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Physics reach of Super + Beta Beams

Summary:

- **Introduction.**
- **SPL-Super Beam.**
- **Beta Beam.**
- **Combined CP sensitivity.**

In collaboration with Mario Campanelli, Dave Casper and Piero Zucchelli

NNN02 - ”Workshop on Large Detectors for Proton Decay, Supernovae and Atmospheric Neutrinos and Low Energy Neutrinos from High Intensity Beams”, January 16-18,2002, - CERN

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.

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

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:

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

Low Energy (Sub-GeV) Beams vs. Neutrino Factories

PROS

- Negligible matter effects: it can be run at the optimal baseline
- Negligible matter effects: reduced correlations between θ_{13} and δ
- Less influenced by uncertitudes on the other mixing matrix parameters

CONS

- Smaller neutrino interaction rate, mostly due to the much smaller neutrino cross section.

  Antineutrino cross sections suppressed (antineutrino/neutrino cross section ratio $\sim$ 1/5 at 300 MeV). This makes a T search attractive.
- Intrinsic beam contamination in case of Super Beam.

The SuperBeam - BetaBeam synergy

The idea behind is to run two neutrino beams to the same detector at the same time.

Both beams need SPL, but the BetaBeam requires only 0.6% of the SPL protons $\rightarrow$ the two beams can run together.

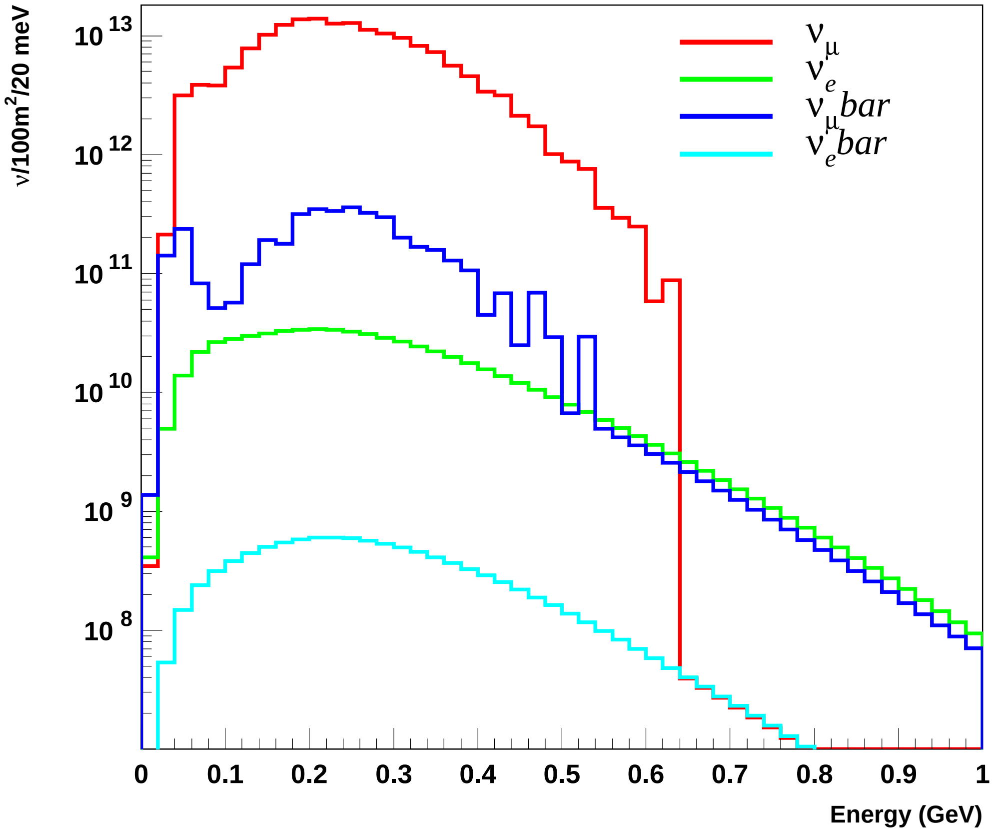
Both beams produce sub-GeV neutrinos $\rightarrow$ same baseline and same detector.

- A CP search using SuperBeam running with ν_μ and $\overline{\nu}_\mu$.
- A CP search with Beta Beam running with ^{6}He ($\overline{\nu}_e$) and ^{18}Ne (ν_e).
- Two T searches combining Super Beam neutrinos ($\nu_\mu \rightarrow \nu_e$) with Beta Beam ^{18}Ne ($\nu_e \rightarrow \nu_\mu$) and Super Beam antineutrinos ($\overline{\nu}_\mu \rightarrow \overline{\nu}_e$) with Beta Beam ^{6}He ($\overline{\nu}_e \rightarrow \overline{\nu}_\mu$).
- A final powerful combination of the CP and the T searches, with redundant physical information and several cross-checks of systematics.
- The most powerful combination would be however a single T search with neutrinos (SuperBeam ν_μ with BetaBeam ν_e).

SPL SuperBeam (π^+ focused)

Fluxes obtained from a full simulation of the beam line. Target and optics are precisely those designed for the neutrino factory (no optimization for the Super Beam, ongoing optimization is very promising).

