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Beta Beams

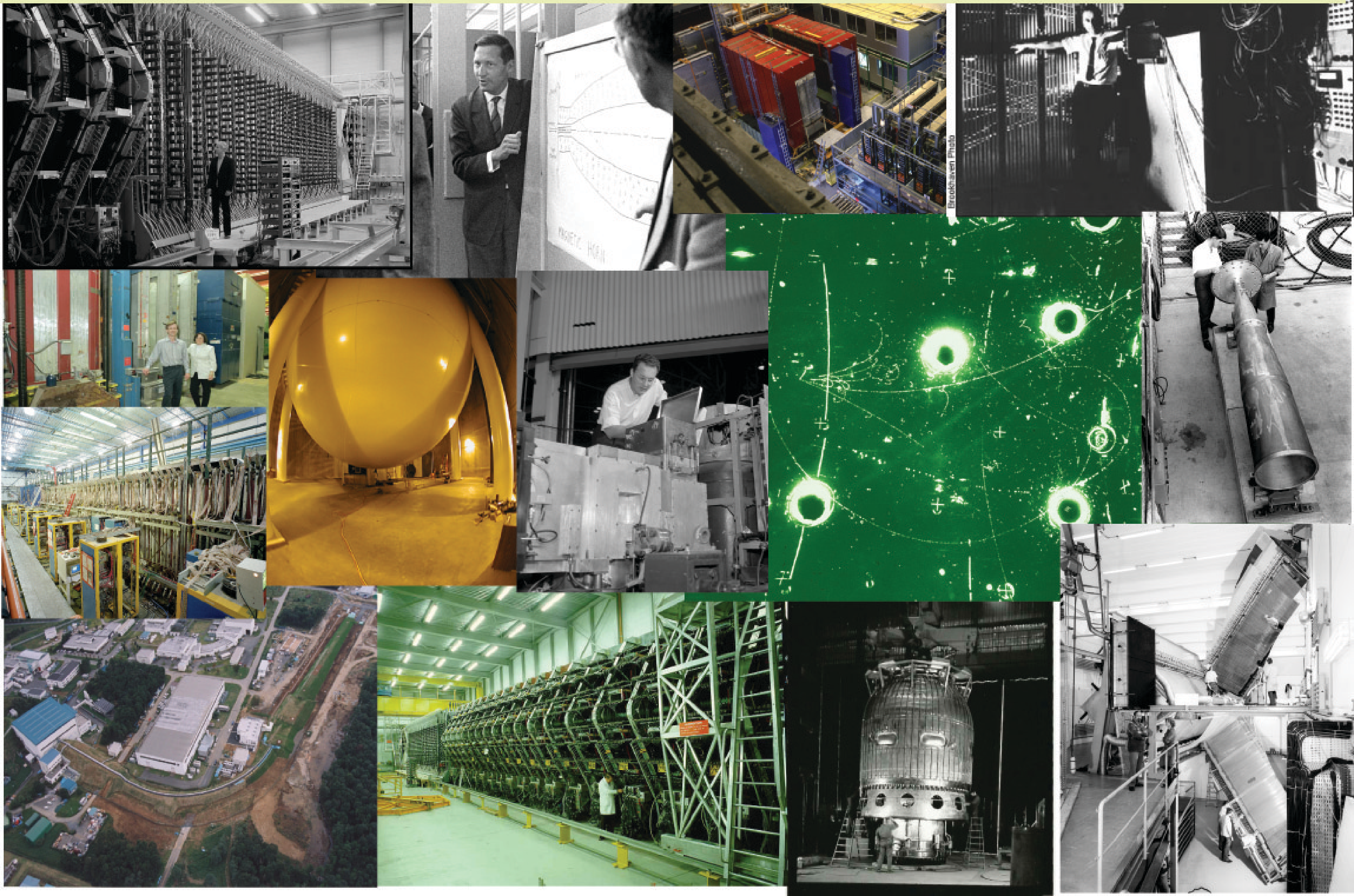
Summary:

- **Introduction.**
- **The accelerator complex.**
- **Physics potential.**
- **Different scenarios.**

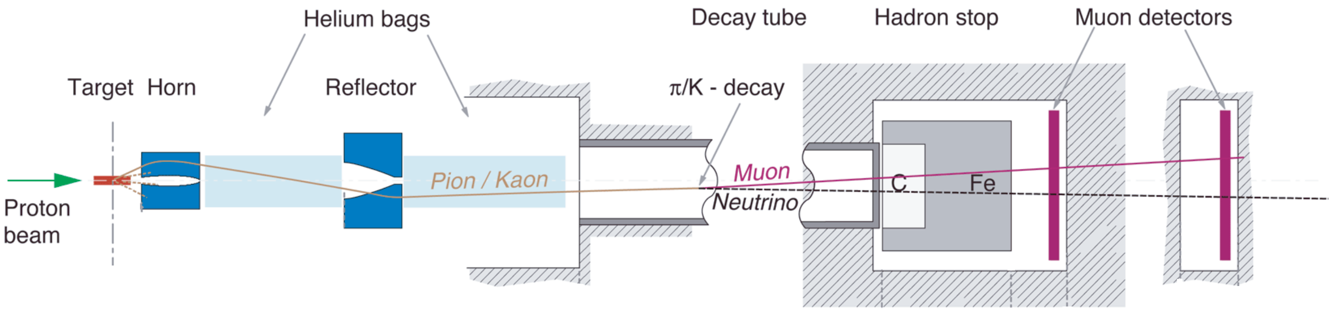
Thanks to: P. Zucchelli, M. Lindroos, J. Bouchez, P. Hernandez, JJ Gomez-Cadenas, J. Burguet-Castell, O. Mena, D. Casper, A. Blondel, S. Gilardoni, C. Volpe, S. Rigolin, A. Donini, P. Migliozzi, F. Terranova, P. Lipari (I hope I'm not forgetting too many people).

Neutrino 2004, College de France, June 14-19 ,2003

Conventional neutrino beams are doing since a long time a great job in hep



. . . but are going to hit their ultimate limitations.



In a **conventional neutrino beam**, neutrinos are produced by 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)**:

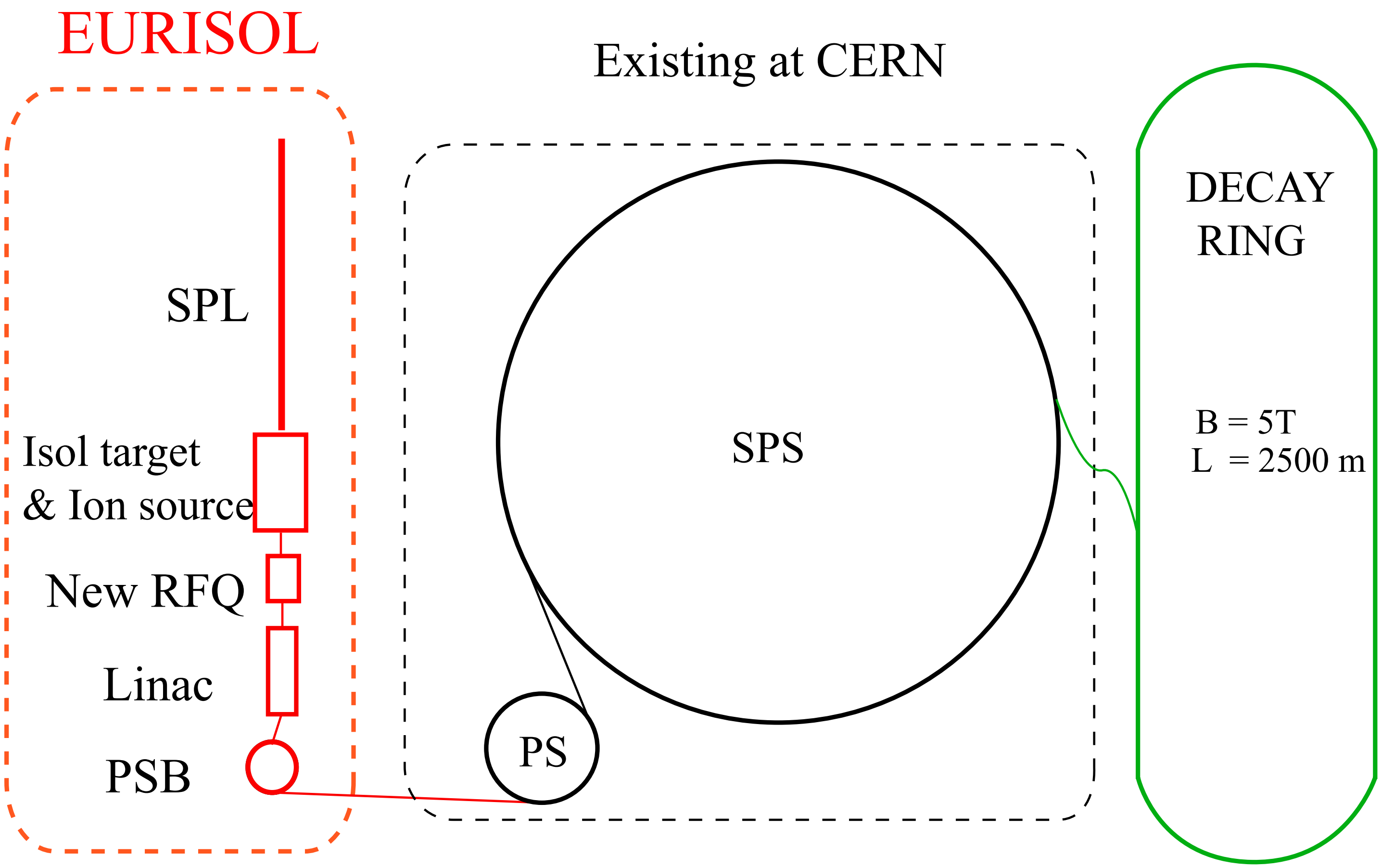
- Just one flavour in the beam
- Energy shape defined by just two parameters: the endpoint energy of the beta decay and the γ of the parent ion.
- Flux normalization given by the number of ions circulating in the decay ring.
- Beam divergence given by γ.

