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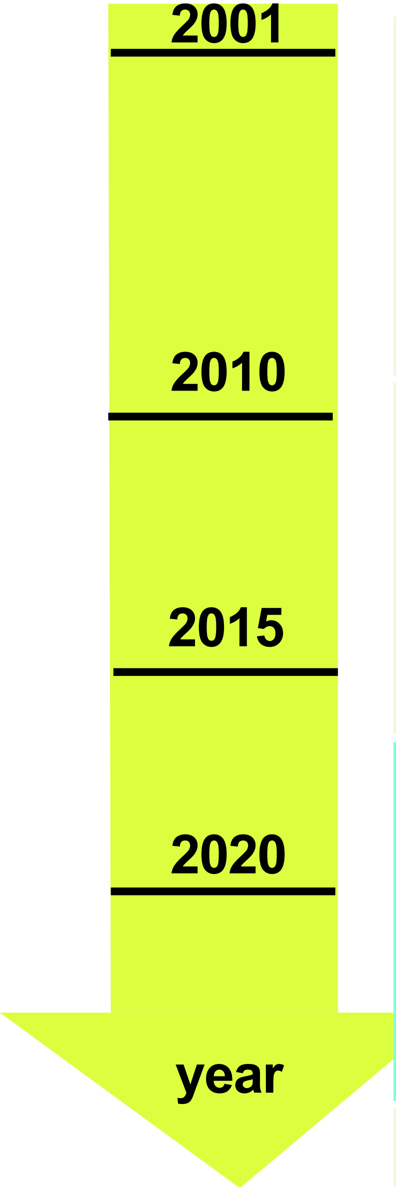
”Physics potential of the Beta Beam and its different options”

Thanks to: P. Zucchelli, M. Lindroos, J. Bouchez, P. Hernandez, JJ Gomez-Cadenas, J. Burguet-Castell, O. Mena, D. Casper, A. Blondel, S. Gilardoni, C. Volpe, S. Rigolin, A. Donini, P. Migliozzi, F. Terranova, P. Lipari.

Villars, September 24th, 2004

At least 4 phases of Long Baseline experiments



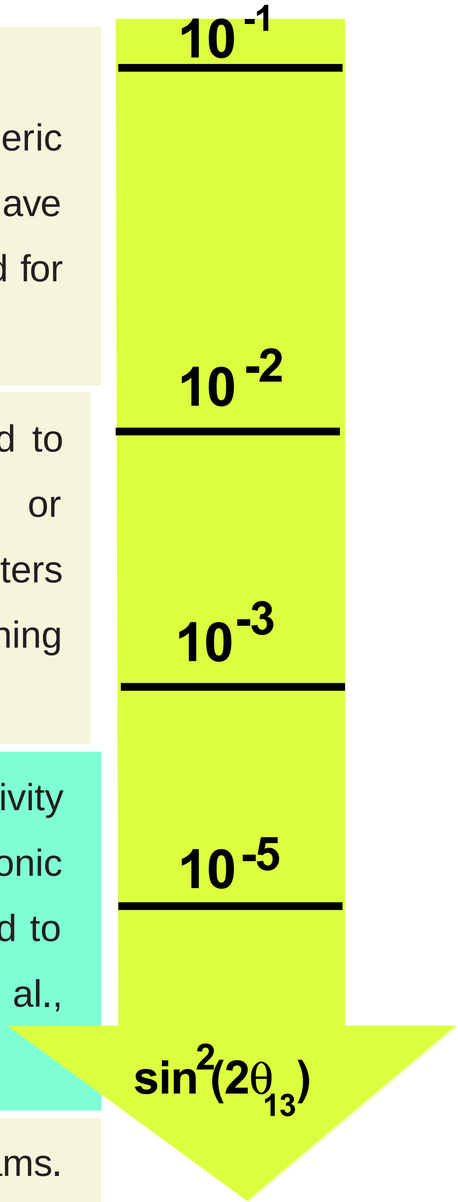
1) 2001-2010. K2K, Opera, Icarus, Minos.

Optimized to confirm the SuperK evidence of oscillation of atmospheric neutrinos through ν_μ disappearance or ν_τ appearance. They will have limited potential in measuring oscillation parameters. Not optimized for ν_e appearance (θ_{13} discovery).

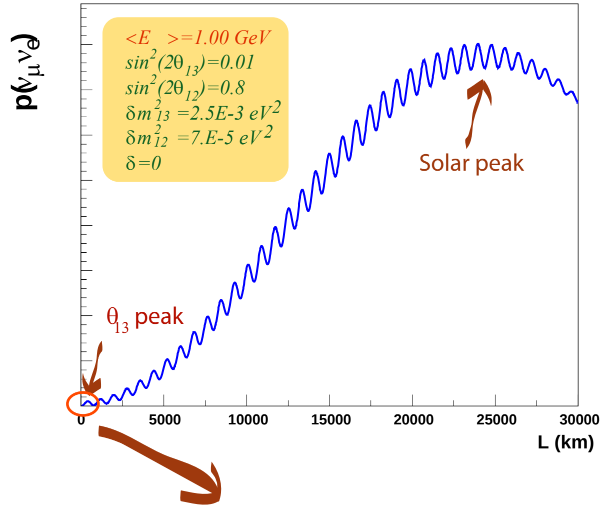
2) 2009-2015. T2K (approved), Noνa, Double Chooz. Optimized to measure θ_{13} (Chooz $\times$ 20) through ν_e appearance or ν_e disappearance. Precision measure of the atmospheric parameters (1 % level). Tiny discovery potential for CP phase δ, even combining their results.

3) 2015 - 2025. SuperBeams and/or Beta Beams. Improved sensitivity on θ_{13} (Chooz $\times$ 200). They will have discovery potential for leptonic CP violation and mass hierarchy for $\theta_{13} \geq 1^\circ$. In any case needed to remove any degeneracy from Nufact results (see P. Hernandez et al., hep-ph/0207080)

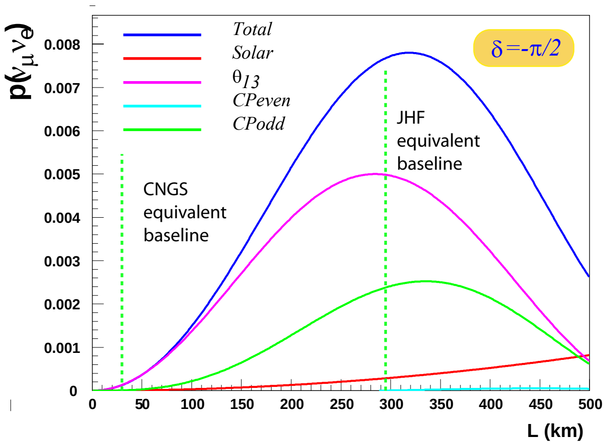
4) Ultimate facility: Neutrino Factories or high energy Beta Beams. Ultimate sensitivity on the CP phase δ, θ_{13} , mass hierarchy.



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



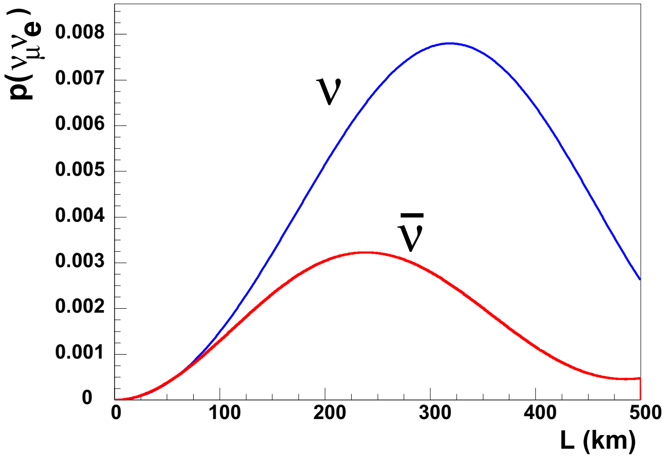
$$
\begin{aligned}
p(\nu_\mu \to \nu_e) ={}& 4c^2_{13}s^2_{13}s^2_{23}\sin^2\frac{\Delta m^2_{13}L}{4E} && \theta_{13}\ \text{driven}\\
&+ 8c^2_{13}s_{12}s_{13}s_{23}(c_{12}c_{23}cos\delta - s_{12}s_{13}s_{23})\cos\frac{\Delta m^2_{23}L}{4E}\sin\frac{\Delta m^2_{13}L}{4E}\sin\frac{\Delta m^2_{12}L}{4E}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