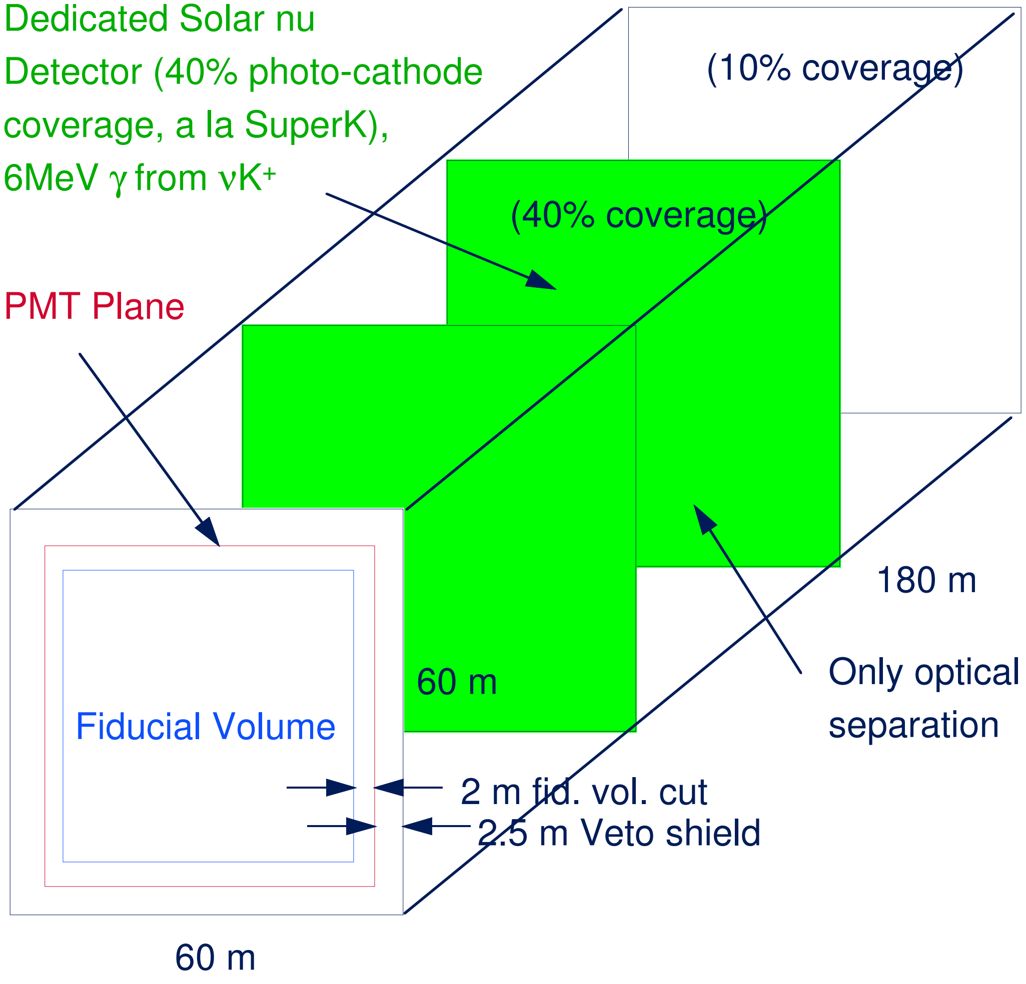
See contributed papers to the Venice Workshop of March 2001 (hep/ex 0105296) and to Nufact01 (”SuperBeam studies at CERN”, Nufact note 95/2001.)



Flux intensities at 50 km from the target

Flavor	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

UNO detector



The optimal detector for sub-GeV neutrinos is a water Čerenkov detector:

- The only viable solution for a $>> 100$ kton detector.
- Good energy resolution.
- Good e/π° rejection.
- Excellent e/μ separation.

The optimal baseline for the SPL-SuperBeam, at $\delta m^2_{23} = 2.5 \cdot 10^{-3}\, eV^2$, is 130 km, precisely the CERN-Frejus distance.

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%

CP sensitivity (I)