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)

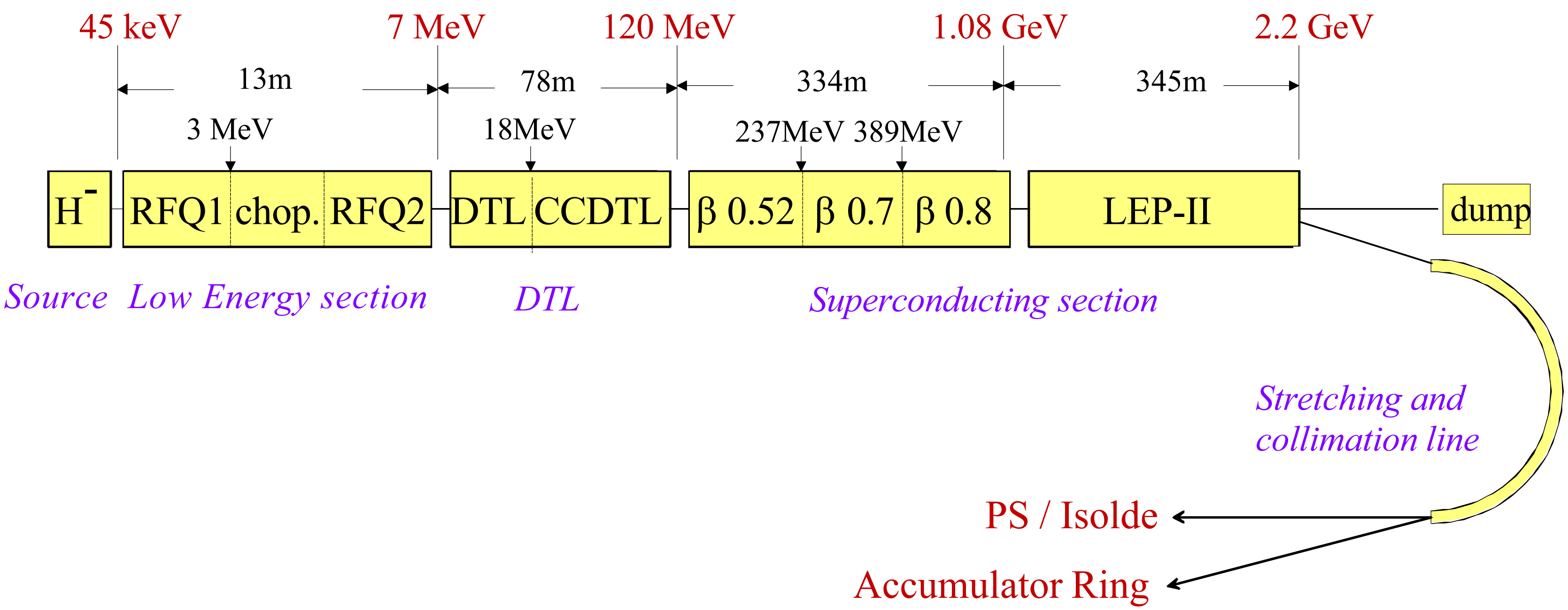
M. Lindroos and collaborators, see http://beta-beam.web.ch/beta-beam



- 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:

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

MW-Linac: SPL (Superconducting Proton Linac)

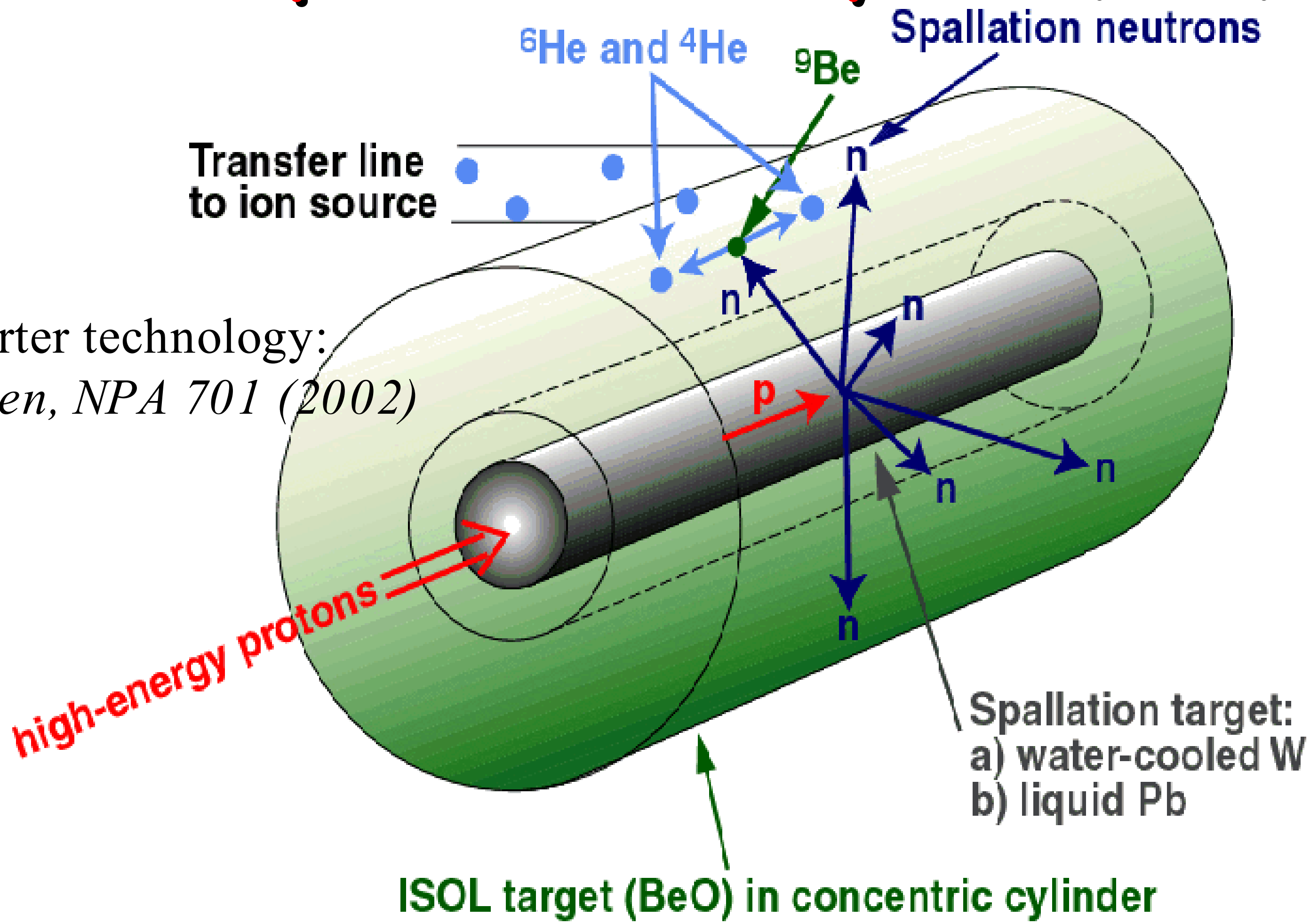


EKIN = 2.2 GeV
Power = 4 MW
Protons/s = 10^{16}

→ **10^{23} protons/year**

2 ma current
100 μa needed by Beta-Beam targets
It can accomodate both a conventional ν beam (SPL-SuperBeam) and a Beta Beam

^{6}He production by ^{9}Be(n,α)

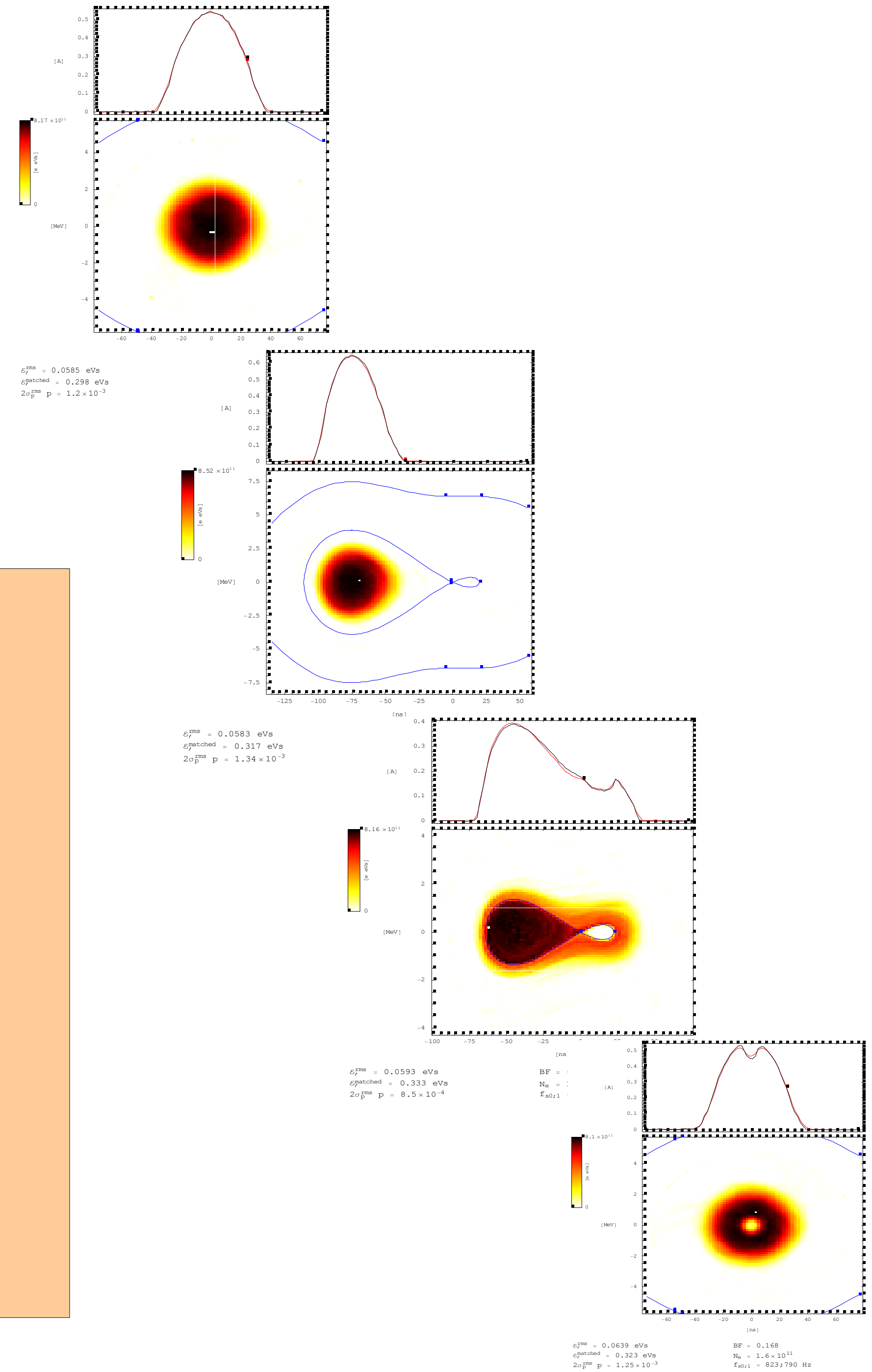


Converter technology:
(J. Nolen, NPA 701 (2002) 312c)

Layout very similar to planned EURISOL converter target aiming for 10^{15} fissions per s.

