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“Physics Potential of Super Beams and Beta Beams”,

Summary:

- **Introduction.**
- **The hunting for θ_{13}**
- **Leptonic CP violation**
- **The SPL-Super Beam**
- **The Beta Beam**
- **Sensitivity to the CP phase δ_{CP}**

ν oscillations are the most important discovery in hep of the last 15 years.

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.**

If you are skeptical about that ....

Experimental articles with more than 500 cites in the last 15 years in the QSPIRES database (at 04/04/03):

1	SK	Evidence for Oscillation of Atmospheric Neutrinos.	1705
2	SCP	Measurements of Ω and Λ from 42 High Redshift SN.	1311
3	SST	Observational Evidence from SuperNovae for an Accelerating Universe and a Cosmological Constant.	1293
4	COBE	Structure in the COBE DMR First Year Maps.	1036
5	CDF	Observation of TOP Quark Production in $\overline{p} - p$ Collisions.	930
6	D0	Observation of the Top Quark.	889
7	SK	Atmospheric ν_μ/ν_e Ratio in the MultiGeV Energy Range.	751
8	Chooz	Initial Results from CHOOZ.	683
9	Boomerang	A Flat Universe from High Resolution Maps of the CMB.	644
10	Chooz	Limits on Neutrino Oscillations from the CHOOZ Experiment.	635
11	Kamiokande	Observation of a Small Atmospheric ν_μ/ν_e Ratio.	628
12	CLEO	First Measurement of the Rate for the Inclusive b —> $s\gamma$.	618
13	SNO	Measurement of the rate of ν_e + d –> p + p + e- ...	592
14	Homestake	Measurement of the Solar ν_e Flux ...	565
15	LSND	Evidence for $\overline{\nu}_\mu$ —> $\overline{\nu}_e$ Oscillations from LSND.	563
16	SK	Measurement of a Small Atmospheric ν_μ/ν_e Ratio.	561
17	CDF	Evidence for TOP Quark Production in $\overline{p} - p$	550
18	SK	Study of the Atm. ν Flux in the MultiGeV Energy Range.	547
19	IMB	The ν_e and ν_μ Content of the Atmospheric Flux.	535
20	SK	Solar Neutrino Data Covering Solar Cycle 22.	504
21	LSND	Neutrino Oscillations from LSND.	500

Most of the parameters are waiting to be measured

δm^2_{12} ☑ SOLARS+KAMLAND $5\,10^{-5} < \delta m^2_{12} < 3\,10^{-4}\,eV^2$

θ_{12} ☑ SOLARS+KAMLAND $0.2 < \sin^2(\theta_{12}) < 0.5$

Addressed by a SuperBeam/Nufact experiment

δm^2_{23} ☑ ATMOSPHERICS $\delta m^2_{23} = 2.6 \pm 0.4\ eV^2$

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 ☐

The capital importance of θ_{13}

Present limit from CHOOZ: $\sin^2 2\theta_{13} \leq 0.1$. Both solar and atmospheric results are compatible with $\theta_{13} = 0$.

Solar+Atmospherics favor a near bi-maximal mixing matrix **(VERY DIFFERENT from CKM matrix!)**

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

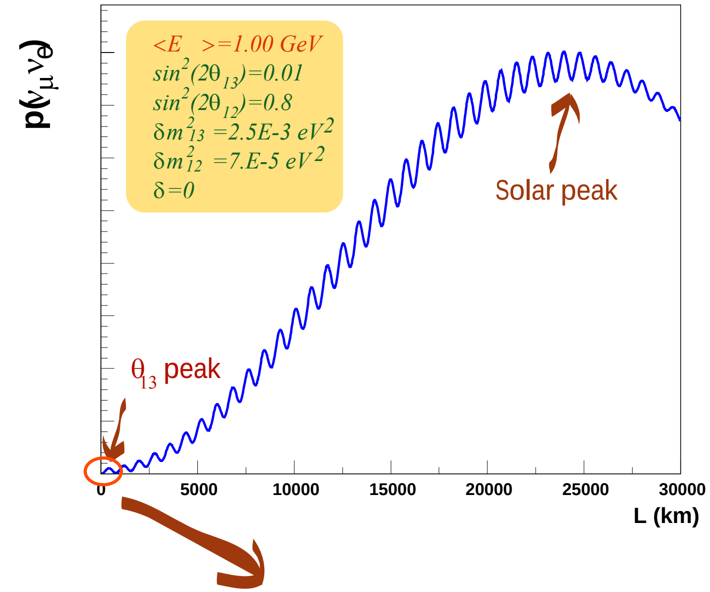
$\theta_{13} \rightarrow 0 \quad \Rightarrow$ The 3x3 matrix is a trivial product of two 2x2 matrixes.

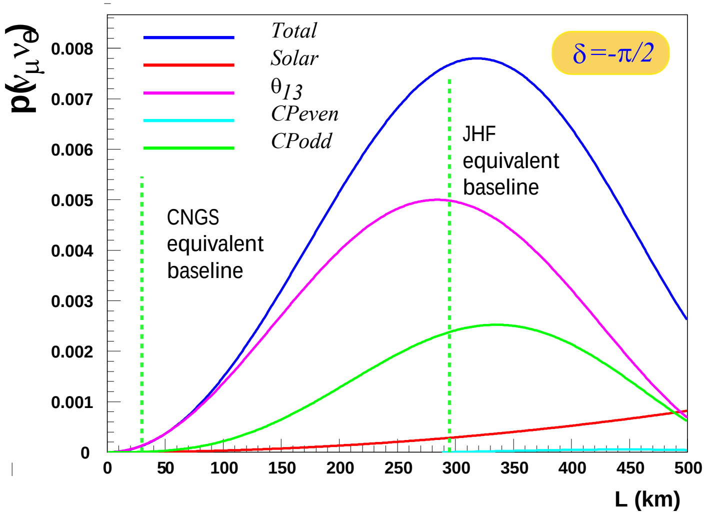
θ_{13} drives $\nu_\mu \rightarrow \nu_e$ subleading transitions $\Rightarrow$

the necessary milestone for any subsequent search:

neutrino mass hierarchy and leptonic CP searches.

Subleading $\nu_\mu - \nu_e$ oscillations





$p(\nu_\mu \rightarrow \nu_e)$ developed at the first order of matter effects

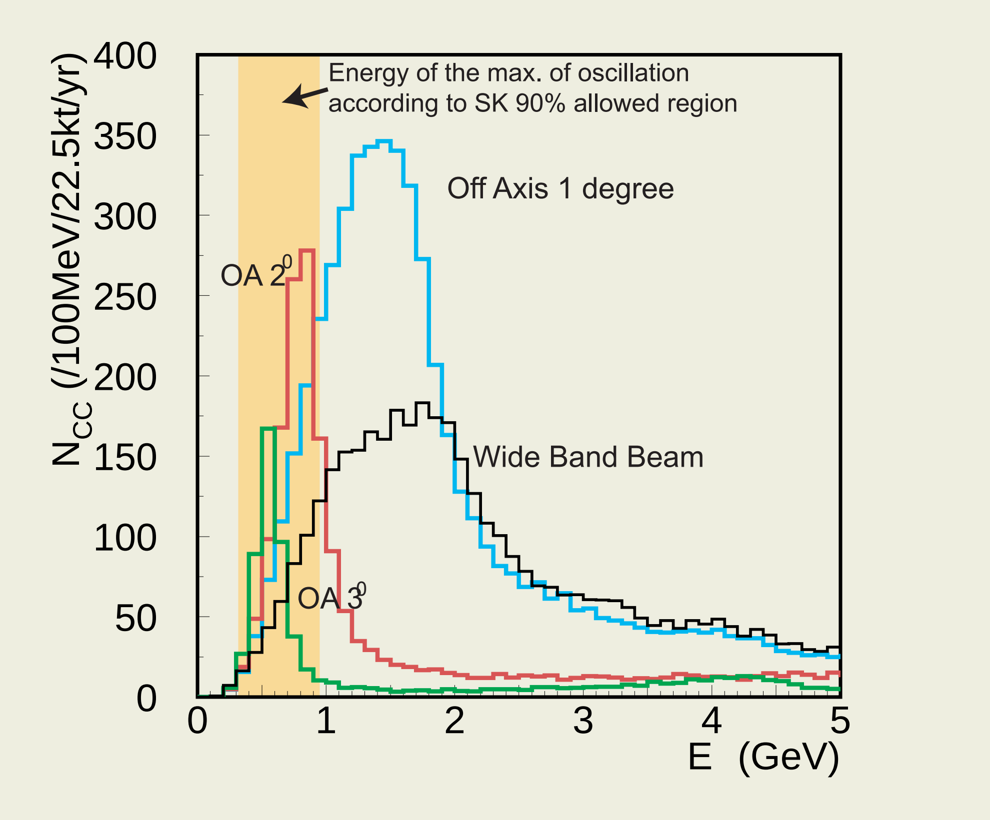
$$
\begin{aligned}
p(\nu_\mu \rightarrow \nu_e) = {} & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} \qquad \theta_{13}\ \text{driven} \\
& + 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} cos\delta - s_{12} s_{13} s_{23}) \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2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

