Mauro Mezzetto

Istituto Nazionale di Fisica Nucleare,

Sezione di Padova

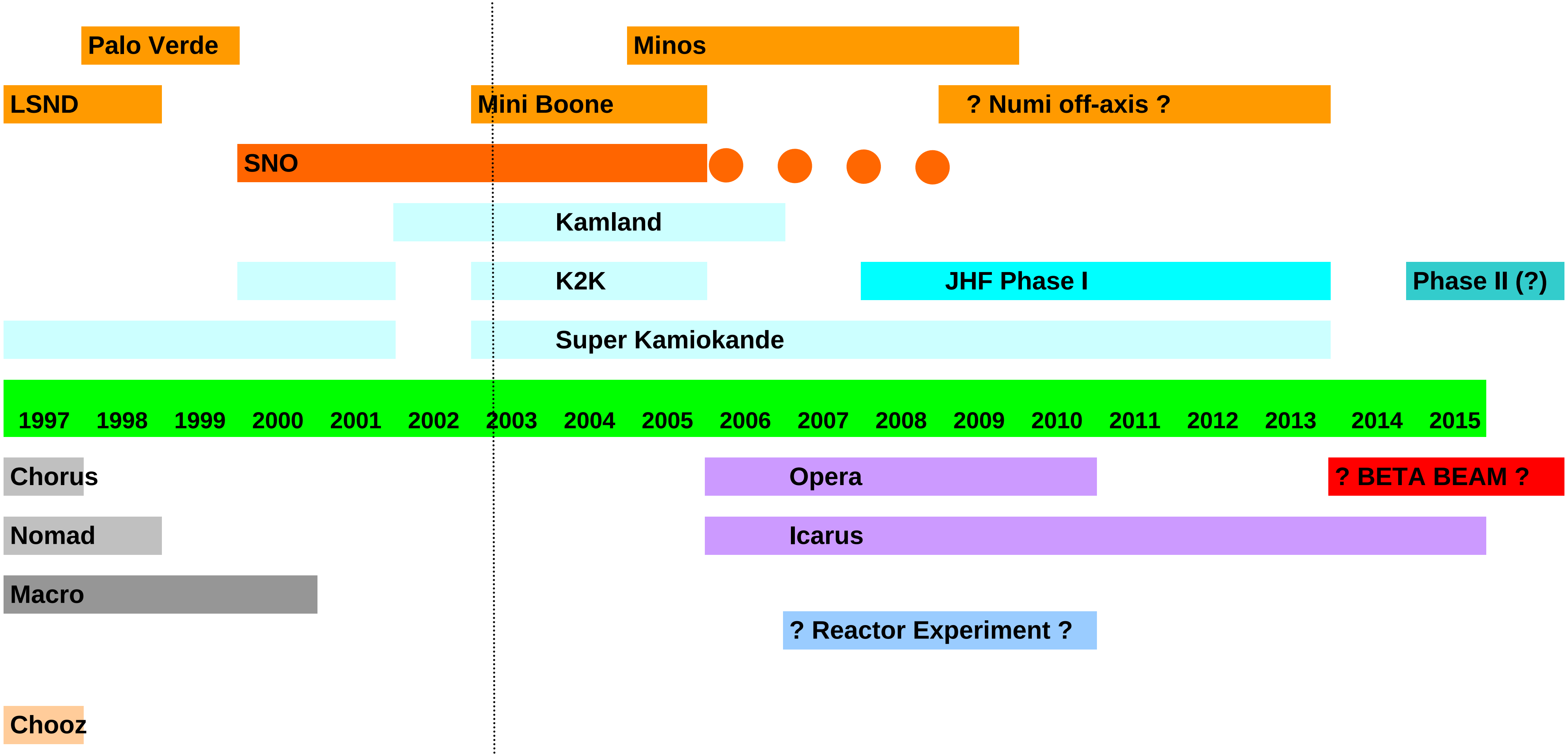
Beta Beam

Summary:

- **The facility.**
- **The synergy with the SPL Super Beam.**
- **Physics performances.**

NOVE 03, Venezia, December 3-5 ,2003

Neutrino Oscillation Experiments



Palo Verde

Minos

LSND

Mini Boone

? Numi off-axis ?

SNO

Kamland

K2K

JHF Phase I

Phase II (?)

Super Kamiokande

1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015

Chorus

Opera

? BETA BEAM ?

Nomad

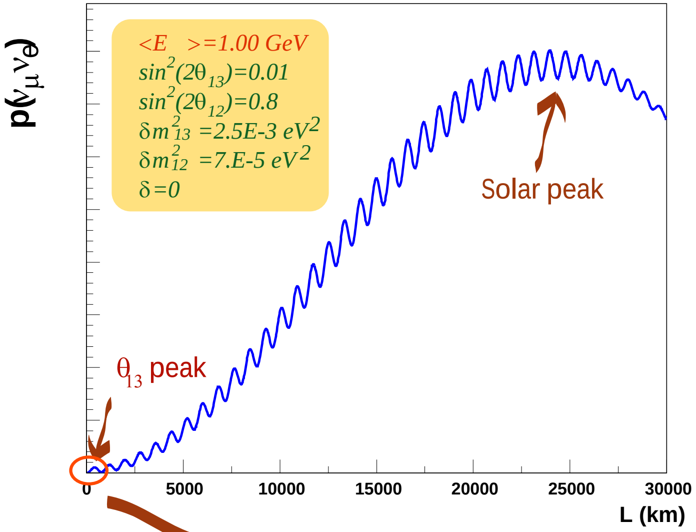
Icarus

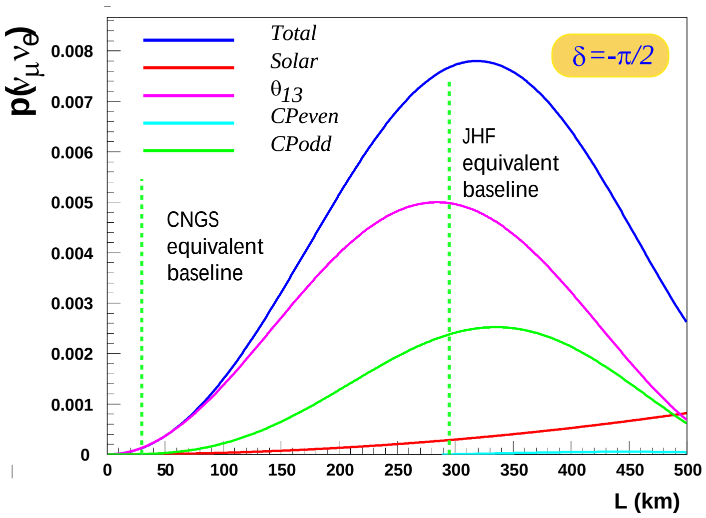
Macro

? Reactor Experiment ?