Asymmetric bunch merging

- There is an absolute need for stacking in the decay ring.
  - Not enough flux from source and injection chain.
  - Life time is an order of magnitude larger than injector cycling (120 s as compared to 8s).
  - We need to stack at least over 10 to 15 injector cycles.
- Cooling is not an option for the stacking process:
  - Electron cooling is excluded because of the high electron beam energy and in any case far too long cooling times.
  - Stochastic cooling is excluded by the high bunch intensities.
- Stacking without cooling creates "conflicts" with Liouville.



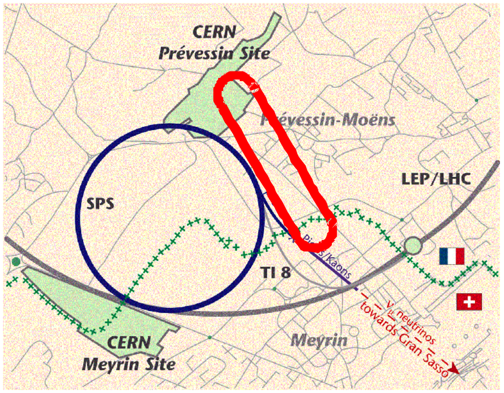
Asymmetric bunch pair merging

(Benedikt, Hancock, Vallet, *A proof of principle of asymmteric bunch pair merging*, AB-note-2003-080 MD))

- Try to cheat Liouville macroscopically by:
  - Stacking longitudinally in the centre of the existing beam.
  - Using the fact that "older" parts of the stack are naturally loosing density because of beta decay.
- Asymmetric bunch pair merging moves the fresh bunch into the centre of the stack and pushes less dense phase space areas to larger amplitudes until these are cut by the momentum collimation system.
- The maximum density is always in the centre of the stack as required by the experiment.

The decay ring

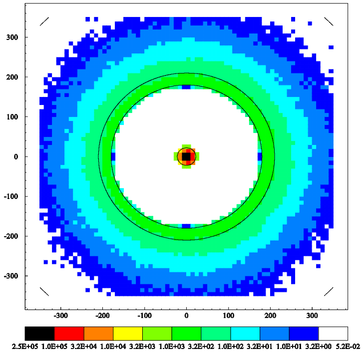
- Civil engineering costs: Estimate of 400 MCHF for 1.3% incline (13.9 mrad)
- Ring length: 6850 m, useful straight session: 36%
- Magnet cost: first estimate at 100 MCHF (SC magnets, 5T)

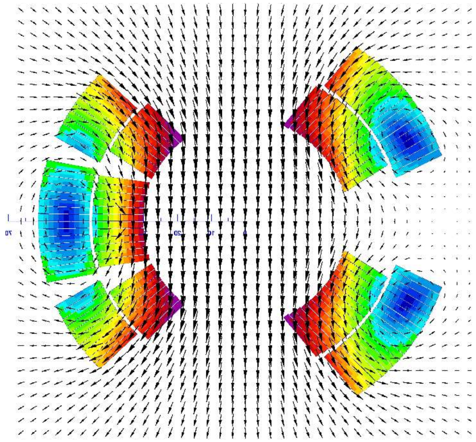


•For γ<75 the length could be halved

•With LHC magnets (10 T) the length could be halved

•A 2 km ring could be feasible under these assumptions





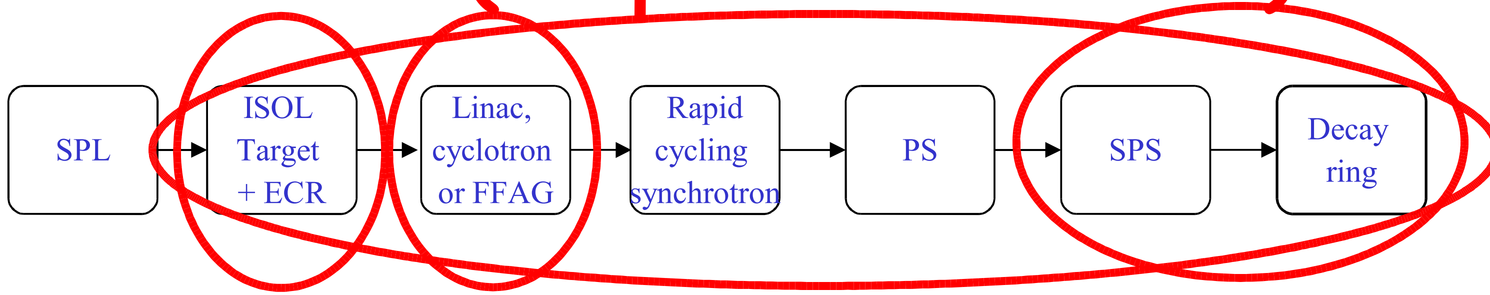
S. Russenschuck, CERN

Dipoles can be built with no coils in the path of the decaying particles to minimize peak power density in superconductor

FLUKA simulated losses in surrounding rock (no public health implications)

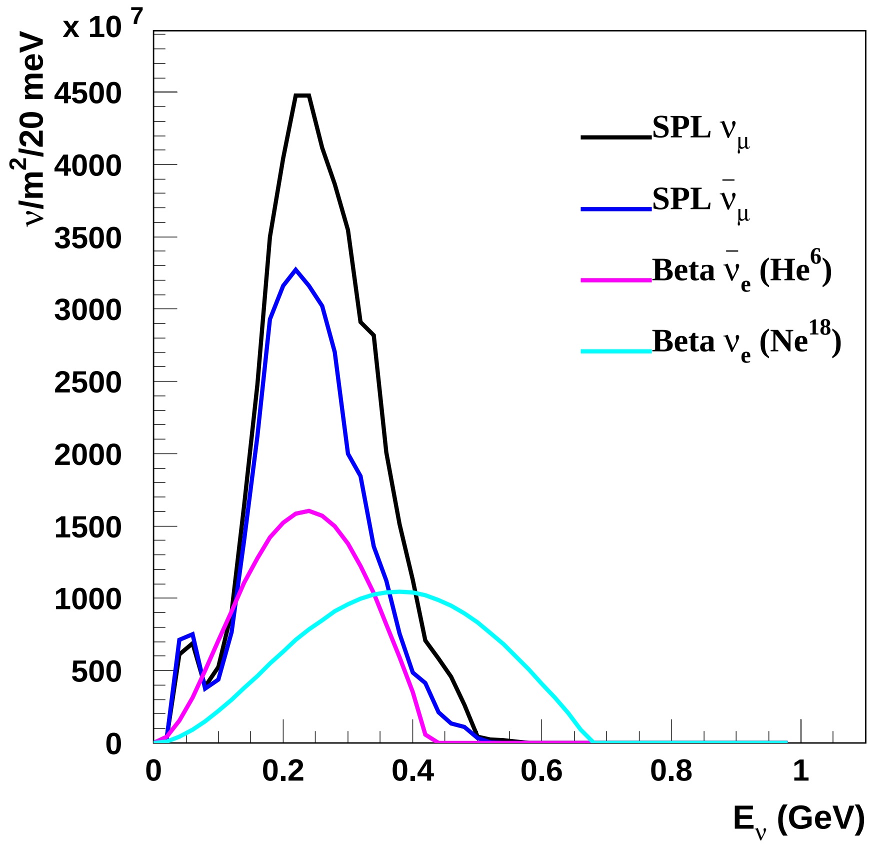
The losses have been simulated and one possible dipole design has been proposed

R&D (improvements)

