Mauro Mezzetto

Istituto Nazionale di Fisica Nucleare,

Sezione di Padova

New developments on Beta Beams physics reach

Summary:

- **The baseline scenario.**
- **Improving the physics reach.**
- **Good news on the degeneracies problem.**

RAL, January 17-18 ,2005

Most of the neutrino parameters are waiting to be measured

δm^2_{12} ✓ SOLARS+KAMLAND $\delta m^2_{12} = (8.2 \pm 0.6)\ 10^{-5}\ eV^2$

θ_{12} ✓ SOLARS+KAMLAND $\sin^2(2\theta_{12}) = 0.82 \pm 0.055$

Addressed by a SuperBeam/Nufact experiment

δm^2_{23} ✓ ATMOSPHERICS $\delta m^2_{23} = (2.4 \pm 0.4)\ 10^{-3}\ eV^2$

θ_{23} ✓ ATMOSPHERICS $\sin^2(2\theta_{23}) > 0.95$

θ_{13} CHOOZ LIMIT $\theta_{13} < 14^0$

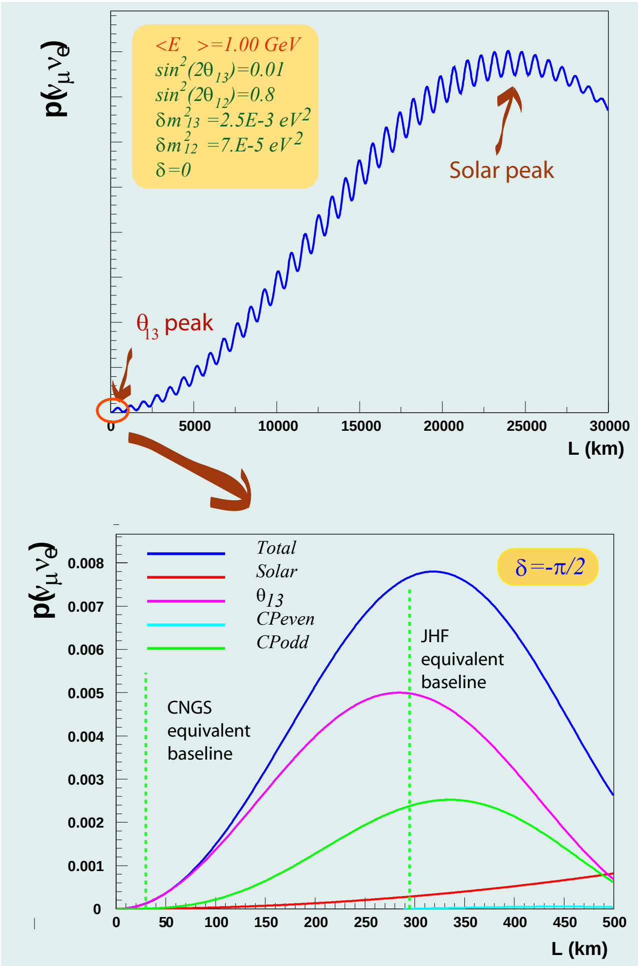
δ_{CP}

Mass hierarchy

Σm_ν BETA DECAY END POINT $\Sigma m_\nu < 6.6$ eV

Dirac/Majorana

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



$$p(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\frac{\Delta m_{13}^2 L}{4E} \qquad \theta_{13} \text{ driven}$$

$$+\,8c_{13}^2 s_{12} s_{13} s_{23}(c_{12}c_{23}cos\delta - s_{12}s_{13}s_{23}) \cos\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \sin\frac{\Delta m_{12}^2 L}{4E} \text{ CPeven}$$

$$-\,8c_{13}^2 c_{12} c_{23} s_{12} s_{13} s_{23} \sin\delta \sin\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \sin\frac{\Delta m_{12}^2 L}{4E} \qquad \text{CPodd}$$

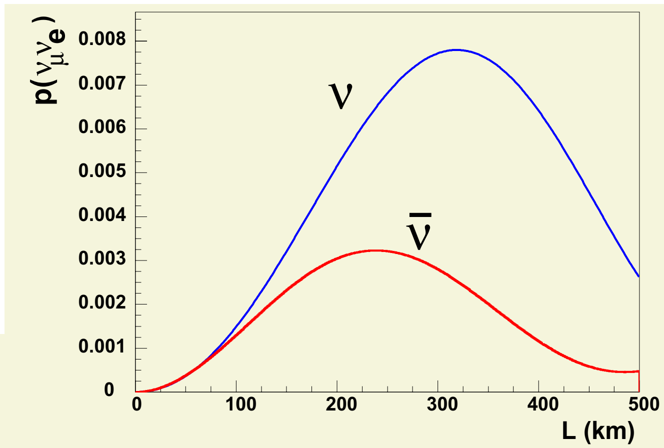
$$+\,4s_{12}^2 c_{13}^2\{c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}cos\delta\} \sin\frac{\Delta m_{12}^2 L}{4E} \qquad \text{solar driven}$$

$$-\,8c_{12}^2 s_{13}^2 s_{23}^2 \cos\frac{\Delta m_{23}^2 L}{4E} \sin\frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E}(1-2s_{13}^2) \qquad \text{matter effect (CP odd)}$$

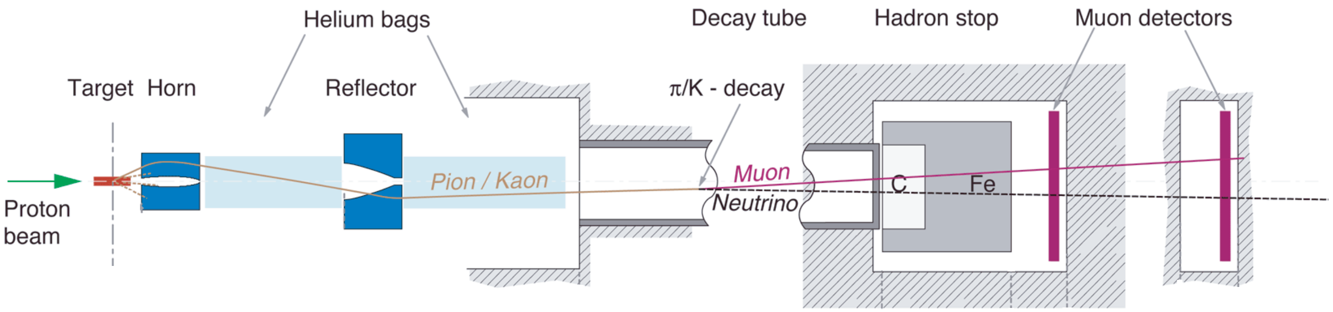
θ_{13} discovery requires total probability greater than solar driven probability

Leptonic CP discovery requires

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



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 flavors are present ($\overline{\nu}_\mu$, ν_e, $\overline{\nu}_e$), generated by wrong sign pions, kaons and muon decays. $\nu_e$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)**:

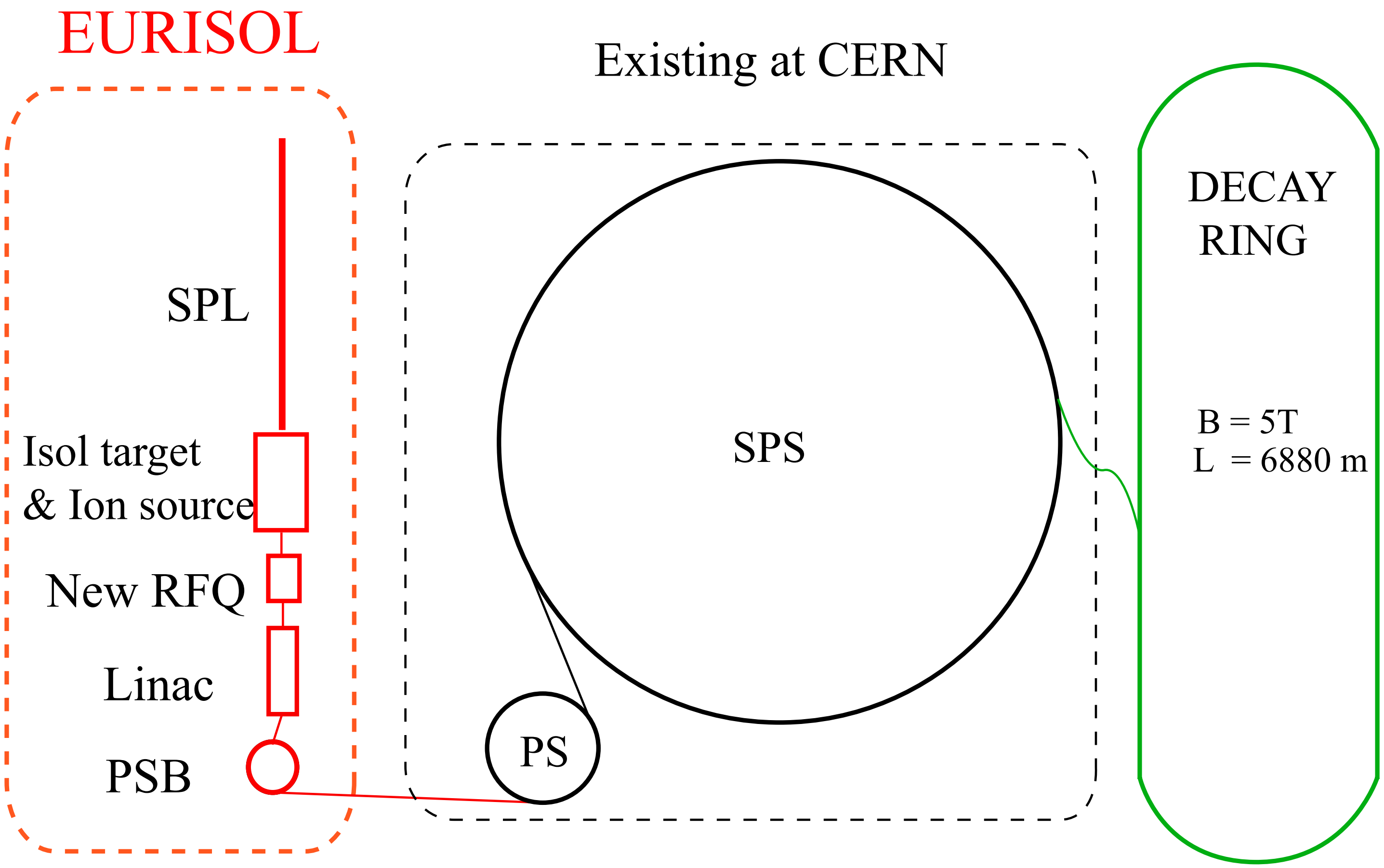
- Just one flavor in the beam
- Energy shape defined by just two parameters: the endpoint energy of the beta decay and the γ of the parent ion.
- Flux normalization given by the number of ions circulating in the decay ring.
- Beam divergence given by γ.