Chooz

Sub leading $\nu_\mu - \nu_e$ oscillations





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

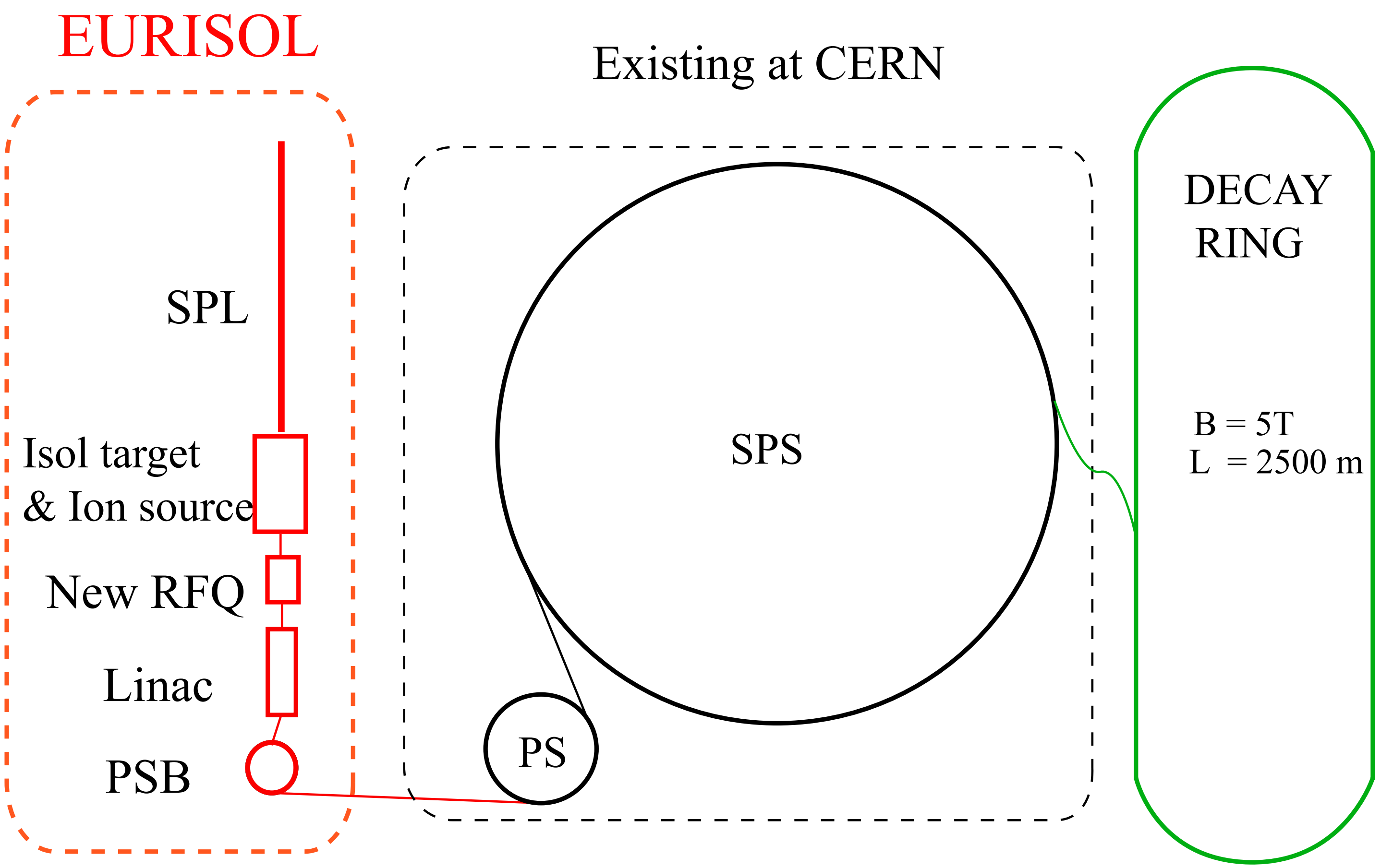
$$
\begin{aligned}
p(\nu_\mu \rightarrow \nu_e) = {} & 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} \qquad \theta_{13} \text{ driven} \\
& + 8c_{13}^2 s_{12} s_{13} s_{23} (c_{12} c_{23} cos\delta - s_{12} s_{13} s_{23}) \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2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

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

M. Mezzetto, "Reach of Neutrino Factories, SuperBeams and Beta Beams", Win 03, October 8th, 2003. .

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

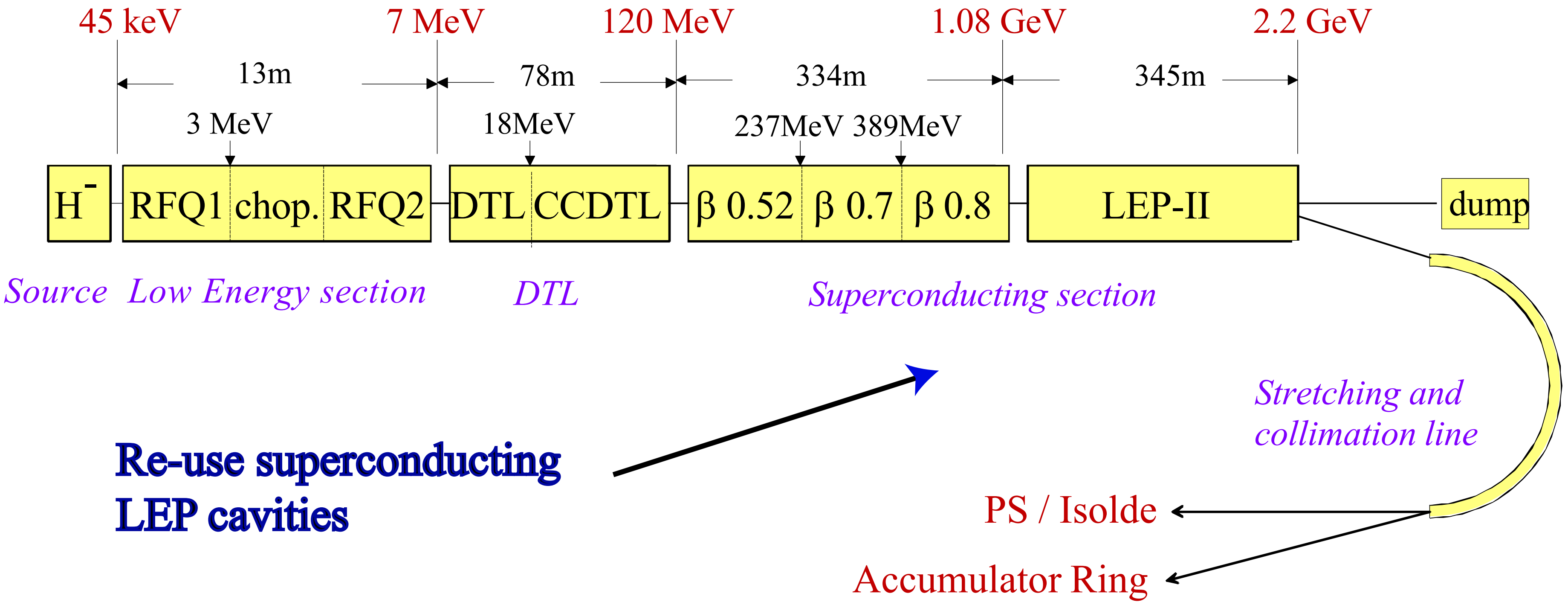
M. Lindroos and collaborators, see http://beta-beam.web.ch/beta-beam



- 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:

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

MW-Linac: SPL (Superconducting Proton Linac)