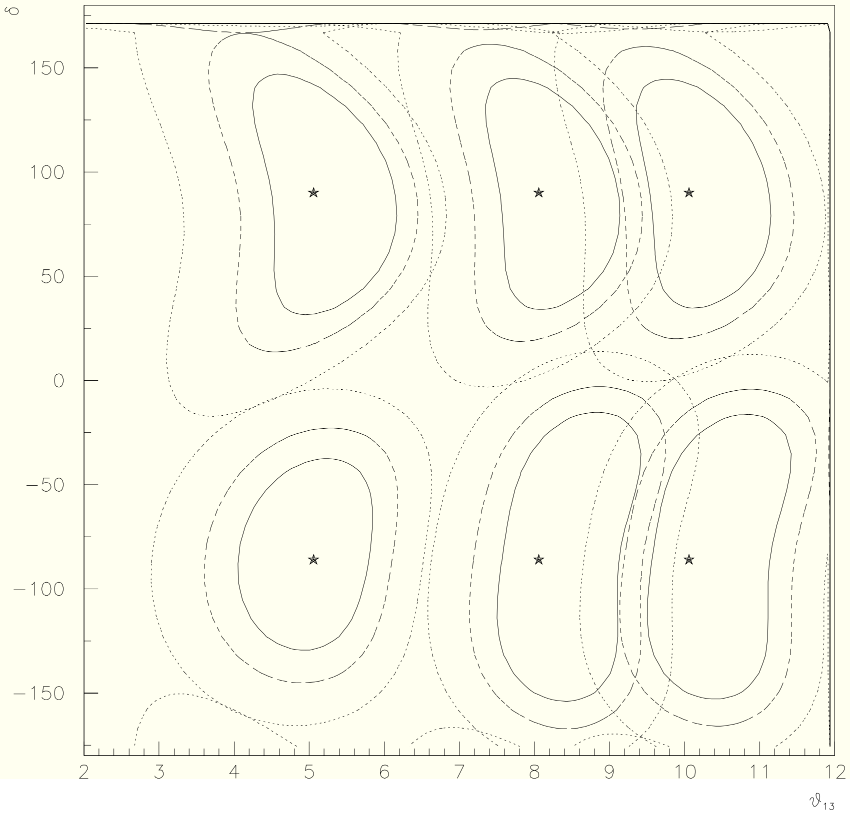
- Assume the central value of LMA: $\delta m^2_{12} = 10^{-4}\ eV^2$
- The CP violating observable is $\frac{N(e^+)-N(e^-)}{N(e^+)+N(e^-)}$, corrected for the different fluxes and cross sections. Here $e^-(e^+)$ indicates all the e-like events selected with the $\pi^+(\pi^-)$ focused beam.
- Run for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

$\Downarrow$ (see figure)

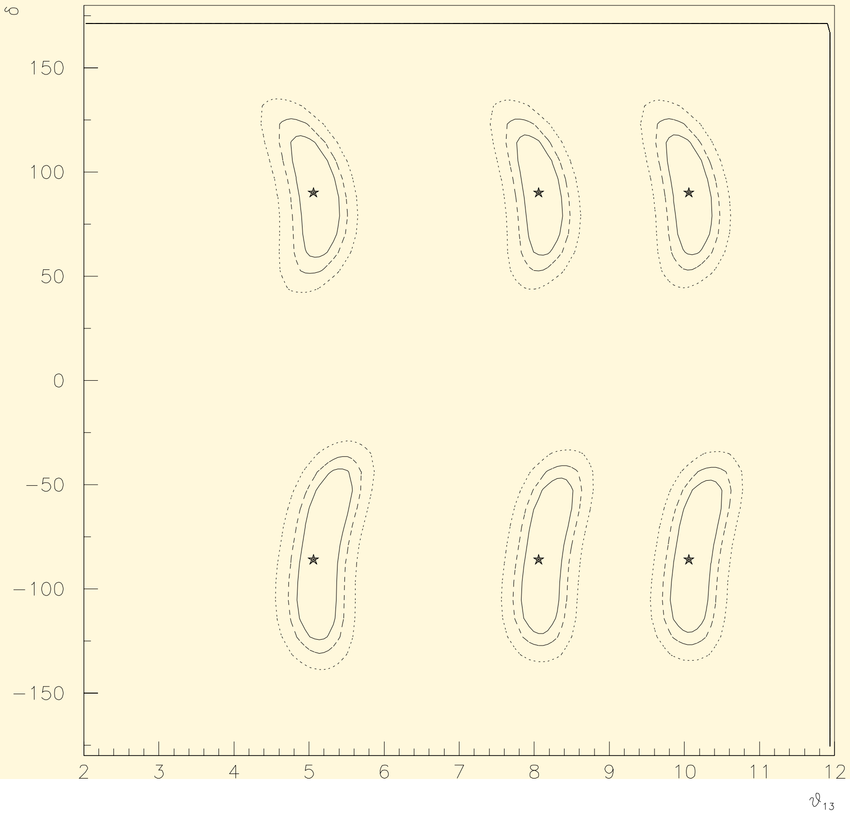
- CP sensitivity does not worsen very much with θ_{13}.
- In the 40 kton detector, 90% CL, a maximally violating CP phase ($\delta = \pm 90°$) would be just distinguishable from a non violating CP phase ($\delta = 0°$).
- With the 400 kton detector the prospects to observe CP violation are much improved.