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)

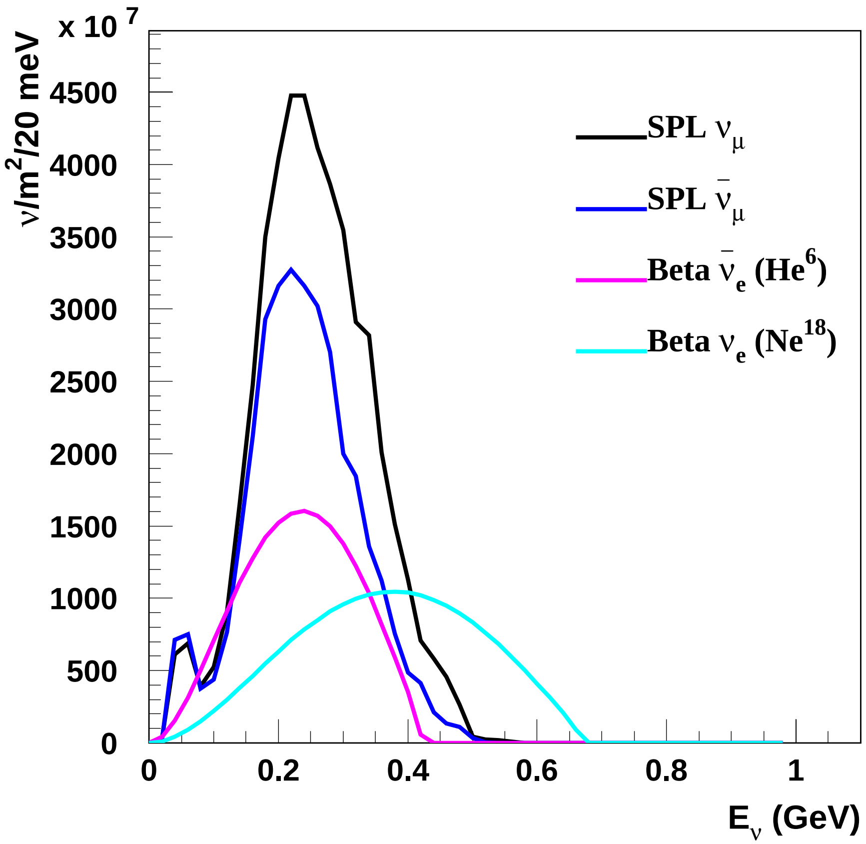
M. Lindroos et al., see http://beta-beam.web.ch/beta-beam



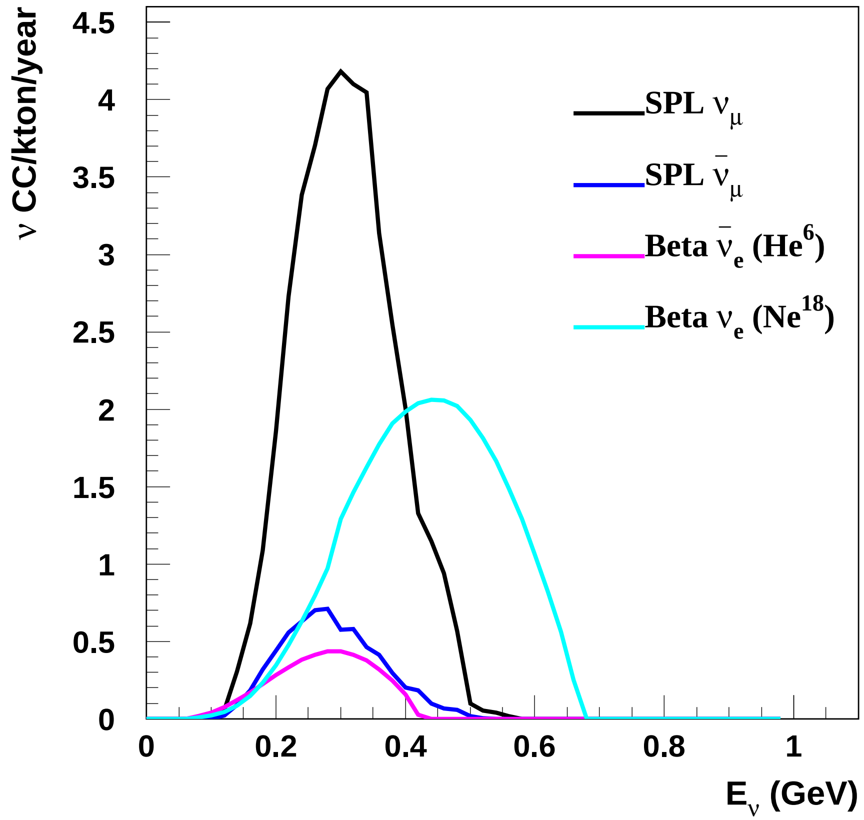
- 1 ISOL target to produce He^6, 100 μA, $\Rightarrow 2.9 \cdot 10^{18}$ ion decays/straight session/year. $\Rightarrow \overline{\nu}_e$.
- 3 ISOL targets to produce Ne^{18}, 100 μA, $\Rightarrow 1.2 \cdot 10^{18}$ ion decays/straight session/year. $\Rightarrow \nu_e$.
- The 4 targets could run in parallel,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

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

Fluxes

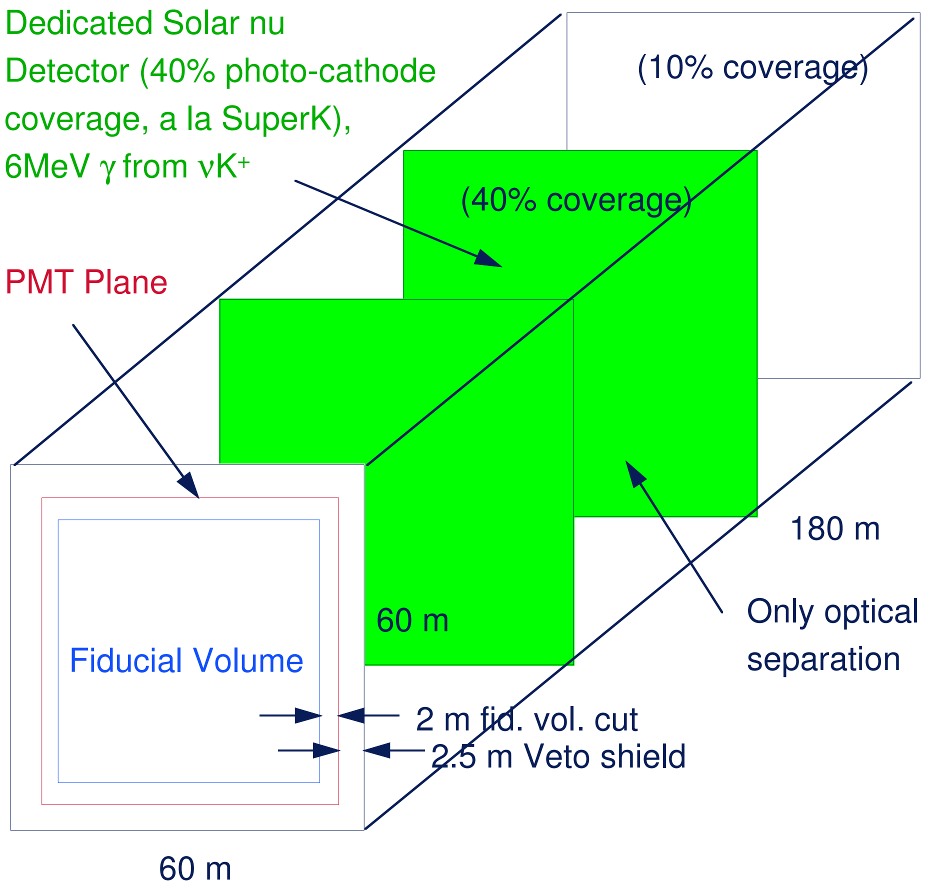


CC Rates



	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 $\times$ 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/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

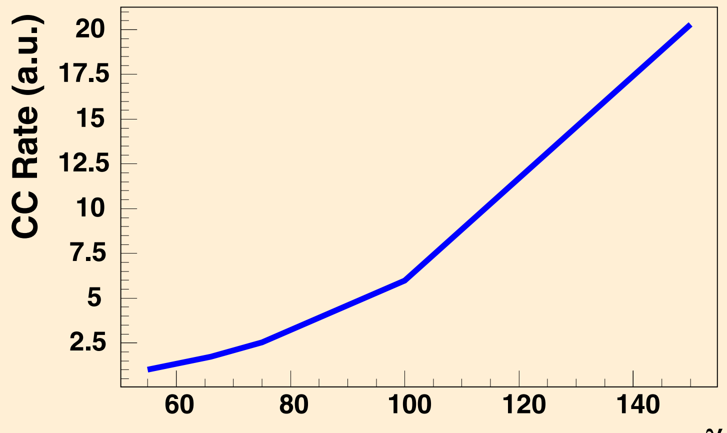
Atmospheric neutrino background can be kept low only by a very short duty cycle of the Beta Beam. A reduction factor bigger than 10^3 is needed.