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

JHF-Japan Hadron Facility at Jaeri

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

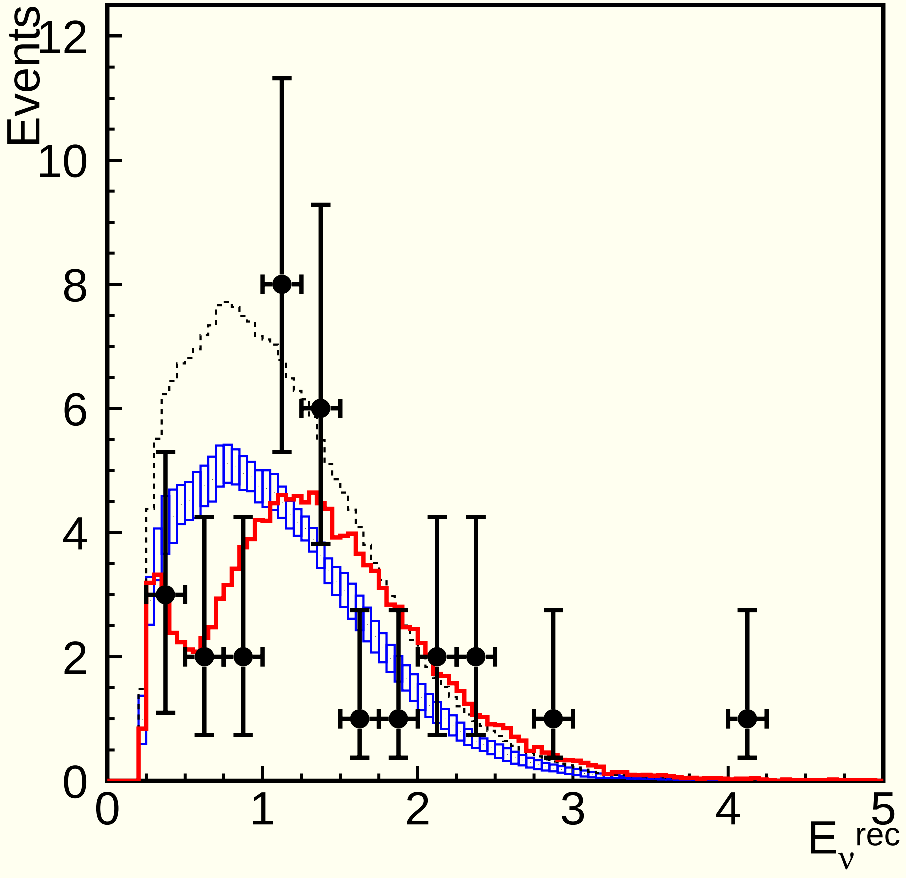
Taken off-axis to better match the oscillation maximum at the SuperKamiokande location (295 km).



K2K		JHF
$6 \cdot 10^{12}$	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

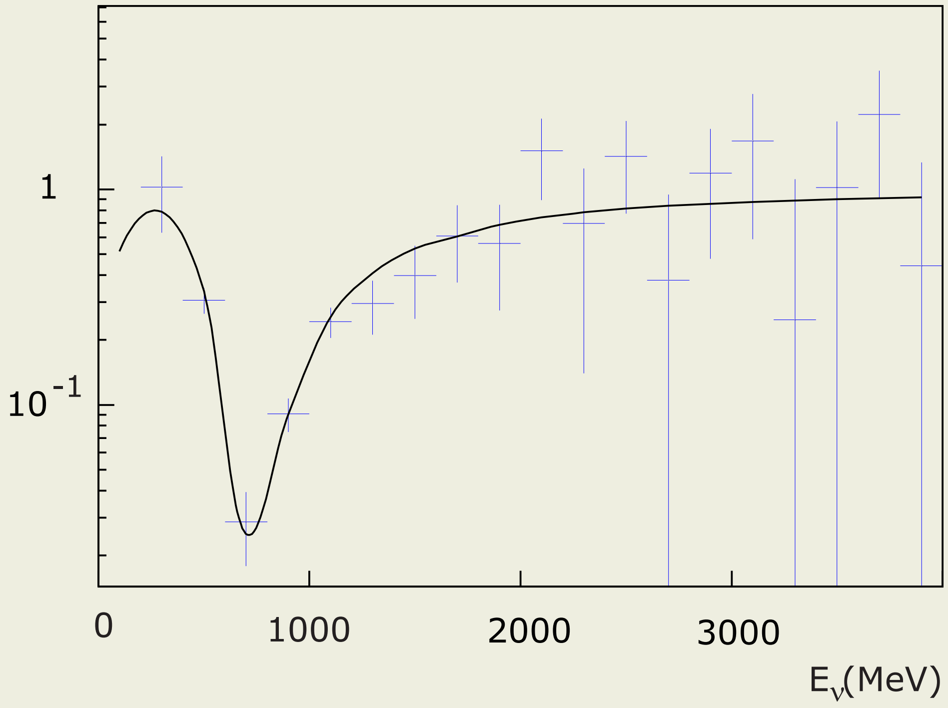
JHF: ν_μ disappearance

K2K at half of its statistics:



JHF in 5 years

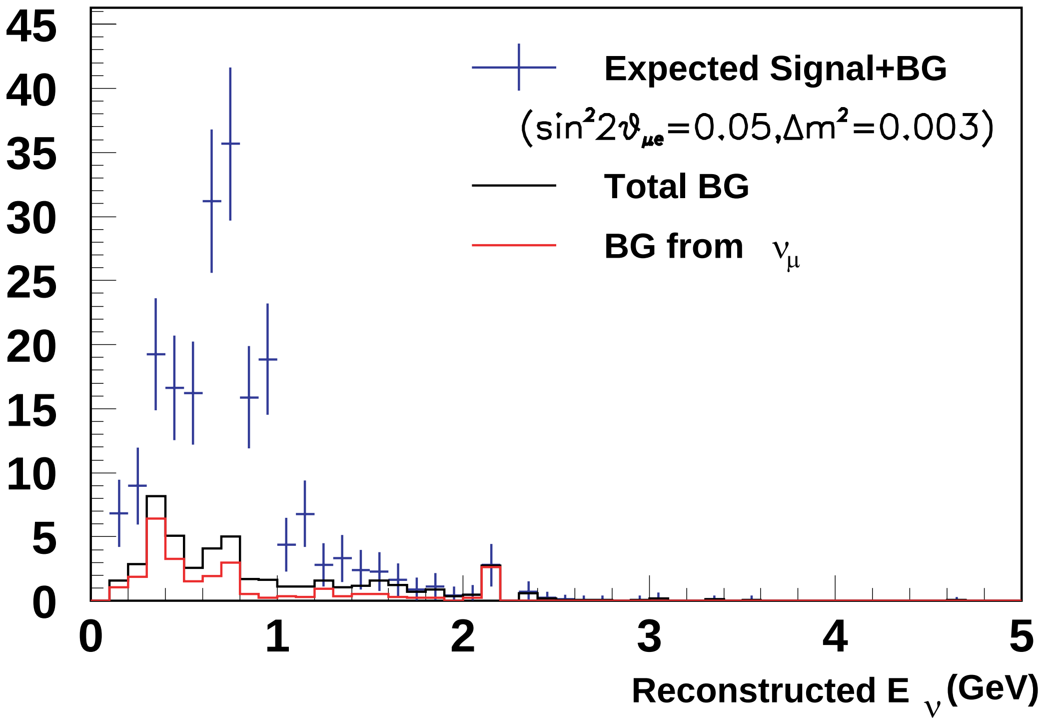
- δm^2_{23} with a resolution of 10^{-4} eV^2.
- $\sin^2 2\theta_{23}$ at $1 \div 2$ %.