θ_{13} discovery requires total probability greater than Solar probability

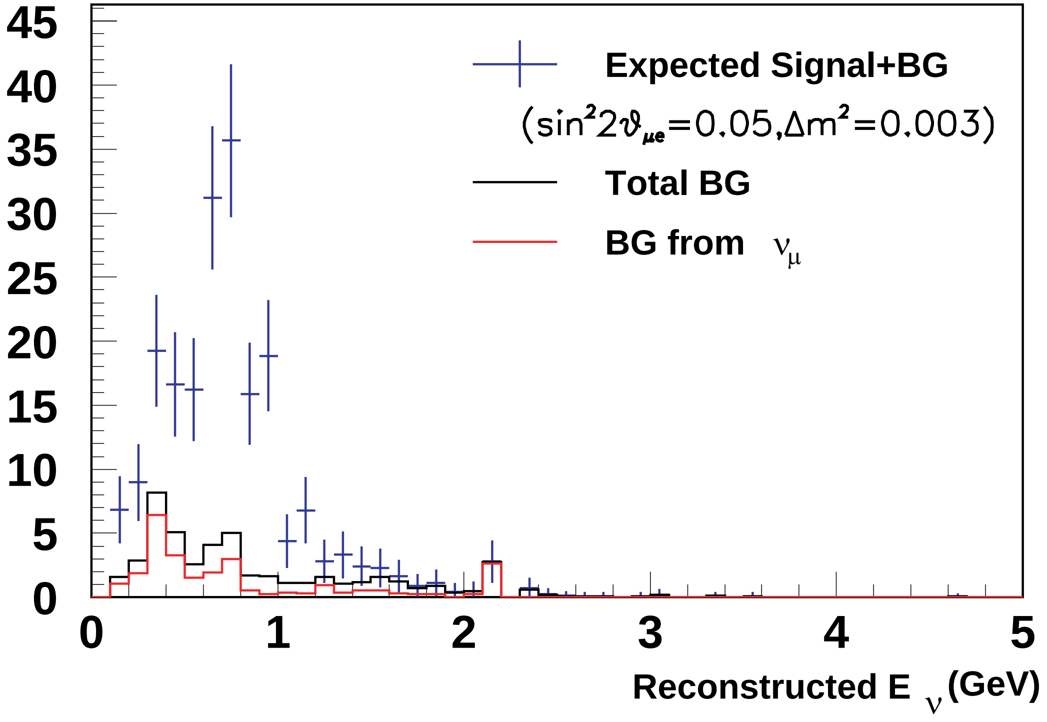
Leptonic CP discovery requires

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} \neq 0$$

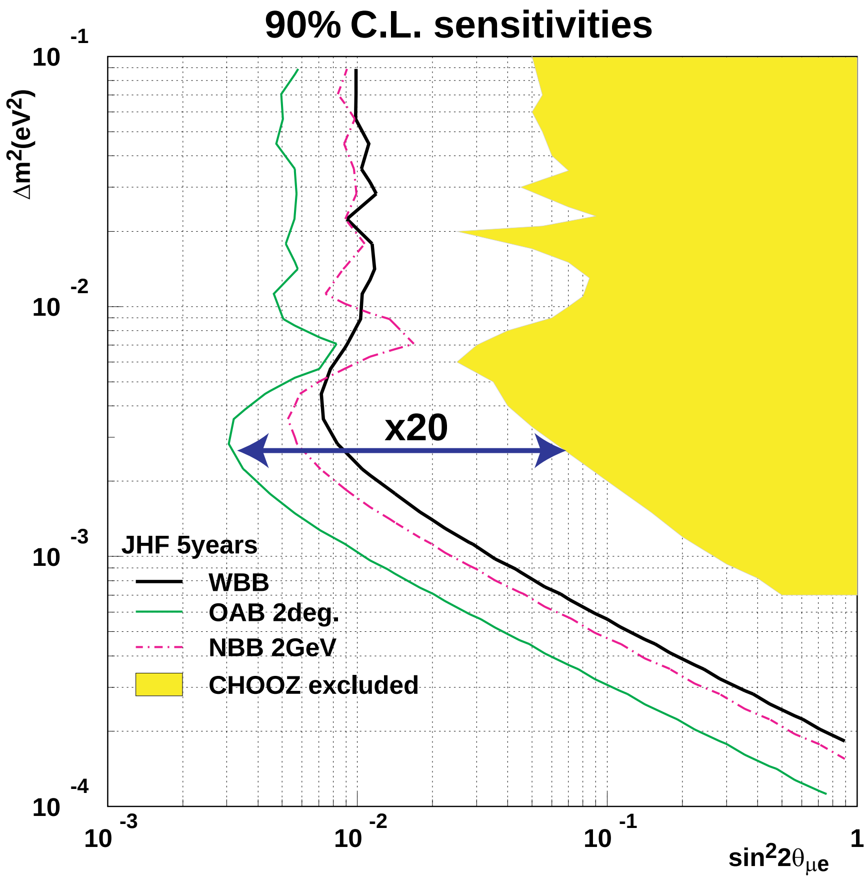


T2K ν_e appearance

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}

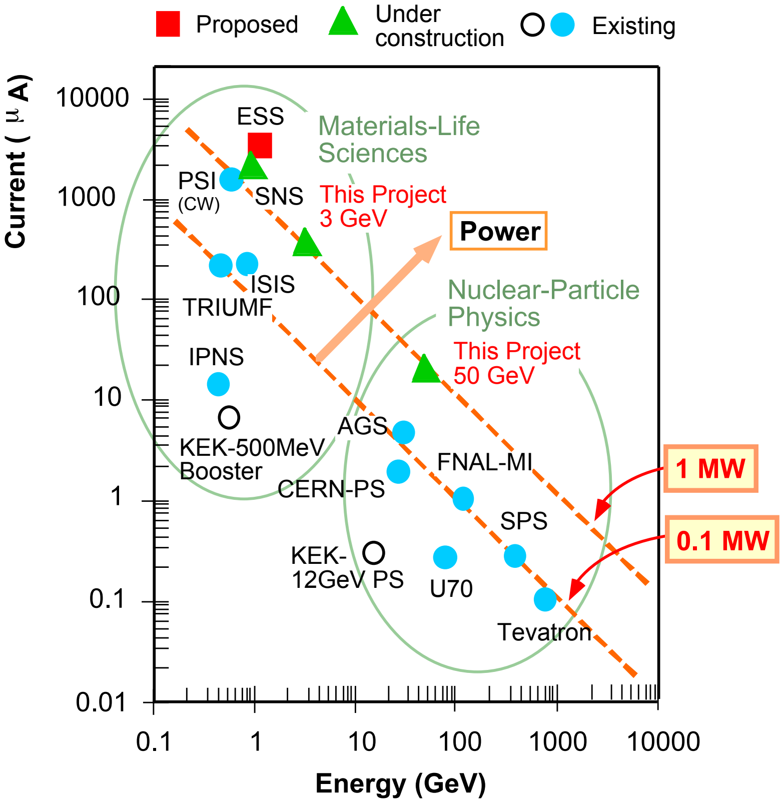


After JPARC, in the standard scenario

- θ_{13}, discovery or precision measure
- Mass hierarchy
- **Leptonic CP violation**

Any major improvement of JPARC will be extremely expensive:

- The proton driver is a next generation machine
- The detector is 10 times bigger of the second biggest: Minos.
- The design of close detectors system is challenging, but T2K will provide a very valuable first setup.



The knowledge of θ_{13} is necessary to guarantee the conditions to measure δ and to optimize the facility.

Any future initiative should have enough physics potential besides neutrino oscillations to justify the risk of starting the Leptonic CP violation searches without any guarantee.

SuperBeams - JPARC phase 2

T. Kobayashi, J.Phys.G29:1493(2003)

Upgrade the proton driver from 0.75 MW to 4 MW

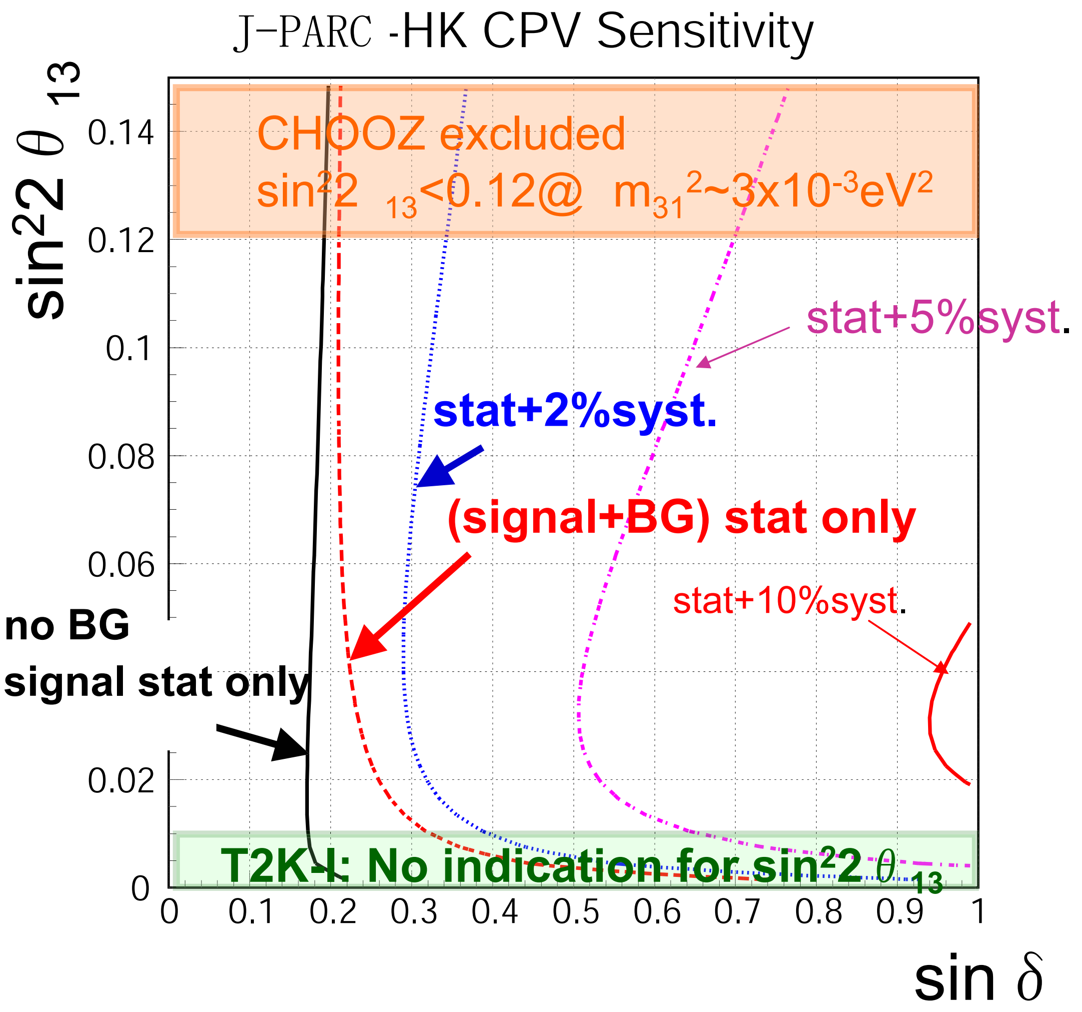
Upgrade SuperKamiokande by a factor $\sim 20 \Longrightarrow$ HyperKamiokande

Both upgrades are necessary to address leptonic CP searches.

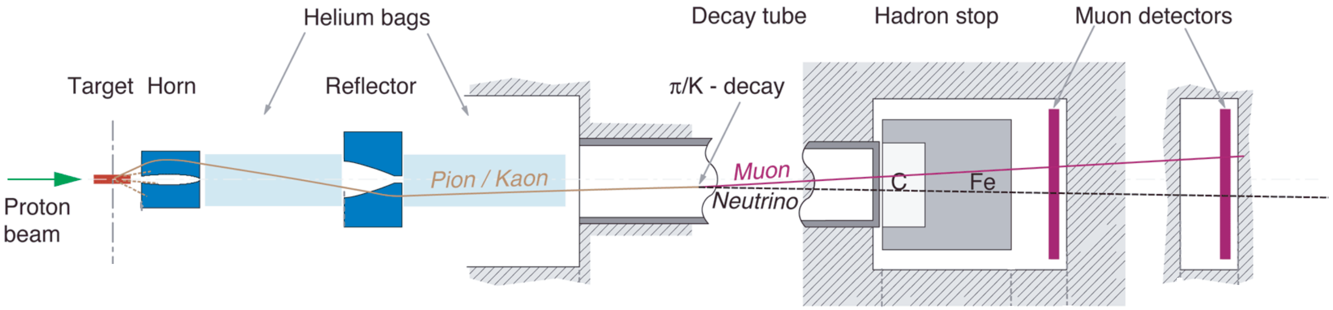
Systematics at 2% are tight

4 MW at 50 GeV/c are tight

Target and optics at 4 MW are tight and will probably require some compromise



Conventional neutrino beams are going to hit their ultimate limitations.



In a **conventional neutrino beam**, neutrinos are produced SECONDARY particle decays (mostly pions and kaons). Given the short life time of the pions ($2.6 \cdot 10^{-8}$s), they can only be focused (and charge selected) by means of magnetic horns. Then they are let to decay in a decay tunnel, short enough to prevent most of the muon decays.

- Besides the main component (ν_μ) at least 3 other neutrino flavours are present ($\overline{\nu}_\mu$, ν_e , $\overline{\nu}_e$), generated by wrong sign pions, kaons and muon decays. ν_e contamination is a background for θ_{13} and δ, $\overline{\nu}_\mu$ contamination dilutes any CP asymmetry.
- Hard to predict the details of the neutrino beam starting from the primary proton beam, the problems being on the secondary particle production side.
- Difficult to tune the energy of the beam in case of ongoing optimizations.

All these limitations are overcome if secondary particles become primary

Collect, focus and accelerate the neutrino parents at a given energy. This is impossible within the pion lifetime, but can be tempted within the muon lifetime **(Neutrino Factories)** or within some radioactive ion lifetime **(Beta Beams)**:

- Just one flavour in the beam
- Energy shape defined by just two parameters: the endpoint energy of the beta decay and the γ of the parent ion.
- Flux normalization given by the number of ions circulating in the decay ring.
- Beam divergence given by γ.