This is achieved by building 10 ns long Ion bunches.

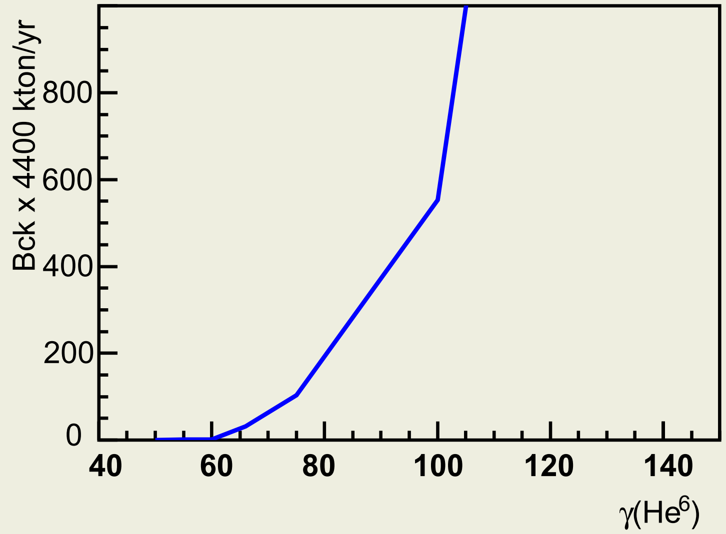
Optimizing the Lorentz Boost γ (L=130 km). Preferred value: $\gamma(^6\mathrm{He}) = 60$

Higher γ produce more CC interactions

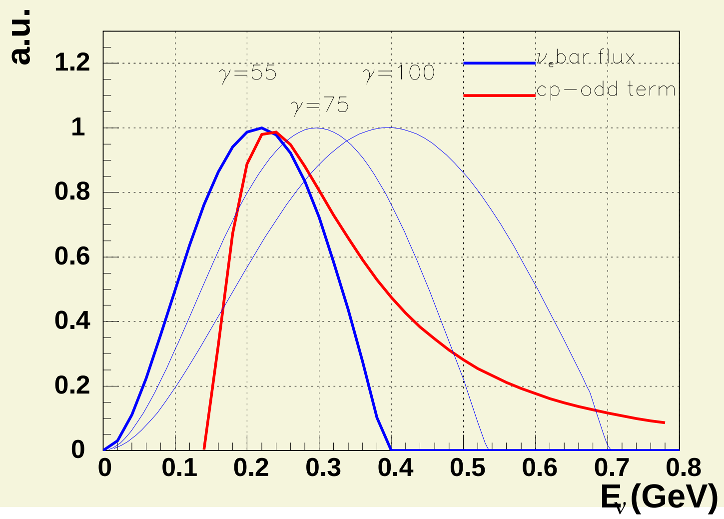
More collimated neutrino production and higher cross sections.



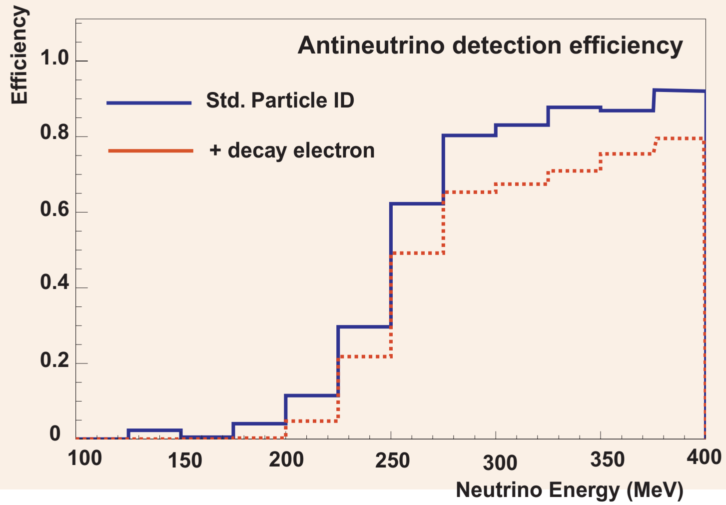
Background rate rises even faster



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).

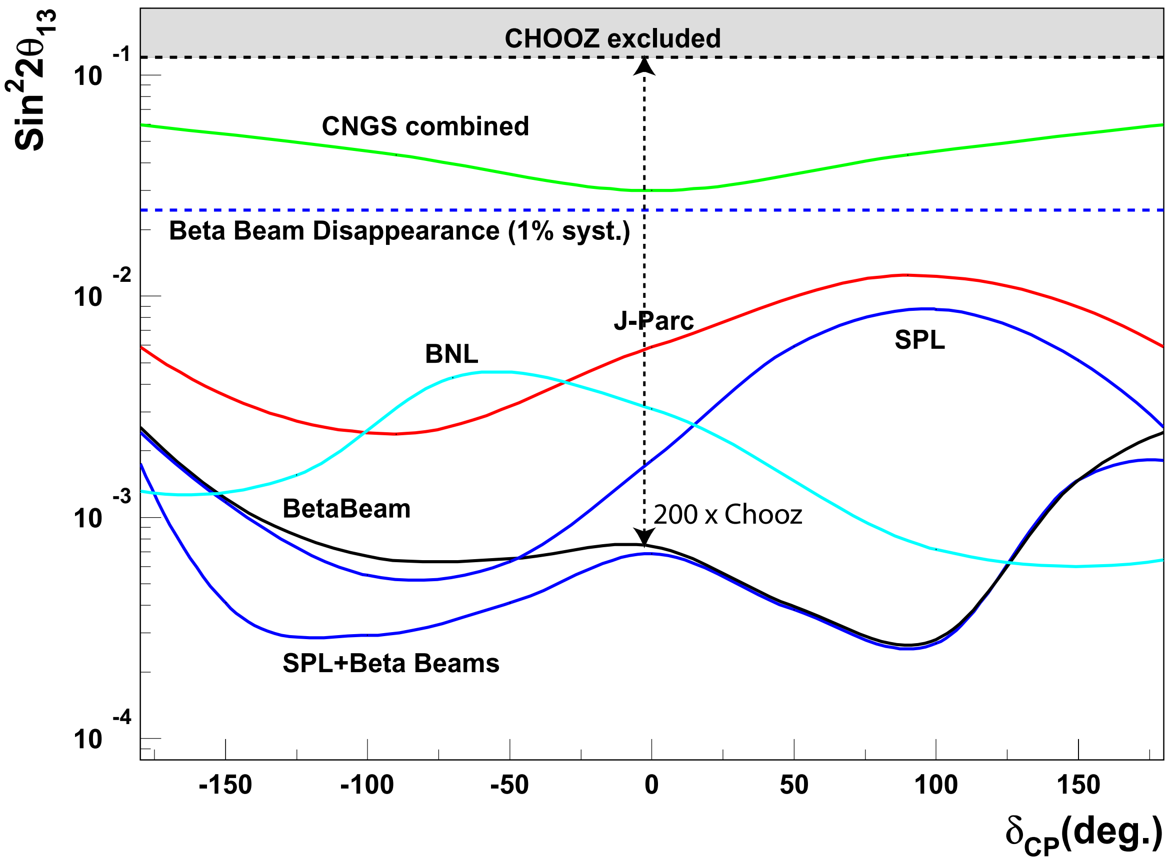
Furthermore when combined with the SPL-SuperBeam

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.