CP sensitivity (II)

40 kton water detector 1σ, 90%CL, 99%CL lines



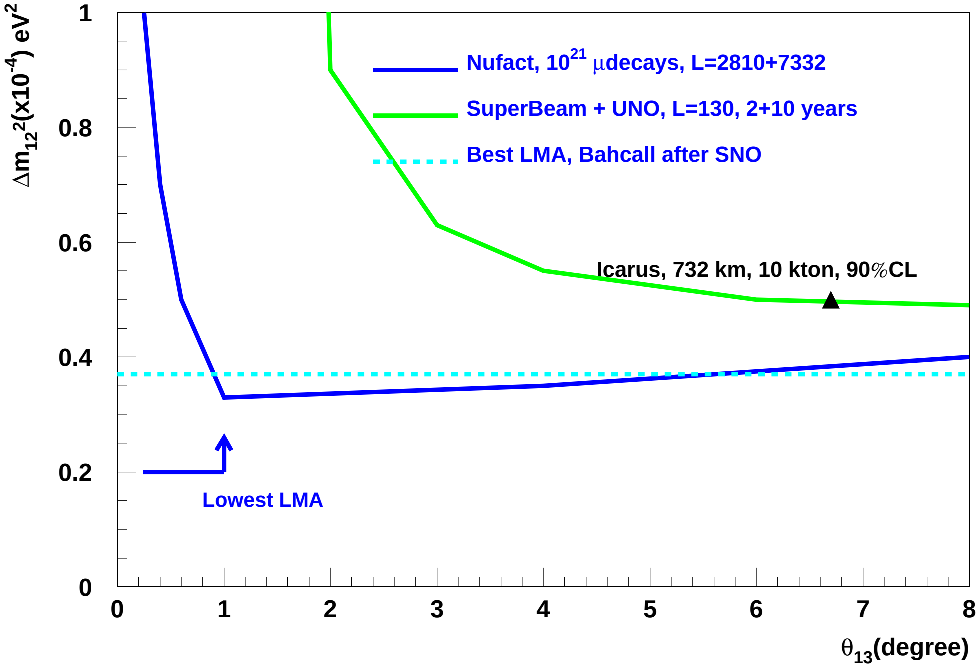
400 kton water detector 1σ, 90%CL, 99%CL lines



A comparison of CP sensitivities of Nufact vs. SuperBeam

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.



The limiting factors for the SuperBeam at small θ_{13} values are:

- The low flux of $\overline{\nu}$ and their small cross section. This limits the overall statistic.
- The beam related backgrounds that increase the statistical errors, hiding the CP signal.

As an example for $\theta_{13} = 3^\circ$, $\delta m_{12}^2 = 0.7 \cdot 10^{-4}\, eV^2$, $\sin^2 2\theta_{12} = 0.8$:

	ν_μ beam 2 years	$\overline{\nu}_\mu$ beam 10 years
μCC (no osc)	14298	13658
Oscillated events (total)	16	68
Oscillated events (cp-odd)	-40	35
Intrinsic beam background	28	33
Detector backgrounds	17	29

Introducing the Beta Beam

- Beta Beam produces just one neutrino flavour, $\overline{\nu}_e$ if running with ^6He 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 $2.9 \cdot 10^{18} \quad {}^6He$ useful decays/year and $3.6 \cdot 10^{17} \quad {}^{18}Ne$ decays/year.

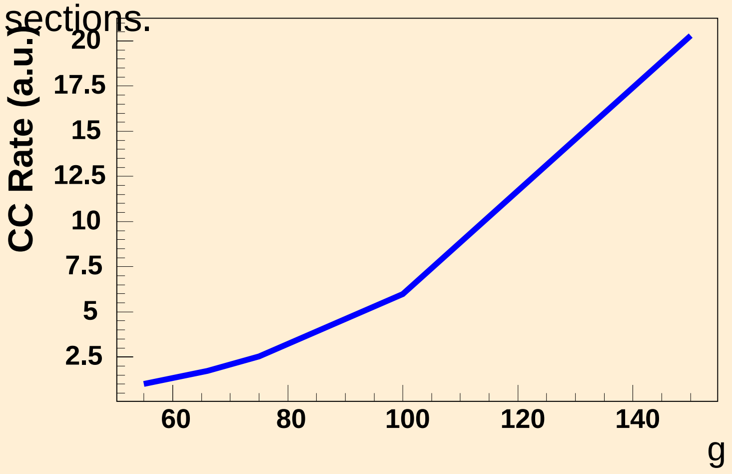
A full simulation of neutrino events in water have been performed with the NUANCE MonteCarlo code. The events are then fully reconstructed and analyzed.

An optimization of the selection criteria is still underway

Optimizing the Lorentz Boost γ, preferred value: $\gamma = 75$

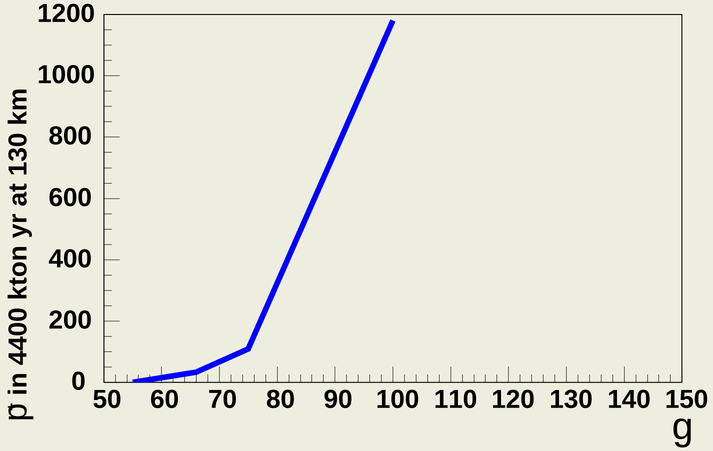
Higher γ produce more CC interactions

More collimated neutrino production and higher cross sections.