The full ^{6}He flux MonteCarlo code

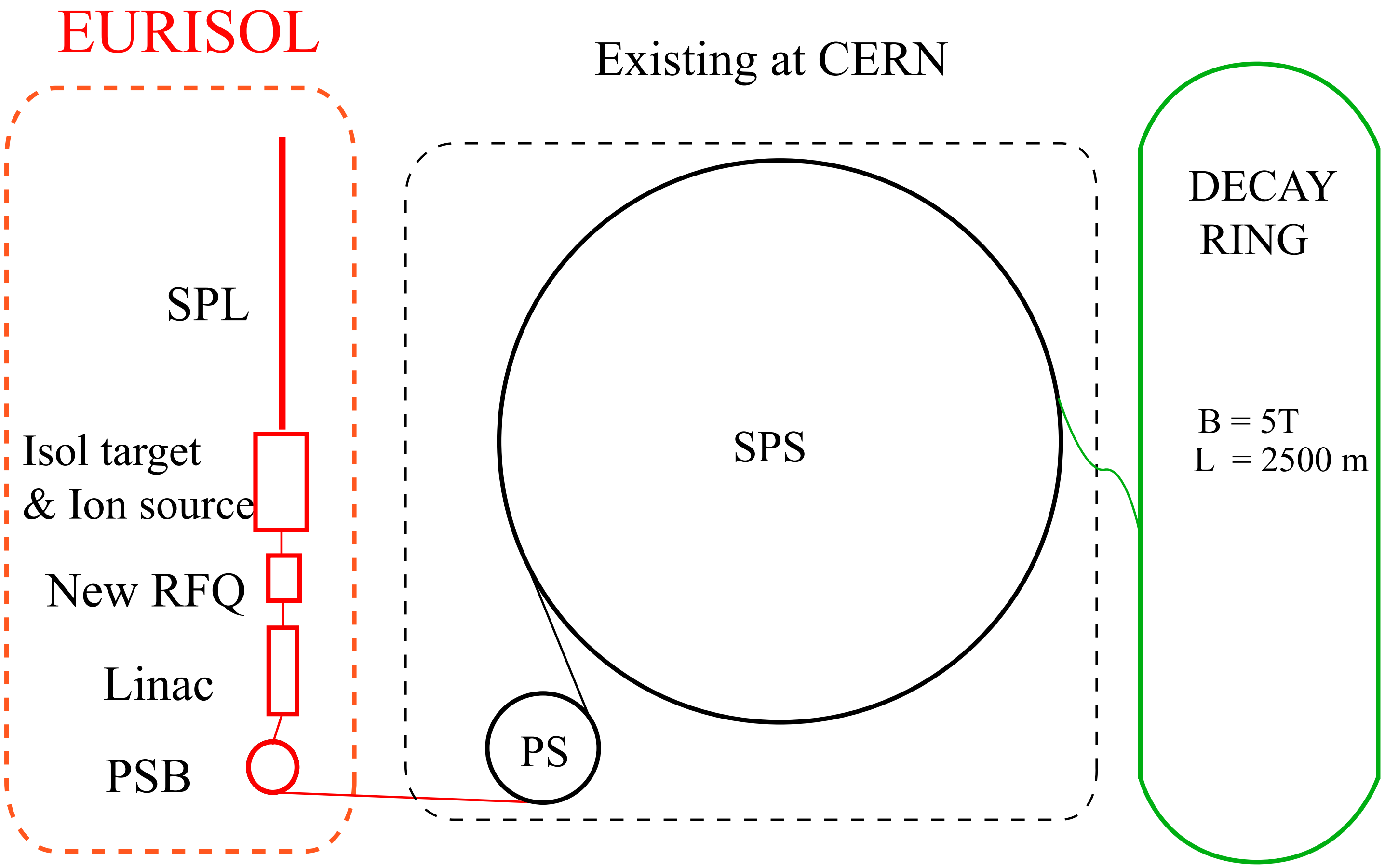
```
Function Flux(E)
Data Endp/3.5078/
Data Decays /2.9E18/

ye=me/EndP
c ...For ge(ye) see hep-ph0312068
ge=0.0300615
2gE0=2*gamma*EndP
c ...  Kinematical Limits
If(E.gt.(1-ye)*2gE0)THEN
   Flux=0.
   Return
Endif
c ...Here is the Flux
Flux=Decays*gamma**2/(pi*L**2*ge)*(E**2*(2gE0-E))/
+ 2gE0**4*Sqrt((1-E/2gE0)**2-ye**2)

Return
```

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

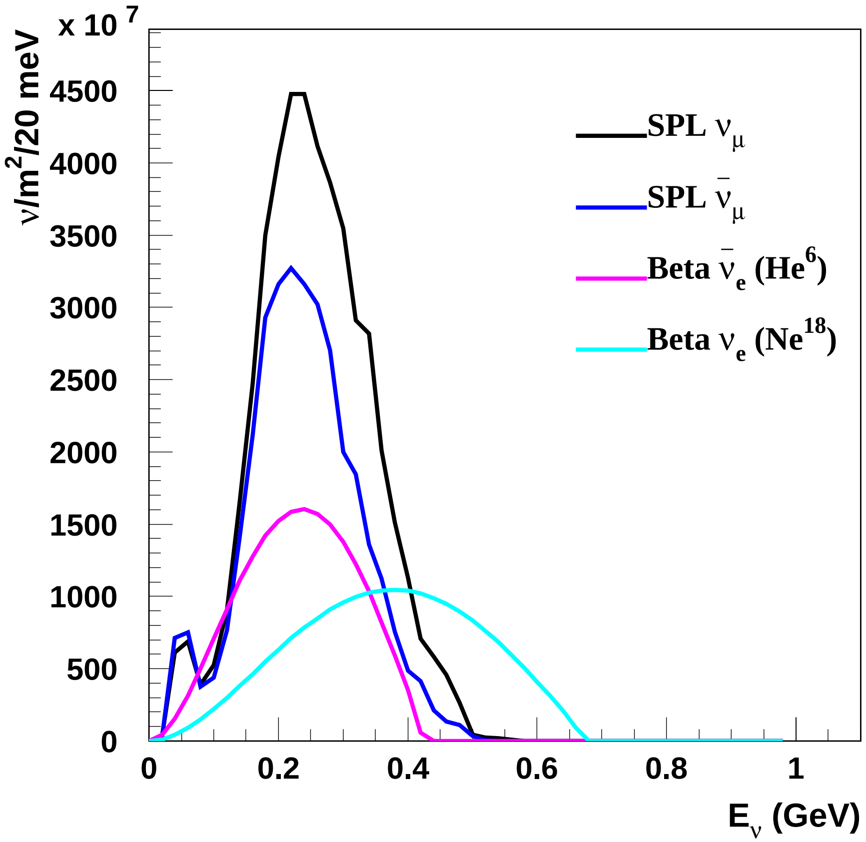
M. Lindroos et al., see http://beta-beam.web.ch/beta-beam



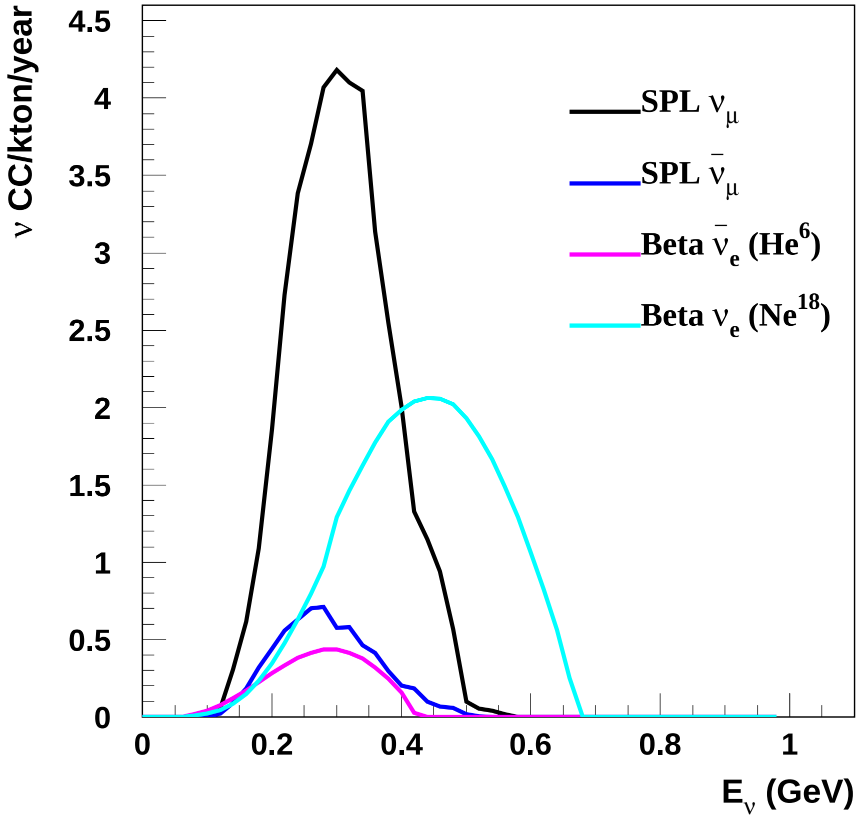
- 1 ISOL target to produce He^6, 100 μA, $\Rightarrow 2.9 \cdot 10^{18}$ ion decays/straight session/year. $\Rightarrow \overline{\nu}_e$.
- 3 ISOL targets to produce Ne^{18}, 100 μA, $\Rightarrow 1.2 \cdot 10^{18}$ ion decays/straight session/year. $\Rightarrow \nu_e$.
- The 4 targets could run in parallel,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

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

Fluxes

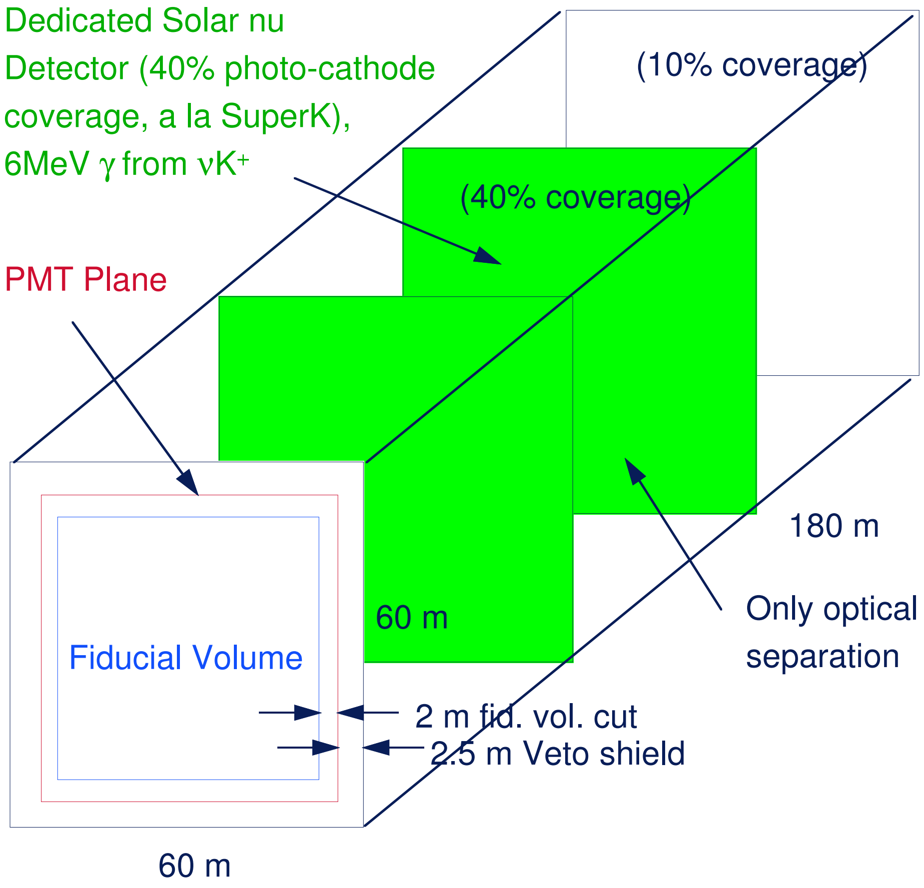


CC Rates



	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
$\nu_e\ (\gamma = 100)$	$1.88 \cdot 10^{11}$	0.36	32.9	0.43	10	144783

UNO/HyperK detector



- Fiducial volume: 440 kton (HyperK has 540 kton): 20 times SuperK.
- 60000 PMTs (20”) in the inner detector, 15000 PMTs in the outer veto detector.
- Energy resolution is poor for multi track events but quite adequate for sub-GeV neutrino interactions.
- Roughly quoted at 500M$ (including excavation). Timescale: 8 years.

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

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 $\simeq 450$ MeV, and the pion must be produced above the Cerenkov threshold.

Angular cuts have not be considered yet.