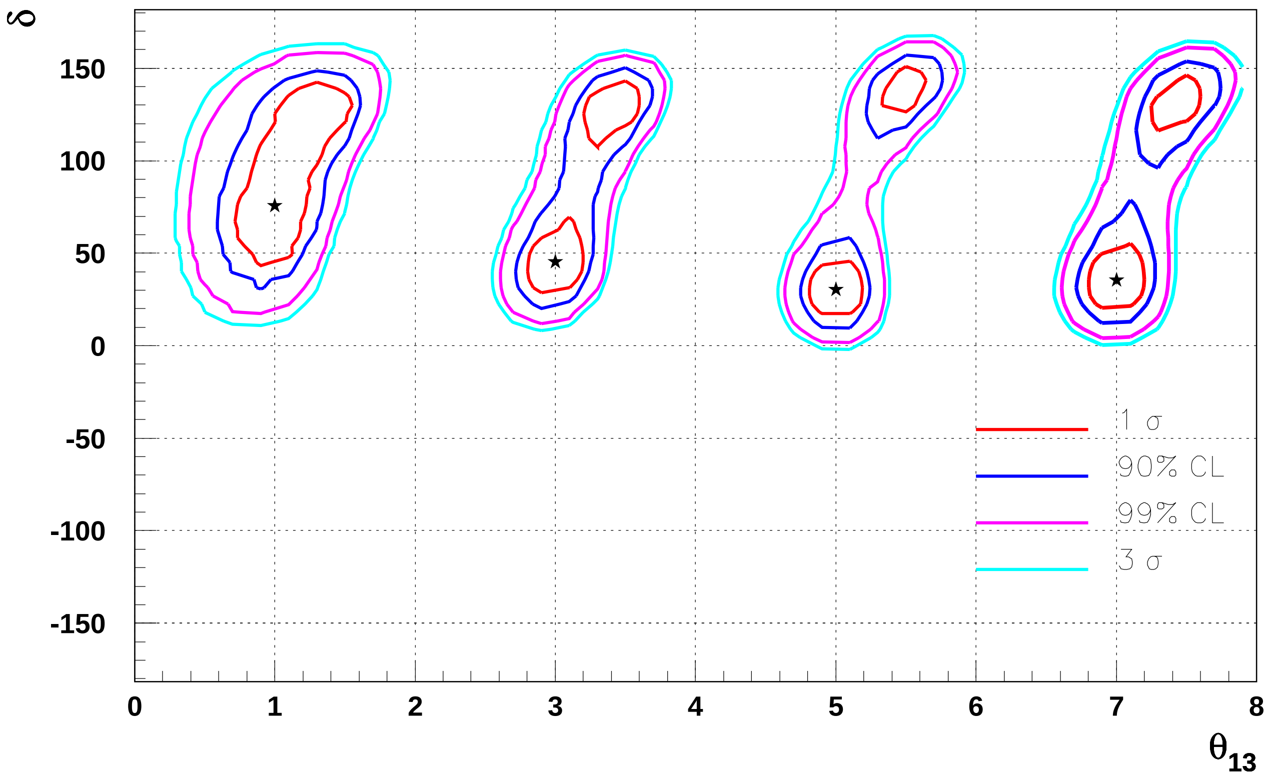
Sensitivity to θ_{13}

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

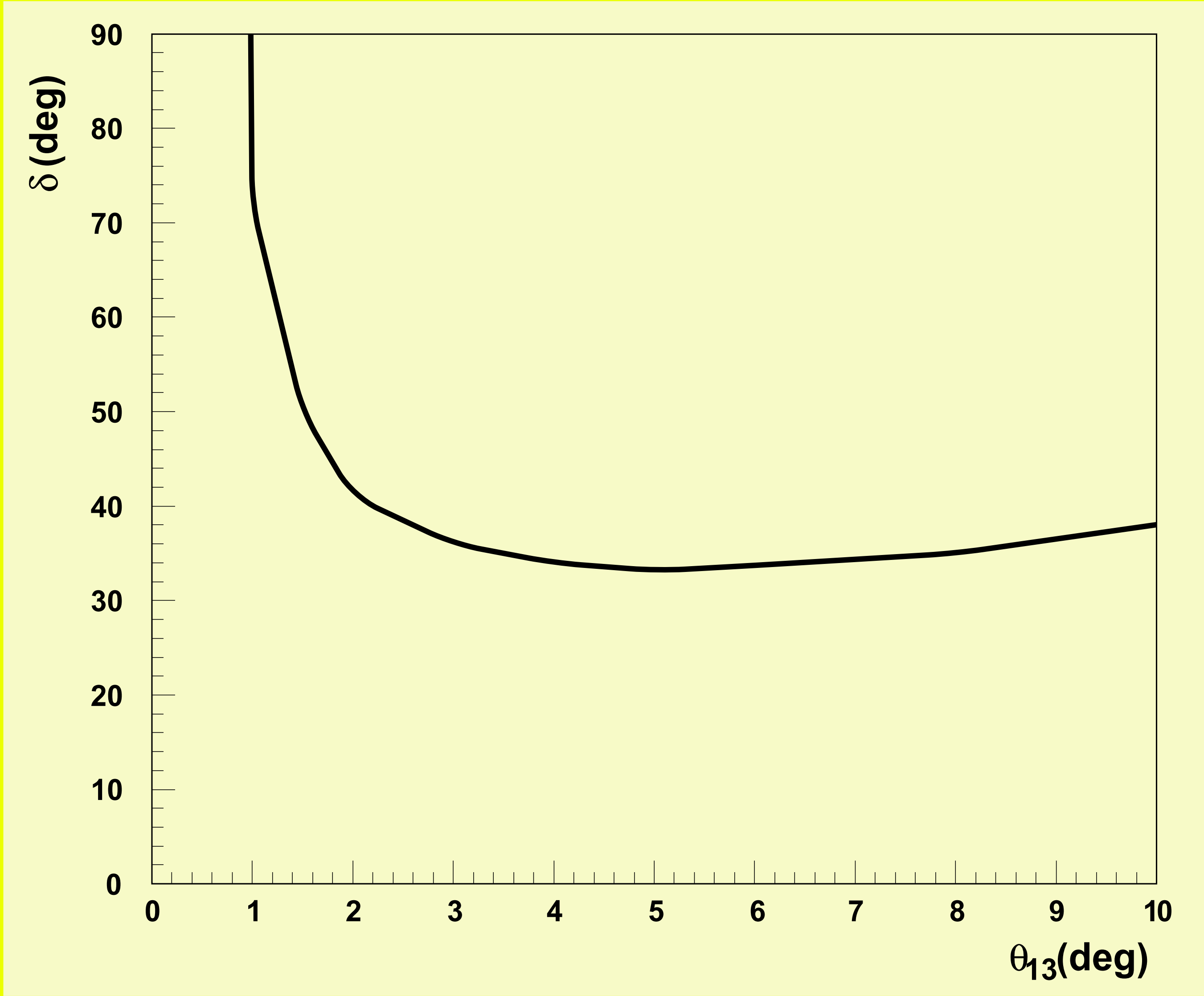
	Beta Beam		SPL-SB	
	^6He $(\gamma = 60)$	^{18}Ne $(\gamma = 100)$	ν_μ (2 yrs)	$\overline{\nu}_\mu$ (8 yrs)
CC events (no osc, no cut)	19710	144784	36698	23320
Oscillated at the Chooz limit	681	5304	1491	1182
Oscillated	1	118	2	34
δ oscillated	-12	54	-27	16
Beam background	0	0	140	101
Detector backgrounds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

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

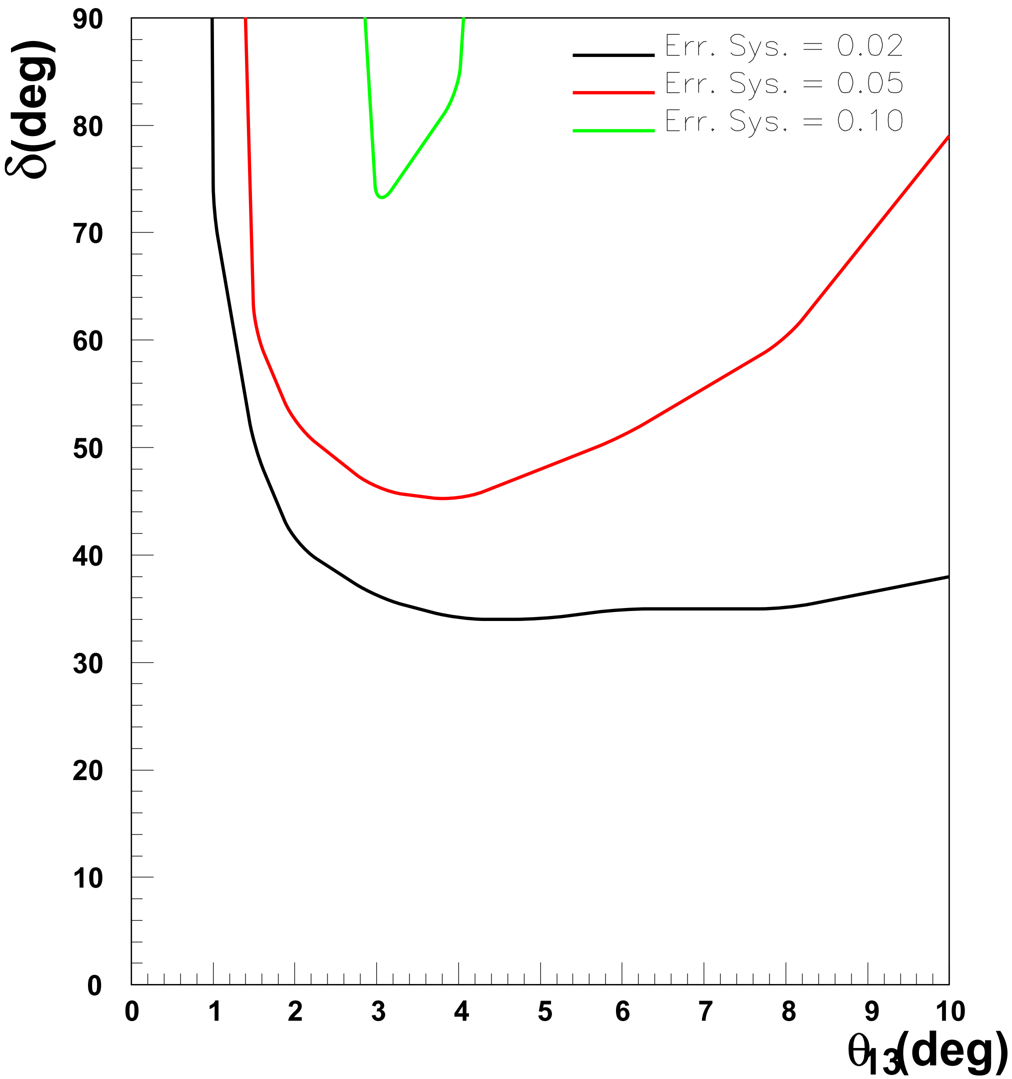
Beta Beam leptonic CP violation discovery potential

Computed with:
$\gamma(^6\mathrm{He}) = 60$
4400 kton/year exposure
Systematic Err. = 2%
$\delta m^2_{atm} = 2.5 \cdot 10^{-3} eV^2$
$\delta m^2_{sun} = 7.1 \cdot 10^{-5} eV^2$
$\sin^2 2\theta_{23} = 1$
$\sin^2 2\theta_{12} = 0.8$
sign(Δ m^2) = +1
$\sigma(\delta m^2_{atm}) = 10^{-4} eV^2$
$\sigma(\delta m^2_{sun}) = 10\%$
$\sigma(\sin^2 2\theta_{23}) = 1\%$
$\sigma(\sin^2 2\theta_{12}) = 10\%$
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 $\gamma = 60$.