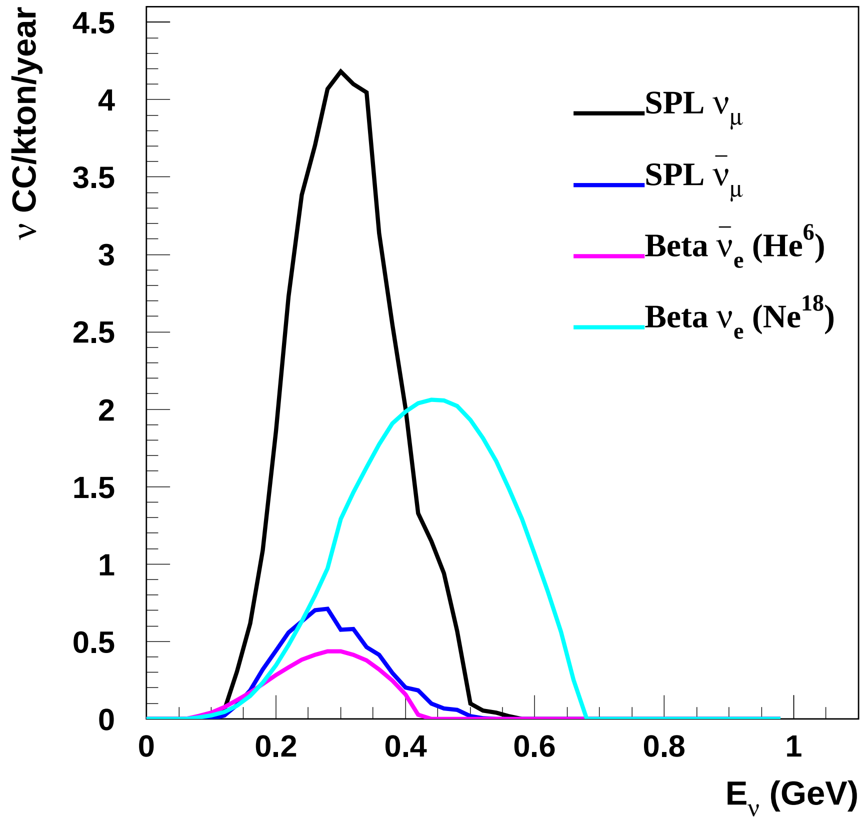


- Production of RIB (intensity)
  - Simulations (GEANT, FLUKA)
  - Target design, only 100 kW primary proton beam in present design
- Acceleration (cost)
  - FFAG versa linac/storage ring/RCS
- Tracking studies (intensity)
  - Loss management
- Superconducting dipoles (γ of neutrinos)
  - Pulsed for new PS/SPS (GSI FAIR)
  - High field dipoles for decay ring to reduce arc length
  - Radiation hardness (Super FRS)

Fluxes

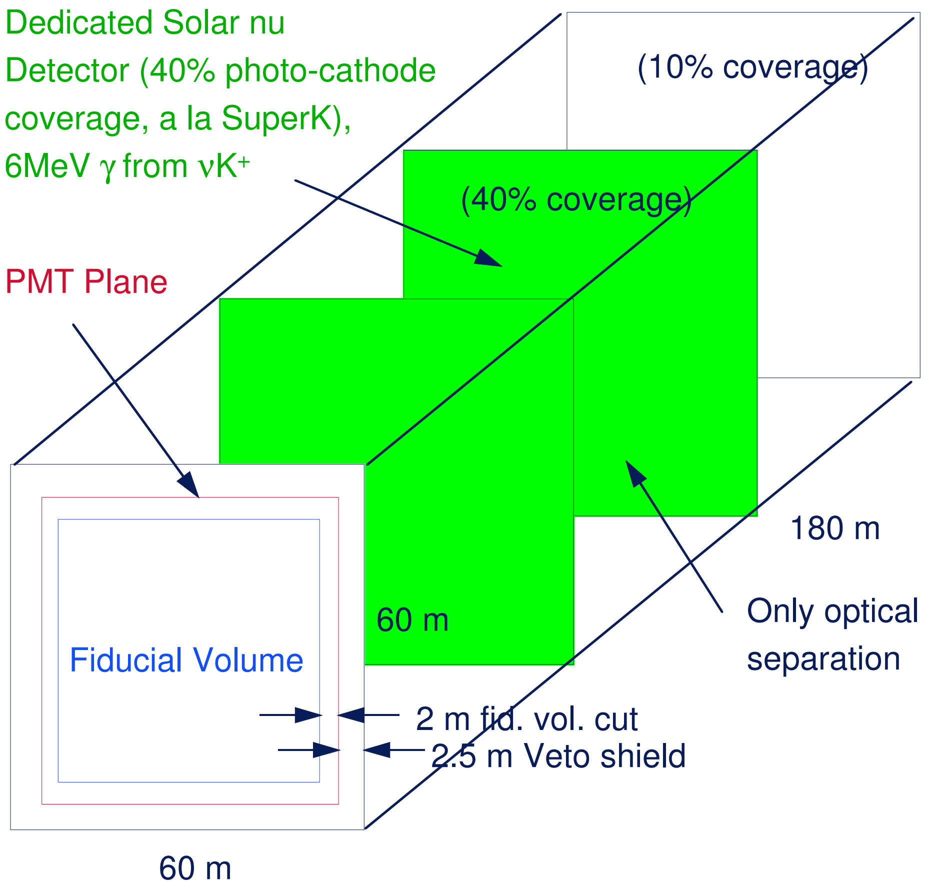


CC Rates



	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 $\times$ 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 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.

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

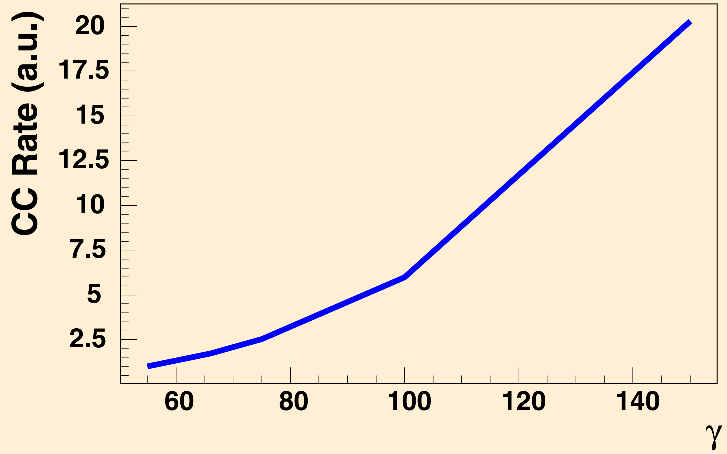
Atmospheric neutrino background can be kept low only by a very short duty cycle of the Beta Beam. A reduction factor bigger than 10^3 is needed.

This is achieved by building 10 ns long Ion bunches.

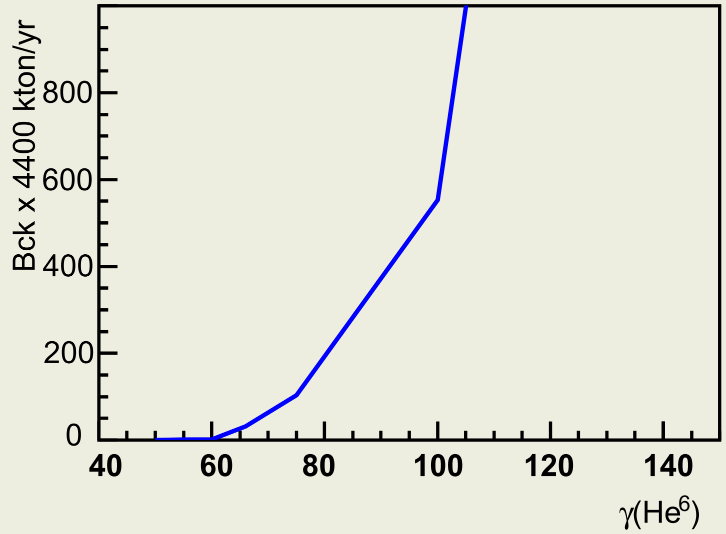
Optimizing the Lorentz Boost γ (L=130 km). Preferred value: $\gamma(^6\mathrm{He}) = 60$

Higher γ produce more CC interactions

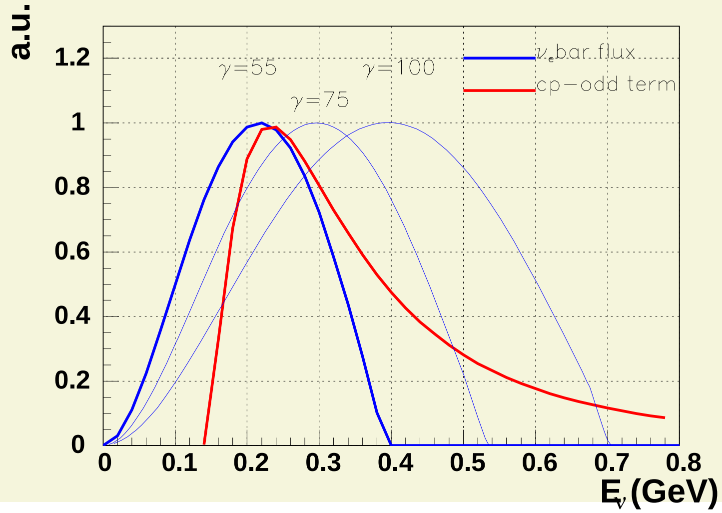
More collimated neutrino production and higher cross sections.



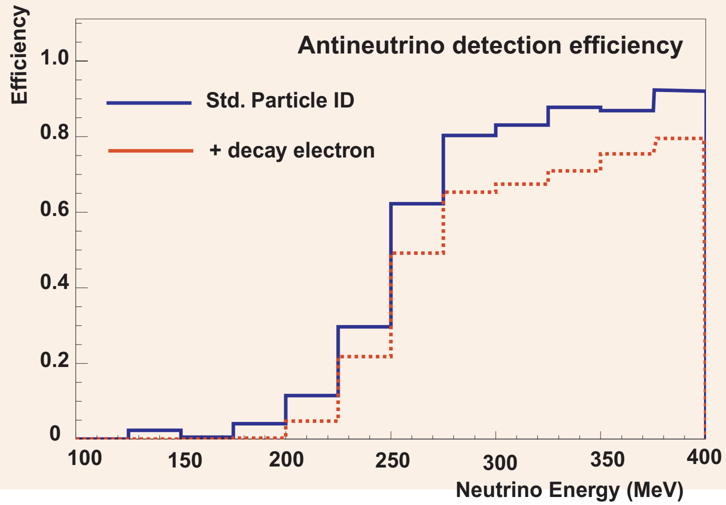
Background rate rises even faster



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 flavour 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

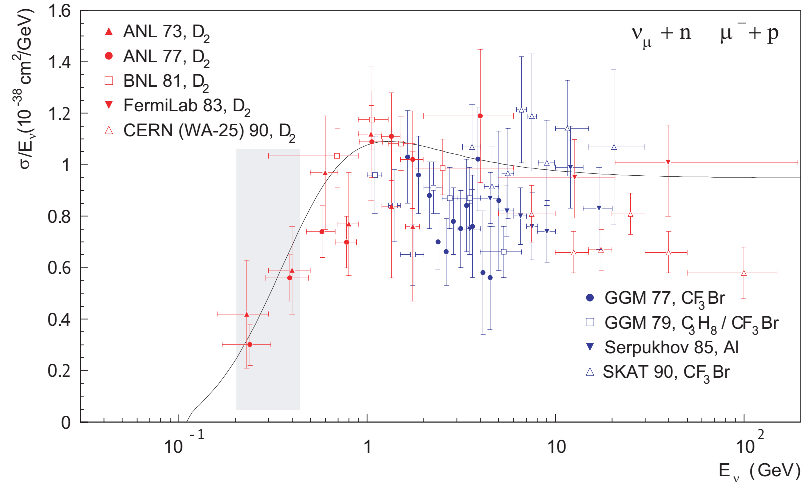
- Cross sections are small $\Rightarrow$ very massive detectors.
- $\overline{\nu}_\mu / \nu_\mu$ cross section ratio at a minimum (1/4).
- Visible energy smeared out by Fermi motion: counting experiment
- No way to measure sign(Δm^2).