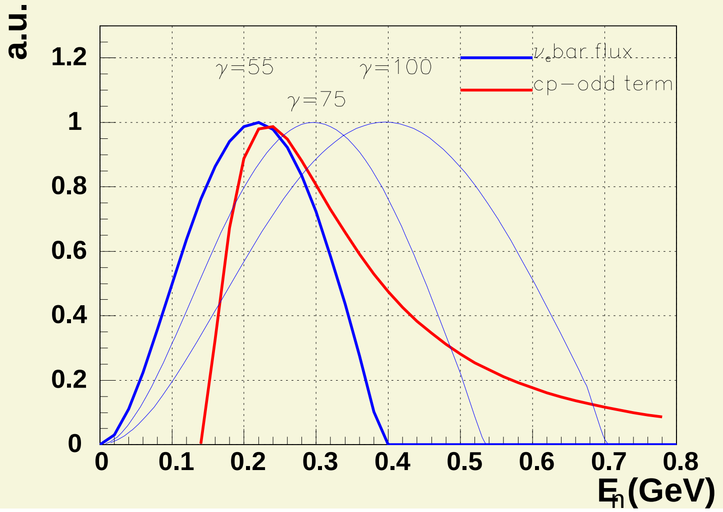


Background rate rises much faster than CC interactions

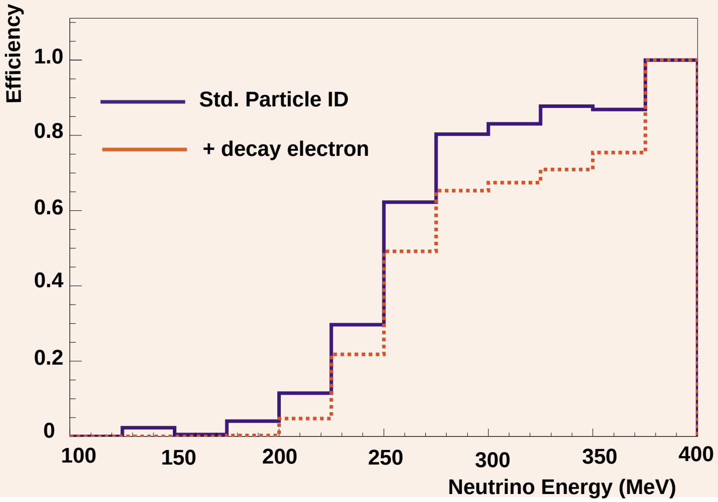
From resonant pion production in $\overline{\nu}_e$ NC interactions



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.

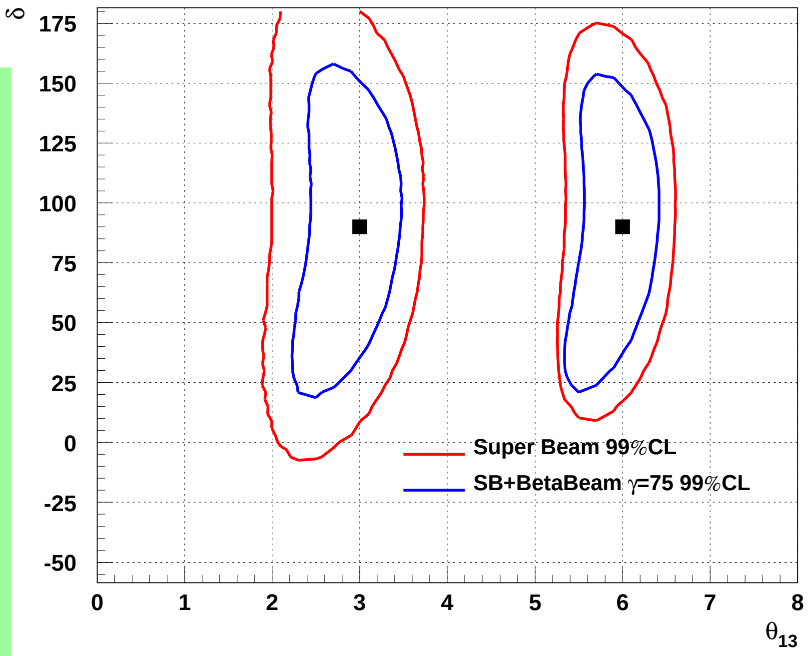
The SuperBeam - BetaBeam synergy: results