45 keV | 7 MeV | 120 MeV | 1.08 GeV | 2.2 GeV

13m | 78m | 334m | 345m

3 MeV | 18MeV | 237MeV 389MeV

H^- | RFQ1 chop. RFQ2 | DTL CCDTL | β 0.52 β 0.7 β 0.8 | LEP-II | dump

Source *Low Energy section* *DTL* *Superconducting section*

Stretching and collimation line

PS / Isolde

Accumulator Ring

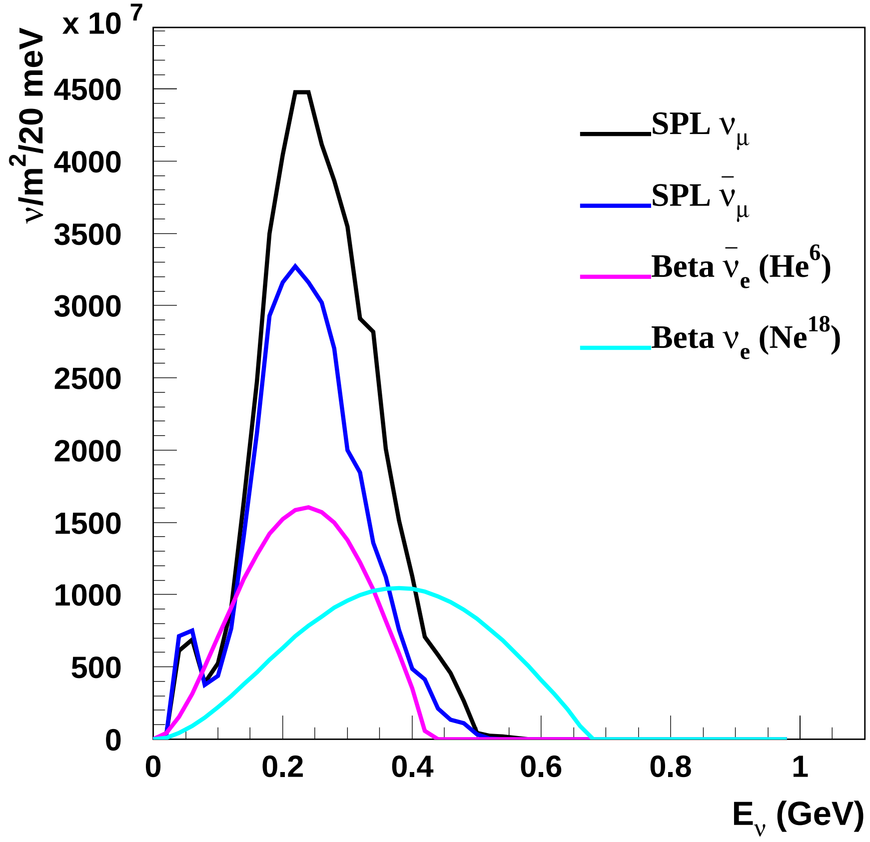
Re-use superconducting LEP cavities

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

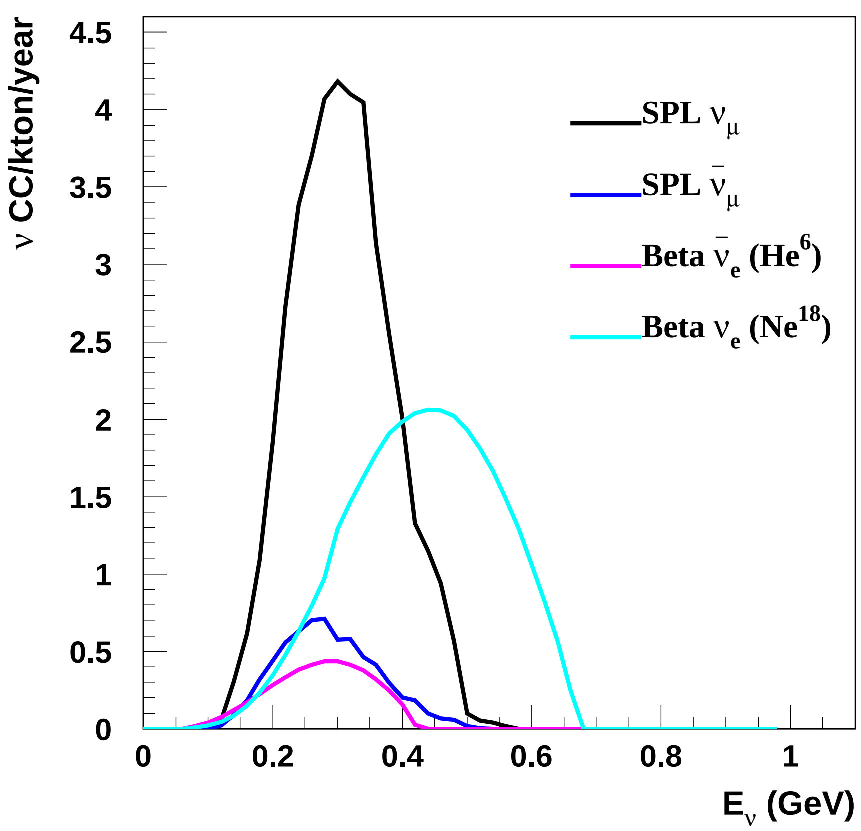
→

10^{23} protons/year

Fluxes

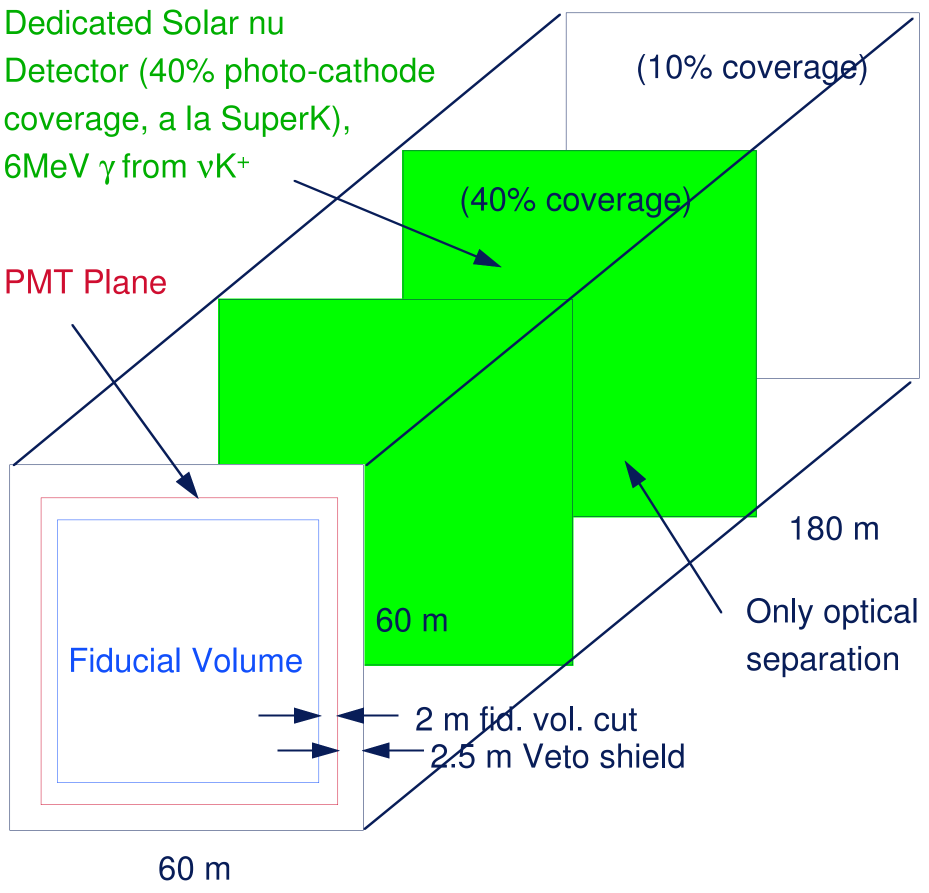


CC Rates



	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	4.5	0.28	10	19709
ν_e $(\gamma = 100)$	$1.88 \cdot 10^{11}$	0.36	32.9	0.43	10	144783