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

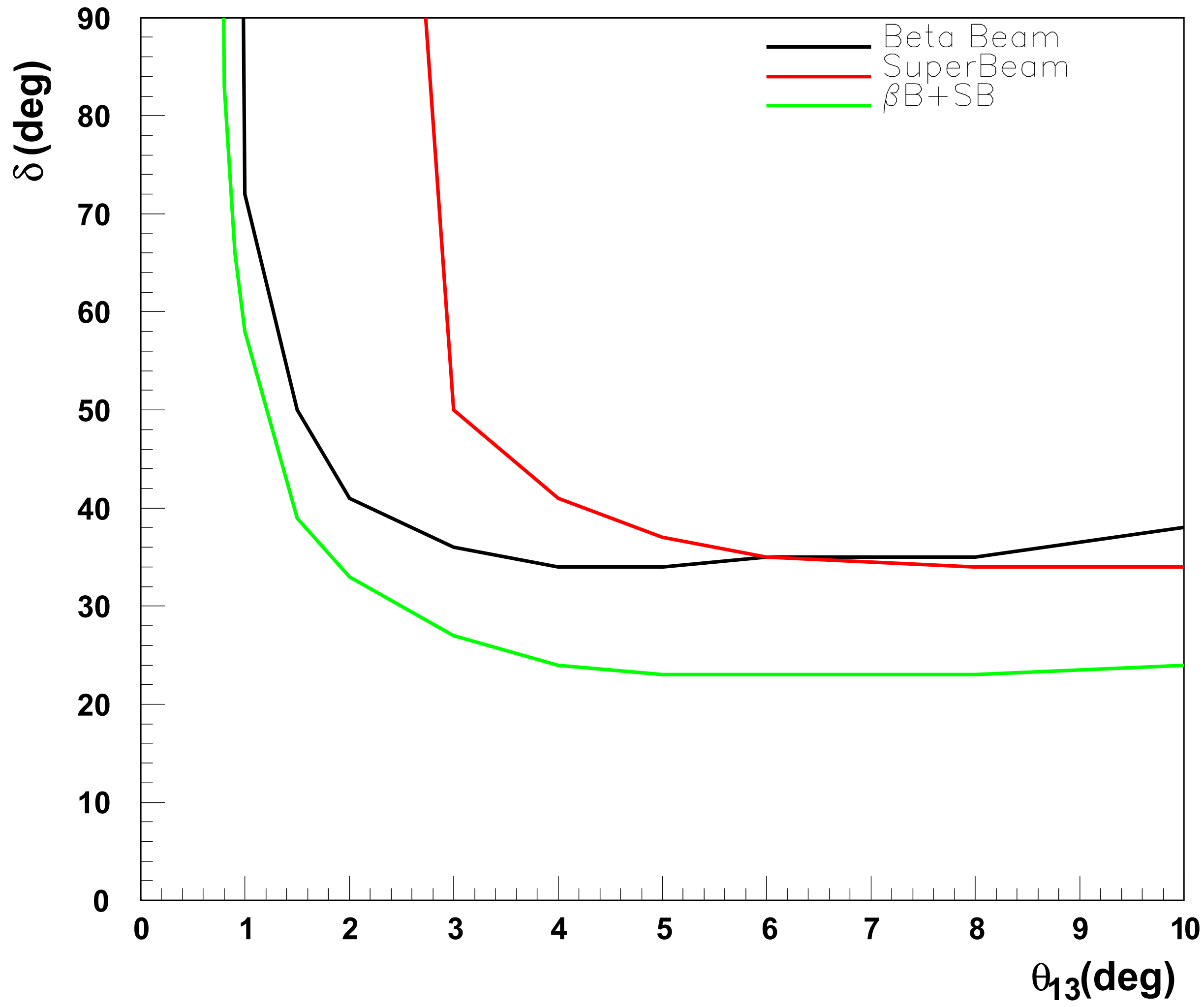
Conclusion: Beta Beam is not immune from systematic errors, but it offers an ideal environment to keep them low. Systematic errors are a critical factor for future facilities.

P.S.: the highest θ_{13} values ARE NOT the easiest condition from the point of the systematic errors: large statistics but small CP asymmetries.

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 $\nu_e$signal with π° backgrounds (SuperBeam) and in term of ν_μ signal with π^+ backgrounds (Beta Beam).



The high energy option

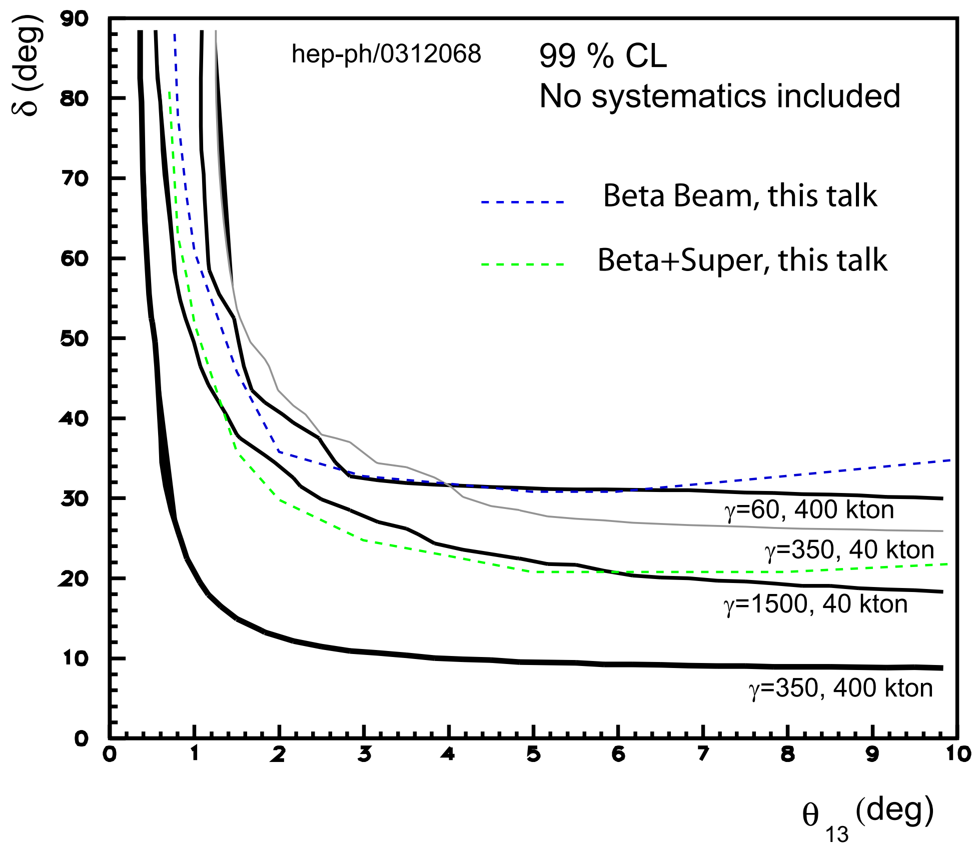
P. Hernandez, J.J. Gomez-Cadenas et al., hep-ph/0312068

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.

Improving Beta Beam physics reach

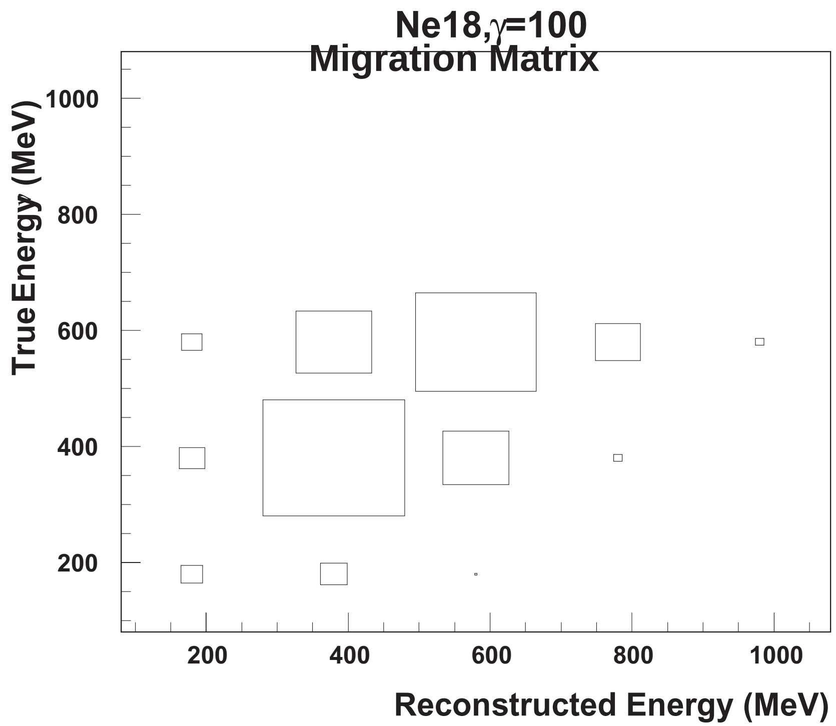
Mat Lindroos et al: You can run one ion at the time maintaining the same overall fluxes. In this way each of the two ions can be run at its optimal value.