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

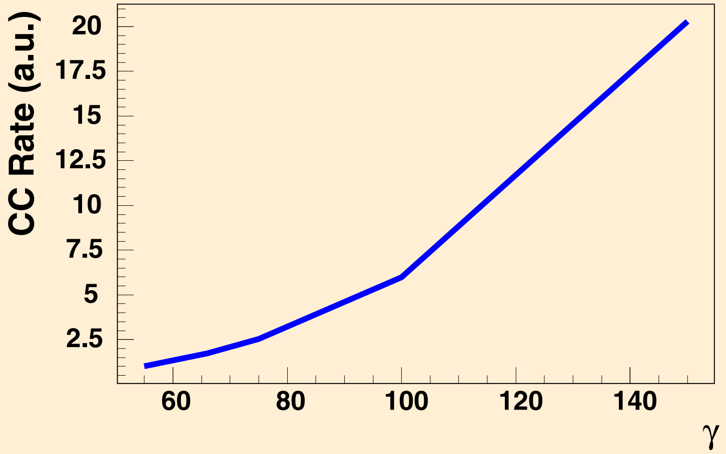
Atmospheric neutrino background can be kept low only by a very short duty cycle of the Beta Beam. A reduction factor bigger than 10^3 is needed.

This is achieved by building 10 ns long Ion bunches.

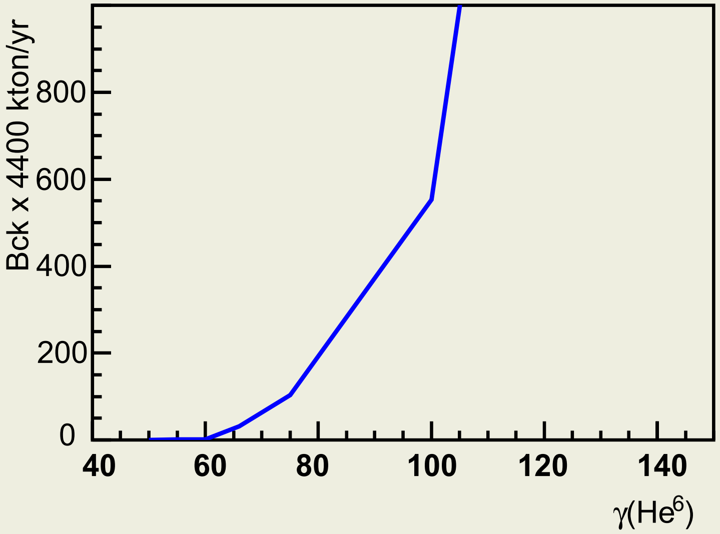
Optimizing the Lorentz Boost γ (L=130 km). Preferred value: $\gamma(^6\mathrm{He}) = 60$

Higher γ produce more CC interactions

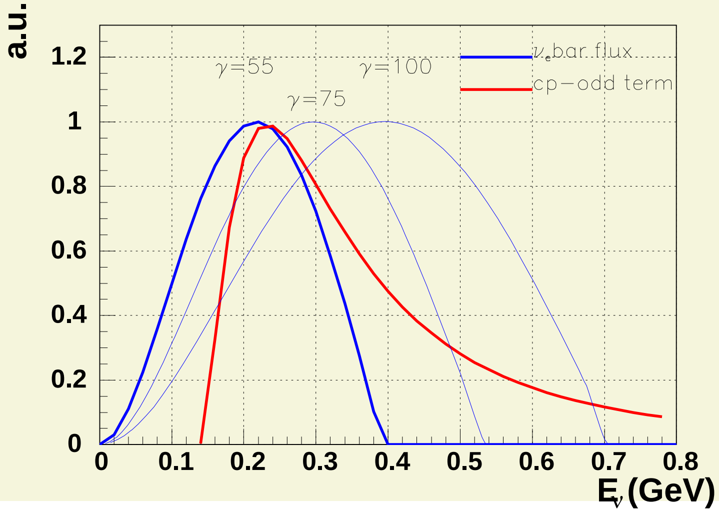
More collimated neutrino production and higher cross sections.



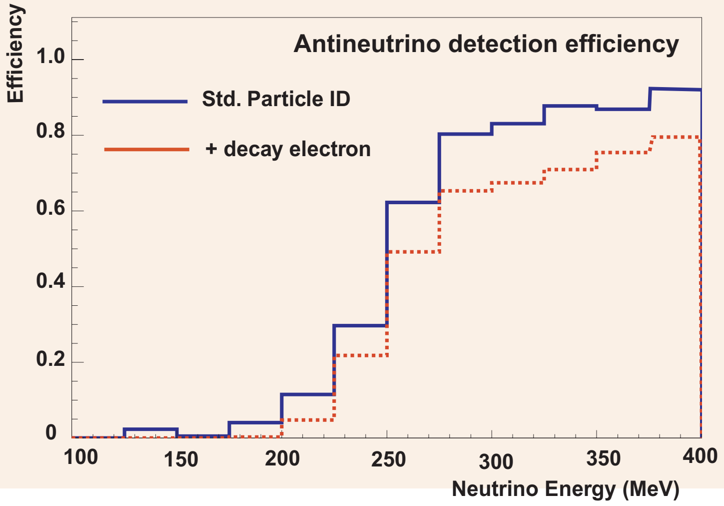
Background rate rises even faster



ν flux must match the CP-odd oscillating term



Detection efficiency as function of ν energy



Distinctive features of the Beta Beam

Just one neutrino flavor in the beam.

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

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

Neutrino fluxes virtually systematics free. Excellent control of 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 and a direct access to θ_{13} . The comparison of these two disappearance channels allows for CPT tests.

However

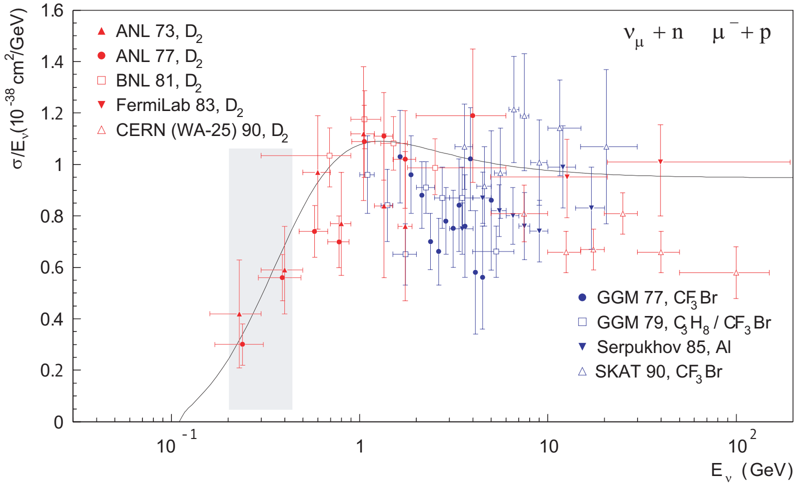
- Cross sections are small $\Rightarrow$ very massive detectors.
- $\overline{\nu}_\mu / \nu_\mu$ cross section ratio at a minimum (1/4).
- Visible energy smeared out by Fermi motion: counting experiment
- No way to measure sign(Δm^2).

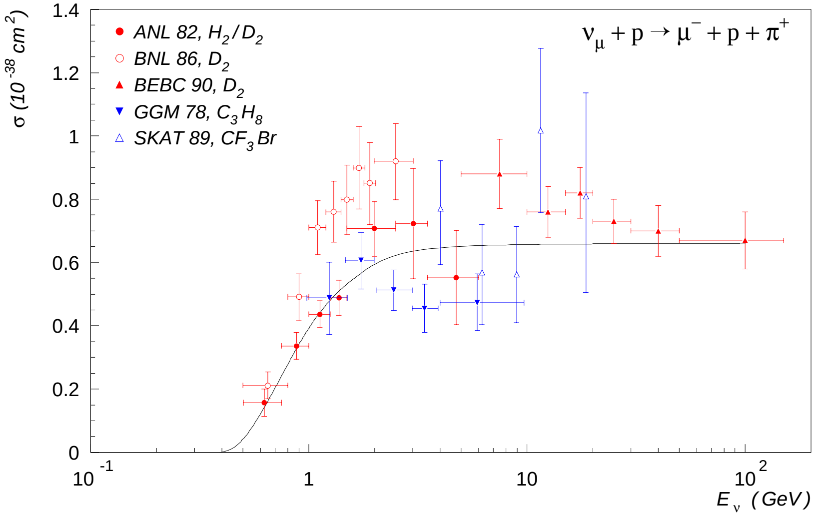
Furthermore when combined with the SPL-SuperBeam

Comparing the ν_μ and $\overline{\nu}_\mu$ SPL beams with the ν_e and $\overline{\nu}_e$ Beta Beams: access to CP, T, and CPT searches.

The cross sections problem

V.V. Lyubushkin et al., internal NOMAD memo





Neutrino cross-sections are badly measured around 300 MeV.

Nuclear effects are very important at these energies.

No surprise that different MonteCarlo codes predict rates with a 50% spread.

On the other hand: Beta Beam is the ideal place where to measure neutrino cross sections

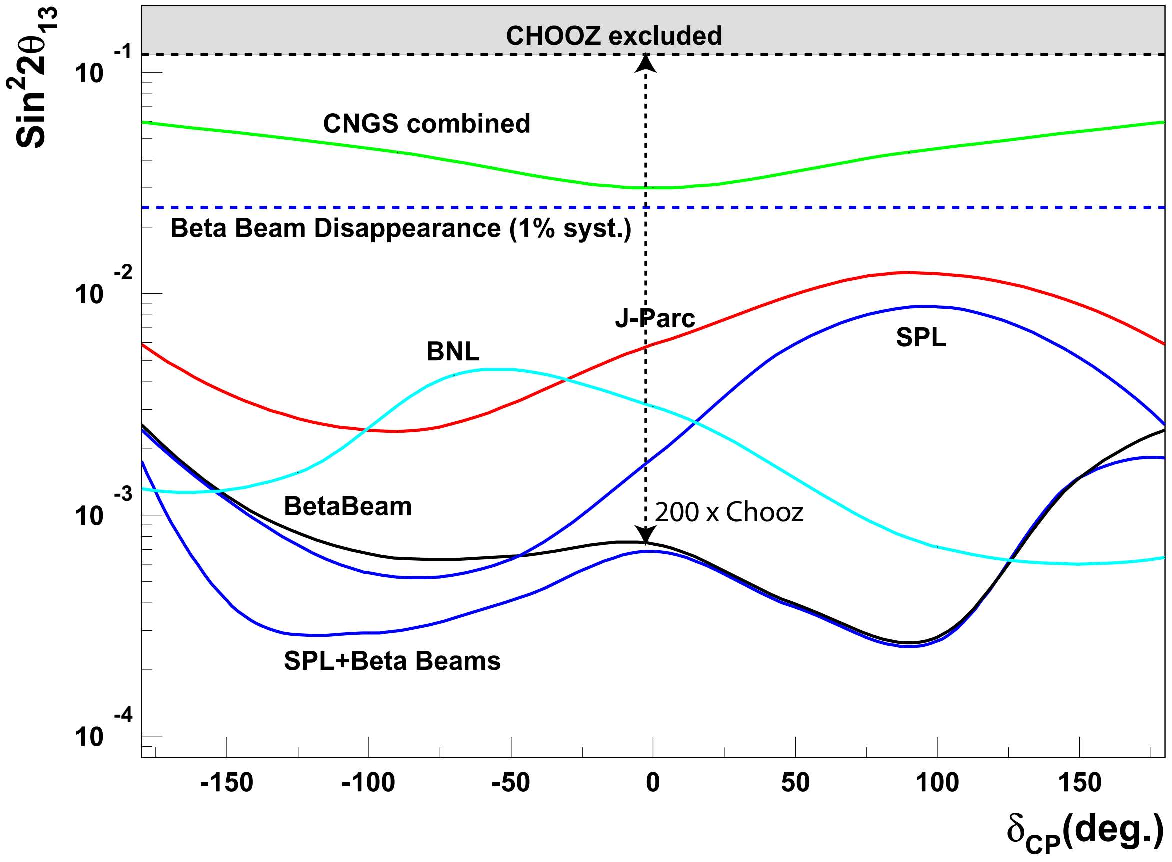
- Neutrino flux and spectrum are completely defined by the parent ion characteristics and by the Lorentz boost γ.
- Just one neutrino flavor in the beam.
- You can scan different γ values starting from below the Δ production threshold.
- A close detector can then measure neutrino cross sections with unprecedent precision.