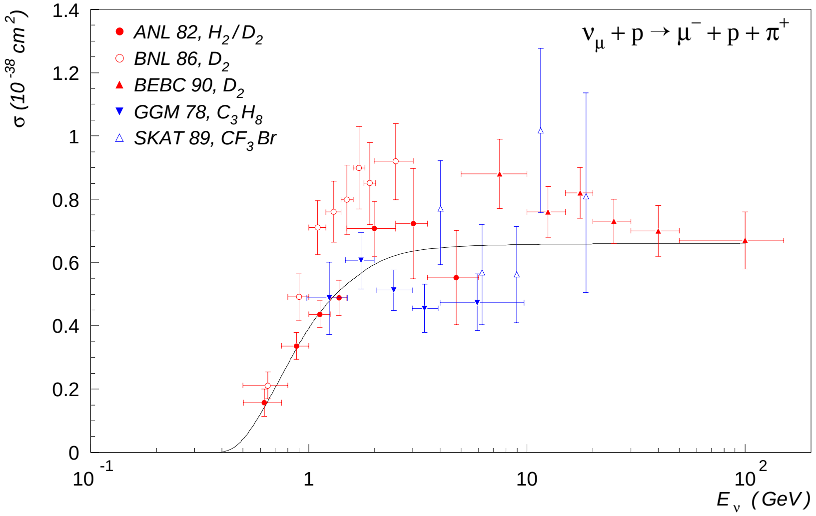
Furthermore when combined with the SPL-SuperBeam

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 30% spread.

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

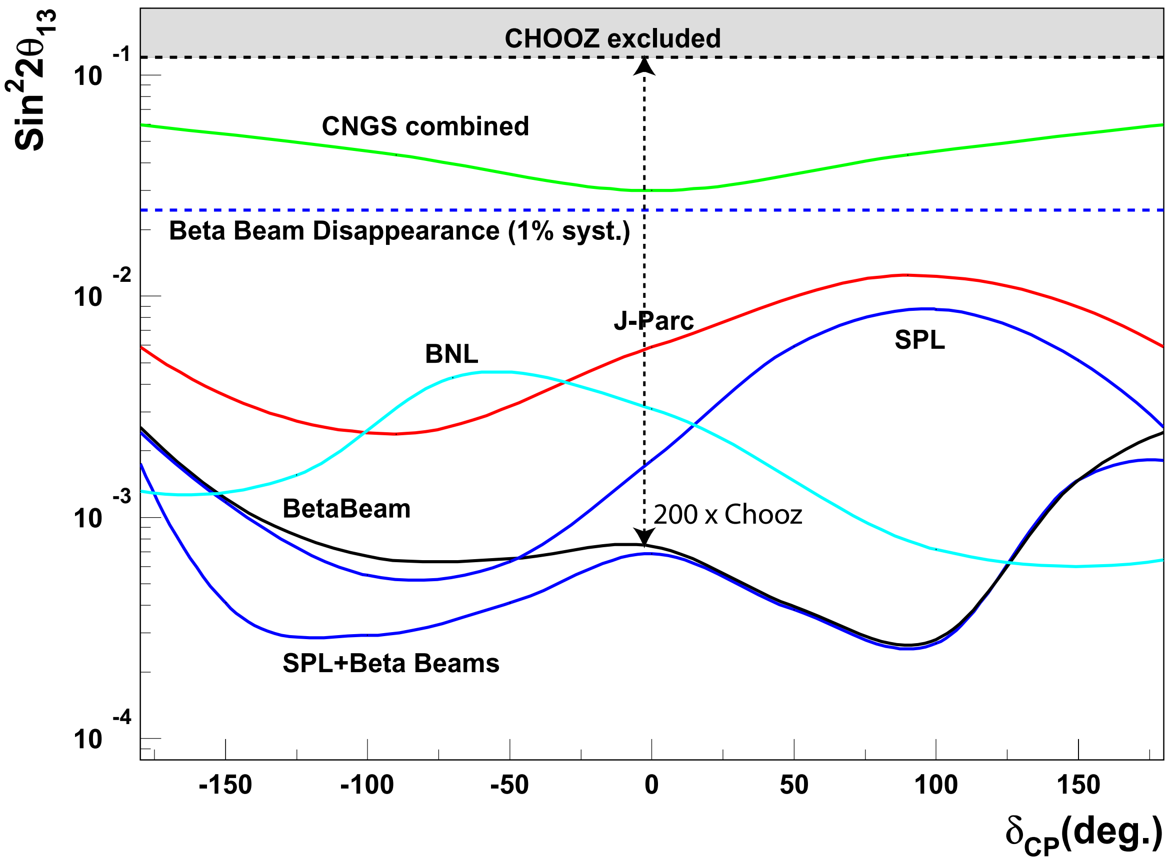
- Neutrino flux and spectrum are completely defined by the parent ion characteristics and by the Lorentz boost γ.
- Just one neutrino flavour in the beam.
- You can scan different γ values starting from below the Δ production threshold.
- A close detector can then measure neutrino cross sections with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

