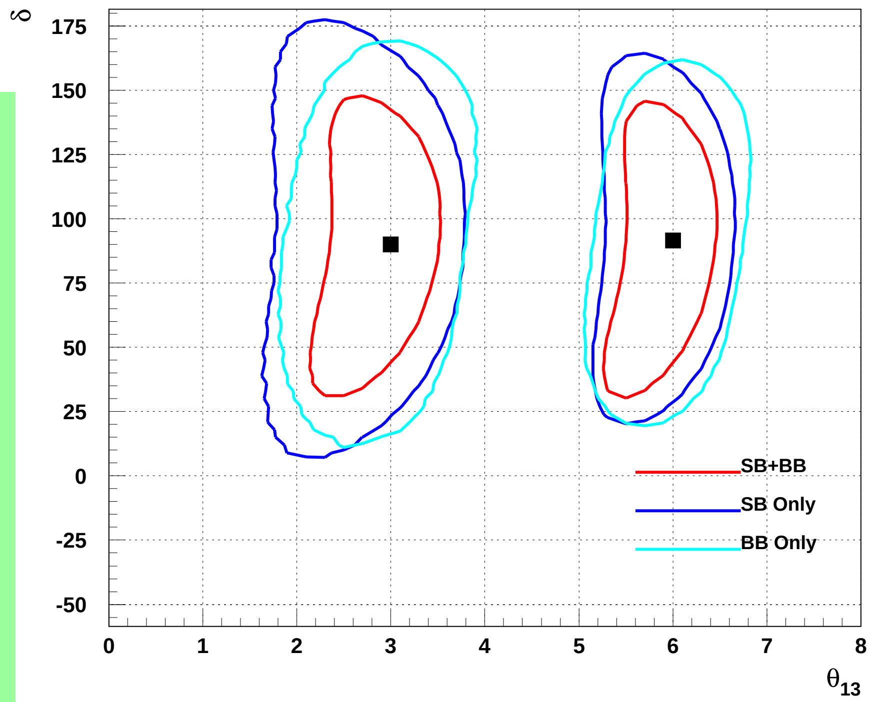
The SuperBeam - BetaBeam synergy: results

A test point running SuperBeam with ν_μ for 10 years and Beta Beam with ν_e for 10 years.