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

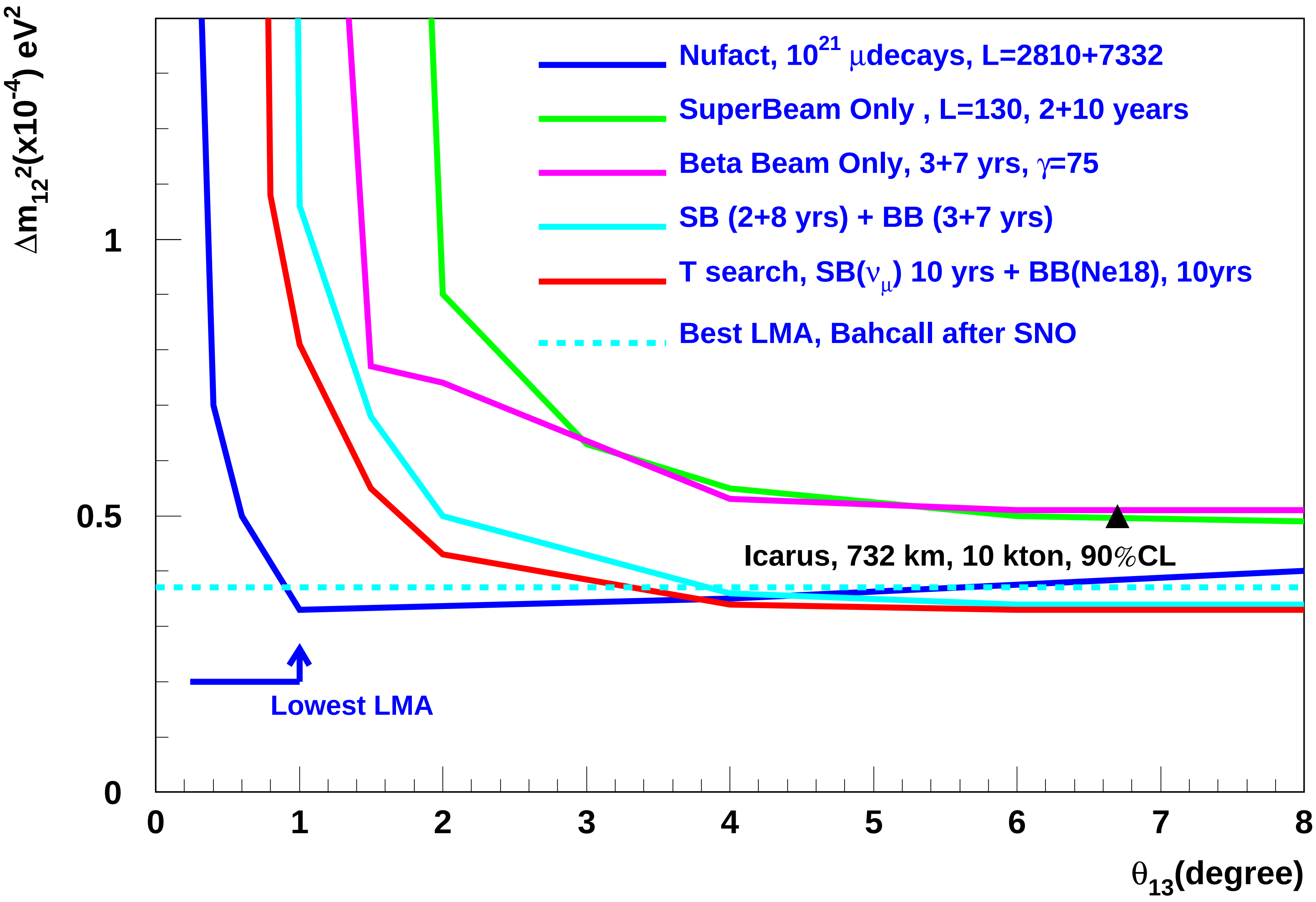
θ_{13} =3°, $\delta m^2_{12} = 0.6 \cdot 10^{-4}\, eV^2$:

10 years	SuperBeam	Beta Beam $\gamma = 75$
CC events (no osc, no cut)	85421	18583
Total oscillated	111	63
CP-Odd oscillated	-151	22
Beam background	165	0
Detector bkg.	100	10

How two particular solutions can be improved by BetaBeam (99%CL curves)



Final CP sensitivity (preliminary).



Two extreme cases

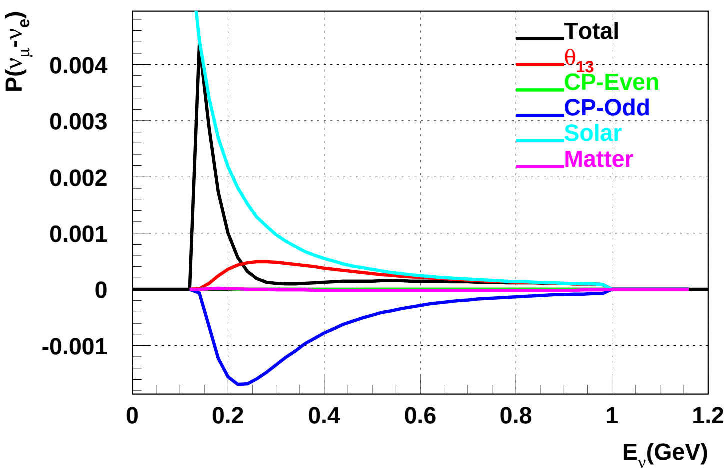
$\theta_{13} = 0.9^\circ,\ \delta m^2_{12} = 9 \cdot 10^{-5}\, eV^2$