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

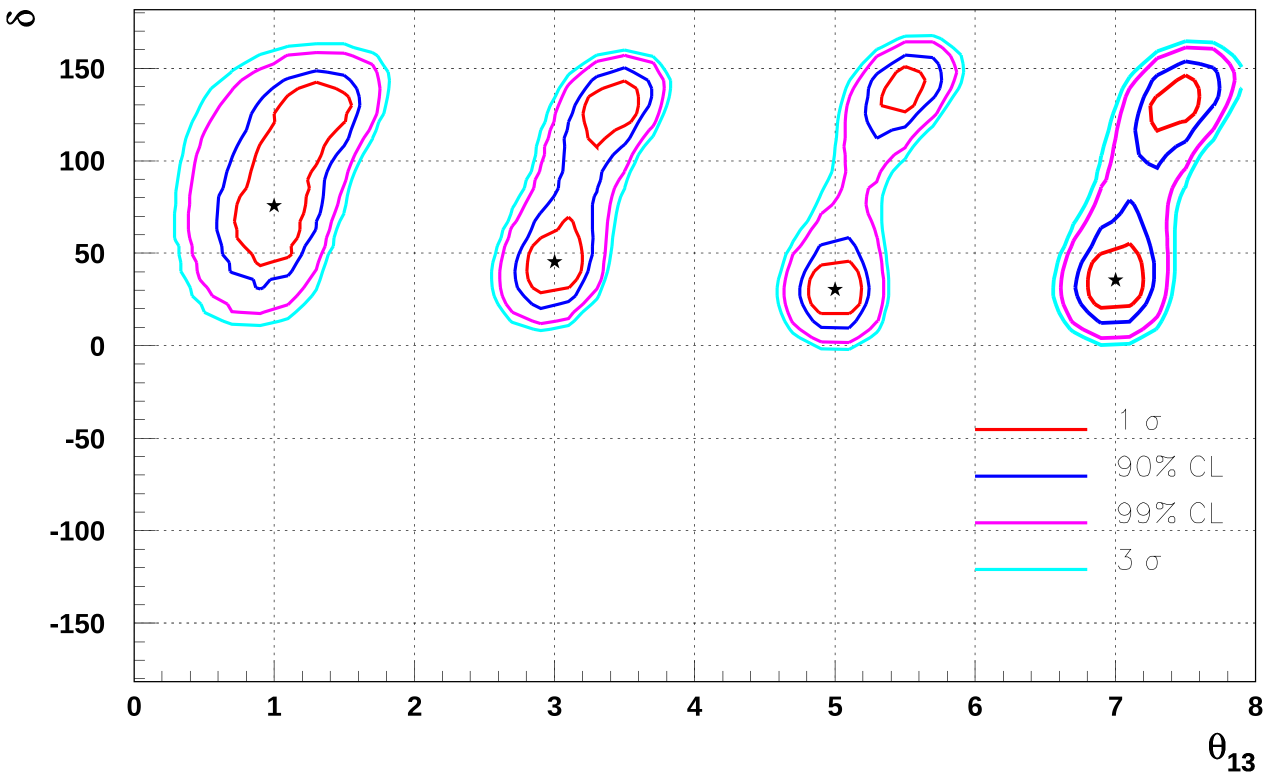
Sensitivity to θ_{13}

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 $\theta_{13} \geq 3.4°$**



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$(\Delta m^2) = +1$

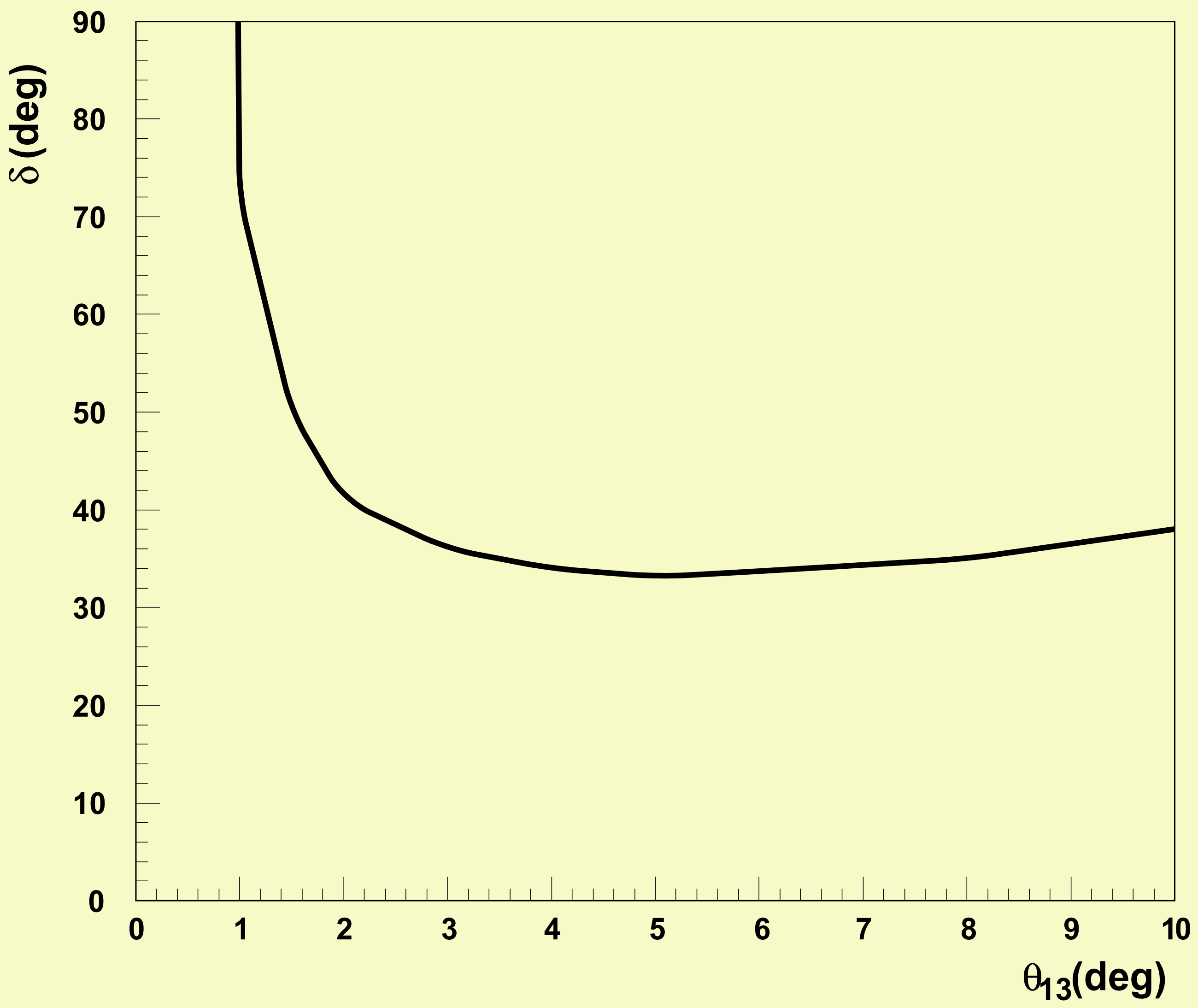
	Beta Beam		SPL-SB	
	^6He $(\gamma = 60)$	^{18}Ne $(\gamma = 100)$	ν_μ (2 yrs)	$\overline{\nu}_\mu$ (8 yrs)
CC events (no osc, no cut)	19710	144784	36698	23320
Oscillated at the Chooz limit	681	5304	1491	1182
Oscillated	1	118	2	34
δ oscillated	-12	54	-27	16
Beam background	0	0	140	101
Detector backgrounds	1	397	37	50

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

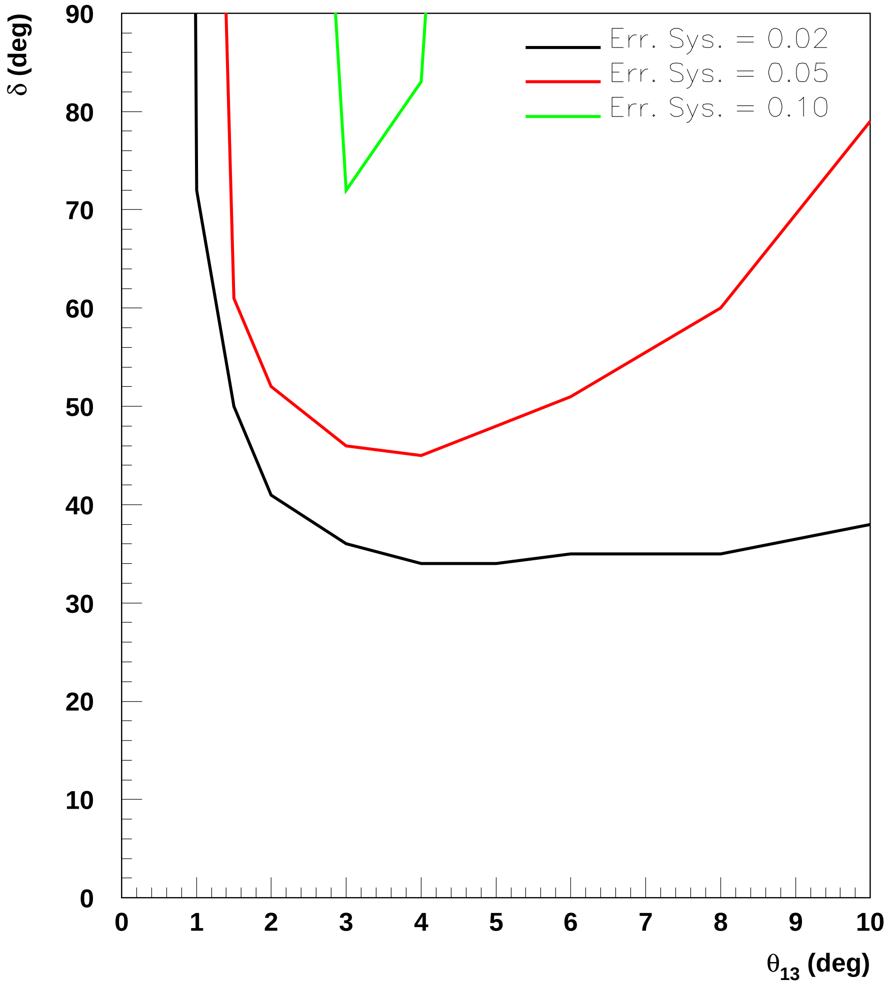
Leptonic CP violation discovery potential

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.

3 σ discovery potential on δ as function of θ_{13}



The role of systematic errors



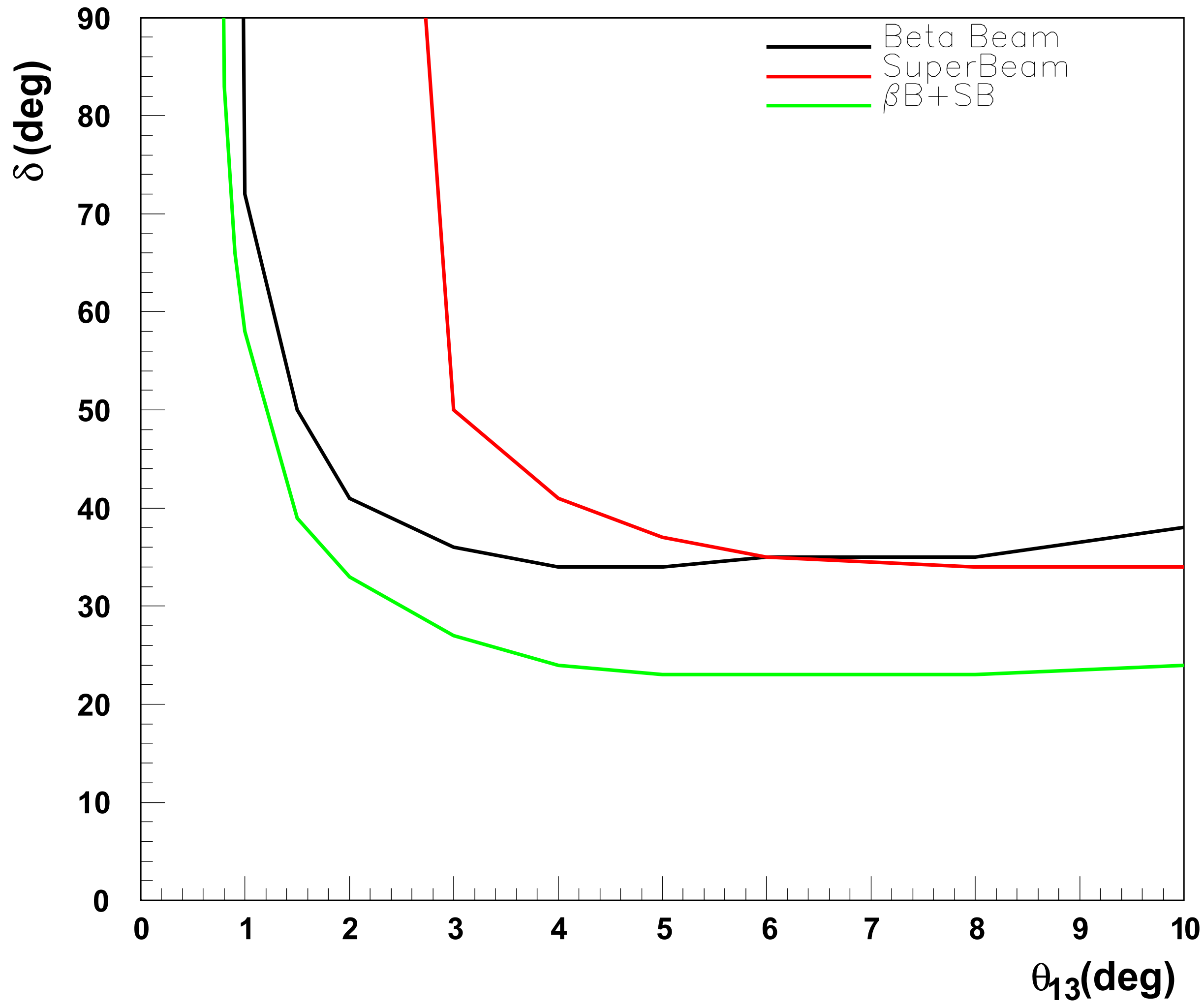
Systematic errors can spoil the sensitivity.