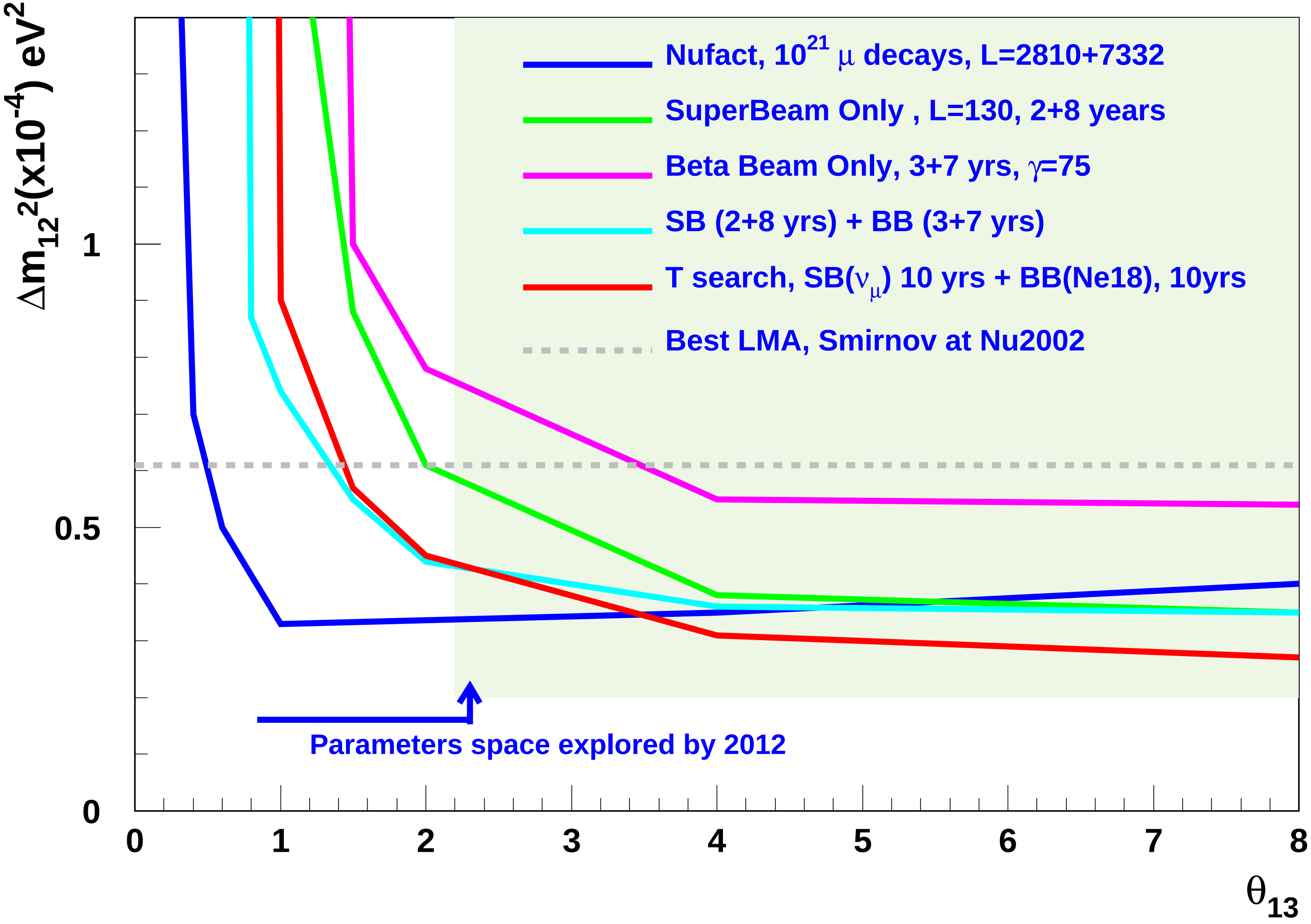
θ_{13} =3°, $\delta m^2_{12} = 0.6 \cdot 10^{-4}\, eV^2$:

10 years	SuperBeam	Beta Beam $\gamma = 75$
CC events (no osc, no cut)	85421	18583
Total oscillated	111	74
CP-Odd oscillated	-151	30
Beam background	165	0
Detector bkg.	100	10

How two particular solutions can be improved by the combination of Super + Beta Beam (99%CL curves)



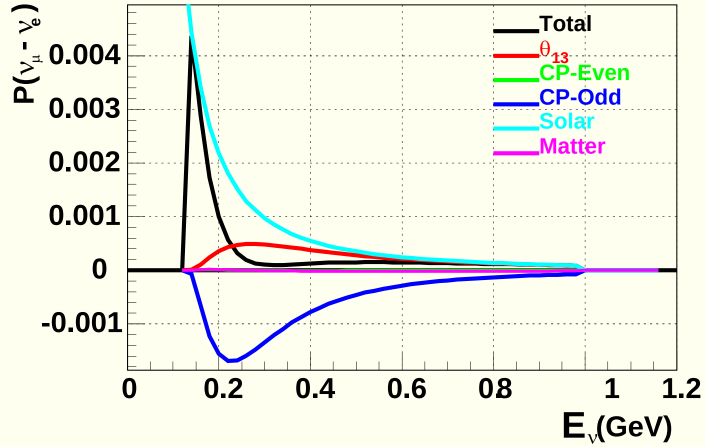
Final CP sensitivity.