A 2% systematic error both in signal and backgrounds is used in the following

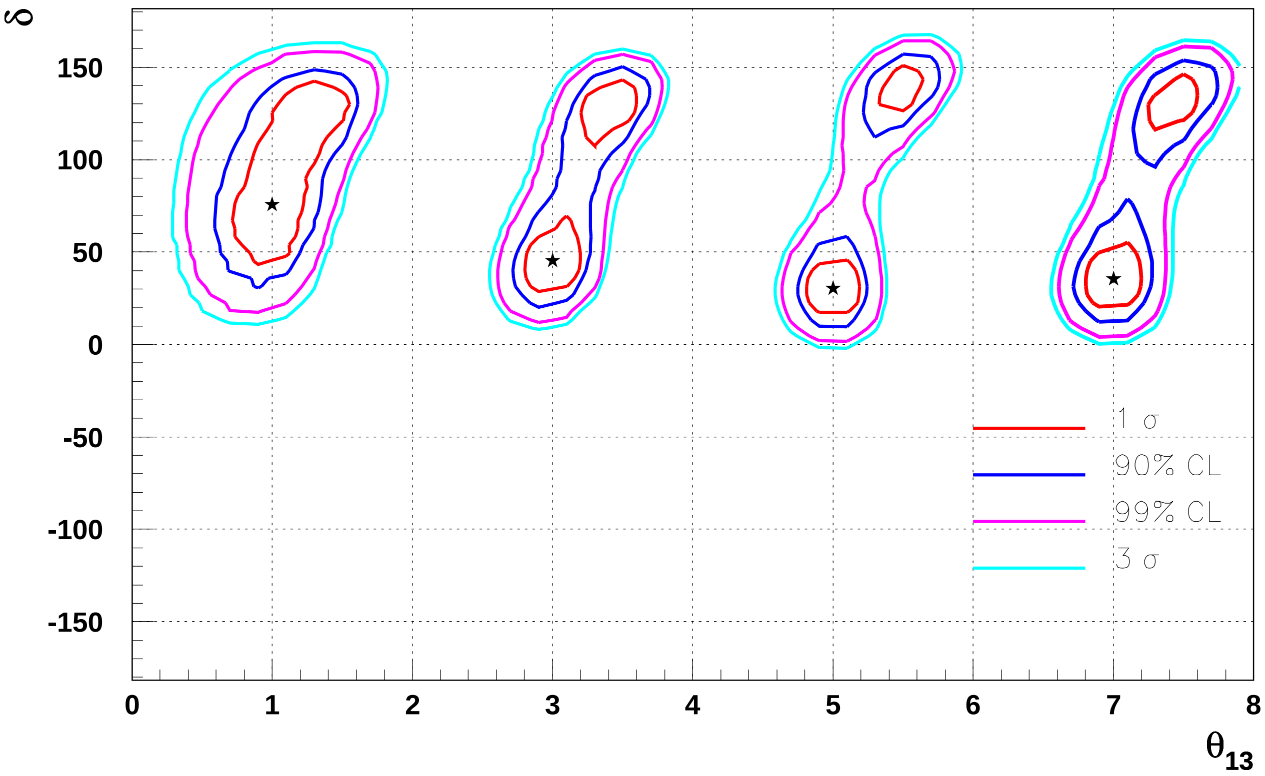
Sensitivity to θ_{13}

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 $\theta_{13} \geq 3.4^\circ$**



Fits to θ_{13} and δ



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

	Beta Beam		SPL-SB	
	^6He $(\gamma = 60)$	^{18}Ne $(\gamma = 100)$	ν_μ (2 yrs)	$\overline{\nu}_\mu$ (8 yrs)
CC events (no osc, no cut)	19710	144784	36698	23320
Oscillated at the Chooz limit	681	5304	1491	1182
Oscillated	1	118	2	34
δ oscillated	-12	54	-27	16
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 $\delta = 0$.

Beta Beam leptonic CP violation discovery potential

Computed with:

$\gamma(^{6}\mathrm{He}) = 60$

4400 kton/year exposure

Systematic Err. = 2%

$\Delta m^2_{23} = 2.5 \cdot 10^{-3} eV^2$

$\Delta m^2_{12} = 7.1 \cdot 10^{-5} eV^2$

$\sin^2 2\theta_{23} = 1$

$\sin^2 2\theta_{12} = 0.8$

sign(Δ m^2) = +1

$\sigma(\Delta m^2_{23}) = 10^{-4} eV^2$

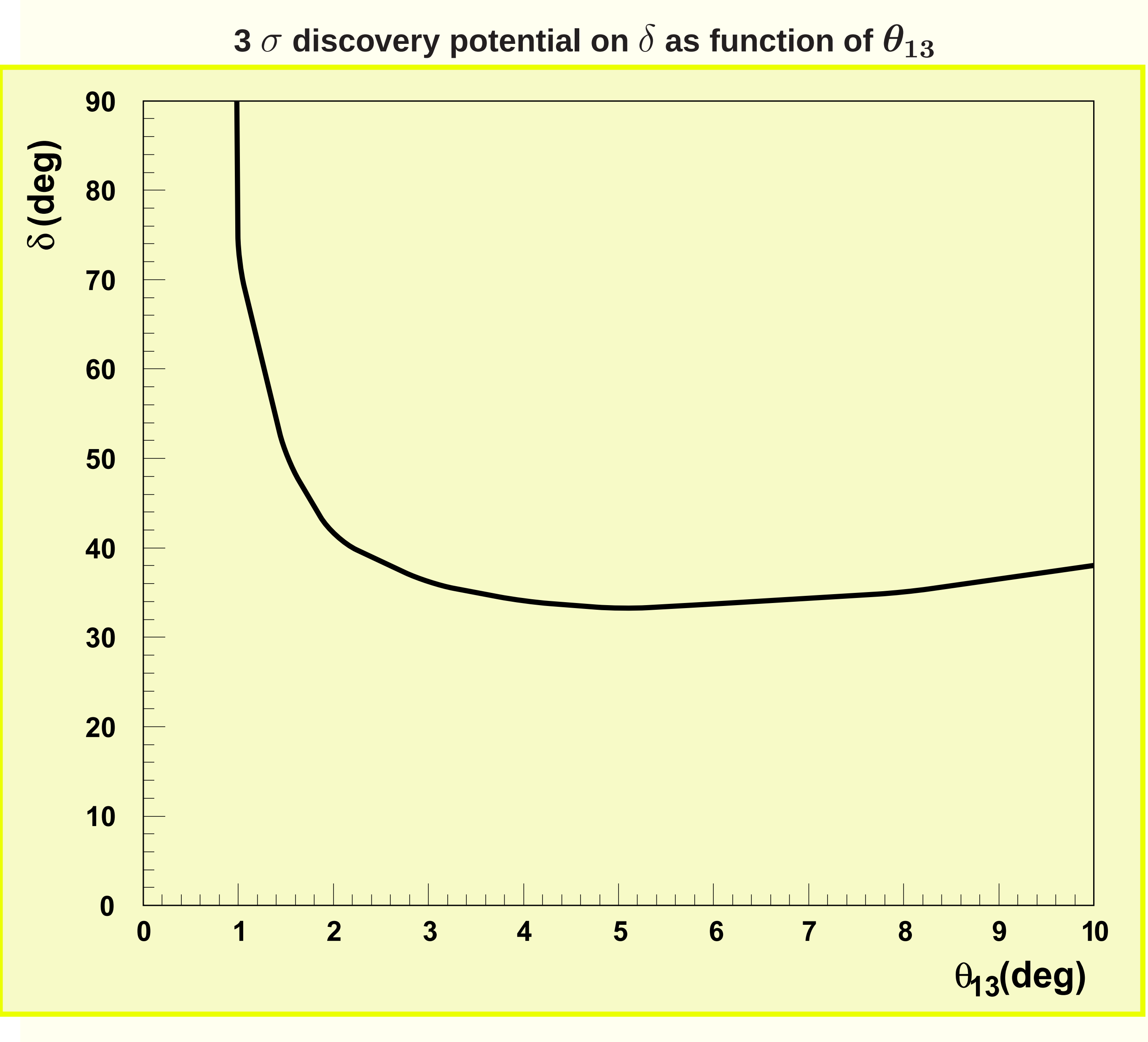
$\sigma(\Delta m^2_{12}) = 10\%$

$\sigma(\sin^2 2\theta_{23}) = 1\%$

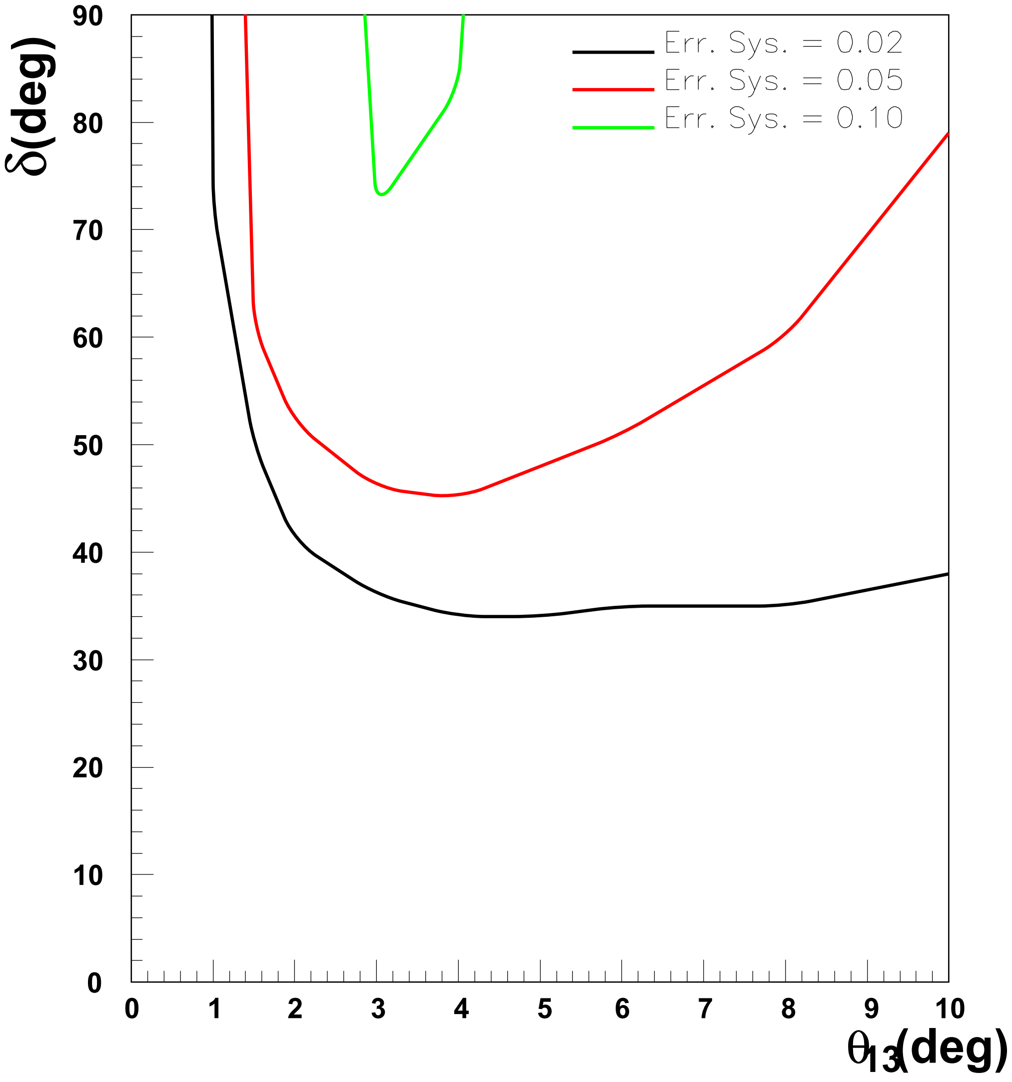
$\sigma(\sin^2 2\theta_{12}) = 10\%$

θ_{13}-δ degeneracy accounted for

Octant and sign(Δ m^2) degeneracies not accounted for.