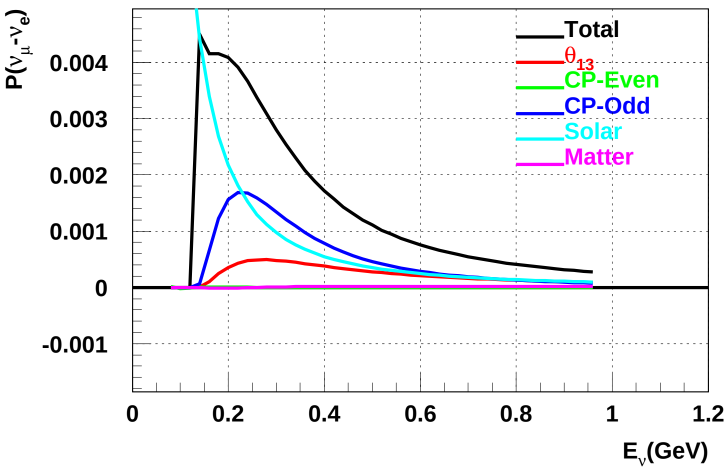
10 years	SuperBeam	Beta Beam
Oscillated events (total/cp)	16(-68)	22 (10)
Backgrounds	264	10
Total Error	18.3	6.1

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

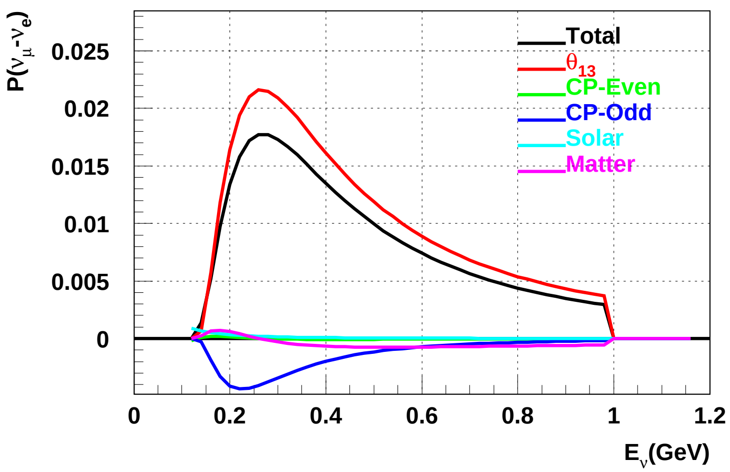
10 years	SuperBeam	Beta Beam
Oscillated events (total/cp)	760 (-175)	174 (26)
Backgrounds	270	10
Total Error	41.6	14.3

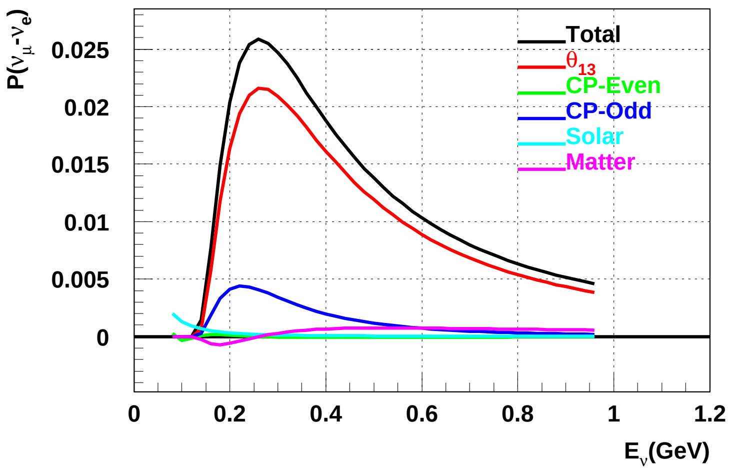
θ_{13}=0.9 Δm^2_{23}=2.5E-03 Δm^2_{12}=9.0E-05 δ=90 L=130 γ=75