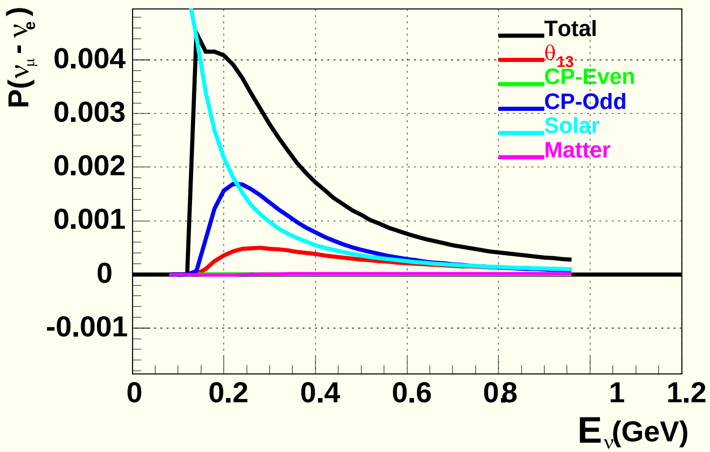


Small θ_{13}

$\theta_{13} = 0.9°, \; \delta m^2_{12} = 9 \cdot 10^{-5} \, eV^2$

10 years	SuperBeam	Beta Beam
Oscillated events (total/cp)	36(-162)	22 (10)
Backgrounds	1256	10