The Megaton detector

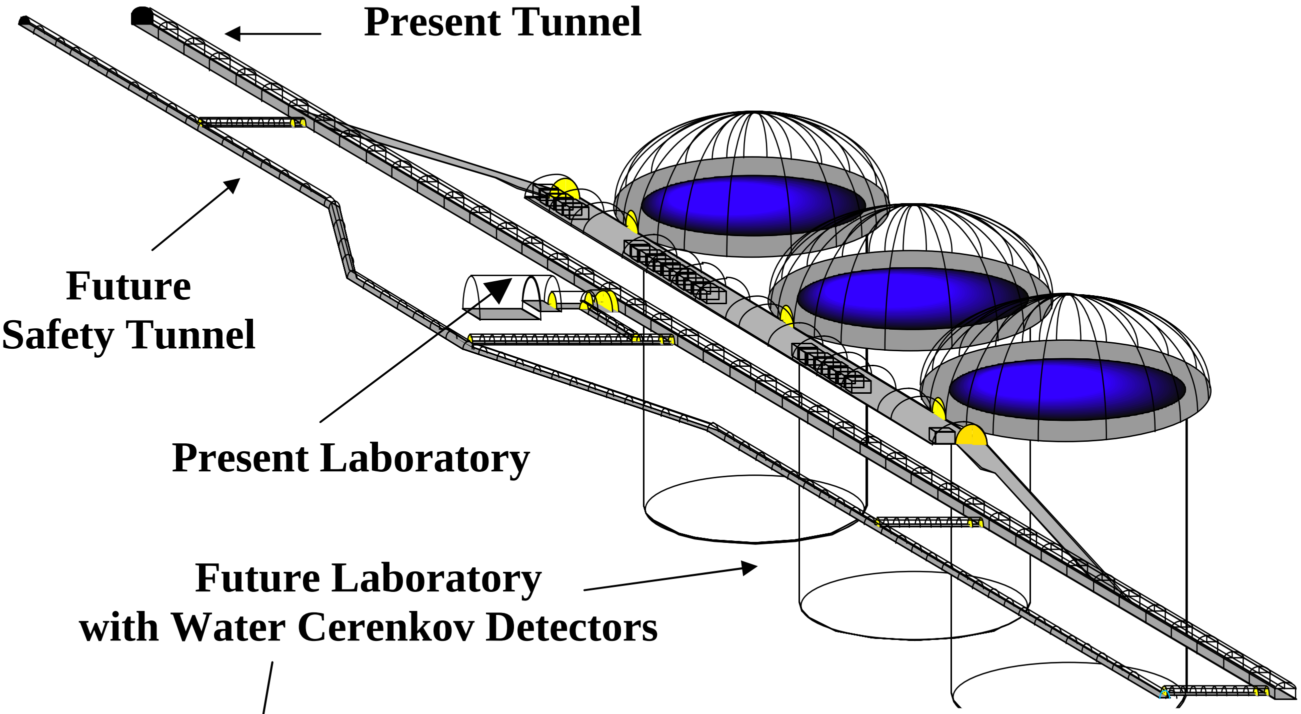


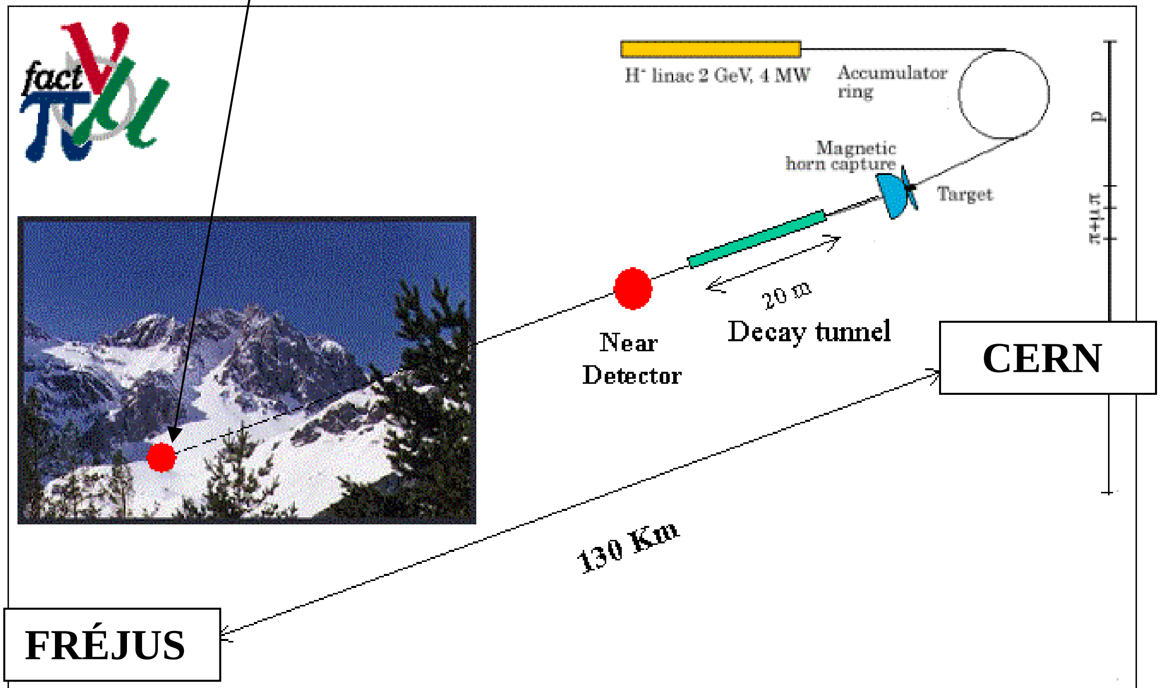
- Fiducial volume: 440 kton: 20 times SuperK.
- 60000 PMTs (20”) in the inner detector, 15000 PMTs in the outer veto detector.
- Energy resolution is poor for multitrack events but quite adequate for sub-GeV neutrino interactions.
- It would be hosted at the Frejus laboratory, 130 km from CERN, in a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

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

2) Components of the Project

-> a **very large Laboratory** to allow the installation of a **Megaton**-scale **Cerenkov** Detector (≈ 10^6 m^3)





A possible layout of a Low Energy Neutrino Super Beam

and (or) neutrino beta-beam

Distinctive features of the Beta Beam

Just one neutrino flavour in the beam. No intrinsic contamination.

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

Tunable: easy to adapt to the optimal Δm^2_{23}.

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

Neutrino fluxes are completely defined by the beta decay properties of the parent ion and by the knowledge of the number of ions in the decay ring. This assures very small systematic errors and a powerful measure of neutrino cross-sections in the close detector.

The ν_e and $\overline{\nu}_e$ beams allow for the disappearance channel with a very good control of the systematics, with a direct access to θ_{13} . Their comparison offers a tool to investigate CPT.

When combined with the ν_μ and $\overline{\nu}_\mu$ SPL beams, the ν_e and $\overline{\nu}_e$ Beta Beams allow for CP, T, and CPT searches.

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

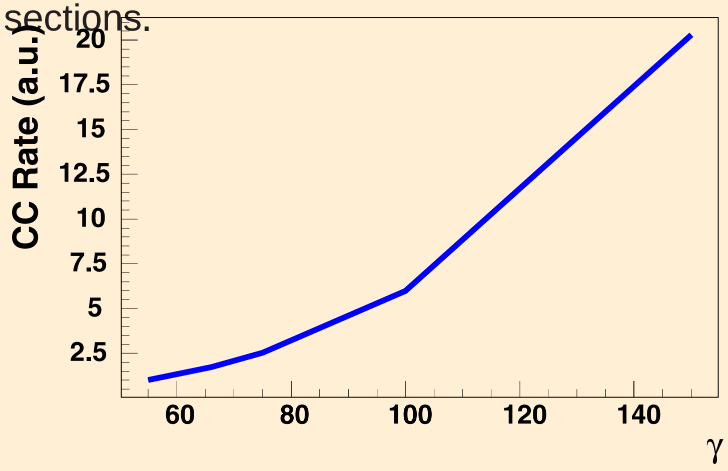
Atmospheric neutrino background can be kept low only by a very short duty cycle of the Beta Beam. A reduction factor bigger than 10^3 is needed.