The role of systematic errors



Systematic errors can spoil the sensitivity.

Particularly affected is $^{18}\mathrm{Ne}$, at $\gamma = 100$, with lots of backgrounds.

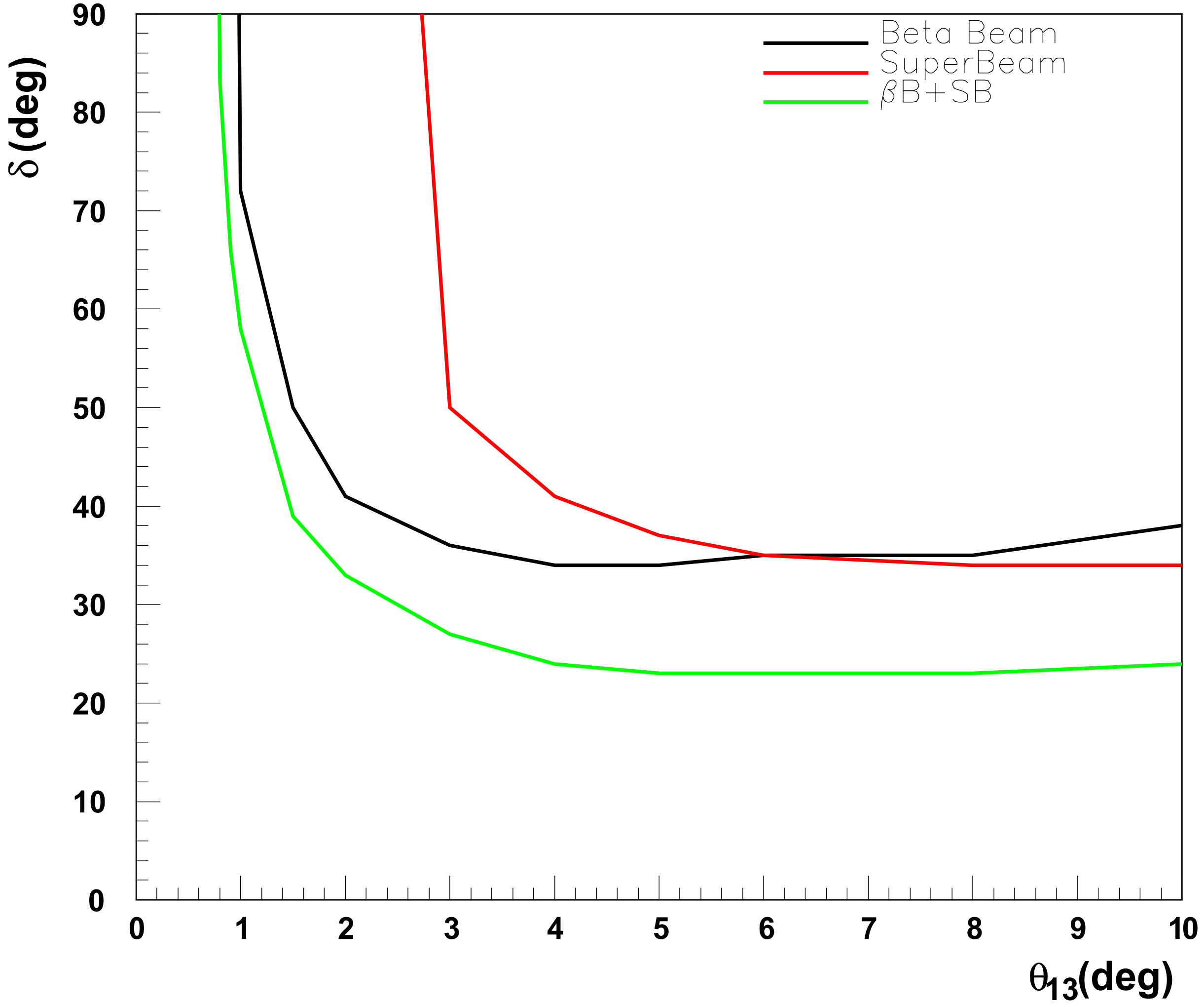
Indeed the 10% systematic error curve is computed running 5 years with $^{6}\mathrm{He}$ and 5 years with $^{18}\mathrm{Ne}$, both at $\gamma = 60$.

The performances at 5% systematic errors are very similar to a detector of half the mass and 2% systematic errors!

Conclusion: Beta Beam is not immune from systematic errors, but it offers an ideal environment to keep them low. Systematic errors are a critical factor for future facilities.

The SPL-SuperBeam- Beta Beam synergy

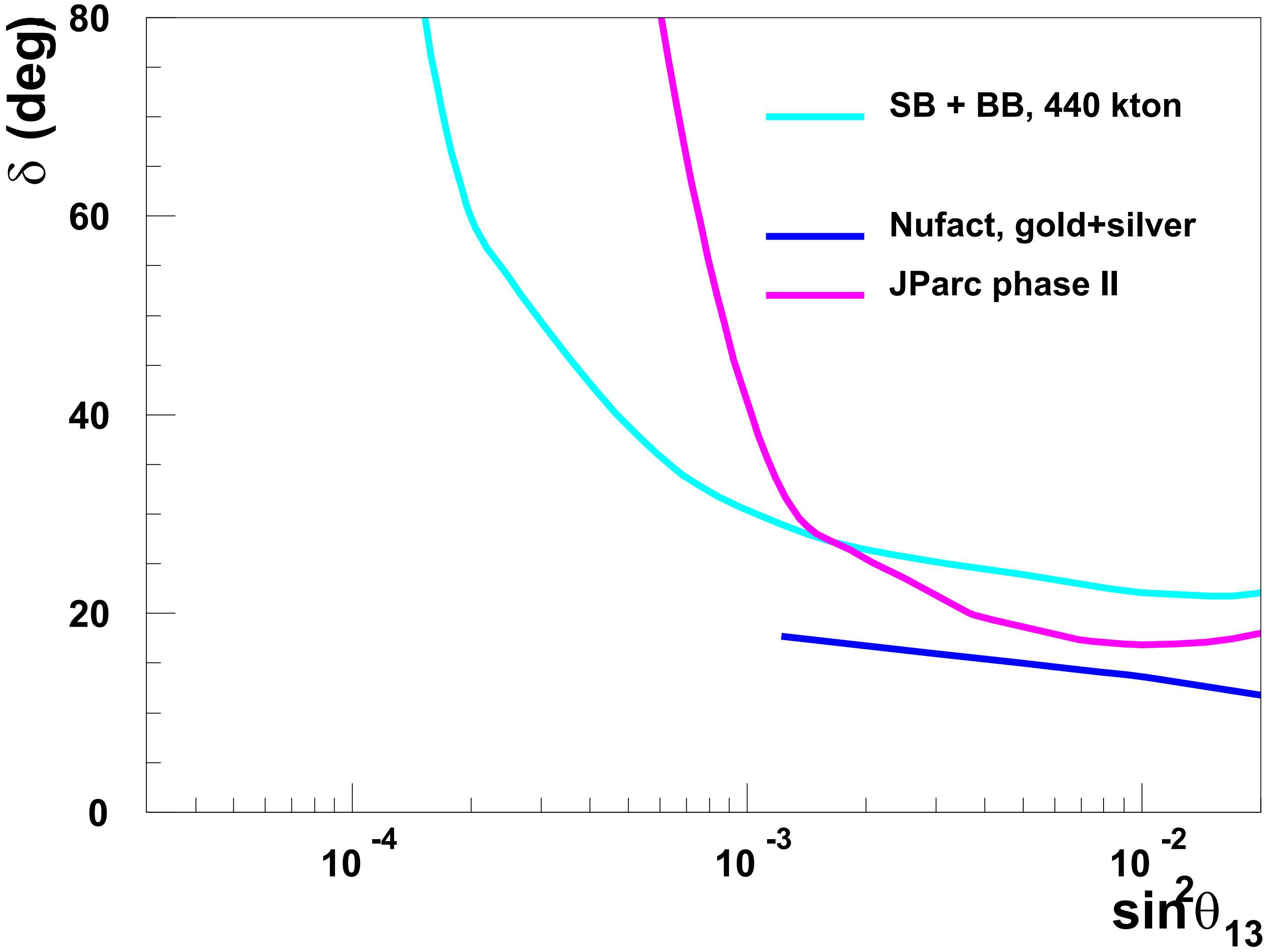
Not in the sense that SuperBeam helps in solving clone solutions. Rather the experimental result can be expressed in term of ν_e signal with π° backgrounds (SuperBeam) and in term of ν_μ signal with π^+ backgrounds (Beta Beam).



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.

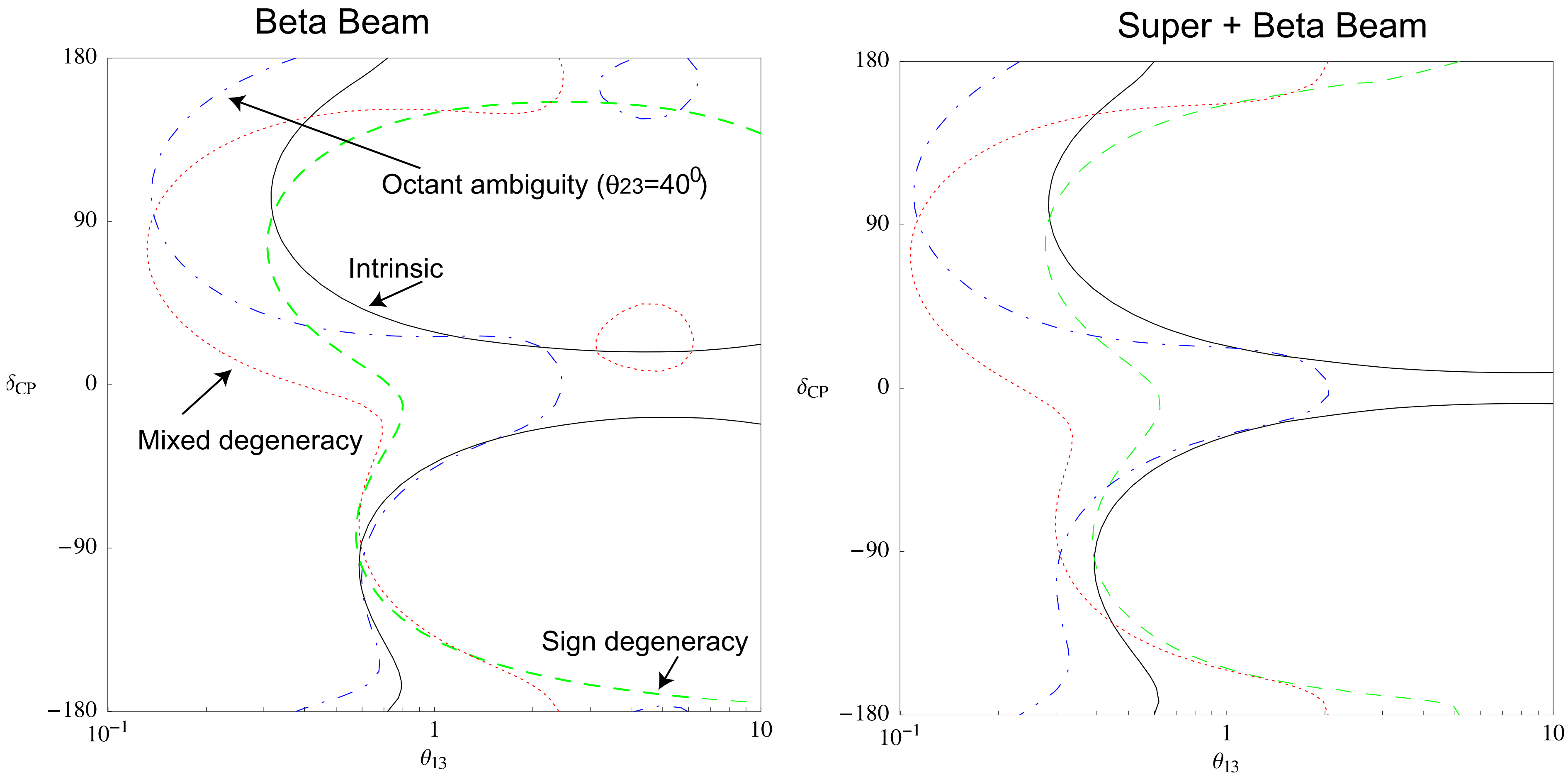
Nufact curve is silver+gold, preliminary, courtesy of O. Mena. Computed with 50 GeV/c μ, $2 \cdot 10^{20}$ useful μ decays/year, 5+5 years. Its extension below 2° is under investigation.