θ_{13}=6 Δm^2_{23}=2.5E-03 Δm^2_{12}=3.5E-05 δ=90 L=130 γ=75

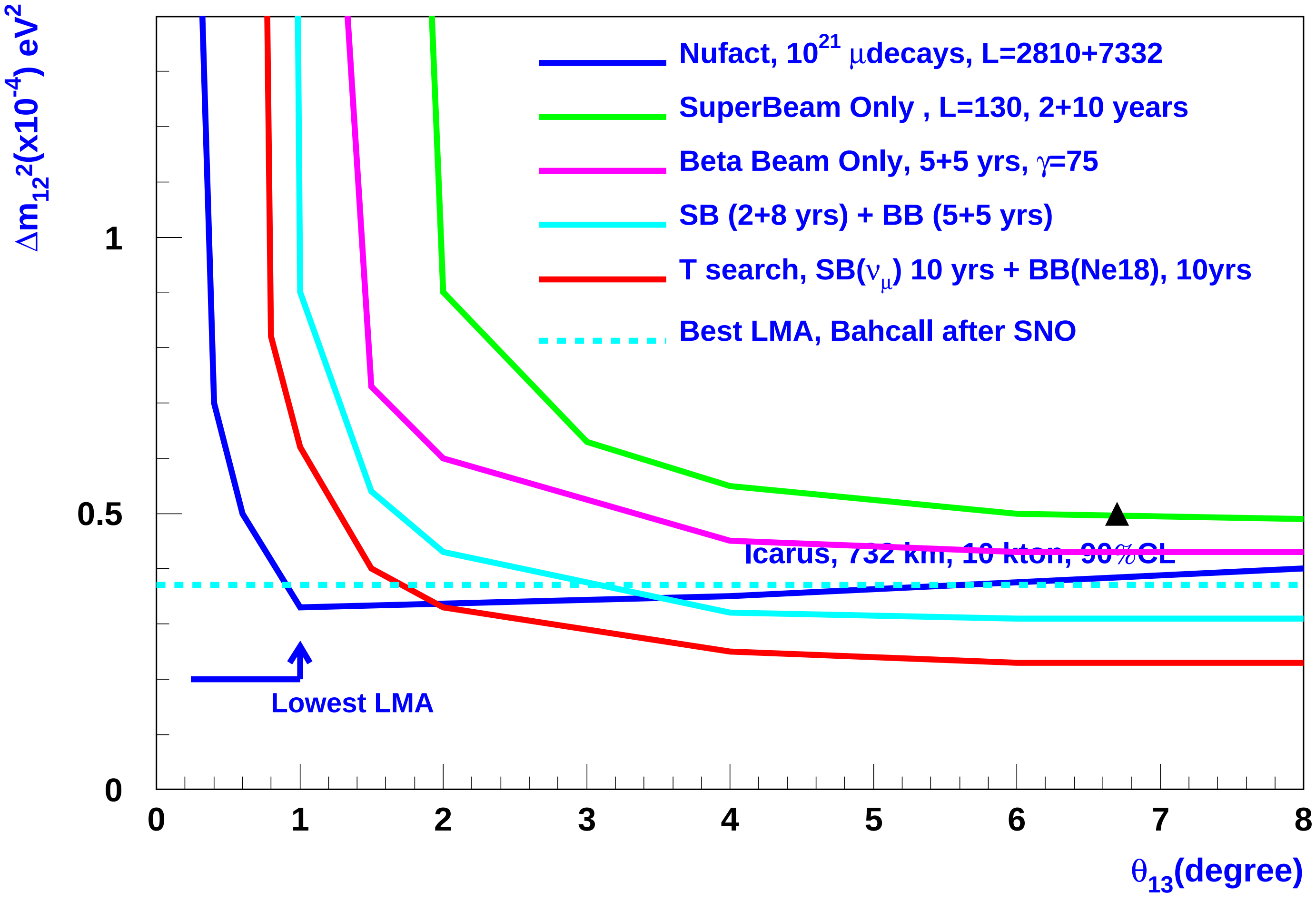




Hoping in the progress (^{18}Ne upgraded).

The limiting factor for the Beta Beam is the ^{18}Ne production rate.

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.



Conclusions

- Leptonic CP will be the ultimate goal of neutrino physics.
- Neutrino SuperBeams, the first stage of Neutrino Factories, can provide the necessary information about θ_{13} , the unavoidable milestone towards CP, and a first investigation of CP.
- Neutrino Beta Beams, a very recent development, can constitute a viable option to detect leptonic CP.
- SuperBeams and BetaBeams require a gigantic water Čerenkov underground detector. A major investment that could offer the ultimate sensitivity in other central fields of high energy physics as proton decay and supernovae, solar and atmospheric neutrinos.

Neutrino Factory are the most intense neutrino beams.

The comparison of neutrino beam intensities is not a trivial task as far as concerns neutrino oscillation experiments.

The optimal baseline to detect sub leading $\nu_\mu \rightarrow \nu_e$ transitions, is

$$L_{\text{eff}} = \frac{\pi}{2} \frac{E_\nu}{1.27 \Delta m^2_{atm}}$$

Beam intensities CC_{eff} (ν CC/kton/yr) are then compared at this optimal baseline L_{eff}.

Beam	$\langle E_\nu \rangle$ (GeV)	Flux $(\nu/m^2/\text{yr})$	L (km)	CC ν/kton/yr	L_{eff} (km)	CC$_{\text{eff}}$ ν/kton/yr	Ratio
CNGS	17.7	$3.5 \cdot 10^{11}$	732	2448	8757	17.1	1.0
SuperBeam	0.26	$2.5 \cdot 10^{11}$	130	16.3	129	16.6	1.0
JHF	0.7	$1.9 \cdot 10^{11}$	295	95.2	346	69.1	4.0
νF^*	30	$2.4 \cdot 10^{12}$	3000	17694	14842	723	42.3
BetaBeam**	0.58	$1.2 \cdot 10^{12}$	130	84	287	17.2	1.0

(*) $E_\mu = 50\ GeV$, $0.2 \cdot 10^{21}$ μ decays/yr, computed for ν_e .

(**) $\gamma = 150$, ${}^6He$ ($\overline{\nu}_e$).