This is achieved by building 10 ns long Ion bunches.

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

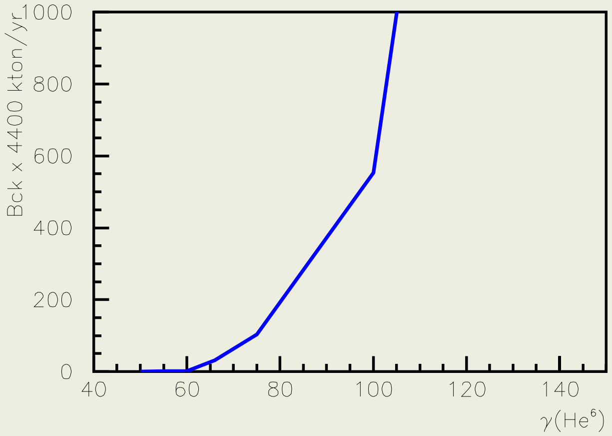
Higher γ produce more CC interactions

More collimated neutrino production and higher cross sections.

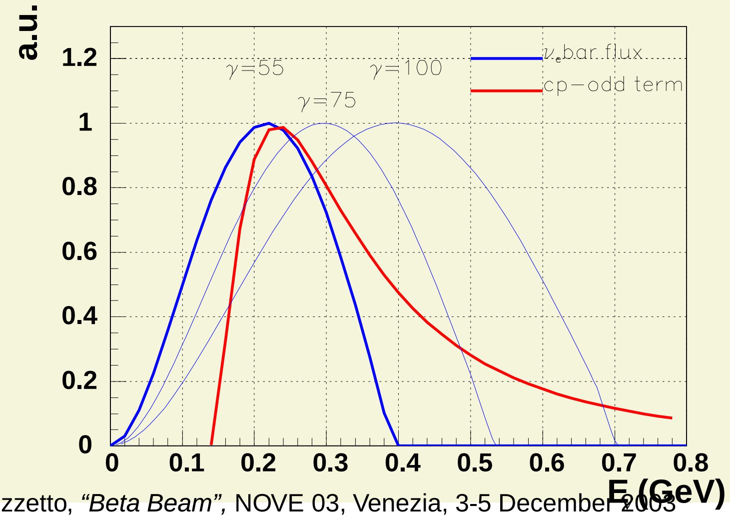


Background rate rises much faster than CC interactions

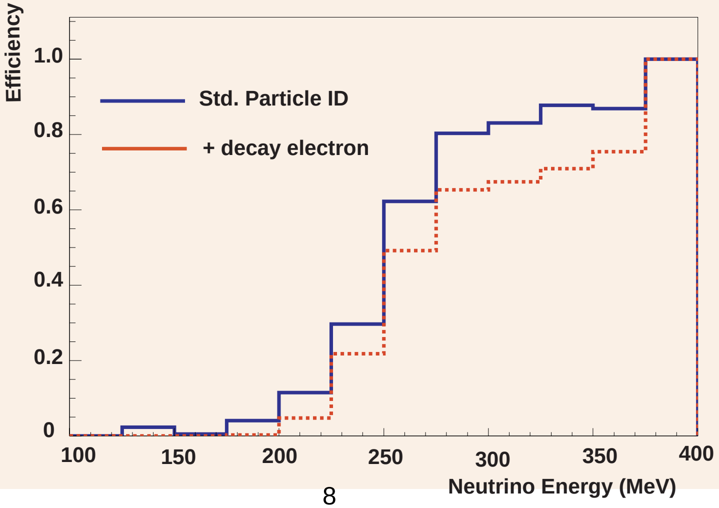
From resonant pion production in $\overline{\nu}_e$ NC interactions



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.

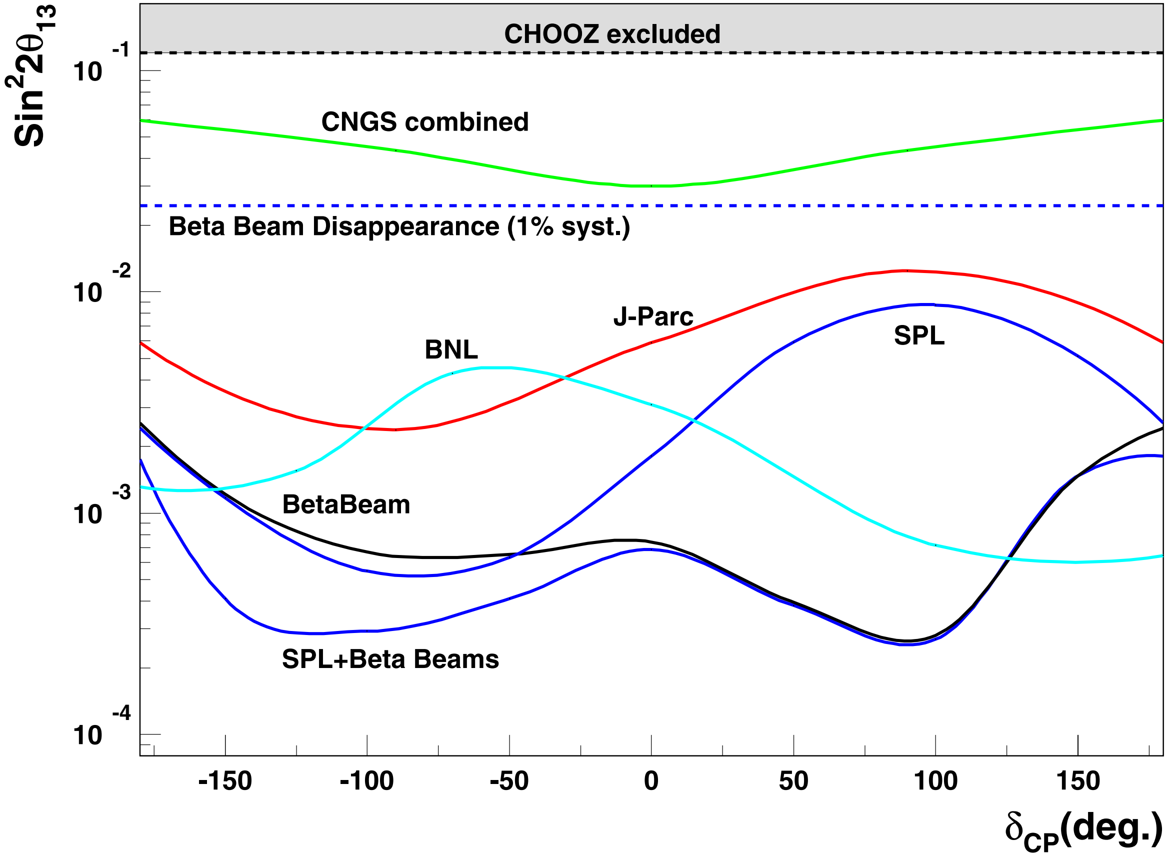
Statistical method

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: a benchmark on θ_{13} sensitivity