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 $\gamma = 60$.

Conclusion: Beta Beam is not immune from systematic errors, but it offers an ideal environment to keep them low.

The SPL-SuperBeam- Beta Beam synergy



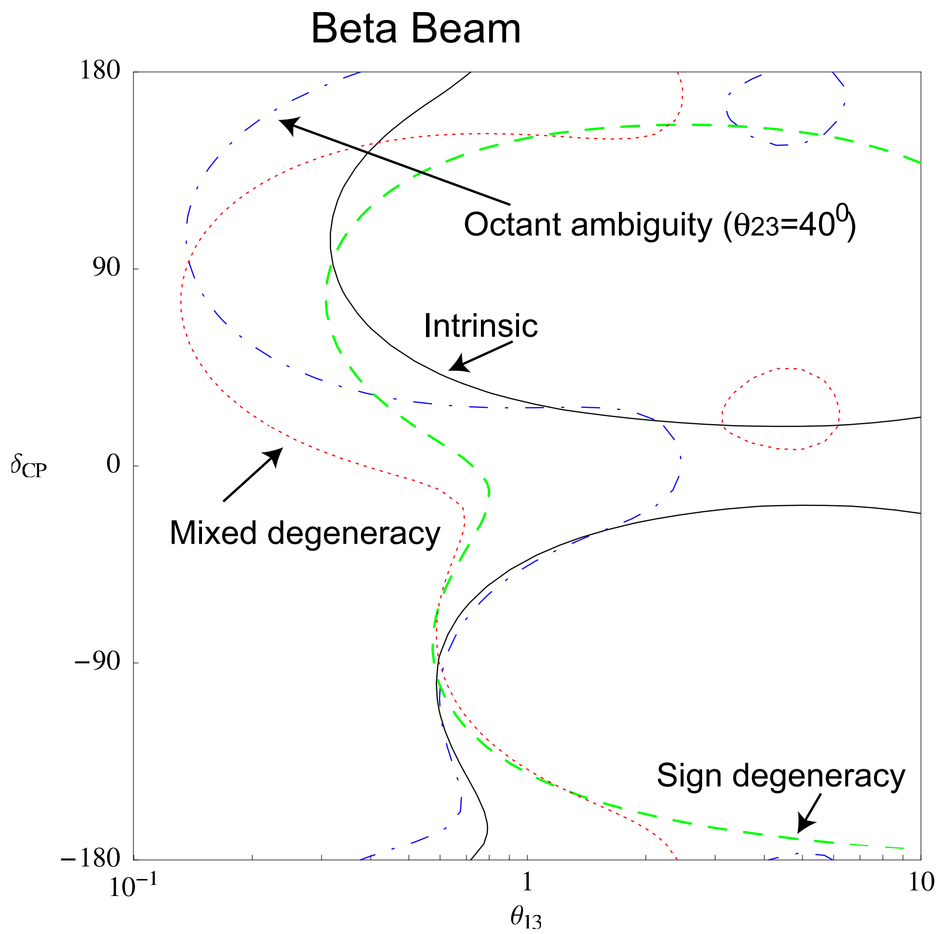
Not in the sense that SuperBeam helps in solving clone solutions.

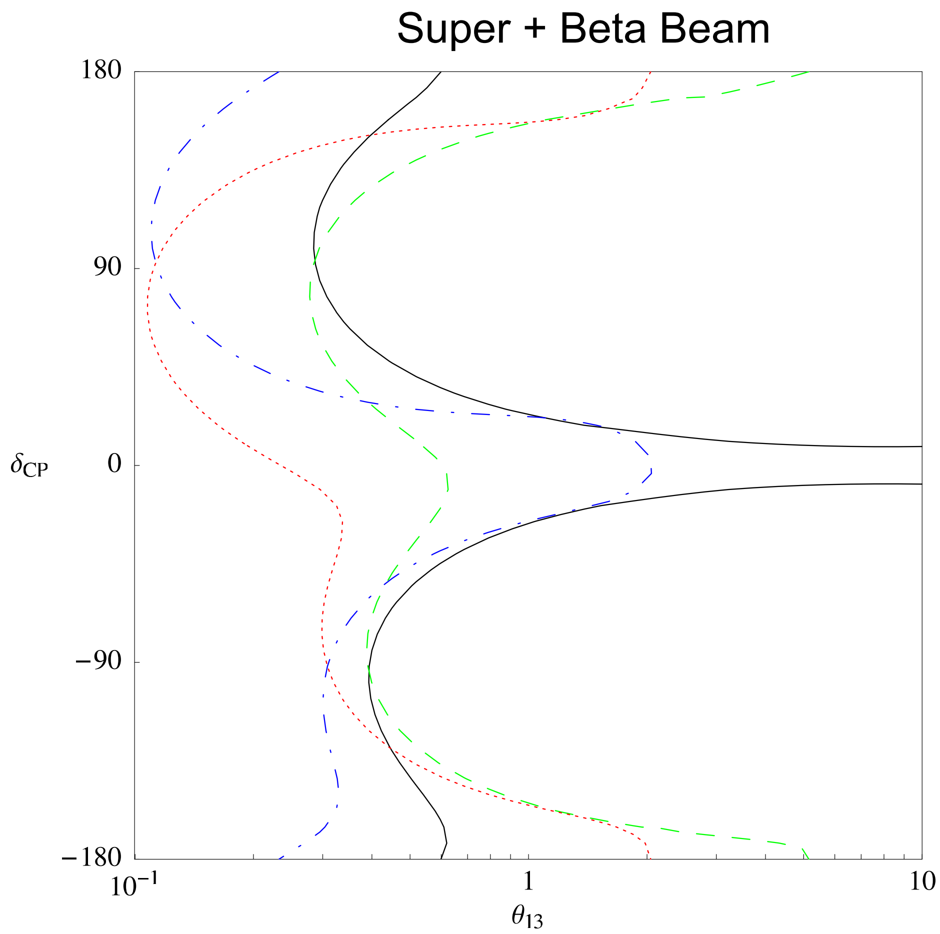
Rather the experimental result can be expressed in term of ν_e signal with π° backgrounds (SuperBeam) and in term of ν_μ signal with π^+ backgrounds (Beta Beam).

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.

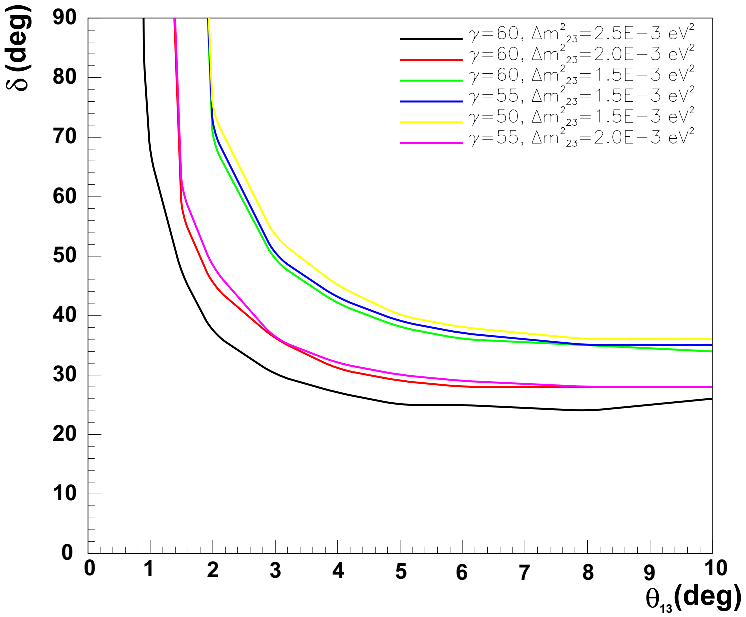
90% CL sensitivity plots assuming $\delta = 0, \theta_{23} = 40°$.



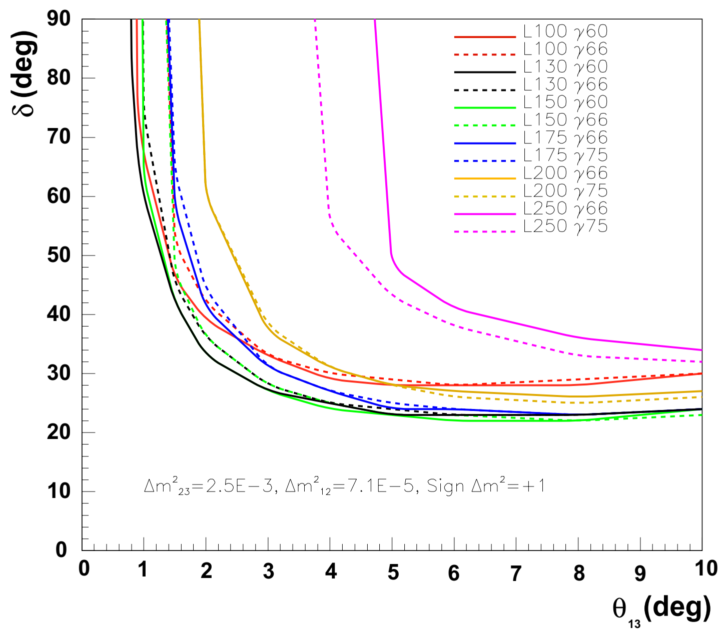


Unsolicited answers to some F.A.Q.