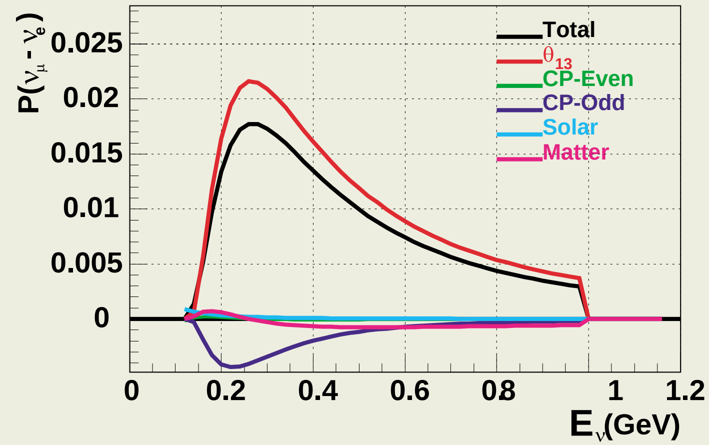


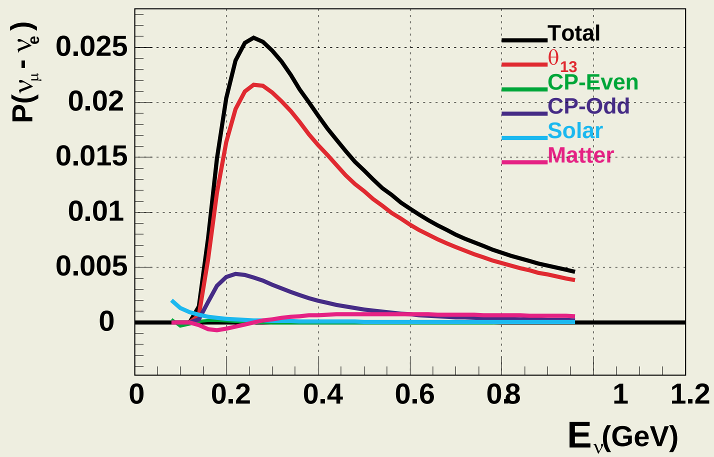


Small δm^2_{12}

$\theta_{13} = 6°, \; \delta m^2_{12} = 0.35 \cdot 10^{-4} \, eV^2$

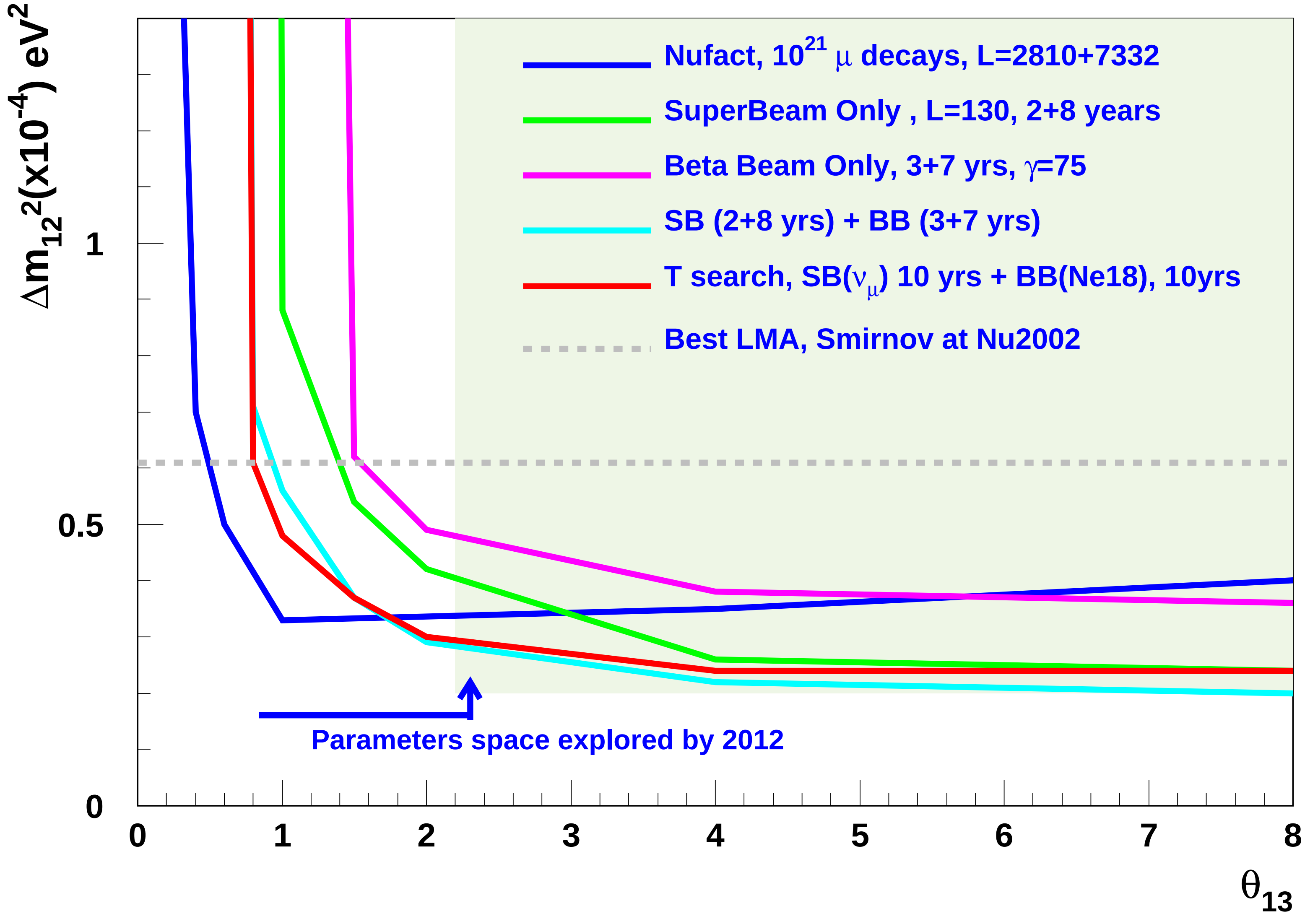
10 years	SuperBeam	Beta Beam
Oscillated events (total/cp)	1808 (-416)	174 (26)
Backgrounds	1256	10