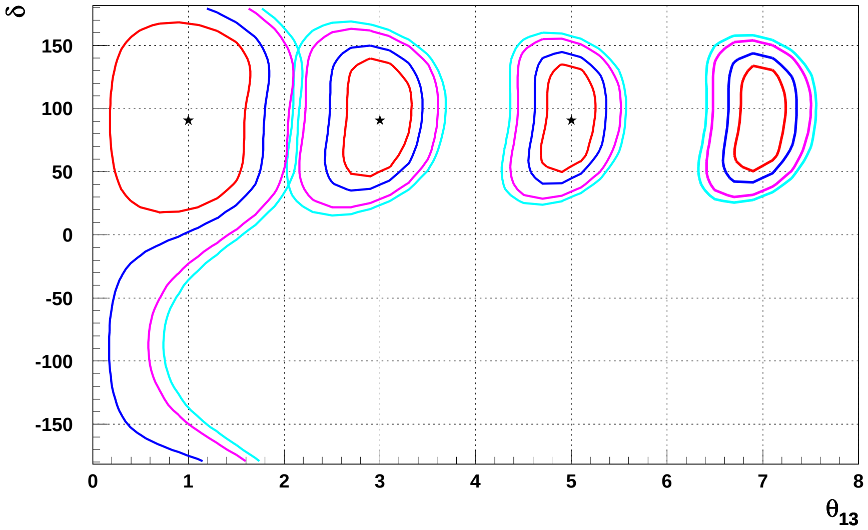
Computed for $\delta_{CP} = 0$, sign$(\Delta m^2) = +1$ and 5 years running.

- No way to disentangle θ_{13} from δ in a high sensitivity experiment.
- The full information of experiment sensitivity is given by a bidimensional θ_{13} vs δ plot.
- **Beta Beam can measure θ_{13} both in appearance and in disappearance mode. All the ambiguities can be removed for $\theta_{13} \geq 3.4°$**

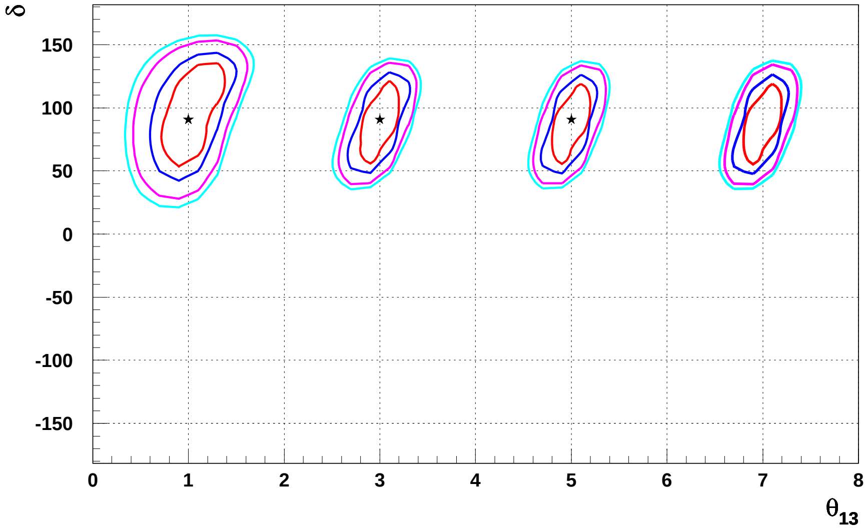


Beta Beam - Super Beam synergy: CP sensitivity

SUPER BEAM ONLY



SUPER BEAM + BETA BEAM



$\delta m^2_{12} = 7 \cdot 10^{-5}\ eV^2,\ \theta_{13} = 3^\circ,\ \delta_{CP} = \pi/2,$ sign$(\Delta m^2) = +1$

	Beta Beam		SPL-SB	
	^6He	^{18}Ne	ν_μ	$\overline{\nu}_\mu$
	$(\gamma = 60)$	$(\gamma = 100)$	(2 yrs)	(8 yrs)
CC events (no osc, no cut)	19710	144784	36698	23320
Oscillated at the Chooz limit	612	5130	1279	774
Oscillated	44	529	93	82
δ oscillated	-9	57	-20	12
Beam background	0	0	140	101
Detector backgrounds	1	397	37	50

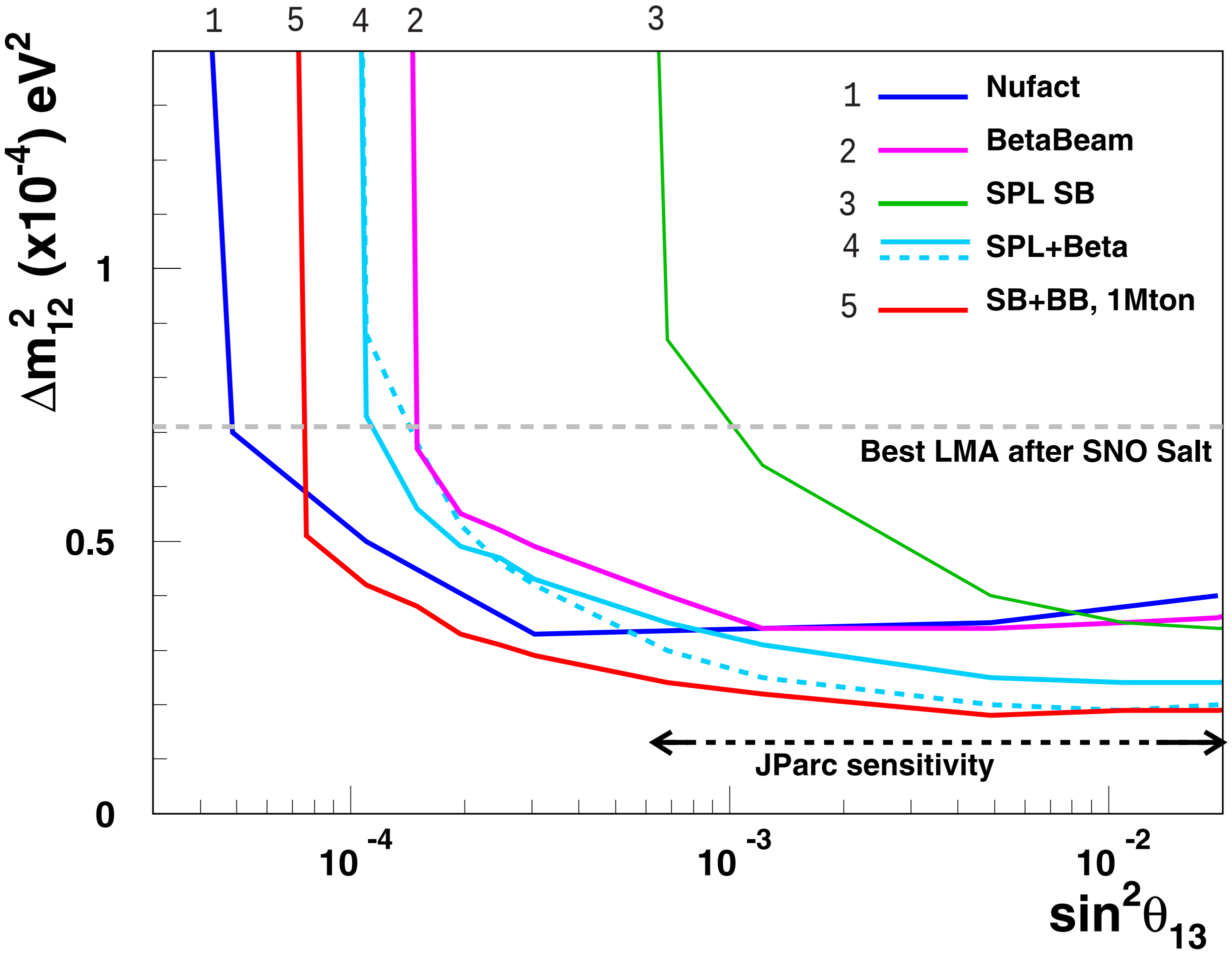
δ-oscillated events indicates the difference between the oscillated events computed with $\delta = 90^\circ$ and with $\delta = 0$.