The eightfold degeneracy

A. Donini et al. *“Study of the eightfold degeneracy with a standard Beta-Beam and a Super-Beam facility”*, hep-ph/0406132.

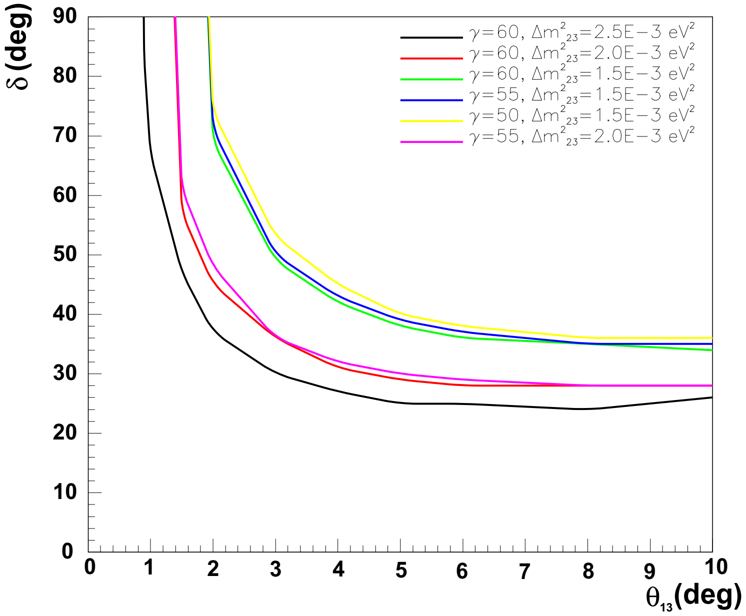
90% CL sensitivity plots assuming $\delta = 0, \theta_{23} = 40^\circ$.


Beta Beam

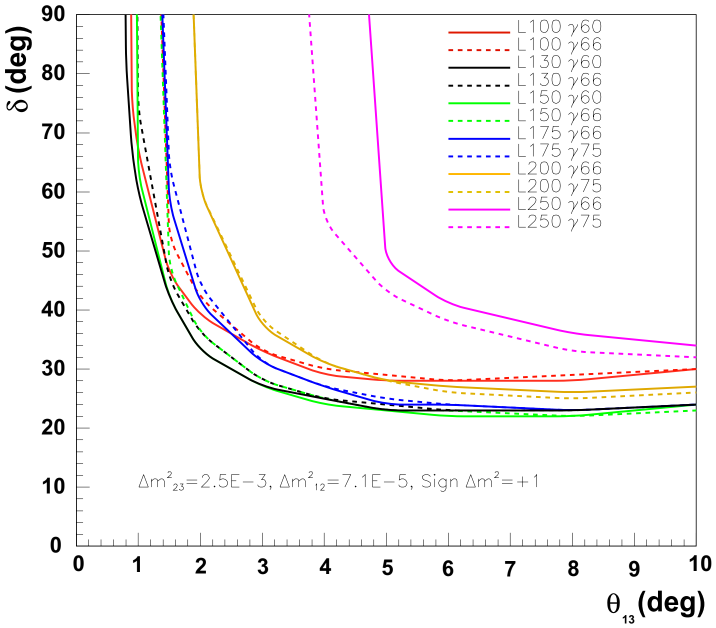
Super + Beta Beam

Unsolicited answers to some F.A.Q.

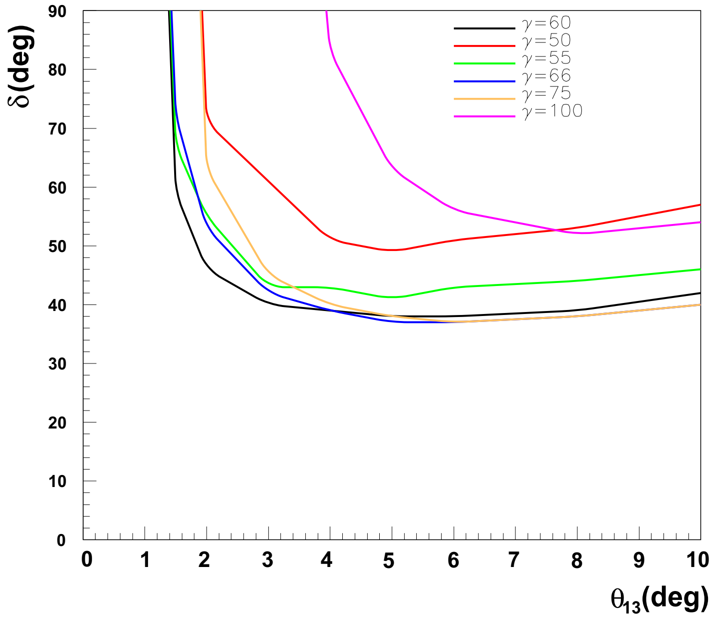
Is the value of Δm^2_{23} critical?



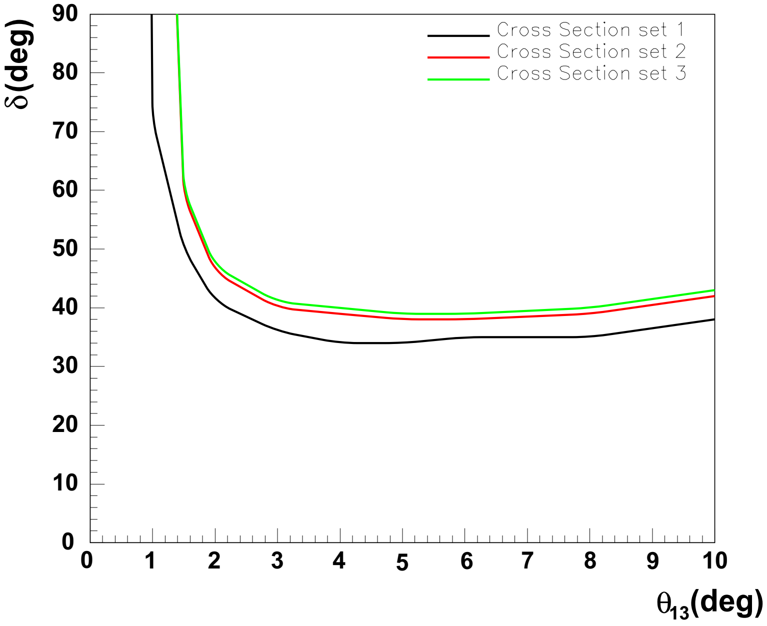
Is the CERN-Frejus a magic baseline?



Is $\gamma = 60$ the absolute optimum?



What is the role of cross section?



The high energy option

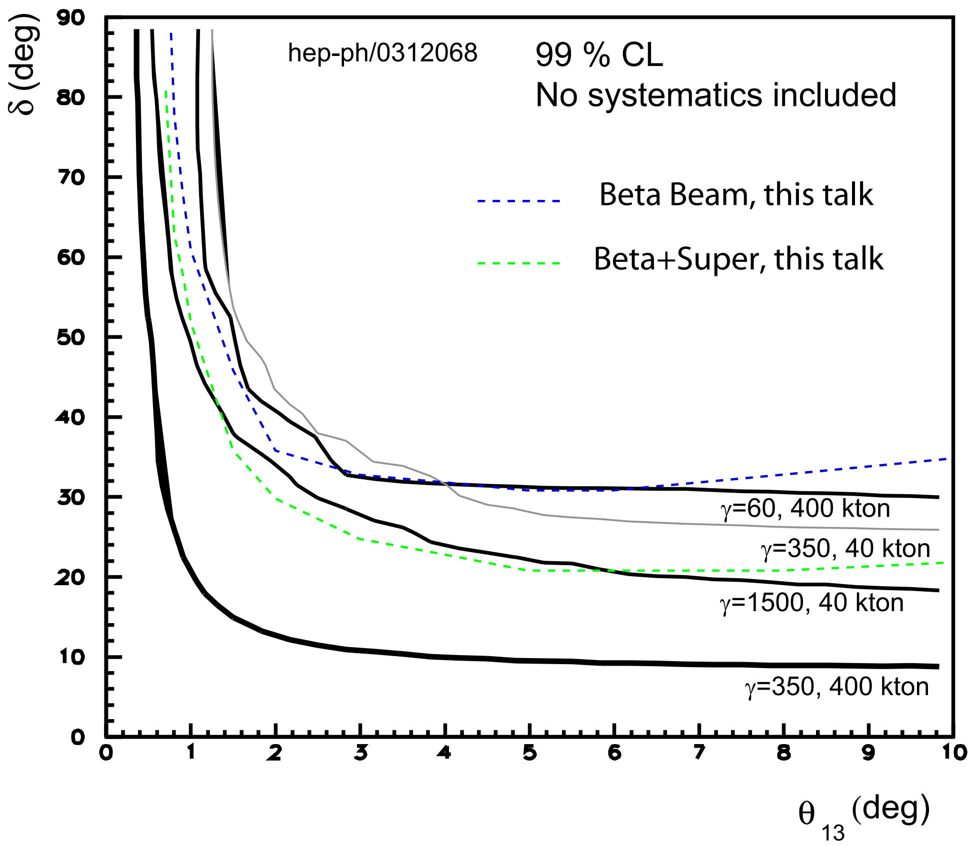
P. Hernandez, J.J. Gomez-Cadenas et al., hep-ph/0312068

SPS allows max. $\gamma(^6He) = 150.$ In this scenario the $\gamma(^6He) = 60,$ baseline=130 km is the optimal configuration. Relaxing the SPS constraint and allowing for higher energies: another advantageous condition can be found at $\gamma(^6He) = 350 (\gamma(^{18}NE) = 580)$ (baseline $\simeq 732$ km).

The advantages

- A ~ 10 increase in CC rates (1.5 increase at constant accelerator power).
- Exploit energy spectrum (more powerful fits to θ_{13} , δ).
- Measure sign(Δm^2).
- At $E_\nu \simeq 1.2 GeV$ water Čerenkov detectors are still suitable.

“.. our results show that a γ in the range of O(500) with a megaton detector at a distance of O(1000 km) will be hard to beat.”



The prices

- Use a 1 TeV, O(1) MWatt accelerator or or use LHC as a third stage accelerator (max γ at LHC: 2488).
- A decay ring longer by a factor 6: the length of the decay ring is proportional to γ.
- A new location for the MegaTon detector.
- No synergy with the SPL-SuperBeam.