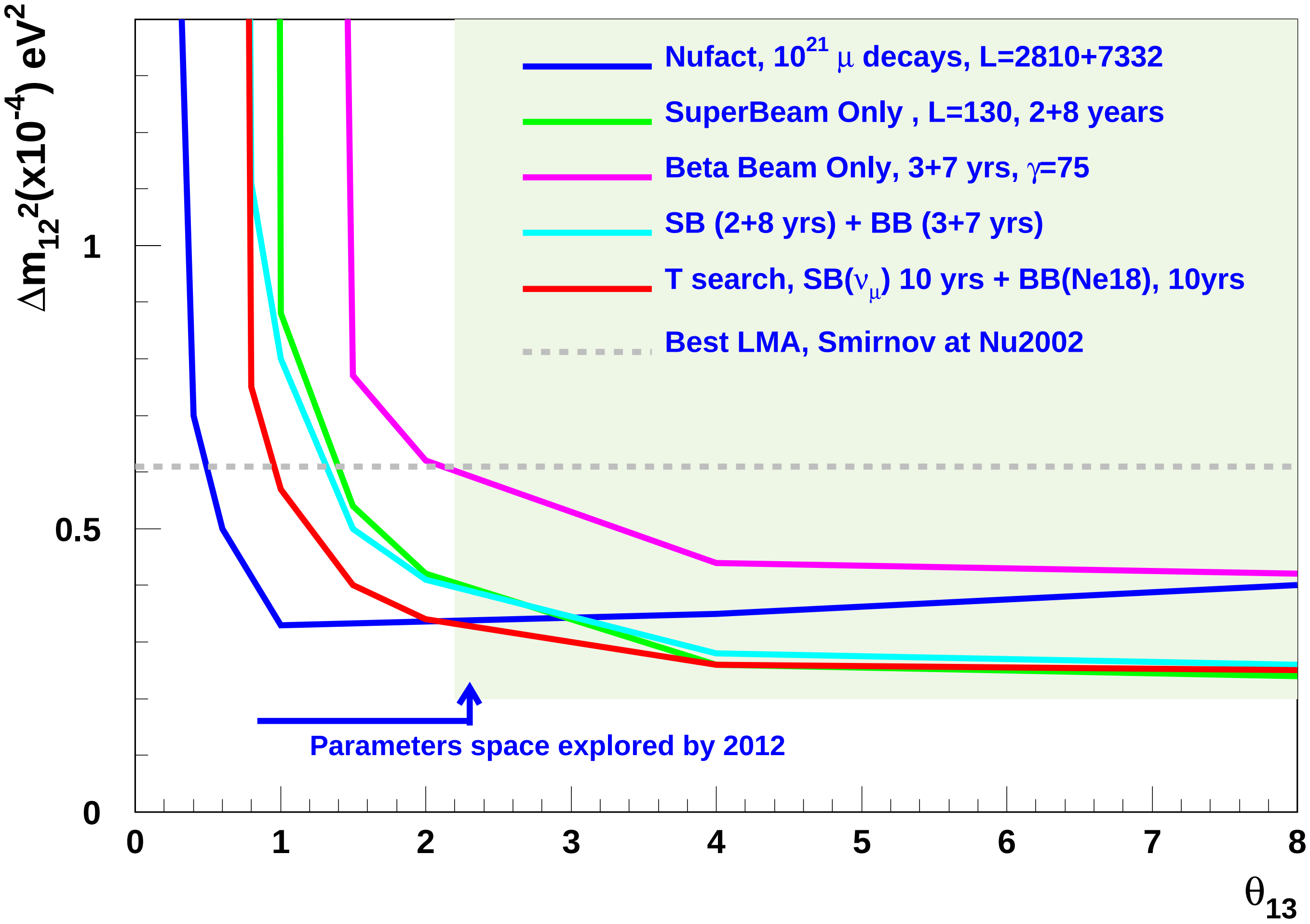
Brute Force (1): Due x UNO

Performances are limited by statistics. Check performances with a 1000 kton detector (HyperK like).