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.

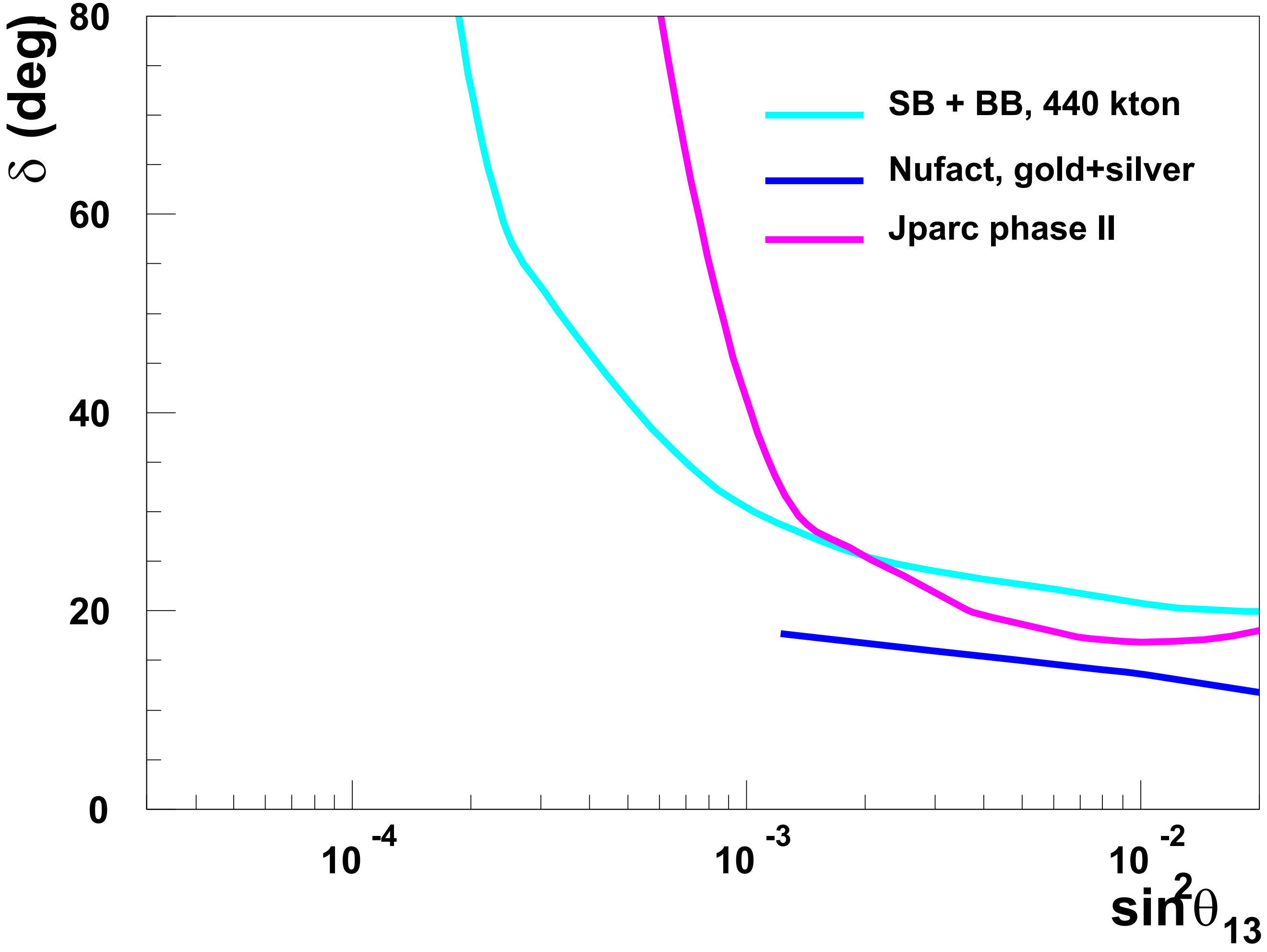


δ sensitivity: Nufact vs SPL SuperBeam + Beta Beam.

Minimum value of δ at 3σ from zero as function of θ_{13} . $\Delta m^2_{12} = 7 \cdot 10^{-3}$ eV^2.

JParc as computed by T. Kobayashi, J.Phys.G29:1493(2003)

Nufact curve is silver+gold, preliminary, courtesy of O. Mena. Its extension below 2° is under investigation.



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}).

The possibility to install at Frejus a megaton detector receiving both a super beam and a beta beam offers to Europe a unique opportunity.

Additional Slides

Comment on BB cost estimates

Educated guess on possible costs	USD/CHF	1.60
UNO	**960**	MCHF
SUPERBEAM LINE	**100**	MCHF
SPL	**300**	MCHF
PS UPGR.	**100**	MCHF
SOURCE (EURISOL), STORAGE RING	**100**	MCHF
SPS	**5**	MCHF
DECAY RING CIVIL ENG.	**400**	MCHF
DECAY RING OPTICS	**100**	MCHF
TOTAL (MCHF)	**2065**	MCHF
TOTAL (MUSD)	**1291**	MUSD
INCREMENTAL COST (MCHF)	**705**	MCHF
INCREMENTAL COST (MUSD)	**441**	MUSD

Estimated losses–CERN scenario

^{6}He

(lost on inside)

Machine	Ions extracted	Batches	Loss power	Power/length
Source+Cyclotron	2 e6 /s	52.5 ms		
Storage ring	1.0 e12	1	3.0 W	19 mW/m
Fast cycling syncrotron	1.0 e12	16	7.4 W	47 mW/m
PS	1.0 e13	1	765 W	1.2 W/m
SPS	0.9 e13	inf	3.63 kW	0.41 W/m
Decay ring	2.0 e14 *		157 kW	8.9 W/m

limit

^{18}Ne

(lost on outside)

Machine	Ions extracted	Batches	Loss power	Power/length
Source+Cyclotron	8 e11 /s	52.5 ms		
Storage ring	4.1e10	1	0.18 W	1.1 mW/m
Fast cycling syncrotron	4.1 e10	16	0.46 W	2.9 mW/m
PS	5.2 e11	1	56.4 W	90 mW/m
SPS	5.9 e11	inf	277 W	32 mW/m
Decay ring	9.1 e12 *		10.6 W	0.6 W/m

These numbers assumes 8s rep rate and only include decay losses from the beta beam!

* denotes equilibrium intensity in decay ring

A. Jansson, Rencontres de Moriond 2003

Ion decays per straight session/year.

1 SPS batch every 8s.

	$^{6}\mathrm{He}$ ($\tau = 1.15$ s, $\gamma = 60$)	$^{18}\mathrm{Ne}$ ($\tau = 2.45$ s, $\gamma = 100$))
From ECR source (ions/s)	2×10^{13}	2.4×10^{11}
PS after acceleration (ions/batch)	1×10^{13}	1.6×10^{12}
SPS after acceleration (ions/batch)	$.9 \times 10^{13}$	1.5×10^{12}
Decay ring (ions in 4 bunches (10 ns long))	7.8×10^{13}	4.5×10^{13}
50% losses	3.9×10^{13}	2.3×10^{13}
Decays/straight session/year	2.0×10^{18}	3.4×10^{17}
Used in the computations	$2.9 \times 10^{18} \quad (\times 1.45)$	$1.2 \times 10^{18} \quad (\times 3.5)$

Why the multiplicative factors?