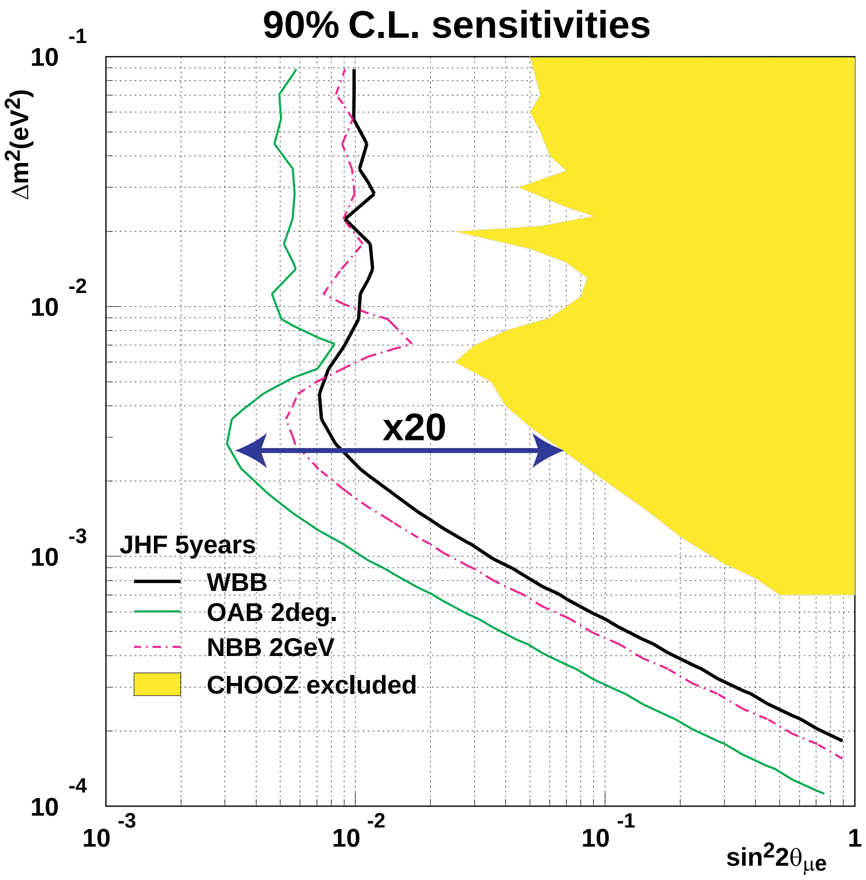
Ratio of the measured ν_μ spectrum with respect to the non-oscillation prediction in case of oscillation.

JHF 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}



M. Mezzetto, *“Physics Potential of Beta Beams and Super Beams”,* Weak Interactions in Nuclei and Astrophysics: Standard Model and Beyond, ECT Trento, 16-21 June 2003.

Leptonic CP

Two conditions to make Leptonic CP detectable:

- Solar LMA confirmed
- $\theta_{13} \geq 0.5^0$ (see the following).

A big step from a θ_{13} search:

$$\text{from } p(\nu_\mu \rightarrow \nu_e) \neq 0 \text{ to } \begin{cases} p(\nu_\mu \rightarrow \nu_e) \neq p(\overline{\nu}_\mu \rightarrow \overline{\nu}_e) & \text{(direct CP)} \\ p(\nu_\mu \rightarrow \nu_e) \neq p(\nu_e \rightarrow \nu_\mu) & \text{(T search)} \end{cases}$$

This will require:

1. Neutrino beams of novel conception.

   Super Beams
   Neutrino Factory
   Beta Beams

2. Detectors of unprecedent mass
3. Improved control of systematics ⇒ Dedicated experiments on neutrino cross-sections, hadron production, particle ID.

Detecting the δ phase.

$$A_\delta = [P(\nu_e \rightarrow \nu_\mu, \delta = +\pi/2) - P(\nu_e \rightarrow \nu_\mu, \delta = 0)]/[P(\delta = +\pi/2) + P(\delta = 0)]$$

Compare the measured $\nu_e \rightarrow \nu_\mu$ oscillation probability, as a function of the neutrino energy E_ν, to a “Monte-Carlo” prediction of the spectrum in absence of δ-phase.

Problems: it's model dependent, requires a precise knowledge of the other oscillation parameters, possible degeneracy between solutions and strong correlation with the θ_{13} parameter.

$$A_{CP}(\delta) = [P(\nu_e \rightarrow \nu_\mu, \delta) - P(\overline{\nu}_e \rightarrow \overline{\nu}_\mu, \delta)]/[P(\nu_e \rightarrow \nu_\mu, \delta) + P(\overline{\nu}_e \rightarrow \overline{\nu}_\mu, \delta)]$$

Compare the appearance of ν_μ ($\overline{\nu}_\mu$) in a beam of stored μ^+(μ^-)decays as a function of the neutrino energy E_ν.

Problems It must compete with the fake CP from matter effects. Run time is more than doubled: $\overline{\nu}$ cross sections are half the ν cross section and matter effects disfavor $\overline{\nu}$ oscillations.

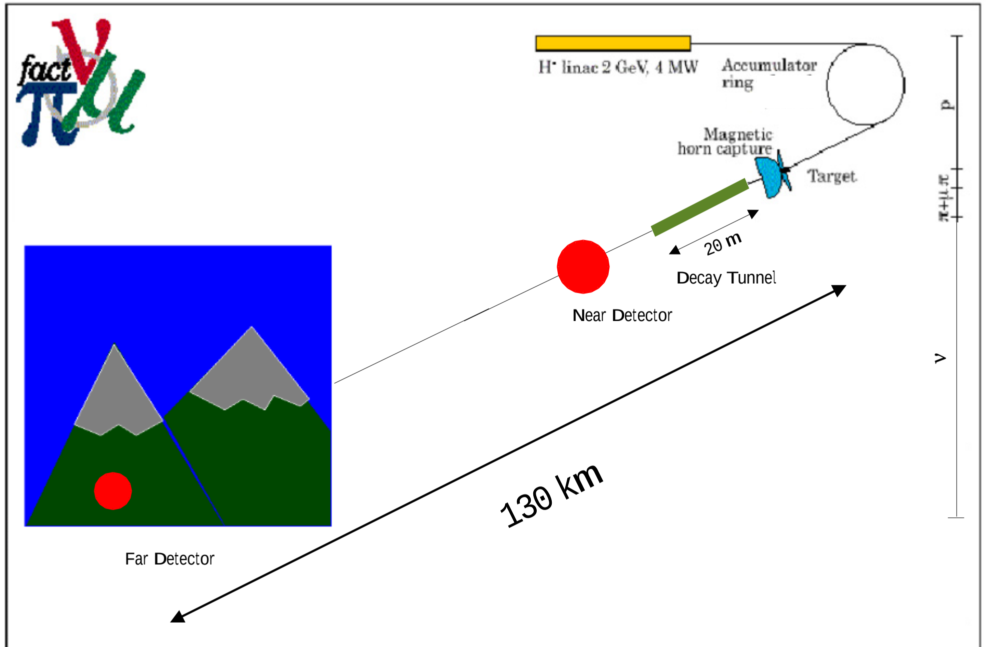
$$A_T(\delta) = [P(\nu_e \rightarrow \nu_\mu, \delta) - P(\nu_\mu \rightarrow \nu_e, \delta)]/[P(\nu_e \rightarrow \nu_\mu, \delta) + P(\nu_\mu \rightarrow \nu_e, \delta)]$$

Compare the appearance of ν_μ in a ν_e beam AND ν_e in a ν_μ beam as a function of the neutrino energy E_ν.

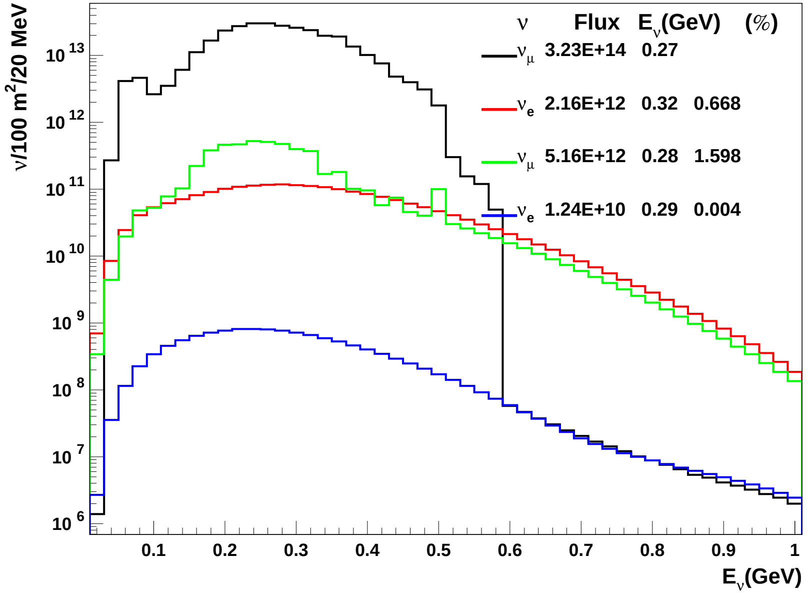
Problems Electron charge must be measured in case of a neutrino factory experiment. Systematics of muon and electron efficiencies must be kept to very small values.