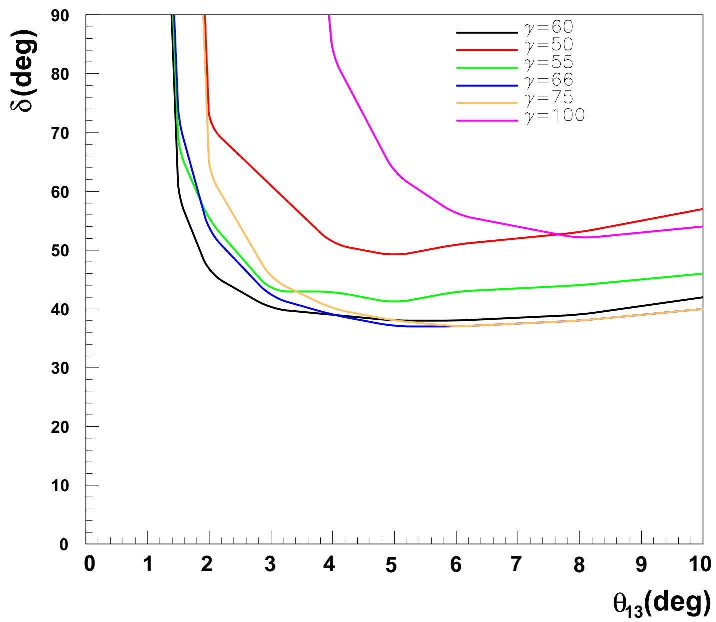
Is the value of Δm^2_{23} critical?



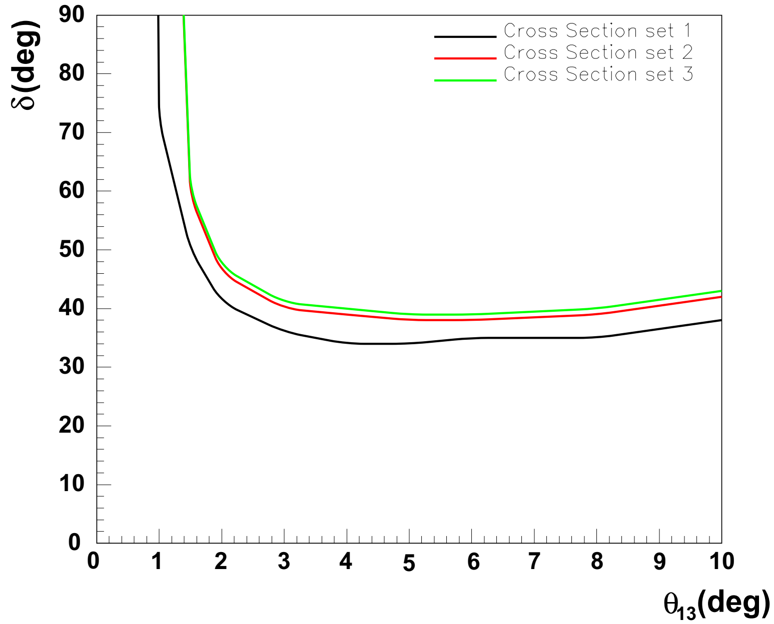
Is the CERN-Frejus a magic baseline?



Is $\gamma = 60$ the absolute optimum?



What is the role of cross section?



The high energy option

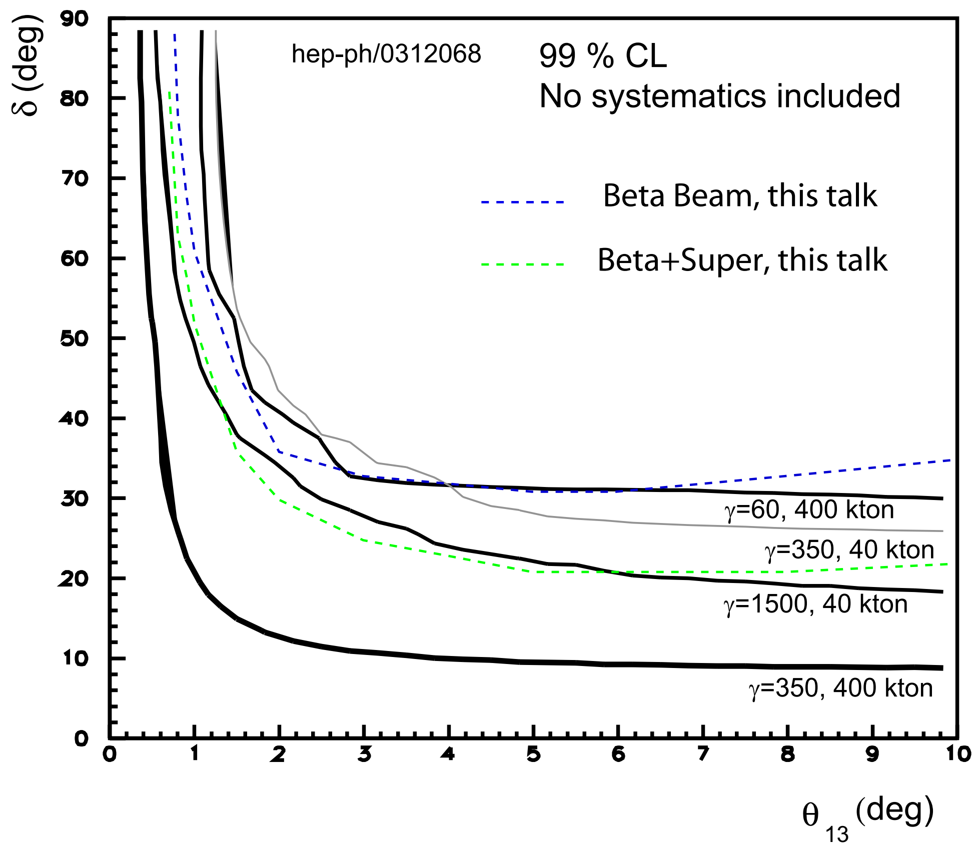
P. Hernandez, J.J. Gomez-Cadenas et al., hep-ph/0312068

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 $E_\nu \simeq 1.2GeV$ 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

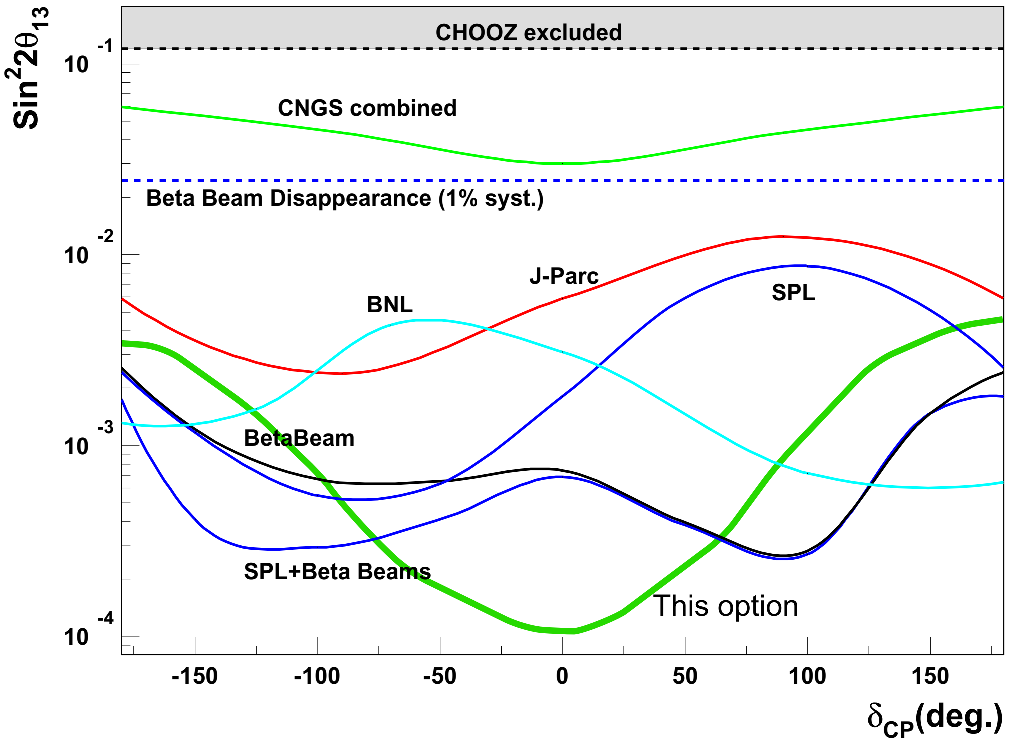
P. Migliozzi, F. Terranova et al., hep-ph/0405081

Consider the maximum possible γ reachable at LHC $\gamma(^6He) = 2488 - \gamma(^{18}NE) = 4147$ and assume that LHC can digest all those ions.

Fire the beam at LNGS.

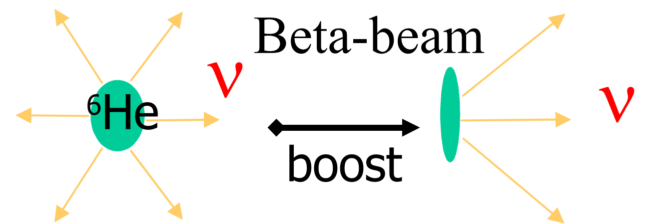
Count the ν_μ interactions in the rock with a very basic 15×15 m^2 iron-active detectors sandwich.

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

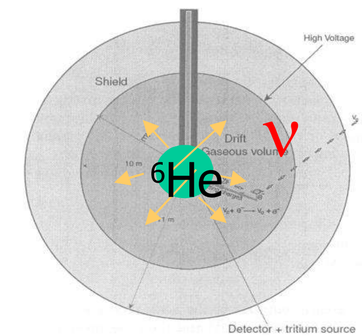


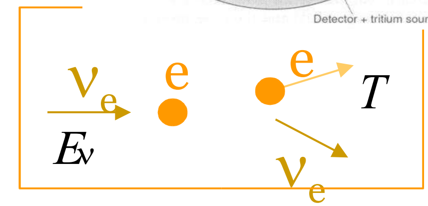
Low energy beta-beam

- 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



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





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.

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