1. Ion production (better target yields, increase number of targets, increase the collection time)
2. Reduce ion decays, especially in the PS
3. Reduce transfer losses

For instance: increase collection time, now fixed at $t_{col} = 1$s. Collect n_{col} ions by a target producing f ions/s with a ion lifetime$= \tau$: $n_{col} = f\tau(1 - exp(-t_{col}/\tau))$

t_{col} (s)	$^{6}\mathrm{He}$ ($\tau = 1.15$ s) $n_{col}/f\tau$	$^{18}\mathrm{Ne}$ ($\tau = 2.45$s) $n_{col}/f\tau$
1	0.58	0.33
2	0.82 ($\times 1.4$)	0.56 ($\times 1.7$)
3	0.92 ($\times 1.6$)	0.71 ($\times 2.2$)
4	0.97 ($\times 1.7$)	0.80 ($\times 2.4$)

Another possibility:

- Transfer waiting time to high energy to avoid decay losses.
- Store ions in a “flat bottom” plateaus at SPS before acceleration.

Up to a factor 4 can be gained for $^{18}\mathrm{Ne}$, with a faster PS (0.1 s cycle time against the present 1.2 s). Up to a factor 2 with the present PS configuration.

Is the $\gamma_{HE} = 60, \gamma_{NE} = 100$ the absolute optimal configuration?

Suggestion of P. Hernandez and J.J. Gomez-Cadenas

- The present SPS configuration allows max. 139 GeV/u. In this scenario the $\gamma_{HE} = 60 - \gamma_{NE} = 100$, baseline=130 km is the optimal configuration.
- Relaxing the SPS constrain and allowing for higher energies:
  - The resonant NC single pion productions cross section saturates.
  - The signal/background ratio starts to be favorable again.
- As for the neutrino factories the number of events per kton/year increases as E_ν when computed at the optimal baseline. In this energy range is even more favorable because below 1 GeV neutrino cross sections raise faster that E_ν^{+1}.
- At higher energies it is possible to bin the events in energy bins.

The $\gamma_{HE} = 360, \gamma_{NE} = 600$ configuration, baseline=732 km, is still comfortable as far as concerns energy reconstruction in a water Čerenkov detector and would have a ~ 10 increase in CC rates.

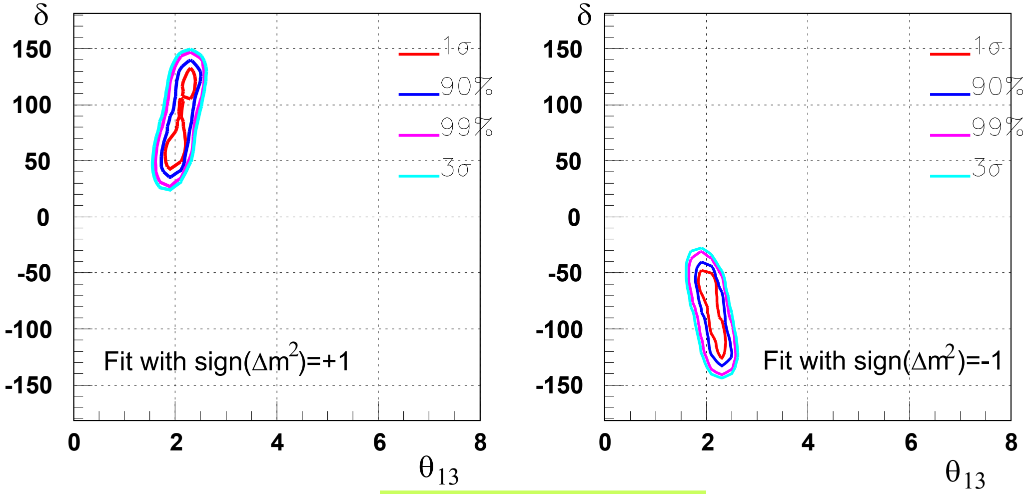
This would require something like a SPS to Tevatron upgrade (that means replace all the magnets with a 2-3 years stop of operations) or the usage of LHC as a third stage accelerator.

The fluxes in these configurations are not yet been studied.

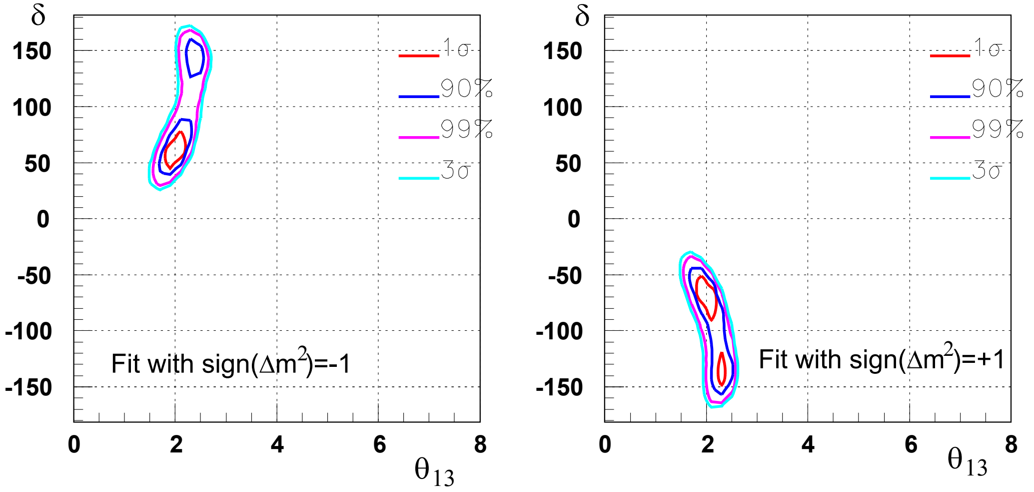
The sign(Δm^2) ambiguity

Being the matter effect terms negligible, the sign(Δm^2) ambiguity makes the sign$(sign\Delta m^2 \times \delta)$ undetectable, but doesn't degrade the overall resolution.

Sign(Δm^2)=+1



Sign(Δm^2)=-1



How a Beta Beam with 2E18 decaying parents can compete with a Nufact with 2E20 decaying parents?

- Quality factor (QF):
  - $\Phi(L) \propto (\frac{P_L}{P_T})^2 \propto \gamma^2$
  - $L_{opt} \propto \frac{E}{\Delta m^2} \propto \gamma E_0$
  - $\Phi_{opt} = \Phi(L_{opt}) \propto E_0^{-2}$
  - $CC\mathrm{rate} \propto \Phi_{opt} \cdot \sigma \propto \Phi_{opt} \gamma E_0 \propto \frac{\gamma}{E_0}$

  $\Rightarrow QF \propto \frac{\gamma}{E_0}$

  A Nufact at 50 GeV/c has $\gamma \sim 460$, $E_0 = 34$ MeV, $QF \simeq 13\ MeV^{-1}$

  $^6\mathrm{He}$ beta beam would have $\gamma = 60$, $E_0 = 1.9 MeV$, $QF \simeq 32\ MeV^{-1}$ ($\times 2.5$)
- Detector mass: $\times 10$.
- No backgrounds (but no energy bins)
- No subtraction of matter effects (fake CP-ODD effects).
- No θ_{13} /δ degenerate solutions