SPL-SuperBeam at CERN

A feasibility study of the CERN possible developments



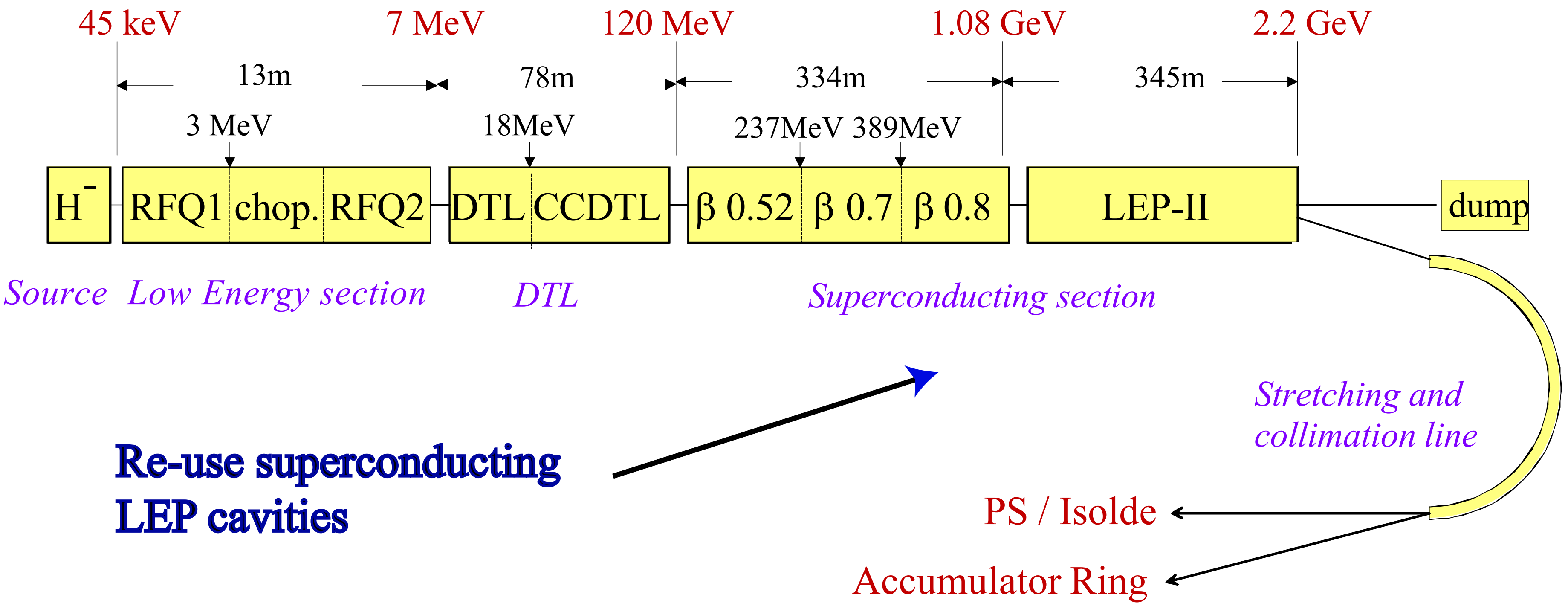
Possible Low Energy Super Beam Layout



Flux intensities at 50 km from the target

Flavour	Absolute Flux	Rel. Flux	$\langle E_\nu \rangle$
	$(\nu/10^{23}\mathrm{pot}/\mathrm{m}^2)$	(%)	(GeV)
ν_μ	$3.2 \cdot 10^{12}$	100	0.27
$\overline{\nu}_\mu$	$2.2 \cdot 10^{10}$	1.6	0.28
ν_e	$5.2 \cdot 10^{9}$	0.67	0.32
$\overline{\nu}_e$	$1.2 \cdot 10^{8}$	0.004	0.29

MW-Linac: SPL (Superconducting Proton Linac)

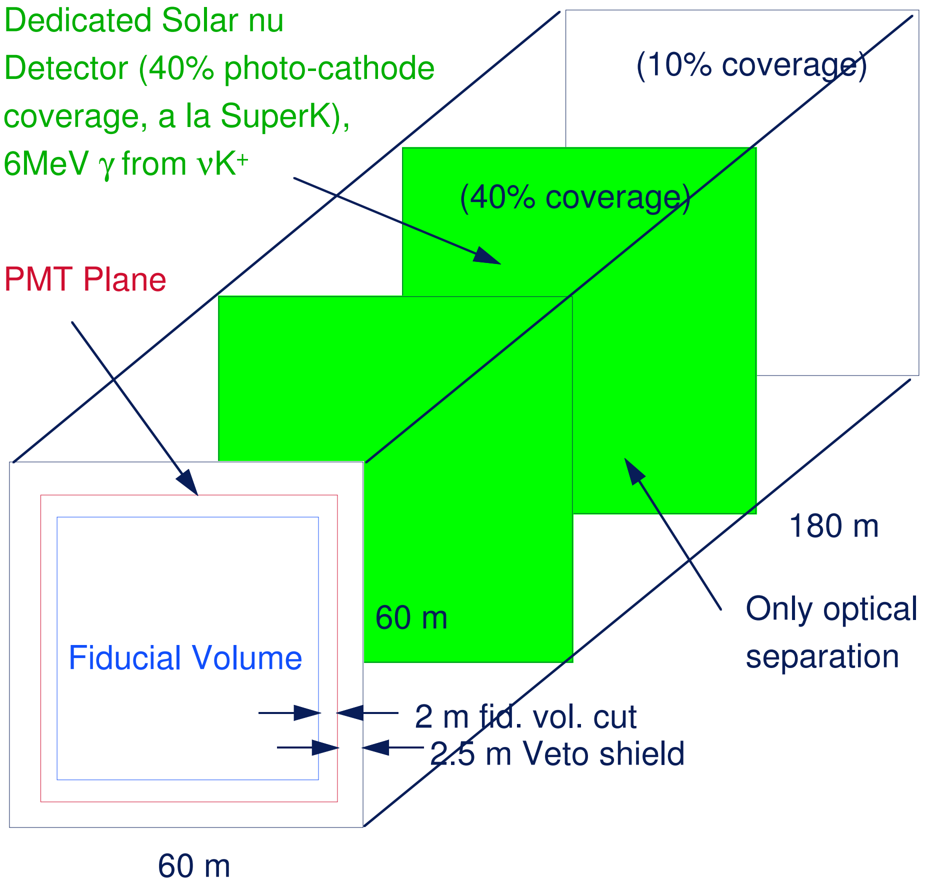


Re-use superconducting LEP cavities

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

→ **10^{23} protons/year**

UNO detector



- Fiducial volume: 440 kton: 20 times SuperK.
- 60000 PMTs (20") in the inner detector, 15000 PMTs in the outer veto detector.
- **The killer detector for proton decay, atmospheric neutrinos, supernovae neutrinos.**
- 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.

Interesting features of a low energy conventional neutrino beam.

ν beam:

- $\langle E_{\nu_\mu} \rangle \simeq 0.25$ GeV $\Rightarrow$ L $\sim$ 100 km $\Rightarrow$ **NO MATTER EFFECTS**.
- ν_e production by kaons largely suppressed by threshold effects.

ν_e in the beam come only from μ decays.

$$\begin{tikzcd}
\pi^+ \arrow[r] & \mu^+\nu_\mu \arrow[d] \\
 & e^+\nu_e\overline{\nu}_\mu
\end{tikzcd}$$

$\Rightarrow$ they can be predicted from the measured ν_μ CC spectrum both at the close and at the far detector **with a small systematic error of $\sim 2\%$.**

Detector Backgrounds

- Good e/π^0 separation following the large $\pi^0 \to \gamma\gamma$ opening angle
- Good e/μ separation in a Čerenkov detector because μ are produced below or just above the Čerenkov threshold.
- Charm and τ production below threshold.