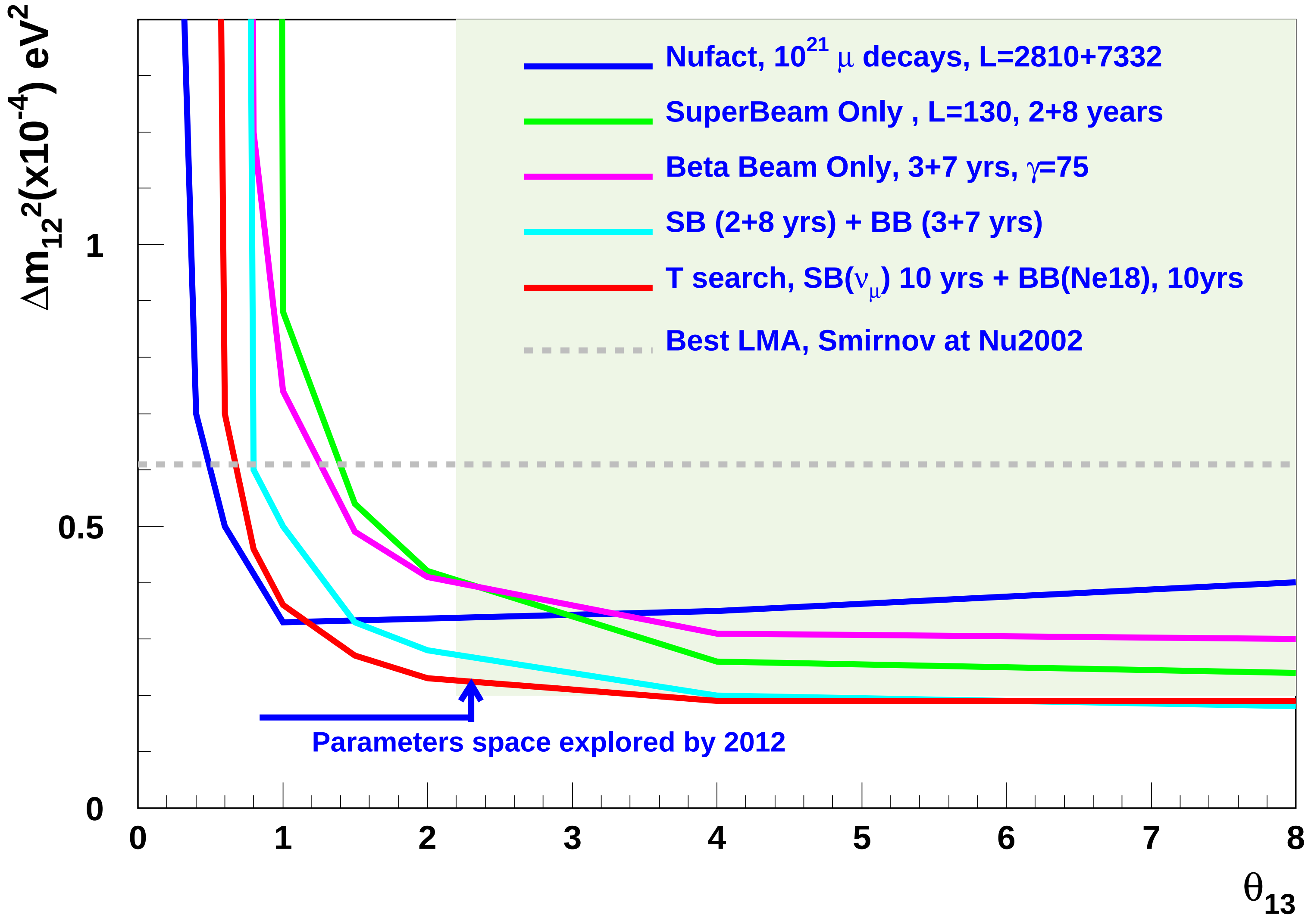
Brute Force (2): Due x ^{18}Ne.

The limiting factor for the Beta Beam is the ^{18}Ne production rate. Higher fluxes are not against mother nature. Let's see the SuperBeam + Beta Beam performances if a lucky R&D program could rise the ^{18}Ne production rate by a factor 2. Otherwhile real brute force could be used: two ISOL targets!



Brute Force (3): Due x Due.

1000 kton detector and $2\times{}^{18}$Ne



Conclusions

The SPL SuperBeam + Beta Beam, together with a gigantic underground water Cerenkov detector at Frejus, can offer excellent physics: proton decay, atmospheric neutrinos, supernovae neutrinos, Eurisol physics, Leptonic CP, Leptonic CPT.

Regarding the CP phase δ, the Super+Beta complex is the unique REALISTIC possibility to combine CP and T searches in the same detector, offering the experimental redundancy needed to define such a subtle effect.

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