P.S. You could also kindly try to attenuate the 10 ns bunch size bound that causes us some headache.

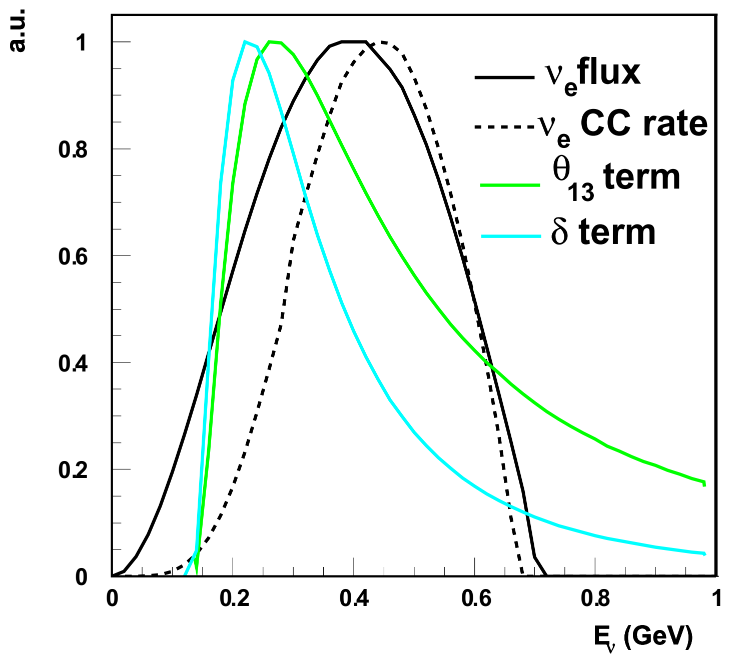
J.J. Gomez Cadenas and many others: A counting experiment is too limited in the leptonic CP violation discovery game.

Restart an optimization process of the SPS based Beta Beam for the Frejus baseline (130 km) and for a free baseline

The $\gamma = 100, 100$ option

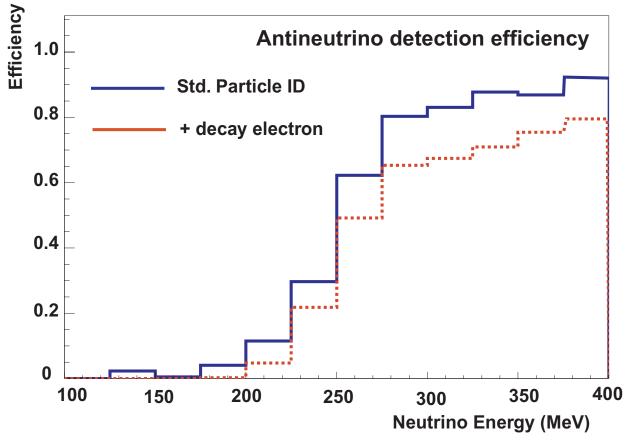


- $^6\mathrm{He}$ and $^{18}\mathrm{Ne}$ have similar end point energy, for the moment keep their gammas equal.
- Energy information can be exploited by raising the ion gammas, too small energies are severely affected by Fermi motion. At higher gamma the atmospheric neutrino background rate decreases, the neutrino flux increases.
- Events are binned with 200 MeV bins. A. Blondel et al. paper: NIM A535 (2004)665 paper suggests a MC based method to further improve energy resolution at those energies.
- After a scan the $\gamma = 100, 100$ option results to be the best one for L=130 km.

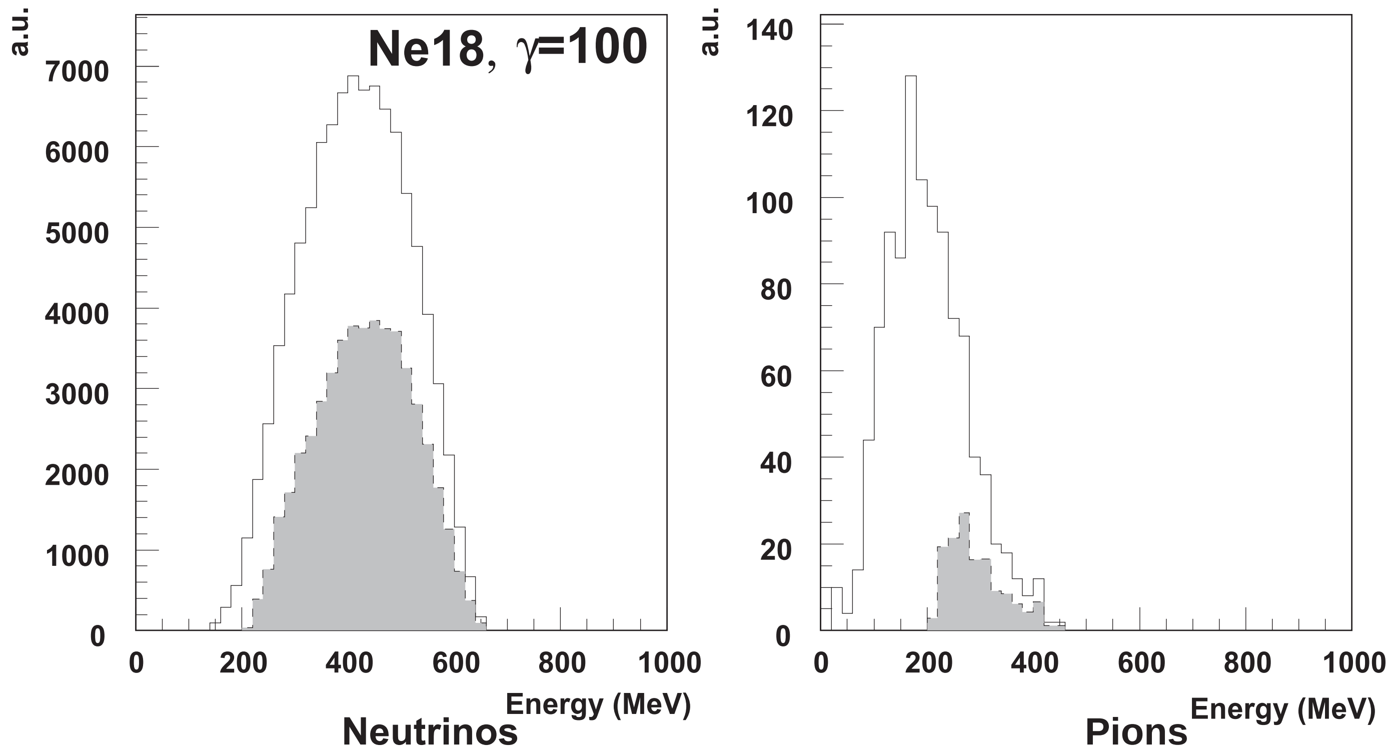


The pion background (the main concern at the higher gammas)

The efficiency function is computed by Nuance by asking a single ring event, one track above the Cerenkov threshold and the signature of the muon through the detection of the Michel electron. For $^{18}\mathrm{Ne}$ events the efficiency is smaller because of the muon absorption in water.



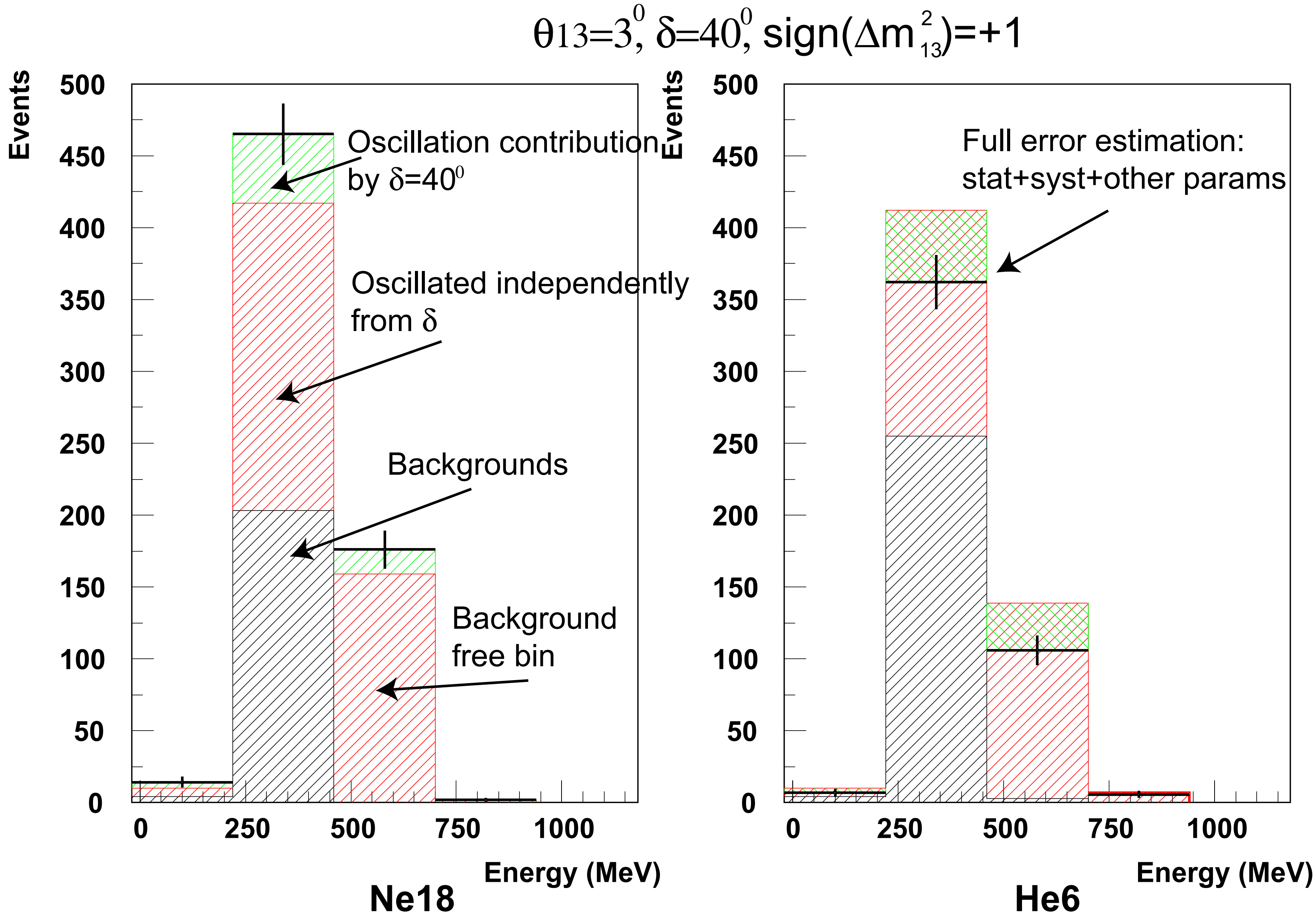
Effect on signal and background events:



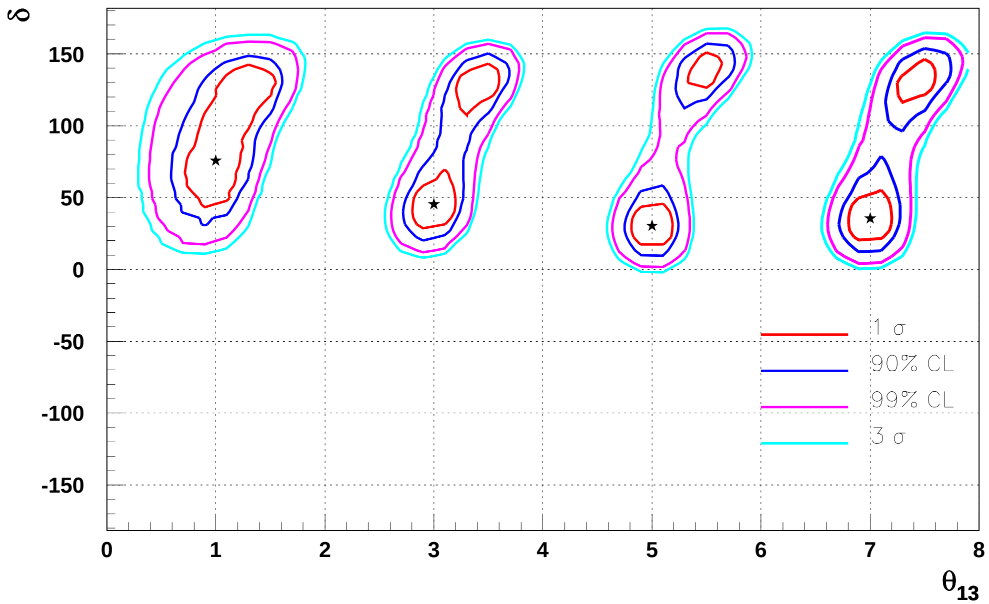
This traced back a bug in the previous background evaluation: pion backgrounds were computed applying the average efficiency for signal events above 200 MeV. This overestimated backgrounds by $\sim 80\%$.

Pions could interact before decaying, missing the Michel electron signature. This requires a dedicated MC and it's not taken into account at the present. So pion background is overestimated in the following.

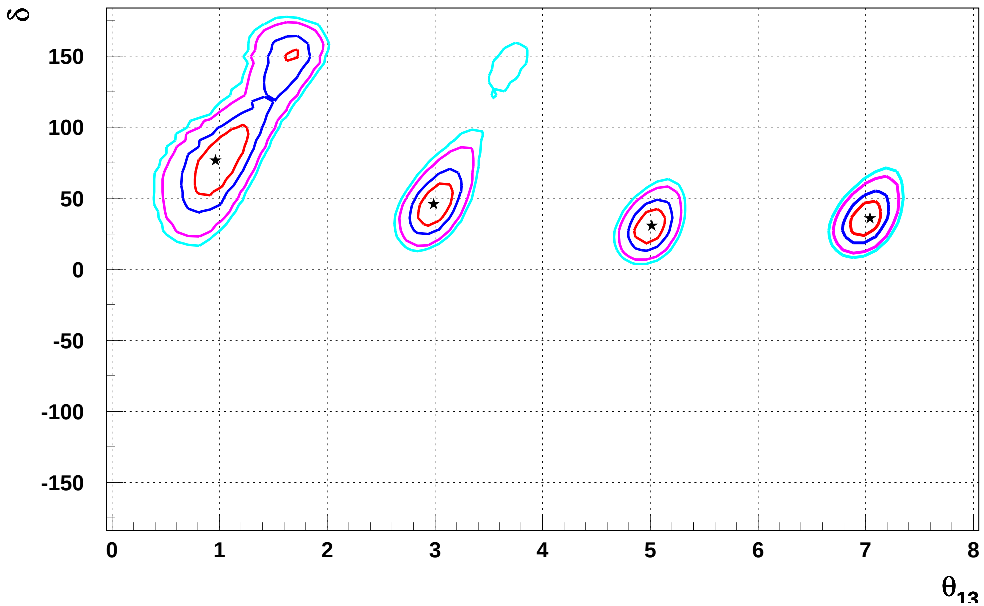
As an example: events for $\theta_{13} = 3°, \delta = 40^0$



$\gamma = 60, 100$



$\gamma = 100, 100$ **with the new bck evaluation**



The improvement

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

	^6He ($\gamma = 60$)	^{18}Ne ($\gamma = 100$)
CC events (no osc, no cut)	19710	144784
Oscillated	1	118
δ oscillated	-12	54
Beam background	0	0
Detector backgrounds	1	397

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

	^6He ($\gamma = 100$)	^{18}Ne ($\gamma = 100$)
CC events (no osc, no cut)	101263	144784
Oscillated	7	118
δ oscillated	-38	54
Beam background	0	0
Detector backgrounds	262	206

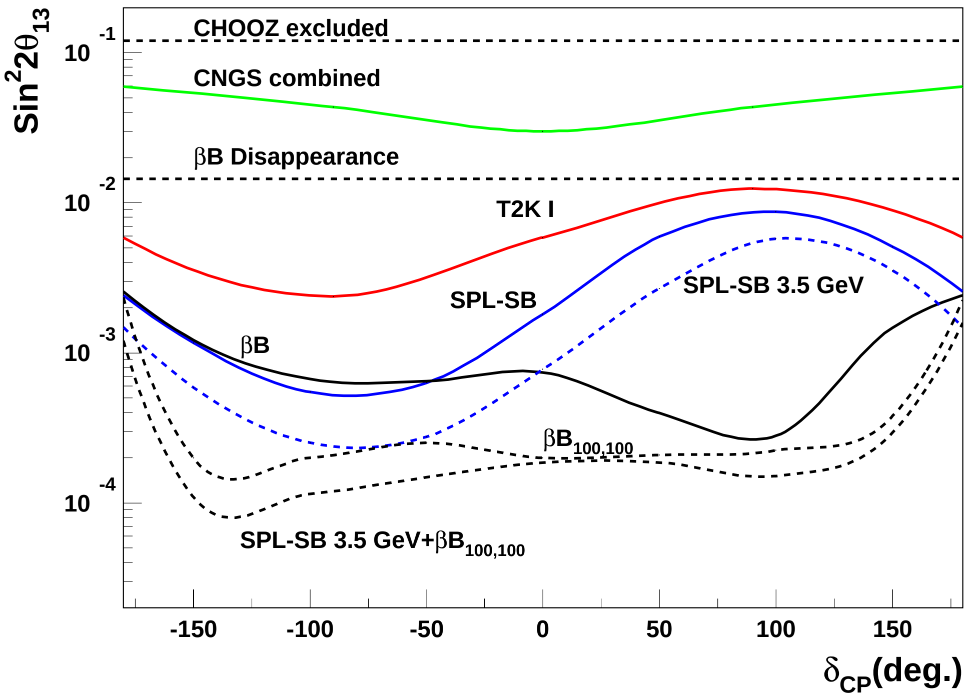
Also the SPL SB performances have been optimized . . .