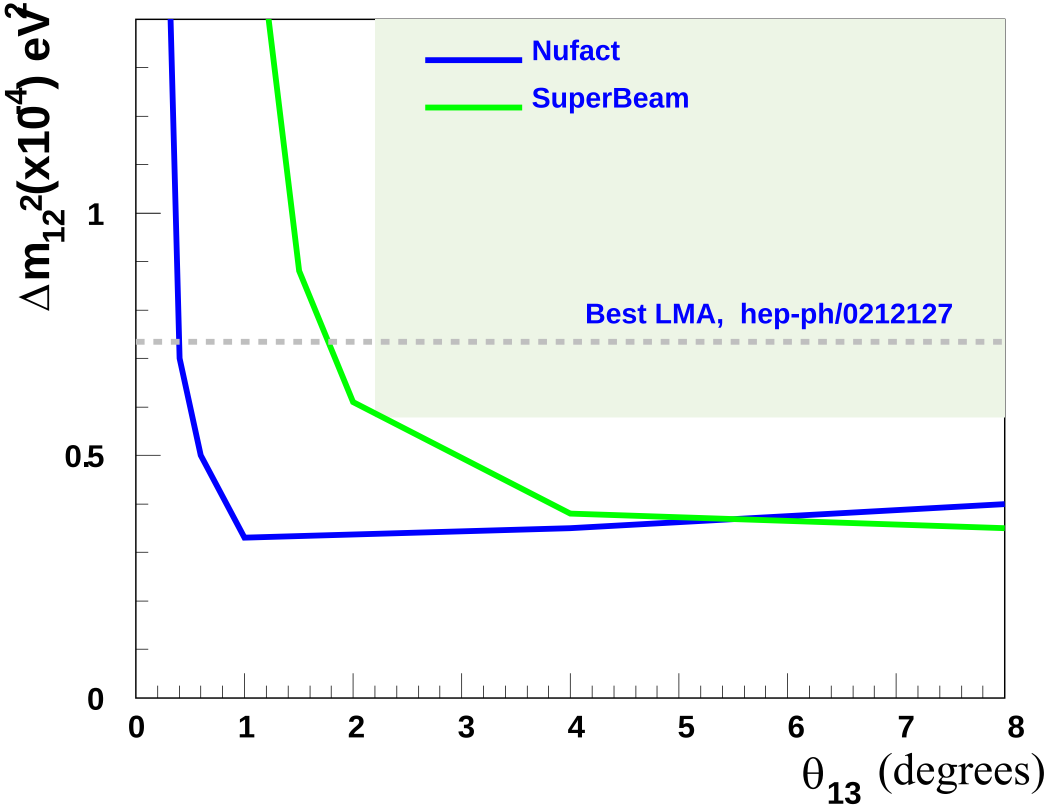
Less exiting aspects of a low energy neutrino beam

- Cross sections are small $\Rightarrow$ large detectors are necessary in spite of the very intense neutrino beam.
- $\overline{\nu}_\mu$ production is disfavored for two reasons:
  - Smaller π^- multiplicity at the target.
  - $\overline{\nu}_\mu / \nu_\mu$ cross section ratio is at a minimum (1/5).
- Visible energy is smeared out by Fermi motion $\Rightarrow$ Counting Experiment.

A comparison of CP sensitivities: 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 and SPL-SuperBeam sensitivities computed with the same conditions.



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 θ_{13} =3°, $\delta m^2_{12} = 0.7 \cdot 10^{-4}\, eV^2$, $\sin^2 2\theta_{12} = 0.8$:

	ν_μ beam 2 years	$\overline{\nu}_\mu$ beam 8 years
μCC (no osc)	36698	23320
Oscillated events (total)	45	133
Oscillated events (cp-odd)	-84	53
Intrinsic beam background	140	101
Detector backgrounds	36	49

Can the SuperBeam+UNO combination be upgraded?

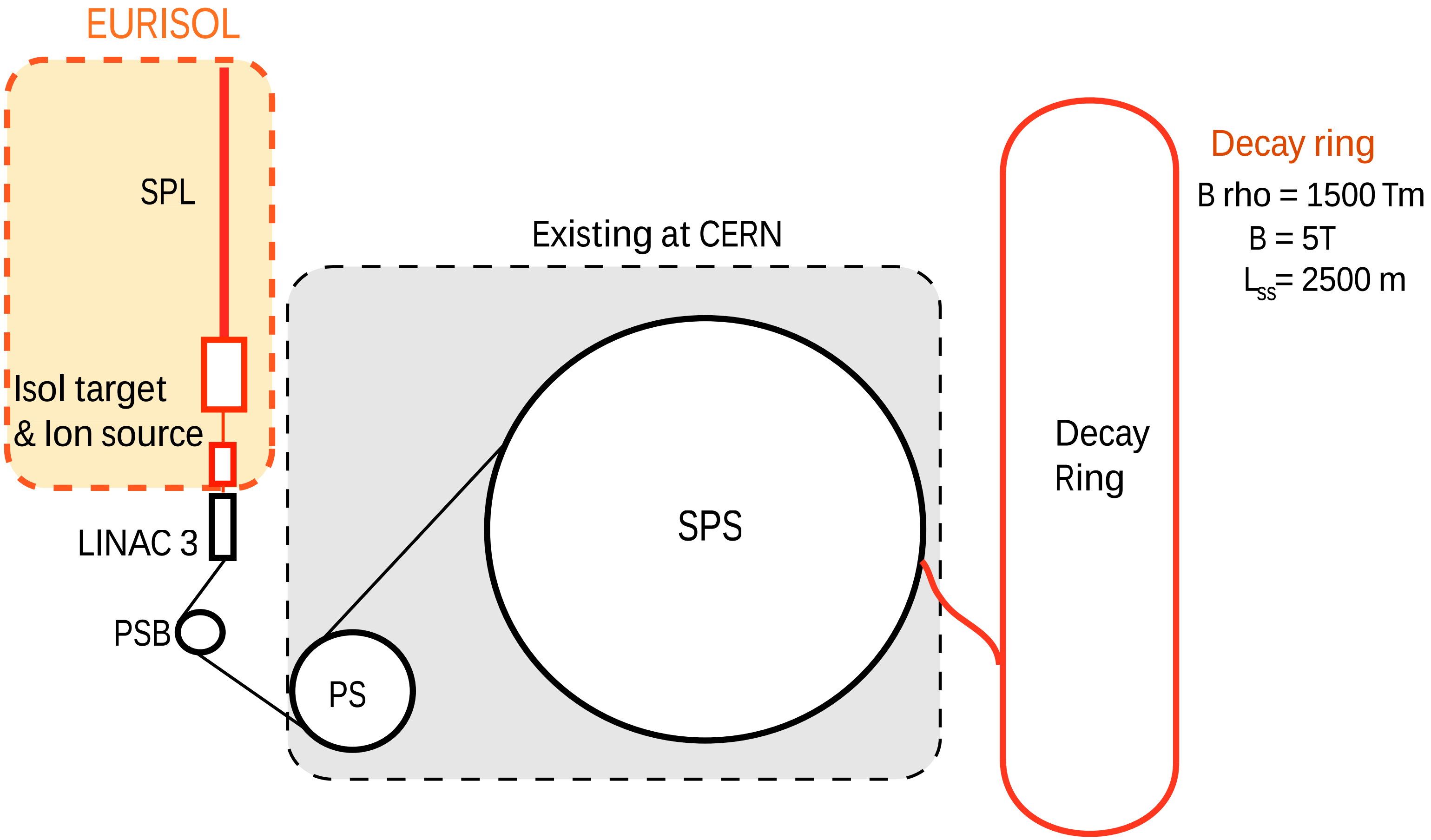
YES

with a novel concept of neutrino beam: BETA BEAM.

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

Beta Beam

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:

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

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

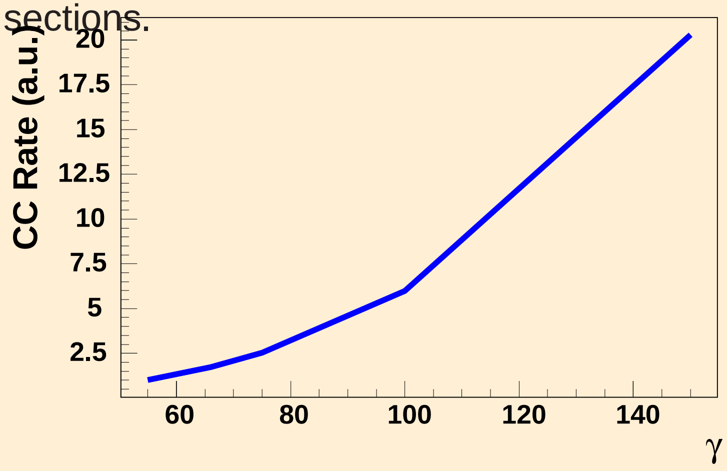
Atmospheric neutrino background can be kept low only by a very short duty cycle of the Beta Beam. A reduction factor bigger than 10^3 is needed.