Another high energy option

P. Migliozzi, F. Terranova et al., hep-ph/0405081

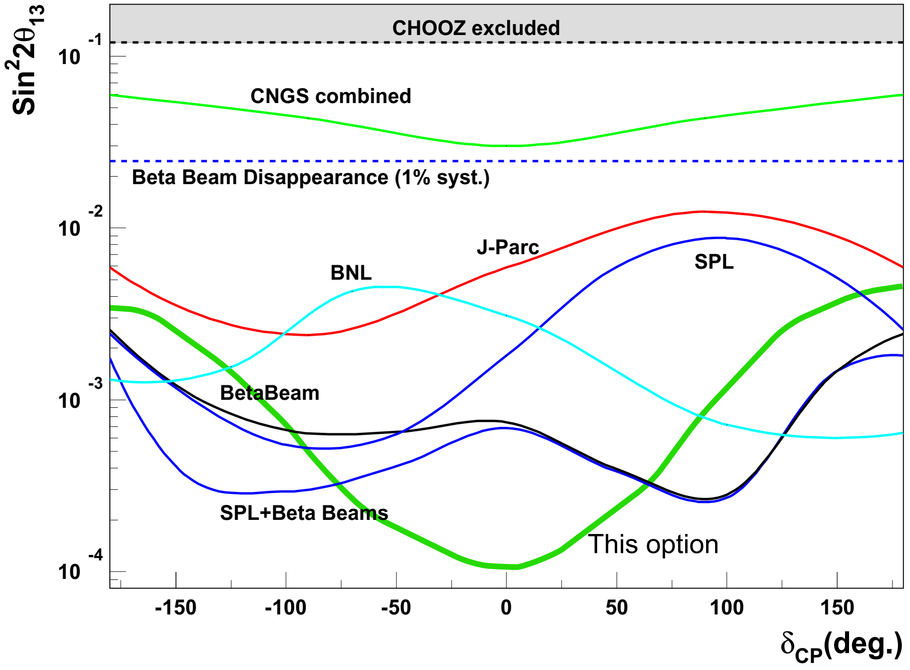
Consider the maximum possible γ reachable at LHC $\gamma(^6He) = 2488 - \gamma(^{18}NE) = 4147$ and assume that LHC can digest all those ions and that you can find a way to accomodate the very long decay tunnel.

Fire the beam at LNGS.

Count the ν_μ interactions in the rock with a very basic 15×15 m^2 iron-active detectors sandwich.

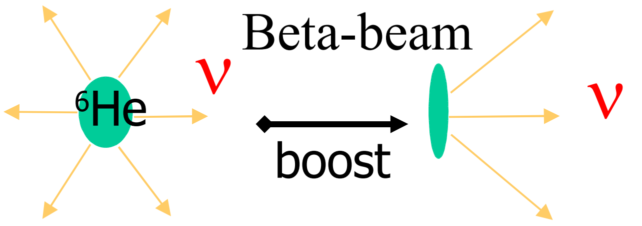
Strongly off-peak, but still capable to measure θ_{13} .

At these γ you can measure $p(\nu_e \rightarrow \nu_e)$, $p(\nu_e \rightarrow \nu_\mu)$, $p(\nu_e \rightarrow \nu_\tau)$ and measure the unitarity of the PMNS matrix.

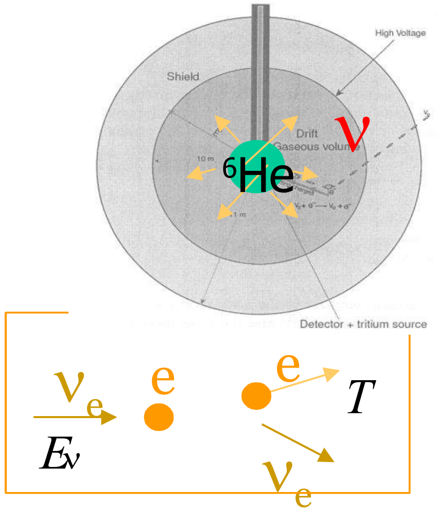


Low energy beta-beam

- The proposal
  - To exploit the beta-beam concept to produce intense and pure low-energy neutrino beams (C. Volpe, Journ. Phys. G. 30(2004)L1, J. Serreau, C.Volpe, hep-ph/0403293, C. Volpe, talk at this conference)
- Physics potential
  - Neutrino-nucleus interaction studies for particle, nuclear physics, astrophysics (nucleosynthesis)
  - Neutrino properties, like n magnetic moment



$^6He \rightarrow {}^6Li+e+\bar{\nu}_e$ Q_β=4. MeV



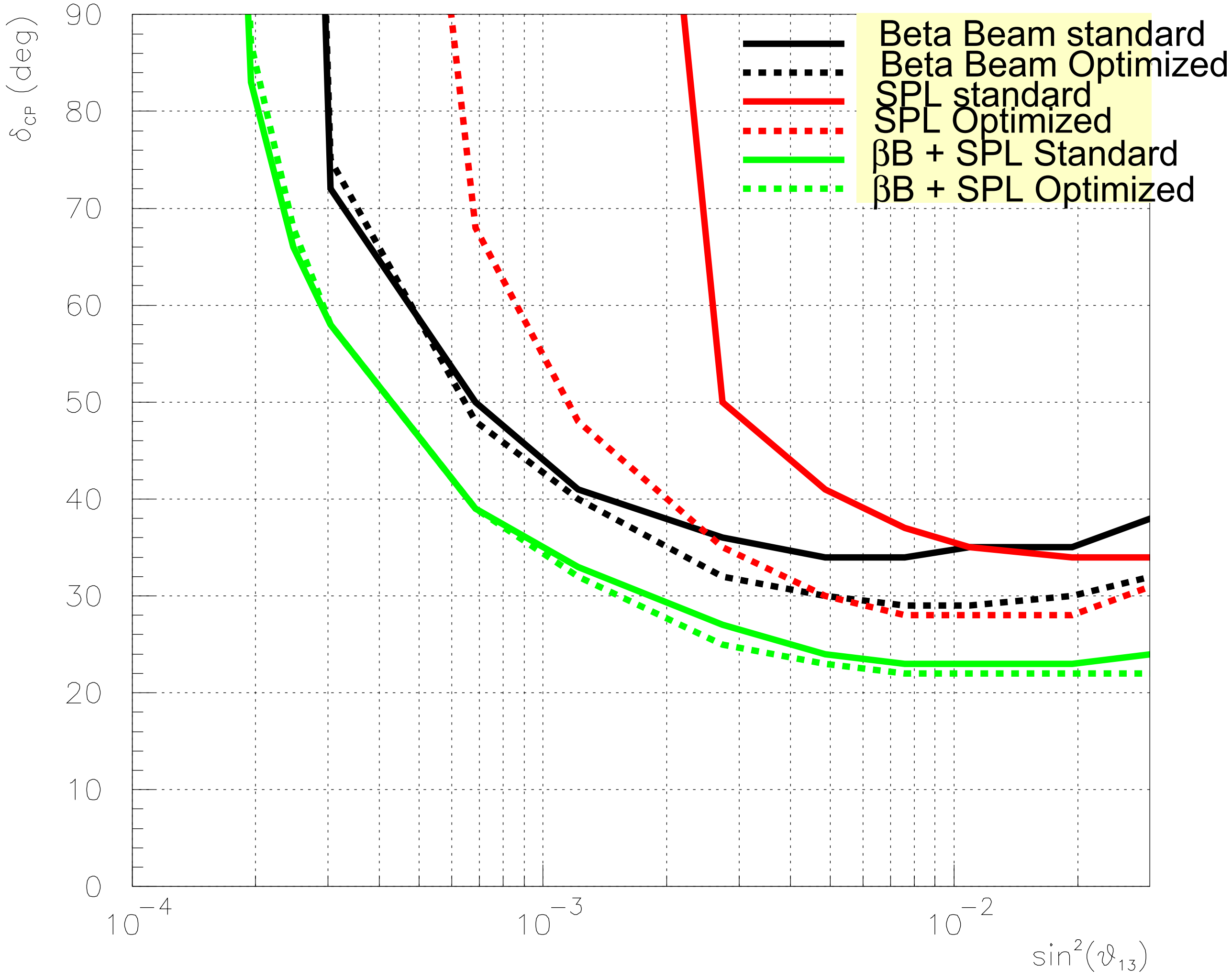
A preliminary Beta Beam optimization

- Ion fluxes already saturate PS and SPS in terms of induced radioactivity in the magnets and machine power
- What is not optimal is the comprimize of the $^{6}\mathrm{He}$ and $^{18}\mathrm{Ne}$ γs (60 and 100 respectively), needed to run the two ions together.
- The flux of the ions at the source can be doubled by doubling the Isol targets. In the baseline scenario 1 target is devoted to $^{6}\mathrm{He}$ and 3 targets (is serie) are devoted to $^{18}\mathrm{Ne}$. One could run with 2 $^{6}\mathrm{He}$ targets (in parallel) and with 6 $^{18}\mathrm{Ne}$ targets (2 sets of 3 targets). In this case the two ions should circulate in separate runs.
- This allows to run each ion at its optimal γ, here $\gamma = 75$ is taken for each ion.

Results of the optimizations (preliminary)

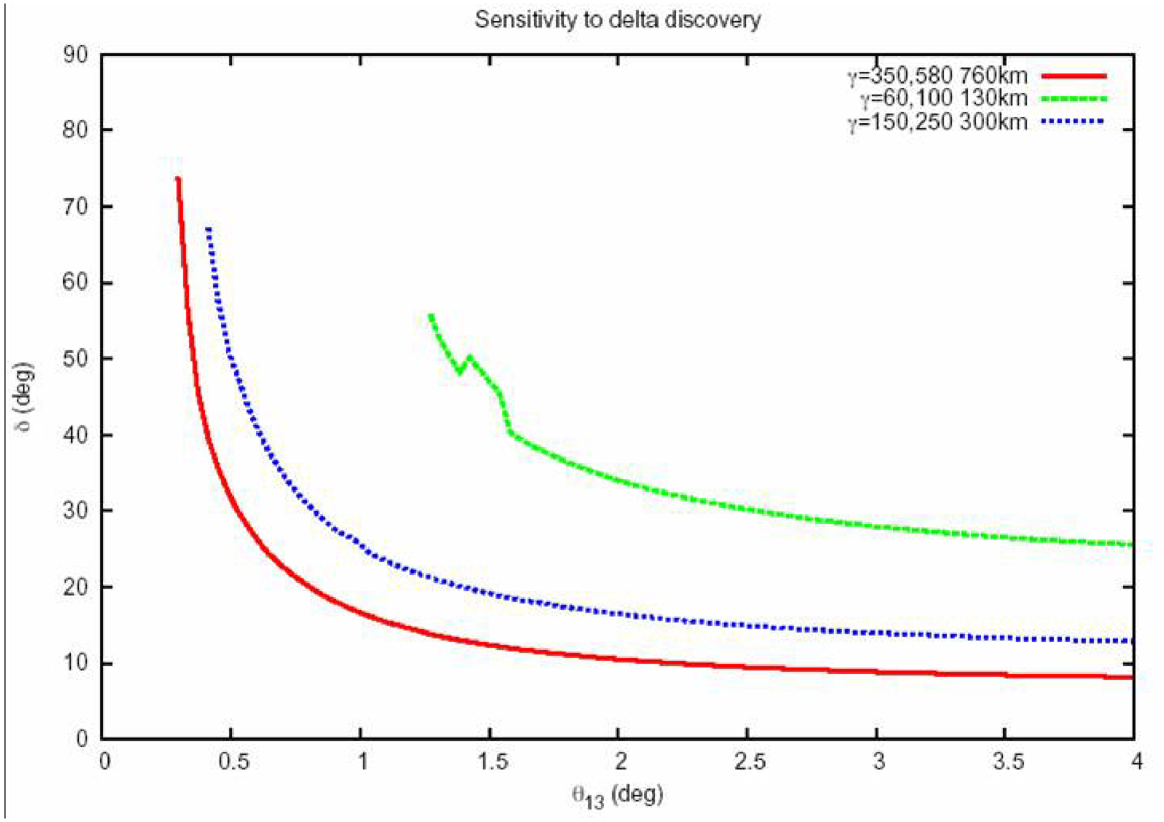
SPL SB optimization as computed by J.E. Campagne and A. Cazes, LAL, paper in preparation.

3 σ discovery potential curves



Another possible otpimization (J.J Gomez-Cadenas, talk at NOW2004, past week)

- Apply the methods developed for the medium energy βB to $\gamma(^{6}\mathrm{He}\,) = 150$, the maximum value with the SPS.
- Optimal baseline: 300 km.
- Systematic errors to be included
- 99% CL discovery potential curves



Conclusions

- Beta-Beams are a novel, innovative concept that could produce neutrino beams virtually free from intrinsic backgrounds and systematics.
- They 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 baseline scenario has not technological show stoppers and could offer excellent physics in a timescale of $\mathcal{O}(10)$ years.
- The Super-Beta Beams combination can address δ_{CP} discovery 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} .
- Additional ideas are growing around this concept attracting the interest of more and more physicists.