SPL SB optimization as computed by J.E. Campagne and A. Cazes, LAL, hep-ex/0411062

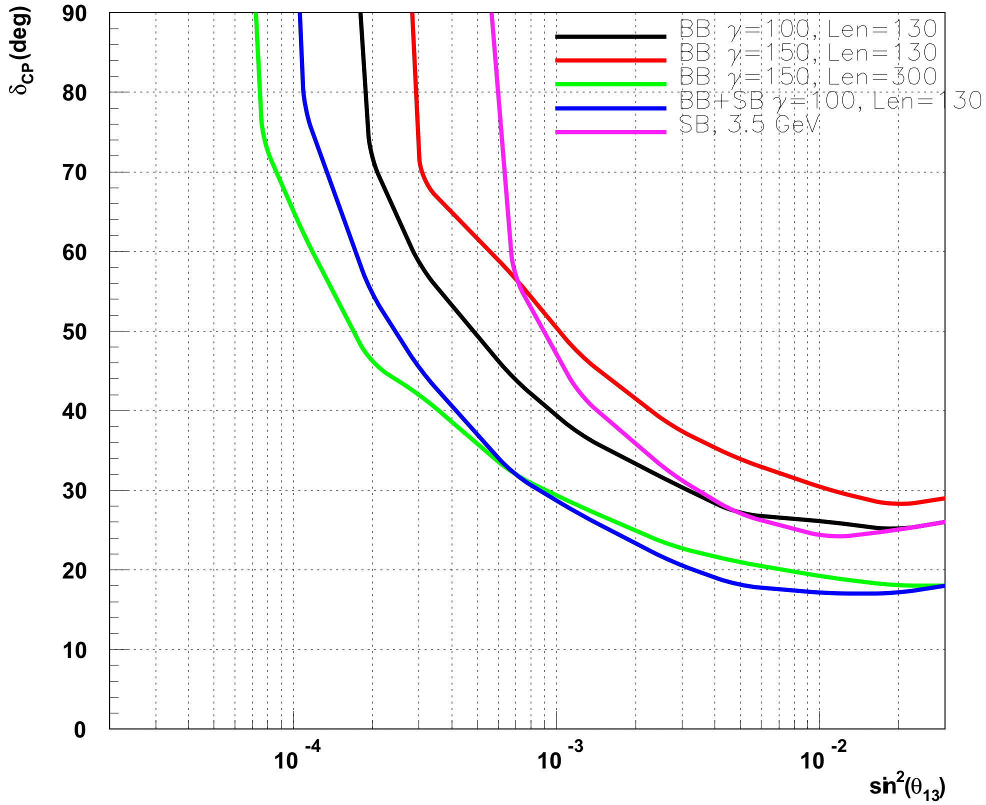
- Scan the proton driver energies from 2.2 to 8 GeV (4MW fixed).
- Keep the baseline fixed to 130 km
- From 3.5 GeV to above explore the possibility to focus higher momentum pions.
- The 3.5 GeV energy, with a neutrino beam with $\langle E_\nu \rangle \simeq 300 MeV$, decay length of 40 m and decay tunnel diameter of 2 m greatly improves the 2.2 GeV performances: ν_μ CC rate at 130 km from 42 to 122 events/kton/year

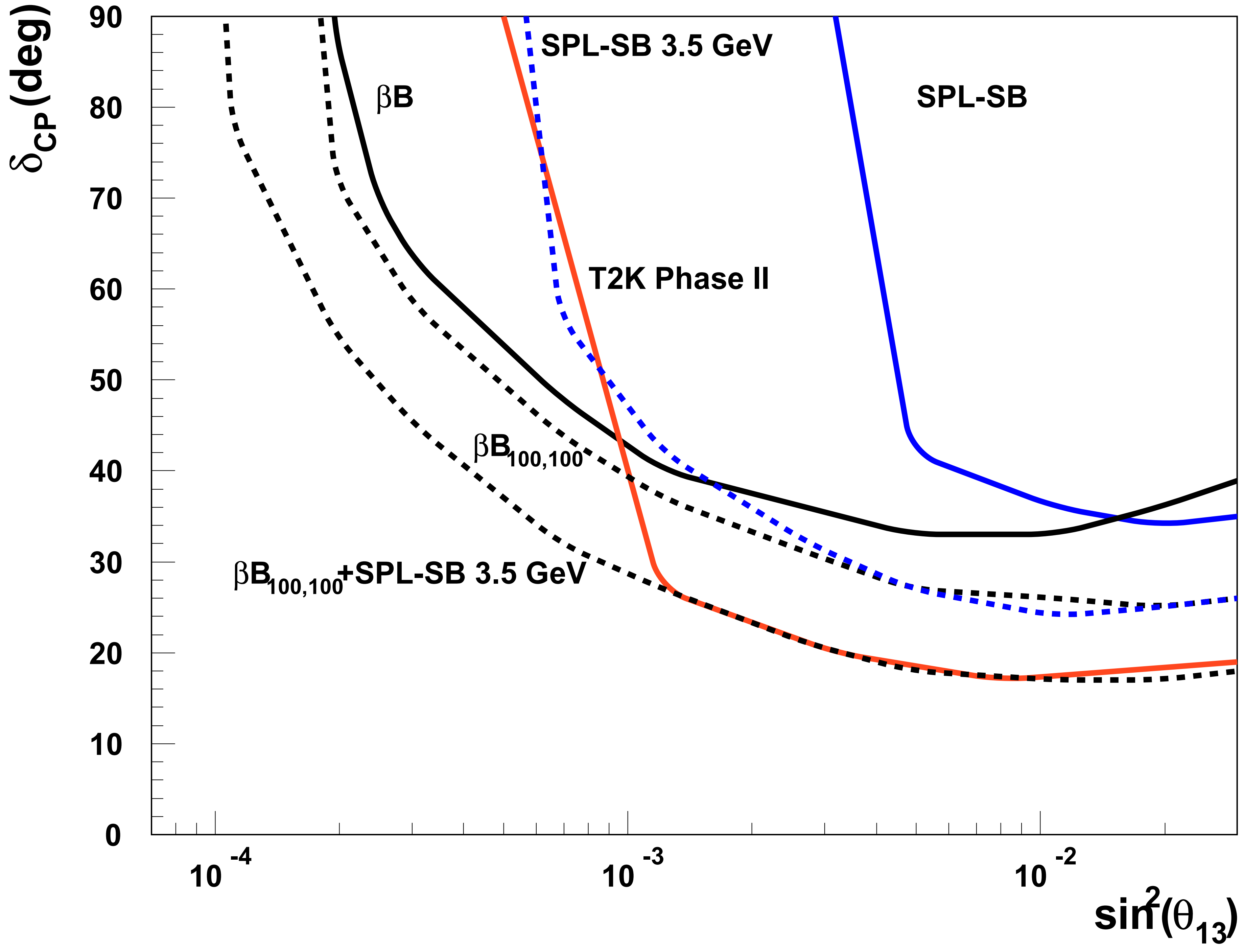
Performances

θ_{13} sensitivity



3σ δ_{CP} discovery potential



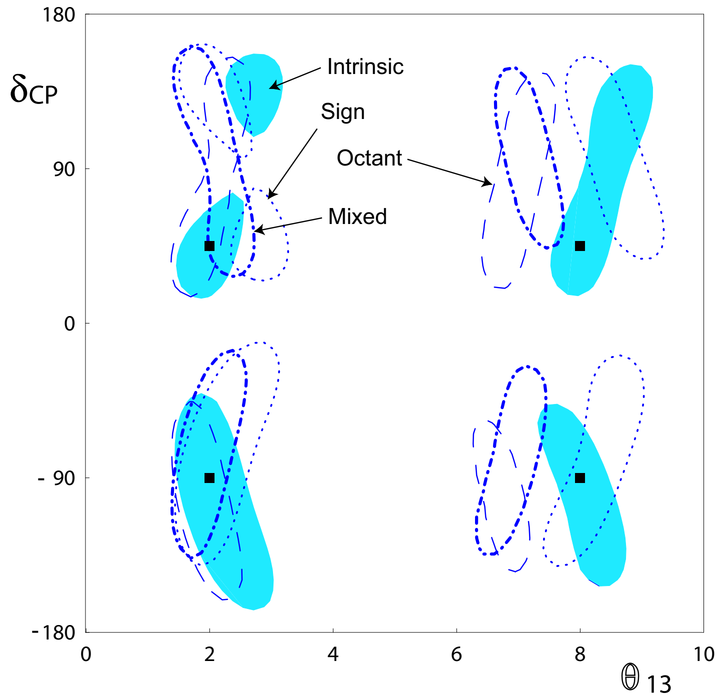


90
80
70
60
50
40
30
20
10
0
δ_{CP}(deg)
βB
SPL-SB 3.5 GeV
SPL-SB
T2K Phase II
$\beta B_{100,100}$
$\beta B_{100,100}$+SPL-SB 3.5 GeV
10^{-4}
10^{-3}
10^{-2}
$\sin^2(\theta_{13})$

Good news for the degeneracies

"I would left the degeneracy problem to theoreticians and invite experimentalists to concentrate in design better and better experiments" H. Minakata, Win04.

- For a long period several authors focused on how clones and degeneracies can destroy SB+BB discovery potential.
- A couple of very recent papers shed a light on the possibility to solve this problem



- **A. Donini et al., hep-ph/0411402:** The sign and octant clones disappear if the $\nu_e$appearance signal is combined with a good quality ν_μ disappearance data. This because clone solution appear with a different δm^2_{23} value. Beta Beam cannot have ν_μ disappearance data, SPL-SB can (as computed in the paper), but T2K phase I data would be enough!

- **P. Huber et al., hep-ph/0501037**: The sign and octant clones can disappear AND $\mathrm{sign}(\delta m^2)$ **can be measured** by combining SuperBeam data (they took T2K phase **II** data) with atmospheric neutrino data measured in the megaton detector:
  - **Octant** e-like events in the Sub-GeV data is $\propto \cos^2\theta_{23}$
  - **Sign** e-like events in the Multi-GeV data, thanks to matter effects, especially for zenith angles corresponding to neutrino trajectories crossing the mantle and core where a resonantly enhancement occurs.

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 physics case of a megaton detector exposed to a Beta Beam and possibly to a SuperBeam is becoming more and more interesting. It could offer the possibility of measuring ALL the missing parameters of the PMNS matrix free from degeneracies through the simultaneous measure of $\nu_\mu \rightarrow \nu_e$ transitions, ν_μ disappearance and very high statistics atmospheric neutrinos.
- The Beta Beam optimization is an ongoing process with very interesting contributions from several different groups. Still to be deeply studied:
  - Systematic errors
  - Pion background from NC events
  - Atmospheric neutrino background and beam bunch size
  - Neutrino energy reconstruction