This is achieved by building 10 ns long Ion bunches.

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

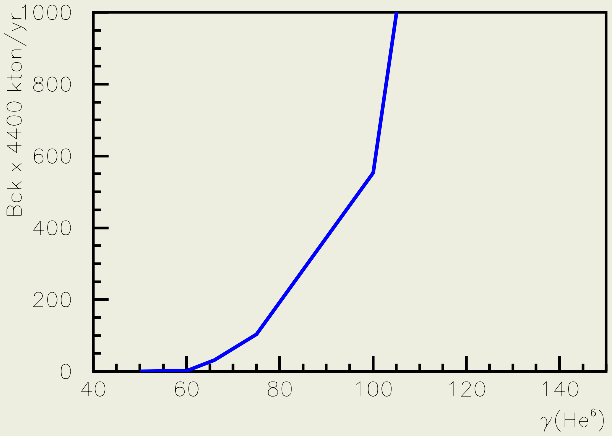
Higher γ produce more CC interactions

More collimated neutrino production and higher cross sections.

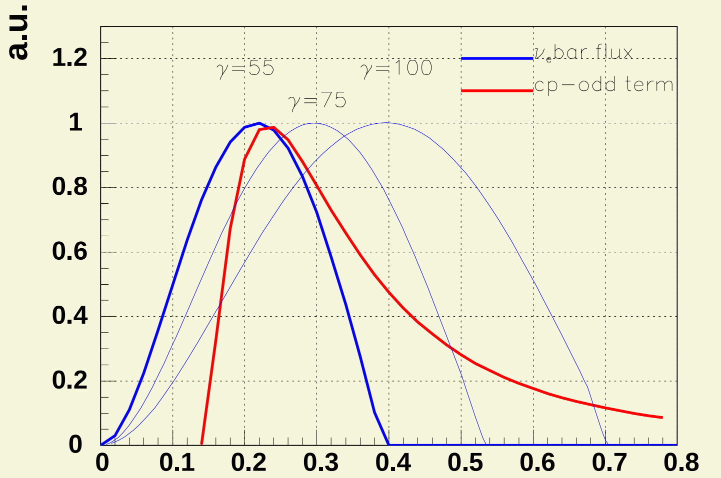


Background rate rises much faster than CC interactions

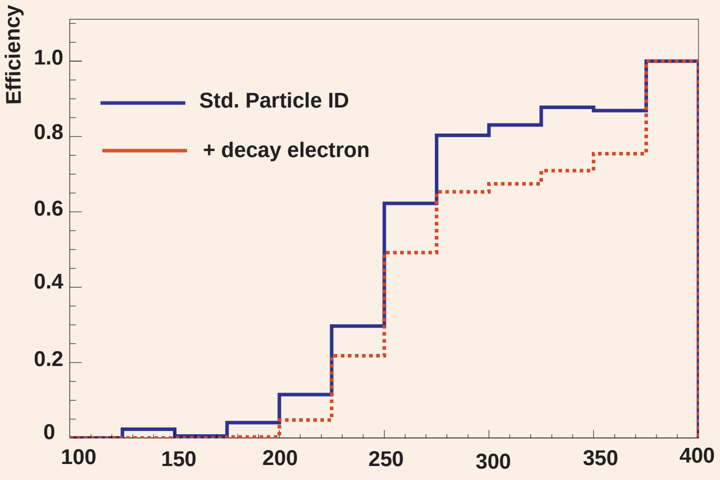
From resonant pion production in $\overline{\nu}_e$ NC interactions



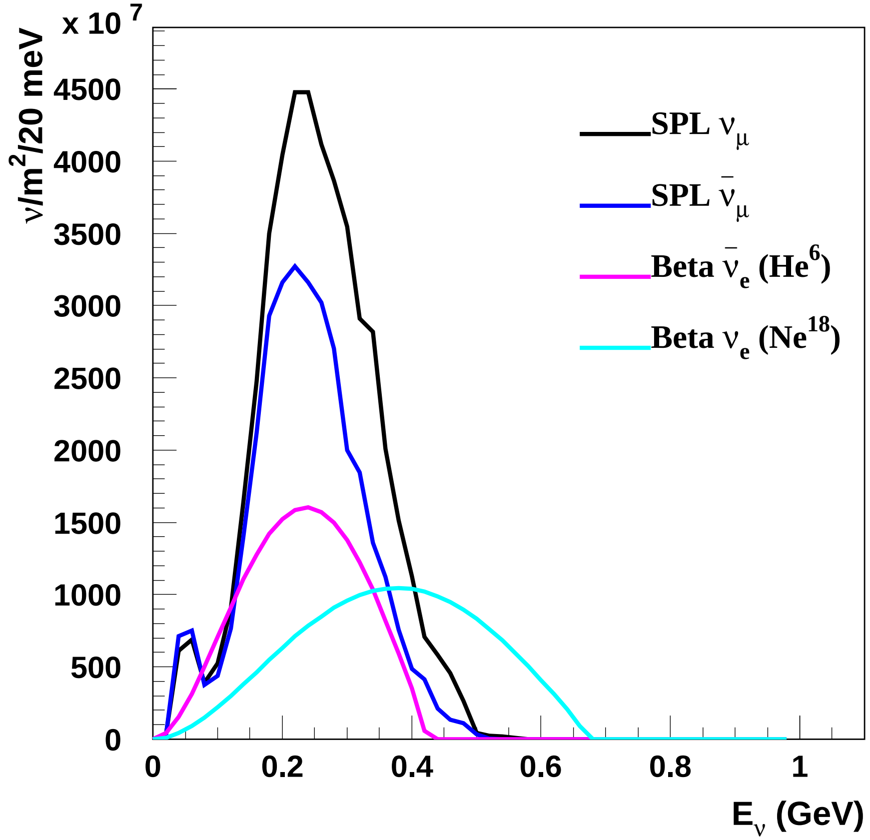
ν flux must match the CP-odd oscillating term



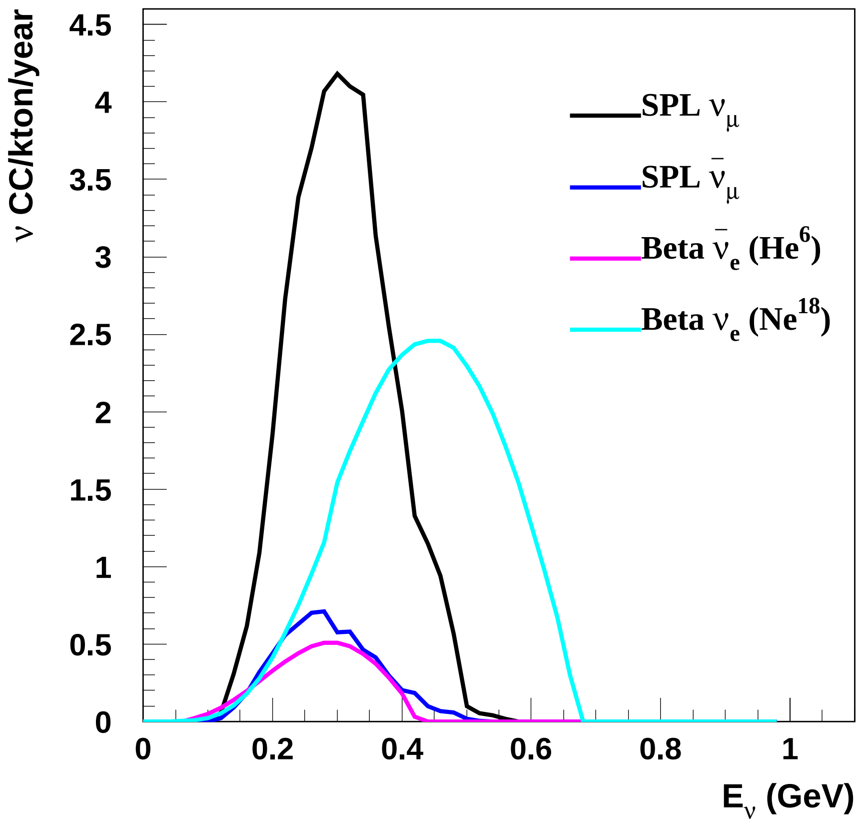
Detection efficiency as function of ν energy



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 × 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

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 $p(\overline{\nu}_e \longrightarrow \overline{\nu}_\mu)$.

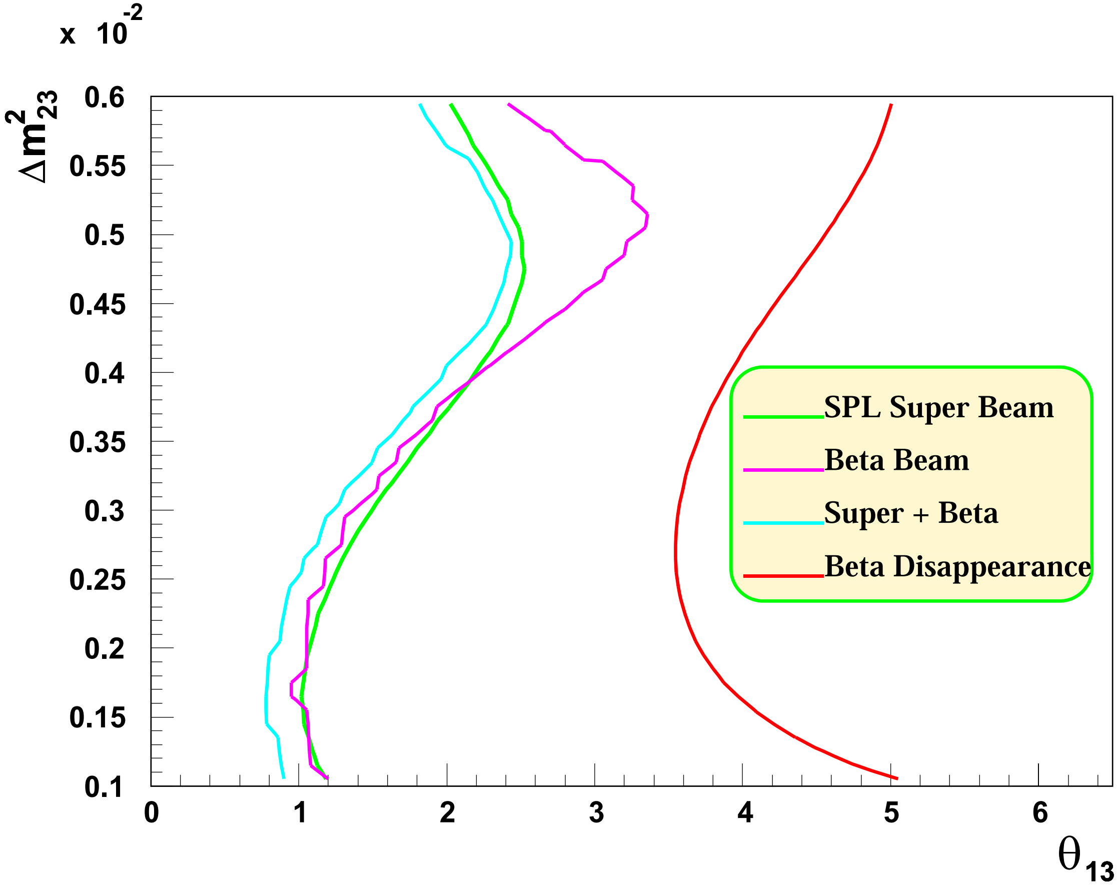
CPT searches

- 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

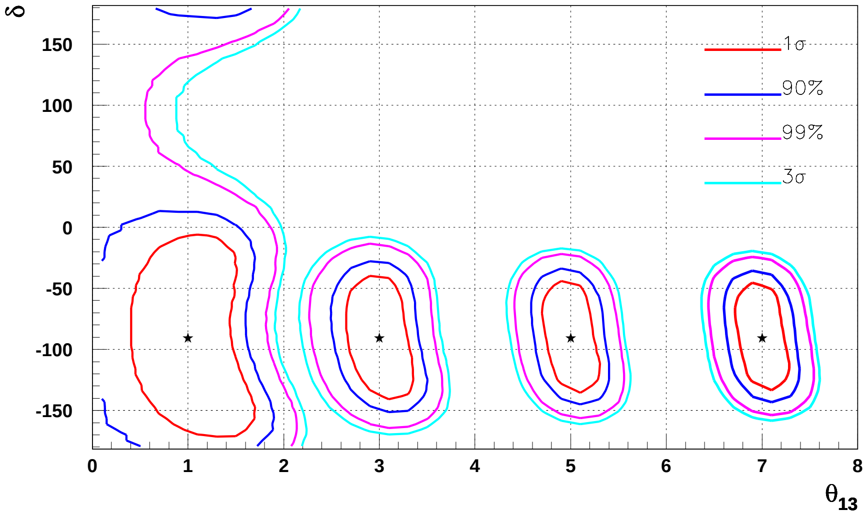
Computed for $\delta_{CP} = 0$ and 5 years running.

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

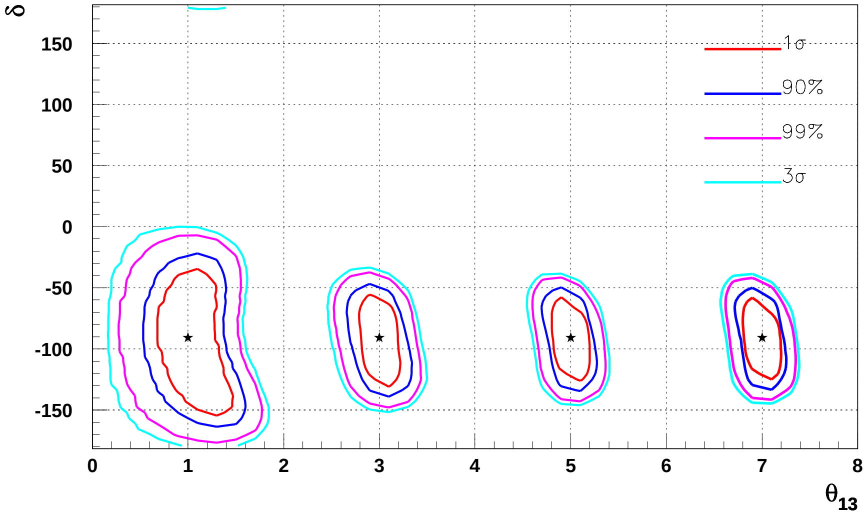


Beta Beam - Super Beam synergy: CP sensitivity

SUPER BEAM ONLY



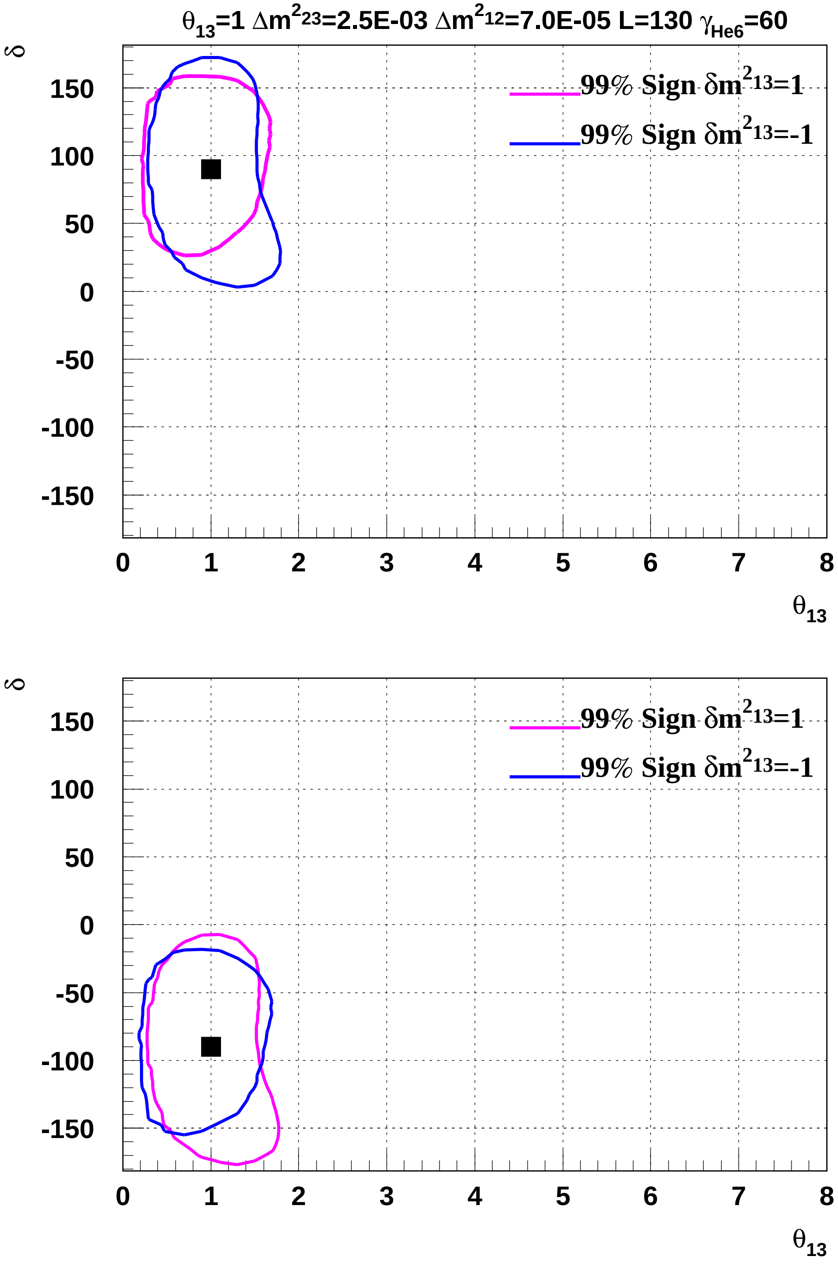
SUPER BEAM + BETA BEAM



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

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

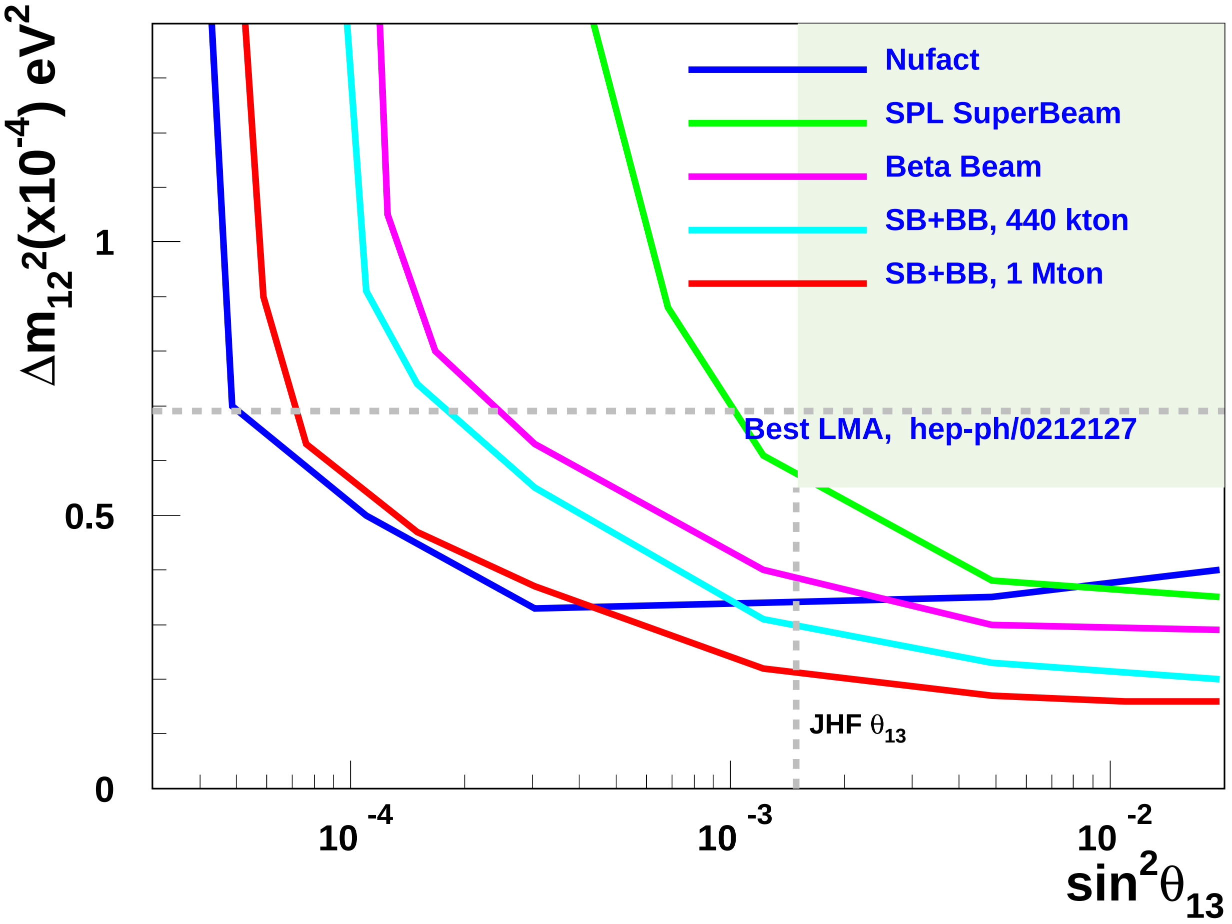


- The asymmetric statistics and background rates in the ν_e and $\overline{\nu}_e$ beams produce an asymmetric response to the positive and negative values of δ.
- Even if the matter effects are negligible, the $p(\nu_\mu \rightarrow \nu_e)$ formula contains odd $\mathrm{sign}(\delta \mathrm{m}^2_{13})$ 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.
  - $\sin^2 2\theta_{12} = 0.8$

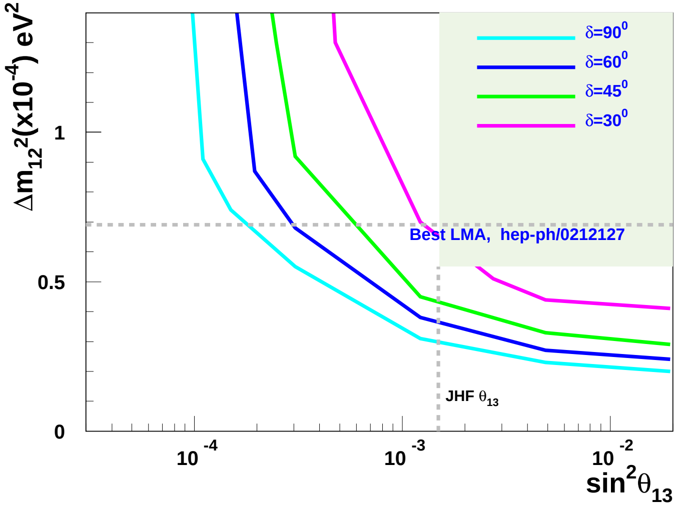
A comparison of CP sensitivities: Beta Beam vs. Nufact

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.



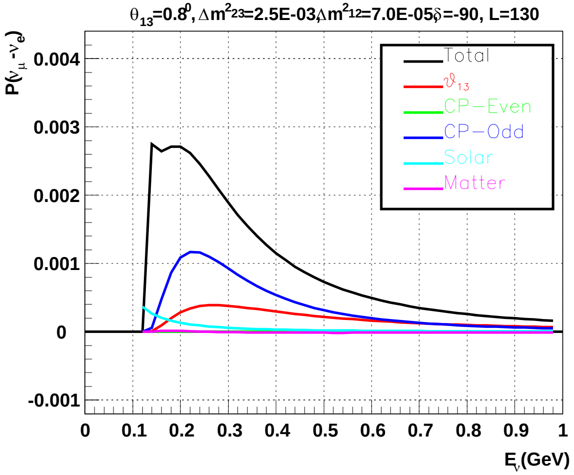
Some comments about the comparison



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

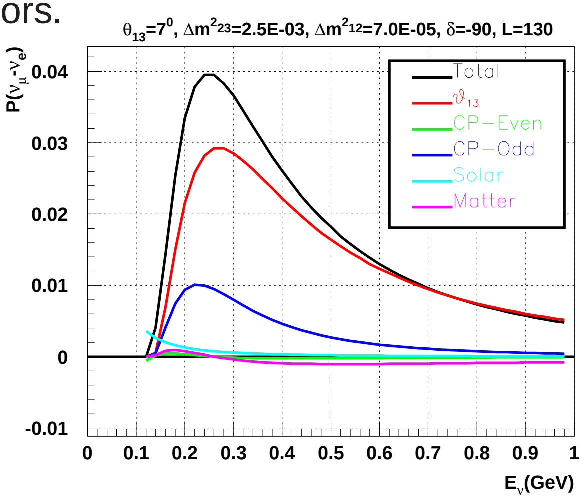
A fair comparison should be made by the same group using the same methods for the different facilities (a call for collaboration ...)

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

The next ($4^{th}, 5^{th}$?) generation of accelerator ν oscillation experiments will address the problem of measuring θ_{13}

Then the difficult, long and very expensive searches for Leptonic CP violations

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} .